40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

168	1	194	17	55
PARTICIPANTS	TOPICS	ANSWERS	REPLIES	VOTES

SUMMARY OF TOPICS

SUBMIT A COMMENT

194 Answers · 17 Replies

Important: All comments will be made available to the public. Please only submit information that you wish to make available publicly. The Office of Administrative Hearings does not edit or delete submissions that include personal information. We reserve the right to remove any comments we deem offensive, intimidating, belligerent, harassing, or bullying, or that contain any other inappropriate or aggressive behavior without prior notification.

Melissa Wenker McGrane · Citizen · (Postal Code: unknown) · Apr 14, 2025 10:30 am

1 Votes

During this open period I want to write to advocate for feedlot rules that protect our water, soil, and animal health. Please limit feedlot animal size and hopefully, reduce it! The waters in this state are polluted and it is unacceptable. Please limit feedlot size for the protection of us all. I am forever frustrated with policies that protect a few farmers, which huring the general population. I recently drove through Nicollet County, MN and it is a crime scene. Intensive farming, drainage and a resulting destroyed ecosystem. The Minnesota River is incredibly polluted. Southwest Minnesota has a small percentage of streams that can support aquatic life. It is time to stand up for what is right. Animal health and humanity should also be considered. I drive past feedlots and am appalled at what I see. Manure, dirt, no bedding, and terrible living conditions are seen for those animals. Please advocate for what is morally sound. Farmers cannot keep polluting to benefit themselves, which hurting us all.

James Salkas · Citizen · (Postal Code: unknown) · Jun 21, 2025 9:53 am

1 Votes

As an annual out of state visitor and trout fisherman I am appalled at the frequent and continuing fish kills. It sickens me. The MPCA must make a greater effort to determine the sources of water pollution and monitor water runoff in the unique and beauriful MN Driftless area. Greater regulation, restrictions, and monitoring are the only ways to prevent future fish kills. Unless changes are made, I will take my tourist dollars else where.

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Response:

Stephan Melson · Citizen · (Postal Code: unknown) · Jul 08, 2025 4:15 pm

James, I agree and am appalled by fish kills in Minnesota. Did you know towns and cities pumped raw sewage into rivers last summer across southern Minnesota? The city of Waseca irrigates their raw sewage onto farm fields. Runoff from roads and other impenetrable surfaces goes into storm sewers then directly into water bodies. If you are outraged by fish kills, you must be outraged by these examples of the MPCA having a double standard by regulating some industries but giving government agencies a pass.

Douglas Moran · Citizen · (Postal Code: unknown) · Jun 22, 2025 6:02 pm

1 Votes

I am writing to ask the MPCA to strengthen the Animal Feedlot Rule, Minnesota Rules, chapter 7020. The state must do more to protect Minnesota’s aquatic resources and feedlots produce large volumes of manure containing nitrogen, ammonia, and other chemicals that wash into waterways and groundwater.

Here's the facts:
-Only 0.5% of the earth's water is available fresh water.
-Humans die in 3-5 days without fresh water
-Fish and other animals die without water

Given the facts above, the MPCA must take action to protect what water we all have available!!

Here's the action that must take place (Remember, .05% of the water on this planet is freshwater and available for us!!!):

1. Require NPDE/SDS permits for feedlots with 600 or more animal units. [permits are currently required only if 1,000 or more animal units]

2. Require all feedlots with 300 or more animal units to prepare a manure management plan and maintain land application records, and submit these to the MPCA and county feedlot pollution control officer. [currently plan development required of only some operations and submittal of plans and records is not required]

3. When manure is transferred by a feedlot owner/operator for application to the land by someone else, require that the transferee also follow the requirements in the manure management plan.

4. Prohibit manure application on frozen or saturated ground, or when rainfall is likely.

5. Require greater setback distances for manure applications from water resources in the karst region and other vulnerable groundwater areas, including prohibiting manure applications within:
300 feet upslope or 100 feet downslope of a sinkhole or other direct conduit to groundwater
300 feet upslope of a public waterway or tributary of a public waterway
250 feet from a private well
1,000 feet from a community well

6. Prohibit livestock of a feedlot or facility capable of holding 100 or more animal units from entering a designated trout stream or tributary of a designated trout stream and prohibit livestock of a feedlot or facility capable of holding 300 or more animal units from entering any water of the State.

Thank you for your attention.

Respectfully,

Douglas E. Moran

Response:

Stephan Melson · Citizen · (Postal Code: unknown) · Jul 09, 2025 7:32 am

Douglas, I can tell by your comments that you are not involved in animal agriculture.
To your point #1, how is the permitting process going to help reduce pollution? Aside from more paperwork and bureaucracy, i think it will be zero. I've gone through the permit process myself and inspections and they have little impact, in my opinion.
Regarding your point #3, all this would do it take the responsibility of large companies to keep track of their manure and put it onto a farmer receiving it. It seems to be companies who own large amounts of livestock should have some sort of responsibility. Companies would love to give up their responsibility for keeping track of manure but that is a bad idea!
To your point #4, if winter manure application is prohibited, small farms will bear the brunt of the regulatory cost. Large newer CAFOs are built to hold large amounts of manure. Small farms typically are not. Do we want to keep small farms around or do we want to regulate them out of existence? Funding must be made available to build storage facilities for small farms otherwise we will only have large ones. In terms of application on saturated ground, the weather conditions take care of that point. When a soil is fully saturated, there is no way your are taking a manure applicator into that field. Unless the farmer enjoys getting stuck and compacting his land.
To your point #6, why are trout streams so special? What makes them any more sensitive than any other stream? There are plenty of ecosystems in the state of Minnesota just as important as trout habitat. Most just don't have the passionate anglers trying to catch them.

Stephan Melson · Citizen · (Postal Code: unknown) · Jun 25, 2025 12:15 pm

2 Votes

I am writing to oppose further regulations on Minnesota feedlots. Manure often gets the blame for fish kills and nitrate in surface and ground waters and I think there is a double standard. In 2024, municipalities all across southern Minnesota pumped raw sewage into rivers due to excessive rainfall. A farmer would never be allowed to do this. A feedlot must follow setbacks for land application of manure and for building new feedlot. Municipalities can build a sewage lagoon right next to a water body. Municipalities have a lot more money and lawyers to lobby for these things than the average feedlot owner.

Some of the proposed ideas are tone deaf. For instance, In the Request for Comments PDF under the Changes in Livestock and Poultry Production Techniques and Practices

heading, the MPCA seems to allude to the fact of more feedlots being permitted with 500 or less animal units just under permit thresholds as being a bad thing. How is this any different than deferring or taking income to change which tax bracket a person is in? The MPCA could set a threshold for permitting at 250 animal units and there would be facilities designed to be under that threshold. Don't hate the player, hate the game the government creates.

In the Request for Comments PDF under the Changes in Livestock and Poultry Production Techniques and Practices heading, increased reliance on commercial application of manure including use of manure pipeline/hoses to move liquid manure further from the point of origin - I think this is a great thing. Often fields adjacent to feedlots have a lot of manure history. Getting manure to other fields with less of a manure history is a good thing, not a bad one.

In the Request for Comments PDF under New Information, Research, and Understanding regarding agriculture and the environment heading, the MPCA's 2014 Nutrient Reduction Strategy is referenced as being a guiding document for updating the feedlot rules. #1 the 2024 Nutrient Reduction Strategy says feedlot runoff contributes less than 2% of all nitrogen and phosphorous to watersheds in Minnesota. #2 if the Nutrient Reduction Strategy is being updated in 2025, how can the MPCA use it to update the feedlot rules? Which version are we commenting on now, the 2014 available version or what might be in the 2025 version whenever that comes out? If the MPCA is to use the Nutrient Reduction Strategy document as a guide, should they wait until it is updated and published first.

Winter applications of manure are always a tough topic. If the MPCA is to restrict winter manure applications, are funds going to be made available to improve manure storage faculties? Without funding to improve manure holding, small farms will be forced to eat the cost of a storage facility or stop raising livestock. Small farms go out of business, large CAFOs keep getting built.

I question whether the University of Minnesota is conducting research that is relevant to crop production. The research on cover crops has saturated the agriculture field yet, the adoption of cover crops is limited. My experience is because cover crops are an additional expense with no return to the farmer and a decrease in yield plus additional management changes to try and make them work. If cover crops were as easy as claimed, why isn't adoption widespread? It's because they don't make the farmer any more money and they don't make life easier. When was the last time the availability of manure was researched at the University of Minnesota? That would be a wiser use of research dollars than cover cropping.

The current rules regarding manure management plans are more than adequate. Transferring manure should be no the seller of the manure not the buyer. I urge the MPCA to keep feedlot rules as is

Stephan Melson

Response:

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Jacob Vogt · Citizen · (Postal Code: unknown) · Jul 16, 2025 9:10 am
I agree with all of this.

Leslie Myint · Citizen · (Postal Code: unknown) · Jun 26, 2025 12:51 pm
1 Votes

I am writing to comment on the new Feedlot Rule and to request stricter requirements for regulating feedlots in Minnesota. As a statistician and environmental activist, I want to underscore the crucial importance of comprehensive and high quality monitoring in providing data. Any feedlot that has a moderate number of animals or is in an area with a vulnerable water source should monitor their groundwater discharges and automatically report their data to MPCA. We also need to require more feedlots to get water pollution permits so that they, at minimum, have to take steps to control their pollution and, ideally, become subject to the automatic monitoring described earlier. Doing this would ensure that a greater portion of our water sources are being regulated.

Akilah Sanders-Reed · Citizen · (Postal Code: unknown) · Jun 26, 2025 12:55 pm
1 Votes

I am writing to ask the MPCA to do more to protect our lakes, rivers, streams, and groundwater by revising the Animal Feedlot Rule to address the crisis of nitrate pollution in our state. Feedlots are a major source of nitrate pollution in our waters, and by adding stronger rules for the handling of manure, MPCA can help ensure that all Minnesotans' water at the tap is safe to drink. This is important to me because nitrate is a human health threat. No one should lose loved ones to preventable pollution.

Response:
Stephan Melson · Citizen · (Postal Code: unknown) · Jul 08, 2025 3:48 pm
Can you cite a source on the last time someone lost their life to nitrate pollution in Minnesota? The 10 ppm nitrate concentration in drinking water came out of thin air and has no scientific value

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LeAnn Charwood · Citizen · (Postal Code: unknown) · Jun 26, 2025 12:55 pm
1 Votes

Norway Beach, a public water access located in Cass County was closed in early-mid May to swimming due to elevated e-coli. Strict rules, regulations and permitting for surface/ground water is needed to protect public and environmental health for recreational purposes.

Response:
Stephan Melson · Citizen · (Postal Code: unknown) · Jul 08, 2025 3:55 pm
Lake Bde Maka Ska, Lake Hiawatha and four other popular lakes in Minneapolis, Minnesota had beaches closed in the summer of 2024 due to high bacteria levels. https://mndaily.com/285003/city/six-minneapolis-beaches-close-due-to-high-levels-of-bacteria/
Correct me if I'm wrong, but there are no feedlots in Minneapolis. The idea that feedlots and manure applications are solely to blame for pollution is a myth. If bureaucrats in the Twin Cities want to regulate livestock, perhaps they should start in

their own backyards.

Kristin Hogquist · Citizen · (Postal Code: unknown) · Jun 26, 2025 12:57 pm
0 Votes

I am a lifelong resident of Minnesota, and swimming, boating, fishing, and camping in our lakes and rivers is a huge part of my life. Over the years, I have seen steady an increase in agriculture in the state, and I am increasingly worried about water pollution resulting from agriculture.

We know that feedlots contribute to water pollution through nitrates and bacteria. The nitrate levels in many Minnesota waters are currently making the water unhealthy for humans to drink and to swim/recreate in. These high levels cause bladder and colon cancer and pregnancy problems among other health issues. E.coli and other fecal coliform bacteria also harm the health of people who drink and swim in these waters. These contaminants are causing fish kills in southern Minnesota in addition to harming human health. For these reasons, I want stricter limits on feedlot pollutants.

Specifically, I think the Minnesota should require more than just the largest feedlots to get water pollution permits. I recommend requiring permits for operation with at least 600 animals.

I would also like to see Minnesota require the largest feedlots to actually monitor discharges to groundwater and drain tile so they (and we) can know what is entering the water system.

I am also worried about those parts of the state that are more vulnerable to groundwater pollution because of the geology of the area. Since we have knowledge about this, I would like to see Minnesota leverage that knowledge and apply stricter rules in those areas. This could include requiring established cover crops if you apply manure in the fall, and no liquid manure application to frozen or snow-covered ground when it will just run off.

Response:

Stephan Melson · Citizen · (Postal Code: unknown) · Jul 08, 2025 4:11 pm
Kristin, you seem to be placing the blame for bacteria and nitrate in surface waters. Minneapolis had to close beaches last summer due to bacteria in those lakes. Where are there feedlots in Minneapolis? https://mndaily.com/285003/city/six-minneapolis-beaches-close-due-to-high-levels-of-bacteria/
Runoff from impenetrable surfaces like roads, concrete, buildings etc. goes straight into water bodies, untreated. Have you ever thought this is a huge pollutant source?.

Municipalities across southern Minnesota pumped raw sewage into rivers due to excessive rainfall. This was permitted by the MPCA. How come this isn't being addressed?

Sarah Stahelin · Citizen · (Postal Code: unknown) · Jun 26, 2025 1:11 pm
0 Votes

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I am writing to submit my comments to the MPCA in support of more expanded protections for Minnesota's waterways, by increasing regulations on Minnesota's feedlots, which are an acknowledged source of groundwater and water pollution in our state. I am concerned with the pollution that has happened in Minnesota's most vulnerable waterways. The recent fish kills in the karst areas of Minnesota have me very concerned for the health and welfare of the wildlife that depend on our clean waters. These fish kills have been directly related to agricultural runoff and the increase of nitrites and ammonia in the water. I worry about the birds that also depend on these clean waterways and fish.
I believe that the rules should be expanded to apply to even more feedlots than are currently covered. Specifically, I would like to see any feedlots with 600 IUs or more be required to get water pollution permits.
I also believe that large feedlots should be required to monitor their discharges to ground water and drain tile in addition to the requirement currently in place that they monitor surface water runoff. I would like to see greater enforcement visits to ensure compliance by these feedlots as well.
Lastly, I would like to see stricter manure land application requirements and lower rates in the most vulnerable groundwater areas in Minnesota – such as those with karst geology and sandy soils. These areas are more susceptible to contamination of the water supply by manure and should be given greater protections.
As a resident of Bemidji, Minnesota, I truly value our waters and worry about how pollution is affecting them.

Signe Steiner · Citizen · (Postal Code: unknown) · Jun 26, 2025 1:27 pm
0 Votes

I'm writing to urge the MPCA to take stronger action to protect our natural waterways in Minnesota by revisiting the Animal Feedlot Rule (Minnesota Rules, Chapter 7020). Nitrate pollution is a growing crisis in our state, and large-scale animal feedlots are a significant contributor to this problem.

By strengthening rules and regulations around manure management, the MPCA has a critical opportunity to protect Minnesota's drinking water and the health of our ecosystems. Clean, safe water is essential for public health and recreation.

As someone passionate about the future of Minnesota's food systems and equitable access to clean water, I respectfully submit the following recommendations for your consideration:

1. Require more feedlots to get water pollution permits
2. Require large feedlots to monitor discharges to groundwater and drain tile
3. Require stricter land application requirements and lower application rates in Vulnerable Groundwater Areas

Thank you for your time and commitment to protecting Minnesota's environment and our communities.

Debbie Wall · Citizen · (Postal Code: unknown) · Jun 28, 2025 6:17 pm
1 Votes

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Animal agriculture is one of the most destructive and violent industries on the planet. In addition to causing suffering on a monstrous scale, it is responsible for creating more greenhouse gases than all forms of transportation combined, environmental degradation, habitat and species loss, fresh water waste and pollution, ocean acidification and dead zones, has negative human health implications, is creating antibiotic resistant microbes and checks off all of the boxes for conditions that could/will lead to the next pandemic. We need to use the billions of dollars this industry receives to help farmers transition to a humane, efficient, sustainable and healthy plant-based food system. Reducing the size of feedlots is but one tiny baby step in the right direction. At the same time, the animals caught up in our food system deserve a life worth living and there must be a commitment to ensuring cattle are provided shelter from the elements and the ability to engage in natural behaviors.

Response:

Stephan Melson · Citizen · (Postal Code: unknown) · Jul 08, 2025 4:03 pm

More power to you if you desire a plant based food system. I like to eat meat and enjoy it on a nice summer day. That's the beauty of living in a free country, we each get to decide what we want to eat.

Has it ever crossed your mind that cattle might like to be out in the elements? You can go to a livestock auction, buy some cattle, and they can live in your house with you, humanely and see how it goes.

Brian Wagenaar · Citizen · (Postal Code: unknown) · Jun 29, 2025 1:35 am

1 Votes

I am writing in regards to the Animal Feedlot rule, Minnesota Rules Chapter 7020.

MPCA should implement stricter rules governing animal feedlots to ensure that all Minnesotans have safe, drinkable water, as well as healthy aquatic ecosystems to boat, fish, and swim in.

As the land of more than 10,000 lakes, the home of the world-renowned Boundary Waters Canoe Area, and the headwaters of the Mississippi River, water is integral to our state’s identity and to Minnesotan’s way of life. Water is synonymous with life, and we must do all that we can to protect this vital resource.

An update to the MPCA’s animal feedlot rules is overdue. We must ensure that our waterways are not contaminated further by excess nutrients like nitrogen, or by pathogens and bacteria like e coli. Rules around which feedlots must seek a permit should be tightened, requiring operations of 600 animal units or more to go through the permitting process.

Additionally, large feedlots should be required to monitor their discharge to groundwater and drain tiles. Vulnerable groundwater areas should be protected with more stringent land application requirements — including mandating the use of cover crops. These common sense rule reforms will make everyone in our state safer.

Animal agriculture has changed in Minnesota, favoring larger operations which produce far more waste that can unfortunately harm humans and the environment. Our

understanding of the potentially expansive environmental impact of feedlot operations has changed too, and the MPCA's new rules should reflect that reality.

Response:

Stephan Melson · Citizen · (Postal Code: unknown) · Jul 09, 2025 7:41 am

Can you explain to me how mandating the use of cover crops is going to reduce bacterial loads in our surface waters? There are plenty of ways to reduce nitrate leaching like applying manure when soils are below 50 degrees, using a nitrification inhibitor, installing saturated buffers, installing bioreactors, etc. My neighbor seeded a cover crop last year that never germinated due to lack of moisture in the fall. Do you think his nitrate leaching was reduced? Not at all. Cover crops are all the rage because they look pretty and you can see them in the field, but are an imperfect management system to reduce nitrogen loss.

Amy Blumenshine · Citizen · (Postal Code: unknown) · Jun 30, 2025 1:43 pm

1 Votes

I am writing to comment on the new Feedlot Rule (Animal Feedlot rule, Minnesota Rules Chapter 7020) and to request stricter requirements for regulating feedlots in Minnesota. I encourage a new rule to be made for feedlots as the circumstances have changed. We now know more about the pollution problems associated with feedlots and they have been increasing in number and size. We now know that our legacy of abundant fresh potable water is threatened even as our climate warming world has increasing pressure on drinking water.

We now know that areas vary in their geological capacity to filter pollutants.

I feel obligated to steward for future generations as the abundant world was brought to me.

Sadly, we now have farm families telling themselves that it's normal to not have safe drinking water in agricultural areas. And sadly, humans are not the only important biological beings that are harmed by water pollution.

Nitrogen pollution has impact nearby and far away. Let's start with the drinking water in the areas of feedlots. I have friends who decided they had to move away from their town because the municipal water was too nitrate intense for their health circumstances. I have other friends who have a farm in the karst region that I get to visit. Their family has already suffered one death by cancer and they are taking steps to try to improve their well water. They are near the Whitewater River, known for trout fishing, and we also fear for the well-being of those fish— and that recreation asset— in particular. My children and I swim in these waters; E-coli is also a risk.

We have to get serious about protecting our water. Water permits should be required for 600 AUs or more. Karst regions and others with higher risks need stricter requirements. There should be basic monitoring and enforcement of feedlot regulations, especially appropriate manure management practices, such as amount, time of year, run-off risk, water discharge, cover crops.

The dead zone in the Caribbean is a serious threat to life/sustainability. While CAFO's are

not the only contributor, every polluting source needs to be diminished. We are all connected.

Charles Phelps · Citizen · (Postal Code: unknown) · Jul 04, 2025 5:54 pm

0 Votes

Happy independence Day!

I am writing to ask the MPCA to strengthen the Animal Feedlot Rule, Minnesota Rules, chapter 7020. The state must do more to protect Minnesota's aquatic resources and feedlots produce large volumes of manure containing nitrogen, ammonia, and other chemicals that wash into waterways and groundwater.

We should all be concerned about this because clean water is vitally important to both people and wildlife. Minnesota needs feedlot rules that not only work for farmers, but that also
protect the environment for humans and wild animals alike. With that in mind, the Feedlot Rule should be changed to:

1. Require NPDE/SDS permits for feedlots with 600 or more animal units. [permits are currently required only if 1,000 or more animal units]

2. Require all feedlots with 300 or more animal units to prepare a manure management plan and maintain land application records, and submit these to the MPCA and county feedlot pollution control officer. [currently plan development required of only some operations and submittal of plans and records is not required]

3. When manure is transferred by a feedlot owner/operator for application to the land by someone else, require that the transferee also follow the requirements in the manure management plan.

4. Prohibit manure application on frozen or saturated ground, or when rainfall is likely.

5. Require greater setback distances for manure applications from water resources in the karst region and other vulnerable groundwater areas, including prohibiting manure applications within:

300 feet upslope or 100 feet downslope of a sinkhole or other direct conduit to groundwater
300 feet upslope of a public waterway or tributary of a public waterway
250 feet from a private well
1,000 feet from a community well
6. Prohibit livestock of a feedlot or facility capable of holding 100 or more animal units from entering a designated trout stream or tributary of a designated trout stream and prohibit livestock of a feedlot or facility capable of holding 300 or more animal units from entering any water of the State.

Respectfully,

Charles Phelps
Maple Plain, MN

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Kent Nicolai Scheer Kent Nicolai Scheer · Citizen · (Postal Code: unknown) · Jul 07, 2025 10:07 am

1 Votes

DOUBTS and DISHONOR !

Previously, In Wadena County citizens blocked the expansion of a 500 unit animal feedlot from growing to 1000 animals due to its near promimity to a tourism waterway and the operator's previous discharge failures and excesses. We were livid it was even possible or permittable considering the known record of the business.

But, that was in the past when citizens had some effective link to governance. Today, it is important for MPCA to understand that you and other state regulatory agencies are not trusted or honored. We see evidences of the cancer of regulatory capture by corporate agriculture. There is belief that no matter what the new regulations are there will be slow and lax enforcement and tactics to divert public attention and delay correction. This is the result of creeping internal origanizational and legislative pollution from industrial ag monies and pressures. Therefore, the MPCA, Department of Ag, and others with power to protect us have become blighted and subservient ...without honor.

Honesty can be clearly demonstrated by speed and absolute certainty in strict enforcement of regulations regardless of the guilty party. Now, accountability by the public and press will follow.

Response:

Stephan Melson · Citizen · (Postal Code: unknown) · Jul 08, 2025 3:57 pm

I happen to agree with you, Kent. A government that can't protect its citizens from dangers needs reform, not further power. I've never understood the mentality, the government fails at a task so the solution is to give them more money and make some new agencies.

Addison Otto · Citizen · (Postal Code: unknown) · Jul 07, 2025 3:46 pm

0 Votes

The Minnesota Pollution Control Agency (MPCA) received the comment cards in the attachment from individuals who attended the in-person information sessions on this rulemaking throughout the state in June 2025.

Gretchen Sabel · Citizen · (Postal Code: unknown) · Jul 07, 2025 4:43 pm

1 Votes

It is good that MPCA is considering revisions to the feedlot rules. Many compromises went into the current rule 25 years ago, the effect of which were not known at the time. An evaluation of the current rule's effectiveness is probably over due.

Nine years ago, my daughter's family was impacted by land application of dairy cow manure on a field adjacent to their home. The application was heavy and not quantified to the land owner, the farmer having requested permission on an emergency basis due to overflowing lagoons at his farm. The application went on for more than 24 hours on

the coarse soils of the field, followed by 3" of rain. My daughter's shallow well was severely impacted, and they had to install a deep well to get safe water. This was particularly dangerous because their baby was just transitioning to formula. While the farmer paid for the well upgrade, the situation was quite difficult for some time.

I advocate for stricter land application requirements and lower application rates in Vulnerable Groundwater Areas: Soils and geology vary across MN. In the most vulnerable parts of the state (karst geology, sandy soils), there should be stricter requirements for the land application of manure.

Anne Schechinger · Citizen · (Postal Code: unknown) · Jul 08, 2025 11:50 am
1 Votes

Environmental Working Group's comments on MPCA's Animal Feedlots Rule are attached. We recommend that the agency strengthen the rule considerably.

Response:

Stephan Melson · Citizen · (Postal Code: unknown) · Jul 09, 2025 7:56 am
In your attached PDF, the following is stated about your claim of nitrogen overloading in nine counties in Minnesota. ""In our report released in May of 2025, EWG analyzed which fields near feedlots likely received manure in 2024."" So you don't know which fields received manure, you don't know what rate of manure was applied, you don't what the nutrient value is of the manure, and you don't what practices were used to apply manure correctly like waiting until soils are below 50 degrees and yet the EWG can determine nitrogen overloading even with little to no actual information? Pardon my French, but that's just throwing sh** at a wall and seeing what sticks.

Jennifer Valentine · Citizen · (Postal Code: unknown) · Jul 08, 2025 2:09 pm
1 Votes

Some of the changes that Land Stewardship Project & I propose are:

More rigorous groundwater monitoring requirements for NPDES and SDS permit-holding feedlots.
More rigorous reporting when it comes to the transferring of manure.
Lowering the animal unit size threshold for feedlots to obtain NPDES and SDS permits to 600 animal units.
Changes to how a collection of small feedlots all under the same ownership structure is permitted.
Updating the new manure management plan mapping tool to include more information about spreading plans and manure infrastructure like digesters. This data should be made available to the public, not just to potential permitees while they are creating their manure management plan.

Ann Fox · Citizen · (Postal Code: unknown) · Jul 09, 2025 7:23 am
0 Votes

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I am writing to ask the MPCA to strengthen the Animal Feedlot Rule, Minnesota Rules, chapter 7020. The state must do more to protect Minnesota's aquatic resources; feedlots are among the biggest producers of nitrogen waste that moves into our groundwater. Clean water is vitally important to both people and wildlife. Minnesota needs feedlot rules that not only work for farmers, but that also protect the environment for humans and wild animals alike. Even those of us that live far from agricultural land are aware of this issue and try our best to avoid heavy use of nitrogen-producing chemicals. Feedlots must be required to do the same. Thank you for efforts to protect all of us.

Leonard Sojka · Citizen · (Postal Code: unknown) · Jul 10, 2025 1:22 pm

1 Votes

I agree with the following comments:
MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.
MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.
MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that "stricter" requirements in existing rules prevent pollution.
MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Lisa Fitzy · Citizen · (Postal Code: unknown) · Jul 10, 2025 1:43 pm

0 Votes

MPCA rules should guarantee protection from toxic nitrate pollution in CAFO feedlots.

Matt Ringquist · Citizen · (Postal Code: unknown) · Jul 10, 2025 1:48 pm

1 Votes

I'm writing to make the following statements: MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.
MPCA rules should set a maximum limit on the size of any single feedlot and a maximum

limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.
MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution.
MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Thomas Anderson · Citizen · (Postal Code: unknown) · Jul 10, 2025 2:14 pm
1 Votes

Regardless of political preferences, it appears that a large majority of Minnesota residents want clean water. Further, they expect Minnesota agencies such as the MPCA to ENFORCE high clean water standards. Nobody wants to wait for a disaster to begin to act. Act now.

As such

MPCA needs to require pollution permits for a wider range of feedlots, say 300-999 animal units whichwhich contribute 43% of Minnesota’s total manure.

MPCA needs to set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

MPCA needs to prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution.

MPCA needs to state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

MPCA needs to strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

MPCA needs to prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

MPCA needs to require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to

noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Annah Gardner · Citizen · (Postal Code: unknown) · Jul 11, 2025 12:00 am

1 Votes

Clean water resources must be preserved for our future generations. The Land of 10,000 Lakes deserves to have a State full of clean, pristine, uncontaminated water. There must be rules that require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots in MN.
There needs to be a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed.
MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution.

Sven Sorge · Citizen · (Postal Code: unknown) · Jul 11, 2025 11:37 am

1 Votes

Dear Sirs and Madams,

MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.

MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution.

MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including

respiratory and neurological harm.

Thank you very much for your help!

Sheila Maybanks · Citizen · (Postal Code: unknown) · Jul 11, 2025 12:28 pm

1 Votes

I'm not a farmer or a trout fishermen but I am concerned about water and air quality. Please amend Rule 7020 to require pollution permits for all feedlots over 600 animals. Minnesota Pollution Control needs to enforce the "no discharge" regulations, as well as air quality regulations.

Thomas Sullivan · Citizen · (Postal Code: unknown) · Jul 11, 2025 1:58 pm

1 Votes

As someone deeply concerned about pollution and its effects on human health, ecosystems, and water quality, I urge the MPCA to adopt stronger rules to better control the environmental and public health impacts of animal feedlots in Minnesota. Manure from feedlots is one of the state's largest sources of pollution—both waterborne and airborne—and the current rules are inadequate to address the scale of the problem, especially in light of climate change and increasing agricultural concentration.

To that end, I strongly recommend the following rule changes:

1. Require NPDES/SDS permits for medium-sized feedlots (300–999 animal units). These operations produce 43% of the state's manure, yet are not required to hold permits that regulate pollution. This is a major regulatory gap that leaves waterways and communities vulnerable to contamination.

2. Set enforceable maximum limits on the size of individual feedlots and total animal units per watershed. Local hydrology, water availability, and community health must determine these limits. Without them, the state risks irreparable harm to both ecological systems and rural quality of life.

3. Prohibit new or expanded feedlots in karst regions. Karst geology is highly susceptible to groundwater pollution. Because contamination in these areas is effectively irreversible, "stricter" requirements are insufficient. The only responsible course is to prohibit development in such high-risk zones.

4. Enforce zero-discharge standards and pollution reduction in impaired waters. The rules must make clear that MPCA will actively enforce no-discharge requirements, require compliance with all pollution limits, and prevent degradation in currently healthy waters. Strong enforcement is essential for public confidence and environmental recovery.

5. Strengthen minimum technology standards for liners and leak detection. The rules must require modern containment systems. It is no longer scientifically defensible to assume that concrete or compacted soils alone are effective at preventing seepage, especially when exposed to years of manure storage.

6. Ban all wintertime manure application. Climate unpredictability has made current

winter spreading guidelines obsolete. Snowmelt and freeze-thaw cycles dramatically increase runoff risk, and rules must reflect these conditions to protect our lakes, rivers, and groundwater.

7. Require feedlots to comply with air quality standards at least 344 days per year. Hydrogen sulfide and other emissions cause serious health impacts. Feedlots should not be allowed to routinely exceed air quality standards. The current 21-day exemption is already generous.

In summary, I support a more proactive, protective approach that aligns MPCA rules with the reality of modern-scale animal agriculture and its pollution risks. The public deserves clean air and water, and the environment deserves robust stewardship.

Sincerely,

Tom Sullivan

Thomas Kunkel · Citizen · (Postal Code: unknown) · Jul 12, 2025 8:43 pm

1 Votes

I am concerned about the increase of the number and size of feedlots increasing drastically over the last 25 years. I realize that the economics of agriculture is driving this, but I feel that the situation is approaching the out of control situation in Iowa. There needs to be an attempt to find common ground that benefits all Minnesota residents, and that isn't happening without discussion. Several years ago, my wife's now deceased uncle bragged about manure being applied on his corn field until the tile lines ran green. That comment has stayed with me ever since. I think we can all agree that such a maneuver should not happen. Without more awareness and discussion of feedlot regulations, I fear that situation could happen again. Being 73 years old, I worry more for what the future holds for my grandkids rather than myself. Not only has the problem of water pollution risen rapidly in the publics eye, but one has to be concerned about the rising cancer risk, particularly in southwest Minnesota. Both of those issues have really raised concerns across Iowa and rightfully should concern us too. Sincerely, Thomas Kunkel

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Lynn Anderson · Citizen · (Postal Code: unknown) · Jul 13, 2025 9:00 am

0 Votes

Minnesota deserves updated and comprehensive protections for clean water and air given the increasing size and number of feedlots across the state. This includes treaty territory protected by federal law that we have a duty to uphold. Climate change is at our doorstep adding additional stress. Future generations deserve good stewardship of Minnesota's land, rivers, and lakes now.

Specifically, I would like to see:

1. MPCA rules requiring pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.

2. MPCA rules requiring a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology

and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

7. MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

As the previous writer mentioned, I support a more proactive, protective approach that aligns MPCA rules with the reality of modern-scale animal agriculture and its pollution risks. The public deserves clean air and water, and the environment deserves robust stewardship.

Thank you for your important work.

Lynn Anderson

Thomas Swedberg · Citizen · (Postal Code: unknown) · Jul 13, 2025 11:58 am

1 Votes

I live n Northern Minnesota and have background in health care. I am firm believer in the need for clear water. We drink it bathe in it and really on it nutrition ally. I have lived alongside the Mississippi in Little Falls and saw municipal water supplies rendered unsafe to drink. A sad reality for those not able to leave the area is reliance on polluted water. With our state’s fresh water resources we should be a leader in protection of this necessity of life. I therefore believe it critical to re evaluate and update failed policy and rules regulating feedlot manure.

On a more personal note I am also a fisherman and fear fish kills across our state related to feedlots and manure containment. Loss of containment equals fish kills. This terrible management of our precious natural resources and should be avoided at all cost.

I believe the following would be a great step in a safer resource respectful direction:
MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.
MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.
MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution.
MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Dennis Middendorf · Citizen · (Postal Code: unknown) · Jul 13, 2025 9:40 pm
1 Votes

I oppose tougher feedlot rules. As a smaller operator we already keep records of manure application, days when hauled and timely incorperation. Manure samples are taken every four years. The crop advisor calculates how much nitrogen is needed per acre to produce a average crop. We don't put any more nitrogen on then we have to otherwise it's wasted money. Many farmers in our area have a custom guy come in to haul their manure and in starts early September and goes until it freezes. We need this time to haul. We have 6.5 months storage for our manure and if we have to go to 9 months it will be a major cost with no benefit to land. Frozen manure hauling is up for debate. I can see liquid manure being a problem but pen pack manure is mostly straw and doesn't hardly move on frozen ground.

These rule changes for small farmers will be a bigger burden money wise on them and won't help the environment. You need to focus on the whole picture. Commercial fertilizer and manure from farms are items we know how much per acre is being put on, how about everyone who fertilizes their lawn submit application rates to mpca? If everyone is willing to do that then I will do the same.

We want the best thing for our land and more regulations will not help. Lets make it simple. More paperwork is not the answer.

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

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Julie Buenger · Citizen · (Postal Code: unknown) · Jul 14, 2025 9:41 am
1 Votes

As a cattle herd operator, I would like to caution against cumbersome legislation, implemented by non agriculture personnel, which could result in eliminating many farms. We are already using many good management practices. I find it unfair to blame the farmers for nearly every pollution problem, when the towns and cities contribute to the pollution situation. Some of the suggestions that have been presented may sound good on paper, but in reality just won't work. Such as using the weather report to determine if a farmer can apply manure. We all know that the weather reporting for a certain area is highly unpredictable. We watch the weather to try to determine when to cut and bale hay and we are lucky if they get it right half of the time. Another example is the suggestion of no manure application in the winter months. Every year is so different thus making this idea unreliable. In the area I live, the streams are thriving and the fishing is great. We are using good management practices. I caution against giving too much emphasis to the voice of those who don't understand agriculture and tend to blame the farmer for problems that they did not create. People are complaining about the high cost of food, yet they want to add more laws, which will only cause the prices to continue to increase. Please consider all the hard work farmers are already doing to put food on our tables and to preserve the environment. We live on our farms and of course we want to be healthy, too. Creating more regulations will only make things more complicated and will not make us any healthier. It will only drive us out of business, thus creating more problems for affordable food sources.

John Zimmerman · Citizen · (Postal Code: unknown) · Jul 14, 2025 1:38 pm
4 Votes

Please do not change the animal unit factor for turkeys in the feedlot rules. The current animal unit system is clear and reflects how turkey farms operate. Splitting AUs based on bird weight or sex might make sense on paper, but not in the real world. There is no meaningful difference in how we raise or manage turkeys based on those traits.
Also, turkey manure is dry and doesn’t pose the same risk as liquid manure. Trying to regulate turkey farms in a once size fits all approach doesn't work. We shouldn’t have to meet rules that don’t match our operations just because they were designed for a different species.
I urge MPCA to keep the rules simple and based on science and actual risk—not unnecessary complexity. We want to protect the environment, but we also need rules that make sense for how our farms work.
Thank you,
John Zimmerman

Jake Vlaminck · Citizen · (Postal Code: unknown) · Jul 14, 2025 2:42 pm
3 Votes

I respectfully ask MPCA to keep the current animal unit numbers for turkeys the same. The current breakdown already fits how our farms operate.
On turkey farms, our management doesn't change depending on whether the birds are

male or female, or by size. We treat them the same in housing, feed, and manure handling. Adding more categories would only confuse things and make the rules harder to follow, without improving environmental protection.
We need rules that reflect how our farms actually function, not a one-size-fits-all approach.
Please don’t make the rules more complicated than they need to be. The current animal unit system works.
Thank you,
Jake Vlaminck

Jim Etzel · Citizen · (Postal Code: unknown) · Jul 15, 2025 12:28 pm
1 Votes

Manure is Manure, whether it comes from a cow, pig, chicken, turkey or human. Nitrogen is Nitrogen and it is in large quantities when you confine animals(two legged or four). If the groundwater, lakes, rivers and streams are being polluted from too much nutrients, then the solution is to decrease the nutrient loading. The landscape before European colonization was diverse biomes with vast amounts of diversity in plants and animals. The wild creatures moved around and fed freely. This provided nutrients to thriving systems that cycled nutrients effectively and created beautiful topsoil. The systems of today are broken and driven by money. Working with the farmers to compost and return these nutrients back to the system in a form that does not leach, holds water and nutrients, and sequestors carbon seems to be a better option. Reducing the number of animals in any given area is a smart decision for those that do not make their living from meat production but it is exactly what is needed. The solution to pollution is dilution. Changing our lifestyle and way of making money is not just a simple rule change. The farmers are already struggling to make things work but we can’t continue down the road of degredation either. We need to work together for better solutions and realize that fresh, clean drinking water is critical to the survival of all life on Earth. It all begins in the SOIL!

John Harrington · Citizen · (Postal Code: unknown) · Jul 15, 2025 1:19 pm
0 Votes

As MPCA proceeds with its rule making on Animal Feedlots, it should clearly and specifically identify who,, how many, and where are the persons affected and which water bodies, surface or groundwater, they are affected by via feedlot contamination. Much of this information should be in the reports on non-compliance, and the WRAPS reports.
The Agency should also include sections that specify how existing or proposed changes are responsive to the 1999 Legislative Auditors report on Feedlots and the 1993 EPA/State Feedlot Workgroup Report. Finally, since both surface and groundwaters are affected by feedlot contamination, and each is or could be a source of drinking water, the Agency should clearly identify and linkages or gaps in the system of rules intended to protect water for domestic consumption

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Randy Wenthold · Citizen · (Postal Code: unknown) · Jul 15, 2025 8:11 pm
0 Votes

Please see attached document with comments to all proposed rule changes.

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Jacob Vogt · Citizen · (Postal Code: unknown) · Jul 16, 2025 10:54 am

0 Votes

I am a licensed CAWT and owner of a 2400 hd finishing barn. We have a been in animal agriculture for over 40 years. There has been vast improvements in that time. I would caution against going overboard on any future regulation. Adding more paperwork will not increase water quality, it will just be more expensive and cause more farms to consolidate.

As a CAWT our business and myself do every thing that we can to make sure the valuable resource of manure and nitrogen stay where we put it in the field. We use manure tanks and incorporate immediately. I am disappointed with the quality of our work if any manure is on top of the soil. We have electronics in the cab to keep the rate consistent across the field and cover the fields corner to corner with very minimal overlap. We take manure samples every year so the farmers know what they are getting on fields and use a three year average to set our rates.

However, there are challenges with manure application. To be able to make the business viable and to keep barns from overflowing; we starting taking manure out of pits and incorporating it on the fields as soon as beans come off. Some farmers plant cover crops but struggle to get a good stand once every three years. Cover crops seem like a good idea on paper but are very hard to make work in real life. We finish applying manure around thanksgiving every year. There are times every year where large rains a forecasted and no rains come and when very little rain is forecasted and large quantities of rain comes. Our weather forecasting is not advanced enough to make rules upon it. Towards the end of season we hope to be finished before the ground is frozen, but sometimes have to incorporate the manure through a few inches of frost. It is far better to apply in the early fall or on half frozen ground that it is to let a barn overflow.

There must be allowances in the rules to allow putting manure on fields to prevent point source pollution from the feedlots.

The vast majority of point source pollution coming from a feedlot that I have seen is when the feedlot is under 300 animal units. I cannot recall an event of point source pollution coming from an area feedlot over 300 au in the 40 years in the business.

More things that I think are worth considering are: Do not lower au below 1000 for NPDES sites. Why are we only regulating down to 300 au? I believe we should lower that to 20 or 50 au. Those of us farmers that are doing every thing we can with the valuable resource that is manure will always think it is a different group that is causing the pollution. Therefore, we need to bring everyone onto the same level; whether that is small farms under 300 au that have cattle directly in the river or pigs playing in the mud next to creek, or municipalities that discharge right into metro area lakes or rivers. There needs to be consistency for everyone! I would support regulation that requires all manure to incorporated with 24 hours. As far as applying manure to vulnerable areas: looking at the map there are "random" small acres of fields all over our area that are listed as vulnerable surrounded by 1000s or acres that are not listed. It is overly burdensome to try to differentiate these acres. But, we do need to protect the karst regions.

In summary, the vast majority of farmers are doing their best to keep their manure in the fields where they need it as a valuable resource; do not over burden them with paperwork. If everyone is not on a level playing field (under 300 au, 300 to 1000 au, NPDES sites, and municipalities), then all the groups will always blame someone else for the problem. The weather is changing, so predicting it or making rules based upon it is unreasonable. Mother nature will always have the upper hand.

Regulating animal agriculture out of the great state of Minnesota will only result in a

negative impact on the world.

Thank you for your time,

Jake Vogt CAWT

Lee Stoe · Citizen · (Postal Code: unknown) · Jul 16, 2025 11:08 am
0 Votes

Re: Animal Feedlot Rule, Minnesota Rules, chapter 7020

I was on Rush Creek three weeks prior to the huge 2022 fish kill, where an estimated 2,500 trout were killed. My 6-yr-old grandson presented his dry fly to the fish and caught his first trout on a fly on that day. The three of us had an amazing day and assumed we'd go do it again. I am compelled to do my part to protect our water for all living organisms, so our grandchildren and their grandchildren can live full, healthy lives and enjoy the stream as many of us do.

Trout are an indicator species needing high oxygen-saturation levels, clean water and invertebrates. They are a sensitive species worth saving. When trout are dying in water that can find its way into well water, we need to take note and take action to protect the fish and our neighbors. Jeff Broberg once told me they'd done dye tracing showing that stream water was making its way into private wells. Jeff was a certified geologist and co-founder of Minnesota Well Owners Organization (MNWOO).

In the past, we've largely been reactive, paying attention only after an event. This has not worked to keep our water safe. We need to keep our water resources clean and safe. Toward this goal, I make the following rule-change proposals.

1. Require feedlots of 300 or more animal units to submit manure management plans and maintain land application records (preferably electronic for ease of auditing), and submit these to the MPCA and county feedlot pollution control officer.

2. In addition to regulating the size of individual feedlots, control animal population density by establishing limits on the number of animal units per watershed. This is akin to carrying capacity. The intent here is to use objective data to limit future increases on CAFO size limits. This reduces the likelihood of a county like Fillmore County doubling or tripling its animal cap limit unless the land can support it. Recall that the Karst geology of SE MN is particularly susceptible to polluted surface water. In this area and in other areas such as the Central Sands area, polluted surface water more quickly reaches groundwater.

Respectfully submitted,
Lee Stoe

Madeline Neenan · Citizen · (Postal Code: unknown) · Jul 16, 2025 11:53 am
0 Votes

Regarding Animal Feedlot Rule, Minnesota Rules, chapter 7020.

I encourage MPCA to update the rules to cap unit size at 600 animal units or less. Each

increase in animal unit size puts an area at greater risk for contamination if there is any flaw in the operator's system. When a smaller system fails, the resulting problem is smaller as well.

Madeline Neenan

GREG REUTER · Citizen · (Postal Code: unknown) · Jul 16, 2025 12:20 pm
0 Votes

It is mutual that we all want clean water. I feel the current rules are sufficient with some being excessive like why do I need to do a permit modification just to add a field to my manure management plan to apply manure on it? If there are issues with the Karst regions, then deal with those areas but don’t do a wide sweeping rule change. I live in the west central part of the state in a dense livestock area. Due to current requirements to test well water on any irrigated fields in our manure plans, I have found the nitrogen levels well below EPA standards with most close to zero. Farmers want to keep as many nutrients available for the crop as possible, it costs a lot to apply manure and for commercial fertilizer, so we apply accordingly. We use cover crops where it makes sense but why should we be required to put a cover crop out that isn’t going to have sufficient time to grow just so we are in “compliance”? As far as anything less than the 1000 animal unit requiring an NPDES or state permit, I feel that it is excessive and will cause an undue burden on small producers. A lot of this comes down to just a lot of extra paperwork that doesn’t provide any benefit. Please consider letting the current rules as they are.

Erika Gilsdorf · Citizen · (Postal Code: unknown) · Jul 16, 2025 1:10 pm
0 Votes

Please see the attached comments submitted by the Prairie Woods Chapter Izaak Walton League in Detroit Lakes on this important issue. Research and expertise has been thoroughly prepared and thoughtfully condensed for this comment opportunity. Thank you.

Loren Brey · Citizen · (Postal Code: unknown) · Jul 16, 2025 1:38 pm
2 Votes

My family has raised turkeys in Minnesota for over 30 years, and I'm writing to ask that MPCA leave the animal unit factors for turkeys unchanged. The current system makes sense and matches how turkey farms are managed. Whether the turkeys are toms or hens, light or heavy, we manage them the same way. Changing the animal unit factors by bird size or sex wouldn't reflect how real farms work-it would only create more regulation for the sake of creating more regulation. It's also important to point out that turkey litter is dry and stored inside. Turkey farms should be treated based on their real environmental risk not a one size fits all regulation. We care about clean water, and we already follow the rules to protect it. Please keep the current animal unit definitions and avoid making things more complicated for no reason. Sincerely, Butch Brey

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Katie Subra · Citizen · (Postal Code: unknown) · Jul 16, 2025 3:12 pm
0 Votes

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

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My family and I are well-owners and we care deeply about the quality of the natural landscape and drinking water for all residents of our state. However, I'm very concerned about the rapid, and seemingly endless growth in large-scale animal agricultural farming and the impact of that on our water systems and air pollution. Given the increase in the number of feedlots with near threshold animal units, the changing climate that contributes to warmer winters, and advancements in manure treatment and storage technologies, I support the MPCAs proposed amendments to the governing rules for Minnesota feedlots, including enhanced use of regulatory strategies and technology, especially the demand for real-time information since farming practices and seasonal changes can make an immediate and irreversible negative impact on our waterways. Also, I support the proposed rule amendments around livestock and poultry production techniques and practices, new research (and dissemination of new findings to the public) for understanding agriculture and the environment, as well as regarding changes in crop production and nutrient management. I think that the additional requirements that apply to feedlots with a total of 1,000 or more AUs should be applied for facilities with as few as 250 AUs if they are in geographically vulnerable regions in terms of groundwater, such as the Southeast Minnesota karst region, places with shallow bedrock, and places along major rivers and their tributaries, including the Minnesota, Red, St. Croix, and Mississippi Rivers.

lisa bergerud · Citizen · (Postal Code: unknown) · Jul 16, 2025 4:55 pm

0 Votes

As a Minnesotan concerned about water quality in our state, I appreciate the MPCA’s work to update the animal feedlots rule and urge the agency to make it stronger. Large areas of the state, especially in vulnerable regions like southeastern Minnesota, are struggling with water quality issues caused by nutrient runoff, to which feedlot manure is a big contributor.

I ask that the MPCA take the following steps:

Lower the size for a feedlot operation to be required to apply for a water pollution permit. Currently, many feedlots skirt greater regulation by operating just under the permitting limit of 1000 animal units, this should be lowered to no more than 600 animal units.
Require feedlots with those permits to closely monitor their manure discharges to protect nearby groundwater and streams.
Set stricter limits on manure application to farm fields in vulnerable areas, like the heavily nitrate-polluted karst region in southeastern Minnesota.
Change how multiple small feedlots with the same owner are regulated. Currently, an owner of multiple feedlots, even feedlots right next to each other, can skirt stronger regulations by keeping them as “separate” operations, though the total pollution is the same as a large feedlot.
Require more rigorous reporting on manure transfers.
Make more manure managing data and mapping available to the public, including information about digesters and manure spreading plans.
Minnesota’s lakes, rivers, and groundwater have been getting more polluted every year. This is a chance to take a step in the right direction rather than continuing business as usual.

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

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Duane Wirt · Citizen · (Postal Code: unknown) · Jul 16, 2025 4:57 pm

0 Votes

Hello MPCA,
Thank you for hosting regional meetings throughout Minnesota.
I would like you to consider these points that I think are important.
1. Fish kills
I have fished the same streams for almost 60 years and continue to fish. Every fish kill I have seen was a 3.5-5 inch downpour in a very short period of time. That is not something that is predictable and we can't regulate it. When I was younger, all trout streams were grazed and cattle stood in the streams during hot weather and pooped. There were no fish kills that I knew of or were publicized.
Today, we have more trout in the streams than ever before. Only 1-2% of fish kills are related to agriculture. Most are temperature elevation of water and stream bank debris. Streambank restoration may help. Let's not penalize agriculture for their minimal role in this problem.
2. Nitrates-Farmers are solely being blamed for nitrates but old septic systems and wells with eroded casings need to be checked as their leaks contaminate water as well. We should also be monitoring municipal sludge spreading practices to consider how they add to the nitrate and heavy metal contamination picture. In Lewiston we have had our municipal sewage pond develop a leak and disappear overnight.
3. Wintertime spread, storage pits, pad sites
Most young livestock are housed in manure packs in Southeast MN. As the packs thaw, they release ammonia in the sheds. The sheds need to be cleaned monthly starting at the end of January or the animals will have pneumonia problems.
We need to work with animal agriculture, like Europe does, to provide engineering plans, pads, or new buildings with financial help. If we don't, farms with under 1000 animal units will disappear due to the increased cost of operation. Dairy farms under 1000 animal units cannot afford this. Our profit margin is small. The cull price of calves have saved the day for the last 2 ½ years but that won't last forever and the milk price has not increased. Federal and state rules have already driven out most of the 50-250 cow sites in Minnesota.
The loss of one dairy cow means the loss of one acre of hay and pasture land. Those acres will be planted to corn and soybeans. We are moving in the wrong direction. We need more alfalfa and pasture for improved water quality.
Manure pads and liquid storage areas will cost 2-4 million dollars per dairy to meet the proposed changes. I asked at the regional meeting if funding from the state would be provided and was told, "Not at this time". Our family farm priced a manure storage pit in 2007 for 555 cows with 7 months storage. This would be 2 units containing 4, 712,591 gallons of liquid manure. The cost was over $800,000. With your proposals, we will need over 12 months storage for wet Spring conditions like we had in 2024 in our area. 3-5 million dollars will be needed for liquid and pen pack.
Exit will be the only option. There is no funding available. I have visited our NRCS and SWCD several times to confirm this.
The rural Minnesota economy will suffer the loss and food security will be at increased risk in the U.S. In 2017, each dairy cow returned $7000 to the local economy through machinery dealers, plumbers, electricians, veterinarians, nutritionists, agronomists, hardware stores, grocery stores, etc. The loss of dairy farms affects not only food availability but also the economic health of our communities.
4. No winter spread of manure also has serious implications.
• The cost of facilities for the manure will mean dairy and cattle farmers will need to sell their herds. The loss of hay and pasture ground to corn and soybeans results in lower

water quality.
• A wet spring would mean increased compaction due to repeated trips across the field to spread manure. Increased compaction reduces soil health.
• The need for more time spreading in the spring means a shorter window for planting and/or the use of shorter day crops, which would mean lower crop yield.
I have seen no study putting a smaller amount, like 3-4,000 gallons per acre, on chiseled fields in winter on fields with less than a 6% slope. In a winter like 2024-2025 (very little snow) all water melts into the chiseling and there is little runoff. With a spring like 2024 (excess rain, wet and saturated soil) there can be a great deal of runoff due to the unpredictable large rainfall.
A broad brush approach does not work. Weather forecasts are only about 50% correct and rainfall is the biggest predictor of runoff.
5. Distance between family farms
There should be no change. Farmers consider the distance between fields and an increased land base increases the opportunity for less manure per acre and less road travel with tankers and spreaders.
Each farm should have its own animal – unit base.
An exit from livestock production is very likely, going from 750 animal units to well over 1000 animal units will have different requirements. We were told not to worry if family members worked together.
6. Animal unit values need to stay the same as they are valued today.
Discharge per animal per day should be the standard, which was set-up by previous laws regarding animal unit total.
Our rural communities are already having difficulty meeting the challenge of school, fire, police, EMS, county taxes, and township taxes.
A loss of animal production will hurt rural communities. Loss of dairy/beef production will decrease alfalfa and pasture ground acres which will affect water quality.
There is no perfect style of farming. There are positives and negatives for everyone. We should encourage education of farming practices that will benefit water quality and provide an opportunity to change when it is affordable-Examples: cover crops, no till planting, manure management, fertilizer application, etc. Public cooperation helps us improve water quality. We can see changes in the last 10 years with adoption of several of these practices.
It will take time to see changes in water quality considering the time it takes for water to move through the soil. All changes will not work every year. Flexibility has to be built into the plan due to changes of rain and snowfall.
As a dairy farmer with the price of milk at $17 per hundred weight and the increased cost of production, there is not much left over for larger pits and stacking slabs.
Changing requirements will only leave 1000 animal unit facilities and rural communities will pay the price.
Thank you for considering these comments.
Attached is information about the costs and profit that is the reality that dairy farmers live with.

Ann Beane · Citizen · (Postal Code: unknown) · Jul 16, 2025 5:53 pm
0 Votes

As a Minnesotan concerned about water quality in our state, I have gained some knowledge through different sources about the negative effects of farm animal feedlots on local water quality, including rivers, lakes. and ground water which leads me to urge

the MPCA agency to make feedlot regulations stronger than existing ones. Large areas of the state, especially in vulnerable regions like southeastern Minnesota, are struggling with water quality issues caused by nutrient runoff, to which feedlot manure is a big contributor. We owe it to our environment and to our future generations.
Continuing to become more knowledgable about Minnesota's precious resources. and learning how to respond.
Thank you for the work you do.
With appreciation,
Ann Beane

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jane martin · Citizen · (Postal Code: unknown) · Jul 16, 2025 6:06 pm
0 Votes

As a Minnesotan concerned about water quality in our state, I appreciate the MPCA’s work to update the animal feedlots rule and urge the agency to do all it can to protect our water quality.

I ask that the MPCA take the following steps:

Lower the size for a feedlot operation to be required to apply for a water pollution permit. Currently, many feedlots skirt greater regulation by operating just under the permitting limit of 1000 animal units, this should be lowered to no more than 600 animal units.
Require feedlots with those permits to closely monitor their manure discharges to protect nearby groundwater and streams.
Set stricter limits on manure application to farm fields in vulnerable areas, like the heavily nitrate-polluted karst region in southeastern Minnesota.
Change how multiple small feedlots with the same owner are regulated. Currently, an owner of multiple feedlots, even feedlots right next to each other, can skirt stronger regulations by keeping them as “separate” operations, though the total pollution is the same as a large feedlot.
Require more rigorous reporting on manure transfers.
Make more manure managing data and mapping available to the public, including information about digesters and manure spreading plans.
Minnesota’s lakes, rivers, and groundwater have been getting more polluted every year. This is a chance to take a step in the right direction rather than continuing business as usual. Thanks for all you do.

Craig Maki · Citizen · (Postal Code: unknown) · Jul 16, 2025 6:27 pm
0 Votes

Comment on Feedlot Rules Update

I believe this work is long overdue and should be done in a shorter time frame in the future, in, perhaps 10 years. Confirmation of what a safe level of nitrates is, should be a priority. In 1962 it was set as 10mg/L. Is that still backed by current science?

Our lives depend on access to non-contaminated water. That’s the fundamental truth. We should protect our water quality with that in mind. As a water-blessed state, Minnesota should have a moral obligation to prioritize preserving our waters as move forward.

To begin with, we should widen the definition of operations that need to have their water runoff monitored and those who should be covered by this rule. 500 large animal units seems to be a fair number for reasonably requiring a need to periodically check outflow of water for nitrates, manure and bacterial content. I don’t know the frequency, but is should be scientifically sound. This of may inconvenience or cost the operators, but the public should demand this, as the water significantly affects the health of those who come in contact with it.

I see some research hinting at lower levels of nitrates than the present 10mg/L should be implemented. Prostrate cancer is a notable concern with minimally elevated nitrates, recent studies have suggested.

My profession as a provider of medical care in a rural setting, has me concerned that we are not being adequately aggressive in our water quality effort. Practicing in rural sw Minnesota, and prostate cancer and other cancers are elevated in their frequency out here. This at a time when the Minnesota River is seriously polluted. Farmers and non-farmers alike who are careless or under informed with their waste products need to be educated to the harm they are doing, and discouraged from doing it (lawn care).

Farmers and anyone using nitrogen fertilizers need to ensure that they are in compliance with other proven means (cover crops and reduction in application) to reduce the excess nitrogen proper timing of fertilizer application to insure the quality of our common public resource. “Water is life.”

Stuart Knappmiller · Citizen · (Postal Code: unknown) · Jul 16, 2025 7:29 pm
0 Votes

I grew up on a farm. We didn't have 600 or 1000 head of livestock. Maybe if we counted the squirrels and birds in the trees. To pay for our land, Dad applied anhydrous ammonia to corn fields. Our daughter took SPRW water to Grandma and Grandpas, because we knew he had poisoned the well water at our rural church. I don't need to say anything about this issue, other than to remind us all, drinking water is pretty important to life. Millions of people drink water from our Mississippi River. Protect it. And protect the water in every farmhouse in the state.

Gretchen Bratvold · Citizen · (Postal Code: unknown) · Jul 17, 2025 12:56 am
0 Votes

As a Minnesotan concerned about water quality in our state, I appreciate the MPCA’s work to update the animal feedlots rule and urge the agency to make it stronger. Large areas of the state, especially in vulnerable regions like southeastern Minnesota, are struggling with water quality issues caused by nutrient runoff, to which feedlot manure is a big contributor.

I ask that the MPCA take the following steps:

- Lower the size for a feedlot operation to be required to apply for a water pollution permit. Currently, many feedlots skirt greater regulation by operating just under the permitting limit of 1000 animal units, this should be lowered to no more than 600 animal units.

- Require feedlots with those permits to closely monitor their manure discharges to protect nearby groundwater and streams.
Set stricter limits on manure application to farm fields in vulnerable areas, like the heavily nitrate-polluted karst region in southeastern Minnesota.

- Change how multiple small feedlots with the same owner are regulated. Currently, an owner of multiple feedlots, even feedlots right next to each other, can skirt stronger regulations by keeping them as “separate” operations, though the total pollution is the same as a large feedlot.

- Require more rigorous reporting on manure transfers.

- Make more manure managing data and mapping available to the public, including information about digesters and manure spreading plans.

Minnesota’s lakes, rivers, and groundwater have been getting more polluted every year. This is a chance to take a step in the right direction rather than continuing business as usual.

Michael Barber · Citizen · (Postal Code: unknown) · Jul 17, 2025 8:48 am
2 Votes

I’m asking the MPCA not to change the animal unit numbers for turkeys. The current numbers work well and make sense for how turkey farms are actually run.
Raising turkeys doesn’t change much based on whether the birds are male or female, or if they’re slightly heavier or lighter. We feed them the same, house them the same, and manage their manure the same. Creating more categories based on bird size or sex would only make things more confusing without helping the environment.
Turkey farms already follow a lot of rules to keep water clean and manage manure responsibly. Adding more complicated rules about animal unit numbers without a scientific reason to do so won’t help and will only make it harder for farmers to understand and follow the rules.
Please keep the current animal unit numbers for turkeys. They’re simple, clear, and they reflect how farms actually work.
Thank you,
Mike Barber
Turkey Farmer – Swanville, MN

Tim Harmening · Citizen · (Postal Code: unknown) · Jul 17, 2025 11:25 am
0 Votes

so, I apply my manure in the fall so cover crops seeded in the late fall will probably not establish as far as reduced tillage I have an applicator on the back of the tank that uses a disk coulter the manure is buried right away the amount applied is controlled by a flow meter. I'm not too interested in a no till unit I still feel you need a well tilled seed bed.

My neighbor I sell manure to will not like the idea of having to fill out an annual report and the MPCA gets a transfer of manure from me the owner and I apply the manure to his land just as responsible as my own. I can agree we should be more responsible in sensitive areas, but I would like to point out that crop farmers don't report fertilizer applications at all it seems that everyone is after the livestock all the time it wouldn't make sense for a crop farmer to over apply but how do we know. As in past statements making winter application tougher could hurt the small farmers maybe make rules to stay away from sensitive areas which are probably in place already. the inspection of facilities is something the MPCA is supposed to be doing anyway not just when it is sold. I would like to point out that there are a lot of people pointing out all this pollution but don't seem to have any real evidence and it seems to me the urban area can pollute just as much. Farmers should not have the right to pollute, and I think we are all trying to do a good job to provide food, fuel and fiber for everyone.

Patricia Moulton · Citizen · (Postal Code: unknown) · Jul 17, 2025 12:35 pm

0 Votes

Request a public hearing.

Patricia Moulton · Citizen · (Postal Code: unknown) · Jul 17, 2025 12:40 pm

0 Votes

Can we agree that over regulation requiring more paperwork and money cobbles EVERY business in MN and US is intentional for the takedown of this nation.

Colleen WERDIEN · Citizen · (Postal Code: unknown) · Jul 17, 2025 1:55 pm

0 Votes

As a Public Health professional I am concerned about the environment, and animal's and human's health and want to see regulations, which encourage practices promoting diversity and resilience and prevent further loss of biodiversity. Elevated nitrogen levels have been shown to cause cancer and neurological defects in infants as well as cause the dead zone Gulf of New Mexico and we need to remedy that. Twenty five per cent of Gulf of Mexico's dead zone is estimated to come from manure. I also would think we need to have family farmers help us come to good decisions for our futures, so we have strong rural communities. To promote the health of animals and prevent disease I think animals need a certain amount of space and access to fresh air in warm weather and to prevent the resistance to antibiotics they should not be given antibiotics unless sick. Manure should not be applied on fields in winter where it can run off and farmers should be given incentives for having cover crops and growing crops besides corn and soybeans. Keeping a continuous cover help promote soil health. I think all CAFOs should be regulated and certified since they have a cumulative effect and they need to be recertified in 5 years. Depending on the size of CAFO there should be a proportional amount in fees and if there is air or environmental pollution a significant fee should be charged, which increases with each incident. Standards need to be set for storage and disposal of manure and there needs to be system to enforce this, which the CAFOs pay for. Ideally say in 20 years manure would no longer be put on the fields but would be converted to energy.

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Mary Vlazny · Citizen · (Postal Code: unknown) · Jul 17, 2025 4:20 pm
0 Votes

As a Minnesotan concerned about water quality in our state, I appreciate the MPCA's work to update the animal feedlots rule and urge the agency to make it stronger. Large areas of the state, especially in vulnerable regions like southeastern Minnesota whee I live, are struggling with water quality issues caused by nutrient runoff, to which feedlot manure is a big contributor.

I ask that the MPCA take the following steps:

Lower the size for a feedlot operation to be required to apply for a water pollution permit. Currently, many feedlots skirt greater regulation by operating just under the permitting limit of 1000 animal units, this should be lowered to no more than 600 animal units.
Require feedlots with those permits to closely monitor their manure discharges to protect nearby groundwater and streams. Avoiding manure spreading in spring and winter.
Set stricter limits on manure application to farm fields in vulnerable areas, like the heavily nitrate-polluted karst region in southeastern Minnesota.
Change how multiple small feedlots with the same owner are regulated. Currently, an owner of multiple feedlots, even feedlots right next to each other, can skirt stronger regulations by keeping them as "separate" operations, though the total pollution is the same as a large feedlot.
Require more rigorous reporting on manure transfers.
Make more manure managing data and mapping available to the public, including information about digesters and manure spreading plans.
Minnesota's lakes, rivers, and groundwater have been getting more polluted every year. This is a chance to take a step in the right direction rather than continuing business as usual.

Jessica Westbrock · Citizen · (Postal Code: unknown) · Jul 17, 2025 5:10 pm
1 Votes

As an independent turkey farmer in west-central Minnesota, I ask the MPCA to keep the current animal unit calculation for turkeys unchanged. The existing framework is straightforward and is the farmwork for how current turkey farm management was designed. Whether we raise hens or toms, our manure handling, housing, and nutrient management practices stay the same based on stocking densities that are appropriate for our barn, not based on the sex of the bird. Adding more animal unit categories based on bird size or sex would not provide any real environmental benefit.
What concerns me even more is the possibility of a one-size-fits-all approach that treats turkey farms like liquid manure operations. Turkey litter is dry, stored indoors, and cleaned out only once or twice a year. Any rules that overlook those differences could unfairly burden farms like mine with unnecessary compliance costs.
I also want to highlight the very real challenge of managing disease outbreaks like HPAI. Our farm has been directly impacted by HPAI, and it turned our entire operation upside down. During a disease event, we can't just move manure or clean barns when we want —those decisions are dictated by quarantine protocols from the Board of Animal Health and USDA. The updated rules must allow flexibility during disease outbreaks.

As someone who has made significant capital investments in our farm in recent years, the financial burden of meeting new regulatory standards is top of mind. Independent growers don't have corporate backing—we carry the risk ourselves. Every change in regulation impacts our ability to stay viable. I urge the MPCA to consider how any changes to these rules affect real farmers on the ground.
Minnesota's turkey farmers are already doing their part to protect water, soil, and air quality. What we need now is a regulatory framework that respects the work we're doing—and gives us the flexibility to keep doing it.

Tim Miller · Citizen · (Postal Code: unknown) · Jul 17, 2025 8:20 pm
1 Votes

As someone who raises turkeys in Minnesota, I want to share my concern about any changes to the animal unit factors in the 7020 feedlot rules that were referenced during recent meetings. The current turkey animal unit factors fit industry standards across the country. Turkeys are not raised differently based on their size or sex, so there's no reason to create more categories - the current stocking densities are already based on current animal unit categories.
What's more important is that turkey manure is very different from liquid manure. Treating all manure the same just doesn't make sense. A one-size-fits-all regulation might work on paper, but it causes problems on farms.
I hope MPCA will stick with the current animal unit factors for turkeys and keep the rules practical for farms of all scopes and sizes.

Ross Greden · Citizen · (Postal Code: unknown) · Jul 17, 2025 10:41 pm
2 Votes

Winona County's Pleasant Valley Creek and Beaver Creek were once listed by MPCA to be "Impaired Waterways" but were de-listed in 2024 due to strong conservation practices by landowners and farmers. This surface water success story will take time to trickle down to the aquifers – science says it may take 30+ years in some cases due to the Karst topography. The city of Altura, MN sealed its old city well in 2024 and partnered with the Winona County SWCD to create a video of groundwater flow. This video documents water flow between aquifers via old abandoned wells – the high-nitrate aquifer is directly contaminating the low-nitrate aquifers below. Historically, Minnesota's rural farmstead settlers dug shallow wells with shallow (or nonexistent) well casings. In the 1800's and early to mid-1900's underground cisterns were created in close proximity to outhouses (there were many decades without indoor plumbing). The nitrates generated by the outhouses leached directly into the underground aquifers via the adjacent well pipe. In this regard, and in response to EPA concerns, the MPCA has a duty to partner with MDOH to create a multi-faceted approach to reducing nitrate contributions from all sources. Abandoned wells need to be located and sealed. Out-of-compliant septic systems and old well casings and wells need to be brought up to code. These pollutant sources are regulated only by the MN Department of Health, but they are equal contributors to nitrate groundwater contamination. At the June 26, 2025 Chatfield MPCA presentation, MPCA's Steven Schmidt presented this scientific statement, "Hundreds to thousands of fish kills are reported every year in Minnesota. 9 out of 10 fish kills have NOTHING to do with agriculture." At the same meeting, MPCA's George Schwint referenced a 2014 Nutrient Reduction Strategy with online reporting of surface water nitrate trends from 2003 to 2022 with NO TREND DETECTED in SE MN.

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NPDES or SDS permits should not be required for feedlots less than 1000 AU. UW Madison studies have shown the annual economic impact of one dairy dairy cow in a small community is more than $30,000 per cow. Minnesota needs all the cows it can get, especially if the goal is vibrant small towns with feed mills, repair shops, tractor dealerships, veterinary clinics, banks, schools, milk truck drivers, custom harvest crews, and etc. It should be noted that MN farmers are producing milk and meat commodities – Minnesota's dairy farms (98% are family-owned) must compete directly with Kansas and Texas dairy farms with 20,000+ dairy cows on the same farm, in a regulatory environment where those MN farms are not allowed to grow in size. SE MN topography has abundant Highly Erodible Land (HEL) classifications and very little Non-Highly Erodible Land (NHEL). Heavy rainfall events require contour stripping, grass waterways, cover crops, conservation tillage, and crop rotations that include alfalfa and perennial forages. Cows are the best tool for converting these forages into milk and meat. If the cows go away, then row crops will dominate the landscape, and the nitrate leaching will increase from 6.6mg/L to 22.3mg/L (SE MN Nitrate Strategies Collaborative Work Group) when alfalfa/corn is replaced with a corn/soybean rotation. Feedlots with less than 1000 AU should not be required to have 9 months storage unless tax dollars pay 100% of the cost (roughly $700 to $1000 per cow). The average Minnesota farmer is older than 55 years old – the smaller to medium sized farms will be unwilling to start over with nearly a million dollars in new debt that will provide them with zero Return On Investment (ROI) – this will greatly expediate vertical integration in the industry. Land application of manure on frozen or snow-covered fields should be allowed for bedding pack manure sources on NHEL fields. This is best for animal welfare. Feedlots under the same ownership in close proximity to each other should see no rule changes. Less than 3% of our family dairy farms survive until the 5th generation. As long as all sites are in full compliance, they should be left alone. After all, the farmers and their children and grandchildren drink the groundwater too, and none of them desire dead fish. "We lose 10% of our dairy farms each decade. And every decade, dairy farm size doubles" – Marin Bozic U of MN professor. More regulations on our dairy farmers will only accelerate this disheartening trend. Planting cover crops was unheard of 20 years ago. As mentioned earlier, two MN "Impaired Waterways" have been de-listed in the past two years - the new conservation practices are working! Science says that we need more time to prove it.

Trevor Russell · Citizen · (Postal Code: unknown) · Jul 18, 2025 3:58 pm
1 Votes

Please see the attached comments from Friends of the Mississippi River on the MPCA's Animal Feedlots Rule.

Response:
Gary Dukes · Citizen · (Postal Code: unknown) · Jul 20, 2025 1:23 pm
Your attached comments make excellent points.

Jean Greenwood · Citizen · (Postal Code: unknown) · Jul 19, 2025 8:12 am
0 Votes

This matters a lot to me. As a Minnesotan concerned about water quality in our state, I appreciate the MPCA's work to update the animal feedlots rule and urge the agency to

make it stronger. Large areas of the state, especially in vulnerable regions like southeastern Minnesota, are struggling with water quality issues caused by nutrient runoff, to which feedlot manure is a big contributor.

I ask that the MPCA take the following steps:

Lower the size for a feedlot operation to be required to apply for a water pollution permit. Currently, many feedlots skirt greater regulation by operating just under the permitting limit of 1000 animal units, this should be lowered to no more than 600 animal units.

Require feedlots with those permits to closely monitor their manure discharges to protect nearby groundwater and streams.

Set stricter limits on manure application to farm fields in vulnerable areas, like the heavily nitrate-polluted karst region in southeastern Minnesota.

Change how multiple small feedlots with the same owner are regulated. Currently, an owner of multiple feedlots, even feedlots right next to each other, can skirt stronger regulations by keeping them as “separate” operations, though the total pollution is the same as a large feedlot.

Require more rigorous reporting on manure transfers.

Make more manure managing data and mapping available to the public, including information about digesters and manure spreading plans.

Minnesota’s lakes, rivers, and groundwater have been getting more polluted every year. This is a chance to take a step in the right direction rather than continuing business as usual. Thank you!

Bonnie Haugen · Citizen · (Postal Code: unknown) · Jul 19, 2025 10:39 pm

0 Votes

Farming is Everybody’s Bread, Butter, and Water. What I do on my farm truly affects the quantity and quality of water for all. CAFO feedlots greatly concern me because of the concentration of manure, nitrogen applications and water use. It is good to examine feedlot rules that are 25 years old.

There should be a statewide cap of 1,000 AUs per feedlot. I am concerned about having too many CAFO’s too close together for manure overload and water use. So, could there be a maximum density of an area using the watershed boundaries? That would take into consideration all the animal units, no matter what building site or farm business entity is responsible.

In karst geology, any feedlots over 300 animal units (AUs) need to have a water pollution permit. In non-karst, feedlots over 600 AUs need to have a water pollution permit.

In karst, feedlots over 300 AUs need to have any discharge to ground water monitored. In non-karst, feedlots over 600 AUs need to have ground water monitored. This includes drain tiles and any possible leakage from a manure storage structure.

Land application of manure should be stricter and monitored more closely, especially in karst. Manure application rates should not be allowed to exceed the agronomic rate in Vulnerable Groundwater Areas. Manure lagoons shall have cells and the cells should not exceed 250,000. Manure storage unit placements need to take into consideration the joints and fractures in karst, not just the sinkholes.

CAFOs should be responsible for any township road expenses beyond their normal expenses.

CAFOs should be responsible for any neighbor property values lost due to the CAFOs operation.
Air quality needs to be monitored on a constant basis, the monitoring equipment owned and maintained by the state. Procedures for violations of air quality be taken seriously, and be taken care of as soon as possible. Violators need a reasonable and fair amount of time to remedy the problem, but should not be allowed to have continued offenses of clean air.

Water is a resource we all need. And we should all have fair access to safe water. Because of my concern that CAFOs can take more water faster than the aquifers can recharge, I wonder about limiting the water any business or CAFO can draw. Setting a reasonable limit would take much work and consideration, but I think it could be done. Further, monitoring the water use of each CAFO would take more equipment, but if it protects the water usage for all of us, it will be a worthwhile expense.

We need to look at the permitting requirements of each CAFO site, and we need to also keep in mind the effect when numerous CAFOs are on the same watershed and aquifer. The accumulation of too much of anything anywhere can allow problems that either can’t be undone, or will take decades or more to remedy.

I was a dairy farmer for thirty years. We transitioned the farm and now I am a beef farmer. I understand that regulations, changing and adding rules can be onerous. Feedlot owners and managers may not like the needed time, effort and expense to work with additional rules. I know farmers are innovative and are very capable of adjusting and abiding by any rules put in place to clean up and maintain safe water above ground and underground for all of us. Farmers, families, livestock, and plant life depend on safe water for living and surviving. Feedlot rules are one of the places that affects our water. We need feedlot rules and protocols to protect our water, air, and neighbor’s basic needs.

Thank you for your attention to the feedlot rules in Minnesota.

Brad Hovel · Citizen · (Postal Code: unknown) · Jul 20, 2025 12:22 pm
0 Votes

I am for clean water and air, as a farmer I consume the water and air that surrounds my livestock farm. There is no need to open up and change the current 7020 rules, these rules have shaped the livestock production in Minnesota. If a famer has fewer than 1000 AU they can choose to get a NPDES permit, which offers them civil protections. As the way we handle and store manure has evolved over the years we are able to more precisely apply and incorporate the manure into our crop nutrient needs. Successful farmers are using “Best Management Practices” that work on their individual farms. On our farm we spring apply some liquid manure on certain fields because it is the best agronomic practice, not because of a Rule. Significant changes to the manure application and storage requirements will create many new challenges. The pure capital cost of additional manure storage is burdensome. MPCA needs to be service to the farmers of Minnesota not rule changers and enforcers. As I’m writing out these comments for a rule that is already comprehensive and scientific based it is taking away time from me spending time with my family because, there is farm work that needs to be done, oil changes, greasing equipment, and most importantly caring for the livestock we raise.

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Gary Dukes · Citizen · (Postal Code: unknown) · Jul 20, 2025 1:08 pm
1 Votes

Minnesota prides itself on its pristine natural environment. However, this cherished identity is increasingly threatened by the unchecked proliferation and expansion of concentrated animal feeding operations, commonly known as CAFOs. These industrial-scale livestock facilities generate prodigious amounts of manure, posing a grave and escalating risk to the state's invaluable water resources. A moratorium on new feedlot construction and expansion in Minnesota is not merely a precautionary measure; it is a critical necessity to safeguard public health, protect aquatic ecosystems, and preserve the state's environmental heritage for future generations.

The sheer volume of waste produced by feedlots is staggering. While manure can be a valuable fertilizer, its immense quantity, coupled with increasingly industrialized agricultural practices, often leads to over-application on land. This excess manure, rich in nutrients like nitrogen and phosphorus, can then seep into groundwater or run off into surface waters, unleashing a cascade of environmental and health problems.

One of the most insidious hazards associated with feedlots is nitrate water pollution. Nitrogen, a key component of manure, readily converts to nitrate when it interacts with soil microorganisms. Nitrate is highly water-soluble, meaning it can easily leach through the soil and into groundwater, contaminating wells and aquifers that supply drinking water to countless Minnesotans. The problem is particularly acute in regions with karst geology, like southeastern Minnesota's Driftless Area, where porous bedrock allows contaminants to quickly reach groundwater and sensitive trout streams. Similarly, central sands regions are highly vulnerable. Furthermore, nitrate can naturally convert into nitrous oxide, a very potent greenhouse gas.

The health implications of nitrate-contaminated drinking water are severe, especially for vulnerable populations. The federal drinking water standard for nitrate is 10 milligrams per liter (mg/L), a limit primarily set to prevent methemoglobinemia, or "blue baby syndrome," a potentially fatal condition in infants under six months old where the blood's ability to carry oxygen is impaired. However, emerging research suggests that even nitrate levels below this federal standard, such as 5 mg/L or even 3 mg/L, are associated with increased risks of other serious health issues, including certain cancers (particularly colorectal), thyroid problems, and adverse pregnancy outcomes. For many Minnesotans relying on private wells, especially in rural areas, the threat of nitrate contamination is a constant concern, often requiring them to seek alternative, costly sources of clean drinking water.

Beyond human health, nitrate pollution wreaks havoc on aquatic ecosystems. Acting as a potent fertilizer in water bodies, nitrates fuel excessive algal blooms. When these algae decompose, they consume vast amounts of dissolved oxygen, leading to oxygen depletion and creating "dead zones" where fish and other aquatic life cannot survive. This can result in widespread fish kills, devastate sensitive trout populations, and fundamentally alter the ecological balance of lakes and rivers. Increased nitrates also stress adult fish, making them more susceptible to disease and impacting their reproductive success, and can reduce the availability of aquatic insects crucial for trout food.

The current regulatory framework in Minnesota has proven inadequate in addressing the

escalating scale and impact of modern feedlot operations. While large feedlots are required to obtain state and federal permits, the vast majority of Minnesota's feedlots are smaller and operate with less stringent oversight. Even for permitted facilities, challenges remain in enforcing manure management plans and ensuring that manure is applied appropriately to prevent runoff and leaching, especially with increasingly unpredictable and extreme weather events. Heavy rainfall can lead to overflows from manure storage basins or wash recently applied manure directly into waterways.

A moratorium on new feedlot construction and expansion would provide a crucial pause, allowing the state to thoroughly re-evaluate and strengthen its feedlot regulations. This time could be used to:

Update and enhance manure management rules: This includes stricter limitations on manure application in vulnerable groundwater areas, requiring more frequent and comprehensive monitoring of fields where manure is applied, and promoting practices that minimize nutrient runoff and leaching.

Invest in sustainable alternatives: A moratorium could incentivize research and investment in manure processing technologies that convert waste into valuable products, reducing the need for land application and mitigating pollution risks.

Support smaller, diversified farms: By slowing the trend towards industrial-scale operations, a moratorium could create a more equitable agricultural landscape that supports smaller, diversified farms with more sustainable manure management practices.

Assess cumulative impacts: The piecemeal approach to feedlot permitting often fails to consider the cumulative environmental impact of multiple feedlots in a watershed. A moratorium would allow for a comprehensive assessment of these impacts and the development of regional strategies.

Protect environmental justice communities: Feedlots are often disproportionately located in low-income and rural communities, leading to environmental justice concerns regarding air and water pollution. A moratorium would offer a chance to address these inequities.

It's crucial to recognize the significant externalized costs of current practices. The costs of environmental degradation, public health crises, and the need for expensive water treatment systems are ultimately borne by taxpayers and affected communities. Furthermore, sustainable, regenerative agricultural practices can offer long-term economic benefits by preserving natural resources and fostering resilient local economies.

In conclusion, the urgency for a moratorium on feedlot construction and expansion in Minnesota is undeniable. The pervasive threat of nitrate water pollution, the detrimental effects on aquatic ecosystems, and the inadequacy of existing regulations demand immediate and decisive action. A moratorium would not only protect Minnesota's vital water resources and the health of its citizens but also provide a much-needed opportunity to forge a more sustainable and responsible path for the state's agricultural future. The time to act is now.

Gary Dukes

Tim Harder · Citizen · (Postal Code: unknown) · Jul 20, 2025 5:53 pm

0 Votes

small organic farmers

It is understood that water quality is paramount. It should also be understood that farmers do take care to preserve the environment, water supply, and resources as all of these are critical to the success of a farmer. Farmers do not want to negatively impact the assets used in the business and to do so would be contrary to the sustainability of the farmer.

There are different issues in different parts of the state due to geographical differences. Why would the entire state be forced to implement rule changes that are not relevant or appropriate in all geographical types? This approach is generally problematic and creates unintended consequences due to a blanket approach versus targeted plans for the various watersheds and geography.

While focus on agriculture is appropriate, why is there not also a focus on population centers and government entities related to water shed and flows? The Star Trib wrote an article that shared that rain gardens implemented in Minneapolis made the water quality worse and made the phosphorus issue worse. This is a small microcosm of metropolitan areas with the chemicals used on roads, lawns, households, industries, etc. Why is it that there is no shortage of water studies in rural areas and not in cities? We need to continue to work to enhance water quality and a question that needs answering is how much of the water quality issues come from farming and how much from cities? Are we focusing on the lowest hanging fruit to make the most change? With only part of the equation, we don’t know if we are being as effective as possible?

Additionally, why would the limit to N of 195 lbs apply only to manure, an organic matter material, and not to commercial fertilizer? Again, why is there such a narrow focus on agriculture and not population? Why is there a narrow focus on manure source N and not all fertilizer? Why is there not a wholistic statewide approach to understand where the challenges are? There have been multiple posts regarding draining city sewage treatment plants emptying into rivers which were approved by MPCA. It certainly feels as though it is a do as I say not as I do approach, and we need to better understand the why. Were there studies and or data points when the MPCA allowed cities to do this? Was there a measurement of the impact of doing so since the MPCA knew this would be done? Seems like a good opportunity to document the impact of doing so.

Regarding setbacks from water features this is something that farmers are concerned with. Farmers do not want to see manure go into waterways as they are concerned with the environment because they live and use water features in their “neighborhoods”. It is also economically foolish and therefore not motivation to do so as there is value in the manure as an organic matter nutrient. I do have concerns with changing the application rules to increase the distance as these rules are applied without consideration of the area, field, geography, time of year, application process. An example is we followed the setback rules for the placement of a hog barn even though there was a county road with no culverts in the area. Meaning, how will the manure rise to the level of flowing across the road and then another 800 feet into a water feature? Additionally we are not in a flood or earthquake zone and the cement pit is sealed. So to leak would create some cataclysmic event where manure leaching would be the least of all of our problems.

Farmers understand rules, we are at a loss of words for complete lack of common sense and willingness to look at a situation to see if it is legitimately required. Another example is having to place a buffer between a water feature and the field when the water feature has a bank that is six feet higher than the field. Again, lack of common sense and willingness to look at the situation.

In organic farming we do not utilize commercial chemicals and fertilizers. There is a suggestion that N be limited to 195 lbs per acre which is problematic for organic farmers that use organic matter such as manure. Since it is organic matter, it takes time for the soil (microorganisms) to break down and release the N, which only 75% is useable the first year. By limiting this we will have smaller crops and not fully use the full potential of the land as well as create potential shortages along with higher prices for consumers. The UofM extension service I believe has recently updated their recommendation for N to 210 lbs / ac in relation to the advancement in farming methods and seed capabilities. With the addition of organic matter to the soil it enhances and improves the soil health. The use of manure has been an effective, betterment, ecologically sound practice that our farm has used for over 75 years.

As organic farmers we use manure which is best to spread in the fall when soil temperatures are 50º which allows the N to be stabilized and not move until needed in the spring. With a suggestion of not starting application until October 1st this will create problems with our Minnesota weather and winters. There are products that conventional farmers can use which allows application before this date and will hold the N so it does not move. If this rule were in place, it will significantly shrink the window of opportunity for application. Many farmers use professional applicators who know the rules and provide an ecologically safe and efficient process to apply manure. As organic farmers, we want to go when it is colder and therefore, we are at the end of the list for application. The last two years we were applying manure right before Thanksgiving. With this smaller window I am extremely concerned that we will not have ours applied until early to mid-December when the ground is too frozen to incorporate which means it would have to be surface applied. This is a less effective method for both the environment and effectiveness of N utilization. Our likely only alternative is to purchase our own equipment which is extremely expensive and not affordable for our small farm operation.

As human beings there are dishonest farmers out there as there are dishonest politicians, dishonest government employees, and dishonest environmentalists because we are all human beings. We do want to stop these individuals from continuing to hurt the environment, but we do not want to regulate based on the 1% exceptions that may exist and create problems. I know in my “neighborhood” the farmers understand that soil and water are the two most important aspects of the farm with the land being the single most capital-intensive asset. No farmer wants to apply manure or any other product on their land that will be wasted or ineffective. Farmers are some of the most protective of nature that I have found. We cherish it, we live in it, and we want to maintain our ability to have this way of life. Wasteful economic decisions do not contribute to the achievement of this way of life.

Thomas Schwarz · Citizen · (Postal Code: unknown) · Jul 20, 2025 9:51 pm
1 Votes

As a young turkey farmer I’m asking the MPCA not to change the animal unit factors for

turkeys. Changing the animal unit rules won't help the environment—they'll add layers of unnecessary beauracracy and burden for farmers.
Turkey manure isn't a liquid. It's dry and easier to handle than other types. The risks are different, so the rules should be too. Please don't include turkey farms in a system that wasn't made for us. I hope MPCA sticks with the current rules that are already working for turkey farms.
Thanks for listening.

Erica Sawatzke · Citizen · (Postal Code: unknown) · Jul 21, 2025 6:34 am
1 Votes

As a Minnesota turkey farmer, I'm asking the MPCA to keep the current animal unit calculation for turkeys as it is. On turkey farms, we manage our birds—regardless of sex or weight—the same way. Our manure handling, housing, and nutrient management systems are based off of stocking densities from the current animal unit categories for turkeys, not whether we're raising hens or toms. Creating more animal unit categories adds complexity without improving the environment.
It's also critical that MPCA understands how different turkey manure is from other livestock manure. Turkey litter is a dry mixture of manure and bedding, and it's stored indoors during the flock cycle. Our current management practices minimize runoff risk. A one-size-fits-all rule designed for lagoons or liquid systems doesn't fit litter-based systems like ours and shouldn't be applied across the board.
Another major concern is biosecurity and disease outbreaks, which are unfortunately common in the poultry industry. During events like HPAI, farms are placed under quarantine, and we often cannot move manure or clean out barns on our regular schedules. The rules must allow flexibility for in-barn storage or delayed manure handling during these times. Disease response is coordinated with the USDA and Board of Animal Health, and any rule that ignores this would risk undermining emergency protocols and biosecurity.
Minnesota's turkey farmers care deeply about protecting water, soil, and air quality—but we need rules that are science-based, practical, and flexible. I hope MPCA will keep that in mind as they review the current 7020 rules. Thank you.

Dave Frisch · Citizen · (Postal Code: unknown) · Jul 21, 2025 8:54 am
0 Votes

During the Chatfield informational meeting, the presenters pointed out approximately 90% of the fish kill events do not have a root cause identified. It makes more sense to put resources into figuring out the root cause before creating additional regulations that may not reduce fish kill events.

Comments on the MPCA list of questions:
1. no comment

2. no changes
I am a relatively small row crop farmer and have brought a small number of cattle back to the farm. Any new or additional permitting restrictions will make the cattle enterprise unviable, and the benefits of livestock to the soil health of my farm will be gone

3. The transferred manure should be managed according to the plan or requirements of the farm at the source of the manure. The source animals are covered by existing

regulations and that shouldn't change just because the manure is applied on another parcel.

Do not implement any of the suggestions in the last 4 bullets of this question. I strongly disagree with restrictions on application base on forecasted or predicted rain. The national weather service forecasts are generally good at predicting temperature for the next 2-3 days, but the ability to predict rain with accuracy is not here yet.

4. any changes regarding manure storage structural integrity should be applied statewide to all systems urban and rural. City septic and holding systems should be included and at the same level of scrutiny. If the Dept of Health and MPCA cannot agree on an item, then it should be discarded entirely.

5. No, smaller sites should not be held to the same requirement. The cost for these types of structures would put an end to small scale cattle enterprises.

One may counter that cost sharing is available for these structures. However, multiple contractors have stated that a project cost basically doubles when it is a government cost share project due to the extra documentation and time required to accomplish the end result.

6. No change. Encourage farmers to work with the local NRCS and Soil & Water Conservation offices.

7. During the Chatfield meeting, the presenter mentioned the current "rule of thumb" is if the distance between lots is more than 1/4 mile it is treated as a separate feedlot.

If more clarity is needed, use the 1/4 mile distance between lots and add a clause that if the property tax parcel identification number is different for the adjacent feedlots they are treated as separate feedlots.

8. Put resources into determination of the root cause before creating more restrictions. "Treat the cause, not the symptom."

9. As a farmer, the manure has value, it is not waste material, and it gets applied such that it provides the most value to my crops.

Dallas Knobloch · Citizen · (Postal Code: unknown) · Jul 21, 2025 9:05 am

1 Votes

MPCA Comment letter
The Rock Nobles Cattlemen are a group of men and women working together to promote, advocate and support the cattle industry in our Rock and Nobles County. Certainly, we would like to begin our comments by thanking you for giving us this opportunity to express our thoughts about the 7020 animal feedlot rules in Minnesota. The thought of change and more regulations always brings a level of anxiety but by collecting a wide array of opinions and ideas hopefully a good plan can bring us to our goals. We appreciate your time and consideration on this matter.
First and foremost, we truly feel that the current 7020 rules go a long way in correcting and reaching our goals of reducing groundwater contamination. One of the biggest issues we see is the lack of education among farmers and ranchers regarding our current rules. Knowing when to haul manure, testing manure prior to application, and applying

correct amounts are some of the first topics that come to mind. When to haul and not to apply manure during those critical months is so very important and many producers simply do not know the rules. The current 7020 animal feedlot rules are adequate, there just needs to be more education and resources for farmers and ranchers. Funding, adequate labor force and time seem to be a problem in many faucets of today business, but this is truly the best investment of our tax dollars, not more regulations. We feel more regular farm visits with county soil and water officers and county meetings helping to understand that region's concerns and rules would see great benefits. More regulations without education only allow for a more severe penalty if enforced.

For producers that have moved from 999 AU to over 1000AU, the many extra steps are very eye opening to them. There seems to be a stigma in Minnesota that if a facility stays under 1000 AU there are no rules that apply, but this is not true. Proper management is included in the current rules. Education is very critical and providing the funding and personnel for this to be done at a local or regional level is of utmost importance!

We brought up the local control and regionalization with county SWCDs and we feel that this is an important topic. Minnesota is made up of very different landscapes and soil types. Regionalizing areas according to the soil types, climate, and areas of sensitivity reduces unnecessary regulations that can truly be a burden to those facilities that have a far reduced chance of pollution based on their specific region. Rock and Nobles County have excellent SWCDs offices and their knowledge of the area and what works for others is truly helpful on their visits.

Proper manure storage as application windows are narrowed is continually becoming a concern among feedlot owners. This is an area that MPCA must be aware of, and the economic resources needed if all we are met with are more regulation and no solutions. Offsite manure storage and transferring this valuable and sustainable resource must be considered. This is a heavy burden for our farmers and ranchers, and this should not be left to them to shoulder.

The Best Management Practices that have been voluntarily added among our farmers and ranchers are very noticeable. The use of cover crops to tie up nutrients and add species to a rotation, strip tilling and incorporating liquid manure directly into these strips and reducing the amounts needed are examples. Flow meters, scales and the use of GPS on application equipment allows very precise use of this valuable nutrient. Composting of solid manure is also becoming more common also. Focusing Minnesota's resources and education in this area will reap the greatest benefits to all our Natural Resources.

Over regulation can truly be a heavy burden to the animal agriculture industry. Financial burdens that lead to a decrease in our industry have a great effect on the state's economy. The industry has made great strides in reducing our impact on the environment due to runoff and leaching. Building higher organic matter soils, increasing water infiltration, reducing tillage, increasing the use of cover crops are just a few to be named. Let's keep building on these positive impacts by using the current set of rules that we currently have and provide education and funding to keep moving us forward.

Sincerely
Rock and Nobles County Cattlemen

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

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Tom Salkowski · Citizen · (Postal Code: unknown) · Jul 21, 2025 10:37 am
0 Votes

Please accept the attached as my comment on this matter.

Robert Karls · Citizen · (Postal Code: unknown) · Jul 21, 2025 10:44 am
0 Votes

Any industry or business that stores materials which have the potential to impact ground water quality have a requirement to do inspections, testing, and monitoring.
The storage of manure in amounts typical of feedlot operation is typically in semi-solid or liquid form in lagoons, pits, or tanks. Any storage of manure in these types of structures with capacities over 5000 gallons individually, or cumulatively within ¼ mile shall be required to have ground water monitoring plan approved by the MPCA. All ground water monitoring plans shall:
1. Have no fewer than 4 monitoring wells installed within 100’ of the perimeter of the outer boundary of the storage structure or container where manure would typically be present. The four wells should be installed in a manner that the well screen must be a minimum of 10’ long and spans the seasonal fluctuation of the water table at the Site. (Due to the uncertain direction of ground water flow at the time of installation and seasonal variations fewer than 4 wells are not allowed).
2. A permit from the commissioner (MDH) is generally required for the construction, deepening, and modification of monitoring wells, including at feedlot locations.
a. A single permit application can cover all monitoring wells on a single property used as release detection devices at a feedlot location.
b. Construction Standards:
i. Monitoring wells must be constructed according to Minnesota Rules 4725.6650.
ii. Casing: Must be steel or plastic casing meeting specific standards, including stainless steel or flush-threaded PVC under certain conditions.
iii. Grouting: The annular space must be grouted from near the screen to the ground surface, with specific requirements for at-grade installations.
iv. Drilling Fluids: Must comply with relevant standards, with an exception for free chlorine residual.
v. Screen or Open Hole: Specific requirements apply to monitoring wells constructed to monitor contaminants at the water surface across unconsolidated formation and bedrock contact.
c. Maintenance Permits:
i. Environmental wells (monitoring wells) constructed after January 1, 1990, that are not sealed within 14 months require an annual environmental well maintenance permit.
ii. These permits are required for all environmental wells, and a single permit application can cover those on a single property.
iii. The permit must be renewed annually until the well is sealed.
d. Sampling and Analysis:
i. Groundwater elevations must be monitored in all monitoring wells semi-annually.
ii. Groundwater samples must be analyzed semi-annually for nitrates, fecal coliforms, and total dissolved solids, and other parameters as identified by the MPCA.
iii. Results of each semi-annual water level elevation measurement and sampling event must be submitted to the MPCA within 90 days of the semi-annual measurement and sampling event.
iv. Laboratory data must be generated by MPCA-recognized certified laboratories.
v. Documentation of sampling events, including specific details about the well sampling

procedures, identification of the sampling personnel, and chain of custody for all samples are required.

Robert Karls · Citizen · (Postal Code: unknown) · Jul 21, 2025 10:48 am
0 Votes

posted comment in Word

Steve Sjostrom · Citizen · (Postal Code: unknown) · Jul 21, 2025 11:18 am
2 Votes

I am writing here in opposition to any stronger regulations to feedlots under 1000 animal units. Any stronger regulations will cause more small farms to disappear. The economics are not there to force more regulations on these size farms. Farmers are constantly improving their practices to do a better job of protecting groundwater and making better use of nutrients for crops. They can't afford not to. New precision ag products are becoming available all the time and farmers will continue to use these as they become available but don't over regulate and create more paperwork. Soon you will cause more small farms (under 1000 au) to disappear and more small towns and businesses to not be able to survive. Farmers are good stewards of the land and the water, they have to be, because they live with it each and everyday!

Glen Groth · Citizen · (Postal Code: unknown) · Jul 21, 2025 11:41 am
1 Votes

Please review the attached comments on behalf of Winona County Farm Bureau.

Response:

Marlin Fay · Citizen · (Postal Code: unknown) · Jul 22, 2025 8:11 am
The Mower County Farm Bureau fully supports these well thought out comments from the Winona County Farm Bureau.

Alison Leathers · Citizen · (Postal Code: unknown) · Jul 21, 2025 12:41 pm
0 Votes

I am writing to ask the MPCA Feedlot Rules update to include:
1. More rigorous groundwater monitoring requirements for National Pollution Elimination System (NPDES) and State Disposal System (SDS) permit holding feedlots.
2. More rigorous reporting for transferred manure, and including winter application regulations for new permits.
3. Lowering the threshold for feedlots to obtain NPDES and SDS permits to 600 animal units to prevent the common regulatory issue of feedlots being built right below the current threshold to avoid the more stringent requirements that come with permitting. This is an issue that has been recognized by the MPCA.
4. Changes to how a collection of small feedlots all under the same ownership structure is permitted. We are requesting that rather than being permitted individually, they are permitted collectively.
5. Updating the new manure management plan mapping tool to include more

information about spreading plans and manure infrastructure like digesters. This information should always be made available to the public, not just to potential permitees while they are creating their manure management plan.
I am making these suggestions to the MPCA as a farmer (we raise sheep on 55 acres in Fillmore County) and as a manager of a tourism-related business. These two industries, agriculture and tourism, greatly fuel the economies of Fillmore County, in the heart of Minnesota's karst geology and the most susceptible area to the effects of feedlots, manure, and nutrient management on our soil health and water health. As a graduate of the U of MN in sustainable agriculture, I was quickly taught and learned that agriculture is a human-made system, it is not perfect, and agriculture must constantly find ways to be sustainable for economic, environmental and social reasons. We have better science and collaboration in the last 25 years where we must make changes to the feedlot rules that are a balance to serve agriculture, tourism, human health, and livability. Please consider my suggestions above from the lens of a Fillmore County resident who farms, manages a small hotel, and chooses to raise my young family here. My, and so many of my neighbors', livelihoods and human health are directly tied to how we manage our feedlots and manure, and those effects on our soil, water, wildlife, livestock, and human health. We must balance these interests to ensure our delicate ecosystems in southeastern Minnesota continue to be livable for humans, plants, and animals; and we can continue to thrive.

Andrea Szabo · Citizen · (Postal Code: unknown) · Jul 21, 2025 1:06 pm
1 Votes

Submitting on behalf of White Earth Nation, please find attached letter.

Bryanna Grefthen · Citizen · (Postal Code: unknown) · Jul 21, 2025 1:07 pm
0 Votes

Please see attached comment letter.

Melissa Lorentz · Citizen · (Postal Code: unknown) · Jul 21, 2025 1:29 pm
0 Votes

Please see the attached comment submitted on behalf of the Lower Sioux Indian Community.

Paula Maccabee · Citizen · (Postal Code: unknown) · Jul 21, 2025 2:17 pm
1 Votes

Please see the attached comment submitted on behalf of WaterLegacy.

Michael Madigan · Citizen · (Postal Code: unknown) · Jul 21, 2025 3:03 pm
0 Votes

Please see the attached comment comment letter. Mike Madigan

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Norm Herron · Citizen · (Postal Code: unknown) · Jul 21, 2025 3:07 pm

0 Votes

Dear Rule Coordinator Addison Otto,

I understand that Minnesota animal feedlot rules have not been updated for 25 years. In that time the number of animal feedlots has increased many fold. Now is a critical time to rewrite these rules and stop toxic nitrate pollution in Minnesota's waters. I am very concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including

respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Linda Herron
2617 E 5th St Duluth, MN 55812-1536

Response:

Jill Nelson · Citizen · (Postal Code: unknown) · Jul 21, 2025 5:58 pm

There actually are not scientifically based levels for nitrate poinsoning. The truth is, if you lower nitrates too low in water systems, you will cause real toxic harm in the form of increased Blue green algae blooms and Methylmercury levels which WILL harm humans.

Ben Lilliston · Citizen · (Postal Code: unknown) · Jul 21, 2025 3:20 pm

0 Votes

The Minnesota-based Institute for Agriculture and Trade Policy is pleased to submit the attached comment on the updating of Minnesota's Animal Feedlot rule. Much has changed since the rule was last updated 25 years ago. Thanks for considering these comments.

Dianna Jax · Citizen · (Postal Code: unknown) · Jul 21, 2025 3:31 pm

0 Votes

Please see attached letter

Shannon Watrin · Citizen · (Postal Code: unknown) · Jul 21, 2025 3:47 pm

0 Votes

Please see my comments attached.

Lori Schneider · Citizen · (Postal Code: unknown) · Jul 21, 2025 4:10 pm

1 Votes

#1, how is the permitting process going to help reduce pollution? i think it will be zero.
#4, if winter manure application is prohibited, small farms will bear the brunt of the regulatory cost. Large newer CAFOs are built to hold large amounts of manure. Small farms typically are not. Do we want to keep small farms around or do we want to regulate them out of existence? Funding must be made available to build storage facilities for small farms otherwise we will only have large ones. In terms of application on saturated ground, the weather conditions take care of that point. When a soil is fully saturated, there is no way your are taking a manure applicator into that field. Unless the farmer enjoys getting stuck and compacting his land!
To your point #6, Lake in the Minneapolis & St Paul area have been closed do to e coli and there are no feedlots near those areas. Farmers always get blamed when they are

actually one of the smaller contributor to the pollution problem. Farmers value the nutrients they receive from field applied manure and do not want to lose any of it. They take precautions to assure this. COVER CROP: Farmers depend on ideal weather to grow and harvest their crops. No one can control the weather. It a cover crop requirement was implemented, it would be done after harvest and manure application. The crop has to be harvested in order to make money so that is the first priority, or there wouldn't be any farms!! The manure also has to be applied before the ground freezes so seeding a cover crop would have to be the last then done in fall. Then often times it would be too late in the year for that cover crop to grow and be of any benefit. It is just not possible and to expect a farmer to do that before completing harvest. It would be financially devastating. It would also put a huge burden on farners in the form of equipment costs, time spent, supplies purchased and labor costs. I feel farmers are an easy target to blame for water pollution and that is not fair. Municipalities have dumped massive amounts of raw human sewage into Minnesota waters. That is far worse than the small amount of cattle manure that may get in. I believe that implementing these changes because it "Might" improve water quality is not right. There need to be more proof that it is cattle manure causing the problem. The drainage ditch buffer strips imposed on famers has cost them money in maintenance and loss of productive land. I don't believe that was thoroughly thought out before hand and also that it has not improved water quality. These proposed MPCA changes will put an undo financial burden, especially on the small family farm. Think this through thoroughly and do not make it harder than it is to get into farmers by unnecessary regulations.

Todd Selvik · Citizen · (Postal Code: unknown) · Jul 21, 2025 4:15 pm

2 Votes

I have grown up in Agriculture. My family was raising livestock many years before I took over the family farm. We are raising our children on the farm, just like I was raised. The biggest goal of all livestock farmers is to make the lives better for the next generation. We do that by treating our animals humanely, taking care of the land, working hard, and following the rules. The MPCA has worked extremely hard to produce clear, comprehensive, and concise rules that are easy to follow by all livestock producers and manure applicators across the state. The current rules make sense for everyone and are easy to understand and follow.

Family farms work hard to be great stewards of the land. We go above and beyond the current rules when they are applicable and we always follow them. Just like most other farms, we adhere by the best management practices policy. We are very concerned about runoff and leaching, because it is bad for the environment and it cost us money. We have been using Nitrogen Stabilizers during our manure applications for over a decade to ensure the nutrients get and stay where they belong, in the soil for the crops. We make sure setbacks are observed and we only apply manure when the environmental conditions are appropriate. Fall manure applications allow us to have the biggest and best window for the most effective application of manure for the soil and the environment. If we are forced to apply manure in the spring, there are greater chances of accidents, spillage and runoff, and it will be a huge addition of workload and cost. During spring field work, our timelines are maxed out. We can barely get a crop planted. If we are forced to apply manure during that timeframe, there will be problems. There aren’t enough custom applicators to hire to spread manure and there isn’t enough time to both plant the crops and apply manure. There will be more instances of entire farms not getting planted, leaving fallow fields with manure applied to them causing more issues and financial hardships.

As farmers we constantly deal with hurtles and obstacles to make the lives better for our livestock, our families and our future. If significant changes are made to the rules, it will only make it harder for family farms like mine to exist. If there needs to be changes, please base them off of sound science and experience of industry experts. The new rules should be flexible enough to consider other management techniques and philosophies. Please make the new rules easy to follow, with options to allow for a diversified livestock industry to follow the best management practices. Farmers who work for the future need more tools in the tool box to keep the family farm alive.

Response:

Don Buhl · Citizen · (Postal Code: unknown) · Jul 22, 2025 12:50 pm

These are excellent comments Todd. I hope the comments of people who are doing things well and following the rules will be given strong consideration. Operations like this do not need more rules!

Steve Dick · Citizen · (Postal Code: unknown) · Jul 21, 2025 5:03 pm

1 Votes

It is always good to revisit ways for improvement. There is data that shows that the identification of water issues or fish kills is not identifiable. What is the causal data that is directly linked to farm operations? And the research has not identified if municipalities and cities are the problem either. Therefore, it is premature to suggest rule changes will correct a problem where the source of the problem has not been identified. Nitrates are problematic and what are the contributing sources and impacts of the source(s)?

We have concerns with the suggested idea of manure application date being October 1st or later. Due to fall harvest, weather, and capacity the ability to apply manure limits our window to complete this in the fall. With moisture and maturity dates this often is pushed into the November time frame which can freeze and limit or stop the ability to apply manure using best practices of incorporation.

The suggestion of limiting the N to 195 lbs is contrary to the efficiency and technology of farming now brings. The UofM Extension service is recommending N rates of 210 lbs based on efficiency of use and plant development and depending on the situation this may not be sufficient. Farmers do not want to over apply N as this is a waste of money. There is an economic and yield curve and farmers run their business for profitability and there is not an advantage to overapplying nutrients.

There are currently setbacks in place for manure application regarding water features. These setbacks can be maintained and when incorporating manure should not be an issue as currently set. Manure management plans are already required.

In reference to the suggestion that lagoons need inspections, currently livestock locations are inspected for compliance if they are 300 animal units. This is already happening.

Each geographical area or zone should be identified to separately solve problems if problems exist. If nitrate levels exceed the EPA standard of 10 ppm, enhanced efforts need to be made to keep the water quality safe. There are rules and regulations in place

and farmers do better than this as it is in their and their family's best interest.

The suggestion to apply manure on based on weather forecasts is problematic. As has been noted, relying on rain forecasts from weather apps and the NWS is at best 50/50 probability of being correct. That is why people joke that it would be great to be a weather forecaster because you can be wrong most of the time and still get paid. Please note, it is not their problem, that is how nature works. It is also problematic because the weather can vary five miles apart. Spring of 2024 there were literally farmers planting across the road from each other and one had to stop because of the rain and the other did not. How will any of this be documented to prove that the conditions were fit? Farmers do not want to work land if it is not fit and to do so is economically costly. Compaction of soil is the enemy and if the ground isn't fit this can create a one to three season soil health problem for the farmer.

Applicators are required to maintain manure samples. Farmers are required to have a manure plan. Farmers are required to soil sample to manage nutrient levels related to manure application. Farmers are required to inject manure into the soil or work in the manure within 24 hours of application. Creating more rules when it is not identified where the problem is not a solution. The MPCA has noted that 9 of 10 fish kills are not associated with agriculture, meaning 90% of the problem is not agriculture. We aim to be part of the solution but if we achieved a 0 ppm there will still be a 9 ppm problem and the result will be a significant to impact to the local family farm.

Response:

Don Buhl · Citizen · (Postal Code: unknown) · Jul 22, 2025 12:57 pm
These comments are extremely well thoughtfull and should be taken very seriously! Until MPCA has a handle on the causes of fish kills, no new regulations should be placed on people who are already following the rules and protecting the environment.

Jill Nelson · Citizen · (Postal Code: unknown) · Jul 21, 2025 5:35 pm
0 Votes

Attached are comments put together by the Brown County Farm Bureau.

Pat Troendle · Citizen · (Postal Code: unknown) · Jul 21, 2025 8:25 pm
0 Votes

To: Minnesota Pollution Control Agency
From: Pat Troendle
Business Names: Full Circle Nutrition LLC, Duschee Hills Dairy LLC
Address: 23962 Grosbeak Rd, Lanesboro, MN 55949
Re: Comments on Proposed Changes to Rule 7020 – Feedlot Program
Greetings,
My name is Pat Troendle. I own and operate two agricultural businesses in southeast Minnesota.
Full Circle Nutrition LLC is a ruminant nutrition and biological fertilizer company. On the agronomy side, we work closely with producers throughout SE Minnesota and NE Iowa. Nearly every operation we support either generates manure or utilizes compost products to build biological activity in the soil. Regardless of operation size, manure is a resource —not a waste product.

Duschee Hills Dairy LLC is our 190-cow dairy farm located in Lanesboro, MN. We manage 560 acres across 92 different fields. Our crop rotation includes about 300 acres of corn and 260 acres of alfalfa, and we follow every corn silage crop with a five-species cover crop. We adhere to a manure management plan developed with our county feedlot officer and are very aware of our region’s environmental sensitivity.
I attended the MPCA meeting held in Chatfield this June. Although no final decisions were presented, it was clear that certain regulatory changes are under serious consideration. I'd like to share a few thoughts, mainly from the perspective of a ruminant livestock operation.

1. Animal Unit Threshold Changes

The idea has been raised to add a fourth regulatory category and increase the requirements under 1,000 animal unit (AU). While I understand the intent is to apply stricter manure storage and application requirements to more operations, it's important to acknowledge that most livestock farms already strive to manage manure responsibly. Ideally, they would have 14 months of storage and apply manure during a narrow window of perfect conditions—but that’s simply not the reality we live in.
If regulators move forward with creating this new category, it is critical to consider the large number of farms that would be newly impacted and the serious economic consequences that could follow. For many of these operations, especially small to mid-sized family farms—the cost of building additional storage, upgrading infrastructure, and complying with stricter application requirements would be overwhelming. In many cases, these improvements would be financially unfeasible and could ultimately force farms out of business.
Any new policy must carefully balance environmental objectives with the economic and operational realities on the ground. Without that balance, we risk accelerating the demise of independent farms and further consolidating the livestock sector, with long-term consequences for rural communities and food security.

2. Limitations on Fall Manure Applications (Soil Temp <50°F)

Restricting fall manure applications based on soil temperature (e.g., below 50°F) is impractical. On our farm, we apply manure after corn silage harvest to make room in our storage basins and to establish fall cover crops in a timely manner.
Fall manure application has key advantages:
• Timely nutrient placement
• Reduced spring workload
• Tillage and incorporation reduce runoff risk
• Freeze-thaw cycles help alleviate compaction
When managed properly, manure incorporated in the fall is a stable and effective nutrient source for the next growing season.
One important issue that wasn’t addressed is that all manure types appear to be treated the same under the proposed changes. However, there are significant differences between liquid manure, bedded pack, and compost. These differences affect not only nutrient availability to plants but also the potential for nutrient loss through runoff or leaching. Bedded pack manure—and especially compost—pose a much lower environmental risk due to their physical form and how nutrients are stabilized within the material.

3. March Application Ban

The suggestion to ban manure applications in March may sound reasonable in theory, but it is unrealistic in practice. March weather in Minnesota is highly variable—conditions can indeed be snowy and wet, making application inappropriate. But just as often, the ground is still frozen, fields are dry enough to support equipment, and conditions are

actually well-suited for responsible manure application. Prohibiting all March applications would force farmers to wait until April, compressing both manure application and spring planting into an already narrow and often unpredictable window. This not only creates significant logistical challenges but could also result in missed opportunities to apply manure under ideal conditions, simply because the calendar says it's too early._____

4. Infrastructure and Time Limitations

The above proposals to temperature and dates assume that farmers have access to unlimited time, labor, and infrastructure. The reality is:

• There is not enough infrastructure (storage, equipment, or labor) to meet such tight timelines.

• Building sufficient storage and logistics capacity would require billions in investment.

• Even with investment, time and variable Minnesota weather remain the biggest limiting factors.

Ruminant operations like Duschee Hills Dairy serve as environmental stewards by using crop rotations which include alfalfa to minimize soil loss and efficiently utilize applied nutrients. Practices such as vegetative buffers, grassed waterways, and low-disturbance manure injection are already used by many producers to mitigate runoff risk

We are not alone, many similar farms across Minnesota do the same. If these operations are regulated out of viability and replaced by continuous row crops or residential developments, the result could be declining soil health and even increased nitrate levels —the very issues these rule changes are trying to prevent.

If Minnesota is serious about improving manure management, then it must be equally committed to funding infrastructure upgrades—such as expanded storage, low-disturbance application equipment, and local composting capacity—so that farmers have the tools needed to comply

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5. Nitrate Levels and Blame

While misapplication of manure can contribute to water quality concerns, the nitrate test maps presented at the meeting appear to correlate more closely with population density than with confirmed agricultural sources. Without reliable source tracking, we must be cautious about placing the full burden of blame on agriculture. Are we asking farmers to solve a problem that we can't definitively trace to their practices—and that we currently don't have the tools to accurately measure?

Furthermore, there has been little detail provided about how the necessary infrastructure improvements will be built or funded. If stricter regulations are going to be proposed, there must be a realistic plan for implementation. Rather than focusing solely on manure application restrictions, we should also consider investing in broader water protection strategies—such as replacing old, shallow wells, which may serve as significant nitrate entry points. A more balanced, evidence-based approach would provide better long-term outcomes for both water quality and the farming community.

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Conclusion

Thank you for the opportunity to comment on these important issues. I support responsible management and environmental stewardship. However, the proposed changes risk placing unrealistic burdens on producers without the necessary tools or support to comply effectively. I urge MPCA to continue working closely with farmers to find practical, science-based solutions that balance environmental protection with agricultural viability.

As someone actively managing a ruminant operation in a sensitive area, I would welcome the opportunity to serve on any future stakeholder or advisory group working on practical rule development.

Sincerely,
Pat Troendle

Ann Thier · Citizen · (Postal Code: unknown) · Jul 21, 2025 8:48 pm
0 Votes

July 21,2025
Office of Administration Hearing
Attn: William Moore
600 N Robert S. PO Box 64620
St. Paul, MN 55164-0620
(transmitted electronically)

RE: Comments on MPCA Rule Amendments Chapter 7020

Dear Mr. Moore,

My name is David Thier and I own and operate a feedlot near Rushmore in Nobles County. I am sending you comments in regards to the MPCA Rules Amendments.

I would first like to thank you for the opportunity to comment. I feel that we as an industry have made great progress in protecting our waters through manure management plans, buffer strips, and overall best management practices. I feel our continued efforts have made improvements. I would however, like to comment on what we cannot do.

Winter time hauling for outside feedlots in Minnesota isn't something we might do. It is a necessity. The prohibition of March hauling is already nearly impossible, let alone proposing a ban on all winter hauling. What, might I ask, should one do with the material (manure and snow) collected and piled during this time? Stockpiling is not an option. I've tried this firsthand, and the material which piled in the winter melts into a puddle of slop that seals the ground on which it sits, making it nearly impossible to manage.

The pollution potential seems much higher to me, than just managing it as we need through the winter. I would strongly urge you to reconsider your ban on March hauling, and continue to let us use best management practices, setbacks and flat slopes for winter application.

The tranferral of manure and its current requirements is also concerning to me. I feel that the state has gone too far in making the recipient of the manure subject to the feedlot owners MMP. While I first question its legality, I also wonder if this won't be enough for those neighbors who had previously purchased manure, to just say "it's not worth the hassle!" Through overly aggressive regulatory reach, we once again achieve a regressive result. Producers who once hauled on neighbors' ground, now have the same manure to apply on less acres.

My question to you, is what part does the livestock industry play in the overall picture of water quality? We are already one of the most regulated states for livestock production, and are at a comparative disadvantage to our neighboring states. Why is the livestock industry singled out as the sole culprit? Is it not possible that row crop operations,

municipalities and lawn fertilization of city residents, could also be a large contributor to nutrient runoff?

In summary, I feel we, as livestock producers and landowners, do a good job in land and water stewardship. We raise our families here, and want to preserve our home. Our operations are family owned and operated, yet we compete not just nationally, but globally. Through this lens, I believe Minnesota has no large livestock operations.

The state thinks that 1000 animal units is large, but in reality this is not so. If we continue to put burdensome requirements on our producers, the family farm will disappear. I struggle with whether I should advocate for my sons to return to the family's operation as 4th generation operators, or give up like so many others and say “you win.” The problem with over regulation, is that it is mostly carried out by those who have never produced. I truly hope that unlike my many other previous comments to MPCA, these comments will have some positive effect.

Sincerely,

David Thier

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brian johnson · Citizen · (Postal Code: unknown) · Jul 21, 2025 9:25 pm

0 Votes

I raise pork, corn and soybeans in southern Redwood county. As I have pursued this endeavor for many years many changes have occurred that can help the environment. We sample our soils in small grids so as to apply the correct amount of nutrients while at the same time manure is applied at economical rates that help us produce a corn crop the next year. Manure is incorporated into the soil and manure is tested so the proper amount is applied. Manure is a valuable organic resource. Over application is avoided to protect water quality and prevent nutrient loss due to the weather. If necessary a minimal application of fertilizer is applied prior to corn planting. Also over application is very unwise for economic reasons.

Where we farm spring application is less than desirable as compaction will occur which will
lead to runoff. We use no till on some of our acres so as to help with water infiltration in subsequent years. We also practice limited tillage which leads to improved soil tilth aiding infiltration of water.

As I have built new buildings and remodeled buildings the feeders for pigs have been selected to limit water and feed wastage. New buildings are designed to aid in comfort for the pigs which helps with water usage and manure production.

I am not what one would call an environmentalist, but am very careful how I treat the land I farm. Hopefully I leave the land in good stead for the next generation.

Adam Barka · Citizen · (Postal Code: unknown) · Jul 21, 2025 10:00 pm

0 Votes

Please find the attached comments. Thank you.

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

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Bonita Underbakke · Citizen · (Postal Code: unknown) · Jul 21, 2025 10:42 pm
1 Votes

I was born and raised in Karst Country and live in Fillmore County, Holt Township. I'm alarmed by policies that continue to allow more application of N than our crops can use, resulting in rising levels of nitrates in our wells.
Rule 7020 needs to be strengthened to adequately protect our groundwater. I support the comments from Responsible Ag in Karst Country (RAKC) and add that the cells of manure lagoons need to have double liners with leak detection systems that would indicate leakage and prevent further contamination of our drinking water.

Sonja Trom Eayrs · Citizen · (Postal Code: unknown) · Jul 21, 2025 10:44 pm
0 Votes

I am a farmer's daughter, attorney and author of 'Dodge County, Incorporated: Big Ag and the Undoing of Rual America.' The long, enduring fight to force corporate restructuring of rural America started years ago—one corporate factory farm at a time—aided primarily with the assistance of Republican-aligned Farm Bureau. In 1993, the first area swine factory farm was installed in 1993 by the son of a Farm Bureau farmer. During the mid-90s, as area hog farmers delivered their animals to market at Hormel Corporation in nearby Austin, Minnesota, farmers noticed that wait times were taking longer and longer for local independent farmers, as semi-loads of hogs from area factory farms were rushed through the plant and given priority. 1998 was the breaking point for independent farmers, as they were no longer able to deliver hogs to market.

The multinationals cleverly reorganized the marketplace and created a pyramid scheme. Today, multinationals such as Hormel, Brazilian-owned JBS, Chinese-owned Smithfield, Tyson and others occupy the top tier of the pyramid. Integrators such as Christiansen Farms, Holden Farms, Schwartz Farms, Pipestone Systems, Prestage, Iowa Select, and others occupy the middle tier of the pyramid and own the supply chain and provide feed and veterinary services to contract growers at the bottom of the pyramid. Contract growers, once known as farmers, occupy the bottom tier of the pyramid. Forced to "get big or get out," famers were compelled to construct a large factory farm in order to compete and participate in this closed market. While thousands of independent farmers were forced out of the marketplace, that son of a Farm Bureau farmer built a second swine factory farm one mile north of our farm in 1998. Today, our family farm in rural Dodge County is surrounded by 12 swine factory farms in a 3-mile radius.
The act of forcing factory farms into rural areas is part of the coordinated, deliberate and intentional corporate effort to force corporatization of rural areas. Working with Republican-aligned Farm Bureau to cement corporate control of rural areas, industry giants used a combination of market power and political power to turn rural areas bright red politically with the blood of dead corporate animals. In the process, farm families have been pushed off the land, hollowing-out neighboring small towns desperate to survive.

This devastating hollowing-out is nowhere more evident than rural Minnesota. During my youth, my hometown, Blooming Prairie, was a bustling community, sharing an attitude of abundance and kinship. When bread was broken, there was enough for everyone. The town boasted two grocery stores, local banks, two drug stores, a dime store, several restaurants and implement dealers, a furniture store, two clothing stores, local barber shops, a doctor's office, a dental office, a liquor store, a pool hall, local accounting firms

and other businesses on the lively main street as local dollars circulated in the small community.

A healthy interdependence permeated the community as residents bought local products and supported local businesses—long before corporate giants constructed factory farms and extracted wealth from the rural area, divided the farming community and created a sick dependency upon industry giants. Succumbing to the corporate takeover that shuttered Main Street in a single generation, local businesses eventually closed their doors.

One-by-one they closed their doors—schools, churches, restaurants and stores.

In this void, dollars that once circulated in Blooming Prairie and other small towns have been stripped, the profit landing on the corporate balance sheet. Dollars have been funneled to multinational corporations which enjoy billions in corporate profits. Never content with corporate performance, “man is the only animal whose desires increase as they are fed; the only animal that is never satisfied.”

In the wake of this corporate takeover of rural areas, manure management of these large industrial operations has been shifted to contract growers at the bottom of the pyramid. One cannot help but admire the thoroughness of the contract that binds contract growers. Contracts frequently specify that growers are required to indemnify and hold the integrator harmless if any claim, cause of action, demand, or regulatory proceeding is commenced or if there is any loss to the integrator on account of manure storage, manure application, dead pig disposal, public or private nuisance, pit pumping and/or cleaning of the facility, operation of the facility or acts or omissions related thereto. Most contract growers have no idea how to manage the millions of gallons of manure that must be spread on the land.

CAFO manure is an uncontrolled environmental disaster. Some CAFO operators only own a few acres theirs CAFOs sit upon, so they enter into what are called "manure easement agreements" with area farmers who agree to take the manure to spread on their nearby fields. In Dodge County, the county is required to take input about feedlot proposals from the pertinent township officers before the pertinent public hearing. We discovered, however, that three township officers signed manure easements contemporaneous with approval of a large swine factory farm just 1/2 mile west of our farm. Something stinks in Dodge County and other rural counties, and it's not just the pigs. Not all bribes take the form of cash in brown envelopes passed under the table. They can take many forms: gift certificates, prepaid credit cards, free travel and entertainment, free meals, or other noncash transfers. Offering free manure to be spread on an elected official's land is an easy non-traceable method to encourage officials to fast-track factory farm approval. No checks. No bank wires. No cash. No paper trails. Just a trail of stench - and I'm not talking about the manure.

In the fall of 2017, I participated in fall harvest with my elderly father. For three consecutive days, neighboring swine factory farm operators spread manure immediately adjacent to our farm. No notice to neighboring farm families, while factory farm operators receive an exemption to spread dangerous levels of manure during pump-out, threatening the lives of neighboring farm families from the toxic gases emitted from these facilities. As my father worked long hours to finish fall harvest, manure spreading occurred within feet of the combine my father expertly maneuvered through the field. He was eventually overcome by dangerous hydrogen sulfide emissions. Forced to step off the combine to vomit, he was sick for days thereafter, likely due to hydrogen sulfide

poisoning.

That weekend, curious to see the manure-spreading activities up close, my husband panicked as a manure hauler nearly ran our vehicle off the road. That weekend, I personally received two visits from the Dodge County Sheriff's Department. Neighboring swine factory farm operators made bogus calls to the sheriff's department, not to report some infraction, but to put the heat on me and get me to shut up.

Over the years, my family has faced tremendous harassment and intimidation as we speak out against industry operatives, including bullet holes shot in the stop sign just hours after my brother and I pulled weeds from the neighboring bean field just feet away, soiled blue farm booties strategically planted every 100 feet or so from the neighboring swine factory farm to our driveway (a reminder that the industry is large and in charge), pure Roundup sprayed on the corn field which caused thousands of dollars in damage (the perpetrator hit the neighbor's field across the road, not our field), harassing phone calls in the middle of the night to my elderly father, and other heavy-handed tactics to silence my family.

My family is not alone, The tactics employed against my family are the same tactics that have been employed against other farm families across the Midwest. But, the industry will do whatever it takes to silence families like mine, including engagement of the Animal Agriculture Alliance, a pro-industry group that watches the activists.

My family has been on the frontlines for years fighting corporate agriculture. We know many of the games that are played by the industry, including (1) the spreading of manure during the middle of the night, as no one knows where and no one knows how much manure is spread on the land, which eventually seeps into the groundwater and area waterways; (2) double-pledging of land for more than one factory farm; (3) failure of local factory farm operators to file manure management plans with the local feedlot officer; (4) failure of factory farm operators to secure water appropriation permits, as these large industrial operations strip millions of gallons of water from the aquifers each year; and other infractions.

For years, we could not drink the water at my husband's family farm on the north end of Dodge County, while neighboring swine factory farms drink pristine water from wells dug over 400 feet deep. Nitrate levels at my husband's family farm and other neighboring farms increased to 24 mg/l, 25 mg/l, and 26 mg/l, far in excess of the safe threshold of 10 mg/l. Eventually, my husband's family had to install a reverse osmosis system at their own expense to strip nitrates from the water.

Just one mile north of my husband's family farm, there is a road which the locals refer to as "Cancer Road." On this one-mile stretch, every single-family reports extremely high nitrates and every single family has been impacted by cancer. The combination of high nitrates and cancer is no surprise to many, as the neighbors fought installation of a large swine gestational facility that is situated at the corner of Cancer Road (County Road B) and Highway 7. Several years ago, the neighbors fought installation of this large gestational facility, which serves as the hub for several area factory farms. Situated on sensitive karst topography, Dodge County officials (then part of the MPCA Delegated County Program) nonetheless recommended approval of this facility in this region known for limestone outcroppings, sinkholes, natural springs, fissures and other characteristic landforms.

Today's corporate agriculture system requires a complete overhaul, including (1)

imposition of steep fines on the multinationals at the top of this pyramid scheme for failure to attend to environmental cleanup from these large industrial operations; (2) imposition of steep fines for failure to file manure management plans; (3) imposition of rules which require factory farm operators to provide ample notice to neighboring farm families regarding the spreading of manure from these industrial operations; (4) reversing the exemption that is extended to factory farm operators during fall "pump-out;" (5) prohibiting local county and township officials from signing manure easements with area factory farm operators; (6) directing local county and township officials to immediately disclose all manure easements with area factory farm operators and the amount paid, if any, for the receipt of manure from area factory farms; (7) immediate review of the MPCA Delegated County program, including abuses associated with this program; (8) immediate re-installation of the MPCA Citizens Board; (9) immediate hiring of additional personnel at the MPCA and other regulatory agencies; and (10), other measures, as appropriate to arm the regulators with appropriate oversight and methods to secure compliance.

I welcome the opportunity to serve on the MPCA Citizens Board or similar board charged with oversight of industry giants.

Sonja Trom Eayrs
Farmer's daughter, attorney and author, Dodge County, Incorporated: Big Ag and the Undoing of Rural America

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William Kuisle · Citizen · (Postal Code: unknown) · Jul 21, 2025 11:37 pm
0 Votes

In 2002 I was chief author of a bill that made the 2000 rules workable. This bill passed the Republican controlled House and the DFL controlled Senate and was signed by the Governor. Through the hearing process we heard time and time again how the rules would put smaller farms out of business. We probably slowed down the exodus of small farm but the bleeding continues.
Since I left the MN House in 2004 I have operated a cattle finishing operation that is permitted up to 300 AU. First thing I want to make clear is the banning up spreading manure in winter months is unworkable. The manure pack in barns has to be managed and that includes the removal of the pack. During time in the winter when you have warmups above 32 degrees the manure pack warms and gives off smell that causes respiratory infections in animals. The easiest way to avoid using drugs is to clean the barns and apply the manure to the field. It is not as simple as piling it until spring. Without a pad that is made to contain the runoff you accomplish nothing. And that is where a huge expense comes in that in todays markets is not financially doable. As we learned in the hearings in the MN House this type of rules puts the small operators at a huge disadvantage and will only speed up operators leaving the business.

Any additional rules the burden operators financially will cause a greater exodus from livestock farming. The average age of livestock farmers has them approaching retirement. I'm 67. We are not going to leverage our equity when we know our sons and daughters have no chance of making it with additional rules. It is just easier to let the big guys (that can spread the cost over more AU) have the headaches.
This is not to say that we do nothing. About 10 years ago I was one of the first to go through the MN Agriculture Water Quality Certification Program and met the requirements. Programs that work with farmers are far superior than ones that use a stick. Blaming farmers for all fish kills when most can't be explained is not fair. There are

groups out there that are using process as a way to destroy animal agriculture. We are not going to sit back and let that happen.
William Kuisle
Olmsted County

Aaron Bishop · Citizen · (Postal Code: unknown) · Jul 22, 2025 12:12 am
0 Votes

Regarding Animal Feedlot Rule, Minnesota Rules, Chapter 7020

Recommendations from Responsible Agriculture in Karst Country

Our citizen group (RAKC) was successful in 2018 in convincing our neighbors and state regulators to reject a large Confined Animal Feeding Operation from being constructed in our community, due primarily to concerns about water quality in our karst region of Fillmore County.

Our input to this feedlot rule will focus on the delicate and usually unseen dangers of karst landscapes. Strict investigations and rules must be enacted before animal feedlots are permitted and before manure disbursement takes place, in order to preserve the public health of all local citizens.

Rationale for Strengthening MN 7020 Rule Regarding Karst Vulnerability

The current Minnesota Rules Chapter 7020, while attempting to regulate animal feedlots and manure management, falls short in adequately protecting groundwater in karst regions like southeastern Minnesota. The core issue lies in the unique hydrogeology of karst, which facilitates rapid and direct pathways for surface contaminants to reach underlying aquifers.

Pervasive Karst Goes Beyond Just Sinkholes: Karst is often visually recognized by dramatic features like sinkholes and caves. However, these are merely the most obvious expressions of a much more pervasive geological phenomenon. Karst landscapes, especially in the Driftless Area of southeastern Minnesota, are characterized by soluble carbonate bedrock (often limestone and dolostone) that has been extensively dissolved by slightly acidic water over geological timescales. This dissolution primarily occurs along existing joints (fractures) and bedding planes within the rock. Karst features are often also found in overlying or underlying sandstone layers; the St. Peter and Jordan Sandstone are primary aquifers for the southeast region of Minnesota.

Near-Surface Joint Sets (Karst Lineations): Networks of bedrock fractures that extend upwards to within a few feet of the ground surface, are often lying beneath a thin soil cover. During dry periods, these joints allow plants to access moisture deeper within the bedrock, leading to patterns of denser, greener vegetation known as "karst lineations" or "crop lines." These lineations are not just curiosities; they are direct evidence of highly permeable pathways that bypass the filtering capacity of surface soils. Water, sediment, and pollutants can rapidly infiltrate through these subtle yet widespread features, directly into the underlying fractured carbonate and sandstone aquifers.

The Arbitrary Nature of Current Rules: The existing 7020 rules, with their fixed setback distances (e.g., 300 feet from a sinkhole) and quantitative triggers (e.g., 4 or more sinkholes within 1,000 feet), are insufficient because they do not fully account for this

pervasive, interconnected nature of karst. A contaminant traveling through a discreet joint or conduit can traverse hundreds of feet in a short period, rendering arbitrary linear distances ineffective. The real vulnerability lies in the hydrogeological connectivity which often extends far beyond visible features or simple numerical thresholds. We now have the knowledge and tools to investigate whether a feedlot or manure application area is vulnerable to excessive pollution of groundwater.

A well-managed presence of animals on the landscape, particularly through practices like rotational grazing and distributed manure application, can significantly improve soil health and water quality by building organic matter, enhancing infiltration, and cycling nutrients naturally. However, the rapidly increasing scale and concentration of confined animal operations (CAFOs) present a fundamentally different and more challenging scenario. These operations concentrate vast quantities of manure, creating an immense nutrient load within a limited geographical area. The old adage, "Dilution is the solution to pollution," holds a profound truth in this context. When pollution levels become too high – when the density of a contaminant source overwhelms the landscape's natural capacity to assimilate or filter – the only effective strategy to protect our shared resources is to decrease the density of the source itself. In the context of concentrated animal agriculture in a highly vulnerable karst environment, this means critically evaluating and, where necessary, limiting the concentration of animal units and associated manure within sensitive geographical areas. This document outlines a set of urgent, scientifically-backed recommendations to strengthen Minnesota Rules Chapter 7020, aiming to protect these critical aquifers for generations to come.

Therefore, strengthening MN 7020 is critical to transition from a reactive approach (addressing pollution after it occurs) to a proactive one (preventing pollution by recognizing and protecting all vulnerable karst pathways).

Recommendations to Improve the 7020 Rule

(1) Agronomic rates for manure applications should be customized for particular soil and geological types, highlighting sensitivity to nutrient-loss.

Relevance: The current understanding of "agronomic rate" often focuses solely on maximizing crop yield, which has demonstrably led to excess nutrient application and subsequent nitrate leaching into groundwater. This issue is critically amplified in karst regions where there is little natural filtration.

Reasoning for Public Comment: Scientific Necessity: Different soil types (e.g., sandy vs. clayey) and underlying geological formations (e.g., fractured limestone vs. thick till) have vastly different capacities to retain or leach nutrients. A "one-size-fits-all" agronomic rate fails to account for this variability.

Environmental Protection: Customizing application rates based on nutrient-loss sensitivity means applying only the amount of nutrients the crop can realistically utilize, given the soil and geological context. This minimizes the excess nitrogen available for leaching, directly reducing the load on vulnerable aquifers. In karst areas, this is paramount to prevent nitrate contamination of drinking water sources. Both manure and fertilizer applications need to be customized.

Economic Efficiency for Producers (Long-Term): While initially perceived as a burden, more precise nutrient management can reduce input costs over time by preventing the waste of expensive fertilizers that are simply lost to the environment. It shifts from

"insurance" application to "precision" application.

(2) Create a Karst Vulnerability Assessment for new or expanding CAFOs that will ensure karst sensitive regions are qualitatively and quantitatively reviewed.

Relevance: The current rule's reliance on arbitrary distances and sinkhole counts is inadequate for truly protecting complex karst systems. A comprehensive, scientifically rigorous assessment is needed.

Reasoning for Public Comment: Accuracy and Effectiveness: While a significant portion of southeastern Minnesota's aquifers is widely recognized as highly sensitive and vulnerable, the precise nature and degree of karst vulnerability is highly site-specific. This underscores the critical need for detailed, localized assessments. A comprehensive Karst Vulnerability Assessment would use multiple, state-of-the-art techniques (e.g., advanced remote sensing, geophysical surveys, detailed drilling, dye tracing) to qualitatively and quantitatively map the actual pathways of water flow to the aquifer. This moves beyond assumptions to data-driven decision-making.

Targeted Protection: By identifying specific "high-vulnerability zones" based on robust scientific data, resources can be more effectively targeted for protection, ensuring that the most sensitive areas receive the highest level of scrutiny and protective measures. This avoids over-regulating low-risk areas while under-protecting critical ones.

Proactive Planning: A karst vulnerability assessment allows for proactive land-use planning and siting decisions, preventing new pollution sources from being placed in extremely sensitive areas where remediation is difficult or impossible once contamination occurs. Existing feedlots of 300 and up AU should also be sent information about karst vulnerabilities discovered in the Karst Vulnerability Assessment.

(3) All Nitrogen sources must be considered in nutrient management plans (not solely manure, nor just synthetic fertilizers).

Relevance: Farmers apply nitrogen from various sources (synthetic fertilizers and manure). If only one of these sources is accounted for, the total nitrogen load applied can still significantly exceed crop needs, leading to leaching.

Reasoning for Public Comment: Complete Nutrient Budgeting: To truly manage nitrogen effectively and prevent excess, multiple forms of nitrogen entering the soil system must be accurately quantified.

Minimizing Surplus: By comprehensively accounting for N sources, nutrient management plans can ensure that the total available nitrogen aligns more precisely with crop requirements, minimizing any surplus that is highly prone to leaching, particularly in karst areas.

Environmental Accountability: This ensures that the environmental impact of nitrogen is considered holistically, promoting a more responsible and sustainable approach to nutrient use that directly benefits groundwater quality. Drinking water supplies will be better protected as well.

(4) Place a cap on animal units within a geographical area, within state-defined and recognized sensitive regions. This will aim to cap and/or lower the density of animal units to decrease the source of nutrients that are leaching into groundwater.

Relevance: Even with stringent management practices, a very high density of animal units in a highly vulnerable karst landscape generates an immense volume of manure and associated nutrients, increasing the cumulative risk of groundwater and surface water contamination.

Reasoning for Public Comment: Source Reduction: This measure directly addresses the source of potential pollution. By capping the density of animal units such as in defined sensitive karst regions, the overall nutrient load (nitrogen and phosphorus) being generated and potentially applied to land in these vulnerable areas is reduced.

Carrying Capacity of the Landscape: Every landscape has a finite carrying capacity for nutrient assimilation, especially in karst where natural filtration is limited. This rule acknowledges that some areas are simply too sensitive to safely accommodate very large concentrations of animal agriculture without incurring unacceptable health and environmental risk.

Preventing Future Cumulative Impacts: This proactive measure would help prevent the exacerbation of existing groundwater quality issues and protect currently unaffected areas from future degradation due to an unsustainable density of nutrient sources.

(5) Monitor air quality, to ensure standards are met, using instruments the state pays for and has access to.

Relevance: While water quality concerns are paramount, feedlots are also significant sources of air pollutants (ammonia, hydrogen sulfide, particulate matter, volatile organic compounds) that impact public health and can contribute to environmental degradation.

Reasoning for Public Comment: Public Health Protection: Feedlot emissions can negatively impact the respiratory health and general well-being of nearby residents. State-funded and operated monitoring provides independent, unbiased data to assess compliance with air quality standards and protect public health.

Accountability and Transparency: State-managed monitoring ensures transparency and accountability, providing objective data for regulatory enforcement and informing community concerns about air quality impacts from feedlot operations.

(6) Cap well size usage for feedlot operations to discourage aquifer overuse (drawdown).

Relevance: Large-scale feedlot operations, especially those with many animal units, can have substantial water demands for drinking, waste flushing, and cooling. Excessive groundwater pumping can lead to aquifer drawdown, impacting other well users nearby, increasing pollution infiltration rates, and may reconfigure groundwater flow direction, thereby expanding the reach of contaminated water to previously unaffected wells and communities.

Reasoning for Public Comment: Sustainable Water Resources: Minnesota's aquifers are a shared public resource. Putting a cap on well size or, more broadly, limiting annual water appropriations for large feedlot operations helps ensure the sustainable use of groundwater for the larger impacted region, preventing excessive drawdown that can deplete aquifers and impact domestic wells, municipal water supplies, and connected surface waters.

Shared Responsibility: This measure ensures that large industrial agricultural operations contribute to the responsible management of water resources, just as other large water users are regulated. It encourages water conservation practices within feedlot operations.

(7) Restrict Liquid Manure Storage Areas to smaller 250,000 gallon cells, within geologically or environmentally sensitive regions.

Relevance: This directly addresses the risk of catastrophic failure of large liquid manure storage areas (LMSAs) in highly vulnerable karst settings, where a rapid loss of stored manure can have devastating, immediate, and widespread environmental and health consequences both above and below ground.

Reasoning for Public Comment: Mitigation of Catastrophic Failure: While sinkholes or liner failures cannot be entirely prevented, limiting the volume of individual cells within a manure containment area dramatically reduces the magnitude of pollution released in a single event. A 250,000-gallon spill, while still serious, is significantly more manageable and less environmentally damaging than a multi-million-gallon release.

Increased Containment Potential: Smaller spills are more amenable to rapid containment and remediation efforts, reducing the spread of contaminants into the broader environment and aquifers.

Risk Management for Sensitive Areas: This cap specifically targets geologically and environmentally sensitive regions (like karst), where the consequences of a large-scale failure are most severe due to direct aquifer connectivity. It prioritizes the protection of vital drinking water sources. Additionally, the line between groundwater and surface water is blurred in karst geology, and such failures can (and have) had major impacts on trout streams which are of huge importance to the local economy and environment.

(8) Polluters pay: Confined Animal Feeding Operations are point sources of pollution, and they are private businesses. They should play by the same rules as every other business if they pollute waters of the state. They should be held accountable for property values of neighbors, road destruction, etc.

Relevance: This principle seeks to shift the financial burden of environmental damage and community impacts from the public and affected individuals back to the polluting entity.

Reasoning for Public Comment: Economic Justice and Fairness: The "Polluter Pays Principle" is a widely accepted environmental and financial tenet. If a private business, regardless of sector, causes harm to public resources (like water or roads) or private property (like neighbor's land values), they should bear the cost of remediation and compensation. This prevents the externalization of costs onto taxpayers and affected communities.

Accountability for Environmental Damage: When CAFOs contribute to nitrate contamination of drinking water wells, they should be held financially responsible for providing alternative safe water sources or for remediation efforts. This aligns with accountability for violating water quality standards.

Addressing Broader Community Impacts: Studies have consistently shown that CAFOs can negatively impact nearby property values due to odors and aesthetic concerns.

Additionally, the heavy truck traffic associated with large feedlot operations can cause significant damage to rural roads, imposing substantial repair costs on local governments and taxpayers. Holding CAFO owners accountable for these documented impacts ensures that the full societal cost of their operations is recognized and addressed.

Respectfully Submitted, Responsible Agriculture in Karst Country

Aaron Bishop, Chair; Bonita Underbakke, Vice Chair; Sue Wiegrefe, Treasurer; Bart Seebach, Secretary; Jenn Ripp, Board Member; Vance Haugen, Board Member; Bonnie Haugen, Board Member; Heidi Eger, Board Member; Loni Kemp, Board Member

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Kay Slama · Citizen · (Postal Code: unknown) · Jul 22, 2025 7:18 am

0 Votes

MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.

MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution.

MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Ashley Kohls · Citizen · (Postal Code: unknown) · Jul 22, 2025 8:45 am

0 Votes

Please see the attached comments submitted on behalf of the Minnesota Turkey Growers Association.

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

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Keriann Cooper · Citizen · (Postal Code: unknown) · Jul 22, 2025 8:47 am
0 Votes

As someone who drinks and swims in Minnesota water, I want the MPCA to enforce safer and stricter policies of animal feedlots to prevent any pollutant runoff. This will not only protect the health of people, but the health of the animals who eat at the feedlots and the health of the watershed. We need healthy animals and healthy ecosystems for us to be healthy too, because all our health is connected.

Marlin Fay · Citizen · (Postal Code: unknown) · Jul 22, 2025 8:55 am
0 Votes

We are NOT opposed to rules and regulations for feedlots in Minnesota. What we ARE opposed to, are rules that are high risk and low reward, meaning the results are projected but not achieved, and they can threaten the existence of animal agriculture in Minnesota. The fact that livestock operations have gotten bigger is not a scenario where “factory farms” have gobbled up small family farms. It is the same economic driver that has caused the loss of the small-town grocery stores, hardware stores, banks and more. It is the economy of scale and size that bring the efficiencies that make them competitive. As costs go higher, farmers need more units to spread the cost over. It doesn’t matter if it is animals, grain, fruit or vegetables. I’m a small farmer and I feel the pinch.
We need common sense rules that have achievable results. We need to keep focusing on the gains that we have achieved, to reach our goal. I live on the farm I run. I’m proud of what I do. It disheartens me when so many people disconnected with agriculture bash an industry that helps provide the safest, most abundant, and lowest cost food supply in the world. Most of the regulations people are proposing here will just aid the demise of the small farmers we have.

Melissa Kuskie · Citizen · (Postal Code: unknown) · Jul 22, 2025 9:05 am
0 Votes

The Minnesota Department of Natural Resources supports the MPCA's rulemaking action updating its feedlot rules to address water quality and avoid fish kills. We look forward to reviewing preliminary rule language and are happy to provide information and assistance to the MPCA throughout its rule development process.

Thank you,
Melissa Kuskie

Scott Hanning · Citizen · (Postal Code: unknown) · Jul 22, 2025 9:07 am
0 Votes

I run a small, family-owned cow-calf grazing operation in Fillmore County's rolling blufflands, which are known for livestock operations. Much of the pastureland in this area is hilly, and highly erodible land, but perfectly suited for grazing. We raise alfalfa and small grains in rotation with corn and soybeans. We have a small (unnamed) stream that meanders through many of our pastures. It would be impossible to fence this; it

stretches miles, and it wanders through sharp hills and sections of solid rock. It will also create many isolated pockets of pasture that cannot be connected -- and without water supply. (Fillmore County has few if any natural ponds, unlike the majority of the state, so livestock have used streams as primary water sources, historically. A blanketed stream fencing mandate will end our cattle operation.

If the state acts to create these barriers, we will be forced to put the land, highly erodible pasture and hay ground, into row crop production. This will be much more detrimental to the Minnesota environment erosion-wise, chemical-wise, fertilizer-wise, pesticide-wise and carbon-wise, compared to the alleged impact of cattle. MPCA has stated that the loss of pastureland, small grains and hay are a loss to the state in terms of environmental impact and in terms of revenue. Please don't impose blanket regulations that will increase this loss and also put small farms out of business.

Frederick Campbell · Citizen · (Postal Code: unknown) · Jul 22, 2025 9:14 am

0 Votes

The MPCA must adopt appropriate rules that limit the maximum size of feedlots for permitting purposes. The rules must not allow any feedlots to be permitted in karst regions or other sensitive areas (e.g. fens). In addition, the rules must consider that feedlots are non-point sources of pollution. Thus, the MPCA must require sufficient monitoring of feedlots and stringent water quality standards to protect surface water and groundwater resources. It is not sufficient for the MPCA to merely consider point source discharges from feedlots. Similarly, the MPCA must require water monitoring to include parameters that fall under MN Rules Chapter 7050, including all classes, including drinking water. Thank you for considering this and all other comments.
Fred Campbell, MPCA hydrologist (retired).

Erik Harris · Citizen · (Postal Code: unknown) · Jul 22, 2025 9:37 am

0 Votes

Thank you for providing this venue on such a vitally important topic on the 40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule. I write to not only support fundamental changes including -
More rigorous groundwater monitoring requirements for NPDES and SDS permit-holding feedlots.
- More rigorous reporting when it comes to the transferring of manure.
- Lowering the animal unit size threshold for feedlots to obtain NPDES and SDS permits to 600 animal units.
- Changes to how a collection of small feedlots all under the same ownership structure is permitted.
- Updating the new manure management plan mapping tool to include more information about spreading plans and manure infrastructure like digesters. This data should be made available to the public, not just to potential permitees while they are creating their manure management plan.

Alternatively to developing additional regulations which will require more cost for the farmer it is vital to look into composting methods as a mean of handling manure in a way that can reduce costs, provide biologically viable inputs that integrates high nitrogen manures that is has high organic matter and improves soil health. In addition to regulation we have provide farmers incentives to find genuine alternatives to address

the needs of the region.

Elizabeth Heublein · Citizen · (Postal Code: unknown) · Jul 22, 2025 9:43 am
0 Votes

Having served on the Winona County Board of Adjustment for several years, I have had the opportunity to to review the history, the science, and the evidence of the nitrate pollution problems in the karste geography in SE MN. From this experience, I have learned that many farmers want to do the “right thing” in protecting our ground water, but not been supported to be able to bring their practices in line with the preventions necessary. The Feed Lot number is only the tip of the iceberg. In addition, we must offer support through education and resources to make the transition to organic regenertive practices. Focusing only on the Feed Lot numbers without tranforming the practices of chemical uses conventional farming uses will not proving a lasting solution. Helping farmers learn how to, for example, use composting as the foundational product for healthy soil and increased productivity will also remediate our present water pollution. With this effort, we must keep the whole scenario in focus. We must “fix” it, not just reduce it.

Theresa Keaveny · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:03 am
0 Votes

I urge MPCA to update the feedlot rules to limit the number of animal units per feedlot to 600 under National Pollution Elimination System (NPDES) and SDS, and to establish a more robust monitoring and enforcement system that protects surface and groundwater of the area. Also, the cumulative effect of livestock feedlots in an area needs to be better assessed before new feedlot permits are allowed, to reduce run off and leaching of pollutants. The consent agreement with MPCA, EPA and MDA offers an opportunity to substantially improve state requirements. It would be helpful to offer incentives to farmers to transition from manure-intensive feedlots to regenerative practices such as managed grazing and pasture-based animal feeding. And, offering free well testing to residents near feedlots, with support to repair or replace wells that are affected by feedlot run off, is long overdue. Thank you for the opportunity to comment.

Lois Norrgard · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:06 am
0 Votes

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule:

As a Minnesotan concerned about water quality in our state, I appreciate the MPCA’s work to update the animal feedlots rule and urge the agency to make it MUCH stronger. Large areas of the state, especially in vulnerable regions like southeastern Minnesota, are struggling with water quality issues caused by nutrient runoff, to which feedlot manure is a big contributor.
This is affecting people in this area, but much overlooked perhaps is that this is also causing a great risk to our “other than human” neighbors. Birds, deer, squirrels, etc., and especially fish and other species living in the water world, need clean water too. They do

not have a choice of filtered water but must drink directly from our streams and rivers, lakes and wetlands.
Several millions of species of teeming life are now under the care of one species – humans. We must have the moral and ethical imperative to value these species as something with a claim to existence in their own right and to ensure their right to thrive and survive into the future.
I ask that the MPCA take the following steps:
• Lower the size for a feedlot operation to be required to apply for a water pollution permit. Currently, many feedlots skirt greater regulation by operating just under the permitting limit of 1000 animal units, this should be lowered to no more than 600 animal units.
• Require feedlots with those permits to closely monitor their manure discharges to protect nearby groundwater and streams.
• Set stricter limits on manure application to farm fields in vulnerable areas, like the heavily nitrate-polluted karst region in southeastern Minnesota.
• Regulate multiple feedlots owned by one owner as a unit not as separate operations. Currently, an owner of multiple feedlots, even feedlots right next to each other, can skirt stronger regulations by keeping them as “separate” operations, though the total pollution is the same as a large feedlot.
• Require more rigorous reporting on manure transfers.
• Make more manure managing data and mapping available to the public, including information about digesters and manure spreading plans.
Minnesota’s lakes, rivers, and groundwater have been getting more polluted every year, this is unacceptable, and we completely rely on the MPCA to protect these resources for all Minnesotans. This is a chance to take a step in the right direction. The present response remains, if not completely negligible, very far from adequate. It is far past time to no longer rely on “business as usual” decision making. It is time to rise to the occasion and take the bold steps needed within this decade.

Scott Winslow · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:14 am
0 Votes

MPCA 7020 Feedlot Rulemaking

No additional restrictions are needed. According to the MN Extension, farmers have reduced manure and fertilizer rates and are now much in line with their recommendations. Farmers are already required to follow setbacks and with the new buffer laws in place adding more rules makes no sense. You still must consider all the problems that do not come from farmers such as wildlife and other people. A lot of the nitrates come from decomposing grass, leaves and other materials and farmers are given the blame.
No, current rules for 1000 AUs are in place. Smaller farmers already must have a manure plan and do manure and soil testing and follow BMP. So, there is no need to reduce the number from 1000. There are current rules on the books and recommendations for fall application of manure. For many of us we must inject the manure and wait till temperatures are below 50 degrees. Let’s all use common sense and please do not strangle us with red tape.
We recently opened and cleaned out a hog manure pit that had been holding manure for 38 years. It was in great shape and showed no signs of cracking. If the engineer does a good job designing the holding structure and checks the quality of the cement or other lining they are using, then there should not be any need for you to make rules on this

matter.
Excessive rules forcing small farmers to pay for long-term storage without the help of the state will force a lot of farmers out of business.
The WRAPS have documents that blame farm livestock for the high nutrients and bacteria in water, but I have seen large flocks of geese as well as other water fowl in the water and along the banks in which you can find a lot of manure that they leave behind as well as the four legged wildlife that visit the streams for a drink.
If a feedlot has a different address, it should be considered a separate facility whether owned by the same person or not.
Fish kills are rare and being caused by a farmer is ever rarer. Promote and encourage farmers to use cover crops when feasible as well as BMP at all times. Many of the fish kills are caused by municipalities flushing out their sewers.
You will have a lot of people making comments and many of those people have never step foot on a farm or ever know a farmer. It is good to get opinions from everyone but please be considerate that it is the farmers who must live with all the new rules, and quite often the rules are not needed, they are written to make a few people feel good. I just read an article in the Star Tribune that stated the Green Gardens that were started in the Twin Cities are showing that a lot more nitrates and extra phosphorus are being generated and going into the storm sewers. It is the exact problem they thought they were going to eliminate. It did help filter out some of the lead and other pollutants, but it increased the nitrate problem. In another story that was just published, migrating birds landed in some dead trees around a lake in the Twin Cities area and they dropped over ten thousand pounds of manure. The local people complain about it but no one has common sense to do anything about it. They say this type of bird only sits in dead trees. All they needed to do was remove the trees but now their nice lake is dead, and they can’t even blame a farmer.

Claudia Oxley · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:26 am
0 Votes

I am writing to strongly request that MPCA feedlot rules are significantly strengthened. The fact is that Minnesota already has a nitrate problem that is killing babies. Groundwater in SE Minnesota in particular is already impacting the health of Minnesotans and without stronger regulation, monitoring and consequences, that part of our state will turn into a sewer that cannot support life. We must do better. I am not a scientist or specialist. I am an average Minnesotan who cares about the livability of our state and the legacy we are passing to ALL our children. The particular rule sections I support changing are as follows (and have been commented on by others):
MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.
MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.
MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.
MPCA rules should stop merely trusting that animal feedlots and manure applications are

“no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.
MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Thank you.

Loren Dauer · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:28 am
0 Votes

Minnesota Farm Bureau Federation appreciates the opportunity to submit comments. Please see the attached document for comments relating to Ch. 7020. Thank you.

Akilah Sanders-Reed · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:31 am
0 Votes

The attached comment has been signed onto by 273 members of the public.

Blair Hoseth · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:35 am
0 Votes

As a livestock farmer in Northern Minnesota I have concerns with the new feed lot proposed rulings. I attended the meeting in Detroit Lakes MN on June 4th and appreciated the open discussion we had. We not only raise beef but we raise our families here we also want safe wells and waterways as well . We have been committed in implementing practices over the years to be compliant with current rules. Our farm is not close to any waterways and we have buffers in place when we spread our manure and till it in right away We also use cover crop on any land we pasture even during the winter which helps with the water infiltration into the soil during rain and snow events and thus less runoff .We feel that changing the feedlot rules will make it more expensive for younger and smaller farmers being profitable in farming. We also feel that any feedlots that are over half mile apart regardless of ownership should be able to maintain their own identities because in the reduction in the concentration of the manure. Being a fifth generation farmer we are stewards of the land that we use to be able to preserve it for the next generation with having blanket restrictions being applied. Thank you for your consideration on these rulings. Blair Hoseth

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

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Emily Erickson · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:40 am
0 Votes

Please see attached comments submitted on behalf of Nobles County Feedlot Owners and Nobles County Commissioners.

John Siekmeier · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:45 am
0 Votes

Please see attached comments submitted by the Minnesota Division Izaak Walton League of America. Thank you.

Veda Kanitz · Citizen · (Postal Code: unknown) · Jul 22, 2025 10:51 am
0 Votes

I am very concerned about water quality in our state, especially in the Karst region of SE Minnesota where nitrate contaminates wells and vulnerable trout streams. I appreciate the MPCA's work to update the animal feedlots rule and urge the agency to protect the public's health and the health of aquatic ecosystems by strengthening them. Nutrient runoff from feedlots are a major contributor to the high levels of nitrates in SE Minnesota. It should be obvious that the current rules are not working.
I ask that the MPCA take the following steps:
Lower the size for a feedlot operation to be required to apply for a water pollution permit. Currently, many feedlots skirt greater regulation by operating just under the permitting limit of 1000 animal units, this should be lowered to no more than 600 animal units.
Require feedlots with those permits to closely monitor their manure discharges to protect nearby groundwater and streams.
Set stricter limits on manure application to farm fields in vulnerable areas, like the heavily nitrate-polluted karst region in southeastern Minnesota.
Change how multiple small feedlots with the same owner are regulated. Currently, an owner of multiple feedlots, even feedlots right next to each other, can skirt stronger regulations by keeping them as "separate" operations, though the total pollution is the same as a large feedlot.
Require more rigorous reporting on manure transfers.
Make more manure managing data and mapping available to the public, including information about digesters and manure spreading plans.
Minnesota's lakes, rivers, and groundwater have been getting more polluted every year. We lost a champion for protecting our trout streams and drinking water this year with the death of Jeff Broberg whose private well became increasingly polluted with nitrates over the years. Please honor his legacy by following the science and strengthening the rules on feedlots.
Thank you,
Veda Kanitz

Akilah Sanders-Reed · Citizen · (Postal Code: unknown) · Jul 22, 2025 11:18 am
0 Votes

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

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Please find attached Minnesota Center for Environmental Advocacy's comments on the feedlot rule revision. Thank you for the opportunity to comment.

Sven Sorge · Citizen · (Postal Code: unknown) · Jul 22, 2025 11:30 am
0 Votes

Dear Sirs and Madams,

MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.
MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.
MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.
MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.
MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Thank you very much for your help!

Lucas Sjostrom · Citizen · (Postal Code: unknown) · Jul 22, 2025 11:35 am
0 Votes

Please find attached comments on behalf of the Minnesota Milk Producers Association.

Don Buhl · Citizen · (Postal Code: unknown) · Jul 22, 2025 11:45 am
1 Votes

I wish to comment on the proposed changes. Fall application is essential to properly utilizing manure nutrients for crop production, avoiding compaction and protecting the environment which is a high priority for us. Fall application allows us to choose a time to apply manure when the soils are cool and in good condition to accept and retain the nutrients applied. Mandated spring application would force producers to compromise because of the time pressure of a short planting window. This would be likely to harm the environment because of increased compaction,increased runoff and the absence of a freeze/thaw cycle after application to condition the soil for crop production. We have had an NPDES permit for many years and have followed the regulations and reporting rules and have preserved our environment.We test our manure and our soils and apply manure in appropriate amounts to raise a crop. We do this on our own land and with the manure we transfer to other landowners. The proposed changes would do nothing to inprove on how we are protecting the envoronment. These changes would only make it harder for us to handle our manure in a way that utilizes the nutrients in a way that protects the enviroment. They may look good on paper, but in the real world this could be a real mess.
Thank you for considering my comments.

Lizzy Haywood · Citizen · (Postal Code: unknown) · Jul 22, 2025 11:50 am
0 Votes

I support changes to the animal feedlot rules and believe the MPCA should update the animal feedlot rules to continue protecting MN groundwater and waterways.
I live near a creek in rural southern MN which is polluted with fecal matter and nitrates to the point it can't be enjoyed for wading or fishing. This sort of degradation of water quality points to the critical nature of updating rules to be relevant to current agriculture practices and to the demands of American consumers and ag trade.
These are the ways the rules should be updated:
1 - More rigorous groundwater monitoring requirements for NPDES and SDS permit-holding feedlots.
2 - More rigorous reporting when it comes to the transferring of manure.
3 - Lower the animal unit size threshold for feedlots to obtain NPDES and SDS permits to 600 animal units.
4 - Change the way a collection of small feedlots all under the same ownership structure is permitted.
5 - Update the new manure management plan mapping tool to include more information about spreading plans and manure infrastructure like digesters. This data should be made available to the public, not just to potential permittees while they are creating their manure management plan.

Throughout Minnesota we can see ways in which improved monitoring and reporting will improve quality of life for our children, our neighbors and the animals. Additionally, by shifting the balance of animal unit thresholds to reduce pressure on our soil and waterways, we will sustain a strong agricultural system and a healthier environment. The MPCA can take steps now to protect many generations in the future.
Thank you for doing this work to improve our great state.

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Olivia Wolle · Citizen · (Postal Code: unknown) · Jul 22, 2025 12:36 pm
0 Votes

I am writing to oppose further regulations on Minnesota feedlots.
Feedlots already follow setbacks for land application and building of new lots.
Farmers deserve the freedom to operate and are diligent in their practices. Using precision agriculture practices farmers are able to apply manure at prescribed rates according to soils samples. Manure is a valuable natural resource used to fertilize crops.
We live where we farm and ensure safe manure practices to keep our family healthy.
Rules now in place are adequate and should stay the same.

Creighton Sauer · Citizen · (Postal Code: unknown) · Jul 22, 2025 1:05 pm
0 Votes

To whom it may concern,

As a multi-generation family farming operation in Southeast Minnesota, the possible changes being considered to the 7020 rules are concerning and are very pertinent to our family's operation.

- As a hog, cattle, and cropping operation, we have manure that we spread in the spring and the fall. We inject most of our hog manure in the fall and do some in the spring. However, we apply the least we can in the spring because spring manure application is harder on crop yields, increases soil compaction, decreases seedbed quality, reduces planting timeliness, and crop evenness. Additionally, bigger rains and wetter soil are much more common in the spring than in the fall. If the rules were to change or narrow the application window in the fall, it would be very tough for our custom manure dragline crew to be able to serve all their customers in that small window.

- Our family uses multiple BMP's to protect the environment and water quality. We apply low amounts of manure over our acres, incorporate our manure into the soil to increase nutrient retention and prevent runoff, vertical tillage to improve nutrient retention and water holding capacity while reducing erosion, water ways to hold and slow water running in big rain events, crop rotation, cover crops, and we are very efficient with our total nitrogen use ratio.

- Separate sites owned by the same farmer should not be merged into one feedlot permit. This will lead to some farmers being put above the 1,000 animal unit threshold, leading to large increases in cost and regulation to be up to feedlot permitting code/rules. Another way to look at it is if there are two farmers that spread manure on their fields, and one farmer decided to retire and sell his farm and land to the other producer. Then there will be the same amount of land and manure, just under one producer. Additionally, farmers owning multiple sites lets them spread out their manure over more acres.

- Another possibility that was brought up was increasing runoff control and making new requirements for feed storage. Feed storage is very expensive, and is not really an upgrade that can cash flow or increase revenue for a farm. Furthermore, feed storage

runoff is a very minor source of nutrient runoff.

- Animal units should not be changed, as they are based on science and have been the same for many years. Additionally, livestock feed and water efficiency has greatly improved over the years, so if anything the animal unit rate could be decreased rather than increased.

- Only 1-2% of fish kills in the state of Minnesota are attributed to agricultural runoff, so farmers should not be blamed or burdened with being the major cause of fish kills.

- Agriculture is not the only source of nitrates and phosphorus in our water sources. The MPCA should also look at other sources of nitrate contamination such as out-of-date septic systems, urban sewage, bad well casings, etc.

- It was brought up that the MPCA may consider reducing livestock access to streams. Depending on how this would be implemented, it would lead to great cost in fencing and drilling a new well with a cost of $40,000 (if there is already an electrical supply available).

In conclusion, we recommend that the MPCA base their recommendations on proven science and the economic impacts on farmers and their communities, not on opinion or emotions. We also recommend that if the MPCA looks at implementing new rules, that it be local to the geography and features of the land, rather than a blanketed rule across the whole state. Farmers have and will continue to better our practices to conserve natural resources and the land we farm for generations to come. When we take care of the land, it takes care of us.

Please work with farmers and give flexibility to help continue the viability of livestock operations and communities in Minnesota.

Thank you,

Sauer’s Valley View Farms

Creighton Sauer

Chris Sauer

Jason Sauer

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Matt Doll · Citizen · (Postal Code: unknown) · Jul 22, 2025 1:08 pm
0 Votes

Minnesota Environmental Partnership (MEP) thanks the Minnesota Pollution Control Agency for working to update the state's Animal Feedlots Rule. Our scientific understanding of the impacts of these feedlots has advanced significantly in the 25 years since the rule was last revised, as has the scale of challenges to our clean water and climate. With both surface waters and groundwater increasingly impaired and our climate warming, Minnesota should use this opportunity to better steward our natural resources with improved feedlot standards.

Please see our specific recommendations, submitted on behalf of our coalition and 18 supporting organizations, in the attached file.

Sophia Patane · Citizen · (Postal Code: unknown) · Jul 22, 2025 1:29 pm
0 Votes

Attached for submittal in the Minnesota Animal Feedlots Rules OAH Discussion Docket 40661, please find 170 signed comments from members of the public requesting stronger Animal Feedlots Rules to protect water quality, fish, wildlife, and human health.

The attached comments were originally submitted by each individual via email to Addison Otto of the Minnesota Pollution Control Agency (MPCA). The MPCA agreed to send them to me so that I could facilitate their submittal through the OAH portal. I converted each email file to a pdf format, and did not alter the comments in any way.

Attachment A Animal Feedlots Rule Comments Emailed to MPCA contains 36 individualized public comments. Attachment B Animal Feedlots Rule Comments Emailed to MPCA contains 134 public comments that appear to sign a template.

Sincerely yours,
Sophia Patane, WaterLegacy Community Engagement Director

Lauren Servick · Citizen · (Postal Code: unknown) · Jul 22, 2025 1:33 pm
0 Votes

Please find the attached comments on behalf of the Minnesota Pork Producers Association.

Kiven Lukes · Citizen · (Postal Code: unknown) · Jul 22, 2025 1:45 pm
0 Votes

As MPCA considers revisions to the 7020 rules, I ask that you consider the relative costs and benefits of these changes as well as unintended consequences. Each year weather gives us a limited and uncertain amount of time each fall for manure application. Our current storage, application systems, and BMPs such as nitrogen stabilizers have been designed to take this into consideration. Our industry's capacity to responsibly complete fall application in a timely manner is already maxed out. We cant just build new storage if winter comes early. Any new requirements that shorten this window will result in the

need for winter application, which is extremely counter productive to proper nutrient management. Adding bigger equipment, more storage, and more labor are very expensive options that would be necessary to accommodate shorter application windows. This is an example of costs and possible consequences of just one factor, absolute soil temperature thresholds for manure application, but it also applies to any other practice or metric you consider. As you consider making any changes to the rules, please consider the costs and consequences as well as benefits.

Amanda Gentry · Citizen · (Postal Code: unknown) · Jul 22, 2025 1:49 pm
0 Votes

The attachment contains the comments submitted by Winona County Soil & Water Conservation District.

Emily Wegener · Citizen · (Postal Code: unknown) · Jul 22, 2025 1:51 pm
0 Votes

Please find the attached comments on behalf of New Fashion Pork.

Lawrence Karnitz · Citizen · (Postal Code: unknown) · Jul 22, 2025 1:58 pm
0 Votes

Minnesota is blessed with incredible amounts of surface water. However, our water quality is terrible in many lakes and rivers. Frankly, this is an embarrassment to the state and a danger to humans and wildlife. Progress needs to occur. The quality of the water is being severely degraded by several sources, but a major one is agriculture. Accordingly, I support the following:

1) MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.

2) MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.

3) MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.

4) MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.

5) MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already

polluted) waters, and prevention of degradation in waters that are not polluted.

6) MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

7) MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

8) MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Genevieve Vavreck · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:02 pm

0 Votes

As a mother, it makes me upset to see that the Minnesota Department of Health has concluded that nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths. Every mother deserves access to clean and safe drinking water for their kids. No mother should have to go through the pain of losing a baby to nitrate contamination. Because of this, I am asking that MPCA consider the following recommended rule changes:
-MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.
-MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.
-MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.
-MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.
-MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
-MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
-MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions

resulting from climate change that increase winter runoff.
-MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Thank you for your time and thoughtful consideration.

JoDee Haala · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:08 pm
0 Votes

On behalf of Schwartz Farms, thank you for the opportunity to comment on the proposed amendments to MPCA Chapter 7020. We appreciate the agency's outreach and willingness to engage with those impacted by these rules.

Our company believes the existing Chapter 7020 rules are effective, practical, and were developed with a rigorous process and extensive research based on sound science, protecting Minnesota's water quality while supporting responsible livestock production. These rules were built on thorough data, thoughtful stakeholder input, and balanced environmental stewardship, and have only become more robust over time with expanded permit requirements, environmental review processes and county level zoning.

We are concerned with, and do not support expanding the scope of farms required to have additional operating permits. Such oversight is not supported by clear evidence of need and may introduce unnecessary complexity without measurable environmental benefits. Similarly, expanding the size of farms required to submit Manure Management Plans (MMPs) and land application records is not reasonable. The agency currently has authority and ability to review these records on-farm. Requiring submission of proprietary business information subjects farmers to unnecessary breach of privacy.

We also urge caution against adopting rigid manure application timing restrictions that do not account for weather, field conditions, and rural infrastructure constraints. Minnesota's climate and geology varies widely across the state, as well as within short distances. We support science-based BMPs for flexible, site and localized, condition specific management to support environmental stewardship and agricultural productivity.

As it relates to additional soil nitrate testing, current language in the 7020 rules allows for such testing. As shown at the community listening sessions as part of this process, nitrate levels have remained stable or are declining in many areas, demonstrating the effectiveness of the existing 7020 rules. Additionally, it is imperative to recognize the complex nature of nitrate presence, sources (not just from livestock) and the naturally occurring cycle to avoid misinformation and well-intentioned rules that have negative, unintended consequences.

Minnesota's livestock producers share the agency's commitment to protecting water resources, and Chapter 7020 has enabled continuous improvements in environmental protection while maintaining the viability of family farms and local food systems.

We appreciate your consideration of these comments in protecting Minnesota's

environment while supporting a practical, science-based approach to regulation.

Jeff Bauman · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:26 pm

0 Votes

Thanks for the opportunity to weigh in on the changing of the 7020 rules. I am a consultant working with farms across MN of all sizes. Farms with more than 1000 AU have sufficient regulations in place. Nutrient management plans and annual reporting are required by MPCA. Daily, weekly and monthly inspections of water lines, manure levels, and perimeter tile lines are required by NPDES or SDS permit holders.

More is not better when it comes to manure applications. Providing the crop what it needs works best for all. That is what we recommend to our clients, and they see and understand the benefit of that. There is a cost to applying manure. Applying more than needed drives up the cost and is not economical.

Farms in the 300 - 999 AU are required to have nutrient management plans. Improvements can be made by asking them to take manure samples yearly. This could benefit the farms by not underapplying or possibly overapplying nutrients. Farms under 1000 AU could be better informed on feedlot rules. This is an opportunity for MPCA and counties to further educate farms. Farms that have resource concerns in the 300 - 999 AU range generally are required to "fix" those issues to the standards of those over 1000 AU. Making rules too restrictive will force some to close their operations. Farms should be given time to adapt to new restrictions. Farms looking to upgrade storage facilities to comply with any new rules should be given priority in funding for any cost share programs. Improving the environment should be a high priority for these programs.

Rules should allow for regional and soil type differences. What works in Rock County may not work in Roseau County. "One size fits all" can make things worse. Mandating only spring application of manure would be disastrous. Many acres would go unplanted with this scenario. The application season is generally three months long in the fall. Forcing spring only application would spread the spring only application season to July or even August well past the planting season. This would be and environmental and economic disaster.

MN farmers generally do a good job in managing their nutrient applications. Good custom applicators take pride in applying nutrients as close to the plan as possible. Adaptation of technology allows farms to do this.

At two of the public information meetings, I attended it was brought up as to what is being done to regulate private homeowners and golf courses on nutrient application. One citizen reported a friend of his was putting the equivalent of 1500 lbs of nitrogen per acre on his lawn. If a farm had applied that much to a field there would be serious consequences.

Tracy Whitney · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:30 pm

0 Votes

Please see attached comments on behalf of Conservation Minnesota, our Policy Director

Nels Paulsen, and 415 of our members.

C. Hanning · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:32 pm

0 Votes

In response to The Minnesota Pollution Control Agency (MPCA) proposing to amend existing Minnesota Rules Chapter 7020 governing animal feedlots, everyone can agree water quality is important to this state. Commenting one is for or against amendments to 7020 is not indicative of a someone's commitment to stewardship or concern for water quality. Increasing a slew of regulations is a slippery slope that might have unintended affects on state industry, income and ecological orders.

Groups such as the Land Stewardship Project (LSP) want a return 'traditional' agriculture, which no one seems to define, yet they also demand 'modernity.' There is cry for "sustainability" and livestock manure application is 100% part of a farm's economic and environmental sustainability, yet for "big farms" it's evil, but for small or family farms it's forward-thinking and innovative. In one breath this group, like others, say they promote "vibrant rural communities that are places of belonging and opportunity for everyone," yet they also "work within a broader movement that is fighting for justice and positive change." So, does that mean farmers, currently within rural communities, are neither considerate stewards, nor "inclusive" enough? Farmers tend to be highly concerned about best practices, land and water stewardship, and proper usage of chemicals/herbicides/pesticides. Sadly agriculture, like any industry, is not immune to mishaps, accidents, or occasional bad apples, who misrepresent the entire industry wrongly (and sometimes dangerously) to consumers.

The MPCA states as background on its website https://www.pca.state.mn.us/get-engaged/animal-feedlots that since the last major revision of Minnesota feedlot rules took place in 2000, there have been "many notable changes" in part due to changes in agricultural practices technology. This must be explained and data quantified. From an agrarian perspective that would be more untrue than true. Are we examining 7020 just because it seems due, or have stewardship practices actually advanced at warp speed? Perhaps there is an agenda couched within that blanket statement. MPCA language comments that the livestock industry has adapted to have "more feedlots with 500 or more animal units (AUs), many designed to be just under permit thresholds." Apparently producers are following rules, yet still being targeted? Is this because self-proclaimed "culturally and racially diverse rural and urban people" in groups like LSP are pushing amendments to Minnesota Rules Chapter 7020 as an act of expropriation because they believe there is "lack of access to land for all farmers [which] has created a consolidated system that favors corporations and the wealthiest landowners?" [LSP’s Long Range Plan: 2025-2030]

Several questions to weigh are: To what extent are "contaminates" [and which one(s) are even being perceived as problematic] seeping into water supplies? Which water supplies? What will be included as "waterways?" [Sackett v. Environmental Protection Agency] How will this be regulated and to what impact to our state budget? What variation is there in regards to this "problem" among counties, as some are more rigid with regulating waterways? How are non-livestock contaminants measured? How and to what extent is agriculture a greater offender than human sewage? How and to what extent are other industries restricted within the state, as far as their contaminant levels,

dumping/release of byproduct, or damage to waterways? What is the impact of loss of business/industry to the state? What incentives should be offered to producers/farms to make them compliant? What could result from pastures being left unused, and overgrown because of water usage restrictions--spread of CWD, encroachment of noxious weeds and/or pests and unwanted wildlife?

Until those questions are sorted, there is no way to understand the parameters of the problem and what meaningful changes could be made, let alone make more laws. In the court of public opinion it's easy to jab at agriculture because of a misnomer that farmers are rich, yet what the public doesn't understand is that commodities prices are sinking, input costs are rising, and livestock is a boon to operations, which translates into state revenue--a state that is facing a budgetary crisis. Regulation is taking a gamble and the greater Midwest is happy to take up our slack.

Sara Felts · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:32 pm

0 Votes

I am writing to support the MPCA actions to rewrite and modernize the feedlot rules. I can’t believe the existing rules are nearly 25 years old. Surely, our agriculture practices have changed a lot - it’s certainly gotten more “corporate”; I am concerned many ground water contaminations go undetected until too much damage has occurred. I am also concerned that my own well water is at risk due to increased animal feedlots along our beautiful riverways . Surely our water quality and environmental sciences have also advanced in 25 years! We can apply improved technologies and methodology to do better. We only have one planet.

I support new rules to: 1) require permits for feedlots with 300 to 999 animal units; 2) set a maximum size for feedlots and prohibit feedlots in sensitive karst areas; 3) set a stringent limit on nitrate pollution of surface waters; 4) monitor feedlots and manure-spread fields and require compliance with “no discharge” rules as well as surface and groundwater limits; 5) set rigorous requirements for manure storage and spreading based on current science; and 6) close loopholes and remove the exemptions that allow noxious and toxic air and water pollution. I don’t see why theses rules need to be a burden to farmers. I support listening to them too so they can be the best stewards of the waters we all depend on.

I an asking the MPCA to protect Minnesotans (and, really, all downstream waters!) from toxic nitrate pollution.

Daniel Roberts · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:38 pm

0 Votes

When evaluating changes to the 7020 feedlot rules, there are a couple key points that I think should be considered.
- Any significant changes to current manure application or manure storage requirements will create significant challenges and hardship for farmers. There is already a very limited time window for manure application. There is no repeatable evidence that making manure application more difficult for farmers will further reduce nitrates. One of the reasons for this is that nitrogen loss is heavily dependent on the weather/climate change. On our farm we use best management practices such as nitrification inhibitors and only applying when soil temperatures are below 50. We could add more

labor/financial/logistical burdens to farmers but at this time, there is likely little to no positive impact.
- We are already using common-sense practices to avoid run-off. For example, not applying to saturated fields and timing applications to avoid heavy rainfall. There is also significantly less winter application in all parts of Minnesota.
- Rule changes need to be based on demonstrable science, not just what feels like a good idea. Changes related to cover crops (at this time) will make any improvement in achieving nitrate goals. Cover crops can work in a few situations, but there are many, many situations where they unfortunately do not work in their current iteration. There is also a very significant cost to cover crops.

BRIAN BUXTON · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:38 pm
0 Votes

MPCA, I am a trout fisherman, camper, outdoorsman and have witnessed the devastating effects of agricultural runoff and groundwater pollution from feedlots. I'm extremely concerned by the lack of environmental protections the MPCA provides to the citizens of Minnesota. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable. MPCA rules should stop merely trusting that animal feedlots and manure applications are "no discharge" facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread. Provide the protections you owe the citizens of Minnesota. Thank you.

Sara Lupolt · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:43 pm
0 Votes

Our comment is attached.

Gregory Punt · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:47 pm
1 Votes

Thank you for the opportunity to provide feedback on the proposed changes to Minnesota Rule 7020.

As a lifelong Minnesotan and hands-on hog farmer managing manure application and row crop acres across West Central Minnesota, I want to express strong concerns about the direction this rulemaking process is heading.

The existing 7020 rules already provide a solid framework for responsible manure management. Like many modern farms, we use GPS-guided injection, digital recordkeeping, and real-time equipment tracking to ensure precision and protect water quality. Rather than layering on new mandates, the MPCA should recognize and support these advancements. Unfortunately, parts of the rule—especially around setbacks—are confusing and inconsistently enforced across counties. Despite injecting all of our

manure and maintaining compliant buffer zones, we're still asked to meet surface application setback distances. It's unclear how these rules interact, and it creates unnecessary regulatory gray areas.

I'm particularly concerned about the push to restrict or eliminate fall application. Fall is the safest and most effective time to apply manure: it preserves soil structure, reduces compaction, and allows nutrients to stabilize in the soil before spring planting. Forcing application into the spring window is impractical, and it risks damaging field conditions. I am not in favor of applying manure on frozen ground, but when soil temps are right and conditions are workable, fall application is the most responsible choice. Similarly, winter application bans should be based on slope and method—not broad assumptions.

Proposals like mandatory cover crops or universal spring application simply don't work on every farm. These choices should remain with the farmer, not dictated by statewide policy. Real-world timing, local climate, and operational scale must be considered. Rules should be flexible, practical, and based on science, not advocacy.

Ultimately, this rulemaking feels like a solution looking for a problem. The current system works when enforced properly. Overregulation risks harming family farms without delivering meaningful environmental gains. We all want clean water and healthy soil. I live here. I farm here. My kids drink the water and play in the fields we work hard to protect. We care. Just give us credit for what's already working, and don't let fear-based narratives write the next 20 years of ag policy.

We simply ask that our voices and experience be taken seriously in shaping rules that affect our livelihoods and stewardship.

Jay Fultz · Citizen · (Postal Code: unknown) · Jul 22, 2025 2:51 pm
1 Votes

My family's farm is now on its third generation of raising hogs and the row crops of corn and soybeans. We continue to strive and be stewards of the land because if we don't take care of it, we won't be able to make a living and be able to pass our farm to the fourth generation.

The MPCA has worked to create clear and concise rules for feedlot owners and custom manure operators. I feel it's important for the current rules to be enforced. We follow BMP's with all our manure applications. We have an agronomist which does soil sampling for us and provides us with recommendations on how many gallons of manure need to be applied in the Fall to obtain the yield we want to achieve the following year. We take samples of the manure every year to know the concentration levels of N, P and K. We don't over apply the manure because it is too valuable, and we want to spread it over as many acres of our crop land as possible. The manure from our hogs is better for the environment than commercial fertilizer which we still have to purchase.

I feel any changes to the 7020 rules need to be based on accepted scientific studies and practices. Consider the geology and topography of an area, when making rules. Buffer strips and setbacks are great tools, and farmers like myself need more tools available, not less.

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

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Alena Stewart · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:01 pm
0 Votes

I come from a farm family, but there's no denying that the dairy farm of my dad's childhood is a far cry from the current industrial feedlots. We need to adapt regulations to our current reality. As a parent, I'm incredibly concerned that unmonitored and unchecked pollution will ruin the water quality for my children. All kids (and all people) deserve clean water. At a minimum, MN needs to implement the following:
MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure. It just doesn't make sense to ignore a category of feedlots when they are cumulatively so important.

MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.

MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.

MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.

MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff. We all know winters and spring weather patterns are changing. Feedlots need to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

As a state, we pride ourselves on our lakes and rivers, but that means actively working to make sure that we are all doing what we can do keep those lakes and rivers clean. We can't afford to turn a blind eye to something we know is a problem.

Richard Syverson · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:05 pm
0 Votes

Comments on the proposed MPCA Feedlot Rules.

I attended the session of the Feedlot rules in Morris at the WCROC. I left the meeting very concerned for the future of the livestock industry in Minnesota. Many of the other attendees there were like me, smaller livestock producers concerned about the impact that changes in these rules would have on our family farms. The current permit and regulation system is at least partly responsible for the growth of larger and larger livestock operations. The reporting and compliance activities required of large operations mean that special expertise is needed, and only operations large enough to hire someone to fill those roles can afford to be in the business. If these rules and reporting requirements are extended to smaller family operations, many of them will be forced out of the livestock business.
Question 2: Permits should address the land application rates of manure. There is a large body of research that shows what nutrient levels are needed for optimum crop production. Accurate tests are widely used by growers to test soil and the different types of manure applied. This should be the primary standard which should be used to set application rates. Crop removal is the gold standard for dealing with nutrients from animal waste. Setting limits on ownership structure or proximity to other livestock operations make no sense from an agronomic or scientific basis.
Question 3: The presenter at our Morris meeting mentioned the visual inspection possibility. Who would do that? Can the state hire people to drive around and watch manure be spread? Can the MPCA accurately predict the weather? The new NDAWN stations will be a good resource for those applying manure, perhaps consulting them might be part of the rules. However, there are very few days a year that manure can be applied under the current standards, further tightening them will lead to larger unintended consequences.
Question 4: If there are no violations reported with existing manure storage systems, it seems that that is perfect evidence that they are functioning.
Question 5: Here I get really concerned. Manure storage is expensive. A requirement of this type will drive small operations out of business, there is no margin for engineering and construction of storage. Further, most if not all of these smaller operations generate such insignificant amounts of waste that the environmental gain from these structures hardly justifies the cost.
Question 6: Programs from agencies like MDA and NRCS are available for fencing and watering livestock on pasture. The rules should encourage the use of these programs and best management practices. These issues are really not needed to be addressed in the feedlot rule unless the feedlot itself has access to a water feature.
Question 7: Why is there a need for MPCA to be involved in how a farm business is structured? As long as there is enough land for the nutrients from manure to be applied at crop removal rates, it should not matter who the livestock belong to or how close together the barns are.
Question 8: Another of the items mentioned at the Morris meeting that concerned me was the idea that manure transferred to third parties be subjected to the same regulations that the original operation has. This kind of restriction will discourage the use of manure on the appropriate number of acres and could have the result of over application on some acres. The MPCA should be encouraging the transfer of manure to as wide a geography as is practical to move manure to acres that need the nutrients and record keeping and nutrient tracking should be as simple and straightforward as possible.
Question 9: My son recently retired as a large animal veterinarian and attended the Morris meeting with me. Many of the attendees were his former clients. As we left the meeting, he said, “It looks like the MPCA is trying to drive the small family livestock

operation out of business." It is my sincere hope that is not the case. Livestock and manure are one of the key principles of soil health. It is my hope that changes to the feedlot rules are based on sound science including agronomy, soil science and livestock care. Thank you for the opportunity to comment.

Jay Eidsness · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:07 pm

0 Votes

Please find attached comments from The Climate Change & Animal Agriculture Litigation Initiative, Law, Environment & Animals Program at Yale Law School, Minnesota Center for Environmental Advocacy, Center for Biological Diversity, Center for Food Safety, Clean Up the River Environment, FarmSTAND, Food & Water Watch, Institute for Agriculture Trade Policy, Minnesota Interfaith Power & Light, MN350 Action, Socially Responsible Agriculture Project, and Third Act Minnesota on the feedlot rule revision. Thank you for the opportunity to comment.

Madison Hokanson · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:10 pm

0 Votes

Please find the attached comments shared on behalf of the team at Schafer Farms. Thank you.

Michele Schroeder · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:16 pm

0 Votes

First of all, I have worked with the 7020 feedlot rules throughout my career in agriculture. In fact, I worked closely with MPCA staff to ensure the rules were user friendly, understandable, and applied to our state's livestock farmers. Our state and MPCA staff have a very good handle on what is happening in livestock production. I hope that MPCA staff can continue to do so. I would also like to mention that when the 7020 feedlot rules were done in the early 2000's, our state lawmakers offered the needed funding to help our state's farmers be compliant with the new rules they created. I am thankful for that.
I am very concerned about the topics that were mentioned at the New Ulm session that were NOT addressed. It was discussed numerous times that our state's municipalities have older wastewater treatment plants that need attention. (I can think of several.) Our state also has wastewater treatments plants that are VERY close to the Minnesota River (St. Peter, MN and Henderson, MN, for example) and the wastewater treatment plants have experienced flooded when the Minnesota River, itself, flooded. Perhaps our state's money would be better spent closely examining the older, out of date, wastewater treatment plants. Above all, Brown County, Minnesota has a landfill next to the Cottonwood River. How many other landfills are close to a water of the state?
I am an appraiser by trade. I have seen more abandoned wells in our state than I should. Abandoned wells offer easy access to contaminate our water supply. I truly hope the agency takes a closer look at the abandoned wells in our state. I have heard the horror stories of junk, garbage and even oil dumped in abandoned wells. This is a statewide issue that needs more awareness and needs to be addressed. This, too, applies to gravel pits, earthen manure basins, and other open pits that have not been

properly closed after being abandoned.
I truly hope that MPCA will do 2 things as they reexamine the need for the 7020 feedlot rules. 1) Create and utilize an advisory/technical committee of people well-verse in agriculture and the environment to guide the re-writing or examining of the 7020 rules. (I have someone I would like to nominate.) 2) Use the proper science that is needed to grow food, care for the land, and raise our state's livestock. As a farmer, I know that our state's land grant university/agriculture university does NOT provide the proper soil nutrient guidelines for all corners of our state. Our state is so diverse, and the soil nutrient guidelines published are a "one-size-fits-all," when the guidelines should be more tuned into our state's diverse soils and topography. We have the technology to do so, but it is not being done. Nutrient guidelines that work well with thick, black, fertile soil do not work for sandy soils with a major slope.
Everyone likes a nice lawn, but are property owners properly testing their lawns for fertilizers and chemicals they are using? Are they closely examining what is needed vs. spreading them heavily to have an impressive lawn? Homeowners that over apply chemicals, fertilizers and more allow those products to leach into our city sewer systems and then to our municipal wastewater treatment plants. Our family soil tests and keeps record of applications to our farm soils, others should too, even if it is a small plot of land used for as a lawn and/or garden.
In Minnesota, non-livestock farmers purchase manure from livestock farmers to apply to their own farmland. In this case, manure is personal property that has been sold. I have heard rumors that MPCA would like the selling farmer (a livestock farmer) to oversee and manage the buying farmer's (non-livestock farmer) manure application. Since the non-livestock farmer opted to purchase the manure at his own free will, the non-livestock farmer should be responsible for his own manure management plan. If I sold a car (again, personal property), I would not tell the buyer to insure it or maintain it. The buyer needs to have the ability to do that for themselves, for example.
Please remember that Minnesota is an agriculture state and agriculture makes our state thrive. We need to keep the 7020 rules applicable, common sense, and viable to our state's farmers. Unfortunately, many forget NEVER CRITIZE A FARMER WITH YOUR MOUTH FULL OF FOOD. Our state's farmers make sure you have food in your month, clothes on your back, leather shoes on your feet, products in your home, and fuel in your car! They also work hard to care for the land, their farms, and our environment - they live here, too!
Thank you for your time and consideration. Please let me know how I can be of assistance to you as you move forward.

Ted Frank · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:17 pm
0 Votes

We have been involved with hog production on our farm since 1974. Over the years, we have totally changed how we raise hogs and handle manure. Going from outdoor lots and surface applying manure year-round, to confinement facilities and injecting manure so we can fully utilize the nutrients in the manure. Airial photographs from the last fifty years document the fact that there was visibly more uncontrolled manure runoff from far fewer animals fifty years ago. All farmers know the benefits of manure and do not consider it a waste product, rather a crop input to be managed and maximized. The changes we have made derive from fact-based decision making, considering environmental, economic, and animal welfare factors. The current 7020 regulations have proven adequate. The changes we have made have been management driven, not regulation driven. The current 7020 aligns those two fairly well as they are common

sense rules that we would follow anyway, even if there were no regulations in place. Increased regulations, while they are intended to target "factory farms" always end up hurting the smaller operations the most as it adds costs, time, and paperwork for those already tight on time and resources.
Farmers are arguably more concerned about water quality and environmental stewardship as we raise our families on this land. We want our land, water and farm to be in better shape when we pass it on, than when we started farming and we enjoy outdoor recreational and sporting activities as well.
I encourage you to use facts and logic when considering changes to these regulations. There are people out there who want to end animal agriculture, not just as we know it today, but end it completely, without regard to the millions of people who rely on our industry to feed their families.
We try every year to be better stewards of our little part of the world. To be more efficient with all our inputs, not just manure, and to keep our nutrients and soil where they belong, on our fields.

Elisabeth Holmes · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:17 pm
0 Votes

Please find attached comments from the Socially Responsible Agriculture Project on the feedlot rule revision. Thank you for the opportunity to comment.

Ben Hernandez · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:18 pm
0 Votes

Please see the attached file containing Riverview, LLP's comments regarding feedlot rulemaking. Thank you!

Kelsey Holtz · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:19 pm
0 Votes

As a part owner in a multigenerational family owned and operated farm, I believe a time and/or seasonal restriction on manure application would be extremely detrimental to anyone in a similar situation as myself. Spring only application would not work, as we already have limited days to prepare and plant the fields. We have limited equipment and man power already, so limiting to spring application would be extremely hard on a small farm. We have had to spring apply in the past, but for whatever reason (compaction, time of application, etc.) the yields were substantially less than the fields that had manure applied in the fall. In our experience, a forced spring application would be extremely detrimental to the famers.
We have been applying liquid hog manure on some of our ground for over 50 years, and it produces at or above county yield averages continuously. We are required to soil sample and follow specific rules regarding the level of manure to be applied to each piece of land. I believe it is important to know the data on your fields and be able to spread the manure appropriately, but I believe limiting the time of application would be extremely hard on small farms.

Minnesota has always been proud of the fact that most farms are family owned, and provided the rules and limitations stay reasonable, this will be able to remain a factor for many years to come. I am proud to be able carry on my family's farming operation, and I

am very proud to be farming in a state that takes the farmers' opinions into consideration when adopting new rules and regulations.

Mike Boerboom · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:20 pm

0 Votes

I had the opportunity to attend the community meeting that was hosted in Marshall, MN and that it was insightful. As a hog farmer on the State of Minnesota, I want to thank you for the opportunity to provide feedback on the proposed changes to Minnesota Rule 7020. As the state prepares to make changes to its feedlot rules careful and thoughtful consideration need to be taken on many levels.

Minnesota already has rules that regulate feedlots extensively. Rules that regulate how, when, and under what conditions manure can be applied. If changes are made to these rules, they need to be done in a manor that is easy for livestock owners and custom applications can understand and comply with. Rules must be easy for livestock owners to understand without the need to hire expensive outside consultants. Keeping reporting straightforward and easy is part of this.

Our farm and others like us already operate utilizing management practices to ensure the best use of manure as fertilizer and ensure its done so safely. Every year we measure the nutrients within our manure, apply at a specified rate utilizing GPS technology, incorporating immediately for the upcoming growing season. All of this is done to minimize nutrient loss and movement.
Rule changes that would limit our ability to apply in the fall and/or only when soil has reached a specific temperature, could become very prohibitive. Fall is always a busy time of year. Weather issues only make it busier and more challenging. If the window of time was narrowed, it would make it even more difficult for farmers get manure hauled in safe and effective manor. Rule changes need to be based on science and the practices they require cannot be prohibitive or ineffective. For example, the blanket expectation that cover crops must be planted after manure is applied is likely ineffective. In many years, that cover crop will never have a chance to establish itself and carry no benefit.

I look forward to seeing additional information on the proposed rules and the ability to comment further as proposed specific rules are proposed. But as stated in the opening, be mindful and thoughtful of all parties involved.

Thank you,
Mike Boerboom

Ben Hernandez · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:20 pm

0 Votes

Please see the attached file containing Riverview, LLP's comments regarding feedlot rulemaking. Thank you!

Freshwater Society · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:25 pm

0 Votes

We support the following updates to Minnesota's feedlot rule:
• Require state feedlot permits for operations with 600 or more animal units instead of 1,000.
• Require feedlots with 300 or more animal units to prepare and follow a manure management plan approved by MPCA.
• Require that manure management plans are also followed by anyone who purchases or accepts manure from another operation.
• Prohibit manure application on frozen or saturated ground, or within 24 hours of previous or forecasted rainfall (50 percent or greater chance of precipitation according to National Weather Service).
• Set stricter limits on manure application and storage in vulnerable areas, including the karst region in southeastern Minnesota. This would include increased setback distances from lakes, rivers, streams, sinkholes, and drinking water wells.

Margaret Levin · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:28 pm
0 Votes

The attached letter provides Sierra Club North Star Chapter comments on proposed amendments to the state animal feedlot rules as requested by the MPCA.

Sierra Club’s Minnesota North Star Chapter represents 50,000 members and supporters working to help our state’s communities flourish through environmental protection. Our concerns include water quality impacts, manure management, environmental assessment of feedlots, feedlot size, regulatory oversight, and health impacts.

Michele Schroeder · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:40 pm
0 Votes

Hello. I have a comment for consideration. Twenty years ago, our family worked diligently to do the needed upgrades our farm to be compliment with the 7020 feedlot rules and have zero discharge. To do this, we had an expensive loan, worked with our county feedlot officer plus MPCA, and FSA officials, enhanced our feedlots, and worked with a consultant to make sure everything was done correctly. We have maintained our farm's compliance and pass inspection when the feedlot officer/MPCA comes for renewal. If the 7020 rules are re-written, I am concerned our farm will no longer be compliant and our money was spent in vain. Thank you.

Rebecca Myerly · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:49 pm
0 Votes

Greetings, Commissioner Kessler, Mr. Schwint, and Ms. Otto.

Living on the Saint Croix River in the area included in the 2024 list of impaired waters in Minnesota and having long experience living on a lake in Iowa vulnerable to pollution from CAFOs, I and my family find it very concerning that CAFOs in Minnesota are subject to few or in some cases even no restrictions and little or no monitoring by the Minnesota Pollution Control Agency. With concern for many manifestations of pollution from CAFOs, including fish kills due to excessive nitrates, e. coli bacteria from animal waste in water, blue-green algae blooms in shallow bodies of water, and increased nitrates in well water,

all harmful to humans and animals, the problems are insidious and dangerous.

Please rewrite the MN animal feedlot rules to stop toxic nitrate pollution and to establish strict rules for CAFOs, including their size and locations, and enforce close monitoring for accountability. Water Legacy has provided a well considered list of eight recommended rule changes for adoption by the MPCA.

1. MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.

4. MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.

5. MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

6. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

7. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

8. MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

I and my family agree with each of these recommendations and think their adoption would go a long way to help with this currently serious and threatening problem. We ask you to adopt them for the well being of all. Thank you.

Sincerely,
Rebecca Myerly

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

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Darin Broton · Citizen · (Postal Code: unknown) · Jul 22, 2025 3:59 pm

0 Votes

Minnesota AgriGrowth submits the following attached comments for consideration. Minnesota needs a strong agriculture and food economy. We can have a strong economy while protecting our water. Minnesota AgriGrowth is a broad statewide coalition of farmers, farm and commodity organizations, agribusinesses, allied industries, and research institutions committed to advancing agriculture and food in Minnesota.

Craig Tangren · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:07 pm

0 Votes

Please find attached the Leech Lake Band of Ojibwe's comments on the planned amendments to rules governing animal feedlots, Minnesota Rules, chapter 7020, Revisor’s ID Number R-04928.

Beth Slocum · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:09 pm

0 Votes

Our farm well in southeast Minnesota has been contaminated by nitrates at a level 3 times the maximum allowed since 1989. We can't drink our water. So we are very concerned about the increasing number of CAFO's being proposed in the hog, dairy and poultry industries. I have several comments and will list them in as orderly a fashion as I can:
1) Neighbors and community members whose water, air, waterways, homes and quality of life should be notified of a proposed feedlot operation in their township and watershed BEFORE the entire permitting process has proceeded so far that the proposer and the MPCA staff have a powerful vested interest in the project moving forward. Folks who will be most affected by the proposed feedlot are left out of the process for too long.
2) Though I understand that the permitting process and the environmental assessment proceed together -- more emphasis should be on the environmental assessment with accurate information about local wells, homes, other feedlots of any size, so that the environmental assessment moves along with more urgency than the permitting process. If they are in lock step, both the proposer and the MPCA staff, again, have a strong investment in the project moving forward, often without adequate public input.
3) Minnesota needs to promote public health and public safety over private profit -- slowing down the permitting process to allow for in-depth study of the environmental issues will allow the state to make wise decisions for the greater good.
4)Reduce consolidation b y limiting feedlots to 1500 animal units. That will support small farmers and rebuild our countryside and our small towns with stronger economies.
5) Feedlot applications for feedlots above 500 animal units should be required to go through an environmental assessment. Any feedlot application for 1500AUs should require an EIS.
6) Create a data base that aggregates all manure application plans in a watershed, from the primary farmer owner and from all farmers to whom manure will be transferred so you know how much manure is being applied to that watershed and then you can trace the impacts by providing state-funded well-testing in those watersheds at regular intervals. Crop acres are already aggregated, certainly manure application acres can be, as well.
7) Listen to farmers about when to apply manure and help them do the best job they can

-- choice of season, soil temp, weather forecasts re: rain events, esp. Grants for better manure storage.
8) Manure application plans that include transfer of manure from the owner to a secondary farmer need to be as well recorded as required of the primary farmer. Bothe manure owner and manure recipient should submit manure application reports electronically immediately after the application. There should be no overlapping of manure application on land from different sources. Spills or over-application should be reported at once.
9) Before any CAFO is permitted, local wells in that watershed should be tested to provide a baseline of test results, followed by water tests at regular intervals.
10) Promote greater use of cover crops to provide nitrogen take up. Encourage increased pasture land, hay fields and other crops for nitrogen take up. Encourage bringing more livestock onto the land.
11) Work with the university to avoid increasing the fertilizer recommendations -- and with local elevator agronomists to resist selling just 20% more commercial fertilizer which too often is used on the same fields that manure is spread. Help make sense of the how much nitrogen is being applied from both sources. Then provide accurate data to farmers so they can make the best choices for the land they are working.
12) Insure that proper setbacks from homes, wells, ditches, sinkholes, waterways, streams, lakes, etc are described in manure application plans, especially when a farmer is unable to apply all their own manure to their own land.
13) Pay attention to what happened in Dodge County -- too much consolidation, too many hog barns, too many cancers.
14) Increase inspection of feedlots over 500AUs. Especially those enormous CAFO's with thousands of animals -- esp. dairies.
Thank you for the opportunity to comment on this important issue. In a way, our lives really do depend on it!

Sophia Patane · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:10 pm
0 Votes

Attached for submittal in the Minnesota Animal Feedlots Rules OAH Discussion Docket 40661, please find three comments from members of the public requesting stronger Animal Feedlots Rules to protect water quality, fish, wildlife, and human health.

Several members of the public sent their comments to WaterLegacy requesting that we submit them on their behalf rather than deal with the OAH submittal portal. These comments are submitted as they were received, except that comments in an email format were converted to a pdf format.

Sincerely yours,
Sophia Patane, WaterLegacy Community Engagement Director

Sophia Patane · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:11 pm
0 Votes

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Sincerely yours,
Sophia Patane, WaterLegacy Community Engagement Director

Dave Mensink · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:12 pm
0 Votes

I have grown up on a family farm in southeast Minnesota. My wife and I now farm with our son and his wife and their 3 daughters. It is very important to our family that we have clean water. We raise hogs in Fillmore County and also raise corn, soybeans and hay. MPCA has implemented rules that all livestock producers must follow. There are some rules and setbacks that are exclusive to the karst region of Minnesota. These current rules make sense for everyone and are easy to understand and follow.

Family farms work hard to be good stewards of land, following many Best Management Practices, and follow many rules set forth in MPCA guidelines.
When it comes to BMP’s one size does not fit every farm. It’s important to have several options to fit a wide variety of farms. One example of this is that cover crops do not fit everyone. I think it’s important to have the option to use a nitrogen stabilizer instead.

The 7020 rules need to serve as a baseline for all feedlots in the state and be based on sound and accepted science and soil and geographic conditions. The rules should take into consideration other requirements like including riparian buffers as part of the setback distances and the required set backs from karst features in our corner of the state.

Thank you for the opportunity to comment
Dave Mensink

Sophia Patane · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:12 pm
0 Votes

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Several members of the public sent their comments to WaterLegacy requesting that we submit them on their behalf rather than deal with the OAH submittal portal. These comments are submitted as they were received, except that comments in an email format were converted to a pdf format.

Sincerely yours,
Sophia Patane, WaterLegacy Community Engagement Director

40661 Minnesota Pollution Control Agency Request for Comments on Animal Feedlots Rule

Closed Jul 22, 2025 · Discussion · 168 Participants · 1 Topics · 194 Answers · 17 Replies · 55 Votes

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Brian Martinson · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:18 pm
0 Votes

The attached letter is submitted on behalf of the Association of Minnesota Counties and the Minnesota Association of County Feedlot Officers.

Warren formo · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:19 pm
0 Votes

The attached comments are submitted on behalf the Minnesota Agricultural Water Resource Center and allied agricultural organizations.

Ariel Kagan · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:21 pm
0 Votes

On behalf of Minnesota Farmers Union, please find our comments related to this issue attached. Thank you for the opportunity.

Dennis Magnuson · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:25 pm
0 Votes

MPCA 7020 Feedlot Rule comments:
Regarding development of animal feedlot rules
-In general simple rules are easier to define and follow.
-Simplify the state rule 7020. Local feedlot offices should be allowed to determine the BMP for their regions based on state guidelines; including nutrient applications and timing of application.
Considerations for BMP:
-Manure is a valuable commodity in Agriculture. Cost of production and climate already limit the application process, to further limit this process would not only be detrimental to the BMP but also the economics of the individual producer. Timing should remain based on a start date and further determined by the individual producer and local offices BMP.
-Feedlot capacities of less than 1,000 AU are currently regulated by county feedlot offices and should remain under their guidelines. Utilizing local office reduced the burden on State MPCA officers and allows local offices to monitor regional changes more closely.
-MPCA enforcement of onsite visits should be limited to emergencies. Bio-security for livestock producers has evolved to protect the livestock from outside diseases and infections. Allowing outside personnel and vehicles would be a liability for both parties. “Onsite” visits could be completed with producer and MPCA approved technology.
-Many of the proposed questions to 7020 changes focus on increasing regulations on the smaller Agricultural producer further burdening the already diminishing local family farms. We need to focus on preserving the family farms not adding more reasons to resign to consolidation.

Agriculture is an ever changing and evolving industry. Providing producers modest but environmentally conscious guidelines and resources will allow the individual producer to make their best choices based on their individual situation.

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Michelle Fuller · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:25 pm

0 Votes

Minnesota has comprehensive rules regulating feedlots. These rules are clear and concise so that individual feedlot owners and custom manure applicators can easily understand and comply with these rules. There is no need to change the current 7020 rules.
Farmers are stewards of the land, who will be passing this land and water onto our children and grandchildren. Why would we not comply with the recommendations for application rates?
With manure sampling, soil sampling and the modern technology used during manure application, we closely monitor the nutrients going into our soil allowing us the certainty that these nutrients are not wasted or unprofitable. We see our manure as a valuable natural fertilizer; therefore, we use it as such. We closely follow the U of M recommendations for the following crop year and follow those guidelines. If the manure is transferred to a neighbor, we have a vested interest in how the manure is applied, as it is a valuable commodity to us. Implementing more regulations, paperwork and expenses to the farmer or manure recipient, who values the land, and is already following the rules that are in place, is not the answer.
I strongly encourage the MPCA to look at other factors that may be contributing to the nitrate levels, and trust that those who have been caring for our land for generations.

Brad Kluver · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:28 pm

0 Votes

Minnesota already has an incredibly comprehensive set of rules for feedlot owners and for custom manure applicators. A better course of action would be to enforce the existing rules, especially as farmers are already committed to operating within the existing rules. Any rule changes to be based on sound science and not be overly prescriptive. We need to incentivize farmers to do the right thing (which most already do) versus creating burdensome rules and penalizing. We differentiate our approach to soil health field by field, as similar to a classroom full of students with different backgrounds and needs, every farm is a little different and has different needs. Split application in spring and fall allows us to maximize the acres we're able to use the manure on and be strategic in that. Fall gives us the ability to apply when ground temps are cooler but gives us a window to get the right nutrients to the right acres. Spring has an incredibly short window for field work and if all manure application falls then it will further strain labor and time resources are family farms that are already at the limit. Giving the flexibility encourages more thorough approach and gives the time to be able to do it right. Our nutrients are expensive, the last thing I want to do is waste them but I only have limited space in the pit during the season.

Dan Schmitz · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:30 pm

0 Votes

Please consider the following comments in relating to Chapter 7020 governing Animal

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Feedlots:
7020.0300 Definitions.
Subpart 1.
Expand the definition of feedlots to include areas that state agencies and departments, including the MN DNR, County and local jurisdictions and municipalities, develop, either intentionally or by accident, that attract and concentrate wildlife, at levels that are not natural, where the wildlife concentration causes animal waste accumulation and concentration to negatively affect public and private lands and waters and the quiet use and enjoyment of said lands and waters and where such wildlife activities are such that vegetative cover cannot be maintained where the wildlife have been attracted.
Subpart 23.B.
Intermittent streams should not include parts of farmland that support agricultural crop production and row crops are farmed through these areas where current farming and land management practices have removed the actual and observed presence of an intermittent stream.
7020.2002
The need for feedlot operators to notify the commissioner or county feedlot officer should be removed to be exempt from the ambient air quality standard. This is an unnecessary and undue burden on feedlot operators.
7020.2225
The current rules for land application of manure in general are acceptable, however, the following points need to be strengthened:
Subpart 3.A.1.
Current record keeping forms and online MPCA tools to not allow for deviations to the University Of Minnesota recommendations as allowed in this section for recommendations from another land grant college in a contiguous state. This option should remain in the rule and record keeping tools need to accommodate this exception. Also, the MPCA must accommodate the entire range of nitrogen recommendations published by the University of Minnesota and not arbitrarily select a value within that range and hold producers to one number as has been the practice of the MPCA in the NPDES permits. The MPCA is also bound to follow the rule and not make judgements on the university recommendations.
It must also be recognized that the correlation and calibration of university nitrogen recommendations were established with commercial fertilizer that has a precise nutrient content. Manure is variable by nature and availability factors used for the nutrients are only estimates and not hard and fast realities, therefore, a range of available nitrogen within 10-15 % of recommendations should be considered compliant.
Additionally, when new information is provided by the University staff responsible for recommendations issue statements that adjust their recommendations, this information must be considered a university recommendation even before it has been included in the bulletin, as was the case in 2017 when sweetcorn N rates where increased and it took several years for the University to update their recommendations.
Subpart 3.A.2.
This is an important part of the rule and the ability to apply remedial applications as guided by the university “Supplemental N needs worksheet” should remain.

Tess Dornfeld · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:30 pm
0 Votes

Research shows that pollution from feedlot manure is a primary driver of algal blooms in our lakes, fish kills in our rivers and streams, and unsafe nitrate levels in our drinking

water. PCA is supposed to protect us from this kind of pollution, and they need to start doing a better job.

I spent the first half of my life in a rural community in southern Minnesota, and it's deeply discouraging to see the ways ballooning feedlots are impacting our residents, our economies, and our quality of life. It's shocking that there is not maximum size for feedlots, and PCA must create this cap now.

Equally bad is the lack of permitting at all for "smaller" feedlots, and PCA must also implement permit requirements for 300-999 animal unit sized operations.

With the nitrate pollution issues in our neighboring karst region, feedlots should be prohibited in these sensitive areas, and nitrate pollution of surface waters should be strictly limited in all other areas.

Existing PCA rules claim “no discharge” is allowed, but neither manure storage areas nor fields where manure is sprayed are monitored to detect polluted discharge, and no rule limits nitrates to protect fish and other sensitive life in surface water.

New rules must monitor feedlots and manure-spread fields and require compliance with “no discharge” rules as well as surface and groundwater limits, and set rigorous requirements for manure storage and spreading based on current science.

The loopholes and exemptions that allow noxious and odorous hydrogen sulfide air emissions as well as toxic water pollution need to be closed and removed as well.

Mike Patterson · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:30 pm

0 Votes

I am a hog farmer from Kenyon, MN and would like to comment on the proposed rule changes.
Question 1 - For the most part I think the rules and regulations we have in place now are reasonable. We should have enforcement around the rules that we have now. I just did my feedlot inspection with my local feedlot officer. We identified a couple of items that I need to work on, but overall a very good visit, showing no issues for pollution from our farm. This was the first time in many years this had been done. If I did have a serious issue, it would have been documented and something would need to be done about it.
Question 2 - I want to caution adding regulations to small and medium sized feedlots. The reality of the economics in agriculture today is that additional rules and regulations cost money to implement. On small and medium sized farms like mine, we don't have the additional resources to implement large changes. We all want clean air and water, and are ensuring that for the next generation. But, additional regulations come at a cost. On our farm, I would like to be able to pass it down to the next generation if possible. If our farm is not economically viable, I see no way to make that happen. Additional regulation favors large systems in agriculture and push smaller and mid sized farms out. Large systems have resources and people dedicated to complying with added rules and regulations.
Question 3 - In terms of manure management, I would like to see us keep the flexibility that we currently have. I think the farmers know better than government when, where and how to apply manure in an environmentally sensitive, and economically feasible way. On our farm, we hire a commercial applicator to apply our manure. Increased

regulation and rules will cost more, and push some commercial applicators out of the business. This would lead to less choice and more cost for myself on our farm. It would also make it more complicated for scheduling and efficient application. Adding rules to fall applied manure would force more manure applied in the spring. Spring applied manure is challenging to got put on in a timely manner, again pushing the limits of the current system for application. Also, we have seen in many cases, fields with spring applied manure yield much less due to compaction and later planting. This puts an additional economic burden on our farmers.
4 - In my feedlot inspection, my manure pits were inspected. I feel that current regulation addresses this if actually carried out.
5 - Requiring additional manure storage, while a good goal, is a costly one. One that would absolutely put smaller and mid-sized farms out of business rather than spend the money to comply. This would further push consolidation and larger scale in animal agriculture in Minnesota.
6 - No Comment
7 - Farmers have played by the rules set forth for them by State and Local Governments. Changing the rules after they have put investment in seems like pulling the rug out from under them.

Dani Replogle · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:31 pm
0 Votes

See attached comments from Food & Water Watch.

Dan Schmitz · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:31 pm
0 Votes

Please consider the following comments in relating to Chapter 7020 governing Animal Feedlots:
7020.0300 Definitions.

Subpart 1.
Expand the definition of feedlots to include areas that state agencies and departments, including the MN DNR, County and local jurisdictions and municipalities, develop, either intentionally or by accident, that attract and concentrate wildlife, at levels that are not natural, where the wildlife concentration causes animal waste accumulation and concentration to negatively affect public and private lands and waters and the quiet use and enjoyment of said lands and waters and where such wildlife activities are such that vegetative cover cannot be maintained where the wildlife have been attracted.
Subpart 23.B.

Intermittent streams should not include parts of farmland that support agricultural crop production and row crops are farmed through these areas where current farming and land management practices have removed the actual and observed presence of an intermittent stream.
7020.2002

The need for feedlot operators to notify the commissioner or county feedlot officer should be removed to be exempt from the ambient air quality standard. This is an unnecessary and undue burden on feedlot operators.
7020.2225

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Additionally, when new information is provided by the University staff responsible for recommendations issue statements that adjust their recommendations, this information must be considered a university recommendation even before it has been included in the bulletin, as was the case in 2017 when sweetcorn N rates where increased and it took several years for the University to update their recommendations.
Subpart 3.A.2.

This is an important part of the rule and the ability to apply remedial applications as guided by the university “Supplemental N needs worksheet” should remain.

Cole Pestorious · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:33 pm
0 Votes

Here are my comments

CJ Lombardi · Citizen · (Postal Code: unknown) · Jul 22, 2025 4:49 pm
0 Votes

As a lifelong Minnesotan who has spent many of my Summers swimming in, floating on, and boating around many lakes in the Twin Cities metro area as well as numerous lakes in Northern and Southern MN, I have great concern for the water quality in our lakes, rivers and creeks. For several decades I've lived within a walk or short bike ride of the Mississippi River, Minnehaha Creek, Lk Nokomis, and Lk Hiawatha. I live two blocks from the latter, which is one of the lakes on the list of most polluted in the state due to e.coli and blue-green algae blooms. It's been sad to see swimming become basically a thing of the past in our lake due to downstream pollution, contaminants and feces from the many birds that pass through this flyway zone. Dogs can't safely drink from or swim in the lake, and surely the abundance of wildlife we have is negatively affected by this extremely poor water quality. We can't control the wildlife that utilizes these waterways

(as no one wants to see the wildlife harmed or displaced), but there is something we can do about the many waterways (as well as soil and air quality) affected by animal agriculture, which has a huge negative impact on our environment.

I attended a meeting with small family farmers from Iowa & MN about a decade ago and can clearly remember the words of warning shared by the Iowa farmers: Most of our lakes and streams are polluted due to waste from factory farms. The soil is contaminated. And the air quality so bad from these CAFOs, that some residents and small family farmers have had to move because the smell is so noxious, Don't let what's happened to our waterways in Iowa, happen in Minnesota.

Well, I'm worried that this is happening in Minnesota. With 23,000 current feedlots here, and these numbers increasing, the problem will continue to get worse if we don't intervene now.

Please rewrite the MN animal feedlot rules to include strict rules for CAFOs, including their size and locations, and enforce close monitoring as rules without effective monitoring are basically as good as no rules at all. Per the suggestions of Water Legacy, I suggest the following eight rule changes for adoption by the MPCA:

MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.
MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.
MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.
MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.
MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

When people think of Minnesota, they think of our amazing lakes and other waterways.

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Let's make sure we keep our lakes and our state great, by protecting our most cherished assets now...before it's too late. Thank you.

RECEIVED
By: OAH on 7/7/2025

Addison Otto Attachment

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

Please address air quality ie odor (think of community members who are impacted) encorporate regular enforcement not just 'ok' permits. Spot checks needed not just on complaints

Regulate applicators

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

Amy Caucutt (Rochester) amycaucutt@gmail.com

Use the back if you need more room.

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

- Technical Advisory Needed.
- # Possible Regionalize Nitrogen requirement
- Buffer Strip should be included in set back.

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

Use the back if you need more room.

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

Changing the WAY A.U. are measured will MAKE the public more AGAINST the numbers BECAUSE if you go By Head count it will seem A Lot Bigger Number

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

Use the back if you need more room.

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

the Star Trib had an article that stated that 90% of nitrate pollution was from non-animal agriculture.. What is PCA doing with the other 90%. Shouldn't more focus be placed there?

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

*Use the back if you need more room.

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

ground water also flows toward the Mississippi River. ground water problem in Houston Co. can be ~~Car~~ from over application in Mower Co.

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

Use the back if you need more room.

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

- Consider age of water when looking at water samples

- only look at water samples from wells that are in compliance/up to code

- Consider more outside sources of nitrogen contamination other than manure.

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

Use the back if you need more room.

Me - Family Farm - Winona Co - 23 yrs

Give us your comments on the **Animal Feedlots Rule**

We want to hear from you!

MINNESOTA POLLUTION CONTROL AGENCY

Maintain Paper Options !!!

Transferred manure →

I can see more regulations required here for farmers buying liquid manure needed.

Feed storage areas should also have more regulation + Standards

Pastures should Not be Considered feedlots — esp. with intermittant waterways

AUS → need proposed Changes

Use the back if you need more room.

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

Need to Consider Age

of the groundwater

- seems like a good idea

Age of Septic systems - rural areas - are we doing enough to regulate them - Should we?

I Can see regional difference reflected in rules and regulations as a good idea.

I worry about <u>small</u> farmers/operators being regulated out of business

Anne Schechinger Attachment
RECEIVED
By: OAH on 7/8/2025

July 8, 2025

Environmental Working Group comments to the Minnesota Pollution Control Agency; request for comments on the Animal Feedlots Rule.

The Environmental Working Group (EWG) thanks you for requesting input about Minnesota's Animal Feedlots Rule. EWG offers the following comments on the rule.

EWG, a nonprofit research and policy organization with teams in Minneapolis, Minn., Washington, D.C. and Sacramento, Calif., has conducted research into agricultural pollution and farm policy programs for over three decades. Our expertise focuses on the environmental and climate impacts of agricultural practices, with a particular emphasis on water quality.

Additionally, we are deep experts in using aerial imagery to geolocate animal feeding operations and we have developed a peer-reviewed methodology[i] that allows us to calculate the number of animals produced in an animal feeding operation and the manure amounts that each feedlot produces in a year. We also have considerable experience modeling which farm fields near feedlots likely receive manure. We analyzed the number of feedlots and animals, the manure they produced, and modeled manure application to nearby farm fields in Minnesota in a 2020 report[ii] and then updated that report in May of 2025.[iii]

We recommend that MPCA makes these changes to the Animal Feedlots Rule:

- Require all feedlots with 600 or more animal units to get a National Pollutant Discharge Elimination System or State Disposal System permit.
- Require the largest feedlots with 1,000 animal units or more to monitor discharges to groundwater as well as discharges to surface water through drain tile.
- Ensure feedlots cannot avoid permit requirements by splitting feedlots.
- Establish stricter manure land application requirements and lower manure application rates in Vulnerable Groundwater Areas[iv]. These requirements should include requiring conservation practices like cover crops or diversified crop rotations if a farmer applies manure in the fall, and no liquid manure application to frozen or snow-covered ground, in Vulnerable Groundwater Areas. Additionally, manure application rates should not be allowed to exceed the agronomic rate in Vulnerable Groundwater Areas.

- Close the manure transfer loophole. Currently, transferred manure is exempt from tracking, so the application location, rate, and date of transferred manure are unknown. Tracking requirements of transferred manure should be established and enforced.

Justification for recommendations

Manure from feedlots causes significant damage to nearby water quality, especially in conjunction with synthetic fertilizer use. The manure these facilities generate are often applied to nearby farm fields as a fertilizer and can wash off farm fields, leach through soil into drainage systems that empty into nearby streams, or get into groundwater.

Nitrogen forms in drinking water as nitrate and consuming this water can increase the risk of birth defects and cancer[v]. This is a particularly widespread issue in Minnesota's Vulnerable Groundwater Areas like the Southeast karst region[vi] and the Central Sands region[vii]. The harm that nitrate in drinking water causes to communities throughout the state is a well-known problem[viii].

Manure runoff can also create potentially toxic algae blooms in recreational waters when nutrients are applied in excess of crops' uptake capacity. EWG has previously reported on algae toxins in bodies of water throughout Minnesota[ix]. When manure is applied to meet the nitrogen recommendation for crops, phosphorus is often overapplied. Algae blooms in recreational water sources can pose a health hazard for humans and pets, as well as the ecosystem harm.

Over-applying nitrogen and phosphorus above crop needs from both animal manure and commercial fertilizer, as well as applying manure at high-risk times of the year such as fall when the ground is bare or winter when ground is frozen, leads to more nitrogen and phosphorus from manure ending up in bodies of water as well as groundwater sources.

In our report released in May of 2025, EWG analyzed which fields near feedlots likely received manure in 2024. The analysis found nine counties that are hot spots for nitrogen overload. This happens when nitrogen from manure, combined with nitrogen in fertilizer sold in the county, exceeds crop recommendations by more than 40 percent.

Nitrogen overload can be a particular problem in Vulnerable Groundwater Areas. In these areas, nitrate applied to farm fields through fertilizer or manure can easily get through soil and pollute groundwater. Many counties with nitrogen overload are within

the Central Sands and Southeast regions of Minnesota. These two regions have a high percentage of land with the MPCA Vulnerable Groundwater Area distinction. In 2024, 6,480 feedlots in the state were located within a vulnerable groundwater area, as can be seen in EWG's map below.

Minnesota counties and vulnerable groundwater areas at risk of nitrogen overload

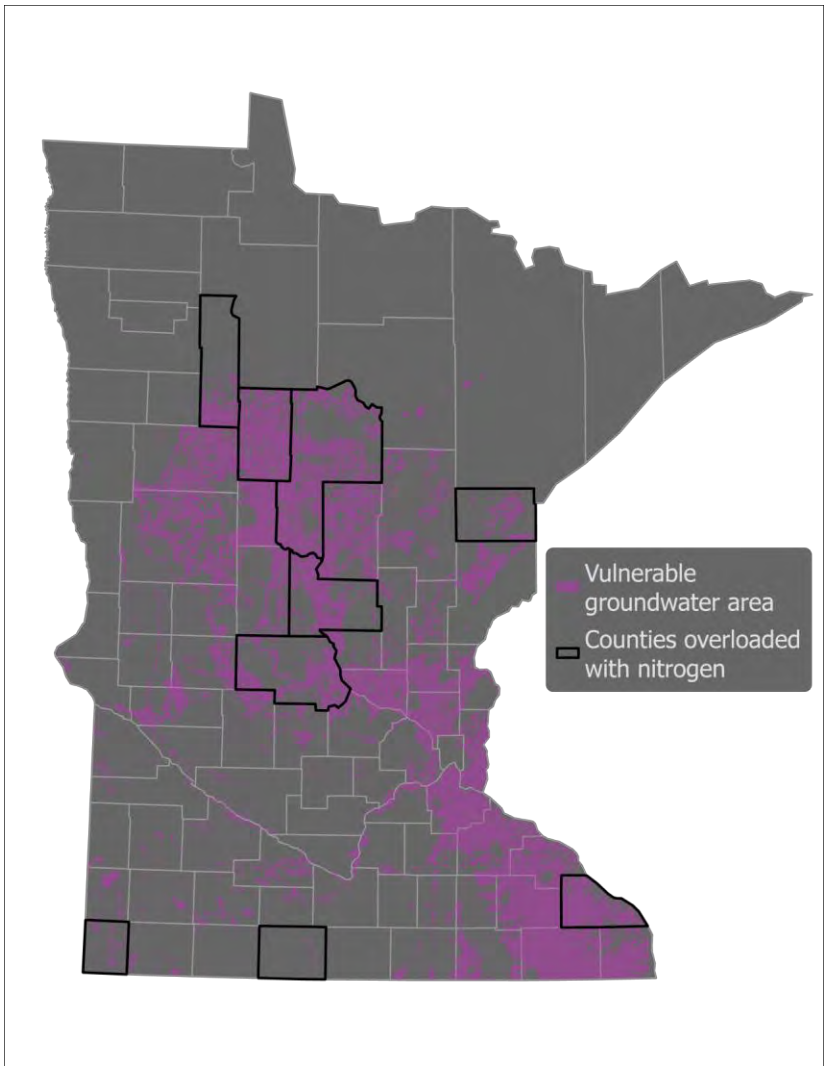

In our analysis we also found that most feedlots in the state are small, but the medium and large facilities produce a disproportionate amount of manure. While 78 percent of facilities were small, they produced just 24 percent of manure in 2024. Medium facilities

made up only 18 percent of all operations but produced the largest share of manure, at 43 percent. Four percent of facilities were large but generated 33 percent of manure.

Because of the large quantities of manure that medium facilities produce, they should also be required to get a NPDES or SDS permit. In Minnesota, 983 facilities housed between 750 and 999 animal units in 2024 – just a few hundred units under the 1,000 animal unit level that requires stricter regulation. These facilities still produced a lot of manure, as they are 14 percent of all facilities in the state, but are hardly regulated. And among these, there were 374 operations that were between 950 and 999 animal units - just 50 animal units short of the large CAFO designation and more stringent permits. So almost 400 facilities are producing manure at levels close to the amounts from large facilities, but are not regulated in the same way.

We recommend requiring NPDES or SDS permits for all feedlots that house at least 600 animal units. According to our calculations, there were 2,316 feedlots with between 600 and 999 animal units in Minnesota in 2024, and these facilities produced 12,640,899 tons of manure. Of those, 329 feedlots were in a Vulnerable Groundwater Area.

In fact, out of the 6,480 total feedlots that are in a Vulnerable Groundwater Area, only 161 are above the 1,000 animal unit threshold, so most feedlots in these areas do not have many restrictions. A significant amount of manure is being produced by facilities that are not regulated stringently because they are not required to get NPDES or SDS permits.

A significant number of facilities, housing animals and producing manure, are also close to the Vulnerable Groundwater Areas while not being directly in the area. The above number only includes the facilities located directly within a Vulnerable Groundwater Area. Over 50% of all feedlots in Minnesota are either in a Vulnerable Groundwater Area or within 1 mile of a Vulnerable Groundwater Area.

In conclusion, we believe that MPCA should make the changes to the Animal Feedlots Rule that we have listed above in the recommendations section. Making these changes would significantly improve water quality and public health throughout Minnesota.

We appreciate the opportunity to comment.

Anne Schechinger
Midwest Director and agricultural economist
Environmental Working Group

Ethan Bahe
Senior GIS Analyst
Environmental Working Group

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[i] https://www.mdpi.com/2073-4395/10/4/480
[ii] https://www.ewg.org/interactive-maps/2020-manure-overload/
[iii] https://www.ewg.org/research/five-years-after-ewgs-first-analysis-manure-still-overloads-minnesota
[iv] https://www.mda.state.mn.us/chemicals/fertilizers/nutrient-mgmt/nitrogenplan/mitigation/wrpr/wrprpart1/vulnerableareamap
[v] https://ehsrc.public-health.uiowa.edu/wp-content/uploads/2024/09/Nitrate-Environmental-Health-and-Cancer-Fact-Sheet.pdf
[vi] https://www.mncenter.org/protecting-drinking-water-in-MNs-karst-region
[vii] https://www.ewg.org/interactive-maps/2020_nitrate_in_minnesota_drinking_water_from_groundwater_sources/
[viii] https://investigatemidwest.org/2023/01/12/a-public-health-crisis-in-the-making-agriculture-pollutes-underground-drinking-water-in-minnesota-well-owners-pay-the-price/
[ix] https://www.ewg.org/research/more-monitoring-needed-keep-people-safe-algae-toxins-iowa-minnesota-and-wisconsin

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In developing the animal feedlot rule, the MPCA would appreciate comments on the following questions:

1. Are there parts of the current rule (Minn. R. Ch. 7020) that are no longer applicable or needed?

2. What specific changes to the current rules, including permit requirements (part 7020.0405), water quality discharge standards (part 7020.2003), all conditions here should be modified to reflect 100 animal units vs 1000 which is astronomical. No SDS permit should be allowed as well since it is ridiculous to assume any discharge would have some form of benefit to the water or organisms living there. location restrictions and expansion limitations (part 7020.2005), if someone from St. Paul were to come and smell the odor from any of these facilities they would understand that no facility should be allowed within 5 miles of any neighboring property and this requirement should be implemented as it will direct healthy free range type raising of animals. liquid manure storage area standards (part 7020.2100), or land application of manure (part 7020.2225) would provide improved regulations that prevent nitrate contamination to ground and surface waters and fish kills? Should any of the following bullets be considered? If so, at what size (in AU)?

• Operating permits (NPDES or SDS) for feedlots less than 1000 AUs. Yes

• Submittal of manure management plans and land application records for feedlots without operating permits.

• Monitoring of feedlots and land application sites for subsurface discharges of manure or nitrate to groundwater. Yes

• Additional restrictions on manure application rates. Yes, be around any field where this is applied in volume and understand the odor level and days of time prior to it diminishing.

• Soil nitrate tests prior to land application of manure. Yes

• Increased setback distance for land application of manure near sensitive features. Yes, dramatically increased as 300 ft is nothing

• Restricting land application of manure in areas with high levels of nitrate in waters or in areas with existing high densities of feedlot operations. Absolutely yes as this is so logical its sad it has to be asked if it should be implemented.

3. The State Disposal System (SDS) and National Pollutant Discharge Elimination System (NPDES) feedlot general permits apply to feedlots that currently have capacity, or are proposing to have capacity, for a total of 1,000 or more AUs (part 7020.0405). These permits include additional requirements as outlined in the following bullets. Should any of

these requirements or other requirements in the permits be incorporated into the rule to apply to facilities with less than 1000 AU capacity?

• Enhanced manure management planning and record keeping requirements for transferred manure. Yes

• Visual inspections of manure land application fields for signs of discharges.

• Additional best management practices for land application of manure during the months of September through November.

• Restricting land application of manure on frozen or snow-covered fields. Yes for liquid solutions due to the odor produced.

• Best management practices for land application of manure when there is a high probability of rain predicted. Absolutely yes

4. How should the MPCA address existing animal manure storage areas that have been used for a long period of time to determine structural integrity (part 7020.2100)? Any well driller now has the equipment to dig underground for multiple feet in a horizontal direction so soil samples can be obtained under such structures for contamination leakage.

5. Currently, feedlots with 1000 AUs or more are required to have 9 months manure storage capacity (part 7020.2100). Should smaller sites be required to have a similar requirement? If so, at what size (in AU)? 100 AU or greater

6. The MPCA has developed Watershed Restoration and Protection Strategy (WRAPS) documents for every one of Minnesota's 80 major watersheds. These WRAPS document high nutrient and bacteria levels in streams and rivers. The reports attribute this to livestock access to streams in many cases. How should the rules be amended to address this documented issue (part 7020.2015)? It makes zero sense to allow livestock of any form to have unlimited access to public waters for drinking purposes. This is not the developing country of the 1800's. Our public waters are under siege from all types of pollutants including this type and this can be easily identified and corrective action enforced.

7. How should the MPCA address feedlots under the same ownership in close proximity to each other? They should be considered as separate facilities How far apart must each feedlot be located in order to be considered a separate facility for the purposes of permitting and/or registration (parts 7020.0405 and 7020.0350)? Any distance greater than 300 ft.

8. State agencies are required to, whenever feasible, develop rules that are not overly prescriptive and inflexible, and rules that emphasize achievement of the MPCA's regulatory

objectives while allowing maximum flexibility to regulated parties and to the MPCA in meeting those objectives (Minn. Stat. § 14.002). How might the MPCA balance this need for flexibility for regulated parties while also addressing the issues of nitrate contamination and fish kills? Rules are rules. There is no such activity as request for a variance from them therefore IF an producer be it private or corporate there should be no acceptance of any rule being not followed to the letter since any other position will simply result in private or corporate representatives doing what they feel is justified and asking for forgiveness following breaking the rule.

9. Other questions or comments relating to the existing animal feedlot rules or this proposal to amend the rules. As I previously stated this in not the US in the 1800's with limited polluting contributions from other sources and the only way to even begin to get control to perhaps try to make some sort of improvement in water ways or sources is TO ENFORCE rules completely. There should be a complete reversal of the statement in 8 regarding allowing maximum flexibility since this position only promotes continued violations and perhaps corrupt behavior of employees responsible for monitoring being compensated for "allowing maximum flexibility" upon review of an identified issue.

Jacob Vogt Attachment

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Erika Gilsdorf Attachment

Comments on MPCA Feedlot Rule Making Submitted by the Prairie Woods Chapter Izaak Walton League, Detroit Lakes, MN

Chapter Committee: Erika Gilsdorf, Sandy Gunderson, Lowell Deede, Matthew Davis, Willis Mattison, William Henke

The following comments pertain to the MPCA's planned amendments to the rules regulating Concentrated Animal Feeding Operations (CAFO's), MN Rules, Chapter 7020.

The Prairie Woods Chapter of the Izaak Walton League of America of Becker County, MN has been concerned about the implications of the statewide proliferation of CAFO's for several years. Because of the threat of these large industrial operations making their way into water rich Becker County, our chapter with the consent of the Becker County Board of Commissioners, completed a comprehensive and well researched report on the ramifications of these confinement operations. This report was submitted to Becker County and is on record as of August 2024.

Amongst the conclusions of this report, it is found that the industry model engenders industrial sized feeding operations aimed at maximizing profits resulting in the continuous loss of small family farms, contributes greatly to surface and ground water pollution, plays a major role in fostering the public health risk of ever increasing antibiotic resistance, has a significant negative impact on the economy associated with our small rural communities and dispels this industry's claims that manure produced is handled responsibly,

While the Prairie Woods Chapter feels that CAFO's are inherently a completely unsustainable model, a form of business that treats animals inhumanely, pollutes our waters with nitrates, phosphorus, fecal coliforms, chemicals and pharmaceuticals, and serves to stifle what could be a growing "local" agriculture economy that provides safe food sourcing, we understand the scope of the MPCA's upcoming task. As a result, we submit the following points for the agency's consideration.

LOCATION

1. Current MN rules do not restrict the location of feedlots except prohibiting them from shoreland. Even then, this does not take into account the hydrology of the site including slope, depth to bedrock/impervious surface, soil composition or inter-connectivity of waterways. This needs to change. The rules regulating location need to be very site specific and not "cookie-cutter."

BEST MANAGEMENT PRACTICES (BMP's)

2. No research has demonstrated effective BMP's. Therefore, a "prove-it-first" principle should be applied for both manure storage, manure transport, and manure application. Currently, use of manure application BMPs are largely voluntary and are not site specific. They must become more stringent, documentable, their use made mandatory, and they should be tied to the specific site. Effectiveness of BMPs depends upon site specific factors including climate conditions, soil type, and drainage system design. These factors must be considered when developing BMPs for a particular farm operation.

PERMITTING

3. One-size-fits-all by rule has proven to be the wrong approach. All permits should require plans and specifications should be site-specific.

4. Rules should apply to most, if not all CAFOs but certainly those below 1000 animal units. The industry's habit of seeking leniency by coming in under the 1000 animal unit limit per operation should not diminish the responsibility to protect water quality.

5. Permittees are not required to demonstrate their manure pits or lagoons meet the design standards. This is unacceptable.

6. To avoid overtaxing limited MPCA staff in reviewing and approving plans, professional engineers and licensed hydrologists should be required to "sign-off" on facility design and manure management plan ensuring performance. Failure of designed facility to perform to standards should threaten professional licensure.

7. The food industry sponsor, rather than farmer/owner, should be the permittee and should propose site-specific facility design and operation compliance plan.

MONITORING

8. Baseline ground and surface water assessment/monitoring is necessary prior to CAFO establishment and ongoing monitoring should be the indicator of compliance rather than documentation that planned BMP's were applied.

9. Monitoring of water to determine compliance should be done by a third party (certified laboratory or MPCA designee) whose certification is at stake for errors or false reporting. Testing valid water samples for the appropriate parameters is critical to ensure that degradation is not occurring. "Trust but Verify" is essential!

10. Water Quality standards should include nitrates, phosphorus and fecal coliform

for both surface and ground water including drain tile water.

DISPOSAL

11. The food industry (especially related to meat production and processing) has externalized the costs of animal waste disposal to the farmer/grower and to the public. The new rules need to internalize these costs to the top of the pyramid---the processors/packers that rule this industry. In addition, reparations need to be required of the industry when surface and ground water is polluted, wells of adjacent farms are degraded or when aquifers are depleted.

12. The current engineering "design" standard that allows manure storage pits and lagoons to leak at up to 500 gal/acre/day is unacceptable.

ACCOUNTABILITY

13. The food industry has successfully hidden behind the farmer/operator to escape liability for pollution, disease spread (ie. growing incidence of cancers in Iowa), and the increasing incidence of antibiotic resistance in not only animal husbandry but very much so in humans. Please note that agriculture use of antibiotics exceeds that in humans! The new rules must place the industry in the key responsible role for the negative consequences provoked by this harmful business model.

14. Pre-established water quality limit exceedance should trigger prompt remedial action.

15. Failure by violators to remediate contamination or operational violations within a pre-established timeframe should result in an immediate cessation of operations until full compliance is achieved. Enforcement of this cessation must be mandated and carried out by the state, with clearly defined penalties for non-compliance. The burden of enforcement should not fall on local residents, who often lack the resources and authority to compel accountability. The Minnesota Pollution Control Agency must ensure that oversight, compliance monitoring, and enforcement actions are fully supported and funded at the state level to protect public health, water quality, and community well-being.

Thank you, Minnesota Pollution Control Agency for considering the Chapter's concerns on this very important topic.

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By: OAH on 7/16/2025
Duane Wirt Attachment

Livestock Enterprise Analysis
Farm Business Management Statewide Data
Excluding Organic & Organic Transition
(Farms Sorted By Return to Overhead)

Dairy -- Average Per Cow

	Avg. Of All Farms		*Low 20%*		*40 - 60%*		*High 20%*	
Number of farms	222		44		45		45	
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Milk sold (hd)	26,271.1	5,610.95	22,350.5	4,603.27	27,604.7	5,745.81	28,103.4	6,224.96
Dairy Calves sold (hd)	0.4	244.63	0.3	166.43	0.5	319.94	0.5	306.42
Transferred out (hd)	0.6	65.44	0.7	81.26	0.5	51.95	0.5	64.56
Cull sales (hd)	0.3	430.11	0.3	407.98	0.3	451.37	0.3	413.52
Insurance income		43.59		12.00		65.94		48.35
Government payments		12.21		14.56		10.57		12.47
Other income		33.97		18.56		15.72		42.38
Purchased (hd)	0.0	-26.05	0.0	-67.83	0.0	-14.12	0.0	-17.15
Transferred in (hd)	0.3	-42.45	0.3	-17.25	0.4	-50.25	0.3	-8.35
Inventory change (hd)	0.0	26.32	0.0	-2.48	0.0	17.70	0.0	41.65
Dairy repl cost		-729.42		-821.57		-759.19		-715.29
Gross margin		5,669.31		4,394.93		5,855.45		6,413.50
Direct Expenses								
Protein Vit Minerals (lb.)	4,029.8	901.58	1,860.0	756.89	4,905.9	1,079.19	5,222.5	935.76
Complete Ration (lb.)	1,178.8	558.51	2,326.1	576.79	1,531.6	537.37	695.5	477.47
Corn (bu.)	73.7	318.03	64.8	281.53	79.4	338.62	81.0	360.37
Corn Silage (lb.)	20,922.0	465.17	21,265.9	467.69	21,014.3	478.06	20,718.5	487.35
Hay, Alfalfa (lb.)	2,387.8	181.85	1,879.5	149.30	2,478.1	197.25	2,557.4	178.36
Other feed stuffs (lb)	5,299.1	253.49	5,522.6	287.27	7,167.9	247.43	3,520.2	203.79
Breeding fees		56.15		59.44		61.86		43.72
Veterinary		109.69		94.27		110.69		107.56
Supplies		162.00		207.72		131.48		162.41
Fuel & oil		98.13		103.82		81.14		112.00
Repairs		234.88		249.75		243.96		229.52
Custom hire		95.04		84.04		129.10		75.53
Hired labor		418.88		451.44		493.81		289.39
Hauling and trucking		128.42		134.14		147.45		132.22
Miscellaneous		265.93		318.73		262.08		238.23
Total direct expenses		4,247.76		4,222.82		4,539.48		4,033.67
Return over direct expense		1,421.55		172.10		1,315.97		2,379.83
Overhead Expenses								
Hired labor		128.29		66.73		74.91		231.44
Building leases		80.22		74.99		72.26		112.77
Interest		120.97		138.42		137.52		107.94
Mach & bldg depreciation		203.23		165.65		182.62		230.75
Miscellaneous		200.69		160.98		166.36		240.69
Total overhead expenses		733.39		606.76		633.66		923.60
Total dir & ovhd expenses		4,981.15		4,829.59		5,173.14		4,957.27
Net return		688.16		-434.66		682.31		1,456.24
Labor & management charge		193.19		233.63		126.86		222.69
Net return over lbr & mgt		494.97		-668.29		555.45		1,233.55
Cost of Production Per Cwt. Of Milk								
Total direct expense per unit		16.10		18.84		16.40		14.28
Total dir& ovhd expense per unit		18.88		21.55		18.68		17.55
With other revenue adjustments		18.71		22.51		18.33		16.95
With labor and management		19.44		23.55		18.79		17.73
Est. labor hours per unit		39.66		42.94		39.24		39.49
Other Information								
Number of cows		303.4		197.1		418.6		344.4
Milk produced per cow		26,380		22,416		27,688		28,240
Energy corrected milk per cow		28,982		24,841		29,829		31,734
Lbs of fat & protein per cow		1,970		1,704		2,011		2,178
Culling percentage		29.2		31.0		30.7		26.2
Turnover rate		34.7		38.8		35.4		31.6
Cows per milking unit		23		18		27		25
Feed cost per cwt. of milk		10.15		11.24		10.39		9.36
Feed cost per cow		2,678.63		2,519.47		2,877.91		2,643.09
Hired labor per cow		547.17		518.17		568.72		520.84
Avg. milk price per cwt.		21.36		20.60		20.81		22.15
Milk price / feed margin		11.20		9.36		10.42		12.79

Livestock Enterprise Analysis
Farm Business Management Statewide Data
Excluding Organic & Organic Transition
(Farms Sorted By Return to Overhead)

Dairy -- Average Per Cwt. Of Milk

	Avg. Of All Farms		*Low 20%*		*40 - 60%*		*High 20%*	
Number of farms	222		44		45		45	
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Milk sold (hd)	99.59	21.27	99.71	20.54	99.70	20.75	99.52	22.04
Dairy Calves sold (hd)	0.00	0.93	0.00	0.74	0.00	1.16	0.00	1.09
Transferred out (hd)	0.00	0.25	0.00	0.36	0.00	0.19	0.00	0.23
Cull sales (hd)	0.00	1.63	0.00	1.82	0.00	1.63	0.00	1.46
Insurance income		0.17		0.05		0.24		0.17
Government payments		0.05		0.06		0.04		0.04
Other income		0.13		0.08		0.06		0.15
Purchased (hd)	0.00	-0.10	0.00	-0.30	0.00	-0.05	0.00	-0.06
Transferred in (hd)	0.00	-0.16	0.00	-0.08	0.00	-0.18	0.00	-0.03
Inventory change (hd)	0.00	0.10	0.00	-0.01	0.00	0.06	0.00	0.15
Dairy repl cost		-2.76		-3.67		-2.74		-2.53
Gross margin		21.49		19.61		21.15		22.71
Direct Expenses								
Protein Vit Minerals (lb.)	15.28	3.42	8.30	3.38	17.72	3.90	18.49	3.31
Complete Ration (lb.)	4.47	2.12	10.38	2.57	5.53	1.94	2.46	1.69
Corn (bu.)	0.28	1.21	0.29	1.26	0.29	1.22	0.29	1.28
Corn Silage (lb.)	79.31	1.76	94.87	2.09	75.90	1.73	73.37	1.73
Hay, Alfalfa (lb.)	9.05	0.69	8.38	0.67	8.95	0.71	9.06	0.63
Other feed stuffs (lb)	20.09	0.96	24.64	1.28	25.89	0.89	12.47	0.72
Breeding fees		0.21		0.27		0.22		0.15
Veterinary		0.42		0.42		0.40		0.38
Supplies		0.61		0.93		0.47		0.58
Fuel & oil		0.37		0.46		0.29		0.40
Repairs		0.89		1.11		0.88		0.81
Custom hire		0.36		0.37		0.47		0.27
Hired labor		1.59		2.01		1.78		1.02
Hauling and trucking		0.49		0.60		0.53		0.47
Bedding		0.35		0.42		0.34		0.31
Miscellaneous		0.66		1.00		0.60		0.53
Total direct expenses		16.10		18.84		16.40		14.28
Return over direct expense		5.39		0.77		4.75		8.43
Overhead Expenses								
Hired labor		0.49		0.30		0.27		0.82
Interest		0.46		0.62		0.50		0.38
Mach & bldg depreciation		0.77		0.74		0.66		0.82
Miscellaneous		1.06		1.05		0.86		1.25
Total overhead expenses		2.78		2.71		2.29		3.27
Total dir & ovhd expenses		18.88		21.55		18.68		17.55
Net return		2.61		-1.94		2.46		5.16
Labor & management charge		0.73		1.04		0.46		0.79
Net return over lbr & mgt		1.88		-2.98		2.01		4.37
Cost of Production Per Cwt. Of Milk								
Total direct expense per unit		16.10		18.84		16.40		14.28
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With labor and management		19.44		23.55		18.79		17.73
Est. labor hours per unit		0.15		0.19		0.14		0.14
Other Information								
Number of cows		303.4		197.1		418.6		344.4
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Lbs of fat & protein per cow		1,970		1,704		2,011		2,178
Culling percentage		29.2		31.0		30.7		26.2
Turnover rate		34.7		38.8		35.4		31.6
Cows per milking unit		23		18		27		25
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Milk price / feed margin		11.20		9.36		10.42		12.79

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FRIENDS OF THE MISSISSIPPI RIVER

Protecting, restoring and enhancing the metro Mississippi River and its watershed since 1993.

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(651) 222-2193 | fmr.org | info@fmr.org

July 18th, 2025

Office of Administrative Hearings
Attn William Moore, OAH
600 North Robert Street, PO Box 64620,
St. Paul, Minnesota 55164.

Greetings, Mr. Moore,

Thank you for the opportunity to provide written comments on planned amendments to Minnesota Rules governing animal feedlots (Chapter 7020, Revisor's ID Number R-04928).

Friends of the Mississippi River is a 501(c)3 non-profit organization dedicated to protecting and restoring the Mississippi River and its watershed in the Twin Cities. We believe it is time for the state to improve its efforts to prevent the unintended contamination of groundwater and surface waters from animal feedlots and the manure they produce.

As you know, it's been 25 years since Minnesota significantly revised the rules for animal feedlots and the manure they produce. We acknowledge that manure can be an important source of nutrients for Minnesota's croplands, and we want Minnesota's farm operations to be successful and sustainable. However, when improperly applied to croplands, manure can contribute to polluting our lakes, rivers, and streams. In addition, manure can contaminate groundwater, making our water unsafe to drink.

This is no small issue. Minnesota is home to more than 18,000 feedlots that, by some estimates, produce nearly 49 million tons of waste per year. This waste has potential consequences for Minnesota's water resources, including the Mississippi River. That's why addressing the impacts of pollution from feedlots and field-applied manure is included in high-level, multi-agency strategies for achieving clean and healthy waters in Minnesota, including:

- The Minnesota Nutrient Reduction Strategy
- The Great Lakes Water Quality Agreement
- The Minnesota Water Management Framework
- The Minnesota State Water Plan
- The Clean Water Council Strategic Plan
- The Minnesota Clean Water Road Map
- The Minnesota Water Sustainability Framework

- Multiple Total Maximum Daily Load (TMDL), Watershed Restoration and Protection Strategies (WRAPS), and Groundwater Restoration and Protection Strategies (GRAPS)

While improved feedlot rules will not resolve Minnesota's water quality challenges, it's equally clear that we can and must improve upon the status quo. Therefore, we respectfully request that the state consider the following amendments to Minnesota's feedlot rules (Chapter 7020):

1. **Permitting and environmental assessment**
    a. Require operating permits (NPDES / SDS) for all feedlots at or above 600 animal units. According to analysis from the Environmental Working Group, there were 2,316 feedlots with between 600 and 999 animal units in Minnesota in 2024, collectively producing more than 12 million tons of manure.
    b. Require operating permits (NPDES / SDS) for all feedlots at or above 300 annual units in vulnerable groundwater areas.
    c. Require monitoring of the largest feedlots for surface and subsurface discharges of manure, nutrients, and bacteria.
    d. Remove the potential for an ownership structure to split larger feedlots into multiple smaller operations for the purposes of permitting and/or registration. For example, the state might establish that feedlots under the same ownership structure located within a county, or within 25 miles but in an adjacent county, are not to be considered separate facilities.

2. **Manure management**
    a. Require all feedlots with 300 or more animal units to prepare a manure management plan and maintain land application records. Such records should be shared with the MPCA in a manner that allows the public to assess the efficacy of feedlot rules in protecting water quality over time.
    b. Require the largest feedlots to monitor the fields where they apply manure to ensure manure is not running off into waterways or seeping into groundwater.
    c. Consider strategies for prohibiting manure application on frozen or snow-covered ground or when there is a high probability of significant precipitation predicted. We acknowledge that this may require additional public cost-share for enhanced manure storage for some smaller facilities.
    d. When manure is transferred from a feedlot owner/operator to a third party for cropland application, require that the recipient also follow all relevant manure management plan requirements.
    e. Consider additional protections on manure application in vulnerable groundwater areas, including the southeastern karst region, the central sands region, and Drinking Water Supply Management Areas. These additional protections could include cover crops, diversified crop rotations, and strict limits on application that account for both manure and non-manure fertilization rates.

3. **Setbacks and livestock access**
    a. Require and enforce a 50-foot setback for land application of manure along certain waters. This includes rivers, lakes, and streams that are (i) impaired due to

excess nutrients or bacteria, or (ii) discharge into downstream waters that are impaired due to excess nutrients or bacteria.

b. Address the risks of livestock access to rivers, lakes, and streams. This includes the prohibition of livestock from a feedlot capable of holding 300 or more animal units from entering any waters that are impaired due to excess nutrients or bacteria, if it is determined that animal manure is a significant contributing factor to the impairment.

Thank you for your consideration,

Trevor Russell



Water Program Director
Friends of the Mississippi River

RECEIVED
By: OAH on 7/21/2025
Tom Salkowski Attachment

RE: Minnesota Pollution Control Agency request for comments on animal feedlots rule

Comments submitted by Tom Salkowski, Buffalo, MN (teesalk@aol.com)

I am in favor of changes to the Feedlot rules and, more importantly, the need to overhaul the feedlot regulation system and devote far more time, human resources and funds to having the rules mean something beyond words on paper. With characteristic understatement, the public notice states that "Rule amendments are necessary to maintain regulations that are protective of human health and the environment." I live in south central Minnesota where most people get their drinking water from wells threatened by long-term pollution by outsized animal factories, and from pesticides and other cancer-causing chemicals dumped on farmland routinely.

In addition, I am very fond of and recreate in the Karst Region of Minnesota, and especially the pristine cold-water streams that are found there. The facts that several fish kills have occurred in streams there in recent years, and that it took prodding from the former federal EPA to get any real action from the MNPCA on this matter, is disturbing, to say the least. Worse, that no one has ever been held to account for poisoning these public waters is a damning comment on the fecklessness of current state programs. Since it has become clear that we cannot rely on the federal EPA to do anything to protect the environment for the next 4 years, it is imperative that the State of Minnesota step up.

Consider the hundreds of millions of public dollars spent on diluting, transporting and treating human waste before it is deemed safe to release back into the environment. Meanwhile, livestock waste, which is no less harmful than human waste (check the inoculations and meds given to livestock as well as the potential for pathogens), is generated in volumes at least ten times higher than human waste statewide. While there are regulations on paper, as a practical matter this livestock waste, especially as compared to the treatment of human waste, is mostly untreated and disposed of in ways which clearly harm natural systems and threaten human health. Paperwork, reports, plans and permits can serve some purpose, but if no one is ever punished for violating the rules, and virtually no one is regularly checking to see if the rules are being followed, the paperwork mostly punishes those who bother to comply. My primary comment is that the state must devote

considerable more resources to support for County Feedlot Officers and to enforcement and education, if rules changes are going to have any real impact.

I am personally aware that there are excellent County Feedlot Officers in Minnesota. But it is also true that there are County Boards who control budgets and employment that often consider environmental protection and regulating farmers very low on their list of priorities. Certainly, the decision by the MPCA years ago to foist as much of the feedlot regulation business as possible upon Counties resulted in some cases of the fox overseeing the henhouse. Water resources do not respect County borders, and there is plenty of justification for the MPCA to be more directly involved, especially in the Karst region. Farmers are no more fond of regulations than any other business operators, but most care as much about clean water and air as the rest of us. Most will abide reasonable regulations if they can be assured that they are applied consistently and fairly. The MPCA must become much more involved in feedlot permits below 1000 animal units, in my opinion down to 250 units, in order to ensure regulatory consistency. If the current system, of devolving all or most responsibilities to the counties which has been tried for many years, was working, then we would not have fish kills, nitrate polluted groundwater and rivers being degraded across the state.

In regard to other and more detailed suggestions, I also agree with the comments being submitted by Minnesota Trout Unlimited, though any thoughts offered herein are mine and do not represent Trout Unlimited. Beyond those, I believe that the recently revised manure application requirements that apply to State permitted sites should be applied to all operations with more than 250 animal units. Further, I believe that the determination of animal units should be based on the maximum number of animals on the farm on any day during a full year. Operators who register 999 animal units should not be able to game the system. Thank you for the opportunity to comment, and I look forward to seeing the results of the rulemaking process. Finally, I would like to repeat my primary concern, that the state must devote considerable more resources to the support for County Feedlot Officers and to enforcement and education, if the purpose of protecting our environment and public health is to be fulfilled.

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By: OAH on 7/21/2025
Robert Karls Attachment

Comments regarding protection of ground water quality – 21 July 2025

Robert Karls – Past President of Minnesota Ground Water Association

Any industry or business that stores materials which have the potential to impact ground water quality have a requirement to do inspections, testing, and monitoring. The storage of manure in amounts typical of feedlot operation is typically in semi-solid or liquid form in lagoons, pits, or tanks. Any storage of manure in these types of structures with capacities over 5000 gallons individually, or cumulatively within ¼ mile shall be required to have ground water monitoring plan approved by the MPCA. All ground water monitoring plans shall:

1. Have no fewer than 4 monitoring wells installed within 100' of the perimeter of the outer boundary of the storage structure or container where manure would typically be present. The four wells should be installed in a manner that the well screen must be a minimum of 10' long and spans the seasonal fluctuation of the water table at the Site. (Due to the uncertain direction of ground water flow at the time of installation and seasonal variations fewer than 4 wells are not allowed).
2. A permit from the commissioner (MDH) is generally required for the construction, deepening, and modification of monitoring wells, including at feedlot locations.
    a. A single permit application can cover all monitoring wells on a single property used as release detection devices at a feedlot location.
    b. Construction Standards:
        i. Monitoring wells must be constructed according to Minnesota Rules 4725.6650.
        ii. Casing: Must be steel or plastic casing meeting specific standards, including stainless steel or flush-threaded PVC under certain conditions.
        iii. Grouting: The annular space must be grouted from near the screen to the ground surface, with specific requirements for at-grade installations.
        iv. Drilling Fluids: Must comply with relevant standards, with an exception for free chlorine residual.
        v. Screen or Open Hole: Specific requirements apply to monitoring wells constructed to monitor contaminants at the water surface across unconsolidated formation and bedrock contact.
    c. Maintenance Permits:
        i. Environmental wells (monitoring wells) constructed after January 1, 1990, that are not sealed within 14 months require an annual environmental well maintenance permit.
        ii. These permits are required for all environmental wells, and a single permit application can cover those on a single property.
        iii. The permit must be renewed annually until the well is sealed.
    d. Sampling and Analysis:
        i. Groundwater elevations must be monitored in all monitoring wells semi-annually.

ii. Groundwater samples must be analyzed semi-annually for nitrates, fecal coliforms, and total dissolved solids, and other parameters as identified by the MPCA.
iii. Results of each semi-annual water level elevation measurement and sampling event must be submitted to the MPCA within 90 days of the semi-annual measurement and sampling event.
iv. Laboratory data must be generated by MPCA-recognized certified laboratories.
v. Documentation of sampling events, including specific details about the well sampling procedures, identification of the sampling personnel, and chain of custody for all samples are required.

RECEIVED
By: OAH on 7/21/2025

Glen Groth Attachment

Winona County Farm Bureau®

July 18th, 2025

To: Office of Administrative Hearings

Attn: William Moore

OAH 600 North Robert Street,

PO Box 64620, St. Paul, Minnesota 55164.

To: Minnesota Pollution Control Agency

Attn: Addison Otto

520 Lafayette Road N

St. Paul MN 55155

Subject: Comments on proposed changes to Minnesota Rules governing animal feedlots Chapter 7020

To Whom it may concern,

Introduction

The Winona County Farm Bureau Ferderation in Southeast Minnesota is comprised of nearly 200 farmer members who represent farms of every size, structure and commodity found in our corner of the state. Winona County is in an area of the state with a robust livestock industry which supports hundreds of farm families directly while providing competitive markets for crop farmers in the region. The farm families who make up our membership have deep concerns over potential changes to the “7020” rules which govern nutrient management on farms below 1000 animal units. Any changes to Chapter 7020 must not be adopted without consideration for the economic viability of Winona County livestock farms. Failure to do so will result in serious financial stress and logistical concerns for producers and users of manure nutrients.

Poorly thought-out rules could incur burdensome expenses on farm families while hampering the use of manure by crop farmers in the region thereby favoring the use of chemical fertilizers.

Comments

- Winona County Farm Bureau members are particularly concerned about any rule change to lower the animal unit threshold where livestock farms would be required to hold a NPDES or similar permit. With an NPDES comes more stringent manure storage requirements, different rules for manure application and more stringent record keeping requirements. Smaller farms simply do not generate enough income to offset these additional costs. When faced with such requirements, farm families may choose to significantly expand operations to cover these costs or may decide to cease operations. Downsizing to an animal unit level where such requirements is also not financially viable as the farm may not generate enough income to support current family members and current capital costs.

- Winona County Farm Bureau opposes any modification to animal units which results in a greater animal unit value per head of actual animals (ie: raising a dairy cow from 1.4 au to 1.6 au). This could place many farm families over the 1000 au threshold potentially requiring them to comply with NPDES requirements without generating any more income to cover the expense.

- Winona County Farm Bureau opposes any rule that combines different feedlots owned by the same farmer into one operated under one permit. Purchasing other farm sites where non lactating cattle, or feeder livestock, are raised is a very common way for farmers to avoid the capital expenses of constructing new facilities while decreasing the concentration of manure at one location. Combining different sites could place a farm above the NPDES threshold causing significant financial stress for the business.

- Winona County Farm Bureau supports the responsible use of manure nutrients; however, we are concerned about new restrictions on winter time manure spreading and any increase of setbacks for manure application. No farmer wants to spread manure in the winter. However many farms began operating in a time when winter application was far more common than today Because of this, some family farms may not be able to store manure for long enough periods of time to get though the frozen months. Instead of a banket rule across the state, farmers should work with MPCA to identify times

throughout the winter when manure application presents little risk to water quality. Because of the geography of Southeast Minnesota, average field size can be very small and odd shaped. Greater setback requirements for manure application could render large number of fields ineligible for manure application requiring more acres for a farmer to meet the manure application requirements. Because some acres might be prohibited from manure application, greater use of commercial fertilizer could be expected.

Conclusion

Winona County Farmers have a long history of land stewardship and share a conservation ethic that is unique to this part of the state. Farmers in our area have worked with conservation groups and voluntarily adopted numerous practices that benefit surface and groundwaters. The local livestock industry understands the importance of being good neighbors by keeping manure nutrients where they are to be stored and applied. Onerous rules that are financially impossible to comply with can, and will result in the decline of family owned livestock farms in Southeast Minnesota. Conservationists should be particularly concerned with the potential to lose cattle and dairy farms in the region. When the cattle leave, farm families often rely on the corn and soybean rotation to generate farm income. According to MPCA's own research (figure 1) grazing land and the alfalfa/corn crop rotation common to cattle and dairy farms reliably contributes water to our aquifers below the 10 ppm drinking water standards. Winona County Farm Bureau looks forward to staying engaged throughout the process of reviewing the 7020 rules and looks forward to collaborating to ensure a financially sound livestock industry while maintaining high water quality standards.

Sincerely,

Glen Groth

Winona County Farm Bureau President on behalf of the Winona County Farm Bureau Federation.

Figure 1

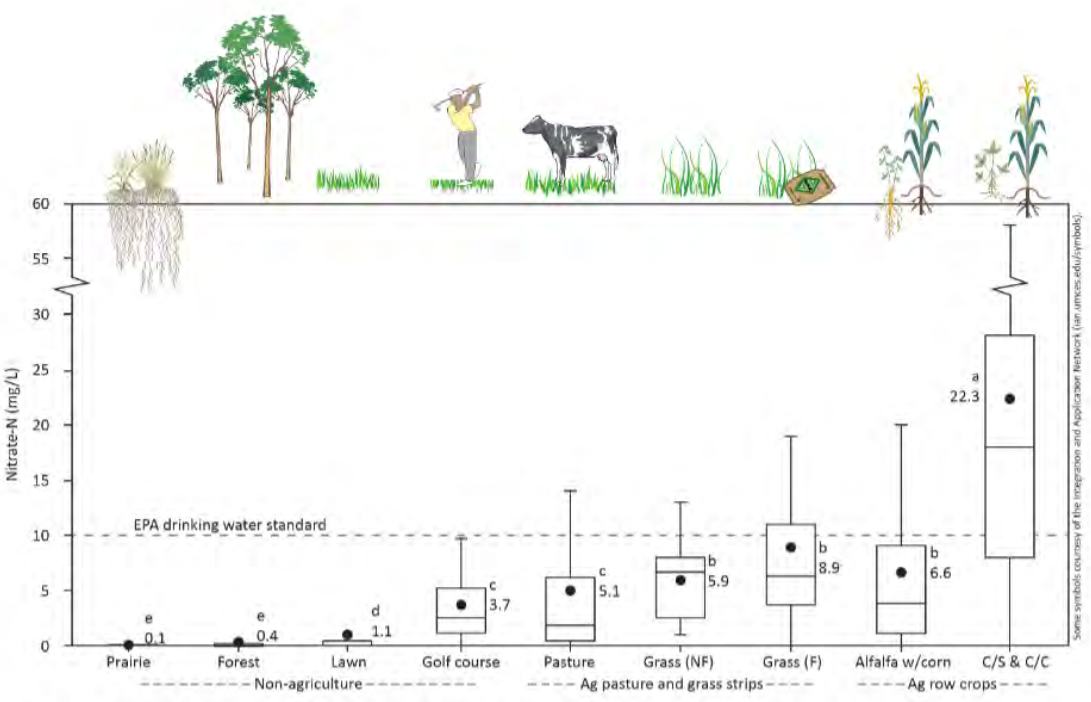

Data source: *Examination of Soil Water Nitrate-N Concentrations from Common Land Covers and Cropping Systems in Southeast Minnesota Karst* (Kuehner et al., 2020).

Graph summarizes nearly 3,000 soil-water nitrate-nitrogen samples collected from 50 suction-cup lysimeters, typically from a depth of four feet.
Black dots = average concentration; horizontal lines = median concentration; whiskers = ranges for top and bottom 25%, excluding outliers.
Land covers that do not share the same letter are statistically different at the 0.05 confidence level.

Abbreviations: NF = no fertilizer, F = fertilizer, C/S = corn/soybean rotations, C/C = continuous corn.

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By: OAH on 7/21/2025
Andrea Szabo Attachment

WHITE EARTH RESERVATION

CHAIRMAN Michael Fairbanks **SECRETARY-TREASURER** Michael LaRoque

DISTRICT I Henry Fox **DISTRICT II** Eugene Sommers **DISTRICT III** Laura Lee Erickson

July 21, 2025

Office of Administrative Hearings
600 North Robert Street | P.O. Box 64620,
St. Paul, MN 55164

Re: Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules Ch. 7020, Revisor's ID No. R-4928, OAH Docket No. 25-9003-40661

Dear Honorable McKenzie,

The White Earth Nation appreciates the opportunity to comment on the proposed rulemaking for Minnesota Feedlot Rules (Chapter 7020). As stewards of the land and waters of northern Minnesota since time immemorial, we assert our responsibility to protect the health of the ecosystems and resources guaranteed to us by treaties, federal laws, and court decisions. These include rights reserved in the 1837, 1855, and other Treaties that affirm our ability to hunt, fish, and gather on lands and waters our ancestors ceded to the United States, rights that are increasingly threatened by the cumulative environmental impact of large-scale animal feedlots.

The fish, water, and wild rice that sustain our people are not merely resources, they are also our relatives. Our culture and our way of life is deeply connected to our ability to exercise these rights in relation with these resources. The presence of nitrates, phosphorous, bacteria, and manure runoff in surface waters directly harms fish populations, wild rice beds, and the ecosystems we depend upon for cultural survival, subsistence, and spiritual continuity. Fish kills, such as those increasingly reported following extreme weather events near manure storage lagoons as well as manure storage failures, undermine our Treaty Reserved Rights to continue to hunt, fish, and gather. Any degradation of these natural resources constitutes a violation of the Treaty obligations by the State of Minnesota and the United States federal government.

We support the MPCA's acknowledgement that agricultural practices and environmental understanding have significantly evolved since the last major feedlot rule update in 2000. These changes include:

- Increased use of liquid manure and high-risk seasonal land application;
- Consolidation of animal agriculture into fewer, larger operations (often just under permit thresholds);
- Growing reliance on manure pipelines and commercial application over long distances;
- Documented overapplication of nutrients, often exceeding crop needs by over 40%, especially in groundwater-vulnerable areas like the Central Sands and karst regions;
- Greater demands for real-time environmental data and digital reporting.

Given these trends, current regulatory structures are insufficient to prevent the contamination of drinking water sources, degradation of surface waters, and destruction of aquatic ecosystems. The White Earth Nation supports and urges MPCA to incorporate the following policy recommendations:

1. **Lowering the Permit Threshold to 600 Animal Units (AU) or less**
   This change would increase permit coverage from 4% to 14% of feedlots in Minnesota which will address a larger portion of the 49 million tons of manure generated annually in Minnesota. More feedlots under permit will mean more manure management planning and pollution prevention which benefits us all.
2. **Water Quality Monitoring Requirements for Large Feedlots**
   We urge the MPCA to require monitoring of discharges to groundwater, drain tile effluent, and surface water. Compliance cannot be presumed without data. Effective enforcement depends on accurate, transparent, and regular environmental monitoring.
3. **Air Quality Monitoring Requirements for Large Feedlots**
   We recommend monitoring of additional air pollutants for large feedlots. While the MPCA has set hydrogen sulfide standards for feedlots and enforces these standards, we suggest requiring the monitoring of ammonia, a significant contributor to PM2.5, as well as PM, VOCs, and greenhouse gases at large feedlots. This data will inform Minnesota of the impact large feedlots may have on climate change and human health and could help in the potential future development of feedlot emissions standards for these harmful air pollutants.
4. **Ensuring Compliance with Air Quality Rules**
   The MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.
5. **Stricter Manure Application Limits in Vulnerable Areas**
   Application rates in karst and sandy-soil regions must not exceed agronomic needs. We strongly support banning liquid manure application of frozen or snow-covered ground and requiring cover crops or divers rotations in fall manure applications.
6. **Prohibition of New or Expanded Feedlots in Vulnerable Groundwater Regions**
   The MPCA rules should prohibit new or expanded animal feedlots where groundwater is most vulnerable to seepage pollution such as karst geology areas or the central sands region of the State. There are no remediation techniques available for contaminated

groundwater. We cannot afford to contaminate our groundwater supplies and should be particularly careful in areas where the groundwater is vulnerable to seepage pollution.

7. **No Permit-by-Design for Large Feedlots**
   Feedlots should not be presumed in compliance based on planning documents alone. A "trust but verify" approach must be adopted. Regulatory enforcement should include frequent, unannounced inspections, a swift plan to come into compliance if non-compliance is found, and penalties for continued non-compliance.
8. **Require Environmental Assessments for Medium and Large Feedlots**
   The current regulations require Environmental Assessment Worksheets (EAWs) for proposed feedlots over 1,000 AU or over 500 AU in a sensitive area. We recommend requiring EAWs for proposed feedlots over 500 AU and over 250 AU in sensitive areas. Feedlots generate large amounts of manure and waste, which can lead to significant air and water pollution. Lowering the threshold for requiring EAWs ensures that potential environmental and public health impacts are evaluated prior to construction. This is especially crucial in sensitive areas where ecosystems, groundwater, or human populations are more vulnerable. Sensitive areas, such as those near water bodies, wetlands, vulnerable groundwater regions, are more prone to contamination. Requiring EAWs for feedlots over 250 Animal Units in these areas ensures that even moderate-sized operations are thoroughly assessed for risks. By lowering the threshold, the regulation becomes more precautionary which allows agencies and communities to identify and mitigate potential problems before they occur, rather than dealing with the consequences after the damage is done. Environmental impacts can occur even from smaller operations, particularly when clustered or located within sensitive areas. Communities are increasingly aware of these risks, and this adjustment aligns policy with both science and public concern. Requiring EAWs for more feedlots encourages better siting, waste management planning, and transparency. This leads to more sustainable agricultural practices that balance economic activity with long-term environmental stewardship.
9. **Limiting Feedlot Size and Animal Units to be Permitted within Each Local Area or Watershed**
   There are currently no limitations to the size of a feedlot or to the number of animal units allowed within a local area or watershed which allows feedlots and concentration of pollution impacts to increase. The MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

The White Earth Nation asserts that any regulatory framework that does not fully account for the protection of Treaty-reserved resources is fundamentally incomplete. Feedlot pollution has tangible and growing impacts on our waters, fisheries, and wild rice ecosystems. The new rules must reflect the science and ethics of our time. This means strong permitting, more monitoring, and applying the precautionary principle, especially in vulnerable landscapes and aquifers.

We ask the MPCA to uphold its duty to all Minnesotans, including Indigenous Nations, by ensuring that feedlot regulation meaningfully protects the ecosystems our people have relied on for generations.

Miigwech (Thank you),

Chairman Fairbanks (Jul 21, 2025 12:12 CDT)

Michael Fairbanks

Chairman, White Earth Nation

WEN comment MPCA rulemaking July 2025

Final Audit Report 2025-07-21

Created:	2025-07-21
By:	Andrea Szabo (andrea.szabo@whiteearth-nsn.gov)
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"WEN comment MPCA rulemaking July 2025" History

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Bryanna Grefthen Attachment

July 21, 2025

Office of Administrative Hearings

Attn: William Moore

600 N Robert St., PO Box 64620

St. Paul, MN 55164-0620

RE: Comments on MPCA RFC for Amendments to Rule Governing Animal Feedlots: Minnesota Rules, Chapter 7020, Revisors ID Number R-4928, OAH Docket No. 25-9003-40661

Mr. Moore,

The Pennington Soil & Water Conservation District, as the delegated county feedlot officer for Pennington County, appreciates the opportunity to provide comments on the MPCA RFC regarding Minnesota Rules, Chapter 7020, governing animal feedlots. As the delegated county feedlot officer, we have direct experience implementing the state's feedlot program. It is important to maintain effective and practical rules to protect our natural resources and the environment while maintaining and supporting the success of the Minnesota livestock industry and operators across the state.

Information presented during the in-person meetings indicated an increasing trend in surface water nitrates at a couple of points in the northwest area. It was noted that an increasing trend did not mean exceeding standards. Looking at the same region, the number of registered feedlots continues to decline, which indicates other nitrate sources that should be reviewed. While animal feedlots may be a source of nitrates, it is one of many sources across the state such as the noted increasing use of sub surface drainage, increased use of synthetic fertilizers, city wastewater discharge, and more. As the MPCA reviews these rules and all available data, we encourage other sources to be taken into consideration and the rules, regulations, and enforcement are equal for all potential sources, not just animal feedlots.

The information presented during the in-person meetings also contained information on groundwater monitoring trends with very few data points in the northwest area, one being above the detection limit, located along a beach ridge. We urge the MPCA to reach out and compile as much information as possible prior to any rule changes. For example, Pennington SWCD has 20 years of lab certified well water testing data from their annual well clinics. With over 800 samples, only 3 samples have exceeded the drinking water standard. Please contact me if you wish to include our data set with your reviews. While nitrates in the groundwater are an issue in parts of the state and is an emerging concern, Minnesota is a large state with different soils, topography, and land uses. Rule revisions should be driven by science and data

for each region as necessary restrictions and corresponding best management practices should vary based on a site's soils, topography, and climate. As discussed in the Thief River Falls meeting, MPCA should consider creating different zones of the state as 'one size fits all' rules are not the best solution and do not provide the same benefits or protection across the state.

When reviewing land application rules, we again ask MPCA to consider utilizing zones when revising rules. As MDA has their fall restriction map for nitrogen application, areas of the state are identified as high vulnerability while others are climate excluded. Minnesota land and climate are different across the state and should be taken into consideration when revising the rule. Also, MPCA should recognize that changes to land application rules, limiting the amount, timing, setbacks, and locations will influence storage needs for existing and new facilities. New regulations regarding manure storage would need to account for the large financial costs to the feedlot owner and the timeframe it would take for owners to become compliant with new restrictions. Engineers, contractors, inspectors are already busy, increased demand from new regulations would create a bottleneck effect for survey, design, construction, installation, and certification of new storage areas that would be required before an owner could be in compliance with new rules.

While the MPCA reviews the current rules and considers changes, we ask the MPCA acknowledges that every region, county, city, site, and operation are unique and have differences. Keeping regulations and technical standards broad would be beneficial and the MPCA could allow, support, and supply the resources to the counties to update their local ordinances to strengthen their regulations as they see fit within their county's needs for restoration and protection of water resources. MPCA has Watershed Restoration and Protection Strategy (WRAPS) documents that could help guide each region in their local ordinances rather than a statewide rule as some areas document high nutrients and bacteria while other watersheds may have recent delisting of impairments. By referring to local WRAPS documents and Comprehensive Watershed Management Plans, it allows flexibility for each region to implement regulations that are needed in their area.

We urge the MPCA to carefully consider any proposed changes to animal unit (AU) calculations as these numbers are used for various determinations such local zoning, cost-share eligibility, manure management, land application, and soil and manure testing requirement thresholds. Small changes in these values could create large impacts to existing operations and feedlot program administration. MPCA should work closely with stakeholders and have a thorough understanding of the effects prior to any rule revisions to the animal unit calculations.

When considering any rule changes, we request the MPCA to consider practicality and balance flexibility and resource protection while also factoring the cost. New requirements could be costly and ultimately detrimental to the small operations that remain, especially in the northwest region. The livestock industry is important in the state and unjustified increased regulations could pressure small sites to close as financial assistance for these projects is very limited. Not only will new rules increase costs for landowners, but there will also be an increase in costs to administer the feedlot program.

With new rule revisions, there will be an increased need for additional outreach, assistance, education, inspections, and likely enforcement. The MPCA's Feedlot Program has very limited funding for administration and enforcement by both MPCA staff and funds distributed to delegated counties. MPCA will need to seek and identify additional funding for state and county staff to adequately and effectively educate feedlot owners and implement the new regulations. This increased financial hardship will be felt stronger in the counties that are minimally funded as the amount these counties currently receive is barely enough to administer the program.

There may also be a need to update the requirements of delegated counties. We support the need to update the rules to remove irrelevant wording and include the use of electronic systems for registrations, permitting, and manure management plans. However, MPCA should only add requirements that are necessary and can be directly tied to environmental protection and avoid creating unnecessary regulations that will only increase administrative costs of running the program. As stated above, the feedlot program is already working on limited funding and additional requirements could force counties to be undelegated, which is not desirable for individual counties and their feedlot owners.

Thank you again for the opportunity to provide comments on the proposed rule revision. Livestock operations are important as is the safety and health of the environment for all residents, tourists, and organisms. We support the MPCA's proposal to update the Chapter 7020 rules in a manner that is science-based, practical, flexible, maintain environmental protection, is region specific, and still preserve Minnesota's livestock industry.

Sincerely,

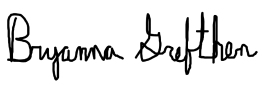

Bryanna Grefthen

Pennington County CFO

Pennington SWCD

Melissa Lorentz Attachment RECEIVED
By: OAH on 7/21/2025

Lower Sioux Indian Community in the State of Minnesota

P.O. Box 308 • 39527 Reservation Highway 1
Morton, MN 56270
Cansayapi Otunwe

July 21, 2025

Via OAH Portal

Minnesota Office of Administrative Hearings
Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Re: Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, Chapter 7020, Revisor's ID Number R-4928, OAH Docket No. 25-9003-40661

To Whom It May Concern,

The Lower Sioux Indian Community in the State of Minnesota (the "Community") submits these recommended amendments to Minnesota Rules Chapter 7020 that would assure minimum protections for tribal water systems in the vicinity of proposed feedlots. Chapter 7020 currently contains certain provisions applicable to a feedlot proposed near a drinking water supply management area ("DWSMA") approved by the Minnesota Department of Health. Those provisions should be amended to recognize similar areas designated by Indian Tribes located within the State of Minnesota.

Background

The Community is a federally recognized tribe with a reservation in southwestern Minnesota. As a sovereign nation, the Community possesses inherent authority over its drinking water systems, which are crucial to Community's health, safety, and welfare.

To ensure adequate protection of its water systems, the Community has developed a source water protection plan in partnership with the U.S. Environmental Protection Agency. A source water protection plan delineates a source water protection area, or a "land area that contributes water to the drinking water supply and where pollution from human activities or natural sources poses the greatest threat to source water quality."[1]

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[1] U.S. Envtl. Protection Agency, *What is a Source Water Protection Area?*, https://www.epa.gov/sourcewaterprotection/delineate-source-water-protection-area.

Minnesota Rules Chapter 7020 currently includes specific provisions applicable to a DWSMA, which is similar to a tribal source water protection area. A DWSMA is delineated based on a "wellhead protection area," which is "the surface and subsurface area surrounding a well or well field that supplies a public water system, through which contaminants are likely to move toward and reach the well or well field."[2] A DWSMA is defined as the "surface and subsurface area surrounding a public water supply well, including the wellhead protection area."[3] A DWSMA, which draws a boundary around that area, is approved by the Minnesota Department of Health.[4]

Proposed Rule Changes

The Community recommends the following rule changes to ensure that tribal source water protection areas are afforded the minimum stop-gap protections that protect a DWSMA from inadvertent contamination. These amendments are not intended to place designation and administration of a tribal source water protection area under the purview of state law. Rather, the amendments would simply ensure that these areas are recognized and accounted for when a feedlot application is processed by the State or a county.

I. The Location Restrictions Applicable to a DWSMA Approved by the Minnesota Department of Health Should Also Apply to Tribal Source Water Protection Area.

Minnesota Rule 7020.2005 currently prohibits animal or manure feedlot storage areas from being located within 1,000 feet of a community water supply well or well serving a public school if it also would be located within a DWSMA.[5] The Minnesota Pollution Control Agency adopted location restrictions "to provide a minimum level of protection" that was "needed to protect human health and the environment."[6]

A tribal source water protection area is defined in the same way, and for the same purpose, as a DWSMA. In short, locating a feedlot within a tribal source protection area endangers human health and the environment in the same manner as locating a feedlot in a DWSMA. Accordingly, the Community recommends the following amendments to Minnesota Rule 7020.2008, specifically in Subpart 1.B.:

> **Subpart 1. Location restrictions.** A new animal feedlot or a manure storage area must not be constructed within a floodplain or within 300 feet of a sinkhole. A new animal feedlot or a manure storage area must not be constructed within the applicable isolation distance required by part 4725.4450 or 100 feet of a water supply well, whichever is greater. Except as provided in items A and B, a new

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[2] Minn. R. 4710.5100, subps. 13, 24.
[3] *Id.* subp. 13.
[4] *See* Minn. R. 4720.5330, subp. 2.A.(2) (stating that the Department shall approve or disapprove "the drinking water supply management area boundary").
[5] See Minn. R. 7020.2005, subp. 1.B.(2) (prohibiting a new animal feedlot or manure storage area within 1,000 feet of a community water supply well or well serving a public school unless it is not within a DWSMA and not within 200 feet of the well).
[6] Minn. Pollution Control Agency, *Statement of Need and Reasonableness*, at 140 (Dec. 8, 1999) (hereinafter "1999 SONAR").

animal feedlot or a manure storage area must not be constructed within shoreland or within 1,000 feet of a community water supply well or other wells serving a public school as defined under Minnesota Statutes, section 120A.05, a private school excluding home school sites, or a licensed child care center where the well is vulnerable according to part 4720.5550, subpart 2.

. . .

B. A new animal feedlot or manure storage area may be constructed within 1,000 feet of a community water supply well or other well serving a public school as defined under Minnesota Statutes, section 120A.05, a private school excluding home school sites, or a licensed child care center if the following three conditions are met:

(1) the Minnesota Department of Health has approved a drinking water supply management area for the well under part 4720.5360 or an Indian Tribe has a tribally designated source water protection area;

(2) the animal feedlot or manure storage area is not within the drinking water supply management area approved by the Minnesota Department of Health or the tribally designated source water protection area; and

(3) the animal feedlot or manure storage area is not within 200 feet of the well.

It should be noted that the Community does not propose that a tribally designated source water protection area be referred to as a DWSMA in the rules, because there are specific requirements applicable to a state-designated DWSMA that may not be precisely the same as the tribal or federal standards that may govern a tribal source water protection area. There are eleven federally recognized tribes within the State of Minnesota, and some specific requirements or procedures may vary among tribes. As sovereign nations, tribes may each have their own processes and requirements.

The Community does not believe it is necessary to add a definition of the rules to describe a tribal source water protection area. However, if necessary, the term "tribally designated source water protection area" could be defined as "a geographic area, designated by an Indian Tribe, that contributes water to the drinking water supply of the Indian Tribe and where pollution from human activities or natural sources pose the greatest threat to water quality."

II. The Processing Requirements Applicable to a DWSMA Approved by the Minnesota Department of Health Should Also Apply to Tribal Source Water Protection Area.

The Minnesota Rules also require a county that is delegated feedlot permitting authority to forward certain permit feedlot applications for review by the MPCA.[7] The rule should be amended to include the forwarding of applications that may affect a tribal source water protection area.

[7] Minn. R. 7020.1600, subp. 4a.B.

As the Minnesota Legislature has recognized, the State of Minnesota has "a unique relationship with federally recognized Indian Tribes, formed by the Constitution of the United States, treaties, statutes, case law, and agreements."[8] State agencies have developed consultation procedures to further a productive government-to-government relationship.[9] Through the consultation process, the MPCA has developed relationships and experience working with Tribes on a government-to-government basis. Because of the status of Tribes as sovereign nations and the experience the MPCA has developed in working with Tribes, it would be appropriate for the MPCA to review applications in areas that Tribes have identified for source water protection.

To ensure effective implementation, a delegated county would first forward the permit application to Indian Tribes for a determination of whether the proposed permit would be within a tribally designated source water protection area. If an Indian Tribe confirms that, based on an existing designation, the permit would be located within a tribally designated source water protection area, then the permit would be forwarded to the MPCA for processing.

To implement these procedures, the Community recommends the following amendments to Minnesota Rule 7020.1600:

> **Subp. 4a. Permit application processing procedures.** The processing of permit applications by a delegated county shall be conducted according to the procedures in items A to F.
>
> > A. The county feedlot pollution control officer shall process permit applications and issue construction short-form and interim permits according to this part and parts 7020.0505 and 7020.0535, except as directed in item B. Upon receiving a permit application, the county feedlot control officer shall forward the permit application to all Indian Tribes located within the state to determine whether the proposed permit would be within a tribally designated source water protection area.
> >
> > B. The county feedlot pollution control officer shall forward to the commissioner for issuance all permit applications and all other applicable documents, comments, and recommendations for the following:
> >
> > > . . .
> > >
> > > (4) all facilities with 500 or more animal units that are within a vulnerable drinking water supply management area, as described on a Minnesota Department of Health approved wellhead protection plan or as described on an Indian Tribe's source water protection plan; ~~and~~
> > >
> > > (5) all facilities for which an application for a variance under part 7020.0505, subpart 6, is submitted; and~~.~~

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[8] Minn. Stat. § 10.65, subd. 1(b).

[9] *See id.* subds. 2(1) (defining "agency"), 3 (describing consultation duties).

(6) all facilities for which the county has received a determination from the Indian Tribe that the proposed permit would be within a source water protection area designated by an Indian Tribe.

The Community recommends forwarding the notification to all Indian Tribes located within the state to ensure that the rule's requirements are clear and easy to follow. In some situations, a county may be unsure which Indian Tribe may be affected. Forwarding the application to all Indian Tribes is the simplest way to ensure that notification is received while relieving counties of the burden of determining where the application must be forwarded.

III. The Recommended Definition of "Indian Tribe" Would Include the Federally Recognized Tribes Located Within the State of Minnesota.

The Community recommends adding the following definition to Minnesota Rule 7020.0300, to ensure clarity as to tribally designated source water protection areas must be considered:

> **Indian Tribe**. "Indian Tribe" means the following federally recognized Tribes that are located within Minnesota: Boise Forte Band; Fond Du Lac Band; Grand Portage Band; Leech Lake Band; Mille Lacs Band; White Earth Band; Red Lake Nation; Lower Sioux Indian Community; Prairie Island Indian Community; Shakopee Mdewakanton Sioux Community; and Upper Sioux Community.

This definition is consistent with the definition of "Minnesota Tribal Government" that is used in Minnesota Statutes Section 10.65, which directs Minnesota state agencies to implement consultation duties with Tribes to address matters that have Tribal implications.[10] It is an appropriate definition for these particular rules because these are the Tribes that may have water systems located within the borders of the State of Minnesota.

Thank you for your time and consideration. The Community looks forward to continued dialogue and consultation on the feedlot rules.

Pidamayado,

Robert L. Larsen
President

[10] *Id.* subd. 2(4).

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By: OAH on 7/21/2025
Paula Maccabee Attachment

Paula Goodman Maccabee, Executive Director and Counsel
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paula@waterlegacy.org or pmaccabee@justchangelaw.com

July 21, 2025

Submitted via https://minnesotaoah.granicusideas.com/discussions

Commissioner Katrina Kessler
George Schwint. P.E.
Minnesota Pollution Control Agency
520 Lafayette Rd.
St. Paul, MN 55155

Re: Minnesota Animal Feedlots Rules, chapter 7020, Revisor's ID Number R-04928
OAH Docket No. 25-9003-40661

Dear Commissioner Kessler, Mr. Schwint,

The comments below are submitted by WaterLegacy to request stronger Animal Feedlots Rules to protect water quality, fish, wildlife, and human health. WaterLegacy appreciates that the Minnesota Pollution Control Agency (MPCA) is seeking comments early in the process of developing new rules for animal feedlots.

Minnesota has more than 23,000 animal feedlots, also known as Concentrated Animal Feeding Operations (CAFOs). Manure and nitrate pollution from these feedlots flows down the Mississippi River and contributes to the Dead Zone in the Gulf of Mexico. Animal feedlot manure runoff, seepage, and spills also cause serious problems here in Minnesota:

- Fish kills result from byproducts of manure decomposition and depletion of oxygen levels in water due to excessive nitrates and algae blooms.

- Swimming is unsafe due to E.coli bacteria from animal wastes. More than 100 Minnesota waterbodies are listed under the Clean Water Act as impaired due to E.coli.

- Excessive nitrates result in blue-green algae blooms in shallow lakes and rivers, producing toxins (cyanobacteria) harmful to wildlife and humans.

- Increased nitrates in well water used to prepare infant formula can cause methemoglobinemia (blue-baby syndrome). The Minnesota Department of Health (MDH) has concluded that nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths in recent decades.[1]

[1] MDH, Nitrate and Methemoglobinemia, last visited July 20, 2025 at https://www.health.state.mn.us/communities/environment/water/docs/contaminants/nitratmethemog.pdf

Minnesotans are literally swimming in and drinking manure. WaterLegacy believes that existing MPCA Animal Feedlot Rules have significant deficiencies, including but not limited to the following:

- Existing rules only require water pollution permits (NPDES/SDS permits) for huge feedlots with 1,000 or more "animal units" (which can mean 3,000 swine, 10,000 sheep, or even 200,000 chickens). "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure[2]–require no permits.

- Existing rules set no maximum size for feedlots and no maximum number of animal units in a local area or watershed, allowing feedlots and concentration of pollution impacts to increase. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.

- Existing MPCA rules claim "no discharge" is allowed, but do not monitor or test manure storage areas or fields where manure is applied to verify what discharge in being released. In addition, despite compelling technical evidence since at least 2010 and multiple petitions for change, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.

- Existing MPCA rules do not apply modern science and technology to require containment of all manure within advanced liner systems. Rules allow application of manure to fields during the winter and under conditions where benefit to soil is unlikely and adverse effects to water quality virtually certain.

- Loopholes and exemptions allow noxious and odorous hydrogen sulfide air emissions as well as toxic water pollution. No existing rule requires a feedlot emitting noxious emissions and odors to demonstrate that at least 344 days a year, all air quality standards have been met.

WaterLegacy hopes that the MPCA will stand up to interested parties and substantially reform the way in which Minnesota regulates animal feedlots. We propose the following changes:

1. Require any animal feedlot with 300 or more animal units—rather than 1,000 or more animal units as currently stated in Minn. R. 7020.0405—to obtain a permit that complies with groundwater and surface water limits on pollution and non-degradation requirements as well as technology-based standards.

2. Define a "feedlot" for the purpose of requiring NPDES/SDS permits to include multiple feedlots with the same or overlapping ownership that are

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[2] Environmental Working Group, Five years after EWG's first analysis, manure still overloads Minnesota, last visited July 20, 2025, https://www.ewg.org/research/five-years-after-ewgs-first-analysis-manure-still-overloads-minnesota.

within a specified distance of each other or affect the same sub-watershed. MPCA should also define what criteria should be used to set a cap or moratorium on additional feedlot animal units in a county or local watershed.

3. Prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that "stricter" requirements in existing rules prevent pollution.

4. State that MPCA will enforce "no discharge" requirements, compliance with all water quality and air quality limits, reduction of contamination in impaired waters based on compliance schedules and/or TMDLs, and prevention of degradation in waters that are not polluted. Increase the degree to which regulations are outcome-oriented to reduce the need to dictate or provide exemptions from specific practices.

5. In order to make the current "prohibition" of discharge from feedlots (Minn. R. 7020.2003) verifiable and enforceable, require monthly monitoring (and public availability of DMR data) for groundwater and surface water quality for every permitted animal feedlot. Monitoring should include boring beneath existing manure storage facilities (vertical or diagonal, if necessary) to determine whether contamination has leaked into groundwater.

6. Require monitoring (and public availability of DMR data) for groundwater and surface water quality at all land application sites where manure from permitted feedlots is applied. For accurate monitoring, MPCA rules should require that feedlot application plans submit tile system maps for all proposed land application sites.

7. Require soil nitrate tests prior to land application of manure and restrict land application in areas with nitrate levels that exceed groundwater or surface water quality standards or would result in "point source nitrate-nitrogen contamination" as described in Minn. R. ch. 1573.

8. Prohibit application of manure, whether wet or dry, in the winter. Land application must be regulated to consider unpredictable and extreme weather due to climate change and to benefit soil and living plants, not to allow cheap disposal for animal wastes.

9. Expedite adoption of surface water quality standards for nitrates, based on technical analyses performed in 2010 and 2022 to ensure prevention of fish kills and protection of endangered, threatened, and species of concern.

10. Set new technology-based standards applicable to all manure storage based on current knowledge regarding liners, leakage, climate, and hydrology. For example, require a synthetic liner system as well as concrete for storage of

liquid manure, a double liner system for manure stockpiles in use for 120 days or more, and verification that projected leakage limits are met. *See* Minn. R. 7020.2100, .2125.

11. Require that all permitted feedlots provide animals with drinking water pumped into tanks and prevent animal access to waters of the state. *See* Minn. R. 7020.2015.

12. Clarify burden of proof for exemption of permitted feedlots from ambient air quality standards so that MPCA on its own or on receipt of a complaint can enforce air emissions and odor violations if a livestock facility does not demonstrate that it has complied with odor and hydrogen sulfide standards a minimum of 344 days per year and has only exceeded standards when removing manure. *See* Minn. Stat. § 116.0713.

WaterLegacy appreciates the MPCA's consideration of the above recommendations. In an era where federal environmental protection is likely to be minimal, Minnesota's action to strengthen and enforce Animal Feedlots Rules to protect water, fish, wildlife, and public health becomes even more important.

Please feel free to contact us if you have any questions about WaterLegacy's comments.

Sincerely yours,



Paula G. Maccabee
WaterLegacy Executive Director and Counsel

RECEIVED
By: OAH on 7/21/2025

COMMENT ON FEEDLOT RULES SUBMITTED BY MICHAEL D. MADIGAN

I appreciate the opportunity to submit comments on the proposed updates to Minnesota's feedlot rule (Minn. R. ch. 7020). Animal feedlots are a significant source of pollution. Without stronger regulations, manure runoff and groundwater contamination will continue to degrade human health, drinking water suppliers, and rural communities. While beyond the scope of my comments, the carcinogenic impact of nitrate pollution is well documented. https://progressreport.cancer.gov/prevention/chemical_exposures/nitrate.

Less well known are the devasting impacts of nitrate pollution to trout streams and the abundant life that they foster. Aquatic ecosystems are vital to Minnesota's outdoor economy, environmental health, and quality of life. Coldwater streams are among the rarest and most sensitive aquatic systems in Minnesota and require the highest level of protection. Anything less puts irreplaceable resources and the public's health at unacceptable risk. Feedlot pollution and agricultural runoff have already resulted in significant fishkills in the Southeast.

When revising the Rules I ask that you consider:

- **The true costs of a weak Rule:** Remediating polluted aquifers and restoring degraded streams is exponentially more expensive than proactively preventing nitrate pollution.
- **Manure and it's byproducts are toxic to aquatic ecosystems:** Nitrates reduce the size and potentially survival of trout populations and impact the macroinvertebrate populations trout depend on for food. Ammonia from manure is directly toxic to fish at even relatively low concentrations and has been tied to recent fish kills in southeast Minnesota.
- **Vulnerable Groundwater Areas must be prioritized:** Many feedlots are in the southeast Minnesota karst region, where groundwater moves quickly through cracks and sinkholes. Nitrate pollution from manure can easily seep into aquifers, threatening groundwater-fed trout streams.
- **Stronger rules help Minnesota mitigate and adapt to climate change:** Ensure resilient clean water supplies and trout streams for future generations and reduce nitrous oxide emissions.

I strongly urge the Minnesota Pollution Control Agency to amend the Rule to include the following:

- Require soil nitrate tests prior to all manure applications in Cass, Carlton, Morrison, Martin, Winona, Hubbard, Rock, Clearwater and Stearns counties which have been shown to be hot spots for nitrogen overload. (7020.2225 Subp.2)
- Require NPDE/SDS permits for feedlots with over 600 animal units. (7020.0405)
- Require robust nutrient management plans that minimizes nitrate loss to both groundwater and surface water for feedlots with more than 300 animal units. (7020.2225 Subp. 4)
- Prohibit manure application on frozen or saturated ground, or when rainfall is likely. (7020.2225 Subp. 6 add to Subp4))
- When manure is transferred for application purposes the transferee must also follow the requirements set forth in the permit. (7020.2225 Subp.5 D)
- Require expanded buffer zones and greater setback distances for feedlots located near trout streams, tributaries, seeps or springs flowing into trout streams, public waters, and public drinking water supplies. You cannot spread manure within 250 feet of a private well, 1000 feet of a community well, or 300 feet upslope or 100 feet downslope of a direct conduit to groundwater (sinkhole, outcrop). (https://cropsandsoils.extension.wisc.edu/articles/best-management-practices-to-use-on-karst-and-silurian-soil/) (7020.2225 Subp.6/8)
- Eliminate the option to delegate county level permit oversight and return oversight to the MPCA. (7020.1500)
- Animals of a CAFO or a facility capable of holding 300 or more animal units must not be allowed to enter waters of the state (7020.2015 Subp 1) Subp. 26.
- Manure and process waterwater application must not be allowed near trout streams and springs, seeps, and tributaries of trout streams. Specifically, I would suggest that manure and process wastewater not be applied land within 300 feet of a trout stream or spring, seep, or tributary to a trout stream or to land within 1000 feet of a trout stream with a slope of 6 degrees.
- Expand mandatory groundwater and surface water monitoring at all large operations, manure storage application sites.

- Consider the density and the maximum number animals units allowed in a particular watershed, with consideration to the vulnerable groundwater areas of the state including the Karst region. Using a cumulative spatial approach as used in the recent EWG report should be considered.

Healthy coldwater ecosystems need clean, cold water. Inadequate feedlot rules jeopardize the health of these precious resources. Recent, massive fishkills in the southeast attest to the failure and inadequacy of the current rules. I urge MPCA to act boldly and adopt stronger feedlot regulations that reflect the scale and urgency of this challenge.

Respectfully,

Michael D. Madigan

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By: OAH on 7/21/2025
Ben Lilliston Attachment

Minnesota Pollution Control Agency

July 21, 2025

Re: Minnesota's Animal Feedlot Rule

https://www.pca.state.mn.us/sites/default/files/wq-rule4-29a.pdf

The Institute for Agriculture and Trade Policy (IATP) appreciates the opportunity to comment on the Minnesota Pollution Control Agency's proposed amendment to Minnesota Rules Chapter 7020 governing animal feedlots.

It has been 25 years since Minnesota significantly revised the rules for animal feedlots and the massive amounts of manure they produce. As the MPCA acknowledges, much has changed since that time. Minnesota now has about 17,000 feedlots and those operations are getting far bigger and far more industrialized, storing much more manure in large waste facilities. We also have increased use of liquified manure systems that are leading to the over-application of manure on farmland and increasing the potential for runoff into waterways.

Our knowledge about how feedlots affect our water, climate, and public health has also improved. We have a better understanding of nitrate pollution and the number of impaired waters in the state.[1] Throughout the state, nitrogen loads in river systems are staying elevated or even increasing in some cases. Manure continues to be a major threat to water quality in the state. As the MPCA reports, the state is experiencing more extreme weather events that have affected the feedlot industry, including manure overflows.[2] The state has also seen a loss of small grains and accompanying grazing lands that could help improve water quality, even as the feedlot system has expanded.

According to a recent analysis by the Environmental Working Group, the state's feedlots house up to 1.03 million dairy cattle, 1.6 million beef cattle, 10.8 million hogs and 58.7 million turkeys and chickens, which together produced over 48.9 million tons of manure that year. Many of the state's feedlots are located near vulnerable groundwater areas. EWG found that almost 6,500 feedlots in the state are located in vulnerable areas.[3]

Facilities under 1,000 animal units do not need a water pollution permit under the EPA's NPDES or the State Disposal System (SDS, just a construction permit. For that reason, many

[1] https://www.pca.state.mn.us/air-water-land-climate/minnesotas-impaired-waters-list

[2] https://www.startribune.com/manure-pits-reportedly-overflow-at-16-large-feedlots-in-southern-minnesota/600376074

[3] https://www.ewg.org/research/five-years-after-ewgs-first-analysis-manure-still-overloads-minnesota

operators keep their animal unit numbers just below the 1,000-animal unit threshold to avoid having a water pollution permit. The EWG analysis found that 374 animal operations in the state had between 950 and 999 animal units in Minnesota in 2024.

We applaud the MPCA for updating the feedlot rule. Given the enormous changes over the last 25 years, we encourage the MPCA to take significant steps to protect the state's water and air. We recommend the following actions to strengthen the current feedlot rules.

1) The feedlot permit should lower the animal unit threshold for feedlots required to complete a NDS or SDS permit to 600 animal units. This simple step will greatly improve the effectiveness of the program by covering more feedlots.
2) The updated rule should include stronger limits on manure applications, including lowering manure application rates, best practice requirements for fall application, limits on winter application, and requirements for enough storage capacity to avoid winter application. These reforms are particularly needed in areas facing water quality problems such as the karst region and the central sands region.
3) Strong groundwater monitoring should be included in the permit. Permitted, large facilities should be required to monitor subsurface discharges, including where manure has been transferred to neighboring farms, to see how much nitrate ends up in water. There is currently no way to make sure these operations do not violate Minnesota's water quality standards.
4) Require permitted feedlots to create a risk-assessment plan to monitor their manure storage areas and land application sites for above-ground discharges to ensure feedlots are not polluting lakes and rivers. Such risk assessment plans should incorporate climate risk, including expected extreme weather events.
5) The state should make more manure managing data and mapping available to the public, including information about anerobic digesters and manure spreading plans. Communities near feedlots deserve to understand the impact of manure on their nearby environment.
6) Feedlots that include anerobic digester plants producing digestate should be required to have a specific digestate application plan to mitigate the unique risks associated with digestate that include higher concentrations of nitrogen and phosphorous, and the potential for PFAS and other chemical contamination.
7) IATP has signed onto and strongly supports a comment submitted in collaboration with other organizations, including the Minnesota Center for Environmental Advocacy, calling for the MPCA to include the regulation of greenhouse gas emissions for large feedlots as part of an updated feedlot rule. This action for greater reporting on climate impacts and mitigation plans aligns with the current Environmental Quality Board's Environmental Assessment Worksheet (EAW) and should include: monitoring and reporting provisions specific to GHG emissions; mitigation strategies to reduce emissions from manure management and livestock operations; and enforcement measures to ensure compliance with existing air emission plan requirements.

We hope the MPCA will consider the feedlot rule within the larger context of the climate crisis, increasing farmland consolidation and the loss of farmers in the state. New feedlot rules should be coupled with farmer-focused programs to support more sustainable, regenerative systems for raising animals that do not require the storage of mass quantities of manure.

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By: OAH on 7/21/2025
Dianna Jax Attachment

July 21, 2025

William Moore

Office of Administration Hearings

600 N Robert St

PO Box 64620

St Paul, MN 55164

RE: MPCA Feedlot Regulations

Mr. Moore,

On behalf of Jax Dairy Farms Inc. I would like to provide a few comments on the proposed MPCA rule changes for feedlots.

1. Please consider the impact of placing limitations on the ability to haul pen pack/semi solid during the winter months. We place the utmost importance on animal welfare and proper husbandry. Depending on the amount of precipitation we receive during winter months, it is critical for us to have the ability to haul manure during this timeframe. We must be able to keep our animals clean and dry for the prevention of sickness.
2. The proposed time structure for hauling of manure in the fall would make it nearly impossible to be able to get all of our manure hauled. We currently hire a custom applicator to do this due to the high cost of owing and operating this type of equipment with the limited profitability of a family owned dairy business, it would be detrimental to the future generations of our family to continue the dairy operation if we had to invest in equipment to do our own manure hauling.
3. The current rules and regulations are taken very seriously by our ag sector. We find it to be our obligation to protect our water sources due to how critical they are to our livestock operations. The current regulations we follow we find to be fair and do what they are supposed to do by protecting our water sources. We are avid fisherman/hunters and take great pride in protecting our resources so they can continue to be enjoyed by future generations.

Sincerely,

Roger Jax

Roger Jax

Jax Dairy Farms Inc

11331 620th Ave

Adams, MN 55909

RECEIVED
By: OAH on 7/21/2025

Letter to the Minnesota Pollution Control Agency Opposing New Regulations

Shannon Watrin

52753 Watrin Road

Sandstone, MN 55072

dairy_queen_shannon@hotmail.com

7/21/2025

Minnesota Pollution Control Agency

520 Lafayette Road North

St. Paul, MN 55155

To Whom It May Concern,

I am writing as a resident and stakeholder in the state of Minnesota in response to the recently proposed set of new environmental regulations. While I appreciate and deeply respect the Minnesota Pollution Control Agency's (MPCA) ongoing commitment to preserving the natural beauty and health of our state, I must voice my concerns and express my lack of support for these new regulatory measures. It is my hope that, by sharing my perspective and highlighting the potential implications of these regulations, my letter may contribute constructively to the ongoing dialogue surrounding environmental policy in Minnesota.

Appreciation for Environmental Stewardship

To begin, I wish to commend the MPCA for its long-standing efforts to maintain Minnesota's clean air, water, and land. Our state's rich natural resources are a source of pride and prosperity, and it is crucial that we continue to safeguard them for future generations. I recognize that robust environmental protection has been a cornerstone of Minnesota's reputation as a great place to live, work, and visit. Through the years, the MPCA has played an important role in upholding these standards and continually striving for improvement.

As a member of a family farm, I have witnessed firsthand the relentless effort required to remain both operational and compliant with MPCA standards. Our farm has worked diligently to meet every expectation, and we have appreciated the opportunity to

collaborate with MPCA representatives—particularly when facilitating dialogue with our neighbors to address concerns and dispel common misconceptions about animal agriculture. These conversations have not only clarified our commitment to responsible stewardship but have also helped foster understanding within our local community.

However, I am deeply concerned that further tightening of regulations could carry unintended consequences, ultimately discouraging the next generation from entering agriculture and jeopardizing the ability of current farmers to sustain their livelihoods and pass on their businesses. For many of us, farming is not just an occupation but a legacy, one that we hope to continue for years to come.

I am concerned that the proposed additional regulations will place a significant financial and administrative burden on family farms like ours. Increased compliance requirements often translate into higher operational costs—not only in terms of necessary equipment or infrastructural upgrades, but also through the increased time and resources needed to manage and document compliance. For many small- and medium-sized agricultural operations, the cost of additional paperwork and mandated procedures can be overwhelming, potentially threatening their long-term viability. These challenges could discourage new generations from continuing the tradition of family farming, ultimately impacting both local economies and our ability to provide fresh, sustainable food for Minnesota communities and maintain a diversified agricultural community.

As we evaluate these recommended practices, I urge the MPCA to recognize that effective regulations must be grounded in the realities of location, geography, and weather. While it is possible to regulate the actions of farms, we cannot control, nor reliably predict, the weather—an ever-changing variable that shapes every growing season. Flexibility in compliance will be essential for the longevity of Minnesota's farms.

In east central Minnesota, for example, we contend with a unique set of challenges due to our cooler climate, greatly influenced by proximity to Lake Superior. The short and unpredictable window for planting cover crops in the fall, compounded by the difficulties of spring forage removal, means success varies considerably from year to year. Some seasons, cover crops flourish; in others, they are simply not viable. This variability is not from lack of effort or care—quite the opposite, as farmers are consistently striving to do what's best for the land and their animals. These are the hallmarks of true sustainability, values at the very heart of family farming.

Moreover, as the state considers layering additional regulations, I ask that funding and support be made available to small- and midsize farmers to help them achieve

compliance. Financial assistance, technical guidance, and cost-sharing opportunities will promote shared success far more effectively than rigid mandates alone. Too often, the fear is not of change, but of being regulated out of common sense and, ultimately, out of business.

Farmers want nothing more than to be responsible stewards, preserving the health of the land and their herds for the next generation. I respectfully ask the MPCA to ensure that new regulations do not unintentionally undermine the sustainability of family farms like ours but rather empower us to continue our vital role in Minnesota's rural communities.

Respectfully submitted,

Shannon Watrin

Dairy Farmer

Sandstone, MN 55072

RECEIVED
By: OAH on 7/21/2025
Jill Nelson Attachment

To Whom It May Concern,

My name is Jill Nelson, and I am the President of the Brown County Farm Bureau. Recently, several of our members attended the listening session in New Ulm, MN. Following that meeting, we met to draw up comments on the proposed changes to Minnesota's feedlot rules on behalf of the livestock producers in our county. Our committee was made up of representatives from all species groups: dairy, beef, poultry and swine.

MPCA states that these updates are needed because "farming practices have changed over the past 25 years." We agree - but not with the conclusion you're drawing. Farming practices *have* changed - for the better. In fact, most of the changes made by farmers in the last two decades have significantly improved water quality and reduced runoff and erosion. This is evidenced in recent research done at the UM and statistics shown at the meetings put on by the MPCA. Adding additional regulations to farmers simply because of pressure from activist groups who work hand in hand with the EPA is nothing but playing into their hands. Hands that never come with real, unbiased science. The sole goal of these groups is to eliminate animal agriculture. It is our hope that the MPCA will be wise in their direction and focus on where the problems are.

Current Reality: Many farms have adopted conservation-based practices that were unheard of a generation ago:

- Manure is now managed through nutrient plans that prioritize timing, placement, and soil health.
- Many farms use buffers, minimum-till or no-till and cover crops to keep nutrients in the field where they belong.
- Modern equipment and technology have made it possible to reduce over-application of fertilizer (including manure) and avoid sensitive areas altogether.

Given this progress, I urge MPCA to consider the following points:

- **Don't punish progress.** These new rules seem to assume agriculture is stuck in the past, when in fact many of us have made voluntary improvements, often without government mandates. The new regulations should reflect and reward that progress, not pile on more restrictions.
- **Ease, don't increase, regulatory burden.** What we need now is simplification and flexibility, not additional permitting hurdles that treat all farms the same regardless of location, stewardship, or impact.
- **Base rules on current science and data.** If the MPCA has clear data showing that feedlot-related pollution is on the rise, it should be shared publicly. From what we've seen in our area and what the newest University research shows,

water quality has improved, not declined. This was also shown in the data presented by the MCPA at the early listening sessions.

- **Hold municipalities responsible.** Farms are constantly being asked to shoulder the burden of pollution control, especially in our MN waters. However, those rules don't apply to municipalities who, in many cases, are allowed to discard directly into lakes, rivers and streams, especially during weather events. Farms would be shut down for doing this. Also, fertilizer and lawn chemicals are applied ad-lib in towns with run-off going directly into the sewer systems and often to lakes, streams and rivers. Any laws applied to farms should also be applied to municipalities and those who live there. Acres upon acres of city lawns have fertilizer and chemicals applied several times each summer. Most often at rates far above what is recommended. Often those granules and sprays fall directly onto the street which are then washed directly into the sewer systems. This is **Direct Point Pollution** and should be the first thing addressed.
- **Test the water in the Mississippi and Minnesota Rivers in the Twin Cities area.** We have been told there are no test zones for the rivers which run through the twin cities and other large metro areas. Why is that, if not to avoid showing the municipalities contribution to the river pollution.
- **Tailor rules to farm size and type.** One-size-fits-all rules often hurt smaller farms that don't have dedicated compliance staff or the capital to completely overhaul existing infrastructure that is still working safely.

Inspection of old lagoons and manure storage – This is infeasible for any size farm. Most are never truly empty to a point they could be inspected. Our county feedlot personnel were told in training that a manure pit/lagoon is designed to last at least for 2 barn cycles. Most barns are good 40 years which means a pit wouldn't be suspect until 80 years of use. Also, we know that the soil seals up from the weight and pressure so any possible cracks in a cement or clay lined pit would seal up and not have water leaching into the ground.

Composting Manure – Research has shown the process of composting manure and other materials does not lead to contamination of the ground under the compost site or the ground where any potential rainwater flows to. Those who have been working with farms to develop compost sites encourage composting on ground rather than impervious surfaces because the compost process works better and faster and will result in less run-off. Manure needs moisture added periodically for the composting process to work. I can provide contact information for a man who is conducting on farm research into large scale composting with great success. I have seen firsthand how quickly a metal building built on top of a compost pile becomes completely corroded within a few years. Check with the city of Middelton, WI about their compost project. The building is like Swiss cheese.

Action plan for Composting manure

- Do not require impervious surfaces – this is unfeasible and works against the process
- Do not require covering – this is an unnecessary waste of resources and will quickly become ruined if it isn't outgrown first.
- Put manure composting under the jurisdiction of the Department of Agriculture for the entire process, not just the finished product
- Encourage more research and farm experimentation in this area – this could be a game changer for manure handling and hauling for farms of all sizes.

The Current Animal Unit Thresholds Are Outdated

Farming practices have improved greatly over the past 2 decades, but what hasn't changed in decades is how MPCA defines farm size under its permitting structure. And that's a problem.

MPCA regulates feedlots by animal unit (AU) size categories. But the thresholds have not been updated to reflect modern economic realities. Farming today requires larger herds just to cover rising input costs, sustain family incomes, and allow younger generations to return home to farm. Holding the same size thresholds year after year, while inflation and expenses climb, effectively penalizes farms for growing just enough to survive.

For example, the threshold for moving into a higher level of regulation (such as feedlots over 300 AUs) has remained stagnant, despite the fact that input costs, land prices, and equipment have all skyrocketed. It is time to **raise the base AU threshold for small farms to at least 500 AUs**, with an automatic annual adjustment based on inflation or USDA cost indexes.

Why This Matters:

- **Farms are growing out of necessity, not greed.** We aren't building mega-operations; we're trying to support family or bring the next generation into the business.
- **Current thresholds don't reflect stewardship.** A well-managed 500 AU farm using modern conservation practices can have less environmental impact than a poorly run 200 AU facility.
- **Staying "small" is becoming economically impossible.** When margins shrink but compliance burdens rise, more farms will close, especially family operations trying to pass the farm on.

- **Example for a small dairy (but similar for all species):** at 1.4 AU per mature Holstein cow. A farm is limited to just over 210 cows if they do not raise any young stock. This is below the level of milking cows that economists agree can sustain one family. This leaves the farm with few options:
    - have a 2nd farm for youngstock and replacements,
    - reduce the milking herd to under 140 milking cows and raise the replacements on site (unsustainable)
    - have a 2nd full time job to sustain the family since the farm can't make enough to cover basic family living costs
    - hope your neighbors and county will allow you to get a permit for higher AU
    - Give up milking cows and tell your farming kids to move on from their dreams.
- **Modern feeding strategies are making animals much more efficient**. In dairy, the huge increase in production per cow over the last 25 years has resulted in much less manure produced to produce the same amount of milk. This should be reflected in the regulations by decreasing the AU designated to a mature cow. The research in dairy cow efficiency is in its infancy and will only improve exponentially with new feeds being produced for this reason. Meat livestock are showing similar improvements in efficiency of getting animals to harvest sooner and with more meat in a shorter time. All of this leads to less waste produced for each food unit produced.

We Urge MPCA To:

1. **Increase the lower AU threshold from 300 to at least 500 AUs.**
2. **Establish a mechanism for annual review and adjustment based on inflation and farm income trends.**
3. **Reassess how environmental impact is measured—based on practice and management, not just headcount.**
4. **Permits for a CAFO should be good for the life of that farm. It is not feasible to invest in building a farm with the thought that the permit may not be renewed when the time comes.**

Nitrate Level

The research on what level of nitrates is dangerous for humans is far from established or clear with science. While nitrate reduction is a valid goal, pushing nitrate levels too low, without considering nutrient balance, can cause more harm than good.

- **Algae Blooms** - Low-nitrogen conditions often lead to increased toxic algae blooms due to a rise in phosphorus dominance. These cyanobacteria outbreaks pose serious risks to human and animal health and can make water unusable for recreation, drinking, or irrigation.
- **Microbial Activity** - overly strict nitrate limits can backfire in soil systems, reducing microbial activity, weakening crops, and accelerating erosion. Instead of setting arbitrary targets, MPCA should prioritize balanced nutrient management, not single-nutrient suppression.
- **Methylmercury Formation** - Another serious concern is the link between nitrate reduction and methylmercury formation. When nitrate levels in soils and sediments are driven too low, it encourages anaerobic microbial activity that converts inorganic mercury into **methylmercury, far more toxic compound.** Methylmercury builds up in fish and enters the human food chain, posing significant health risks including neurological damage, especially in unborn children. Ironically, well-intentioned nitrate reductions can unintentionally increase this far more dangerous pollutant.

Other

1. **There should be an active farmer from each major species represented on each of the committees formed to address the feedlot rule changes**
2. **Trying to regulate manure application by weather and temperature is not feasible on any level**
3. **Do not change the designation of animals units for variations in weight for any particular animal (large vs small turkey)**
4. **All of the issues outlined in the MPCA meeting can be attributed to both farms and cities/towns. From drain tiling (think house foundations) to animal and human waste. Just because it's easier to regulate farms doesn't mean it's the right thing to do.**

This is not about deregulation, it's about realistic, modern regulation that allows farms to evolve responsibly. Minnesota's farmers are not asking for a free pass, we're asking for rules that match the realities we live with every day. And we ask that every municipality is held to the same standards and measures.

Minnesota farmers are not standing still. We've already evolved. These proposed rules should reflect that, not take us backward with blanket regulations that disregard our progress and make it impossible to continue on with livestock.

Thank you for considering my comments and for allowing public input on these decisions.

Sincerely,
Jill Nelson
President, Brown County Farm Bureau
Bown County, Minnesota
507-220-0730

RECEIVED
By: OAH on 7/21/2025

To: Minnesota Pollution Control Agency
From: Pat Troendle
Business Names: Full Circle Nutrition LLC, Duschee Hills Dairy LLC
Address: 23962 Grosbeak Rd, Lanesboro, MN 55949

Re: Comments on Proposed Changes to Rule 7020 – Feedlot Program

Greetings,

My name is Pat Troendle. I own and operate two agricultural businesses in southeast Minnesota.

Full Circle Nutrition LLC is a ruminant nutrition and biological fertilizer company. On the agronomy side, we work closely with producers throughout SE Minnesota and NE Iowa. Nearly every operation we support either generates manure or utilizes compost products to build biological activity in the soil. Regardless of operation size, manure is a resource—not a waste product.

Duschee Hills Dairy LLC is our 190-cow dairy farm located in Lanesboro, MN. We manage 560 acres across 92 different fields. Our crop rotation includes about 300 acres of corn and 260 acres of alfalfa, and we follow every corn silage crop with a five-species cover crop. We adhere to a manure management plan developed with our county feedlot officer and are very aware of our region's environmental sensitivity.

I attended the MPCA meeting held in Chatfield this June. Although no final decisions were presented, it was clear that certain regulatory changes are under serious consideration. I'd like to share a few thoughts, mainly from the perspective of a ruminant livestock operation.

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1. Animal Unit Threshold Changes

The idea has been raised to add a fourth regulatory category and increase the requirements under 1,000 animal unit (AU). While I understand the intent is to apply stricter manure storage and application requirements to more operations, it's important to acknowledge that most livestock farms already strive to manage manure responsibly. Ideally, they would have 14 months of storage and apply manure during a narrow window of perfect conditions—but that's simply not the reality we live in.

If regulators move forward with creating this new category, it is critical to consider the large number of farms that would be newly impacted and the serious economic consequences that could follow. For many of these operations, especially small to mid-sized family farms—the cost of building additional storage, upgrading infrastructure, and complying with stricter application requirements would be overwhelming. In many cases, these improvements would be financially unfeasible and could ultimately force farms out of business.

Any new policy must carefully balance environmental objectives with the economic and operational realities on the ground. Without that balance, we risk accelerating the demise of independent farms and further consolidating the livestock sector, with long-term consequences for rural communities and food security.

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2. Limitations on Fall Manure Applications (Soil Temp <50°F)

Restricting fall manure applications based on soil temperature (e.g., below 50°F) is impractical. On our farm, we apply manure after corn silage harvest to make room in our storage basins and to establish fall cover crops in a timely manner.

Fall manure application has key advantages:

- Timely nutrient placement
- Reduced spring workload
- Tillage and incorporation reduce runoff risk
- Freeze-thaw cycles help alleviate compaction

When managed properly, manure incorporated in the fall is a stable and effective nutrient source for the next growing season.

One important issue that wasn't addressed is that all manure types appear to be treated the same under the proposed changes. However, there are significant differences between liquid manure, bedded pack, and compost. These differences affect not only nutrient availability to plants but also the potential for nutrient loss through runoff or leaching. Bedded pack manure—and especially compost—pose a much lower environmental risk due to their physical form and how nutrients are stabilized within the material.

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3. March Application Ban

The suggestion to ban manure applications in March may sound reasonable in theory, but it is unrealistic in practice. March weather in Minnesota is highly variable—conditions can indeed be snowy and wet, making application inappropriate. But just as often, the ground is still frozen, fields are dry enough to support equipment, and conditions are actually well-suited for responsible manure application. Prohibiting all March applications would force farmers to wait until April, compressing both manure application and spring planting into an already narrow and often unpredictable window. This not only creates significant logistical challenges but could also result in missed opportunities to apply manure under

ideal conditions, simply because the calendar says it's too early.

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4. Infrastructure and Time Limitations

The above proposals to temperature and dates assume that farmers have access to unlimited time, labor, and infrastructure. The reality is:

- There is not enough infrastructure (storage, equipment, or labor) to meet such tight timelines.
- Building sufficient storage and logistics capacity would require billions in investment.
- Even with investment, time and variable Minnesota weather remain the biggest limiting factors.

Ruminant operations like Duschee Hills Dairy serve as environmental stewards by using crop rotations which include alfalfa to minimize soil loss and efficiently utilize applied nutrients. Practices such as vegetative buffers, grassed waterways, and low-disturbance manure injection are already used by many producers to mitigate runoff risk

We are not alone, many similar farms across Minnesota do the same. If these operations are regulated out of viability and replaced by continuous row crops or residential developments, the result could be declining soil health and even increased nitrate levels—the very issues these rule changes are trying to prevent.

If Minnesota is serious about improving manure management, then it must be equally committed to funding infrastructure upgrades—such as expanded storage, low-disturbance application equipment, and local composting capacity—so that farmers have the tools needed to comply

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5. Nitrate Levels and Blame

While misapplication of manure can contribute to water quality concerns, the nitrate test maps presented at the meeting appear to correlate more closely with population density than with confirmed agricultural sources. Without reliable source tracking, we must be cautious about placing the full burden of blame on agriculture. Are we asking farmers to solve a problem that we can't definitively trace to their practices—and that we currently don't have the tools to accurately measure?

Furthermore, there has been little detail provided about how the necessary infrastructure improvements will be built or funded. If stricter regulations are going to be proposed, there must be a realistic plan for implementation. Rather than focusing solely on manure application restrictions, we should also consider investing in broader water protection strategies—such as replacing old, shallow wells, which may serve as significant nitrate entry points. A more balanced, evidence-based approach would provide better long-term outcomes for both water quality and the farming community.

Conclusion

Thank you for the opportunity to comment on these important issues. I support responsible management and environmental stewardship. However, the proposed changes risk placing unrealistic burdens on producers without the necessary tools or support to comply effectively. I urge MPCA to continue working closely with farmers to find practical, science-based solutions that balance environmental protection with agricultural viability.

As someone actively managing a ruminant operation in a sensitive area, I would welcome the opportunity to serve on any future stakeholder or advisory group working on practical rule development.

Sincerely,
Pat Troendle

RECEIVED
By: OAH on 7/21/2025
Adam Barka Attachment

July 21, 2025

Minnesota Pollution Control Agency
ATTN: George Schwint
12 Civic Center Plaza, Ste 2165
Mankato, MN 56001

RE: Christensen Farms comments for the Chapter 7020 Planned Amendments to Rules Governing Animal Feedlots (Chapter 7020)

Thank you for the opportunity to comment on the amendments to the Minnesota Pollution Control Agency (MPCA) Chapter 7020. We appreciate the outreach and conversation held throughout this process to provide input from those who are impacted by changes to Chapter 7020.

Christensen Farms (CF) firmly believes that the existing Chapter 7020 rules are effective and reasonable in protecting the State's water quality. The strength of Chapter 7020 lies in the rigorous process behind its development. Around the new millennium, extensive data driven research, engagement, and thorough review were completed to ensure regulations balanced environmental protection with practical implementation. Since original implementation, regulations on feedlots have only become more stringent. Permit requirements have expanded, environmental review processes have grown more comprehensive, and county-level zoning rules have become more robust. For one to claim that feedlot regulations have remained unchanged since Chapter 7020 was implemented isn't just inaccurate, but a willful disregard of fact and reality.

While Chapter 7020 has been highly effective in protecting Minnesota's water resources, some now argue that facility size alone determines the environmental risk posed by a feedlot. This notion is fundamentally flawed and lacks any basis in sound science. The size of a feedlot is not a reliable indicator of environmental impact. In fact, the largest facilities in the state are subject to the most rigorous environmental assessments and must continually prove their compliance and low-risk status. In contrast, many smaller operations undergo far less scrutiny, even less than moderately sized sites. These smaller feedlots often have limited capacity to store manure before land application. The MPCA's stated goal to "prevent manure from entering surface and groundwater" is incomplete at best if it ignores these smaller facilities. Bluntly put, every gallon of manure, regardless of the size of farm it comes from, carries the same risk to Minnesota's water if mismanaged. Anything less than equal scrutiny across

operations of all sizes is policy by convenience, not protection.

The MPCA has stated that “the concentration of feedlots has resulted in concentration of manure generation volumes.” This statement is not only inaccurate, but it also reflects a concerning lack of understanding of the facts. Further, it reveals a potential bias within parts of the agency that must be addressed to ensure a fair and impartial review of the rules. When Chapter 7020 was originally developed, the landscape was characterized by a larger number of smaller, more widely distributed feedlots. These operations, despite their smaller size, could collectively generate comparable concentrations of manure nutrients and volumes, especially when land availability for application was limited given their smaller operations. In the swine industry today, feeding strategies have advanced significantly, reducing both the volume of manure and the nutrient content per animal. In many cases, today’s feedlots, even those that house more animals, produce fewer gallons and lower nutrient loads per head than in the past. CF maintains that the existing rules in Chapter 7020 were crafted to reflect practical realities, and the evolution of the industry only reinforces their continued reasonableness.

It is important to recognize that when Chapter 7020 was originally developed, it was thoughtfully designed to allow for the reasonable operation of livestock facilities while ensuring strong environmental protection. Some have recently argued that an increase in the number of feedlots over 500 animal units warrants significant changes to the rule. However, the presence of more permitted sites at or above that threshold does not inherently equate to increased environmental risk, and such claims lack supporting evidence. The State should not penalize or cast doubt on operations simply because they are permitted at certain animal unit levels. Feedlot owners carefully evaluate and understand the regulatory framework before making substantial investments, and they are committed to complying with those requirements. Maintaining respect for this permitting process is essential to ensuring fairness and continued environmental stewardship.

When it comes to manure transfer, one thing is clear: the agency has provided no evidence that transferring manure ownership increases environmental risk. Chapter 7020 has long permitted this practice, and it has proven to be an effective way to maximize the value of manure as a fertilizer while maintaining environmental compliance. By allowing manure to be transferred, feedlot owners can share its agronomic benefits beyond the land they personally own. In fact, increased manure transfers demonstrate that farmers are using manure more strategically, as an organic crop nutrient, thereby reducing the overall environmental footprint of agriculture. The current provisions in Chapter 7020 set reasonable, science-based requirements that ensure manure nutrients are applied for beneficial use.

It is a simple fact that the volume of liquid manure does not diminish the

effectiveness or reasonableness of Chapter 7020. In reality, liquid manure can often be stored, handled, and applied more efficiently. This represents continued improvements in feedlot operations and reinforcing the strength of the current rule. Chapter 7020 has enabled the adoption of advanced land application practices that have benefited both feedlot operators and the State's environment. Revising these rules without grounding changes in sound science would be unjustified. Practices such as the use of commercial applicators, manure pipelines and hoses, and transporting manure further from the source are all advancements that should be encouraged, not hindered, as they are under the current framework. Chapter 7020 supports innovation while maintaining environmental protection, and that balance must be preserved.

Some have suggested that a feedlot ownership structure should be a reason to amend Chapter 7020. CF firmly disagrees. Responsibility for each site is clearly assigned to accountable parties, and the form of entity incorporation has no bearing on environmental risk. This issue appears to be yet another example of bias that offers no real protection for Minnesota's waters and only serves to complicate effective regulation.

Extreme weather events have been considered in Chapter 7020 and the underlying Clean Water Act. The Clean Water Act clearly sets a level of reasonableness for the rules. There are specific standards of extreme weather that are acknowledged as outside the level of reasonableness.

Changes to sections 7020.0405, 7020.2003, 7020.2005, and 7020.2100 are unwarranted. The current rules are both reasonable and effective, and they have consistently supported strong environmental protection across the state. Importantly, no science-based, data-driven evidence has been presented to justify these proposed revisions. Without clear evidence demonstrating that the existing rules are failing, or that changes would improve environmental outcomes, it is neither necessary nor prudent to amend them. Regulatory changes must be grounded in measurable need and scientific justification, not assumption or perception.

For consideration by the agency, CF proposes amendments to Chapter 7020.0505.4D and 7020.2000.4, concerning public notice requirements, these sections add no value to the permitting process. Requiring yet another notice provides no measurable benefit to the public and merely creates a redundant layer of bureaucracy. The MPCA already maintains a well-established public notice system for all permits, and many counties also impose their own feedlot notification requirements. Repeating public notices for the same permit only increases the potential for confusion rather than improving transparency. Additionally, mandating communication methods, such as newspaper notices or mailed letters, directly contradicts the agency's direction of modernizing and streamlining permitting through electronic systems.

To support consistent and effective protection of Minnesota's water resources, CF proposes changes to the rules in Chapter 7020.2225.2 and 7020.2225.2A. In the interest of protecting all of Minnesota's waters and natural resources, one might suggest the agency give serious consideration to requiring manure nutrient testing from every registered feedlot in the state, regardless of size. Environmental stewardship is a shared responsibility among all livestock producers. Nutrients that are over-applied or improperly managed can impact water quality regardless of the number of animals on a site. Without consistent testing requirements across all feedlots, one might question how the Agency is able to ensure compliance or to confidently verify that manure is being applied at agronomic rates. To uphold its stated goal of protecting surface and groundwater, the agency should clearly explain and detail why the exemption for operations under 300 animal units remains appropriate and how it aligns with a comprehensive and science-based approach to environmental protection for all Minnesotans.

CF proposes an amendment to Chapter 7020.2225.6.B.2.a. to provide greater clarity around the definition of "intermittent streams." Specifically, it would be beneficial to limit this restriction to intermittent streams that exhibit a defined channel or channelized flow at the time of land application. Currently, some intermittent streams identified on maps may no longer exist or have been significantly altered since the maps were created. By clarifying that the restriction applies only to features with a visible channel or active flow, the rule can continue to provide reasonable environmental protection while allowing for the agronomic use of manure as a beneficial crop nutrient.

CF firmly opposes any requirement for additional operating permits, such as NPDES or SDS, for feedlots with fewer than 1,000 animal units. There are already mechanisms in place to permit and manage sites with pollution concerns, and no data has been presented to justify that expanding permitting requirements to smaller feedlots would result in measurable environmental benefits.

Similarly, requiring these feedlots to submit Manure Management Plans (MMPs) and land application records is not reasonable. Existing inspection and compliance procedures already provide the agency with authority and ability to review these materials on-site. Mandating submittals only adds to the regulatory burden without offering clear improvements to environmental protection beyond what current law already ensures.

Furthermore, the MPCA has not explained how it would meaningfully review or act upon the additional data submitted under these proposed rules. This raises significant concerns particularly since MMPs and land application records often contain proprietary business information. These privacy concerns have been raised with the agency as early as 2006 and have been repeated during multiple public comment periods. To date, the MPCA has offered no clear assurance to

feedlot operators or crop farmers that sensitive data will be protected.

Lastly, by requiring submittals exclusively through MPCA-provided forms, the agency imposes an unreasonable and unnecessary burden especially on producers without access to broadband internet or those lacking the technical skills to complete digital submissions. Flexibility in reporting format is not only practical but essential for ensuring fairness across Minnesota's diverse agricultural community.

Given the continued strength and effectiveness of Chapter 7020, changes related to groundwater monitoring at feedlots are not well-founded. No evidence has been presented to suggest that the current prohibitions on discharges to groundwater are inadequate or failing. Similarly, additional restrictions on manure application rates, particularly those that impose arbitrary or artificially limited thresholds, do not serve a reasonable purpose.

Animal manure is a valuable organic nutrient source that supports healthy soils and productive crop systems. It is both reasonable and responsible to allow manure application rates to be guided by crop nutrient needs and actual yield results, grounded in sound agronomic science rather than modeled economic assumptions. Importantly, Chapter 7020.2225.A.2 already allows for individualized nutrient management, acknowledging that the University of Minnesota recommendations are based on averages and may not reflect the advanced practices employed by many Minnesota farmers.

Notably, the MPCA's claim in its Nutrient Management Tool that such deviations are "limited" does not align with the intent of Chapter 7020, which recognizes the importance of flexibility, site-specific management, and the use of real-world data in supporting both environmental stewardship and agricultural productivity.

As it pertains to additional requirements for soil nitrate testing, subject matter experts have cautioned that changes do not align with sound science. Current language in Chapter 7020 already allows for the use of soil nitrate testing in accordance with science, that balances environmental benefit with practical implementation. It is important to recognize that nitrate presence in soil and water systems results from a highly complex cycle influenced by multiple sources, both anthropogenic and naturally occurring.

Available data indicate that nitrate levels have remained stable or are declining in many areas, pointing to the effectiveness of the existing Chapter 7020 framework. As the MPCA oversees numerous programs related to nutrient management, a comprehensive and transparent understanding of the broader nitrate item, including its sources and contributing factors, should be clearly communicated before introducing new regulatory burdens under Chapter 7020. Without this context, further requirements risk mischaracterizing the issue and undermine the progress that has already been achieved.

The Minnesota Department of Agriculture, members of the Minnesota State Legislature, and farm commodity groups have all placed a growing emphasis on practices that enhance soil health. CF shares the concerns of livestock producers who believe that increasing manure application setbacks in so-called "sensitive areas" would be both unreasonable and counterproductive to this shared objective. The current rules already support the responsible use of manure as a crop nutrient promoting healthy soils while protecting water resources. Proposals to restrict land application based on undefined "high densities" of feedlot operations undermine the benefits manure provides to soil health and represent a departure from science-based regulation. The agency must clearly define what constitutes "high density," and more importantly, provide evidence that restricting land application in such areas yields measurable environmental improvements.

Arbitrary or vaguely defined restrictions, especially those not grounded in sound agronomic science or reflective of actual farmer practices, impose unnecessary burdens on producers. The term "high density" offers no clear environmental rationale and instead appears to penalize regions where livestock and manure are responsibly integrated into crop production. Its use in the request for comments reflects a troubling pattern of bias that risks undermining trust in the rulemaking process and the agency's commitment to practical, science-based solutions.

CF has previously expressed serious concerns regarding the imposition of additional NPDES and SDS requirements on smaller livestock operations. We maintain that the existing framework under Chapter 7020 has proven effective in protecting Minnesota's water resources while remaining practical and workable for producers. At a high level, changes do not enhance environmental protection and instead place unnecessary regulatory and administrative burdens on Minnesota's livestock industry:

- Amendments requiring "enhanced" manure management planning and recordkeeping for transferred manure are excessive. Current rules already provide adequate safeguards to protect water quality.
- Mandating the submission of additional sensitive business information, without any demonstrated environmental benefit, is unreasonable and unjustified.
- Requiring more frequent visual inspections of land application fields is unnecessary, as existing rules already prohibit exceeding the soil's hydraulic loading capacity, ensuring proper manure application and environmental protection.

CF respectfully but firmly emphasizes that additional restrictions on the land application of manure are neither reasonable nor grounded in sound science. Agricultural production is highly variable, shaped by the unique characteristics of each field and the

unpredictability of localized weather conditions, factors that often do not align with rigid calendar dates. Imposing blanket application windows fails to account for this variability and does not necessarily lead to improved environmental outcomes.

Manure is a locally sourced, low-carbon fertilizer that not only supports crop production but also contributes to long-term soil health. Restricting its use in favor of commercial fertilizers would increase greenhouse gas emissions and undermine Minnesota's stated goals for improving soil health. MPCA has provided minimal data demonstrating that the proposed application timing restrictions would meaningfully reduce nitrogen loss. In fact, research previously cited by the agency has shown that timing alone is not a primary driver of nutrient loss.

Moreover, shifting manure application primarily to spring introduces significant logistical challenges, particularly for rural infrastructure. Spring road weight restrictions—enforced by both the State and local governments—limit transport capacity and would result in more trips, more fuel use, and increased wear on rural roads. While dragline hoses are a useful tool, they are not universally applicable. Factors such as the location of wind turbines, field distances, and required application rates can make their use impractical or impossible.

If the agency is committed to science-based regulation and practical implementation, it must account for these realities and reconsider restrictions that lack both evidence and feasibility.

CF urges caution regarding changes related to animal manure storage areas that have been in use for an undefined "long period of time." The current rules already establish reasonable and science-based requirements for the monitoring, operation, and maintenance of these storage structures. The term "long time" is inherently subjective and open to interpretation, which introduces unnecessary ambiguity into regulation.

It is not uncommon for well-constructed and properly maintained manure storage facilities to remain in service for many years without presenting environmental risks. In fact, there are documented cases where older storage areas have been voluntarily removed from service or upgraded for various operational reasons, demonstrating that the current standards are effective in protecting water quality. Additional requirements based solely on age, rather than on performance or condition, risk undermining confidence in existing rules that have consistently delivered sound environmental outcomes.

CF maintains that the current Chapter 7020 rules align with the requirements and intent of Minnesota Statutes 14.002. In contrast, several elements of the request for comment, as well as the use of seemingly biased terminology, appear to deviate from those statutory principles. Specifically, the MPCA has not provided evidence that would justify the need for significant regulatory changes. Claims suggesting increased environmental harm, such as a rise in fish kills tied to feedlot operations,

are not supported by available data. A review of the Environmental Quality Board (EQB) Monitor reveals no trend indicating an increase in fish kills attributable to feedlots.

Furthermore, the agency has not demonstrated that existing nitrate concerns are the result of current feedlot practices governed by Chapter 7020, rather than legacy issues stemming from practices that occurred prior to the rule's implementation. Without clear, data-driven evidence linking current feedlot operations to these environmental concerns, the rationale for revising Chapter 7020 remains unsubstantiated and contrary to the standards outlined in Minnesota Statutes 14.002.

Agriculture functions as an interconnected ecosystem, where the relationship between crop and livestock production creates important synergies, especially through the use of livestock manure as a local, organic fertilizer that promotes soil health and reduces greenhouse gas (GHG) emissions. This integration is critical to meeting Minnesota's long-term goals for both environmental protection and agricultural sustainability.

Changes to Chapter 7020 risk placing unreasonable burdens on feedlot operators without demonstrating a meaningful or measurable cumulative environmental benefit. For more than 25 years, Minnesota's livestock producers and permittees have operated under the current Chapter 7020 framework and have consistently demonstrated a strong commitment to environmental stewardship.

To date, the MPCA has not provided clear, data-driven evidence showing that the existing regulations under Chapter 7020 are contributing to environmental harm. Rather, the revisions appear to be a response to isolated concerns that fall outside the scope of what Chapter 7020 is designed to address. CF remains concerned that moving forward with these changes will add complexity and cost to livestock operations without delivering improved environmental outcomes.

Thank you for your consideration of our comments and concerns regarding Chapter 7020. If you need further clarification or have questions, please feel free to contact me.

Thank you

Adam Barka
Director of Environmental Stewardship
Christensen Farms

RECEIVED
By: OAH on 7/22/2025
Ashley Kohls Attachment

MINNESOTA TURKEY GROWERS ASSOCIATION

108 Marty Drive, Suite 1, Buffalo, MN 55313-9338
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July 17, 2025

Minnesota Pollution Control Agency
520 Lafayette Road North
St. Paul, MN 55155
Submitted via: Office of Administrative Hearings Comments On

Re: Comments on Minnesota Feedlot Rule (7020) Review OAH Docket No. 25-9003-40661

Dear MPCA Staff,

The Minnesota Turkey Growers Association (MTGA) appreciates the opportunity to provide comments on the Minnesota Pollution Control Agency's (MPCA) review of the state feedlot rule (7020). As the representative voice of Minnesota's turkey farmers, and the nation's largest turkey-producing state, we represent 703 turkey farmers and supporting industry members. MTGA members support science-based, practical rules that safeguard water quality while supporting voluntary innovation for turkey farms of all scopes and sizes. The current 7020 rules work for Minnesota's turkey farmers.

Voluntary commitment to environmental stewardship:
Minnesota's turkey farmers are committed to protecting our state's land, water, and air. Many turkey operations already exceed regulatory requirements through voluntary adoption of nutrient management plans, annual soil testing, precision manure application, and use of grass buffer strips. We believe the 7020 rules should continue to enable and encourage voluntary stewardship and allow for innovation.

Turkey farms are distinct and must be considered separately:
Turkey farms operate with litter-based manure systems—solid, dry material mixed with bedding. Litter is stored indoors throughout the flock cycle and removed only during barn clean-out, typically twice per year. Therefore, regulatory frameworks should reflect these fundamental differences and avoid applying lagoon-based standards to litter systems.

Modifications to turkey animal unit calculations:
We urge the MPCA not to add complexity to the rule by modifying turkey animal unit calculations. In commercial turkey operations, male and female turkeys are raised in separate flocks, and manure management practices do not differ between the two. The existing permit framework already accounts for animal unit calculations based on standard weights, and modifications or additional distinctions would introduce unnecessary complexity without improving environmental outcomes.

Support for flexibility and innovation:
Any revision to the 7020 rules should promote flexibility in best management practices (BMPs), recognizing Minnesota's diversity in farm size, topography, and climate. One-size-fits-all approaches are not effective. Instead, the rules should allow producers to tailor BMPs to their specific conditions, incorporating modern conservation tools and precision technology. Farmers must be empowered to voluntarily adopt innovative solutions that enhance both environmental outcomes and farm viability.

MINNESOTA TURKEY GROWERS ASSOCIATION

108 Marty Drive, Suite 1, Buffalo, MN 55313-9338
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Biosecurity and emergency response considerations:
Turkey farms often face significant challenges from diseases like Highly Pathogenic Avian Influenza (HPAI). Movement of manure and clean-out schedules are sometimes restricted by quarantine and emergency protocols. Revised rules must allow flexibility for in-barn storage or delayed manure handling during disease outbreaks, in coordination with USDA and Board of Animal Health protocols.

Manure as a valuable resource, not waste:
Manure should be recognized as a vital contributor to soil health, not a waste product. When managed according to nutrient value, it supports soil structure, fertility, and water retention, reducing reliance on synthetic fertilizers and enhancing long-term productivity. Rules should reflect this perspective and avoid imposing unnecessary hurdles that disincentivize responsible manure use, like onerous manure transfer requirements.

Economic viability and practical implementation:
The cost of compliance must be considered. Small and mid-sized farms often face disproportionate financial burdens when rules are updated without regard to economic feasibility. Nearly 90% of Minnesota's turkey farmers are independently owned small farms. Any changes to the 7020 rules should align with achievable timelines, measurable outcomes, and clear guidance to avoid confusion and inconsistent enforcement.

The current 7020 rule works for Minnesota's turkey farmers. MTGA urges MPCA to maintain current environmental protections while fostering flexibility, voluntary innovation, and the long-term viability of Minnesota's diverse livestock farms—including our state's vital turkey industry.

Respectfully submitted,

Ashley Kohls
Executive Director
Minnesota Turkey Growers Association

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By: OAH on 7/22/2025

Marlin Fay Attachment

We are NOT opposed to rules and regulations for feedlots in Minnesota. What we ARE opposed to, are rules that are high risk and low reward, meaning the results are projected but not achieved, and they can threaten the existence of animal agriculture in Minnesota. The fact that livestock operations have gotten bigger is not a scenario where “factory farms” have gobbled up small family farms. It is the same economic driver that has caused the loss of the small-town grocery stores, hardware stores, banks and more. It is the economy of scale and size that bring the efficiencies that make them competitive. As costs go higher, farmers need more units to spread the cost over. It doesn’t matter if it is animals, grain, fruit or vegetables. I’m a small farmer and I feel the pinch.

We need common sense rules that have achievable results. We need to keep focusing on the gains that we have achieved, to reach our goal. I live on the farm I run. I’m proud of what I do. It disheartens me when so many people disconnected with agriculture bash an industry that helps provide the safest, most abundant, and lowest cost food supply in the world. Most of the regulations people are proposing here will just aid the demise of the small farmers we have.

RECEIVED
By: OAH on 7/22/2025

Loren Dauer Attachment

Minnesota Farm Bureau

July 22, 2025

Office of Administrative Hearings
c/o Administrative Law Judge Megan J. McKenzie
600 N. Robert St
St. Paul, MN 55164

RE: Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, chapter 7020, Revisor's ID Number R-04928.

Dear Judge Megan J. McKenzie,

On behalf of the 31,000 members of the Minnesota Farm Bureau Federation (MFBF), I appreciate the opportunity to provide comments in response to the Minnesota Pollution Control Agency's Request for Comments on proposed amendments to Minnesota Rules Chapter 7020, which governs animal feedlots and manure management. MFBF is the largest grassroots, general farm organization committed to advancing the future of agriculture and rural communities in the state.

Minnesota's farmers and ranchers are leaders in environmental stewardship and have long embraced science-based practices to manage manure and protect water quality. Our state's regulatory framework has historically balanced environmental protection with agricultural productivity, and MFBF members are committed to continuing that legacy. As this rulemaking process advances, we encourage the Minnesota Pollution Control Agency (MPCA) to ensure that any revisions support practical, flexible, and outcome-driven approaches that reflect both environmental goals and the realities of livestock farming in Minnesota.

Question 1: Are there parts of the current rule (Minn. R. Ch. 7020) that are no longer applicable or needed?

Some parts of the current rule are outdated and could be updated to better reflect current practices.

Some transitional language and outdated references, such as those related to permit types used before 2000, still appear in the rule. These legacy references, like mentions of SW-A permits, no longer serve a practical purpose. Removing this outdated section would help simplify the rule and ensure it reflects the current permitting system.

The rule's requirement for feedlot owners to update registrations every four years may unintentionally create confusion, particularly when registration deadlines do not match up with other regulatory timelines or reporting requirements. As the MPCA and counties shift to more flexible, digital systems, the fixed four-year schedule could be re-evaluated to reduce confusion and streamline administrative tasks for producers, especially those who already maintain current records through other regulatory processes.

<u>Question 2:</u> What specific changes to the current rules, including permit requirements (part 7020.0405), water quality discharge standards (part 7020.2003), location restrictions and expansion limitations (part 7020.2005), liquid manure storage area standards (part 7020.2100), or land application of manure (part 7020.2225) would provide improved regulations that prevent nitrate contamination to ground and surface waters and fish kills? Should any of the following bullets be considered? If so, at what size (in AU)?

At this time, MFBF recommends not adding additional rule amendments, including the bulleted suggestions. The changes outlined here would disrupt the balance that the current rule strikes between environmental protection, regulatory flexibility, and economic impact. Justification as to why each bullet should not be considered is below.

- **Operating permits (NPDES or SDS) for feedlots less than 1000 AUs.**
  The existing NPDES/SDS permit has a threshold of 1,000 animal units (AUs) which aligns with the federal large CAFO permitting standards that were designed to ensure that regulatory resources are focused on operations with the greatest potential environmental impact.

- **Submittal of manure management plans and land application records for feedlots without operating permits.**
  Part 7020.2225, subpart 4, item A grants the MPCA and county feedlot officers the ability to access any feedlot's manure management plan (MMP) by request. Subpart 5 requires all feedlots 300 AUs and over to keep detailed records of manure application for a six-year timeframe. The same requirement applies to feedlots 100 AUs and over located in drinking water supply management areas (DWSMAs) with vulnerable aquifers. Mandating submission of every MMP to MPCA would increase administrative costs for the agency, increase staff workload, and slow targeted enforcement. Feedlot registration already requires current AUs, acreage, and location.

- **Monitoring of feedlots and land application sites for subsurface discharges of manure or nitrate to groundwater.**
  In responding to comments on the draft NPDES/SDS permits, MPCA laid out the challenges of water-quality monitoring near feedlots and also asserted it would be

unreasonable to require groundwater monitoring of every field in Minnesota. The same response details the robustness of Minnesota construction standards for manure storage areas, which far exceed those of the Natural Resources Conservation Service (NRCS). There are even more protections for storage of liquid manure and storage in areas with Karst geology.[1]

- **Additional restrictions on manure application rates.**
  Part 7020.2225 already limits nutrient application according to realistic nitrogen use rates on crops.

- **Soil nitrate tests prior to land application of manure.**
  The current rule already prescribes soil nitrate testing when a MMP is required (permit applications ≥ 100 AUs; all feedlots ≥ 300 AUs). Under part 7020.2225, subpart 4, item D, subitem (12) the MMP must include "plans for soil nitrate testing in accordance with University of Minnesota Extension Service recommendations." Part 7020.2225, subpart 1, item D states that manure transfer recipients must follow the MMP of the feedlot that generated the manure and complete the missing pieces of the MMP for application on their own land.

- **Increased setback distance for land application of manure near sensitive features.**
  Part 7020.2225 already provides reasonable restrictions on manure application near sensitive features. Subpart 4, item D, subitem (9) stipulates that a MMP must include protective measures for application of manure in special protection areas and floodplains.

  Subpart 7, item B requires all manure applied within 300 feet of open tile intakes to be injected or incorporated within 24 hours of application, or other agency-approved practices that demonstrate equal water quality protection. Similarly, subpart 8 prohibits manure application within 50 feet of wells, sinkholes, mines, and quarries. Manure applied within 300 feet of a sinkhole without diversions must be injected or incorporated within 24 hours of application. University of Minnesota Extension data shows that getting manure below the surface sharply cuts nutrient and pathogen runoff risk compared with leaving it on top.[2]

  The buffer law requires up to 50-foot perennial vegetation along public waters, providing an additional filtering strip. Buffer strips can remove approximately 50 percent or more of nutrients, about 60 percent of some pathogens, and about 75 percent of sediment.[3]

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[1] https://www.pca.state.mn.us/sites/default/files/wq-f3-64.pdf See Common Issue #4 - Increased Water Quality Monitoring.
[2] https://extension.umn.edu/manure-management/manure-application-methods-and-nitrogen-losses
[3] https://files.dnr.state.mn.us/publications/waters/buffer_strips.pdf

- **Restricting land application of manure in areas with high levels of nitrate in waters or in areas with existing high densities of feedlot operations.**
  In vulnerable areas, Chapter 7020 already compels additional water protection measures for feedlots required to have a MMP. Under part 7020.2225, subpart 4, item D, subitem (9) MMPs must spell out protective measures for land application in DWSMAs with vulnerable aquifers and to soils within three feet of limestone bedrock.

  In addition, the Minnesota Department of Agriculture's Groundwater Protection Rule separately restricts fall and frozen soil nitrogen fertilizer applications in vulnerable groundwater areas and in DWSMAs with elevated nitrate, ensuring that those areas receive targeted nitrogen controls across all sources, not just manure. Geology, like the Karst Region in southeast Minnesota, strongly influences where nitrate reaches water, meaning a manure restriction or prohibition in "high nitrate" zones would likely prompt substitution with commercial nitrogen.

  Limiting manure application would not necessarily reduce nitrogen in the watershed, it would likely shift the nutrient source rather than reduce it, increasing costs for farmers without improving water quality. Restricting manure application based on feedlot density would result in more manure hauling or transfers and substituting manure with commercial fertilizer.

<u>Question 3:</u> The State Disposal System (SDS) and National Pollutant Discharge Elimination System (NPDES) feedlot general permits apply to feedlots that currently have capacity, or are proposing to have capacity, for a total of 1,000 or more AUs (part 7020.0405). These permits include additional requirements as outlined in the following bullets. Should any of these requirements or other requirements in the permits be incorporated into the rule to apply to facilities with less than 1000 AU capacity?

- **Enhanced manure management planning and record keeping requirements for transferred manure.**
- **Visual inspections of manure land application fields for signs of discharges.**
- **Additional best management practices for land application of manure during the months of September through November.**
- **Restricting land application of manure on frozen or snow-covered fields.**
- **Best management practices for land application of manure when there is a high probability of rain predicted.**

Generally speaking, the additional requirements found in NPDES and SDS permits should not be incorporated into the base feedlot rule under Chapter 7020. These permit conditions are designed to address the higher level of risk associated with the largest livestock operations, typically those with 1,000 animal units or more. As such, they include more detailed management,

recordkeeping, and application restrictions that go beyond what is necessary for smaller and mid-sized operations.

Chapter 7020 is intended to serve as a baseline standard for feedlot management across the state. It provides consistent, science-based protections without imposing the full set of requirements needed for large-permit holders. Incorporating permit-level requirements into the general rule would undermine the flexibility that smaller operations need and eliminate the important regulatory distinction between basic compliance and enhanced permit conditions.

Maintaining this distinction ensures that the rule remains practical and proportionate for the wide variety of livestock operations in Minnesota.

To the specific bullet points outlined in the question, MFBF would caution against any mandated best management practices that are tied strictly to calendar dates or seasons since weather and temperature patterns can vary considerably year to year. There is also concern with imposing more limits on manure applications during the winter months when sufficient rules already exist.

Question 4: How should the MPCA address existing animal manure storage areas that have been used for a long period of time to determine structural integrity (part 7020.2100)?

Any potential issues should be handled on a case-by-case basis when inspected by MPCA or a county feedlot officer. As mentioned previously in response to Question 2, Minnesota regulates manure storage construction to a more detailed and conservative engineering standard than national baselines. Minnesota imposes numeric seepage performance limits plus minimum 5-inch reinforced concrete floors and detailed liner-penetration controls, all backed by mandatory engineer-stamped design plans, construction notifications, in-process inspections, and engineer certification reports to MPCA or the county feedlot officer. By contrast, the federal standard does not prescribe liner thicknesses or seepage rates. NRCS Code 313 provides design guidance but defers to state rules for karst restrictions, storage period, and seepage criteria.

Question 5: Currently, feedlots with 1000 AUs or more are required to have 9 months manure storage capacity (part 7020.2100). Should smaller sites be required to have a similar requirement? If so, at what size (in AU)?

While manure storage capacity is an important part of protecting water quality, MFBF does not support a blanket extension of the nine-month storage requirement to smaller feedlots. The current requirement in part 7020.2100 for feedlots with 1,000 AUs or more recognizes the scale and potential impact of larger operations, many of which already manage liquid manure systems where long-term storage is necessary.

For feedlot operations under 1,000 AUs, a one-size-fits-all storage mandate would impose significant costs and may not align with how those farms manage manure.[4] Many smaller feedlots operate with solid manure systems, seasonal cleanouts, or daily hauling, all of which can be low-risk if managed properly. Mandating nine-month storage for these operations could be unnecessary and economically unviable.

Finally, MFBF affirms its support for using the original animal unit determinations as defined in part 7020.0300 as the appropriate basis for any regulatory thresholds related to feedlot permitting or management standards.

Question 6: The MPCA has developed Watershed Restoration and Protection Strategy (WRAPS) documents for every one of Minnesota's 80 major watersheds. These WRAPS document high nutrient and bacteria levels in streams and rivers. The reports attribute this to livestock access to streams in many cases. How should the rules be amended to address this documented issue (part 7020.2015)?

Existing regulations prohibit uncontrolled, direct feedlot runoff to waters of the state and surface waters. As stated in part 7020.2015, animals from ≥1,000 AUs facilities are restricted from entering waters of the state. Even smaller feedlots are required to fence animals out of DNR-classified lakes. Much of what WRAPS flags as "livestock access" occurs in pasture or grazing settings, areas which are expressly exempt from the feedlot rule.

Of the 80 WRAPS documents that report high nutrient and bacteria levels, how many specifically attribute the cause to livestock access to streams? And which watersheds?

Question 7: How should the MPCA address feedlots under the same ownership in close proximity to each other? How far apart must each feedlot be located in order to be considered a separate facility for the purposes of permitting and/or registration (parts 7020.0405 and 7020.0350)?

The MPCA should follow the existing federal standard under the Clean Water Act for determining when feedlots under common ownership and located near each other should be considered a single operation. Under 40 CFR § 122.23(b)(2), the federal rule provides a clear and well-established framework: operations may be aggregated when they are under common ownership, located within one-half mile of each other, and share a common manure handling or land application system. This test is applied on a case-by-case basis and considers both physical proximity and operational integration.

[4] https://www.pca.state.mn.us/sites/default/files/wq-rule4-29d.pdf See slide 39 for average cost of manure infrastructure.

This federal framework is already integrated into Minnesota's NPDES and SDS permitting process and gives regulators the discretion needed to assess environmental risk appropriately. Creating a new aggregation rule within Chapter 7020 would be unnecessary, duplicative, and could create confusion for both producers and regulators. The existing federal standard is sufficient and should remain the guiding policy.

Question 8: State agencies are required to, whenever feasible, develop rules that are not overly prescriptive and inflexible, and rules that emphasize achievement of the MPCA's regulatory objectives while allowing maximum flexibility to regulated parties and to the MPCA in meeting those objectives (Minn. Stat. §14.002). How might the MPCA balance this need for flexibility for regulated parties while also addressing the issues of nitrate contamination and fish kills?

Chapter 7020 as it currently stands strikes a balance between achieving regulatory objectives and providing flexibility to farmers and ranchers. In addressing nitrate contamination, it is important to recognize that increased regulation alone may not deliver the outcomes sought by the agency. Fortunately, Minnesota already has a strong network of voluntary programs and cost-share initiatives that can support this approach while advancing measurable water quality improvements.

The Minnesota Agricultural Water Quality Certification Program (MAWQCP) shows how voluntary, outcome-based programs drive real reductions. MPCA analysis cited in the program's 2024 biennial report estimates certified farms have achieved up to approximately 45 percent reductions in modeled nitrogen loss.[5]

The Minnesota Department of Agriculture's (MDA) Soil Health Financial Assistance Program offers up to 50 percent cost-share for farmers, producer groups, and local units of government to purchase or retrofit soil-health equipment. In 2024, the Minnesota Legislature appropriated $2.375 million, plus an additional $495,000 for targeted southeast Minnesota counties. This investment supports practices like no-till planting and cover crops, critical tools for reducing soil erosion and improving nutrient retention, directly benefiting water quality.[6]

Another state program that assists farmers is the Agricultural Best Management Practices (AgBMP) Loan Program. The AgBMP Loan Program is a water quality program that provides low-interest loans to farmers, rural landowners, and agriculture supply businesses. The purpose is to encourage best management practices that prevent or reduce runoff from feedlots, farm fields, and other pollution problems identified by the county in local water plans.[7]

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[5] https://www.lrl.mn.gov/docs/2025/mandated/250186.pdf
[6] https://content.govdelivery.com/accounts/MNMDA/bulletins/3aa8444?
[7] https://www.mda.state.mn.us/agbmploan

As the MPCA moves forward in this rulemaking process, it is important to note that voluntary practices and cost-share support from the state are strongly viable options that drive results when it comes to managing our nutrients. The MPCA should consider utilizing all available options to balance the interests of those impacted by future regulatory changes.

<u>Question 9:</u> Other questions or comments relating to the existing animal feedlot rules or this proposal to amend the rules.

Justification for Rule Updates:

The MPCA's Request for Comments (RFC) document emphasizes fish kills as a recurring concern throughout the proposed rule changes. It connects fish kills to manure runoff and land application, especially in sensitive areas like southeastern Minnesota.

The 2024 multi-agency report "Preventing fish kills in Minnesota's driftless region" found only four trout stream fish kill events in southeast Minnesota with confirmed pollutant causes since 2015. This incidence rate is too low to justify animal feedlot rule amendments aimed toward preventing fish kills. The report concluded many high-value prevention steps fall within existing authorities without the need for changes in rule or statute. While the report's recommendations contained some regulatory measures, it also contained many nonregulatory recommendations.[8]

How does the agency justify fish kills as an impetus for rule changes?

Advisory Committees:

MFBF believes it is necessary to convene advisory groups for vetting rule amendment areas. Given that these changes will directly affect how livestock and poultry farmers operate, it is essential that farmers and ranchers with on-the-ground experience are included as representatives or subject-matter experts on each advisory committee.

Producers manage the day-to-day realities of feedlot operations, manure storage, and land application. Their insight is critical to ensuring that any proposed rule changes are practical, science-based, and adaptable to diverse agricultural systems across Minnesota. Without meaningful producer representation, there is a risk that recommendations may lack feasibility or fail to reflect the wide variety of livestock systems in the state.

Moreover, we strongly recommend the creation of a dedicated farmer and rancher advisory committee to review and provide oversight on all rule recommendations before they are

[8] https://www.lrl.mn.gov/docs/2025/mandated/250186.pdf

finalized. This would ensure producers have a consistent, structured role in shaping policies that affect their livelihoods and environmental stewardship responsibilities.

Recognizing Progress:

It is important to recognize the significant statewide measures that have been adopted since the last major revision of Minnesota's feedlot rules. Mandates aimed at improving water quality have strengthened protections across the landscape. In addition, producers have taken on voluntary efforts to improve nutrient management, including precision application, cover cropping, and improved timing of manure application. As MPCA considers rule updates, it is essential that these changes remain focused on areas clearly within the agency's jurisdiction and not attempt to compensate for groundwater or surface water contamination that falls outside the scope of feedlot and manure regulation.

Here are key statewide measures adopted since the last major revision of Chapter 7020 in 2000, highlighting ongoing improvements in manure and nutrient management:

NPDES and SDS Permit Updates

Since the early 2000s, the MPCA has reissued and updated its National Pollutant Discharge Elimination System (NPDES) and State Disposal System (SDS) general permits for feedlots on a five-year cycle, with the most recent revisions made this past year. These updates incorporate changes to federal CAFO (Concentrated Animal Feeding Operation) regulations, clarify compliance expectations, and strengthen water quality protections for large livestock operations. The NPDES/SDS permitting system is distinct from the Chapter 7020 rule and applies to operations with 1,000 animal units or more or those with potential to discharge. These permits reflect a performance-based, site-specific regulatory tool that continues to evolve in response to science, technology, and environmental needs.

Minnesota Buffer Law

The Buffer Law (Minn. Stat. § 103F.48), passed in 2015, requires vegetated buffers of 50 feet along public waters and 16.5 feet along public drainage systems on agricultural land. This law plays a critical role in protecting surface water quality by reducing sediment and nutrient runoff from adjacent cropland, including fields receiving manure applications. Implementation is led by the Board of Water and Soil Resources (BWSR) and enforced locally. As of July 2019, approximately 98% of parcels adjacent to Minnesota waters are compliant with the Buffer Law.[9]

[9] https://bwsr.state.mn.us/minnesota-buffer-law

Minnesota Nutrient Reduction Strategy

First released in 2014, this statewide strategy outlines goals and timelines for reducing nitrogen and phosphorus loading to Minnesota's waters. It emphasizes both point and nonpoint source reductions, including manure, and promotes adoption of precision application technologies, improved timing and placement of nutrients, and soil health practices. A 2025 update is underway to reflect new research and emerging practices.

MDA Groundwater Protection Rule

Adopted under the Nitrogen Fertilizer Management Plan, this rule targets nitrate contamination risks in vulnerable groundwater areas. While it primarily applies to commercial nitrogen fertilizer, it has encouraged greater awareness and adoption of voluntary best management practices among livestock producers managing manure. This effort complements the nitrogen application standards already embedded in part 7020.2225.

These statewide measures demonstrate that Minnesota has made significant progress in environmental protection, nutrient management, and technological modernization since the last major revision to Chapter 7020.

Minnesota's farmers and ranchers remain committed to environmental stewardship and the high quality of our state's water resources. The existing feedlot rule has supported this commitment by providing a workable framework that encourages sound management while maintaining water quality standards. As the MPCA considers updates to Chapter 7020, we urge the agency to recognize the progress already made and avoid changes that would introduce unnecessary complexity or economic strain for farmers and ranchers. We appreciate the opportunity to provide comments and look forward to working with the agency throughout the remainder of the rulemaking process.

Respectfully,



Dan Glessing, President
Minnesota Farm Bureau Federation

RECEIVED
By: OAH on 7/22/2025

July 22, 2025

Katrina Kessler
Commissioner
Minnesota Pollution Control Agency
520 Lafayette Road North
St. Paul, MN 55155

Dear Minnesota Pollution Control Agency,

We appreciate that MPCA is considering revisions to its Animal Feedlots Rule and urge the agency to draft a Rule that will address dangerous levels of nitrate, other nutrients, and bacteria in surface waters and groundwater across Minnesota. Everyone in Minnesota should have safe tap water to drink; and our state's many lakes, streams, and rivers should be safe for people, fish, and wildlife.

Specifically, we urge MPCA to consider the following changes:

- Require water pollution permits not only for the largest feedlots, but also for feedlots with 600 or more animal units.

- Add stricter limitations on manure application in areas that are particularly vulnerable to groundwater pollution, including the southeastern karst region and the central sands region, such as additional best management practices for fall manure application and lowering manure application rates.

- Prohibit application of manure on frozen or snow-covered ground, which creates a high risk of runoff.

- Prohibit the application of manure when there is a high likelihood of rainfall, which creates a high risk of runoff.

- Require permitted feedlots to create a risk-assessment plan to monitor their manure storage areas and land application sites for above-ground and below-ground discharges to water to ensure feedlots are not polluting lakes, rivers, and groundwater.

- Require anyone who receives manure from a feedlot with a manure management plan to follow the permit requirements and manure management plan for that feedlot.

With this rulemaking, MPCA has a critical opportunity to help address a serious and long-standing environmental and public health threat to our state. High levels of nitrate, other nutrients, and bacteria in our waters kill our fish, make our lakes unswimmable and unfishable, and put Minnesotans' health at risk. We ask MPCA to create a robust rule that addresses water pollution from feedlots and protects all of Minnesota.

Sincerely,

Janet Ackerman
Mair Allen
H. Ande
Angela Anderson
Chel Anderson
David Anderson
Jeanne Anderson
Lynn Anderson
Christine Andrews
Cindy Angerhofer
Mary Arps Thompson
Neely Atha
Peter Bachman
Sharon Bachman
Amanda Barbeau
Susan Beltz
James Berg
Lawrence Bogolub
Julia Bohnen
Dean Borgeson
Bruno Borsari
Meghan Boster
Kristin Bransford
David Brockway
Kelsey Brodt
Frank Bures
Elizabeth Burr
Megan Cahill
Dave Carlson
JL Charrier
Kathleen Chesney
Steven Chesney
Barbara Clark
Anthony Comer
Meghan Conway
Amy Cordry
Lori Cox
Jill Crafton
Jill Crawford-Nichols
Dennis Cuchna
Cathy Curtis
Michael Degerstrom
Steven DeLapp
Susan Delattre
Jon Dennis
Barry Drazkowski
Joel Dunnette
Kim Dupre
Valerie Eastland
Ann Elward
Stephanie Emerich
John Enblom
Peggy Endres
Barbara Erickson
Elizabeth Erpelding-Garratt
Jim Etzel
Carolina Fernandez Branson
Barbara Finley-Shea
Bonnie Fox
Joyce Frohn
Sharon Frykman
Peg Furshong
Greta Gaard
Mary Gallagher
Jane Gfrerer
Mark Giese
Mitchell Gilbert
Mary Gleason
Nona Goertz
Yazmin Gonzalez
Leanna Goose
Cameron Gordon
River Gordon
Mary Grahek
Maxime Groen
Anna Mae Gronert
Gary Gronert
Peter Gunther
Brent Gurtek
Duane Gustafson
Ashley Haase
Ellen Hadley
Marc Hadley
LuAnn Hagel
Cherie Hales
Sue Halligan
Verlaine Halvorsen
Mary Hamann
John Harrington
Paul Harris

Nett Hart
Barbara Hassing
Natalie Hatoum
Sharon Hattenberger
Bob Haugen
Jim Head
Chris Heeter
William Henke
John Herbst
Norman Herron
Susan Hix
Barbara Hoch
Kristin Hogquist
Philip Holtegaard
Sarah Horner
Tanya Hovi
Joycanne Hoyem
Marjorie Huebner
Sarah Hunt
Daniel Iverson
Carolyn Jahns
Wendy Jerome
Julie Marie Johnson
Jeff Jones
Nelson Jorgenson
Molly Joyce
Julie July
Gregory Kapphahn
Karl Karst
Margaret Kearns
Sirid Kellermann
Loni Kemp
Dianna Kennedy
Audrey Kingstrom
Kathrin Kirmeier
Andrew Kistler
Robert Klein
Mike Klinefelter
Dag Knudsen
Carol Koepp
Lauren Kofsky
Joseph Krall
Eugene Kremer
Leonard Kremer
John Krenn
Jennifer Krinke
Marianne Krljic
Diane Kroll
Sharon Kunau
Thomas Kunkel
Janelle Kuznia
Lynn Lang
Victoria Larsen
Mark Larson
Phedra Larson
Anna Larsson
Susan Lasoff
Thomas Leaf
Karen Leno
Peter Leschak
Joel Levie
Richard Libbey
Christopher Loch
Karen Locke
Patricia Lockyear
Gail Loverud
Mark Lundholm
Mary Ann Lundquist
Kelly MacGregor
Thomas Mahoney
Kathleen Malecki
Helen Manion
Jennifer Manner
Laurence Margolis
Linda Maylish
Keygan McClellan
Mary McGilligan
Carol Mertesdorf
Kathleen Mickelsen
Keith Miller
Lynn Mizner
Marianne Moesch
Ji Montgomery
Anne Morrow
Kathryn Mosher
Paul Moss
George Muellner
Bonnie Nelson
Jeffrey Nelson
Robert Nesheim
Kimberly Nieman
Randall Nies
Angela North
Megan O'Hara

Michele O'Kane
Jesse Okie
Ellen Ott
Peder Otterson
Michael Overend
Craig Parsons
JoAnn Pasternack
Andrew Pearson
Jennifer Pearson
Ken Pearson
Linda Peck
Marcie Peeters
John Pegg
Keith Peterson
Candice Pierce
Peter Pierce
Todd Pierson
Meryl Pinque
Christine Popowski
Betsey Porter
Barbara Possin
Margaret Preus
Robin Raplinger
Susan Reichel-Halverson
Doretta Reisenweber
Karen Renaud
Staci Revers
James Reynolds
Juliann Rule
Ann Sandritter
Kent Scheer
Robert Scheierl
Jane Schuler
Corinne Segal
Caroline Sévilla
Kevin Shannon
John Siekmeier
William Sierks
Wesley Sisson
Katherine Slama
Jacqueline Smolen
Gregory Solberg
Sue Sonn
Catherine Spaeth
Richard Staffon
Sarah Stahelin
Greg Stawinoga
William Steele
Signe Steiner
Heidi Steinert-Bresilge
DeeAnn Stenlund
Ron Sternal
Cleone Stewart
David Stewart
Kathleen Stuebner
Katie Subra
Debra Swanson
Suzanne Swanson
Thomas Swedberg
Patricia Thomas
Anne Tisel
Kathleen Todd
Sheila Tran
Cheryl Utecht
Anne Vail
Tracy van der Leeuw
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Clayton Watercott
Carol Weber
Joel Weisberg
Colleen Werdien
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Mary Lou Wilm
Carolyn Wolski
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July 22, 2025

Office of Administrative Hearings
Attn: William Moore
600 N Robert St., PO Box 64620
St. Paul, MN 55164-0620
(transmitted electronically)

RE: Comments on MPCA RFC for Amendments to Rules Governing Animal Feedlots: Minnesota Rules, Chapter 7020, Revisor's ID Number R-4928, OAH Docket NO. 25-9003-40661

Dear Mr. Moore:

Thank you for this opportunity to voice our thoughts on the opening of the Chapter 7020 Rulemaking process.

We are writing to first say that we are in full agreement that we need to do what we can to protect our state waters. We see the data. Specifically, the nitrate increases in our waters, and we wholeheartedly agree with MPCA that we, as feedlot owners, play a critical role in protecting our waters. In fact, being good stewards of our water sources and preserving the quality of the land we manage is the basis for all of our decisions we make on the farm.

However, we oppose any further regulation through potential changes to the MN Chapter 7020 Rules. We understand the need to update certain pieces of the rules to address technology advancements, such as online registration and applications, and we are in support of well-developed and user friendly technology to be created and implemented. We do not support MPCA creating further restriction or regulation to any of the current rules—instead, we believe we can do better with what we already have.

Mr. Moore, water pollution is not caused by a one-source pollutant. It takes a collective effort to create the pollution and a collective effort to clean up the pollutants. Can the MPCA affirm that feedlots are the one-source cause for the increase of nitrates in our waters, or are there other sources at fault for these increased levels?

The commercial fertilizer industry has very few regulations for applying nitrogen to crop ground. Commercial fertilizer is not required to be treated with a nitrogen stabilizer (although some retailers do this), like manure is. And individuals applying commercial fertilizer have very few, if any setbacks from waterways they need to follow during application. As feedlot owners, we have been following land application setback rules for years—20+ years (not to mention the additional setbacks we now have due to the Buffer Law). Where is the regulation on

the agronomy side of crop production? Why are we already distancing our land application of manure from waterways, but there is no regulation to be followed for commercial fertilizer application?

What regulation is in place for applying fertilizer to lawns in municipalities? Who monitors that application of lawn-specific nitrogen? In town, lawn fertilizer doesn't even have natural setbacks from the curb or buffer strips in place to slow the flow of nitrogen to the city sewers. Why are we not discussing this as a source of nitrate pollution?

Manure is not the only nitrogen pollutant in our state. And we would go so far to say that we are currently the most regulated piece of this high nitrate puzzle.

That said, the questions we pose to the MPCA and to you, Mr. Moore, is, do we need further regulation? Or, can we do better with our current set of rules?

Within the current 7020 rulebook, MPCA and delegated county feedlot officers are required to routinely inspect feedlots across the state each year. Of the 17,000 registered feedlot in the state of Minnesota, how many state-permitted feedlots and county-permitted feedlots are inspected on an annual basis? There is also opportunity for inspections to be conducted on manure stockpiles, on land application of manure, and on manure management plans. How many of each of these types of inspections get done on an annual basis for county-permitted feedlots and state-permitted (NPDES/SDS) feedlots? If we had these data sets, we could show how many feedlots are being inspected annually, how many are "in compliance" during inspection, and eventually, we could track all the feedlots returning to compliance (those that were found to have an environmental concern that MPCA or the County Feedlot Officers assisted in finding a solution to). From there, we can adjust our target number of inspections annually to improve our data sets, as needed.

If we do not have a good set of data that shows our feedlot owners across the state are doing what they currently need to be doing, then why are we even considering stronger regulation? And, why does it seem like we are the only group actively working on improving water quality through best management practices? What push back has MPCA had on other agencies to own their part in this situation?

While we would like to comment on each of the MPCA-suggested items on the Request for Comments PDF that was provided, we will, instead, address our concerns on what we feel could be the most impactful proposals.

<u>Land Application of Manure:</u>

In the Request for Comments PDF, under item #2., the MPCA asked: What specific changes to the current rules...would provide improved regulations that prevent nitrate contamination into ground and surface waters and fish kills? Should any of the following bullets be considered? If so, at what size (in AU)?

We do not support any of the suggested bullet points listed below #2 in the Request for Comments PDF (i.e. operating permits for county sites, additional restrictions on manure application rates, increased setback distance for land application of manure near sensitive features, restricting land application of manure in areas with high levels of nitrate in waters or in areas with existing high densities of feedlots) being required of any feedlot under 1000 AU.

We do not want our manure to wash into the creeks, waterways and field tile. The manure our livestock produce is our second most valuable commodity on the farm, second only to our livestock. The ability to apply manure is time sensitive, and further restriction will only make the decision making process of when to apply their manure more difficult for farmers everywhere. Moving all manure application to the spring is just not feasible. Some of our local Certified Commercial Applicators have 9-12 weeks of land application work (12+ hour days), and there is absolutely no feasible or safe way to fit that amount of work into a 4 week window in the spring—that's if we get four weeks of dry weather. We are already constantly questioning where and when we should apply the manure from our farms due to weather and these proposed ideas will only add to the stress we face in making on-farm decisions.

We would invite you to visit with our feedlot owners—from both our county-permitted feedlots and our state-permitted feedlots—to hear for yourself the value that having a working manure management plan on our farm has brought us, and also the knowledge we carry from working our land year after year. Every field we work, plant and harvest in has different needs. And there's no blanket research or blanket rate-of-application that will compare to the knowledge we have of these acres. In fact, there's been such advancements in technology and GPS capabilities in our farm equipment that we can now map our fields based on the soil testing we do and spot-apply the manure and manure rates as-needed, ensuring that we are never over applying! These discussions will be invaluable to your research and consideration of any further regulation.

We also do not see how a one size-fits-all land application of manure approach is appropriate for feedlots in Minnesota. We would suggest to the MPCA to consider using MNDOT's Seasonal Load Limit Zone Boundary Descriptions as a starting point for determining a more regional or zoned approach if any new land application of manure regulations are considered. This map was developed to follow roads across the state, frost and thaw dates across the state, and also partially considers soil profile across the state, as well. In speaking with representatives from MNDOT, there would also be opportunity to further split the zones they have by selecting a north/south road in each zone to compensate for easterly portions of the state thawing sooner than their western counterparts. You can view the seasonal load limit zone boundary description map here: https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/download?docId=15860170. Using a regional approach to manure application best management practices seems more applicable than requiring the whole state to follow the same rule.

In the Request for Comments PDF, under #3., the MPCA suggested restricting land application of manure on frozen or snow-covered fields. There is literally no amount of power that any of us have to stop livestock from producing manure during winter months. Furthermore, building four months of manure storage at every feedlot in Minnesota is not financially feasible.

We would like MPCA to further research and reconsider the current rule of not applying manure in March. It is extremely difficult to not apply manure in March. We understand that March is historically the month our soils thaw and that we are at an increased risk for runoff. The manure we scrape from our open lots in these late winter months is often mixed heavily with snow, making application rates less than a normal fall application. We are constantly monitoring the weather and field conditions. It is always our goal to land apply manure in the best of conditions, but perfect conditions happen far less than imperfect conditions.

Perhaps the MPCA could consider a March manure application permit, that could be applied for annually, that would allow feedlots to land apply manure in March, on a case by case basis—similar to the emergency application acres listed in every manure management plan.

Transferred manure:

In the Request for Comments PDF, under #3., the MPCA suggested an "enhanced manure management planning and record keeping requirements for transferred manure." This is in reference to NPDES and SDS permit updates from 2024 and suggesting this item should apply to county-permitted sites, too.

After the 7020 rules update in 2000, it was a requirement for all feedlot owners transferring manure to maintain documentation for who was receiving the transferred manure. According to MPCA, this practice eventually fell out of practice, and today, the only requirement for documenting where the transferred manure is going is via the manure management plan for each site. There is no enforced requirement for the recipient of the manure to maintain their own manure management plan, although it is loosely worded that MPCA may enact additional measures, if needed. With the updated NPDES/SDS permits, the permit holder must now maintain records on who is receiving manure AND the recipient must be applying the received manure according the feedlot owners MMP, all of which must be recorded by the permit-holder.

How does this even make sense? To go from almost zero documentation for transferred manure to the feedlot owner having to maintain records and dictate application rates and measures to take for the manure they sold when the feedlot owner has no knowledge of the manure recipient's field data? Furthermore, how will MPCA monitor any of this information? Who will be required to receive the documentation from these NPDES/SDS sites and verify that all rules are being followed? And, what sort of follow up will occur to ensure the new rule rules will be followed correctly? There are roughly 1,000 NPDES/SDS sites in the state, how will the MPCA monitor and follow up on any of these new rules if the 16,000 county-permitted sites are required to follow the same type of rules?

We would be in favor of documenting where that manure is being transferred to, but we do not feel it is our responsibility, or that it would even be legal for us to regulate how that recipient of the manure applies that manure to their land whether we have a state or county permitted feedlot.

Common Ownership:

On the Request for Comments PDF #8., the MPCA asks: "How should the MPCA address feedlots under the same ownership in close proximity to each other? How far apart must each feedlot be located in order to be considered a separate facility for the purposes of permitting and/or registration?"

We propose that the MPCA leave these questions up to the determination of each county. At this time, the Environmental Protection Agency (EPA) generally considers any feedlot within .25 miles from another feedlot with the same ownership "common ownership" and may be considered a multi-site location in need of an NPDES or SDS permit.

Our county is zoned as "Agriculture Preservation". Minnesota State Statute 40A.18 LAND USE. states that "Land within an agricultural preserve must be maintained for agricultural production. The average maximum density of residential structures within an agricultural preserve and the location of a new structure must conform to locally applicable plan or zoning regulations. Commercial and industrial uses are not permitted except as provided in subdivision 2 after the user is issued a permit by the local government. *The local government is responsible for enforcing this section*."

Every county is different in how they permit feedlots beyond the Chapter 7020 requirements. Do not muddy the water further by making it more difficult to build the family farm and bring our children back to the farm when they graduate. Leave distance between feedlots and ownership decisions up to each local government.

According to the USDA's Economic Research Service, there were nearly 6.8 million farms in the United States in 1936. Today, there is roughly 1.88 million. The average number of acres of land per farm is 466 acres. According to the 2022 Census of Agriculture County Profile for Nobles County, 95% of the reporting farms indicate that they are family farms. Just under 50% of the farms in Nobles County farm an average of 50 – 499 acres of land.

In today's economy, it is not feasible to bring any child back to the farm with only 466 active acres, which is why we've seen a steady decrease in total number of farms and an increase in overall number of acres owned per farm. This is also why we see an increase in number of livestock on these farms—because our kids want to come home and do what they love. However, this is a testament to how competitive it can be to build a family farm.

In order to bring our children home to the farm we either need to purchase more land to crop or diversify our farms to include livestock. Further federal or state regulation only hinders the ability of family farm to expand. Let our local governments determine how far apart our feedlots need to be and what ownership rules need to look like.

Pasture:

Finally, on the Request for Comment PDF, #6., the MPCA questions, "How should the rules be amended to address this documented issue (WRAPS documents indicating high nutrient and bacteria levels in streams and rivers)?"

We ask that the MPCA leave pasture ground alone and do not require pastures to be registered as documented feedlots in the future. Nobles County has just over 6,700 acres of land in pasture ground, according to the 2022 Census of Agriculture County Profile. Pasture landowners are generally not restricted from providing access to waters on their property to their livestock (Department of Natural Resources). We do not want our livestock to create any pollution hazard to these rivers and streams, but how does the MPCA propose we monitor how much the livestock manure is contaminating the rivers and streams in comparison to wildlife feces contaminating rivers, streams and lakes?

Again, this seems like another suggestion that MPCA is proposing that would be difficult to provide the means to monitor or verify is being done correctly. This is another topic that should be left to the individual counties to decide how to monitor.

Final Thoughts:

As feedlot owners, we want to protect our water sources and keep our land fertile and usable for the future generations—we truly want to leave both in better condition than how we found them. We also understand that rules and regulations are part of the process, that if we didn't have them, we'd be dealing with much larger concerns than we are today. We believe there is a balance between trusting us with the land that we've farmed for multiple generations, that we know better than you do, and creating a space to ensure that everyone is being good stewards of our land and water. We have the same goal: to ensure these natural resources are here and healthy for future generations.

As a state, we have to remain competitive with our neighbors, too. Have you noticed the explosion of dairy herds along I-29 in South Dakota in the last 10 years? According to the USDA, South Dakota dairy herds totaled 208,000 head as of January of 2024, up 70.5% since 2019. That means that South Dakota's dairy herd has added 118,000 cows over the past 12 years. That's not because they are competitively closer to feed, or to road systems that provide easier transportation access than we do here in Nobles County. Our county is a 60 mere miles from I-29 and closer to the feed than South Dakota farms are. Minnesota's feedlot regulations are restrictive and deter farm growth in the state, in our opinion.

We stand by our overall sentiments that there is a lot of opportunity for the MPCA to improve on what they already have in place for rules, instead of further regulating feedlot operations. Let's work on getting feedlots compliant with the current set of regulations via more inspections and monitoring data trends, instead of slapping together a new rule book with stricter rules for Minnesota feedlots to follow.

And, we must repeat our sentiments that there is also opportunity for MPCA (and feedlot owners themselves) to have further conversations with other state agencies, and press those agencies to look into what the Minnesota Department of Agriculture is doing to regulate the agronomy industry through the land application of commercial fertilizer and regulate homeowners/business owners applying fertilizer to their lawns in town.

Respectfully,
Nobles County Feedlot Owners
Nobles County Commissioners

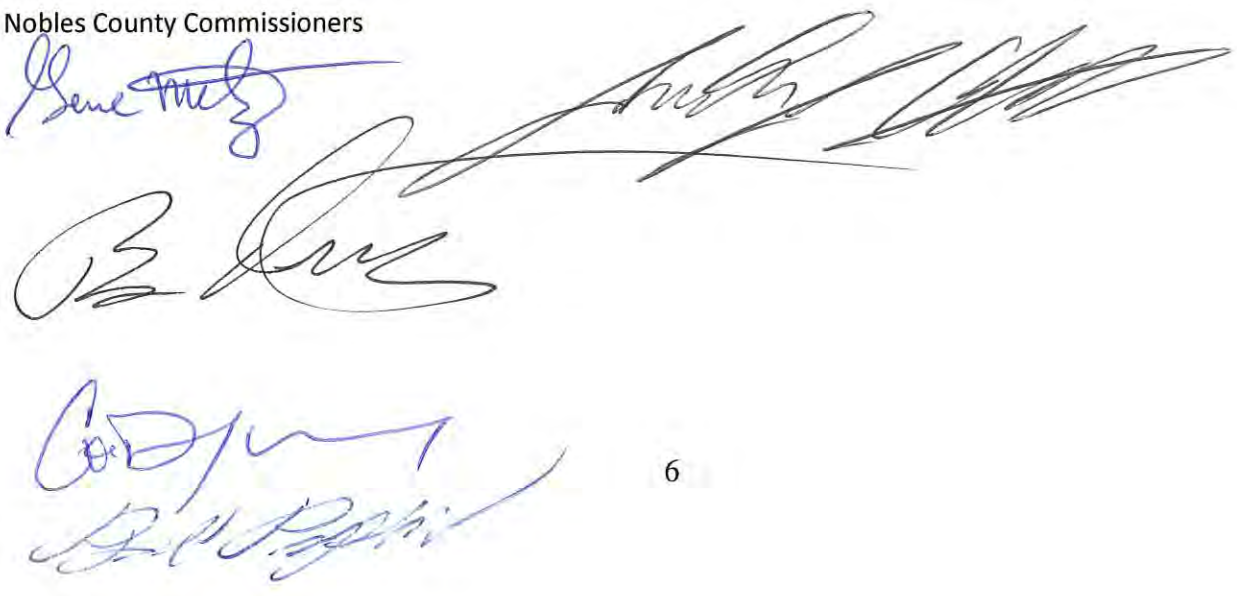

2022 Census for Agriculture County Profile:
https://www.nass.usda.gov/Publications/AgCensus/2022/Online_Resources/County_Profiles/Minnesota/cp27105.pdf
MN DOT Seasonal Load Limit Zone Boundary Descriptions: https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/download?docId=15860170
MPCA Multiple Site Determination for NPDES and SDS Feedlot Permits (2021):
https://www.pca.state.mn.us/sites/default/files/wq-f6-63.pdf
2024 Minnesota Statures 40A.18 Land Use: https://www.revisor.mn.gov/statutes/cite/40A.18
USDA Economic Research Service, "The number of U.S. farms continues slow decline": https://www.ers.usda.gov/data-products/chart-gallery/chart-detail?chartId=58268
Dairy Herd Management: https://www.dairyherd.com/news/dairy-production/south-dakota-governor-supports-states-massive-dairy-industry-growth

Seasonal Load Limit Zone Boundary Descriptions (2022)



North Zone Extends south from the Canadian border to a line following and **including** TH 1 at the North Dakota state line east to TH 89, TH 89 south to US 2, US 2 east to TH 33, TH 33 south through Cloquet to I-35, I-35 north to the Carlton/St. Louis county line, south on that line to TH 210, east along TH 210 **excluding** TH 210 to TH 23, then west along TH 23 **including** TH 23 to the Wisconsin state line.

North-Central Zone Extends south from the southern limit of the North Zone (TH1 – TH 89 – US 2 – TH 33 – I-35 – Carlton/St. Louis county line – TH 210 – TH 23 – WI state line) to a line following and **including** US 10 from the North Dakota state line east to Motley, TH 210 east to Brainerd, TH 18 east to I-35, I-35 south to TH 48, and then TH 48 east to the Wisconsin state line.

Central Zone Extends south from the southern limit of the North-Central Zone (US 10 – TH 210 – TH 18 – I-35 – TH 48 – WI state line) to a line following and **including** US 12 from the South Dakota state line to the Wright county line.

Metro Zone Minneapolis – St. Paul Twin City Metro Area includes the following counties: Anoka, Carver, Chisago, Dakota, Hennepin, Ramsey, Scott, Sherburne, Washington and Wright. This zone does not include TH 19 along the southern borders of Scott and Dakota counties.

South Zone Extends south from the southern limit of the Central Zone (US 12 – Wright county line) to the Iowa state line and east to the Metro Zone and then a line following and **including** I-35. This zone includes TH 19 along the southern border of Scott county.

Southeast Zone Extends south from the southern limit of the Metro Zone along, but not including, I-35 to the Iowa state line and east to the Wisconsin state line. This zone includes TH 19 along the southern border of Dakota county.

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John Siekmeier Attachment

MINNESOTA DIVISION OF THE IZAAK WALTON LEAGUE OF AMERICA

COMMENTS ON MPCA FEEDLOT RULE-MAKING

by

THE IZZAK WALTON LEAGUE OF AMERICA'S MINNSOTA DIVISION
John Siekmeier, President
6601 Auto Club Road, Bloomington, MN 55438

July 22, 2025

The comments that follow are submitted by the Izaak Walton League of America (IWLA) Minnesota Division and pertain to the Minnesota Pollution Control Agency's planned amendments to rules governing animal feedlots, Minnesota Rules, chapter 7020, Revisor's ID Number R-4928 - OAH Docket No. 25-9003-40661.

Statement of Qualifications and Standing

The Izaak Walton League of America is one of the nation's oldest and most successful conservation organizations. Founded in 1922 the "Ikes" have for over 100 years stood for the protection and restoration of the nation's fish, wildlife and natural areas and is especially focused on matters affecting water quality.

Wherever these comments refer to "the League" this reference should be understood to be the collective opinions of members of the Izaak Walton League here in Minnesota that include a wide variety of experts in the natural sciences, water quality, hydrology, agriculture, public health and regulatory governance. The League is especially well positioned to make these comments on feedlot rules because many of our members are retired agency professionals from the Departments of Agriculture, Natural Resources, Pollution Control Agency, Health, Transportation, Board of Soil and Water Resources, Soil and Water Conservation Districts, U.S. Army Corps of Engineers, U.S. Geological Survey, U.S. Fish and Wildlife Service, the U.S. Environmental Protection Agency and more. Many League members are or were academics researching or teaching in colleges and universities in these disciplines. Other members have doctorate degrees and have been practicing family or specialty medicine for years, while still others are active citizens in natural resource protection in the League and other advocacy groups and have dedicated extraordinary amounts of time studying these matters and developing organizational policies to address conservation, pollution and environmental degradation.

Scope and Perspective for Comments

In the agency's request for public comments the MPCA has stated that the agency's three main areas of focus for these rule amendments include:

1. Updates to address changes in livestock and poultry operations and business practices, new agency data services, and outdated language.
    - Permit and registration applicability;
    - Animal unit factors;
    - Clarity of definitions and requirements;
    - Legislative alignment; and,
    - Utilization of agency data services.
2. Land application of manure practices to address nitrates, bacteria, and fish kills.
    - Transferred manure requirements;
    - Nitrogen Best Management Practices (BMPs);
    - Setbacks;
    - Manure Management Plan (MMP) applicability;
    - Visual monitoring; and,
    - Compliance monitoring.
3. Technical standards to protect water quality and avoid fish kills.
    - Manure storage capacity;
    - Feed storage design and operation;
    - Existing Liquid Manure Storage Area (LMSA) integrity;
    - Ground water monitoring; and,
    - Livestock access to waters.

The agency then asks: "Should any of the following bullets be considered? If so, at what size (in AUs - animal units)?"

- Operating permits (NPDES or SDS) for feedlots less than 1000 AUs.
- Submittal of manure management plans and land application records for feedlots without operating permits.
- Monitoring of feedlots and land application sites for subsurface discharges of manure or nitrate to groundwater.
- Additional restrictions on manure application rates.
- Soil nitrate tests prior to land application of manure.
- Increased setback distance for land application of manure near sensitive features.
- Restricting land application of manure in areas with high levels of nitrate in waters or in areas with existing high densities of feedlot operations.

MPCA's Three Area of Focus

The League generally agrees that the MPCA's three areas of focus listed above are appropriate. But, of particular concern to our members is the first one in this list: the significance of "*changes in livestock and poultry operations and business practices".*

There has been dramatic shift in animal and crop agriculture toward larger industrialized models over the past few decades that are thought to be primarily the result of government subsidy and world trade policy. As profit margins narrow and farm land prices rise the response has been to increase production rates to maintain viability. As

costs of inputs increase, the income from production has not been keeping pace. To hedge financial risks, producers (both crop and animal producers) have taken advantage of hidden subsidies that externalizes a major cost of production at the expense of a public asset: *degraded water quality and quantity.* By maximizing fertilization of crops with commercial fertilizer and manure to boost production (as recommended by established "agronomic rates") producers are encouraged to gamble on having a bumper crop every year. And there is an understandable tendency to augment the production benefits using less of the of higher cost commercial fertilizer, with more of the lower cost manure. But this gamble depends on having ideal weather conditions every year, which seldom happens. The result is that total nutrient inputs on an annual average, almost always exceed uptake and removal by harvested crops. The excess application of both forms of fertilizer accumulates each year that a "bumper" crop is not realized. Soil testing will not detect either form of nutrients that has leached below the root zone. As the build-up of excess fertilizer either washes off or leaches down below the root zone, this fertilizer is "released" as pollutants to groundwaters, surface waters, or both.

Current best management practices, even deployed to their maximum capability, which they seldom are, have not proven sufficient to recover, treat or retain these excess applications or the discharges to surface and groundwater. Uncontrolled discharges, "releases" of pollutants by these means, should be prohibited by the new rules because they are intentional, measurable and preventable.

As the MPCA works to develop rules for feedlot operations that reduce or eliminate this avoidable source of water pollution, the agricultural community's hidden profit subsidy *(degraded water quality and quantity*) that depends on continued release of pollutants will be significantly threatened. Powerful political forces will push back claiming that regulatory over-reach by the MPCA is threating the economic viability of farming in Minnesota.

Special attention must be given to this predictable political argument well in advance of the agency's proposed new rules that will make this unwarranted subsidy clear to the public, to the agricultural community and to our elected officials. Failure to anticipate and successfully dispel this argument in advance would imperil the success of the new rules.

The League believes that the MPCA must work with social scientists and other experts to carefully craft an educational campaign that exposes this unwarranted subsidy and builds support for ending it. The current industrial models for both crop and livestock production are seriously flawed in this regard and there are viable alternatives. The League stands ready to work with the MPCA, other state agencies and our partner non-profits to develop and roll out this educational campaign.

Later in these comments we will propose a structure and cite the authority for assembling an expert advisory panel to assist the agency and cooperating entities in

developing and implementing this plan based on existing statutory mandate and an Iowa example.

MPCA's Bullet-Points

The next section of our comments is directed toward the several bullet-points the MPCA offered for considerations. These summary responses on those points will be followed by more detailed discussion of them in a later section.

Overall, it is the League's position that the amended feedlot rules must not only be effective at reducing feedlot pollution, but should eliminate it to the degree necessary to support all classified uses of the state's surface and groundwaters. This has been and remains the goal of the Federal Clean Water Act, and actually provides the name of the federal NPDES permits many feedlots and all other discharges require. NPDES is short for the National Pollutant Discharge *Elimination* System.

The business and operating models for industrial-scale livestock and poultry production is vastly different from the conventional, family-farm model, and its waste handling and disposal methods are largely experimental. The industrial model has outside entities called integrators that own the animals. The "farmer" landowner owns the buildings, manure storage and handling equipment, and only some of land needed for manure disposal. Liquid manure rather than dry storage became the norm due to technical advances in manure handling equipment, but this required retention or addition of water to the manure. This business arrangement tends to bifurcate the responsibilities and liabilities of manure ownership, complicates storage and disposal options, and tends to shield the animal owner from any responsibilities.

Conventional family farms had the farmer owning both the animals and the all the related capitol infrastructure and all the land needed for manure. Dry handling storage of manure, depending on site conditions, has less tendency for run-off or seepage pollution because the manure inherently had more bulk (i.e. added bedding such as straw) and less added water.

Our research reveals that the industry's adoption of a wide variety of recommended best management practices have failed markedly at protecting surface and groundwaters nation-wide, and thus cannot continue to be the basis for either the voluntary norms or the regulatory requirements for permitting. Our recommendations for rule changes are premised on this fact. Unproven methods for manure storage and handling should be deemed "experimental" by rule. And these experimental waste management methods should only be allowed on a trial-and-error basis with close monitoring, and have prompt, pre-determined correction, remediation and compensation measures built in (for harms to public or private water supplies).

The comments below and the findings and recommendations in the League's Prairie Woods Chapter's AFO/CAFO report (attached) on feedlots to Becker County[1] are each

[1] See attached report entitled: ADDRESSING AFO & CAFO IMPACTS IN BECKER COUNTY'S COMPREHENSIVE LAND USE PLAN, ZOINING MAPS & ORDINANCES – August 1, 2024.

offered as useful information in regard to the MPCA's rule revisions. That report details gaps or deficiencies in federal and state rules governing feedlots that the League recommended Becker County address in their revised comprehensive land use plan. We also refer the agency to a recent Iowa report entitled *"Currents of Change*" [2] and offer that report into the record by reference. The Iowa report is offered here because it fortifies the findings of the League's AFO/CAFO report. The MPCA is encouraged to review the findings of each of these reports and address the identified deficiencies.

Our experience in Becker County is instructive. The League and specifically the members of the League's Prairie Woods Chapter in Detroit Lakes have examined the pollution potential of industrial-scale animal feeding operations and manure disposal in depth and on a national scale. This was done in preparation for a large swine operation that was proposed for a western Becker County township that requires a conditional use permit and an SDS or NPDES permit from the MPCA (application to MPCA yet filed). When the League challenged the adequacy of the county's zoning ordinances as being inadequate to control pollution from the facility, the county opted to update its Comprehensive Land Use Plan and review its ordinances. At the conclusion of that year-long process, county officials concluded that they were relying on the MPCA's rules to protect water quality. The county viewed their role and ordinances as intended to prevent land use conflicts, not protecting water quality. This, they concluded, was entirely the purview of the MPCA.

Our chapter members prepared the referenced report to demonstrate the inadequacy of Minnesota's and other states feedlot rules nation-wide. The report references the MCEA, et. al., petition to EPA that led to the current proposal for rule-revisions. Becker County officials were not convinced that they were obliged to fill this gap and have proceeded to issue the county permit.

This, and the *Currents of Change* report from Iowa, are offered to point out that local units of government are relying on the state governments (MPCA) to not only provide needed regulation of the design and operation of feedlots to prevent pollution, but to also to help them apply appropriate land use controls to avoid locating large feedlots in sensitive or already degraded areas of the state.

Summary Responses to the MPCA's Bullet Point Consideration Questions:

The League supports that construction and operating permits be required for feedlots far less than 1000 animal units in size. We suggest that all permitted feedlots should have both manure management plans, and require not only manure application records be kept, but water quality monitoring records as well. Because there is no evidence that feedlots below a certain number of animal units should be exempted as a class on the

[2] Currents of Change – An Analysis of the Racoon and Des Moines Rivers in Central Iowa - Final Scientific Assessment of Source Water Research Report available on-line at: https://www.polkcountyiowa.gov/media/lixlchbz/ciswra-currents-of-change_final-scientific-assessment-of-source-water-research-report_jun272025.pdf

basis of their low pollution risk, we recommend that small operators should apply for site-specific exemptions (variances) instead of being offered blanket exemptions based on their being below a certain number of animal units. Such exemptions could be applied for with assistance and documentation provided by county Soil and Water Conservation Districts or County Feed Lot officers. Criteria for exemptions would necessarily have to be spelled out in the new MPCA feedlot rules.

For example, traditional family-farm-scale feedlots often use dry handling and stacking methods for storing manure before field spreading. As mentioned above, dry stacked manure has far less potential for runoff or seepage than liquid manure handling and storage systems. If suitable vegetated setbacks are observed, slopes are moderate to level and runoff deflection and detention berms are constructed these operations could be considered exempt by rule.

We suggest that all permitted feedlots (that are not exempted) be required to record not only manure application rates, but additional commercial fertilizer rates as well. Permits should require active sampling and analysis of both surface and subsurface discharges for specific pollutants associated with animal manure storage and disposal and for other polluting chemicals associated with large feedlot operations. Monitoring for nitrates alone is not enough and parameters such as bacteria[3], biological oxygen demand (BOD), phosphorus and any other chemicals or pharmaceuticals being administered at the site for example, should also be required. Rates of manure application should be dictated by the site-specific character of the lands used for manure disposal from each permitted facility. Removal of nutrients such as nitrogen and phosphorus, through crops and residue harvested from fields receiving manure should be documented and compared to combined commercial and manure fertilization rates to assure excesses are not accumulating or being discharged. Determining the need for additional restrictions on manure application are again, site specific and should be proposed for each unique facility by licensed engineers and hydrologists who are experts at manure management for water quality protection purposes.

Setbacks from any and all surface waters should also be determined on a case-by-case basis, because a setback that may function well in one location may be inadequate for others, depending on slopes, ground cover, soil types and other site-specific characteristics.

Land application of manure in areas that already have high levels of nitrates or other pollutants associated with feedlots in either surface or groundwaters, should not only be more restrictive, but manure production, storage and land application should be prohibited in these areas until remedial actions are successful at reducing these

[3] U.S. Department of Agriculture studies in Wisconsin have shown that bacteria from feedlot seepage into ground water can travel several miles from the source underground so bacteria should be a monitored parameter for both surface and groundwaters. See section entitled GREEN BAY WISCONSIN – ON LAKE MICHIGAN on pages 22-23 of Leagues AFO/CAFO Report to Becker County attached.

excessive levels to a predetermined point. The term "high levels" are parameter specific and needs better definition. But, to be preventative, nitrates should have a trigger level well below the drinking water standard of 10 mg/l. This margin accounts for the lag time between a pollutant's discharge and its detection in receiving waters by monitoring.

The fact that the MPCA has not yet promulgated surface water nitrate standards for all waters other than those used for drinking water, is now being drawn into the public spot light. While adopting new nitrate water quality standards is not up for consideration in the current rule-making for feedlots, the League strongly encourages the agency to move forward with that long-delayed, much overdue process.

Detailed Discussion of Summary Above and Other Comments

The League respectfully suggests that any attempts to specify technical standards that are protective or remedial practices for most animal feeding operations by rule, are unlikely to accomplish the agency's statutory mission to: *"enforce reasonable orders, permits, variances, standards, rules, schedules of compliance, and stipulation agreements, under such conditions as it may prescribe, in order to prevent, control or abate water pollution."*[4] Minnesota's landscape, topography, soils, ground cover and the state's surface and groundwater vulnerabilities are far too varied in aspects relating to pollutant movement, retention and processing to allow a single "one-size-fits-all" approach. It is the League's strongly held opinion that most if not all permitted livestock or poultry operations should be required (by rule) to submit site-specific designs that take into account the unique natural or humanly altered features of a proposed feedlot and accompanying manure application locations. This is because animal feeding operations at or below 100 animal units in higher risk locations have been found to be major sources of pollution.

A Proposed "prove it first" Policy

The findings of the Prairie Woods Chapter's AFO/CAFO Report and the Iowa *Currents of Change* report referenced above, demonstrated that the intensification (concentration) of animals in what has become the industrial model for producing meat, has created a high risk for water pollution. The report also finds that in many other states that have experience with this scale of feedlot operations, citizens, environmental NGOs and regulatory entities alike have concluded that the array of pollution prevention methods (best management practices or BMPs) currently being deployed (whether mandatory or voluntary) have been inadequate to satisfactorily prevent feedlot pollution from entering public waters.

Based on this finding, the League recommends that the MPCA adopt a policy that declares this intensified method of livestock farming an experimental, high-risk polluting enterprise that must demonstrate new and improved controls before qualifying for permits. This would in effect, place the industry representatives (permit applicants) on

[4] Minnesota Pollution Control Agency enabling legislation at: Mn Statutes Chapter 115.03 POWERS AND DUTIES Subd 1(5).

notice that they must prove they have solved the heretofore unsolved problems associated with this industrial-scale enterprise.

To provide this "proof" the plans and specifications for new or expanding animal feeding operations should be required to be prepared by licensed engineers and hydrologists qualified and experienced in this specialized field. Existing permits should have renewal (expiration) dates after which time they would be required to meet these new rules. The licensed professionals responsible for the siting and design of these experimental operations should be required to affirm that the plans and specifications they submit will, in their professional opinion "prevent, control or abate" pollution.

This should not be viewed as an unusual hardship on even the smallest feedlot operation, considering that individual homeowners in rural areas of Minnesota are required to have licensed professionals design and install on-site sewage treatment and disposal systems that are reviewed by qualified professional in permitting units of government.

Furthermore, this is equitable, because municipalities and other industries in Minnesota, by rule, must hire qualified and licensed engineers to prepare plans and specification for wastewater treatment facilities before they can be permitted for construction and operation. Effluents from these facilities must submit monthly discharge monitoring reports that demonstrate compliance with effluent standards specifically designed to protect the public uses of the receiving waters. By "signing off" on these plans and specification, the designing engineers and hydrologists effectively warrant, by peril of their professional certification, that the facility, when built and operational can and will meet the prescribed water quality standards.

Permits for feedlots should be required to have both a construction and operation permits to detail the specifications by which this unique kind of pollution will be controlled and problems remedied.

Establishing a Point of Discharge as Compliance Boundary

The League recommends that the agency adopt a "point of discharge" policy as a compliance boundary that identifies the soil layer below land applied manure that represents the uncontrolled release of agricultural pollutants. This point would be below the root zone of current or planned crops that could capture or recover nutrients and biologicals applied to the land. Detection of "released" pollutants should be provided by monitoring devices such as lysimeters installed prior to a facilities operation and at locations representative of the areas, included in a facility's manure management plans.

To show whether or not surface or groundwater pollution is or has been originating from an animal feeding operation the permittee should be required to submit pre-construction (for new or expanding operations) monitoring data from representative locations in the water table or aquifer both upstream and downstream of the existing or proposed operation. Where the groundwater flow paths are uncertain due to karst or other geologic character the monitoring plan should demonstrate schemes for collecting data

that does documents the rates, routes and reservoirs of feedlot pollutants escaping (discharging) from a facility and its associated manure application fields. If the groundwater regime proves too complicated to monitor, these facts should constitute grounds for permit denial. Lack of information or the inability to collect it should not be used to justify avoidable risks.

Plans for the groundwater water quality monitoring regime should be submitted to the MPCA for prior approval before the monitoring system is put into operation. The plan should include the professional hydrologist's opinion on whether the existing pre-construction water quality condition will be adequately characterized by the sampling locations, frequency and duration of sampling and the parameters to be monitored. Parameters to be monitored should reflect not only the nutrient and microorganisms that could be discharged from the facility, but all other "pollutants" used at the facility relating to the feeding and raising animals.

In areas having heavy clay soils that a design engineer has determined to be an adequate barrier to downward movement of "released" pollutants, any and all drainage systems serving these fields, including surface ditches, natural waterways or underground tile, should have sampling locations and methods identified to detect "releases" of feedlot related pollutants.

If pre-construction monitoring demonstrates that an existing animal feeding operation owned and or operated by the applicant has already contributed to surface or ground water pollution, the prospective permittee must submit a remedial action plan to be approved by the MPCA. This remediation plan should be successfully implemented before new or expanded animal feeding operation can be permitted. Here, successfully implemented would mean the pollution levels are reduced to comply with applicable surface or groundwater standards.

Available tools for early detection of existing degradation include the MPCA's Watershed Restoration and Protection Plans, coupled with the One-Watershed-One-Plan documents prepared by each county or watershed boards if they exist. These plans are intended to gather and survey existing data on surface and groundwater and identify contributors (stressors) on these water bodies. The plans often include remedial measure needed to address impaired waters. If animal feeding operations are identified as one of the stressors causing impairments, new or expanding feedlot permit applications should be reviewed in light of these findings. As existing permits come up for renewal, the new monitoring and discharge control requirements in the new rules should then apply to these existing lots with a compliance schedule.

Joint Permits for Industrial Model Feedlots

The industrial model for large feedlots often includes a three-layer pyramid of agreements between the land-owner (farmer) and the animal owners (called integrators) and the contracted industrial meat processors. The new feedlot rules must include ways to obligate each of these entities to the responsibility for compliance with permit limitations on discharges, and for financial assurance necessary for remediation upon

discovery of a release. The integrators and the meat processors have been attempting to place the farmer/landowner in the position of responsibility for manure disposal in an effort to protect themselves from this liability. The farmer is not likely to have the financial wherewithal to withstand the costs of remediation should the manure threaten or contaminate surface or groundwater. Faced with this problem, the landowner/farmer may declare bankruptcy leaving the state (taxpayers) to bear the costs of the pollution and remediations.

The need for joint permitting of the parent companies and the intermediate integrators, along with the farmer/land owner must be addressed in the new rules.

Interstate Transport of Manure

Large feedlot operators are generating such large quantities of manure that they may need to seek lands in neighboring state for disposal options. The new rules should anticipate the issues raised by these circumstances. A Minnesota feedlot operator disposing of manure in a neighboring state should be required to comply with rules for long-distance transportation of manure through Minnesota. It is unlikely that the MPCA would have control of that manure once it crosses state lines. However, there may be opportunity for interstate cooperative agreements that provide a seamless protection for water quality. On the other hand, an importer of manure from another state should be required to prepare manure management plans that include the same level of monitoring and release response required of a Minnesota operator. Interstate agreements may also be needed to alert the MPCA to planned importation of manure. The same level of joint permitting for land and animal owners as discussed above would seem appropriate for these circumstances as well.

Importation of manure raises another issue that may be outside the MPCA's authority but nevertheless requires regulatory attention. The interstate transport of manure carries the potential for spread of livestock and poultry disease. If other state departments have the authority to regulate the interstate transport of animal disease, the MPCA should work toward some interagency agreement to address these issues. The MPCA could perform this courtesy for neighboring states receiving manure exported from Minnesota.

Groundwater Supply Impacts

Private well owners in agricultural areas have little or no protection for their water supplies and seldom have their wells tested. When they do test, they may only get results for nitrates and coliform bacteria and they may be unaware of fluctuations in supply aquifer levels influenced by high-capacity wells such as those needed to supply large feedlots.

These are data gaps that the proponents of industrial scale agriculture must help fill. Published studies[5] from N.E. Iowa have shown that

[5] Juxtaposition of intensive agriculture, vulnerable aquifers, and mixed chemical/microbial exposures in private-well tapwater in northeast Iowa available on-line at: https://pubmed.ncbi.nlm.nih.gov/36657670/

"… contaminant exposure in unregulated private-well point-of-use tapwater (TW) is a recognized public-health data gap and an obstacle to both risk-management and homeowner decision making.

The current results address a critical lack of directly comparable data on broad contaminant exposures in TW in agriculturally-developed settings and document commonplace simultaneous exposures to inorganic, organic, and microbial contaminants of human-health concern.

Heterotrophic bacteria detections were near ubiquitous (94 % of the samples), with detection of total coliform bacteria in 28 % of the samples and growth on at least one putative-pathogen selective media across all TW samples. Health-based hazard index screening levels were exceeded frequently in private-well TW and attributed primarily to inorganics (nitrate, uranium). Results support incorporation of residential treatment systems to protect against contaminant exposure and the need for increased monitoring of rural private-well homes."

The Prairie Woods Chapter's AFO/CAFO report also cited studies in Wisconsin where manure pit related bacteria traveled over three miles to neighboring private wells. To assess potential impacts of a proposed feeding operation on both the quality and quantities of available groundwater supplies, the permittee should be required to submit appropriate assessments of these water supplies that identify other area users (both public and private) potentially impacted and what measure will be taken to ensure supplies will be adequate in quantity and quality to serve all existing and planned future uses of these waters. Once again, these assessments should be prepared by licensed professional engineers and/or hydrologists.

Permits for sites that have downstream private wells within five miles should be required to pay for well water analysis of these wells prior to beginning operation, to establish background levels of indicator pollutants. If indicators of agricultural pollution are found, more exhaustive sampling and analysis should be required to determine if other agriculturally related biologicals or chemicals, including pharmaceuticals, are present. Likewise, pumping tests on new water supplies for large feedlots should be required, with water level impacts on existing private wells within five miles being reported. If no existing wells are located within five miles, special monitoring wells should be installed temporarily to determine the zone of depression caused by the new well and neighboring property owners should be formally notified if the aquifer they may rely on in the future may be impacted.

If these requirements should exceed the MPCA's authority or expertise, the League strongly suggests that either a memorandum of understanding or other agreement be developed between the MPCA, the Departments of Natural Resources, Health and Agriculture, to assure this impact is adequately addressed. For example, some form of written commitment between agencies to prepare a joint discretionary environmental assessment worksheet (EAW) or an environmental impact statement (EIS) may provide the level of scrutiny and public comment this problem requires.

Reasonableness of Requiring Compliance With Discharge Standards

The current MPCA policies and rules and the similar laws and policies in other states nation-wide have allowed feedlots to discharge both directly and indirectly into both surface and groundwaters causing serious pollution and impairment of these waters in many parts of the state, and only required that feedlots employ "best management practices" to "minimize" the discharges.

The League's position advocating the agency strengthen its policies and rules is supported by provisions of the Minnesota Environmental Policy Act (MEPA) which, in Chapter 116.04 subdivision 6 states:

> ***"Prohibitions**. No state action significantly affecting the quality of the environment shall be allowed, nor shall any permit for natural resources management and development be granted, where such action or permit has caused or is likely to cause pollution, impairment, or destruction of the air, water, land or other natural resources located within the state, so long as there is a feasible and prudent alternative consistent with the reasonable requirements of the public health, safety, and welfare and the state's paramount concern for the protection of its air, water, land and other natural resources from pollution, impairment, or destruction. Economic considerations alone shall not justify such conduct."*

This is a powerful mandate and a provision in state statute that would appear to compel the MPCA to prohibit (by denying permits) feedlot operations that pollute, impair or destroy the state's waters. Should the agency decide otherwise, it is the Leagues pointed request that the agency provide its explanation for allowing such pollution or impairment in their statement of need and reasonableness for any proposed rule that continues to allow this pollution.

Economic considerations

As discussed above, the League recognizes that the economics of livestock and poultry farming may have influenced landowners to increase that scale of their operations in order to increase or even maintain their profit margins as market prices for their livestock varied. However, manure storage and management practices that routinely allow pollution also increase profit margins, but do so at the expense of our precious water resources, a public trust to be managed for the public good. We maintain that feasible and prudent alternatives to the industrial-scale CAFO model do exist, thus this MEPA policy requires the agency to apply far more stringent standards for those feedlots. It is not our intention in these comments to list or outline these alternatives but instead recommend the MPCA, in conjunction with other state agencies and universities fully explore the available alternatives and make them known to the farming community.

In the section of the League's AFO/CAFO report to Becker County entitled *Economic Impact of CAFOs on Rural Communities (*on page 13) we present the economic arguments based on the work of Dr. John Ikerd, who holds a PhD in Agricultural Economics from University of Missouri-Columbia, that this form of industrialized meat

production is by many indicators, detrimental to the economies of communities where large feedlots of this type exist.

The League is sympathetic to the plight of farmers who may lack the technical or engineering resources to choose a less polluting alternative to the industrial CAFO model. Another section of MEPA requires agencies to do some of this work. *Minnesota Statutes* 116D.04 subdivision 2 (1&2) to establish advisory councils and forums to consult with experts on such matters:

> *"Subd. 2. Duties. All departments and agencies of the state government shall:*
>
> *(1) on a continuous basis, seek to strengthen relationships between state, regional, local and federal-state environmental planning, development and management programs;*
>
> *(2) utilize a systematic, interdisciplinary approach that will insure the integrated use of the natural and social sciences and the environmental arts in planning and in decision making which may have an impact on the environment; as an aid in accomplishing this purpose there shall be established advisory councils or other forums for consultation with persons in appropriate fields of specialization so as to ensure that the latest and most authoritative findings will be considered in administrative and regulatory decision making as quickly and as amply as possible;"*

The League strongly recommends that the MPCA act on this legislative mandate to create a feedlot advisory council to provide independent and objective input not only on these rules but to develop information and the means for its distribution to farmers who need to explore alternatives to the prevailing industrial CAFO model. The past practice of the MPCA, the EQB and other agencies to appoint "stakeholder" panels that includes those with obvious conflicts of interest should be avoided. The statute citation above emphasizes that advisory councils be populated *"with persons in appropriate fields of specialization so as to ensure that the latest and most authoritative findings will be considered in administrative and regulatory decision making as quickly and as amply as possible;"*

We offer instead the example of the panel of science advisors involved in preparing Iowa *Currents of Change* report. The report lists the names, qualifications and an indication of the independence of those panel members that contributed to the report.

<u>Currents of Change Panel of Science Advisors as Listed in the Report</u>

Currents of Change's depth, breadth, and comprehensive interpretation are due to approximately 4,000 hours of analysis and assessment by CISWRA's science advisors—all respected researchers and experts across multiple disciplines. The County is grateful for the passion and commitment devoted to CISWRA on the part of the science advisors.

Dr. Elliot Anderson, Lead Data Coordinator, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Elizabeth Bolton, Argonne National Laboratory
Dr. Molly Finster, Argonne National Laboratory

Dr. Matthew Helmers, Iowa State University
Dr. Robert Hirsch, United States Geological Survey Emeritus
Dr. Claire Hruby, Drake University
Dr. Thomas Isenhart, Iowa State University
Mr. Dana Kolpin, United States Geological Survey
Dr. Peter Levi, The Nature Conservancy
Dr. Keith Schilling, Iowa Geological Survey, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Jerald Schnoor, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Mary Skopec, CISWRA Science Co-lead, Iowa Lakeside Laboratory, University of Iowa
Dr. Martin St. Clair, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Larry Weber, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Michael Weber, Iowa State University Mr. Calvin Wolter, Iowa Geological Survey, IIHR—Hydroscience & Engineering, University of Iowa

Request for On-going Public Participation

Finally, the League respectfully requests that the current comment period not be the only opportunity for the public to have input into the new amendments to the feedlot rules before the draft rules are published. We request that the MPCA hold regular update forums around the state to provide transparency into the direction the agency is going and to what extent any of the public's comments (including those of the League) are being taken into account by the agency.

The League thanks the MPCA for providing this opportunity to submit comments on the agency's plan to revise the state's feedlot rules. We look forward to working closely with the MPCA throughout this rule-making process and beyond.

Lucas Sjostrom Attachment RECEIVED
By: OAH on 7/22/2025

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July 22, 2025

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Minnesota Pollution Control Agency
520 Lafayette Road North
St. Paul, MN 55155
addison.otto@state.mn.us

RE: Comments on Planned Amendments to Animal Feedlot Rules – Minn. R. ch. 7020 (Revisor's ID R-04928)

Dear Ms. Otto and MPCA Feedlot Rulemaking Team,

Thank you for the opportunity to comment at this *early* and important stage in MPCA's review of Minnesota's animal feedlot rules. Minnesota Milk Producers Association represents dairy farm families of every size in every region of the state. Our members care deeply about water quality, soil health, community vitality, animal care, and the future of the next generation that hopes to farm here.

We appreciate MPCA's stated intent to modernize the rules to reflect 25 years of change in data systems, farm management, climate variability, and environmental expectations. We fully share the goal of protecting water resources and preventing fish kills. At the same time, we must be direct: **if this rulemaking proceeds primarily as a "stick" that layers expensive NPDES-style mandates onto smaller farms, it will accelerate farm loss without delivering proportionate environmental benefit.**

Minnesota's NPDES requirements are already viewed as a major regulatory and financial hurdle; many producers stay below 999 animal units *solely* to avoid those costs and risks, throttling natural business efficiencies and delaying environmental technology investments that scale with herd size.

Minnesota needs a rule framework that (1) protects water, (2) works in *all* landscapes, and (3) is economically, logistically, and technologically feasible for the smallest regulated farm — we suggest using a *10-animal-unit feasibility screen* for any new statewide provision. Larger farms already can and do go further through permits, market programs, and voluntary cost-share; but baseline rule text must not presume the capital, labor, engineering, or land base of a 1,000+ AU facility. That presumption is what drives the avoidance behavior we documented in prior comments.

The easiest way to define the rules may simply be to add a multiple to the thresholds for current rules at the NPDES/SDS level and various 7020 levels – as economies of scale have changed agricultural feedlots, permitting could save time, money and provide ecological benefit by simply ensuring we scale-up the size of operations in a manner that keeps them equivalent to what was begun in the year 2000.

We also urge MPCA to **build more "carrots" into the system**. Natural incentives will lower cost and improve compliance faster than using a punitive approach.
Recognize the dramatic progress in farm-level technologies since the late 1990s "feedlot war" era: dragline/direct-injection systems; GPS-guided variable-rate nutrient application; digital recordkeeping; remote soil, moisture, and weather sensors; and satellite imagery that helps time applications and verify residue cover. These tools deliver more nutrient where the crop needs it and keep more out of surface and ground water — yet current permit structures rarely credit those advances.

Finally, instead of having agency staff review permits individually, leveraging these effective conservation practices—either on their own or in combination with enrollment in the Minnesota Ag Water Quality Certification Program—can free up staff to concentrate on areas that need the most improvement.

Executive Summary of Key Concerns for Minnesota Dairies

Below are cost and feasibility flashpoints we ask MPCA to *exclude from mandatory rule text* or to implement only as **voluntary, incentivized best practices**:

- **Impervious pads for calf hutches** (capital outlay, grading/drainage, runoff collection) would be financially devastating to most sub-1,000 AU family dairies; siting is often fixed and difficult to retrofit — a regulatory risk we've flagged when future rules change after facilities are built. The economic benefit is minimal, and the requirement for 1,000+ AU dairies today is questionable.
- **Universal cover-crop requirements** ignore climatic windows, manure timing conflicts, and low establishment success documented in Minnesota research and farmer surveys; mandatory use could eliminate many transferee acres from accepting manure.
- **Mandated long-duration manure storage** (e.g., 9 months) for smaller feedlots would force massive capital expenditures, more engineered structures, and labor/custom pumping constraints that smaller dairies cannot meet. Surveyed producers already struggle to schedule applicators under current seasonal limits.
- **Expanded recordkeeping & transferee tracking** will deter non-livestock neighbors from taking nutrient-rich manure, pushing acres toward synthetic fertilizer and devaluing manure — the opposite of shared environmental goals. Discouraging manure use ultimately encourages the import of additional nutrients into Minnesota.
- **Weather-calendar rigidities (e.g., "vulnerable groundwater area" blackout periods)** fail to match real agronomic conditions across Minnesota's diverse microclimates and produce

costly storage, labor, and fertilizer work-arounds. The current NPDES rules eliminated daily hauling in Minnesota. Expanding this further to smaller animal unit feedlots would be devastating, impractical and only minimally environmentally beneficial in some areas of the state.

- **Expanded field inspection mandates** raise costs, biosecurity risk, and practical scheduling burdens; producers are already concerned there aren't enough inspectors, and we should use the technology incorporated over the past 25 years to replace the time and manpower spent in inspections.

Minnesota Milk Responses to MPCA's Nine RFC Questions

Q1. Which parts of current Minn. R. ch. 7020 are no longer applicable or needed?

Response: Remove or streamline provisions that presuppose large engineered systems for all facilities; clarify that site design elements built to prior code remain grandfathered unless a demonstrated discharge risk exists. Farms invest heavily in fixed infrastructure (feed centers, calf facilities) that cannot be economically re-sited each time rules shift — a "regulatory risk" that suppresses investment and herd growth. As dairies modernize, they build manure systems to last 40+ years. We will see advancement in this technology through voluntary adoption and lower public and private cost where it is needed without any new rules. Meanwhile, MPCA should look outside the Minn. R. ch. 7020 for cost-share opportunities for dairy farms – funding through the Minnesota Department of Agriculture, Board of Water and Soil Resources and Department of Natural Resources, along with federal programs, should be sending a singular message to farmers as to what the state agencies prefer in regulation.

Eliminate duplicative paperwork that replicates NPDES reporting for small or non-NPDES sites; excessive administrative overhead devalues manure exchanges and discourages participation by neighboring crop farms.

Q2. What specific rule changes (permit applicability, discharge standards, siting, storage standards, land application) would better prevent nitrate contamination & fish kills? Consider bullets in RFC.
Targeted, risk-based updates we *support*, if implemented flexibly and affordably:

1. **Acres are the single greatest limitation to compliance, and not taken into much consideration.** Rather than treating feedlots as riskier based on animal unit size, their contracted acres for manure application and yield potential (as an indicator of nutrient uptake) should be the main risk factor. Farms with a good animal unit to acreage ratio should be the lowest risk, and need the least additional work from MPCA to ensure a limited environmental risk.

2. **Outcome-based land application tied to soil temperature, crop uptake stage, and risk modeling — not fixed calendar dates.** Minnesota's diverse climates mean "average" weather station dates don't align with field reality; rigid seasonal bans trigger costly storage and increased spill risk while missing good application windows. When we draw county, regional or size lines, inevitably we leave some farms behind. Allow farmers always to find alternative ways to meet the spirit of the requirements without rigid rules. For example, if they've used an environmental planner or TSP to help create their manure management plan, could that overcome new requirements (in addition, consider MAWQCP as an incentive to replace inspection time)?
3. **Recognize & credit direct-injection / dragline systems** (including low-disturbance incorporation) with extended application windows and reduced setback needs where injection depth and soil conditions protect water. These technologies improve nutrient recovery, reduce odor, and lessen surface runoff potential — a clear environmental upgrade that current permits fail to credit. MPCA has never acknowledged the role of this significant change in the past 25 years, whereas numerous soil health specialists will agree that it is better than what we were doing 25 years ago.
4. **Allow nitrogen stabilizers, split applications, and temperature triggers (<50°F soils) as BMP alternatives** in sensitive areas instead of blanket prohibitions. Producers need these tools to match manure N availability to crop demand without building unaffordable extra storage.
5. **Do *not* mandate cover crops statewide as a nitrate control surrogate.** Research and producer data confirm inconsistent establishment, tight fall planting windows, manure integration conflicts, and likely loss of transferee acres if required.
6. **If MPCA considers increased setbacks or soil testing triggers, scale them by hydrologic risk.** Many transferee acres will simply withdraw rather than absorb compliance costs, pushing more manure onto fewer fields or into commercial fertilizer substitution.

Q3. Should NPDES/SDS permit requirements (e.g., enhanced planning, visual inspections, fall BMPs, frozen-ground restrictions, wet-weather BMPs) extend below 1,000 AU?
No. For the scale of the dairies we are talking about we don't believe these changes are practical nor reflect the environmental risk with the practices voluntarily adopted since 1999.

Q4. How should MPCA address long-used existing manure storage areas for structural integrity?
Use a **risk-screen matrix**: age, design, proximity to water, liner type, documented leakage, and storage *duration actually used*. But moreover, this is the only area where we believe a regional

focus makes sense. Find the highest-risk areas of the state and start there to help farmers find cost-share or other opportunities for improvement.

Many smaller dairies rely on short-term stacks, daily haul, or seasonal reception pits; forcing full engineering assessments on low-volume, short-duration storages will divert scarce capital from higher water-quality returns. Where rule changes create retrofit triggers, grandfather compliant legacy systems built under prior code; unpredictable retrofit mandates exacerbate the regulatory risk we've highlighted.

Q5. Should smaller sites be required to have 9 months storage (current ≥1,000 AU standard)? If so, at what AU?

We **strongly oppose** a uniform 9-month storage mandate below 1,000 AU. Seasonal climates, cash-flow limits, land base access, and custom pumping capacity already strain application windows; additional storage would require large capital builds and create cascading scheduling conflicts across regions. Producers report they would need *additional storage*, *new cover crops*, and *more custom applicator availability* if seasonal restrictions tighten — signals that a 9-month rule is economically unrealistic.

Instead, allow a **menu**: daily haul, short-term stacking with weather contingency plans, shared/co-op storages, or incremental expansion supported by cost-share. Tie longer required storage only to documented high-risk hydrogeology plus available funding. Education on manure and nutrient value will provide far greater return to the state and dairy farmers than forcing additional storage – which will put smaller farms out of business.

Q6. WRAPS show nutrient/bacteria issues tied to livestock access to streams. How should rules address this?

First, educate: Help farmers and farm organizations understand which areas of the state have the highest risk and current "issues".

Encourage site-specific exclusion + managed access systems (fencing with stabilized crossings or limited watering points) rather than categorical bans that ignore topography, herd size, or season. Provide cost-share and credit participation in MAWQCP and similar conservation certifications to satisfy rule intent. Many dairies already implement rapid incorporation and manure transfer strategies to minimize runoff risk; do not couple stream access fixes with broad unrelated mandates (e.g., universal cover crops) that will sour participation. Producer feedback indicates that when compliance burdens rise too high, neighbors exit manure agreements, reducing the very land base that buffers nutrient loading.

Q7. How to address multiple feedlots under same ownership in close proximity (aggregation / separation distances)?

Allow farmers to be flexible. MPCA has changed, revised, and then revised again these rules in effort to find a best path forward. In the end, each situation is different. Two unrelated feedlots

across the road from each other can be seen as separate, where as the “mileage test” might pull two feedlots that are very related but use totally separate manure systems into one permit. This causes problems triggering NPDES and unplanned requirements.

Moreover, the current size limits of today cause more issues than they solve, and we’d suggest looking more at animal units over acreage x yield potential versus animal units alone. MPCA does not regulate feedlots so much as they regulate where and how the manure from feedlots is applied. Stay consistent in this and create more measures on ratios of animals to land rather than animal units.

Use a functional-system test rather than a pure distance rule: Are manure systems integrated? Are animals managed as a single herd? Is storage shared? A rigid distance threshold will incentivize paperwork games and discourage reasonable expansions. Because many farms stayed just under 999 AU to avoid permit burdens, overly broad aggregation triggers could retroactively force NPDES complexity onto modest, dispersed sites.

Q8. Minnesota law directs agencies to avoid overly prescriptive rules and to allow maximum flexibility while achieving environmental goals (Minn. Stat. §14.002). How to balance flexibility with nitrate & fish-kill concerns?
Adopt a **performance + incentives framework**:

- Offer a **scaled SDS bridge** and **fee waivers for compliant operators** (e.g., MAWQCP certified; multi-year good compliance record). Incentives to increase participation and data quality, and some sort of protection similar to the litigation protection provided by NPDES permits would allow this.
- Credit **advanced technologies** (direct injection, GPS-logged application, stabilizers, digital records) with extended windows/setback flex, delivering equal or better environmental outcomes at lower cost.
- Provide **BMP “menus”** producers can choose from based on soils, crop rotations, and weather rather than one-size mandates (e.g., cover crop *or* multi-year perennial *or* delayed fall application). Producer data show that multi-year crops can substitute for cover crop nitrate control where seasonal windows fail.

Flexibility is necessary because calendar cutoffs derived from limited weather stations don’t reflect actual field conditions statewide.

Q9. Other comments on existing rules or proposal.

- **Do not expand field inspection mandates** that add cost, delay, and biosecurity risk; focus inspection resources on complaint-driven or high-risk events. Producers report insufficient inspector timeliness and disease-transfer concerns when multiple sites are visited in a day – technology can replace or enhance these inspections.

- **Recognize labor scarcity** in rural areas; additional paperwork, seasonal bottlenecks, and infrastructure builds will divert labor from animal care and environmental practices that deliver real results.
- **Economic ripple effects:** When rules drive up compliance costs, counties often face unfunded mandates and declining tax bases as farms exit or shrink; please include fiscal notes that reflect these community impacts.
- **Market alignment:** Many processors and downstream brands are now investing in carbon intensity (CI) scoring, data platforms, and sustainability premiums. Rules that devalue manure or discourage data participation (by overburdening transferee acres) undercut those market opportunities. Producers already worry that heavier data / recordkeeping loads will push neighbors to synthetic fertilizer, severing nutrient recycling loops.
- **Commercial applicator capacity is limited;** tightening fall windows will overwhelm available services and strand manure in storages, increasing overflow risk. Survey respondents in our NPDES survey work flagged this capacity gap if new seasonal restrictions take effect.
- **Truly exempt pasture, as required by law.** There have been several instances of pasture-based dairies being turned into “feedlots” and being pulled into the program. The MPCA should work to exempt all pasture areas, even with a feedlot attached, and focus only on the feedlot areas. If an animal is on pasture, that means the growing nutrients do well to eliminate risk in that acreage. If the ground is bare or it is impervious surface, it makes sense to regulate within the feedlot program.

  One easy qualification to this pasture rule, to help save time and confusion, is any USDA Certified Organic facility. Those facilities should be exempt from the rule altogether in the areas that are growing vegetation where animals graze. This eliminates confusion and dedicates resources to higher risk areas.

Recommended Guiding Principles for MPCA Rule Drafting

1. Statewide Environmental Goals, Local Agronomic Flexibility
Environmental processes cross township and county boundaries; baseline rules should apply statewide. Yet the *pathways* to reach those goals must flex with soils, crop rotations, and climate bands. Avoid region-only mandates that stigmatize certain areas and fragment compliance — a concern we’ve heard repeatedly from producers and neighbors.
2. 10-AU Feasibility Screen
Before codifying any new requirement, ask: *Could a 10-AU farm comply with minimal capital and record burden?* If not, move it to guidance, BMP menu, cost-shared tier, or permit condition rather

than baseline rule. The regulatory risk of retrofits to fixed facilities (e.g., calf housing pads) is real and expensive.

3. Incentives Over Penalties

Rebuild the SDS tier (300-999 AU) as a voluntary incentive-rich, lower-burden bridge that encourages data sharing and BMP adoption without the full NPDES cost profile.

4. Credit Proven Technologies

Direct-injection/dragline systems, GPS logging, stabilizers, rapid incorporation, and digital manure transfer tools all reduce environmental risk and should earn compliance flexibility.

5. Keep Transferee Acres in the System

Simplify downstream recordkeeping; otherwise, transferee fields will default to commercial fertilizer and the nutrient recycling loop will collapse.

6. Science-Based Alternatives to Blanket Cover Crop Mandates

Given documented establishment limits and survey data, allow perennial crops or other N-mitigation practices to substitute for cover crops in rule compliance matrices.

7. Practical Inspection & Biosecurity Protocols

Target inspections where risk warrants; producers fear inadequate inspector timeliness and pathogen transfer.

Voluntary Practices Widely Adopted Since 1999 (Support & Build Upon)

Minnesota dairy farms — large and small — have steadily adopted advanced nutrient stewardship practices without blanket mandates. These include:

- Site-specific Nutrient Management Plans (NMPs) tied to soil and yield goals.
- Manure injection / low-disturbance incorporation and dragline delivery systems that reduce surface loss.
- Routine manure nutrient testing; increasing use of mobile labs and rapid analysis to match crop needs.
- GPS-enabled variable-rate placement and auto-logged application records.
- Solid-liquid separation and composting that stabilize nutrients and reduce hauling burdens.
- Covered / lined storages (where feasible and funded) that improve runoff control.
- Adoption of multi-year perennials (alfalfa) as functional nutrient capture where cover crops are impractical.

These farmer-led improvements demonstrate why incentive-based approaches work — and why punitive, one-size mandates risk reversing progress.

Appendix A – Cost & Feasibility Screen for Potential Rule Elements (<1,000 AU Focus)

Impervious Calf Hutch Pads: High capital retrofit; limited environmental return when managed solids are scraped to fields per NMP; retrofit challenge documented where facility siting cannot be easily changed after construction.
Cover Crop Mandates: Low establishment success; conflicts with manure timing; risk of losing transferee acres.
Extended Storage (9 mo.): Drives need for new pits; survey respondents anticipate needing added storage and commercial applicator scheduling; significant capital outlay.
Expanded Transferee Records: Likely to push recipients to synthetic fertilizer; undermines recycling loop.
Seasonal Blackouts / Vulnerable Area Limits: Poor alignment with real weather; increases storage/labor costs; relies on incomplete statewide averages.
Expanded Field Inspection Windows: Producer concerns about inspector availability and biosecurity.

Appendix B – Incentive & Equivalency Concepts

- **Voluntary SDS Bridge Permit (300-999 AU)** with reduced fees and phased reporting to encourage voluntary enrollment and data sharing.
- **Fee Waivers / Reduced Administrative Burden** for certified MAWQCP farms or multi-year clean compliance records to keep manure moving to transferee acres.
- **Technology Credits:** Extended windows or reduced setbacks for documented direct injection, GPS-logged application, or rapid incorporation.
- **BMP Menu Substitutions:** Allow perennial stands in lieu of cover crops where agronomically justified.

Closing

Minnesota's dairy farmers want practical, science-based regulation that protects water and allows farms to thrive. The advances in nutrient management technology over the past quarter century — and the voluntary adoption we've achieved together — prove that **collaborative, incentive-driven pathways deliver results**. We stand ready to work with MPCA, sister agencies, counties, and community partners to co-design rules that achieve environmental goals *and* keep family dairy farms viable across Minnesota.
Please contact me with any questions or to schedule further discussion.
Respectfully,



Lucas Sjostrom
Minnesota Milk Executive Director
320-429-4838
Lucas@MNMilk.org

Matt Doll Attachment RECEIVED
By: OAH on 7/22/2025

Minnesota Environmental Partnership

318 Landmark Center
75 West Fifth Street
Saint Paul, MN 55102
www.MEPartnership.org
(651) 290–0154

July 22, 2025

Minnesota Environmental Partnership (MEP) thanks the Minnesota Pollution Control Agency for working to update the state's Animal Feedlots Rule. Our scientific understanding of the impacts of these feedlots has advanced significantly in the 25 years since the rule was last revised, as has the scale of challenges to our clean water and climate. With both surface waters and groundwater increasingly impaired and our climate warming, Minnesota should use this opportunity to better steward our natural resources with improved feedlot standards.

MEP and our member organizations support the following updates to the rule to protect water quality and human and ecological health:

- Implement stricter limits on manure application to farm fields in areas where groundwater is especially vulnerable. These areas, including the karst region in the southeast, are struggling with the impacts of nutrient pollution linked to cancer, birth defects, and other conditions.

- Lower the number of annual units at which National Pollution Elimination System (NPDES) and State Disposal System (SDS) are required to 600 animal units. Currently, many feedlots skirt greater regulation by operating just under the permitting limit; lowering the threshold will enable more waters to be more adequately protected.

- Require feedlots with NPDES and SDS permits to closely monitor their manure discharges to protect nearby groundwater and streams. Permit conditions are only effective if enforced and can only be enforced with accurate information on discharges.

- Change how multiple small feedlots with the same owner are regulated. Currently, an owner of multiple feedlots, even feedlots right next to each other, can skirt stronger regulations by keeping them as "separate" operations, though the total impact is the same as a large feedlot. Minnesota's environment isn't protected by creative accounting measures, only by science-based standards.

- Require more rigorous reporting on manure transfers.

- Make more manure managing data and mapping available to the public, including information about digesters and manure spreading plans. Communities near feedlots deserve the opportunity to understand the impacts that manure uses may have on their nearby environment.

We appreciate the opportunity to share our views - and the priorities of our member groups and the thousands of Minnesotans they represent - during this comment opportunity. MEP will remain engaged on this important rulemaking process as it moves forward. We urge the MPCA to prioritize the health of Minnesotans, our waters, and our climate in the development of this rule.

Sincerely,

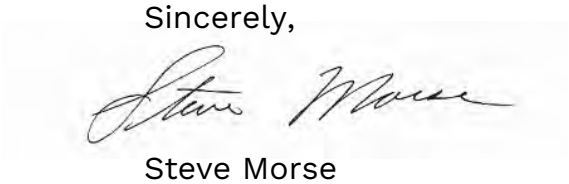

Steve Morse
Executive Director

Submitted with the support of the organizations listed below:

Alliance for Sustainability

Austin Coalition for Environmental Sustainability

Clean River Partners

Clean Water Action Minnesota

Climate Land Leaders

Environmental Working Group

Friends of Minnesota Scientific and Natural Areas

Institute for Agriculture and Trade Policy

Izaak Walton League Minnesota Division

Lakeville Friends of the Environment*

Land Stewardship Project

League of Women Voters Minnesota

League of Women Voters Upper Mississippi River Region*

Pollinator Friendly Alliance

Renewing the Countryside

Saint Paul Bird Alliance

Save Lake Superior Association

Save Our Sky Blue Waters

**denotes non-MEP member*

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By: OAH on 7/22/2025

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Bryan Winget <imagemakersphoto@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

Now it's the time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Asa Laker, fisherman, and parent I am concerned about manure runoff in Minnesota waters resulting in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Bryan Winget
2385 Buford Ave Saint Paul, MN 55108-1642
imagemakersphoto@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Angela Anderson <pulverfass1946@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
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Dear Rule Coordinator Addison Otto,

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Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. The manure from lagoons is not regular manure, it is a toxic nitrate brew laced with antibiotics and who knows what else the animals are treated with when they are held in close confinement.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. Angela Anderson
11214th St N Stillwater, MN 55082
pulverfass1946@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Betsy Blume <samannahara@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
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Dear Rule Coordinator Addison Otto,

Dear Minnesota Pollution Control Agency,

Thank you for all you do to protect one our most precious resources, water. Water connects all of us and this is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,

Betsy Blume

Sincerely,
Betsy Blume
PO Box 873 Grand Marais, MN 55604-0873
samannahara@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Mary Busch <Busch019@everyactioncustom.com>
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Dear Rule Coordinator Addison Otto,

Minnesota has water resources,a treasure to protect so it's critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure. As a public health trained professional I discern consequences of failure to regulate in people's health.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mary Busch
3030 45th Ave S Minneapolis, MN 55406-2320
Busch019@umn.edu

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Gwen Chynoweth <therestlesscrayon@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
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Dear Rule Coordinator Addison Otto,

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Sincerely,
Gwen Chynoweth
Prior Lake MN

Sincerely,
Ms. Gwen Chynoweth
15367 Wilderness Ridge Rd NW Prior Lake, MN 55372-3610
therestlesscrayon@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Nancy Conger <NANCYCONGER@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

I dream of clean water to swim in. Of pure water coming out of my rural well. Of healthy lakes, rivers, and water bodies that support the life we all depend on.

It's not a pipedream -- it's possible if we CHOOSE IT. Now is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. Nancy Conger
8010 275Th Ve NE North Branch, MN 55056
NANCYCONGER@YAHOO.COM

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Sharon Coombs <sharon-coombs@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

I used to canoe the Cannon River. Since I learned what is in it (poop), I no longer do so. I also don't let my dog go into rivers or lakes anymore.

This is past time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots

based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Sharon Coombs
3400 Owasso St Shoreview, MN 55126-4132
sharon-coombs@hotmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Loni Coppin <lonicoppin@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

As someone who knows that clean water is necessary for the health of all life on Earth, and who cares about the quality of water in Minnesota, I am writing to express my concern about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

As someone has stated, "We are literally drinking and swimming in manure." Nitrates in manure runoff from Minnesota's 23,000 Concentrated Animal Feeding Operations (CAFOs), have even contributed to the Gulf of Mexico Dead Zone. Yet each year, these feedlots continue to get bigger, and the pollution becomes more concentrated.

In Minnesota, manure runoff waters result in fish kills. Swimming is unsafe due to E. coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning, which has likely
contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

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4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of

degradation in waters that are not polluted.

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MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Thank you for the opportunity to comment. I urge you to remember that water if life and to please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. Loni Coppin
1021 E 6th St Apt B Duluth, MN 55805-3825
lonicoppin@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Amy and Val Cordry <aacordry@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

Feedlot response
Amy and Val Cordry
26006 County Road 9
Winona, Mn 55987

Nitrates in manure runoff from Minnesota's 23,000 feedlots, also known as Concentrated Animal Feeding Operations (CAFOs), even contribute to the Gulf of Mexico Dead Zone. But each year, pollution becomes more concentrated and feedlots get bigger in Minnesota. Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health.
Nitrates in manure runoff from Minnesota's 23,000 feedlots, also known as Concentrated Animal Feeding Operations (CAFOs), even contribute to the Gulf of Mexico Dead Zone. But each year, pollution becomes more concentrated and feedlots get bigger in Minnesota. Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths. Row crop agriculture is the main source of nitrate in southeast Minnesota. A comprehensive study completed in 2013 of nitrogen sources in the Lower Mississippi River Watershed in Minnesota (the basin covering most of southeast Minnesota) estimates that 89% of the nitrogen loading to surface waters originates from cropland, with a substantial portion moving downward through groundwater to surface waters.
Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health.
Safe drinking water is essential for the health and well-being of all Minnesotans. In southeastern Minnesota, approximately 300,000 people rely on 93 community water systems that all rely on groundwater as their source and more than 93,000 rely on private wells.
GENERAL RECOMMENDATIONS:

More living roots on the ground for longer periods.
Support alternative crops and land use
Support and increase implementation of nitrogen Best Management Practices
Education and outreach
Focus on sustainability for future generations.
Lift up locally driven community collaboration.
Outreach, education, and building trust are important components of making systems change.
Speak with one voice on the importance of testing wells and protecting health.
Use the best available science and data.
Agree that we have enough information about the causes of nitrate contamination to act.
Recognize solutions require both taking responsibility and supporting those willing to take risks in the interest of change.
Recognize that investment is needed at multiple scales for farming systems and markets to change.
Structure programs to be simple to use – remove red tape.
Embrace flexibility rather than a one-size-fits-all approach.
Make sure affected groups are at the table.
Drilling wells into deeper aquifers will not solve nitrate contamination in southeast Minnesota.
Additional approaches are needed to address the nitrate issue in southeast Minnesota.

SPECIFIC RECOMMENDATIONS:
a. Replicate programs like the Olmsted County Groundwater Protection and Soil Health Program model to other counties throughout the region. The program should have these core principles: locally led, flexible, streamlined implementation, and outcome-based/tiered payments.
b. Support federal and state programs that enroll more acres in conservation

Sincerely,
Amy and Val Cordry
26006 County Road 9 Winona, MN 55987-5922
aacordry@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Donna Crider <dcrider@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

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3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

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MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. As our protections are being eroded at the federal level, please make this a priority. We only have one place to live. We are counting on you.

Sincerely,
Donna Crider
5640 County Road 12 Kettle River, MN 55757-8645
dcrider@frontiernet.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Scott Doblar <henryboldar@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

Ridgeway, a small community very near where i live in Winona Minnesota, has a community well. They had to drill a new one into another aquifer due to nitrates in the water. What happens if this aquifer becomes too high in nitrates? And why is this happening in the first place?? If we cant even have clean and pure drinkable water somethng is terribly wrong!!
Please stand up for clean drinking water for us, our children and grandchildren. That is YOUR job. Thank You.

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mr. Scott Doblar
712 E King St Winona, MN 55987-4527
henryboldar@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From sally downings <mfordbroth@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

We Minnesotans say we love our lakes and rivers but we have allowed them to be polluted terribly. This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
sally downings
622 8th St SE Minneapolis, MN 55414-1302
mfordbroth@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Russ Erickson <russee4@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

Feed lot pee & poop should be captured and processed just like human waste is. Build mini sewer and treatment. Or truck it to human waste treatment plants.
This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mr. Russ Erickson
3915 Grand Ave S Minneapolis, MN 55409-1534
russee4@msn.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Barbara Evan <barbarakevan@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

I am concerned about the runoff, seepage, and spills caused by animal feedlot manure

1. MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.

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Thank you for the opportunity to comment. Please protect the health of Minnesota’s waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,

Barbara Evan

Sincerely,
Barbara Evan
525 Burlington Rd Saint Paul, MN 55119-5315
barbarakevan@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Judy Gronquist Grant <judyggrant@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

It is essential that the animal feedlot rules be rewritten to stop toxic nitrate pollution in Minnesota's waters. I am very concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Clean water is essential and manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure results in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. And manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. Let that sink in. It poisons babies. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths. That is beyond intolerable.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. It is essential that the MPCA address these dangerous impacts by developing strong rules. Therefore, I am requesting that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

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7. MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year. Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Thank you for the opportunity to comment. I urge you to take strong measures to protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. I am counting on you, and the State of Minnesota needs strong action from you.

Sincerely,
Judy Gronquist Grant
3807 Garfield Ave Apt 5 Minneapolis, MN 55409-1135
judyggrant@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Seymour Gross <sygross494@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure. Please do the necessary changes now!

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

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3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you. It is urgent that you rewrite the feedlot rules. Thanks.

Sincerely,
Seymour Gross
1941 Drew Ave S Minneapolis, MN 55416-3617
sygross494@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Jaden Hansen <hansen1167@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

Please act now to keep our water clean. As an avid outdoor adventurer of MN waterways, I can tell you how this is showing up, and it's terrible. The waters are full of every danger they've outlined such as algae blooms coating river surfaces and shores. My doctor and my vet confirmed that my dogs and I have both gotten infections from being near polluted water too long—this is in state parks!!!

Right now, is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. There are so few checks and balances and this is one within reach in order to preserve water quality. I am gravely concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. Please, we ask that you make the following changes to the Animl Feedlot Rules:

1. MPCA rules must require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules must set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules must prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules must state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of

degradation in waters that are not polluted.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. Please, we are counting on you.

Sincerely,
Jaden Hansen
2141 Minneapolis Ave Minneapolis, MN 55406-4239
hansen1167@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Linda Herron <larkspurherron@everyactioncustom.com>
Date Mon 7/21/2025 2:32 PM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

I understand that Minnesota animal feedlot rules have not been updated for 25 years. In that time the number of animal feedlots has increased many fold. Now is a critical time to rewrite these rules and stop toxic nitrate pollution in Minnesota's waters. I am very concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. Linda Herron
2617 E 5th St Duluth, MN 55812-1536
larkspurherron@q.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Adrianne Johnson <adriannejohnsonster@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

Stop polluting our water. This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mrs. Adrianne Johnson
1172 Ivy Ave E Saint Paul, MN 55106-2049
adriannejohnsonster@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From John Kantar <jkantar@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

We must clean up our land and water. No water, no life!

Sincerely,
John Kantar
3426 Saint Paul Ave Minneapolis, MN 55416-4343
jkantar@comcast.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Ben Karlgaard <ben.karlgaard@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

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Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ben Karlgaard
1917 Greysolon Rd Duluth, MN 55812-2019
ben.karlgaard@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Dylan Koltz-Hale <dylan@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

I have been making personal choices to protect Minnesota water ways, one of them is refusing to purchase or consume meat. I do this for many reasons, but one is the protection of the environment from containments thats are a result of inhumane concentrated animal feedlots, particularly in water.

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Please consider our concerns with the same weight as you might industrialists and their legal representatives. Do the right thing!

Sincerely,
Mr. Dylan Koltz-Hale
1310 E 10th St Duluth, MN 55805-1510
dylan@mesabadigital.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Peter Leschak <paxleschak@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

As a natural resources professional I know this is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

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Sincerely,
Mr. Peter Leschak
PO Box 51 Side Lake, MN 55781-0051
paxleschak@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Pete McDonnell <petemcd@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

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7. Thank you for the opportunity to comment, and for all that you do. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you!

Sincerely,
Pete McDonnell
2407 Birchmont Dr NE Bemidji, MN 56601-2327
petemcd@paulbunyan.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Peder Otterson <ottersnorth@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

I thank you for the opportunity to provide comments on the MPCA proposed revisions to the Animal Feedlot Rules. I am submitting these comments through the personalized response provided by Water Legacy after repeated efforts to provide direct comments on your Website failed. Often, this effort ended in a "Website Time Out" message. This is no way to foster public comment. I'll begin with a bit of background information on myself. Much of this experience is based upon my work with MDNR. However, I wish to emphasize that in no way should my words be construed to mean that I speak for the MDNR; they are my own words based on my experiences.

I am a retired hydrogeologist with some 37 years of experience in the fields of limnology, hydrogeology and hydrology. I consider myself to be a field geologist; that is, most of my experience has been based on field observation. This work began in 1976 as a research scientist on the Regional Copper-Nickel Study. From there, I became the first DNR Area Hydrologist to represent NE Minnesota where I managed DNR's water permit program and assisted local governments in the development and management of their shoreland and floodplain management programs. Later, I helped lead in the development and management of the 1989 revision of the statewide shoreland management rules through a series of workshops across the state. Here is what I learned from Region V located in SE Minnesota that relates directly to the current issue.

As many know, SE Minnesota is part of the Driftless Area. That is, it was never covered by glaciers or glacial outwash. The native rock is composed largely of limestone where karsts and fractured limestone has led to sinkholes, but also the emergence of springs whose clear, cool water has resulted in many DNR designated trout streams.

Why is this important? Simply because improper placement or enlargement of feedlots can easily result in the pollution of these sensitive waters. It is of utmost concern in SE Minnesota, but also a concern anywhere feedlot runoff has the potential for polluting adjacent streams and wells. Therefore, I urge you to specifically address these issues in your proposed rules changes.

Sincerely,

Peder H. Otterson

Sincerely,

Mr. Peder Otterson
7113 Muirfield Ln Eden Prairie, MN 55346-3440
ottersnorth@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Mauren Pierson <maurenpierson@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

As a young person, the health and future of our waterways is very important to me. This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mauren Pierson
1815 E 7th St Duluth, MN 55812-1306
maurenpierson@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Roger A Powell <newf@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure. Although concern for water quality in and near the Boundary Waters is widespread in Minnesota and beyond, that is a concern to maintain high quality water. Feedlots and their pollution are in important PRESENT concern that must be handled. We must deal with agricultural runoff NOW to prevent increased environmental degradation across all of agricultural Minnesota.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

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3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots

based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Dr Roger A Powell
2428 Stebly Rd Ely, MN 55731
newf@ncsu.edu

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Thomas Probst <thomas777cl@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

Frankly, I am embarrassed. As a Minnesota citizen, I have seen the ongoing damage to our state's lands and waters, flora and fauna caused by manure spills and excess runoff from manure spread on farm fields.

Living in the land of 10,000 lakes, we should know better. Actually, we do know better.

It's time to take a stand.

As you work to rewrite the feedlot rules, please keep the destruction caused by runoff, seepage, and spills from animal feedlots foremost in your thoughts.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that “stricter” requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all

pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

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MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. The people of this state, nation and world are counting on you.

Sincerely,
Mr. Thomas Probst
9340 84th St N Stillwater, MN 55082-8308
thomas777cl@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Anne Reich <reichmn@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

It's past time to clean up Minnesota's waters so that we're not drinking and swimming in cow manure runoff and seepage. Do you think allowing such pollution is ok? Then please DO SOMETHING in your role with MPCA. It's past time to value people's health above corporate profit.

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming (hey, we're Minnesotans -- this is what we do, swim in our lakes and streams!) is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers (ugh), producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Anne Reich
751 Pine Cone Trl Marine On Saint Croix, MN 55047-9642
reichmn@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Doretta Reisenweber <dorierduluth@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

We must, YOU must rewrite animal feedlot rules to halt toxic nitrate pollution in Minnesota's waters. I worry about the future and the very present when I read about the serious problems of runoff, seepage, and spills caused by animal feedlot manure. Size doesn't matter. Manure in any amount pollutes.

Manure runoff in Minnesota waters results in fish kills, makes swimming unsafe due to E.coli bacteria, leads to blue-green algae blooms in shallow lakes and rivers where it produces toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. I thought that happened only in third world nations. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Currently, Minnesota animal feedlot rules fail to protect water, fish, wildlife or human health. I urge the MPCA to address the following dangerous impacts by developing strong rules and enforcing them. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution, the rules must be enforced,

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or

compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide does have adverse health effects, including respiratory and neurological harm.

Thank you for letting me share my concerns. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. Minnesota depends on you to protect our waters, our precious life-giving resource.

Sincerely,
Doretta Reisenweber
101 W Kent Rd Duluth, MN 55812-1152
dorierduluth@hotmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Rebecca Shedd <beckysmpls@everyactioncustom.com>
Date Mon 7/21/2025 10:13 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

We're going to continue getting stagnant weather yielding extensive rain. Now is the time to plan for it.

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

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based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

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MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Rebecca Shedd
4554 Wentworth Ave Minneapolis, MN 55419-4944
beckysmpls@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Michael Shoop <shoophoto@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

I am concerned about the serious problems caused by animal feedlot manure.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits for feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. I am counting on you.

Sincerely,
Mr. Michael Shoop
8200 W 33rd St Minneapolis, MN 55426-3884
shoophoto@aol.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Wesley Sisson <Sisso040@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

I am writing to urge the Minnesota Pollution Control Agency to rewrite and strengthen the state's animal feedlot rules to stop toxic nitrate pollution from concentrated animal feeding operations (CAFOs).

Current rules are failing to protect our water, wildlife, and public health. Nitrate and manure runoff from feedlots are directly responsible for:
- Mass fish kills,
- Toxic blue-green algae blooms,
- E. coli contamination that makes over 50% of southern Minnesota's lakes and rivers unsafe for swimming and recreation.

Nitrate pollution threatens rural Minnesotans who rely on private wells. It can make infant formula preparation dangerous, leading to blue baby syndrome which has contributed to at least 24 infant deaths over recent decades.

Minnesota's feedlot rules do not protect our water or health:
- No maximum size for feedlots;
- No permit required for medium-sized feedlots, which produce 43% of manure;
- No prohibitions in sensitive karst regions;
- No monitoring of manure storage or runoff from application fields;
- No enforceable nitrate limits to protect surface waters;
- No restrictions on antibiotics in feed, which harm aquatic life;
- No meaningful control of hydrogen sulfide emissions affecting nearby communities.

Even worse, our state's pollution contributes to the Gulf of Mexico dead zone.

I urge the MPCA to:
1. Set maximum feedlot sizes that will drastically reduce pollution;
2. Require permits for all feedlots, including medium-sized;
3. Prohibit CAFOs in karst areas;
4. Enforce nitrate limits for both groundwater and surface water;
5. Ban routine antibiotic use in livestock feed;
6. Require modern, lined manure storage systems;

7. Monitor storage facilities' and manure runoff from application fields;
8. Regulate hydrogen sulfide emissions.

Minnesotans deserve rules that prioritize clean water, healthy communities, and a livable environment. Please act accordingly.

Sincerely,
Mr. Wesley Sisson
21120 Shallow Lake Rd Warba, MN 55793-1634
Sisso040@d.umn.edu

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Thomas Sullivan <tsullivan79@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical moment to rewrite Minnesota's animal feedlot rules and put a stop to the toxic nitrate pollution threatening our waters. I'm deeply concerned about the serious damage being caused by manure runoff, seepage, and spills from feedlots.

In Minnesota, manure runoff leads to fish kills. E. coli from animal waste makes swimming dangerous. Excess nitrates from manure fuel toxic blue-green algae blooms in shallow lakes and rivers—harming wildlife and putting people at risk. When manure seeps into well water, it can contaminate the water used to prepare infant formula, leading to nitrate poisoning (methemoglobinemia or "blue baby syndrome"). Over the past few decades, nitrate-contaminated drinking water likely contributed to the deaths of 24 infants in Minnesota.

Right now, Minnesota's feedlot rules don't do enough to protect water, wildlife, or human health. I urge the MPCA to take meaningful action and adopt stronger rules. Specifically, I'm asking for the following changes:

Require pollution permits (NPDES/SDS) for medium-sized feedlots with 300–999 animal units—this group is responsible for 43% of all manure produced in Minnesota.

Set maximum limits on the size of individual feedlots and the total number of animal units allowed within any watershed or local area. These limits should be based on hydrology and the impact on ecosystems and public health.

Ban new or expanded feedlots in areas with karst geology, where groundwater is especially vulnerable. There's no evidence that existing "stricter" standards in these areas are actually preventing pollution.

Enforce "no discharge" requirements. Ensure all feedlots meet pollution limits, reduce contamination in already-impaired waters, and prevent degradation in clean ones.

Strengthen the minimum technology requirements for permitted feedlots. This includes modern liner systems and leak detection. Concrete or compacted soils shouldn't be assumed to prevent manure seepage.

Ban all winter application of manure, both wet and dry. Current rules don't account for increasingly unpredictable freeze-thaw and snowmelt patterns due to climate change, which increase the risk of runoff.

Require feedlots to comply with air quality rules at least 344 days per year. State law only allows 21 days of exemption annually, and that doesn't justify the health impacts of prolonged exposure to emissions like hydrogen sulfide, which is known to cause respiratory and neurological harm.

Thank you for the chance to comment. I'm asking you to act now to protect Minnesota's waters, wildlife, and communities from toxic nitrate pollution. We're counting on you.

Sincerely,
Thomas Sullivan
4061 209th Ln NW Anoka, MN 55303-8705
tsullivan79@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From MaryAnn VandeVusse <mavandevusse@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure. While all of the following points are valid and important to Minnesotans, imagine what it would be like to walk into a cloud of airborne manure being spread over a field. It happened to me while riding my bicycle on a country road. The ag worker did not stop spreading manure until I was past or moderate his path even though the wind had caught up the noxious fumes. We nedd more rules tom protect our youth in the future!

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

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2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. MaryAnn VandeVusse
13960 Kentucky Ave Savage, MN 55378-5648
mavandevusse@aol.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Rose Welch <rose@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

It is shocking that in MN, the land of 10,000 lakes the water in half of our state is too polluted to swim. That our state is willingly putting the health of all of it's residents in danger by permitting the feedlot runoffs is frightening. This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Rose Welch
6100 Cliff Estate Rd Little Marais, MN 55614-4238
rose@organicconsumers.org

RECEIVED
By: OAH on 7/22/2025

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Dawnette Davis <dawnettedavis@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mrs. Dawnette Davis
26767 Blue Heron Dr Grand Rapids, MN 55744-5624
dawnettedavis@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Norm Herron <larkspurherron@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr Norm Herron
2617 E 5th St Duluth, MN 55812-1536
larkspurherron@q.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Lawrence Landherr <ljl71504@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr Lawrence Landherr
2925 Lincoln Dr Roseville, MN 55113-1344
ljl71504@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Heyward Nash <hlnash2006@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Heyward Nash
1425 10th Ave S Minneapolis, MN 55404-1309
hlnash2006@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Jen Pearson <pearhoff@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Jen Pearson
4532 London Rd Duluth, MN 55804-2340
pearhoff@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Sven Sorge <othberlin@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr Sven Sorge
35 BARSTR Berlin, DE 10713
othberlin@web.de

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Tim Wallace <timjwallace@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Tim Wallace
8982 Norway Ridge Rd Forbes, MN 55738-8037
timjwallace@centurylink.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Michael Alexander <msalexander1955@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Michael Alexander
78 10th St E Saint Paul, MN 55101-2206
msalexander1955@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From H Ande <shredbetty70@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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H Ande
3310 69th St E South St Paul, MN 55076-2149
shredbetty70@gmail.com

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Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mr. Mark Anderson
2015 Gearhart St Duluth, MN 55811-5311
sierraorion1@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Steve Anthony <Tishkits@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Steve Anthony
2837 37TH Avs Minneapolis, MN 55406
Tishkits@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Sharon Bachman <Bachmansphotography@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mrs. Sharon Bachman
13000 Sylvan Ave Lindstrom, MN 55045-9414
Bachmansphotography@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Mary Beaudoin <beaudmj@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Mary Beaudoin
473 Howell St S Saint Paul, MN 55105-1711
beaudmj@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Pat Becchetti <patbecchetti@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Pat Becchetti
513 5th St S Stillwater, MN 55082-4921
patbecchetti@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Karen Bell-Brugger <bugglipps@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms Karen Bell-Brugger
5207 Humboldt Ave S Minneapolis, MN 55419-1121
bugglipps@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Richard Bjorum <bjohenry@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Richard Bjorum
2038 Town Road 492 International Falls, MN 56649-8707
bjohenry@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Larry Bogolub <lbogolub@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Larry Bogolub
2170 Passi Rd Ely, MN 55731-8135
lbogolub@comcast.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From A Bonvouloir <ra3ajw@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
A Bonvouloir
PO Box 70185 # 70185 Sunnyvale, CA 94086-0185
ra3ajw@sbcglobal.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Jenny Bramlette <bramlettejenny4@everyactioncustom.com>
Date Mon 7/21/2025 10:13 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Mrs. Jenny Bramlette
893 Broadway Ave Bridgeport, AL 35740-6247
bramlettejenny4@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Lyle Brandt <lylebrandt@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mr. Lyle Brandt
5820 Amy Ln Maple Plain, MN 55359-9303
lylebrandt@hotmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Ray Cage <raycg4@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr Ray Cage
2842 N Laurel Ave Tucson, AZ 85712-1611
raycg4@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Beth Carpenter <bzjz_55806@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Beth Carpenter
315 N Lake Ave Apt 224 Duluth, MN 55806-2731
bzjz_55806@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Gio Cerise <giocerise@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Gio Cerise
16421 Olivine St NW Ramsey, MN 55303-3612
giocerise@icloud.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From JL Charrier <jcharrier21@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
JL Charrier
1910 Heritage Dr Wayzata, MN 55391-9341
jcharrier21@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Thomas Childs <tomnkitty@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Thomas Childs
PO Box 213 Babbitt, MN 55706-0213
tomnkitty@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Laura Chinofsky <lzchin@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Laura Chinofsky
422 Wendy Rd Southampton, PA 18966-3521
lzchin@hotmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Jaci Christenson <jacichristenson@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Jaci Christenson
12309 Fiona Ave N White Bear Lake, MN 55110-1147
jacichristenson@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Nancy Claussen <nclauss1@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Nancy Claussen
2550 38th Ave NE Unit 410 Minneapolis, MN 55421-5039
nclauss1@frontiernet.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Emma Corbet <emmac.orbet17@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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From Jill Crawford-Nichols <jnadinen@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

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Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Jill Crawford-Nichols
1505 W Morgan St Duluth, MN 55811-4445
jnadinen@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Dave Crawford <naturalistdave@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Dave Crawford
1520 Lexington Pkwy N Saint Paul, MN 55117-3315
naturalistdave@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Dennis Cuchna <mncampy48@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Dennis Cuchna
2108 Irvine Pl Alexandria, MN 56308-8595
mncampy48@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Melinda Cummins <Melinda.Irons@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mrs. Melinda Cummins
4023 Cooke St Duluth, MN 55804-1943
Melinda.Irons@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Catherine Dahir <cfd5310@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms Catherine Dahir
47211 Government Rd Hinckley, MN 55037-7397
cfd5310@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Carl Dawson <dawsoc1@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Carl Dawson
40 Judith Dr Chaska, MN 55318-1256
dawsoc1@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Patricia DeLuca <rickscustompainting@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Dr. Patricia DeLuca
45 Inlets Blvd Fl 34275 Nokomis, FL 34275-4109
rickscustompainting@comcast.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Cecilia Dingledy <ceceding56@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Cecilia Dingledy
3443 Jasper Ct NE Rochester, MN 55906-5436
ceceding56@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Mairi Doerr <doerrmairi@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mairi Doerr
29555 23Rd Avenue Way Cannon Falls, MN 55009-7011
doerrmairi@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Kay Drache <kdrache@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Ms. Kay Drache
3067 Zarthan Ave S Saint Louis Park, MN 55416-2025
kdrache@comcast.net

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MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Kathy Dunn <lilbitdunn@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. Kathy Dunn
8657 Maplebrook Pkwy N Brooklyn Park, MN 55445-1943
lilbitdunn@yahoo.com

Outlook

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From Alicia Edmunds <bnclynde@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Alicia Edmunds
1308 SW Summit Woods Dr Topeka, KS 66615-1440
bnclynde@gmail.com

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From Erin Enger <erin.enger@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Erin Enger
5941 Wisconsin Cir N Minneapolis, MN 55428-2758
erin.enger@allina.com

Outlook

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From Brandan Fiedler <blfiedler74@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Brandan Fiedler
100 Central Ave NE Apt 206 Chisholm, MN 55719-1847
blfiedler74@gmail.com

Outlook

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From Anne Franklin <labradoritesky@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Anne Franklin
9914 Penn Ave S Bloomington, MN 55431-2914
labradoritesky@gmail.com

Outlook

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From Johanna Fritzke <thefritzkes@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mrs. Johanna Fritzke
5385 Stacy Trl Trlr 324 Stacy, MN 55079-9485
thefritzkes@aol.com

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From Joyce Frohn <jeffrohn@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Ms. Joyce Frohn
425 Congress Ave Oshkosh, WI 54901-2967
jeffrohn@gmail.com

Outlook

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From Josh G <mxrider_7@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Josh G
5222 Grand Forks, ND 58201
mxrider_7@hotmail.com

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From Mae Gackstetter <maegackstetter@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Mae Gackstetter
2955 Devonshire St Duluth, MN 55806-1401
maegackstetter@gmail.com

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From Annah Gardner <annahgardner@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Annah Gardner
1906 1st Ave S Minneapolis, MN 55403-3715
annahgardner@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Nancy Giguere <giguerenj01@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Nancy Giguere
209 1st Ave E Grand Marais, MN 55604-3139
giguerenj01@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Leanna Goose <leannagoose7@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Leanna Goose
9983 Battle Point Dr NW Federal Dam, MN 56641-6722
leannagoose7@gmail.com

Outlook

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From Roseanne Gough <rosieboogie@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Roseanne Gough
8 Amelia Opie Way Schenectady, NY 12345
rosieboogie@yahoo.co.uk

Outlook

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From Buff Grace <buff@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Buff Grace
722 Everett St S Stillwater, MN 55082-5937
buff@mnipl.org

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Amy Grace <amy3grace@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Amy Grace
722 Everett St S Stillwater, MN 55082-5937
amy3grace@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From David Greene <dgreene624@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. David Greene
806 Francis Ave Columbus, OH 43209-5412
dgreene624@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Solo Greene <solog@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Solo Greene
803 Lawyer St Lapwai, ID 83540-7749
solog@nezperce.org

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Ellen Hadley <ellene798@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ellen Hadley
1948 Parkmont Ln Anoka, MN 55303-1928
ellene798@msn.com

Outlook

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From Sue Halligan <tokyosue@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Ms. Sue Halligan
5350 Nolan Pkwy Oak Park Heights, MN 55082-5594
tokyosue@yahoo.com

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From Verlaine Halvorsen <verlaineh@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Ms. Verlaine Halvorsen
3510 The Mall Minnetonka, MN 55345-1241
verlaineh@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Lisa Hanes Goodlander <lisa.goodlander@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Dr. Lisa Hanes Goodlander
2323 Windsor Ln Saint Paul, MN 55125-1686
lisa.goodlander@comcast.net

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From Sandra Hartmann <sdhartmann@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Sandra Hartmann
4515 Lyndale Ave S Minneapolis, MN 55419-4823
sdhartmann@msn.com

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From Noah Haydon <noahhaydon@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr Noah Haydon
405 91st St Daly City, CA 94015-1963
noahhaydon@gmail.com

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Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Mr. Jon Hayenga
421 2nd St NW Stewartville, MN 55976-1135
jdhayenga@gmail.com

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From Susan Heath <forbux@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Susan Heath
2552 Mount Vernon St SE Albany, OR 97322-8898
forbux@hotmail.com

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From Drew Hempel <voidisyinyang@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Drew Hempel
18003 Saint Croix Trl N Marine On Saint Croix, MN 55047-9523
voidisyinyang@gmail.com

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From Norm Herron <larkspurherron@everyactioncustom.com>
Date Mon 7/21/2025 3:35 PM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Mr Norm Herron
2617 E 5th St Duluth, MN 55812-1536
larkspurherron@q.com

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From Joshua Howe <joshua@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
mr Joshua Howe
2202 Parklands Ln Minneapolis, MN 55416-3806
joshua@optimisticpartners.com

Outlook

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From patricia huberty <patsyhuberty@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
patricia huberty
1774 Trail Rd Mendota Heights, MN 55118-3730
patsyhuberty@gmail.com

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From Dianne Hudson <dianne.hudson01@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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114 N 8th Ave E Ely, MN 55731-1657
dianne.hudson01@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Joan Hughes <joanhughes03@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

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4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. Joan Hughes
4088 Utica Ave S Minneapolis, MN 55416-2905
joanhughes03@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Julie Hukriede <jhukriede@everyactioncustom.com>
Date Mon 7/21/2025 2:39 PM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mrs. Julie Hukriede
1785 Stewart River Rd Two Harbors, MN 55616-5064
jhukriede@granitegear.com

Outlook

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From jason husby <jcobainfan@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
jason husby
3531 N 3rd St Minneapolis, MN 55412-2651
jcobainfan@aol.com

Outlook

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From Kathleen Iverson <kciverson26@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Kathleen Iverson
2641 Jersey Ave S Minneapolis, MN 55426-3301
kciverson26@gmail.com

Outlook

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From Bob Jalonen <bobjalonen@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Bob Jalonen
918 E Washington St Ely, MN 55731-1672
bobjalonen@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Jan Jensen <jensen149@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Jan Jensen
10045 Russell Ave N Brooklyn Park, MN 55444-1050
jensen149@aol.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From arielle johnson <johnsas2012@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
arielle johnson
3348 34th Ave S Minneapolis, MN 55406-2110
johnsas2012@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Bruce Johnson <johnsonbruce169@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Bruce Johnson
6763 253rd Ave NE Stacy, MN 55079-3142
johnsonbruce169@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Betty Karpen <loonscats2@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Betty Karpen
6114 Birch Cliff Rd Silver Bay, MN 55614-4232
loonscats2@gmail.com

Outlook

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From Lauren Kofsky <keshet1963@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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9701 Sandra Ln Hopkins, MN 55305-4632
keshet1963@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Raleigh Koritz <tabbykat7285@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. Raleigh Koritz
4505 Nathan Ln N Minneapolis, MN 55442-3153
tabbykat7285@outlook.com

Outlook

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From Linda Kriel <linda.e.k@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Linda Kriel
1314 3rd Ave Newport, MN 55055-1141
linda.e.k@hotmail.com

Outlook

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From Susan Lasoff <susanlasoff@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Susan Lasoff
1235 Yale Pl Minneapolis, MN 55403-1949
susanlasoff@comcast.net

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From Sharon Lehrman <sharonlehrman@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Sharon Lehrman
2610 Vernon Ave S St Louis Park, MN 55416-1708
sharonlehrman@gmail.com

Outlook

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From Brad Lehrman <brad.lehrman@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Brad Lehrman
14805 Minnehaha Pl Wayzata, MN 55391-2525
brad.lehrman@gmail.com

Outlook

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From Doris Malkmus <doris.malkmus@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Dr. Doris Malkmus
1122 W 5th St Duluth, MN 55806-2335
doris.malkmus@gmail.com

Outlook

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From Pamela Martin <pzambert@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mrs. Pamela Martin
767 Orchard Ave Saint Paul, MN 55103-1450
pzambert@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Terry McCarthy <jtmjourneys@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Terry McCarthy
127 E Calvary Rd Duluth, MN 55803-1508
jtmjourneys@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Nettie Monroe <njmcraftqueen@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Nettie Monroe
174 Galtier Pl Shoreview, MN 55126-2163
njmcraftqueen@gmail.com

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From Michael Motta <msumichael1967@everyactioncustom.com>
Date Mon 7/21/2025 10:19 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Michael Motta
100 Vanderveen Ave Holland, MI 49424-2114
msumichael1967@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Mitchell Multer <mitchmulter@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mr. Mitchell Multer
1037 Davern St Saint Paul, MN 55116-2477
mitchmulter@comcast.net

Outlook

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---

From heyward nash <hlnash2006@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
heyward nash
1425 10th Ave S Minneapolis, MN 55404-1309
hlnash2006@yahoo.com

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From Robin Nicholson <rcrwnicholson@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms Robin Nicholson
4386 Cottage Park Rd White Bear Lk, MN 55110-3804
rcrwnicholson@yahoo.com

Outlook

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From Kimberly Nieman <thaliast.james@everyactioncustom.com>
Date Tue 7/22/2025 7:39 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Kimberly Nieman
4550 Orchid Cir Minneapolis, MN 55446-2137
thaliast.james@yahoo.com

Outlook

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From Randy Nies <randy.nies80@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Randy Nies
4525 Nicollet Ave Apt 4 Minneapolis, MN 55419-5009
randy.nies80@gmail.com

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From Alan Olander <aolander@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Dr. Alan Olander
27826 Howling Wolf Dr Nevis, MN 56467-1002
aolander@arvig.net

Outlook

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From Sophia Patane <sophiapatane01@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Sophia Patane
1610 Bluewater Ln Saint Paul, MN 55129-6220
sophiapatane01@gmail.com

Outlook

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From Lynda Pauling <lmp5812@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Lynda Pauling
5812 Olene Ave N Stillwater, MN 55082-6316
lmp5812@comcast.net

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From Karen Peters <kkpeters@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Karen Peters
3420 Cleveland St NE Minneapolis, MN 55418-1533
kkpeters@usfamily.net

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Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Jodi Peterson
9508 Russell Ave S Minneapolis, MN 55431-2434
jodipisyoda@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Craig Poorker <moosedoexist@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mr. Craig Poorker
11231 Balsam Pointe Trl Dayton, MN 55327-3101
moosedoexist@hotmail.com

Outlook

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From Karen Reichensperger <klmncic@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Dr. Karen Reichensperger
1199 Minnesota Blvd Ely, MN 55731-8021
klmncic@frontiernet.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Connie Ridge <connie@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Connie Ridge
10595 Bluebird St NW Minneapolis, MN 55433-6318
connie@connieridge.com

Outlook

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From Matt Ringquist <mattx20@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Matt Ringquist
300 S Minnesota St Apt 414 Redwood Falls, MN 56283-1565
mattx20@live.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Win Rockwell <win@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Win Rockwell
2733 Thomas Ave S Minneapolis, MN 55416-4346
win@winrockwell.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Aron Rolnitzky <aron.rolnitzky@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Aron Rolnitzky
3405 Chandler Rd Saint Paul, MN 55126-3915
aron.rolnitzky@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Riha Rothberg <riha_ha@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Riha Rothberg
303 E Oxford St Duluth, MN 55803-2327
riha_ha@icloud.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Paul Ryals <pcryals@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Paul Ryals
74 375th Ave NW Stanchfield, MN 55080-8917
pcryals@yahoo.com

Outlook

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From John Sadusky <johnsaduskyjr@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Mr John Sadusky
2108 E 43rd St Minneapolis, MN 55407-3050
johnsaduskyjr@gmail.com

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From Dennis Schaef <dshifdy@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Dennis Schaef
715 Limber Rd Meadville, PA 16335-8070
dshifdy@aol.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Bill Schnell <bschnel50@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Bill Schnell
701 SW 11th Ave Grand Rapids, MN 55744-3563
bschnel50@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Barb Schroeder <pschroeder54@everyactioncustom.com>
Date Mon 7/21/2025 10:13 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Barb Schroeder
2237 Forest Shores Rd Ogilvie, MN 56358-3927
pschroeder54@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Jennifer Scull <jenscull@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mrs. Jennifer Scull
319 South St Chardon, OH 44024-1322
jenscull@yahoo.com

Outlook

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From Caroline Sévilla <caronyna@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Caroline Sévilla
All Marc Chagall Schenectady, NY 12345
caronyna@msn.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Pat Shea <pshea2@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Pat Shea
5317 Blake Rd S Minneapolis, MN 55436-1129
pshea2@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Shailendra Singh <shailneelu@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Shailendra Singh
6150 Fernbrook Ln N Minneapolis, MN 55446-3742
shailneelu@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From DeeAnn Stenlund <deeannstenlund@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
DeeAnn Stenlund
2687 Matilda St Roseville, MN 55113-2416
deeannstenlund@hotmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

---

From Peggy Stern <263310@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Peggy Stern
6124 45th St N Oakdale, MN 55128-2305
263310@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Nan Stevenson <nanstevenson@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Nan Stevenson
172 Galtier Pl Saint Paul, MN 55126-2163
nanstevenson@yahoo.com

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From Kimberly Swenson-Zakula <jamie3040@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms. Kimberly Swenson-Zakula
2500 County Road 92 Minnetrista, MN 55359-9330
jamie3040@msn.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Diane Tessari <dctessa@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

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7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Ms. Diane Tessari
5375 Eureka Rd Excelsior, MN 55331-7963
dctessa@gmail.com

Outlook

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From William Thomas <W.Thomas.MN@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Dr. William Thomas
3415 Harriet Ave Minneapolis, MN 55408-4234
W.Thomas.MN@gmail.com

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From Barbara Thomborson <bt@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Barbara Thomborson
3133 Humboldt Ave S Minneapolis, MN 55408-2559
bt@bt.gen.nz

Outlook

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To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Paul Thompson
13823 County 18 Park Rapids, MN 56470-6153
pthompson2920@msn.com

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From Mary Vanhorn Harris <frankiegone2dogs@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Mrs. Mary Vanhorn Harris
901 Williams Ditch Rd Cantonment, FL 32533-8268
frankiegone2dogs@aol.com

Outlook

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From Peter Veits <pveits@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Mr. Peter Veits
14644 Hanover Ln Apple Valley, MN 55124-6370
pveits@hotmail.com

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Date Mon 7/21/2025 10:18 AM
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Sincerely,
Frank Verderame
20635 Manor Rd Excelsior, MN 55331-7202
fverdjr@yahoo.com

Outlook

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From Reggie Weber <reggie1722@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Ms Reggie Weber
21610 Fondant Ave N Forest Lake, MN 55025-9761
reggie1722@gmail.com

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Date Mon 7/21/2025 10:16 AM
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Ms. Alice West
315 1st Ave E Apt 11 Grand Marais, MN 55604-3109
alice.m.west@gmail.com

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To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Ron Wetzell
4837 E Upland Crst Columbia Heights, MN 55421-2028
ronalanwetzell@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Naomi Yaeger <naomi.yaeger@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Dear Rule Coordinator Addison Otto,

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Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

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Sincerely,
Ms. Naomi Yaeger
817 E Skyline Pkwy Duluth, MN 55805-1149
naomi.yaeger@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Lauren Young <loloyo@everyactioncustom.com>
Date Mon 7/21/2025 8:41 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Lauren Young
14507 183rd Ave NW Elk River, MN 55330-3218
loloyo@charter.net

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Gary Zarling <gzarling@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Mr. Gary Zarling
710 TAYLOR St NE Minneapolis, MN 55434
gzarling@yahoo.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

From Therese Zemlin <tzemlin411@everyactioncustom.com>
Date Mon 7/21/2025 10:18 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Therese Zemlin
1461 Kent St Saint Paul, MN 55117-3508
tzemlin411@gmail.com

Outlook

MPCA Animal Feedlot Rules - Comment Requesting Stronger Rules to Protect Minnesota Waters

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From Jenni Zickert <j_zickert@everyactioncustom.com>
Date Mon 7/21/2025 10:16 AM
To addison.otto@state.mn.us <addison.otto@state.mn.us>

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Sincerely,
Jenni Zickert
1715 Marshall St NE Minneapolis, MN 55413-1045
j_zickert@hotmail.com

RECEIVED
By: OAH on 7/22/2025
Lauren Servick Attachment

July 22, 2025

Minnesota Pork Producers Association Comments on Planned Amendments to Rules Governing Animal Feedlots – Minnesota Rules, Chapter 7020

Revisor's ID Number R-4928
OAH Docket No. 25-9003-40661

Thank you for the opportunity to provide input during the scoping period of the 7020 Feedlot Rule review. On behalf of Minnesota's more than 3,000 family pig farmers, the Minnesota Pork Producers Association (MPPA) submits these comments to support a rules framework that protects water quality, sustains rural economies, and enables science-based, practical compliance by farms of all sizes.

Pig farmers in Minnesota care deeply about being good neighbors, good stewards of the land, and responsible food producers. A revised 7020 Rule should reflect shared values: environmental protection, regulatory clarity, and the flexibility needed to innovate and improve.

Anchor the Rules in Science, Practicality, and Flexibility

Rule revisions must be grounded in sound science, agronomic practicality, and a recognition of on-farm diversity.

Minnesota's 7020 rules are already among the most comprehensive in the Midwest and exceed the requirements in many neighboring states. This includes more robust permitting for feedlots over 1,000 animal units (AU). Any changes should modernize standards—not add unnecessary burdens—and continue to allow farmers to manage their operations in ways that protect water, land, and air while maintaining generational viability.

We urge the MPCA to preserve flexibility and avoid one-size-fits-all mandates that do not account for regional differences in soil type, cropping systems, and manure handling and storage systems.

Recognize Data-Driven Nutrient Management as a Best Practice

Farmers should be explicitly allowed to use actual farm-level crop data (3–5 year averages) to calculate manure application rates.

University of Minnesota recommendations offer a valuable baseline but do not always reflect the precision agriculture tools and management data available on today's farms. Feedlot rules should:

- Allow farmers to use their own data to match nutrient supply to crop removal.

- Recognize that data-driven management can improve nutrient use efficiency and reduce loss.
- Avoid imposing rigid regional rules that would complicate compliance and reduce effectiveness. Data-driven management will allow farmers to be responsible for their unique cropping and field features, without the need to physically draw lines and increase confusion for compliance and enforcement.

Integrate Existing Buffer and Setback Protections

Account for existing riparian buffers (103F.48 statute) and setbacks when considering additional manure application restrictions.

Current rules already require setbacks for sensitive features such as karst, wells, and water bodies. Farmers also comply with the 103F.48 statute requiring vegetative buffers along public waters and ditches. These should be acknowledged in the rules as contributing to nutrient management and water protection goals.

Adding additional buffer or setback requirements without crediting existing compliance would be duplicative and inequitable.

Expand and Diversify Best Management Practices (BMPs)

Broaden the menu of BMPs available to farmers rather than limiting or prescribing specific practices.

No two farms are the same. Feedlot rules should recognize a variety of BMPs that can achieve the same environmental outcomes. For example:
- Manure injection, variable rate application, and cover cropping can all enhance nutrient retention and reduce runoff.
- Allowing choice among effective practices encourages adoption and continuous improvement while leaving room for innovation and technology adoption.

Limiting options or prescribing a narrow set of BMPs would undermine flexibility and innovation. Farmers need adaptable tools to match local conditions and available resources.

Evaluate Practical and Economic Impacts of Proposed Changes

All proposed rule changes should be subject to agronomic, technical, and financial analysis, especially those involving infrastructure or timing constraints.

- Revisions that affect construction, application timing, or equipment needs may significantly increase costs with little environmental benefit. These should be avoided.
- Shortening application windows could exacerbate labor shortages during peak seasons, risking noncompliance or operational delays.

MPCA should conduct impact assessments and consult with farmers, engineers, and financial experts before finalizing rule language.

Support Education and Implementation Resources
Accompany rule updates with targeted education and training for feedlot owners and manure applicators.

Chapter 7020 applies to farms of all sizes. Effective implementation depends on clear communication, accessible training, and support materials that reflect real-world conditions.

MPCA and its partners should:
- Invest in farmer-focused guidance materials.
- Offer timely workshops and re-education opportunities.
- Ensure that revised rules are not just enforceable, but understandable and achievable.

Collaboration builds trust and results in smarter regulations.

Minnesota's pig farmers are committed to protecting water quality, strengthening rural communities, and producing food sustainably. The 7020 Feedlot Rules are critical to that mission. We encourage MPCA to adopt revisions that reflect flexibility, data-based decision making, and a strong partnership with farmers.

Thank you for your leadership and for considering these comments. We look forward to continued collaboration throughout the rulemaking process.

Sincerely,

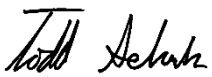

Todd Selvik
President, Minnesota Pork Producers Association

RECEIVED
By: OAH on 7/22/2025
Amanda Gentry Attachment

Winona County SWCD

Providing conservation assistance in Winona County since 1938.

Mission

Promote soil and water conservation through technical, educational and financial assistance.

Vision

Comprehensive use of our natural resources for all generations.

PO Box 39
400 N Wilson St
Lewiston MN 55952
507-523-2171 - Ext 3
Monday-Friday 8:00-4:30
winonaswcd.org

July 22, 2025

OAH Attn: William Moore, OAH
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Re: Public Comment on OAH Docket No. 25-9003-40661
Planned Amendments to Rules Governing Animal Feedlots, *Minnesota Rules*, Chapter 7020

Dear Mr. Moore,

Thank you for the opportunity to provide public comments on planned amendments to rules governing animal feedlots under *Minnesota Rules*, Chapter 7020. Winona County Soil and Water Conservation District (SWCD) staff have participated in MPCA listening sessions and offer the following comments and recommendations for consideration:

Comments

1. **Cost of Compliance**
   Many producers are concerned about the financial burden associated with the planned amendments. Implementing feedlot improvements, manure storage and other best management practices (BMPs) is costly. Currently, state and federal cost-share funds - administered by SWCDs, NRCS, watershed districts and similar agencies - are limited. Without additional or dedicated funding, producers may be unable to comply with the planned feedlot rule changes.

2. **Limited Technical Assistance Capacity**
   Agencies like SWCDs and NRCS, providing technical assistance, lack the staff capacity to support producers in planning and implementing feedlot improvements, manure storage systems and related BMPs projects. Increased technical demand from these rule changes will further strain existing limited resources unless staffing support is expanded.

3. **Challenges for Small Operations**
   Small producers in the bluff regions of SE Minnesota face unique barriers. Limited labor, aging operators and difficult terrain make implementation of new practices challenging. For example, transitioning from winter manure hauling to long-term storage necessitates more spring application - coinciding with planting season. This may result in delayed planting or the need for hired labor, both financially burdensome.

   Producers unable to comply may leave livestock production which will reduce distributed feedlots and increase row crop acreage operated by renters. Renters are often less invested in conservation, leading to fewer BMPs, increased erosion and degraded water quality.

4. **Impact on the SE Minnesota Bluff Landscape**
   Rule changes could unintentionally encourage the consolidation of small contour strip fields into larger row cropped parcels using larger equipment - practices that increase erosion on sloped fields. Livestock declines also reduce hay and pasture acres, weakening perennial cover crucial for protecting fragile bluffland soils. Expansion of row crops in this area could further contribute to erosion, nitrate leaching and water quality decline.

Recommendations

1. **Expand Cost-Share and Loan Funding**
   Provide expanded state and federal funding for cost-share and AgBMP loan programs to assist producers in implementing practices meeting new feedlot rule changes.

2. **Revise the Animal Unit (AU) Cap**
   Adjust the current 500 AU cap to allow all affected producers - regardless of size - to access financial assistance for feedlots.

3. **Increase Funding for Technical Assistance**
   Provide increased funding to SWCDs, NRCS and private Technical Service Providers (TSPs) to expand capacity and support services for plan writing, design and engineering services.

4. **Implement a Stepped Timeline**
   Allow for phased implementation and flexible timelines so producers can reasonably adapt to new feedlot requirements.

5. **Retain Contour Strips and Perennial Vegetation**
   Prioritize support for producers in the SE Minnesota bluff region that utilize contour strips and perennial vegetation in their crop rotations.

6. **Offer Compliance Alternatives**
   Provide additional voluntary compliance pathways, such as participation in the Minnesota Agricultural Water Quality Certification Program (MAWQCP), to acknowledge producers who already implement conservation practices.

Please feel free to contact Winona County SWCD with any questions or requests for clarification.

Sincerely,



Amanda Gentry
Resource Conservationist
Winona County SWCD
amanda.gentry@winonaswcd.com
507-523-2171 Ext 114

RECEIVED
By: OAH on 7/22/2025
Emily Wegener Attachment

At New Fashion Pork we are committed to raising our pigs and farming our land in ways that are better than the generations before us, utilizing modern methods and current technologies available in our industry. Doing more with less by embracing the natural processes nature provides. As pork producers it is our responsibility to protect and preserve our water resources. We actively embrace state and local requirements to safeguard and improve water quality. We implement and aggressively monitor water-conservation practices as part of our nutrient management plans. At NFP our goal is to be on the proven cutting-edge of new technologies that are relevant and applicable to the pork industry. We oppose greater regulations to Minnesota feedlots but rather a more logical approach.

Currently the manure recommendations are based off the University of Minnesota's maximum return to nitrogen (MRTN). We believe this recommendation is not best suited for the entire state and can be to variable based off of things happening in the economy. We believe application rate recommendations could be improved by basing them off field specific data.

First reason to change to a yield-based recommendation would be due to Minnesota having varying soil types and field landscape throughout the entire state. By basing the manure recommendations from actual field or county yield data this will better align with regional best practices without having to define specific regions. This may result in an increased nutrient balance and would better align with the surrounding states like Iowa and South Dakota who use this same approach for nutrient recommendations.

Secondly the MRTN is designed to optimize nitrogen application rates based on economics which is constantly changing each year due to comparing the value of manure to commercial fertilizer prices. Commercial fertilizer prices can change rapidly to things that may not be occurring in our region as well as change throughout the year due to supply and demand. Having a crop removal rate based on actual yield ensures replacing what the crop takes off to best capture the economic value of all nutrients not just

nitrogen. This helps better reflect the true value of the manure as it would be applied in line with field specific nutrient removal.

Lastly by following a crop removal recommendation based on actual crop yield data, encourages a data driven management approach and may encourage more precision or variable rate technology that increases plant nitrogen utilization. A targeted nitrogen removal rate can be used to allow for some consistency in nitrogen management. Data driven yield rates with anticipated nitrogen removal rate allows flexibility for those who may not have the most up to date technology.

Over time this helps maintain the soil test levels within optimal ranges for a balanced fertility management program. Manure is a very valuable asset that needs to be used to enhance and protect crop production, not restrain it, all while still protecting our water resources. We believe a science and data driven approach accomplishes this. Not all farms are the same, allowing flexibility and a variety of BMP's allows for options to choose what will be the most impactful for each field.

As equipment costs have increased there has been an increase in custom applicators applying the manure. Increased education to custom applicators would be very beneficial in ensuring the current rules are understood instead of just increasing regulation. This would be an opportunity for feedlot owners and custom applicators to stay up to date with any new research that the University of Minnesota is working on or has completed. Education should be led by the University of Minnesota, MPCA and watershed quality organizations. It is a collaborative effort to spread information and education to continue to improve water quality. Bridging the gap between all parties involved in the application of manure could help increase the efficacy of the current rules in place without creating new ones.

We don't believe there needs to be any changes to the current permitting thresholds. Regardless of what the thresholds are, producers are going to build their operations for what it is capable regardless of what the threshold is. Changing these thresholds will not accomplish any benefit to water quality improvements.

The opportunity to provide feedback is greatly appreciated.

Tracy Whitney Attachment RECEIVED
By: OAH on 7/22/2025

CONSERVATION MINNESOTA

July 22, 2025

Minnesota Pollution Control Agency
520 Lafayette Road N
Saint Paul, MN 55155

Pollution Control Agency,

Minnesotans should be able to trust that the water we drink, swim in, and fish in is clean and safe. But pollution from animal feedlot manure threatens all of this—and Minnesota is home to 18,000 feedlots that collectively produce tens of millions of tons of manure each year.

We collected 415 signatures from Minnesotans who support strong protections from animal feedlot pollution. As you begin the process of revising the rules around how animal feedlot operators manage the manure they produce, these members would like to ask you to prioritize safe, clean water for all Minnesotans.

Members have signed on with this statement:

> "**I support strong protections from animal feedlot pollution. Safe, clean water for all Minnesotans should be our top priority.**"

Thank you for your consideration,

Nels Paulsen
Policy Director
Conservation Minnesota

Petition Signers

1 Harmon Abrahamson, Minneapolis
2 Daniel Abramson, Esko
3 Brian Adams, White Bear Lake
4 Leonard Addington, Edina
5 Chuck Addison, Hopkins
6 Joseph Adler, Blaine
7 Stanley Adler, Anoka
8 Michelene Agerter, Kasson
9 Barbara Ahlstrom, Minneapolis
10 Andrew Anderson, Hutchinson
11 Dale Anderson, Minneapolis
12 Eileen Anderson, Minnetonka
13 Gary Anderson, Saint Paul
14 Kristen Anderson, Lino Lakes
15 Matt Anderson, Savage
16 Philip Anderson, Maple Grove
17 Scott Anderson, Owatonna
18 Scott Anderson, Scandia
19 Michael Andreasen, Minnetonka
20 Susan Andrews, White Bear Lake
21 Pat Arnold, Minneapolis
22 Linda Ashland, Minneapolis
23 Harvey Aslakson, Minneapolis
24 James Ayres, Otsego
25 Ryan Baka, Minneapolis
26 Dawn Baker, Minneapolis
27 Jan Baker, Lino Lakes
28 Myles Bakke, Northfield
29 Timothy Bardell, Minneapolis
30 James Barnett, Anoka
31 Harvey Bartz, Stillwater
32 Margaret Beegle, Minneapolis
33 Carey Bell, Saint Paul
34 Karen Bell-Brugger, Minneapolis
35 Hannah Benson-Cahoy, Minneapolis
36 George Bentley, White Bear Lake
37 Richard Bergslien, Shorewood
38 Susan Beseke, Maplewood
39 Erin Betlock, Saint Paul
40 Jean Bierly, Blue Earth
41 Linda Bisdorf, Apple Valley
42 Linda Bisdorf, Apple Valley
43 Dan Bitterman, Ely
44 Richard Black, Bemidji
45 Lori Blauwet, Rochester
46 Grace Bocek, Minneapolis
47 Loretta Boegeman, Prior Lake
48 Gregory Boertje, Duluth
49 Larry Bogolub, Ely
50 Karen Bohnert, Stillwater
51 Penn Bowen, Mound
52 Jim Boyle, Hopkins

1101 West River Parkway, Suite 250 / Minneapolis, MN 55415 / 612.767.2444 / conservationminnesota.org

Petition Signers (continued)

53 Elizabeth Brack, Chanhassen
54 Tom Brandes, Plymouth
55 Megan Brennan, Minneapolis
56 Michele Brennan, Braham
57 Luann Brenno, Long Lake
58 Charles Britz, Waterville
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Sara Lupolt Attachment

July 21, 2025

Minnesota Pollution Control Agency
520 Lafayette Road N
St. Paul, MN 55155-4194

Disclaimer: The opinions expressed herein are our own and do not necessarily reflect the views of the Johns Hopkins University.

Dear Commissioner Kessler,

Thank you for the opportunity to comment on the Minnesota Rules Chapter 7020 governing animal feedlots (Revisor ID: R-04928).

We are researchers at the Johns Hopkins Center for a Livable Future (CLF), an interdisciplinary academic center at the Johns Hopkins Bloomberg School of Public Health dedicated to advancing equitable, resilient, and sustainable food systems through science and systems-based approaches. CLF has actively researched the public health implications of industrial animal agriculture since our founding in 1996.

As the Minnesota Pollution Control Agency (MPCA) begins rulemaking on planned amendments to the rules governing animal feedlots, we commend your efforts to gather new information, research and understanding regarding agriculture and the environment. In this comment, we first provide a brief explanation of the link between agriculture and public health as it pertains to feedlots and the application of manure to agricultural land. Next, we provide references to key research on manure application and water quality, including the health effects of high nitrate levels in surface and groundwaters.

1. Impacts of feedlots on environmental public health

Agriculture is a major contributor to the degradation of local community environments and water sources in the US. Research has shown that many of these communities located near large animal feedlots bear the undue burdens of poor environmental quality, poor health and poor economic conditions and that this is experienced disproportionately more by communities of color, low-socioeconomic status and vulnerable populations.[1] These conditions are emblematic of the environmental justice issues faced by many rural communities. We highlight this point as the MPCA has highlighted its commitment to environmental justice in decision-making. We urge the agency to consider this lens and the disproportionate impacts that revisions to the animal feedlot rules may have on already burdened communities in Minnesota.

The agricultural application of chemical fertilizers and manure are key sources of environmental and water pollution that compromise our environment and harm public health. Overapplication of manure and waste from these facilities can contaminate surface and groundwater with an array of health hazards.[2,3] For example, antimicrobial residues[4], pathogenic bacteria and antibiotic resistance genes[5] have been found in surface and groundwater near concentrated poultry feeding operations. One study conducted in the Chesapeake Bay watershed found higher levels of nitrates (a form of nutrient pollution) and antibiotic-resistant pathogenic *E. coli* in waterways

closer to poultry farms with larger numbers of animal[6]. Similarly, antibiotic-resistant *Salmonella* and *enterococci*, as well as fecal indicator bacteria[7], were detected in the surface waters where swine waste runoff occurs. Numerous studies have demonstrated that humans can be exposed to waterborne contaminants from livestock and poultry operations through the recreational use of contaminated surface water and the ingestion of contaminated drinking water.[8,9]

2. Additional resources on the application of manure and water quality

Given that the MPCA is seeking new information and research on the impacts of manure practices on water quality and public health, we strongly recommend that the agency review and incorporate findings from the following (and referenced) scientific studies and resources into its rulemaking:

- Jones, CS (2024). Water Pollution – Regional, National and Global Impacts. In J. Merchant & R. Martin (Eds.), *Industrial Farm Animal Production, the Environment, and Public Health*. Johns Hopkins University Press.

Specifically, regarding high levels of nitrate in surface and drinking waters:

- Exposure to elevated levels of nitrates in drinking water is associated with adverse health effects, including cancer[10,11] and birth defects[12].

Specifically, regarding nutrient runoff and the impacts of climate change:

- Nutrient runoff (including nitrogen and phosphorus) has also been implicated in the growth of harmful algal blooms which may pose health risks for people who swim or fish in recreational waters, or who consume contaminated fish and shellfish.[3,13] Exposure to algal toxins has been linked to acute gastrointestinal illness, liver damage, and other adverse health effects.[14,15] Harmful algal blooms and water contamination events are expected to occur more frequently due to extreme weather events induced by climate change[16].

We look forward to reviewing and further commenting on any forthcoming revisions to the Rule. Thank you for considering our comments.

Sincerely,

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References

1. Donham KJ, Wing S, Osterberg D, et al. Community health and socioeconomic issues surrounding concentrated animal feeding operations. *Environ Health Perspect* 2007; **115**(2): 317–20.
2. Graham JP, Nachman KE. Managing waste from confined animal feeding operations in the United States: the need for sanitary reform. *Journal of water and health* 2010; **8**(4): 646–70.
3. Burkholder J, Libra B, Weyer P, et al. Impacts of waste from concentrated animal feeding operations on water quality. *Environ Health Perspect* 2007; **115**(2): 308–12.
4. Campagnolo ER, Johnson KR, Karpati A, et al. Antimicrobial residues in animal waste and water resources proximal to large-scale swine and poultry feeding operations. *The Science of the total environment* 2002; **299**(1-3): 89–95.
5. Hubbard LE, Givens CE, Griffin DW, Iwanowicz LR, Meyer MT, Kolpin DW. Poultry litter as potential source of pathogens and other contaminants in groundwater and surface water proximal to large-scale confined poultry feeding operations. *Science of The Total Environment* 2020; **735**: 139459.
6. Amato HK, Wong NM, Pelc C, et al. Effects of concentrated poultry operations and cropland manure application on antibiotic resistant Escherichia coli and nutrient pollution in Chesapeake Bay watersheds. *The Science of the total environment* 2020; **735**: 139401.
7. Heaney CD, Myers K, Wing S, Hall D, Baron D, Stewart JR. Source tracking swine fecal waste in surface water proximal to swine concentrated animal feeding operations. *The Science of the total environment* 2015; **511**: 676–83.
8. Rosenberg Goldstein RE, Cruz-Cano R, Jiang C, et al. Association between community socioeconomic factors, animal feeding operations, and campylobacteriosis incidence rates: Foodborne Diseases Active Surveillance Network (FoodNet), 2004-2010. *BMC Infect Dis* 2016; **16**(1): 354.
9. Murray RT, Cruz-Cano R, Nasko D, et al. Association between private drinking water wells and the incidence of Campylobacteriosis in Maryland: An ecological analysis using Foodborne Diseases Active Surveillance Network (FoodNet) data (2007-2016). *Environmental research* 2020; **188**: 109773.
10. Essien EE, Said Abasse K, Cote A, et al. Drinking-water nitrate and cancer risk: A systematic review and meta-analysis. *Archives of environmental & occupational health* 2022; **77**(1): 51–67.
11. Picetti R, Deeney M, Pastorino S, et al. Nitrate and nitrite contamination in drinking water and cancer risk: A systematic review with meta-analysis. *Environmental research* 2022; **210**: 112988.
12. Brender JD, Weyer PJ, Romitti PA, et al. Prenatal nitrate intake from drinking water and selected birth defects in offspring of participants in the national birth defects prevention study. *Environ Health Perspect* 2013; **121**(9): 1083–9.
13. Backer LC, Manassaram-Baptiste D, LePrell R, Bolton B. Cyanobacteria and algae blooms: Review of health and environmental data from the Harmful Algal Bloom-Related Illness Surveillance System (HABISS) 2007-2011. *Toxins (Basel)* 2015; **7**(4): 1048–64.
14. Lad A, Breidenbach JD, Su RC, et al. As We Drink and Breathe: Adverse Health Effects of Microcystins and Other Harmful Algal Bloom Toxins in the Liver, Gut, Lungs and Beyond. *Life (Basel)* 2022; **12**(3): 418.
15. Young N, Sharpe RA, Barciela R, et al. Marine harmful algal blooms and human health: A systematic scoping review. *Harmful Algae* 2020; **98**: 101901.

16. Schaffer-Smith D, Myint SW, Muenich RL, Tong D, DeMeester JE. Repeated Hurricanes Reveal Risks and Opportunities for Social-Ecological Resilience to Flooding and Water Quality Problems. *Environmental science & technology* 2020; **54**(12): 7194–204.

• CHAPTER 2

Water Pollution—Regional, National, and Global Impacts

Christopher Jones

The increased commercial availability of macronutrients in the decades following World War II enabled farmers to decouple the production of commodity crops from livestock production. For example, use of nitrogen fertilizers derived from the Haber Bosch process of ammonia synthesis[1] increased 13-fold from 1945 to 1972.[2] As a result, farmers no longer needed to rely on nutrients supplied by animal manures or, in the case of nitrogen, biological fixation of atmospheric nitrogen by legumes in symbiosis with bacteria.[3]

As the demand for meat has continued to remain strong, especially in First World countries,[4,5] food animals have been concentrated onto fewer and fewer farms where efficiencies of production can be optimized. In the US state of Iowa, the number of farmers raising hogs decreased from 65,000 in 1980 to 10,000 in 2002 and to fewer than 5,000 at present.[6] However, the average number of hogs raised by an individual farmer has increased from 200 to 4,700 in that time span, while the total number of hogs in the state has grown from 13 million to 25 million.[6] Similar scenarios have played out with other farm animals. The number of egg-laying chickens in Iowa increased from 21.5 million in 1997 to 56.5 million in 2021, and an astonishing 19 of

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20 Iowa chickens reside in operations that house 100,000 or more birds.[6] For beef cattle, the number of operations with greater than 500 head increased 82% between 1997 and 2017.[7] Clustering animals in this manner has occurred in other parts of the United States as well as the European Union, Eastern Europe, China, and many other countries.

Concentrating livestock animals in animal feeding operations (concentrated animal feeding operation [CAFO]) has meant more reliance on feedstuffs composed of corn (*Zea mays*) and soybeans (*Glycine max* [L.] Merr.) and less reliance on forage crops and small grains. Likewise, US Corn Belt farmers choosing not to raise livestock have been able to simplify their crop production systems to continuous corn, a two-year rotation of corn–soybean, or a two-year rotation of corn–soybean/wheat double crop in the eastern portion of the region. The introduction of soybean, which displaced not corn but rather crops like oat, alfalfa, clovers, and sorghum, correlates strongly with the use of commercial fertilizer for corn (Fig. 2.1).

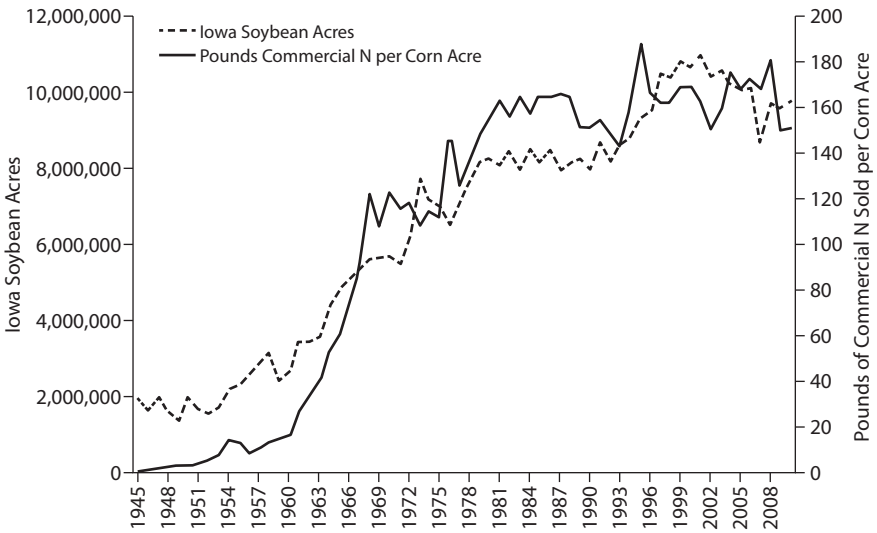

Figure 2.1 Area planted to soybeans in the US state of Iowa and the pounds of nitrogen fertilizer sold per planted acre of corn. *Data sources*: Census of Agriculture, National Agriculture Statistics Service.

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Concentrating animals on fewer and fewer farms coupled with the displacement of diverse crop rotations by soybean meant a greater reliance on chemical fertilizers. At the same time, the total number of animals continued to increase, and thus manure nutrients have also been concentrated into smaller geographical areas. This has had consequences for the environment in places where livestock production is intense: Iowa (hogs and chickens), Wisconsin (dairy and beef cattle), and the western Lake Erie basin (hogs, cattle, poultry), to name three.

Managing manure from concentrated livestock operations can be a colossal challenge. For example, the manure waste generated by a hog contains about 3 times as much nitrogen and phosphorus as a human being (8), and thus an Iowa operation raising the average number of hogs (4,700) is managing the nutrient waste equivalent of a community with a population greater than 14,000 people. When the volume of hog waste is considered, the challenge appears even larger. The waste just from Iowa's hog population exceeds that excreted by the human population by 20–30 times.[8] This waste is stored in belowground pits or surface lagoons for 6–12 months before it is applied to crop fields.[8–10]

In Iowa, large livestock operations are required to create a manure storage and application plan as part of the permitting process for CAFO construction.[9] This Manure Management Plan maps the fields where waste will be applied, along with the timing and amount of application. The amounts are weakly restricted by the yield goal formula for nitrogen (N)[11] and the phosphorus (P) index for that nutrient, neither of which has been shown to be protective of water quality.[12] The credibility of the 50-year-old yield goal formula (multiply the expected corn yield potential in bushels per acre by 1.2 for pounds per acre N application) has been questioned, if not wholly discredited, as a sound approach for optimum environmental and agronomic outcomes.[13,14] All available forms and sources of nitrogen need to be considered for efficient management of that nutrient and optimization of environmental outcomes. These include mineralization of soil organic matter

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(mobilization) and biological fixation in addition to synthetic products and manure. Immobilization of nitrogen within the soil matter also occurs as inorganic forms are incorporated into biomass through biological processes. Monitoring and managing these pools of nitrogen in synchrony can help align inputs with crop nutrient demands. Farmers, however, can be highly motivated to overapply manure because of economic considerations related to transport of the material, which is much less nutrient dense than commercial formulations (Fig. 2.2).[10]

Dissolved and solid forms of nitrogen (ammonia, ammonium, nitrate, nitrite, organic forms) contained within manure wastes can offgas to the atmosphere as ammonia (NH_3), nitrous oxide (N_2O), nitric oxide (NO), and nitrogen gas (N_2). Volatilization losses of N from both pit and lagoon storage are also difficult to control and minimize, and atmospheric deposition of N, usually ammonia (NH_3), ammonium (NH_4^+), and nitrate (NO_3^-), sourced to these facilities is a significant environmental consideration. There is evidence that much of the volatilized N is deposited within 1 km of the confinement operation,[15] and McGinn et al.[16] reported a 50% decline in deposition 200 m from a cattle confinement. In most circumstances, the farmer is not required to consider these inputs in their fertilization scheme, and Jackson et al.[9] concluded that in some scenarios, it makes clear economic sense for large livestock confinements to maximize N volatilization losses. Thus, in some circumstances, manure becomes a waste product and the practice of squandering manure nutrients is not necessarily economically wasteful.[17,18]

Effect of Livestock Production on Water Resources

The post–World War II transition from diverse, multispecies farms to operations devoted to cash crops like corn and soybean, with a subset raising livestock at high densities, has produced both efficiencies and negative environmental consequences. It has long been known that

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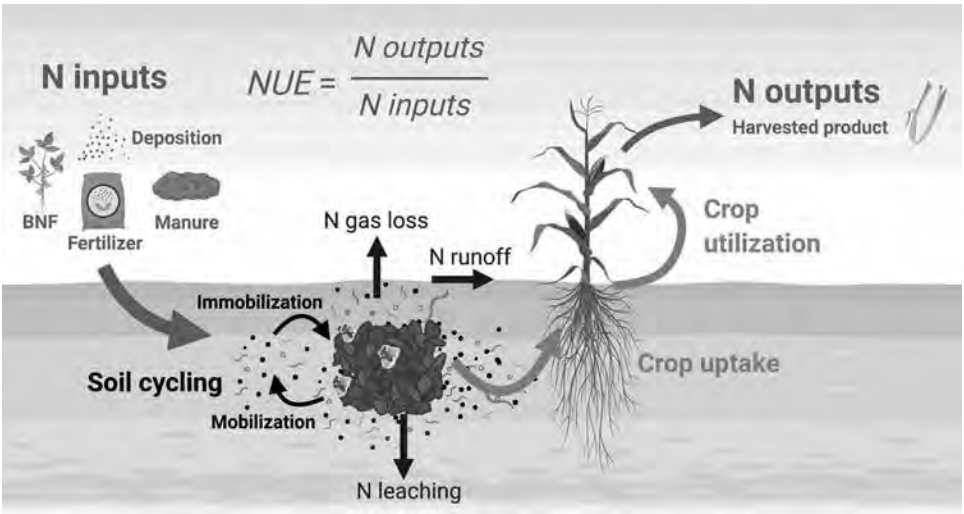

Figure 2.2 Conceptual model of nitrogen inputs and flow paths in a corn production system. BNF = biological N fixations; NUE = nitrogen use efficiency. *Source*: Udvardi, M., F. E. Below, M. J. Castellano, A. J. Eagle, K. E. Giller, J. K. Ladha, X. Liu, T. M. Maaz, B. Nova-Franco, N. Raghuram, and G. P. Robertson. (2021). A research road map for responsible use of agricultural nitrogen. *Frontiers in Sustainable Food Systems* 5:660155.

nitrogen fertilization correlates with stream nitrate pollution in the US Corn Belt[19] with impacts on municipal water supply[20] and Gulf of Mexico hypoxia.[20] Nitrate is a regulated pollutant in the United States under the federal Safe Drinking Water Act and an important driver of eutrophication in both freshwater and marine environments. Infants consuming high-nitrate water alone or with that mixed with baby formula are vulnerable to methemoglobinemia, which impairs red blood cells' ability to transport oxygen throughout the body.[21]

Because nitrogen inputs to crops cycle through plant biomass and into and out of soil organic matter, and because of the time lag of pollutant transport to streams via groundwater pathways,[22] it is nearly impossible to trace stream nitrate back to commercial fertilizer, animal manure, legumes, or soil organic matter. Hence, many have attempted to gain insights on nitrate sources and pathways using nitrogen budgeting.[23,24] Similar approaches have been used for the other major

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macronutrient driving eutrophication, phosphorus.[8,25] Much of this and other research has shown that nutrient and other types of water pollution tend to be particularly bad in watersheds with a high density of livestock.[10,26–28] A few of these are discussed below.

Gulf of Mexico

Coastal Gulf of Mexico eutrophication driven by nutrient enrichment from livestock and crop production in the US Corn Belt draining to the Mississippi River basin has been observed and documented since at least 1974.[29] Waters off the coast of Louisiana become degraded as algae and phytoplankton exploit nutrient-rich water and bacterial consumption of their remains consumes dissolved oxygen (DO). Marine food webs are altered,[30] mobile species flee,[31,32] and immobile species perish[33] in areas where DO levels drop below 2 mg L^{-1} (hypoxic/hypoxia areas). Economic consequences include decline of commercial fishing and shellfish catches and recruitment failure of valuable species.[34] In recent years, harmful algae blooms requiring closure of beaches on the Gulf Coast have been blamed on nutrient pollution in the Mississippi River.[35] Livestock animal waste is the third-leading contributor of both phosphorus and nitrogen to the Gulf of Mexico, while commercial fertilization of crops largely grown to feed these animals is the leading contributor of both (Fig. 2.3).[36,37]

A consortium of state agencies, tribal governments, and federal agencies was formed in 1997 to address the issues of Mississippi River basin nutrient pollution and Gulf of Mexico hypoxia, with an objective of reducing the areal extent of hypoxia to the 1980–1996 baseline average by 2015. Seeing this goal would go unmet, the task force pushed back the goal date to 2035 (Fig. 2.4).[38]

Lake Erie

The shallowest of the five Great Lakes in North America, Lake Erie, has been plagued with algae blooms attributed to livestock, row crop

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Figure 2.3 A plume (green) of freshwater enriched in nutrients and sediments enters the Gulf of Mexico from the Mississippi River. *Credit*: Nancy Rabalais, Louisiana Universities Marine Consortium.

production, and point sources in both the United States and Canada (Figs. 2.5 and 2.6). Point sources are pollutants sourced back to the end of a regulated pipe discharge; nonpoint sources are disperse and not easily traceable from the stream to the source(s). Although water quality in the lake improved in the 1980s and 1990s following the implementation of the US Clean Water Act, which regulated point source discharges, a "re-eutrophication" has occurred over the past 20 years linked to unregulated nonpoint sources of nutrients from agriculture.[39] Degrading amounts of N and P from productive agricultural land in Ohio, Indiana, Michigan, and Ontario drain to the western basin via rivers such as the Maumee, Raisin, and Thames, impairing the lake for recreation, aquatic life, and municipal drinking water.[40,41]

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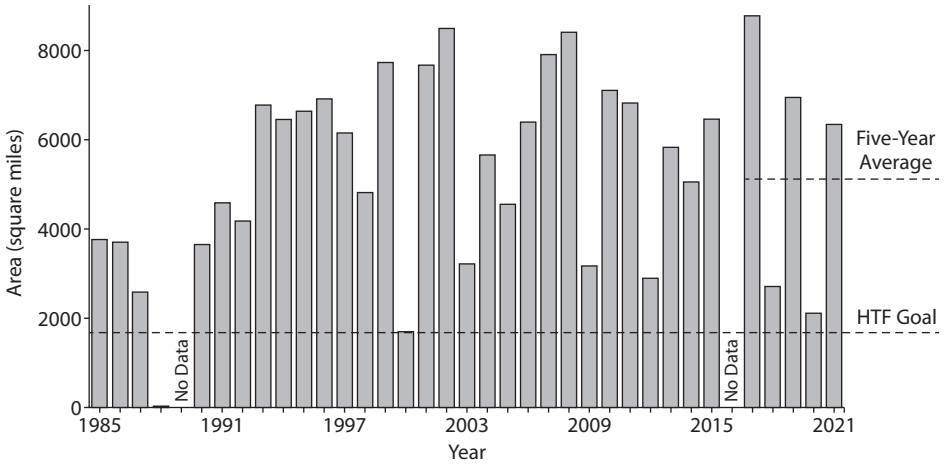

Figure 2.4 Gulf of Mexico hypoxia area. Also shown are the Environmental Protection Agency–led Hypoxia Task Force (HTF) improvement goal, along with the 5-year running annual average.

Unlike marine eutrophication in the Gulf of Mexico, where nitrogen is limiting,[42,43] anthropogenic sources of phosphorus are thought to be the main driver of eutrophication and degradation in Lake Erie.[39] The farmed landscape left level by glacial advance 2.5 million to 11,000 years ago requires constructed drainage in cropped fields to lower the water table, thereby drying out soggy soils and enhancing conditions for field work and increasing crop yields. This drainage consists primarily of networks of porous pipe (tile) installed to a depth of ~1 m that ultimately discharge to the stream network. Dissolved and particulate phosphorus, applied to or incorporated into the soil surface as manure or commercial fertilizer formulations, infiltrates to the tile via preferential pathways in the soil profile. Although commercial formulations have been found to contribute more than manure sources to the Maumee River, the proportion of applied manure phosphorus lost to Lake Erie is larger than the proportion of applied commercial P lost.[44] This is important since populations in the basin have increased since 2007, while the amount of commercial phosphorus application has likely declined since the 1970s.[45]

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Figure 2.5 Lake Erie (dark gray) and the rest of the Great Lakes. *Source*: Wikimedia commons.

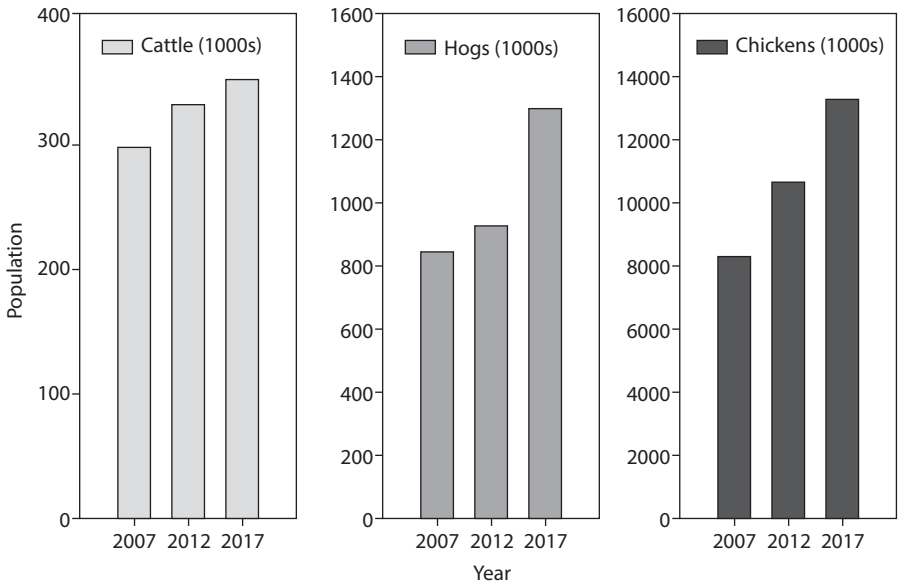

Figure 2.6 Livestock populations in the US portion of the Western Lake Erie basin. *Source*: USDA Quickstats (6).

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Chesapeake Bay

Land covering 64,000 square miles in six states drains to Chesapeake Bay, the largest estuary in the United States. Much of the land area in the Baltimore, Maryland, to Norfolk, Virginia, corridor is densely populated. The entire watershed is home to 17 million people, about 5% of the US population. By comparison, the area of the agricultural state of Iowa is only slightly less but is home to only 3 million people (Fig. 2.7).

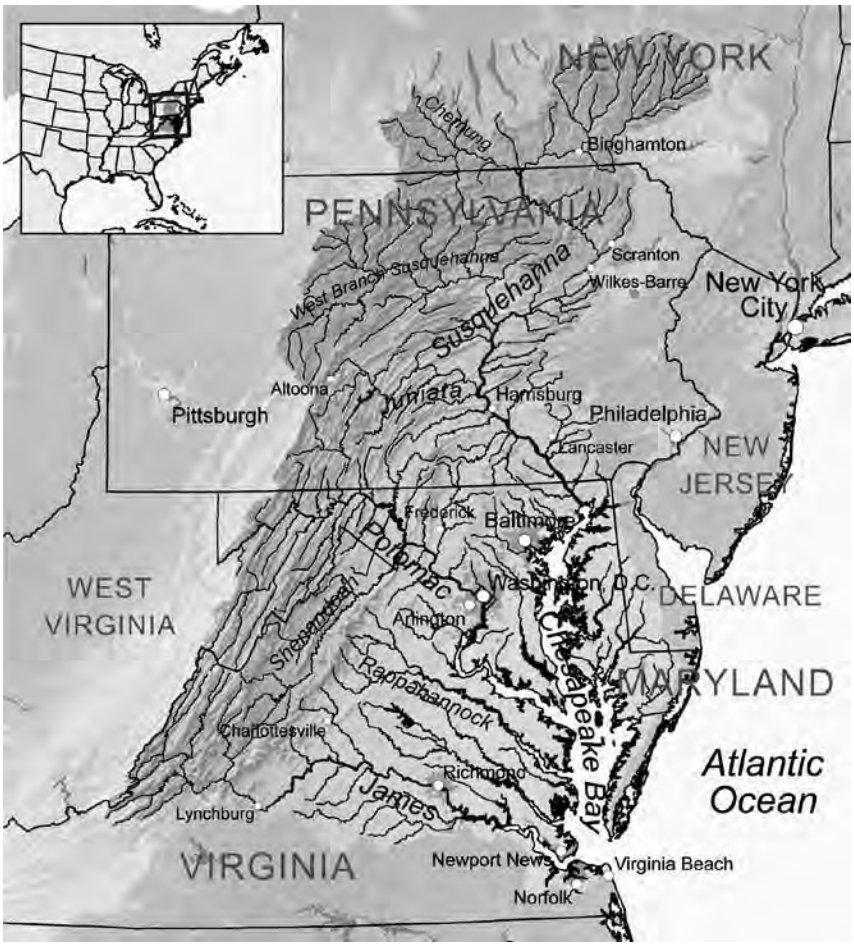

Figure 2.7 Chesapeake Bay watershed.

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Concern over degradation of water quality in Chesapeake Bay from nutrient and a myriad of other types of pollution was increasingly heightened during the 1960s and 1970s. The US Clean Water Act addressed many types of industrial and municipal discharges after its passage in 1972 but left nutrient pollution from nonpoint (disperse) sources mostly unregulated. Although only 22% of the land area is in agricultural production[46] (small compared to many areas of the US Corn Belt), these lands are disproportionately large contributors of both nitrogen (45%) and phosphorus (44%) to the Bay's feeder streams, which include the Potomac, Rappahannock, Susquehanna, and James rivers.[46]

Much of the Bay's nutrient pollution problems link to livestock production geographically decoupled from the production of the feed used to raise animals. As grain yields increased in the US Corn Belt and elsewhere with the widespread adoption of crop hybrids and chemical fertilizers following World War II, Chesapeake Bay livestock producers found it easier, more efficient, and economically prudent to feed their animals with grain formulations grown elsewhere. Import of animal feed also means import of nutrients (N and P) contained within the feed. Without adequate crop area to apply the excreted nutrients, nutrient imbalances result, and the excess enters the environment, which in this case means the Chesapeake Bay estuary. Areas draining to the Chesapeake Bay (Susquehanna, Rappahannock, Potomac, and James rivers, along with the Upper Chesapeake and Lower Chesapeake basins proper) are home to 1.2 million hogs, 2.4 million cattle, and 220 million chickens.[6] These animals excrete 138 million pounds of phosphorus and 560 million pounds of nitrogen in a year.[47] Our most nutrient-hungry crop, corn, needs about 25 pounds of phosphorus and 200 pounds of nitrogen per acre, meaning Chesapeake Bay animals excrete enough phosphorus and nitrogen to fertilize 5.5 million (P) and 2.8 million (N) acres of corn. Around 1.5 million acres of Chesapeake Bay land is committed to corn.[48] This illustrates the nutrient imbalances created by current configurations of livestock production in this region. These nutrient imbalances result in eutrophication of the estuary, reduced water

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clarity and biodiversity, and degraded recreational and aesthetic qualities of this major water resource, and once-thriving commercial fish and shellfish industries have been severely degraded.[46]

Black Sea

The California-sized Black Sea is bordered by Russia, Ukraine, Bulgaria, Romania, Georgia, and Turkey. It receives freshwater from several major European rivers (especially the Danube), but Mediterranean Sea saltwater also intrudes through a hydrological connection known as the Bosphorus. Thus, Black Sea water is saltier than a lake but fresher than the ocean, producing a diverse ecosystem and productive fishery. Resorts along its shoreline have promoted Black Sea water as therapeutic for at least two centuries (Fig.2.8).

In the 1960s, USSR agricultural policy increased the use of chemical fertilizers. In addition, huge animal production systems were established in Soviet-bloc countries[49] (one Romanian CAFO had more than

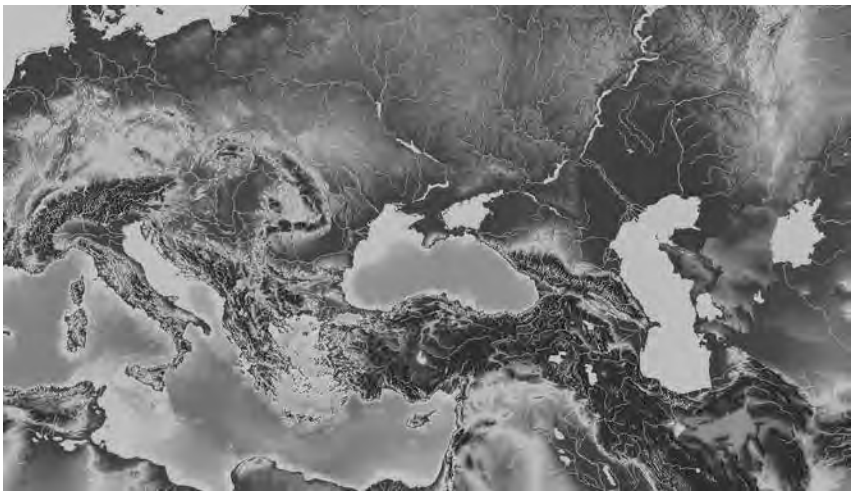

Figure 2.8 Black Sea is shown in the middle of this map. *Source*: By Kamel 15-own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=5623711.

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a million hogs). By the 1970s, the Black Sea beaches of Ukraine and Romania were graveyards of fish, clams, and crabs doomed by a hypoxic dead zone in the Black Sea created by nitrogen and phosphorus pollution discharged by the Danube River. The excess of nutrients stimulated large blooms of phytoplankton, causing a collapse of the diverse brackish water ecosystem.

Following the collapse of the USSR in 1989, many of the huge CAFOs closed and use of chemical fertilizers declined. Only six years later in 1995, it was apparent that the Black Sea was recovering. By 2002, sensitive mussel beds were reestablished, and other ecological indicators were improving.

Baltic Sea

Of the world's 400 or so known "dead zones" (i.e., low- or no-oxygen coastal areas degraded by excess nutrients), the Baltic Sea may host the largest and may in fact have seven distinct areas of reduced oxygen. Although nutrients from agriculture are also a main driver here, industrial and municipal discharge have contributed, along with the collapse of the cod fishery, which has caused ecosystem disruption favorable to harmful algae.

Large-scale hog production in Denmark, Poland, and other countries has been a strong contributor of nutrients to the Baltic Sea.[50] At any given time, Danish farmers are raising 13 million hogs[51] within the 16,600 mi^2 country, a density that exceeds even that of the largest hog-producing state in the United States, Iowa. And some individual Polish farms raise more than 60,000 hogs.[50] Management of manure nutrients from confined animal feeding operations is a difficult task on many farms.

The Baltic Sea is similar to the Black Sea in that they both are surrounded by land, are minimally connected to the larger ocean, and have salinity levels between that of the ocean and freshwater. The Baltic has also warmed substantially with climate change, a condition favorable for the algae that contribute to hypoxic zone formation. Water turnover

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rate is naturally slow (~30 years), and intrusion of salt water is restricted by shallow areas known as sills.[52] These natural conditions, coupled with anthropogenic inputs of nutrients, have expanded the Baltic Sea hypoxia zones 10-fold over the past century.[53]

Iowa

The US Corn Belt state of Iowa has long been one of the country's leading producers of hogs, cattle, and poultry. Currently, Iowa exceeds all other states in egg and pork production and is fourth in production of feeder cattle.[6] Iowa has also been a leading producer of both corn and soybeans, frequently topping all other US states in harvested acres of these commodities.[6] To achieve this level of carbohydrate, protein, and vegetable oil production, nutrient inputs have been required that far exceed those present in the natural system that existed prior to European settlement. A consequence of this supercharged production system has been leakage of nutrients and other pollutants to the environment and especially the streams, lakes, and aquifers of the state (Fig 2.9).

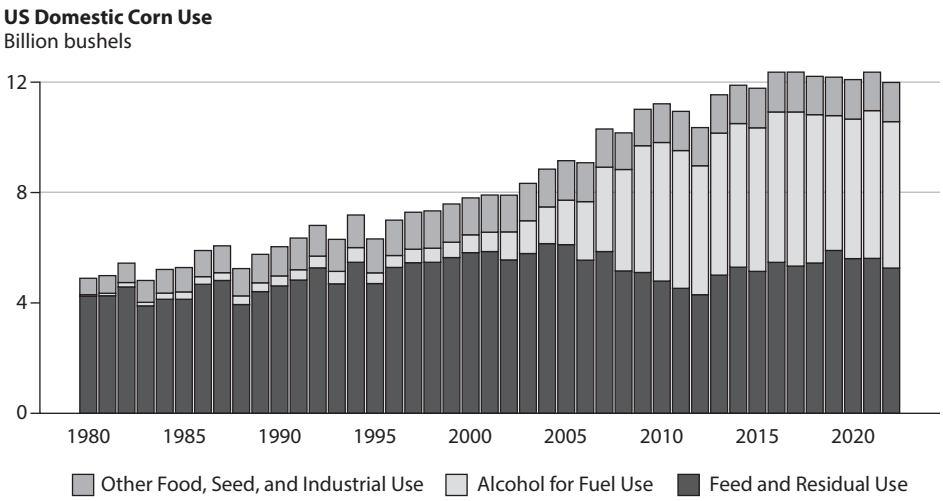

Figure 2.9 US domestic corn use. *Source*: US Department of Agriculture.

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More than half of Iowa's corn is used to produce fuel ethanol, and most of the rest is used as livestock feed. Residuals from ethanol production—distillers dried grains (DDGs)—are also fed to livestock; in all, about half the calories contained within Iowa's corn crop end up in livestock feed. This is an enormous number of calories that nearly equals the caloric needs of the entire population of the United States. And an even greater percentage of the soybean crop is used in livestock feed.

While livestock production is geographically co-located with the growth of feed grain in a general way, most Iowa farms do not raise livestock; that is, most are committed solely to crop production. These crop farms do serve as end points for manure if a livestock producer has an inadequate crop area to dispose of the manure at rates that are allowed by Iowa rules. It has been found, however, that these rules do little to constrain farmers from applying manure and synthetic fertilizer nutrients far beyond recommended rates for crops.[9,10]

Livestock density strongly correlates with the nitrate concentration of adjacent streams in Iowa. Jones et al.[10] found that nitrate concentrations linked to total nitrogen inputs and generated manure but not with commercial nitrogen fertilizer amounts in nine Iowa watersheds. Manure nutrients applied to fields that were already fertilized with commercial nitrogen (implying a wastage of manure) created a surplus nitrogen condition that drives stream nitrate (Fig. 2.10).

Iowa has approximately 3,500 large concentrated animal feeding operations (CAFOs) as defined under the Clean Water Act[54] and several thousand smaller ones with even fewer regulations. CAFOs are operations that contain at least 700 dairy cows, 1,000 beef cows, 2,500 hogs, or 30,000 chickens. The state with the second-highest number of CAFOs, Minnesota, has only one-third as many (1,300). The neighboring states of Wisconsin and Illinois have fewer than 300. Livestock density in Iowa could explain why the state's stream phosphorus levels are two to three times higher than that of Illinois,

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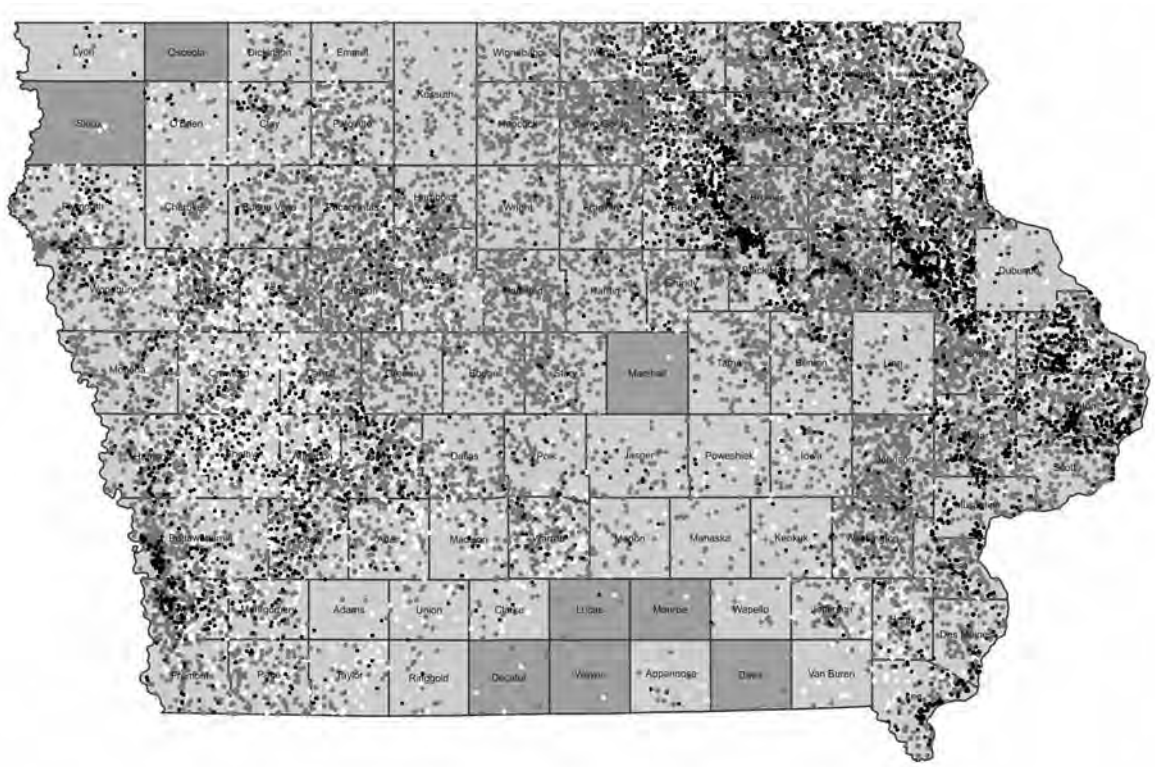

Figure 2.10 Correlations of 2017 watershed flow weighted average (FWA) NO3–N concentrations in nine Iowa watersheds with nitrogen (N) surplus (a); sum of commercial, manure, and fixation N (b); sum of commercial and manure nitrogen (c); commercial nitrogen (d); generated manure nitrogen (e); and area portion in corn and soybean (f). The dotted portion of the regression line in (a) is an extrapolation backward to a zero-surplus condition. FWA is defined as total NO3–N load divided by total discharge for 2017. Fixation is nitrogen sequestered into the soil in a microbe-mediated process with legumes, in this case, soybeans grown the previous year. *Source*: Anne Schechinger, Environmental Working Group.

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even though Illinois has a large urban phosphorus contributor (Chicago metropolitan area) and about the same corn and soybean crop area as Iowa.[55]

Leakage of excess nutrients from Iowa's landscape has had dire environmental consequences that degrade recreational opportunities, reduce biodiversity, and increase the cost of drinking water for the state's residents. The largest city (Des Moines) and its surrounding area require nitrate removal at the municipal drinking water treatment plant, a process that creates a pollution stream of its own. Also, around 6,600 private wells (most in rural areas) in the state have tested above safe limits for nitrate since 2000, and many more have been contaminated with bacteria.[56]

Iowa streams drain to the Missouri and Mississippi rivers, and the nutrients contained within ultimately discharge to the Gulf of Mexico (Fig. 2.11). Iowa has been identified as a strong contributor of both nitrogen and phosphorus, the primary drivers of the Gulf's hypoxic (dead) zone.[55,56]

Iowa area comprises 3.3% of the Missouri River basin while contributing 12% of the water and 55% of the nitrate. Likewise, the state comprises 21% of the land area while contributing 21% of the water and 45% of the nitrate to the Upper Mississippi River basin. Finally, Iowa comprises 4.5% of the entire Mississippi basin area (including the Missouri River basin) while contributing 5.9% of the water and 29% of the nitrate,[57] as well as 15% of the phosphorus.[55]

Clearly, livestock populations and the crop production system that supports it are large drivers of degraded water quality in Iowa and in states downstream. Both Denmark and the Netherlands have livestock densities on the scale of Iowa. As a result, both countries have in the past suffered environmental consequences similar to Iowa's, but both countries' governments have intervened in more forceful ways than Iowa's leaders have. Going forward, desired environmental outcomes in this intense production system will need to be reconciled with economic and regulatory considerations important to the agricultural industry.

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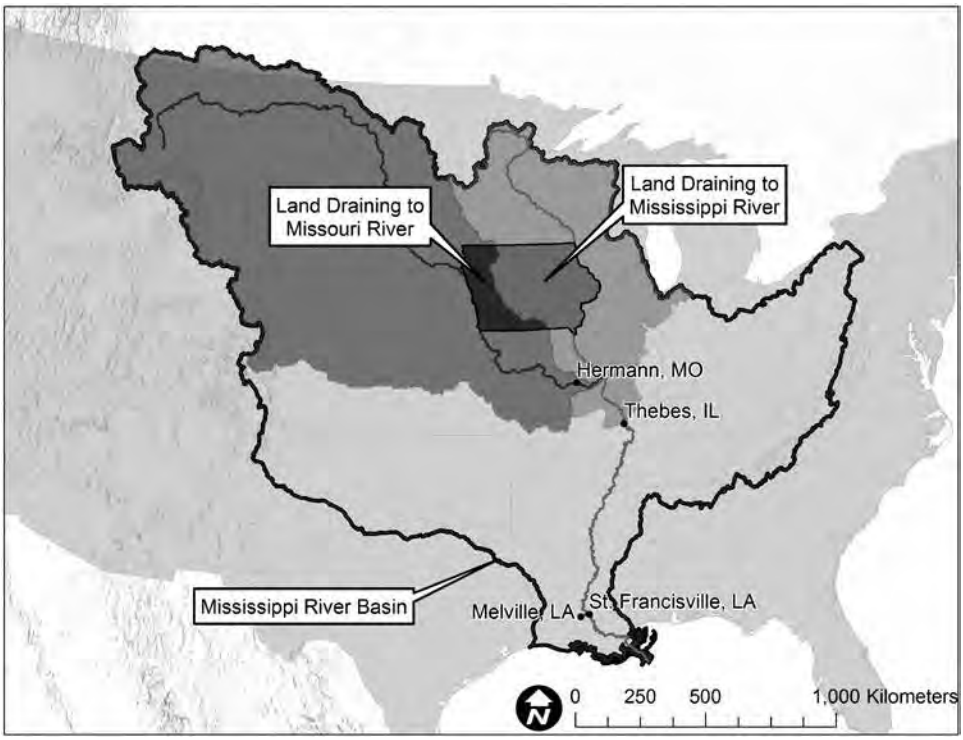

Figure 2.11 Areas of Iowa draining to the Missouri River and Mississippi River but not the Missouri River. *Source*: C. S. Jones, J. K. Nielsen, K. E. Schilling, and L. J. Weber. (2018). Iowa stream nitrate and the Gulf of Mexico. *PLOS ONE* 13(4): e0195930. https://doi.org/10.1371/journal.pone.0195930

Potential Policies for Improved Environmental Outcomes

The existing livestock production schemes in the United States and other developed countries did not happen by accident—policy, or the absence thereof (such as weak regulatory frameworks), incentivizes the concentration of production in places like Iowa and the Western Lake Erie basin. Industrialized farm animal production (IFAP), which here could be defined as feeding animals cash crop grains in confined or restricted living conditions, links closely to other agricultural systems. For example, the US renewable fuel standard guarantees a market for corn. DDGs are a by-product of fuel ethanol production and can be fed

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to animals. Corn is a nutrient-hungry crop that can be fertilized with animal manure. Thus, ethanol production relates to mono-cropping corn (continuous corn versus corn–soybean rotation) and livestock production in indirect but important ways.

Efficiencies of production in concentrated animal schemes have influenced consumer prices. For example, the early stages of consolidation in the hog industry did reduce pork prices $29 per year for the average US customer.[58] These efficiencies can only be realized, however, when the costs of the externalities of water and air pollution and water resource depletion are distributed to the public at large and not to the farmers, packers, and retailers. This is where policy must intercede if improved environmental outcomes are to result.

What might these policies look like? Of course, this will depend on the type of production system. Incentivizing the return of cattle to pasture (from open feed lots and buildings) would be one first step. The renewable fuel standard catalyzed the conversion of pasture to corn crops and reduced available area for grazing.[59] Much of this converted land was marginally suitable for corn and thus more vulnerable to soil erosion and/or nutrient loss tied to corn production practices. Growing corn for ethanol also displaces forage crops like alfalfa, which could be grown without irrigation in much of the Corn Belt but require enormous amounts of irrigation water in the arid western United States (alfalfa/hay consumes the most irrigation water across all water sources).[60] This has had profound environmental and sociological consequences across the Colorado River basin and in fact most of the farmed western United States.[61] Likewise, corn grown for confinement cattle and fuel ethanol have helped to deplete the Ogallala aquifer in Kansas and other states to alarmingly low levels.[62] Around 6,000 years are required to recharge the aquifer naturally.[63]

Grazing cattle on pasture emulates the native grassland ecosystem that was grazed by bison and elk. Grazing would reduce the burden of manure management intrinsic to confined systems. Several existing policies help farmers construct water systems that enable them to restrict grazing animals from streams and eliminate or reduce stream

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degradation associated with animal wading. Programs of this sort, coupled with a retreat from the renewable fuel standard, could make meat production more sustainable.[64]

Recoupling livestock and crop production on individual farms could help farmers "close" nutrient cycling and avoid exporting grain to feed animals in distant areas that lack sufficient crop ground to utilize manure nutrients judiciously. Much of modern livestock production in the United States and elsewhere has been decoupled from crop production. Instead of grazing on forage crops, animals are fed with cash crop grains, mainly corn and soybeans, in a system designed for efficiency and rapid animal growth to market weights. This scheme requires large inputs of fossil fuel for nitrogen fertilizer, pesticides, grain drying, and equipment manufacturing, and other input costs, notably seeds modified with biotechnology, are also high. But because the renewable fuel standard guarantees a market for corn, these costs have become justified on lands that once were marginal for corn production but were productive pasture ground for grazing cattle. Thus, many Corn Belt farmers are indirectly incentivized to focus solely on crops, leaving a small minority to only raise livestock or link their own crop fertilization schemes to their animals' manure. The emergence of soybeans as a livestock feed helped that crop displace oats, alfalfa, and clovers, all crops with lower input costs and that degrade the environment far less than corn and soybean.[65] Return of Corn Belt land to alfalfa production could potentially reduce production of this crop in areas of the western United States where irrigation with dwindling water supplies is necessary. Feeding livestock with corn and soybean requires concentration of animals and subsequently has made manure management an enormous challenge, with consequences for both water and air.

A return of cattle to pasture would help diversify farms. Farmers are incentivized to crop marginally productive land when animals are confined and fed cash crop grains. These lands are often hilly and vulnerable to soil erosion, which increases losses of phosphorus to the stream network.[55] In the United States, federal cost share programs exist that help farmers set up fencing and watering systems that enable rotational

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grazing and restrict cattle from damaging stream banks and beds and defecating and urinating in streams. A return to these sorts of schemes very likely would reduce nutrient and other types of pollution. Likewise, a move away from the large hog confinement model and a return to hog production in pasture farrowing systems[66] would very likely increase the number of hog operations, bring diversity to farms, and make manure management less perilous to the environment. Animals can also be grazed in multispecies systems[67] that are more sustainable and humane environments for livestock.

Creative government policies favorable to these types of systems would produce positive environmental outcomes for the public. The transition away from these less intense production systems to the IFAP model was clearly made possible, at least in part, by the absence of regulations limiting CAFO pollution.

If animals are to remain in concentrated systems, laws that focus on and enforce measurable environmental outcomes could reduce the pollution inherent to these production systems. Such laws might include limiting the number of animals such that the watershed can meet water quality goals, government agency tracking of manure nutrients, aligning nutrient inputs to crops with their expected uptake, and prohibitions on manure application when the likelihood of loss from fields is high (i.e., winter, onto snow and frozen ground, just prior to expected storms, on steep slopes, near streambanks, etc.). Enforceable nutrient and pathogen standards for streams could force livestock facilities in those watersheds to suspend operation until they implement pollution-trapping or pollution-reducing methods. Stream nutrient standards have been used to help reduce phosphorus pollution of the Illinois River in Arkansas and Oklahoma.[68] The river and an impoundment on the river (Ten Killer Lake) are some of the most valuable and highly used water resources in Oklahoma. Poultry waste, primarily from concentrated broiler operations in Arkansas, is used to (over) fertilize pasture ground for cattle production, and its runoff seriously degrades the river and the lake.[69] Oklahoma sued Arkansas poultry producers in 2005 and

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ultimately won the case in 2023.[70] While the stream is improving, the limit of 0.037 mg/L phosphorus is still not being met at all times.[69] Similar regulatory frameworks that focus on air quality could also be developed in areas with high concentrations of livestock.

Many have considered anaerobic manure digesters as a means of making manure waste more manageable.[71] These also present the opportunity to reduce greenhouse gas emissions (CO_2 and methane-CH_4) from manure waste.[72] Methane has about 80 times the warming power of CO_2 and animal agriculture generates 32% of worldwide emissions.[73] Manure biogas systems (anaerobic digesters) potentially reduce emissions by capturing methane and then using it to displace the use of fossil fuels, namely, natural gas. This solution is intuitive, and in fact, the US federal government has tried to incentivize this strategy.[74] Digesters concentrate most of the manure nitrogen and phosphorus into a liquid that can then be used to fertilize crops. Solids are then usually applied as a soil amendment to farmed fields. This solution does have detractors, mainly because digesters do not reduce the overall volume of waste and fail to address the main driver of livestock-related water pollution: overpopulation of animals in polluted watersheds and consequently quantities of manure nutrients that exceed crop needs. Digesters are not mechanically foolproof and require skilled operators, and those that malfunction can seriously degrade nearby waterways.[75] There are also questions surrounding worker safety related to these systems.[76] Expense is also a concern for many operators.

Demand for meat products ultimately drives the level of production in many societies. Availability seldom limits consumption of meat in most Western countries where meat consumption is high. Globally, meat consumption increased 58% from 1998 to 2018, and only half of this was due to human population increase.[77] The United States leads the world in per capita meat consumption (except for Hong Kong) at 128 kg/year,[78] an amount that has increased 45% since 1961. Total meat consumed in the United States has increased fivefold since 1909.[79]

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This demand for meat clearly links to the environmental consequences of livestock production. In Europe, total meat consumption, especially meat from ruminant animals, explains most of the country-to-country variation in the environmental footprint of food production.[80] In the modern era, the biomass contained within human bodies outweighs that of Earth's wild mammals 8:1, and when we add in our domesticated food animals, that ratio jumps to 23:1.[81] This last ratio must be enormous in places like Iowa and Denmark, where livestock production is intense, and where water quality and other environmental degradation is a serious concern.

Policymakers take great risks when they attempt to improve animal welfare and environmental outcomes by steering consumer choices toward alternatives. Attitudes about food and eating in general can be strongly held and are embedded within a myriad of religious, cultural, geographical, and economic factors. While meat rationing was common among countries during World War II, even then strong moral appeals were needed to convince people of the necessity of the policy.[82] It seems unlikely that this approach would be politically viable in the present day, especially in high-income countries. Certainly, some people are aware of the environmental consequences of meat consumption and feel those outcomes are unavoidable and a fair trade-off for the pleasure of consuming meat.

If farmers, food processors, and retailers were required through regulation to reduce the environmental pollution resulting from meat production, and those costs were passed on to the consumer, would meat consumption decline? The evidence is not clear. Modestly increasing the price of beef (£0.20 per meal) did not reduce consumption in the United Kingdom,[83] while another study in the same country showed consumption declining with price increases.[84] And it is a near certainty that many people would be unhappy with price increases linked to environmental objectives. These are difficult problems for countries to confront, but a reckoning will be imperative. Climate change, air and water pollution, increased wealth in developing countries, and

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continued population growth may force societies into more sustainable food production systems.

REFERENCES

1. Mittasch, A., and W. Frankenburger. 1929. The historical development and theory of ammonia synthesis. *Journal of Chemical Education* 6 (12): 2097.
2. Commoner, B. 1977. Cost-risk-benefit analysis of nitrogen fertilization: A case history. *Ambio* 157–161.
3. Fujita, K., K. G. Ofosu-Budu, and S. Ogata. 1992. Biological nitrogen fixation in mixed legume-cereal cropping systems. *Plant and Soil* 141 (1): 155–175.
4. Yates-Doerr, E. 2012. Meeting the demand for meat? *Anthropology Today* 28 (1): 11–15.
5. Delgado, C., M. Rosegrant, H. Steinfeld, S, Ehui, and C. Courbois. 2001. Livestock to 2020: The next food revolution. *Outlook on Agriculture* 30 (1): 27–29.
6. USDA, National Agricultural Statistics Service (NASS). https://www.nass.usda.gov/
7. Legislative Services Agency, Iowa Legislature. 2019. Livestock inventory historical trends. https://www.legis.iowa.gov/docs/publications/IR/1048437.pdf
8. Libra, R. D., C. F. Wolter, and R. J. Langel. 2004. Nitrogen and phosphorus budgets for Iowa and Iowa watersheds. https://s-iihr34.iihr.uiowa.edu/publications/uploads/Tis-47.pdf
9. Jackson, L. L., D. R. Keeney, and E. M. Gilbert. 2000. Swine manure management plans in north-central Iowa: Nutrient loading and policy implications. *Journal of Soil and Water Conservation* 55 (2): 205–212.
10. Jones, C. S., C. W. Drake, C. E. Hruby, K. E. Schilling, and C. F. Wolter. 2019. Livestock manure driving stream nitrate. *Ambio* 48 (10): 1143–1153.
11. Stanford, G. 1966. Nitrogen requirements of crops for maximum yield. Agricultural anhydrous ammonia technology and use (agriculturalanh): 237–257.
12. Mallarino, A. P., B. M. Stewart, J. L. Baker, J. D. Downing, and J. E. Sawyer. 2002. Phosphorus indexing for cropland: Overview and basic concepts of the Iowa phosphorus index. *Journal of Soil and Water Conservation* 57 (6): 440–447.
13. Fox, R. H., and W. P. Piekielek. 1987. Yield response to N fertilizer and N fertilizer use efficiency in no-tillage and plow-tillage corn. *Communications in Soil Science and Plant Analysis* 18 (5): 495–513.
14. Camberato, J. 2012. A historical perspective on nitrogen fertilizer rate recommendations for corn in Indiana (1953–2011). Purdue Extension. https://extension.purdue.edu/extmedia/ay/ay-335-w.pdf
15. Loubet, B., W. A. Asman, M. R. Theobald, O. Hertel, Y. S. Tang, P. Robin, M. Hassouna, U. Dämmgen, S. Genermont, P. Cellier, and M. A. Sutton. 2009. Ammonia deposition near hot spots: processes, models and monitoring methods. In *Atmospheric Ammonia: Detecting Emission Changes and Environmental Impacts*, edited by Mark A. Sutton, Stefan Reis, and Samantha M. H. Baker, 205–267. Springer.

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NOT FOR SALE OR DISTRIBUTION

Merchant_Health_int_1pgs.indd 39 03/06/24 3:14 PM

16. McGinn, S. M., H. H. Janzen, T. W. Coates, K. A. Beauchemin, and T. K. Flesch. 2016. Ammonia emission from a beef cattle feedlot and its local dry deposition and re-emission. *Journal of Environmental Quality* 45 (4): 1178–1185.
17. Fleming, R. A., B. Babcock, and E. Wang. 1998. Resource or waste? The economics of swine manure storage and management. *Applied Economic Perspectives and Policy* 20 (1): 96–113.
18. Sheriff, G. 2005. Efficient waste? Why farmers over-apply nutrients and the implications for policy design. *Applied Economic Perspectives and Policy* 27 (4): 542–557.
19. Klepper, R. 1974. Fertilizer application rates and nitrate concentrations in Illinois surface waters. National Agricultural Library. http://agris.fao.org/agris-search/search.do?recordID=US201300533223
20. Hatfield, J. L., L. D. McMullen, and C. S. Jones. 2009. Nitrate–nitrogen patterns in the raccoon river basin related to agricultural practices. *Journal of Soil and Water Conservation* 64:190–199.
21. Fan, A. M., and V. E. Steinberg. 1996. Health implications of nitrate and nitrite in drinking water: An update on methemoglobinemia occurrence and reproductive and developmental toxicity. *Regulatory Toxicology and Pharmacology* 23 (1): 35–43.
22. Van Meter, K. J., N. B. Basu, and P. Van Cappellen. 2017. Two centuries of nitrogen dynamics: Legacy sources and sinks in the Mississippi and Susquehanna river basins. *Global Biogeochemical Cycles* 31:2–23.
23. David, M. B., L. E. Gentry, D. A. Kovacic, and K. M. Smith. 1997. Nitrogen balance in and export from an agricultural watershed. *Journal of Environmental Quality* 26:1038–1048.
24. Jones, C. S., A. Seeman, P. M. Kyveryga, K. E. Schilling, A. Kiel, K.-S. Chan, and C. F. Wolter. 2016. Crop rotation and raccoon river nitrate. *Journal of Soil and Water Conservation* 71:206–219.
25. Alexander, R. B., R. A. Smith, G. E. Schwarz, E. W. Boyer, J. V. Nolan, and J. W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River basin. *Environmental science & technology*, 42 (3): 822–830.
26. Mee, L. 2006. Reviving dead zones. *Scientific American* 295:78–85.
27. Wang, J., Q. Liu, Y. Hou, W. Qin, J. P. Lesschen, F. Zhang, and O. Oenema. 2018. International trade of animal feed: Its relationships with livestock density and N and P balances at country level. *Nutrient Cycling in Agroecosystems* 110:197–211.
28. Oenema, O., D. Oudendag, and G. L. Velthof. 2007. Nutrient losses from manure management in the European Union. *Livestock Science* 112: 261–272.
29. Oetking, P., R. Back, R. Watson, and C. Merks. 1974.. *Hydrography on the nearshore continental shelf of south central Louisiana: Final Report of Offshore Ecology Investigation for Gulf Universities Research Consortium, Galveston, Texas*. Corpus Christi, TX: Southwest Research Institute. Project. (03 ± 3720).

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NOT FOR SALE OR DISTRIBUTION

Merchant_Health_int_1pgs.indd 40 03/06/24 3:14 PM

30. Justić, D., N. N. Rabalais, and R. E. Turner. 1995. Stoichiometric nutrient balance and origin of coastal eutrophication. *Marine Pollution Bulletin* 30 (1): 41 ± 6. 5.
31. Leming, T. D., and W. E. Stuntz. 1984. Zones of coastal hypoxia revealed by satellite scanning have implications for strategic fishing. *Nature* 310 (5973):136. 6.
32. Renaud, M. L. 1986. Hypoxia in Louisiana coastal waters during 1983: Implications for fisheries. *Fishery Bulletin* 84 (1): 19 ± 26. 7.
33. Ferber, D. 2001. Keeping the stygian waters at bay. *Science* 291:968–973.
34. Diaz, R. J., and A. Solow. 1999. Ecological and economic consequences of hypoxia. Topic 2 report for the integrated assessment on hypoxia in the Gulf of Mexico. https://repository.library.noaa.gov/view/noaa/21436
35. Tian, H., R. Xu, S. Pan, Y. Yao, Z. Bian, W. J. Cai, C. S. Hopkinson, D. Justic, S. Lohrenz, C. Lu, and W. Ren. 2020. Long-term trajectory of nitrogen loading and delivery from Mississippi River basin to the Gulf of Mexico. *Global Biogeochemical Cycles* 34 (5): e2019GB006475.
36. Greenhalgh, Suzie, and Paul Faeth. 2001. A potential integrated water quality strategy for the Mississippi River basin and the Gulf of Mexico. *The Scientific World Journal* 1:982595. https://doi.org/10.1100/tsw.2001.354
37. Armstrong, B. N., M. K. Cambazoglu, and J. D. Wiggert. 2021. Modeling the impact of the 2019 Bonnet Carré Spillway opening and local river flooding on the Mississippi Sound. In *OCEANS 2021: San Diego–Porto*, 1–7. IEEE.
38. Rabalais, N. N., and R. E. Turner. 2019. Gulf of Mexico hypoxia: Past, present, and future. *Limnology and Oceanography Bulletin* 28 (4): 117–124.
39. Kane, D. D., J. D. Conroy, R. P. Richards, D. B. Baker, and D. A. Culver. 2014. Re-eutrophication of Lake Erie: Correlations between tributary nutrient loads and phytoplankton biomass. *Journal of Great Lakes Research* 40: 496–501.
40. Ludsin, S. A., M. W. Kershner, K. A. Blocksom, R. L. Knight, and R. A. Stein. 2001. Life after death in Lake Erie: Nutrient controls drive fish species richness, rehabilitation. *Ecological Applications* 11 (3): 731–746.
41. Steffen, M. M., T. W. Davis, R.M.L. McKay, G. S. Bullerjahn, L. E. Krausfeldt, J. M. Stough, M. L. Neitzey, N. E. Gilbert, G. L. Boyer, T. H. Johengen, and D. C. Gossiaux. 2017. Ecophysiological examination of the Lake Erie Microcystis bloom in 2014: Linkages between biology and the water supply shutdown of Toledo, OH. *Environmental Science & Technology* 51 (12): 6745–6755.
42. Turner, R. E., N. N. Rabalais, and D. Justic. 2006. Predicting summer hypoxia in the northern Gulf of Mexico: Riverine N, P, and Si loading. *Marine Pollution Bulletin* 52 (2): 139–148. https://doi.org/10.1016/j.marpolbul.2005.08.012
43. Howarth, R. W., and R. Marino. 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnology and Oceanography* 51 (1, pt 2): 364–376.
44. Kast, J. B., A. M. Apostel, M. M. Kalcic, R. L. Muenich, A. Dagnew, C. M. Long, G. Evenson, and J. F. Martin. 2021. Source contribution to phosphorus loads from the Maumee River watershed to Lake Erie. *Journal of Environmental Management* 279:111803.

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NOT FOR SALE OR DISTRIBUTION

Merchant_Health_int_1pgs.indd 41 03/06/24 3:14 PM

45. Han, H., J. D. Allan, and N. S. Bosch. 2012. Historical pattern of phosphorus loading to Lake Erie watersheds. *Journal of Great Lakes Research* 38 (2): 289–298.
46. Beegle, D. 2013. Nutrient management and the Chesapeake Bay. *Journal of Contemporary Water Research & Education* 151 (1): 3–8.
47. Libra, R. D., C. F. Wolter, and R. J. Langel. 2004. Nitrogen and phosphorus budgets for Iowa and Iowa watersheds. https://s-iihr34.iihr.uiowa.edu/publications/uploads/Tis-47.pdf
48. Baxter, R., A. Plakkat, G. Camargo, M. Dubin, C. A. Rotz, G. Roth, and T. L. Richard. 2009. Biofuels for the bay: Cellulosic double crops in the Chesapeake watershed. In ASABE - Bioenergy Engineering Conference 2009, 259–264. American Society of Agricultural and Biological Engineers.
49. Mee, L. 2006. Reviving dead zones. *Scientific American* 295 (5): 78–85.
50. Wetzels, H. 2020. Poland, drowning in algae: Dead zones in the Baltic Sea. Paper presented at the Agriculture and Rural Convention, November 18. https://www.arc2020.eu/poland-drowning-in-algae-dead-zones-in-the-baltic-sea/#:~:text=Marine%20life%20in%20the%20Baltic,largely%20unchecked%20by%20EU%20regulations
51. Statista. Number of pigs on farms in Denmark from 2011 to 2021. https://www.statista.com/statistics/643196/number-of-pigs-on-farms-in-denmark/
52. Carstensen, J., and D. J. Conley. 2019. Baltic Sea hypoxia takes many shapes and sizes. *Limnology and Oceanography Bulletin* 28 (4): 125–129.
53. Carstensen, J., J. H. Andersen, B. G. Gustafsson, and D. J. Conley. 2014. Deoxygenation of the Baltic Sea during the last century. *Proceedings of the National Academy of Sciences* 111 (15): 5628–5633.
54. Rock, K. 2018. Growing number of concentrated animal feeding operations raises water quality concerns. Center for Rural Affairs, January 18. https://www.cfra.org/blog/growing-number-concentrated-animal-feeding-operations-raises-water-quality-concerns
55. Schilling, K. E., M. T. Streeter, A. Seeman, C. S. Jones, and C. F. Wolter. 2020. Total phosphorus export from Iowa agricultural watersheds: Quantifying the scope and scale of a regional condition. *Journal of Hydrology* 581:124397.
56. Environmental Working Group and Iowa Environmental Council. 2019. Iowa's private wells contaminated by nitrate and bacteria. https://www.ewg.org/interactive-maps/2019_iowa_wells/
57. Jones, C. S., J. K. Nielsen, K. E. Schilling, and L. J. Weber. 2018. Iowa stream nitrate and the Gulf of Mexico. *PLoS ONE* 13 (4): e0195930.
58. U.S. hog giant transforms Eastern Europe. 2009. *New York Times*, May 5. https://www.nytimes.com/2009/05/06/business/global/06smithfield.html
59. Lark, T. J., N. P. Hendricks, A. Smith, N. Pates, S. A. Spawn-Lee, M. Bougie, E. G. Booth, C. J. Kucharik, and H. K. Gibbs. 2022. Environmental outcomes of the US renewable fuel standard. *Proceedings of the National Academy of Sciences* 119 (9): e2101084119.

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NOT FOR SALE OR DISTRIBUTION

Merchant_Health_int_1pgs.indd 42 03/06/24 3:14 PM

60. Ruess, P. J., M. Konar, N. Wanders, and M. Bierkens. 2023. Irrigation by crop in the Continental United States from 2008 to 2020. *Water Resources Research* 59 (2): e2022WR032804.
61. Wheeler, K. G., B. Udall, J. Wang, E. Kuhn, H. Salehabadi, and J. C. Schmidt. 2022. What will it take to stabilize the Colorado River? *Science* 377 (6604): 373–375.
62. Rhodes, E. C., H. L. Perotto-Baldivieso, E. P. Tanner, J. P. Angerer, and W. E. Fox. 2023. The declining Ogallala aquifer and the future role of rangeland science on the North American High Plains. *Rangeland Ecology & Management* 87: 83–96.
63. Little, J. B. 2009. The Ogallala aquifer: Saving a vital U.S. water source. *Scientific American*, March 1.
64. Jackson, R. D. 2022. Grazed perennial grasslands can match current beef production while contributing to climate mitigation and adaptation. *Agricultural & Environmental Letters* 7 (1): e20059.
65. Hatfield, J. L., L. D. McMullen, and C. S. Jones. 2009. Nitrate-nitrogen patterns in the Raccoon River basin related to agricultural practices. *Journal of Soil and Water Conservation* 64 (3): 190–199.
66. Reich, D., and J. B. Kliebenstein. 2006. Economics of breeding, gestating and farrowing hogs in "natural pork" production; financial comparison. *Iowa State University Animal Industry Report* 3 (1). https://porkgateway.org/wp-content/uploads/2015/07/economics-of-breeding-gestating-and-farrowing-hogs-in-natural-pork-production-financial-comparison1.pdf
67. Martin, G., K. Barth, M. Benoit, C. Brock, M. Destruel, B. Dumont, M. Grillot, S. Hübner, M. A. Magne, M. Moerman, and C. Mosnier. 2020. Potential of multi-species livestock farming to improve the sustainability of livestock farms: A review. *Agricultural Systems* 181:102821.
68. Oklahoma Water Resources Board. XXXX. Water quality standards. 2020–2021 Illinois River watershed total phosphorus criterion. https://www.owrb.ok.gov/rules/wqs/revisions/totalphosphorous.php
69. Crawford, G. 2023. Report: Phosphorus in river watershed still too high. *Tahlequah Daily Press*, February 23. https://www.tahlequahdailypress.com/news/report-phosphorus-in-river-watershed-still-too-high/article_fdb58ac6-c0e9-55fc-b22b-4254f863adc1.html
70. Thompson, D. 2023. Arkansas poultry companies pollute Illinois River, federal judge rules. *Arkansas Democrat Gazette*, January 20. https://www.arkansasonline.com/news/2023/jan/20/arkansas-poultry-companies-pollute-illinois-river/
71. Khanal, S. K. 2011. *Anaerobic biotechnology for bioenergy production: Principles and applications*. John Wiley & Sons.
72. Lazenby, R. 2022. Rethinking manure biogas. Policy considerations to promote equity and protect the climate and environment. Vermont Center for Agriculture and Food Systems. https://www.vermontlaw.edu/academics/centers-and-programs/center-for-agriculture-and-food-systems/reports/manure-biogas

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NOT FOR SALE OR DISTRIBUTION

Merchant_Health_int_1pgs.indd 43 03/06/24 3:14 PM

73. Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. DeClerck, A. Wood, and M. Jonell. 2019. Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* 393 (10170): 447–492.
74. Schneider, K. 2023. 'A national scandal': How US climate funding could make water pollution worse. *The Guardian*, February 8. https://www.theguardian.com/environment/2023/feb/08/biden-climate-law-pollution-midwest
75. Strong, J. 2022. Company filled massive manure container despite signs of a leak, DNR says. *Iowa Capital Dispatch*, July 6.
76. Jordan, E. 2021. No OSHA probe of man who died in dive into farm digester. *Cedar Rapids Gazette*, June 17.
77. Whitnall, T., and N. Pitts. 2019. Global trends in meat consumption. *Agricultural Commodities* 9 (1): 96–99.
78. Ritchie, H., P. Rosado, and M. Roser. 2019. Meat and dairy production. Our World in Data. https://ourworldindata.org/meat-production
79. Barclay, E. 2012. A nation of meat eaters: See how it all adds up. National Public Radio, June 27. https://www.npr.org/sections/thesalt/2012/06/27/155527365/visualizing-a-nation-of-meat-eaters#:~:text=As%20Allison%20Aubrey%20and%20Dan,plants%20to%20raise%20and%20transport
80. Mertens, E., A. Kuijsten, H. H. van Zanten, G. Kaptijn, M. Dofková, L. Mistura, L. D'Addezio, A. Turrini, C. Dubuisson, S. Havard, and E. Trolle. 2019. Dietary choices and environmental impact in four European countries. *Journal of Cleaner Production* 237:117827.
81. Kolbert, E. 2019. Louisiana's disappearing coast. *The New Yorker*, April 1.
82. Carruth, A. 2009. War rations and the food politics of late modernism. *Modernism/Modernity* 16 (4): 767–795.
83. Garnett, E. E., A. Balmford, T. M. Marteau, M. A. Pilling, and C. Sandbrook. 2021. Price of change: Does a small alteration to the price of meat and vegetarian options affect their sales? *Journal of Environmental Psychology* 75:101589.
84. Charlebois, S., M. McCormick, and M. Juhasz. 2016. Meat consumption and higher prices: Discrete determinants affecting meat reduction or avoidance amidst retail price volatility. *British Food Journal* 118 (9): 2251–2270
Rabalais, N. N., R. E. Turner, and W. J. Wiseman Jr. 2002. Gulf of Mexico hypoxia, aka "the dead zone." *Annual Review of Ecology and Systematics* 33: 235–263.
Iowa Corn Growers Association. https://www.iowacorn.org/corn-uses/ethanol#:~:text=57%25%20of%20Iowa's%20corn%20is,for%20you%20and%20your%20family!

Other Resources

Clark, M., J. Hill, and D. Tilman. 2018. The diet, health and environment trilemma. *Annual Review of Environment and Resources* 43:109–134. https://doi.org/10.1146/annurev-environ-102017-025957.

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NOT FOR SALE OR DISTRIBUTION

Merchant_Health_int_1pgs.indd 44 03/06/24 3:14 PM

Lemaire, G., A. Franzluebbers, P. César de Faccio Carvalho, B. Dedieu. 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agriculture, Ecosystems and Environment*. http://dx.doi.org/10.1016/j.agee.2013.08.009.

Magdoff, F., L. Lanyon, and B. Liebhardt,1997. Nutrient cycling, transformations, and flows: Implications for a more sustainable agriculture. *Advanced Agronomy* 60:1–73. https://doi.org/10.1016/S0065-2113(08)60600-8.

Martin, M., M. Moraine, J. Ryschawy, M.A. Magne, M. Asai, J.-P. Sarthou, M. Duru, and O. Olivier. 2016. Crop–livestock integration beyond the farm level: A review. *Agronomy for Sustainable Development* 36:53.

Sulc, R. M., and B. Tracy. 2007. Integrated crop–livestock systems in the U.S. Corn Belt. *Agronomy Journal* 99:335–345.

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Madison Hokanson Attachment

July 22, 2025

Comments on Planned Amendments to Rules Governing Animal Feedlots
Minnesota Rules – Chapter 7020

We appreciate the opportunity to give our comments on the 7020 Feedlot Rule review here in Minnesota. As pig and cattle farmers in Goodhue County, we are proud to call Southeast Minnesota home, and environmental and land stewardship is something we take very seriously. Our family has been farming livestock and crops on the same land for nearly 140 years, and that has only been possible because of the dedication our family and so many other family farms across Minnesota have to continuously improve our farming practices and protect our natural resources.

The current MPCA 7020 Feedlot Rules originally implemented in 2000 have done a lot in the way of improving the farming practices of livestock farmers across the state of Minnesota. As this consideration for rule review takes place, it would be logical to first look at the ways the current 7020 Feedlot Rules are being enforced to see how we can continue to improve our environmental stewardship in agriculture within the boundaries that have already been set before seeking to add additional regulations.

As farmers in the bluffs and valleys leading to the Mississippi River, we work hard to implement best management practices (BMPs) that ensure water quality (both surface water and groundwater) is not compromised, the nutrients from manure applied onto our pasture and crop ground can be utilized fully by the plants they are intended for, and the varied topography of our ground will remain intact now and into the future. Having flexibility with our current liquid manure application windows in both fall and spring enables us to apply that natural fertilizer when the environmental conditions are most fit to do so. If manure application were to only be allowed in the spring – a season of high weather variability – the outcome would likely be more rushed application, corners being cut just to get the job done, and not following environmental indicators to determine the true best time to apply the manure.

We are proud to call ourselves farmers, but our goals are not so different from those of our rural neighbors. We live on the same ground, drink the same water, and breathe the same air as the people who live in our communities, and it is a farmer’s goal to leave their farm for the next generation better than how it was passed to them. In order for us to do that, we will steward our land well by continuously improving our farming practices, using science-based research as our guide. It is our strong suggestion that any changes or additions to the 7020 Feedlot Rules be implemented and enforced only when that same sound science-based research agrees with and supports those modifications.

Once again, we appreciate the opportunity to provide comments on the 7020 Feedlot Rule review, and we hope the current efforts of farmers across the state are fully understood and taken

into consideration before undue regulation is put into place that will likely have a very negative impact on livestock farms of all sizes and types.

Sincerely,

Brandon Schafer
Max Schafer
Maddie Hokanson

Schafer Farms, Inc.

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By: OAH on 7/22/2025
Elisabeth Holmes Attachment

SRAP
Socially Responsible Agriculture Project

July 22, 2025

Via Online Portal
https://minnesotaoah.granicusideas.com/discussions/40661-minnesota-pollution-control-agency-request-for-comments-on-animal-feedlots-rule

Office of Administrative Hearings
600 North Robert Street, P.O. Box 64620
St. Paul, Minnesota 55164-0620

RE: Comments on Amending Minnesota Ch. 7020 Animal Feedlot Rules

Dear Office of Administrative Hearings:

Socially Responsible Agriculture Project (SRAP) is a nonprofit 501(c)(3) organization. For more than 20 years, SRAP has served as a mobilizing force to help communities protect themselves from the damages caused by industrial livestock operations, and to advocate for a food system built on regenerative practices, justice, democracy, and resilience. SRAP offers free support, providing communities with the knowledge and skills to protect their rights to clean air, water, and soil and to a healthy, just, and vibrant future. Across the U.S., SRAP receives requests for help from communities on the frontlines of industries streaming from industrial livestock business. SRAP has worked with several communities across Minnesota over the last few years to help them protect themselves from industrial livestock operations, and SRAP submitted comments on the Minnesota NPDES and SDS draft permits issued in 2024. SRAP submits these comments regarding the first round of public comments for the Chapter 7020 rulemaking and SRAP also incorporates by reference the comments submitted by Yale, Minnesota Center for Environmental Advocacy, and Food & Water Watch.

MPCA's stated purposes of this rulemaking process are to address changes in livestock and poultry operations and business practices, account for new agency data services, modernize outdated rule language, amend existing feedlot rules to improve land application of manure practices to address nitrates, bacteria, and fish kills, and establish additional technical standards to protect water quality and avoid fish kills. SRAP's comments focus on: (1) size of feedlot operations; (2) ownership transparency; (3) cumulative impacts of feedlot operations; (4) surface and groundwater contamination; (5) restricting land applications; (6) anaerobic digestion.

(1) Chapter 7020 Revisions Must Address Industry Changes in Operation Size.

Minnesota's animal agriculture program regulates "large" operations (1,000 animal units "or more") via the NPDES and SDS permit program, and all other operations via the feedlot rules. Neither federal rules or Minnesota rules establish any upwards cap on the number of animals or animal units subject to regulation in the "large" operation category. And neither federal rules or Minnesota rules recognize mega factory farms' outsized environmental impacts. These gaps can be corrected through the Chapter 7020 rulemaking process; without MPCA taking action, industry will only be obligated to follow an inappropriately designed regulatory framework that is acutely inadequate to protect Minnesotans from environmental pollution.

According to public records, Minnesota currently has approximately 38,158 feedlots subject to Chapter 7020.[1] One of the critical questions MPCA is evaluating through this rulemaking process relates to the size of operations covered by Chapter 7020 and corresponding rules. Since MPCA promulgated Chapter 7020 in 1971 and updated it in 2000, across the U.S. significant changes have occurred in the industry relating to facility size. Livestock operations increased in size, creating "extremely large" operations colloquially called megafarms. USDA National Agricultural Statistics Service (NASS) data confirms that the number of "mega" factory farms in the U.S. has essentially doubled since 2000 for chickens, egg layers, dairy cows, and pigs.[2] Some examples of "mega" factory farms include, for instance: Blackshirt Feeders (Nebraska) (under permitting to house 150,000 head of cattle and 36 digesters);[3] Simplot's Grand

[1] MPCA datasets "Feedlots Minnesota annotated" (accessed July 6, 2025) available at https://gisdata.mn.gov/dataset/env-feedlots (some feedlots may be "inactive" or "not required to registered" but most of the more than 38,000 feedlots are required to actively participate in Chapter 7020).
[2] See, e.g., USDA NASS trend data summarized in Bolotnikova, M. and Torrella, K. "9 charts show US factory farming is even bigger than you realize: Factory farms are now so big that we need a new word for them." Vox (Feb. 26, 2024) available at https://www.vox.com/future-perfect/24079424/factory-farming-facts-meat-usda-agriculture-census
[3] Hammel, P. "Largest feedlot in Nebraska to start taking feeders later this month." Nebraska Examiner (Sept. 3, 2024) available at https://nebraskaexaminer.com/2024/09/03/largest-cattle-feedlot-in-nebraska-to-begin-taking-feeders-later-this-month/

View (Idaho) feedlot (authorized to manage up to 150,000 head of cattle);[4] Innovative Livestock Solutions (Kansas) (recently permitted to operate a facility with a capacity of 88,000 head of cattle);[5] and in Coffee County (Georgia), community members are currently opposing a proposed 60-barn poultry operation that would confine up to three million chickens.[6] Minnesota is no stranger to the mega factory farm problem; MPCA has permitted Golden Oaks Dairy to house 43,385 dairy cattle, and Woitalla Dairy LLC to operate a facility with 48,446 cows.[7]

Operation size plays into all other problems in the livestock production industry, including for example over generation of manure, overapplication of waste, expansive reach of waste within and across watersheds, and the generation of methane and GHG emissions (see also Yale comments submitted for this public comment period). Mega factory farms significantly magnify these problems and their impacts on communities, including heightened risks of groundwater and surface water contamination, air pollution, and increased greenhouse gas emissions. Additionally, the logistics of storing, transporting, and disposing of such massive volumes of waste present an additional layer of environmental and regulatory challenges. At the most basic level, decades of using current regulatory frameworks for the "small", "medium", and "large" size CAFOs have already clearly demonstrated that existing rules are completely insufficient to protect the environment from the livestock industry.[8] It would thus be unreasonable for MPCA to take the position that pollution from mega factory farms could be eliminated, or lessened, or controlled by relying on the same rules. As part of the rulemaking review here, we strongly encourage Minnesota to conduct its due diligence and seriously consider at least the following points:

- How other states have *started* to respond to mega factory farms by proposing different regulatory and permitting frameworks, and consider those frameworks as the *floor* for what needs to be done to protect the environment.
- Whether there should be a baseline number of animal units or headcount at which a facility is categorically considered a "mega" feedlot, factory farm, or CAFO.
- Whether there should also be an upper cap on the total number of animal units allowed under a single mega facility, beyond which no new CAFO or feedlot may be permitted.

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[4] Tobier, L. "Idaho environmentalists sue an alleged polluter to protect state's water." Investigate Midwest (July 31, 2024) available at https://investigatemidwest.org/2024/07/31/idaho-environmentalists-sue-an-alleged-polluter-to-protect-states-water/; see also Wickersham, B. "The biggest CAFO in the United States". Wickersham's Conscience (Blog) (March 20, 2020) available at https://wickershamsconscience.wordpress.com/2020/03/20/the-biggest-cafo-in-the-united-states/

[5] Gilmore, M. "KDHE issues WPC permit for ILS facility." Great Bend Tribune (April 28, 2025) available at https://www.gbtribune.com/news/local-news/kdhe-issues-wpc-permit-for-ils-facility/?utm_source=chatgpt.com

[6] Sotelo, G. "How Georgia residents hope to protect their river from an industrial poultry farm." Sentient Media (July 9, 2025) available at https://sentientmedia.org/georgia-residents-protect-their-river-from-industrial-farm/

[7] https://gisdata.mn.gov/dataset/env-feedlots

[8] See, e.g., MPCA Enforcement Case Summaries for 2022, 2023, 2024 (identifying multiple feedlot rules violations over the years) available at https://www.pca.state.mn.us/trending-topics/compliance-and-enforcement

- How MPCA should improve current inadequate setback, manure management, and land application requirements, recordkeeping and monitoring requirements, and surface and groundwater protection measures to withstand the intensified increased risks posed by mega feedlots.
- How MCPA should improve its enforcement of Chapter 7020 rules, especially for mega feedlots.
- Mega feedlots must trigger a more rigorous permitting process, including mandatory cumulative impact assessments and full environmental reviews that go deeper into the basic framework provided in Minnesota's existing Environmental Assessment Worksheets.
- Mega feedlots must be categorically prohibited from being constructed over, and from land applying over or into sensitive groundwater areas or geologic formations such as karst terrain.
- Given the sheer volume of waste produced by mega CAFOs, additional considerations must be required to ensure the safe, transparent, and environmentally responsible storage, transfer, transport, and land application of manure (on-site and exported manure).

One simple starting point is to establish a modest, reasonable upward cap on the number of animal units allowed within a single feedlot (or in jointly owned feedlot operations) until Minnesota solidifies a protective regulatory framework that ensures all feedlots can meet existing rules, and mega operations do not pollute the environment.

We also suggest that MPCA's review of the animal units / animal number question try to address what is colloquially called the "one under" problem. In many states, SRAP regularly sees operations regulated under lower standards simply because they report on paper being "one (cow, chicken, pig) under" the next regulatory (more stringent) threshold. This practice intentionally subverts regulatory compliance, and we recommend that MPCA consider incentives to eliminate this practice in Minnesota.

(2) <u>Ownership Transparency.</u>

Another concerning trend SRAP is seeing across the U.S., which MPCA can address in its Chapter 7020 rule review, relates to ownership transparency. Here,

- Chapter 7020.0350(1)(B) (relating to registration) requires the disclosure of "all owners" of the feedlot or manure storage area. Chapter 7020.0505(4)(A) (relating to permit applications) requires the names and addresses of the owners. Neither provision requires disclosure of the owners of land application areas owned, or used, by the feedlot or permitted operation.

- Mega feedlots and mega operations are increasingly owned by multiple individuals, businesses, and partnerships in shared ownership models … which in turn may be owned by other business entities. The layers make it difficult for the public to understand the true interests of a registration or permit applicant.
- Update rules to prohibit field sharing and self-transfers of manure (see SRAP's September 2, 2024 Comments to MPCA on the NPDES and SDS permits, p. 3-5).

Additionally, SRAP has observed a growing trend of intermingled ownership between feedlot and CAFO owners and anaerobic digester investors and operators, which raises significant concerns regarding transparency, liability, enforcement abilities, and regulatory oversight. If OAH incorporates anaerobic digesters into the revised rule, SRAP recommends the following points relating to ownership transparency:

- Expand the definition of "owner" to include anaerobic digester owners. "Owner" should be defined as any person or entity with possession, control, or title to an animal feedlot, manure storage area, or an anaerobic digester.
- Update Chapter 7020 to accommodate for shared ownership structures where the feedlot or CAFO and the anaerobic digester operation are not owned or operated by the same party or parties.
- Bind both parties to regulatory conditions. The rule should make clear that both the feedlot or CAFO owner(s) and the anaerobic digester owner(s) are independently and jointly bound to comply with all applicable terms and conditions of either Chapter 7020, the SDS Permit, the NPDES Permit, and all other applicable laws.
- Require written formal public agreements between feedlot owner(s) and digester owner(s). The owner and the anaerobic digester owner or operator must enter into a written agreement that clearly affirms shared responsibility for compliance. This agreement must be signed by both parties or their legally authorized representatives. Signatures must follow the appropriate authority level, as outlined below:

    - Corporation: Signed by a principal executive officer (at least the level of vice president), or their designated representative, if the representative is responsible for the overall operation of the facility. Documentation must be provided to verify this authority.
    - Limited Liability Company (LLC): Signed by a managing member.
    - Limited Liability Partnership (LLP): Signed by a managing partner.
    - Partnership: Signed by a general partner.
    - Sole Proprietorship: Signed by the proprietor.
    - Municipal, state, or other public entity: Signed by a principal executive officer, such as a mayor.

This last requirement is important because for decades state agencies have allowed parties with little vested interest in a livestock operation's compliance to sign for the facility. With the combined increased risk of mega feedlots and anaerobic digesters, greater security for accountability is essential and the appropriate signature is the minimum way to establish this.

(3) <u>Cumulative Impacts</u>

Minnesota's Environmental Policy Act (Minn. Stat. 116D) and accompanying regulations (Minn. R. Chapter 4410) "promote efforts that will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of human beings." Minn. Stat. 116D.01(2). MEPA further recognizes "particularly the profound influences of …industrial expansion." Minn. Stat. 116D.02(1). To address the increasing number of public health impacts stemming from feedlots in small geographic areas, in 2019 the American Public Health Association issued a precautionary moratorium on new and expanding CAFOs.[9]

We propose that as part of this rule review, MPCA require certain operations to complete the detailed environmental impact statement process, not merely the environmental assessment worksheet. The EIS process is appropriate when there is a "potential for significant environmental effects." Minn. Stat. 116D.04(2a) (2024, 2025 1st session). While the statute exempts some feedlots from environmental review (Minn. Stat. 116D.04(2a)(f)), the exemption only applies to operations < 1,000 animal units and feedlots that execute a "written commitment" to comply with MPCA feedlot rules. Id. at (f)(2). Given the impacts of large, and mega, feedlots, greater environmental disclosure and mitigation should be required through the EIS process.

Increasingly, the siting of feedlots is occurring in close proximity to existing, or other new feedlot facilities. The localized increased impacts of animals, waste generation and storage, land applications, and attendant activities (transportation of feed, waste) must be identified, disclosed, considered, and addressed through mitigation measures. While Minnesota's EAW Form can identify some cumulative impacts, we remain concerned that some of the following scenarios that we are seeing across the U.S. may not be identified through the current environmental review process or their cumulative impacts mitigated.

- **Neighboring feedlot concerns**
    - For example, feedlots across the road from each other, where they may or may not be under separate ownership, magnify and intensify the impacts on local communities.

[9] American Public Health Association, Precautionary Moratorium (Nov. 5, 2019) ("Over the last several decades, food animal production in the United States has shifted from an extensive system of small and medium-sized farms to one characterized primarily by large-scale industrial operations that concentrate large numbers of animals in small geographic areas.") available at https://www.apha.org/policies-and-advocacy/public-health-policy-statements/policy-database/2020/01/13/precautionary-moratorium-on-new-and-expanding-concentrated-animal-feeding-operations

- **Expansion rates of multiple feedlots in small areas**
    - For example, states like Georgia, Missouri, and Nebraska have recently seen a proliferation of new feedlots within small areas / similar watersheds. See, e.g., Missouri DNR's review of nine poultry applications within a small area of Southwest Missouri;[10] the Coffee County, Georgia, proposal to build 60 poultry barns on a 1,000 acre parcel;[11] the expansion of Summit pork swine CAFOs in Nebraska.[12]

- **Field sharing**
    - This occurs when a manure generator and/or recipient simply uses a different Field ID. This practice of field sharing occurs without MPCA or the public knowing. If Minnesota were to require at a minimum the level of information that states like Michigan require, Minnesota would greatly increase transparency, enabling the state and the public to ensure that the improper practice of field sharing is not occurring in Minnesota, and thus offer an additional opportunity to protect Minnesota waters. See SRAP NPDES and SDS Comments to MPCA p. 3-5 (Sept. 3, 2024).

- **Self-transfers of manure**
    - Under Minnesota rules, a CAFO's ownership of manure ends when the manure is physically transferred or relinquished to a manure recipient. The manure recipient then land applies the manure to its fields, or fields the manure recipient has access to. Manure recipients must follow the protective measures identified in the CAFO permittee's approved manure management plan to minimize the risk of surface and groundwater contamination from manure applications. See Minnesota R. 7001.0150. However, SRAP sees a practice occurring across the U.S. where CAFOs play a "shell game" of land ownership, trucking ownership, and/or manure recipient ownership. In those scenarios, manure is being treated as "exported" off site to another recipient, even though a CAFO may own or control the manure recipient, and the CAFO may own or control—through shell ownership or strawman relationships—the land where the manure is being applied. Similar to the first problem above, this practice can result in inaccurate nutrient balance tallies, surface and groundwater discharge, contamination problems, and excessive nutrient loading in Minnesota's

[10] Missouri DNR, Water Pollution Control Sites of Interest available at https://dnr.mo.gov/water/business-industry-other-entities/sites-interest/southwest-mo-concentrated-animal-feeding-operation-cafo-facilities
[11] See n. 6 supra.
[12] Investigate Midwest, "Pigs and Power" 2023-2024 series available at https://investigatemidwest.org/pigs-and-power/

watersheds. Without accurate land ownership and manure recipient disclosures, fields will be over-applied with amounts of waste that compromise water quality. SRAP encourages MPCA to develop rules and a Nutrient Management Tool[13] to account for this problem, so that a Nutrient Management Tool minimizes runoff and contamination risks of every field, and that does not consider waste "transferred" when in fact it is still within the permitted CAFO's ownership or control.

Lastly, we appreciate Minnesota's inclusion of GHG factors in the EA Worksheet, and note that there is additional room for improvement as raised in the Yale comments submitted during this public comment period.

(4) Surface and Ground Water Contamination Require Stronger Monitoring.

There is significant surface and groundwater contamination in Minnesota that is persisting and that MPCA must address through improved Chapter 7020 feedlot rules. The 2024 Minnesota Impaired Waters List is an indicator of significant water contamination in Minnesota.[14] In 2024, there were:

- 739 waterways impaired for *nutrients*
- 671 waterways impaired for *E. coli*
- 239 waterways impaired for *fecal coliform*
- 31 waterways impaired for *nitrate*

The majority of these impaired waterways occur in the southern half of the state, which is also where MPCA's Feedlot Nutrient Management Planning Map confirms the majority of Minnesota feedlots are sited.[15] State agencies,[16] and reports and studies, have repeatedly found[17] that feedlots have significant negative impacts on water quality in Minnesota.

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[13] SRAP acknowledges MPCA has recently released its Nutrient Management Tool, which we intend to separately review for how it addresses this issue.
[14] Available at https://www.pca.state.mn.us/air-water-land-climate/minnesotas-impaired-waters-list (approved by EPA April 2024).
[15] See MPCA Feedlot Program NMP Map available at https://experience.arcgis.com/experience/b99690542f364a6dace31df6fab2e55a/page/Page
[16] See, e.g., MPCA, "The Minnesota Nutrient Reduction Strategy." (2014) available at https://www.pca.state.mn.us/sites/default/files/wq-s1-80.pdf; MPCA "Work Plan: Addressing Nitrate in Southeast Minnesota (2024) available at https://www.health.state.mn.us/communities/environment/water/docs/wells/waterquality/epaworkplan.pdf
[17] See, e.g., Environmental Working Group, "Manure Overload: Manure Plus Fertilizer Overwhelms Minnesota's Land and Water." (May 28, 2020) available at https://www.ewg.org/interactive-maps/2020-manure-overload/; Hanson, M. et al., "The Debate about Farm Nitrates and Drinking Water." Choices: Agricultural & Applied Economics Association. (2016 Q1) (see Minnesota example highlighting feedlots as contributors to nitrate pollution) available at https://www.jstor.org/stable/choices.31.1.07.

Subsurface discharges of manure to groundwater from feedlots is a significant issue in Minnesota[18] and in the United States.[19] In 2016, MPCA found that between 44% and 59% of groundwater monitoring wells sampled in central Minnesota (Central Sands area) were contaminated with nitrates beyond the federal drinking water standard.[20] Feedlot manure contamination can occur anywhere, but vulnerable groundwater areas in the state as identified by the Minnesota Department of Agriculture's Vulnerable Groundwater Area Map[21] are particularly problematic. Other states (e.g., Washington, Wisconsin) with risks to groundwater contamination from feedlots, factory farms, or CAFOs require groundwater monitoring. During the Chapter 7020 rule review, we suggest that MPCA explore options for advancing and progressing groundwater monitoring requirements, and we look forward to participating in that process.

(5) Restricting Land Applications

Restricting land application of manure in areas with high levels of nitrate in surface or groundwater, and in areas with existing high densities of feedlot operation is vital to protect Minnesota's water resources. Land applications of feedlot manure contribute significantly to nitrate contamination in surface and ground water, and MPCA should update the Chapter 7020 Feeldot Rule to implement the following regulations for land application in vulnerable groundwater areas or in areas with high concentrations of feedlots, for example:

- Decrease current allowable quantities of manure land applied.
- Increase manure application setback distances from surface waters.
- Require groundwater monitoring.
- Strengthen soil monitoring
- Require soil moisture sensors.
- Strengthen visual inspection requirements.
- Eliminate practices such as field sharing and self-transfers of manure (see (3) above).

SRAP looks forward to further participation in this process and discussing land application proposals in more detail.

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[18] See, e.g., Schneider, K. "US regulators order Minnesota to clean up nitrate contaminated water." Investigate Midwest (Nov. 13, 2023) available at https://investigatemidwest.org/2023/11/13/us-regulators-order-minnesota-to-clean-up-nitrate-contaminated-water/#:~:text=Nitrates%20form%20when%20nitrogen%20from,of%20ovarian%20cancer%20in%20women.

[19] See, e.g., USDA Economic Research Service, "Groundwater organizations see nitrate as a top concern." (May 15, 2023) available at https://www.ers.usda.gov/data-products/charts-of-note/chart-detail?chartId=106487

[20] See MPCA, "Groundwater Protection Recommendations Report" at 5 (January 2016) available at https://www.pca.state.mn.us/sites/default/files/lrwq-gw-1sy16.pdf

[21] See Minnesota Department of Agriculture available at https://www.mda.state.mn.us/chemicals/fertilizers/nutrient-mgmt/nitrogenplan/mitigation/wrpr/wrprpart1/vulnerableareamap

(6) Anaerobic Digesters

Anaerobic Digesters Are Industrial Fuel Operations, Not Livestock Facilities

The concept of a digester is not new. In Minnesota, the first manure digester was installed in 1990.[22]. The early, first-generation anaerobic digesters were designed primarily to manage manure from a single farm. Their key purposes were odor and fly reduction, generation of heat, and limited on-site electricity production. However, their indented scale has dramatically shifted over the last 30 years

In contrast, modern industrial anaerobic digesters are fundamentally different in scale, purpose, and environmental impact. These systems are engineered to process large volumes of input streams, including not only manure but also other waste materials such as food waste. Their primary purpose is the production of methane, which is then either converted into compressed natural gas (CNG) or liquefied natural gas (LNG) for off-site transport via truck or pipeline injection, or used to generate electricity. These facilities can potentially produce several megawatts (MW) of electricity, enough to power entire cities. The electricity generated can then be sold to utility companies and fed into the electrical grid, underscoring the industrial scale of these operations. However, currently, the technology and infrastructure to actually connect to grids is underdeveloped; in fact most anaerobic digesters SRAP hears about simply load explosive gas onto trucks and transport gas to utilities.

In Minnesota, six permitted anaerobic digesters are currently on big dairy farms drawing from 26,385 cows.[23] Of these farms, two use the energy onsite for cogeneration (generating both electricity and useful heat), three exclusively produce methane for CNG, and one sells electricity to the grid.[24] In the past year, the Minnesota Public Utilities Commission approved two more anaerobic digesters of manure facilities to serve Xcel and CenterPoint.[25]

The clear trend is a shift away from first-generation facilities toward building anaerobic digesters as fuel conversion facilities. In fact, MPCA has opted to classify anaerobic digesters as "fuel conversion facilities" under Minnesota Rules, part 4410.4400, subpart 5, which are subject to mandatory environmental review when processing 25,000 dry tons or more per year of input. This regulatory classification reinforces that industrial-scale anaerobic digesters are not agricultural in nature, but are instead large-scale industrial energy operations.

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[22] MPCA, "Regulatory requirements for anaerobic digesters." (Document No. WQ-F8-54)" (Sept. 2023) available at https://www.pca.state.mn.us/sites/default/files/wq-f8-54.pdf

[23] EPA, Agstar Livestock Anaerobic Digester Database. Last visited Jul. 22, 2025. Available at https://www.epa.gov/agstar/livestock-anaerobic-digester-database

[24] Id.

[25] Citizen Utility Board of Minnesota. "PUC approves $55 million Xcel gas-decarbonization pilots." (Feb. 12, 2025) available at https://cubminnesota.org/puc-approves-55-million-xcel-gas-decarbonization-pilots

Thus feedlots that include industrial anaerobic digesters to produce methane should not be allowed to include the anaerobic digesters under the rubric of an NPDES or SDS General Permit or the Chapter 7020 feedlot rule, because anaerobic digesters are wholly separate point sources under 33 U.S.C. § 1362(14) and industrial activities separate from agriculture. Moreover, the trend in the anaerobic digester industry is now moving towards developing "hubs", facilities designed to generate methane gas for transport or injection into pipelines, or methane "refineries" flaring gas produced from waste. These activities are well outside the realm of the core operations of a livestock feedlot, such as housing and raising livestock, storing feed and manure, and land-applying manure, and are fundamentally different from anaerobic digestion and methane production that Chapter 7020 was designed to address. Unfortunately, the MPCA has missed the mark by misusing its permitting authority and shoehorning digesters—a completely separate point source—into the recently revised SDS CAFO Permit (MN450000) and NPDES CAFO Permit (MNG440000). The approach in the new SDS and NPDES CAFO Permits only confuses the issue. MPCA can use this rulemaking process to carve out digesters from feedlot rules, placing their management and oversight back in the "fuel conversion facility" domain where they belong.

By allowing anaerobic digesters to operate under a CAFO permit, the Minnesota Pollution Control Agency is impermissibly conflating two entirely different industries. Anaerobic digesters are not merely an accessory to animal agriculture, they are independent industrial operations and a significant source of pollution in their own right. However, OAH has the authority to correct this error and we urge OAH to exclude anaerobic digesters from the NPDES and SDS permits and the feedlot rules, and to explicitly clarify in Chapter 7020 that anaerobic digesters require separate and distinct permits that align more appropriately with industrial fuel conversion operations.

Anaerobic Digester Construction Should Constitute a Major Permit Modification

If an anaerobic digester is proposed after a NPDES or SDS CAFO permit has already been issued, or a feedlot has been registered under the Chapter 7020 rules, its addition should be considered a "major modification" of the existing permit or registration. Anaerobic digesters are distinct industrial operations that introduce new environmental, operational, and regulatory considerations, including additional point source discharges, air emissions, and off-site waste transport concerns. Their inclusion warrants a rigorous review process that should, at a minimum, require a life cycle analysis, a full environmental impact review, and meaningful public participation under the framework of a major permit modification. We ask that MPCA account for these impacts in revising Chapter 7020 and consider how the modification would be regulated under Minnesota Rules, part 4410.4400, subpart 5 as well.

Conclusion

Thank you for your consideration of the issues identified above. The emergence of mega factory farms represents a scale of industrial livestock production that current regulations were not designed to govern. Minnesota now has the opportunity to proactively address gaps in Chapter 7020 before these operations take further root in the state. By updating registration and permitting requirements, strengthening operation controls, recordkeeping and reporting mechanisms, environmental review, setting enforceable limits on scale and siting, as well as enforcement mechanisms, the state can move towards safeguarding its water, air, lands, and communities. We look forward to participating in the rulemaking process.

Sincerely,

s/ Elisabeth Holmes
Elisabeth Holmes, Senior Counsel
Charline Whyte, Staff Attorney
Cole Dickerson, Water Rangers Program Manager
Socially Responsible Agriculture Project
elih@sraproject.org

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RIVERVIEW

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July 22, 2025

Minnesota Pollution Control Agency
Watershed Division
520 Lafayette Road North
St. Paul, MN 55155

RE: Planned Amendments to Rules Governing Animal Feedlots

Dear Mr. Schwint:

Riverview appreciates the opportunity to comment on the Minnesota Pollution Control Agency's (MPCA) proposed feedlot rulemaking process. MPCA and its staff have the important responsibility of regulating and safeguarding the well-being of our state's natural resources and environment. Riverview has been a participant in the feedlot permit program for over 50 years, and we strive to be responsible stewards of the natural resources that are essential to our state. As a regulated party that values collaborating and working in partnership with governmental agencies, we respectfully submit the following comments

1. **Have the "need" and "reasonableness" to undergo a rewriting of the feedlot rules been sufficiently established?**

   Minnesota's Administrative Procedures Act requires MPCA to issue a statement regarding the "need" and "reasonableness" of a proposed rulemaking[1]. The agency states that "the main purpose of this rulemaking is to address changes in livestock and poultry operations and business practices, account for new agency data services, modernize outdated rule language, amend existing feedlot rules to improve land application of manure practices to address nitrates, bacteria, and fish

[1] Minn. Stat. § 14.131

kills, and establish additional technical standards to protect water quality and avoid fish kills.[2]" However, Minnesota's existing regulatory and permitting framework is already comprehensive and robust. Feedlots from 50 to over 1,000 animal units have registration, permitting, and/or reporting requirements with MPCA[3]. And feedlots over 1,000 animal units are particularly well-vetted before construction and operation can even begin. These types of facilities are subject to a comprehensive environmental review process, and they operate under permits that are typically revisited every five years. The environmental review process allows the agency to determine if a proposed feedlot has the potential for significant environmental impacts. Similarly, periodically updating feedlot permits provides the opportunity to modernize requirements and standards to keep pace with changes and advancements in the livestock and poultry industries. Further, MPCA can also require feedlots to obtain Individual permits. These can be effective tools that allow the agency to address circumstances and challenges that are not expressly contemplated within the rules or the General NPDES or SDS permits. Individual permits give MPCA the ability to impose additional, more stringent requirements during feedlot construction and/or operation.

Given that MPCA is currently equipped with numerous flexible methods of reviewing and regulating feedlots, we would like to better understand the need to amend the feedlot rules.

2. What research is driving MPCA's rulemaking action?

MPCA has referenced research and how it is influencing the agency's decision to begin the feedlot rulemaking process. However, to the best of our knowledge, this research has not been specifically cited. While research can provide valuable insight, it seems that it should be specifically identified, reviewed, and understood by all interested stakeholders. Providing this research would be beneficial for agency staff and feedlot operators alike. Not only could operators review the information and evaluate its applicability, but the agency could also receive relevant feedback.

[2] Minnesota Pollution Control Agency. Request for Comments. Planned Amendments to Rules Governing Animal Feedlots, *Minnesota Rules*, chapter 7020, Revisor's ID Number R-04928. (wq-rule4-29a)
[3] Minnesota Pollution Control Agency. Feedlot registration. (wq-f4-01)

3. **What are the implications and costs for feedlot operators and other stakeholders?**

   Feedlot operations and the farmers that work with them will bear the costs to implement any new regulations. Furthermore, if the costs of compliance are disproportional to the identified need, any new regulations could be an unreasonable burden that reduces farm economic viability, discourages innovation, and stifles growth. Minnesota's dairy industry has seen particularly sharp declines in herd numbers over the last 70 years. The state's dairy herd size went from approximately 1.47 million cows in 1950 to around 460,000 in 2015, a 69 percent decline[4]. In addition to lower cow inventory numbers, this also represents a decline in economic activity and rural vitality. Rulemaking should not unreasonably interfere with feedlot viability and growth, and MPCA should consider the economic implications of new proposals relative to the identified need. However, to further assess the reasonableness of new rulemaking, we would like to better understand the probable costs of complying with any new rules.

Riverview has a long history of operating feedlots in Minnesota. We are committed to being stewards of and protecting our shared natural resources. We thank the MPCA and its staff for their work protecting and preserving our state's environment. The above comments are submitted with the hope that they will lead to substantive conversations and a more productive process for all stakeholders involved.

Sincerely,

Riverview, LLP

[4] Zimmerman, Curt, *2015 Livestock Industry Study*, Page 8. Minnesota Department of Agriculture. February 2016. 2015 Livestock Industry Study

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By: OAH on 7/22/2025
Margaret Levin Attachment

Sierra Club North Star Chapter
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William Moore, Office of Administrative Hearings
Via portal
Office of Administrative Hearings
600 North Robert Street
P.O. Box 64620, St. Paul, Minnesota 55164-0620

July 22, 2025

Dear Mr. Moore:

This letter is to provide Sierra Club North Star Chapter comments on proposed amendments to the state animal feedlot rules as requested by the Minnesota Pollution Control Agency (MPCA). Sierra Club's Minnesota North Star Chapter represents 50,000 members and supporters working to help our state's communities flourish through environmental protection. Our concerns include water quality impacts, manure management, environmental assessment of feedlots, feedlot size, regulatory oversight, and health impacts.

Water Quality Concerns

1. **Contamination of surface water**

Feedlots in Minnesota significantly impact surface water quality due to runoff from manure. This is especially true when it is applied on frozen ground or just before heavy rainfall. It also occurs when livestock have direct access to nearby water bodies or when there is excessive application of manure and fertilizer on croplands. If the crops cannot take up the nutrients, it will lead to runoff. These situations lead to several results that degrade or damage our surface waters.

- Create algal blooms due to runoff with excessive nutrients. The algae may produce toxins that are hazardous to humans and biota
- Causes eutrophication in lakes and rivers, which leads to oxygen depletion
- Increase turbidity with decreasing light penetration
- Causes fish kills that occur due to low oxygen and ammonia from spills and runoff.

Drainage systems and best management practices (BMPs) are designed and implemented to prevent, treat, and manage runoff and any contamination. BMPs entail techniques to maintain proper environmental conditions for feedlots, such as preventing contaminated runoff using well-designed drainage and treatment systems. They also

entail effectively managing manure via proper storage, handling, and application methods. The following activities can enhance feedlot water quality management.

A. All feedlots required to have feedlot permits should complete water quality monitoring at the edge of the fields where manure is applied, from any drainage structures that discharge to nearby waters, and within the body of water itself. This monitoring will assist with determining the effectiveness of drainage and BMPs in preventing, treating, and managing feedlot drainage and runoff.
B. Ensure proper timing and application techniques to minimize runoff and maximize nutrient uptake by crops.
C. Require the use of cover crops to reduce nutrient runoff and improve soil health.
D. As in the Southeast Minnesota Nitrate Strategies Collaborative Work Plan, utilize teams of experts, agronomists, water quality specialists, Soil and Water Conservation District staff. and well management experts, to go on-site to assess and consult with farmers and feedlot owners on their use of best management practices and provide recommendations on improvements and changes that would best prevent water quality impacts

2. Contamination of groundwater

In addition to surface water quality effects, feedlots can impact groundwater through poor manure management, causing the contamination of drinking water by nitrates, bacteria, and other harmful substances. Improper storage and handling of manure, both solid and liquid, can result in leaching and runoff into the surrounding environment and to groundwater. These contaminants contribute to health risks and cause the need for high-cost drinking water treatment, especially in the vulnerable karst area in southeast Minnesota, the Central Sand Plain, and shallow overutilized aquifers in northwestern Minnesota.

A. To help mitigate groundwater contamination, the same BMPs and management actions listed above under surface water contamination apply. Monitoring of groundwater for parameters due to feedlot runoff and leaching pollutants should be increased on a routine basis in areas where wells are used for drinking water, in the areas where feedlots are concentrated, and in sensitive areas where feedlots are located.
B. Assess and mitigate subsurface discharges such as leaking tanks and lagoons, improperly abandoned wells, landfills, and septic tanks.

Manure Management

1. Oversight of Manure Management Plans

The MPCA has excellent guidance and assistance for the development of manure management plans required for feedlots with 300 or more Animal Units (AU). Inspection and

follow-up to determine if the plans are being used and used correctly is needed. This includes the use of more frequent enforcement along with technical assistance such as recommended in the Southeast Minnesota Nitrate Strategies Collaborative Work Plan,

2. Spills and their Impacts

Spills are a continuing problem for facilities that utilize tanks, lagoons, and treatment of runoff. Spills of agricultural runoff and manure can lead to fish kills and surface and groundwater contamination. Examples are the Rush Creek in July 2022, Trout Valley Creek in July 2021, and Garvin Brook in September 2019. Effective prevention includes the use of secondary containment equal to the volume of the tanks or lagoons and development and implementation of spill prevention and response plans in the case of a spill, and these requirements should be mandated in a more complete way in future regulations.

3. Overload of Manure and Fertilizer Applied in Minnesota

The combination of the use of nitrogen fertilizer and manure on crops in Minnesota is likely overloading nitrogen in the cropland, impacting nitrate contamination in ground water and surface water. There are several areas in Minnesota documented by the Environmental Working Group most impacted by this overload, and this should be considered in the location and evaluation of new and expanding feedlots. Large, concentrated operations are a significant concern and threaten water quality. Feedlot size and location should be considered in new or expanding feedlot environmental assessment and permitting to prevent further overload and decrease the nitrate burden in Minnesota water quality.

4. Tile Drainage Treatment

Tile drainage systems, while beneficial for agricultural productivity, can contribute to the nitrate burden in Minnesota waters. Treatment of tile drainage resulting from croplands where manure from feedlots is used as fertilizer through treatment techniques such as saturated buffers, constructed wetlands, and bioreactors, requires further promotion in Minnesota. There is little treatment of tile drainage but there is a large contribution of nitrate to our surface and groundwaters, leading to documented, serious environmental and health effects.

Environmental Assessment

1. Feedlot Registration

A complete database of feedlots is essential to allow for research on their impacts to the environment and public health, which can be accomplished by requiring registration of all feedlots, existing, new, and any with new expansion, not only those with 50 or more animal units (AU) or 10 or more in the shoreland.

2. Environmental Assessment

New or expanding feedlots with a capacity of 500 AU or more should be required to complete environmental assessment before being granted any permit to construct or operate. In sensitive areas, such as shorelands, floodplains, or other sensitive areas (karst features, the Central Sand Plain, and shallow overutilized aquifers in northwestern Minnesota), and drinking water supply areas, all new or expanding feedlots should be required to complete environmental assessment.

Regulatory Oversight of Feedlots

1. **Need for increased oversight and use of enforcement authorities**

MPCA is responsible for regulatory activities of permitted feedlots including permit issuance, permit compliance, inspections, and enforcement. USEPA is also involved in feedlot permit compliance and will conduct inspections routinely. With the large number of feedlots in MN, MPCA cannot likely routinely inspect all those that are regulated, which is a form of effective deterrence. More frequent and routine inspections are the basis for enforcement. MPCA must review the agency's current staffing levels, inspection frequency, and enforcement protocols to promote compliance, act on violations of permits, and prevent the continued contamination of surface and ground water impacting both health and the environment.

2. **Continued and increased oversight of county activity in feedlot regulation**

Most feedlots (60%) are in delegated counties in Minnesota. These counties are responsible for feedlot permitting and oversight outside of shoreland of feedlots that hold 50 to 299 AU in their county. There are approximately 3000 registered feedlots in MN located outside of shoreland that delegated counties oversee. A review of the feasibility and effectiveness of this arrangement should be completed. There are reports of political influence affecting the management of feedlots in delegated counties leading to lack of enforcement and oversight.

Health Impacts Due to Feedlots

Feedlots are a source of health issues and concerns for the community. Without effective regulation, health impacts are a much larger concern and potential source of disease and public health risk. Examples include air quality, pathogens and other health concerns included in the comments below. Animal feedlots demonstrate a wide range of health impacts, and enforcing environmental regulations on these facilities protects the public health and informs policymakers on the need to mitigate negative effects of feedlots through regulation and adequate program funding.

1. **Air quality**

Sources of air quality concerns due to feedlots include dust and particulate matter, especially fine particles like PM2.5 that can infiltrate deep into lungs, affecting respiratory function and premature death. Gas emissions, including ammonia, hydrogen sulfide, and

methane due to breakdown of animal waste, can exacerbate asthma and bronchitis. Neighbors of feedlots note irritation of eyes, nose, throat, headaches, and nausea, which can negatively impact mental well-being and stress.

2. Pathogens

The organisms E. coli and Salmonella can contaminate water supplies, contributing to foodborne illness when crops are irrigated with water impacted by feedlot runoff. Dust due to feedlots can also contribute to this. Another concern related to pathogens is that when antibiotics are heavily used at feedlots, the bacteria can become antibiotic-resistant causing illness to be harder to treat, and is a public health concern.

3. Other Health Concerns

Health issues due to feedlots include an increased risk of death due to impacts to cardiac health when living close to feedlots. Birth defects are noted with exposure to nitrogen compounds due to feedlots, including spina bifida and anencephaly. Other health conditions associated with feedlots are increased rates of thyroid disease, kidney disease, tuberculosis, septicemia, and methemoglobinemia in infants.

The North Star Sierra Club appreciates your consideration of our comments as you move forward with changes and updates to the state feedlot rules and programs. Please feel free to contact us at 612-659-9124 or north.star.chapter@sierraclub.org.

Sincerely,

Margaret Levin, State Director
Sierra Club North Star Chapter

Water & Wetlands Stewards
Sierra Club North Star Chapter

RECEIVED
By: OAH on 7/22/2025

Darin Broton Attachment

July 22, 2025

RE: Revisor's ID Number R-4928 [OAH Docket No. 25-9003-40661]

Our farmers are dedicated to ensuring Minnesota's waters are protected for future generations while creating a healthy, vibrant agriculture economy for their families and communities. Although the agency's current feedlot rules were last updated nearly 30 years ago, they are considered concise, clear, and comprehensive.

In fact, Minnesota has some of the most thorough feedlot regulations in the country. Feedlots with fewer than 1,000 animal units are already developing and adhering to manure management plans, following the state's buffer law that protects streams and lakes from potential runoff.

As the MPCA determines its next steps regarding feedlot regulations and the 7020 rules, Minnesota AgriGrowth encourages the agency to consider the following principles and strategies.

Maintain flexibility and innovation

The 7020 rules must promote flexibility and innovation for agriculture. Best management practices evolve as new technologies and advancements in science become available. Minnesota farmers have been dealing with extreme weather and a rapidly changing climate for almost 20 years. Precision agriculture has experienced significant growth over the past 15 years, enabling the more targeted allocation of resources needed for crop growth and the reduction of nutrient runoff. Yet the agency's 7020 rules do not reflect those new realities. Agency regulations will never keep pace with new science and technology. That's why creating more flexibility and avoiding a one-size-fits-all approach must be considered in any changes to the 7020 rules.

Recognize and utilize farm-specific data

Today's farms operate with a wealth of data. While the University of Minnesota and other land-grant universities' research is comprehensive and offers a baseline of recommendations, it does not recognize the data-driven management that can improve the efficient use of nutrients and reduce possible loss to ground and surface water. Feedlot rules should allow farmers to use five-year average crop-level data to make informed decisions for their fields. This is a great opportunity for a working group of precision

agriculture experts to develop flexible and responsive rules that adapt to changing field conditions.

Incorporate existing protections

Minnesota farmers underwent an extensive process to incorporate buffer strips and setbacks to protect water quality. While state agencies have not provided clear data on how buffer strips have improved water quality, Minnesota's buffer law should be recognized in feedlot rules as a means of enhancing nutrient management and water quality.

Assess better alignment between federal and state definitions of animal units and animal numbers

The federal government's decision to use animal heads is inconsistent with Minnesota's use of animal units. Additionally, the calculation of animal units for various species in Minnesota can vary when compared to our neighboring states, including Iowa and South Dakota. The MPCA should convene a working group to examine the varying definitions and calculations and determine the best approach for Minnesota that ensures consistency with the federal government and neighboring states, while avoiding unnecessary complexity and unintended consequences for livestock farmers, including new permitting thresholds.

Raise the threshold for the NPDES and SDS permits

The decision to require feedlots with at least 1,000 animal units to acquire a NPDES and SDS permit was never based on science. It was a political decision by the agency and the legislature at the time. The MPCA's 1,000-animal unit threshold has created a regulatory environment in which many farmers are unwilling to expand their operations due to the additional obstacles posed by the construction and operating permit requirements. Instead, the state has a significant number of feedlots with 999 animal units, an unintended consequence of the current regulations.

If the agency considers new regulations for farms with less than 1,000 animal units, the MPCA should strongly consider raising the threshold to require a SDS permit. The 1,000-animal unit threshold does not reflect the current state of the livestock industry. The NPDES and SDS permits should only be used when a facility may have the greatest environmental impact. There is no evidence that a 1,000-animal unit operation has any greater impact on the environment than a 999-animal unit operation. We can strengthen the livestock industry by reducing regulatory burdens while ensuring the protection of water quality. This is another opportunity for a working group to establish a commonsense threshold based on best practices and science.

For full consideration,



Darin Broton, Executive Director
Minnesota AgriGrowth
952.905.8901
dbroton@agrigrowth.org

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By: OAH on 7/22/2025

Craig Tangren Attachment

LEECH LAKE BAND OF OJIBWE
DIVISION OF RESOURCE MANAGEMENT

Via Web Submission:
OAH Attn: William Moore
Minnesota Office of Administrative Hearings
600 North Robert Street
PO Box 64620
St. Paul, Minnesota 55164-0620

July 22, 2025

RE: Planned Amendments to Rules Governing Animal Feedlots, *Minnesota Rules*, chapter 7020, Revisor's ID Number R-04928

As a sovereign Tribal government located in northern Minnesota, the Leech Lake Band of Ojibwe (LLBO) is taking this opportunity to comment on proposed rulemaking for Minnesota Feedlot Rules (Chapter 7020). The Leech Lake Band of Ojibwe has Treatment as a State authorities under Sections 106, 319, 401, & 303(c) of the Clean Water Act and holds usufructuary rights to hunt, gather and fish within the Leech Lake Reservation and 1855 Ceded Territory. Protection of the environment, water quality, and treaty protected resources in this region is of utmost importance to Leech Lake Band members for their spiritual and physical wellbeing.

A healthy environment is vital to supporting the Leech Lake Band of Ojibwe as well as our plant and animal relatives. Long before modern agriculture and feedlots, people in what is now Minnesota lived off the bounty of wild rice, fish, and other natural resources. Proper regulation of feedlots and manure is needed to ensure protection of the environment and our way of life.

We support the Minnesota Pollution Control Agency's (MPCA) proposed rulemaking to update rules governing animal feedlots. In response to the request for comments, we recommend MPCA consider the following policy recommendations when drafting a future rule:

1. Lower the threshold to require NPDES/SDS permits for large feedlots with 600 or more animal units.

2. Water quality monitoring requirements for feedlots with 300 or more animal units. This monitoring should include groundwater and surface water at feedlots and manure storage sites.

3. Require sufficient storage of manure that capacity is not exceeded during the period when manure cannot be applied due to frozen or saturated soil conditions. A double liner system with groundwater monitoring should be required for liquid manure.

4. Require manure management plans for feedlots with 300 or more animal units and online reporting of manure application amount, location, and date.

5. When manure is transferred, the owner of feedlot must report that transfer to MPCA or delegated county. Transferees must report to MPCA or delegated county the amount, location, and date of manure application.

6. Require soil and shallow groundwater nitrate tests prior to manure application in locations with known nutrient issues, such as the central sands region or the Karst region.

7. Prohibit application of solid or liquid manure to frozen or saturated soils, or when rainfall is likely.

8. MPCA should establish a limit to maximum feedlot size and a limit to animal units and manure application within HUC-12 watersheds to limit cumulative effects.

9. Include Tribal source/drinking water protection areas in setback requirements.

10. Animals must be restricted from accessing and entering public waters or their tributaries and feedlots should be fenced to prevent such access.

11. Require delegated counties to submit annual reports to MPCA and explicitly authorize MPCA to revoke or rescind delegated authority if a county fails to perform its duties.

The Leech Lake Band of Ojibwe would like to express our appreciation for the opportunity to comment on possible rulemaking for feedlots at this early stage. We look forward to continued engagement in this process. If you have any questions or require clarification please do not hesitate to contact me.

Sincerely,



Craig Tangren
Environmental Deputy Director, Leech Lake Band of Ojibwe
craig.tangren@llojibwe.net
(218) 335-7429

RECEIVED
By: OAH on 7/22/2025
Sophia Patane Attachment 3

July 22, 2025

Dear Rule Coordinator Addison Otto,

It is past time to clean up Minnesota's waters so that we're not drinking and swimming in high nitrate cow manure runoff and seepage. May I assume that you think allowing such pollution in our waters is NOT ok? Then please DO SOMETHING in your role with MPCA. It's past time to value people's health above corporate profit.

This is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. Animal feedlot manure causes serious problems of runoff, seepage, and spills that not only are odorous and disgusting, but are unsafe for humans and damage the environment.

Manure runoff in Minnesota waters results in fish kills. Swimming (hey, we're Minnesotans -- this is what we do, swim in our lakes and streams!) is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers (ugh), producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Anne Reich
751 Pine Cone Trl Marine On Saint Croix, MN 55047-9642
reichmn@gmail.com

RECEIVED
By: OAH on 7/22/2025

Tuesday, July 22, 2025 at 3:51:09 PM Central Daylight Time

Subject: (none)
Date: Tuesday, July 22, 2025 at 9:36:02 AM Central Daylight Time
From: alek roslik
To: info@waterlegacy.org

Water is a precious resource and a huge part of our state's acclaim. Protecting helps our environment, our tourism, and our bodies. We need to strengthen regulation regarding manure runoff.

Thanks.

RECEIVED
By: OAH on 7/22/2025
Sophia Patane Attachment 5

Tuesday, July 22, 2025 at 3:54:16 PM Central Daylight Time

Subject: MPCA comments
Date: Tuesday, July 22, 2025 at 8:47:27 AM Central Daylight Time
From: Brad Lehrman
To: WaterLegacy

Dear MPCA

1. MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.
2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.
3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.
4. MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.
5. MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
6. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
7. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
8. MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

--
Brad Lehrman
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612 382 7080

@blehrman

RECEIVED
By: OAH on 7/22/2025

TO: Minnesota Pollution Control Agency

FROM: Jennifer Pearson, MD

4532 London Rd. Duluth, MN 55804

RE: Feedlot rules

I am a family medicine physician and medical school faculty in Duluth Minnesota. I am very concerned about the connection between environmental pollution/toxins and resulting deleterious effects to human health. I would like to comment on the Animal Feedlot rules, given the fact that Minnesota has over 23,000 feedlots: aka concentrated animal feeding operations (CAFOs). These feedlots generate manure and nitrate pollution that flow down the Mississippi River and are not only contributing to the worsening Dead Zone in the Gulf of Mexico but to environmental conditions that are hazardous to ecological and human health.

The current manure runoff, seepage and spills from animal feedlots cause serious problems in our state:

- Fish kills result from byproducts of manure decomposition and depletion of oxygen levels in water due to excessive nitrates and algae blooms.
- Swimming is unsafe due to E.coli bacteria from animal wastes. More than 100 Minnesota waterbodies are listed under the Clean Water Act as impaired due to E.coli.
- Excessive nitrates result in blue-green algae blooms in shallow lakes and rivers, producing toxins (cyanobacteria) harmful to wildlife and humans.
- Increased nitrates in well water used to prepare infant formula can cause methemoglobinemia (blue baby). In recent decades, even without a tracking system for these cases, the Minnesota Department of Health has concluded that nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Current MPCA Animal feedlot rules are inadequate to protect Minnesotans:

- Existing rules require water pollution permits for huge feedlots with 1,000 or more “animal units”. “Medium-sized” feedlots with 300-999 animal units (which contribute 43% of Minnesota’s total manure) require no permits at all.

- Existing rules set no maximum size for feedlots and no maximum number of animal units in a local area or watershed, allowing feedlots and concentration of pollution impacts to increase. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.
- Existing MPCA rules claim “no discharge” is allowed, but neither manure storage areas nor fields where manure is sprayed are monitored or tested to detect discharge and pollution levels. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.
- Existing MPCA rules do not apply modern science and technology to require containment of all manure within advanced liner systems. Rules also allow spreading of manure on fields even during the winter.
- Loopholes and exemptions allow noxious and odorous hydrogen sulfide air emissions as well as toxic water pollution. No existing rule requires a feedlot emitting noxious emissions and odors to demonstrate that at least 344 days a year, all air quality standards have been met.

Given these many concerns, I advocate that the following changes be made by the MPCA:

1. MPCA rules should require pollution permits for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.
2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.
3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.

4. MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.

5. MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired waters, and prevention of degradation in waters that are not polluted.

6. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

7. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.

8. MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year. Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

Thank you for considering my comment and concerns.

RECEIVED
By: OAH on 7/22/2025
Sophia Patane Attachment 7

July 22, 2025

To: Minnesota Pollution Control Agency
Commissioner Kessler, Mr. Schwint, and Ms. Otto

Reference: Individual Comment / MPCA Animal Feedlots Rule

I am hereby submitting my comments to the Minnesota Pollution Control Agency (MPCA) regarding the need to rewrite animal feed lot rules and stop toxic pollution of Minnesota waters.

Feedlots globally, nationally, and in our own state of Minnesota are huge polluters and a menace to public health. Nitrates in manure runoff from Minnesota's 23,000 CAFOs contribute to the Gulf of Mexico Dead Zone. Manure runoff results in fish kills, swimming is unsafe in some areas due to E.coli bacteria from animal waste. The excessive amount of nitrates from manure cause blue-green algae blooms in shallow lakes and rivers, producing toxins that harm wildlife and humans. Increased nitrates in well water used to prepare infant formula can cause methemoglobinemia, a condition of elevated methemoglobin in the blood that can be fatal to infants.

I am a proud Minnesotan and know we, as a forward thinking and acting state, can do much better, and now is our chance to make the needed course correction to protect our people and the fish, animals, and lakes/rivers/streams that are being irreparably damaged due to unnecessary and unchecked pollution caused by loose or non-existent rules and requirements around the management of feedlots.

The existing rules are unrealistic and ineffective if they are meant to check water pollution, and the following steps must be taken to better protect our water resources, wild life, and human population:

Covering only the largest of feedlots (1000 animal units), these rules don't affect medium-sized feedlots, which can still be very large in nature with up to 999 animal units, and which are, in fact, responsible for over 40% of all manure.

1. **Recommended rule change**: **MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units.**

Existing rules lack caps in terms of the size of feedlots and the number of animal units they can hold in any given local area or watershed, allowing for uncontrolled growth and ensuring concentrated, run-away pollution in adjacent areas.

2. **Recommended rule change: MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in**

any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. **Recommended rule change: MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that "stricter" requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.**

While MPCA rules claim there is no allowance for "discharge", this rule is impossible to enforce as neither manure storage areas nor fields where manure is sprayed are tested or monitored. This lack of standard monitoring and reporting further contributes to the pollution of our waters and to the dangerous environmental hazards people living nearby are subjected to.

4. **Recommended rule change: MPCA rules should stop merely trusting that animal feedlots and manure applications are "no discharge" facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.**

5. **Recommeded rule change: MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.**

The MPCA rules as they exist today are archaic and in no way serve to curb the spread of toxins that reach our water and harm the health of residents living in the affected areas. New technologies using liners to contain manure runoff are not employed and the MPCA actually allows manure to be spread on fields throughout the year, including in winter months that causes harmful results during the spring thaw with toxic runoff.

6. **Recommended rule change: MPCA rules should strengthen minimum technology** requirements for all permitted **animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.**

7. **Recommended rule change: MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.**

Loopholes and exemptions allow for the emission of noxious and odorous hydrogen sulfide as well as toxic water pollution.

8. **Recommended rule change: MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.**

Thank you for your consideration.

Jude A. Thimke
5198 Greenwood Road
Duluth MN 55804

218 730 7058

RECEIVED
By: OAH on 7/22/2025

Dear MPCA:

Just because our federal government is abandoning all health and safety regulations doesn't mean that Minnesota should do the same.

We need permits required of feedlots above 300 head, caps on feedlot size, prohibition of feedlots in sensitive karst areas, a stringent limit on nitrate pollution of surface waters, monitoring of feedlots and manure-spread fields for compliance with "no discharge" rules and surface- and groundwater limits, current/rigorous requirements for manure storage and spreading, and the elimination of loopholes and exemptions that allow SHIT in our air and water.

Thank you,

Dr. Kristina Boerger

3445 Oakland Ave., Mnpls

RECEIVED
By: OAH on 7/22/2025
Sophia Patane Attachment 9

Tuesday, July 22, 2025 at 3:54:59 PM Central Daylight Time

Subject: Feedlot rules
Date: Tuesday, July 22, 2025 at 9:37:55 AM Central Daylight Time
From: Russ Erickson
To: info@waterlegacy.org

Simple suggestion:
Require animal manure and liquid waste be put through a treatment plant just like we do with human waste. Mini treatment on site or trucking to a treatment plant.

Why - I lived in an area in Iowa where the Fairfield town water was undrinkable due to surrounding farm practices. Although people did drink the nitrate laden water because there was nothing, they could do about it and we all needed water. I hope no one has long term health issues there.

Thanks
Russ Erickson
612-267-6605
russee4@msn.com

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By: OAH on 7/22/2025

July 22, 2025

Dear MPCA,

I hope you will revise rules for animal feedlots to more effectively protect Minnesota's surface waters and groundwater from additional nitrate pollution.

We need to reduce nitrates in our water, and feedlots are increasingly adding nitrates to our environment.

I have lived in Minnesota for most of my 67 years and grew up drinking well water and swimming and boating in our lakes and rivers. I am saddened at the degradation of our waters, knowing that much of Minnesota's well water is no longer good to drink and that many of our surface waters are impaired and contribute, eventually, to the so-called dead-zone at the mouth of the Mississippi River.

Animal feedlots and their pollution of our waters need to be regulated--including "medium-sized" feedlots.

We know that the condition of our waters has much to do with what we do to our land.

Animal feedlots should be treated essentiallly as a kind of industrial point-source for pollution; and spreading manure on fields, particularly in winter, should be considered a form of discharge and be regulated and monitored accordingly.

I hope you will act in the interest of Minnesota's waters, which belong to all of us. No one has the right to ruin them now or for future generatons.

Sincerely,
Tim Larson
3113 Wellington Street
Duluth, MN 55806
(218) 724-6963
Tslduluth9@gmail.com

RECEIVED
By: OAH on 7/22/2025

Tuesday, July 22, 2025 at 3:56:21 PM Central Daylight Time

Subject: mpca feedlot rules
Date: Tuesday, July 22, 2025 at 2:03:28 PM Central Daylight Time
From: Winston Kaehler
To: info@waterlegacy.org

It sounds like the MPCA needs to tighten rules for feedlot operations, especially in the karst region, where topsoil is such a thin layer, leading to groundwater pollution. It is high time for feedlot operations to be regulated to protect the general public. The MPCA has a duty to do that.

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By: OAH on 7/22/2025

Association *of* Minnesota Counties

Minnesota Association of County Feedlot Officers

July 22, 2025

Office of Administrative Hearings
Attn: William Moore
600 N. Robert St., PO Box 64620
St. Paul, MN 55164-0620
(*Transmitted electronically*)

Re: Comments on MPCA RFC for Amendments to Rules Governing Animal Feedlots: Minnesota Rules, Chapter 7020, Revisor's ID Number R-4928, OAH Docket No. 25-9003-40661

Dear Mr. Moore:

The **Association of Minnesota Counties (AMC)** and the **Minnesota Association of County Feedlot Officers (MACFO)** appreciate the opportunity to **provide comments on the Minnesota Pollution Control Agency's (MPCA) Request for Comments (RFC) regarding proposed amendments to Minnesota Rules, Chapter 7020, governing animal feedlots.** As organizations representing county governments and feedlot officers with direct experience in implementing the state's feedlot program, we are committed to supporting effective, flexible, and practical rules that protect the environment while maintaining the viability of Minnesota's livestock industry.

Manure Management and Storage

Any proposed changes to manure application restrictions—such as expanded setbacks or application restrictions—must consider their impact on storage needs. Any new restrictions on manure storage should be accompanied by evaluations of manure storage feasibility, accounting for financial costs, and regional differences in climate and infrastructure.

To address the structural integrity of aging manure storage areas, we suggest developing practical inspection standards. The MPCA or county feedlot officers could provide checklists or guidelines to assist feedlot owners in assessing structural integrity. Any inspection requirements should clearly define who conducts inspections, whether owners, certified professionals, or state/county staff, assessing the capacity and costs to do this work, and outline documentation expectations to ensure consistency and clarity.

Feedlots Under Common Ownership

MPCA policy documents and local ordinances currently address facility size questions. State guidance could be clarified for "separate facilities" based on operational and physical separation rather than arbitrary distance thresholds that are not consistently applied. Having specific and consistent standards will assist livestock producers in planning for the future of their farm(s). Local governments do and should continue to set separation distances, as local thresholds are already established and reflect regional needs.

Technical and Minor Rule Revisions

We recommend reviewing certain existing provisions to determine if they remain necessary. The Open Lot Agreement may be outdated given changes in management practices and should be re-evaluated for relevance. Similarly, the certified letter requirement for pit closures is overly prescriptive; digital reporting or alternative verification methods may be more efficient and equally reliable.

Feedlot-related well setback rules should also align more clearly with the Minnesota Department of Health Well Code to eliminate confusion and streamline compliance.

Balancing Flexibility with Environmental Protection

To balance regulatory flexibility with environmental protection, the MPCA should take a data-driven and regionally sensitive approach. Providing multiple compliance options—such as MPCA-approved alternative manure management practices referenced in NPDES Permit 13.5—can accommodate the diverse operational realities across the state. Before adopting new regulations, the MPCA should present data on current inspection rates, compliance performance, and stockpile oversight for both NPDES/SDS facilities and smaller sites to ensure that any changes address true gaps in effectiveness.

Additionally, a cost-benefit analysis is essential to assess the financial impact on producers and the availability of cost-share support. Counties should also be permitted to implement alternative compliance methods, leveraging local knowledge to develop flexible and effective environmental solutions.

We urge the MPCA to carefully evaluate any proposed changes to permit thresholds and Animal Unit (AU) calculations, as these figures have wide-reaching implications. AU values influence local zoning decisions, eligibility for cost-share programs, manure management plan (MMP) thresholds, and NPDES/SDS permitting requirements. Even small changes could create significant impacts for feedlot operators and state and county program administration. We encourage the agency to work closely with stakeholders to understand any implications before proceeding with revisions in this area.

Finally, we emphasize that the delegated county program is minimally funded. Any rule changes that increase administrative responsibilities for counties must be paired with additional resources to ensure successful implementation. Without adequate funding, expanded mandates risk creating bottlenecks and undermining program goals.

AMC and MACFO support the MPCA's intent to modernize Chapter 7020 in ways that strengthen environmental protections while preserving the vitality of Minnesota's livestock sector. We urge the agency to pursue rule changes that are cost-effective, flexible, and grounded in current data and field realities.

We look forward to continuing collaboration throughout the rulemaking process, including direct discussions with MPCA staff to refine proposed changes. If you have any questions or would like to discuss these comments further, please contact Brian Martinson, AMC Policy Analyst, at 651-246-4156 or bmartinson@mncounties.org.

Sincerely,



Brian Martinson, Policy Analyst
Association of Minnesota Counties



Mark Koep, Douglas County Feedlot Officer
President, Minnesota Association of County Feedlot Officers

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By: OAH on 7/22/2025
Warren formo Attachment

RE: Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, chapter 7020, Revisor's ID Number R-04928

The Minnesota Agricultural Water Resource Center is comprised of general farm organizations, crop, livestock and poultry producer associations, and trade groups providing services and support to Minnesota farmers. Our efforts focus on ensuring a prosperous future for farmers while fostering improved environmental stewardship.

We offer the following comments in response to the MPCA's proposal to amend the current Chapter 7020 Rules governing feedlots. As part of this comment and rulemaking process, we hope you receive comments from many individual farmers, and we encourage you to carefully consider their input as it comes from those who derive their livelihood from farming, and specifically in this process, livestock and poultry production. You will also hear from farmer groups providing representative voices for those farmers who may be uncomfortable providing input, some out of fear of reprisal. Their comments should also be highly valued.

As stated in the request for comments, "the main purpose of this rulemaking is to address changes in livestock and poultry operations and business practices, account for new agency data services, modernize outdated rule language, amend existing feedlot rules to improve land application of manure practices to address nitrates, bacteria, and fish kills, and establish additional technical standards to protect water quality and avoid fish kills." For input on operations, data management, and related issues, comments from farm groups and farmers are of utmost importance, as it comes from those most directly affected by the rule.

In the request for comments, you specifically ask for comments relating to several questions. Our comments focus on those questions most directly related to water quality and stewardship.

• Are additional restrictions on manure application rates needed?

No additional restrictions are necessary. The current rule is adequate. Ongoing research should be supported and the results disseminated to livestock and poultry farmers enabling continued improvement in manure use efficiency. As pointed out in the recently published Nutrient Reduction Strategy, manure and fertilizer application rates are trending closer over time to Extension recommendations, without regulation.

• Are increased setback distance for land application of manure near sensitive features needed?

Simply, no, the current list of sensitive features and required setback distances are adequately protective of water quality and should not be increased. MN Buffer Law requirements should be included when factoring setback distances. The law was intended to protect the state's water resources from runoff pollution. BWSR reports that compliance with buffer requirements exceeds 99%. MPCA needs to provide scientific evidence that the existing setback distances are inadequate.

• Should land application of manure in areas with high levels of nitrate in waters or in areas with existing high densities of feedlot operations be further restricted?

Manure applications are already in place for those feedlots required to have a manure management plan. Additional limits on manure beyond agronomic optimums would incentivize the use of other nitrogen sources. How would MPCA define areas as having "high" feedlot operation density? From a statewide mass balance perspective, commercial nitrogen provides approximately three times as much nitrogen for crop production as does manure. As economics and markets dictate, there is room for

significant expansion of livestock and poultry production in our state without environmental harm, and potentially significant water quality improvement due to benefits of manure to soil health as compared to commercial fertilizer.

• Should additional best management practices be required for land application of manure during the months of September through November?

The current rule requiring cover crops following manure applications in June, July and August for feedlots required to have a manure management plan is adequate. MPCA should support other agencies in promoting all identified improved manure management practices, including cover crops and nitrification inhibitors, on a voluntary basis. The MPCA should support an exemption to current requirements for pesticide applicator training for nitrification inhibitors applied with manure in order to increase adoption of this recommended practice. These voluntary, incentive-based activities represent our best efforts to protect water resources, as documented in MPCA's Nutrient Reduction Strategy.

• Should land application of manure on frozen or snow-covered fields be restricted?

Many small farms lack the storage capacity and/or equipment to eliminate winter spreading. Restrictions would result in undue economic hardship, possibly forcing some farmers to discontinue operations. When winter manure applications can't be avoided, University of Minnesota Extension recommends applying manure at the lowest necessary rate, on fields with flat slopes, in accordance with all applicable setbacks including waterways, and avoided before a significant snowmelt event (www.extension.umn.edu/manure-management/manure-timing).

• Should additional best management practices be required for land application of manure when there is a high probability of rain predicted?

In order to assist farmers in avoiding such situations, the MPCA should work with the Minnesota Department of Agriculture to increase awareness and assist farmers in utilizing the MDA's brand new, state-of-the-art weather network and other tools that equip farmers with technology to inform the implementation of best management practices.

• The MPCA has developed Watershed Restoration and Protection Strategy (WRAPS) documents for every one of Minnesota's 80 major watersheds. These WRAPS document high nutrient and bacteria levels in streams and rivers. The reports attribute this to livestock access to streams in many cases. How should the rules be amended to address this documented issue (part 7020.2015)?

This is very misleading. Some WRAPS address feedlots without specificity and few refer to livestock access to streams. For those WRAPS reports that do include discussion of livestock and manure management, most call for increased support for voluntary efforts and practice incentives.

• State agencies are required to, whenever feasible, develop rules that are not overly prescriptive and inflexible, and rules that emphasize achievement of the MPCA's regulatory objectives while allowing maximum flexibility to regulated parties and to the MPCA in meeting those objectives (Minn. Stat. § 14.002). How might the MPCA balance this need for flexibility for regulated parties while also addressing the issues of nitrate contamination and fish kills?

The agency needs to demonstrate, using data, that the current rules are inadequate concerning the impact of manure on nitrate concentrations in surface water and fish kills. Fish kills are unfortunate, but extremely rare, and fish kills associated with manure are rarer still. In contrast, this is an opportunity for MPCA to promote wider adoption of cover crops and use of the MDA's weather network to improve manure management and protect surface waters from contamination.

9. Other questions or comments relating to the existing animal feedlot rules or this proposal to amend the rules.

As noted by the agency as justification for initiating this rulemaking process, livestock and poultry production have changed. Rulemaking cannot keep pace with technology and often inhibits innovation. Best management practices such as split rate manure applications, low disturbance manure application equipment, variable rate manure application, on-the-go manure nutrient content testing, on-farm processing of manure to separate liquids and solids, and improved manure distribution utilizing draglines have improved manure management on livestock and poultry farms. Some of these practices are very recent innovations, while others have become relatively common. This evolution of manure management clearly demonstrates that voluntary practices, supported by science, will be readily adopted.

Through this rulemaking the MPCA has an opportunity to provide clarity and efficiency in its programs in order to protect and improve water quality in Minnesota. In recent decades many livestock producers have exited the industry, often citing regulatory requirements or the threat of additional requirements as a primary factor in their decision. The solution to improving manure storage, handling and land application practices lies in on-farm innovations supported by research and incentives for early adopters. Regulation should be the last option and provide a practical baseline that works for farms of different sizes, types and locations.

We look forward to working with MPCA in coming years as you work through this process.

Tim Velde, Chairman, Minnesota
Agricultural Water Resource Center

Jim Kanten, President
Minnesota Corn Growers Association

Darin Johnson, President
Minnesota Soybean Growers Association

Kevin Leiser, President
Minnesota Association of Wheat Growers

Dan Glessing, President
Minnesota Farm Bureau Federation

Gary Wertish, President
Minnesota Farmers Union

Todd Selvik, President
Minnesota Pork Producers Association

Garrett Luthens, President
Minnesota Milk Producers Association

Jake Thompson, President
Minnesota State Cattlemen's Association

Jake Vlaminck, President
Minnesota Turkey Growers Association

Darin Broton, Executive Director
Minnesota AgriGrowth Council

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By: OAH on 7/22/2025
Ariel Kagan Attachment

Minnesota Farmers Union

305 Roselawn Ave E | Suite 200 | St. Paul, MN 55117
Phone: (651) 639-1223 | www.mfu.org

July 22, 2025

Minnesota Office of Administrative Hearings
600 Robert St. N
Saint Paul, MN 55101

RE: Response to Request for Comments, Feedlot Rulemaking, Chapter 7020, Revisors ID Number R-04928

Dear MPCA and Office of Administrative Hearings staff:

On behalf of Minnesota Famers Union (MFU), I write to submit our organization's comments on potential updates to Minnesota feedlot rules. We appreciate the opportunity to share our thoughts and hope that they, along with comments from farmers across the state, help inform your work. We understand that changes to the 7020 rules could have consequences for our members of all sizes and production types. And we look forward to engaging with you and helping ensure our members are informed throughout the rulemaking process.

First, and broadly, promoting water quality is a fundamental value for all Minnesotans, including our members. And we recognize that—along with other programs and technical assistance—clear, practical, and science-based rules for feedlots help ensure farmers are doing all they can to protect the environment.

Second, and as a matter of our grassroots policy, our members support a graduated approach to regulation wherein permits are required for the largest facilities. We also recognize that, as you've worked to make clear, the 7020 rules apply to all sizes of livestock operations across a broad range of production types.

With that, here are some comments that come from conversations with our members about these potential changes:

- **Protect the viability of family farms** – as you note in the request for comments, the structure of agriculture is changing and with small farms leaving production. For example, between the 2017 and 2022 Census of Agriculture, Minnesota lost 40 percent of our dairy farms, while the overall number of cows remained largely the same. We believe that is a loss not just for those families, but also for our rural schools, main streets, and communities.

  We believe strongly that Minnesota is better for having more distributed, independent, livestock producers. Our Department of Agriculture (MDA) and others have led in supporting generational farms and helping new farmers build a life in agriculture. Policies across state government, including the 7020 rules, should promote the continued sustainability and viability of family farms across our state.

- **Promote livestock** – relatedly, we believe that livestock represent an important way that many farmers diversify their farm income, bring the next generation to their operation, and improve the health of their soil. Livestock also does a great deal to support local economies and provide value added markets for other farmers.

With that, any proposed rules should recognize the value of manure for soil health. It also promotes independence and resilience, allowing farmers to supply their own fertilizer rather than depending on the often-volatile market for chemical fertilizers produced outside the state.

- **Provide clarity** – farmers should be able to easily determine what rule changes apply to their operations, what is required of them, and on what timeline. In discussions with members about the potential rule changes, we encountered a variety of knowledge about current regulations and their applicability. Investments in outreach, farmer-facing materials, and other support is welcome. Clear rules are also important for training and retaining technical service and regulatory staff, who rely on working relationships with operators.

- **Ensure practicality and flexibility** – any rule changes should acknowledge and incorporate the complexity of farming and the decisions that farmers make across their operations from year to year depending on conditions. Any changes to the rules should ensure that farmers can meet the new requirements, and that there are tools and resources available to help them implement any changes.

  Any rule changes should also recognize—as you have in your request for comments—that farmers are always innovating with the goal of lowering costs, improving efficiency, promoting environmental outcomes, and otherwise improving their operations. From technology like variable rate application to practices like winter bale grazing, farmers of all sizes and production types are working to incorporate and inform the latest available science. Rule changes should allow farmers flexibility where supported for promoting water quality.

- **Leverage voluntary, incentive-based conservation programs** – recent years have seen significant investment in and adoption of voluntary and incentive-based conservation programs. These programs, including the Minnesota Agricultural Water Quality Certification Program, the Soil Health Financial Assistance Grant Program, various programs offered through Soil and Water Conservation Districts and the Board of Water and Soil Resources, as well as many private sector and non-profit organization run programs, offer a variety of options for farmers to add cover crops, reduce tillage, and implement edge-of-field practices which promote soil health, water quality, and biodiversity. Any updates to 7020 rules should leverage and be informed by these programs and their boots-on-the-ground technical staff. Continued investment and promotion of these programs is also an important strategy for reaching state soil health and water quality goals.

Thank you for your attention to these comments and your efforts to travel across the state and connect directly with farmers who will be affected by changes to 7020 rules. And to communicate the scope and potential impact of proposed changes. Please count on us as partners in this process going forward. If you have any questions, please contact our Government Relations Director, Stu Lourey, at stu@mfu.org or (320) 232-2047. Thank you for considering the needs and perspectives of our members and for your important work.

Sincerely,

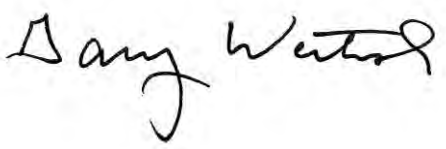

Gary Wertish
President, Minnesota Farmers Union

RECEIVED
By: OAH on 7/22/2025
Dani Replogle Attachment 1

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foodandwaterwatch.org

July 22, 2025

Addison Otto

Minnesota Pollution Control Agency

520 Lafayette Rd. N.

St. Paul, MN 55155-4194

Submitted Online via Office of Administrative Hearings Rulemaking e-Comments Website

Re: Comments on Planned Amendments to Rules Governing Animal Feedlots, Minn. Rules Ch. 7020, Revisor's ID No. R-04928

Dear Addison,

Food & Water Watch respectfully submit these comments in response to the request for comment on planned amendments to the Minnesota state feedlot regulations issued by the Minnesota Pollution Control Agency ("MPCA" or "the Agency") on February 25, 2025. We appreciate the opportunity for early input on a rulemaking that is critical to safeguarding water quality, human health, and wildlife from feedlot pollution. Without much-needed revisions to the state feedlot regulations, underregulated livestock waste and other feedlot pollutants will continue to degrade waters of the state in contravention of state and federal law. As discussed in detail below and supported by scientific studies and other documents submitted as exhibits to these comments, we ask that MPCA redress adverse impacts caused by feedlots by ensuring that all discharging concentrated animal feeding operations ("CAFOs") obtain National Pollutant Discharge Elimination System ("NPDES") permits, codifying requirements to implement best

management practices proven to control feedlot pollution, requiring feedlots to attain effluent limits based on pollutant reductions attainable through advanced wastewater treatment technologies, and mandating effluent monitoring and reporting to ensure compliance with major regulatory requirements. Food & Water Watch also supports and incorporates by reference comments submitted by the Minnesota Center for Environmental Advocacy.

I. Feedlots Harm Water Quality and Public Health in Minnesota

Unlike traditional livestock rearing operations that raise animals on pasture according to the land's capacity to feed the herd/flock and assimilate the waste generated, feedlots confine large numbers of animals in crowded enclosures. Many feedlots are essentially livestock factories that operate much like sewerless cities.[1] These facilities generate, store, handle, and dispose of enormous quantities of pollutant-laden waste.[2] Though managing feedlot waste poses many of the same risks as managing human waste, most feedlots do not treat their waste using the advanced treatment techniques required of sewage plants or any equivalent treatments. Rather, feedlots are largely permitted to store untreated liquid waste in leaky liquid manure storage areas ("LMSAs" or "lagoons"), and to spray or spread this waste onto land application areas at rates that are not designed to safeguard water quality or public health. Feedlots also manage solids like compost and silage in ways that allow pollutants to seep, leach, and runoff into waters of the state. When feedlots discharge their waste to ground- and surface waters, pollutants degrade water quality, creating severe health and environmental consequences that Minnesotans are unfairly forced to endure and pay for. Clearly, the status quo is not working for Minnesota's waters or residents.

A. Feedlot Waste Contains a Slurry of Harmful Pollutants

[1] U.S. GAO, CONCENTRATED ANIMAL FEEDING OPERATIONS: EPA NEEDS MORE INFORMATION AND A CLEARLY DEFINED STRATEGY TO PROTECT AIR AND WATER QUALITY FROM POLLUTANTS OF CONCERN, GAO-08-944 at 18, 20 (2008), available at https://www.gao.gov/products/gao-08-944 ("[T]he amount of manure produced by [CAFOs] can exceed the amount of waste produced by some large U.S. cities.").

[2] *See, e.g.,* AM. PUB. HEALTH ASS'N, *Precautionary Moratorium on New and Expanding Concentrated Feeding Operations* (Nov. 5, 2019), https://www.apha.org/policy-and-advocacy/public-health-policy-briefs/policy-database/2020/01/13/precautionary-moratorium-on-new-and-expanding-concentrated-animal-feeding-operations; CARRIE HRIBAR, NATIONAL ASS'N OF LOCAL BOARDS OF HEALTH, UNDERSTANDING CONCENTRATED ANIMAL FEEDING OPERATIONS AND THEIR IMPACT ON COMMUNITIES 2–3 (Mark Schultz, 2010), https://stacks.cdc.gov/view/cdc/59792; DOUG GURIAN-SHERMAN, UNION OF CONCERNED SCIENTISTS, CAFOS UNCOVERED: THE UNTOLD COST OF CONFINED ANIMAL FEEDING OP 42 (Apr. 2008), https://www.ucsusa.org/sites/default/files/2019-10/cafos-uncovered-full-report.pdf

Feedlot waste contains numerous pollutants that harm human and ecological health when they enter the environment.[3] These pollutants include nitrogen, phosphorus, sediments, salts, and ions such as magnesium, sodium, potassium, and chlorides.[4] Feedlot waste also contains a hazardous cocktail of bacteria, pathogens, pesticides, pharmaceuticals, and metals.[5] Though feedlot waste is often referred to exclusively as manure, this characterization is misleading as feedlot waste contains many pollutants not found in non-feedlot manure, and feedlots also dispose of hair, feathers, bedding materials, cleaning products, mortalities, and other pollutants from non-manure sources.[6] These pollutants pose unique threats to water quality that threaten human health and the public resources MPCA is statutorily bound to protect.

Nutrients

Nutrients in feedlot waste include nitrogen, phosphorous, and potassium. Because naturally occurring nutrients in soil help sustain plant life, feedlot waste is often applied to cropland under the guise of fertilization. However, nutrients harm animal and plant life when unnatural quantities are added to ecosystems, particularly aquatic ecosystems. Animal agriculture is a major source of nitrogen and phosphorus to state waters. As a result, feedlot-dense watersheds often suffer severe water quality impacts from excessive nutrients that endanger human health and the environment.

High concentrations of nitrogen and phosphorus in water create low-oxygen dead zones where fish and other aquatic species cannot survive.[7] Both nitrogen and phosphorus spur eutrophication, the process by which excessive marine plant growth saps the water of oxygen.[8] The proliferation of algae and other plant life under eutrophic conditions "can harm or kill fish by clogging their gills. Algal blooms can also reduce the ability of fish and other aquatic life to

[3] *Id.*
[4] National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations (CAFOs), 68 Fed. Reg. 7,176, 7,181 (Feb. 12, 2003); JoAnn Burkholder et al., *Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality*, 115(2) ENV'T HEALTH PERSPS. 308, 308 (Feb. 2007), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1817674/
[5] 68 Fed. Reg. at 7,181; Burkholder, *supra* n.4 at 308.
[6] EPA, RISK ASSESSMENT EVALUATION FOR CONCENTRATED ANIMAL FEEDING OPERATIONS, EPA/600/R-04/042, at 63, 72–73 (May 2004), https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryId=85107 (hereinafter, "EPA CAFO RISK ASSESSMENT"); EPA, MANAGING MANURE NUTRIENTS AT CONCENTRATED ANIMAL FEEDING OPERATIONS at 2-1–2-4 (Dec. 2004), https://www.epa.gov/sites/default/files/2015-08/documents/cafo_manure_guidance.pdf.
[7] EPA, *The Effects: Environment* (April 11, 2025), https://www.epa.gov/nutrientpollution/effects-environment.
[8] EPA CAFO RISK ASSESSMENT, *supra* n.6 at 28, 53.

find food and can cause entire populations to leave an area or even die."[9] Hypoxic conditions and high levels of the nitrogen-based compound ammonia observed following feedlot discharges "have caused major kills of freshwater fish of all species … from minnows and gar to largemouth bass."[10] Waterbirds like the endangered horned grebe and amphibians like the endangered Blanchard's cricket frog are also susceptible to adverse impacts from nutrient pollution. The Minnesota Department of Natural Resources specifically attributes the horned grebe's habitat loss to agricultural pollution, explaining that "[s]everal serious threats to Horned Grebe habitat in Minnesota are the direct result of agricultural activities including eutrophication."[11]

High nutrient concentrations also create hazardous algal blooms that can be toxic to humans, pets, and wildlife that come into contact with impacted waters.[12] Exposure to toxic algae from skin contact or ingestion can cause serious symptoms, including rashes, headaches, coughing, and gastrointestinal distress.[13] These health risks—which are elevated for vulnerable populations like children and the elderly—lead local governments to temporarily close recreational waters throughout the state each year.[14] The economic cost of a single major harmful algal bloom can climb to tens of thousands of dollars.[15]

Nutrient pollution also causes dangerously high nitrate concentrations in Minnesota waters.[16] Bacteria in the environment convert nitrogen from manure into nitrate, a pollutant

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[9] EPA, The Effects: Environment, https://www.epa.gov/nutrientpollution/effects-environment.
[10] Burkholder, *supra* n.4 at 309.
[11] Minn. Dep't of Nat. Res., *Rare Species Guide: Podiceps auritus*, https://www.dnr.state.mn.us/rsg/profile.html?action=elementDetail&selectedElement=ABNCA03010 (citing S. J. Stedman, *Horned Grebe (Podiceps auritus), Number 505 in* THE BIRDS OF NORTH AMERICA (A. Poole and F. Gill, eds. 2000)).
[12] MPCA, 5-YEAR PROGRESS REPORT ON MINNESOTA'S NUTRIENT REDUCTION STRATEGY at 2 (Aug. 2020), https://www.lrl.mn.gov/docs/2021/other/210420.pdf (hereinafter "5-YEAR PROGRESS REPORT"); Minn. Dep't of Health, *Harmful Algal Blooms (HABs) Fact Sheet* (June 25, 2025), https://www.health.state.mn.us/diseases/hab/hab.html (last visited July 21, 2025); GAO, supra n.1 at 9, 24-25, 72; 68 Fed. Reg. at 7,235; Burkholder, *supra* n.4 at 309; U.S. Office for Harmful Algal Blooms, *HAB Impacts on Wildlife*, https://hab.whoi.edu/impacts/impacts-wildlife/.
[13] MPCA, *Blue-green Algae and Harmful Algal Blooms*, https://www.pca.state.mn.us/air-water-land-climate/blue-green-algae-and-harmful-algal-blooms.
[14] *Id.*
[15] National Centers for Coastal Ocean Science, *Assessing Environmental and Economic Impacts*, https://coastalscience.noaa.gov/science-areas/habs/assessing-environmental-and-economic-impacts.
[16] *See generally* MINNESOTA CENTER FOR ENVIRONMENTAL ADVOCACY ET AL., PETITION FOR EMERGENCY ACTION PURSUANT TO THE SAFE DRINKING WATER ACT, 42 U.S.C. § 300I, TO PROTECT THE CITIZENS OF THE KARST REGION OF MINNESOTA, 18-20 (2023) [hereinafter SDWA PETITION].

associated with many dangerous health conditions. Ingesting water contaminated with nitrates is associated with various kinds of cancer, thyroid disease, birth defects, premature births, and methemoglobinemia (a potentially fatal condition commonly known as "blue baby syndrome").[17] Minnesota's standard for nitrates in drinking water (10 mg/L) was designed to mitigate the risk of blue baby syndrome; however, recent research demonstrates that significant health risks are associated with much lower nitrate concentrations.[18]

The Minnesota Department of Health reports that between 1994 and 2022, eight community public water systems in the state spent over $15 million on nitrate treatment and management plans, often at a cost of thousands of dollars per household.[19] Similarly, the Northeast Wisconsin Karst Task Force recounts "millions of dollars spent helping municipalities, farmers, and rural homeowners address [pervasive nitrate and bacteria contamination issues]," without any meaningful progress toward reducing the number of contaminated wells or the severity of the contamination.[20] Once drinking water sources are contaminated with nitrate, it is often impossible to reduce concentrations to safe levels within the ordinary human life span.

Minnesota's porous karst soils are especially vulnerable to nitrate contamination, and private well testing in the karst region has shown dangerous levels of nitrate in drinking water.[21] Over 4.4 million Minnesotans rely on groundwater for their drinking water, including over 1.1 millions residents who rely on private wells.[22] The Minnesota Department of Health has found that fewer than 20 percent of Minnesotans regularly test their well water for common pollutants,

[17] Polk County, Currents of Change: An Analysis of the Racoon and Des Moines Rivers in Central Iowa 112 (2025); Mary Ward et al., *Drinking Water Nitrate and Human Health: An Updated Review*, 15 INT. J. RES. PUBLIC HEALTH 1, 22 (2018); Burkholder, supra n.4 at 310; Jason Semprini, *Early Prenatal Nitrate Exposure and Birth Outcomes: A Study of Iowa's Public Drinking Water (1970-1988)*, 4 PLOS Water (2025).
[18] Polk County, *supra* n.17 at 112; Semprini, *supra* n.17 at 12.
[19] MINN. DEP'T OF HEALTH, 2020-2022 NITRATE ANNUAL REPORT (Sept. 2024), 8-12, https://www.health.state.mn.us/communities/environment/water/docs/contaminants/nitrpt20202022.pdf.
[20] SDWA PETITION, *supra* n.**Error! Bookmark not defined.**6 at 26.
[21] Ethan Bahe, *Five years after EWG's first analysis, manure still overloads Minnesota*, ENVIRONMENTAL WORKING GROUP (May 15, 2025), https://www.ewg.org/research/five-years-after-ewgs-first-analysis-manure-still-overloads-minnesota.
[22] Minnesota Dep't of Health, *Minnesotans with Private Wells Urged to Test Their Drinking Water For Five Common Contaminants* (March 11, 2024), https://www.health.state.mn.us/news/pressrel/2024/wellsprivate031124.html (last visited June 18, 2024).

meaning that hundreds of thousands of residents could be unknowingly drinking water polluted with dangerous concentrations of nitrate.[23]

Critically, the health risks associated with high nitrate levels are often compounded by the synergistic effects of pesticides like those used in cattle ear tags or on nearby fields monocropped with corn and other livestock feed inputs.[24]

Pathogens

In addition to containing dangerous levels of nutrients, feedlot waste is laden with fecal coliform bacteria and other harmful pathogens that threaten the health of humans, pets, and wildlife.[25] Zoonotic pathogens commonly found in manure include *E. coli*, *Campylobacter*, *Salmonella*, *Listeria*, *Cryptosporidium parva*, and *Giardia*, all of which can cause acute gastrointestinal distress, fever, and other dangerous symptoms in humans who drink or have recreational contact with contaminated water.[26] EPA has found that "[m]ore than 150 pathogens associated with industrial livestock production are also associated with risks to humans, including the six human pathogens that account for more than 90% of food and waterborne diseases."[27]

Livestock waste is a leading cause of bacteria in Minnesota's lakes and streams.[28] In the Minnesota River basin, feedlot density is so high that MPCA considers livestock waste—and particularly waste from unpermitted feedlots—a "high priority" that must be addressed to return

[23] Minn. Dep't of Health, *Minnesotans with Private Wells Urged to Test Their Drinking Water For Five Common Contaminants* (March 11, 2024), https://www.health.state.mn.us/news/pressrel/2024/wellsprivate031124.html.
[24] *See* Balkissa S. Ouattara et al., *Investigation of a Possible Relationship between Anthropogenic and Geogenic Water Contaminants and Birth Defects Occurrence in Rural Nebraska*, 14 Water 1, 13 (2022), https://www.mdpi.com/2073-4441/14/15/2289 (2022 study finding that high levels of nitrate and atrazine—a carcinogenic pesticide widely used on livestock feed crops in the U.S.—were correlated with an increased likelihood of birth defects); *see also* Louise Boyle, INDEPENDENT, *US Meat Industry Using 235m Pounds of Pesticides a Year, threatening Thousands of At-Risk Species, Study Finds*, https://www.independent.co.uk/climate-change/news/pesticides-factory-farm-wildlife-food-chain-vegan-b2017811.html (Feb. 22, 2022).
[25] 68 Fed. Reg. at 7,186; Xunde Li et al., *Fecal Indicator and Pathogenic Bacteria and Their Antibiotic Resistance in Alluvial Groundwater of an Irrigated Agricultural Region with Dairies*, 44 J. ENVTL. QUALITY 1435, 1435 (2015).
[26] Tucker Burch et al., *Fate of Manure-Borne Pathogens during Anaerobic Digestion and Solids Separation*, 472 J. ENVTL. QUALITY 336, 336 (2018); 68 Fed. Reg. 7,176, 7,263.
[27] 68 Fed. Reg. at 7236 (codified at 40 C.F.R. pts. 9, 122, 123, 412).
[28] MPCA, Water Pollutant: Bacteria, https://www.pca.state.mn.us/pollutants-and-contaminants/bacteria.

E. coli concentrations to safe levels.[29] Strategies MPCA determined were necessary to reach water quality goals in the basin include ensuring 100 percent regulatory compliance with the feedlot regulations (presumably through permitting), not increasing the current livestock inventory, and expanding livestock exclusions on tributaries.[30]

Pharmaceuticals

Feedlot waste also contains pharmaceuticals that can adversely impact humans and animals. Antimicrobials, including medically important antibiotics, are common constituents of feedlot waste, and have been detected in both surface and groundwater samples collected near feedlots.[31] EPA has found that 80 to 90 percent of some administered antibiotics end up in animal waste.[32] Antibiotics used to hasten livestock growth and combat disease in crowded, unsanitary confinements also promote the proliferation and dissemination of antibiotic-resistant bacteria in waterways near feedlots. These antibiotic-resistant bacteria make it more difficult to treat infections in humans, significantly increasing both the likelihood of hospitalization and duration of hospital visits.[33]

Hormones present in feedlot waste pose additional threats to humans and wildlife.[34] Heightened levels of hormones commonly administered to livestock have consistently been found in surface waters, groundwater, and spring water surrounding feedlots.[35] These hormones,

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[29] MPCA, MINNESOTA RIVER E. COLI TOTAL MAXIMUM DAILY LOAD AND IMPLEMENTATION STRATEGIES 34–35 (2019).
[30] *Id.* at 68–69.
[31] Jim O'Neil, ANTIMICROBIALS IN AGRICULTURE AND THE ENVIRONMENT: REDUCING UNNECESSARY USE AND WASTE (Dec. 2015), available at https://amr-review.org/sites/default/files/Antimicrobials%20in%20agriculture%20and%20the%20environment%20-%20Reducing%20unnecessary%20use%20and%20waste.pdf; Li et al., *supra* n.25 at 1445
[32] EPA, National Pollutant Discharge Elimination System (NPDES) Concentrated Animal Feeding Operation (CAFO) Reporting Rule, Proposed Rule, 76 Fed. Reg. 65431, 65434 (Oct. 21, 2011).
[33] Shane Rogers & John Haines, DETECTING AND MITIGATING THE ENVIRONMENTAL IMPACT OF FECAL PATHOGENS ORIGINATING FROM CONFINED ANIMAL FEEDING OPERATIONS: REVIEW, EPA/600/R-06/021 15 (Sept. 2005).
[34] EPA, LITERATURE REVIEW OF CONTAMINANTS IN LIVESTOCK AND POULTRY MANURE AND IMPLICATIONS FOR WATER QUALITY 56-57 (June 2013), EPA 820-R-13-002, https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100H2NI.TXT [hereinafter EPA LITERATURE REVIEW]; GOV'T ACCOUNTABILITY OFFICE, CONCENTRATED ANIMAL FEEDING OPERATIONS: EPA NEEDS MORE INFORMATION AND A CLEARLY DEFINED STRATEGY TO PROTECT AIR AND WATER QUALITY FROM POLLUTANTS OF CONCERN 24 (2008); HRIBAR, *supra* n.2 at 5; Edward F. Orlando, et al., *Endocrine-Disrupting Effects of Cattle Feedlot Effluent on an Aquatic Sentinel Species, the Fathead Minnow*, 112 ENV'T HEALTH PERSPECTIVES 353, 356–357 (2004); Burkholder, *supra* n.16 at 308; SCOTT BRADFORD, U.S. ENV'T PROT. AGENCY, TRANSPORT AND FATE OF NUTRIENTS AND INDICATOR MICROORGANISMS AT A DAIRY LAGOON WATER APPLICATION SITE: AN ASSESSMENT OF NUTRIENT MANAGEMENT PLANS, 1, 12, 66 (2011).
[35] Orlando, et al., *supra* n.34 at 353–354; HRIBAR, *supra* n.2 at 5.

particularly synthetic hormones with longer half-lives, alter the reproductive biology and development of aquatic species in waters near CAFOs.[36] Changes observed include demasculinization and defeminization of fish, decreased fertility in female fish, and abnormal reproductive proteins in turtles.[37] One study that specifically examined the impacts of CAFO effluent on fathead minnows found that "[w]ild fish collected below a feedlot exhibited altered reproductive biology."[38]

Other Pollutants

Lastly, feedlots generate and discharge sediments, salts, heavy metals, semimetals, and other trace elements added to feed and eventually expelled by livestock.[39] Though impacts stemming from these feedlot pollutants have been chronically under-monitored and under-researched, each pollutant creates individual and cumulative water quality impacts. For instance, sediments carried to surface waters by erosion, runoff, and air deposition "may prove a significant stressor to a watershed as sediment itself or as a medium for the transport of other stressors such as nutrients, pathogens, or chemical stressors."[40] "Bottom sediments in manure lagoons or natural waters can serve as a very effective reservoir for pathogens" like fecal bacteria, which can survive for "weeks or months" in sediments.[41]

These pollutant contaminated sediments threaten Minnesota's wildlife. For example, Minnesota Department of Natural Resources listed lake sturgeon as a species of special concern after impairments caused in part by agricultural practices limited its natural habitat range and caused a catch rate decline of over 99 percent over the 20th century.[42] A multinational coalition of tribal and state governments have been working to restore a stable lake sturgeon population to the Red River Basin for decades.[43] In 2022, these efforts were rewarded with the first confirmed

[36] Orlando, et al., *supra* n.34 at 357.
[37] *Id.* at 353, 356–357; HRIBAR, *supra* n.2 at 5.
[38] Orlando, et al., *supra* n.34 at 356
[39] *Id.*; BRADFORD, *supra* n.34, 12, 66 (2011); Xueping Liu, et al., *Arsenic pollution of agricultural soils by concentrated animal feeding operations (CAFOs)*, 119 CHEMOSPHERE 273, 280 (2015).
[40] EPA CAFO RISK ASSESSMENT, *supra* n.6 at 48.
[41] EPA LITERATURE REVIEW, *supra* n.34 at 22.
[42] Minn. Dep't of Nat. Res., *Rare Species Guide: Acipenser fulvescens*, https://www.dnr.state.mn.us/rsg/profile.html?action=elementDetail&selectedElement=AFCAA01020 (last accessed June 30, 2025).
[43] JAMISON WENDEL, MINNESOTA DEP'T OF NATURAL RESOURCE, RESTORATION OF EXTIRPATED LAKE STURGEON (ACIPENSER FULVESCENS) IN THE RED RIVER WATERSHED—PHASE TWO (2019-2029), https://files.dnr.state.mn.us/fisheries/rivers/red-river/sturgeon-phase-2.pdf?v=2025.01.24-05.00.19

natural sturgeon spawning observed in the basin for over 100 years.[44] This hard won success is threatened by feedlot runoff that contributes to poor water quality conditions that endanger sturgeon, as well as other fish and wildlife in the ecosystem.[45]

Salts, metals, other trace elements, and even carcinogenic PFAS in feedlot waste also pollute water while providing no benefit to agricultural lands. Livestock feed, and therefore waste, is known to contain many of the same elements found in sewage sludge, including "cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, and zinc," yet these pollutants are not regulated under the feedlot rules.[46] Because these compounds are not agronomically useful, they persist in feedlot waste, resulting in on-field accumulation and contaminated runoff.[47] In North Carolina, for example, accumulations of zinc and copper in areas with high concentrations of industrial animal agriculture have degraded soil quality to toxic levels.[48] Excessive salts in feedlot waste also adversely impact soil quality to such an extent that they can restrict crop establishment and growth.[49] In this manner, allowing land application of feedlot waste that has not been treated or even tested for PFAS, salts, metals, and other trace elements directly undermines plant growth and contributes to overapplication of manure, fertilizer, and soil amendments that further reduce water quality.

B. Feedlots Discharge Pollutants to Waters of the State

EPA estimates that approximately 75 percent of all CAFOs discharge pollutants to waterways[50] and, as discussed below, feedlots in a Minnesota are no exception. Feedlots

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[44] Minn. Dep't of Nat. Res., *Red River of the North Sturgeon Restoration*, https://www.dnr.state.mn.us/fisheries/red-river-sturgeon.html.

[45] MINNESOTA DEP'T OF NATURAL RESOURCES ET AL., RED RIVER OF THE NORTH FISHERIES MANAGEMENT PLAN 6, 19 (2017-2027), https://files.dnr.state.mn.us/fisheries/rivers/red-river/red-river_mp.pdf?v=2025.01.24-05.00.19; *see also* Minnesota Dep't of Nat. Res., *Red River of the North State Water Trail*, https://www.dnr.state.mn.us/watertrails/redriver/index.html (describing other wildlife that rely on the Red River, including but not limited to beavers, bears, moose, and a variety of bird species).

[46] EPA, WHAT ENVIRONMENTAL AND HUMAN HEALTH IMPACTS ARE POTENTIALLY CAUSED BY CAFOS?, https://www3.epa.gov/npdes/pubs/cafo_ch5.pdf at 44-45; Burkholder et al., *supra* n.4 at 308.

[47] EPA, WHAT ENVIRONMENTAL AND HUMAN HEALTH IMPACTS ARE POTENTIALLY CAUSED BY CAFOS? 44-45, https://www3.epa.gov/npdes/pubs/cafo_ch5.pdf; Clare Death et al., *Per- and Polyfluoroalkyl Substances (PFAS) in Livestock and Game Species: A Review*, 774 Sci. Total Env't 1, 3–8 (2021).

[48] Steph Kulesza et al., *Mitigating Zinc and Copper Toxicity in North Carolina Soils* (March 27, 2024) https://content.ces.ncsu.edu/mitigating-zinc-and-copper-toxicity-in-north-carolina-soils.

[49] BRADFORD, *supra* n.34 at 14-15

[50] 73 Fed. Reg. 70,418, 70,469 (Nov. 20, 2008) (explaining that only about 25 percent of CAFOs are not designed to discharge).

discharge pollutants to water through various pathways from both production areas and land application areas, leading EPA to conclude that animal agriculture is a "primary source of nitrogen and phosphorus" in groundwater and surface water systems.[51] As discussed in greater detail below, well-established discharge pathways include seepage through corrals, waste storage structures, and below land application areas; overflows from waste storage structures; and runoff from land application fields and production areas.[52]

1. Production Area Pathways

Production areas—even those constructed and operated in compliance with NPDES or SDS permitting requirements—inevitably discharge harmful pollutants into the state's surface waters and groundwater. LMSAs are a primary source of production area discharges. However, compost piles and other solid waste storage also pose significant discharge risks.

Storing large amounts of feedlot waste in LMSAs creates an ever-present risk that the "lagoons will fail or rupture and pollute surface waters or allow waste to seep into groundwater."[53] Such risks are only increasing as climate change makes extreme weather events—like more powerful and more frequent extreme rainfall—more common.[54] For example, in June 2024, extreme rainfall in Southwest Minnesota caused seventeen manure storage areas to overflow.[55] Inundation of surrounding fields limited the state's ability to effectively contain or disperse the contaminated waters away from surface waters.[56] The changing climate may also increase the frequency and/or intensity of freeze and thaw cycles that destabilize clay lagoon

[51] EPA, *Estimated Animal Agriculture Nitrogen and Phosphorus from Manure* (June 5, 2025), https://www.epa.gov/nutrientpollution/estimated-animal-agriculture-nitrogen-and-phosphorus-manure (last visited June 18, 2025)
[52] BRADFORD, *supra* n.34 at 66; Michael A. Mallin & & Lawrence B. Cahoon, *Industrialized Animal Production—A Major Source of Nutrient and Microbial Pollution to Aquatic Ecosystems*, 24 POPULATION AND ENV'T 369, 377 (2003); *see also* THOMAS HARTER ET AL., NICHOLAS INSTITUTE FOR ENVIRONMENTAL POLICY SOLUTIONS, ASSESSING POTENTIAL IMPACTS OF LIVESTOCK MANAGEMENT ON GROUNDWATER 4–7 (2014) (charting studies that documented leaching from CAFO corrals and feedlot surfaces, manure lagoons, and land application areas).
[53] Thomas R. Head, *Local Regulation of Animal Feeding Operations: Concerns, Limits, and Options for Southeastern States*, 6 Env't Law. 503, 515–16 (2000).
[54] *See* Greg Stanley, *Seventeen Manure Pits Reportedly Overflow at Large Feedlot in Southern Minnesota* (June 26,2024), https://www.startribune.com/manure-pits-reportedly-overflow-at-16-large-feedlots-in-southernminnesota/600376074
[55] *Id.* (where the MPCA feedlot program manager noted that many of the spill mitigation options were "off the table" due to field inundation from excessive precipitation).
[56] *Id.*

liners and manure seals currently allowed under the feedlot rules, further increasing the likelihood of cracks and tears under the existing regulatory regime.[57]

Even intact LMSAs designed to the permeability rate mandated by the existing feedlot rules are not sufficiently protective of groundwater and hydrologically connected surface waters. Currently, the rules permit pollutants to seep from lagoons at a rate of 1/56 (0.018) inches per day.[58] While this rate may seem inconsequential, LMSAs often span an acre or more, allowing pervasive seepage to occur over the entirety of the subsurface area.[59] Numerous scientific studies demonstrate that pollutants such as ammonia-N and antibiotic-resistant bacteria seep from inadequately-lined lagoons into groundwater where they are then transported downstream.[60] This and other evidence has led multiple courts to conclude that even LMSAs constructed to permeability standards more stringent than Minnesota's leach pollutants into groundwater because the "the lagoons are designed to leak."[61] While depth gauges intended to prevent overflows may alert a feedlot operator to a catastrophic lagoon breach, they are not designed to notify operators about slow and steady—but still significant—seepage and leaking to the subsurface.

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[57] NRCS, Part 651 Agricultural Waste Management Field Handbook App'x 10D 10D-26; Noah Rudko et al., *Development of a Point-Source Model to Improve Simulations of Manure Lagoon Interactions with the Environment*, 325 J. ENV'T MGMT. 1, 9 (2023); *see also* Minn. R. § 7020.2100, subp. 3(C)(1) (allowing any liner so long as it meets the 1/56 inch per day permeability standard).

[58] Minn. R. § 7020.2100(3)(C) (permitting a theoretical seepage rate of 1/56 inch—or 0.018 centimeters—per day).

[59] Expert Opinion of David J. Erickson, PG CPG (hereinafter, "Erickson Report") at 4 (attached as Exhibit A).

[60] J.C. Chee-Sanford et al., *Occurrence and Diversity of Tetracycline Resistance Genes in Lagoons and Groundwater Underlying Two Swine Production Facilities*, 67 APPLIED ENV'T MICROBIOLOGY 1494, 1499 (2001) (detecting tetracycline-resistant bacteria from lagoons at swine CAFOs in groundwater); S. Koike, et al., *Monitoring and Source Tracking of Tetracycline Resistance Genes in Lagoons and Groundwater Adjacent to Swine Production Facilities Over a 3-Year Period*, 73 APPLIED AND ENV'T MICROBIOLOGY 4813, 4822 (2007) ("[A]nimal waste seeping from unlined lagoons at two swine confinement facilities had an impact on the dissemination of tetracycline resistance genes in groundwater near the facilities."); Noah Rudko et al., *Development of a Point-Source Model to Improve Simulations of Manure Lagoon Interactions with the Environment*, 325 J. ENV'T MGMT. 1, 5 (2023) ("The groundwater monitoring wells downgradient of the lagoon had elevated concentrations of each of the sampled water quality parameters, indicating that the lagoon was the only factor driving elevated ammonia-N concentrations in the downgradient wells.");

[61] *Food & Water Watch v. U.S. EPA*, 20 F.4th 506, 509 (2021) (quoting *Cmty. Ass'n for Restoration of the Env't, Inc. v. Cow Palace, LLC*, 80 F. Supp. 3d 1180, 1223 (E.D. Wash. 2015)). The permeability standard at issue in those cases was 1 x 10^{-7} centimeters per second, more stringent than Minnesota's 1/56 inch per day standard which equates to 5.29 x 10^{-7} centimeters per second.

Storing large amounts of liquid waste in open lagoons also allows pollutants like ammonia to volatilize and deposit onto surrounding land and water.[62] Volatilized ammonia can account for up to 70 percent of nitrogen excreted by confined livestock.[63] EPA has long recognized that aerial deposition is a significant source of pollution to surface waters, that feedlots discharge pollutants through aerial deposition, and that such discharges are subject to NPDES permitting requirements.[64] Atmospheric deposition accounts for an estimated 9% of nitrogen contributions to surface waters in Minnesota.[65] The rate of atmospheric deposition is highest is the southern and southeastern parts of the state, where agricultural and urban sources of nitrogen are more prevalent.[66]

In addition to manure, feedlots also store large amounts of other solid wastes, including silage and compost.[67] When stockpiled, these organic wastes release significant amounts of nitrate through ammonia volatilization and pollutant-laden leachate that can infiltrate groundwater or contaminate stormwater runoff.[68] Controlling leachate is critical, as researchers estimate the liquid

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[62] National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitations Guidelines and Standards for Concentrated Animal Feeding Operations, 66 Fed. Reg. 2960, 3104 (Jan. 12, 2001).
[63] Horacio A. Aguirre-Villegas & Rebecca A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, 143 J. CLEANER PRODUCTION 169, 169 (2017); *see also* EPA, DEVELOPMENT DOCUMENT FOR THE FINAL REVISIONS TO THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM REGULATION AND THE EFFLUENT GUIDELINES FOR CONCENTRATED ANIMAL FEEDING OPERATIONS 6-30 (Dec. 2002), [hereinafter 2003 TDD] (estimating that a quarter of total nitrogen deposition onto beef feedlot surfaces is lost to volatilization).
[64] 66 Fed. Reg. at 2980 (acknowledging that "atmospheric deposition is the third leading cause of water quality impairment for estuaries, and the fifth leading cause of water quality impairment for lakes, ponds, and reservoirs," and identifying land application as a source of aerial deposition); *see also id.* at 3104 ("A fraction of the air emissions from AFOs [including those from manure management systems and animal housing] are subsequently redeposited on land or in surface waters."); 68 Fed. Reg. at 7236, 7240 (listing volatilization and subsequent redeposition along with direct discharge and leaching to groundwater as primary pathways by which CAFO pollutants reach surface waters); 2003 TDD, *supra* n.63 at 6-30, 8-153–8-154 (estimating that a quarter of total nitrogen deposition onto beef feedlot surfaces is lost to volatilization); *see also Nat'l Pork Prods. Council*, 635 F. 3d 738, 754-56 (5th Cir. 2011) (describing EPA's position that aerial deposition of dust from poultry CAFO ventilation systems are discharges that must be permitted).
[65] MINNESOTA POLLUTION CONTROL AGENCY, NITROGEN IN MINNESOTA SURFACE WATERS: CONDITIONS, TRENDS, SOURCES, AND REDUCTIONS (June 2013), 1, 9, https://www.pca.state.mn.us/sites/default/files/wq-s6-26a.pdf [hereinafter "NITROGEN IN MN SURFACE WATERS"]
[66] *Id.* at 11.
[67] While "composting is a well-suited technology for on-farm management of agricultural residues, [] it is not an environmentally sustainable technology for treating manure alone. Certain chemical and physical characteristics of animal manures are not adequate for composting and could limit the efficiency of the process . . . ." M.B. Vanotti et al., *Removing and Recovering Nitrogen and Phosphorus from Animal Manure, in* 67 ANIMAL MANURE PRODUCTION, CHARACTERISTICS, ENVIRONMENTAL CONCERNS, AND MANAGEMENT 283 (H.M. Waldrip et al. eds. 2020).
[68] *See* M.M. Gebrehanna et al., *Silage Effluent Management: An Overview*, 143 SOIL, WATER, & CLIMATE 113, 113 (Oct. 2014) ("Silage effluent is a potent wastewater that can be produced when ensiling crops that have a high moisture content. Silage effluent can cause fish-kills and eutrophication."); Vanotti, *supra* n.67 at 283.

can be "40 times stronger than dairy parlor wastewater and up to 200 times stronger than raw sewage."[69] Because leachate contains such high nutrient concentrations, even seemingly negligible amounts can signify major nutrient losses that reduce the nutritional value of feed and contribute to water quality impairments.[70] In fact, "silage bunkers [are] one of the highest concentrated runoff nutrient loss areas on a farm in terms of loading per unit area."[71] Leachate from compost, which often includes mortalities on feedlots, contains similar pollutants of concern as well as elevated risks that pathogens will infiltrate groundwater.[72]

For decades, EPA has acknowledged that groundwater contaminated by feedlot pollutants is a "significant transport mechanism" for surface water discharges due to the prevalence of hydrologic connections.[73] Investigations in Washington and California show nitrates that seep into groundwater from feedlot lagoons can and do travel downgradient to surface waters.[74] During MPCA's recent feedlot permit update, the agency admitted that "a number of very site-specific factors" are used to determine whether a hydrologic connection exists between Minnesota's surface waters and groundwater underlying feedlots.[75] However, MPCA has not disclosed what these factors are or how the agency applies them to consistently protect surface waters from feedlot pollutants conveyed by groundwater.

2. Land Application Pathways

Land application areas also discharge pollutants to surface waters. Known discharge pathways from land application areas to state waters include runoff, infiltration to hydraulically

[69] JOSEPH P. HARNER, KANSAS ST. UNIV., SILAGE LEACHATE: A PROBLEM WITH POTENTIAL BENEFITS (May 2006), https://bookstore.ksre.ksu.edu/download/silage-leachate-a-problem-with-potential-benefits_MF2728; *see also* Dr. Rebecca Larson, U. WISC., *Silage Runoff Characterization* 6 (Apr. 3, 2013), https://www.slideshare.net/slideshow/silage-runoff-characterization-mah/19908018 (chart comparing concentrations of pollutants typical of silage leachate to pollutant concentrations of residential wastewater).
[70] PETER WRIGHT ET AL., EFFECTIVENESS OF SILAGE LEACHATE TREATMENT WITH VEGETATIVE FILTER AREAS (Aug. 2004), https://socwisconsin.org/wp-content/uploads/2016/05/Wrightetal_2004_SilageLeachateTrtmtVTA.pdf (noting that leachate losses from silo storage can equate to 15 percent of total feed nutrients or 7 pounds of phosphorus per cow per year).
[71] Michael A. Holly et al., *Silage Storage Runoff Characterization: Annual Nutrient Loading Rate and First Flush Analysis of Bunker Silos*, 264 AG. ECOSYSTEMS & ENV'T 85, 90 (2018).
[72] BRADLEY A. CLEARY, ASSESSMENT OF THE TRANSPORT OF BURIED LIVESTOCK LEACHATE THROUGH A SYNTHETIC CLAY LINER 35 (July 2009), https://central.bac-lac.gc.ca/.item?id=MR55444&op=pdf&app=Library&is_thesis=1&oclc_number=745898967.
[73] 66 Fed. Reg. at 2980; EPA, RISK ASSESSMENT EVALUATION FOR CONCENTRATED ANIMAL FEEDING OPERATIONS 52–53 (May 2004) [hereinafter EPA RISK ASSESSMENT].
[74] Erickson Report, *supra* n.59 at 7.
[75] MPCA, Response to Comments on the General NPDES and SDS Animal Feedlot Permits 14 (

connected groundwater, and aerial deposition.[76] Overapplication of feedlot waste to nearby cropland leads to runoff and infiltration when a field is oversaturated or when conditions are such that manure cannot reach crop roots.[77] The potential for runoff and infiltration "increases greatly" when "continual applications are made year after year," as many manure management plans ("MMPs") allow feedlots to do.[78] Minnesota's extensive drainage system, including subsurface tile drains and aboveground irrigation ditches, act as direct conduits to surface waters.[79] Pressurized irrigation systems and other land application methods cause discharges due to volatilization and aerial deposition, faulty equipment, and imprecise application.[80]

The combination of polluting land application methods and the use of yield-maximizing—as opposed to pollution-minimizing—application rates, has made land application of feedlot waste a significant source of water contamination.[81] According to models examining the overapplication of nitrogen to cropland throughout Minnesota, there are at least nine "hotspot" counties where cumulative nitrogen from feedlot waste and fertilizer purchased in the county "exceeds crop recommendations by more than 40 percent."[82] The model showed that in

[76] 68 Fed. Reg. at 7,181; EPA, MANAGING MANURE NUTRIENTS AT CONCENTRATED ANIMAL FEEDING OPERATIONS 4-15 (Dec. 2004), https://www.epa.gov/sites/default/files/2015-08/documents/cafo_manure_guidance.pdf (describing risks from land applying feedlot waste with irrigation systems), O-10 (explaining that fields with subsurface (tile) drainage "creat[e] a surface water pollution hazard from direct tile discharge"); EPA, CAFO RISK ASSESSMENT at 53 ("Interflow (e.g., subsurface runoff and artificial drainage) and ground water may deliver pollutants to surface waters through hydraulic connections."), 72–73 (discussing land application risks).
[77] Erickson Report, *supra* n.59 at 8–9.
[78] EPA CAFO RISK ASSESSMENT at 28.
[79] Erickson Report, *supra* n.59 at 3; *see also* EPA, NPDES Permit Writers' Manual (Sept. 2010) at 4-16, https://www.epa.gov/sites/default/files/2015-08/documents/cafo_permitmanual_chapter4.pdf (requiring NPDES permit writers to assess the risk of pollutant discharges from land application activities and create effluent limits appropriate to minimize such discharges).
[80] *See* WIS. MANURE IRRIGATION WORKGROUP, CONSIDERATIONS FOR THE USE OF MANURE IRRIGATION PRACTICES 3, 39–42 (Apr. 2016), https://fyi.uwex.edu/manureirrigation/files/2016/04/Manure-Irrigation-Workgroup-Report-2016.pdf (discussing potential for surface water discharge); *Parris v. 3M Co.*, 595 F. Supp. 3d 1288, 1322 (N.D. Ga. 2022) (collecting cases in which "land application systems, spray head sprinklers, and trucks constitute point sources when used to spread treated wastewater and manure on land"); EPA, IMPLEMENTATION GUIDANCE ON CAFO REGULATIONS—CAFOS THAT DISCHARGE OR ARE PROPOSING TO DISCHARGE 9 (May 28, 2010), https://19january2021snapshot.epa.gov/sites/static/files/2015-08/documents/cafo_implementation_guidance.pdf (photograph of spray irrigation equipment causing dry weather discharge at CAFO); *see also Cmty. Ass'n for Restoration of the Env't v. Henry Bosma Dairy*, 65 F. Supp. 2d 1129, 1147 (E.D. Wash. 1999) (noting a "verified discharge of animal wastes from a spray gun"); Burkholder, *supra* n.**Error! Bookmark not defined.** at 309; 2017 PETITION, *supra* n.**Error! Bookmark not defined.** at 52–53; Horacio A. Aguirre-Villegas & Rebecca A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, 143 J. CLEANER PRODUCTION 169, 169 (2017).
[81] See MPCA, 2013 Nitrogen in Minnesota Surface Waters 9 (estimating that more than 70 percent of nitrate in Minnesota's surface waters comes from cropland).
[82] Bahe, *supra* n.21; *see also* Food & Water Watch, Factory Farm Manure Is Overwhelming U.S. Counties (2025).

areas of concentrated livestock production, "almost all crop fields are needed to achieve safe use of manure produced by nearby feedlots."[83] Although the model found dramatic nitrogen overapplication in nine counties, it "likely *understates* the risk of this overload, because we assumed every field within 5 miles of a cattle or hog feedlot and 25 miles of a poultry feedlot is available to take manure, while in most real situations, manure does not travel that far."[84]

Accordingly, land application of feedlot waste in Minnesota is a major contributor to the nitrate crisis, especially in rural communities.[85] Other states have also recognized the risk land application poses; for example, California's State Water Resources Control Board recently acknowledged that land application of dairy waste "is responsible for the vast majority of dairies' nitrogen impacts to groundwater quality."[86]

C. Minnesota Is Especially Susceptible to Harmful Effects from Feedlot Pollution

Environmental quality in Minnesota is particularly susceptible to degradation from feedlot pollution due to the industry profile and the state's unique geography. Minnesota has one of the largest and most consolidated livestock industries in the country, second only to Iowa in terms of overall number of factory farms.[87] Cattle and swine feedlots dominate the industry, with these operations producing over 90 percent of manure in the state.[88] Swine and dairy feedlots are particularly damaging to water quality because they handle and store waste in liquid or slurry form. According to a soil scientist with USDA's Natural Resources Conservation Service, liquid waste "behaves like water,"[89] allowing pollutants to easily move through the environment and discharge to state waters.

Minnesota's feedlot industry is also increasingly consolidating, confining larger numbers of animals on smaller tracts of land.[90] For instance, the number of dairy farms decreased by 40

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[83] Bahe, *supra* n.21.
[84] Bahe, *supra* n.21 (emphasis added).
[85] SDWA Petition
[86] STATE OF CALIFORNIA STATE WATER RESOURCES CONTROL BOARD, DRAFT ORDER 2024-00XX, IN THE MATTER OF REVIEW OF WASTE DISCHARGE REQUIREMENTS GENERAL ORDER NO 05-2013-0122 FOR MILK COW DAIRIES IN THE CENTRAL VALLEY REGION at 6 (Oct. 1, 2024) [hereinafter CA DAIRY ORDER].
[87] EPA, NPDES PERMITTING STATUS REPORT: NATIONAL SUMMARY, ENDYEAR 2023 (May 14, 2024) https://www.epa.gov/system/files/documents/2024-06/cafo-status-report-2023.pdf
[88] Bahe, *supra* n.21.
[89] David Green and Frank Gibbs, *Liquid Manure Is Too Wet*, STATE LINE OBSERVER (2006) ("The problem is simple. We're watering manure down to where it behaves like water. Let me repeat that. We're watering manure down to where it behaves like water. You don't need to be a rocket scientist to understand that.")
[90] Bahe, *supra* n.21.

percent between 2017 and 2022, even as the overall number of dairy cows remained relatively stable.[91] This consolidation causes pollution hotspots in feedlot-dense areas where cropland simply cannot assimilate all the nutrients generated in the vicinity and waterways are overloaded with feedlot pollutants that do not benefit agriculture at all.[92]

Minnesota is especially vulnerable to adverse impacts stemming from groundwater pollution because the state's geology and hydrology lend themselves to rapid subsurface pollutant transport. In fact, the need to address rampant groundwater pollution in Southeastern Minnesota is a primary impetus for MPCA's decision to update its feedlot regulations.[93] Southeastern Minnesota—where many of the state's feedlots are concentrated—is dominated by karst topography, a landscape defined by a layer of porous sediment atop highly fractured bedrock which creates high connectivity between surface water and groundwater.[94] Groundwater flows easily and unpredictably through karst geology, aided by the region's extensive network of tile drains.[95] Pollutants that enter groundwater in Minnesota's karst region can reach domestic wells located miles from the source of contamination.[96] Subsurface pollutant plumes from liquid manure storage areas that reach groundwater also travel to surface waters.[97] Permitting liquid

[91] Madison Mcvan, *Minnesota Farms Are Consolidating and Other Takeaways from the Census of Agriculture* (Feb. 14, 2024), https://minnesotareformer.com/2024/02/14/minnesota-farms-are-consolidating-and-other-takeaways-from-the-census-of-agriculture/.
[92] *See* Bahe, *supra* n.21 (conservatively identifying 9 counties where nitrogen from manure and fertilizer exceeds crop recommendations by more than 40 percent); MPCA, MINNESOTA RIVER E. COLI TOTAL MAXIMUM DAILY LOAD AND IMPLEMENTATION STRATEGIES 28–30 (2019) (discussing high feedlot concentrations in the Minnesota River basin and their contribution to the River's E. coli impairment).
[93] MPCA, Request for Comments – Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, chapter 7020, Revisors ID Number R-04928 at 3 (describing this rulemaking as necessary to protect human health and the environment, and address EPA's response to a Safe Drinking Water Act petition raising concerns about nitrate contamination in Minnesota's karst region).
[94] SDWA Petition; *see also* FRACTRACKER ALL., Minnesota Confined Animal Feeding Operations or CAFOs (May 11, 2016), https://www.arcgis.com/apps/mapviewer/index.html?layers=6d119156229d4e908e22f027bdaee6be.
[95] Anthony Runkel et al., *Geologic Controls on Groundwater and Surface Water Flow in Southeastern Minnesota and its Impact on Nitrate Concentrations in Streams* (2014), https://conservancy.umn.edu/items/b927dcae-f4cb-4a6f-96ff-24178aa9b66a
[96] JEFFREY ST. ORES ET AL., UNIV. OF MINN. EXTENSION BULLETIN 465, GROUNDWATER POLLUTION PREVENTION IN SOUTHEAST MINNESOTA'S KARST REGION 6 (1982), https://conservancy.umn.edu/bitstream/handle/11299/169069/mn_2000_eb_465.pdf?sequence=1
[97] Erickson Report, *supra* n.59 at 5; *see also* MPCA, MINNESOTA'S WATER QUALITY MONITORING STRATEGY 2021-2031 (Aug. 2021) at 3, https://www.pca.state.mn.us/sites/default/files/p-gen1-10.pdf [hereinafter "MPCA WATER QUALITY MONITORING STRATEGY"] (acknowledging the interconnected nature of surface and groundwater in Minnesota).

waste generating feedlots to operate atop karst landscapes therefore increases the risks feedlot pollution poses to state waters.

Pollution impacts are also elevated in the Central Sands. This region is characterized by widespread sandy soils which are especially vulnerable to groundwater contamination.[98] Nitrate contamination, in particular, is an ongoing concern in this region.[99] Of the nine "hotspot" counties where manure and fertilizer sales exceed crop recommendations by over 40 percent, four were counties in the Central Sands region, indicating a risk of continuing groundwater contamination.[100] Indeed, monitoring in the region shows nearly 10 percent of private wells have nitrate concentrations above 3 mg/L,[101] a threshold that is increasingly associated with elevated risks of cancer, suboptimal birth outcomes, and other health problems.

Widespread tile drainage in these vulnerable karst and Central Sands regions further increases the risk of groundwater contamination. Minnesota is the third most-extensively tile drained state in the country, with over 3,266,234 acres of tile drained fields[102] conducting excess nutrients and other contaminants to the state's waters.[103] Accordingly, fields receiving feedlot manure are likely outfitted with direct pathways for pollutants to reach surface waters.

II. MPCA Must Strengthen Its Feedlot Regulations to Comply with Federal and State Law and Protect Public Health.

Despite broad authority to regulate feedlot pollution under section 116.07 of the Minnesota Statutes,[104] MPCA's feedlot rules are failing to protect Minnesota's residents and our

[98] Minnesota Department of Agriculture, *Central Sands Private Well Network*, https://www.mda.state.mn.us/central-sands-private-well-network (last visited June 18, 2025).
[99] The state has conducted annual tests to monitor nitrate contamination in the Central Sands region since 2011. See Minnesota Department of Agriculture, *Central Sands Private Well Network 2023 Results*, https://wrl.mnpals.net/node/4339 (last visited June 23, 2025).
[100] Bahe, *supra* n.21.
[101] Minn. Dep't of Agric., Central Sands Private Well Network 2023 Results, https://wrl.mnpals.net/node/4339
[102] Prasanth Valayamkunnath et al., *Mapping of 30-Meter Resolution Tile-Drained Croplands Using Geospatial Modeling Approach*, 7 SCI. DATA 1, 5 (2020), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7406500/pdf/41597_2020_Article_596.pdf
[103] *See* Gary R. Sands, *Impact of agricultural drainage in Minnesota* (2018), https://extension.umn.edu/agricultural-drainage/impact-agricultural-drainage-minnesota#prevalence-of-drainage-1360160 (last visited June 23, 2025).
[104] *See* Minn. Stat. §§ 116.07, subd. 4(a) (granting MPCA expansive authority to condition feedlot permits to prevent pollution), Minn. Stat. § 116.07, subd. 4(b) (authorizing MPCA to adopt rules necessary to regulate solid waste—which includes any animal waste not used as fertilizer—in a manner that will prevent, abate, and control water, air and land pollution), Minn. Stat. § 116.07, subd. 2(a) (requiring MPCA to "improve air quality by promoting. . . waste disposal methods which produce or emit the least air contaminants consistent with the agency's overall goal of reducing all forms of pollution.").

invaluable natural resources. Further, MPCA's rules controlling the development and issuance of National Pollutant Discharge Elimination System ("NPDES") permits for feedlots do not meet the minimum requirements established by the federal Clean Water Act.

A. New Feedlot Rules must Expand and Clarify Permitting

Minnesota's feedlot regulations currently offer four permitting options: (1) state disposal system ("SDS") permits; (2) NPDES permits; (3) construction short-form permits; and (4) interim permits.[105] Which permit a feedlot is required to obtain depends on the size of the operation, whether a facility believes or admits it is discharging, and whether it has been labeled a pollution risk by the state.[106] Further complicating matters, MPCA measures the number of animals on a feedlot differently than EPA does under the federal concentrated animal feeding operation ("CAFO") regulations.[107] These complex and subjective permitting requirements have resulted in low permit coverage that leaves many large and polluting feedlots without much-needed MPCA and public oversight.[108] To ensure feedlots in the state are properly permitted, MPCA should update section 7020.0405 of the regulations to establish a rebuttable presumption that any facilities that exceed the federal size thresholds for a Medium CAFO discharge and therefore must obtain coverage under a NPDES permit.

A straightforward permitting requirement based on a rebuttable presumption of discharge is preferable to a permit structure based on the existing permit structure because the vast majority of feedlots that store and land apply liquid waste are designed to discharge through production area and land application area pathways. Under the current approach, many discharging CAFOs are evading regulation under NPDES permits. EPA has found that approximately 75 percent of CAFOs nationally actually discharge due to their characteristics and how they are operated. In Minnesota, that percentage is certainly much higher due to the state's prevalence of rivers, streams, and lakes; its groundwater-surface water interactions; and its many CAFOs using liquid manure management. Yet fewer than two thirds of Minnesota CAFOs have NPDES permits.[109]

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[105] Minn. R. § 7020.0405.
[106] *Id.*
[107] *Compare* Minn. R. § 7020.0300, subp. 5 (defining "animal unit") with 40 C.F.R. § 122.23(b) (defining medium and large CAFOs according to number of animals).
[108] *See, e.g.*, EPA, NPDES CAFO Permitting Status Report National Summary, Endyear 2023 (May 2024) (showing approximately a third of Large CAFOs in Minnesota do not have NPDES permit coverage).
[109] https://www.epa.gov/system/files/documents/2024-06/cafo-status-report-2023.pdf

Allowing self-selection for permit coverage ignores the likelihood of undiscovered discharges, a category that encompasses many subsurface discharges and discharges resulting from human error or faulty equipment. Determining whether a feedlot is discharging is often outside the area of expertise of the operator who may lack knowledge about subsurface hydro-connectivity that could lead to a functionally equivalent discharge that requires an NPDES permit. Moreover, feedlot operators lack incentive to voluntarily subject themselves to regulatory controls that may undercut their bottom line. Establishing a presumption of discharge will help to resolve Minnesota's under-permitting problem.

MPCA should also require that qualifying feedlots get NPDES permits as opposed to SDS permits. The federal Clean Water Act requires discharging feedlots that meet or exceed the size threshold for a Medium CAFO under the federal rules to obtain coverage under a NPDES permit.[110] By streamlining permitting options for these facilities to include just NPDES permits, MPCA would reduce confusion about which permit a feedlot is required to obtain and help ensure Minnesota's feedlots are compliant with federal law. The contents of Minnesota's NPDES general permit and SDS general permit for feedlots are largely the same, so requiring feedlots currently operating under an SDS permit to switch to NPDES will have little impact on those operations. However, requiring unpermitted feedlots that are discharging to obtain NPDES permit coverage will subject those facilities to important pollution controls, monitoring, and reporting requirements that are necessary to ensure compliance with state and federal law and prevent pollution.

Additional permitting that will result from adjusting MPCA's permitting requirement from the existing 1,000 animal unit standard to a standard based on EPA's Medium CAFO threshold is necessary to combat pollution. At present, the majority of feedlot waste generated in the state (43 percent) originates on unpermitted feedlots with fewer than 1,000 animal units.[111] Many of these facilities are clustered just below the 1,000 animal unit cutoff, avoiding regulation while generating negligibly less waste than their permitted peers.[112] However, even feedlots well below the 1,000 animal unit cutoff produce waste in quantities that should undoubtedly be

[110] 40 C.F.R. § 122.23.
[111] Bahe, *supra* n.21 (Finding that while only 4% of Minnesota's feedlots have more than 1,000 animal units, those feedlots produced 33% of the total manure in the state annually).
[112] Bahe, *supra* n.21.

regulated via permit. For instance, a 500-animal unit mature dairy feedlot produces approximately the same amount of feces and urine waste as a city with a human population of 25,200 yet lacks any discharge permitting or monitoring.[113] A rebuttable presumption of discharge for all feedlots that exceed the Medium CAFO size threshold accounts for the significant pollution risks posed by facilities that handle such magnitudes of harmful waste, while allowing feedlots that can demonstrate they do not discharge to avoid unnecessary permitting.

Notably, adopting this requirement would appropriately obviate construction short-form and interim permits as they currently exist because facilities that would have been required to obtain those permits would be subject to NPDES permitting instead.

B. MPCA Must Mandate Updated BMPs for Land Application

Under MPCA's existing regulations, land applied feedlot waste is a major source of pollutants to waters of the state. This is largely due to the regulations' failure to prohibit common land application practices known to cause pollutant discharges. To remedy these discharges and improve environmental quality, MPCA should incorporate the following provisions to section 7020.2225 of the Minnesota Administrative Rules.

1. Replace the Agronomic Approach to Land Application Rates with a Pollution Reduction Approach

In regulating polluting entities like feedlots, MPCA's overarching duty is to protect and improve water quality.[114] Despite this clear mandate, the feedlot regulations overwhelmingly allow land application rates that are based on crop needs rather than what is necessary to safeguard water quality and protect public health.[115] As EPA and other state pollution control agencies have acknowledged, application rates that focus on maximizing yields rather than

[113] Michael Van Amburgh & Karl Czymmek, *Series: Phosphorus and the Environment, 2. Setting the Record Straight: Comparing Bodily Waste Between Dairy Cows and People*, CORNELL FIELD CROPS: WHAT'S CROPPING UP? BLOG (June 21, 2017), https://blogs.cornell.edu/whatscroppingup/2017/06/21/series-phosphorus-and-the-environment-2-setting-the-record-straight-comparing-bodily-waste-between-dairy-cows-and-people/ (last accessed June 30, 2025) (calculating that one cow produces as much waste as between 42-47 people); Minnesota State Demographic Center, *Our Estimates*, MINNESOTA DEPARTMENT OF ADMINISTRATION (Sept. 2024), https://mn.gov/admin/demography/data-by-topic/population-data/our-estimates/ (last accessed June 30, 2025).
[114] Minn. Stat. § 116.02, subd. 1(5) (vesting in MPCA the powers and duties laid out in Minn. Stat. § 115.03, subd. 1(5)).
[115] *See* Minn. R. § 7020.2225, subp. 3 (authorizing application rates within 20 percent of expected crop needs).

preventing excess pollutant runoff are insufficient to protect water quality.[116] To correct Minnesota's existing approach for calculating land application rates, MPCA must amend section 7020.2225 to require that application rates conform to realistic expectations about land's capacity to assimilate pollutants and adjust based on water quality impairments in receiving waters.

As a first step toward reducing nutrient pollution from land application activities, MPCA must develop land application rates that are designed to prevent discharges to surface or groundwater as opposed to maximize crop yields. While the ability of crops on a receiving field to uptake nutrients may be one factor in this calculation, it cannot be the primary or only factor. The University of Minnesota Extension Service's history of establishing maximum return to nitrogen ("MRTN") values (the primary basis for land application rates) demonstrates the fundamental mismatch between application rates designed to benefit crops and application rates designed to protect water quality. Since the feedlot regulations were last updated, the University has increased MRTN values multiple times.[117] As a result of these updates, recommended nitrogen application rates for corn have increased from 155 pounds per acre to 190 pounds per acre.[118] One of the two primary factors for the increase is increased precipitation causing higher nitrate losses.[119] In other words, higher application rates are being used to compensate for increased losses to the

[116] EPA, Confined Animal Feeding Operations: A Primer On The Federal Program 18 (Dec. 2021) (emphasis added) [hereinafter EPA CAFO Primer] (presentation on EPA regulation of CAFOs); *see also* Andrew Sharpley, *Agricultural Phosphorous Water Quality and Poultry Production: Are They Compatible?*, 78 POULTRY SCI. 660, 668 (1999) ("It cannot be assumed that there is a direct relationship between soil test calibration for crop response to [nutrients] and surface runoff enrichment potential . . ."); CA DAIRY ORDER at 6 (noting that existing practices guiding land application of dairy waste are "primarily [] a method of disposing of dairy waste that has secondary benefits of fertilizing crops, rather than a method of crop fertilization that may have incidental impacts to groundwater" and calling those practices "an inadequate approach for regulating dairy waste discharges")
[117] George Rehm, et al., Fertilizing Corn in Minnesota, U. of Minn. Extension (2006), https://s3.amazonaws.com/media.agricharts.com/sites/968/Crop%20Prod/Fertilizing%20Corn%20in%20MN_DC3790.pdf (last accessed July 17, 2025).
[118] *Compare id. with* Daniel E. Kaiser et al., *Fertilizing Corn in Minnesota - AG-FO-3790-D (REVISED 2016)*, U. of Minn. Extension (2016), https://wrl.mnpals.net/islandora/object/WRLrepository%3A3034 (last accessed July 17, 2025) *and* Daniel E. Kaiser, et al., *Fertilizing Corn in Minnesota - REVISED 2023*, U. of Minn. Extension (2023), https://drive.google.com/file/d/1f3-BrF4bD5EMu4pq4ofCQXUbgnzxeTwy/view (last accessed July 17, 2025).
[119] Paul McDivitt, On-Farm Research Helps To Complement, Challenge Minnesota's Corn Nitrogen Guidelines, MN SOIL FERTILITY (Mar. 31, 2021), https://mnsoilfertility.com/crop-fertility-findings/on-farm-research-helps-to-complement-challenge-minnesotas-corn-nitrogen-guidelines/ (accessed July 16, 2025)

environment.[120] If this process is allowed to continue, feedlot pollution from land application activities will only ever increase.

Ultimately, MPCA must use representative monitoring data to determine how much waste a receiving field can assimilate without causing or contributing to water pollution.[121] However, until such data is available, MPCA should, at minimum, prohibit land application of feedlot waste at rates that exceed receiving crops' phosphorus needs. Researchers have known for decades that "[e]ven under ideal conditions, with a well-planned system, there is still a significant risk of losses to the environment"[122] because land application of animal waste at rates recommended by state universities frequently overloads fields with far more nutrients than plants can uptake or soil can retain, creating serious water pollution risks.[123] This is particularly the case for phosphorous.[124] Because most crops require more nitrogen than phosphorous, nitrogen-based approaches to manure application are more common than phosphorous-based plans. This "presents a special problem because the N-to-P ratio in manures is lower than that needed by crops . . . [causing] excess P [to] build[] up to environmentally harmful levels in fields that received repeated applications."[125] This nutrient mismatch "invariably means [phosphorous] is overapplied relative to needs," and has led some researchers to conclude that nitrogen-based application rates "are much higher than agronomic requirements."[126]

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[120] Emerson F.C. Souza, et al., Precipitation Influences Pre-Sidedress Soil Nitrate Thresholds for Corn Production, SOIL SCIENCE SOCIETY J. OF AMERICA 1, 8 (May 2025).
[121] *See infra* Section II.D (discussing representative effluent monitoring).
[122] L.M. Risse, et al., *Land Application of Manure for Beneficial Reuse*, *in* NATIONAL CENTER FOR MANURE AND ANIMAL WASTE MGMT. WHITE PAPERS 17 (J.M. White et al., eds. 2001).
[123] *See e.g.*, Kimberly A Rosov, et al., *Waste Nutrients from U.S. Animal Feeding Operations: Regulations are Inconsistent Across States and Inadequately Assess Nutrient Export Risk*, 269 J. ENV'T MGMT. l, 8 (2020) (finding "standing operating procedures for land application of swine wastes create significant potential for nutrient overloads of soils and potential export of excess nutrients from CAFOs to surrounding environment; Burkholder, *supra* n.**Error! Bookmark not defined.** at 308 (surveying literature that found high concentrations of nitrogen in surface waters adjacent to spray fields where animal waste was applied at recommended rates).
[124] BRADFORD, *supra* n.34 at 8 ("[A] potential problem arises when the relative content of nitrogen and phosphorous in lagoon water differs from that in the crop. In this case, NMPs that are designed to meet the nitrogen requirement for crops may result in the over-application of phosphorous.").
[125]Risse, *supra* n.122 at ii.
[126] UNIVERSITY OF KENTUCKY RESEARCH FOUNDATION, DEMONSTRATION OF ENHANCED TECHNOLOGIES FOR LAND APPLICATION OF ANIMAL NUTRIENT SOURCES IN SENSITIVE WATERSHEDS: FINAL PROGRESS REPORT 2 (2008); E. Osei et al., *Environmental Benefits and Economic Costs of Manure Incorporation on Dairy Waste Application Fields*, 68 J. ENV'T MGMT. 1, 6 (2003).

Indeed, in an EPA study "designed to test the assumption that a well-designed and executed NMP is protective," the author concluded that only a highly conservative plan that treated wastewater prior to application to remove most of the suspended solid content and "depleted the soil organic reservoir . . . by applying only a fraction of" the crop's nitrogen needs actually minimized pollution.[127] In contrast, a "more aggressive" plan—like those currently allowed under MPCA's feedlot regulations—led to increased "leaching and contaminant migration."[128] While defaulting to phosphorus-based planning is not a panacea for pollution impacts from land applying feedlot waste,[129] it is a commonsense solution to widespread phosphorus contamination in feedlot dense watersheds.

Even with phosphorus-based application rates as a baseline, MPCA must also update the regulations at Section 7020.2225 to be directly responsive to site-specific land application area soil conditions and water quality impairments in receiving waters. At present, feedlots with more than 300 animal units are only required to test and report soil phosphorus levels.[130] At minimum, this requirement must be expanded to include nitrogen as well. Land applying feedlot waste to fields with nutrient levels that indicate a high risk of runoff or leaching should be outright prohibited. Similarly, MPCA should consider instating a conservative cap on land application of feedlot waste to fields that drain to waters that are already impaired for

2. *Impose Numeric Limits on Pollutant Concentrations for Land Applied Waste That Exceeds Water Quality-Based Application Rates*

Once MPCA has developed land application rates based on water quality considerations as opposed to crop needs, the Agency should develop numeric limits for any waste permitted feedlots intend to land apply. These limits should be based on pollutant reductions attainable through the use of advanced treatment technologies. For instance, Terra Blue (formerly known as Super Soils)[131] is a three-step system that processes liquid feedlot waste through (1) SLS

[127] BRADFORD, *supra* n.34 at 67.
[128] *Id.*
[129] Matthew T. Streeter, et al., *Effects of Cattle Manure and Soil Parent Material on Shallow Groundwater Quality*, 6 AGROSYS. GEOSCIS. & ENV'T 1, 6 (2023) (explaining "if cattle manure (and any other nutrient input) is applied at agronomic rates for [phosphorous] while not accounting for manure [nitrogen] in the total budget for that nutrient, the potential to degrade groundwater resources with No3-N is high.").
[130] Minn. R. § 7020.2225, subp. 3(C).
[131] Viney P. Aneja et al., *From Pollution to Resource: Advancing Swine Waste Treatment in the USA*, 8 FRONTIERS SUSTAINABLE FOOD SYS. 1, 6 (2024), https://scholarship.law.duke.edu/cgi/viewcontent.cgi?article=7037&context=faculty_scholarship.

enhanced by a polymer (polyacrylamide, or "PAM") to encourage flocculation; (2) biological treatment to enhance nitrification (the chemical process by which ammonia is transformed into nitrite and nitrate); and (3) alkali chemical precipitation to remove phosphorus and destroy pathogens.[132] A 4,400-animal swine feedlot in North Carolina that installed and operated the system for a full year shortly after the consent decree was reached was able to remove 97.6 percent of suspended solids, 99.7 percent of biological oxygen demand, 98.5 percent of total Kjeldahl nitrogen, 98.7 percent of ammonia, 95 percent of total phosphorus, 98.7 percent of copper, 99 percent of zinc.[133] Notably, a majority of suspended solids, zinc, copper, and phosphorus were removed during the polymer-assisted solids separation portion of the process.[134] The researchers working on the demonstration project concluded that "the technology was technically and operationally feasible," and met the technical performance standards that define an Environmentally Superior Technology.[135] Since these initial tests, additional data have been collected from other feedlots that have installed versions of the Super Soils/Terra Blue system, verifying its capacity for significant pollution reductions.[136]

The Terra Blue system also redresses adverse non-water quality environmental impacts. Field studies of facilities employing the system have seen up to 100 percent removal of odorous compounds in liquid waste thanks in large part to denitrifying bacteria in the system's second step.[137] This means that Terra Blue has the capacity to significantly abate odor nuisances caused by swine CAFOs (and likely other CAFOs using liquid manure management) across the country.

Further, emissions reductions that would result from broad implementation of Terra Blue could significantly reduce the swine industry's climate footprint and local air quality impacts. Between reductions in ammonia (a precursor to nitrous oxide formation) and methane emissions, researchers estimate that facilities using Terra Blue can expect approximately 96.9 percent reductions in greenhouse gas emissions from manure management. These emissions reductions

[132] *Id.*; M.B. VANOTTI ET AL., DEVELOPMENT OF ENVIRONMENTALLY SUPERIOR TECHNOLOGY IN NORTH CAROLINA: THE SUPER SOIL PROJECT 4 (2005), https://www.ars.usda.gov/ARSUserFiles/60820000/Manuscripts/2005/Man707.pdf; *see also* Vanotti, *supra* n.67 at 281.
[133] Vanotti, *supra* n.132 at 4–5.
[134] *Id.* at 4; Vanotti, *supra* n.67 at 281–82.
[135] Vanotti, *supra* n.132 at 5.
[136] Aneja, *supra* n.132 at 9.
[137] *Id.*

are critical to combatting the existential threats posed by climate change, as well as improving local air quality to benefit frontline communities.

Even requiring land applied waste that exceeds water quality-based application rates to meet pollutant standards based on a single step of the Terra Blue process would have significant benefits. For instance, in slaughterhouse effluent (a waste with a similar pollutant profile to feedlot waste), full denitrification via biological processes and activated sludge has been shown to achieve "95 percent reductions in BOD, suspended solids, and reductions in ammonia nitrogen."[138] Several of these systems have been proven effective in treating swine wastewater for not only nutrients and conventional pollutants, but for antibiotics as well.[139]

Alternatively, chemical precipitation has also been proved to aid in removing phosphorus from feedlot waste. Chemical additives proven to remove phosphorus from CAFO wastewater include magnesium phosphate (struvite) in combination with ethylenediaminetetraacetic acid (70 to 80 percent effective at removing phosphorus from swine and dairy wastewater, 90 to 98 percent effective at removing phosphorus from poultry manure); lime (79.8 to 94.7 percent effective in removing phosphorus from pig waste); a combination of acid, hydrated lime, and organic polyelectrolytes (80 to 90 percent effective in removing phosphorus from poultry litter and swine waste); and metal salts like alum, aluminum chloride, ferric sulfate, and ferric chloride, alone or in combination with polymers (variety of phosphorus removal efficacies depending on the dose applied).[140]

3. *Codify Land Application Restrictions in Existing General Permit and Prohibit Application in Winter Conditions*

In its latest revision to the NPDES General Permit for feedlots, MPCA significantly updated timing restrictions on land application activities to account for increased risks associated with applying waste to warm soils, fields without cover crops, and frozen and snow-covered ground.[141] As detailed in the response to comment issued along with that Permit, MPCA has

[138] 89 Fed. Reg. at 4482–83.
[139] Vanotti, *supra* n.**Error! Bookmark not defined.** at 299–307; *see also* David Townsend et al., *The Premium Standard Farms Nitrification and Denitrification Experience* (June 6, 2006), https://porkgateway.org/resource/the-premium-standard-farms-nitrification-and-denitrification-experience/ (describing an advanced nitrification and denitrification system consisting of multiple basins installed in a pig CAFO to treat waste from 52,800 animals).
[140] Vanotti, *supra* n.67, at 285–92; EPA LITERATURE REVIEW, *supra* n.**Error! Bookmark not defined.** at 67.
[141] Feedlot General Permit at 9-12 (Section 13, Land Application of Manure - Timing).

thorough scientific justification for these restrictions. Accordingly, these provisions should largely be incorporated into the feedlot land application restrictions.

The one exception is that MPCA should entirely prohibit the spreading of feedlot waste on frozen, saturated, or snow-covered grounds. "Considerable research has demonstrated that runoff from manure application on frozen or snow-covered ground has a high risk of water quality impact." [142] The increased likelihood of runoff associated with application of manure to frozen, saturated, or snow-covered ground is widely recognized by agricultural experts, including agricultural extension program technical staff, state agencies, and EPA. Liquid or semi–liquid manure cannot easily permeate ground that is already saturated or that is frozen, and thus is much more likely to run off into nearby waterways, particularly when snow or frozen ground begins to melt.[143] EPA has collected considerable research documenting "extremely high concentrations of nitrogen and phosphorous in runoff" due to winter application of waste. [144] Per this research, winter application of dairy manure can result in a 1,480 percent increase in soluble phosphorus concentrations found in nearby surface waters, and up to 576 percent increases in ammonia-nitrogen concentrations. [145] One study of Vermont streams and lakes concluded that 40 percent of studied waterbodies experienced significant water quality impairments from the addition of just two winter-spread fields in their watersheds.[146] A Wisconsin study similarly estimated that 25 percent of annual phosphorous loading was directly attributable to winter spreading of animal wastes.[147]

Other authorities, ranging from the state level to international, have also recognized the harms likely to result from land application in winter months and on frozen ground. The International Joint Commission, an international organization created by the Boundary Waters Treaty (ratified by the United States and Canada in 1909), recommends that to protect Lake Erie, all adjacent states should ban the spreading of manure on frozen or snow-covered ground because of the likelihood of those practices polluting surface waters.[148] The Iowa State University Extension acknowledges that "[b]roadcasting manure onto frozen, snow-covered, water-saturated

[142] CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.**Error! Bookmark not defined.** at G-14.
[143] INT'L JOINT COMM'N, A BALANCED DIET FOR LAKE ERIE: REDUCING PHOSPHOROUS LOADINGS AND HARMFUL ALGAL BLOOMS 75 (2014), https://ijc.org/sites/default/files/2014%20IJC%20LEEP%20REPORT.pdf; EPA RISK ASSESSMENT, *supra* n.**Error! Bookmark not defined.** at 23, 71.
[144] CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.**Error! Bookmark not defined.** at G-14. (citing research finding a 1,480 percent increase in soluble P concentrations and 576 percent increases in ammonia-nitrogen concentrations following winter application of dairy manure).
[145] *Id.* (citing 1990 and 1991 Clausen studies).
[146] *Id* (citing 1989 Clausen and Meals study).
[147] *Id.* (citing 1985 Moore and Madison study).
[148] INT'L JOINT COMM'N, *supra* n.143 at 9.

soils increases the potential for nutrient losses with rainfall or snowmelt runoff to surface water systems."[149] Similarly, the Penn State Extension warns that "[s]preading manure in the winter is discouraged because it is a high-risk time period for nutrient losses and contamination of surface water,"[150] and the Ohio State University Extension advises that "[w]inter application should not be part of a manure management plan and it should only be viewed as a last resort."[151]

As such, NRCS advises that "[n]utrients must not be surface–applied if nutrient losses offsite are likely" and warns against spreading on "frozen and/or snow-covered soils, and when the top 2 inches of soil are saturated from rainfall or snow melt."[152] MPCA should abide by this regulation and prohibit land application to frozen, snow-covered, and saturated ground in its revision of section 7020.2225.

4. Prohibit Pivots, Guns, and Other High-Pressure Broadcast Irrigation Technologies

In general, MPCA's rules currently permit feedlots to use any method to land apply waste so long as applications comply with the facility's MMP and do not violate setback requirements for open tile intakes, sinkholes, mines, quarries and water supply wells.[153] The exception to this rule is land application within "special protection areas."[154] Special protection areas include any land within 300 feet of DNR-listed protected waters or wetlands and land within 300 feet of USGS-listed intermittent streams or ditches, excluding bermed drainage ditches and grassed waterways.[155] Applying feedlot waste with a traveling gun, center pivot, or other irrigation equipment that allows liquid waste to travel more than 50 feet in the air is prohibited in special protection areas. Though this restriction correctly acknowledges the pollution risks created by

[149] IOWA STATE UNIV. EXTENSION & OUTREACH, USING MANURE NUTRIENTS FOR CROP PRODUCTION 6 (May 2016), http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1089&context=extension_pubs.
[150] Charles White & Robert Meinen, PENN STATE EXTENSION, *The Do's and Don'ts of Winter Manure Spreading* (Dec. 13, 2022), https://extension.psu.edu/the-dos-and-donts-of-winter-manure-spreading.
[151] Amanda Meddles, OHIO STATE UNIV. EXTENSION, *Properly Applying Manure on Frozen Ground*, OHIO'S COUNTRY JOURNAL (Jan. 24, 2012), http://ocj.com/2012/01/properly-applying-manure-on-frozen-ground/; *see also* UTAH FARMSTEAD ASSESSMENT FOR GROUND WATER AND SURFACE WATER PROTECTION, HOW TO MANAGE STORED MANURE AND PROTECT YOUR WATER 7 (Mar. 2012), http://extension.usu.edu/files/publications/factsheet/WQFA-13.pdf (advising on proper manure handling and storage for water protection, and directing that "[m]anure should not be applied to frozen or snow-covered ground unless all runoff can be controlled."); OHIO DEP'T AGRIC. ET AL., OHIO LAKE ERIE PHOSPHORUS TASK FORCE II FINAL REPORT 51 (Nov. 2013), https://www.motherjones.com/wp-content/uploads/task_force_report_october_2013.pdf.
[152] NRCS STANDARD 590 at 4.
[153] Minn. R. § 7020.2225.
[154] *Id.* § 7020.2225, subp. 6.
[155] *Id.* § 7020.0300, subp. 23.

these technologies, it provides insufficient protections to mitigate these risks. To better protect water quality, MPCA must amend its land application regulations to prohibit high-pressure broadcast irrigation methods outright.

High-pressure spray equipment like irrigation guns and center pivots are not appropriate for land application of CAFO waste because of the likelihood of discharge to waters.[156] The special protection area regulations attempt to mitigate this risk by prohibiting the use of some broadcast spray irrigation technologies within 300 feet of surface waters and some conduits to surface waters. For a number of reasons, these measures are not sufficiently protective. First, pressurized spray irrigation equipment is known to jettison volatilized pollutants up to 10 kilometers away from the source.[157] Thus, a prohibition on using these technologies within 300 feet of waters or pathways to water will not stop volatilized pollutants from depositing in surface waters. Second, even if 300 feet were a large enough setback, MPCA's designated "special protection areas" do not include all surface waters. For instance, special protection areas inexplicably exclude bermed drainage ditches, even though berms do nothing to prevent the discharge of volatilized pollutants. Further, because DNR's Public Waters Inventory maps do not include Type 1 and Type 2 wetlands,[158] existing protections also exclude seasonal and ephemeral wetlands despite the elevated discharge risks known to accompany application of waste to

[156] *See* EPA, Risk Assessment Evaluation for Concentrated Animal Feeding Operations 71 (May 2004; WIS. MANURE IRRIGATION WORKGROUP, *supra* n.80 at 39–42 ((discussing potential for surface water discharge); *Parris v. 3M Co.*, 595 F. Supp. 3d 1288, 1322 (N.D. Ga. 2022) (collecting cases in which "land application systems, spray head sprinklers, and trucks constitute point sources when used to spread treated wastewater and manure on land"); EPA, IMPLEMENTATION GUIDANCE ON CAFO REGULATIONS—CAFOS THAT DISCHARGE OR ARE PROPOSING TO DISCHARGE 9 (May 28, 2010), https://19january2021snapshot.epa.gov/sites/static/files/2015-08/documents/cafo_implementation_guidance.pdf (photograph of spray irrigation equipment causing dry weather discharge at CAFO); *see also Cmty. Ass'n for Restoration of the Env't v. Henry Bosma Dairy*, 65 F. Supp. 2d 1129, 1147 (E.D. Wash. 1999) (noting a "verified discharge of animal wastes from a spray gun").

[157] *See* ROBERT L. KELLOGG ET AL., USDA, MANURE NUTRIENTS RELATIVE TO THE CAPACITY OF CROPLAND AND PASTURELAND TO ASSIMILATE NUTRIENTS: SPATIAL AND TEMPORAL TRENDS FOR THE UNITED STATES 69 (2000) ("Deposition (both wet and dry) of ammonia and ammonium has been shown in some studies to occur in close proximity to the source of emission, sometimes within 100 meters and often within 10,000 meters."); R.S. Dungan, *Fate and Transport of Bioaerosols Associated with Livestock Operations and Manures*, 88 J. ANIMAL SCI. 3693, 3699 (2010) (table of studies, including one showing elevated bacteria levels 200 meters downwind of a land application site); WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.80 at C-14 (reprinting Mark A. Borchardt & Tucker R. Burch, *Airborne Pathogens from Dairy Manure Aerial Irrigation and the Human Health Risk*, which found risk of contracting *Salmonella* from aerosolized manure-borne pathogens exceeded EPA's drinking water risk threshold at distances below 1,000 feet).

[158] *See* Minn. Dep't Nat. Res., *Public Waters Inventory Maps*, https://www.dnr.state.mn.us/waters/watermgmt_section/pwi/maps.html.

saturated soils.[159] Third, prohibiting pressurized spray irrigation equipment based on proximity to the nearest surface water overlooks the risk that dry deposited pollutants will seep into groundwater and flow through the subsurface into surface waters. Finally, the existing regulations only bar the use of irrigation equipment that allows liquid waste to travel more than 50 feet in the air. It is not clear that this is an evidence-backed standard proven to reduce pollutant discharges, particularly if irrigation occurs during periods of strong wind.

In addition to reducing water pollution throughout the state, amending section 7020.2225 to prohibit high pressurized spray irrigation techniques would also serve the interests of justice by alleviating harm to frontline communities and benefitting family farms. Pollutants expelled by spray irrigation technologies include aerosolized bacterial and viral pathogens that create serious health risks when inhaled by neighboring residents or deposited on food crops.[160] Indeed, multiple studies have confirmed that communities situated near CAFOs suffer higher infection rates[161] and that farmworkers and CAFO employees bear the brunt of these unnecessary hazards.[162] Crucially, health harms attributable to spray irrigation technologies include significant mental and physical health impacts from unbearable odor.[163] Residents who work and live near CAFOs report experiencing stenches so foul that they "interfere with daily activities, preventing neighbors from opening windows, drying clothes, gardening, and hosting family and

[159] NRCS STANDARD 590 at 4 (warning against spreading on "frozen and/or snow-covered soils, and when the top 2 inches of soil are saturated from rainfall or snow melt");
[160] Dungan, *supra* n.157 at 3693–96; Steve Wing et al., *Environmental Injustice in North Carolina's Hog Industry* 108 ENV'T HEALTH PERSPECTIVES 225, 225 (2000); Risse et al., *supra* n.122 at 298; Burkholder, *supra* n.**Error! Bookmark not defined.** at 309.
[161] *See generally* Joan A. Casey et al., *Industrial Food Animal Production and Community Health*, 2 CURRENT ENV'T HEALTH REPORTS 259 (2015) (literature review concluding that communities living near industrial food animal production suffered heightened risk of respiratory illness, MRSA, Q fever, and adverse stress and mood conditions); Kravchenko, *supra* n.**Error! Bookmark not defined.** at 284 (describing a variety of adverse health impacts in communities near CAFOs even when controlling for confounding variables).
[162] SARAH GOLDMAN ET AL., JOHNS HOPKINS CENTER FOR A LIVABLE FUTURE, ESSENTIAL AND IN CRISIS: A REVIEW OF THE PUBLIC HEALTH THREATS FACING FARMWORKERS IN THE US 44 (2021); Wing, *supra* n.160160.
[163] Casey, *supra* n.161; Letter of Concern from Lilian S. Dorka, External Civil Right Compliance Office, EPA Office of General Counsel, to William G. Ross, N.C. Dep't Env't Quality 4-7 (Jan. 12, 2007), https://www.epa.gov/sites/default/files/2018-05/documents/letter_of_concern_to_william_g_ross_nc_deq_re_admin_complaint_11r-14-r4_.pdf; Kaitlin Kelly-Reif & Steve Wing, *Urban-Rural Exploitation: An Underappreciated Dimension of Environmental Injustice*, 47 J. RURAL STUDIES 350, 355 (2016).

friends."[164] Regulating pressurized spray irrigation more stringently would help to mitigate these environmental justice impacts.

Moreover, removing pressurized spray irrigation as a waste disposal option for feedlots removes a tool that the largest feedlots frequently abuse to their competitive advantage and to the disadvantage of smaller, family-owned livestock operations. Industrial broadcast irrigation technologies are generally employed by and primarily benefit large feedlots as opposed to smaller scale operations that do not generate enough waste to necessitate long-term manure storage and bulk disposal.[165] As such, use of these technologies on feedlots has contributed to increased concentration and consolidation of Minnesota's livestock industry—a trend that inherently increases pollution risks. Pressurized irrigation equipment also facilitates nighttime land application of waste, a practice that should be disallowed due to inadequate oversight and accountability as well as increased likelihood of pathogen transmission in absence of the neutralizing impact of ultraviolet radiation from the sun.[166]

Evidence of water pollution and air quality related health hazards supports a full ban on using high-pressure broadcast irrigation equipment to land apply feedlot waste. However, if MPCA does not prohibit these technologies outright, the agency must at least consider updating section 7020.2225 to include mandatory BMPs such as nozzle settings that ensure waste droplets meet minimum size thresholds, foregoing spray application when winds are above 5 mph, and limiting spray irrigation to the late morning and early afternoons to reduce odor and pathogen transmission.[167]

5. Require Liners for Stockpiles

Minnesota law prohibits fines for discharges of manure that is land applied or stockpiled in accordance with agency rule.[168] Given this restriction, MPCA's land application and stockpiling regulations must provide maximum protection against water pollution to ensure feedlot operators

[164] Title VI Letter, *supra* n.163 at 4–7; Kelly-Reif & Wing, *supra* n.163; WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.80 at 35.
[165] Tucker R. Burch et al., *Quantitative Microbial Risk Assessment for Spray Irrigation of Dairy Manure Based on an Empirical Fate and Transport Model*, 125 ENV'T HEALTH PERSPECTIVES 067003-1, 067003-1 (2017) (pagination in accordance with submitted copy).
[166] Andrew D. McEachran et al., *Antibiotics, Bacteria, and Antibiotic Resistance Genes from Cattle Feed Yards via Particulate Matter*, 122 ENV'T HEALTH PERSPECTIVES 337, 341 (April 2015); Risse, *supra* n.122 at 298.
[167] WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.80 at 37 (recommending droplet sizes greater than 150 micrograms to reduce odors), 36 (recommending avoiding application when air is warming or windy).
[168] Minn. Stat. § 116.07, subd. 7(o).

are able to be held accountable for risky management practices that endanger the public interest. Yet, the current feedlot regulations allow for allow for a "temporary" manure stockpile to be maintained on bare soil for up to one year.[169] This allowance for temporary solids stockpiling, even with setback requirements, creates a significant risk of groundwater contamination because leachate release generally peaks within a few days.[170] Further, short term solids stockpiling areas are not subject to the same degree of clean water diversion requirements that permanent solid storage sites are, creating a risk of contaminated run-off.[171]

To stem the flow of production area pollution and reduce the risk of nitrate contamination posed by feedlots, MPCA should update the feedlot regulations to require liners and covers for all waste stockpiles, thereby closing the loophole for temporary stockpiling. The most effective methods for controlling leachate pollution generally consist of a liner and leachate collection system paired with covers and stormwater diversions to prevent contaminated runoff. Pollution reduction rates attributable to such a system depend on the material being stored and the composition of the liner. Silage leachate, for example, is extremely corrosive and can damage both concrete and steel.[172] MPCA should update the Feedlot Rule to prohibit the practice of stockpiling on bare ground, even for temporary stockpiles, and should include minimum standards for liner composition that better protect against groundwater contamination.

6. Mandate Incorporation Within 24 Hours for All Land Applied Waste

Although MPCA already requires incorporation of land applied feedlot waste under certain circumstances, significant losses from failure to timely incorporate land applied waste persist. According to data collected as part of Minnesota Department of Agriculture's Farm Nutrient Management Assessment Program, up to 60 percent of nitrogen in applied manure was lost to the environment and therefore not available for crop fertilization due primarily to feedlot operators' failure to incorporate manure within 24 hours of application.[173] As such, the agency should simply

[169] Minn. R. 7020.2125(2)(A).
[170] *See* PETER WRIGHT ET AL., EFFECTIVENESS OF SILAGE LEACHATE TREATMENT WITH VEGETATIVE FILTER AREAS 2 (Aug. 2004), https://socwisconsin.org/wp-content/uploads/2016/05/Wrightetal_2004_SilageLeachateTrtmtVTA.pdf ("The amount of juice from silage peaks quickly after harvest and then decreases to a trickle over time.").
[171] Minn. R. 7020.2125(2)(D).
[172] Harner, *supra* n.69; Gebrehanna, *supra* n.68 at 114.
[173] Minn. Dep't of Agric., Farm Nutrient Management Assessment Program for Hog Producers in South Central MN and Dairy Farmers in Southeast MN, available at https://www.mda.state.mn.us/farm-nutrient-management-assessment-program-fanmap.

amend Section 7020.2225 to mandate that all land applied feedlot waste be incorporated within 24 hours.

Numerous studies show that incorporating manure likely helps to conserve nutrients in soil and reduce nutrient runoff. During EPA's consideration of its CAFO regulations in 2002, the Agency recognized that incorporation and injection can reduce erosion and runoff, keeping nutrients and other pollutants on land application sites.[174] Incorporation has proven particularly effective at reducing off-field transport of phosphorus. For instance, modeling based on dairy feedlots in Texas indicated that incorporation of land-applied waste could achieve up to 45 percent reductions in soluble phosphorus losses to edge-of-field runoff.[175] Field studies confirm the phosphorus reduction potential of incorporation as a BMP. In a study of swine manure applied to Iowa cropland, total phosphorus concentrations in runoff from unincorporated fields were more than two times higher than concentrations in runoff from fields that incorporated manure after application.[176]

Incorporation can also significantly reduce nitrogen pollution. Mixing promotes conversion of organic nitrogen to plant-available inorganic nitrogen, increasing the percentage of nitrogen that is taken up by crops and reducing the nitrogen content of runoff.[177] According to a 2005 literature review conducted by USDA, incorporation significantly reduces nitrogen losses from land application fields for hog, dairy, poultry, and beef operations.[178] Part of this reduction in nitrogen water pollution is due to incorporation's ability to control nitrogen volatilization.[179] As discussed, deposition of aerosolized pollutants—and particularly ammonia—is a major pathway by which feedlots discharge pollutants to surface waters. Because incorporation has been shown

[174] 2003 TDD, *supra* n.63 at 8-179.
[175] Osei, *supra* n.126 at 1.
[176] Brett L. Allen et al., *Effect of Liquid Swine Manure Rate, Incorporation, and Timing of Rainfall on Phosphorus Loss with Surface Runoff*, 37 J. ENV'T QUALITY 125, 135–36 (2008).
[177] U. MINN., *Manure Application Methods and Nitrogen Losses*, https://extension.umn.edu/manure-management/manure-application-methods-and-nitrogen-losses.
[178] MARCEL AILLERY ET AL., USDA-ERS, MANAGING MANURE TO IMPROVE AIR AND WATER QUALITY 12 (2005), https://ers.usda.gov/sites/default/files/_laserfiche/publications/46336/29004_err9.pdf
[179] CORNELL U. COOP. EXTENSION, *supra* n.**Error! Bookmark not defined.** ("Liquid manure injection in the spring or into a growing crop reduces N volatilization loss, resulting in much greater retention of plant-available N."); Gabriella Burkett et al., *Influence of Manure Injection Versus Surface Application on Corn for Silage and Winter Rye Yield, Quality, Phosphorus Balance and Soil Test Phosphorus*, 16 J. AG. & FOOD RES. 1, 1 (2024) ("[S]urface application of manure often results in loss of ammonium-N (NH_4-N) fraction through ammonia volatilization.") (pagination in accordance with submitted copy).

to dramatically reduce ammonia emissions,[180] feedlots that incorporate their manure can be expected to contribute far less ammonia to waters.

Replacing broadcast spray irrigation with injection of liquid waste may produce even greater pollution reductions than incorporation of solid waste.[181] One study examining land application activities in the Mid-Atlantic region found that replacing broadcast irrigation with low-disturbance injection reduced total nitrogen in the watershed by 19 percent and total phosphorus by 44 percent.[182] Similarly, experiments conducted in Pennsylvania showed phosphorus lost to runoff was reduced by 68 percent on fields that injected dairy waste in place of broadcast irrigation.[183]

Incorporation has also been shown to reduce hormone transport to surface waters and overall runoff volume, indicating incorporation may be effective in reducing the off-field movement of other feedlot pollutants.[184] Cumulatively, this research supports a requirement that all permitted feedlots incorporate land applied waste within 24 hours of application.

C. Best Management Practices for Production Areas

MPCA's feedlot regulations could also be improved by adding provisions that mandate compliance with science-backed best management practices for production areas where livestock is confined and wastes are stored.

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[180] MARCEL AILLERY ET AL., USDA-ERS, MANAGING MANURE TO IMPROVE AIR AND WATER QUALITY 54 (2005), https://ers.usda.gov/sites/default/files/_laserfiche/publications/46336/29004_err9.pdf (estimating that injecting manure resulted in just 12 percent of ammonia emissions attributable to surface application); Michael Holly et al., *Greenhouse Gas and Ammonia Emissions from Digested and Separated Dairy Manure During Storage and After Land Application*, 239 AG. ECOSYSTEMS, AND THE ENV'T 410, 414 (2017). ("There is abundant literature on reductions of NH_3 when manure is rapidly incorporated (40–90%)."); UNION OF CONCERNED SCIENTISTS, CAFOS UNCOVERED: THE UNTOLD COSTS OF CONFINED ANIMAL FEEDING OPERATIONS 59 (2008) (estimating that injection can reduce ammonia emissions by 50 to 100 percent depending on the method used).

[181] *See* I.J. ROSS ET AL., U. KENTUCKY WATER RES. RSCH. INST., EFFECTS OF SOIL INJECTION OF LIQUID DAIRY MANURE ON THE QUALITY OF SURFACE RUNOFF 63 (1978) ("Injection of the manure into the soil essentially eliminated any pollutant yield in the runoff from the test plots as compared to surface application.").

[182] Arghajeet Saha et al., *Water Quality Benefits of Weather-Based Manure Application Timing and Manure Placement Strategies*, 333 J. ENVTL. MGMT. 1, 2 (2023) (pagination in accordance with submitted copy).

[183] Emad Jahanzad et al., *Varying Influent of Dairy Manure Injection on Phosphorus Loss in Runoff over Four Years*, 48 J. ENVTL. QUALITY 450, 450, 454 (2019).

[184] Odette Mina et al., *Estrogen Transport in Surface Runoff from Agricultural Fields Treated with Two Application Methods of Dairy Manure*, 45 J. ENVTL. QUALITY 2007, 2013 (2016) (finding shallow disc injection reduced estrogen transport to runoff by two orders of magnitude compared to broadcast irrigation); MINNESOTA POLLUTION CONTROL AGENCY, RUNOFF REDUCTIONS WITH INCORPORATED MANURE 2 (May 2018), https://www.pca.state.mn.us/sites/default/files/wq-f1-08.pdf.

1. Require LMSA covers

Allowing feedlots to store waste in uncovered lagoons is an outdated practice that should no longer be permitted under Minnesota law. Uncovered lagoons are more susceptible to overflows that pollute state waters. Moreover, lagoon covers reduce emissions of odors and other harmful airborne pollutants that plague frontline communities. In particular, covers help reduce emissions of ammonia, a pollutant that harms human health and travels through air to deposit on surrounding land and surface waters. Aerial ammonia deposition is a significant contributor to nitrate contamination in Minnesota.[185] The feedlot regulations do not currently require any sort of lagoon cover; updating the rule to require that feedlots managing liquid waste use this affordable best management practice will advance MPCA's water protection goals while simultaneously protecting the health and quality of life in farming communities.

While the current Feedlot Rule requires feedlots to maintain minimum capacity necessary to contain precipitation from 25-year, 24-hour rainfall events,[186] uncovered lagoons continue to overflow due to human error and severe storms.[187] Lagoon covers can prevent rainfall from overwhelming storage capacity and causing catastrophic overflows that contaminate waterways.[188] This feature is increasingly important for pollution control as rainfall events become heavier and more unpredictable due to anthropogenic climate change.[189] The highest annual rainfall events in

[185] Minnestoa Pollution Control Agency, Nitrogen in Minnesota Surface Waters: CONDITIONS, TRENDS, SOURCES, AND REDUCTIONS (June 2013), 1, 9, https://www.pca.state.mn.us/sites/default/files/wq-s6-26a.pdf (last accessed June 30, 2025) [hereinafter "NITROGEN IN MN SURFACE WATERS"] (finding that atmospheric deposition accounts for an estimated 9% of nitrogen contributions to surface waters in Minnesota).

[186] Minn. R. 7020.2100(3)(B). As discussed in Food & Water Watch's 2017 Petition, this standard is itself outdated, as it relies on weather data from 1961. *See* 40 C.F.R. § 412.2(i); 2017 PETITION, *supra* n.**Error! Bookmark not defined.** at 56–58.

[187] *See, e.g.*, Greg Stanley, *Seventeen Manure Pits Reportedly Overflow at Large Feedlots in Southern Minnesota* (June 26, 2024), https://www.startribune.com/manure-pits-reportedly-overflow-at-16-large-feedlots-in-southern-minnesota/600376074 (quoting Minnesota feedlot operator who stated "we get 100-year floods every other year it seems"); Kendra Pierre-Louis, *Lagoons of Pig Waste Are Overflowing After Florence*, https://www.nytimes.com/2018/09/19/climate/florence-hog-farms.html (Sept. 19, 2018); *see also* Rudko, *supra* n.**Error! Bookmark not defined.** at 5–6 (finding the primary causes of lagoon overflows at Washington dairies are mismanagement and extreme rainfall).

[188] 2003 TDD, *supra* n.63 at 4-21.

[189] *See* University of Minnesota Climate Adaptation Partnership, *Extreme Events*, U. OF MINN., https://climate.umn.edu/our-changing-climate/extreme-events (last accessed July 9, 2025) (discussing increasing "mega-rain" events in Minnesota); Our Minnesota Climate, *Mega-Rains Overwhelm Rivers, Roads, and Budgets*, https://climate.state.mn.us/mega-rains-overwhelm-rivers-roads-and-budgets (last accessed July 9, 2025) (same).

Minnesota have increased in size by 13% since the early 20th century,[190] and these trends are expected to continue in the future.[191] Clearly, the Feedlot Rule must include greater protections against precipitation driven overflows.

In addition to preventing catastrophic overflows, lagoon covers also help control odors and volatilized pollutants.[192] While the scope of emission reductions depends on the material used, covers can reduce odor emission by 40 to 99 percent.[193] Covers are also effective at reducing gaseous pollutants like ammonia, hydrogen sulfide, and methane.[194] According to the University of Colorado, manure slurry stored in covered lagoons can retain 3.5 times more nitrogen than slurries stored in open lagoons where nitrogen freely volatilizes.[195] Controls for odor and other air pollutants from feedlots are desperately needed to mitigate harmful impacts to nearby residents who experience disproportionately high rates of respiratory illness, high blood pressure, and psychological distress.[196] Moreover, lagoon covers provide more reliable methane emissions reductions than manure crusts, helping to mitigate the livestock industry's contribution to climate change.[197]

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[190] Our Minnesota Climate, *Minnesota is Getting Warmer and Wetter*, https://climate.state.mn.us/minnesota-getting-warmer-and-wetter (last accessed July 9, 2025).
[191] Minn. Interagency Climate Adaptation Team, BUILDING RESILIENCY TO EXTREME PRECIPITATION IN MINNESOTA (July 24, 2018), https://bwsr.state.mn.us/sites/default/files/2018-12/Building_Resiliency_to_Extreme_Precipitation_in_Minnesota-ICAT_White_Paper%20%282%29.pdf (last accessed July 9, 2025).
[192] 2003 TDD, *supra* n.63 at 4-18.
[193] University of Minnesota Extension, *Covers for Manure Storage* (2024), https://extension.umn.edu/manure-management/covers-manure-storage (citing Rose M. Steinglein et al., Covers for Mitigating Odor and Gas Emissions in Animal Agriculture: An Overview (2011)).
[194] Id. ; see also Consent Decree Between United States of America and Citizens Legal Environmental Action Network, Inc. and Premium Standard Farms, Inc. and Continental Grain Company, Inc. at App'x A, Citizens Legal Action Network, Inc. v. Continental Grain Company, Inc., No. 98-6099-CV-W-6 (consent decree requiring a swine feedlot to install covers to control odors, ammonia, and hydrogen sulfide emissions).
[195] S.G. Lupis et al., *Best Management Practices for Reducing Ammonia Emissions: Lagoon Covers*, U. COLO. (Dec. 2012), https://extension.colostate.edu/topic-areas/agriculture/best-management-practices-for-reducing-ammonia-emissions-lagoon-covers-1-631b/.
[196] Joan A. Casey et al., *Industrial Food Animal Production and Community Health*, 2 CURRENT ENV'T HEALTH REPORTS 259, 262-65 (2015) (literature review concluding that communities living near industrial food animal production suffered heightened risk of respiratory illness, MRSA, Q fever, and adverse stress and mood conditions); Kaitlin Kelly-Reif & Steve Wing, *Urban-Rural Exploitation: An Underappreciated Dimension of Environmental Injustice*, 47 J. RURAL STUDIES 350, 355 (2016); Steve Wing, *Air Pollution from Industrial Swine Operations and Blood Pressure of Neighboring Residents*, 121 ENV'T HEALTH PERSPECTIVES 92, 94–95 (2013).
[197] Jonah M. Greene et al., National Greenhouse Gas Emission Reduction Potential from Adopting Anaerobic Digestion on Large-Scale Dairy Farms in the United States, 58 ENV'T SCI. & TECH. 12409, 12412– 13 (2024) (explaining that the assumption that natural crusts will reduce lagoon methane emissions by up to 40 percent is rarely justified).

By controlling volatilized pollutants, LMSA covers also help mitigate aerial deposition of manure pollutants. Mandating lagoon covers is therefore an efficient means of reducing a significant source of nitrate contamination in Minnesota's waters, supporting the state's long-term goal to protect drinking water.[198]

2. Strengthen LMSA liner requirements

Subsurface seepage through LMSA walls is a significant source of pollution to groundwater. Minnesota's existing feedlot LMSA design specifications provide incomplete protection against these discharges to state waters. To better control subsurface lagoon seepage, MPCA must strengthen LMSA liner requirements for all feedlots that exceed the minimum size thresholds in the federal definition of a Medium CAFO. Updated liner requirements are also necessary to prevent permitted feedlots from discharging to surface waters via hydraulically connected groundwater in violation of CWA requirements that generally prohibit production area discharges, including hydrologic discharges are the "functional equivalent" of surface water discharges.[199]

MPCA's existing feedlot regulations include a complicated series of LMSA design specifications, delineated by feedlot size and site-specific features such as distance to bedrock. At present, the primary constraint on seepage from non-concrete-lined lagoons is the requirement that LMSA permeability not exceed 1/56 inch per day.[200] While requiring elevated protections in areas with elevated pollution risks is a logical approach, the existing regulations are under-protective because they do not account for all vulnerable areas. Further, merely requiring that LMSAs meet a specified permeability standard has not adequately protected groundwater because wear, tear, and improper installation or upkeep are often not apparent to the naked eye.[201]

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[198] MINN. DEP'T OF AGRIC. ET AL., WORK PLAN: ADDRESSING NITRATE IN SOUTHEAST MINNESOTA (Jan. 2024), https://www.health.state.mn.us/communities/environment/water/docs/wells/waterquality/epaworkplan.pdf (last accessed July 10, 2025).
[199] *Cnty. of Maui v. Hawaii Wildlife Fund*, 590 U.S. 165, 186 (2020).
[200] Minn. R. § 7020.2100 subp. 3(C)(1).
[201] *See infra* nn.55–59 and accompanying text (Sec. I.B.1); *see also* MELANIE REDDING, WASH. STATE DEP'T OF ECOLOGY, MANURE & GROUNDWATER QUALITY: LITERATURE REVIEW 69 (June 2016) (". . . it has been determined that design permeability data do not adequately predict actual seepage rates."); Erickson Report**,** *supra* n.59 at 5.

Since MPCA last updated the feedlot rule, the Minnesota Department of Agriculture promulgated the Groundwater Protection Rule.[202] This rule was passed to "minimize[] potential sources of nitrate pollution to the state's groundwater and protects [Minnesota's] drinking water,"[203] and operates by restricting nitrogen fertilizer application in both Drinking Water Supply Management Areas and Vulnerable Groundwater Areas. Vulnerable Groundwater Areas include all areas with coarse textured soils, soils that are shallow to bedrock, and karst regions, all of which increase the likelihood of significant groundwater contamination.[204] Accordingly, these areas are deserving of maximum protection against feedlot lagoon seepage.

Double synthetic lined lagoons are currently the most effective practice advised for use at feedlots.[205] Double synthetic liners are composed of two geomembranes—high-density polyethylene, polyvinyl chloride, or low linear density polyethylene processed to certain specifications[206]—and often include leak detection and collection systems between the synthetic layers.[207] Double liners are necessary for feedlot lagoon liners because, as explained in a study that examined the efficacy of various landfill liners in controlling seepage of many of the same pollutants of concern in CAFO waste, simple composite designs limited to a single geomembrane over soil attenuation layer "should not be used" where frequent filling and emptying disrupt tensile stress on the geomembrane.[208] EPA has used the double synthetic liner requirement to abate groundwater contamination from feedlots in Washington State.[209] Further, Meat & Poultry Products (MPP) facilities use double liners to control chlorides—a pollutant also of concern in feedlot waste—that otherwise seep from evaporation ponds.[210]

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[202] Minn. R. § 1573 et seq.
[203] Minn. Dep't. of Agric., *Groundwater Protection Rule*, https://www.mda.state.mn.us/nfr (last accessed July 17, 2025).
[204] Minn $. 1573.0010(23)
[205] WASH. STATE DEP'T OF ECOLOGY, LAGOON AND LINER DESIGN GUIDELINES at T7-10, T7-12–T7-13.
[206] MINN. POLLUTION CONTROL AGENCY, LIQUID MANURE STORAGE AREA HANDBOOK App'x F (Feb. 2017).
[207] *Id*.
[208] Wash. State Dep't of Ecology, Lagoon and Liner Design Guidelines T7-9 (April 2023).
[209] Letter from Eric Winiecki, EPA Region 10, to David Erickson (March 29, 2017), at 4; *see also* WESTERN ENVIRONMENTAL LAW CENTER, *WA Industrial Dairy Installs Court-Ordered Manure Lagoon Liners to Protect Groundwater* (Dec. 12, 2016), https://westernlaw.org/wa-industrial-dairy-installs-court-ordered-manure-lagoon-liners-protect-groundwater-news-rel/ (opining that, with the installation of the new lagoon design, "Cow Palace has set the standard that the rest of the CAFO industry must now follow in order to protect people's health.").
[210] EPA, Response to FOIA 2025-EPA-04763 at 10.

To make MPCA rules consistent with MDA rules, simplify the feedlot regulatory regime, and protect groundwater and hydraulically connected surface waters, MPCA should update section 7020.2100 to prohibit the construction of new feedlot lagoons in vulnerable groundwater areas and require all existing lagoons in vulnerable groundwater areas to install composite double synthetic liners with leak detection. Additionally, in conjunction with the recommended updated monitoring requirements, *see infra*, Section II.D., the State should require that feedlots that show elevated levels of nutrients or fecal coliform pathogens in representative sampling of groundwater around the production area install a composite liner with double synthetic layers.

Mandating leak detection in coordination with synthetic liners would mark a significant improvement over MPCA's existing LMSA requirements by minimizing uncertainty. If a liner is breached, leak detection allows feedlot operators to take immediate remedial action that can prevent discharges entirely. Without leak detection or groundwater quality monitoring, enforcing a lagoon permeability standard is impossible, illegally undermining one of the pillars of the CWA.[211] Simply requiring double-lined synthetic composite liners with leak detection mechanisms would facilitate straightforward enforcement and provide a better safeguard against pollution that threatens Minnesota's drinking water and surface waters.

3. Liners for solids storage

To effectively control groundwater contamination from all production areas, the Feedlot Rule should include updated liner requirements for manure stockpile sites, feed storage areas, and compost areas. To stem the flow of production area pollution and reduce the risk of nitrate contamination posed by feedlots, MPCA should update the Feedlot Rule to require liners and covers for all waste stockpiles.

Both the Minnesota SDS and NPDES permits include similar requirements for permanent manure stockpile areas, which include manure compost sites, and feed storage areas.[212] Permanent manure stockpiles and feed storage areas must have a liner or base made of group III or IV soils,

[211] *See* 33 U.S.C. § 1251(e) ("Public participation in the development, revision, and enforcement of any regulation, standard, effluent limitation, plan, or program established [under the CWA] shall be provided for, encouraged, and assisted by [EPA].").
[212] Minnesota Pollution Control Agency, Authorization To Construct And Operate An Animal Feedlot And/Or Manure Storage Area Under The State Disposal System (SDS) Program MNG450000, 6.1-6.2, 7.1-7.5,18.1-18.4;19.1-19.5, https://www.pca.state.mn.us/sites/default/files/wq-f3-63.pdf; Feedlot General Permit at 6.1-6.2, 7.1-7.5,18.1-18.4;19.1-19.5, https://www.pca.state.mn.us/sites/default/files/wq-f3-62.pdf

asphalt, concrete, or other materials that "achieve a hydraulic conductivity less than 1 x 10^{-7} cm/sec."[213] However, the Feedlot Rules allow for a "temporary" manure stockpile to be maintained on bare soil for up to one year.[214] This allowance for temporary solids stockpiling, even with setback requirements, creates a significant risk of groundwater contamination because leachate release generally peaks within a few days.[215] Further, short term solids stockpiling areas are not subject to the same degree of clean water diversion requirements that permanent solid storage sites are, creating a risk of contaminated run-off.[216]

The most effective methods for controlling leachate pollution generally consist of a liner and leachate collection system paired with covers and stormwater diversions to prevent contaminated runoff. Pollution reduction rates attributable to such a system depend on the material being stored and the composition of the liner. Silage leachate, for example, is extremely corrosive and can damage both concrete and steel.[217] MPCA should update the Feedlot Rule to prohibit the practice of stockpiling on bare ground, even for temporary stockpiles, and should include minimum standards for liner composition that better protect against groundwater contamination.

4. Solid liquid separation

With the understanding that a portion of land-applied waste will be discharged to waters, EPA should consider imposing maximum pollutant concentrations for land-applied waste based on demonstrated reductions attained by solid-liquid separation ("SLS"). SLS reduces the organic load in feedlot wastewater, thereby decreasing nutrient and pathogen concentrations in liquid containment structures and land-applied liquid waste and reducing water quality risks.[218] The solids can then be composted either on or offsite to create valuable fertilizer without the heightened leaching risks associated with higher inorganic nutrient concentrations.[219] Meanwhile, SLS

[213] Minn. R. 7020.2125(4)(B).
[214] Minn. R. 7020.2125(2)(A).
[215] *See* PETER WRIGHT ET AL., EFFECTIVENESS OF SILAGE LEACHATE TREATMENT WITH VEGETATIVE FILTER AREAS 2 (Aug. 2004), https://socwisconsin.org/wp-content/uploads/2016/05/Wrightetal_2004_SilageLeachateTrtmtVTA.pdf ("The amount of juice from silage peaks quickly after harvest and then decreases to a trickle over time.").
[216] Minn. R. 7020.2125(2)(D).
[217] Harner, *supra* n.69; Gebrehanna, *supra* n.68 at 114.
[218] BRADFORD, *supra* n.34 at 13.
[219] *Id.*; Vanotti, *supra* n.67 at 277; *see also* M. Hjorth et al., *Solid-liquid Separation of Animal Slurry in Theory and Practice: A Review*, 30 AGRONOMY SUSTAINABLE DEVEL. 153, 155 (2010) (contrasting manure management in Asia with management in North America); MINN. POLLUTION CONTROL AGENCY, RESPONSE TO COMMENTS ON THE

improves the liquid fraction's nutrient ratio, total suspended solids concentration, and pathogen content for plant growth compared to unseparated slurry.[220] For many SLS methods, estimated dry matter, total nitrogen, total phosphorus, volatile solids, and pathogen indicators removal efficiencies have already been documented.[221] Thus, MPCA could easily develop maximum limits for these pollutants in land applied waste and check that feedlots are complying through regular manure testing and reporting requirements.

In addition to helping CAFOs achieve water pollution reductions, SLS has many non-water quality benefits that EPA must consider. For instance, removing volatile solids prior to long-term liquid waste storage reduces greenhouse gas emissions.[222] In fact, a 2017 study of dairy CAFOs concluded that SLS reduced methane emissions by 46 percent and overall greenhouse gas emissions by 44 percent, indicating it was more effective than anaerobic digestion in combatting emissions from manure storage.[223] Relatedly, solids suspended in liquid waste are a primary source of odors that plague residents near CAFO lagoons.[224] Removal of these solids can help reduce odors.[225] Finally, CAFOs that rely on flushing systems to remove manure from production areas can reuse SLS liquids, reducing dewatering of aquifers and waterways.[226]

5. Ventilation outlet filters

GENERAL NPDES AND SDS FEEDLOT PERMITS 7–9 (2025), https://www.pca.state.mn.us/sites/default/files/wq-f3-64.pdf.

[220] *Id.*

[221] *See* Giorgia Cocolo, Assessment of Different Solid-Liquid Separation Techniques for Livestock Slurry 12–20, 36, 49–50, 62 (2013) (PhD thesis, Scuola di Dottorato), https://air.unimi.it/retrieve/dfa8b990-f12e-748b-e053-3a05fe0a3a96/phd_unimi_R09277.pdf; Vanotti, *supra* n.67 at 279–82; Hjorth, *supra* n.219 at 160–176; Rotz, *supra* n.**Error! Bookmark not defined.** at E128 (estimating 25 percent N reduction in liquid portion); Liang Wang, *Nutrient Reduction of Dairy Manure through Solid-Liquid Separation with Flocculation and Subsequent Microalgal Treatment*, 190 APPLIED BIOCHEM. & BIOTECH. 1425, 1429–36 (2020); BRADFORD, *supra* n.34 at 43 (estimating that the combination of inclined screen separator, sedimentation tank, and sand filter removed over 90 percent of pathogen indicator microorganisms); Greene, *supra* n.**Error! Bookmark not defined.** at 12415 (estimating 15 percent N removal and up to 30 percent removal of volatile solids attributable to SLS); Lide Chen & Hernan Tejeda, *Estimating the Efficiency and Cost of an On-Farm Centrifuge Separator* (Dec. 2020), https://www.uidaho.edu/extension/publications/bul/bul991#Study (providing tons of nutrients removed by screen separators on their own and in combination with centrifuge separators).

[222] Lazenby, supra n.**Error! Bookmark not defined.** at 10.

[223] Michael Holly et al., *Greenhouse Gas and Ammonia Emissions from Digested and Separated Dairy Manure During Storage and After Land Application*, 239 AG. ECOSYSTEMS, AND THE ENV'T 410, 416 (2017).

[224] USDA-NRCS, *supra* n.**Error! Bookmark not defined.** at 4-22.

[225] *Id.* at 4-45, 4-129, 4-133; Hjorth, *supra* n.219 at 154, 165; IOWA STATE U. EXTENSION, *Solids Separation*, https://www.extension.iastate.edu/ampat/solids-separation (visited March 3, 2025).

[226] *See* Vanotti, *supra* n.67 at 277 (describing availability of separated liquids for water reuse).

To combat aerial deposition of feedlot pollutants and improve health and wellbeing in surrounding communities, MPCA should require the largest confinements to demonstrate compliance with ammonia emission standards. A variety of filters and scrubbers are available and effective in reducing ammonia emissions and other air pollutants from feedlot housing. Much like the composite liners recommended for use with liquid manure storage structures, the most effective air deposition reduction systems have multiple components designed to provide extra layers of protection. Filters and scrubbers use physical, biological, and chemical processes to trap or neutralize pollutants.[227] Removal efficiencies depend on the type of filter used, but data are available for a variety of designs and pollutants at various livestock confinements.[228] Notably, ventilation outlets with acid scrubbers can remove up to 99 percent of ammonia before air leaves a feedlot, while biofilters can remove up to 67 percent of ammonia while also providing significant odor mitigation.[229] Multistage scrubbers, such as those that use a combination of water, acid, and a biofilter, have been shown to achieve 90 percent reductions in particulate matter while also significantly cutting emissions of airborne bacteria.[230] Filters with gas permeable membranes or electrostatic spinning technologies have also been proven effective in removing particulate matter, bacteria, and viruses.[231]

Installing filters and scrubbers in feedlot ventilation systems will reduce air pollution in addition to improving water quality. Filters that reduce ammonia and particulate matter emissions can protect health outcomes of nearby communities. Many filters that target odorous ammonia and particulate matter also reduce emissions of hydrogen sulfide, an odorous and toxic gas that is responsible for many human and animal deaths in livestock facilities.[232] Due in part to this ability

[227] Li Guo, *Mitigation Strategies of Air Pollutants for Mechanical Ventilated Livestock and Poultry Housing – A Review*, 13 ATMOSPHERE 9–11 (2022).
[228] *Id.* at 12–13 (providing ammonia, particulate matter, and bacteria removal efficiencies for various filter types at swine and poultry CAFOs); Vanotti, *supra* n.67 at 293 (listing studies).
[229] Guo, supra n.227 at 12; *see also* R. W. Melse & N.W.M. Ogink, *Air Scrubbing Techniques for Ammonia and Odor Reduction at Livestock Operations: Review of On-Farm Research in the Netherlands*, 48 TRANSACTIONS AM. SOC'Y AG. ENG'RS 2303, 2306, 2308 (2005), https://edepot.wur.nl/31455 (noting that scrubbers are capable of attaining up to 99 percent ammonia removal and describing a long term farm study that showed an average of 90 percent removal).
[230] Guo, *supra* n.227 at 13–14.
[231] *Id.* at 15–16.
[232] Guo, *supra* n.227 at 12–13; Ji-Qin Ni et al., *Emission Factors and Characteristics of Ammonia, Hydrogen Sulfide, Carbon Dioxide, and Particulate Matter at Two High-Rise Layer Hen Houses*, 154 ATMOSPHERE 260, 261 (2017).

to trap hydrogen sulfide, many filters are effective in reducing odor impacts on surrounding communities.[233] Lastly, filters and scrubbers installed at ventilation outlets in animal housing have the capacity to capture and neutralize pathogens and antibiotic-resistant genes that could otherwise wreak havoc on other animal feeding operations, wildlife populations, and even global human health.[234]

MPCA has broad authority to regulate air and water pollution from feedlots, including through emissions standards.[235] The agency should therefore refer to well-documented removal efficiencies and available data on per-animal emissions to establish standards that will effectively reduce air-deposited water pollutants like ammonia.[236]

D. The Feedlot Rule Must Include Representative Compliance Monitoring and Reporting.

The federal Clean Water Act requires that MPCA implement its NPDES program according to minimum federal standards.[237] Under that Act, all NPDES permits must include representative monitoring and reporting provisions sufficient to ensure compliance with the permit effluent limits.[238] Minnesota's Water Pollution Control Act largely mirrors the Clean Water Act's requirements and provides MPCA with the authority to impose monitoring requirements necessary to control feedlot pollution.[239] Publicly available compliance monitoring data are critical to ensuring permit compliance and holding violators accountable; yet MPCA's feedlot regulations lack specific monitoring and reporting requirements sufficient to measure compliance with all applicable water quality discharge standards.[240] To improve the feedlot rules, MPCA must codify monitoring requirements designed to ensure any discharges of feedlot waste to the environment are detected, sampled, and reported in a timely manner.

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[233] Melse & Ogink, *supra* n.229 at 2310–11.
[234] Guo, *supra* n.227 at 9.
[235] Minn. Stat. § 116.07, subd. 2.
[236] Melse & Ogink, *supra* n.229 at 2304.
[237] 33 U.S.C. § 1342(b).
[238] *Id.* § 1318(a)(2)(A)(iii); 40 C.F.R. §§ 122.44(i)(1), 122.48(b); *see also FWW v. EPA*, 20 F.4th 506 (2021); *Wash. State Dairy Fed'n v. Wash. Dep't of Ecology*, 18 Wn. App. 2d 259 (Wash. Ct. App. 2021); *see also Nat. Res. Def. Council v. EPA*, 808 F.3d 556 (2d Cir. 2015); *NRDC v. Cnty. of L.A.*, 725 F.3d 1194 (9th Cir. 2013).
[239] Minn. Stat. § 115.03, subd. 1(vii); Minn. R. § 7001.0150, subp. 2(B).
[240] *See* Minn. R. § 7020.2003

1. Land Application Area Effluent Monitoring

Feedlots discharge to state waters from land application areas via three primary pathways: (1) overapplication of waste to fields that results in runoff to tile drains, irrigation ditches, or other conveyances to surface waters; (2) seepage of land applied waste to groundwater below crop root zones; and (3) aerial deposition from high-pressure broadcast spray irrigation technologies. Thus, to detect and redress feedlot discharges, MPCA's regulations must include provisions designed to monitor each of these pathways.

MPCA recently added monitoring for runoff resulting from land application activities to the NPDES general permit for feedlots. There, MPCA included a provision requiring feedlot operators and anyone land applying feedlot waste to visually inspect "downgradient field edges and any other potential discharge locations such as sensitive features, tile intakes, ditches, or other conveyances to waters" after land application.[241] MPCA should codify this monitoring requirement as it is necessary to detect feedlot contributions to water pollution and evaluate appropriate measures to mitigate adverse impacts. Further, MPCA should update the regulations to mandate that feedlots immediately sample any effluent discharged to a water of the state; test the sample for total nitrogen, nitrate nitrogen, ammonia nitrogen, total phosphorus, *E. coli*, five-day biochemical oxygen demand (BOD5), total suspended solids, pH, and temperature, and any other pollutants of concern in the watershed; and report the results of such testing to MPCA such that they are publicly accessible.

While all feedlot discharges should be monitored and reported to protect water quality and inform better regulation, it is particularly important for enforcement purposes that MPCA collect information sufficient to determine whether a discharge is the result of noncompliance with a facility's MMP. The NPDES general permit currently requires that equipment used for land application be calibrated such that actual application rates "are known."[242] However, there is no requirement that this information be submitted to MPCA to ensure compliance with MMPs—one of the primary pollution controls applicable to feedlots.[243] Modern irrigation

[241] MPCA, AUTHORIZATION TO CONSTRUCT AND OPERATE A CONCENTRATED ANIMAL FEEDING OPERATION UNDER THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM (NPDES) PROGRAM (MNG440000) at 12 (permit section 14) ("Feedlot General Permit).
[242] NPDES
[243] *See* Minn. R. § 7020.2225, subp. 5.

equipment is capable of monitoring and recording the amount of waste used during an individual application. To enforce overall application rates as well as timing restrictions,[244] MPCA must require that these records be submitted to the agency shortly after the application rather than cumulatively as annual totals once a year.

Critically, MCPA must also monitor for subsurface discharges from land application areas. EPA specifically recommended that MPCA institute subsurface discharge monitoring requirements to deal with Minnesota's nitrate crisis and, as California's State Water Resources Control Board recently acknowledged, land application of dairy feedlot waste "is responsible for the vast majority of dairies' nitrogen impacts to groundwater quality."[245] This is because existing application practices (e.g. agronomic rates) are primarily a waste disposal method with "secondary benefits of fertilizing crops, rather than a method of crop fertilization that may have incidental impacts to groundwater.[246] Difficulties in accounting for the precise water demands of crops, other sources of plant available water beyond irrigation, and preferential flow paths in soil that allow feedlot wastewater to bypass the root zone all impede the ability of MMPs to minimize surface and groundwater contamination.[247] Nutrients from land-applied waste that seep below a crop's root zone cannot be appropriately utilized,[248] indicating the feedlot applying the waste is either not following its—a permit violation meriting enforcement action—or that the feedlot must revise its MMP (such as by lowering application rates or specifying operational practices to avoid cracks or other preferential flow paths) in order to comply with state and federal law.[249]

[244] *See infra* Section II.B.3 (requesting that MPCA incorporate the timing restrictions from the current NPDES general permit into the feedlot rules).
[245] CA DAIRY ORDER at 6.
[246] *Id.*
[247] BRADFORD, *supra* n.34 at 66.
[248] As discussed elsewhere in this memo, CAFO waste contains numerous pollutants that provide no benefit to crops at any application rate. Waste must be treated to reduce or remove these pollutants prior to land application.
[249] *See* Minn. R. § 7020.2003, subp. 1 (prohibiting discharges to any "natural or constructed channels that convey fluids to groundwater); 40 C.F.R. § 412.4(c) (requiring CAFOs to implement a nutrient management plan that minimizes nutrient transport to surface waters); *see also Cnty. of Maui,* 590 U.S. at 185 (explaining that discharges to groundwater that are "functionally equivalent" to surface water discharges are jurisdictional under the Clean Water Act).

To monitor subsurface discharges on land application areas and "assure compliance with permit limitations" as required by law,[250] MPCA must consider updating its regulations to require that permitted feedlots conduct representative subsurface monitoring of land application areas using readily available soil moisture probes or lysimeters installed to measure moisture below crop roots.[251] Again, the regulations should also specify that the results of such monitoring be reported to MPCA and made available to the public shortly after each land application activity. Monitoring and reporting soil moisture below the root zone would help safeguard water quality by providing regulatory agencies and the public with data necessary for EPA to effectively review and revise the ELGs going forward, as well as to facilitate enforcement against CAFOs that over- or mis-apply waste.

2. Production Area Effluent Monitoring

Subsurface monitoring is also necessary to detect, correct, and enforce against discharges to groundwater and hydrologically connected surface waters. EPA has pointed MPCA to the most recent NPDES General Permit for CAFOs in Idaho as an example of how to implement site-specific discharge monitoring at feedlots.[252] That permit requires all permittees to develop and implement a subsurface discharge monitoring plan that includes site-specific procedures for monitoring subsurface discharges from lagoons.[253] MPCA's regulations should make clear that subsurface discharge monitoring plans should include monitoring, sampling, and reporting requirements not only for LMSAs, but also for solid storage areas (compost piles, silage storage, etc.) and any other known subsurface discharge pathways in a facility's production area. MPCA should consider specifying that the baseline requirement for any subsurface discharge monitoring plan include at least two upgradient and three downgradient wells and routine sampling.[254]

[250] Minn. R. § 7001.0150; 40 C.F.R. §§ 122.44(i)(1), 122.41(j)(1).
[251] Erickson Report, *supra* n.59**Error! Bookmark not defined.** at 10–11; *see also* CENTRAL VALLEY DAIRY REPRESENTATIVE MONITORING PROGRAM, SUMMARY REPRESENTATIVE MONITORING REPORT v (April 1, 2019), https://leadershipcounsel.org/wpcontent/uploads/2019/10/Dairy-report.pdf (reporting that, in 2019, flow meters were "at hand" and "could be implemented in relatively short order" in California at a cost of $300 to $1,000 per dairy feedlot).
[252] Letter to Brooke Cunningham, Commissioner, Minnesota Dep't of Health, from Debra Shore, Regional Administrator & Great Lakes Nat'l Program Manager, EPA at 4 (Nov. 3, 2023).
[253] EPA, AUTHORIZATION TO DISCHARGE UNDER THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM FOR CONCENTRATED ANIMAL FEEDING OPERATIONS IN IDAHO at 21 (Dec. 12, 2024).
[254] Erickson Report, *supra* n.59 at 10.

Importantly, the Idaho permit includes an exemption to the subsurface discharge monitoring plan requirement for feedlots that can prove the land underlying their facilities has no hydrologic connection to a Water of the United States. To reduce regulatory burden, MPCA's regulations could contain a similar exemption. However, because Minnesota's definition of waters of the state includes groundwater, any such exemption in MPCA's regulations would need to be narrower and based on the conclusion of a professional engineer or hydrogeologist that the facility has no risk of discharging to groundwater, regardless of whether that groundwater is hydrologically connected to a Water of the United States.

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Expert Opinion
David J Erickson, PG CPG
Idaho CAFO General Permit

Introduction

I, David J. Erickson, have worked in the Hydrogeology/Geology field for 35 years. I am currently the Principal/Founder of Water & Environmental Technologies (WET), a 130-person engineering firm started in 2000 that provides engineering, environmental, and remediation services in a 10-state region to a wide variety of clients including private, industrial, and State agencies based in Butte, Montana. I previously served as President of WET for 20 years. I am a registered Professional Geologist in Utah and Wyoming and a Certified Professional Geologist with the American Institute of Professional Geologists.

I received my Geological Engineering degree from Montana Tech in 1988. I worked in the petroleum industry in Houston for 1 year and later in the engineering consulting field. My technical focus has been on water related issues: investigation, development, remediation, permitting, litigation, and compliance. I serve as lead expert on several litigation issues as well as Project Manager/ Principal Hydrogeologist on complex remediation and investigation projects in the region including management of waste and water related environmental issues at coal fired generation facilities in Wyoming and Utah.

I have worked on more than 30 Concentrated Animal Feeding Operations (CAFOs) across the nation. I have successfully implemented long-term monitoring programs, lagoon lining projects, and management of CAFO facilities to minimize water quality impacts. Many of these projects are a result of litigation where I provided recommendations for the CAFO to achieve and maintain compliance. My full CV is attached as Attachment 1.

I started working CAFOs in the early 2000's in Montana and in 2013 in the Yakima, Washington area and currently work in several States investigating, characterizing and remediating the impacts to ground water, soil and surface water from these facilities. The principles, pathways and science behind the discharge of pollution by CAFOs is both simple and proven throughout industry. After completing an environmental investigation of more than 30 of these facilities, the sources of contributing contamination to the ground water and surface water include:

1. Lagoons designed to the standards mandated by the draft modified Idaho CAFO Permit (seepage rate of 1 x 10^{-6} cm/sec) leak and seep substantial volumes of process wastewater.
2. Manure applications to fields are both imprecise and often overapplied, intentionally and unintentionally.
3. Other sources, such as underground piping, compost areas, silage storage, cattle pens, and manure applications are potential sources of contamination.
4. Seepage, leaching, and surface discharges from these sources negatively impact water quality.
5. CAFO contaminated ground water flows toward and causes detrimental impacts to surface water.
6. Pollutants discharging from all areas of CAFOs are a significant threat to human health and the environment.

Figure 1, below, illustrates some of the ways that CAFO pollutants infiltrate or seep into ground water and then discharge to surface waters. Once in groundwater, pollutants will migrate in whatever direction the ground water flows.

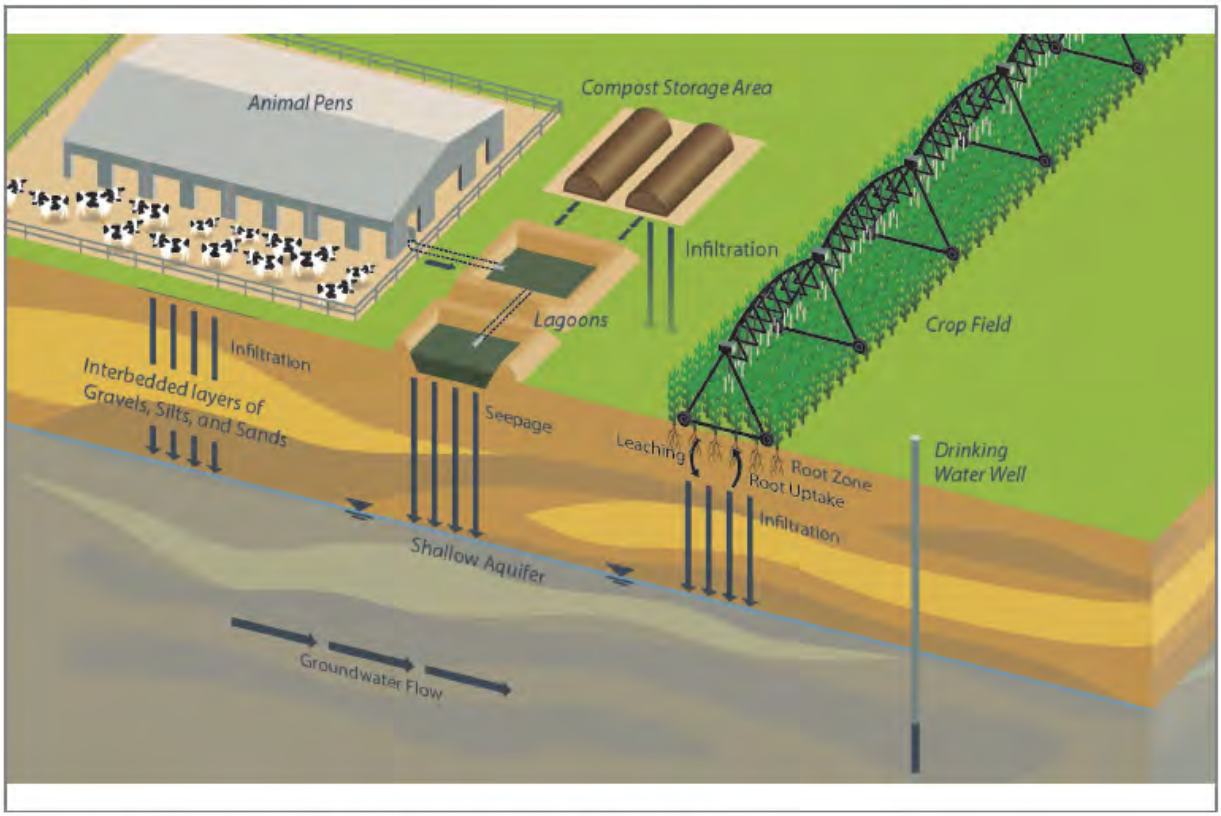

Monitoring of groundwater, surface water, and soil conditions to assess a CAFO's pollution discharges does not require new or innovative technologies. These types of monitoring activities have been a well-established practice for decades. The only scientifically sound method of ensuring that a CAFO is not unlawfully discharging into jurisdictional waters is to: 1) monitor the places where the facility may discharge to surface water, and 2) monitor both groundwater contamination and migration. Such monitoring data are also essential to assessing the effectiveness of CAFO waste management practices and the relationship between precipitation, infiltration, ground water amount and quality, and surface water amount and quality.

CAFO monitoring plans must be tailored to individual facilities and land application areas, similar to how nutrient management plans are facility specific. These site-specific plans must be designed by a professional engineer or geologist with experience in monitoring methodology, systems, and analytical requirements (hereinafter, a "qualified professional"). All monitoring methodologies and systems must be documented in a Discharge Monitoring Plan and all resulting data must be included in publicly available reports, such as Discharge Monitoring Reports or their equivalent. The monitoring plan should be included as part of a CAFO's permit application and made available for public review and comment to ensure it can generate high-quality, representative data capable of demonstrating whether the CAFO has complied with the Permit's discharges restrictions.

Opinions specific to the modified Idaho CAFO General Permit

I. The construction and pollution management requirements in the Permit are not sufficient to prevent or detect discharges from CAFO production areas to surface water through ground water.

The water cycle is well documented and well understood throughout the world. Ground water almost always flows toward a surface water body, whether it be a stream, lake or the ocean. Many States have recognized this interconnection and limit ground water rights because it depletes surface water volumes.

Starting with the lagoon permeability allowance that is deemed protective by EPA, a simple analysis using Darcy's Law proves this position false. Darcy's Law is used to calculate the water movement through soil of a specific permeability. It is expressed as:

$$Q=Kia$$

Where:

Q= water flow (gallons)
K = liner permeability (cm/sec)
i = hydraulic gradient through the material (ft/ft)
a = cross sectional area where flow occurs (ft^2).

The table below provides a range of allowed seepage rates and volumes out of a CAFO lagoon that meets the requirements of the Idaho general permit because it does not exceed the permit's maximum seepage rate of 1 x 10^{-6} cm/sec. Per NRCS guidelines, the majority of lagoons hold approximately 9 feet of liquid manure. Most CAFOs have 2 to10 acres of lagoons, depending on several operational factors. Each 1-acre lagoon on a typical CAFO releases approximately 3,000,000 gallons of contaminated seepage per year or 8,313 gallons per day to the subsurface, clearly neither insignificant nor protective.

The table below uses the CAFO permit's allowed seepage rate times the different gradients based on the liquid level in the lagoon and calculates the seepage rate over a 1-acre lagoon. The highlighted row shows the seepage rate for the common allowed 9-foot depth of a lagoon. To summarize, the general permit allows 8,313 gallon of seepage per day or over 3,000,000 gallons of seepage per year per acre of CAFO lagoon.

Table 1. Typical Lagoon seepage rates

Permeability		Gradient	Q =Seepage per Acre per Day (Gallons)	Q =Seepage per Acre per Year (Gallons)
K (cm/sec)	K (ft/day)	i (ft/ft)		
1.00E-06	2.84E-03	1	923.7	337,159
		2	1847.4	674,319
		3	2771.2	1,011,478
		4	3694.9	1,348,638
		5	4618.6	1,685,797
		6	5542.3	2,022,957
		7	6466.1	2,360,116
		8	7389.8	2,697,276
		9	**8313.5**	**3,034,435**
		10	9237.2	3,371,595
		11	10161.0	3,708,754
		12	11084.7	4,045,914
		13	12008.4	4,383,073
		14	12932.1	4,720,233
		15	13855.9	5,057,392

Nitrate, the main contaminate from CAFO lagoons, has a very low partitioning coefficient, which causes nitrate to migrate quickly in the water and not sorb or diffuse into the soil. As a result, nitrate migrates very quickly through ground water and forms large ground water contamination plumes traveling long distances that can and do reach surface water.

CAFOs discharge contaminants from several areas of the operation; however, lagoon seepage and leakage cause large pollutant contamination including nitrate plumes in ground water that have a high likelihood of impacting surface water.

Construction requirements do not substitute for a leak detection system. Construction issues or mistakes result in leaks and the operator does not know if there is an impact to ground water or surface water without routine monitoring. Routine monitoring can be a set of monitoring wells downgradient of the system or a designed leak detection sump. These systems must be sampled on a routine basis to establish background conditions and sampled for the correct analytes to identify a wastewater discharge.

The Permit also requires visual inspections and routine cleaning. I have reviewed years of inspection data forms for lagoons in several States, and an inspector cannot visually see a leak below the liquid. The liquid is opaque and the leak rate would have to be catastrophic to be visible. As a result, these inspections are not effective in determining if a lagoon is leaking or seeping to a degree that will impact surface waters.

Also, the routine cleaning of manure solids results in excavation, erosion and liner damage over the life of the lagoon. A lagoon that meets the Permit requirement most likely will fail the requirements after the first cleaning. In addition, erosion of an earthen liner at the inlet is well documented and causes a liner breach resulting in a much higher leak rate than is documented above.

II. The liquid manure waste generated by CAFOs has a mix of contaminants that can cause impacts to human health and the environment. Pollution from CAFO wastewater harms the environment and endangers public health.

In addition to nitrogen contamination from lagoons, I have detected fecal coliform, hormones, bovine antibiotics, growth hormones, phosphorus, and chloride in the seepage and in the receiving ground water. These are all problematic contaminants in the environment; however, nitrate is the most mobile contaminant since it does not sorb to soil. These contaminants have known and recognized health effects to humans. Nitrate causes blue baby syndrome and other health effects, while the pharmaceuticals are known endocrine disrupters. Fecal coliform can cause severe gastrointestinal distress.

Data collected by EPA and WET in Washington State show a variety of contaminants are present.

The following table provides average concentration in CAFO wastewater from the Yakima Valley, Washington. These data were collected from sampling conducted by the EPA and WET.

Table 2. Contaminant concentrations in CAFO Wastewater

.pH	TDS	Chloride	Ammonia	TKN	Phosphorus	Calcium	Potassium
s.u.	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L

7.6	3100	230	330	1600	358	122	80

The following list of contaminants is directly from an EPA study of the Dairy Cluster in Yakima, Washington. These compounds have been detected in the drinking water aquifer and are a result of leaking lagoons and overapplication of dairy wastewater.

Table 3. Contaminants found in CAFO Lagoons and Drinking Water Wells, Yakima Washington

Nutrients & Minerals	**Antibiotics**
Nitrate Nitrite Ammonia TKN Chloride	Tylosin Enthromycin Lincomycin Sulfamethazine Tiamulin Virginiamycin Monensin Chlortetracycline Tetracycline
Hormones	**Pesticides & Herbicides**
Estradiol Androsterone Testosterone 7-a-estradiol Androstadienedione 17- β-trenbolone Epitestosterone	Atrazine Alachlor DEHP DEET Bentazon

These compounds are all linked to animal wastes and fall into the general categories of nutrients, antibiotics, and growth hormones. All compounds were detected in both the dairy lagoons and in the drinking water aquifer serving hundreds of residents in the Lower Yakima valley.

III. Pollution from CAFO impoundments and land application areas can reach surface water through ground water due to the hydrological connection between surface water and ground water.

Based on years of performing remedial investigations at industrial facilities and over a decade of investigating CAFOs, the contaminant migration pathway from the source to ground water beneath the facility, with migration to or toward surface water is almost always complete (*i.e.*, ground water almost always flows toward and recharges surface water). It is a natural part of the water cycle. While dilution changes the discharge concentration, the migration pathway is easily characterized using standard ground water investigation techniques. The disturbing data from

these facilities is that the nearby neighbor's drinking water well can be as high as 200 ppm nitrate and have a mix of bacteria and other contaminants.

Since nitrate is very conservative, as discussed above, ground water plumes from CAFO operations have been documented to travel several miles. An investigation I completed in Wisconsin showed nitrate traveling in ground water over two miles from the dairy CAFO and impacting Lake Petenwell with concentration above drinking water standard in many of the private drinking water wells along the flowpath. In Washington, hundreds of private water supply wells over a mile downgradient from the CAFO facility are contaminated above drinking water standards. Similarly in California, nitrate has migrated over 2 miles downgradient. Nitrate, the primary contaminant from CAFO waste, moves unattenuated with ground water, migrating to the next receptor: ground water withdrawal or nearby surface water discharge.

Since the Wisconsin site mentioned above was a detailed investigation, cross sections of the site are attached for reference as Attachment 2. These cross sections and data clearly show impacts from a manure lagoon constructed to NRCS standards with a concrete bottom and impacts from overapplication of both manure and chemical fertilizer to the land application areas. They also show a complete contaminant pathway to human exposure and discharge to surface water.

Given the conservative nature of nitrate contamination, a minimal setback from any surface water (100 to 300 feet) is not protective of surface waters. Both the mobility of nitrate and the size and volume of the sources easily cause plumes to migrate more than 300 feet. The Wisconsin site has nitrate migration in excess of 8000 feet through ground water.

Similar to other States, Idaho CAFO density is focused on large alluvial valleys where there is abundant water and large areas favorable for agriculture. These alluvial aquifers are permeable with relatively shallow water tables and fertile soils for crop growth. The areas around the CAFOs are generally rural, relying on ground water wells for drinking water supply.

Due to low precipitation, most of the facilities are open pen facilities that generate large amounts of stormwater runoff, pen scrapings and compost. Compost is a mix of wet manure and bedding that is windrowed in specific areas until the composting process is complete. The compost is moved out of the pens at >50% plus moisture and turned until the moisture is reduced to approximate 30-40% when it starts to heat up and compost. This material drains 40% of the moisture from the manure mix into the ground or the stormwater collection system, if one exists. In my experience, these compost areas are a significant source of soil and ground water contamination where the areas were not managed properly.

IV. Pollution from CAFO land application areas can directly discharge to surface water through a variety of pathways.

CAFO pollution from land application areas can reach surface water directly in several ways in addition to transport via ground water. If CAFO waste is overapplied it can runoff into nearby

surface water features such as ditches, canals, rivers, and streams. Also, If CAFO waste is applied on frozen ground or prior to a precipitation event there is a much higher probability of direct discharge to surface water. If waste application equipment malfunctions, for example if an irrigation center pivot malfunctions during application, CAFO waste can reach surface waters as runoff or directly. CAFO waste can also reach surface waters if an operator improperly conducts waste application, such as not observing setbacks, mis-calibrating application equipment, applying to saturated soil, or overapplying.

V. Effective and feasible monitoring techniques are available.

As stated above, the types of monitoring activities sufficient to determine a CAFO's water pollution impacts have been a well-established practice for decades. Below I outline select monitoring options that can be effective and feasible if implemented properly.

A. Ground water monitoring

Purpose: To determine if a CAFO has discharged pollution to surface waters via groundwater.

Available monitoring methodology/system: Groundwater monitoring is a simple and well-established process. Monitoring wells are placed upgradient and downgradient of the field or lagoon to be monitored. Typically, 1-2 upgradient monitoring well(s) and 2-5 downgradient monitoring wells are installed using standard drilling technology. If ground water flow direction and seasonality are already understood at the site, fewer wells can be used to effectively monitor each area (*i.e.*, upgradient wells for 1 field can be downgradient wells for the next field). Sampling is conducted quarterly or semiannually according to the SAP to establish seasonal fluctuation in ground water quality or quantity, to collect representative data, and to establish statistically significant background data. Semiannual sampling is typically sufficient for detection monitoring, with sampling occurring a high ground water and low ground water conditions or prior to application in the spring and after harvest in the fall. If other fluctuations that directly affect ground water flow and transport are identified, more frequent monitoring may be required.

Well drilling, sampling and analysis protocols are documented in both Idaho and EPA documents.[1] Data analysis requires statistical evaluation of the data to determine if upgradient water quality is different than downgradient water quality. A statistically significant delta between these two data sets establishes that the monitored area is contributing pollutants to groundwater.

Multiple regulations have been promulgated that are examples of effective groundwater monitoring regulations, such as 40 CFR 257.90-.98, which applies to Coal Combustion Residuals

[1] *E.g.* 40 C.F.R. §§ 257.91–.95; Idaho Dept. of Env't Quality, Statistical Guidance for Determining Background Ground Water Quality and Degradation (Mar. 2014), https://www2.deq.idaho.gov/admin/LEIA/api/document/download/4807.

("CCR") in landfills and surface impoundments. These regulations are relevant for CAFO waste management because they provided the basis for ground water monitoring and data analysis documenting the facilities impact to ground water. These regulations also detail construction standards to prevent discharges and corrective measure to remediate those discharges, if they occur. For example, 40 C.F.R. § 257.91(a)-(c) should inform monitoring of CAFO lagoons, silage storage, and manure composting areas and potentially land application areas:

> The groundwater monitoring system must include the minimum number of monitoring wells necessary to meet the performance standards specified in paragraph (a) of this section, based on the site-specific information specified in paragraph (b) of this section. The groundwater monitoring system must contain:
>
> **(1)** A minimum of one upgradient and three downgradient monitoring wells; and
>
> **(2)** Additional monitoring wells as necessary to accurately represent the quality of background groundwater that has not been affected by leakage from the CCR unit and the quality of groundwater passing the waste boundary of the CCR unit.

Groundwater monitoring system should be progressively more rigorous depending on the type of waste impoundment liner used.

1. Earthen liners with a constructed seepage rate of 1×10^{-6} require a full groundwater monitoring plan with 2 upgradient and 3 downgradient wells and routine sampling;
2. Synthetic liners with 2' compacted clay subbase require an abbreviated monitoring scenario (1 upgradient and 2 downgradient) and routine sampling; and
3. Double synthetic liner with leak detection or a sump and pump design would not require a groundwater monitoring system.

The monitoring well network in the monitoring plan must be developed by a qualified professional with knowledge of well network design and sampling programs.

The Sample analyte list for groundwater should be, at a minimum:

- Major Mineral: Alkalinity, Calcium, Chloride, Magnesium, Potassium, Sodium, Sulfate
- Nutrients: Nitrate, Ammonia, TKN, Phosphorous
- WQ Parameters: pH, Temp, SC, DO, TDS, total coliform bacteria.

B. Soil monitoring at land application areas

1. Soil sampling

Purpose: Detect nutrient migration through the soil column to identify nutrient leaching to groundwater.

Available monitoring methodology/system: Soil collected with hand auger or mechanical soil probe and analyzed for nutrient and other characteristics.

In order to obtain quality data that are representative, soil samples will be collected at a density of at least 1 per 20 acres of crop. Larger fields of 220-640 acres or fields with consistent soil types could be decreased. The table below presents a recommended sampling density. A minimum of 4 locations should be sampled across each application field. Samples must be collected in each soil type present in the field and should not be composited with other soil types. Together these data provide a representative dataset for the entire application area. The samples will be collected at depth intervals of 0-1', 1-2', and 2-3'.[2] Soil core collection methodology can include hand auger or mechanical soil probe.

Field Acreage	Samples Required
0-20	4
20-40	6
40-160	8
160-640	12

Soil samples should be taken before each application to facilitate proper nutrient application; sampling soil only annually or every three years is not representative and does not enable an operator to make responsible application decisions.

Analysis of the soils should include:

- Ammonia
- Nitrate as N
- Phosphorus
- Potassium
- pH
- Electrical conductivity
- Soil Organic Matter

2. **Soil moisture monitoring**

Purpose: To determine if soils are saturated above field capacity and causing nutrients to leach to groundwater.

[2] The additional depths allow determination of plant uptake of nutrients versus nutrients leaching past the root zone and contaminating groundwater.

Available monitoring methodology/system: Soil moisture probes are a simple but readily available technology that are easier to operate than lysimeters and provide faster, continuous monitoring.

A soil moisture monitoring program is easily implemented with existing data that the CAFO facility already should have in its Nutrient Management Plan ("NMP"). These can be simple devices that indicate when the soil moisture is above field capacity and leaching of nutrients is occurring. The soil moisture data, combined with routine soil nutrient sampling described above, provide a more accurate assessment of a field's ability to receive and retain CAFO waste. This data collection provides the operator with the information necessary to identify whether nutrients are leaching to groundwater.

Current soil moisture probe technology has data logging capabilities so the monitoring can continue without operator attention and the data can be downloaded at any time during the year to prevent overapplication that results in discharges to surface waters.

For each field that receives CAFO waste, each soil type present in the application area should contain 1 to 3 soil moisture probes as necessary to collect a representative sample of soil moisture. Operators must identify low lying areas of fields where liquid may pond and install at least 1 soil moisture probe in such areas.

Soil Type Acreage	Soil Moisture Probes Required
0-20	1
20-40	2
40-160	3
160-640	4

C. Above ground discharge monitoring for land application areas

Purpose: To identify surface water features and potential discharge points and monitor the quantity and quality of surface water discharges from a specific CAFO.

Available monitoring methodology/system: Visual monitoring that is representative of the land application area; in stream water quality sampling (up and down stream of a discharge point); and grab sampling of effluent discharges. Surface water sampling technology can be very simple, with grab samples collected by a sampling professional or a trained operator if a discharge point is accessible safely. The grab sample location should be permanently marked to allow collection in the same location over the monitoring period.

Surface water sampling can also be more complex. For example, an ISCO automatic flow proportionate sampling device could be considered, but these devices require experienced

operators. Similarly, an operator could use time- or event-controlled samplers such as Isco 6712 or 6712c.

Surface water sampling requires identifying monitoring locations that ensure collection of representative data. It is important to establish minimum requirements and standards, but due to the variability in where such monitoring locations will be for a given CAFO, a qualified professional should determine the correct location for representative sample collection to provide the necessary flexibility. The professional should also provide a monitoring plan that describes monitoring locations during and immediately following applications near surface water features. This assessment must be included in the facility's monitoring plan. This qualified professional must certify that the details contained in the monitoring plan are appropriately tailored to the specific CAFO and will generate representative data.

As discussed above, land application events can result in discharges to nearby surface water features. Land application often occurs over many acres, sometimes via largely automated systems such as pumps that deliver CAFO waste via pipes to irrigation center pivot systems.

Surface water monitoring must include, at a minimum,

- Frequency:
    - Visual monitoring to identify all pollutant discharges must occur during and after each land application event.
    - When a discharge occurs, analytical monitoring of both the effluent discharge and receiving water during the discharge event.
- Location:
    - For visual monitoring, operators must choose locations that are designed to produce data representative of the entire application area. This may require monitoring along the length of a downgradient edge of field, monitoring at the four corners of a field, or other set of locations tailored to the specific field's discharge potential. Visual monitoring must monitor for conduit discharges (e.g., tile drains) and sheet flow.
    - Grab sample at the point of discharge, if accessible safely.
    - For waters immediately adjacent to production or land application areas, 1 monitoring location immediately upstream of the CAFO and 1 monitoring location immediately downstream of the CAFO. If there are multiple discharge points, a monitoring plan may be able to collect representative data with 1 upstream and 1 downstream monitoring location, but if non-CAFO contributions are present operators should choose monitoring locations as close to the discharge point(s) as is practical to isolate the CAFO's impacts to the receiving water's quality.
    - Tile drain outfalls.
    - Furrows or other topographical features likely to discharge liquid from a field.
    - Application equipment must be inspected by a trained operator prior to each land application event.

The analyte list for CAFOs is provided below but EPA may require additional analysis to better characterize the surface water seasonality or local surface water variation.

Analyte List

- Major Mineral: Alkalinity, Calcium, Chloride, Magnesium, Potassium, Sodium, Sulfate
- Nutrients: Nitrate, Ammonia, TKN, Phosphorous
- WQ Parameters: pH, Temp, SC, DO, TDS, TSS, total coliform bacteria (e-coli P/A).

VI. The operation of multiple CAFOs in one concentrated area aggravates the impact of CAFO pollution on water quality.

Several States recognize cumulative effects from multiple facilities that discharge pollutants. This was especially evident in the Dairy Cluster Investigation completed by the EPA in the Yakima Valley (Lower Yakima Valley Groundwater | US EPA). The dairy cluster investigation identified leaking lagoons, overapplication in the fields and a general nitrate plume increasing from no detect to over 200 ppm nitrate in ground water. It also identified contamination of private drinking water supply wells above EPA Maximum Contaminant Levels (MCL) above which health effects are known and recognized in humans.

The increasing trend in nitrates along ground water flowpath are a direct result of cumulative effects from the multiple sources of soil and water contamination at the CAFO. In many investigations, the application fields are the major contributor to cumulative effects since they represent a constant nutrient load over each application field. The constant flux of nutrients from multiple sources at a single CAFO to ground water results in increasing concentrations along the ground water flowpath. Multiple CAFOs in the same area only increase the number of contaminant sources and result in increasing contaminant concentration along the ground water flowpath and subsequently in surface water.

The current knowledge base in the science of hydrogeology, hydrology and contaminants in the environment make clear that the Permit is not precluding the discharge of CAFO pollution to Idaho's surface waters. As these CAFOs continue to increase in size, the volume of manure generated becomes overwhelming and the facility is forced to become a waste handling operation. CAFO waste represents a highly mobile mixture of contaminants with known and recognized detrimental effects on human health and the environment, typically placed in an area with many human and environmental receptors.

To further illustrate this point, each dairy cow produces an estimated 140 pounds per day of waste and 22 pounds of produced milk per day per dairy cow. The waste to milk ratio is 6.36 lbs waste/ 1 lb of milk. At the same time the trend in the industry is less facilities confining greater numbers of animals. These data indicate that waste management issues at the CAFO are growing faster than actual milk production.

Dated August 23rd, 2023.

s/ Dave Erickson
David J. Erickson

Exhibit A

Expert Opinion of David J. Erickson, PG CPG

RECEIVED
By: OAH on 7/22/2025

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June 27, 2025

William Moore
Office of Administrative Hearings
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Subject: Comments on Proposed Amendments to Minnesota Feedlot Rules (Minn. R. Chapter 7020)

Dear Mr. Moore and the Minnesota Pollution Control Agency,

I am writing to provide input on the Minnesota Pollution Control Agency's (MPCA) rulemaking process to amend the animal feedlot rules (Minn. R. Chapter 7020), last significantly updated in 2000. As a sixth generation farmer, I am committed to ensuring these regulations balance environmental protection with the economic realities of modern agriculture. Given the 25-year gap since the last major update, I offer the following comments to ensure the rules remain relevant and effective.

The Future of Agriculture in 25 Years: If feedlot rules are updated only every 25 years, the MPCA must anticipate long-term agricultural trends. By 2050, I foresee precision agriculture dominating, with widespread use of variable rate technology (VRT), advanced nutrient management, and diversified rotations including specialty crops, and cover crops. Larger feedlots will increase manure production, requiring rules that incentivize innovations to manage nutrient runoff effectively while supporting farm viability.

Nitrogen Management and Efficiency: Minnesota's nitrogen regulations, such as the Groundwater Protection Rule, often rely on average application rates, which do not reflect the variability of high-yield operations or regional differences. In a commodity market, "average" performance risks economic failure. Minnesota's diverse agricultural regions, ranging from tile drained soils of the Red River Valley, lower yielding sandy soils of central and northern areas, and high yielding southern Minnesota require tailored nutrient management. In northwest Minnesota a 200-bushel corn crop may be a record-breaking achievement, whereas in south-central Minnesota, it represents a failure, reflecting the regions potential for 220+ bushels per acre. The nitrogen recommendation table (1) (e.g., 195 lb N/acre following group 2 crops at 200+ bushels per acre vs 145 lbs N/acre for <100 bushels per acre) highlights this variability, yet current rules often average nutrient standards across the state. This approach is invalid, as it may encourage farmers to over apply nutrients to meet high yield targets in a low yield area or penalizes south central farmers for underperforming relative to their potential. A recent study in Nature Communications found that optimal nitrogen fertilizer rates for maize in the US Midwest have increased by 33% from 1985 to 2018 (from 150 to 200 kg N/ha), driven by higher-yielding hybrids and improved practices, yet nitrogen use efficiency

(NUE) has remained stable or improved due to precision application (2). Compared to states like Iowa and North Dakota, which adjust nitrogen rates based on soil tests and crop needs, Minnesota's approach may disadvantage efficient producers. For instance, North Dakota's recommendations incorporate soil nitrate tests. Recent research also indicates high-yield soybeans may not provide the assumed nitrogen credit, as they consume more nitrogen than they fix, creating residue challenges rather than surplus nitrogen. Additionally, corn's nitrogen uptake is shifting later in the season, particularly with fungicides extending plant health. In-season manure applications, supported by stabilizers, are more efficient than fall applications, which are restricted in vulnerable areas. I urge the MPCA to adopt NUE metrics over flat caps, using tools like the University of Minnesota's nitrogen rate trials, regional yield data, and the Nature study's findings to guide manure application rates. Also, nitrogen rate studies should incorporate farming practices that include fungicide and in season nutrient applications. As plants stay alive longer in the season with fungicides, they require more nitrogen to "get to the finish line". A study from Pioneer (3) also shows that as yields go up, less nitrogen is getting remobilized in the plant, therefor requiring higher amounts of nitrogen. Following the current guidelines in the table over applications in a low yielding region could increase nitrate leaching, while in under-application in a high yielding region reduces crop health, both harming water quality and farm viability. MPCA should adopt a tiered nitrogen standard based on county level yield averages, soil productivity zones, and other data sources that follow the potential of the region.

Phosphorus Management and Variable Rate Technology: Phosphorus regulations often treat fields uniformly, despite variability in soil test levels. VRT allows precise application, reducing high soil phosphorus levels while building low ones, unlike blanket restrictions based on field averages. MPCA should incorporate a more detailed approach to manage P levels based on grid or zone testing, not whole field averages.

Setback Requirements: Minnesota's setback distances for manure application exceed those in other states which allows smaller setbacks for in-season applications due to lower runoff risks. Given that in-season applications align with crop uptake and reduce leaching, the MPCA should consider tiered setbacks based on application timing and soil conditions to balance water quality protection with practical land use.

Crop Rotations and Specialty Crops: Diversified rotations, including small grains and cover crops, can reduce nitrogen and phosphorus runoff by up to 70%, as demonstrated in Iowa's Nutrient Reduction Strategy. Encouraging these practices in feedlot rules could enhance soil health and nutrient cycling, especially in high-manure regions. The MPCA should offer incentives for operators adopting such rotations.

Nitrogen Stabilizers: Nitrogen stabilizers, like nitrification inhibitors, improve NUE by reducing nitrate leaching and volatilization. Given their effectiveness, the MPCA should incorporate stabilizer use into manure management plans, allowing flexibility in application timing and rates to reward innovative producers.

In some recent conversations with growers in Canada, they are surface applying manure in corn with 90-foot-wide booms with drop hoses to the ground, and they are experiencing a 50% reduction in nitrogen losses. The crop is immediately using the nutrients, and the nutrients are not subject to weather from fall until the crop needs it. Practices like this would be too restrictive with current setbacks, even though very beneficial for crop yields and water quality. In Europe, which is densely

populated and very concerned with farm practices, applies in season with top dress applications on wheat. Any in season application should utilize nutrients far better than up front applications. Ideas like these need to be considered in the next 25 years. As fertilizer prices are and will most likely remain high, we need to think of practices that are not currently used here to gain better efficiency.

The MPCA's rulemaking process, extending through 2027, is a critical opportunity to modernize feedlot regulations. I encourage continued public engagement through accessible sessions and clear summaries of proposed changes. By adopting science-based, flexible rules informed by studies like the Nature Communications analysis, the MPCA can protect Minnesota's water resources while supporting a competitive agricultural sector.

Thank you for considering my input.

Sincerely,

Cole Pestorious
Farmer, Owner, Frontier Family Farms

(1) Screenshot from the MMP tool.

Nitrogen Recommendations

Crop Grown Last Year	Organic Matter	Expected Yield (bu/acre) <100	100-124	125-149	150-174	175-199	200+	Irrigated Sands
Alfalfa 2+ year old stand	low	0	0	40	40	40	40	150
	med/high	0	0	40	40	40	40	150
Alfalfa 1 year old stand	low	30	30	80	80	80	80	170
	med/high	30	30	80	80	80	80	170
Soybeans	low	100	100	150	150	150	150	205
	med/high	100	100	150	150	150	150	205
Edible beans, field peas	low	125	125	175	175	175	175	215
	med/high	125	125	175	175	175	175	215
Group 1 Crops: Clover, fallow, grass/legume hay, grass/leg, pasture, etc.	low	70	70	120	120	120	120	160
	med/high	70	70	120	120	120	120	160
Group 2 Crops: Corn, wheat, oats, potatoes, sugar beets, grass, rye, etc.	low	145	145	195	195	195	195	235
	med/high	145	145	195	195	195	195	235

(2) This highlights that over time increasing soybean yields are not giving the corresponding increase in nitrogen back to the corn crop since it's slope is greater than following corn.

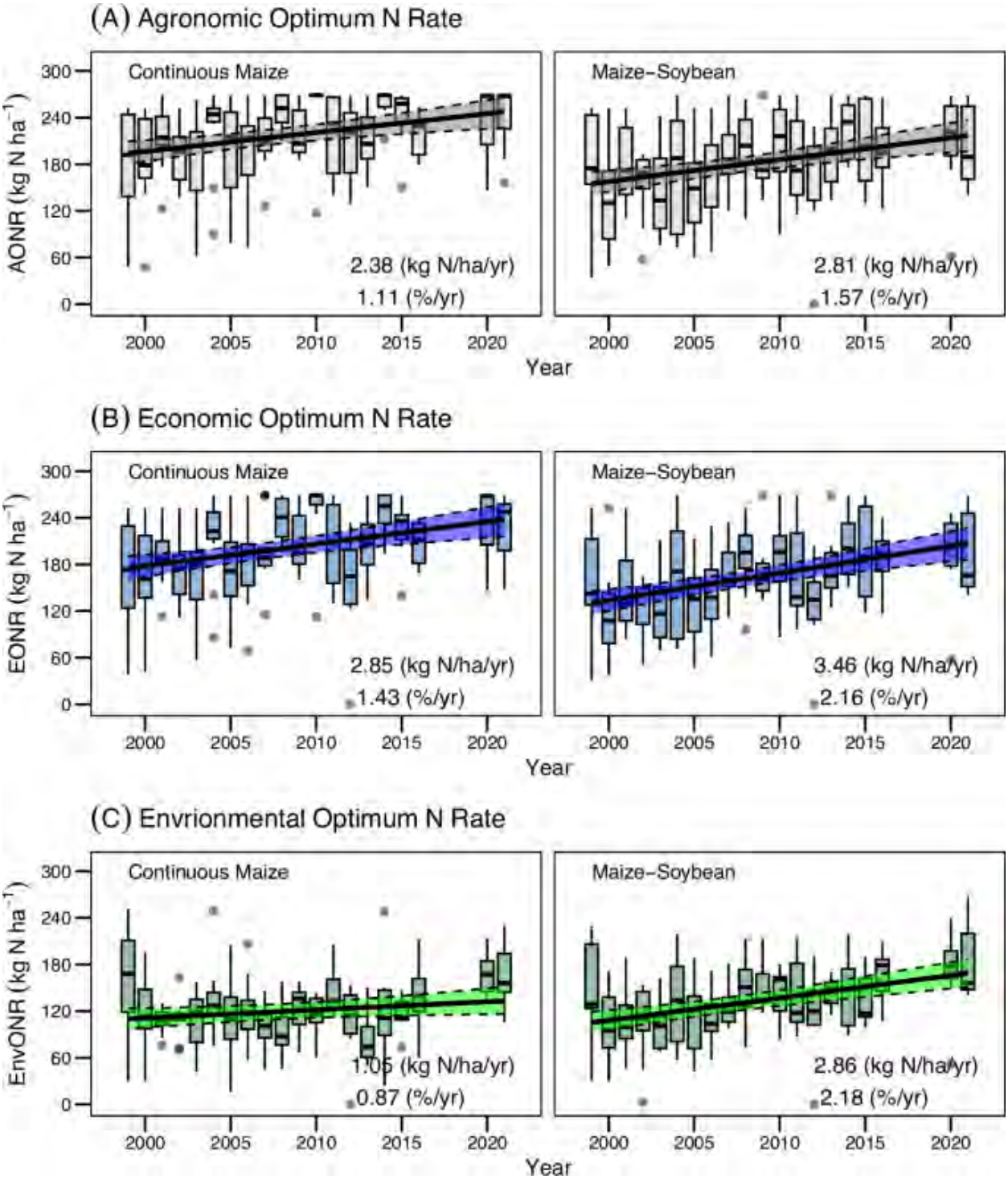

https://www.nature.com/articles/s41467-024-55314-7
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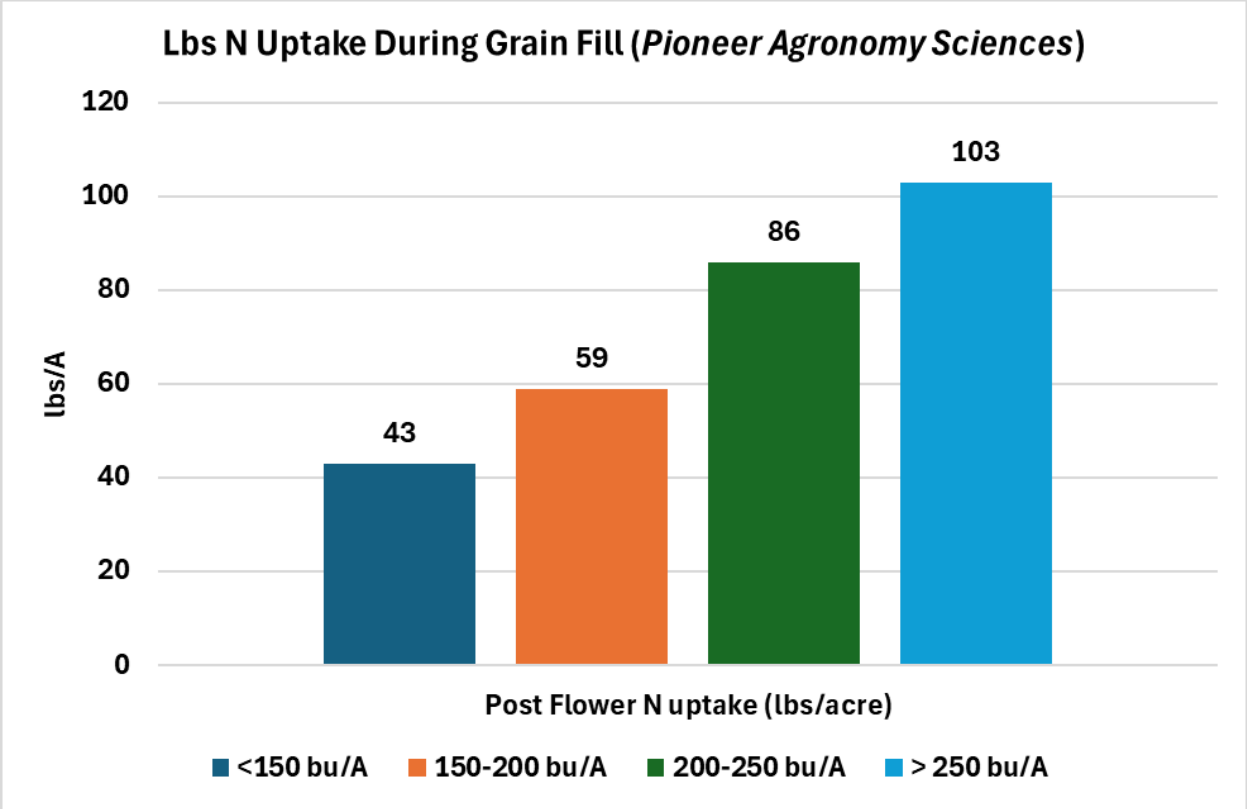

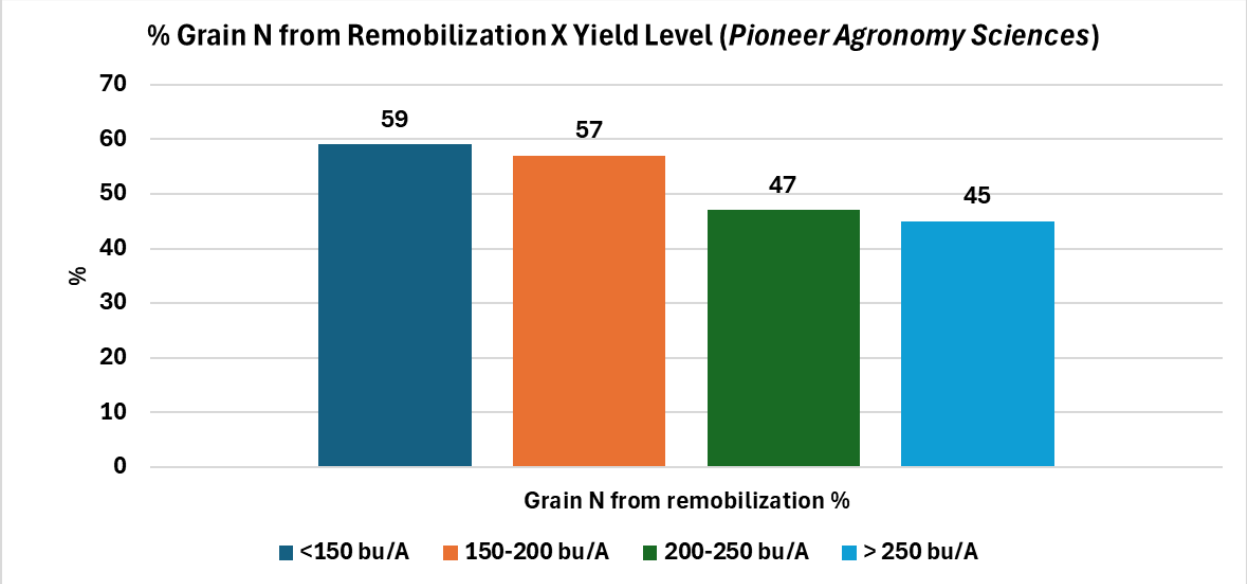

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

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I care about this because...

awe
artist water ecology

Name: Sarah Nassif

Address:

Phone:

Email:



MAY 1 9 2025

OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

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I care about this because...

Name: Nancy Reigada

Address: 456 Summit Ave #308 St. Paul MN 55102

Phone: _____

Email: _____

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OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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I care about this because...

Protect our waters

Name: Mary Crampton

Address:

Phone:

Email: mary.crampton@gmail.com

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St. Paul, MN 55164-0620

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I care about this because...

Water purity is crucial to our health and sustainability.

Name: Lynn Peggs

Address: 4300 W. River Pkwy

Phone: 218-348-3048

Email: carolynpeggs@yahoo.com

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St. Paul, MN 55164-0620

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I care about this because...

Name: Frank Josri

Address: 1810 Hartford Ave. St Paul 55116

Phone:

Email: Frankjosri@comcast.net

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St. Paul, MN 55164-0620

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major source of nitrate pollution in our waters, and
by adding stronger rules for the handling of
manure, MPCA can help ensure that all
Minnesotans' water at the tap is safe to drink.

I care about this because...

Name: Dave Combs
Address: 745 Grand Ave #403 St Paul 55105
Phone: 612 965 5484
Email:

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I care about this because...

I drink water

Name: Lisa Morgan

Address: 746 Holly

Phone: 651 602-0337

Email:

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I care about this because...

Clean Drinking water is limited

Name: Jenifer McGuire

Address: 3408 31st Avenue 55416

Phone: 520-591-9421

Email: jenifermcguire@gmail.com

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I care about this because...

Farm runoff is a source of significant nitrate pollution. Feedlots concentrate nitrates and damage surface water and aquifers. I spent many years in Fairmont, MN and saw the detrimental effects

Name: Tom Pederson

Address: 5605 Cocoa Ave

Phone: 651-283-7983

Email: tom@pedersondivetravel.com

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I care about this because...

We need clean water to drink + for life. We are responsible to care for all animals

Name: Robyn Stephan

Address: 13760 · 365th St Lindstrom MN 55045

Phone:

Email: robyn.stephan@gmail.com

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I care about this because...

Clean water is non negotiable! Nothing is worth polluting them!

Name: Jeremy Winter

Address: 2851 Hennepin Ave S Minneapolis MN 55408 APT 519

Phone: 551 795 5734

Email: jeremydwinter@gmail.com

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I care about this because...

the health of our state & people relies on clean water--

Name: Debbie Green

Address: 6670 Vernon Ave S
Edina MN 55436

Phone: 952-221-5312

Email: northstarshiving@gmail.com

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I care about this because...

Name: Susan Jackson
Address: 804 Meadowlark LN. St. Peter
Phone:
Email: smbjackson246@gmail.com

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I care about this because...

Water is life!

Name: W. Gary Wright

Address: 5210-12th Ave S
Mpls 55417

Phone:

Email:

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St. Paul, MN 55164-0620

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I care about this because...

Name: Josefina Garcia-Lugo
Address: 735 Marshall Ave.
Saint Paul, MN, 55104
Phone: 651-331-1156
Email: josefina1gh@gmail.com

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I care about this because...

Water is life and we only get one planet. ♡

Name: Neva Ballard

Address: 3928 Quail Ave N
Robbinsdale MN 55422

Phone: 602-570-9178

Email: nballard33@gmail.com

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St. Paul, MN 55164-0620

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I care about this because...

Name: Kai Johnson
Address: 7420 Ridgeway Rd
Golden Valley, MN 55427
Phone: 701-388-9087
Email: Kai.J.Johnson@outlook.com

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600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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I care about this because... I care deeply about water quality for my communities!

Name: Ellen Mueller

Address: 6005 Dupont Ave S, Mpls 55419

Phone: 701-330-1055

Email: ellen.mueller@protonmail.com

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I care about this because...

human health and water quality is essential!

Name: Rachel Lindholm

Address: 817 Cleveland Ave S Apt. 21 St. Paul, MN 55116

Phone: 651-354-7493

Email: rachel.lindholm@gmail.com

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St. Paul, MN 55164-0620

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major source of nitrate pollution in our wate
by adding stronger rules for the handling of
manure, MPCA can help ensure that all
Minnesotans' water at the tap is safe to drink

I care about this because...

water is life. Clean water sources protect + support not only us as human but wildlife. My family has work and leisure based on clean water

Name: Kaydelle Kvarnfor-Leverty
Address: 221 Fairview Ave S
St. Paul, MN 55105
Phone: 651-285-2792
Email: KayKvL@comcast.net

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St. Paul, MN 55164-0620

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I care about this because... WE HAVE PROPERTY IN WI, NEAR A 2,000 HEAD CAFO.. NITRATES & WATER QUALITY DEGRADATION HAS BEEN QUICK & AWFUL

Name: MIKE FERSTLE

Address: 705 VICTORIA ST S ST. PAUL, MN 55102

Phone: 651 329 4155

Email: MIKE@GREATRIVERPRODUCE.COM

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I care about this because...

it's not being addressed ~ get started.

Name: Sue Nissen

Address: Edina, MN

Phone: 952-221-9624

Email: n.sue4408@gmail

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I care about this because...

Water, especially clean water is core to Minnesota's identity!

Name: Allie Palmer

Address: 5441 83rd Ave S

Phone: 763-222-7581

Email: arpalmer@uwalumni.com

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I care about this because... of Quality Water = Life, Thanks!

Name: Anna Barker

Address: 6135-C Courtly Woodbury, MN 55125

Phone: 651-578-7453705

Email: annafbarker63@gmail.com

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I care about this because...

Name: Mike Vant

Address: 495 Mackubin Circle
Shoreview, MN 55126

Phone:

Email: mjvante gmail.com

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I care about this because...

Name: Paul Brown

Address: 510 Oak St. W

Phone: 651-643-0709

Email: sanpaul00@yahoo.com

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I care about this because...

Clean and safe water is important for people and the environment.

Name: Melissa Nonnemacher

Address: 852 Holly Ave St Paul MN 55104

Phone: 651-358-8471

Email: nonn0004@mac.com

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I care about this because...

It's logical!

Name: Samuel Soltermann

Address: 784 Holly Ave
St. Paul, MN 55104

Phone:

Email: fencingSam@gmail.com

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I care about this because...

Concern about animal welfare

Name: Jerry Dastych

Address: 2809 42nd Ave S.
Mpls MN 55406

Phone: 612-724-1570

Email: dastj@aol.com

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OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

I am writing to ask the MPCA to do more to protect our lakes, rivers, streams, and groundwater by revising the Animal Feedlot Rule to address the crisis of nitrate pollution in our state. Feedlots are a major source of nitrate pollution in our waters, and by adding stronger rules for the handling of manure, MPCA can help ensure that all Minnesotans' water at the tap is safe to drink.

I care about this because...

IT'S WHAT BINDS US ALTOGETHER. SANCTITY OF MUTUAL RESPECT.

Name: JOHN FORDE

Address: 2108 SARGENT ST PAUL 55105

Phone: 651 387 3333

Email: 40.JOHN.GMAIL.COM

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OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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I care about this because...

Name: Sharon Nolte

Address: 8815 Colfax Ave So

Phone: Bloomington MN 55420

Email:

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I care about this because...

Clean water is our most precious resource!

Name: Alana Horny

Address: 991 Parker Ave

Phone: 651 398 2485

Email: alana.horny@gmail.com

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I care about this because...

Name: TERRENCE SHAUGHNESSY
Address: 716 OSCEOLA AVE
ST. PAUL MN 55105
Phone: _____
Email: _____

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I care about this because...

Name: Leslie Myint

Address:

Phone:

Email: leslie.myint@gmail.com

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I care about this because...

Name: MaryAnn Jackson

Address: 2114 Bohlen St Paul

Phone:

Email: Mjackson1290@yahoo.com

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I care about this because...

Name: AL ReigADA

Address: 456 SUMMIT AVE
ST PAUL 55102

Phone: _____

Email: _____

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I care about this because...

We need to take steps to protect our land + water

Name: Chris Kilbrath

Address: 670 Portland Ave

Phone: 651-224-6005

Email: cdm6005@duck.com

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I care about this because...

I have lived in rural farm country - in a time when the cultures CARED about the earth

Name: KEVIN SHANNON

Address: 1870 BEAR PATH T. EAGAN MN 55122

Phone:

Email: kshannonmn@gmail.com

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I care about this because...

Not only is clean water a human right, it is vital to all life.

Name: Maisie Van Bossum

Address: 1967 Grand Ave, St. Paul

Phone: 612-267-2943

Email: maisie.a.vr@icloud.com

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I care about this because...

We all need clean water!

Name: Jane Batcheller

Address: 525 So Fairview Ave 55116

Phone: 651-767-7394

Email:

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I care about this because...

Name: Ande Saunders

Address: 555 Summit Ave #4, St Paul, MN 55102

Phone: (612) 306-8721

Email: amsaunders90@gmail

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Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

SAINT PAUL MN 550
21 MAY 2025PM 6

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I care about this because...

it pollutes our drinking water

Name: Kristen Salkas

Address: 857 Portland Ave
St. Paul. MN 55104

Phone: 319-431-7530

Email: salkas.kristen@gmail.com

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600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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I care about this because...

Name: Catharine C. Reed

Address: 941 Osceola Ave St. Paul 55105

Phone: 651-402-2969

Email: catharinecreed@mac.com

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OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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I care about this because...

Name: Kate Cole

Address:

Phone: 651-270-1468

Email: kateauncole@gmail.com

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St. Paul, MN 55164-0620

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I care about this because...

Name: LARRY Kluch

Address: 599 Pascal St. N

Phone: 651-235-0565

Email: klueh47@yahoo.com

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OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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I care about this because...

I want us to preserve water resources for our community and those that rely on us.

Name: Lauren Ballard

Address: 3928 Quail Ave N
Robbinsdale MN 55422

Phone: 623-680-1876

Email: messages.and.email@gmail.com

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St. Paul, MN 55164-0620

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I care about this because...

Everyone in Minnesota should have access to clean water. The issue is preventable and we need to eliminate the issue!

Name: Maureen Kenney

Address: 911 Portland Ave
St. Paul, MN 55104

Phone:

Email: mkenx2010@gmail.com

ST PAUL MN 550

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St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

SAINT PAUL MN 550
21 MAY 2025PM 6 L

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I care about this because...

Name: Clarissa Casecke
Address: 833 Holly Ave
St Paul MN 55104
Phone: 6123869636
Email: CLASECKE@gmail

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OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

SAINT PAUL MN 550
21 MAY 2025PM 7 L

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I care about this because... Clean water is critically important. We can't live without it.

Name: Craig Sterle

Address: 2676 Co. Rd. 104 Barnum, MN

Phone: 218-576-3650

Email: csterle777@gmail.com

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I care about this because...

Everyone deserves clean water!

Name: Lacy Tucker-Kirkwold

Address: 3414 10th AVE S
Minneapolis, MN 55407

Phone: 763-300-0063

Email: Lacytk95@hotmail.com

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I care about this because...

Name: Ron Dubis

Address: 10917 Sheridan Bloomington MN 55431

Phone: _____

Email: _____

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OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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I care about this because...

Rural Americans Health Matters! What big-Ag sprays + lets run off from feedlots does not belong in our wate

Name: Faith Bickner

Address: 1695 Sherburne Ave St Paul MN 55104

Phone: 6126182881

Email: Faith.bickner@gmail.com

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600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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I care about this because...

we all Need clean water for Next gen erection

Name: Randy Holst

Address: Edina Mn

Phone: 612 741 784Q

Email: 46willy4x4@gm

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I care about this because...

Name: Dawn Doering
Address: 13078 347th St. Lindstrom 55045
Phone: 651.257.9626
Email: ddd4556@gmail.com

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I care about this because...

MAY 27 2025

Office of Administrative Hearings

Name: Sherry PJohnson

Address: 820 Osceola Ave SP

Phone: 651-776-3060 55105

Email: facilitator.sher@gmail.com

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St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

SAINT PAUL MN 550

21 MAY 2025PM 6 L

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I care about this because...

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Name: Michael Fletcher

Address: 796 Laurel Ave
St Paul MN 55104

Phone: 612

Email:

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OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

05/23

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I care about this because...

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Name: Kathleen Stoddart

Address: 942 Fairmount Ave

Phone:

Email: kathleenstoddart@gmail.com

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I care about this because... water quality is vital to human life + the environment

Name: Mark Stephan

Address: 13700 263rd St Lindstrom MN 55045

Phone:

Email: bittercreekportal@gmail.com



JUN 02 2023

Office of Administrative Hearings

OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

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I care about this because...

I care about the quality of our ground water, steams & oceans

Name: Dolores Voorhees

Address: #430 525 Fairview Ave S.

Phone: 952 220 1236

Email: dolores voorhees

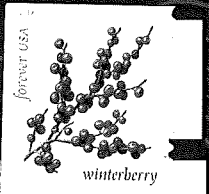

JUN 02 2025

Office of Administrative Hearings

OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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JUN 30 2025

Office of Administrative Hearings

June 26, 2025

William Moore, OAH:

RE: OAH Docket # 25-9003-40661, Revisor # R-4928

My concern about the CAFOs is due to the impact on water quality because of the manure runoff that contaminates the adjacent soil, waterways, and impacts human health

The USFWS has documented reduced populations of aquatic invertebrates that are bioindicators of water quality, such as reported using the EPT index (Ephemeroptera, Plecoptera, Trichoptera) is leading to fish kills.

For the last few years I have heard farmers in many rural communities speak at legislative hearings about the nitrate levels in their wells from manure and fertilizers that are above what is considered safe drinking water. In addition, there are reports of blue baby syndrome and other birth defects, cancers and illness from bacterial contamination from E. coli.

This is more than enough evidence to require more feedlots to have water pollution permits, to require medium and large confinement operations to monitor discharges to groundwater and drain tiles, to enforce stricter land application requirements and to require lower application rates in especially vulnerable groundwater areas such at the Karst regions in southeastern MN.

In this state that has so many farmers in rural communities, growing food for us and for other countries, we need to be protecting them *and* our environment.

Please give this your serious consideration.

Sincerely, Margot Monson

Margot Monson, aquatic entomologist

St Paul, MN

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

The information that I share with you should not be shared with the public. This will make it harder for me to transfer manure to neighbors some of them will not want there fertility info and yield shared publicly.

With all reporting having to be done online many are going to have to hire someone to do it for them or just not do and then what are we going to do put them out of business.

Cover crop for all maybe is not the answer for all. Soil type and typography is more important then time of year. Weather and time in the Fall can make this hard to get done.

I have been doing it for the last few years

Use the back if you need more room.

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

and if I get a good stand I need to to put more N on early into the year because the Cover Crop has all the N tide up and this is when the yield potential is being set, After the cover Crop breaks down later in the Season its ok but I have lost yield by then. Non Cover Crop field's allway out yield Cover Crop Fields, It comes at a cost of 40-50 ac to plant and kill.

Greg Jans
51036 310st
Grove City, Mn. 56243
320-221-4221

RECEIVED
JUN 30 2025
Office of Administrative Hearings

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

I am a hog producer in SE MN. There are several rules, standards, guidelines that we have to follow each year to be able to haul manure and are watched over closely by goverment officials.

Major rainfalls are hard to control. In MN 90% of reported fish kills are non agricultural related and I think that stat is imortant to share.

Matt Hellickson
matthellickson@hotmail.com

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JUL - 3 2025
Administrative Hearings

3 ways to submit your comments:

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Send via mail to:
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Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

7 JUL 2025 PM 8 L

I am writing to ask the MPCA to do more to protect our lakes, rivers, streams, and groundwater by revising the Animal Feedlot Rule to address the crisis of nitrate pollution in our state. Feedlots are a major source of nitrate pollution in our waters, and by adding stronger rules for the handling of manure, MPCA can help ensure that all Minnesotans' water at the tap is safe to drink.

I care about this because...

I live 1 mile east of the proposed Daley expansion given preliminary approval by MPCA and the DNR. My private well far exceeds the safe level for nitrates.

Name: Karen M. Ahrens

Address: 200 West Main Street
Lewiston, MN 55952

Phone: 507-523-3657

Email: karichahrens@email.com



OAH attn: William Moore, OAH

600 N Robert St PO Box 64620

St. Paul, MN 55164-0620

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Transferring manure to a non-producer requiring him to come under the same rules of recording, it will make it very difficult to find a place for my storage.

If you tell them they have to do this, they will turn it down. Farmers in my area do not put much interest in manure, do not recognize it for much value

Corn on corn - The nitrogen allowance is very inadequate

Larry Larsen
President
Larsen Products Inc.

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JUL - 9 2025
Office of Administrative Hearings

Give us your comments on the

Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

Steve Schmidt MPCA

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JUL - 9 2025

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3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
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600 N Robert St.
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St. Paul, MN 55164-0620

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Use the back if you need more room.

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

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I care about this because... Our family has already been harmed by industrial farming by the likes of Daley Farms Lewiston. We've addressed our concerns about CAFOs, biogas digesters, community discord + water quality. Our well test 20.

Name: Richard E. Ahrens

Address: 200 West Main Street
Lewiston, MN 55952

Phone: 507-523-3657

Email: Karichahrens@email.com



RECEIVED
JUL 10 2025

OAH attn: William Moore, OAH

Office of Administrative Hearings

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

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I care about this because...

wells in SE Minn are showing increased nitrate levels. We have to lower inputs. We can't "technology" our way out of this

Name: Bonita Underbakke

Address: 34526 State Hwy 16
Lanesboro MN 55949

Phone: 507-273-9578

Email: bonita.underbakke@gmail.com

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JUL 11 2025

OAH attn: William Moore, OAH
Office of Administrative Hearings
600 N Robert St. PO Box 64620
St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

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I care about this because...

CES Mowe has to ration water now due to nitrate pollution. If cities of 3000 need sewer systems, why not feedlots?

Name: Deirdre Flesche

Address: PO Box 180, Lake City MN 55041

Phone: 651-345-2873

Email: dedert@me.com

RECEIVED
JUL 09 2025

JUL 11 2025

OAH attn: William Moore, OAH
Office of Administrative Hearings
600 N Robert St. PO Box 64620
St. Paul, MN 55164-0620

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

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I care about this because...

Purer H_2O for swimming fishing boating and for wildlife!!!

Name: PATSY GAVIN

Address: PO Box 1425
WINONA MN 55987

Phone: [redacted]

Email: [redacted]

SAINT PAUL

2000321894
ZIP 55104

RECEIVED

JUL 14 2025

Attn: William Moore, OAH
Office of Administrative Hearings
600 N Robert St. PO Box 64620
St. Paul, MN 55164-0620

RECEIVED

JUL 14 2025

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JUL 14 2025

Office of Administrative Hearings

7-11-2025

MPCA

I am contacting you regarding proposed New Feedlot rules I Feel leave things as they are Any changes would make smaller producer decide to Quit and play into the hands of larger Factory corporate Farms also Further drive up the price of Animal protein with less live stock Numbers espically Beef.

as a live stock producer we work to clean our yards and prevent run off of animal waste and to apply it over as many acres as possible due to the cost of commercial Fertilizer.

We work to take care of our environment because we live here with our Families

Jim Wendt

RECEIVED

JUL 14 2023

Office of Administrative Hearings

Mr. Moore:

I'm John Weiss, I live in Rochester, I fish trout in SE streams and I'm worried about feedlots. Therefore, I'm encouraging you to be as strict as possible with rewriting rules for Chapter 7020.

I am a member of Trout Unlimited and endorse the changes they would like to see. They are more the experts in this.

I'm writing more as an angler and someone who loves the blufflands and our waters.

I'm not opposed to feedlots, though there are questions about just how big they should be. That is not the purpose of these rules. But how well they work with the land and our water are part of the rules. Good farmers are some of the best friends trout and trout streams have. If they control runoff, keep nitrates out of the water - both ground water and surface water - they are helping everyone.

There is no reason farmers shouldn't be required to have good plans for the manure. Yes, it's probably more work for them but they are part of society, we all need to control what we do that affects water. I live in the city and try to keep down use of salt in winter to not pollute the Zumbro River, we don't dump grass clippings into the sewer so they go into the river. This is only a smaller thing compared with the effect a large feedlot can have but we are all responsible for our water. I've learned over nearly 50 years in the Southeast that it all comes down to water - what we do on the land ends up in the water.

So please, update the rules, make them as strict as possible so farmers can still farm but our waters are kept clean.

Finally, it's the right thing to do.

John Weiss

RECEIVED

JUL 16 2025

Office of Administrative Hearings

July 11, 2025

Dear Mr. Moore,

I attended the Minnesota Pollution Control Agency meeting in Paynesville MN in June where they informed us that any size animal unit will be considered a feedlot if there is soil without grass cover. That could be as low as a few poultry, 1 to 5 sheep, goats, pigs or calves (etc.) as this would lead to annual costly registration.

The next speaker spoke on nitrates and said a nitrate is a nitrate. They can't tell the difference whether it came from rain fall, snow melt, decaying vegetation, exhaust fumes, manure, urban runoff, commercial fertilizer or where it exactly came from.

In my opinion, this appears to be a way of getting rid of small producers through a paper work jungle or computer nightmare. As a small animal farmer, along with my two sons, we can't afford to lose valuable nutrients from manure due to the high costs of commercial fertilizer. In fact, we planted 52 foot buffers on lakeshore and stream or ditch where needed (requirements were 0 to 50 feet) so we could harvest the buffers for hay and still protect water quality.

This appears to me that this is being pushed to eliminate animal agriculture. If need be, break the southeast corner of Minnesota off but please don't include the whole state. I believe the current feedlot rules are very good and keep them as currently being used and enforced.

Sincerely yours,

Vernon J Pooch

32158 County Road 28, Farwell, MN 56327

Cell 320 815 8360

RECEIVED

JUL 16 2025

Office of Administrative Hearings

July 10, 2025

Dear Mr. Moore:

I am a member of Trout Unlimited and an avid fly fisherman. Trout require cold, clean water and a healthy aquatic insect population. I am writing to ask the MPCA to strengthen the Animal Feedlot Rule, Minnesota Rule Chapter 7020 to prevent large volumes of manure which contain high levels of nitrogen, ammonia and other chemicals from washing into trout streams and groundwater.

I recommend amending the existing Feedlot Rules to improve land application of manure practices as follows:

1. Require NPDE/SDS permits for feedlots with 600 or more animal units.

2. Prohibit manure application on frozen or saturated ground, or when rainfall is likely.

3 Require greater setback distances for manure applications from water resources in the karst region and other vulnerable groundwater areas, including prohibiting manure applications within:

- 300 feet upslope or 100 feet downslope of a sinkhole or other direct conduit to groundwater
    - 300 feet upslope of a public waterway or tributary of a public waterway
    - 250 feet from a private well
    - 1,000 feet from a community well

4. Prohibit livestock of a feedlot or facility capable of holding 100 or more animal units from entering a designated trout stream or tributary and prohibit livestock of a feedlot or facility capable of holding 300 or more animal units from entering any water of the State.

MDA's current approach to Feedlots is failing to protect Minnesota's trout streams from fish kills and groundwater from harmful levels of contamination and I urge you to take action.

Thank you for considering my letter.

Joseph L Mac

Sincerely,
Joe Maccani
9540 Yosemite Rd.
Bloomington, MN 55437
jmaccani@comcast.net

Give us your comments on the
Animal Feedlots Rule

MINNESOTA POLLUTION CONTROL AGENCY

We want to hear from you!

To whom it may concern:
We are a small family farm. We need to haul manure every day. It would be devastating if were unable to do so.
Farmers have enough to worry about. Please don't make us give up our dreams.

Thank you
Philip

3 ways to submit your comments:

Hand this card to an MPCA staff member

Send via mail to:
OAH Attn: William Moore
600 N Robert St.
PO Box 64620
St. Paul, MN 55164-0620

Scan the QR code to submit comments online

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Use the back if you need more room.

Share Your Story and Thoughts About MN's Animal Feedlot Rules Here:

Please Print clearly

(1.) ALL MANURE Holding AREAS FROM FEED LOTS NEED SHALLOW Test WELLS UNDER AND AROUND THEM, To TAKE WATER SAMPLES BY STATE AGENCIES To DETERMINE IF CONTAMINATES ARE PRESENT. So PREVENTIVE MEAURES CAN PROTECT GROUND WATER.

(2) Test DISCHARGE FROM Field TILE going into Public WATERS. IF Tested And Found OVER STATE LEVELS, CORRECTIVE MEAURES ARE IMPLEMENTED, ON TILED LAND WHERE MANURE IS USED.

RECEIVED
JUL 17 2025
Office of Administrative Hearings

Your Name: GARY TROGSTAD City: EYOTA State: MN.

7-14-2025

RECEIVED
By: OAH on 7/17/2025

John P. Lenczewski, Executive Director
Minnesota Trout Unlimited
PO Box 845
Chanhassen, MN 55317
612.670.1629
John.lenczewski@mntu.org

July 17, 2025

Minnesota Pollution Control Agency

Re: Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, chapter 7020, Revisor's ID Number R-04928

I am writing on behalf of Minnesota Trout Unlimited ("MNTU") and its thousands of members around the state to comment on changes to Minnesota's Animal Feedlot Rule. Minnesota Trout Unlimited is a grassroots conservation organization working to protect, restore and sustain coldwater fisheries and their watersheds across Minnesota. Our several thousand members living and working in communities across Minnesota understand that activities on the land determine the quality of the water in streams and lakes, and the health of trout and aquatic organisms that live in these waters. We are very concerned about the impacts that animal feedlot operations, including manure applications, can have on trout streams.

MNTU urges the Minnesota Pollution Control Agency to amend the Animal Feedlot Rule to include the following:

1. Require NPDE/SDS permits for animal feedlots with more than 600 animal units. *7020.0405, Subp. 1 B (1)*
2. Require all feedlots with 300 or more animal units to prepare a manure management plan and maintain land application records, and submit these to the MPCA and county feedlot pollution control officer (in counties with a delegated county animal feedlot program pursuant to 7020.1500 to 7020.1800). These requirements should apply to **all** feedlots of this size, regardless of whether they use a commercial applicator or not. (see Minn. R. 7020.2225, subp. 4)
3. Require all owners and operators of animal feedlots with 300 or more animals to use the online nutrient management tool, including for development of manure management plans.

4. When manure is transferred by a feedlot owner/operator for application to the land by someone else, require that the transferee also follow the requirements in the manure management plan. (see Minn. R. 7020.2225, subp. 5 D)
5. Prohibit manure application on frozen or saturated ground, or when rainfall is likely. (see Minn. R. 7020.2225, subp. 6; add to Minn. R. 7020.2225, subp. 4)
6. Require greater setback distances for manure applications from water resources in the karst region and other vulnerable groundwater areas, including prohibiting manure applications within:
    - 300 feet upslope or 100 feet downslope of a sinkhole or other direct conduit to groundwater
    - 300 feet upslope of a public waterway or tributary of a public waterway
    - 250 feet from a private well
    - 1,000 feet from a community well

    (see 7020.2225, subp.6 and 8)

7. 7020.2015 should be amended to require that:
    "Animals of any animal feedlot of any size must not be allowed to enter any public water, nor any spring which flows into a Class 2A water (per MPCA rule), designated trout stream (per DNR rule), or tributary of a Class 2A water or designated trout stream. The feedlot operation must be fenced to prohibit livestock entry into these water resources."
    Note that pasture operations are not subject to 7070.2015.
8. Revise the definition in special waters in 7020.033, subpart 23 by adding a provision C: "C. Class 2A waters, designated trout streams, tributaries of Class 2A waters and designated trout streams, and springs and groundwater seeps that flow into these waterways."
9. Require soil nitrate tests prior to all manure applications in Cass, Carlton, Morrison, Martin, Winona, Hubbard, Rock, Clearwater and Stearns counties, since they are hot spots for nitrogen overload. (7020.2225 Subp.2)
10. Require annual reports to be submitted by delegated counties to the MPCA, that the MPCA review and audits these, and explicitly authorize the MPCA to revoke or rescind the delegated authority where a county regularly fails to perform its duties or does so poorly.
11. Expand mandatory groundwater and surface water monitoring at all permitted feedlot operations and associated manure storage and application sites.

12. Prohibit feedlot expansion and construction in sensitive groundwater areas and near trout streams without stringent environmental review. Consider the density and the maximum number animals units allowed in a particular watershed, with consideration to the vulnerable groundwater areas of the state including the Karst region. Use a spatial analysis to examine cumulative impacts by HUC 12 watershed.
13. Require the owner of an animal feedlot who transfers manure to another person or entity to regularly report to MPCA and the county who the manure transferees are, and the amounts and locations of manure applications by the transferee(s).
14. Require transferees to regularly report to MPCA and county when and where manure applications are made, and the amounts applied.
15. Permit applications: Add these provisions to 7020.0505, Subp. 4:
    a. require the identification of all Class 2A waters (per MPCA rule), designated trout streams (per DNR rule), tributaries of Class 2A waters and designated trout streams, and springs and groundwater seeps that flow into these waters on land where manure will or may be applied and locations where any land within 100' of these water resources where slope exceeds 6%.
    b. identify any land proposed for manure applications where manure is already being applied from another source, and identify the source and amount
    c. identify the number and locations of all sinkholes on the property where manure will be applied
16. Increase funding for manure storage and management grants to animal feedlot operations with less than 600 animal units.
17. The cumulative impact of animal feedlot operations and manure applications must be considered at the HUC 12 watershed scale to protect water quality of public waters of this size. A moratorium on permitting new feedlot operations should be instituted in HUC 12 watersheds that are already saturated with feedlot operations.
18. All animal feedlots located within a 3-mile radius that are owned by the same owner or group of owners should be treated as a single operation for purposes of determining whether the combined operations exceed various permitting or environmental review thresholds.
19. Address phosphorus requirements of plants and testing of soil and manure before application.
20. Increase funding to the MPCA to add staff necessary to manage and enforce permits for all animal feedlots with more than 600 animal units.

Thank you for this opportunity to comment on changes needed to the Animal Feedlot Rule.

Respectfully,

/s/John P. Lenczewski

From:

Chad Johnson

33599 815th Ave

Ellendale Mn. 56026

RECEIVED

JUL 21 2025

Office of Administrative Hearings

To:

William Moore

Office of Administration Hearings

600 N Robert St

PO Box 64620

St Paul Mn. 55164-0620

Subject: MPCA Feedlot Rules

Dear Mr. Moore

My name is Chad Johnson, I am a third generation farmer from southern Minnesota. I have been a Minnesota livestock producer for my entire career. I would just like to give a few points from my perspective as the MPCA decides rule changes for feedlots.

1. I would ask that the MPCA please consider realistic yield goals from certain parts of the state when determining the amount of realistic fertilizer it takes and time of application to reach those goals so livestock producers can compete with the commercial fertilizer markets.
2. Please consider the financial aspects of rule changes to new and existing feedlots as dramatic changes and demands could lead to hardships and even farm closures.
3. Please take a look at surrounding states that use different regulations and yield goals for different areas of their state. (application rates and setbacks)
4. Technology and science are helping the Mn livestock farmer become more efficient thru variable rate applications, new tools to apply when it's the most efficient, nitrogen stabilizers to help keep fertility available for the plant longer, etc.

Thank You for listening to my concerns. Nobody cares more for the natural resources of the state than the Mn farmer. I am just asking for a practical and efficient process to work for everyone.

Chad Johnson

Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

SAINT PAUL

I am writing to ask the MPCA to do more to protect our lakes, rivers, streams, and groundwater by revising the Animal Feedlot Rule to address the crisis of nitrate pollution in our state. Feedlots are a major source of nitrate pollution in our waters, and by adding stronger rules for the handling of manure, MPCA can help ensure that all Minnesotans' water at the tap is safe to drink.

I care about this because...

Everyone deserves safe, clean drinking water.

Name: Cherie Holes

Address: 511 E King St
Winona MN 55987

Phone: 507/454-8204

Email: cherieholes@gmail



Administrative Hearings

OAH attn: William Moore, OAH

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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JUL 21 2025
Office of Administrative Hearings

MPCA Feedlot rules update

I lived rurally for 40 years and am aware that our groundwater in the Drfitless is seriously contaminated with nitrates and agricultural chemicals, and has been for decades. Despite numerous programs and countless dollars spent, our water is not improving.

Confined animal operations have grown in number and size, resulting in more liquid manure stored, transferred and applied, primarily in nearby fields because of cost of transport. Ag practices have changed as well, with few animals on the land and less alfalfa and small grains being grown. The primary crops are corn and soybeans, both demanding inputs. Over application of manure and commercial fertilizer has become a huge problem. More ag land has been tiled creating severe point-source pollution to our streams and ground water.

One step in improving the crisis of contaminated water would be to reduce the permit threshold of 1,000 AUs to 600. More confined operations would then need an NPDES or SDS permit. They would need to have a manure management plan, adequate storage and follow certain BMPs.

Feedlots of over 300 AUs should be required to prepare a manure management plan, maintain application records and submit them to the MPCA and county feedlot officer.

Permits and manure management plans aren't of much use however without monitoring and reporting. Permitted feedlots should be required to monitor discharges to groundwater and drain tiles below crop fields along with monitoring surface water runoff.

It should be prohibited to spread manure on frozen ground, and application rates in vulnerable areas should be lower.

Applying manure and commercial fertilizers too close to sinkholes and waterways has impacted groundwater and caused fish kills. There should be required setback distances, and they should be marked/posted so there will be no mistakes.

Everyone deserves clean, safe drinking water, and the state agencies tasked with protecting this precious resource have failed to do so.

Cherie Hales

Cherie Hales
Winona MN

RECEIVED
JUL 21 2025
Office of Administrative Hearings

TO: William Moore, MPCA
FROM: Amy Caucutt, Rochester citizen
RE: comments on feedlot rules update

DATE: July 17, 2025

On June 24, 2025, I attended the MPCA information meeting on this topic in Albert Lea. THANK-YOU FOR TAKING THIS ON! We need to update these rules to protect the ground and surface water for all of us in SE Minnesota.

I have become aware of this need by the news about the EPA actions in our region based on high nitrate levels in our water. I have also been informed about the need for action by reading "Dodge County Inc" by Sonja Trom Eayrs. Years ago, when I was a new member of the League of Women Voters, I lamented to an older member that we seemed to be studying clean water issues again and again. She advised me that government never fully solves a problem, so we have to address it over and over. There are always changes, so government and citizens need to react. That is what you are doing now.

In 1988-9, Olmsted County created its first water plan. I, as chair of the Rochester Planning and Zoning Commission was appointed to the group that wrote it. We were very aware of the need to protect our ground water in this karst geology by the then recent work of Calvin Alexander from the U of MN. His work was horrifyingly startling....dye added to disappearing streams in a Fillmore County feedlot, emerging in less than a day in a beautiful artesian spring, which wasn't clean, 1000 year old water from the center of the earth after all. At the time, my view on how to protect the public water supply, from a planning commission perspective, was to regulate the number and placement of septic systems. From what I am now learning about concentrated feedlots, septic systems are a drop in the bucket.

Some members of this group writing the 1989 county water plan, tried to dissuade us by claiming that regulation would undermine the economy (at least of farmers). Our response was to say consider the huge health care economy of "Destination Medical Center", if we do not regulate and ground water becomes poisonous to those with fragile health... Imagine the impact of 1 headline: "Mayo Patients succumb to water born illness"

Please consider these upgrades to the current feedlot rules:

1) ground water monitoring for NPDES and SDS permit holding feedlots
2) lowering animal unit size
3) changes to how a collection of feedlots under same ownership are permitted
4) institute a manure mapping tool available to the public
5) oversight of those who spread manure, especially if not on land owned by permitted feedlots
6) there needs to be found a way thru air quality monitors to control odor so that other people can live, work, and thrive near feedlots...zoning is not enough
7) BUMP UP ENFORCEMENT to occasional spot checks as well as quick response to complaints.

Thanks for the work you are doing for all of us,

Amy Caucutt, 716 28th St NW, Rochester, MN 55901, (c)507-993-9897, amycaucutt@gmail.com

Amy C Caucutt

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JUL 21 2025
Office of Administrative Hearings

7-16-25

Good Morning William More,

I have also included the financial summary for Farm Business Management Education Programs for 2024 calender year.

It includes 222 dairy farms from Southeast Mn. As shown, there is not a lot of profit to reinvest in dairy, equipment and possible larger structures for manure storage.

Thank you for considering.

Duane Wild

7-16-25

RECEIVED
JUL 21 2025
Office of Administrative Hearings

Hello MPCA,

Thank you for hosting regional meetings throughout Minnesota.

I would like you to consider these points that I think are important.

1. Fish kills

   I have fished the same streams for almost 60 years and continue to fish. Every fish kill I have seen was a 3.5-5 inch downpour in a very short period of time. That is not something that is predictable and we can't regulate it. When I was younger, all trout streams were grazed and cattle stood in the streams during hot weather and pooped. There were no fish kills that I knew of or were publicized.

   Today, we have more trout in the streams than ever before. Only 1-2% of fish kills are related to agriculture. Most are temperature elevation of water and stream bank debris. Streambank restoration may help. Let's not penalize agriculture for their minimal role in this problem.
2. Nitrates-Farmers are solely being blamed for nitrates but old septic systems and wells with eroded casings need to be checked as their leaks contaminate water as well. We should also be monitoring municipal sludge spreading practices to consider how they add to the nitrate and heavy metal contamination picture. In Lewiston we have had our municipal sewage pond develop a leak and disappear overnight.
3. Wintertime spread, storage pits, pad sites

   Most young livestock are housed in manure packs in Southeast MN. As the packs thaw, they release ammonia in the sheds. The sheds need to be cleaned monthly starting at the end of January or the animals will have pneumonia problems.

   We need to work with animal agriculture, like Europe does, to provide engineering plans, pads, or new buildings with financial help. If we don't, farms with under 1000 animal units will disappear due to the increased cost of operation. Dairy farms under 1000 animal units cannot afford this. Our profit margin is small. The cull price of calves have saved the day for the last 2 ½ years but that won't last forever and the milk price has not increased. Federal and state rules have already driven out most of the 50-250 cow sites in Minnesota.

   The loss of one dairy cow means the loss of one acre of hay and pasture land. Those acres will be planted to corn and soybeans. We are moving in the wrong direction. We need more alfalfa and pasture for improved water quality.

   Manure pads and liquid storage areas will cost 2-4 million dollars per dairy to meet the proposed changes. I asked at the regional meeting if funding from the state would be provided and was told, "Not at this time". Our family farm priced a manure

storage pit in 2007 for 555 cows with 7 months storage. This would be 2 units containing 4, 712,591 gallons of liquid manure. The cost was over $800,000. With your proposals, we will need over 12 months storage for wet Spring conditions like we had in 2024 in our area. 3-5 million dollars will be needed for liquid and pen pack.

Exit will be the only option. There is no funding available. I have visited our NRCS and SWCD several times to confirm this.

The rural Minnesota economy will suffer the loss and food security will be at increased risk in the U.S. In 2017, each dairy returned $7000 to the local economy through machinery dealers, plumbers, electricians, veterinarians, nutritionists, agronomists, hardware stores, grocery stores, etc. The loss of dairy farms affects not only food availability but also the economic health of our communities.

4. No winter spread of manure also has serious implications.
    - The cost of facilities for the manure will mean dairy and cattle farmers will need to sell their herds. The loss of hay and pasture ground to corn and soybeans results in lower water quality.
    - A wet spring would mean increased compaction due to repeated trips across the field to spread manure. Increased compaction reduces soil health.
    - The need for more time spreading in the spring means a shorter window for planting and/or the use of shorter day crops, which would mean lower crop yield.

I have seen no study putting a smaller amount, like 3-4,000 gallons per acre, on chiseled fields in winter on fields with less than a 6% slope. In a winter like 2024-2025 (very little snow) all water melts into the chiseling and there is little runoff. With a spring like 2024 (excess rain, wet and saturated soil) there can be a great deal of runoff due to the unpredictable large rainfall.

A broad brush approach does not work. Weather forecasts are only about 50% correct and rainfall is the biggest predictor of runoff.

5. Distance between family farms

    There should be no change. Farmers consider the distance between fields and an increased land base increases the opportunity for less manure per acre and less road travel with tankers and spreaders.

    Each farm should have its own animal – unit base.

    An exit from livestock production is very likely, going from 750 animal units to well over 1000 animal units will have different requirements. We were told not to worry if family members worked together.
6. Animal unit values need to stay the same as they are valued today.

Discharge per animal per day should be the standard, which was set-up by previous laws regarding animal unit total.

Our rural communities are already having difficulty meeting the challenge of school, fire, police, EMS, county taxes, and township taxes.

A loss of animal production will hurt rural communities. Loss of dairy/beef production will decrease alfalfa and pasture ground acres which will affect water quality. There is no perfect style of farming. There are positives and negatives for everyone. We should encourage education of farming practices that will benefit water quality and provide an opportunity to change when it is affordable-Examples: cover crops, no till planting, manure management, fertilizer application, etc. Public cooperation helps us improve water quality. We can see changes in the last 10 years with adoption of several of these practices.

It will take time to see changes in water quality considering the time it takes for water to move through the soil. All changes will not work every year. Flexibility has to be built into the plan due to changes of rain and snowfall.

As a dairy farmer with the price of milk at $17 per hundred weight and the increased cost of production, there is not much left over for larger pits and stacking slabs. Changing requirements will only leave 1000 animal unit facilities and rural communities will pay the price.

Thank you for considering these comments.

Duane Wirt

Livestock Enterprise Analysis
Farm Business Management Statewide Data
Excluding Organic & Organic Transition
(Farms Sorted By Return to Overhead)

Dairy -- Average Per Cow

	Avg. Of All Farms		Low 20%		40 - 60%		High 20%	
Number of farms	222		44		45		45	
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Milk sold (hd)	26,271.1	5,610.95	22,350.5	4,603.27	27,604.7	5,745.81	28,103.4	6,224.96
Dairy Calves sold (hd)	0.4	244.63	0.3	166.43	0.5	319.94	0.5	306.42
Transferred out (hd)	0.6	65.44	0.7	81.26	0.5	61.95	0.5	64.56
Cull sales (hd)	0.3	430.11	0.3	407.98	0.3	451.37	0.3	413.52
Insurance Income		43.59		12.00		65.94		48.35
Government payments		12.21		14.56		10.57		12.47
Other Income		33.97		18.56		15.72		42.38
Purchased (hd)	0.0	-26.05	0.0	-67.83	0.0	-14.12	0.0	-17.15
Transferred In (hd)	0.3	-42.45	0.3	-17.25	0.4	-50.25	0.3	-8.35
Inventory change (hd)	0.0	26.32	0.0	-2.48	0.0	17.70	0.0	41.65
Dairy repl cost		-729.42		-821.57		-759.19		-715.29
Gross margin		5,669.31		4,394.93		5,855.45		6,413.50
Direct Expenses								
Protein Vit Minerals (lb.)	4,029.8	901.58	1,860.0	756.89	4,905.9	1,079.19	5,222.5	935.76
Complete Ration (lb.)	1,178.8	558.51	2,326.1	576.79	1,531.6	637.37	695.5	477.47
Corn (bu.)	73.7	318.03	64.8	281.53	79.4	338.62	81.0	360.37
Corn Silage (lb.)	20,922.0	465.17	21,265.9	467.69	21,014.3	478.06	20,718.5	487.35
Hay, Alfalfa (lb.)	2,387.8	181.85	1,879.5	149.30	2,478.1	197.25	2,557.4	178.36
Other feed stuffs (lb)	5,299.1	253.49	5,522.6	287.27	7,167.9	247.43	3,520.2	203.79
Breeding fees		56.15		59.44		61.86		43.72
Veterinary		109.69		94.27		110.69		107.56
Supplies		162.00		207.72		131.48		162.41
Fuel & oil		98.13		103.82		81.14		112.00
Repairs		234.88		249.75		243.96		229.52
Custom hire		95.04		84.04		129.10		75.53
Hired labor		416.88		451.44		493.81		289.39
Hauling and trucking		128.42		134.14		147.45		132.22
Miscellaneous		265.93		318.73		262.08		238.23
Total direct expenses		4,247.76		4,222.82		4,539.48		4,033.67
Return over direct expense		1,421.55		172.10		1,315.97		2,379.83
Overhead Expenses								
Hired labor		128.29		66.73		74.91		231.44
Building leases		80.22		74.99		72.26		112.77
Interest		120.97		138.42		137.52		107.94
Mach & bldg depreciation		203.23		165.65		182.62		230.75
Miscellaneous		200.69		160.98		166.36		240.69
Total overhead expenses		733.39		606.76		633.66		923.60
Total dir & ovhd expenses		4,981.15		4,829.59		5,173.14		4,957.27
Net return		688.16		-434.66		682.31		1,456.24
Labor & management charge		193.19		233.63		126.86		222.69
Net return over lbr & mgt		494.97		-668.29		555.45		1,233.55
Cost of Production Per Cwt. Of Milk								
Total direct expense per unit		16.10		18.84		16.40		14.28
Total dir& ovhd expense per unit		18.88		21.55		18.68		17.55
With other revenue adjustments		18.71		22.51		18.33		16.95
With labor and management		19.44		23.55		18.79		17.73
Est. labor hours per unit		39.66		42.94		39.24		39.49
Other Information								
Number of cows		303.4		197.1		418.6		344.4
Milk produced per cow		26,380		22,416		27,688		28,240
Energy corrected milk per cow		28,982		24,841		29,829		31,734
Lbs of fat & protein per cow		1,970		1,704		2,011		2,178
Culling percentage		29.2		31.0		30.7		26.2
Turnover rate		34.7		38.8		35.4		31.6
Cows per milking unit		23		18		27		25
Feed cost per cwt. of milk		10.15		11.24		10.39		9.36
Feed cost per cow		2,678.63		2,519.47		2,877.91		2,643.09
Hired labor per cow		547.17		518.17		568.72		520.84
Avg. milk price per cwt.		21.36		20.60		20.81		22.15
Milk price / feed margin		11.20		9.36		10.42		12.79

Livestock Enterprise Analysis
Farm Business Management Statewide Data
Excluding Organic & Organic Transition
(Farms Sorted By Return to Overhead)

Dairy -- Average Per Cwt. Of Milk

	Avg. Of All Farms		*Low 20%*		*40 - 60%*		*High 20%*	
Number of farms	222		44		45		45	
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Milk sold (hd)	99.59	21.27	99.71	20.54	99.70	20.75	99.52	22.04
Dairy Calves sold (hd)	0.00	0.93	0.00	0.74	0.00	1.16	0.00	1.09
Transferred out (hd)	0.00	0.25	0.00	0.36	0.00	0.19	0.00	0.23
Cull sales (hd)	0.00	1.63	0.00	1.82	0.00	1.63	0.00	1.46
Insurance income		0.17		0.05		0.24		0.17
Government payments		0.05		0.06		0.04		0.04
Other income		0.13		0.08		0.06		0.15
Purchased (hd)	0.00	-0.10	0.00	-0.30	0.00	-0.05	0.00	-0.06
Transferred in (hd)	0.00	-0.16	0.00	-0.08	0.00	-0.18	0.00	-0.03
Inventory change (hd)	0.00	0.10	0.00	-0.01	0.00	0.06	0.00	0.15
Dairy repl cost		-2.76		-3.67		-2.74		-2.53
Gross margin		21.49		19.61		21.15		22.71
Direct Expenses								
Protein Vit Minerals (lb.)	15.28	3.42	8.30	3.38	17.72	3.90	18.49	3.31
Complete Ration (lb.)	4.47	2.12	10.38	2.57	5.53	1.94	2.46	1.69
Corn (bu.)	0.28	1.21	0.29	1.26	0.29	1.22	0.29	1.28
Corn Silage (lb.)	79.31	1.76	94.87	2.09	75.90	1.73	73.37	1.73
Hay, Alfalfa (lb.)	9.05	0.69	8.38	0.67	8.95	0.71	9.06	0.63
Other feed stuffs (lb)	20.09	0.96	24.64	1.28	25.89	0.89	12.47	0.72
Breeding fees		0.21		0.27		0.22		0.15
Veterinary		0.42		0.42		0.40		0.38
Supplies		0.61		0.93		0.47		0.58
Fuel & oil		0.37		0.46		0.29		0.40
Repairs		0.89		1.11		0.88		0.81
Custom hire		0.36		0.37		0.47		0.27
Hired labor		1.59		2.01		1.78		1.02
Hauling and trucking		0.49		0.60		0.53		0.47
Bedding		0.35		0.42		0.34		0.31
Miscellaneous		0.66		1.00		0.60		0.53
Total direct expenses		16.10		18.84		16.40		14.28
Return over direct expense		5.39		0.77		4.75		8.43
Overhead Expenses								
Hired labor		0.49		0.30		0.27		0.82
Interest		0.46		0.62		0.50		0.38
Mach & bldg depreciation		0.77		0.74		0.66		0.82
Miscellaneous		1.06		1.05		0.86		1.25
Total overhead expenses		2.78		2.71		2.29		3.27
Total dir & ovhd expenses		18.88		21.55		18.68		17.55
Net return		2.61		-1.94		2.46		5.16
Labor & management charge		0.73		1.04		0.46		0.79
Net return over lbr & mgt		1.88		-2.98		2.01		4.37
Cost of Production Per Cwt. Of Milk								
Total direct expense per unit		16.10		18.84		16.40		14.28
Total dir& ovhd expense per unit		18.88		21.55		18.68		17.55
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Est. labor hours per unit		0.15		0.19		0.14		0.14
Other Information								
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Milk price / feed margin		11.20		9.36		10.42		12.79

RECEIVED
By: OAH on 7/21/2025

From: Larry M Bogolub
To: Moore, William (He/Him/His) (OAH)
Subject: Rewrite Feedlot Rules
Date: Monday, July 21, 2025 3:17:16 PM

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Mr. Moore,

his is a critical time to rewrite animal feedlot rules and stop toxic nitrate pollution in Minnesota's waters. I am concerned about the serious problems of runoff, seepage, and spills caused by animal feedlot manure.

Manure runoff in Minnesota waters results in fish kills. Swimming is unsafe due to E.coli bacteria from animal wastes. Excessive nitrates from manure result in blue-green algae blooms in shallow lakes and rivers, producing toxins harmful to wildlife and humans. Manure seeping into well water used to prepare infant formula causes methemoglobinemia (blue baby) nitrate poisoning. In recent decades, nitrate contamination of drinking water likely contributed to 24 Minnesota infant deaths.

Right now, Minnesota animal feedlot rules do not protect water, fish, wildlife or human health. I urge the MPCA to address these dangerous impacts by developing strong rules. I ask that you make the following changes to the Animal Feedlot Rules:

1. MPCA rules should require pollution permits (NPDES/SDS permits) for "Medium-sized" feedlots with 300-999 animal units–which contribute 43% of Minnesota's total manure.

2. MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits.

3. MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. It has not been shown that "stricter" requirements in existing rules prevent pollution.

4. MPCA rules should state that MPCA will enforce "no discharge" requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.

5. MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.

6. MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure

and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm.

7. Thank you for the opportunity to comment. Please protect the health of Minnesota's waters, fish, wildlife, and people from toxic nitrate pollution. We are counting on you.

Sincerely,
Mr. Larry Bogolub
2170 Passi Rd Ely, MN 55731-8135
lbogolub@comcast.net
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Comment on Planned Amendments to Animal Feedlot Rule, Minn. Rs. Ch. 7020

I am writing to ask the MPCA to do more to protect our lakes, rivers, streams, and groundwater by revising the Animal Feedlot Rule to address the crisis of nitrate pollution in our state. Feedlots are a major source of nitrate pollution in our waters, and by adding stronger rules for the handling of manure, MPCA can help ensure that all Minnesotans' water at the tap is safe to drink.

I care about this because...

Water is vitally important to all life and our existence! Protect our water!

Name: Pam Kelly

Address: 742 W. 4th St.

Phone: Winona, MN. 55987

Email: pk4peace@hbci.com

USA/POSTCARD

SWEETGUM

RECEIVED

JUL 22 2025

OAH attn: William Moore, OAH

Office of Administrative Hearings

600 N Robert St. PO Box 64620

St. Paul, MN 55164-0620

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JUL 22 2025

Office of Administrative Hearings

Share Your Story and Thoughts About MN's Animal Feedlot Rules Here:

Please Print clearly

There Are 2 MAIN issues I would cite. 1. Odor/Air pollution - there is the odor in & around the confinement building itself & that associated with failing to carefully knife in manure when spread. This is exacerbated by allowing multiple such facilities near one established homesites in a rural township. Cumulative effects need to be considered. 2. Water pollution - both surface water & well water are at issue. Manure if not properly knifed in or over applied runs into streams, killing fish & bugs. Nitrates pollute well water, especially in MN's Karst area. Also water demand for multiple CAFO's in an area overstresses water supply.

Your Name: Joe Wieners City: rural Kasson State: Mn

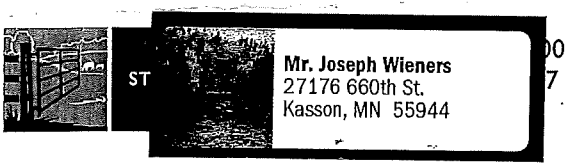

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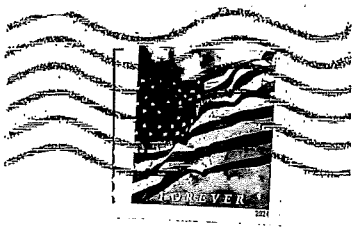

MPCA Feedlot Commentary Due July 22

The MPCA has begun the process of reviewing and potentially changing Minnesota's existing feedlot rules (MN Rules Ch. 7020, ID Number R-4928). This is the first time since 2000 that these rules have come up for review.

This comment period is open until July 22 and closes at 4:30pm. Writing a personalized comment to the MPCA before then is the best way to make your voice heard, and have an impact on the future of Minnesota's feedlot rules. Comments are being taken both online and by mail. Fill out this card and mail or you can comment online at bit.ly/feedlotcomments or at QR code below.

You can also fill out the form online here!

OAH Attn: William Moore
PO Box 64620
600 N Robert St.
St. Paul, MN 55164-0620.

55146-6000

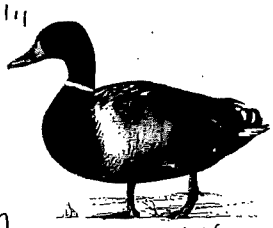

USA / FOREVER

OAH attn: William Moore, OAH
600 N. Robert St, PO Box 64620
St Paul, MN 55164-0620

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7-17-25

Dear William Moore:

Please ask the MPCA to do more to protect our lakes, rivers, streams & groundwater by revising the Animal Feedlot Rule regarding nitrate pollution. We need stronger rules to insure that MN H_2O at the tap is SAFE to drink!

Sincerely,
Patsy Gavin
PO Box 1425
Winona, MN 55987

RECEIVED
JUL 22 2025
Office of Administrative Hearings

RECEIVED
By: OAH on 7/21/2025

From: Lynette Kerce
To: Moore, William (He/Him/His) (OAH)
Subject: MPCA Feed lot comments
Date: Monday, July 21, 2025 10:00:09 PM

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Hello;
I was directly impacted by one of these Fish kills. We own land on Rush Creek just off of HW. 29 in Winona County. As I am sure you are aware, Fishing in Minnesota brings in an estimated 2.4 Billion dollars a year to state coffers. Aside from that, the animals in that stream are a wonderful biological indicator for water health. I have had several years to mull over the incident and after reading the law have some suggestions that may help to alleviate these situations from continuing to occur. They are as follows;
1) wouldn't it be easier and faster to use one set of rules for all the agencies? Unhear of you say, not so I worked on a county level to help design a water quality study that involved MPCA, MDH, Soil and water and county public health. All parties were able to use the data, all got along and it did a lot of good for the state and county.
2) I did not see anything in the law about inches of overburden, if I remember correctly that should be included when determining manure rates.
3)under the description of the protection method please describe the differences of floodplain, special protection area. It would clarify the requirements.
4)I am wondering why vegetative buffers are 100 feet for lakes, but 50 feet for streams. It seems that they may be backwards, why not have them the same. Especially in the steep valleys of the driftless area.
5) I would expect that most dairies feed a slightly different diet, there is probably a slightly different microbial profile. If that is the case then testing each herds manure a couple times a year may help the point source problem. A fingerprint so to speak.
6) I know how hard regulation is, however if you are considerate, true and educate them. You can mostly get the contractor in my case,
farmers in your,going in the same direction. You will have to do some big fines at first, but once they know you and understand you are a straight shooter, I have confidence they will come around.
Thank you for the opportunity to comment

RECEIVED
By: OAH on 7/22/2025

From: Jan Blevins
To: Moore, William (He/Him/His) (OAH)
Subject: Comment on Planned Amendments tp Rules Governign Animal Feedlots Minnesota Rule Chapter 7020 Revisor ID @R-04928
Date: Tuesday, July 22, 2025 8:13:57 AM

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Please share these comment with the appropriate staff as we discussed since I am unable to access your server. Thank you.

As a small organic farmer and a member of the Concerned Citizens of Olmsted CountyI have the following comments.

1. Do not permit any manure storage pits or holding tanks that would be separate from the source where the manure is produced
2. Do not permit manure storage that is near a quarry that is or may be actively dynamiting to get to more gravel or rock access

A. If these are permitted the result of such action could be a major loss of manure into our streams, lakes, and aquifers.The containment loss could ruin our recreational swimming, drinkable water supply, and kill fish in our streams.

B. Locating a manure storage away from the source manure means that private citizens that do not gain any profit from the farming operation have to see their property values reduced, their quality of life in their home jeopardized,bacteria contamination in the air they breath and the obnoxious smell to deal with.

3. Drag lines that are used to transfer manure must be emptied after each transfer to fields so they do not burst under pressure and contaminate the soil and groundwater, Some of these drag lines are 5 miles long and they have no secondary containment and hold tons of manure.Drag lines must be inspected prior to any use.
4. Owner of manure will be designated as the responsible party and not defer the responsibility to the applicator. As any other industry the farm industry should be held accountable for the pollution from cradle to grave.
5. Polluter pays for loss of property value, loss of drinkable water,all fish kill restoration any harm they have done to adjacent or non adjacent property owners impacted such as trees killed, loss of revenue for parks that have to shut down because of pollution to their recreational facilities and proven health effects to the citizens that have their health has been negatively impacted.
6. Citizens with complaints of fields that look like lakes after manure has been applied should not just be dismissed when they call the hotline. They should be listened too and action taken by the MPCA
7. All manure storage should have monitoring wells,covers to contain bacteria from getting into the air and at the very least annual inspections. Field tile outlets should have water tests to measure nitrates and other contaminates leaving the field.. An allowable limit should be agreed upon and if surpassed the perpetrator should be heavily fined.

Respectfully submitted by Jan Blevins

Olmsted County Concerned Citizens

RECEIVED
By: OAH on 7/22/2025

The Minnesota State Cattlemen's Association (MSCA) is a membership-based organization representing cattle farmers and individuals who are part of the cattle community in Minnesota. We represent nearly 1,000 members in the state of Minnesota.

Our members are aware of the importance of caring for the land and water, as these resources are crucial to the success of their farm or ranch. The MSCA does not feel that new and increased rules and regulations for feedlots in Minnesota will improve land and water quality, rather they will put family farms out of business. In Minnesota, there are over 18,000 beef farmers, and 97 percent of these farms are family owned and managed, according to the Minnesota Department of Agriculture.

These family farms go above and beyond to protect natural resources and with the help of technology, farmers continue to find new ways to increase production while decreasing inputs and giving back to the land. Often, farmers and ranchers do everything in their power to pass on their land to the next generation, that is what this industry is all about.

Manure is not waste to beef producers, it is valuable. Producers do not want to overspread or overuse manure. Instead, they use best management practices (BMPs) to apply during the correct conditions and apply the correct amounts. This practice is best for the farmer and for the soil. Farmers and ranchers ensure they are protecting lakes, rivers and streams through the state buffer law which is reported to have 99 percent of Minnesota farmland compliance. Farmers have also shown their dedication towards protecting water through enrolling over 1.1 million acres in the Minnesota Department of Agriculture's voluntary Ag Water Quality Certification program.

Many farmers have also taken part in cost-share programs to increase practices such as cover crops and feed efficiency and purchase or upgrade soil health equipment. Beef producers take the correct steps to ensure proper manure management, storage and application methods are being followed as well.

The MSCA supports increased education for feedlot owners and operators. We feel there are currently ample rules in place governing feedlots in Minnesota, there just needs to be increased education on these rules and BMPs.

The MSCA does not support lowering the 1,000 AU threshold for NPDES/SDS permits. We instead strongly urge the MPCA to structure the rule review process to protect and improve water quality while keeping livestock farms of all sizes viable and prosperous. Requiring NPDES/SDS permits for operations under the 1,000 AU threshold will likely make it increasingly difficult for farms to stay in business due to the lengthy and expensive NPDES/SDS permitting process. Many of these farms are operated by one or two family members that do not have the means to hire contracted services to accurately submit and maintain permitting status.

The MSCA is concerned with additional restrictions on manure application rates. The University of Minnesota Extension provides guidelines for manure application rates in Minnesota, emphasizing the importance of balancing nitrogen and phosphorus needs for optimal crop growth and minimizing environmental impact. These application rates are backed by science and should be followed. We are also concerned with restricting farmers from spreading manure in certain areas of the state. Again, manure is a valuable nutrient, not waste, and many farms do not have enough storage for this to be an option. Manure storage is expensive, and many farmers do not have the resources to increase manure storage.

The MSCA does not support enhanced manure management planning and record keeping requirements for transferred manure from feedlots. This devalues manure and will lead to an increase in commercial fertilizer usage.

The MSCA supports 7020 rules being practical for every size feedlot in the state and for the rules to serve as the baseline for all feedlots in the state. We feel that flexibility is key with any changes made

to the rules. Farmers need options for BMPs so they can choose which best fits their operation. Not every BMP will work well for each farmer, but it is important they are given options.

Sincerely,

Kaitlyn Root
Executive Director
Minnesota State Cattlemen's Association
(763) 479-1011
kaitlyn@mnsca.org

RECEIVED
By: OAH on 7/22/2025

From: carneson@frontiernet.net
To: Moore, William (He/Him/His) (OAH)
Subject: Feedlot regulations
Date: Tuesday, July 22, 2025 3:52:32 PM

[You don't often get email from carneson@frontiernet.net. Learn why this is important at https://aka.ms/LearnAboutSenderIdentification]

This message may be from an external email source.
Do not select links or open attachments unless verified. Report all suspicious emails to Minnesota IT Services Security Operations Center.

My father grew up on a farm, I grew up on a farm.

Farming was once done in environmentally sustainable ways, both in how crops were rotated to let the soil recover, and in protecting runoff by using buffer zones and tree cover along fence lines. That ethic is essentially gone with the advent of so-called factory farms. Our waters are taking the hit in multiple ways.

Feedlots are one of those ways.

"MPCA rules should require pollution permits (NPDES/SDS permits) for “Medium-sized” feedlots with 300-999 animal units–which contribute 43% of Minnesota’s total manure.
MPCA rules should set a maximum limit on the size of any single feedlot and a maximum limit on the number of animal units in any local area or watershed. Hydrology and effects on both ecosystems and human welfare should be used to determine maximum limits. Existing rules do not prohibit feedlots even in the most sensitive karst regions where groundwater is most vulnerable.
MPCA rules should prohibit new or expanded animal feedlots in karst geology where groundwater is most vulnerable to seepage pollution. Groundwater contamination cannot be remedied, and it has not been shown that “stricter” requirements in existing rules prevent pollution. In addition, despite 15 years of technical evidence, no MPCA rule limits nitrates to protect fish and sensitive aquatic life.
MPCA rules should stop merely trusting that animal feedlots and manure applications are “no discharge” facilities. The permits should require regular monitoring and reporting of surface water and groundwater pollution levels both at the feedlot and on the fields where manure from that feedlot is spread.
MPCA rules should state that MPCA will enforce “no discharge” requirements, compliance with all pollution limits, reduction of contamination in impaired (already polluted) waters, and prevention of degradation in waters that are not polluted.
MPCA rules should strengthen minimum technology requirements for all permitted animal feedlots based on modern liner systems and leak detection. Rules should not assume that concrete or compacted soils containing manure will prevent seepage and discharge.
MPCA rules should prohibit application of manure, whether wet or dry, in the winter. Existing rules fail to consider the unpredictable snow, freeze, and melt conditions resulting from climate change that increase winter runoff.
MPCA rules should require feedlots to demonstrate that they comply with air quality rules at least 344 days a year (Minnesota statutes only exempt feedlots from compliance when removing manure and for 21 or less cumulative days per year). Exposure to noxious air emissions, like hydrogen sulfide has adverse health effects, including respiratory and neurological harm."

RECEIVED
By: OAH on 7/22/2025

DEPARTMENT OF HEALTH

Protecting, Maintaining and Improving the Health of All Minnesotans

July 22, 2025

Office of Administrative Hearings
Attn William Moore, OAH
600 North Robert Street, PO Box 64620,
St. Paul, Minnesota 55164

Dear Mr. Moore,

The Minnesota Department of Health (MDH) would like to provide MPCA suggestions and comments for consideration in the revision of Minnesota Rules Chapter 7020 regulating animal feedlots.

The mission of MDH is to protect, maintain and improve the health of all Minnesotans. One key approach in carrying out this mission involves protecting and safeguarding water resources used for drinking water supply. MDH is responsible for implementing programs under the federal Safe Drinking Water Act and plays a key role in providing the state response to nitrate contamination of groundwater supplying private wells in southeast Minnesota.

MDH also recognizes that agriculture, including animal feedlot and livestock operations provide significant economic benefits for the state. While we desire such operations to be financially successful, we also need them to be environmentally sustainable. There are known risks in such operations. Our comments focus on opportunities and regulations that support opportunities to improve management of feedlots and manure that will minimize impacts on vulnerable drinking water resources and protect public health.

Our three priority resource concerns focus on and include:

1) **Management and placement of feedlot sites and application of manure in Vulnerable Drinking Water Supply Management Areas (DWSMAs).** The MDH Source Water Protection (SWP) Program assists public water suppliers in delineating and assessing the vulnerability of their DWSMAs. These water supplies are susceptible to land surface contaminant sources such as feedlots, manure and other nonpoint and point source threats. There are approximately 240 community water supply systems that are considered to have vulnerable aquifers or rely on surface water sources
2) **Vulnerable Groundwater Areas.** Due to the geologic conditions in some parts of Minnesota, groundwater is particularly vulnerable to land use activities such as in Southeastern Minnesota. In addition to public water supplies, MDH has been a partner in addressing nitrate contamination concerns in SE Minnesota. As a result, MDH would request similar consideration be given for manure and feedlot management in these areas to reduce manure and feedlot impact on private wells and groundwater resources in vulnerable areas. The MPCA Feedlot General Permit Vulnerable

Groundwater Areas - Overview website is a State wide tool that should be used to protect vulnerable groundwater areas as part of the implementation of MPCA Feedlot Rules 7020 and manure management efforts in the State. MDH supports the use and application of the tool as part of MN Rules Chapter 7020.

3) **Community public water supply systems that rely on surface water as their source of drinking water.** Similar to Vulnerable DWSMAs, delineated-State approved Surface Water (SW) DWSMAs are developed and approved by MDH for public water systems using surface water. Similar restrictions in the construction and restrictions on manure application should be considered in these areas given the immediate impact that can result from feedlot management and manure application. There are 23 community public water suppliers in the State. MDH can provide the latest source water assessment information for each surface water public water supply system.

Vulnerable DWSMAs and *Vulnerable Groundwater Areas* of the State should be defined and identified in the revised 7020 Feedlot Rule. In relation to the priority resource concerns identified above, considerations and changes to the rule should include:

a. **Include the same requirements found in the State Feedlot NPDES permit for all feedlots for the fall application of manure in a vulnerable DWSMA.** MDA is responsible for implementing the Groundwater Protection Rule for commercial nitrogen fertilizer. Conversely, MPCA Feedlot rules should prioritize and require more compliance monitoring and enforcement for the application, proper crediting and agronomic rate for manure application in Vulnerable DWSMAs working with delegated feedlot counties.
b. **Include the same requirements found in the 2025 Feedlot NPDES permit for the fall application of manure in MN Rules 7020 for feedlots greater than 300 animal units located or applying manure in a vulnerable groundwater area.** Greater awareness and broader recognition by feedlot operators of all sizes is needed to reduce nitrogen impacts from both commercial and organic forms of nitrogen. Recognition locally of vulnerable groundwater areas and enhanced manure management techniques such as the use of cover crops and other practices is needed to reduce N loss to groundwater.
c. **Provide training, new technology and the resources necessary to support delegated feedlot counties monitor and verify compliance with new feedlot rule requirements**. Target and prioritize monitoring and compliance in Highly Vulnerable DWSMAs and Vulnerable Groundwater Areas based on public health concerns from potential virus and nitrate contamination risks to drinking water resources. Provide tools or a web application that allow for better tracking, review and sharing of manure application data within High Vulnerable DWSMAs and Vulnerable Groundwater Areas of the State.
d. **Clarify and refine language in MN Rules 7020 that a new feedlot shall be a minimum of 1,000 feet from a public water supply well located in a Vulnerable DWSMA.** Work with MDH to clarify and improve some of the nomenclature used in MN Rules 7020 to ensure consistent use of terms and definitions are used between State agency programs.
e. **Require the new or expanding feedlots between 300 – 1000 animal units located within a Vulnerable DWSMA, vulnerable groundwater area or Surface Water DWSMA**

be required to have 9 months of manure storage capacity. In order to properly manage manure adequate storage is essential to being able to apply manure at the right time and rate.

f. **Restrict the construction of a new feedlot or manure application within the emergency response area of a Surface Water DWSMA.** MDH would like to explore with MPCA options for restrictions in the delineated SW – DWSMAs. Of particular concern is construction and manure application within the Emergency Response Area (ERA) that is closest to the intake (8 hour time of travel) and the spill management area (24 hour time of travel area).

g. **Clarify the language and use of an interim permit to correct a feedlot permit deficiency or pollution problem in a Vulnerable DWSMA.** It is not clear how and when an interim feedlot permit would be used to correct a deficiency in the existing rule in a DWSMA. Consider rule language or clarify in the rule how a manure management plan or feedlot permit would be modified or changed to address a pollution problem that impacts waters of the State, vulnerable groundwater areas or priority public drinking water sources that have been identified.

h. **Require all feedlots larger than 10 animal units be identified and registered in a vulnerable DWSMA.** Small feedlots improperly operated or managed can have impacts on public drinking water supplies.

i. **Require training and licensing of commercial manure applicators.** Ensure that training includes specific responsibilities and liabilities in terms of manure application requirements identified in Feedlot Rules Chapter 7020.

j. **Provide clear definition of manure ownership in Chapter 7020 including transfer of manure and timing of other entities responsibilities for application and management.** Apply similar language and restrictions in Chapter 7020 for manure ownership and transfer for feedlots between 300 and 1000 animal units.

k. **Include similar cover crop / perennial requirements, application timing in the fall and manure application restrictions defined for Vulnerable DWSMAs, SW – DWSMAs and vulnerable groundwater areas for feedlots between 300 and a 1000 animal units similar to the language included in the revised NPDES General Permit for feedlots over 1,000 animal units.** This provides some level of equity, fairness and consistency in the implementation of best practices that allow for the protection of groundwater, surface water drinking water resources.

l. **Work with MDA, MDH and MGS in the consistent use and maintenance of a vulnerable groundwater areas of the state website**. Presently, MDA and MPCA maintain two separate websites that depict vulnerable groundwater areas related to commercial fertilizer and manure. Explore the option to have one website that would make it easier for agricultural producers and government entities to use. See website Fall Nitrogen Fertilizer Application Restrictions (2024) (arcgis.com)

m. **Work with MDA to have a common website where growers can go to find nitrogen restrictions from both commercial and livestock fertilizer sources to protect vulnerable groundwater areas from nitrogen loss to groundwater.**

MDH would like to work closely with the MPCA to ensure protection of public drinking water sources and private wells through ongoing discussions regarding feedlot permitting of large and small facilities, manure management best practices, compliance monitoring and enforcement of permitted feedlots.

MDH wishes to encourage thoughtful consideration of drinking water resources and public health protection as part of updating the Feedlot NPDES General Permit. Thank you again for the opportunity to provide comments. Feel free to contact me at (651) 201-3724 or Chris.Elvrum1@state.mn.us if you have any questions regarding this letter.

Sincerely,

Christopher Elvrum, Manager
Drinking Water Protection Section
Minnesota Department of Health
PO Box 64975
St. Paul, MN 55164-0975

CC via email:
Tom Hogan, MDH Environmental Health Division
Steve Robertson, MDH Drinking Water Protection Section
Tannie Eshenaur, MDH Water Policy Center
Mark Wettlaufer, MDH Source Water Protection Unit

RECEIVED
By: OAH on 7/22/2025

P.O. Box 6275
Rochester MN 55903
22 July 2025

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OAH600 N Robert St.
PO Box 64620St. Paul, MN 55164-0620
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The Minnesota Well Owners Organization
Comments on Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, chapter 7020, Revisor's ID Number R-04928

The Minnesota Pollution Control Agency (MPCA) requested comments on amendments to Minnesota Rules Chapter 7020 (Animal Feedlots), referred to as the Animal Feedlots Rule. The rulemaking is intended to address changes in livestock and poultry operations and business practices, account for new agency data services, modernize outdated rule language, amend existing Animal Feedlot Rules to improve land application of manure practices to address nitrates, bacteria, and fish kills, and establish additional technical standards to protect water quality and avoid fish kills.

Minnesota Well Owners Organization (MNWOO) is a nonprofit corporation created to provide education, technical and legal services, and advocacy to those who own and who rely on private wells for their drinking water, and to preserve, protect, and restore the quality and quantity of Minnesota's water resources and to ensure the safety of those who use them.

MNWOO submits the following comments.

General Comments

How do the Animal Feedlot Rules address climate change and what are effects of feedlots on the increase or decrease of carbon in the atmosphere and on the land? How can these effects be mitigated?

Given the reasons given above for the planned amendments to the Animal Feedlot Rules and concerns for human and animal safety, damage to the geography, land, soil, water, MNWOO questions the necessity for feedlots. MNWOO poses the possibility of banning feedlots altogether.

Strengthening the Animal Feedlot Rules is critical to transition from a reactive approach that addresses pollution after it occurs to a proactive one to prevent pollution by recognizing and protecting Minnesota's Nature, Air, Water, Land, its cultivated soil, its people, and the animals in the feedlot.

In general, the MPCA should undertake and formulate detailed health risk assessments and drinking water safety plans to address the tangible and ongoing threats from widespread nitrate contamination of drinking water resulting from feedlots. The health risk assessments and the drinking water safety plans should focus specifically on each township, each Drinking Water Supply Management Area, and each watershed. Public health risks need to be considered by accounting for manure and commercial fertilizers and damage to the environment and for all facets connected to feedlot operations.

MPCA should incorporate the Safe Drinking Water Act's, 42 U.S.C. §300f et seq., principles of coordination with other Minnesota regulatory agencies, communication, well testing, alternative water supplies, risk assessments, and long-range source water protection. These principles should be cited and woven into the fabric of the Animal Feedlot Rules. Thus MNWOO urges MPCA to actively reach out and coordinate with other state agencies including but not limited to the Minnesota Department of Natural Resources (MDNR), Minnesota Department of Health (MPH); Board of Water and Soil Resources (BWSR), the Minnesota Department of Agriculture (MDA), the Minnesota Department of Transportation (MDOT), the Minnesota Attorney General, pertinent Federal agencies, affected Indian Nations when promulgating the Animal Feedlot Rules and other rules.

MNWOO recommends that citizen complaints, MPCA investigations and responses be publicly available. For example, citizens with complaints about fields that look like lakes after an application or applicators applying in the middle of the night while it is raining should be followed up and not ignored by MPCA.

Summary of General Comments
•Address Climate Change
•Consider Banning Feedlots
•Be Proactive, not reactive
•Protect Surface and Ground Waters
•Coordinate and cooperate with federal, Indian, and other state agencies
•Be more responsive to citizens

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Polluter Pays

The "Polluter Pays" principle is a widely accepted environmental and financial tenet. If a private business, regardless of sector, causes harm to public resources or private property, such as odor, other nuisance, land values, the polluter should bear the cost of remediation and compensation. The financial burden of environmental damage and community impacts from feedlots should not be borne by the public and affected individuals but should be pushed back to the polluting entity. This prevents the externalization of costs onto taxpayers and affected communities.

Animal feedlots and Confined/Containment Animal Feeding Operations (CAFOs) are point sources of pollution, and are private businesses. They should play by the same rules as every other business if they pollute waters of the state. Studies have consistently shown that feedlots can negatively impact nearby property values because of, at the very least, odors and aesthetic concerns. Additionally, the heavy truck traffic associated with large feedlot operations can cause significant damage to rural roads, imposing substantial repair costs on local governments and taxpayers. Polluters, i.e., the feedlot owners and sponsors, should thus be accountable and compensate for loss of property value, unsafe drinking water, fish kill restoration, harm to adjacent property owner such as dead trees, parks that lose revenue because the recreational waters were polluted, replacement of wells or added systems to make water drinkable. The feedlot owners and their sponsors, moreover, should resolve and mitigate the reason for any pollution. Holding operators accountable for these documented impacts ensures that the full societal costs and consequences of their operations are recognized and addressed.

Placing the financial liability for pollution and community impacts on the feedlots and their sponsors, moreover, creates a strong economic incentive for feedlot operators to invest in the best available technologies, implement stringent management practices, and choose locations that minimize harm.

Summary of Polluter Pays
•Make the feedlot owner and its sponsor/contractor pay for any and all damage and pollution

Definitions

Given that there the Animal Feedlot Rules are intended manage the feedlots, MNWOO asks for clarity of definitions. What is a feedlot? Does the definition include all animals that are confined - beef cattle, dairy cattle, swine, poultry, fish, sheep, goats? What animals? What does "confined" mean - how much space does an animal not have? How many animals?

MNWOO recommends that the Animal Feedlot Rules discontinue the use of the phrase "animal units." The use of the word "units" robotizes living creatures that have awareness, suffer, have feelings for families, have empathy. Count the living animals, not "units" for consumption and profit. The people of Minnesota ask that the Animal Feedlot Rules consider the health and well-being of the animals; not just the profit for the feedlot owners and their corporation sponsors/contractors for confining and slaughtering *animal units*.

Summary of Definitions
•Number of animals
•Species of animals
•Space requirements for animals
•Animals are not UNITS

Feedlot Permit Applications

A paramount goal of the Animal Feedlot Rules should require applicants for a feedlot permit to inform themselves and the public of potential environmental and health and safety risks from feedlot operations and manure storage and use.

Require the feedlot permit applicant to disclose the number and location of other feedlots owned or leased by or under contract to the applicant. Currently, an owner of multiple feedlots, even feedlots right next to each other, can evade regulations by applying each feedlot as a "separate" operation, though the total pollution is the same as a large feedlot.

Require the feedlot applicant to disclose if it is under contract with a larger supplier to produce, feed, provide animals and the terms of the contract, such as whether specific sources of animals, specific food and nutrients, specific veterinary services, specific slaughter houses, etc.

The principles of coordination with other Minnesota regulatory agencies, communication, well testing, alternative water supplies, risk assessments, and long-range source water protection should be cited and woven into the fabric of the permit application and its manure management plan. The permit applicant should be required to coordinate with federal, Indian, and state agencies regarding the potential effects on wildlife, nature preserves, fish, ground and surface water, air quality including odor, noise, local water planning, use of agricultural and biological chemicals, etc.

MNWOO earnestly recommends that the MPCA adopt a policy that declares confined animal feeding operations be declared “a polluting enterprise” that must demonstrate new and improved controls before qualifying for permits. This would in effect, place the industry representatives (permit applicants) on their proof that they have addressed risks and have means to manage the risks and solve the heretofore unsolved problems associated with this enterprise. To provide this "proof" the plans and specifications for new or expanding animal feeding operations should be required to be prepared by qualified and experienced licensed engineers and hydrologists familiar with confined/concentrated animal feeding operations and other feedlots. The licensed professionals responsible for the siting and design of these operations should be required to affirm that the manure management plans and safety water plans and specifications they submit will "prevent, control or abate" pollution that may be shown to be or have been originating from the operation. This is not an unusual hardship on even the smallest feedlot operation considering that individual homeowners in rural areas of Minnesota are required to have licensed professionals design and install on-site sewage treatment and disposal systems that are reviewed by qualified professional in permitting units of government.

The permit application should also discuss the contributions of the proposed feedlot to climate change and mitigation thereof.

Prior to or as part of a permit application under the Animal Feedlot Rules, an applicant should be required to submit, as an integral part of the permit application, an assessment of the site's existing conditions and surroundings as well as the available data on trends in the area’s water quality, air quality, and ecological and biological integrity. For feedlots, the risk factors are well known and can be mapped, tabulated, and summarized using fundamental tools like the USDA Web Soil Survey Suitability and Limitations maps, the County Geologic Atlas and Hydrologic Atlas plates, the MPCA Watershed Assessments (Stressor Analysis, WRAPS and GRAPS), local One Watershed One Plan (1W1P) plans, the Ag Department Runoff Forecast Advisory, MDNR Explore Watershed Health website, and the University of Minnesota Natural Resource Atlas website. and other peer-reviewed risk assessment maps. (*See* Appendix I for list of pertinent maps.)

The permit application must delineate the risks by location and activity, and prepare a risk management plan for each feedlot and each manure spreading field. If the potential risks are not avoided, the applicant should describe a response plan, a receptor survey, and a mitigation plan.

MNWOO advocates that MPCA require a standard set of risk assessment tools, maps, and strategies already adopted across the State. A standard set of risk assessment maps would eliminate many errors and omissions from the applicants and the Regulating Government Units (RGUs). As part of the standardized permit application, the prospective feedlot operator should delineate the risks of feedlot operation and include how such risks will be managed and how the operator will engage the community, government decision-makers, and permitting agencies of the tools to control significant environmental effects, as well as the project location, purpose, design, construction, and operations. By requiring complete transparency about known and probable risks, applicants are better prepared to manage the risks, the public is better informed, and permits and regulations can be applied to protect the health, safety, and welfare of all Minnesotans.

MNWOO can offer a template for assessment and management of these risks, such as nutrient runoff, leaks and spills, infiltration of pollution in groundwater and drinking water, odor and noise from feedlots, ecological and biological harm such as fish kills and deforestation, destruction of native environments, community and land use impacts.

Each feedlot permit application should develop a water safety plan based on groundwater testing and source water protection. The feedlot permit should assess feedlot and potable water well risks on abutting property. The water safety plans should define the risk, the appropriate risk managers, and the plans to ensure drinking water quality. The water safety plan of the permit application should identify local private wells, water systems, and drinking water quality.

The permit applicant should also acknowledge the 1W1P applicable to the watershed in which the feedlot will be located. These plans are often exhaustive but rarely followed, even as they promise that local efforts to implement protection, enhancement, and restoration strategies can be successful.

Summary of Feedlot Permits
•Identify multiple feedlots of same applicant
•Identify sponsor/contractor for whom feedlot owner is providing animals
•Feedlot owner coordinate with other federal, Indian, and state agencies
•Assessment of existing conditions
•Standardize feedlot application to address climate change and mitigation
•Standardize feedlot application to include risk management plan
•Standardize feedlot application to include water safety plans

Water Appropriation Permits

Minnesota's aquifers are a shared public resource. Large-scale feedlot operations, especially those with many animals can have substantial water demands for drinking, waste flushing, and cooling. Excessive groundwater pumping can lead to aquifer drawdown, impacting other well users nearby, increasing pollution infiltration rates, and potentially altering groundwater flow paths, e.g., in the karst region of southeastern Minnesota and the central sands.

Limiting annual water appropriations for large feedlot operations, such as limiting the size of a well and the volume of water to be pumped, ensures the sustainable use of groundwater for the larger impacted region, prevents excessive drawdown that depletes aquifers and impacts domestic wells, municipal water supplies, and connected ponds, wetlands, creeks, streams, rivers. Limiting groundwater appropriation ensures that large industrial agricultural operations contribute to the responsible management of water resources, just as other large water users are regulated. It encourages water conservation practices within feedlot operations.

Because of local surface water impairments and the existing trends in groundwater quality in shared underground drinking water sources, the feedlot permit application should review and cite existing and proposed water appropriation permits, or the lack of permits, and annual water use reports. For existing, re-permitted, and new applicants, disclosure of water appropriation permits, permit compliance records and links to pump tests should be required.

Water quality assessments of wells and aquifers in the area that are likely to be impacted should be documented from data available from the MDA Township Testing Plans or the MDH new well testing, or the local/regional testing programs. The appropriate maps and their applicability to the feedlot operation should be discussed in the permit and annually after a feedlot permit has been granted . To show whether or not surface or groundwater pollution is or has been originating from an animal feeding operation the feedlot should be required to submit pre-construction (for new or expanding operations) monitoring data from representative locations in the water table or aquifer both upstream downstream of the feedlot, as well as annual reporting requirements on groundwater quantity and quality.

Many smaller farms are not required to obtain water appropriation permits. Any farm with over 200 animals should have a water appropriations permit unless pumping data shows less water use.

All manure storage and field tile of existing or proposed feedlot operations should be monitored by monitoring wells and testing field tile outlets for nitrates and other agricultural contamination, such as phosphorus, pesticides, fungicides, biologics, etc. Plans for the groundwater water quality monitoring regime should be submitted to the MPCA for prior approval before the monitoring system is put into operation. The plan should include the professional hydrologist's opinion on whether the existing pre-construction water quality condition will be adequately characterized by the sampling locations, frequency and duration of sampling and the parameters to be monitored. Parameters to be monitored should reflect not only the nutrient and microorganisms that could be discharged from the facility but all other "pollutants" used at the facility relating to the feeding and raising animals.

If pre-construction monitoring demonstrates that an existing animal feeding operation owned and or operated by the applicant has already contributed to surface or ground water pollution, the prospective permittee must submit a remedial action plan to be approved by the MPCA. This remediation plan should be successfully implemented before new or expanded animal feeding operation can be permitted. Here, successfully implemented would mean the pollution levels are reduced to comply with applicable surface or groundwater standards.

Summary of Water Appropriation Permits

•Groundwater is public
•Assess existing water quality and quantity
•Require disclosure of water appropriation and compliance thereof
•Limit water appropriation if Nature and others impacted
•Require/establish monitoring wells and pump reports

Manure Storage

Applicants should submit the maps and address how the feedlot and manure storage will avoid, control, and mitigate the risks.

MNWOO advocates to restrict Liquid Manure Storage Areas (LMSAs) to smaller 250,000 gallon cells, within geologically or environmentally sensitive regions. This directly addresses the risk of catastrophic failure of LMSAs in highly vulnerable karst, central sands, and near recreational areas, rivers, lakes, and other locations where a rapid loss of stored manure can have devastating, immediate, and widespread environmental and health consequences both above and below ground.

While sinkholes or liner failures cannot be entirely prevented, limiting the volume of individual cells within a manure containment area dramatically reduces the magnitude of pollution released in a single event. A 250,000-gallon spill, while still serious, is significantly more manageable and less environmentally damaging than a multi-million-gallon release. Smaller spills are more amenable to rapid containment and remediation efforts, reducing the spread of contaminants into the broader environment and aquifers.

Geologically and environmentally sensitive regions, like the vulnerable groundwater area, drinking water supply management areas, near recreational and natural preservation areas, may pose higher risks wherein the consequences of a large-scale failure are most severe due to direct aquifer connectivity. This limitation of the size of manure storage ponds prioritizes the protection of vital drinking water sources. In Minnesota the line between groundwater and surface water is not always distinct, as in karst geology, and such failures of manure storage ponds have had and can devastate trout streams which are of huge importance to the local economy and environment.

Manure should be stored near the manure source. While the manure source owners are gaining financially so that they and the animals need not endure the smell and pollution of a feedlot, property owners near the manure storage are the ones who endure the consequences of manure storage, e.g., lower property values, reduction of quality of life on their property they own, polluted wells and unsafe drinking water, pollution of creeks and streams they may swim in or use for recreation, fish that are unsafe to eat. For example, a manure storage is being proposed near a quarry that dynamites often; this should not be permitted because if there is a loss the overflow from rain or if the storage pond is compromised, the manure would flow into Chesterwood Park where kids swim and adults recreate. This is not acceptable. Plan ahead for possible risks to health.

All manure storage should have secondary containment and covers to prevent leakage and bacteria to the air.

Summary of Manure Storage
•Risk assessment and mitigation
•Smaller capacity
•Restrict in vulnerable geologies and geographies
•Store manure by its source
•Secondary containments

Manure transfers

Under the existing Animal Feedlot Rules, transferred manure is exempt from tracking. So the application location, rate, and date of transferred manure are unknown. When manure is transferred by a feedlot owner/operator for application to the land by someone else, MNWOO advocates that the transferee adhere to the requirements in the manure management plan. Tracking requirements of transferred manure should be established and enforced.

Drag lines that are used to transfer manure to fields must be emptied after use. They have no secondary containment if they burst from the pumping pressure. Some of these drag lines are 5 miles long you can imagine the amount of manure they hold. Drag lines should be inspected by independent agency. Drag lines should be inspected.

Summary of Manure Transfers
•Regulate
•Include in manure management plan
•Inspect drag lines

Manure application to land

Manure applications are one of only a few agronomic practices the farmers can use to improve their soil quality and build organic matter. Nutrients and microbes contained within manure can feed a nation if they remain on or and within the soil on a farmer's field; those same nutrients is misapplied or over applied can move to nearby streams or rivers and poison all the aquatic life therein and thereby eutrophy whole river systems and estuaries, and contaminate the groundwater used for drinking of nearby residents for generations. The necessity of strictly regulating manure storage, handling, and applications practices has been brought about by the many failures of farmers to keep manure on their fields.

Best Management Practices are voluntary, as is certification in the Minnesota Agricultural Water Quality Certification Program (MAWQCP). Documentation of the Best Management Practices (BMPs) for runoff and infiltration should be mandatory. Practices associated with BMPs and MAWQCP should be mandatory and monitored to ensure compliance. Field audits under Minn. Stat. §103H.151, subd. 4 should be mandatory for all feedlots and agricultural operations.

Farmers apply nitrogen from various sources (synthetic fertilizers and manure). If only one of these sources is accounted for, the total nitrogen load applied can still significantly exceed crop needs, leading to leaching. To truly manage nitrogen effectively and prevent excess, multiple forms of nitrogen entering the soil system must be accurately quantified. All Nitrogen sources must be considered in nutrient management plans (not solely manure, nor just synthetic fertilizers). By comprehensively accounting for nitrogen sources, nutrient management plans can ensure that the total available nitrogen aligns more precisely with crop requirements, minimizing any surplus that is highly prone to leaching, particularly in karst areas. This ensures that the environmental impact of nitrogen is considered holistically, promoting a more responsible and sustainable approach to nutrient use that directly benefits groundwater quality. Drinking water supplies will be better protected as well.

Set stricter limits on manure application to farm fields in townships wherever the nitrate concentrations in ground and surface waters are above background levels, and especially in vulnerable groundwater protection areas, drinking water supply management areas, recreation areas, near protected wildlife and nature preserves.

Require all feedlots, regardless of whether having a NDPES/SDS permit, to prepare a manure management plan and maintain land application records, and submit these to the MPCA and county feedlot pollution control officer. By rule, MPCA should require all livestock and poultry operations to submit site-specific designs that take into account the unique natural or humanly-altered features of a proposed feedlot and accompanying manure application location. MNWOO and the Isaak Walton notes that animal feeding operations at or below 100 animals in high risk locations have been found to be major sources of pollution.

All permitted feedlots should be required to monitor not only manure application rates but both surface and subsurface discharges of specific pollutants associated with animal manure and other polluting chemicals and biologics associated with feedlot operations. Monitoring for nitrates alone is not enough and parameters such as bacteria and biological oxygen demand (BOD) for surface discharges for example, should also be required. Rates of manure application should be dictated by the site-specific character of the lands used for manure disposal from each permitted facility. Determining the need for additional restrictions on manure application are again, site specific and should be proposed for each unique facility by licensed engineers and hydrologists who are experts at manure management for water quality protection purposes.

Establish stricter manure land application requirements and lower manure application rates. These requirements include requiring conservation practices like cover crops or diversified crop rotations if a farmer applies manure in the fall, and no liquid manure application to frozen or snow-covered ground. Manure application rates must not be allowed to exceed the agronomic rate, especially in Vulnerable Groundwater Areas.

Land application of manure in areas that already have high levels of nitrates or other pollutants associated with feedlots in either surface or groundwater should not only be more restrictive, manure application should be prohibited in areas until remedial actions are successful at reducing these levels to a predetermined point. The term "high levels" are parameter specific and needs better definition. Nitrates above the background level of 3 milligrams per liter (mg/l)

should trigger groundwater monitoring and private well testing thus accounting for the lag time between a pollutant's discharge and its detection in receiving waters by monitoring.

Agronomic rates for manure applications should be customized for particular soil and geological types, highlighting sensitivity to nutrient-loss. The current understanding of "agronomic rate" often focuses solely on maximizing crop yield, which has demonstrably led to excess nutrient application and subsequent nitrate leaching into groundwater. This issue is critically amplified in karst regions where there is little natural filtration.

Different soil types (e.g., sandy vs. clayey) and underlying geological formations (e.g., fractured limestone vs. thick till) have vastly different capacities to retain or leach nutrients. A "one-size-fits-all" agronomic rate fails to account for this variability. Customizing application rates based on nutrient-loss sensitivity means applying only the amount of nutrients the crop can realistically utilize, given the soil and geological context. This minimizes the "excess" nitrogen available for leaching, directly reducing the load on vulnerable aquifers. Both manure and fertilizer applications need to be customized. While initially perceived as a burden, more precise nutrient management can reduce input costs over time by preventing the waste of expensive fertilizers that are simply lost to the environment. It shifts from "insurance" application to "precision" application.

Summary of Manure application to land
•Regulate more vigorously
•Conduct Field Audits
•Consider all nitrogen sources
•Restrict when nitrate and other chemicals levels are above background levels
•Require NDPES/SDS permit
•Require manure management plan and compliance thereof
•Maintain application records - when, where, how much, who

Locations and Setbacks

MNWOO notes that setbacks from any and all surface waters should also be determined on a case-by-case basis because a setback that may function well in one location may be inadequate for others depending on slopes, ground cover, soil types and other site-specific characteristics. MNWOO, nonetheless, advocates for greater setback distances for manure applications and manure storage ponds from water resources in the karst region and other vulnerable groundwater protection areas, including prohibiting manure applications within: 300 feet up slope or 100 feet downslope of a sinkhole or other direct conduit to groundwater; 300 feet up slope of a public waterway or tributary of a public waterway; 250 feet from a private well, 1,000 feet from a community well.

Summary of Locations and Setbacks
•Determine using specific and local conditions
•Increase setbacks

Livestock access to waters

Prohibit livestock of a feedlot or facility capable of holding 100 or more animals from entering a designated trout stream or tributary of a designated trout stream and prohibit livestock of a feedlot or facility capable of holding 300 or more animals from entering any water of the State.

Summary of Livestock Access to Waters
•DON'T

Air Quality

Monitor air quality, to ensure standards are met, using instruments provided by the MPCA to which MPCA and public has access to data obtained therefrom.

Feedlots are significant sources of air pollutants (ammonia, hydrogen sulfide, particulate matter, volatile organic compounds) that impact public health and contribute to environmental degradation. Feedlot emissions can negatively affect the respiratory health and general well-being of nearby residents. State-funded and state-managed monitoring ensures transparency and accountability with independent, unbiased data to assess compliance with air quality standards and protect public health. State-managed monitoring also provides regulatory enforcement and objective data to inform the public about air quality impacts from feedlot operations.

Summary of Air Quality
•Monitor Air Quality with MPCA-provided instrumentation
•Odor, Noise, Chemicals
•Make data public

How many animals

MNWOO supports requiring permits for the construction, expansion, and operation of feedlots with far less than 600 animals. MNWOO is aware that animal feeding operations at or below 100 animals in high risk locations have been found to be major sources of pollution. MNWOO supports that all feedlots have publicly available manure management plans, as outlined below. All feedlots should require not only manure application records but water quality monitoring records as well. There is no evidence that feedlots below a certain number of animals should be exempted as a class on the basis of their low pollution risk; small operators should apply for site-specific exemptions (variances) instead of being offered blanket exemptions based on the number of animals.

Require NDPES/SDS permits for feedlots with 600 or more animals. Lower the size for a feedlot operation to be required to apply for a water pollution permit. Limit the number of animals within a geographical area, within drinking water supply management areas, within state-defined and recognized sensitive regions, such as vulnerable groundwater area, and areas where the nitrate levels in ground and surface water exceed the background level.

Even with stringent management practices, a very high density of animals in a highly vulnerable karst landscape generates an immense volume of manure and associated nutrients, increasing the cumulative risk of groundwater and surface water contamination.

This measure directly addresses the source of potential pollution. By capping the density of animals such as in defined sensitive karst regions, the overall nutrient load (nitrogen and phosphorus) being generated and potentially applied to land in these vulnerable areas is reduced.

Every landscape has a finite carrying capacity for nutrient assimilation, especially in karst where natural filtration is limited. This rule acknowledges that some areas are simply too sensitive to safely accommodate very large concentrations of animal agriculture without incurring unacceptable health and environmental risk.

This proactive measure would help prevent the exacerbation of existing groundwater quality issues and protect currently unaffected areas from future degradation due to an unsustainable density of nutrient sources.

Summary of How Many Animals
•Decrease the number of allowed animals in a feedlot
•Consider land for nutrient assimilation
•Consider surrounding communities
•Consider possible ground and surface water contamination
•Consider the welfare of the animals

Vulnerable Groundwater Protection Areas

The existing Animal Feedlot Rules falls short in adequately protecting groundwater in vulnerable groundwater protection areas, like the karst region in southeastern Minnesota and the central sands in central Minnesota.

In the eight karst counties of SE MN, the US Environmental Protect Agency (EPA) Ordered the State of Minnesota to immediately address the imminent health risk of nitrate contamination in drinking water. The order demands that the Safe Drinking Water Act principles be applied to private well owners and community water supplies who share underground drinking water sources in these eight counties. Permit applications for new and expansion of feedlots in these counties should acknowledge the EPA Orders in the permit application and discuss how the feedlot will protect drinking water.

The unique hydro geology of karst facilitates rapid and direct pathways for surface contaminants to reach underlying aquifers. Karst landscapes, especially in the Drifters Area of southeastern Minnesota, are characterized by soluble carbonate bedrock (limestone and dolomite) that has been extensively dissolved by slightly acidic water over geological timescales. This dissolution primarily occurs along existing joints (fractures) and bedding planes within the rock. Networks of bedrock fractures that extend upwards to within a few feet of the ground surface are often beneath a thin soil cover. During dry periods, these joints allow plants to access moisture deeper within the bedrock, leading to patterns of denser, greener vegetation known as "karst lineations" or "crop lines." These lineations are not just curiosities; they are direct evidence of highly permeable pathways that bypass the filtering capacity of surface soils. Water, sediment, and pollutants can rapidly infiltrate through these subtle yet widespread features, directly into the underlying fractured carbonate aquifers.

The existing Animal Feedlot Rules with their fixed setback distances (e.g., 300 feet from a sinkhole) and quantitative triggers (e.g., 4 or more sinkholes within 1,000 feet), are insufficient

to protect groundwater quality because they do not fully account for this pervasive, interconnected nature of karst. A contaminant traveling through a discreet joint or conduit can traverse hundreds of feet in a short period, rendering arbitrary linear distances ineffective. The real vulnerability lies in the hydrogeological connectivity which often extends far beyond visible features or simple numerical thresholds.

The current rule's reliance on arbitrary distances and sinkhole counts is inadequate for truly protecting complex karst systems. Karst vulnerability is highly site-specific. A comprehensive Karst Vulnerability Assessment using multiple, state-of-the-art techniques (e.g., advanced remote sensing, geophysical surveys, detailed drilling, dye tracing) to qualitatively and quantitatively map the actual pathways of water flow to the aquifer. This moves beyond assumptions to data-driven decision-making. By identifying specific "high-vulnerability zones" based on robust scientific data, resources can be more effectively targeted for protection, ensuring that the most sensitive areas receive the highest level of scrutiny and protective measures. This avoids over-regulating low-risk areas while under-protecting critical ones. A karst vulnerability assessment allows for proactive land-use planning and siting decisions, preventing new pollution sources from being placed in extremely sensitive areas where remediation is difficult or impossible once contamination occurs. Existing feedlots of at least 100 animals in vulnerable groundwater protection areas should be sent information about karst vulnerabilities discovered in the Karst Vulnerability Assessment.

Thus, MNWOO supports the establishment of a Karst Vulnerability Assessment for new or expanding feedlots that will ensure karst sensitive regions are qualitatively and quantitatively reviewed.

While MNWOO advocates for a Karst Vulnerability Assessment, MNWOO also notes that all geography, land, water, and Nature is vulnerable to continued human consumption.

Summary of Vulnerable Groundwater Protection Areas
•Be Aware of Unique Geohydrology
•Establish Karst Vulnerability Assessment
•Establish Vulnerability Assessment throughout the State

MNWOO thanks the MPCA and the State of Minnesota for the opportunity to share its concerns and comments regarding protection of Minnesota's groundwater and safety of drinking water for human and animals from private water wells.

Respectfully Submitted,

Minnesota Well Owners Organization Board of Directors
Prepared by Karuna Ojanen, MN Board

APPENDIX I

Regional or County Scale Maps:

The list of maps should be expanded to include a small number of published risk assessment maps from the USDA Web Soil Survey, the Minnesota Geological Survey, the Department of Natural Resources, the Pollution Control Agency, the Department of Agriculture, the Department of Health and Board of Water and Soil Resources. All the proposed maps are in addition to the other required maps, and all maps should have a scale, north arrow, and legend and must accurately identify and delineate the feedlot, the manure storage site, and all the fields used for manure application.

I. HUC-10 Watershed maps from MDNR and US EPA for all watersheds with feedlots and manure applications.
II. One-Watershed, One-Plan watershed maps, and link to website.
III. Groundwater Province Map from MDNR.
IV. MDNR Groundwater Pollution Sensitivity Maps: (https://www.dnr.state.mn.us/waters/groundwater_section/mapping/mn-hydro-atlas.html)
    A. Pollution sensitivity of bedrock surface (HG-01)
    B. Pollution sensitivity of near-surface materials (HG-02)
    C. Water table elevation and depth to water table (HG-03) from MDNR
V. Regional Hydrological Assessments, where applicable: (https://www.dnr.state.mn.us/waters/groundwater_section/mapping/regional-hydro-assess.html).
    A. Surficial Geology
    B. Water table hydrology
    C. Geologic sensitivity to the uppermost aquifer
VI. Map of Groundwater Advisory Areas, DWSMAs, Wellhead advisory areas, and the EPA Safe Drinking Water area.
VII. Karst features maps where applicable.
VIII. MN Dept of Agriculture Township Well Testing:
    A. Initial and Final Test Results
    B. Pesticide Analysis

Township Scale Maps

I. Township Plat Map and Legend showing public land survey sections, roads, and parcel ownership with location of occupied building sites.
II. Minnesota Well Index/County Well Index map with a Legend and Scale.
III. County Geologic Atlas Maps, each with a legend, scale, and north arrow:
    A. Part A: Geologic Atlas:
        1. Bedrock geology
        2. Surficial geology
            I. Quaternary Stratigraphy and Sand Distribution Model where applicable
            ii. Karst Features, where applicable
        3. Bedrock Topography and Depth of Bedrock

4. Nearest geological cross-sections that identify the approximate distance and direction from the center of the cross-section

B. Part B Hydrologic Atlas map or citations from the Hydrology Report:

1. Each Part B atlas is different and usually has three or four maps and cross-sections. Regional factors apply, and appropriate mas should be required based on the area.

I. Bedrock hydrology

ii. Multiple aquifer pollution sensitivity

iii. Sinkholes, springs, seeps, and spring-sheds (dye trace studies)

iv. Water chemistry

v. Hydrogeologic cross-sections

IV. Land Cover (NASS).

VI. County Land Use Plan and Zoning maps.

Site and abutting properties maps

I. LiDAR topography in greyscale

A. Stream power index

II. USDA Web Soil Survey Maps with 1.5-mile radii
https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

A. Soil Map

B. Suitability and Limitations for Use

1. Waste Management Manure and Food Waste

2. Waste Management Sensitive Lands for Nutrient Management

C. Water Management

1. Subsurface Water Management Outflow/Effluent Quality

2. Other valuable maps include data on soil qualities, parent materials, water features, depth to water table, flood frequency, and pending.

RECEIVED
By: OAH on 7/22/2025

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July 22, 2025

Minnesota Pollution Control Agency

c/o Addison Otto

520 Lafayette Road North
Saint Paul, Minnesota 55155

Dear Ms. Otto and Commissioner Kessler,

The Land Stewardship Project's Animal Agriculture Policy Steering Committee, on behalf of all of the Land Stewardship Project's members, submits these comments on what we see needs amended in Minnesota's feedlot rules.

The Land Stewardship Project is a grassroots, member-driven, nonprofit organization that works with farmers and rural communities across Minnesota and has organized with thousands of small and mid-sized farmers, rural residents, and others to build a more just and sustainable farm and food system. We work with our members every day to build an agricultural system in which small and mid-sized farms and farming families can thrive, our air and water is clean, our soil is healthy, rural communities can prosper, and our climate is resilient. Currently, our membership includes approximately 1,500 small and mid-sized farming households and an additional 3,000 households in rural, suburban, and urban areas.

For 43 years, our members have worked together to advance our shared vision for agriculture and rural communities in the Upper Midwest. We have done that by advancing policies that promote and support farmers, farming practices, and food systems that can sustain everyone involved, from the farmer that grows the food to the person that eats it. We also do this through direct programming that allows farmers to learn from each other about how to implement crop and livestock production practices that build soil health and reduce input costs, and by facilitating a nationally-recognized beginning farmer training program. This work has put over 1,000 new farmers on the land, won tens of millions of dollars in public funding for farmers who are building soil health, helped create regional food systems, created tax incentive programs that make it easier for beginning farmers to gain access to land, and put in place moratoriums on farm foreclosures during times of financial stress in agriculture.

We also move this vision forward by working with our members to push back against the agricultural practices and policies that undermine our shared vision. Small and mid-sized farms, and by extension, rural communities, cannot thrive, or even survive, in an environment where the agricultural sector

becomes increasingly consolidated. This consolidation includes the proliferation of large-scale feedlots that threaten our air, water, soil, climate, wildlife, farm economy, local rural economies, human health, and more. This work is has been centered around preventing the expansion of the "get big or get out" model of agriculture by stopping over 40 large-scale feedlots from being built or expanding, and protecting our shared air, water, land, climate, and communities from the harmful effects of factory farms.

The Land Stewardship Project has a deep familiarity with building an agricultural system that is good for our planet and our communities in a way that works for farmers and rural communities. That is why we and our members advocate for a more robust permitting process for the largest livestock operations in Minnesota and are committed to making the Minnesota Pollution Control Agency's proposed changes the best that they can be.

Unfortunately, over the past few decades public policy and corporate interests have driven the agriculture industry toward fewer, larger farms, mainly in the pursuit of maximization of profit, and the consolidation of profits into fewer and fewer hands. This has come at the expense of other farmers, rural economies, and public health, as well as our land, water, and climate. In animal agriculture, this has resulted in increasingly larger feedlots that concentrate millions of gallons of liquid manure in lagoons, or thousands of tons of solid manure collected into one spot. This causes the nutrients in the manure to become more potent and concentrated, while also increasing the risk of manure running off a field and into a waterway.[9]

This shift has had significant consequences. Crop and livestock production accounts for roughly 70% of the state's nitrate pollution, putting the health of our families at risk.[10] Currently, nearly 80,000 people[11] in southeastern Minnesota alone have unsafe drinking water due to nitrate contamination. But it's important to note that this issue is not limited to the karst region. Tens of thousands of Minnesotans live in communities or have personal wells with elevated nitrate levels, and these people live both inside and outside the new designation of Vulnerable Groundwater Areas[12], which to our understanding corresponds with the map created by the Minnesota Department of Agriculture to comply with the Groundwater Protection Rule.[13] This designation would exclude parts of northwestern Minnesota and points in southern and western Minnesota that have had wells test high for nitrates but were excluded from the groundwater protection rule map.

This is an expensive issue to remedy and Minnesotans with contaminated water face undue financial burdens. The families and residents that are affected by this contamination face the hard financial choice of installing a reverse osmosis system or a point-of-use ion exchange filter. They may even have to pay tens of thousands of dollars to drill a new and deeper well. Some are forced to rely on bottled water or to even move out of the community entirely. If none of those options are financially viable for them, oftentimes folks end up with large medical bills from nitrate-caused health conditions.[14] These are costs these citizens are forced to take responsibility for, even though they are not the source of the contamination in the first place.

And in addition to keeping groundwater free from contamination, we need to also focus on protecting our shared surface waters in Minnesota. Minnesota's lakes and rivers are something our state is incredibly proud of. Millions of people each year rely on Minnesota having clean surface waters that they can swim, fish, paddle, and float in, as well as irrigate their plants or crops with. Not only are clean surface waters something that people individually appreciate, but tourism around water recreation is also a large economic driver for many in Minnesota.[15] These permits need to be designed to protect these surface waters from the kind of feedlot runoff or contamination that can contribute to fish kills and large algae blooms.[16] This contamination can come from single events like manure spills or discharges due to extreme weather events, which are projected to continue to increase in frequency over the coming years. It can also happen by simply operating one of these facilities under the stipulations of a permit. Allowing "routine" manure runoff to happen under an active permit is not acceptable and must change.

The status quo simply isn't and hasn't been working. Even though these rules have been in place for decades, our communities are still seeing an increase in the harmful effects of mismanaged and over-applied manure. And, as we've said, while there are some good steps in your initial proposal, they are not adequate to address the issues our members and rural communities are facing. All Minnesotans, regardless of their zip code, deserve safe drinking water. Gaining access to clean water should not be a luxury good. These permits must protect our common resources so that every Minnesotan can have equal access to them.

We request that you amend the current feedlot rules to address some of the longstanding environmental and economic injustices that have been taking place under the current feedlot rules and that are having direct negative impacts on our members, as well as on the communities that we represent. We have detailed a few improvements below that we believe must be implemented, and look forward to continuing the conversation about what Minnesota's feedlot rules look like in the future.

Improvement 1: Everyone deserves to have their surface and groundwaters protected, not just individuals in vulnerable groundwater areas.

While protecting water sources in Minnesota's vulnerable groundwater areas is particularly important, all Minnesotans, regardless of where they live, deserve to have access to clean water. These permits should be proactive in keeping Minnesotans protected from surface and groundwater contamination. The MPCA should not be creating rules that will only protect people once they have proven that they are at risk and have a well that is unusable. The additional requirements to the October, November, and winter manure application restrictions and practices that NPDES and SDS permit holding facilities are now required to adhere to must be extended to all feedlots that are required to complete or comply with a manure management plan (currently all operations over 300 animal units or operations receiving manure from a manure management plan covered site). This is a commonsense measure that is easy for farmers to comply with once some pre-planning is done through the manure management plan creation

process, and when adequate storage space is maintained to act as a buffer for any unexpected issues such as large rains or long winters.

The role of the MPCA is to protect all Minnesotans, regardless of where their property is or what the vulnerability status is of their well. The most impactful way for the MPCA to do that is to be a proactive partner and prevent contamination from happening in the first place.

Improvement 2: Record-keeping requirements must be strengthened.

While it is good that record-keeping of manure applications — including documentation related to water sampling results and applications that are done by manure buyers or custom applicators — will be required of NPDES and SDS permit holders to help make sure that permits are being followed by everyone, the requirements around this recordkeeping need to be much more robust to meet the needs of Minnesotans.

The information that the agency gathers from these records should be made available to the public. Communities dealing with the risks of feedlot contamination deserve to know that permits are being followed and deserve to have the ability to check that information for themselves. What lands are part of the manure management plans of permit holders, the results of water sample tests, and other information gathered in these records should be mapped, and this information should be made publicly available. This will allow community members to know what is going on around them and help them identify risks. In this way, they can help the agency ensure that permit requirements are being met.

We believe that increasing communication between permit holders and feedlot officers will be beneficial to everyone involved. Nobody — farmers, agency staff, or community members — likes surprise inspections or surprise contamination events. If permit holders are sharing information with feedlot officers regularly, it helps the permit holder if they have more clarity around what is being asked of them. It also helps the agency ensure permits are being followed, and helps community members become more confident that they are being protected. Making this requirement a role that the agency holds also means that this change would not affect the day-to-day role of the permit holder to comply with their permits and manure management plan, making this a reasonable requirement of the permitting structure.

Improvement 3: On their own, the proposed water sampling requirements are inadequate and more must be done to proactively protect our shared waters.

While the new requirements of NPDES and SDS permit holders and those who receive manure from a permitted facility to do water sampling/testing after a discharge event is a good start, all NPDES and SDS permitted facilities must be required to do more proactive water sampling and testing to not only ensure long-term compliance with the permit, but also to help ensure accountability, and to ensure that feedlots are being permitted, constructed, maintained, and operated in a way that is not negatively effecting the surrounding area. Regular water sampling

and testing near the permit holding site and where manure from the permitted site is being spread is vital so that the agency and the public can know that long-term damage and contamination is not occurring. This testing should take place at locations of potential surface water contamination like drain tile outlets, streams, drainage ditches, or field low points where stormwater typically runs off. Groundwater access sites like wells should also be tested regularly. These locations should be listed on the manure management plan as well, so that whatever entity analyzes water samples taken after a discharge event has a baseline to compare to, and so repeated tests can be accurately compared.

This requirement is particularly important for any new construction of manure basins and new lands used for spreading or when a permitted facility plans to expand. Undergoing water sampling and testing before construction begins or manure is spread to establish a baseline nutrient load at that location is the only way that the agency can ensure the public that these permits meet our goals of reducing contamination. If this kind of testing is done, the agency will be able to speak more effectively to the public about what is and is not causing contamination issues in their communities. This kind of information is critical, and because Minnesota is a state that values local control, local people who are being impacted by any contamination have the authority to make decisions about what is and is not allowed in their community through their local planning and zoning process. Being able to compare water quality tests at specific sites and sharing that information with the public through the more open sharing of manure management plans will give communities, through the local zoning process, the ability to more accurately address the issues they are experiencing on their own. While we know that the NPDES and SDS permits are designed to only allow discharges during extreme weather events, these kinds of events are becoming more frequent.[1] It is important that we prepare for this reality and are proactive in protecting our communities. We understand that this would be an additional requirement of the permitting, feedlot building, and manure management plan creation process, but once the initial tests are done, there would be no additional requirements that are not already part of the new version of Minnesota's NPDES and SDS permits.

Improvement 4: The work done to improve Minnesota's NPDES and SDS permits should be expanded upon.

We were encouraged by the steps the agency took to modernize Minnesota's feedlot permitting structure and want to see that work built upon. We believe that while those permits do leave room for improvement, they include quite a few good, commonsense rules for the largest feedlots in Minnesota to follow and are a good step towards a place where Minnesota's feedlot rules are working well for everyone.

Unfortunately, our members who live, farm, and are connected to the communities where large feedlots are being built have shared with us that time-and-time again they see operations trying to skirt around the additional requirements by crafting building or expansion proposals that put their operation's animal unit count at just below the threshold where operators are required to

[1] https://www.pca.state.mn.us/air-water-land-climate/climate-change-impacts

apply for these permits. We do not feel that this is within the spirit of what Minnesota's feedlot rules seek to accomplish and allows for a small subset of operators to avoid the requirements that Minnesotans have asked them to comply with. Because of this, we believe that the threshold that a feedlot should be required to obtain both an NPDES and SDS permit to build and operate should be lowered to 600 animal units.

Improvement 5: Adjusting how feedlots under the same ownership structure are addressed when in close proximity to one another.

In addition to seeing many proposals brought forward in their communities that are proposed just below the NPDES and SDS permit threshold, our members have noted that many proposals are being brought forward by already existing feedlot owners and are located near an already existing site, but are listed under a different site name. This adds confusion as to who is the actual owner of the site, and that is often left unaddressed in the local permitting process. The local permitting process is the key manner in which community members are informed about what is happening with feedlots in their community.

Because of this, we believe the agency must change the way that facilities under the same ownership structure are permitted to account for proximity to one another. Our suggestion would be to create a calculation tool that utilizes a facility's proposed animal unit size to calculate a radial distance for how far away it must be from another barn under the same ownership structure. Anyone who is applying to build or expand a feedlot who has another site connected to them under the same ownership structure must then do this calculation for each operation that is under that ownership structure before siting their new facility or expanding their operation. If the radius around the new operation intersects with another facility, a new site must be found. Our suggestion would be to make the distance per animal unit in this calculation five feet and three inches for every animal unit.

Improvement 6: Minnesota's new feedlot rules must address the elephant in the room for livestock producers: consolidation.

In Minnesota and across the country, increasing attention is being drawn to the animal agriculture industry and the anti-competitive practices that are being used to benefit a small minority of parties along the food supply chain. From lower milk check amounts and issues related to accessing processing at a fair price, to higher prices at the grocery store, everyone — farmers, the communities they are a part of, and eaters — is being affected by this.

For example, during the summer of 2023, dairy farmers in the Upper Midwest Federal Milk Marketing Order Region received the lowest milk check prices in the nation. At the same time, consumers in the Upper Midwest were paying extremely high prices for their milk. More recently, we have heard stories of farmers having a new generation ready to take over the operation only to be told by their local processor that they are not taking any more producer contracts. This is occurring while the processor is turning around and accepting multiple

shipments of milk from large operations every day. All of these issues are symptoms of the problem of consolidation in the dairy and livestock industries, and it is pushing producers off the land, stifling communities and local economies, and degrading the land and water that we all rely on.

Over the past five years, we have been building a farmer-led campaign to address the problem of consolidation, and time-and-time again we have heard from producers that there needs to be a halt to the expansion of huge feedlots in Minnesota. Mega-sized operations use their massive economies of scale to influence every part of the livestock economy. Having to compete with operations like that is the main reason farmers are seeing their friends, neighbors, and relatives leave the land.

Operations of this scale are also one of the major risk factors when it comes to protecting land and water resources in rural parts of the state. A spill from a feedlot with 200 cows is an issue that is addressable; a failure of manure infrastructure on a 10,000 animal-unit facility is a disaster that puts the wastewater equivalent of a whole town's annual output spilling out onto the land. Your agency, as the main permitting authority for large feedlots in Minnesota, has a duty to help producers and communities deal with this issue and must institute a moratorium on permitting large operations until our state finds a way to give all farmers a fair shake.

In summary, we are encouraged by the steps the Minnesota Pollution Control Agency has taken to strengthen Minnesota's NPDES and SDS permits to help keep us, our communities, and our shared water and land safe, but we respectfully insist that more must be done. We believe that, just like your initial proposed changes, the improvements we have detailed here to Minnesota's feedlot rules are good, commonsense requirements that will help these rules have the effect that all Minnesotans need them to have, while still not being onerous for feedlot operators. We hope you incorporate these improvements into your review of Minnesota's current rules and are happy to discuss the best way these changes can be implemented as your process progresses.

Sincerely,

Matthew Sheets,

Policy Organizer with the Land Stewardship Project

On behalf of the Land Stewardship Project's Animal Agriculture Policy Steering Committee

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MINNESOTA DIVISION OF THE IZAAK WALTON LEAGUE OF AMERICA

COMMENTS ON MPCA FEEDLOT RULE-MAKING

by

THE IZZAK WALTON LEAGUE OF AMERICA'S MINNSOTA DIVISION
John Siekmeier, President
6601 Auto Club Road, Bloomington, MN 55438

July 22, 2025

The comments that follow are submitted by the Izaak Walton League of America (IWLA) Minnesota Division and pertain to the Minnesota Pollution Control Agency's planned amendments to rules governing animal feedlots, Minnesota Rules, chapter 7020, Revisor's ID Number R-4928 - OAH Docket No. 25-9003-40661.

Statement of Qualifications and Standing

The Izaak Walton League of America is the nation's oldest and most successful conservation organization. Founded in 1922 the "Ikes" have for over 100 years stood for the protection and restoration of the nation's fish, wildlife and natural areas and is especially focused on matters affecting water quality.

Wherever these comments refer to "the League" this reference should be understood to be the collective opinions of members of the Izaak Walton League here in Minnesota that include a wide variety of experts in the natural sciences, water quality, hydrology, agriculture, public health and regulatory governance. The League is especially well positioned to make these comments on feedlot rules because many of our members are retired agency professionals from the Departments of Agriculture, Natural Resources, Pollution Control Agency, Health, Transportation, Board of Soil and Water Resources, Soil and Water Conservation Districts, U.S. Army Corps of Engineers, U.S. Geological Survey, U.S. Fish and Wildlife Service, the U.S. Environmental Protection Agency and more. Many League members are or were academics researching or teaching in colleges and universities in these disciplines. Other members have doctorate degrees and have been practicing family or specialty medicine for years, while still others are active citizens in natural resource protection in the League and other advocacy groups and have dedicated extraordinary amounts of time studying these matters and developing organizational policies to address conservation, pollution and environmental degradation.

Scope and Perspective for Comments

In the agency's request for public comments the MPCA has stated that the agency's three main areas of focus for these rule amendments include:

1. Updates to address changes in livestock and poultry operations and business practices, new agency data services, and outdated language.
    - Permit and registration applicability;
    - Animal unit factors;
    - Clarity of definitions and requirements;
    - Legislative alignment; and,
    - Utilization of agency data services.
2. Land application of manure practices to address nitrates, bacteria, and fish kills.
    - Transferred manure requirements;
    - Nitrogen Best Management Practices (BMPs);
    - Setbacks;
    - Manure Management Plan (MMP) applicability;
    - Visual monitoring; and,
    - Compliance monitoring.
3. Technical standards to protect water quality and avoid fish kills.
    - Manure storage capacity;
    - Feed storage design and operation;
    - Existing Liquid Manure Storage Area (LMSA) integrity;
    - Ground water monitoring; and,
    - Livestock access to waters.

The agency then asks: "Should any of the following bullets be considered? If so, at what size (in AUs - animal units)?"

- Operating permits (NPDES or SDS) for feedlots less than 1000 AUs.
- Submittal of manure management plans and land application records for feedlots without operating permits.
- Monitoring of feedlots and land application sites for subsurface discharges of manure or nitrate to groundwater.
- Additional restrictions on manure application rates.
- Soil nitrate tests prior to land application of manure.
- Increased setback distance for land application of manure near sensitive features.
- Restricting land application of manure in areas with high levels of nitrate in waters or in areas with existing high densities of feedlot operations.

MPCA's Three Area of Focus

The League generally agrees that the MPCA's three areas of focus listed above are appropriate. But, of particular concern to our members is the first one in this list: the significance of "*changes in livestock and poultry operations and business practices".*

There has been dramatic shift in animal and crop agriculture toward larger industrialized models over the past few decades that are thought to be primarily the result of government subsidy and world trade policy. As profit margins narrow and farm land prices rise the response has been to increase production rates to maintain viability. As

costs of inputs increase, the income from production has not been keeping pace. To hedge financial risks, producers (both crop and animal producers) have taken advantage of hidden subsidies that externalizes a major cost of production at the expense of a public asset: *degraded water quality and quantity.* By maximizing fertilization of crops with commercial fertilizer and manure to boost production (as recommended by established "agronomic rates") producers are encouraged to gamble on having a bumper crop every year. And there is an understandable tendency to augment the production benefits using less of the of higher cost commercial fertilizer, with more of the lower cost manure. But this gamble depends on having ideal weather conditions every year, which seldom happens. The result is that total nutrient inputs on an annual average, almost always exceed uptake and removal by harvested crops. The excess application of both forms of fertilizer accumulates each year that a "bumper" crop is not realized. Soil testing will not detect either form of nutrients that has leached below the root zone. As the build-up of excess fertilizer either washes off or leaches down below the root zone, this fertilizer is "released" as pollutants to groundwaters, surface waters, or both.

Current best management practices, even deployed to their maximum capability, which they seldom are, have not proven sufficient to recover, treat or retain these excess applications or the discharges to surface and groundwater. Uncontrolled discharges, "releases" of pollutants by these means, should be prohibited by the new rules because they are intentional, measurable and preventable.

As the MPCA works to develop rules for feedlot operations that reduce or eliminate this avoidable source of water pollution, the agricultural community's hidden profit subsidy *(degraded water quality and quantity*) that depends on continued release of pollutants will be significantly threatened. Powerful political forces will push back claiming that regulatory over-reach by the MPCA is threating the economic viability of farming in Minnesota.

Special attention must be given to this predictable political argument well in advance of the agency's proposed new rules that will make this unwarranted subsidy clear to the public, to the agricultural community and to our elected officials. Failure to anticipate and successfully dispel this argument in advance would imperil the success of the new rules.

The League believes that the MPCA must work with social scientists and other experts to carefully craft an educational campaign that exposes this unwarranted subsidy and builds support for ending it. The current industrial models for both crop and livestock production are seriously flawed in this regard and there are viable alternatives. The League stands ready to work with the MPCA, other state agencies and our partner non-profits to develop and roll out this educational campaign.

Later in these comments we will propose a structure and cite the authority for assembling an expert advisory panel to assist the agency and cooperating entities in

developing and implementing this plan based on existing statutory mandate and an Iowa example.

MPCA's Bullet-Points

The next section of our comments is directed toward the several bullet-points the MPCA offered for considerations. These summary responses on those points will be followed by more detailed discussion of them in a later section.

Overall, it is the League's position that the amended feedlot rules must not only be effective at reducing feedlot pollution, but should eliminate it to the degree necessary to support all classified uses of the state's surface and groundwaters. This has been and remains the goal of the Federal Clean Water Act, and actually provides the name of the federal NPDES permits many feedlots and all other discharges require. NPDES is short for the National Pollutant Discharge *Elimination* System.

The business and operating models for industrial-scale livestock and poultry production is vastly different from the conventional, family-farm model, and its waste handling and disposal methods are largely experimental. The industrial model has outside entities called integrators that own the animals. The "farmer" landowner owns the buildings, manure storage and handling equipment, and only some of land needed for manure disposal. Liquid manure rather than dry storage became the norm due to technical advances in manure handling equipment, but this required retention or addition of water to the manure. This business arrangement tends to bifurcate the responsibilities and liabilities of manure ownership, complicates storage and disposal options, and tends to shield the animal owner from any responsibilities.

Conventional family farms had the farmer owning both the animals and the all the related capitol infrastructure and all the land needed for manure. Dry handling storage of manure, depending on site conditions, has less tendency for run-off or seepage pollution because the manure inherently had more bulk (i.e. added bedding such as straw) and less added water.

Our research reveals that the industry's adoption of a wide variety of recommended best management practices have failed markedly at protecting surface and groundwaters nation-wide, and thus cannot continue to be the basis for either the voluntary norms or the regulatory requirements for permitting. Our recommendations for rule changes are premised on this fact. Unproven methods for manure storage and handling should be deemed "experimental" by rule. And these experimental waste management methods should only be allowed on a trial-and-error basis with close monitoring, and have prompt, pre-determined correction, remediation and compensation measures built in (for harms to public or private water supplies).

The comments below and the findings and recommendations in the League's Prairie Woods Chapter's AFO/CAFO report (attached) on feedlots to Becker County[1] are each

[1] See attached report entitled: ADDRESSING AFO & CAFO IMPACTS IN BECKER COUNTY'S COMPREHENSIVE LAND USE PLAN, ZOINING MAPS & ORDINANCES – August 1, 2024.

offered as useful information in regard to the MPCA's rule revisions. That report details gaps or deficiencies in federal and state rules governing feedlots that the League recommended Becker County address in their revised comprehensive land use plan. We also refer the agency to a recent Iowa report entitled *"Currents of Change*" [2] and offer that report into the record by reference. The Iowa report is offered here because it fortifies the findings of the League's AFO/CAFO report. The MPCA is encouraged to review the findings of each of these reports and address the identified deficiencies.

Our experience in Becker County is instructive. The League and specifically the members of the League's Prairie Woods Chapter in Detroit Lakes have examined the pollution potential of industrial-scale animal feeding operations and manure disposal in depth and on a national scale. This was done in preparation for a large swine operation that was proposed for a western Becker County township that requires a conditional use permit and an SDS or NPDES permit from the MPCA (application to MPCA yet filed). When the League challenged the adequacy of the county's zoning ordinances as being inadequate to control pollution from the facility, the county opted to update its Comprehensive Land Use Plan and review its ordinances. At the conclusion of that year-long process, county officials concluded that they were relying on the MPCA's rules to protect water quality. The county viewed their role and ordinances as intended to prevent land use conflicts, not protecting water quality. This, they concluded, was entirely the purview of the MPCA.

Our chapter members prepared the referenced report to demonstrate the inadequacy of Minnesota's and other states feedlot rules nation-wide. The report references the MCEA, et. al., petition to EPA that led to the current proposal for rule-revisions. Becker County officials were not convinced that they were obliged to fill this gap and have proceeded to issue the county permit.

This, and the *Currents of Change* report from Iowa, are offered to point out that local units of government are relying on the state governments (MPCA) to not only provide needed regulation of the design and operation of feedlots to prevent pollution, but to also to help them apply appropriate land use controls to avoid locating large feedlots in sensitive or already degraded areas of the state.

Summary Responses to the MPCA's Bullet Point Consideration Questions:

The League supports that construction and operating permits be required for feedlots far less than 1000 animal units in size. We suggest that all permitted feedlots should have both manure management plans, and require not only manure application records be kept, but water quality monitoring records as well. Because there is no evidence that feedlots below a certain number of animal units should be exempted as a class on the

[2] Currents of Change – An Analysis of the Racoon and Des Moines Rivers in Central Iowa - Final Scientific Assessment of Source Water Research Report available on-line at: https://www.polkcountyiowa.gov/media/lixlchbz/ciswra-currents-of-change_final-scientific-assessment-of-source-water-research-report_jun272025.pdf

basis of their low pollution risk, we recommend that small operators should apply for site-specific exemptions (variances) instead of being offered blanket exemptions based on their being below a certain number of animal units. Such exemptions could be applied for with assistance and documentation provided by county Soil and Water Conservation Districts or County Feed Lot officers. Criteria for exemptions would necessarily have to be spelled out in the new MPCA feedlot rules.

For example, traditional family-farm-scale feedlots often use dry handling and stacking methods for storing manure before field spreading. As mentioned above, dry stacked manure has far less potential for runoff or seepage than liquid manure handling and storage systems. If suitable vegetated setbacks are observed, slopes are moderate to level and runoff deflection and detention berms are constructed these operations could be considered exempt by rule.

We suggest that all permitted feedlots (that are not exempted) be required to record not only manure application rates, but additional commercial fertilizer rates as well. Permits should require active sampling and analysis of both surface and subsurface discharges for specific pollutants associated with animal manure storage and disposal and for other polluting chemicals associated with large feedlot operations. Monitoring for nitrates alone is not enough and parameters such as bacteria[3], biological oxygen demand (BOD), phosphorus and any other chemicals or pharmaceuticals being administered at the site for example, should also be required. Rates of manure application should be dictated by the site-specific character of the lands used for manure disposal from each permitted facility. Removal of nutrients such as nitrogen and phosphorus, through crops and residue harvested from fields receiving manure should be documented and compared to combined commercial and manure fertilization rates to assure excesses are not accumulating or being discharged. Determining the need for additional restrictions on manure application are again, site specific and should be proposed for each unique facility by licensed engineers and hydrologists who are experts at manure management for water quality protection purposes.

Setbacks from any and all surface waters should also be determined on a case-by-case basis, because a setback that may function well in one location may be inadequate for others, depending on slopes, ground cover, soil types and other site-specific characteristics.

Land application of manure in areas that already have high levels of nitrates or other pollutants associated with feedlots in either surface or groundwaters, should not only be more restrictive, but manure production, storage and land application should be prohibited in these areas until remedial actions are successful at reducing these

[3] U.S. Department of Agriculture studies in Wisconsin have shown that bacteria from feedlot seepage into ground water can travel several miles from the source underground so bacteria should be a monitored parameter for both surface and groundwaters. See section entitled GREEN BAY WISCONSIN – ON LAKE MICHIGAN on pages 22-23 of Leagues AFO/CAFO Report to Becker County attached.

excessive levels to a predetermined point. The term "high levels" are parameter specific and needs better definition. But, to be preventative, nitrates should have a trigger level well below the drinking water standard of 10 mg/l. This margin accounts for the lag time between a pollutant's discharge and its detection in receiving waters by monitoring.

The fact that the MPCA has not yet promulgated surface water nitrate standards for all waters other than those used for drinking water, is now being drawn into the public spot light. While adopting new nitrate water quality standards is not up for consideration in the current rule-making for feedlots, the League strongly encourages the agency to move forward with that long-delayed, much overdue process.

Detailed Discussion of Summary Above and Other Comments

The League respectfully suggests that any attempts to specify technical standards that are protective or remedial practices for most animal feeding operations by rule, are unlikely to accomplish the agency's statutory mission to: *"enforce reasonable orders, permits, variances, standards, rules, schedules of compliance, and stipulation agreements, under such conditions as it may prescribe, in order to prevent, control or abate water pollution."*[4] Minnesota's landscape, topography, soils, ground cover and the state's surface and groundwater vulnerabilities are far too varied in aspects relating to pollutant movement, retention and processing to allow a single "one-size-fits-all" approach. It is the League's strongly held opinion that most if not all permitted livestock or poultry operations should be required (by rule) to submit site-specific designs that take into account the unique natural or humanly altered features of a proposed feedlot and accompanying manure application locations. This is because animal feeding operations at or below 100 animal units in higher risk locations have been found to be major sources of pollution.

A Proposed "prove it first" Policy

The findings of the Prairie Woods Chapter's AFO/CAFO Report and the Iowa *Currents of Change* report referenced above, demonstrated that the intensification (concentration) of animals in what has become the industrial model for producing meat, has created a high risk for water pollution. The report also finds that in many other states that have experience with this scale of feedlot operations, citizens, environmental NGOs and regulatory entities alike have concluded that the array of pollution prevention methods (best management practices or BMPs) currently being deployed (whether mandatory or voluntary) have been inadequate to satisfactorily prevent feedlot pollution from entering public waters.

Based on this finding, the League recommends that the MPCA adopt a policy that declares this intensified method of livestock farming an experimental, high-risk polluting enterprise that must demonstrate new and improved controls before qualifying for permits. This would in effect, place the industry representatives (permit applicants) on

[4] Minnesota Pollution Control Agency enabling legislation at: Mn Statutes Chapter 115.03 POWERS AND DUTIES Subd 1(5).

notice that they must prove they have solved the heretofore unsolved problems associated with this industrial-scale enterprise.

To provide this "proof" the plans and specifications for new or expanding animal feeding operations should be required to be prepared by licensed engineers and hydrologists qualified and experienced in this specialized field. Existing permits should have renewal (expiration) dates after which time they would be required to meet these new rules. The licensed professionals responsible for the siting and design of these experimental operations should be required to affirm that the plans and specifications they submit will, in their professional opinion "prevent, control or abate" pollution.

This should not be viewed as an unusual hardship on even the smallest feedlot operation, considering that individual homeowners in rural areas of Minnesota are required to have licensed professionals design and install on-site sewage treatment and disposal systems that are reviewed by qualified professional in permitting units of government.

Furthermore, this is equitable, because municipalities and other industries in Minnesota, by rule, must hire qualified and licensed engineers to prepare plans and specification for wastewater treatment facilities before they can be permitted for construction and operation. Permittees from these facilities must submit monthly discharge monitoring reports that demonstrate compliance with effluent standards specifically designed to protect the public uses of the receiving waters. By "signing off" on these plans and specification, the designing engineers and hydrologists effectively warrant, by peril of their professional certification, that the facility, when built and operational can and will meet the prescribed water quality standards.

Permits for feedlots should be required to have both a construction and operation permits to detail the specifications by which this unique kind of pollution will be controlled and problems remedied.

Establishing a Point of Discharge as Compliance Boundary

The League recommends that the agency adopt a "point of discharge" policy as a compliance boundary that identifies the soil layer below land applied manure that represents the uncontrolled release of agricultural pollutants. This point would be below the root zone of current or planned crops that could capture or recover nutrients and biologicals applied to the land. Detection of "released" pollutants should be provided by monitoring devices such as lysimeters installed prior to a facilities operation and at locations representative of the areas, included in a facility's manure management plans.

To show whether or not surface or groundwater pollution is or has been originating from an animal feeding operation the permittee should be required to submit pre-construction (for new or expanding operations) monitoring data from representative locations in the water table or aquifer both upstream and downstream of the existing or proposed operation. Where the groundwater flow paths are uncertain due to karst or other geologic character the monitoring plan should demonstrate schemes for collecting data

that does documents the rates, routes and reservoirs of feedlot pollutants escaping (discharging) from a facility and its associated manure application fields. If the groundwater regime proves too complicated to monitor, these facts should constitute grounds for permit denial. Lack of information or the inability to collect it should not be used to justify avoidable risks.

Plans for the groundwater water quality monitoring regime should be submitted to the MPCA for prior approval before the monitoring system is put into operation. The plan should include the professional hydrologist's opinion on whether the existing pre-construction water quality condition will be adequately characterized by the sampling locations, frequency and duration of sampling and the parameters to be monitored. Parameters to be monitored should reflect not only the nutrient and microorganisms that could be discharged from the facility, but all other "pollutants" used at the facility relating to the feeding and raising animals.

In areas having heavy clay soils that a design engineer has determined to be an adequate barrier to downward movement of "released" pollutants, any and all drainage systems serving these fields, including surface ditches, natural waterways or underground tile, should have sampling locations and methods identified to detect "releases" of feedlot related pollutants.

If pre-construction monitoring demonstrates that an existing animal feeding operation owned and or operated by the applicant has already contributed to surface or ground water pollution, the prospective permittee must submit a remedial action plan to be approved by the MPCA. This remediation plan should be successfully implemented before new or expanded animal feeding operation can be permitted. Here, successfully implemented would mean the pollution levels are reduced to comply with applicable surface or groundwater standards.

Available tools for early detection of existing degradation include the MPCA's Watershed Restoration and Protection Plans, coupled with the One-Watershed-One-Plan documents prepared by each county or watershed boards if they exist. These plans are intended to gather and survey existing data on surface and groundwater and identify contributors (stressors) on these water bodies. The plans often include remedial measure needed to address impaired waters. If animal feeding operations are identified as one of the stressors causing impairments, new or expanding feedlot permit applications should be reviewed in light of these findings. As existing permits come up for renewal, the new monitoring and discharge control requirements in the new rules should then apply to these existing lots with a compliance schedule.

Joint Permits for Industrial Model Feedlots

The industrial model for large feedlots often includes a three-layer pyramid of agreements between the land-owner (farmer) and the animal owners (called integrators) and the contracted industrial meat processors. The new feedlot rules must include ways to obligate each of these entities to the responsibility for compliance with permit limitations on discharges, and for financial assurance necessary for remediation upon

discovery of a release. The integrators and the meat processors have been attempting to place the farmer/landowner in the position of responsibility for manure disposal in an effort to protect themselves from this liability. The farmer is not likely to have the financial wherewithal to withstand the costs of remediation should the manure threaten or contaminate surface or groundwater. Faced with this problem, the landowner/farmer may declare bankruptcy leaving the state (taxpayers) to bear the costs of the pollution and remediations.

The need for joint permitting of the parent companies and the intermediate integrators, along with the farmer/land owner must be addressed in the new rules.

Interstate Transport of Manure

Large feedlot operators are generating such large quantities of manure that they may need to seek lands in neighboring state for disposal options. The new rules should anticipate the issues raised by these circumstances. A Minnesota feedlot operator disposing of manure in a neighboring state should be required to comply with rules for long-distance transportation of manure through Minnesota. It is unlikely that the MPCA would have control of that manure once it crosses state lines. However, there may be opportunity for interstate cooperative agreements that provide a seamless protection for water quality. On the other hand, an importer of manure from another state should be required to prepare manure management plans that include the same level of monitoring and release response required of a Minnesota operator. Interstate agreements may also be needed to alert the MPCA to planned importation of manure. The same level of joint permitting for land and animal owners as discussed above would seem appropriate for these circumstances as well.

Importation of manure raises another issue that may be outside the MPCA's authority but nevertheless requires regulatory attention. The interstate transport of manure carries the potential for spread of livestock and poultry disease. If other state departments have the authority to regulate the interstate transport of animal disease, the MPCA should work toward some interagency agreement to address these issues. The MPCA could perform this courtesy for neighboring states receiving manure exported from Minnesota.

Groundwater Supply Impacts

Private well owners in agricultural areas have little or no protection for their water supplies and seldom have their wells tested. When they do test, they may only get results for nitrates and coliform bacteria and they may be unaware of fluctuations in supply aquifer levels influenced by high-capacity wells such as those needed to supply large feedlots.

These are data gaps that the proponents of industrial scale agriculture must help fill. Published studies[5] from N.E. Iowa have shown that

[5] Juxtaposition of intensive agriculture, vulnerable aquifers, and mixed chemical/microbial exposures in private-well tapwater in northeast Iowa available on-line at: https://pubmed.ncbi.nlm.nih.gov/36657670/

"… contaminant exposure in unregulated private-well point-of-use tapwater (TW) is a recognized public-health data gap and an obstacle to both risk-management and homeowner decision making.

The current results address a critical lack of directly comparable data on broad contaminant exposures in TW in agriculturally-developed settings and document commonplace simultaneous exposures to inorganic, organic, and microbial contaminants of human-health concern.

Heterotrophic bacteria detections were near ubiquitous (94 % of the samples), with detection of total coliform bacteria in 28 % of the samples and growth on at least one putative-pathogen selective media across all TW samples. Health-based hazard index screening levels were exceeded frequently in private-well TW and attributed primarily to inorganics (nitrate, uranium). Results support incorporation of residential treatment systems to protect against contaminant exposure and the need for increased monitoring of rural private-well homes."

The Prairie Woods Chapter's AFO/CAFO report also cited studies in Wisconsin where manure pit related bacteria traveled over three miles to neighboring private wells.
To assess potential impacts of a proposed feeding operation on both the quality and quantities of available groundwater supplies, the permittee should be required to submit appropriate assessments of these water supplies that identify other area users (both public and private) potentially impacted and what measure will be taken to ensure supplies will be adequate in quantity and quality to serve all existing and planned future uses of these waters. Once again, these assessments should be prepared by licensed professional engineers and/or hydrologists.

Permits for sites that have downstream private wells within five miles should be required to pay for well water analysis of these wells prior to beginning operation, to establish background levels of indicator pollutants. If indicators of agricultural pollution are found, more exhaustive sampling and analysis should be required to determine if other agriculturally related biologicals or chemicals, including pharmaceuticals, are present. Likewise, pumping tests on new water supplies for large feedlots should be required, with water level impacts on existing private wells within five miles being reported. If no existing wells are located within five miles, special monitoring wells should be installed temporarily to determine the zone of depression caused by the new well and neighboring property owners should be formally notified if the aquifer they may rely on in the future may be impacted.

If these requirements should exceed the MPCA's authority or expertise, the League strongly suggests that either a memorandum of understanding or other agreement be developed between the MPCA, the Departments of Natural Resources, Health and Agriculture, to assure this impact is adequately addressed. For example, some form of written commitment between agencies to prepare a joint discretionary environmental assessment worksheet (EAW) or an environmental impact statement (EIS) may provide the level of scrutiny and public comment this problem requires.

Reasonableness of Requiring Compliance With Discharge Standards

The current MPCA policies and rules and the similar laws and policies in other states nation-wide have allowed feedlots to discharge both directly and indirectly into both surface and groundwaters causing serious pollution and impairment of these waters in many parts of the state, and only required that feedlots employ "best management practices" to "minimize" the discharges.

The League's position advocating the agency strengthen its policies and rules is supported by provisions of the Minnesota Environmental Policy Act (MEPA) which, in Chapter 116.04 subdivision 6 states:

> ***"Prohibitions**. No state action significantly affecting the quality of the environment shall be allowed, nor shall any permit for natural resources management and development be granted, where such action or permit has caused or is likely to cause pollution, impairment, or destruction of the air, water, land or other natural resources located within the state, so long as there is a feasible and prudent alternative consistent with the reasonable requirements of the public health, safety, and welfare and the state's paramount concern for the protection of its air, water, land and other natural resources from pollution, impairment, or destruction. Economic considerations alone shall not justify such conduct."*

This is a powerful mandate and a provision in state statute that would appear to compel the MPCA to prohibit (by denying permits) feedlot operations that pollute, impair or destroy the state's waters. Should the agency decide otherwise, it is the Leagues pointed request that the agency provide its explanation for allowing such pollution or impairment in their statement of need and reasonableness for any proposed rule that continues to allow this pollution.

Economic considerations

As discussed above, the League recognizes that the economics of livestock and poultry farming may have influenced landowners to increase that scale of their operations in order to increase or even maintain their profit margins as market prices for their livestock varied. However, manure storage and management practices that routinely allow pollution also increase profit margins, but do so at the expense of our precious water resources, a public trust to be managed for the public good. We maintain that feasible and prudent alternatives to the industrial-scale CAFO model do exist, thus this MEPA policy requires the agency to apply far more stringent standards for those feedlots. It is not our intention in these comments to list or outline these alternatives but instead recommend the MPCA, in conjunction with other state agencies and universities fully explore the available alternatives and make them known to the farming community.

In the section of the League's AFO/CAFO report to Becker County entitled *Economic Impact of CAFOs on Rural Communities (*on page 13) we present the economic arguments based on the work of Dr. John Ikerd, who holds a PhD in Agricultural Economics from University of Missouri-Columbia, that this form of industrialized meat

production is by many indicators, detrimental to the economies of communities where large feedlots of this type exist.

The League is sympathetic to the plight of farmers who may lack the technical or engineering resources to choose a less polluting alternative to the industrial CAFO model. Another section of MEPA requires agencies to do some of this work. *Minnesota Statutes* 116D.04 subdivision 2 (1&2) to establish advisory councils and forums to consult with experts on such matters:

> *"Subd. 2. Duties. All departments and agencies of the state government shall:*
> *(1) on a continuous basis, seek to strengthen relationships between state, regional, local and federal-state environmental planning, development and management programs;*
> *(2) utilize a systematic, interdisciplinary approach that will insure the integrated use of the natural and social sciences and the environmental arts in planning and in decision making which may have an impact on the environment; as an aid in accomplishing this purpose there shall be established advisory councils or other forums for consultation with persons in appropriate fields of specialization so as to ensure that the latest and most authoritative findings will be considered in administrative and regulatory decision making as quickly and as amply as possible;"*

The League strongly recommends that the MPCA act on this legislative mandate to create a feedlot advisory council to provide independent and objective input not only on these rules but to develop information and the means for its distribution to farmers who need to explore alternatives to the prevailing industrial CAFO model. The past practice of the MPCA, the EQB and other agencies to appoint "stakeholder" panels that includes those with obvious conflicts of interest should be avoided. The statute citation above emphasizes that advisory councils be populated *"with persons in appropriate fields of specialization so as to ensure that the latest and most authoritative findings will be considered in administrative and regulatory decision making as quickly and as amply as possible;"*

We offer instead the example of the panel of science advisors involved in preparing Iowa *Currents of Change* report. The report lists the names, qualifications and an indication of the independence of those panel members that contributed to the report.

<u>Currents of Change Panel of Science Advisors as Listed in the Report</u>

Currents of Change's depth, breadth, and comprehensive interpretation are due to approximately 4,000 hours of analysis and assessment by CISWRA's science advisors—all respected researchers and experts across multiple disciplines. The County is grateful for the passion and commitment devoted to CISWRA on the part of the science advisors.

Dr. Elliot Anderson, Lead Data Coordinator, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Elizabeth Bolton, Argonne National Laboratory
Dr. Molly Finster, Argonne National Laboratory

Dr. Matthew Helmers, Iowa State University
Dr. Robert Hirsch, United States Geological Survey Emeritus
Dr. Claire Hruby, Drake University
Dr. Thomas Isenhart, Iowa State University
Mr. Dana Kolpin, United States Geological Survey
Dr. Peter Levi, The Nature Conservancy
Dr. Keith Schilling, Iowa Geological Survey, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Jerald Schnoor, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Mary Skopec, CISWRA Science Co-lead, Iowa Lakeside Laboratory, University of Iowa
Dr. Martin St. Clair, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Larry Weber, IIHR—Hydroscience & Engineering, University of Iowa
Dr. Michael Weber, Iowa State University Mr. Calvin Wolter, Iowa Geological Survey, IIHR—Hydroscience & Engineering, University of Iowa

Request for On-going Public Participation

Finally, the League respectfully requests that the current comment period not be the only opportunity for the public to have input into the new amendments to the feedlot rules before the draft rules are published. We request that the MPCA hold regular update forums around the state to provide transparency into the direction the agency is going and to what extent any of the public's comments (including those of the League) are being taken into account by the agency.

The League thanks the MPCA for providing this opportunity to submit comments on the agency's plan to revise the state's feedlot rules. We look forward to working closely with the MPCA throughout this rule-making process and beyond.

ADDRESSING AFO & CAFO IMPACTS IN BECKER COUNTY'S COMPREHENSIVE LAND USE PLAN, ZOINING MAPS & ORDINANCES

An Izaak Walton League of America

Prairie Woods Chapter Special Report

to

The Becker County Board, the County Zoning Administrator, the County Planning Commission, the Comprehensive Planning Consultants and the Public on Confined Animal Feeding Operations (CAFOs)

August 1, 2024

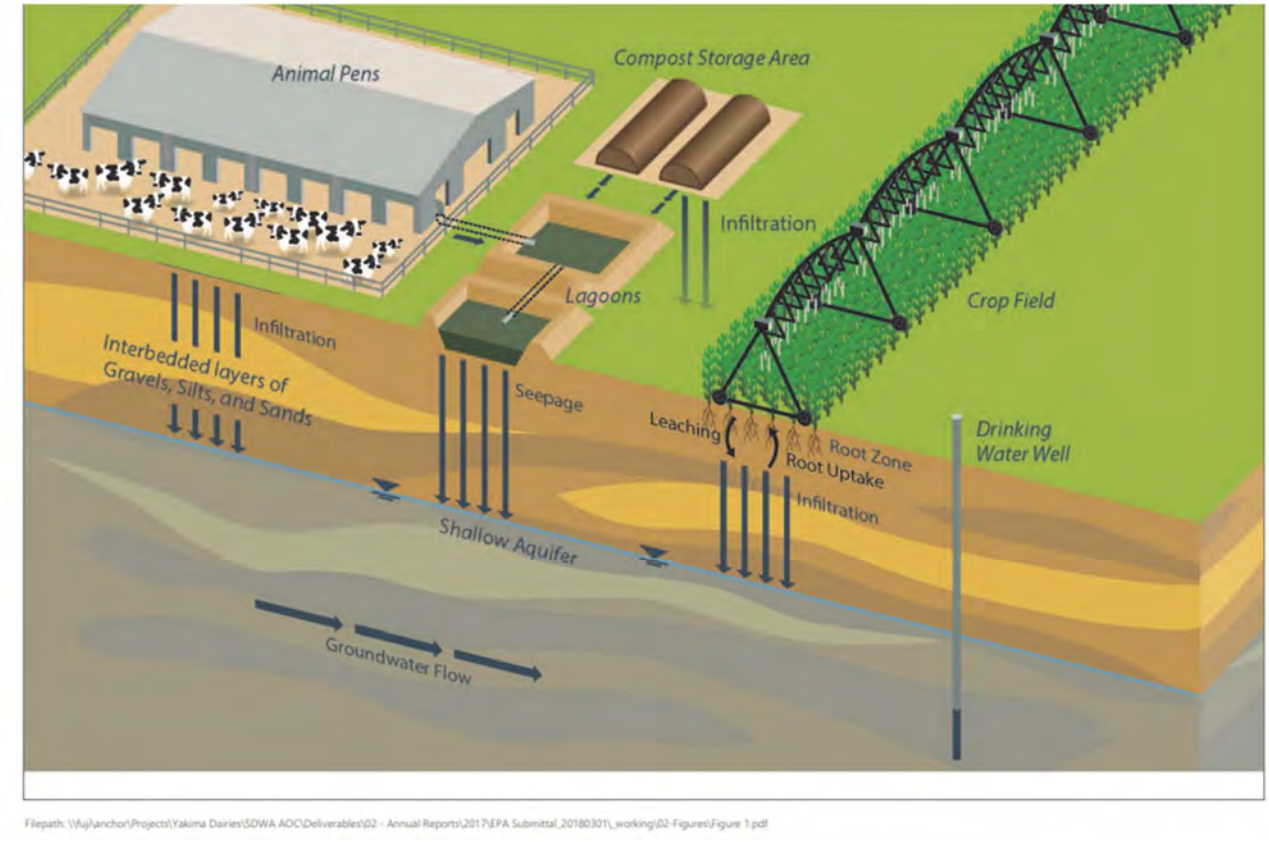

Photo Credit: Anchor QEA – Anchor Project – Yakima Dairy – 2017 Report to the Environmental Protection Agency

EXECUTIVE SUMMARY

The Becker County Board's decision to use a comprehensive plan update to address CAFO and Wake Boat issues has afforded the public and non-profit organizations unique opportunities to participate and even contribute their unique resources to the effort. With County Board Chair approval, members the local Izaak Walton League's Prairie Woods Chapter offered to perform research to fill technical information gaps that neither the staff or the planning consultant could fill. Thus, written reports were prepared on CAFOs and Wake Boats.

This report explains that the trend of more CAFOs migrating north into Becker County is real. The report dispels industry claims that they handle manure responsibly, by surveying other states and region's experiences. It describes how the evolving food industry model engenders industrial-sized feeding operations to maximize their profits, but to the detriment of smaller family farms and water quality. The report discloses that all manure storage facilities leak and can significantly affect sensitive groundwater, like that found in some regions of Becker County. State and Federal rules and permits are found to be too lax because the rules allow manure to be applied excessively enough to pollute both surface and ground waters. Manure leaks and spills are directly linked to fish kills. The spills resulted from heavy rainfall causing overflow from manure pits or were associated with manure transport tank wagon or pipeline accidents or failures.

The economic impact section of the report finds evidence that disputes nearly all industry claims that communities will benefit economically from industrialization of livestock farming. CAFOs are shown to ultimately be harmful to local economies because they displace family-scale family farms, reduce the number of farm worker needed, reduce hourly pay and can actually depopulate counties where CAFOs become dominant. Decreasing property values in counties with higher numbers of CAFOs is documented while lower CAFO counties experience increased property values. And many counties have been forced to raise taxes to offset increased costs of repairs to rural roads and bridges.

Credible monitoring of existing area wells and surface waters in any area designated for CAFO introduction or expansion, both before and after the first facilities are approved, is strongly recommended to establish baseline data. Therefore, private wells in areas zoned for more

intensive animal agriculture (CAFOs) in Becker County should have base-line testing done well in advance to protect well-owners, followed by regular sampling. Other states, and counties in the S.E. corner of Minnesota having experiences with CAFO's, are reviewed through published articles and each reveal significant unresolved levels of surface and groundwater pollution attributable to large and industrial scale feedlots. State and federal rules are reviewed and found inadequate to prevent or mitigate water pollution from CAFOs.

Minnesota is under Federal (EPA) orders to improve regulations for these areas, and new rules affecting eastern Becker County have already been judged as inadequate. Clean water supplies in quantities essential to Becker county's present and future economy, and for drinking purposes, are found to be inadequately regulated or apportioned by the state's water appropriation permitting program. Proposals for water quality and quantity (well-levels) monitoring for private well-owners could be recommended in the comprehensive plan. With state and federal regulations of CAFOs found inadequate to protect the health and welfare of Becker County citizens, zoning ordinances and permit conditions are considered quite important to fill these gaps. CAFO disease control methods are linked to the growing ineffectiveness of antibiotics in humans.

Testimonials are cited as evidence that small farmers can actually get financially trapped and even punished, by the CAFO industry when they find contract demands are draining their available capitol. A host of educational resources are included in the report that the League, other civic groups, county staff and the media can use to better inform the decision-makers and the public about these issues. Some of the resources listed in the full report are shown here below.[1]

Izaak Walton League Chapter Produced Videos with CAFO experts and Citizen Testimonials at: https://drive.google.com/file/d/17fEX-Wfztuq39zN4T4uXgnFkLOzasGNf/view

Freshwater Futures' Webinar - Great Lakes HABs & CAFO Manure Conference Series | May 2, 2024 Freshwater Future
https://www.youtube.com/playlist?list=PL_JsLZuTdlRu96Q1tarJmgjsWOHEdoIYv

[11] links in black font are not active, to access these files please cut and paste the URL into your browser.

Explosion of CAFOs in Iowa and its Impact on Water Quality and Public health at:
https://roadactivist.org/wp-content/uploads/2018/01/Explosion-of-CAFOs-in-Iowa-and-Its-Impact-on-Water-Quality-and-Public-Health.pdf

Economic Realities of CAFOs – Dr. John Ikerd - University of Missouri-Columbia at:
https://ikerdj.mufaculty.umsystem.edu/presentation-papers/factory-farms-cafos/economic-realities-of-cafos

Antibiotic Use in Animal Medicine and Antibiotic Resistance.
https://www.cidrap.umn.edu/antimicrobial-stewardship/study-predicts-global-increase-antimicrobial-use-food-producing-animals

https://www.cidrap.umn.edu/antimicrobial-stewardship/report-slams-beef-industry-overuse-antibiotics

Addressing AFO & CAFO Impacts in Becker County's Comprehensive Land Use Plan, Zoning Maps & Ordinances

A Special Report to the Becker County Board, Zoning Administrator, the County Planning Commission the Comprehensive Planning Consultants and the Public on Confined Animal Feeding Operations (CAFOs)

from

The Izaak Walton League of America's Prairie Woods Chapter

Dr. Bill Henke, President
Erika Gilsdorf, Research Committee Chair
Charles Becker, Wake Boat Research Subcommittee Chair
Willis Mattison, Chief Science Advisor

August 1, 2024

Comprehensive Land Use Planning for CAFOs

Most land use decisions are inherently local. In Minnesota local governments create their own "comprehensive plan" for growth and development. The plan, in conjunction with zoning maps and ordinances establishes the way development occurs in that area. The primary purposes of the plan, zoning maps and the ordinances that implement it, is to "promote and protect the health, safety and general welfare" of the public, to "preserve and enhance the quality of surface waters" and to "provide for the wise use of water and related land resources of the County"[2]

Decisions about local planning and zoning, local utilities and other infrastructure are all made pursuant to the plan and maps. State law requires certain minimum elements in the plans, but leaves it to local units of government to develop and implement them through ordinances. The plans, maps and ordinances are ordinarily reviewed, updated and approved every 10 years.

The Becker County Public Engagement Survey used to gauge citizen priorities for the current planning effort found that 70% of Becker County citizens thought more should be done to protect the water quality of lakes and streams. When the nearly 500 respondents were asked to note their top priorities in terms of issues facing the county, 83% considered housing one of the three highest concerns. Further over 70% consider jobs and economic development a key priority and slightly more than 50% see the environment as an issue to be prioritized. Additionally,

[2] Quotes from statement of purpose section 101 in Becker County Zoning Ordinance

citizens raised two new issues to be addressed by the plan, animal feeding operations (AFOs) and confined animal feeding operations (CAFOs).

A county's land-use decisions about these livestock and poultry operations can have significant effects on the county's water quality, natural resources and human health, and economy, but impacts vary widely depending on sizes and locations of the operations. Factors such as soil types, depth to groundwater, topography and proximity to surface waters, proximity to neighbors, and compatibility of activities are important to consider along with the cumulative impacts of all other land uses on valued natural, cultural and aesthetic resources. Highly sensitive water bodies may need special protections and waters already impaired may need remedial measures in a land use plan. The impact of a single livestock or poultry project may seem small, but when we look at the bigger picture, the challenges to the environment and human health from both the small and industrial scale agriculture projects added together can be dramatic.

The livestock industry has experienced increasingly adverse conditions attributable to over-crowding; too many large facilities in close proximity, increasing animal disease risks, depletion of available clean water supplies, saturation of available crop lands with manure, and growing community animosity stemming from nuisance odor, traffic and insect (fly) populations.

Because industrial scale livestock agriculture is a recent arrival in Becker County the current comprehensive plan update is particularly well timed to perform its purpose serving to protect the county's water quality, natural resources and human health, as well as its economy.

The information provided here will serve to inform the County Board, the Planning Commission, County Planning and Zoning staff, and the public, on the consequences of allowing industrial scale animal feeding operations to first become established and then to possibly expand in Becker County. Potential impacts and risks to the public health and welfare of its current and future residents are identified. Factors that may potentially degrade the value of the county's natural resources and potential threats to the vitality of the County's rural economy are described in detail.

Filling the AFO/CAFO Information Gap

Conventional wisdom expressed in recent deliberations about these divisions of government responsibility for livestock facilities, led Becker County officials to defer to state and federal laws, permits and standards, to protect surface and ground water, as well as look after the general welfare and economic well-being of the county's citizens. The reliance on other entities to fill this role was examined for this report and was determined, at least in part, to be misplaced. And it was determined that neither the county zoning staff nor planning commission members had the assignment and neither had the time or resources to fully research the laws or the literature on large confined feeding operations. Zoning staff stated that no one had alerted them to issues relating to these operations and invited the public's assist in gathering more information.

Furthermore, the county planning a zoning staff found they did not have the necessary capacity or resources to research the impacts of, or find solutions to, either the industrial scale feedlot or the wake boat issues. And, the needed research was determined to be beyond the scope of work the consultants could be authorized to do for the money available.

When alerted to the need, the local IWLA chapter members met with county officials offering the League's wealth of expertise and volunteer time to research the controversial issues and generate fact-based reports and recommendations for inclusion in the draft comprehensive plan before the final plan was published.

The Izaak Walton League of America (IWLA) is well positioned to perform this public service. The League is a nation-wide, grassroots conservation organization that just celebrated its 100-year anniversary in 2022. Chapter membership includes conservation, natural resource, medical, pollution control, scientific research professionals, and other volunteers, many who are current, retired or former natural resource agency, university or consulting firm employees. Others are skilled, self-taught citizen scientists.

The local ILWA Prairie Woods Chapter, established in the 1940's has a long-standing collaborative relationship with area communities in a variety of conservation matters. Most recently, chapter members worked cooperatively with the Becker County Board the "Save the Trees Coalition" and other citizens to prevent unnecessary tree removals in the Smoky Hills

State Forest along the Lake Country Scenic Byway. The successes realized from these and other collaborations helped build the County Board's, the staff's and the public's trust in the IWLA member's scientific credibility and civic-mindedness.

The Izaak Walton League's Prairie Woods Chapter located in Detroit Lakes, the Becker County seat, has offered to help fill information gaps for both the livestock feedlot issue and for wake boats as well. This report will address the livestock feedlot issues while a separate companion report will similarly address wake boats.

CAFOs Are Migrating North Into the Lakes Region– Why?

New industrial scale feeding operations have been migrating north from Iowa and southern Minnesota, into northwestern Minnesota, in order to reduce animal disease risks, and have access to more clean water. In Iowa, an analysis by the Environmental Work Group produced a report that stated in part:

> *"The number of large concentrated animal feeding operations, or large CAFOs, in Iowa increased nearly fivefold in the past two decades, a new study from Environmental Working Group (EWG) reveals, with almost all of the growth from big hog-feeding operations.*
>
> *EWG found that in 1990, Iowa had 789 large CAFOs – those housing 1,000 or more animal units – swelling to 3,963 in 2019. The findings are supported by the federal Census of Agriculture, which reported that Iowa, the top hog-producing state, housed more than 22.7 million hogs in 2017, an increase of 8.5 million since 1992.*
>
> *Swine and other livestock raised in Iowa's large CAFOs now produce 68 billion pounds of manure a year – conservatively, 68 times the total amount of fecal waste produced each year by the state's 3.15 million residents.*
>
> *Large hog CAFOs house a minimum of 2,500 pigs each, and the largest hog CAFO in Iowa houses 24,000 animals. In total, more than 60 percent of the animal waste produced*

by the largest CAFOs in Iowa comes from hogs. The mountains of animal waste produced by these facilities pose a serious and growing threat to human health, the environment and water resources in the state.

EWG used satellite and aerial imagery to pinpoint where and when the new large CAFOs appeared in Iowa. The interactive map (found at the link in footnote 2) below shows their locations, the type of facility, the animals housed there and the growth in facilities over the past two decades.[3]

Industry Claims That They Handle Manure Responsibly Examined

Industrial farming representatives often claim farmers don't contribute to water nitrate or phosphorus pollution by over-applying fertilizers or manure because these materials cost too much, and to do so would be wasteful. However, Jeff Mitchell, Laboratory Supervisor for the Des Moines Iowa Water Works has found ever increasing concentrations of nitrates in the Des Moines and Racoon Rivers, primary sources of the city's drinking water over the past 50 years. In an August, 2023 webinar entitled "*Nitrate in Drinking Water – Public and Private*" to the Izaak Walton League, Michell presented nitrate concentration trends for the Raccoon River from 1972-2023, shown in the graph below that was included in the presentation. By multiplying river concentrations, by river flow volumes, Michell calculated the total amount of nitrogen flowing past the city in 2018. If applied as anhydrous ammonia, it would have cost $10 million and could have fertilized 400,000 acres, over 20% of the watershed. Since 1974, he calculated that 1.8 billion pounds of nitrogen had flowed past the city in the river. Using similar calculations Mitchell demonstrated that in 2015, 116,000,000 pounds of nitrogen was lost to the river at a cost of $35,000,000, and as fertilizer it would have adequately treated (fertilized) 800,000 acres (40% of the watershed).[4]

[3] EWG Study and Mapping Show Large CAFOs in Iowa Up Fivefold Since 1990 – See interactive map at: https://www.ewg.org/interactive-maps/2020-iowa-cafos/

[4] Jeff Mitchell – 2023 Izaak Walton League Clean Water Webinar Series *"Nitrate in Drinking Water: Public and Private"* at: https://www.youtube.com/watch?v=OpSnuGti2k0

These data and calculations clearly show that farmers do over-apply both commercial and manure fertilizers at a great economic loss to the farmers themselves, and at great expense to municipal water suppliers such as Des Moines to remove that fertilizer. Nitrate removal has cost the city over $317,000 in 2016 and over $750,000 in 2015.



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Number of Days in Operation	76	28	177	65	24	3	9	-	-	20
Number of Vessels Operated	313	96	726	265	72	9	58	-	-	70
Marginal Cost Per Vessel	$1,015	$1,015	$1,038	$1,159	$1,045	$1,090	$1,199	$1,199	$1,199	$1,199
Marginal Cost to Operate Facility	$317,695	$97,440	$753,588	$307,135	$75,240	$9,810	$69,542	$0	$0	$83,930

Public water supplies must meet drinking water standards (10 ppm), are routinely tested, and as shown above, treatment can be effective when the nitrate contamination is found to exceed safe levels, but it is expensive.

On the other hand, private well owners in rural areas lack testing or are tested only at the owner's expense, no standards are being enforced, and well-owners are "on their own" when contamination comes from their neighbor's activities. More information on private well contamination and aquifer draw-down issues can be found in the sections that follow.

All Manure Pits and Lagoons Leak

In Wisconsin and other states, including Minnesota, manure pits and lagoons are designed and allowed to leak, under provisions of regulatory permits, with a leak rate limit of less than 500 gallons/acre/day. This means that a three-acre lagoon is allowed to leak 1,500 gallons per day

and could total over one half-million gallons per year into the groundwater below. This has the potential to cause major problems for rural well owners.

A USDA study in Wisconsin examined this problem and found that not only nitrates were reaching private drinking water wells, but that fecal coliform bacteria from the manure pits were traveling over three miles from the source. (more on Wisconsin's experience issue later in this report)

The Minnesota Pollution Control Agency's construction standards for manure pits and lagoons are "theoretical" rather than practical. This means that if construction standards are followed, the pits should theoretically not leak more than the amount allowed, but the owner/builder need not demonstrate that they are not leaking in excess of the standard. Pits and lagoons are allowed to leak slightly less than 500 gal/acre/day leakage, but the standard is generally understood to be 500 gal/acre/day.

> *"Minn. R 7020 requires that non-concrete liners for LMSAs be designed to achieve a theoretical seepage rate of no more than 1/56 of an inch per day. The required seepage standard is routinely considered to be approximately 500 gal/acre/day; however, this is slightly more than the actual 485 gal/acre/day allowed by the rule. Long-term protective and maintenance measures are required to meet this limit throughout the life of the structure."*[5]

This maximum leak-rate standard applies to manure storage facilities no matter what kind of liner is provided, including concrete, clay, Geotech (bentonite) or petroleum (plastic) liners.

It is important to note that while the MPCA rule requires this leak rate be maintained throughout the life of the pit or lagoon, and maintenance aimed at preventing greater leaking is required, there are no requirements for monitoring and actually demonstrating that the structures are not leaking more than this rate at the time of construction or after years of use and system deterioration.

[5] **Liquid Manure Storage Areas MPCA guidelines for design, construction, and operation of all types of liquid manure storage areas** – p 30 of 60, found at: https://www.pca.state.mn.us/sites/default/files/wq-f8-04.pdf

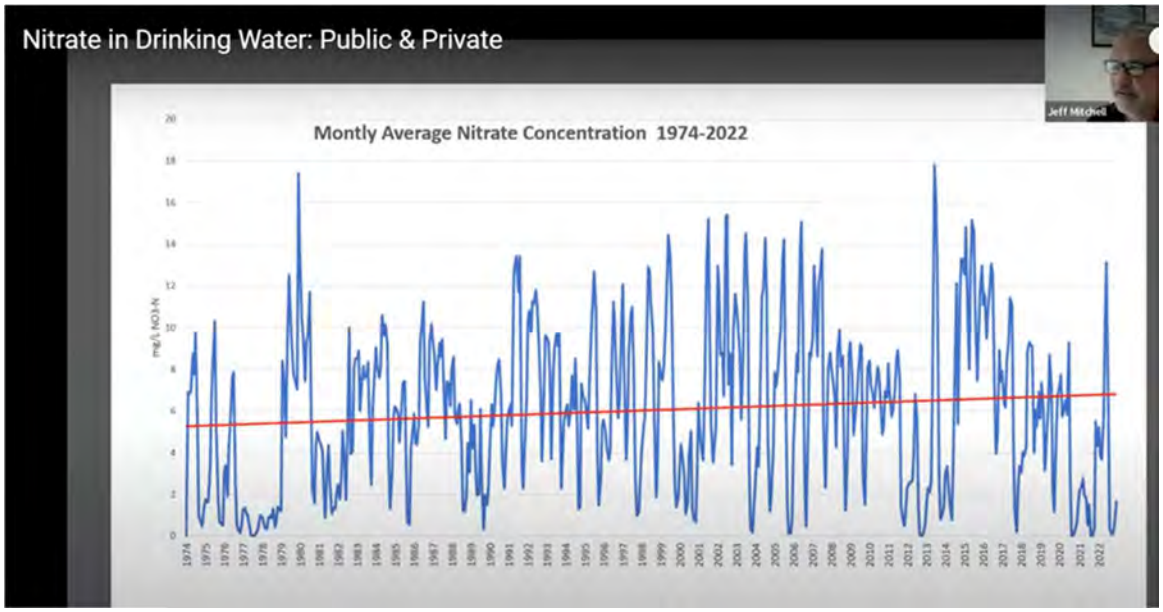

As part of the same Izaak Walton League webinar, Jesse Campbell, the Private Well Coordinator for the Midwest Assistance Program, shared information the Iowa Environmental Council had gathered about the presence of nitrate in groundwater and the challenges faced by private well users in avoiding nitrate contamination. In a 2019 Water and Land News report, Campbell revealed that "more than 6,600 private wells (12% of those tested) had nitrate averages at or above the EPA's legal limit (10 ppm) for drinking water systems and more that 12,330 wells (22%) had nitrate levels at or above 5 ppm. Natural background nitrate levels in Iowa groundwaters are generally less than 1 ppm.

Becker County, like most other rural counties, does not have private well protection strategies in place via policy or ordinances, other than well setbacks from on-site sewer systems. And private well-owners seldom, if ever, have their wells tested to see if drinking water standards are being met. If a neighbor's feed lot or CAFO should contaminate a private well, the well-owner has little recourse and will have the choices of either continuing to drink the contaminated water, purchase bottled water or drill a deeper well. In-home reverse osmosis treatment systems are effective at removing nitrates as well and may be more affordable than a new well. However, reverse osmosis technology is not designed to remove bacteria and viruses. If bacteria enter these systems, it can continually grow in pre-filters and deteriorate the osmotic membrane over time. Thus, most reverse osmosis system manufacturers specify that the system "must be used with biologically safe water".

Economic Impact of CAFOs on Rural Communities

Dr. John Ikerd[6], who holds a PhD in Agricultural Economics, now retired from University of Missouri-Columbia, in a Freshwater Futures May 15, 2024 webinar presentation entitled *"Economic Fallacies of CAFOs*[7]*,* presented the following conclusions from multiple peer reviewed studies[8]:

- 2008 Review: Reams of research dating to the 1940's shows local economies suffer economically and socially from industrial agriculture;
- 2001 Study: Many CAFO counties are forced to raise taxes to offset increased costs of repairs to rural roads and bridges;
- 2008 Study: Lower income, greater income inequality, more poverty, less active "Main Street", fewer stores, and less retail trade are found in CAFO counties;
- 2015 Study: Property values up to 7 miles from CAFO were lowered from 3.1% to 26%; while property values next to CAFOs were down 88%;
- 2022 Study: Personal incomes dropped 8% from 1982 to 2017 in Iowa counties with most CAFOs. Other rural counties with fewer CAFOs rose 41%.

Dr. Ikerd, in his own paper entitled: *Economic Realities of CAFOs*[9] draws the same conclusions and more. He includes an extensive list of reference publications that support his findings in his paper. Below are some excerpts from that paper on rural community impacts:

> *"Defenders claim that regardless of the need for CAFOs to meet the needs of consumers, CAFOs are necessary for the economic survival of many farming communities. They point specifically to community economic benefits from local investments in CAFOs,*

[6] Dr. John Ikerd - University of Missouri-Columbia, in a Freshwater Futures May 15, 2024 webinar presentation entitled *"Economic Fallacies of CAFOs*

[7] **Freshwater Futures' Great Lakes HABs & CAFO Manure Conference Series,** May 9, 2023. YouTube Recordings from the Conference can be found at: https://www.youtube.com/playlist?list=PL_JsLZuTdlRu96Q1tarJmgjsWOHEdoIYv

[8] The many studies referenced by Dr. Ikerd will be made available to all who want to read them upon request.

[9] *Economic Realities of CAFOs- Dr. John Ikerd, May, 2020 at:* https://ikerdj.mufaculty.umsystem.edu/presentation-papers/factory-farms-cafos/economic-realities-of-cafos

local sales of animals and animal products, and local employment in CAFOs and related local industries. However, decades of socioeconomic research and actual experience in CAFO communities reveal something very different. Whatever CAFOs contribute to local tax bases is more than offset by increased costs of maintaining rural roads and bridges that were not built to accommodate the heavy truck traffic associated with CAFOs. Also, local CAFOs operators typically source construction materials and labor from outside their local communities. Feeder animals, feed, and other supplies are shipped in from elsewhere. Even animal health care is typically provided by corporate veterinarians. Few of the economic benefits from CAFOs remain in local communities.

The most frequent claim for community benefits is probably that CAFOs will increase local employment, which is sorely needed in many farming communities. However, the economic reality is that CAFOs employ far fewer people per dollar invested or unit of production than do the independent family farms they inevitably displace. The first research I personally did on this subject was an evaluation of CAFOs as a rural economic development strategy. I evaluated the employment implications of PSF's planned operation in north Missouri. My conclusion was that if PSF came into Missouri, their CAFOs would displace up to three independent Missouri hog farmers for every job they created.[26] CAFOs came to Missouri, and Missouri lost more than 90% of its independent hog producers. I doubt that the number of workers employed in CAFOs in Missouri exceeds more than one-third of the independent hog farmers they displaced.

In the case of CAFOs, once livestock and poultry production became specialized, previously diversified family farms became specialized producers of either livestock or crops. Livestock and poultry were major sources of farm income that had made many diversified family farms economically viable. So, farmers who specialized in grain production were forced to farm more acres of land than before to maintain adequate family incomes. Larger crop and livestock operations meant fewer economic opportunities for farmers. With the industrialization of agriculture, the percentage of the U.S. labor force employed in agriculture dropped from 4.4% in 1970[27] to less than 1.5% in recent years.[28] Even in the communities where they locate, CAFOs do not actually

create jobs. They simply relocate and concentrate fewer lower-paying jobs in CAFO communities than had previously existed on family farms elsewhere.

In addition, this loss of farm families cannot be offset by people moving into rural communities from elsewhere. No one really wants to move to a CAFO community. A 2015 study reviewed thousands of assessed property values for residences located up to 7 miles distant from CAFOs. The review concluded: "Overall, the new studies confirm the [negative] valuation impacts reported in earlier studies, as they range from 3.1% to 26% losses depending on multiple factors, and that properties immediately abutting an AO [CAFO] can be diminished as much as 88%." [29] It takes people, not just production, to support rural communities. It takes people not only to buy farm supplies and equipment but also to shop on Main Street for cars, clothes, shoes, and haircuts. It takes people to send their kids to local schools, to attend local churches, and to serve on volunteer fire departments and local town councils. When independent family farmers are displaced by CAFOs, it's not just a matter of losing employment; it's a matter of losing the essence of what it takes to be a viable rural community."

The map below depicts the northerly progression of large confined animal feeding operations AFOs into Minnesota now stretching to the far northwestern corner of the state. [10]

[10] Source: MPCA on-line, data may not be current: https://hub.arcgis.com/datasets/mpca::feedlots-2/explore?layer=3&location=45.932764%2C-92.791165%2C6.00

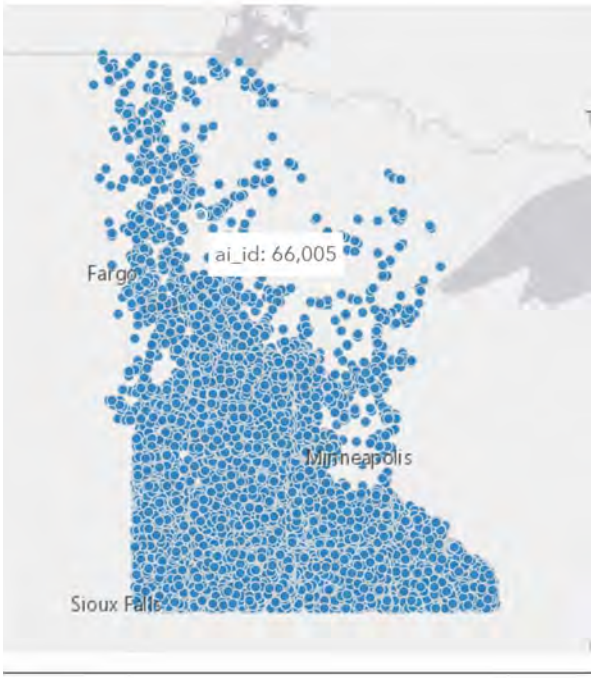

These realities highlight the importance and necessity of using local land use plans and ordinances for proper siting, inspection and monitoring of large livestock facilities, so the public can have greater confidence local economies will thrive and that pollutants are not and will not enter surface or groundwaters without detection. Becker County has set an important protective precedent by requiring water sampling for large feedlots needing conditional use permits. But the design for the water sampling regime requested lacked science-based specificity and thus did not include sufficient sophistication to assure the monitoring would accomplish the intended purpose of detecting pollution and in turn, protecting surface and groundwater.

Industrialized Food System Engenders CAFOs.

Eric Schlosser in his recent book, *Barons – Money, Power, and the Corruption of America's Food Industry* states:

> *"Over the last 250 years, almost every sector of the American economy has become dominated by a handful of corporations. The forces that drove that trend have also come together to transform the most important sector of the American economy: the food system. The way in which the United States produces and distributes is food has a profound effect on worker rights, animal welfare, air quality, water quality, the landscape, rural communities, public health, international trade, and the global climate.*

Livestock and poultry DNA are now owned, manipulated and sold to American farmers by a handful of corporations. Four companies control 66 percent of the hog genetics; three companies control 95 percent of the broiler chicken genetics; two companies control 99 percent of turkey genetics.[11]

Iowa Select Farms employes more than 7,400 people, including contractors, and brings about five million pigs to market annually. Since Iowa Select was founded in 1992, the states pig population has increased more than 50 percent while the number of hog farms has declined by over 80%. Pigs now outnumber human residents by a ratio of more than seven to one, and they produce a volume of manure equivalent to the waste of nearly eighty-four million people, more than the populations of California, Texas and Illinois combined.[12] *One expert estimated that each confinement facility produces "the same amount of waste as a city of 90,000 to 150,000 people," spread over 640 acres with no sewage system."*[13]

State and federal laws do regulate some environmental impacts of livestock operations, but other than prohibiting siting in flood plains and wetlands, these regulations do little else to control the location of this particular agricultural land use. Recent findings by the Environmental Protection Agency show that Minnesota's regulations are inadequate to protect surface and groundwaters from nitrate pollution (more details on these findings are found later in this report).

Therefore, local governments have an important role to play in the proper siting of industrial scale livestock facilities in Minnesota. And, this local government role takes on new importance now that the State and federal government's protective network has not only been found to be incomplete, but has been shown to be ineffective as well. This means that local governments must exercise their authority and responsibility for deciding if and where large livestock facilities are located in their county, in order to close this loophole in the state and federal regulatory structure.

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[11] From forward by Eric Schlosser in **Barons – Money, Power, and the Corruption of America's Food Industry –** by Austin Frederick-Island Press 2024

[12] CNBC Interview with Warren Buffet, Feb 27, 2017 quoted in "BARONS" by Fredrick – See footnote #11 above

[13] Natalie Gagliordi, "Walmart CEO outlines Omnichannel Retail Strategy to Stakeholder Associates", SDNET, June 5, 2015 as cited in BARONS by Fredrick – See footnote #11 above.

How the Clean Water Act and U.S. Farm Bill Remedies Fail to Protect Water

Under the Federal Clean Water Act, *direct* discharges of manure to surface waters from livestock holding pits and lagoons is prohibited for large Confined Animal Feeding Operations (CAFOs are over 1000 animal units). However, the controls for on-land spreading of manure from both larger CAFOs or smaller AFOs (animal feeding operations under 1000 animal units) for disposal or as fertilizer are strictly voluntary. Furthermore, penalties for discharging manure, even when it kills fish, are small, and therefore have not served as an effective deterrent; spills, leaks and ruptures continue to occur in every state that has these facilities.

Manure management plans, whether for CAFOs or AFOs, generally adopt what is known as best management practices (BMPs) for manure spreading, based on so-called "agronomic rates" of application. Such agronomic rates are designed to maximize the crop growth that is nurtured by manure application. Because these rates are designed to maximize crop production alone, it becomes clear that they are not designed for surface or groundwater quality protection. These BMPs have time and time again, been demonstrated to be ineffective, not only in Minnesota, but in a number of states and watersheds around the country.

Once surface and groundwaters are degraded by concentrated livestock feeding operations (or other source, for that matter) little can be done to reverse these impacts. Given the Becker County's location in the heart of the lake country's tourism region, degraded surface water quality has potential significant adverse economic consequences. Therefore, Becker County officials can benefit greatly from the experience of other states and regions, by insisting on more effective pollution prevention measures for feedlots in the comprehensive planning process. Chapter members are aware of other proven measures and are prepared to do further research to identify more effective pollution prevention strategies if county officials indicated their interest.

The chapter has researched other regions of Minnesota and several other states, to gather the experience of others with industrial scale agriculture, beginning with the Chesapeake Bay.

Chesapeake Bay

Over forty years ago, Chesapeake Bay watchers and state officials noticed significant water quality and aquatic life deterioration. Chesapeake Bay's watershed drains part of six states so an umbrella foundation was formed to fund and coordinate point and non-point pollution remedies. In 2004, studies investigating severely degraded water in the bay revealed the primary causes were increased nitrogen and phosphorus from several sources, but mainly from agriculture, and especially from intensive livestock agriculture. A 2004 Report by the Chesapeake Bay Foundation stated:

> *"The Chesapeake Bay is choking on nutrient pollution from a myriad of sources – from urban runoff, industry, automobiles, and human sewage, but the largest source is agriculture and, increasingly, from the manure produced by livestock, which now outnumber the watershed's human population by 11 to 1. Most of that manure is spread on the surface of nearby cropland, and studies show that within two years as much as half of its nutrient pollution washes out of the soil and into rivers and streams or seeps into groundwater. Both of these pathways lead to pollution in local waterways and, ultimately, in the Bay.*
>
> *"Of the nitrogen and phosphorus that reach the Bay, agriculture is the largest source and animal manure is the largest agricultural component. Chemical fertilizers and airborne pollutants such as ammonia gas—a common manure by-product – make up the rest of the agricultural sources. This makes animal manure not only the largest source of nitrogen and phosphorus deposited on the land, but also the second largest source that reaches the Bay, behind sewage, which is deposited directly into the water. Animal manure is a major source of the Bay's pollution and must be addressed swiftly and comprehensively.[14]"*

After the 40 years of intensive, watershed wide efforts to restore water quality from this severe degradation caused by non-point pollution, the Chesapeake Bay is barely holding its own,

[14] **Manure's Impact on Rivers, Streams and the Chesapeake Bay- Keeping Manure Out of the Water, A Report by the Chesapeake Bay Foundation** July 28, 2004 at: https://www.cbf.org/document-library/cbf-reports/0723manurereport_noembargo_7567.pdf

because crop and farm animal sources of nutrients have proven difficult if not impossible to cure. A 2024 Chesapeake Bay Foundation report[15] (that is well worth reading) states:

> *"Controlling agricultural runoff, the largest source of nutrients, has turned out to be more complex. Significant regionwide reductions have proven difficult. Data suggest, though, that efforts over the last 15 years have held the line, despite increases in crop production and growing numbers of chickens and other farm animals."*
>
> *Now, as the Bay Program celebrates its 40th anniversary, its partners are contemplating what comes after 2025, the deadline for meeting most of the 31 outcomes set in its 2014 agreement. Of those, 15 are on track, 10 are off-course and the status of four others is unclear. Nutrient goals will be missed by a large margin."*

Maumee River in Ohio and Western Lake Erie in Michigan

Lake Erie water quality improved greatly in the 1980s-90s when point sources of nutrient pollution were mostly remedied by the Clean Water Act. However, recent expansion of intensive crop and animal agriculture (factory farms) have reversed these gains, and frequent toxic algae blooms have once-again become the norm. A recent joint report by the Environmental Working Group and the Environmental Law and Policy Center states:

> *"The Maumee River, overloaded with fertilizer and manure, is the single largest source of the phosphorus that triggers blooms of toxic algae in Lake Erie. Over half of the manure in the Maumee River watershed comes from an exploding number of unregulated factory farms, a new EWG and Environmental Law & Policy Center investigation reveals.*
>
> *Outbreaks of toxic algae, fueled by pollution from manure and fertilizer from farm fields, are increasing in frequency and severity across the U.S. In 2014, a toxic bloom in Lake*

[15] **After 40 years, Chesapeake Bay Program Yields Mixed Results** – Bay Journal at: https://www.bayjournal.com/news/pollution/after-40-years-chesapeake-bay-program-yields-mixed-results/article_4af88180-92b0-11ee-9d06-ab0f3bb0d72f.html

Erie imperiled the drinking water of 500,000 residents in Toledo, Ohio. The Lake Erie outbreak, now an annual event, is getting much worse.[16]

Tim Boring, a sixth-generation farmer and Director of Michigan's Department of Agriculture and Rural Development, has bad news about Michigan's efforts to curb the farm pollution that fuels Lake Erie's toxic green algae. He finds that farm programs designed to protect water quality aren't working and that "factory-sized megafarms" are detrimental to the traditional farm economy.[17]

Lake Erie's phosphorus pollution problems have grown worse amid decades of consolidation in farm country. Diverse family farms have been steadily gobbled up by massive operations that primarily grow either cattle feed such as corn, or cows — and not on the same piece of land. The corn grown on one megafarm is shipped to a separate factory-sized livestock operation, which produces huge amounts of manure yet lacks the cropland on which cow poop becomes a valuable fertilizer.

The corn farm, in contrast, has plenty of acreage but no cows to fertilize it. So the farmer resorts to chemical fertilizers.

"It's not the problem that we have too much manure, it's that we have manure in all the wrong places," Boring said. Boring sees the state playing a bigger role in protecting small farms, which tend to grow more diverse crops while also raising livestock, and helping them succeed without expanding their acreage.

In doing so, he said, Michigan can bolster rural communities that rely on farming and food processing jobs.

Freshwater Futures based in Petroskey, Michigan recently hosted a day-long conference on CAFO manure impacts on surface and groundwater, and especially their contributions to harmful algae blooms (HABs) on Western Lake Erie. The conference was recorded and featured technical experts in all fields of concern, an attorney, a local politician, a pollution control engineer, and others. The recording of individual speakers and their PowerPoint slides can be

[16] **Explosion of Unregulated Factory Farms in Maumee Watershed Fuels Lake Erie's Toxic Blooms** at: https://www.ewg.org/interactive-maps/2019_maumee/

[17] Michigan farm czar: Our fight against Lake Erie pollution isn't working: https://www.bridgemi.com/michigan-environment-watch/michigan-farm-czar-our-fight-against-lake-erie-pollution-isnt-working

accessed at the links below. These programs would be well suited for viewing by Becker County elected officials, the Zoning Commissioners, and the public. The Izaak Walton League is prepared to co-sponsor a screening of these conference recordings, and possibly invite selected presenters to visit Becker County to explain their knowledge and first-had experience in their fields of specialty.

Great Lakes HABs & CAFO Manure Conference Series.[18]

- Great Lakes HABs & CAFO Manure Conference Recording
- Speaker Presentations - Power Point Slides

For additional questions and concerns on the conference information on how to contact speakers please contact Sandy Bihn (sandylakeerie@aol.com) or Alexis Smith (alexis@freshwaterfuture.org) Jill M. Ryan, Executive Director, Freshwater Futures.

GREEN BAY WISCONSIN – ON LAKE MICHIGAN

The Green Bay Press Gazette[19] carried this headline after covering the *Midwest Manure Summit* in Green Bay in 2019:

> *"Scientists are one step closer to understanding how dangerous contaminants from fecal matter are entering private wells in Kewaunee County. New research by U.S. Department of Agriculture microbiologist Mark Borchardt shows nitrate and coliform in the water mostly comes from agriculture — and not human waste.*

[18] See links to YouTube video recordings at the end of this report. This webinar, while useful to disclose the wide variety of environment, human health and economic problems with CAFOs may not be suitable for comp plan content. It may be better suited for a series of public education events for the Becker County Board, Planning Commission members and the public. Citizens, once well informed on CAFOs by these means can build fact-based support for the County's leaders taking appropriate actions.

[19] Green Bay Press Gazette, March 2019 by Sarah Whites-Koditschek and Coburn Dukehart -Wisconsin Public Radio and Wisconsin Center for Investigative Journalism found on line at;
https://www.greenbaypressgazette.com/story/news/investigations/2019/03/04/tainted-kewaunee-county-drinking-water-wells-tied-manure-pits/3054018002/

"Where we see the strong relationships, the strong linkages, those are with agricultural factors. So that would suggest that agriculture is primarily responsible for those two contaminants," he said in an interview.

Borchardt presented his updated findings on the risk factors associated with contamination in wells at the Midwest Manure Summit in Green Bay on Wednesday. In 2017, his research found over 60 percent of wells sampled in Kewaunee County were contaminated with fecal microbes, which can come from both septic systems or animal waste.

The new study aims to understand the precise sources of contamination and how certain factors can reduce or increase the risk of tainted drinking water. Borchardt used models to predict how those factors — like the distance of a well from a manure lagoon or agricultural field, weather and the quality of well construction — can impact contamination levels.

Borchardt's study found that the No. 1 risk factor for contamination was the proximity of a well to a manure storage pit. Borchardt said the closest well in the study was 150 feet from a manure pit, but even wells three miles away still have some risk of being contaminated with coliform."

Identifying and notifying owners of private (and public) wells within a 3-to-4-mile radius of any proposed industrial-scale feedlot may be an important public health function for consideration in Becker County's planning process for these facilities. And zoning maps that are updated to depict where large or industrial scale feedlots can be allowed by standard permit or conditional use permits could be used as a guide for a county-sponsored and targeted private-well monitoring program.

EPA Intervenes to Protect Southeast Minnesota's Ground and Surface Water – Orders Permit and Guideline Improvements

In April, 2023, citizens petitioned the U.S. Environmental Protection Agency, saying nitrate in the groundwater in southeast Minnesota's karst region — largely from fertilizer and manure applied to crop land — poses an imminent danger to human health. They asked the Federal Environmental Protection Agency (EPA) to use its emergency authority under the Safe Drinking Water Act to intervene. [20]

In response to the citizen's petition, in an August 2023 letter to four Minnesota State agencies, the EPA stated that the MPCA's permit and manure management requirements for CAFOs were inadequate and needed to be "more protective" of sensitive groundwater resources. The federal agency says state agencies need to take additional steps to protect drinking water in southeast Minnesota from nitrate contamination.

> *"While this letter is largely focused on addressing immediate health concerns regarding nitrate contamination in drinking water in the Karst Region, Minnesota must also develop and implement a long-term solution to achieve reductions in nitrate concentrations in drinking water supplies. Developing a complete understanding of potential sources of nitrate contamination is an important immediate step for the state. A risk analysis of current and future nitrate contamination of the impacted groundwater will be critical for determining long-term solutions, and such analysis should incorporate the latest science and technologies. Minnesota has tools to effect reductions in nitrate concentrations through the National Pollutant Discharge Elimination System (NPDES) and State Disposal System permit programs, including development and implementation of more protective NPDES/SDS CAFO permits. In addition, Minnesota should consider adopting monitoring requirements in NPDES/SDS permits related to (1) subsurface discharges from manure, litter, and process wastewater storage, as well as (2) discharges from land application, similar to those proposed by EPA as modifications to* the EPA-issued CAFO general permit for Idaho: https://www.epa.gov/npdes-*permits/npdes-general-permitconcentrated-animal-feeding-operations-cafos-idaho.*

[20] EPA says 'further actions' needed to protect human health from nitrate in southeast Minnesota by Kristi Marohn - November 8, 2023 at: https://www.mprnews.org/story/2023/11/08/epa-says-further-actions-needed-to-protect-human-health-from-nitrate-in-southeast-minn

> *We also encourage Minnesota to consider modifications to the state's Technical Standards for Nutrient Management with regard to land application of manure, litter or process wastewater, and any Minnesota guidelines for land application of commercial fertilizer, specific to Karst areas.*[21]

In response to the citizen petition and an order from the EPA, MPCA has drafted revised permit conditions and manure management rules for large CAFOs, but the draft rules are drawing strong criticism from experts for falling far short of what the EPA ordered and what is needed to protect the state's waters, and private well-owners. This is especially true in sensitive ground water and high value surface waters (trout streams) in S.E. Minnesota, and the central sand plains area, which includes eastern Becker County.

The Straight River is known as a premier trout stream although trout populations and species have declined and shifted to more tolerant species (i.e. Brown trout rather than Brook Trout.) Soils in the area known as the Ponsford Prairie consist primarily of glacial outwash sands and gravel, where the shallow ground water is not protected by less porous clay or silty soil layers nearer the surface. Many private wells in this rural area were developed to use these shallow waters because these wells are lower in cost than deeper water aquifer wells, and this water historically was fairly high quality in spite of its vulnerability to pollution from various land uses like those described above.

Minnesota Outdoor News published an article in July, 2024[22] that quoted a groundwater hydrologist who is focused on private well owner interests:

> *Jeff Broberg is a founder of the Minnesota Wells Owners Organization and former president of the Minnesota Trout Association. Broberg, who lives in southeastern Minnesota, said the new proposed rules on the two feedlot permits are welcomed but long overdue and don't go far enough.*
>
> *"I'm pleased that the MPCA is finally starting this effort," said Broberg, adding that*

[21] US Environmental Protection Agency August 2023 Letter to Minnesota Agencies found at: https://www.epa.gov/system/files/documents/2023-11/ao-rmod-reponse-letter_20230510-508.pdf

[22] **MPCA Seeks Comments on Plan to Curb Pollution in State Waters** -Outdoor News Minnesota, Vol. 57, No. 29, Page 1 By Tori J. McCormick

Minnesota's "regulatory environment for feedlots is far too friendly."

"I'm dubious that it will have any effect. But we'll see," he said.

Broberg said if the MPCA is serious about tackling nitrate contamination in state lakes, rivers, and streams, the agency needs to better regulate all state feedlots – not just the largest 1,000. That's a sentiment shared by other state groups, including the Minnesota Center for Environmental Advocacy and Land Stewardship Project.

"Feedlots are altering our environment and our public health," said Broberg, who urged water quality advocates of all stripes to comment on the proposed changes to MPCA feedlot permits. "We need to recognize that … and how our surface and groundwater are so vulnerable and being impacted."

A similar petition to EPA has recently been filed by citizen groups in the Northeast corner of Iowa, where nearly identical topography and groundwater sensitivity exist. Private wells and public water treatments systems in this and other parts of Iowa, have experienced rapidly increasing nitrate concentrations in both ground and surface waters. In an article posted in their publication[23] Food & Water Watch staff attorney Dani Replogle said:

"The state's failure to regulate industrial agriculture pollution has steadily eroded Iowans' right to clean drinking water. For decades, Northeast Iowa residents have been exposed to dangerous levels of nitrate contaminated water. As the state reckons with high cancer levels and ongoing pollution regulation rollbacks, federal action is needed to safeguard the right to clean water. EPA must exercise emergency authority to hold polluters accountable and deliver safe drinking water in Iowa."

With this information and the additional reference material below, Becker County can benefit from other's experiences and take more effective planning and zoning actions to avoid the predictable outcome of industrial-scale agriculture migrating into the county without the necessary safeguards and monitoring in place.

Becker County's sensitive surface and groundwater regions include its eastern Becker County sand plain areas, with its high value trout streams, its more highly developed central lakes area, and its western agricultural areas served by extensive patterned drain tile and drainage ditch

[23] https://www.foodandwaterwatch.org/2024/04/16/iowa-environmental-groups-petition-epa-for-emergency-action-on-iowa-drinking-water/

systems. Having sufficient, pre- and post-CAFO project construction ground and surface water monitoring in place, can be a useful tool for holding industrial agriculture accountable for its operations and providing the assurances Becker County citizens need to keep from reliving the regretful experience of others.

The MNDNR has recently completed a groundwater atlas for Becker County that could serve as a preliminary baseline for groundwater quality before industrial livestock agriculture has a greater impact. Groundwater sensitivity maps are also available from the MPCA. The MPCA also publishes an impaired (surface) waters list that is updated and submitted to the EPA and released to the public periodically. This information, along with the Watershed Restoration and Protection Plans (WRAPS) co-produced by the MPCA and local water management entities, provides much of the historical background information on water quality in Becker County. Here again, this background information can be used proactively to gauge and even predict the water quality trends attributable to increases in industrial agriculture, both in crops and livestock.

These realities highlight the importance of using local land use plans, zoning maps and ordinances for proper siting, inspection and monitoring of large livestock facilities, where the public can have greater confidence that pollutants are not and will not enter surface or groundwaters.

Importance of Water Sampling and Monitoring

The feedlot industry persistently claims that manure management plans limited to "agronomic rates" of application are sufficient to protect surface and groundwaters. The information presented in sections above demonstrate that this is not true.

One of the best strategies to test the performance of such plans is to actually monitor the water. New Mexico began requiring performance monitoring for large confined dairy operations as early as the 1990's. During the first six years of monitoring, significant increases in ammonia and nitrates were found in groundwater. A 1999 state agency report entitled: *Dairy Feedlot Contributions to Groundwater Contamination - A Preliminary Study in New Mexico* states:

"Feedlot milk production has increased dramatically in New Mexico in the past decade, along with the potential for groundwater contamination from animal wastes. State statutes require animal feedlots to maintain groundwater-monitoring wells and report water quality analyses quarterly to the New Mexico Water Quality Control Commission. This preliminary study analyzed six years of groundwater quality data from seven dairy feedlots and found elevated levels of nitrate, ammonia, chloride, total Kjeldahl nitrogen, and total dissolved solids. Samples were obtained from groundwater-monitoring wells located around dairy wastewater lagoons that were lined with clay, concrete, or synthetic membranes. Mean nitrate concentrations were significantly higher in groundwater samples taken in the vicinity of lagoons with clay liners. Lagoons with synthetic liners produced the lowest mean groundwater concentrations of ammonia and nitrate. Mean concentrations for all contaminants tended to increase as the size of dairy herds increased. Nitrate was the only groundwater contaminant measured that showed a consistently increasing trend from 1992 to 1997. [24]

In 2015, the state adopted the Dairy Rule, which requires dairies to monitor groundwater impacts and to line waste lagoons. The rule came following a 2009 study by NMED's Groundwater Protection Division that found 60 percent of the state's dairies were polluting groundwater. [25]

The Public Engagement Survey used to gauge citizen priorities for the current land use planning effort found that 70% of Becker County citizens thought more should be done to protect the water quality of lakes and streams.

Becker County has already set an important protective precedent by requiring a modicum of water sampling for large feedlots needing conditional use permits. But the water sampling required in a recent Conditional Use Permit lacks sufficient sophistication to ensure the

[24] **Dairy Feedlot Contributions to Groundwater Contamination - A Preliminary Study in New Mexico** – Sept, 1999. At:
https://go.gale.com/ps/i.do?id=GALE%7CA55884900&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=00220892&p=HRCA&sw=w&userGroupName=anon%7Ee4bab884&aty=open-web-entry

[25] **New report looks at dairy operations in NM** -March 29, 2022
https://nmpoliticalreport.com/news/new-report-looks-at-dairy-operations-in-nm/

monitoring would provide useful information. Becker County could take a page from the New Mexico playbook and begin to require "performance monitoring" from new or expanding AFOs and CAFOs.

The comprehensive plan could present guidelines or suggest qualified consultants for designing appropriate ground or surface water monitoring regimes. Monitoring has been shown to clearly gauge the effectiveness of manure lagoon or pit containment and manure management plans that are supposed to protect both the surface and ground waters of the county. As has been found in New Mexico and Wisconsin, state and federal rules have, thus far, not proven effective enough. So, water quality monitoring, may be the county's best defense to protect the public's health.

MANURE PIT OVERFLOWS BECOME MORE FREQUENT WITH CHANGING WEATHER PATTERNS

Manure spills and pit overflow incidents present serious pollution risks to receiving waters and to human health. Risks that are increasing as the number of CAFOs increase and severe storms with high rainfall amounts increase in frequency under changing climate conditions. In June of this year seventeen CAFO owners were obliged to report overflows after heavy rains occurred in southern Minnesota. The state's largest feedlots, which include dairies and pig and turkey operations that have roughly 1 million pounds of total livestock or more, are required to report any manure overflows to the state. There are about 1,000 feedlots of that size in the state. State regulators ask smaller farms to report overflows as well, but they are not required to."

The Minneapolis Tribune account[26] of these overflows is quoted here below:

> *"Relentless rains this month have caused 17 manure pits at 15 large farms in southwestern Minnesota to overflow, releasing livestock waste into the environment.*

[26] **Seventeen manure pits reportedly overflow at large feedlots in southern Minnesota**
Heavy rain has spilled an unknown amount of livestock waste into the environment. By Greg Stanley
Star Tribune JUNE 26, 2024. At: https://www.startribune.com/manure-pits-reportedly-overflow-at-16-large-feedlots-in-southern-minnesota/600376074

The overflows, all at open pit lagoons, happened in Rock, Nobles and Jackson counties, said Andrea Cournoyer, a spokeswoman for the Minnesota Pollution Control Agency (MPCA). The agency is working to monitor and mitigate any potential damage from the spills, she said.

High concentrations of manure can be dangerous to human health and can cause fish kills and threaten water quality even after floodwaters recede. But the manure in the basins overflowing from the extreme rainfall is heavily diluted, said Randy Hukriede, feedlot program manager for the MPCA. None of the basins that overflowed contained pure manure.

Manure pit overflows in Southeast Minnesota and Iowa have been linked to numerous fish kills. An Investigate Midwest report[27] in 2023 stated:

"Over the past four decades, 35% of fish kills are related to the state's primary industry — agriculture, according to an Investigate Midwest analysis of state data from 1981 to 2022."

What causes the fish kills in Iowa waterbodies?

Over four decades, animal wastes and fertilizers have been responsible for 34% of fish kill events.

[27] **Animal waste and agrochemicals are leading cause of fish kills in Iowa waterways**
Agriculture is the lifeblood of Iowa, but it also contributes to mass die-offs of fish in the state's waterways.
https://investigatemidwest.org/2023/06/01/animal-waste-and-agrochemicals-are-leading-cause-of-fish-kills-in-iowa-waterways/

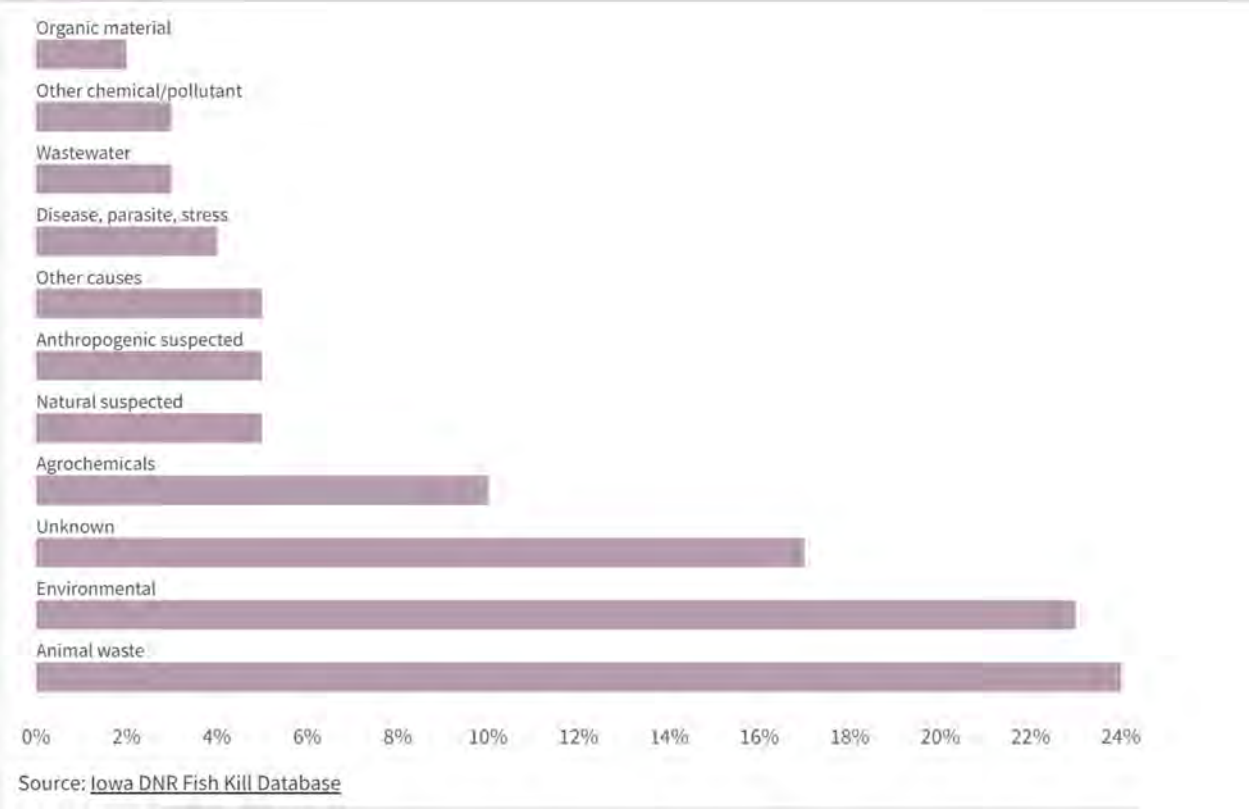

Becker County has experienced similar increases in frequency and severity of storms dropping 3-6 or more inches of rain in a single event so it is predictable that manure pit overflows and potential fish kills will occur in our area. It is reasonable to predict that these risks will continue to increase if the number of CAFOs is allowed to grow given our changing climate in Becker or any other state or county.

CAFOs DEMAND LARGE QUANTITIES OF GROUND WATER

Industrial scale animal agriculture concentrates livestock in small areas and must extract all the water these animals need from just one or two wells. Large groundwater extraction from aquifers that are either small or are slow to recharge can cause supply problems for neighbors who rely on the same aquifer.

Some compare the water demands of CAFOs to that of small cities. One cow (one animal unit) consumes as much water as four adult humans. Therefore, a 10,000 cow CAFO requires as

much water as a city of 40,000 people. Becker County's population was 35,183 (2020 census), so just one industrial size CAFO would demand more water than all the people in the county.

State rules for protecting aquifers from over-extraction are fragmented and have been shown to be ineffective at protecting individual well-owners whose wells go dry or suffer reduced yield. One of the earliest systematic reviews of the CAFO impacts was found in a 2019 paper entitled: *WATER USE IN CONFINED ANIMAL FEEDING OPERATIONS (CAFOS) IN MINNESOTA: WHO'S KEEPING TRACK?* by Dara Meredith Fedrow. In his graduate thesis, prepared for Minnesota's Land Stewardship Project, Fedrow analyzed how effective Minnesota's water appropriation permit system was in overseeing water usage by large CAFOs. This research, conducted to inform the work of Land Stewardship Project (LSP), which is an advocacy nonprofit based in Minnesota, was published to inform state government agencies, water researchers, and local citizens. The entire paper can be read at the link in the footnote[28] below. Fedrow cites research by others that warned that:

> *"Groundwater is unequally distributed throughout Minnesota which can pose issues as agricultural groundwater use increases. Groundwater pumping is unsustainable in some parts of Minnesota and could deprive ecosystems and humans of water needed to survive."*

One of the recommendations Fedrow offers that is useful for the Becker comprehensive planning effort, is inserted here below.

> *"New areas of CAFO development should be watched closely to ensure CAFOs are obtaining the proper permits and for their impacts to the surrounding communities and watersheds. Hog CAFOs are reporting increasingly more water use in the south eastern part of Minnesota. This is particularly apparent in Mower and Steele Counties, corresponding to the Cannon River, Cedar River, and Upper Iowa River. Dairy CAFOs*

[28] *WATER USE IN CONFINED ANIMAL FEEDING OPERATIONS (CAFOS) IN MINNESOTA: WHO'S KEEPING TRACK?* by Dara Meredith Fedrow accessed on line at https://scholarworks.umt.edu/cgi/viewcontent.cgi?article=12430&context=etd

appear to be opening in Norman and Kandiyohi counties. Norman county corresponds to a large percent increase in use of the Wild Rice River."

Fedrow's paper is recommended reading for those who seek to know more about CAFOs' demand for water, and the regulatory and societal problems foreseen for the ever-increasing demands on Minnesota's limited "clean" water supplies by industrial animal agriculture.

Becker County could use is Comprehensive Plan to alert well-owners to potential groundwater drawdown in the vicinity of proposed CAFO sitings and assist rural home-owners in monitoring their wells for signs of draw-down that may be caused by the facility. Well water levels could be added to a nitrate and fecal coliform county-wide well-monitoring program similar to the Midwest Assistance Program in Iowa. This program obtained grant funds to initiate and maintain the Iowa private well monitoring. The IWLA Chapter is willing to assist Becker County in designing a similar program and seeking the necessary grant funds to implement and maintain it.

Meanwhile, Becker County should request that MDNR monitor stream flows to establish the background and trend levels necessary to detect changes in critical low steam flows attributable to large groundwater appropriation by CAFOs. Low stream flows can impact Becker County's recreation and tourism economies including river-tubing, kayaking, canoeing, wildlife watching and stream fishing.

Ordinary Small Farmers Can Get Financially Trapped and Even Punished by the Industry

Conventional scale (small) farmers are not at fault or in any way to be blamed for being attracted to the offers from the industry representatives. With persistently narrow profit margins it makes a lot of sense to scale up and grow overall profits even though margins remain slim. But once "in the contract system" farmers all too often discover they are on a financial treadmill that is extremely difficult to escape. Some who try unsuccessfully to escape have suffered retribution from the industry. Some farmers who once were "contract farmers" are speaking out to alert

others of the risks and their efforts to transition back out. Modern Farmer's on-line magazine published one farmer's story.

> *When Paula and Dale Boles took over Dale's father's farmland in North Carolina, they thought that poultry farming would be a good way to work the land until they were ready to pass it on to their children. They obtained a contract with Case Farms, eventually switching over to Tyson, and built two poultry barns to company specifications, going $300,000 in debt to do so. It seemed like a good situation, though—as long as they could make their annual mortgage payment of $40,000, they'd be able to pay it off within 10 years.*
>
> *But soon, other expenses started getting tacked on. Tyson required a new computer system to control the temperature in the barns. This was another $70,000. Their propane bill averaged around $25,000 per year. Not making the updates wasn't really an option—no matter how much time and money you invested to be a farmer for the company, they could cut your contract at any time.*
>
> *And the income wasn't quite what they expected. Companies like Tyson pay their farmers in what's called a tournament system. There's a base pay, but whoever raises the best flock and has the best "feed conversion"—the biggest birds for the least feed— makes the most money, and payment decreases the further you go down the ladder. This essentially pits all the regional farmers against each other.*
>
> *"While contract farming, or "factory farming," has been exposed in the media for being exploitative of animals, the farmers who sign contracts with companies like Tyson, Perdue or other big players in animal agriculture also find themselves backed into a financial corner. But, over the last several years, there has been a wave of efforts to find ways to support farmers transitioning out of factory farming.*
>
> *"The way that the current structure of factory farming is designed is that the steps that carry with it the most risk and the most debt and the most liability are transitioned to the farmers," he says. "And so what you have is you have farmers building these extremely expensive facilities at the very specific direction [and] design of the company that they're working for. But they don't own the animals.*[29]

Antibiotic Resistance Linked to Feedlots

Becker County may not have the authority to address or curb the contribution of large animal feeding operations to antibiotic resistance, but the Comprehensive Plan could provide or suggest

[29]**They Once Worked in Factory Farming. Not Anymore.** Modern Farmer, May 07, 2024 at: https://modernfarmer.com/2024/05/they-once-worked-in-factory-farming-not-anymore/

tools to educate the public about the problem. This in turn could influence policy-makers at the appropriate level of authority to take remedial steps.

> *A **report** in 2020 by the Natural Resources Defense Council (NRDC), reveals that US cattle producers use more than 40% of all medically important antibiotics—those that are also used in human medicine—sold for use in US livestock, and use them three to six times more intensively than many of their European counterparts.*
>
> *NRDC says this overuse of antibiotics is a strategy used by the beef industry to offset heightened disease risks in feedlots, where cattle are routinely fed antibiotics to prevent disease whether or not they are ill, a practice that the World Health Organization discourages and that the European Union will no longer allow starting in 2022.*
>
> *The reports also argues that there is little transparency or accountability in the beef industry regarding its use of medically important antibiotics, and little urgency to rectify the problem.*
>
> *"Many infectious disease and antibiotic resistance experts believe such use is improper and helps contribute to reservoirs of drug-resistant bacteria on farms that can spread easily to humans through consumption of meat, exposure to soil or water contaminated with manure containing antibiotic-resistant pathogens, or contact with animals. They also worry that it reduces the effectiveness of antibiotics that are needed to fight infections in people."*[30]

This concludes our report. There are several other issues relating to large feedlot pollution problems that time did not allow Chapter researchers to investigate fully enough for inclusion here. While we make general references to the health impacts of nitrates that exceed regulatory standards, there is growing evidence that the standards are not seen as being fully protective of human health and linking nitrates to certain cancer risks.

[30] https://www.cidrap.umn.edu/antimicrobial-stewardship/report-slams-beef-industry-overuse-antibiotics

Also, there could be a chapter in the plan that informs citizens about the risks to public health when storms cause overflows of these storage facilities. A derecho or other storm or series of storms like those that occurred in S.E. Minnesota recently, could have similar impacts here in Becker County.

This concludes this report.

The IWLA Chapter, at the invitation of the planning consultants is preparing a narrative based on this and the Wake Boat Report for inclusion in or attachment to the draft Becker County Comprehensive Land Use Plan. Additional sources of information compiled by the League are shown below.

SOURCES OF OTHER USEFUL INFORMATION AND PUBLIC EDCUCATION TOOLS ON CAFOs.

The IWLA Chapter members compiled other authoritative reference materials, including video interviews with groundwater experts, lawyers, and citizens from Minnesota and neighboring states, that provide testimonials on their knowledge and experience with AFOs and CAFOs. Some of the content includes discussion of local economic impacts and describes how other local units of government are working to adopt plans and ordinances to address industrial scale feedlots. Interactive MPCA maps of feedlot locations in Minnesota are also provided.

Izaak Walton League Chapter Produced Videos with CAFO experts and Citizen Testimonials at: https://drive.google.com/file/d/17fEX-Wfztuq39zN4T4uXgnFkLOzasGNf/view

Freshwater Futures' Webinar - Great Lakes HABs & CAFO Manure Conference Series | May 2, 2024 Freshwater Future
https://www.youtube.com/playlist?list=PL_JsLZuTdlRu96Q1tarJmgjsWOHEdoIYv

Explosion of CAFOs in Iowa and its Impact on Water Quality and Public health at:
https://roadactivist.org/wp-content/uploads/2018/01/Explosion-of-CAFOs-in-Iowa-and-Its-Impact-on-Water-Quality-and-Public-Health.pdf

Economic Realities of CAFOs – Dr. John Ikerd - University of Missouri-Columbia at:
https://ikerdj.mufaculty.umsystem.edu/presentation-papers/factory-farms-cafos/economic-realities-of-cafos

Antibiotic Use in Animal Medicine and Antibiotic Resistance.
https://www.cidrap.umn.edu/antimicrobial-stewardship/study-predicts-global-increase-antimicrobial-use-food-producing-animals

https://www.cidrap.umn.edu/antimicrobial-stewardship/report-slams-beef-industry-overuse-antibiotics

RECEIVED
By: OAH on 7/22/2025

7020 Rule comment

I have grown up on a family farm in southeast Minnesota. My wife and I now farm with our son and his wife and their 3 daughters. It is very important to our family that we have clean water. We raise hogs in Fillmore County and also raise corn, soybeans and hay. MPCA has implemented rules that all livestock producers must follow. There are some rules and setbacks that are exclusive to the karst region of Minnesota. These current rules make sense for everyone and are easy to understand and follow.

Family farms work hard to be good stewards of land, following many Best Management Practices, and follow many rules set forth in MPCA guidelines.

When it comes to BMP's one size does not fit every farm. It's important to have several options to fit a wide variety of farms. One example of this is that cover crops do not fit everyone. I think it's important to have the option to use a nitrogen stabilizer instead.

The 7020 rules need to serve as a baseline for all feedlots in the state and be based on sound and accepted science and soil and geographic conditions. The rules should take into consideration other requirements like including riparian buffers as part of the setback distances and the required set backs from karst features in our corner of the state.

Thank you for the opportunity to comment

Dave Mensink

RECEIVED
By: OAH on 7/22/2025

From: Mike Tauber
To: Moore, William (He/Him/His) (OAH)
Subject: unable to load feedlot comments
Date: Wednesday, July 23, 2025 8:07:26 AM

You don't often get email from mjtauber42@gmail.com. Learn why this is important

This message may be from an external email source.
Do not select links or open attachments unless verified. Report all suspicious emails to Minnesota IT Services Security Operations Center.

Hello Mr. Moore,
I am trying to use the granicus portal to load our **Cass County Minnesota Chapter of the Izaak Walton League of America** Comments on Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, chapter 7020, Revisor's ID Number R-04928.
It seems that the email validation process is not working at this time.
Please see that these comments find their way to the appropriate staff. I cannot be on the computer anymore as I am heading to work.
Thanks much,
Mike Tauber

7-20-25

https://minnesotaoah.granicusideas.com/discussions

OAH attn: William Moore

OAH600 N Robert St.

PO Box 64620St. Paul, MN 55164-0620

Cass County Minnesota Chapter of the Izaak Walton League of America Comments on Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, chapter 7020, Revisor's ID Number R-04928

Any changes to the current inadequate rules governing feedlots in Minnesota should consider the following. References and citations are excluded for brevity, and with the understanding that reasons for the rules changes are well established and have been for decades. Thorough investigations and rules must be in place before feedlots are permitted, before manure applications take place. This is vital to preserve the public health of all local citizens.

1.

The Cass County Minnesota Izaak Walton League Chapter has members with direct experience of soil and water contamination due to industrial agriculture operations on the vulnerable soils of the Pineland Sands. The effects of row cropping and CAFOs

are easily understood to be the largest contributors to water contamination, and the effects are very predictable before operations begin. Many tools are available for risk assessment of industrial ag in Minnesota. These should be employed before feedlots are permitted and the responsibility for remediation of any contamination of surface or groundwater should be established beforehand. Some soils of the state are simply not able to handle large feedlots, areas such as karst or sandy, outwash plains like the Pineland Sands. The most vulnerable soils need the most protection.

2. Any existing or potential feedlot will have a connected row cropping activity for feedstocks. These operations have been shown to be quite problematic for water quality without feedlots involved, therefore a feedlot should be considered as a risk multiplier for water contamination due to associated row cropping.

3. Any feedlot of 100 animal units or more should be considered a CAFO with an inherent risk of contamination of resources.

4. All feedlots should begin composting manure immediately. This would create a resource instead of a liability.

5. A bioremediation plan for any spills or contamination associated with feedlots and row cropping should be established beforehand. A bond could be issued by feedlot owners to the state to aggregate funds for such. A ¨polluter pays¨ approach is justified.

6. Water testing should be done in advance (to establish baselines) and during operations of feedlots. A detrimental effect on water quality or quantity should be grounds for rescinding permits.

7. Livestock access to water such as riverbanks should be prohibited. Manure brought directly to water bodies is unacceptable.

8.

A feedlot rehabilitation/retirement plan should be created for instances where a feedlot demonstrates a repeated deleterious effect on neighboring resources or properties. CAFOs are well known to have a negative effect on neighboring property values.

Thank you for considering these items. Should there be questions regarding these comments feel free to contact :

Cass County Minnesota Chapter of the Izaak Walton League of America

Secretary Mike Tauber

mjtauber42@gmail.com

218 675 5717

RECEIVED
By: OAH on 7/22/2025 11:18am
Akilah SandersReed Attachment 2

Minnesota Center for Environmental Advocacy

**Comments to Minnesota Pollution Control Agency on
Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules Chapter 7020,
Revisor's ID Number R-04928**

July 22, 2025

I. Introduction

Minnesota Center for Environmental Advocacy ("MCEA") appreciates the opportunity to submit these comments on the Minnesota Pollution Control Agency's ("MPCA") planned amendments to the rules governing animal feedlots, Minnesota Rules ch. 7020 ("Animal Feedlot Rule"). Minnesota has more than 20,000 feedlots, which produce 49 million tons of manure each year.[1] This manure, when stored in massive lagoons or spread on fields as fertilizer, runs off into surface waters, leaches into groundwater, and volatilizes into the air, ultimately polluting Minnesota's waters with dangerous bacterial coliforms and nutrients, particularly nitrate. The Animal Feedlot Rule, which governs these feedlots in order to limit discharges of pollutants, has not been comprehensively revised for 25 years. During that time, feedlot practices and our knowledge about nitrate pollution have changed significantly—but nitrate pollution in the state remains widespread, persistent, and dangerous to the health of Minnesota's residents and its rivers, lakes, and streams. Both MPCA and the U.S. Environmental Protection Agency ("EPA") have acknowledged that the state's current approach is not sufficient to address nitrate pollution in the state's surface waters and groundwater.

[1]Ethan Bahe, *Five Years After EWG's First Analysis, Manure Still Overloads Minnesota*, Environmental Working Group (May 15, 2025), https://www.ewg.org/research/five-years-after-ewgs-first-analysis-manure-still-overloads-minnesota (MCEA Ex. 23) ("EWG, Manure Overloads Minnesota").

In this context, MPCA has proposed considering changes to the Animal Feedlot Rule. To protect Minnesota's health and environment, and to comply with the strict protections for surface waters and groundwater in Minnesota law, MPCA must make significant changes to the Animal Feedlot Rule, including the following:

- Require State Disposal System Permits for feedlots with more than 600 animal units.
- Require Manure Management Plans to be submitted through the online Nutrient Management Tool for feedlots with more than 300 animal units, including feedlots from out of state that apply manure in Minnesota, and make manure application information from the online tool publicly available.
- Require monitoring of feedlot production areas and land application areas, including visual inspections for surface discharges, and underground monitoring for subsurface discharges based on the requirements of a Subsurface Discharge Monitoring Plan.
- Require additional best management practices for fall application of manure in Vulnerable Groundwater Areas, similar to practices required by the revised feedlot water pollution permits.
- Prohibit risky manure application practices statewide by (1) requiring larger setbacks from sensitive features, (2) prohibiting application of manure on frozen or snow-covered ground, and (3) prohibiting manure application when the risk of runoff from rainfall is high.
- Reduce allowed manure application rates to the rates recommended by the University of Minnesota Extension Service, with no deviations allowed or use of rates from contiguous states.
- Explicitly prohibit discharges from production areas or land application areas that may limit the use of groundwater as a potable water supply or may pollute the underground waters.
- Prohibit livestock from all feedlots from entering waters of the state, or at a minimum livestock from medium and large feedlots.
- Ensure multiple feedlots are considered a single feedlot for purposes of permit determinations when they (1) have common ownership, including ownership by entities that share some common owners, and (2) are located within three miles of each other or share a common liquid or solid manure storage area.

II. Minnesota has an ongoing nitrate pollution crisis, and a major source is manure from feedlots

Nitrogen is a nutrient that is applied to crops, in the form of animal manure or commercial fertilizer, to help them grow.[2] Once it has been applied to cropland, some of the nitrogen converts to different forms, including nitrate and ammonia, that can be used by plants.[3] When commercial fertilizer and manure are applied to croplands at too-high rates, at inopportune times, in vulnerable areas or near sensitive features, some of the nitrate may not be taken up by crops.[4] Nitrate is highly soluble in water, and it moves easily through soil, so unused nitrate is likely to leach through the soil and ultimately enter the groundwater.[5] As MPCA has stated, "[I]f it is not managed correctly, manure can result in pollution, and it can be a threat to human health."[6]

A. Nitrate is dangerous to humans, animals, and aquatic life

When too much nitrate makes its way to surface waters and groundwater, it endangers human health and aquatic life. [7] For humans, federal and state regulatory standards set the limit for nitrate in drinking water at 10 mg/L.[8] Drinking water with nitrate levels above this limit can cause methemoglobinemia, or blue-baby syndrome, which can lead to severe injury or death,

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[2] MDA, *Groundwater Protection Rule Statement of Need and Reasonableness* 10 (April 30, 2018), https://www.mda.state.mn.us/sites/default/files/2018-08/sonargwprule.pdf ("Groundwater Protection Rule SONAR").
[3] *Id*. at 11.
[4] *See* MDA, *Nitrogen Fertilizer Management Plan* 40 (March 2015), https://www.mda.state.mn.us/sites/default/files/inline-files/NFMP%202015.pdf ("2015 Nitrogen Fert. Mgmt. Plan").
[5] Groundwater Protection Rule SONAR at 12, 85; Minn. Pollution Control Agency, *Animal Feedlot Rule Statement of Need and Reasonableness* 14 (Dec. 8, 1999), https://www.winonacounty.gov/DocumentCenter/View/1688/MN-Feedlot-Rule-7020-SONAR-PDF ("1999 Feedlot Rule SONAR").
[6] MPCA, *Animal Feedlot Rule Statement of Need and Reasonableness* 2 (May 20, 2013), https://www.leg.mn.gov/archive/sonar/SONAR-04109.pdf.
[7] MPCA, *The Condition of Minnesota's Groundwater Quality*, 2013-2017, at 13 (July 2019), https://www.pca.state.mn.us/sites/default/files/wq-am1-10.pdf.
[8] 40 C.F.R. § 141.62(b)(7); Minn. R. 7050.0221, subps. 2-4 (incorporating the federal standard).

particularly for infants or pregnant people.[9] Recent research, however, has demonstrated that long-term exposure to nitrate levels well below the 10 mg/L limit is also linked to serious health risks.[10] Peer-reviewed medical research demonstrates that exposure to nitrate at or above 3 mg/L—less than one-third of the 10 mg/L limit—is linked to a variety of cancers, birth defects, and pregnancy complications. Numerous human-based epidemiological studies now show that exposure to nitrate at levels below the 10 mg/L limit and as low as 3 to 5 mg/L leads to a statistically significant increase in the risk for colorectal cancer,[11] thyroid cancer,[12] ovarian cancer,[13] and pregnancy/birth complications.[14]

In addition, the MPCA has concluded that nitrate levels of more than 5 mg/L for cold waters and 8 mg/L for other waters are unsafe for aquatic life, although it has not adopted a water quality standard based on this conclusion.[15] For ammonia, another form of nitrogen, Minnesota has set an aquatic life water quality standard of 4.1 mg/L for cold waters and 10.1 mg/L for other waters, but MPCA has recommended adopting EPA's even stricter, temperature-dependent standards for total

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[9] MPCA, *The Condition of Minnesota's Groundwater Quality, 2013-2017*, at 13 (July 2019), https://www.pca.state.mn.us/sites/default/files/wq-am1-10.pdf.

[10] Groundwater Protection Rule SONAR at 63; MPCA, *Nitrogen in Minnesota Surface Waters* A2-7 (June 2013), https://www.pca.state.mn.us/sites/default/files/wq-s6-26a.pdf ("Nitrogen in Minnesota Surface Waters").

[11] Nadia Espejo-Herrera et al., *Colorectal cancer risk and nitrate exposure through drinking water and diet*, 139 Intl. J. of Cancer 334-346 (2016) (MCEA Ex. 1); Jorg Schullehner et al., *Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study*, 143 Intl. J. of Cancer, 73-79 (2018) (MCEA Ex. 2).

[12] *See* Mary H. Ward et al., *Drinking Water Nitrate and Human Health: An Updated Review*, Intl. J. Envtl. Research and Public Health 12 (2018) (internal citations omitted) (MCEA Ex. 3).

[13] *See* Maki Inoue-Choi et al., *Nitrate and nitrite ingestion and risk of ovarian cancer among postmenopausal women in Iowa*, 137 Intl. J. of Cancer, 173-182 (2015) (MCEA Ex. 4).

[14] *See* Ward et al., *Drinking Water Nitrate and Human Health: An Updated Review* (internal citations omitted) (MCEA Ex. 3); Jason Semprini, *Early prenatal nitrate exposure and birth outcomes: A study of Iowa's public drinking water (1970-1988)*, PLOS 4(6) (2025) (MCEA Ex. 5).

[15] MPCA, *Aquatic Life Water Quality Standards Draft Technical Support Document for Nitrate* (Oct. 2022), https://www.pca.state.mn.us/sites/default/files/wq-s6-13.pdf.

ammonia nitrogen.[16] Excess nitrate is toxic to fish and other aquatic life, and elevated levels of nitrate and other nutrients in surface waters cause algae blooms and eutrophication, which harm aquatic life by lowering oxygen levels in the water.[17] Exposure to nitrate and ammonia at toxic levels can lead to massive fish population die-offs, called "fish kills." In heavily agricultural areas, fish kill events have increased in intensity and frequency: the Rush Creek fish kill in July 2022, where MPCA concluded contaminated runoff killed more than 2,500 fish, was the fourth major fish kill in the Winona County area since 2015.[18]

Unfortunately, the effects of nitrate pollution do not stop in Minnesota. The 158 million pounds of nitrate that leave Minnesota annually via the Mississippi River are in part to blame for the hypoxic "dead zone" that forms every year in the Gulf of Mexico.[19] As of a 2025 draft update to the state's Nutrient Reduction Strategy, Minnesota needs to reduce total nitrogen loads from agriculture to the Mississippi River by 62 million pounds to meet its goals to improve downstream water quality.[20] One study estimates that nitrate from the Mississippi has caused $2.4 billion in annual damages to fish stocks and habitat for more than 30 years.[21]

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[16] MPCA, *Aquatic Life Quality Standards for Ammonia: Draft Technical Support Document* 19 (July 2022), https://www.pca.state.mn.us/sites/default/files/wq-rule4-25b.pdf.
[17] Nitrogen in Minnesota Surface Waters at A2-11.
[18] MPCA, *Rush Creek fish kill response – Winona County,* at 2, 4 (April 2023), https://www.pca.state.mn.us/sites/default/files/tdr-g1-24.pdf (MCEA Ex. 24).
[19] Nitrogen in Minnesota Surface Waters, at A2-14 – A2-16, B2-24.
[20] MPCA, *Minnesota Nutrient Reduction Strategy – DRAFT* at 179 (July 2025), https://www.pca.state.mn.us/sites/default/files/wq-s1-87a.pdf.
[21] Rebecca Boehm, *Reviving the Dead Zone: Solutions to Benefit both Gulf Coast Fishers and Midwest Farmers* 12, Union of Concerned Scientists (2020), https://www.ucs.org/sites/default/files/2020-06/reviving-the-dead-zone.pdf (MCEA Ex. 25).

B. Nitrate pollution in Minnesota's groundwater is widespread and longstanding, particularly in vulnerable groundwater areas

The contamination of Minnesota's surface waters and groundwater with nitrate is a pervasive problem that has been well documented for decades.[22] Contamination has remained persistent over time. In groundwater, an analysis from 2019 showed that 16% of wells in shallow aquifers tested had significant increases in nitrate, and another 63% had no improvement, between 2005 and 2017.[23] A more recent analysis by MDA of nitrate trends in 253 monitoring wells and 14 springs showed "that most sites continued to exhibit no change in nitrate concentrations from 2013-2023."[24] While some sites had downward trends, these trends "should not be interpreted to mean that concentrations are below the [10 mg/L limit]. Several sites, primarily in the state's agricultural areas, have downward trends in nitrate from 2013-2023, but the most recent concentration measured still was above 10 mg/L."[25] One monitoring well in Morrison County, for example, still showed a nitrate level of 33 mg/L despite a downward trend.[26]

Similarly, in surface waters, trends do not show significant improvement. A 2020 analysis of trends over the previous 20 years in the state's major rivers found increasing trends at half of the sites, with increases ranging from 21% to 55%.[27] Narrowing the focus to only the previous

[22] 2015 Nitrogen Fert. Mgmt. Plan at 21-30 (describing sampling results from monitoring wells, private wells, and public water systems); MPCA, *Five-Year Progress Report on Minnesota's Nutrient Reduction Strategy* 30-31 (Aug. 2020) ("Five Year Progress Report on NRS"), https://www.pca.state.mn.us/sites/default/files/wq-s1-84a.pdf; Nitrogen in Minnesota Surface Waters at C1-1 – C2-10.
[23] Five Year Progress Report on NRS at 31.
[24] MPCA, *The Condition of Minnesota's Groundwater Quality, 2018-2023*, at 16-17 (April 2025), https://www.pca.state.mn.us/sites/default/files/wq-am1-11.pdf.
[25] *Id.*
[26] *Id*.
[27] Five Year Progress Report on NRS at 18.

decade showed that nitrate levels increased or at best showed no clear trend—none of the 38 sites studied by MPCA showed nitrate decreases in that time period.[28]

The problem of nitrate groundwater contamination is particularly acute in areas identified by MPCA as vulnerable groundwater areas—areas with karst geology, shallow depth to bedrock, or coarse textured soils, which are particularly susceptible to pollutants from the surface moving through soil to underground aquifers.[29] MPCA created a map of these regions, which will be referred to as "Vulnerable Groundwater Areas" or "VGAs."[30] This includes the Central Sands area, with its coarse-textured soil, in the middle of the state, and the southeastern karst region, which has significant areas of karst geology and shallow bedrock; these two areas "were determined to be the most vulnerable to and the most impacted by nitrate contamination."[31]

Nitrate pollution in groundwater in the karst region has been well-documented for decades. In karst geology, fractured bedrock is generally overlaid with shallow soils, allowing nitrate in soil water to move easily down into groundwater.[32] More than 30 years ago, MPCA documented high nitrate concentrations in wells in Minnesota's karst region, with nearly half of wells tested already exceeding the 10 mg/L limit.[33] In the past dozen years, numerous state studies have documented

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[28] *Id.* at 20.
[29] Groundwater Protection Rule SONAR at 85; MPCA, *MPCA proposes changes to feedlot permits to protect waters from nitrate pollution*, https://www.pca.state.mn.us/news-and-stories/mpca-proposes-changes-to-feedlot-permits-to-protect-waters-from-nitrate-pollution.
[30] MPCA, *Vulnerable Groundwater Areas Map*, https://resources.gisdata.mn.gov/pub/gdrs/data/pub/us_mn_state_pca/env_feedlot_vuln_gw_areas/preview/preview.jpg.
[31] Groundwater Protection Rule SONAR at 46.
[32] *Id*. at 91.
[33] MPCA, *Water Quality and Sensitivity of the Prairie du Chien-Jordan Aquifer in Western Winona County*, Executive Summary (June 1991), https://www.leg.mn.gov/docs/pre2003/other/910740.pdf.

wide-spread and persistent exceedances of the 10 mg/L limit in southeastern Minnesota's groundwater in both shallow wells and drinking wells. For example:

- From 2008–2018, the Southeast Volunteer Nitrate Monitoring Network tested approximately 300-500 private drinking water wells each year. Results ranged from a low of 7.5% (in 2012) to a high of 14.6% (in 2008) of wells testing above the 10 mg/L standard.[34]

- From 2013-2019, the Township Testing Program tested wells in vulnerable townships and found that 12.1% of the private drinking water wells tested across eight karst counties had nitrate levels above the 10 mg/L standard.[35] In two townships in Winona County, samples taken in 2017 showed more than 40% of wells in the initial testing set had more than 10 mg/L of nitrate.[36]

- In 2023, the Southeast Volunteer Nitrate Monitoring Network tested 374 private drinking water wells and found that 8% were over the 10 mg/L limit.[37]

- From 2014-2024, Minnesota Department of Agriculture ("MDA") analyzed between 37 and 43 samples of groundwater each year from ambient groundwater monitoring sites in southeastern Minnesota (PMR 9). Every year between 24% (in 2015) and 34% (in 2017 and 2018) of wells tested had nitrate levels above the 10 mg/L limit.[38]

Coarse-textured, or sandy, soils like those in the Central Sands pose a similar susceptibility to nitrate pollution[39] because sandy soils have a lower water-holding capacity and accordingly have more potential to lose nitrate from leaching than do finer textured soils.[40] One study showed that background losses of nitrogen in coarse-textured soils were around 20 to 50 pounds per acre,

[34] MDA, *Nitrate Results and Trends in Private Well Monitoring Networks 2008-2018*, at 3 (June 2019), https://wrl.mnpals.net/islandora/object/WRLrepository%3A3395 (MCEA Ex. 26).
[35] Letter from U.S. Env. Prot. Agency to Minn. Dep't of Health, MDA, and MPCA re: Safe Drinking Water Act Petition 2 (Nov. 3, 2023) (MCEA Ex. 27).
[36] MDA, *Winona County: Final Overview of Nitrate Levels in Private Wells (2016-2017)*, at 2 (Sept. 2019), https://wrl.mnpals.net/islandora/object/WRLrepository%3A3853 (MCEA Ex. 28).
[37] MDA, *Southeast Minn. Volunteer Nitrate Monitoring Network 2023 Results* 1 (Nov. 2024), https://wrl.mnpals.net/node/4338 (MCEA Ex. 29).
[38] *See* MDA, *Water Quality Monitoring Reports* (2014-2024), available at the Minnesota Digital Water Research Library, https://wrl.mnpals.net/ (MCEA Ex. 30).
[39] Groundwater Protection Rule SONAR at 80.
[40] Univ. of Minn. Extension Serv., *Understanding Nitrogen in Soils* (2021), https://extension.umn.edu/nitrogen/understanding-nitrogen-soils (MCEA Ex. 31).

as compared to 10 pounds per acre for fine-textured soils.[41] Data from state agencies show that exceedances of the 10 mg/L limit are also widespread and persistent in the Central Sands in both shallow wells and drinking water wells. For example:

- From 2011-2018. MDA's Central Sands Private Well Network tested approximately 300-500 private drinking water wells each year. Results ranged from a low of 2.2% (in 2017) to a high of 4.5% (in 2015) of wells tested above the 10 mg/L limit.[42]

- From 2013-2019, MDA's Township Testing Program tested thousands of private drinking water wells in vulnerable townships and found many violations of the 10 mg/L limit. In Morrison County, 15% of the 1,222 wells tested in the initial set were over the limit.[43] In Wadena County, 11.9% of the 269 wells in the initial set were over the limit.[44] In Hubbard County, 10.5% of the 1,106 wells in the initial set were over the limit.[45]

- From 2014-2024, a study by MDA analyzed between 74 and 86 samples of groundwater each year from ambient groundwater monitoring sites in the Central Sands region (PMR 4) and found that between 48% (in 2022) and 72% (in 2015 and 2016) had nitrate levels above the 10 mg/L limit.[46]

- In 2024, the Central Sands had the highest median concentration (14.7 mg/L); the highest 90th percentile concentration (28.0 mg/L), and the highest nitrate level (an astonishing 81.2 mg/L) of any region in the state.[47]

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[41] Groundwater Protection Rule SONAR at 35.

[42] MDA, *Nitrate Results and Trends in Private Well Monitoring Networks 2008-2018*, at 11-12 (June 2019), https://wrl.mnpals.net/islandora/object/WRLrepository%3A3395 (MCEA Ex. 26).

[43] MDA, *Morrison County: Overview of Nitrate Levels in Private Wells (2013-2015)* at 2 (Aug. 2016), https://www.mda.state.mn.us/sites/default/files/inline-files/nitrate2015morrison.pdf (MCEA Ex. 32).

[44] MDA, *Initial Township Testing of Nitrate in Private Wells, Wadena County 2013 Summary* 20 (April 2015), https://www.mda.state.mn.us/sites/default/files/inline-files/wadena2013summary.pdf (MCEA Ex. 33).

[45] MDA, *Hubbard County: Overview of Nitrate Levels in Private Wells (2016)*, at 1 (Jan. 2017), https://www.mda.state.mn.us/sites/default/files/inline-files/hubbard2016initial_0.pdf (MCEA Ex. 34).

[46] *See* MDA, *Water Quality Monitoring Reports* (2014-2024), available at the Minnesota Digital Water Research Library, https://wrl.mnpals.net/ (MCEA Ex. 30).

[47] MDA, *2024 Water Quality Monitoring* Report, at 6-3, 6-6 (June 2025), https://wrl.mnpals.net/node/4355 (MCEA Ex. 30).

Unfortunately, many of these vulnerable areas are also heavily agricultural, which makes the risks of nitrate pollution higher. More than 6,400 feedlots are located within VGAs.[48]

C. Most of Minnesota's nitrate groundwater pollution comes from croplands, including from manure applied to croplands

MPCA has acknowledged that the greatest source of Minnesota's groundwater nitrate pollution, including in the VGAs, is croplands. According to MPCA, "More than 70% of the nitrate in Minnesota waters is coming from cropland, the rest from regulated sources such as wastewater treatment plants, septic and urban runoff, forests, and the atmosphere."[49] In intensively agricultural areas of the state, nitrogen loads from cropland sources are even higher; such sources produce an estimated 89 to 95 percent of the load in the Minnesota, Missouri, and Cedar rivers, and the Lower Mississippi River basin.[50] State studies confirm this by showing intense groundwater pollution in agricultural areas. Groundwater monitoring data shows median nitrate concentrations in shallow wells in agricultural areas are four to eight times higher than the concentrations in urban areas.[51] Almost 40% of shallow wells in agricultural areas had nitrate levels above the 10 mg/L limit.[52] Water in soil beneath fields where corn is grown had far higher levels of nitrate—an average of 22.3 mg/L—than other lands uses, such as forests, lawns, or golf courses.[53]

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[48] EWG, Manure Overloads Minnesota (MCEA Ex. 23) ("In 2024, 6,480 animal feeding operations were located within a vulnerable groundwater area").
[49] MPCA, *Nitrogen*, https://www.pca.state.mn.us/pollutants-and-contaminants/nitrogen (MCEA Ex. 35); *see also* Five Year Progress Report on NRS at 21.
[50] MPCA, Nitrogen, https://www.pca.state.mn.us/pollutants-and-contaminants/nitrogen (MCEA Ex. 35).
[51] MPCA, *The Condition of Minnesota's Groundwater Quality 2018-2023*, at 12 *(*April 2025), https://www.pca.state.mn.us/sites/default/files/wq-am1-11.pdf.
[52] *Id.*
[53] Kevin Kuehner et al., *Examination of Soil Water Nitrate-N Concentrations from Common Land Covers and Cropping Systems in Southeast Minnesota Karst* 14 (Oct. 2020), https://wrl.mnpals.net/islandora/object/WRLrepository%3A3654 (MCEA Ex. 48).

The main cropland sources of nitrate pollution are both commercial fertilizer and manure applied as fertilizer, MPCA has acknowledged.[54] These two sources together accounted for 1.8 *billion* pounds of the nitrogen added to land in Minnesota in 2013, compared to 12 million pounds for lawn fertilizer and 9 million pounds for septic system drain fields.[55] Although manure accounts for only about 25% of the nitrogen applied to fields in the state (as compared to 75% for commercial fertilizer),[56] the use of manure is particularly problematic for nitrate pollution because producers often overapply nitrogen when they use manure as one of their nitrogen sources.

There are two key reasons why producers commonly overapply nitrogen when they use manure as fertilizer. First, manure often is treated as a waste product. Minnesota's feedlots house up to 1.6 million beef and dairy cattle, 10.8 million hogs, and 58.7 million turkeys and chickens, which produce nearly 49 million tons of manure every year—which is disposed of by spreading it, untreated, on croplands.[57] The need to dispose of manure leads some producers to apply it not in response to crop needs but instead because storage space is running out or because of the need to work around wet weather or other production processes.[58] Manure also may be overapplied at fields nearest the livestock operation to free up storage capacity without incurring the expense of transporting the manure further away.[59]

Second, producers often fail to accurately account for the amount of nitrogen in manure, and thus overapply it. The nitrogen content in manure is highly dependent on many variables,

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[54] MPCA, *The Condition of Minnesota's Groundwater Quality 2018-2023*, at 11 *(*April 2025), https://www.pca.state.mn.us/sites/default/files/wq-am1-11.pdf.
[55] Nitrogen in Minnesota Surface Waters, at D1-2.
[56] *Id.*
[57] EWG, Manure Overloads Minnesota (MCEA Ex. 23).
[58] Chryseis Modderman, *Manure Is Complicated: 5 Reasons You Need a Manure Management Plan*, Minn. Crop News (June 26, 2023), https://blog-crop-news.extension.umn.edu/2023/06/manure-is-complicated-5-reasons-you.html (last visited Jan. 24, 2025) (MCEA Ex. 11).
[59] *See id.*

including type of manure, storage methods, climatic conditions, and more,[60] and the nitrogen in manure is not all immediately available for plants to use for growth.[61] The uncertainties mean producers "frequently over-apply manure" because they do not properly credit the amount of nitrogen in the manure.[62] Encouraging this practice, the University of Minnesota Extension Service ("Extension Service") recommends applying *more* nitrogen per acre when manure is used, as compared to commercial fertilizer.[63] Studies and farmer interviews show producers apply more nitrogen when manure and fertilizer are applied than when only non-manure sources are used.[64]

Across the state, Minnesota's producers are simply applying more nitrogen than crops need through a combination of commercial fertilizer and manure. In 2018, MDA stated that by a conservative estimate, Minnesota producers could reduce nitrogen application by 200 million pounds each year while still maintaining "optimum yields."[65] With respect to the southeastern karst region in particular, an analysis by environmental scientist Christopher Jones found that between the commercial fertilizer sold and the animal manure produced in the region, producers are applying 60 million pounds of nitrogen more than their crops need each year.[66] This amount of nitrogen could contaminate approximately 722 billion gallons of water to a level exceeding the

[60] Groundwater Protection Rule SONAR at 54.
[61] Univ. of Minn. Extension Serv., *Guidelines for Manure Application Rates* 1 (2022) (MCEA Ex. 6).
[62] Groundwater Protection Rule SONAR at 51, 54; 1999 Feedlot Rule SONAR at 20, 205.
[63] *Compare* Univ. of Minn. Extension Serv., *Guidelines for Manure Application Rates* 2 (2022) (MCEA Ex. 6) (recommendation for corn after corn is a maximum of 195 pounds of plant available nitrogen per acre) *with* Univ. of Minn. Extension Serv., *Fertilizing Corn in Minnesota* 2 (2024) (MCEA Ex. 7) (recommendation for corn after corn is a rate of 185 pounds of nitrogen per acre when the ratio of the nitrogen price to crop value is .10).
[64] Groundwater Protection Rule SONAR at 51-52; Five Year Progress Report on NRS at 78; 1999 Feedlot Rule SONAR at 205.
[65] Groundwater Protection Rule SONAR at 51.
[66] Christopher S. Jones, Ph.D., *Report on Nitrogen Surplus in Minnesota Driftless* 12 (2025) (MCEA Ex. 21).

10mg/L limit and water quality standard.[67] A 2025 study by the Environmental Working Group found that in nine Minnesota counties, nitrogen in manure produced by feedlots combined with nitrogen in fertilizer purchased in the county exceeded recommendations for the Extension Service's nitrogen application rates by more than 40%.[68]

D. Unsafe manure management practices also lead to coliform impairments

Beyond the widely documented nitrate contamination trends in public and private water supplies, there are also other microbial contaminants associated with manure that impact public health—further emphasizing the need for responsible manure management. Coliforms are a standard indicator of drinking water quality associated with acute gastrointestinal illness, and the goal under the Safe Drinking Water Act for these contaminants is set at zero.[69] Yet 243 Minnesota waters are listed as impaired for fecal coliform, and another 672 are listed as impaired for E. coli (one of the main fecal coliforms).[70]

One of the main sources of bacteria in surface waters—including coliforms—is runoff from feedlots and land application sites. MPCA has stated that one of the most effective ways to reduce coliforms in water is to ensure this runoff is controlled.[71] This is supported by a 2021 study in Northeastern Wisconsin that analyzed private well contamination data across a five-county region with vulnerable fractured bedrock and concentrated dairy feedlot production, similar to the karst region of Southeastern Minnesota. Of the 6,739 wells sampled for microbial contamination, 23%

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[67] *Id.*
[68] EWG, Manure Overloads Minnesota (MCEA Ex. 23).
[69] EPA, *Revised Total Coliform Rule and Total Coliform Rule* (January 2017), https://19january2017snapshot.epa.gov/dwreginfo/revised-total-coliform-rule-and-total-coliform-rule_.html (MCEA Ex. 36).
[70] MPCA, *2024 Impaired Waters List*, https://www.pca.state.mn.us/air-water-land-climate/minnesotas-impaired-waters-list.
[71] MPCA, *Bacteria*, https://www.pca.state.mn.us/pollutants-and-contaminants/bacteria (MCEA Ex. 37).

tested positive for total coliforms.[72] The primary risk factors for coliform detection were bedrock depth (which determines groundwater vulnerability) and distance to the nearest manure storage structure, with wells located within 48 meters of manure storage structures 87% more likely to have coliform detection than wells 4,000 meters away.[73] The single risk factor most associated with an increase in coliform concentration levels was the distance to the nearest field with a nutrient management plan where commercial fertilizer and animal manure were land applied.[74] Practices that reduce manure runoff, accordingly, are critical to addressing not only nitrates but also dangerous bacteria.

E. Minnesota's efforts to control nitrate pollution have not met the state's nutrient reduction goals or adequately protected drinking water supplies

Although the causes and dangers of nitrate and bacterial pollution have long been known, Minnesota state agencies have not taken effective steps to control this pollution, despite express direction from the Legislature to the state agencies to address groundwater pollution from agricultural sources.[75] For decades, Minnesota's agencies have implemented programs, policies, and even rules—including the Animal Feedlot Rule—that attempt to address nitrate pollution. Yet groundwater and surface waters across the state continue to show persistent levels of contamination and even increases in nitrate loads and concentrations. The state's Clean Water Fund alone has directed at least $148 million to the nitrate problem since 2010, according to a Star Tribune analysis, and millions more in federal and state funding have paid for efforts that include nitrate research, programs and training to encourage farmers to make voluntary changes to

[72] Mark A. Borchardt et al., *Sources and Risk Factor for Nitrate and Microbial Contamination of Private Household Wells in the Fractured Dolomite Aquifer of Northeastern Wisconsin*, Environmental Health Perspectives 129(6), at 3-4 (June 2021) (MCEA Ex. 8).
[73] *Id.* at 26.
[74] *Id.* at 23-24.
[75] *See generally* Groundwater Protection Act, Minn. Stat. § 103H.001–.280.

practices, and nitrate filtration systems for several cities.[76] The response from state agencies has included a combination of regulatory and voluntary conservation programs, with an emphasis on voluntary incentives. These voluntary incentives, encouraged by technical and financial assistance from governmental programs, have not achieved the necessary reductions in nitrate pollution.[77] Despite the development of the updated Nitrogen Fertilizer Management Plan, the Groundwater Protection Rule, and the Nutrient Reduction Strategy over the past decade, there have not been significant decreases in nitrate levels in surface waters or groundwater.

MPCA has acknowledged that its current regulations and voluntary best management practices are insufficient to protect groundwater from pollution.[78] MPCA's own progress report on nutrient management practices in 2020 admitted that none of the nutrient management practices adopted during the past decade were "expected to yield measurable nutrient reductions to surface waters at a large scale."[79] MPCA's website acknowledged that refinements in fertilizer rates and application timing could reduce nitrate loads by roughly 13% statewide, but "additional and more costly practices will be needed to make further reductions."[80] As the agency has stated, "statewide reductions of more than 30% are not realistic with current practices."[81] In making incremental

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[76] Jeff Hargarten and Jennifer Bjorhus, *Nitrate contamination of Minnesota waters shows little sign of going away, despite years of effort*, Star Tribune (Nov. 28, 2023), https://www.startribune.com/nitrate-pollution-minnesota-groundwater-farm-fertilizer-mpca-wells-epa/600310942 (MCEA Ex. 38).

[77] *See* Kurt Stephenson et. al, *Confronting our Agricultural Nonpoint Source Control Policy Problem*, 58(4) Journal of the Am. Water Resources Assn. (June 2022) (MCEA Ex. 9) (explaining that programs to reduce agricultural non-point source pollution that depend on voluntary adoption, with technical and financial assistance from federal and state programs, have not been successful in reducing pollution loads).

[78] MPCA, *Groundwater quality*, https://www.pca.state.mn.us/air-water-land-climate/groundwater-quality (MCEA Ex. 39).

[79] Five Year Progress Report on NRS at 53.

[80] MPCA, *Nitrogen,* https://www.pca.state.mn.us/pollutants-and-contaminants/nitrogen (MCEA Ex. 35).

[81] *Id.*

changes to the water pollution permits that govern the state's largest feedlots, MPCA stated, "There are serious nitrate issues in the vulnerable areas of Minnesota that will necessitate changes to current crop production practices."[82] Only with significant regulatory changes—and enforcement of those changes—will Minnesota make progress on the nitrate pollution problem.

F. EPA has instructed Minnesota to make changes to address nitrate pollution

Not only are changes to address Minnesota's nitrate pollution compelled by the facts, the EPA has instructed MPCA to address this problem. In April 2023, MCEA led a coalition of 11 national, regional, and local organizations in submitting a petition that asked the EPA to use its powers under the Safe Drinking Water Act to address the "imminent and substantial endangerment to human health" posed by groundwater nitrate contamination in Minnesota's karst region.[83]

On November 3, 2023, the EPA responded with a letter to the MPCA, MDA, and Minnesota Department of Health regarding nitrate pollution in the karst region, stating "there is an evident need for further actions to safeguard public health."[84] The EPA directed state agencies to take immediate action to safeguard public health in the region, and to "hold sources of nitrate accountable using all available tools to reduce the amount of nitrate they release to ground water."[85] Specifically, the EPA encouraged the state to consider modifications to its nutrient management standards in karst areas with regard to land application of manure.[86]

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[82] MPCA, *Responses to Comments on the General NPDES and SDS Animal Feedlot Permits* 10 (Jan. 2025), https://www.pca.state.mn.us/sites/default/files/wq-f3-64.pdf ("MPCA Responses to Feedlot Permit Comments").
[83] *See* MCEA et al., *Petition to EPA for Emergency Action Pursuant to the Safe Drinking Water Act* (April 24, 2023) (MCEA Ex. 10).
[84] Letter from EPA to Minn. Dep't of Health, MDA, and MPCA re: Safe Drinking Water Act Petition 2 (Nov. 3, 2023) (MCEA Ex. 27).
[85] *Id.* at 4.
[86] *Id.*

II. MPCA has the authority and the duty to change the Animal Feedlot Rule to comply with water protection requirements in state and federal law

MPCA has the authority and the duty under Minnesota and federal law to protect the state's groundwater and surface waters from manure-related pollution, but its current Animal Feedlot Rule does not fulfill this duty, based on the widespread and persistent violations of water quality standards caused by feedlot-related pollution.

Federal and state laws contain critical and stringent protections for the state's surface waters and groundwater, and MPCA has the duty to enforce these protections.[87] Under the Clean Water Act, MPCA has the obligation to set and enforce water quality standards to protect "designated uses" in particular water bodies—such as waters used for drinking, recreation, or aquatic life.[88] These water quality standards must protect public health or welfare, enhance the quality of water, and ensure that the water is clean enough to be safe for the designed uses.[89] Under state law, this authority is confirmed and expanded, with MPCA required to protect "waters of the state," which include both surface waters and groundwater.[90] The agency's duties include adopting

[87] Minn. Stat. § 115.03, subd. 1(a)(1).
[88] *See* 33 U.S.C. § 1313; 40 C.F.R. §§ 131.3(f), .10, .11.
[89] 33 U.S.C. § 1313(c)(2)(A); 40 C.F.R. § 131.11(a)(1).
[90] Minn. Stat. § 115.01, subd. 22 ("'Waters of the state' means all streams, lakes, ponds, marshes, watercourses, waterways, wells, springs, reservoirs, aquifers, irrigation systems, drainage systems and all other bodies or accumulations of water, surface or underground, natural or artificial, public or private, which are contained within, flow through, or border upon the state or any portion thereof.").

and enforcing rules "in order to prevent, control or abate water pollution."[91] Specifically, MPCA must issue rules that:

- Prohibit the discharge of wastes[92] into the waters of the state, or to deposit wastes "where the same is likely to get into any waters of the state" in violation of Minnesota's rules and pollution standards.[93]
- Require adoption of remedial measures "to prevent, control or abate any discharge or deposit of … wastes by any person."[94]
- Require establishment of systems of recordkeeping, sampling, monitoring, and reporting by dischargers for provision of information to the agency.[95]
- Include additional limits if technology-based standards are not adequate to maintain water quality standards.[96]

Pursuant to this authority, MPCA has set policies and rules to protect both groundwater and surface waters. For groundwater, MPCA has adopted an antidegradation policy, under which it must "consider the actual or potential use of the underground waters for potable water supply as constituting the highest priority use and as such to provide maximum protection to all underground waters."[97] For surface waters, MPCA's policy "is to protect and maintain surface waters in a condition which allows for the maintenance of all existing beneficial uses."[98] In other words, surface waters should not be polluted in a way that stops a current use—such as for drinking water or sustaining aquatic life.

[91] Minn. Stat. § 115.03, subd. 1(a)(5).
[92] Although certain components of land-applied manure may be used by plants, where manure, nutrients, or other pollutants escape their intended use and are instead discharged into waters of the state those pollutants are properly characterized as "other wastes," which as defined includes "agricultural waste" and "biological materials." Minn. Stat. § 115.01, subd. 9.
[93] Minn. Stat. § 115.03, subd. 1(a)(5)(ii).
[94] Minn. Stat. § 115.03, subd. 1(a)(5)(iv).
[95] Minn. Stat. § 115.03, subd. 1(a)(5)(vii).
[96] Minn. Stat. § 115.03, subd. 1(a)(5)(viii).
[97] Minn. R. 7060.0200.
[98] Minn. R. 7050.0150, subp. 1.

To implement these policies, MPCA has adopted water quality standards to protect surface waters and groundwater. For Class 1 waters—all waters used for drinking water, including all groundwater in the state—MPCA has set a water quality limit for nitrate at 10 mg/L.[99] MPCA also prohibits any wastes from point or nonpoint sources to be discharged into or permitted to gain access to any Class 1 waters in the state "so as to cause any material undesirable increase in the . . . nutrient content, or in any other manner to impair the natural quality or value of the waters for use as a source of drinking water."[100] As an additional protection for groundwater, MPCA adopted a prohibition against discharges of waste and pollutants into the unsaturated zone (the area between the land surface and the water table) that "may actually or potentially preclude or limit the use of the underground waters as a potable water supply, nor shall any such discharge or deposit be allowed which may pollute the underground waters."[101]

For Class 2 waters—those that may support aquatic life, which includes virtually all surface waters in Minnesota—there is no numeric standard for nitrate. However, there is a "narrative" water quality standard—an enforceable, descriptive standard—that prohibits degrading the water quality "in any material manner." The narrative standards also require that

> there shall be no material increase in undesirable slime growths or aquatic plants, including algae, nor shall there be any significant increase in harmful pesticide or other residues in the waters … the normal aquatic biota and the use thereof shall not be seriously impaired or endangered, … and the propagation or migration of aquatic biota normally present shall not be prevented or hindered by the discharge of any sewage, industrial waste, or other wastes to the waters.[102]

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[99] Minn. R. 7050.0221, subps. 2–4 (incorporating the limit from 40 C.F.R. § 141.62(b)(7)).
[100] Minn. R. 7050.0221, subp. 6.
[101] Minn. R. 7060.0600, subp. 2. This rule does not prohibit the use of chemicals and fertilizers for crops only if "such practices do not pose a significant pollution hazard." Minn. R. 7060.0600, subp. 5. As land application of manure is causing pollution of groundwater—as admitted by MPCA—this exception for fertilizer does not apply.
[102] Minn. R. 7050.0150, subp. 3.

Additionally, for Class 2 waters, ammonia is limited to 4.1 mg/L in cold waters and 10.1 mg/L for other waters.[103]

Accordingly, under state and federal law, MPCA is required to take actions to protect both surface waters and groundwater from nitrate, nutrient, and bacterial pollution in excess of these standards. As the Animal Feedlot Rule self-evidently is not ensuring that these standards are met, it is inadequate under state and federal law, and it must be revised to ensure these water quality standards are not subject to further exceedances due to pollution from manure.

III. MPCA must make changes to its Animal Feedlot Rule to comply with state and federal law and address nitrate pollution

Based on decades of research, MPCA knows of practices that significantly reduce or prevent nitrogen loss from croplands. However, these practices have not been required in the Animal Feedlot Rule, making it inadequate to protect Minnesota's surface waters and groundwater. MPCA must make extensive changes to make the rule more effective and address nitrate pollution.

A. MPCA should require water pollution permits for feedlots with more than 600 animal units

Under the current Animal Feedlot Rule, only the largest feedlot operations, called Concentrated Animal Feeding Operations, or CAFOs—those with more than 1,000 animal units[104]—require federal National Pollutant Discharge Elimination System ("NPDES") or State

[103] MPCA, *Aquatic Life Quality Standards for Ammonia: Draft Technical Support Document* 19 (July 2022), https://www.pca.state.mn.us/sites/default/files/wq-rule4-25b.pdf.

[104] An animal unit is a way of comparing different-sized animals by the amount of manure they produce. One animal unit is equal to one 1,000 lb. beef steer, .3 hogs of 55 to 300 lbs., or .005 chickens over 5 lbs. Minn. R. 7020.0300, subp. 5. To require a water pollution permit, then, a feedlot would need to have more than 1,000 beef cattle, 3,334 market hogs, or 200,000 chickens. *See* Minn. R. 7020.0300, subp. 5 (defining animal units under Minnesota Rules); Minn. R. 7020.0405, subp. 1(B) (requiring an SDS permit for feedlots with 1,000 or more animal units). MPCA, *Livestock and the Environment* 4 (Jan. 2021), https://www.pca.state.mn.us/sites/default/files/wq-f1-01.pdf (MCEA Ex. 40).

Disposal System ("SDS") permits for water pollution.[105] This means only about 4% of Minnesota's more than 23,000 feedlots require federal or state water pollution permits.[106] It is critical for these largest feedlots to have permits, because they produce about one-third of the state's manure.[107] However, the remaining feedlots produce two-thirds of the manure generated in Minnesota and have fewer restrictions on their management and application of manure because of their lack of permit coverage. MPCA should lower the SDS permit threshold to 600 animal units to ensure that more feedlots are required to follow the stricter provisions of state water pollution permits. Based on current registration data, this would cover approximately 10% of registered cattle, poultry, and swine feedlots in Minnesota and an additional 26% of manure generated by animal feedlots in the state.[108]

The benefit of this rule change to better protect groundwater from the improper application of nutrients from animal manure on cropland is clear: when combined with the current permit coverage under state and federal law, this would mean that approximately 60% of the manure generated by animal feedlots in Minnesota would be subject to the land application requirements of state and federal permits. These permit requirements were revised in January 2025 to better

[105] 40 CFR § 122.23; Minn. R. 7020.0405, subp. 1(B)(1) (requiring SDS permits for feedlots with 1,000 or more AUs).
[106] EWG, Manure Overloads Minnesota (MCEA Ex. 23).
[107] *Id.* ("Four percent of facilities were large [CAFOs] but generated 33 percent of manure").
[108] *See Environmental Work Group Comments to the Minnesota Pollution Control Agency; request for comments on the Animal Feedlots Rule* (July 8, 2025), https://speakup-us-production.s3.amazonaws.com/uploads/attachment/file/686d4c6544253872de02e4eb/EWG_Feedlot_Rule_Comment__2025_pdf.pdf ("EWG Response to MPCA Request for Comments") (noting that facilities with 600+ animal units produced 12,640,899 tons of manure annually); EWG, Manure Overloads Minnesota (MCEA Ex. 23) (stating that "[l]ivestock facilities in the state generated almost 49 million tons of manure in 2024"). *See also* EWG Response to MPCA Request for Comments ("there were 2,316 feedlots with between 600 and 999 animal units in Minnesota in 2024); EWG, Manure Overloads Minnesota (MCEA Ex. 23) ("Minnesota had 25,503 animal feeding operations in 2024").

protect VGAs of the state with additional steps to minimize the risk of nitrate loss to groundwater when manure is land-applied in the fall or on frozen, snow-covered ground. Of the registered feedlots that fall between 600 and 999 animal units that would be covered under a lower permit threshold, approximately 14% are located within VGAs as defined in the January 2025 permit feedlot revision, and approximately 35% of all feedlots in the 600-999 animal units range are within a one-mile buffer of VGAs and therefore likely land apply manure within VGAs[109] (see Figures 1 and 2).

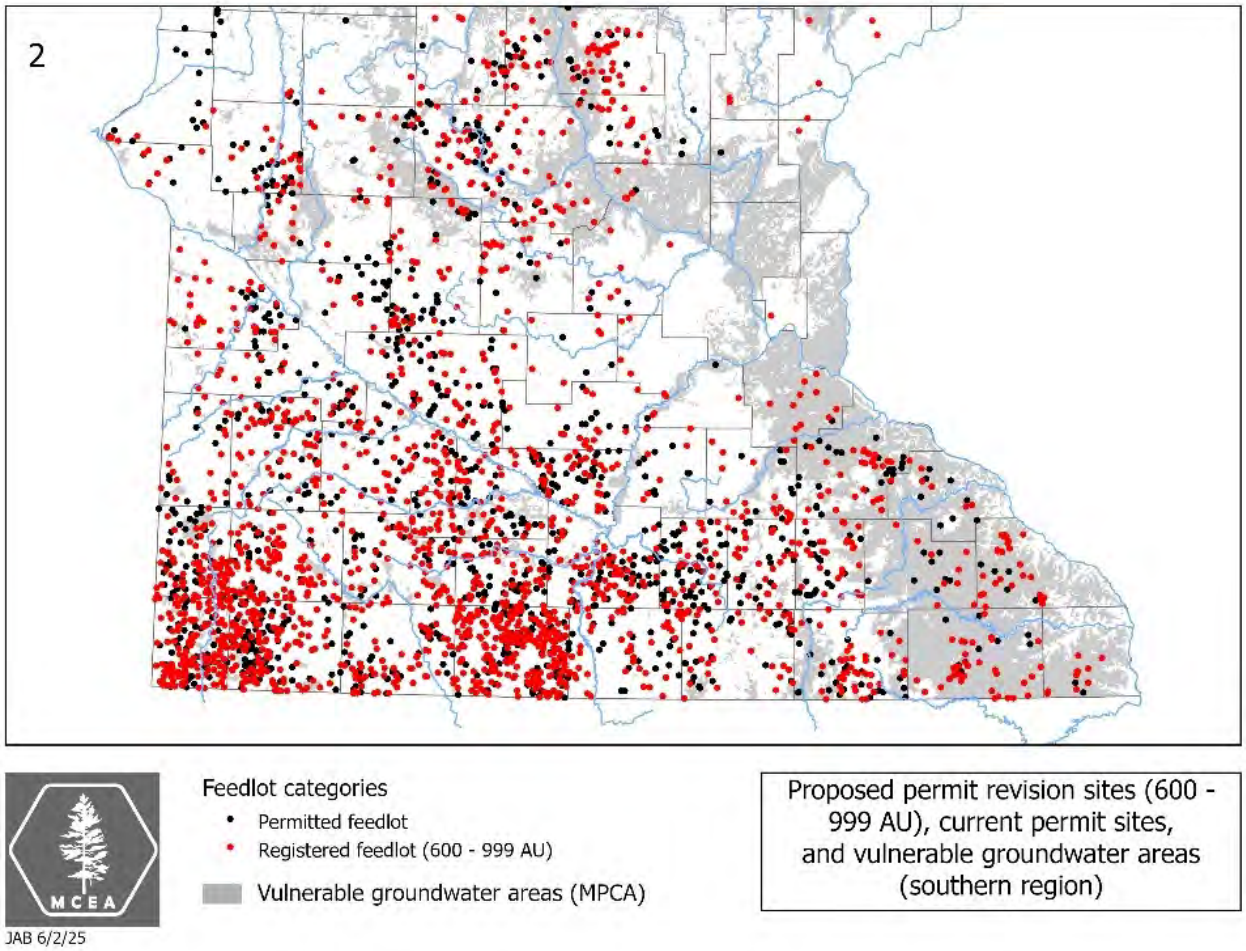

Figure 1: Proposed permit revision feedlot sites in southern region vulnerable groundwater areas. Map created by Jim Berg with data from the Minnesota Geospatial Commons.

[109] Data from Minnesota Geospatial Commons, *Feedlots in Minnesota*, https://gisdata.mn.gov/sv/dataset/env-feedlots and *MPCA Feedlot Program Vulnerable Groundwater Areas*, https://gisdata.mn.gov/sv/dataset/env-feedlot-vuln-gw-areas.

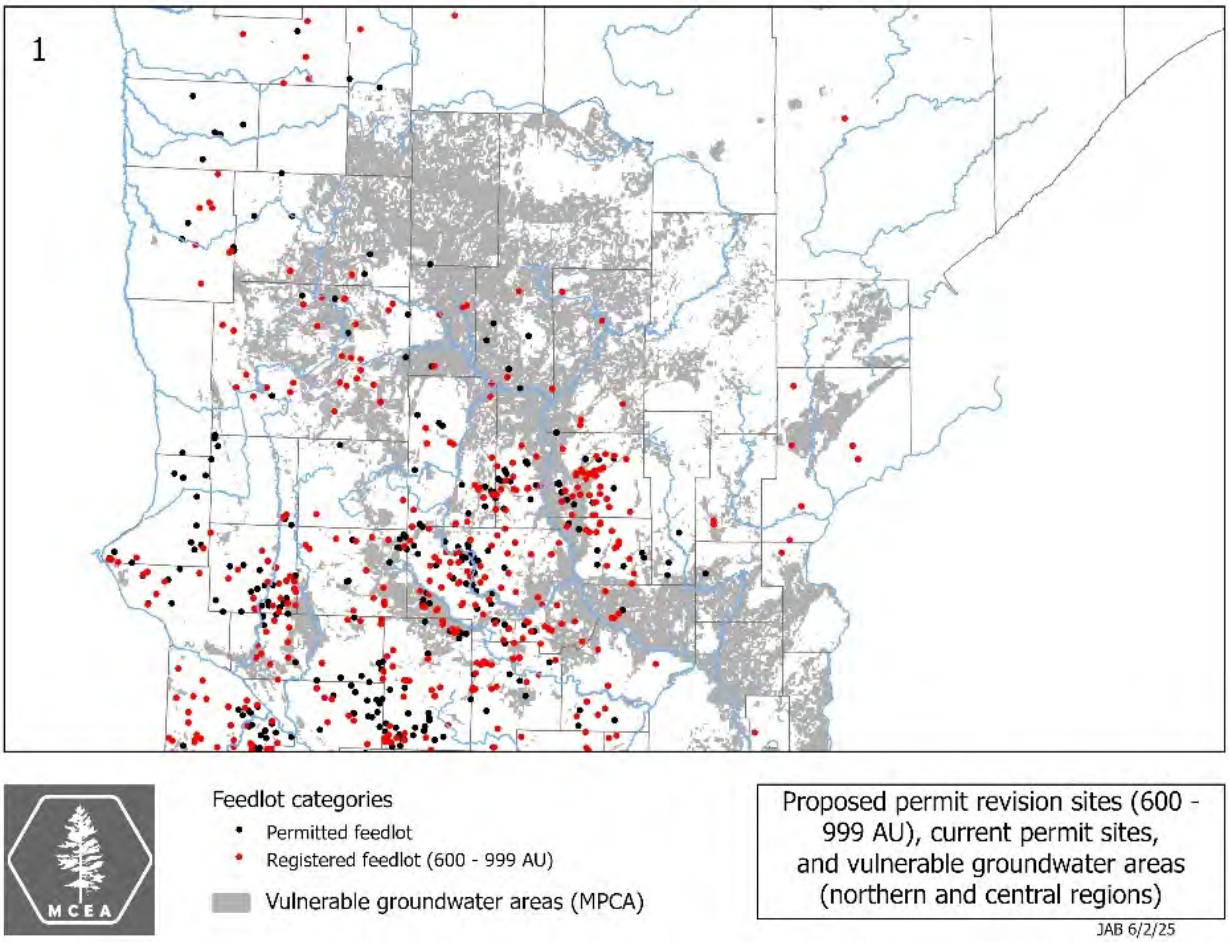

Figure 2: Proposed permit revision feedlot sites in northern and central regions vulnerable groundwater areas. Map created by Jim Berg with data from the Minnesota Geospatial Commons.

MPCA's NPDES and SDS permits impose a number of conditions that are not explicitly set forth in the Animal Feedlot Rule in order to "achieve compliance with state and federal statutes/rules" and "to protect human health and the environment."[110] For example, both permits impose additional limits on application of manure, including requiring manure to be incorporated into the soil if rainfall is predicted[111] requiring manure applied in June, July, August, or September to be added to a growing crop or cover crop[112] imposing additional restrictions on application of

[110] MPCA Responses to Feedlot Permit Comments at 11.
[111] MPCA, *Permit to Construct and Operate a CAFO under the NPDES Program* §13.3 (2026-2031), https://www.pca.state.mn.us/sites/default/files/wq-f3-62.pdf/.
[112] *Id*. at § 13.4.

manure in October and November in VGAs,[113] and restricting application of manure to frozen or snow-covered ground.[114] The permits also require some visual inspections and monitoring of discharges[115] and that manure transferees follow the feedlot's manure management plan,[116] along with other provisions to control pollution discharges. Feedlots with permits are also required to follow additional reporting requirements,[117] including submission of their manure management plans and manure application records,[118] construction reports,[119] facility maintenance reports,[120] and discharge reports.[121] These are important provisions for nitrate pollution, but the vast majority of the state's feedlots do not have to follow them.

Minnesota has many feedlots that are quite large, and that produce many tons of manure every year, but that are not subject to these rules. More than 2,300 cattle, poultry, and swine feedlots fall between 600 and 999 animal units, and these feedlots produce 25.8% of all the manure generated in the state.[122] For certain animal categories like swine, feedlots that fall between 600 and 999 animal units account for approximately 44% of the manure generated by swine feedlots statewide.[123] While currently not subject to the state SDS permit, each of these feedlots still produces a massive amount of manure. For example, a feedlot with 600 animal units of beef cows, or about 600 cows, would produce around 10,000 tons of solid manure or 2.4 million gallons of

[113] *Id*. at §§ 13.5-13.7.
[114] *Id*. at § 13.8-13.10.
[115] *Id*. at §§ 14.3, 28.3-28.4.
[116] *Id*. at §§ 9.3, 9.4, 24.7.
[117] *Id*. at § 25.2.
[118] *Id*. at §§ 10.2-10.5, 24.7.
[119] *Id*. at § 5.4.
[120] *Id*. at § 24.3.
[121] *Id*. at §§ 27.2, 28.4.
[122] EWG Response to MPCA Request for Comments; EWG, Manure Overloads Minnesota (MCEA Ex. 23).
[123] Data from Minnesota Geospatial Commons, *Feedlots in Minnesota*, https://gisdata.mn.gov/sv/dataset/env-feedlots.

liquid manure each year.[124] This quantity of manure should require careful handling in order to minimize water pollution. The practices required by the permits have been determined by MPCA to be useful for reducing pollution and reasonable for feedlots to follow. Accordingly, requiring certain feedlots of less than 1,000 animal units to follow these requirements would help reduce water pollution.

MPCA has the authority to reduce the permit threshold for SDS permits to 600 animal units. NPDES permits are federal permits, and federal law requires that they be issued for feedlots with more than 1,000 animal units that discharge to the waters of the United States.[125] SDS permits, however, are state permits, and MPCA has the authority within the Animal Feedlot Rule to set the threshold for these permits at a different level than 1,000 animal units.[126] Currently, a feedlot that is required to obtain an SDS permit may choose to obtain a NPDES permit instead, so if the threshold for SDS permits decreased, producers might choose to obtain a NPDES permit instead.[127] As the provisions of the SDS and NPDES permits are largely similar with respect to land application of manure, inspection requirements, reporting obligations, and other provisions, allowing producers to obtain NPDES permits instead of SDS permits would provide many of the same protections. Lowering the SDS threshold to 600 animal units would increase the number of feedlots that have to follow critical regulation that would reduce water pollution, and MPCA should revise Minnesota Rule 7020.0405, subpart 1 to make this change.

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[124] *See* MDA & University of Minnesota, *Nutrient & Manure Management Tables*, at 1, https://www.mda.state.mn.us/sites/default/files/2018-05/nutmantables.pdf (last visited July 17, 2025) (MCEA Ex. 41).
[125] 40 C.F.R. § 122.23(b)(4).
[126] *See* Minn. R. 7020.0405, subp. 1(B) (setting SDS permit threshold).
[127] MPCA, *NPDES and SDS permits for feedlots*, https://www.pca.state.mn.us/business-with-us/npdes-and-sds-feedlot-permits (MCEA Ex. 42).

B. MPCA should require Manure Management Plans to be submitted for feedlots with more than 300 animal units through the new Online Nutrient Management Tool

Although the current Animal Feedlot Rule requires most feedlots with more than 300 animal units to create a Manure Management Plan ("MMP"),[128] only the largest feedlots—those that are required to apply for an SDS or NPDES permit (and feedlots that need interim permits because they were identified as pollution hazards)—are required to submit that plan to MPCA (or the county feedlot officer).[129] Requiring all feedlots with more than 300 animal units to create and submit MMPs annually through MPCA's new online Nutrient Management Tool would ensure that more feedlots manage and apply their manure according to appropriate plans, which would help to reduce pollution. It would also ensure that those plans are readily available for review by the MPCA or, in delegated counties, by the county feedlot officer. In addition, information from the online tool regarding manure application in fields should be made publicly available to community members for review. This rule change would provide greater oversight and accountability for the land application of manure from medium feedlots in Minnesota, which accounted for 18% of all feedlot operations in the state as of 2025 but generated the largest share of manure at 43%.[130]

[128] Under Minn. R. 7020.2225, subp. 4(A)(1), a facility must prepare a Manure Management Plan when it applies for a NPDES, SDS, or construction short-form permit construction permit for a facility capable of holding 100 or more animal units. Facilities with 300 or more animal units need to obtain a construction short-form permit under Minn. R. 7020.0405, subp. 1(D). A feedlot with 300 or more animal units that is not required to obtain a permit must prepare a manure management plan when manure is applied by someone other than a professional applier. Minn. R. 7020.2225, subp. 4(A)(2). Accordingly, under the rules, most feedlots with more than 300 animal units need to create an MMP and once it is created, to update it annually. Minn. R. 7020.2225, subp. 4(C).
[129] Minn. R. 7020.2225, subp. 4(B).
[130] EWG, Manure Overloads Minnesota (MCEA Ex. 23).

Manure, "in general, is complicated."[131] When manure is applied to fields, the risks of nitrate pollution can depend on factors such as "rate calculations, sampling, setbacks and buffers, [and] spreader calibration [application]."[132] MMPs are critical to ensuring that manure is applied at appropriate rates, times, and places, as such plans require producers to identify the amount of manure that will be spread, where and how it will be spread, the planned application rate, the other sources of nutrients that will be applied, and a description of the protective measures to minimize water pollution when applying manure in sensitive areas.[133] Without creating such a plan, it is difficult for producers to determine whether they are applying their manure appropriately to minimize the risk of water pollution.[134] Because overapplication of nitrogen is so common in Minnesota, particularly when manure is used, the use of MMPs is crucial for decreasing the risk of water pollution.

Changes to the rule will make the use of MMPs more effective. First, requiring all medium feedlots of 300 to 999 animal units (hereinafter, "medium feedlots")[135] to submit an MMP to a regulatory authority will ensure that medium-sized feedlots are required to do critical annual planning to ensure excess nitrogen is not applied to their fields. Most of these feedlots are already supposed to create a MMP,[136] so simply requiring them to use the online Nutrient Management Tool to submit it would provide little extra burden on producers.

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[131] Chryseis Modderman, *Manure Is Complicated: 5 Reasons You Need a Manure Management Plan* (MCEA Ex. 11).
[132] *Id.* at 2.
[133] *See* Minn. R. 7020.2225, subp. 4(D).
[134] Chryseis Modderman, *Manure Is Complicated: 5 Reasons You Need a Manure Management Plan* (MCEA Ex. 11).
[135] Medium feedlots are defined by the EPA as those with more than 300 animal units. EPA, *Regulatory Definitions of Large CAFOs, Medium CAFO, and Small CAFOs*, https://www3.epa.gov/npdes/pubs/sector_table.pdf (last visited July 18, 2025) (MCEA Ex. 43).
[136] *See* Minn. R. 7020.2225, subp. 4(A).

Second, requiring all feedlots to use MPCA's new Nutrient Management Tool will make MMPs more effective at minimizing water pollution. Currently, only feedlot operators that submit permits directly to the MPCA, rather than to delegated county feedlot officers, are required to use the online tool. The new tool incorporates maps with information on where manure application restrictions apply, including VGAs, sinkholes, tile inlets, wells, surface waters, ditches, and floodplains.[137] These features will help users identify sensitive features at the field scale and are an improvement from previous MMP practices, when MPCA merely provided a list of sensitive features that the feedlot operator had to then identify themselves in their fields. The new tool will also allow an analysis of acres used for land application to ensure that the same fields are not being used by more than one feedlot.[138] Operators that receive manure from a registered feedlot operator should be required to use the digital Nutrient Management Tool as well to ensure they are following the requirements of the land application rule, and if appropriate, the feedlot's permit.[139]

Third, any medium and large feedlots located outside of Minnesota that intend to spread manure inside the state should be required to create, submit, and follow an MMP that meets the requirements of the Animal Feedlot Rule (and require their transferees to follow that MMP) if they have more than 300 animal units. Manure does not become less polluting merely because it crosses state lines, and in recent years more large feedlots constructed on the borders of the state have sent—or plan to send—their manure into Minnesota for field application. For example, Riverview Dairy plans to build a 12,500-cow dairy new Abercrombie, N.D., and a 25,000-cow dairy near

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[137] *See* MPCA, Nutrient Management Planning Map, https://experience.arcgis.com/experience/b99690542f364a6dace31df6fab2e55a/page/Page (last visited July 18, 2025) ("MPCA Nutrient Management Map"); MPCA Responses to Feedlot Permit, at 95.

[138] MPCA Responses to Feedlot Comments, at 93.

[139] The January 2025 revision of the Minnesota General Feedlot Permit requires people who receive transferred manure from feedlots with a NPDES or SDS permit to follow the requirements of the permit in addition to the requirements of the feedlot rule.

Hillsboro, N.D., both along the Minnesota border.[140] Both of these facilities intend to apply some of the 321 million gallons of manure they will produce[141] across the border in Minnesota—the dairy near Hillsboro intends to spread its manure on around 1,180 acres in Minnesota.[142] This may only be the vanguard of more across-the-border feedlots, as North Dakota is taking steps to encourage more livestock production.[143] Facilities should not be allowed to circumvent regulations that protect the health of Minnesotans and its waters by simply locating across state lines.

Finally, the information from the new tool regarding how manure will be applied should be made public through the Minnesota Geospatial Commons, so that community members can confirm that producers are following their MMPs and that fields are not receiving manure from multiple feedlots. Because of MPCA's and delegated counties' limited resources for enforcement and inspections, enlisting the public will help ensure MMPs are properly followed.

These proposed rule changes are particularly important in VGAs. In a May 2025 report, the Environmental Working Group found significant overlap between counties overloaded with nitrogen (defined as counties where nitrogen from manure and commercial fertilizer inputs exceed the Extension Service crop recommendations by more than 40%) and VGAs as defined by the MPCA (see Figure 3). Of the 6,480 feedlot operations that fell within VGAs in 2024, only 161 are above the 1,000-animal unit permit threshold and required to submit MMPs directly to MPCA

[140] Delaney Otto, *As dairy declines in ND, could new facilities prompt a renewal? Boosters, and opponents, are watching*, Grand Forks Herald (June 14, 2025), https://www.grandforksherald.com/news/north-dakota/amid-dairy-decline-in-north-dakota-planned-facilities-could-prompt-a-renewal-in-the-industry-2 (MCEA Ex. 44).
[141] *Id*.
[142] Herberg Dairy Manure Application Fields (MCEA Ex. 45).
[143] Delaney Otto, *As dairy declines in ND, could new facilities prompt a renewal? Boosters, and opponents, are watching*, Grand Forks Herald (June 14, 2025), https://www.grandforksherald.com/news/north-dakota/amid-dairy-decline-in-north-dakota-planned-facilities-could-prompt-a-renewal-in-the-industry-2 (MCEA Ex. 44).

through the new online Nutrient Management Tool. Nearly five times that number (791 facilities) fall into the medium category.[144] Therefore, this proposed rule change would increase the number of feedlot operations within VGAs that have to submit MMPs through the MPCA's online Nutrient Management Tool from approximately 2% to just under 15%,[145] further ensuring that more feedlots are creating appropriate plans to reduce pollution.

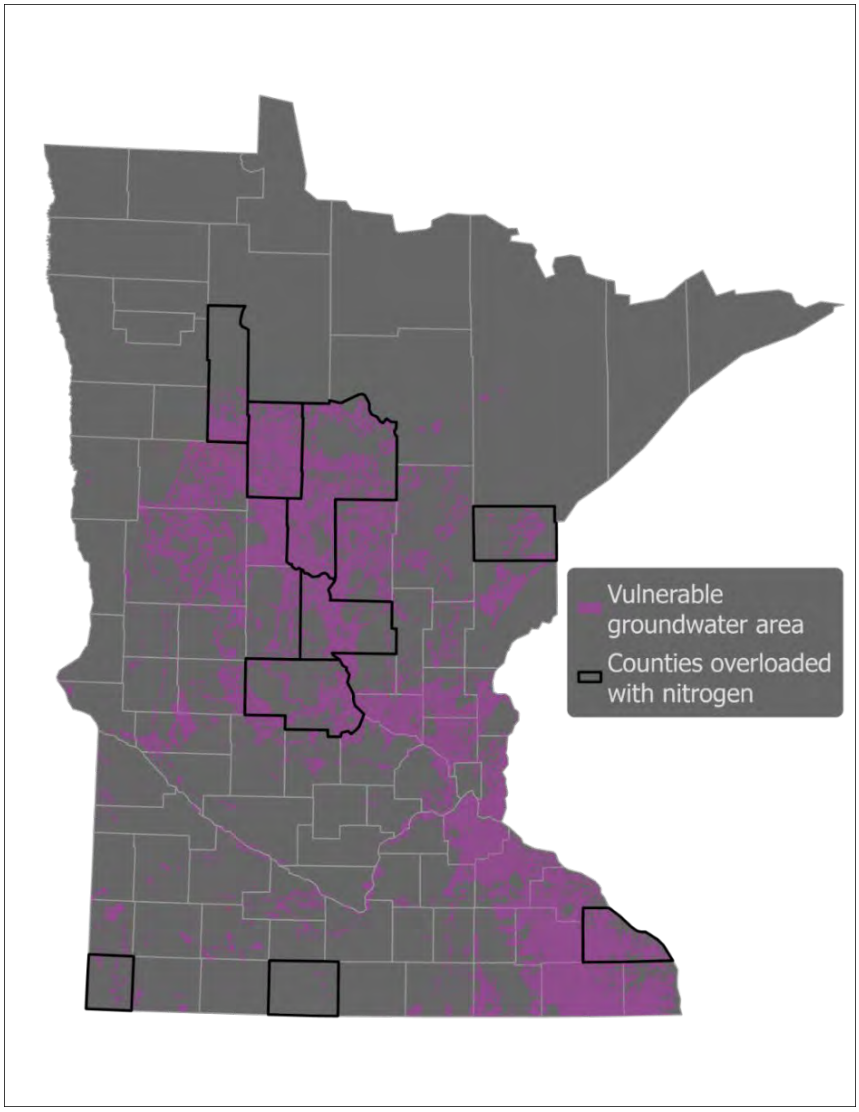

Figure 3: Minnesota counties and vulnerable groundwater areas at risk of nitrogen overload. EWG, Manure Overloads Minnesota (MCEA Ex. 23).

[144] EWG, Manure Overloads Minnesota (MCEA Ex. 23).
[145] *Id.* (161 facilities represents just under 2.5% of the 6,480 feedlots in VGAs; adding the 791 medium facilities to this figure results in just under 15% of the 6,480 feedlots in VGAs).

C. MPCA should require monitoring of feedlot production areas and land application areas for surface and subsurface discharges

Although MPCA added some minimal visual inspection requirements to its new NPDES and SDS permits for feedlots, the Animal Feedlot Rule currently has few requirements for inspections or monitoring to ensure that Minnesota's feedlots are not causing water pollution. The rule has some provisions for inspections of newly constructed liquid manure storage areas, manure compost sites, and poultry barn floors,[146] but it contains no other requirements for inspections or monitoring of production areas or land application areas. To ensure compliance with the Animal Feedlot Rule and identification of facilities that are causing pollution problems, MPCA should add inspection and monitoring requirements, both for production areas and land application sites.

The Animal Feedlot Rule has several prohibitions on discharges to Minnesota's waters. It prohibits discharges of manure from any feedlots into any channels that convey fluids to groundwater or from CAFOs to surface waters of the state unless authorized by a permit.[147] The rule also prohibits land application of manure in a manner that will result in a discharge to the waters of the state during the application process or cause pollution of the waters of the state due to manure-contaminated runoff.[148] In addition, Minnesota's rules prohibit the discharge of wastes to the unsaturated zone that "may pollute the underground waters"[149] and for surface waters prohibit significant increases in harmful residues and pollutants that harm aquatic life. [150] However, there are essentially no monitoring or inspection requirements to ensure that these prohibitions are

[146] Minn. R. 7020.2100, subp. 6; Minn. R. 7020.2150, subp. 2(C); Minn. R. 7020.2120, subp. 2(B).
[147] Minn. R. 7020.2003, subps. 1-2.
[148] Minn. R. 7020.2225, subp. 1(A)(1)-(2).
[149] Minn. R. 7060.0600, subp. 2. This rule does not prohibit the use of chemicals and fertilizers for crops only if "such practices do not pose a significant pollution hazard." Minn. R. 7060.0600, subp. 5.
[150] Minn. R. 7050.0150, subp. 3.

met. Nor do inspections by MPCA's feedlot staff fill this hole. MPCA has only a limited staff to inspect the state's more than 20,000 feedlots—generally, the goal is for agency staff to inspect each MPCA-permitted feedlot once per decade. For counties with delegated authority over feedlots, the goal is to inspect at least 7% of the total number of registered feedlots in the county per year:[151] in counties with many feedlots this can lead to inspections even less frequently than once per decade.

Clearly, neither feedlot inspections nor monitoring are sufficient to prevent discharges from production facilities and land application areas that are causing or contributing to water pollution. While the NPDES and SDS feedlot permits in Minnesota require regular visual inspections of liquid manure storage area freeboard markers and perimeter drain tile, there are no requirements to monitor impacts to groundwater below production areas or to groundwater or drain tile below land application fields.[152] This makes it impracticable or even impossible to consistently identify facilities that meet the definition of a pollution hazard or have violated the Animal Feedlot Rule or the terms of the NPDES and SDS permits.

Multiple courts have held that feedlot permits that do not include monitoring provisions sufficient to ensure compliance with their terms do not meet the requirements of the law, as such permits are of little use.[153] For example, the Washington Court of Appeals found that "[m]onitoring is necessary because it is meant to ensure that dischargers act in compliance with permit

[151] Minn. Stat. § 116.0711 subd. 2c.

[152] *See* MPCA, *Feedlot Inspection Records: NPDES and SDS Permitted Sites* (2025), https://www.pca.state.mn.us/sites/default/files/wq-f5-21.pdf (MCEA Ex. 46).

[153] *Food & Water Watch v. Env't Prot. Agency*, 20 F.4th 506, 515 (9th Cir. 2021) ("Our case law confirms that NPDES permits must contain monitoring provisions sufficient to ensure compliance with the terms of a permit.") (internal citation omitted); *Nat. Res. Def. Council v. Env't Prot. Agency*, 808 F.3d 556, 583 (2d Cir. 2015) (quoting *Nat. Res. Def. Council, Inc. v. Cnty. of Los Angeles*, 725 F.3d 1194, 1207 (9th Cir. 2013)) ("Generally, 'an NPDES permit is unlawful if a permittee is not required to effectively monitor its permit compliance.'").

conditions."[154] The court explained that without such monitoring, permits "contain inherent contradictions that would render them unenforceable," because they prohibit certain discharges while simultaneously allowing conduct which would result in those same discharges.[155] The court found this concept specifically applied to groundwater monitoring. The previous permits contained a condition "that '[d]ischarges conditionally authorized by this permit must not cause or contribute to a violation of water quality standards.'"[156] The Washington Court of Appeals stressed that "[e]nsuring compliance with this condition requires analyzing the effects of a CAFO's activities on groundwater"; and that the agency's own research concluded that "groundwater monitoring . . . is the single method available to ascertain a CAFO's direct impact on groundwater quality."[157]

Similarly, the Ninth Circuit vacated an Idaho permit due to lack of monitoring requirements. The Idaho permit prohibited "discharges of pollutants from production areas" (with a single exception) and "[d]ry-weather discharges from the land-application area," but had no monitoring provisions to ensure these prohibitions were met.[158] The court concluded that "[w]ithout a requirement to monitor runoff from irrigated CAFO fields, there is no way to ensure that a CAFO is complying with the Permit's dry weather no-discharge requirement for land-application areas."[159] In reaching this conclusion, the Ninth Circuit relied on a prior ruling in which

[154] *Washington State Dairy Fed'n v. State*, 18 Wash. App. 2d 259, 301 (2021) (citing *Nat. Res. Def. Council, Inc. v. Cnty. of Los Angeles*, 725 F.3d 1194, 1207 (9th Cir. 2013)). *See also id.* at 303 (internal citation omitted) (stressing the importance of monitoring requirements in permits for groundwater as well)).
[155] *Id*. at 300.
[156] *Id*. at 301 (internal citation omitted).
[157] *Id*. at 302.
[158] *Food & Water Watch v. U.S. Env't Prot. Agency*, 20 F.4th 506, 513, 517-18. (9th Cir. 2021).
[159] *Id*. at 518 (internal citation omitted).

it found explicitly that "an NPDES permit is unlawful if a permittee is not required to effectively monitor its permit compliance."[160]

To address the Ninth Circuit's decision in that case, the EPA established new permit requirements for CAFOs in Idaho.[161] For production areas, the Idaho permit now requires all permitted feedlots to prepare a Subsurface Discharge Monitoring Plan ("SDMP") "to identify and monitor any functionally equivalent subsurface discharges to Waters of the United States ["WOTUS"] from each wastewater or manure storage structure."[162] The only exceptions to this requirement are if one of the following criteria are met: either a) a "Professional Engineer, geologist, hydrogeologist or another qualified individual" documents that the storage structure does NOT have a subsurface discharge to WOTUS; or b) the permittee confirms and maintains documentation in the MMP "that each wastewater and manure storage structure is constructed of concrete or steel, or with a double-layer synthetic liner with leak detection."[163] The SDMP itself must include "site-specific information and procedures" that outline routine, periodic monitoring "adequate to identify leaks, damage, and other issues that could cause a functionally equivalent subsurface discharge, including the frequency of monitoring and the site-specific technology or protocols that will be used."[164]

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[160] *Nat. Res. Def. Council v. Env't Prot. Agency*, 808 F.3d 556, 583 (2d Cir. 2015) (quoting *Nat. Res. Def. Council, Inc. v. Cnty. of Los Angeles*, 725 F.3d 1194, 1207 (9th Cir. 2013)).
[161] *Authorization to Discharge under the National Pollutant Discharge Elimination System: Idaho,* EPA, https://www.epa.gov/system/files/documents/2024-12/r10-npdes-idaho-cafo-gp-idg010000-final-permit-mod-2024.pdf (MCEA Ex. 12) ("Idaho Permit") ("The general permit was modified to includes [sic] new and revised conditions to address the Ninth Circuit Court of Appeal's Order and Opinion filed on December 16, 2021").
[162] *Id.* § III.A.2.a.iii.
[163] *Id.* § III.A.2.iii.a-b.
[164] *Id.* § IV.D.6.b.

To assess compliance with the prohibition on dry weather discharge for land application areas, the Idaho Permit imposes specific monitoring requirements, including the collection of grab samples "prior to mixing with the receiving waters" as well as upstream and downstream of the point of discharge to the receiving stream.[165] The permit also requires soil samples to be "taken from every field to which manure, litter, and process wastewater will be applied."[166] The soil samples must be analyzed by a certified laboratory for pH, soil organic matter, Nitrate-Nitrogen, Ammonium-Nitrogen, and phosphorus.[167] Finally, the results of these soil sample analyses must be included in the MMP and used to determine application rates.[168]

This concept established in both the Washington and Idaho court decisions that permits must include adequate monitoring to ensure compliance applies equally to the Animal Feedlot Rule—a rule that requires feedlots to take no steps to ensure they are complying with its prohibitions is not an effective rule. MPCA has the authority to include monitoring and inspection provisions in the rule. It has been specifically entrusted by the Legislature with the authority to require owners or operators of point sources to install and maintain monitoring equipment needed to prevent and abate pollution.[169] Accordingly, it should add provisions to the Animal Feedlot Rule to require adequate monitoring both at land application areas and production areas to ensure compliance with the Rule.

1. Land application areas

At a minimum, the Animal Feedlot Rule should be revised to add visual inspection requirements for land application areas for all medium (over 300 animal units) and large feedlots,

[165] *Id.* § IV.E.1.
[166] *Id.* § III.A.2.g.ii.
[167] *Id.* § III.A.2.g.ii-iii.
[168] *Id.* § III.A.2.g.ii.
[169] Minn. Stat. § 115.03, subd. 1(a)(5)(vii).

similar to those added to the NPDES and SDS feedlot permits. The new feedlot permits have added requirements for visual inspections of land application fields at all downgradient field edges; sensitive features including tile intakes, sinkholes, and wells; ditches; and other features that could convey manure to waters.[170] These inspections must take place at least once on each day of manure application, at the end of each day of application, and after any significant rainfall within 14 days after application unless the manure is injected or incorporated.[171] Any discharge must be responded to and reported to the State Duty Officer and the MPCA.[172] These requirements are not overly burdensome; they do not require investing in expensive equipment or even expending a significant amount of time. Instead, they are common-sense provisions that take the first necessary step toward adding monitoring provisions that will ensure compliance with Minnesota's rules protecting groundwater. Producers cannot know whether they are causing pollution if they do not—at an absolute minimum—look to see if manure is visibly running from their fields during or immediately after application, or after a significant rainfall. To comply with state and federal law, MPCA should include *at least* these monitoring provisions in the Animal Feedlot Rule.

In addition to visual inspections, MPCA should require groundwater monitoring on fields with the highest risk of nitrate loss to groundwater for feedlots with a NPDES or SDS permit. Subsurface monitoring of this kind is the only way to ensure that unauthorized discharges to groundwater, which would not be discovered by a visual inspection, are not occurring in violation of the prohibitions in the Animal Feedlot Rules and Minnesota's water quality standards. Based on conversations with MPCA feedlot staff, there are currently fewer than 20 feedlots statewide where

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[170] *See* MPCA, *Authorization to Construct and Operation a Concentrated Animal Feeding Operation Under the National Pollutant Discharge Elimination System (NPDES) Program*, § 14.3 https://www.pca.state.mn.us/sites/default/files/wq-f3-62.pdf ("Minnesota NPDES Permit").
[171] *Id.*
[172] *Id.* §§ 14.3, 27.2, 27.3.

MPCA has installed a well network to monitor groundwater discharges. At a minimum, MPCA should undertake a risk-based assessment to determine whether further well networks are necessary, such as investigatory geo-probes to collect temporary well data at permitted feedlots located in VGAs or where contamination exceeds a certain threshold. Possible thresholds include townships with a highly vulnerable Drinking Water Supply Management Area ("DWSMA")[173] where nitrate levels have exceeded 5.4 mg/L nitrate or a township where more than 10% of private wells have tested above the 10 mg/L limit.

Such risk assessments are already used in Wisconsin. There, the state's Department of Natural Resources "may require the installation of a leakage collection of monitoring system or secondary containment."[174] The Wisconsin rule provides a series of factors to consider in determining whether to require installation of such a system:

a. Whether facilities are located on or near areas that are susceptible to groundwater contamination such as direct conduits to groundwater, sandy soils, and sites with minimal separations between bedrock and high water tables.
b. The size and depth of the facility.
c. The type of liner used.
d. Characteristics of waste being stored.
e. Other considerations based on potential impacts to waters of the state.[175]

In addition to the above, the Wisconsin Department of Natural Resources "may require the installation of groundwater monitoring wells in the vicinity of manure storage facilities, runoff control systems, permanent spray irrigation systems and other treatment systems where [it]

[173] The Minnesota Department of Health defines vulnerable DWSMAs as those where the land is "highly vulnerable to contamination from the land surface because of their geologic conditions." *Protecting Vulnerable Drinking Water Sources*, Minn. Dep't of Health (Mar. 23, 2021), https://www.health.state.mn.us/communities/environment/water/docs/cwf/vulnacres.pdf (MCEA Ex. 47). "Currently, there are approximately 400,000 acres in vulnerable groundwater DWSMAs" that "represent less than 1% of the overall land area of the state." *Id.*
[174] Wi. Admin. Code DNR § 243.15(3)(c)(2).
[175] Wi. Admin. Code DNR §§ 243.15(3)(c)(2)(a)-(e).

determines monitoring is necessary to evaluate impacts to groundwater and geologic or construction conditions warrant monitoring."[176] MPCA should adopt a similar approach to protect groundwater from pollution.

MPCA has already determined that fields in the VGAs are those most at risk of discharging nitrate and other pollutants to groundwater because of their soil and geologic conditions. State agency data and producer surveys demonstrate that producers who land apply manure in addition to commercial fertilizer are likely to exceed recommended nitrogen application rates. And MPCA has determined that the largest feedlots, those that are required to obtain NPDES or SDS feedlots, should be required to comply with additional regulations because of the dangers of overapplication that come with the vast amounts of manure they produce. Based on this combination of risk factors, the Animal Feedlot Rule should require that feedlots that need a NPDES or SDS permit should create a SDMP for any land application fields within the VGAs as part of their MMPs.

For land application areas in VGAs, a SDMP would require the use of soil probes to take annual soil samples to inform agronomic application rates, as well as soil moisture probes or lysimeters to monitor water quality within high-risk fields. These steps would allow the feedlot operator and the MPCA to determine whether manure applications are likely to "cause pollution of waters of the state due to manure-contaminated runoff."[177] Annual soil sample requirements in the SDMP could be modeled on the recently revised Idaho Permit: samples should be taken from every field to which manure, litter, and process wastewater will be applied and should then be analyzed by a certified laboratory for pH, soil organic matter, Nitrate-Nitrogen, Ammonium-

[176] Wi. Admin. Code DNR § 243.15(7).
[177] Minn. R. 7020.2225, subp. 1(A)(2).

Nitrogen, and phosphorus. The results of these analyses must be included in the MMP and used to determine application rates.

Informed by the language in the recent Washington state court decision, the SDMP for land application areas in VGAs should also include the use of soil moisture probes or lysimeters to monitor for subsurface discharges to groundwater. Soil moisture probes and lysimeters require uniform installation across a field to generate representative data,[178] so a field-wide system must be used. Generally, one sample should be taken for every 20 acres, and monitoring should occur during land application or irrigation of fields where manure has been land applied. If a discharge is discovered at a land application area and it is clear that there has not been an appropriate agronomic utilization of nutrients, the producer must have a professional engineer or hydrogeologist review the MMP.[179] Results of the assessment would then be uploaded to the new online Nutrient Management Tool and any deficiencies would have to be addressed by the feedlot to ensure no additional discharges occurred. This combination of visual and subsurface monitoring would ensure that feedlots were not discharging from land application areas in violation of Minnesota's water quality standards, the Animal Feedlot Rule, and their permits.

2. Production areas

The few inspection requirements imposed by the Animal Feedlot Rule on production areas are entirely inadequate to stop the many ways feedlots discharge from production areas. MPCA should require more monitoring of feedlot production areas—specifically, requiring that all

[178] Kevin Kuehner et al., *Examination of Soil Water Nitrate-N Concentrations from Common Land Covers and Cropping Systems in Southeast Minnesota Karst* at 9, MDA (Oct. 2020), https://bearworks.missouristate.edu/cgi/viewcontent.cgi?article=4638&context=articles-cnas (MCEA Ex. 48).
[179] *See* Idaho Permit, § III.A.2.a.ii (MCEA Ex. 12).

feedlots conduct frequent visual inspections of production area elements and requiring feedlots that need NPDES or SDS permits to create a SDMP.

At a minimum, the Animal Feedlot Rule should require regular visual inspections of the production areas most prone to polluting—specifically, Liquid Manure Storage Areas ("LMSAs"), manure stockpiling areas, manure composing areas, and any other areas where manure or process wastewater accumulate. All of these areas should be inspected at least weekly to determine whether visible leaks or runoff are occurring in violation of the Animal Feedlot Rule's prohibition on discharges. For feedlots with LMSAs "designed and operated to provide storage for only manure-contaminated runoff or process wastewater," this should include weekly visual inspection of the LMSA freeboard marker to ensure that the LMSA has adequate capacity "to accommodate the volume generated from a 25-year, 24-hour storm event and any additional volume needed to be consistent with the proposed [MMP] application frequency" to ensure compliance with the design standards of the Animal Feedlot Rule.[180] This is not a theoretical problem— as one example, in June 2024, 17 manure pits in the state overflowed due to heavy rains.[181] Regular visual inspections could ensure that leaks or runoff are found earlier and steps taken to address discharges.

In addition, feedlots that require a NPDES or SDS permit should be required to create a SDMP as part of their MMP. Visual inspections of LMSAs cannot determine whether the pit is leaking below the surface, because an inspector cannot visually see a leak below the opaque manure-laden process wastewater. With visual inspections only the most catastrophic leaks will be detected, as measuring lagoon seepage and leakage through observation of a freeboard measuring

[180] Minn. R. 7020.2100 subp 3(B).
[181] Greg Stanley, *Seventeen manure pits reportedly overflow at large feedlots in southern Minnesota*, Minnesota Star Tribune (June 26, 2024), https://www.startribune.com/manure-pits-reportedly-overflow-at-16-large-feedlots-in-southern-minnesota/600376074 (MCEA Ex. 49).

stick alone is imprecise, particularly given that the level of manure within any LMSA will change as its inputs and outputs change. In addition, LMSAs are *designed to leak*—leaks of 500 gallons per acre per day are allowed by the design standards under the Animal Feedlot Rule.[182] When MPCA explicitly allows feedlots to store manure in a manner that allows the subsurface discharge of thousands of gallons of liquid manure into the unsaturated zone every day, it must require monitoring to determine whether that seepage is polluting groundwater in violation of Minnesota's water quality standards and groundwater protection rules.

Requiring SDMPs would prevent discharges that would cause pollution while also ensuring that permittees are not burdened with a "one-size-fits-all" groundwater monitoring plan that might impose more monitoring than their feedlot truly needs. For each feedlot, the SDMP would (a) identify the structures and locations to be monitored, (b) establish a routine periodic inspection schedule adequate to identify leaks, damage, and other issues that could cause a subsurface discharge, (c) identify "[c]riteria or protocols that will be used to determine whether a . . . subsurface discharge has occurred," and (d) establish site-specific protocols for monitoring subsurface discharges.[183] Monitoring equipment could include a series of up and downgradient groundwater monitoring wells, or a designed leak detection sump system to determine whether discharges are occurring in violation of Minnesota's rules against pollution of groundwater.[184] The type of monitoring system used could be progressively more rigorous depending on the type of

[182] Minn. R. 7020.2100, subp. 3(C)(1) (LSMAs "must be designed and constructed to achieve a maximum theoretical seepage rate of not more than 1/56 inch per day," which allows a discharge of approximately 500 gallons per acre per day. *See* Natural Resources Conservation Service, *Agricultural Waste Management Field Handbook, Agricultural Waste Management System Component Design*, Appendix D, 10D-3 (2009), https://nrcspad.sc.egov.usda.gov/distributioncenter/pdf.aspx?productID=565 (MCEA Ex. 50).
[183] *See* Idaho Permit, § IV.D.6.a-d (MCEA Ex. 12).
[184] Well drilling, sampling and analysis protocols are well documented in EPA regulations. *See* 40 C.F.R. §§ 257.91, .93-.95.

waste impoundment liner used. Earthen liners should require a full groundwater monitoring plan,[185] while synthetic liners could require an abbreviated monitoring scenario, and a double synthetic liner with leak detection or a sump and pump design would not require a groundwater monitoring system at all *if* the operation and maintenance standards outlined in Minnesota Rule 7020.2100 subpart 6 were met. This is consistent with the requirements of the revised Idaho Permit, which requires a SDMP for production areas unless a professional engineer, geologist, hydrogeologist or other qualified individual documents that the storage structure does not have a subsurface discharge to WOTUS or if the storage structure is constructed of concrete or steel, or with a double-layer synthetic liner.[186]

To ensure that feedlots are actually complying with the requirements of the Animal Feedlot Rule and Minnesota's water quality standards, and to identify feedlots that are creating water pollution problems in violation of the rules, MPCA should include revisions or add a new provision that would (1) require visual inspections of land application areas similar to those included in the NPDES and SDS feedlot permits, (2) require regular visual inspections of elements at production areas that pose the greatest risk of water pollution for all medium and large feedlots, and (3) require SDMPs for land application areas within VGAs and production areas for all feedlots that are required to obtain NPDES or SDS permits.

[185] For a full groundwater monitoring plan, wells should be placed upgradient and downgradient of the lagoon or area to be monitored, and sampling should be conducted quarterly or semiannually to establish seasonal fluctuation in groundwater quality or quantity, to collect representative data, and to establish statistically significant background data. Data analysis requires statistical evaluation of the data to determine if upgradient water quality is different than downgradient water quality. A statistically significant delta between these two data sets establishes that the monitored area is contributing pollutants to groundwater.

[186] Idaho Permit, § III.A.2.iii.a-b (MCEA Ex. 12).

D. MPCA should require additional restrictions on manure application in the Vulnerable Groundwater Areas to protect groundwater

The Animal Feedlot Rule provides no additional protections for the VGAs, the areas with the most vulnerable and polluted groundwater in the state. The rule should be revised to require additional restrictions on land applying manure in the VGAs, at a minimum similar to those included in the NPDES and SDS permits.

Minnesota's water quality rules not only set an antidegradation standard for all groundwater that calls for "maximum protection to all underground waters,"[187] but also set an enforceable limit of 10 mg/L for nitrate,[188] and prohibit discharge of wastes into the unsaturated zone in a manner that will cause pollution of underground waters.[189] But the current Animal Feedlot Rule does not control pollution in a way that meets these standards; it vaguely forbids application of manure in a way that will "cause pollution of waters of the state due to manure-contaminated runoff,"[190] and includes some manure setbacks from some specific features.[191] Largely, however, the Animal Feedlot Rule imposes few restrictions aimed at preventing groundwater pollution from land applied manure, and those restrictions that exist have proven remarkably ineffective, particularly in the VGAs, as shown by the state's own data and the EPA direction to take further action to address nitrate groundwater pollution in the karst region.

This is particularly problematic when the Minnesota Legislature has specifically directed MPCA to adopt mandatory "water source protection requirements" as needed to "prevent and minimize the pollution to the extent practicable."[192] When voluntary best management practices

[187] Minn. R. 7060.0200.
[188] Minn. R. 7050.0221, subps. 2–4; *see* 40 C.F.R. § 141.62.
[189] Minn. R. 7060.0600, subp. 2.
[190] Minn. R. 7020.2225, subp. 1(A)(2).
[191] Minn. R. 7020.2225, subps. 7-8.
[192] Minn. Stat. § 103H.275, subd. 2.

("BMPs") have proven to be ineffective—as the state agency data showing widespread and persistent violation of the 10 mg/L limit has shown that they are—MPCA is obligated to adopt mandatory rules to protect groundwater.[193] In particular, the Legislature directed MPCA to consider the specific risks to groundwater in sensitive areas, which include the VGAs, in imposing water source protection requirements.[194] But the Animal Feedlot Rule includes no additional rules taking the VGAs into account.

One of the most serious issues in the VGAs is the application of nitrogen to cropland in the fall when there are no crops to take it up.[195] Applying manure in the fall greatly increases the risk of nitrogen loss—in fact, the Extension Service states that any nitrate left in the soil in the fall "is usually lost during the spring before the next year's crop can take it up."[196] For this reason, the Extension Service does not even recommend taking a nitrogen credit for late season nitrate; according to their recommendations, producers should simply assume that *all nitrate from the fall has been lost* over the winter and spring unless it has been a particularly dry year.[197]

In vulnerable groundwater areas, fall application becomes even more risky. As early as 1990, MDA stated, "The risk of leaching loss of nitrate from fall nitrogen application is heightened in southeastern Minnesota due to the high average annual precipitation, the well-drained and permeable nature of the soils and the presence of karstic terrain."[198] For that reason, the practice

[193] Minn. Stat. § 103H.275, subd. 1.
[194] Minn. Stat. § 103H.101, subd. 5.
[195] Groundwater Protection Rule SONAR at 58–59.
[196] Brad Carlson, *Taking soil samples for nitrogen analysis could pay big this year* (Mar. 30, 2022) (MCEA Ex. 13).
[197] *Id.* This is contrary to the feedlot rules, which require producers to take credit for *all* sources of nitrogen, but the recommendation is nevertheless telling with regard to how much nitrogen the Extension Service expects to remain in the soil. *See* Minn. R. 7020.2225, subp. 3(A)(1).
[198] MDA, *Nitrogen Fertilizer Management Plan* 59 (Aug. 1990), https://www.lrl.mn.gov/docs/pre2003/mandated/900659.pdf.

of not applying expensive chemical fertilizer (as opposed to manure, which producers already have on hand in massive quantities and which must be disposed of) in the fall has been widely adopted by crop producers in the VGAs. MDA-funded research showed that in 2009 only 5% of producers in areas of the state with karst geology or coarse-textured soils applied commercial fertilizer to corn in the fall.[199] In 2015, MDA said that fall and winter application in these areas was "clearly inappropriate, and that the vast majority of Minnesota farmers and their crop advisors do not fall apply or apply fertilizer when it is not recommended by the U of M."[200]

What is true for commercial fertilizer is also true for manure—applying nitrogen in this form in the fall comes with a high risk of nitrate loss to groundwater.[201] Mandating that producers who apply manure in the fall use BMPs can help address this problem. Some of these BMPs are already required by MPCA's feedlot permits and applying them more broadly could be accomplished by either (1) lowering the permit threshold to 600 animal units, as stated above, or (2) mandatory adoption of certain BMPs for medium and large feedlots. These BMPs include:

Use of cover crops. Cover crops, which take up leftover nitrogen in the soil at a time when fields are generally fallow, are a "well-established" way to reduce nitrate loss.[202] The Draft Nutrient Reduction Strategy Update highlighted the importance of cover crops, stating plainly that

[199] Pete Bierman et al., *Survey of Nitrogen Fertilizer Use on Corn in Minnesota*, MDA (2011) at 22, https://www.mda.state.mn.us/sites/default/files/inline-files/nfertilizersurvey2011_0.pdf (MCEA Ex. 51).
[200] 2015 Nitrogen Fert. Mgmt. Plan at 82.
[201] With manure the situation is more complex, because while commercial fertilizer contains inorganic forms of nitrogen such as nitrate and ammonium that are immediately plant-available, manure contains both inorganic and organic forms of nitrogen. The organic forms of nitrogen need to be converted into inorganic forms by soil microbes, and therefore some of the nitrogen applied in the fall may remain in the soil when a crop is planted in the spring. However, the risk of nitrate loss to groundwater remains exceedingly high with the fall application of manure.
[202] Univ. of Minn. Extension Service, *Cover Crops*, https://extension.umn.edu/soil-and-water/cover-crops (last visited July 18, 2025) (MCEA Ex. 52).

"Nitrogen water quality goals cannot be achieved without transformative changes in crop system rotations and more months of living cover each year."[203] Research supports the effectiveness of cover crop practices: One study on nitrate reduction strategies showed that planting cover crops such as rye can reduce nitrogen loads by more than 45%,[204] and a literature review showed that cover crops can result in approximately 20 to 40% reductions in nitrogen loss.[205] Despite doubts from producers, research shows that certain cover crops may reliably be planted in October and even into November.[206] Accordingly, one option for fall application is to apply manure only to fields where cover crops are growing or will be planted imminently.

Perennial crops in rotation: Rotating annual crops with perennials decreases leaching losses because perennial grasses have greater root biomass that extends deeper into the soil.[207] Diversified crop rotations can reduce nitrogen loads by more than 77%.[208] A three-year study in Lamberton, Minnesota found losses of nitrate through subsurface drains were four to five times greater for a corn-soybeans or continuous corn rotation compared to a rotation with alfalfa and 13 to 15 times greater than in rotations with perennial grasses.[209] Another study from the University of Minnesota showed that one year of planting wheatgrass decreased soil nitrate-N concentrations

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[203] MPCA, *Minnesota Nutrient Reduction Strategy – DRAFT* at 154 (July 2025), https://www.pca.state.mn.us/sites/default/files/wq-s1-87a.pdf.
[204] Laura Christianson et al., *Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage*, 2-3 Water Resources and Economics 30, 44 (2013) (MCEA Ex. 14).
[205] MPCA, *Minnesota Nutrient Reduction Strategy – DRAFT* at 159 (July 2025), https://www.pca.state.mn.us/sites/default/files/wq-s1-87a.pdf.
[206] MPCA Responses to Feedlot Permit Comments at 2-3.
[207] Evelyn C. Reilly et al., *Reductions in soil water nitrate beneath a perennial grain crop compared to an annual crop rotation on sandy soil*, Frontiers in Sustainable Food Systems (Sept. 2022) at 2 (internal citations omitted) (MCEA Ex. 15).
[208] Laura Christianson et al., *Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage*, at 44 (MCEA Ex. 14).
[209] David Huggins et al., *Subsurface drain losses of water and nitrate following conversion of perennials to row crops*, 93 Agronomy Journal 477, 484 (2001) (MCEA Ex. 16).

by 77%.[210] Another BMP option, therefore, is to apply manure only to fields that have perennial crops for at least two years in the previous five-year period.

Cool soils and nitrogen inhibitor: When manure is applied to soil that has a temperature of 50 degrees or less, the cool soil temperatures slow conversion of nitrogen into nitrate, the form that most easily leaches into groundwater.[211] Less nitrogen in the form of nitrate means less water pollution. However, this BMP is not as effective as cover crops or perennials, because it does not remove the nitrogen from the soil, but merely slows its conversion to nitrate. In addition, for this BMP to be effective, the soil must be at and remain at 50 degrees when the manure is applied. If soils remain at 50 degrees or lower until freeze up, only around 15% of the nitrogen will nitrify, but if soils are just slightly warmer—55 degrees for 10 days—approximately 40% of the nitrogen will nitrify.[212] Because of the risk of this occurring, in the NPDES and SDS permits, MPCA combined this BMP with the use of a nitrate inhibitor, which further slows the nitrification process. However, nitrate inhibitors are also rendered less effective by warmer soils.[213] This means that nitrate loss will increase significantly if soil temperatures unexpectedly rise, and as MPCA has acknowledged, average temperatures in Minnesota continue to rise as the state experiences climate change.[214] Accordingly, if MPCA includes this as a BMP option for fall application, it should be allowed only in November, when soils reliably remain under 50 degrees.[215]

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[210] Reilly, *Reductions in soil nitrate* at 5-6 (MCEA Ex. 15).
[211] MPCA Responses to Feedlot Permit Comments at 4.
[212] *Id.* at 6.
[213] *Id.* at 7.
[214] MPCA, *Climate Change Impacts*, https://www.pca.state.mn.us/air-water-land-climate/climate-change-impacts (last visited July 18, 2025) (MCEA Ex. 53).
[215] MPCA Responses to Feedlot Permit Comments at 9. Allowing this BMP only in November will also eliminate the need to define how to determine when soils have reached 50 degrees. As a comparison, in its Groundwater Protection Rule, MDA considered whether to define "frozen soil" as soil with a temperature of 32 degrees. However, MDA decided there could be variability in soil temperature at different depths as well as different locations, and it would be difficult for producers

E. MPCA should prohibit risky manure application practices that threaten waters statewide

While the VGAs have the most sensitive and most polluted groundwater in the state, nitrate and bacterial pollution are not limited to these areas. The rules that require MPCA to limit surface water and groundwater pollution in the VGAs also require MPCA to limit nitrate pollution across the state, but the current Animal Feedlot Rule land application rules have not adequately addressed nitrate pollution.[216] Some manure application practices are sufficiently risky—and provide such little benefit for crop nutrient needs—that they should not be allowed anywhere in the state. Accordingly, these practices should be prohibited not only in the VGAs, but across the state.

1. Requiring larger setbacks for manure spreading from sensitive features

The Animal Feedlot Rule prohibits application of manure within 50 feet of water supply wells, sinkholes, mines, or quarries, and requires incorporation of manure within 300 feet from a sinkhole where the land slopes toward the sinkhole.[217] This is important, because these features provide channels for pollutants to enter surface and groundwaters.[218] However, federal feedlot rules for CAFOs require that manure and wastewater not be applied closer than 100 feet to any down-gradient surface waters, "sinkholes, agricultural well heads, or other conduits to surface

to take temperature measurements and for MDA to verify them. (Groundwater Protection Rule SONAR at 82.) Accordingly, MDA decided to take a more practical approach to defining "frozen soil." (*Id.*) Similarly, here it would be difficult for both producers and MPCA to know when soil temperatures had fallen below 50 degrees. MPCA should, therefore, simply reserve this BMP for November, when soil temperatures are reliable below this level, preventing confusion and the need for producers to measure soil temperatures.

[216] *See* Minn. R. 7020.2225.

[217] Minn. R. 7020.2225, subp. 8(A)-(B).

[218] Minn. Pollution Control Agency, *Applying Manure in Sensitive Areas* 1 (2005), https://www.pca.state.mn.us/sites/default/files/feedlots-manureapplication.pdf (MCEA Ex. 54).

waters" unless a compliance alternative is exercised.[219] While this federal rule applies only to CAFOs, the danger from applying manure near to these sensitive features does not change whether the manure comes from a feedlot with 10,000 animal units or 100 animal units. The Animal Feedlot Rule, accordingly, should be revised to require at least a 100-foot setback from these sensitive features. For the VGAs, even greater setbacks are appropriate. In Wisconsin, producers in areas of shallow bedrock are prohibited from spreading manure "within 250 feet of a private well, 1,000 feet of a community well, or 300 feet upslope or 100 feet downslope of a direct conduit to groundwater" such as a sinkhole because of the unique vulnerabilities of shallow bedrock areas.[220] MPCA should similarly consider stricter setback distance standards in its VGAs.

2. Prohibiting application of manure on frozen or snow-covered ground

Applying manure in winter conditions, when it cannot sink into the ground, creates a significant risk of runoff and volatilization to the air, and therefore increases the risk of nitrate pollution.[221] When the ground is frozen or snow-covered, manure applied to the surface cannot seep into the ground, creating a significant risk of runoff and consequent loss of nitrate.[222] In an average year in Minnesota, nearly half of the total surface runoff volume occurs when the soil is

[219] 40 C.F.R. § 412.4(c)(5). The federal rule also prohibits application within 100 feet of open tile intakes, *see id.*; however, the Animal Feedlot Rule already prohibits application of manure within 300 feet of open tile intakes. Minn. R. 7020.2225, subp. 7.

[220] Christine Anne Clark & Laura Paletta, *Best Management Practices to Use on Karst and Silurian Soil*, University of Wisconsin-Madison, Division of Extension, https://cropsandsoils.extension.wisc.edu/articles/best-management-practices-to-use-on-karst-and-silurian-soil/ (last visited July 17, 2025) (MCEA Ex. 17).

[221] Univ. of Minn. Extension Serv., *Reducing Water Quality Issues from Manure* (2020), https://extension.umn.edu/manure-management/reduce-water-quality-issues (MCEA Ex. 18) ("Do not apply on saturated or frozen soils as this will increase runoff").

[222] Melissa Wilson, *Manure applied on frozen soil or snow—what will happen to my nitrogen?* Minnesota Crop News, (Jan. 1, 2024), https://blog-crop-news.extension.umn.edu/2019/01/manure-applied-on-frozen-soil-or-snow.html (MCEA Ex. 19).

frozen.[223] In addition, when the manure remains on the surface of the frozen ground, there is a longer opportunity for volatilization—in which ammonium-nitrogen on the surface is turned into ammonia gas.[224] Ultimately, most of this gas turns back into ammonium and is redeposited on the ground, generally in the same watershed—meaning that it remains a local pollution hazard.[225] Accordingly, the Extension Service advises producers not to apply manure to frozen soils.[226] MDA also has recognized that this is not an effective practice, stating unequivocally, "No benefit[s] were identified from the application of nitrogen fertilizer to frozen soils."[227] Although this statement was made with regard to commercial fertilizer, application of manure to frozen soils similarly would have no benefits for crops. The Animal Feedlot Rule should be revised to prohibit applying manure to frozen or snow-covered soils throughout the state.

3. Prohibiting manure application when the risk of runoff from rainfall is severe

Applying manure before a significant rainfall creates a significant risk of runoff, and thus of nutrient loss. However, the Animal Feedlot Rule has no explicit prohibition on applying manure before—or even during—a rain event. MPCA should decrease the risk of manure runoff by requiring producers to use the Runoff Risk Advisory Forecast ("RRAF")—a tool specifically

[223] Five Year Progress Report on NRS at 27.
[224] Melissa Wilson, *Manure applied on frozen soil or snow—what will happen to my nitrogen?* (MCEA Ex. 19). While freezing temperatures slow down volatilization, research suggests that the process does not stop entirely. In addition, freezing and thawing cycles mean that there will be at least some time for volatilization to occur but make it difficult to determine how much nitrogen has been lost. *Id.*
[225] Christopher S. Jones et al., *Livestock manure driving stream nitrate*, 48 Ambio 1143, 1148 (Dec. 2018) (internal citation omitted) (MCEA Ex. 20).
[226] Univ. of Minn. Extension Serv., *Reducing Water Quality Issues from Manure* (MCEA Ex. 18).
[227] Groundwater Protection Rule SONAR at 102.

created by MDA to help producers determine the best time to apply manure—and prohibiting application of manure when the risk of runoff is severe.[228]

The RRAF was created specifically to help reduce manure nutrient runoff.[229] Rainfall during or immediately after manure application is a significant source of runoff—in one study, more than half of the runoff from fields was caused by one or two rain events each year.[230] The RRAF is more accurate in predicting a runoff risk than a weather report, as it considers not only upcoming rainfall, but also soil moisture content, temperatures, snow melt, and other factors.[231] It is more precise than a weather report as well, as it assigns a specific runoff risk to each 2 square kilometer area of the state: No Runoff Expected, Low, Moderate, or Severe. Producers can sign up to receive texts on their phones for their fields, making the system extremely user-friendly. However, relatively few producers have signed up to use the tool, despite its usefulness. To reduce the risk of runoff—at times when the state's own model has determined risk of runoff is high—MPCA should add a provision to the Animal Feedlot Rule that prohibits feedlots from applying manure in fields when the risk of runoff is "severe."

F. MPCA should reduce the allowed manure application rates to the Extension Service recommended rates

The Animal Feedlot Rule limits manure application rates, essentially, to the "most recent published recommendations of the University of Minnesota Extension Service or of another land grant college in a contiguous state."[232] However, the rule allows application rates to deviate up to

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[228] MDA, *Runoff Risk Advisory Forecast*, https://www.mda.state.mn.us/protecting/cleanwaterfund/toolstechnology/runoffrisk (last visited July 18, 2025).
[229] *Id.*
[230] MDA, *Field Runoff: Root River Field to Stream Partnership*, https://www.mda.state.mn.us/sites/default/files/inline-files/rootrivfieldrunoff.pdf (last visited July 18, 2025) (MCEA Ex. 55).
[231] MDA, *Runoff Risk Advisory Forecast*, https://www.mda.state.mn.us/protecting/cleanwaterfund/toolstechnology/runoffrisk (last visited July 18, 2025).
[232] Minn. R. 7020.2225, subp. 3(A)(1).

20% from Extension Service recommendations "where site nutrient management history, soil conditions, or cool weather warrant additional nitrogen application," and even further "[w]hen crop nitrogen deficiencies are visible or measured."[233] But the loopholes in this rule mean that in effect there are few restrictions on the rates at which producers can apply manure to their fields. The Animal Feedlot Rule should be revised to allow feedlots to apply at the Extension Service's recommended rates as a maximum, without additional deviations or the ability to resort to the recommendations of other states.

The most important factor in avoiding nitrate pollution is applying nitrogen at appropriate rates, commensurate with the needs of the crops currently growing.[234] Once application rates exceed the Extension Service's recommended nitrogen application rates, "losses tend to increase in a quadratic response."[235] Reducing nitrogen application rates can lower nitrogen losses by as much as 70%, according to a review by MPCA.[236] More recently, the Draft Nutrient Reduction Strategy Update stated that a 25% reduction to lower the nitrogen application rate to the MRTN resulted in approximately a 20% nitrate loss reduction.[237] In addition, overapplication is a well-documented problem in Minnesota, particularly when manure is combined with commercial fertilizer as a nutrient source.[238] Producers in the southeastern karst region of the state are overapplying nitrogen by approximately 60 million pounds[239] and in nine counties across the state,

[233] Minn. R. 7020.2225, subp. 3(A)(2).
[234] Groundwater Protection Rule SONAR at 52.
[235] Groundwater Protection Rule SONAR at 35; 2015 Nitrogen Fert. Mgmt. Plan at 37 (nitrate leaching losses "increase dramatically" above recommended rates).
[236] Nitrogen in Minnesota Surface Waters, at F1-3.
[237] MPCA, *Minnesota Nutrient Reduction Strategy – DRAFT* at 159 (July 2025), https://www.pca.state.mn.us/sites/default/files/wq-s1-87a.pdf.
[238] Groundwater Protection Rule SONAR at 51-52; *Five Year Progress Report on NRS* at 78.
[239] Christopher S. Jones, Ph.D., *Report on Nitrogen Surplus in Minnesota Driftless* 12 (2025) (MCEA Ex. 21).

nitrogen from a combination of manure produced and fertilizer purchased exceeded the Extension Service's recommendations by more than 40%.[240] Yet the Animal Feedlot Rule does little to control this overapplication, allowing applications 20% higher than recommendations for essentially any reason or applications with no apparent restrictions if nitrogen deficiencies are "visible."[241]

Requiring producers to apply only at the Extension Service's recommended rates would not harm crop yields or profitability for producers, while producing important environmental benefits. Notably, the Extension Service's recommendations are *not* aimed at preventing nitrogen loss to the environment—their environmental effects are incidental. Instead, they are intended to maximize profitability for producers, so following the recommendations should not harm producers.[242] Right now, there is well-documented evidence that nitrogen inputs (both commercial fertilizer and manure) continue to exceed crop nitrogen needs statewide. By one estimate, producers could reduce application by 200 million pounds per year while still maintaining optimum yields.[243] In the draft update to the Minnesota Nutrient Reduction Strategy, state agencies documented that nitrogen inputs (fertilizer and manure) continue to exceed crop nitrogen needs in pounds per cropland acre by an estimated statewide average of 18%. In most of the sensitive karst region, the documented surplus is over 30 pounds per acre.[244] By following the Extension Service recommendations, producers can save money, improve their economic return, and reduce nitrate pollution at the same time.

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[240] EWG, Manure Overloads Minnesota (MCEA Ex. 23).
[241] Minn. R. 7020.2225, subp. 3(A)(2).
[242] 2015 Nitrogen Fert. Mgmt. Plan, *Appendix D: Maximum Return to Nitrogen (MRTN) Values for Fertilizer* 1, https://www.pca.state.mn.us/sites/default/files/wq-s1-84g.pdf.
[243] Groundwater Protection Rule SONAR at 51.
[244] MPCA, *Minnesota Nutrient Reduction Strategy – DRAFT* at 170 (July 2025), https://www.pca.state.mn.us/sites/default/files/wq-s1-87a.pdf.

Allowing applications of up to 20% over the recommended rates is entirely unnecessary because—concerningly—the Extension Service's current recommended rates have steadily grown over past years. As of 2025, the general recommendation for non-irrigated corn is 195 lbs./acre. For irrigated corn in sandy soils, the recommendation is even higher, at 235 lbs./acre—an unfortunate recognition that these soils are going to lose more nitrogen than other soils.[245] Even for non-irrigated corn, the current recommendation is *40 lbs. higher* than the recommended rate in 2006 (at the .05 MRTN usually considered appropriate for manure). The following chart shows the increase in the MRTN:

	2006[246]	2016[247]	2025[248]
Corn after corn (nonirrigated)	155	180	195
Corn after soybeans	120	140	150

Considering that the recommended rate is 26% higher than it was in 2006 for corn after corn, and 25% higher than it was in 2006 for corn after soybeans, allowing an additional 20% application is unnecessary. The recommended rate clearly has flexibility written into it already, as it allows for the application of so much more nitrogen than was considered appropriate only 20 years ago, and it is specifically labeled as a "maximum," not a mid-range recommendation.[249]

[245] The fact that the recommendations allow *higher* nitrogen application rates in the state's leakiest soils is alarming—instead of allowing additional nitrogen on these soils, appropriate recommendations would allow less.
[246] 2015 Nitrogen Fert. Mgmt. Plan, *Appendix D: Maximum Return to Nitrogen (MRTN) Values for Fertilizer* 1-2, https://www.pca.state.mn.us/sites/default/files/wq-s1-84g.pdf.
[247] *Id*.
[248] Univ. of Minn. Extension Serv., *Guidelines for Manure Application Rates* 2 (2022) (MCEA Ex. 6).
[249] *Id*.

Nor should producers be allowed to seek out higher rate recommendations from other states. The Extension Service recommendations are based on 170 experiments throughout the state, mostly within the last five years.[250] The recommendations are specific to our state, and allowing producers to follow recommendations of other states could result in far higher rates than are appropriate for Minnesota conditions. As of 2019, South Dakota's recommendation (at the .10 MRTN considered appropriate for commercial fertilizer) was 27 lbs./acre higher than Minnesota's, and North Dakota's recommendation was an astonishing 57 lbs./acre higher than Minnesota's.[251] This example shows that allowing producers to "shop around" for the highest recommendation to justify their manure application could be disastrous for Minnesota's water quality.

For these reasons, MPCA should revise Minnesota Rule 7020.2225, subpart 3 to require producers to follow the Extension Service's recommendations for manure application as a maximum rate, without additional deviations and without resort to other states' recommendations.

G. MPCA should amend the Animal Feedlot Rule to explicitly prohibit discharges that pollute groundwater

The Animal Feedlot Rule includes two main water quality discharge standards. The first prohibits any feedlot from discharging manure into a "sinkhole, fractured bedrock, well, surface tile intake, mine, quarry, or other natural or constructed channels that convey fluids to groundwater."[252] The second prohibits a CAFO from discharging manure to waters of the United States or surface waters of the state except as allowed by a permit.[253] These water quality discharge standards are entirely inadequate to protect surface waters and groundwater in the state, and they

[250] *Id*. at 6-7.
[251] 2015 Nitrogen Fert. Mgmt. Plan, *Appendix D: Maximum Return to Nitrogen (MRTN) Values for Fertilizer* 2 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-s1-84g.pdf.
[252] Minn. R. 7020.2003, subp. 1.
[253] Minn. R. 7020.2003, subp. 2.

are inconsistent with the state's water quality standards protecting groundwater. MPCA must revise Minnesota Rule 7020.2003 to explicitly prohibit discharges that would pollute the groundwater.

As explained above, Minnesota has robust protections in its rules for groundwater, which is the source of drinking water for 75% of the state's residents. The state has designated all groundwater as potential drinking water and has put strict protections in place to ensure that this critical resource is preserved in as close to its natural state as possible. MPCA has adopted a nondegradation policy for groundwater, which recognizes this resource's "immeasurable value" and states that it must be "protected as nearly as possible in its natural condition."[254] In other words, no pollution of the state's groundwaters should be allowed, at all, to the extent possible. MPCA also has adopted a prohibition against the discharge of wastes into the unsaturated zone that "may actually or potentially preclude or limit the use of the underground waters as a potable water supply, nor shall any such discharge or deposit be allowed which may pollute the underground waters."[255] Discharges that cause exceedances of the 10 mg/L nitrate limit for groundwater or that contaminate the groundwater with bacteria would unquestionably limit the use of the groundwater as a potable water supply and would be considered to pollute the underground waters.

While the nondegradation policy is a goal, the prohibition on discharges of wastes to the unsaturated zone and the 10 mg/L nitrate limit for groundwater are MPCA's own rules, which it adopted and which it is required to enforce. Accordingly, no feedlot should be allowed to discharge manure or other pollutants to the unsaturated zone if such discharge would pollute the groundwater. But the Animal Feedlot Rule only prohibits discharges to *channels* that convey fluids to

[254] Minn. R. 7060.0200.
[255] Minn. Stat. 7060.0600, subp. 2.

groundwater. It does not include an explicit prohibition on all discharges of manure that would pollute the groundwater—and much of the contamination that enters groundwater from manure application simply leaches through the soil, not a specific sinkhole, well, or other channel. To protect Minnesota's groundwater as required by the state's water quality rules, MPCA should revise Minnesota Rule 7020.2003 to explicitly prohibit all discharges of manure or pollutants from manure, both from feedlots and from land application areas, into groundwater in a manner that would pollute the groundwater.

H. MPCA should amend the animal feedlot rule to prohibit all livestock from medium or large feedlots from accessing waters of the state

The Animal Feedlot Rule prohibits "[a]nimals of a CAFO or of a facility capable of holding 1,000 or more animal units" from entering waters of the state.[256] Non-CAFO animals, however, are only prohibited from entering "a lake classified by the Minnesota Department of Natural Resources as a natural environment lake, recreational development lake, or a general development lake, as defined in part 6120.3000."[257] As a result, non-CAFO animals are currently permitted to enter other waters of the state not identified in the rule, such as streams and ponds.[258] MPCA should revise Minnesota Rule 7020.2015 to prohibit all livestock from entering waters of the state or, at a minimum, prohibiting animals from any medium (over 300 animal units) or large feedlot from entering waters of the state.

[256] Minn. R. 7020.2015, subp. 1.
[257] Minn. R. 7020.2015, subp. 2.
[258] *See* Minn. R. 7050.0130, subp. 2 ("The terms 'waters of the state,' 'groundwater,' 'water pollution,' and 'toxic pollutants,' . . . as used herein have the meanings given to them in Minnesota Statutes, sections 115.01 and 115.41, with the exception that disposal systems or treatment works operated under permit or certificate of compliance of the agency are not 'waters of the state.'"). *See also* Minn. Stat. § 115.01, subd. 22 (defining "waters of the state" as including streams and ponds).

1. Livestock access to waters of the state negatively impacts water quality

Pollution from non-CAFO livestock access to waters of the state is a widespread issue in Minnesota: Watershed Restoration and Protection Strategy Reports ("WRAPs") covering 52 of Minnesota's watersheds (including some updates) specifically identified livestock access to streams as an issue for the area.[259] Although non-CAFO animals are, by definition, part of smaller feedlots, they can still cause significant damage, causing not only nitrate pollution, but significant and dangerous bacterial pollution. The Mississippi River – Brainerd WRAP noted that "[w]hile smaller, these feedlots are the most likely to be contributing bacteria directly via defecation in the stream, and indirectly from field runoff that livestock grazes and defecates on."[260]

[259] *See* Annex I (MCEA Ex. 56). Livestock in CAFOs are prohibited from entering waters of the state, therefore the "livestock" referred to here are likely to be non-CAFO livestock. Note that some watersheds are combined in a single WRAP and some are divided into multiple WRAPs. Thus, this comment refers to the total number of WRAPs and total number of watersheds in the state as two separate figures. MCEA reviewed a total of 73 distinct WRAPs covering 79 of the major watersheds in Minnesota. Some watersheds also had updates since the original filing, which MCEA reviewed as well. MCEA was unable to review WRAPs for the Lower St. Croix River Watershed and the Mississippi River – Twin Cities Watershed.

[260] *Mississippi River – Brainerd WRAP* 40 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-65a.pdf.

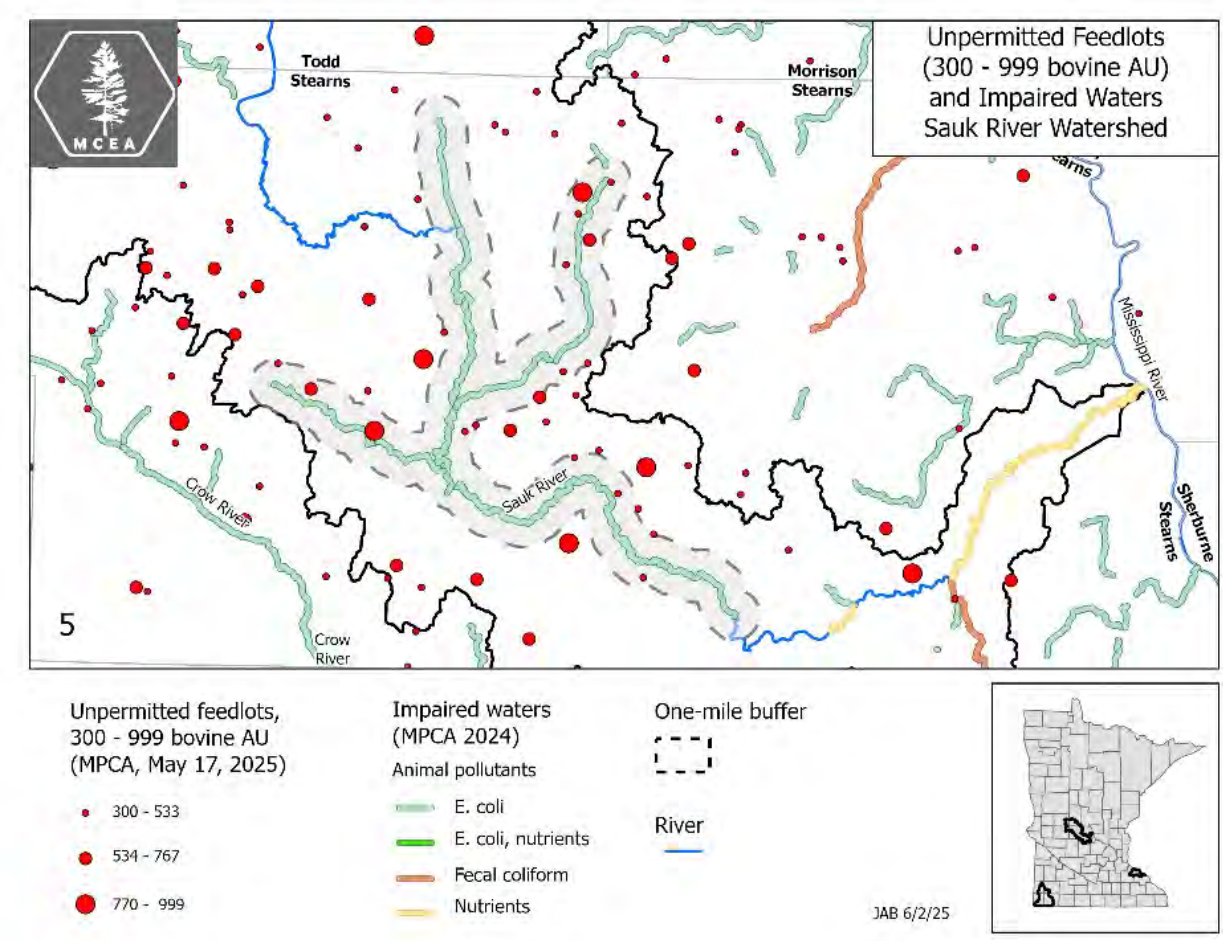

Figure 4 showing impaired waters in the Sauk River Watershed in relation to bovine feedlots with 300-999 AUs. Map created by Jim Berg with data from Minnesota Geospatial Commons.

Many WRAPs detailed specific harms caused by livestock access to waters of the state. For example, "[d]irect access of cattle to the Sauk River and its tributaries is causing damage, loss of habitat, increased nutrient concentrations, and increased fine sediment transport that is filling coarse substrate used by fish and macroinvertebrates."[261] The Big Fork River WRAP identified livestock access to streams as a common source of pollution in the watershed, noting that "[l]ivestock grazing/watering in the riparian zone can cause localized damage and erosion of the

[261] *Sauk River WRAP* 11 (Mar. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-08a.pdf.

stream bank, and is a source of phosphorus and bacteria pollutants."[262] Similar language was included in WRAPs for Crow Wing River,[263] Mississippi River – Brainerd,[264] and Mississippi River – Headwaters.[265] Additionally, "[l]ivestock are potential sources of bacteria, phosphorus, and nitrogen to streams in the Blue Earth River Watershed, particularly when direct access is not restricted and/or where feeding structures are located adjacent to riparian areas";[266] similar findings were reported in Cottonwood River,[267] La Sueur River's 2025 Update,[268] and Redwood River.[269]

[262] *Big Fork River WRAP* 16-17 (Oct. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-37a.pdf.
[263] *Crow Wing River WRAP* 15 (Jan. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-09a.pdf.
[264] *Mississippi River – Brainerd WRAP* 15 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-65a.pdf.
[265] *Mississippi River – Headwaters WRAP* 34 (Aug. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-50a.pdf
[266] *Blue Earth River Wrap* 22 (July 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-95a.pdf.
[267] *Cottonwood River WRAP* 21 (Dec. 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-93a.pdf ("Livestock animals are potential sources of bacteria, phosphorus, and nitrogen to streams in the Cottonwood River Watershed, particularly when direct access is not restricted and/or where feeding structures are located adjacent to riparian areas.").
[268] *La Sueur River WRAP Update* 36 (May 2025), https://www.pca.state.mn.us/sites/default/files/wq-ws4-102a.pdf ("Livestock are potential sources of bacteria, phosphorus, and N to streams in the Le Sueur River Watershed, particularly when direct access is not restricted and/or where feeding structures are located adjacent to riparian areas.").
[269] *Redwood River WRAP* 27 (Apr. 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-94a.pdf. ("Livestock animals are potential sources of bacteria phosphorus, and nitrogen to streams in the Redwood River Watershed, particularly when direct access is not restricted and/or where feeding structures are located adjacent to riparian areas.").

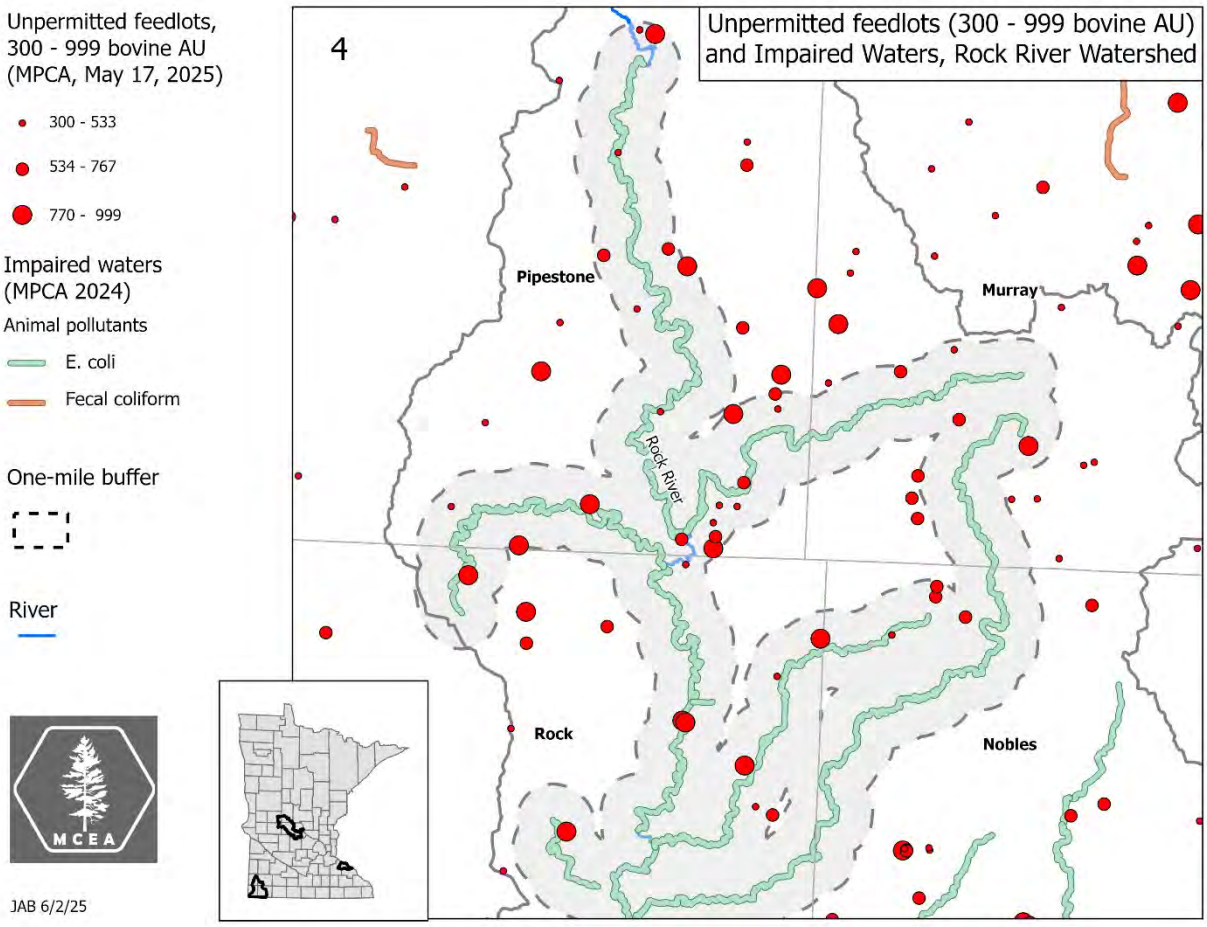

Figure 5 showing impaired waters in the Rock River Watershed in relation to bovine feedlots with 300-999 AUs. Map created by Jim Berg with data from Minnesota Geospatial Commons.

In the Rock River, nearly one-third of fecal bacteria in the watershed is attributed to livestock access to streams;[270] an astonishing two-thirds of fecal bacteria is attributed to crop-applied manure (both surface-applied and subsurface applied) and runoff from feedlots combined.[271]

[270] *Missouri River Basin Watersheds WRAP* 48 (Jan. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-40a.pdf (explaining the graphs and that the "pastures adjacent waterways" indicates livestock access to streams).
[271] *Id.*

The current Animal Feedlot Rule, permitting non-CAFO animals to access waters of the state not otherwise identified in the Animal Feedlot Rule, results in widespread pollution and fails to adequately protect the state's watersheds.

2. Prohibition of livestock access to waters of the state is already used in many areas to protect waters of the state in Minnesota

Livestock exclusion (or limitation) is a common conservation method. The National Resource Conservation Service identifies access control (Code 472) as a Conservation Practice Standard.[272] Many WRAPs cross-reference NRCS Code 472 in the watersheds' proposal to limit or fully exclude livestock from access to streams.[273]

Livestock exclusion/limitation is also a common strategy in Minnesota: the vast majority (three-quarters) of watersheds identified livestock exclusion and/or limitation as a strategy for improving water quality in their respective watersheds.[274] Some of the WRAPs go so far as to say that livestock exclusion is *necessary* to reduce *E. coli*: the WRAP for Red River of the North – Marsh River specified that "[r]educing *E. coli* concentrations within the waterbodies of the MRW will require livestock to be kept away from waterbodies," among other strategies.[275] The Mississippi River – Brainerd WRAP uses similarly strong language, opining that "limiting

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[272] *Conservation Practice Standard: Access Control, Code 472*, NATURAL RESOURCES CONSERVATION SERVICE, (Oct. 2017), https://www.nrcs.usda.gov/sites/default/files/2022-08/Access_Control_472_CPS_Oct_2017.pdf (MCEA Ex. 58).

[273] *See, e.g. Lake of the Woods WRAP* 76 (Feb. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-66a.pdf; *North Fork Crow River WRAP* 62 (Dec. 2014), https://www.pca.state.mn.us/sites/default/files/wq-ws4-06a.pdf; *Rainy River – Headwaters WRAP* 78 (June 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-87a.pdf; *Roseau River WRAP* 55-64 (Dec. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-76a.pdf; *Sand Hill River WRAP* [Red River of the North – Sand Hill River] 67 (Oct. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-26a.pdf; *Sauk River WRAP* 60 (Mar. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-08a.pdf.; *Snake River – St. Croix Basin WRAP* 38 (Aug. 2014), https://www.pca.state.mn.us/sites/default/files/wq-ws4-04.pdf.

[274] *See* Annex II (MCEA Ex. 57).

[275] *Marsh River WRAP* [Red River of the North – Marsh River] 27 (July 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-83a.pdf.

livestock access to streams and properly managing manure application rates and runoff is vital to addressing the bacteria impairments."[276] The Minnesota River – Headwaters WRAP also acknowledges that livestock exclusion is a necessary part of the long-term effort to reduce *E. coli* in the watershed.[277] WRAPs generally do not distinguish between *E. coli* and other impairments from animals from a CAFO or non-CAFO animals,[278] and as such, MPCA should similarly forgo such a distinction and prohibit all livestock from entering waters of the state.

Livestock exclusion strategies are effective measures to protect waters of the state. In providing an update on its original WRAP, the Pomme de Terre Watershed reported that, in one area, "[e]fforts to control access of cattle to the creek in the past 10 years appear to have improved instream habitat enough to remove the macroinvertebrate AQL impairment suggesting that further efforts upstream may do the same."[279] Although voluntary adoption on a watershed-by-watershed basis (or even stream-specific basis) is a step in the right direction, significant progress will not be achieved on a statewide level unless the Animal Feedlot Rule is revised to prohibit livestock access to waters of the state. Even though livestock exclusion/limitation is a common strategy discussed

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[276] *Mississippi River – Brainerd WRAP* 40 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-65a.pdf.

[277] *Minnesota River – Headwaters WRAP* 134 (Mar. 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-75a.pdf ("Although restoration efforts have been taking place since the initial impairment listings in 2006, further reductions of *E. coli* concentrations within the waterbodies of the MRHW will require livestock to be kept away from waterbodies. . ." among other points.).

[278] *See., e.g. St. Louis River WRAP* 72 (Sept. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-46a.pdf (identifying "[a]ll livestock and hobby farms practicing livestock exclusion and appropriate manure management" as a recommended goal, without delineating between CAFO- and non-CAFOs.); *Thief River WRAP* 113 (Mar. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-49a.pdf (discussing issues of livestock access to the Mud River, but not identifying whether the animals were from a CAFO, although the farm is no longer operational); *But see Mississippi River – Brainerd WRAP* 40 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-65a.pdf (delineating and noting that smaller AFOs *still* cause problems in the watershed).

[279] *Pomme de Terre WRAP Update* 70 (Aug. 2024), https://www.pca.state.mn.us/sites/default/files/wq-ws4-100a.pdf.

in the WRAPs, its implementation varies widely between watersheds.[280] Additionally, while it may be possible to work with landowners to reduce livestock access to streams voluntarily,[281] this may not always be the case without a rule in place.

Because of the effectiveness of livestock exclusion strategies in reducing *E. coli* concentrations and water polllution, MPCA should revise Minnesota Rule 7020.2015, subpart 2 to prohibit all livestock from entering waters of the state to protect our watersheds. Alternatively, MPCA should, at a minimum, extend this prohibition to all medium feedlots so that animals from feedlots with more than 300 animal units are prohibited from entering waters of the state.

I. MPCA should amend the animal feedlot rule to reflect existing agency policy regarding multi-site feedlots

The Animal Feedlot Rule currently does not have any provisions regarding multi-site feedlots, but dividing feedlots between multiple different sites is a potential way for feedlots to avoid obtaining a NPDES or SDS feedlot permit (or other feedlot permit) and the additional regulatory requirements that come along with such a permit. Accordingly, MPCA should include a new provision in the Animal Feedlot Rule that explains the scenarios under which two or more feedlots should be considered to be one for purposes of meeting the permit threshold.

1. Current MPCA policy on multi-site feedlots

While the Animal Feedlot Rule does not contain specific guidance on the matter, MPCA has a policy regarding multi-site feedlots for the purposes of permit determinations under

[280] *Compare Blue Earth River Wrap* 102 (July 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-95a.pdf (showing that 0.1% of the watershed area adopted livestock restrictions) *with Lake of the Woods WRAP* 57 (Feb. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-66a.pdf (showing a 75% adoption rate, with a goal of 100%).

[281] *See, e.g., Pine River WRAP* 22-23 (Oct. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-33a.pdf (noting that "[t[he landowners have been willing to work with the team to fence off key areas and keep livestock away from stream banks to allow them to re-vegetate with native grasses, sedges, and shrubs.").

Minnesota Rule 7020.0405. MPCA's current policy is modeled on federal regulations. Federal regulations anticipate potential multi-site feedlots and include in the definition of "CAFOs" that "[t]wo or more AFOs under common ownership are considered to be a single AFO for the purposes of determining the number of animals at an operation, if they adjoin each other or if they use a common area or system for the disposal of wastes."[282] "MPCA policy is to use the same criteria to determine the need for [state] permit coverage as well."[283] As such, multi-site feedlots exist in Minnesota when:

- The sites have common ownership and
- One of the following conditions apply:
    - Any portion of the animal feedlots are located within ¼ mile of each other.
    - The animal feedlots share a liquid or solid manure storage area.[284]

MPCA defines common ownership as "when at least one person or entity is the full or partial owner of two or more animal feedlots."[285] Common ownership also "includes instances where a single person owns one site but is a partner in a group that owns a second site" and when a married couple each own one feedlot.[286]

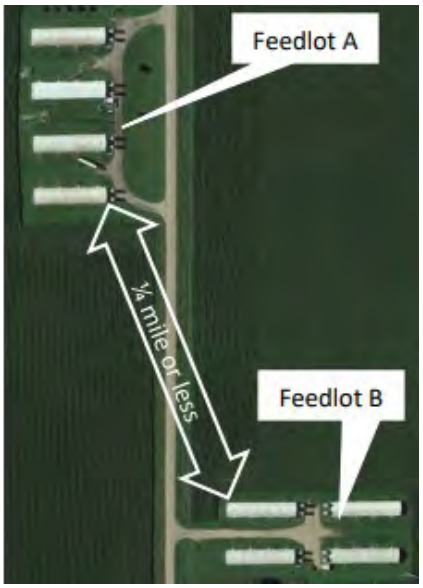

Figure 6: MPCA Illustration of Distance Requirement

After ownership, the considerations of (1) proximity and (2) shared manure storage are the two criteria for multi-site feedlots. With respect to the distance requirement, MPCA policy

[282] 40 CFR § 122.23(b)(2).
[283] MPCA, *NPDES and SDS Permits for Multi-Site Feedlot Operations* (Oct. 2021), https://www.pca.state.mn.us/sites/default/files/wq-f6-83.pdf (MCEA Ex. 59).
[284] *Id.*
[285] *Id.*
[286] *Id.*

is to measure distance from the closest components of each of the feedlots; see Figure 6 for MPCA's example,[287] included in the policy.[288] For shared manure storage, "[f]eedlots that transport solid or liquid manure from one feedlot site to storage structures at another feedlot site are considered to share a manure storage area."[289] MPCA clarifies that the following conditions do not constitute "[s]haring a liquid or solid manure storage area":

- Two or more animal feedlots including the same fields in a manure management plan.
- Manure transfer to a third party who collects from numerous feedlots then manages the manure as a separate entity.
- Manure/litter transfer to another site to be used as bedding material. [sic] (i.e., litter from a turkey brood barn transported with the birds to a finishing barn)[290]

This policy applies to NPDES and SDS permit determinations under Minnesota Rule 7020.0405;[291] it does not apply to registration under Minnesota Rule 7020.0350.[292]

2. MPCA should amend the animal feedlot rule to strengthen existing agency policy regarding multi-site feedlots

MPCA should codify its policy on multi-site feedlots to provide clarity regarding identification and operation of multi-site feedlots. The current policy, however, has some shortcomings, which can be addressed by the current rulemaking. MPCA should address both the distance provision of its current policy and the definition of "common ownership" to strengthen the Animal Feedlot Rule.

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[287] *Id.*
[288] *Id.*
[289] MPCA, *NPDES and SDS Permits for Multi-Site Feedlot Operations* (Oct. 2021), https://www.pca.state.mn.us/sites/default/files/wq-f6-83.pdf (MCEA Ex. 59).
[290] *Id.*
[291] *See id.* ("It is important to note that this is only used to determine the need for a NPDES or SDS permit and does not affect other aspects of Minnesota Rule 7020 implementation"). *See also* Minn. R. 7020.0405, subp. 1 (A)-(B) (defining when permits are required).
[292] MPCA, *NPDES and SDS Permits for Multi-Site Feedlot Operations* (Oct. 2021), https://www.pca.state.mn.us/sites/default/files/wq-f6-83.pdf (MCEA Ex. 59). *See also* Minn. R. 7020.0350 (registration requirements).

i. Distance

With respect to distance, the current MPCA policy designates multi-site feedlots as operations within ¼ mile of each other.[293] MPCA should extend the distance to 3 miles so that multi-site feedlots operating within close enough proximity to one another to share land application fields are subject to the permitting requirement under Minnesota Rule 7020.0405.

MPCA's Request for Comments identified that since the last revision of the Animal Feedlot Rule, there are "[m]ore feedlots with 500 or more animal units (animal units), many designed to be just under permit thresholds."[294] Currently, two feedlots owned by the same individual or entity could operate feedlots with 750 animal units each without a permit if the feedlots were located only ½ mile away from each other (and did not share manure storage). In this circumstance, the two feedlots would not have less environmental impacts than one 1,500 AU feedlot, and yet they would be regulated very differently.

Given that the environmental effects of CAFOs are largely related to land application, it is important to consider the distance between CAFOs and land application sites when determining whether a multi-site feedlot operation exists. A 2017 study of CAFOs in southeastern Michigan found that 51% "of field acreage used for manure application . . . was within 5 km (3.1 mi)."[295] For on-site manure application, the median distance was 3.5 miles.[296] This means that for CAFOs within 3 miles one of another, their land application sites are highly likely to overlap or abut. The greatest factor in nitrate loss from land application areas is applying nitrogen at too high of rates[297]

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[293] MPCA, *NPDES and SDS Permits for Multi-Site Feedlot Operations* (Oct. 2021), https://www.pca.state.mn.us/sites/default/files/wq-f6-83.pdf (MCEA Ex. 59).
[294] MPCA, *Request for Comments*, 1-2 (2025).
[295] Long et al., *Use of Manure Nutrients from Concentrated Animal Feeding Operations*, J. OF GREAT LAKES RESEARCH 3 (2018), https://graham.umich.edu/media/files/WLEB/WLEB-Science-Panel-Long-et-al.-2018.pdf (MCEA Ex. 22).
[296] *Id.*
[297] Groundwater Protection Rule SONAR at 52.

and when more manure is produced in one area, the risk that overapplication will occur increases because of the expense of transporting manure.[298] For permitting purposes, accordingly, it is critical that operations with land application sites that overlap or abut should be required to create one coordinated plan for their manure application.

To account for multi-site feedlots operating within close proximity, MPCA should add its current policy to the Animal Feedlot Rule and extend the distance from ¼ mile to 3 miles so that the operations described above are considered multi-site feedlots subject to the permitting requirements under Minnesota Rule 7020.0405.

ii. Common Ownership

MPCA considers common ownership to exist "when at least one person or entity is the full or partial owner of two or more animal feedlots";[299] this "includes instances where a single person owns one site but is a partner in a group that owns a second site" and when a married couple each own one feedlot.[300] MPCA should adopt and expand this definition in the Animal Feedlot Rule to avoid potential obfuscation by larger entities. Under this definition, if two separate corporate entities each owned a feedlot, and those two entities shared some shareholders (or members or partners), arguably this would not meet the definition of "common ownership," which refers to a *single person* who owns one site and is a partner in an entity owning the other.

The Animal Feedlot Rule currently lacks a definition of "common ownership." While the definition of "owner" under Minnesota Rule 7020.0300, subpart 17 refers to "all persons having possession, control, or title to an animal feedlot or manure storage area",[301] *common* ownership is

[298] *See* Chryseis Modderman, *Manure Is Complicated: 5 Reasons You Need a Manure Management Plan* (MCEA Ex. 11).
[299] MPCA, *NPDES and SDS Permits for Multi-Site Feedlot Operations* (Oct. 2021), https://www.pca.state.mn.us/sites/default/files/wq-f6-83.pdf (MCEA Ex. 59).
[300] *Id.*
[301] Minn. R. 7020.0300, subp. 17.

not defined. MPCA should formally adopt its definition of "common ownership" from the multi-site feedlot policy in the Animal Feedlot Rule, and expand it as follows to ensure that other common shared ownership scenarios are also covered:

> Common ownership exists when at least one person or entity is the full or partial owner of two or more animal feedlots, or when two entities that own two or more feedlots share one or more common shareholders, members, partners, or other holders of ownership interests. This includes instances where a single person owns one site but is a partner in a group that owns a second site. This also includes instances where spouses own sites individually.

This is particularly important because it helps ensure that individuals and entities are not able to avoid permitting requirements by creating multiple entities with common ownership.

MPCA should add a new provision to the Animal Feedlot Rule that explains when two or more feedlots are considered to be multi-site feedlots for the purposes of permitting under Minnesota Rule 7020.0405. This provision should strengthen existing MPCA policy regarding multi-site feedlots by (1) extending the distance in the policy to cover feedlots within 3 miles of each other; and (2) defining "common ownership" to ensure that separate corporate entities are not able to skirt permit requirements.

V. Conclusion

As a final point, MPCA has asked for feedback on how to maintain flexibility for feedlots within the rules, based on the Legislature's direction that "whenever feasible," state agencies should develop regulatory programs that "emphasize superior achievement in meeting the agency's regulatory objectives and maximum flexibility for the regulated party and the agency in meeting those goals."[302] Notably, this policy does not direct MPCA to only ensure flexibility for regulated parties—it explicitly requires MPCA to develop programs that *achieve regulatory objectives*. Indeed, this policy of encouraging flexibility "whenever feasible" cannot overcome MPCA's

[302] Minn. Stat. § 14.002.

obligations to ensure compliance with federal and state water quality standards. Nor does this policy bar MPCA from adopting rules that regulated parties may consider inflexible if they are necessary to achieve water quality standards.[303] For too long, MPCA has depended on "flexibility" for feedlots, encouraging BMPs and voluntary measures instead of imposing regulatory measures known to be more effective. These measures have not addressed nitrate and bacterial pollution. Due to the demonstrated ineffectiveness of voluntary measures, it is past time for MPCA to adopt further regulatory measures to address pollution from feedlots.

For decades, Minnesota has attempted, with tepid results to date, to address the crisis of nitrate pollution in its surface waters and groundwater, which threatens its residents, its livestock and wildlife, its aquatic ecosystems, and the health of its lakes, rivers, and streams. The EPA has directed MPCA to do more to address nitrate pollution and hold polluters accountable, and MPCA itself has recognized that current practices are not adequately addressing the problem. MPCA now has an opportunity to make transformational changes that will address this long-standing, widespread, intractable problem, and it should do so by making the following changes:

- Minn. R. 7020.0405, subp. 1: Lower the threshold for State Disposal System permits to feedlots with 600 or more animal units.
- Minn. R. 7020.2003: Add an explicit prohibition on all discharges of manure or pollutants from manure from a feedlot or land application area that may limit the use of groundwater as a potable water supply or may pollute the underground waters.
- Minn. R. 7020.2100, subp. 4(N): Add a requirement for weekly visual inspections of Liquid Manure Storage Areas and freeboard markers.
- Minn. R. 7020.2015: Revise to prohibit livestock from all feedlots from entering waters of the state, or at a minimum livestock from medium and large feedlots.
- Minn. R. 7020.2125: Require weekly visual inspections of manure stockpiling sites.

[303] *See Coal. of Greater Minnesota Cities v. Minnesota Pollution Control Agency*, 765 N.W.2d 159, 169 (Minn. App. 2009) (finding rule allowing MPCA to deny exemptions from effluent limit of 1 mg/L of phosphorus was consistent with Minn. Stat. § 14.002).

- Minn. R. 7020.2150: Require weekly visual inspections of manure compost sites.

- Minn. R. 7020.2225, subp. 3: Revise to limit manure application rates to a maximum of the recommendations by the University of Minnesota Extension Service, with no deviations allowed or rates from contiguous states.

- Minn. R. 7020.2225, subp. 4: Require feedlots with more than 300 animal units to submit a Manure Management Plan each year to MPCA or the county feedlot officer through the online Nutrient Management Tool. Feedlots located out of state with more than 300 animal units that apply manure to fields within Minnesota must submit and follow a Manure Management Plan. Information about manure application fields from the online tool must be made publicly available.

- Minn. R. 7020.2225, subp. 4: Require Manure Management Plans to include Subsurface Discharge Monitoring Plans for both land application areas and production areas for feedlots that are required to obtain NPDES or SDS permits.

- Minn. R. 7020.2225, subp. 8: Revise this section to prohibit application of manure within 100 feet of surface waters, water supply wells, sinkholes, mines, quarries, or other conduits to surface waters. For the Vulnerable Groundwater Areas, application of manure should be prohibited within 250 feet from private wells, 1,000 feet from a community well, and 300 feet upslope or 100 feet downslope of other conduits to groundwater including sinkholes, mines, or quarries.

- Minn. R. 7020.2225: Add a new subpart that would require visual inspections of land application areas similar to those included in the NPDES and SDS feedlot permits.

- Minn. R. 7020.2225: Add a new subpart that would require additional best management practices in Vulnerable Groundwater Areas when manure is applied in the fall, including cover crops, perennial crops, and waiting for cool soils and using a nitrate inhibitor.

- Minn. R. 7020.2225: Add a new subpart that would prohibit applying manure to frozen or snow-covered ground statewide.

- Minn. R. 7020.2225: Add a new subpart that would require producers to use the Minnesota Department of Agriculture's Runoff Risk Advisory Tool and prohibiting application of manure when the risk of runoff is "severe."

- Minn. R. 7020.0405: Add a new subpart that would require permits for multi-site feedlots that meet the other criteria included in the existing Rule.

- Minn. R. 7020.0300: Add new subparts that would define "multi-site feedlot operations" to ensure that feedlots with common owners that are located within three miles of each other are considered a single feedlot for purposes of permit determinations and to broaden the definition of "common ownership" to include multiple entities with some common owners.

With these changes, MPCA would take a necessary step toward addressing the nitrate pollution crisis in our state as well as the bacterial contamination of surface waters.

Respectfully submitted,

MINNESOTA CENTER FOR ENVIRONMENTAL ADVOCACY

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Colorectal cancer risk and nitrate exposure through drinking water and diet

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Cancer Epidemiology

Ingested nitrate leads to the endogenous synthesis of N-nitroso compounds (NOCs), animal carcinogens with limited human evidence. We aimed to evaluate the risk of colorectal cancer (CRC) associated with nitrate exposure in drinking water and diet. A case-control study in Spain and Italy during 2008-2013 was conducted. Hospital-based incident cases and population-based (Spain) or hospital-based (Italy) controls were interviewed on residential history, water consumption since age 18, and dietary information. Long-term waterborne ingested nitrate was derived from routine monitoring records, linked to subjects' residential histories and water consumption habits. Dietary nitrate intake was estimated from food frequency questionnaires and published food composition databases. Odd ratios (OR) were calculated using mixed models with area as random effect, adjusted for CRC risk factors and other covariables. Generalized additive models (GAMs) were used to analyze exposure-response relationships. Interaction with endogenous nitrosation factors and other covariables was also evaluated. In total

Key words: colorectal cancer, nitrate, drinking water, diet, case-control studies
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1,869 cases and 3,530 controls were analyzed. Average waterborne ingested nitrate ranged from 3.4 to 19.7 mg/day, among areas. OR (95% CIs) of CRC was 1.49 (1.24, 1.78) for >10 versus ≤5 mg/day, overall. Associations were larger among men versus women, and among subjects with high red meat intake. GAMs showed increasing exposure-response relationship among men. Animal-derived dietary nitrate was associated with rectal, but not with colon cancer risk. In conclusion, a positive association between CRC risk and waterborne ingested nitrate is suggested, mainly among subgroups with other risk factors. Heterogeneous effects of nitrate from different sources (water, animal and vegetables) warrant further research.

What's new?

Nitrate ingested in food and water can react with amines and amides in the gastrointestinal tract, leading to the formation of N-nitroso compounds (NOCs), which are carcinogenic in animals. In humans, nitrate and several NOCs are probable carcinogens. The aim of the present investigation, a case–control study in Europe, was to examine links between nitrate intake and colorectal cancer (CRC). The findings indicate that CRC risk is increased for waterborne nitrate intake at levels below current international guidelines, particularly in subgroups with other risk factors. Nitrate intake from animal sources was further associated with increased rectal cancer risk.

Introduction

Nitrate is a widespread contaminant in drinking water due to the overuse of fertilizers in agriculture[1] and urban sewage.[2] Expensive and infrequently used methods such as reverse osmosis are necessary to effectively remove nitrate from drinking water.[3] In addition, nitrate is a main dietary component of vegetables, and an approved food additive for preserved meat, together with nitrite.[4]

Nitrate ingestion through diet and drinking water are the main routes of human exposure. Ingested nitrate is reduced to nitrite, which subsequently reacts with amines and amides to produce N-nitroso compounds (NOCs) in the gastrointestinal system. The intake of vitamins C and E may inhibit endogenous nitrosation, whereas meat intake and chronic gastrointestinal acidic or inflammatory conditions, may increase it.[5] Additionally, exogenous NOCs are ingested through processed meat, canned or cured food, alcohol and tobacco smoking.[6] NOCs are carcinogenic in several animal species,[7] but human evidence is limited, therefore nitrate is classified as probable human carcinogen (group 2A) under conditions resulting in endogenous nitrosation.[8]

Colorectal cancer (CRC) is one of the most frequent cancers worldwide, representing 10% of the global cancer incidence. More than 1 million new cases and 694,000 deaths are registered annually in both sexes.[9] The high intake of energy, red or processed meat[10] and alcohol, as well as physical inactivity and obesity, are established risk factors.[11] Increased CRC risk has been suggested with dietary nitrite[12] or dietary NOCs.[13,14] Recently, a prospective study found an increased risk among subjects with high dietary nitrate and low vitamin C intake.[15] However, few studies have evaluated the risk of CRC associated with nitrate in drinking water. Existing evidence provided by case–control or cohort studies is inconsistent,[5,16] particularly for levels below the current regulatory limit (50 mg/L of nitrate as NO_3^- in the European Union, or 10 mg/L as NO_3-N in the United States),[17] which is a common scenario in high-income countries.

We evaluated the association between CRC risk and the exposure to nitrate through drinking water and diet, taking into account endogenous nitrosation factors and other covariates.

Methods

Study design and population

We pooled data from two case-control studies conducted in Spain (the Spanish Multi-case Control study on Cancer, MCC-Spain)[18] and Italy (part of the European Union Project on Health Impacts of long-term exposure to Disinfection by-products in Drinking Water, HI-WATE),[19] between 2008 and 2013. Study areas comprised eleven provinces (nine from Spain, two from Italy) (see Table 1). CRC cases were identified as soon as possible after the diagnosis through active searches including periodical visits to the hospital departments (*i.e.*, oncology, gastroenterology, general surgery, radiotherapy and pathology). Participant hospitals (17 in Spain, 10 in Italy) were the reference centers for oncologic diseases in each study area. Only CRC cases diagnosed within the recruitment period, with histological confirmation (ICD-10 codes: C18, C19, C20, D01.0, D01.2), without previous cancer history, aged 20-85 years, living in the hospitals' catchment areas, and being able to answer an epidemiological questionnaire, were enrolled. Controls were hospital-based (Italy) or population-based (Spain), and were frequency matched to cases by sex, age and residence area. Hospital-based controls were randomly selected among patients admitted to the same hospitals as cases for acute, non-chronic diseases, unrelated to alcohol, tobacco, dietary habits or to known CRC risk factors (52.2% had acute surgical conditions, 9.0% non-traumatic orthopedic disorders, 6.0% trauma and 32.8% other illnesses). Population-based controls were randomly selected

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Table 1. Characteristics of the study population included in the analyses of waterborne ingested nitrate: 1,869 cases of colorectal cancer (1,285 colon and 557 rectum)[1] and 3,530 controls

	Cancer cases				
	Colon *n* (%)	Rectum *n* (%)	Colorectal *n* (%)	Controls *n* (%)	*p* values[2]
Study area					
Spain					
Asturias	38 (3.0)	21 (3.8)	59 (3.2)	202 (5.7)	
Barcelona	430 (33.4)	189 (33.9)	629 (33.6)	910 (25.8)	
Cantabria	79 (6.2)	40 (7.2)	119 (6.4)	279 (7.9)	
Gipuzkoa	83 (6.5)	24 (4.3)	107 (5.7)	333 (9.4)	
León	162 (12.6)	77 (13.8)	243 (13.0)	352 (10.0)	
Madrid	143 (11.1)	62 (11.1)	206 (11.0)	658 (18.6)	
Murcia	13 (1.0)	12 (2.2)	25 (1.3)	39 (1.1)	
Navarra	72 (5.6)	24 (4.3)	98 (5.2)	230 (6.5)	
Valencia	52 (4.0)	24 (4.3)	76 (4.1)	131 (3.7)	
Italy					
Milan	118 (9.2)	56 (10.0)	184 (9.8)	270 (7.6)	
Pordenone/Udine	95 (7.4)	28 (5.0)	123 (6.6)	126 (3.6)	<0.001
Sex					
Men	784 (61.0)	382 (68.6)	1,184 (63.4)	1,840 (52.1)	
Female	501 (39.0)	175 (31.4)	685 (36.6)	1,690 (47.9)	<0.001
Age (quartiles)					
≤57 years	226 (17.6)	109 (19.6)	341 (18.2)	947 (26.8)	
58-65 years	294 (22.9)	151 (27.1)	449 (24.0)	870 (24.6)	
66-72 years	335 (26.1)	110 (19.8)	455 (24.3)	833 (23.6)	
>72 years	430 (33.5)	187 (33.6)	624 (33.4)	880 (24.9)	<0.001
Education					
<Primary school	334 (26.0)	147 (26.4)	484 (25.9)	585 (16.6)	
Primary school	478 (37.2)	222 (39.9)	707 (37.8)	1,176 (33.3)	
Secondary school	345 (26.8)	147 (26.4)	505 (27.0)	1,101 (31.2)	
University	128 (10.0)	41 (7.4)	173 (9.3)	668 (18.9)	<0.001
Physical activity (METs hour/week)[3]					
<8 (<8.5)	862 (67.1)	376 (67.5)	1,252 (67.0)	2,266 (64.2)	
8–16 (8.5–34.4)	178 (13.8)	80 (14.4)	266 (14.2)	550 (15.6)	
>16 (>34.4)	245 (19.1)	101 (18.1)	351 (18.8)	714 (20.2)	0.121
Smoking[4]					
Never	549 (43.2)	202 (36.3)	761 (41.0)	1,535 (43.6)	
Ever	723 (56.8)	354 (63.7)	1,093 (59.0)	1,986 (56.4)	0.073
Non-steroidal anti-inflammatory drugs use[4]					
Never	848 (68.4)	371 (68.2)	1,241 (68.6)	2,134 (62.6)	
Ever	391 (31.6)	173 (31.8)	569 (31.4)	1,274 (37.4)	<0.001
Oral contraceptives use[4,5]					
Never	355 (71.1)	124 (72.5)	486 (71.6)	940 (55.9)	
Ever	144 (28.9)	47 (27.5)	193 (28.4)	742 (44.1)	<0.001
Colorectal cancer in first degree relative[4]					
No	1,005 (83.8)	450 (85.6)	1,479 (84.5)	3,065 (91.5)	
Yes	194 (16.2)	76 (14.4)	271 (15.5)	285 (8.5)	<0.001

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Table 1. Characteristics of the study population included in the analyses of waterborne ingested nitrate: 1,869 cases of colorectal cancer (1,285 colon and 557 rectum) and 3,530 controls (Continued)

	Cancer cases				
	Colon *n* (%)	Rectum *n* (%)	Colorectal *n* (%)	Controls *n* (%)	*p* values[2]
Body mass index (Kg/m^2)[4]					
≤18.5–24.9	407 (31.7)	194 (34.8)	610 (32.7)	1,338 (37.9)	
25–29.9	585 (45.6)	243 (43.6)	840 (45.0)	1,482 (42.0)	
≥30	292 (22.7)	120 (21.5)	418 (22.4)	707 (20.1)	0.001
Energy intake (kcal/day)[4]					
<1,626	366 (31.7)	132 (26.0)	508 (30.2)	1,058 (33.4)	
>1,626–2,071	341 (29.6)	167 (32.9)	513 (30.4)	1,058 (33.3)	
>2,071	446 (38.7)	208 (41.0)	664 (39.4)	1,057 (33.3)	<0.001
Fiber intake (g/day)[4]					
<17	439 (38.1)	195 (38.5)	646 (38.3)	1,058 (33.4)	
17–23.5	373 (32.4)	156 (30.8)	537 (31.9)	1,058 (33.3)	
>23.5	341 (29.6)	156 (30.8)	502 (29.8)	1,057 (33.3)	0.002
Alcohol intake (g/day)[4]					
≤8	512 (44.4)	217 (42.8)	740 (43.9)	1,615 (50.9)	
>8	641 (55.6)	290 (57.2)	945 (56.1)	1,558 (49.1)	<0.001
Vitamin C (mg/day)[4]					
<117	415 (36.0)	208 (41.0)	634 (37.6)	1,058 (33.4)	
117–186	405 (35.1)	168 (33.1)	583 (34.6)	1,058 (33.3)	
>186	333 (28.9)	131 (25.8)	468 (27.8)	1,057 (33.3)	<0.001
Vitamin E (mg/day)[4]					
<8.5	420 (36.4)	177 (34.9)	603 (35.8)	1,058 (33.4)	
8.5–12.0	382 (33.1)	168 (33.1)	562 (33.4)	1,058 (33.3)	
>12.0	351 (30.4)	162 (32.0)	520 (30.9)	1,057 (33.3)	0.138
Red meat (g/day)[4]					
<20	321 (27.8)	117 (23.1)	444 (26.4)	1,058 (33.4)	
20–40	362 (31.4)	167 (32.9)	537 (31.9)	1,058 (33.3)	
>40	470 (40.8)	223 (44.0)	704 (41.8)	1,057 (33.3)	<0.001
Processed meat (g/day)[4]					
<17	355 (30.8)	132 (26.0)	498 (29.6)	1,058 (33.4)	
17–34	369 (32.0)	148 (29.2)	520 (30.9)	1,058 (33.3)	
>34	429 (37.2)	227 (44.8)	667 (39.6)	1,057 (33.3)	<0.001
Water intake (L/day)					
<0.9	389 (30.3)	185 (33.2)	584 (31.2)	1,181 (33.5)	
≥0.9–1.4	410 (31.9)	167 (30.0)	584 (31.2)	1,209 (34.2)	
>1.4	486 (37.8)	205 (36.8)	701 (37.5)	1,140 (32.3)	0.001

[1]Numbers of colon and rectum cases do not add 1,869 since 27 cases were undefined.
[2]*p values for Chi2 test* comparing controls versus CRC cases, calculated ignoring missing values in covariables.
[3]METs: Metabolic equivalents of task. Categories for physical activity were specific for each country. Cut offs for Italy are between parenthesis.
[4]Numbers do not add total cases and controls because of missing observations.
[5]Descriptive for women.

from administrative records of primary health care centers located within the hospitals' catchment areas in Spain, where universal health coverage is available. Potential participants were contacted telephonically on behalf of their family physician. For each control needed, five potential participants of similar age, and same sex and hospital catchment area were

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selected. If contact with the first person of the list was not achieved (after at least five attempts at different times of the day), or if he/she refused to participate, the following person of the list was approached.[20] The study protocol was approved by the ethics committees of the participating institutions, and all participants signed an informed consent before recruitment.

Individual information and response rates

Study subjects were interviewed face-to-face by trained study personnel. Interviews were conducted in the hospitals (cases and hospital-based controls) and in primary health care facilities or nearby research centers (population-based controls). Questionnaires used are available online (http://mccspain.org). Data collected included sociodemographic characteristics; residential history from age 18 years to recruitment; water type consumed in each residence (municipal/bottled/well/other); amount of daily water intake (including water per-se, coffee, tea and other water-based beverages); smoking habits; history of gastric ulcer, diabetes, inflammatory bowel disease or Crohn's disease, use of non steroidal anti-inflammatory drugs (NSAIDs); oral contraceptive (OC) use, and hormonal replacement therapy (HRT); leisure physical activity since age 16 (Spain) or 15 years (Italy); family history of CRC, and information on the quality of the interview. Long-term exposure levels to trihalomethanes (THMs) in drinking water were available for the study population. Dietary information, corresponding to 2 years before recruitment, was collected using validated food frequency questionnaires (FFQs).[21,22] The FFQs included 140 (Spain) or 78 (Italy) food-items, and were administered during the interview in Italy (as part of the main questionnaire) or self-administered in Spain. Average response rates among cases were 58% in Spain (ranging from 33% to 80% among areas) and 95% in Italy, and among controls were 52% Spain (ranging from 30% to 68% among areas) and 95% in Italy. Average response rate for the FFQ in Spain was 88%. In total, 2,371 cases (1,905 Spain, 466 Italy) and 4,159 controls (3,590 Spain, 569 Italy) were interviewed.

Nitrate levels in municipal drinking water

We collected data for the municipalities covering 80% of total person-years in each area. We sent a standardized questionnaire to local authorities and water companies to ascertain current and historical nitrate measurements at the distribution system, and water source characteristics (surface/groundwater proportion). Monitoring levels for 2004–2010 were provided in Spain by the SINAC (*Sistema de Información Nacional de Aguas de Consumo*), and by the Regional Environmental Health Agency (Milan) and the Local Health Authority (Pordenone/Udine) in Italy. Measurements below the quantification limits (QL) (5% of measurements) were imputed half the QL value. If the QL value was missing, the measurement was imputed half of the most frequent QL reported (1.0 mg/L). More details on environmental data available are presented in Supporting Information (Table 1).

Nitrate levels in non-municipal drinking water

Data from the most consumed bottled water brands were available from previous reports in Spain[23] and Italy.[24] Nitrate levels in wells and springs outside the municipal water distribution system were measured in September 2013 in the area of León (Spain), where non-municipal well water consumption was the highest among the study areas (28% of controls in the longest residence). A total of 28 water samples were collected in 21 municipalities. The proportion of well water consumption in other areas ranged from 0.3% to 24% in the longest residence (33 years long, on average). These were considered as missing values given the lack of well water data in those areas.

Estimation of long-term nitrate levels in drinking water

We explored heterogeneity of nitrate levels within each municipality, by comparing the levels available for different sampling points, to identify water zones, defined as geographical areas supplied from a homogeneous water source and with similar nitrate levels. Most of the municipalities comprised only one water zone, and some of the municipalities (*e.g.*, Barcelona and Milan) had water zones already defined with different water sources. Long-term nitrate levels were estimated for 349 water zones, in total (Supporting Information Table 1). We calculated annual average by water zone using available measurements. For years without measurements, we back extrapolated the average of total measurements in the water zone back to 1940, as long as water source remained constant. Nitrate levels in ground water sources are usually higher than in surface sources.[25] Therefore, we used ground water percentage as a weight to calculate nitrate estimates when water source changed, assuming that levels increased proportionally to the percentage of ground water supplied. This assumption was evaluated for each water zone, and was applied uniformly in all municipalities where data was not sufficient to conduct this evaluation. In municipalities without nitrate measurements (covering 0.5% of the total person-years), we assigned the levels of neighboring municipalities supplied with similar surface/ground water proportion $\pm 10\%$. We defined a reliability score for each annual nitrate estimate, ranging from 0 (lowest reliability) to 2 (highest), that penalized estimates that were imputed, calculated based on few number of measurements, and more distant in time to an actual measurement. We used this score for sensitivity analyses.

Estimation of waterborne nitrate exposure

We linked nitrate levels with residential histories by year and municipality (or water zone) covering an exposure period from age 18 to 2 years before the interview ("adult life"), among cases and controls. Since more nitrate measurements were available in recent decades, our "main exposure period"

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covered from 30 to 2 years before the interview. We also evaluated an exposure period from age 18 to 30 years ("early adult life"). We calculated average residential levels (mg/L as NO_3^-) and average waterborne ingested nitrate (mg/day) for each exposure period.

We calculated waterborne ingested nitrate according to amount and type of water consumed. We assigned residential levels when subjects reported tap water consumption. Published levels in bottled water brands were averaged using the sales frequency of each brand as a weight and were assigned when bottled water consumption was reported (6.1 mg/L in Spain and 3.8 mg/L in Italy). Levels from well water samples in León (range 0.5–93 mg/L) were assigned to well water consumers in this area, according to the postal code of wells' location. The annually assigned levels were averaged and multiplied by the daily water intake (mean ± SD = 1.4 ± 0.8 L/day in cases and 1.3 ± 0.9 L/day in controls). Water intakes above the 99th percentile (4 L/day), considered non plausible, were treated as missing values in the analyses.

To address the potential misclassification of the water type consumed (municipal/bottled) in recent residences, we calculated an alternative variable of waterborne ingested nitrate. We assumed that subjects reporting bottled water consumption and living during at least 10 years in the current (or previous) residence, consumed municipal water before the year 2000 and bottled water thereafter. This was assumed based on results from a subgroup with information on water type changes within residences ($n = 174$), showing that among 86% of subjects reporting bottled water consumption in the current residence, actually switched from municipal to bottled water after the year 2000. Similar calculations were done for Italy, using the cutoff at 1980 according to Italian data.

Estimation of dietary nutrients and nitrate

Data collected through FFQs were used to estimate the average daily intake of food groups and nutrients (vitamins C, E, and energy). Nutrients' contents were calculated using published food composition databases.[26,27] Dietary nitrate intake (mg/day) was estimated based on average intake of food items (g/day) and published nitrate content (mg/100 g) in food items including vegetables,[4] animal products and others.[28,29] Nitrate contents (mg/100 g) were calculated for 21 vegetables (including tubers), 13 fruits, 17 foods from animal sources (including red, white, processed meat and dairy products), 3 frequently consumed foodstuff (bread, rice and pasta) and 1 alcoholic beverage (beer). For these calculations "red meat" included: beef, lamb and pork meat. "Processed meat" included: bacon, hot dogs, smoked ham, Spanish cured ham and other cured sausages.

Statistical analyses

Subjects with nitrate exposure covering less than 70% of the last 30 years before the interview, and with unsatisfactory quality interview ($n = 24$) were excluded, leading to 1,869 cases and 3,530 controls analyzed. Nitrate exposure variables were categorized attempting to have subjects from different areas in all categories and high numbers in the reference. Odds ratios (OR) and 95% confidence intervals (CI) of CRC were calculated using mixed models with "area" as random effect. Basic models were adjusted for sex, age, study area and education. Potential confounders were explored overall and separately for men and women, including: smoking (never/ever), physical activity (measured in METs Metabolic equivalents of task/hour/week), body mass index (BMI), history of CRC in first degree relatives, NSAIDs use, OC use and HRT (in women), intake of energy, fiber, alcohol and endogenous nitrosation modulators (intake of vitamin C, vitamin E, red meat, processed meat and gastric ulcer history). Only variables that changed the risk estimates ≥10% were retained in the adjusted models.[11] In alternative analyses, models were adjusted for THM levels (residential and waterborne ingested) in the main exposure period. Missing values in categorical covariables were coded as another category. We evaluated the exposure-response relationship between waterborne nitrate exposure and CRC risk using generalized additive models (GAMs).

We stratified analyses of waterborne ingested nitrate by sex, cancer site, endogenous nitrosation modulators and other potential effect modifiers. Strata of quantitative variables (≤ or > median) were defined according to the distribution in controls. We compared the models with and without the interaction term using the likelihood ratio test, and p values less than 0.10 were considered indicative of multiplicative interaction. Stratified analyses by endogenous nitrosation factors were also conducted for men and women separately. We conducted several sensitivity analyses including the use of alternative variables of waterborne ingested nitrate in different exposure windows, and excluding exposure estimates (residential levels) with low reliability score (score value <0.50 $N = 1,077$). STATA version 12.0 (Stata Corp, College Station, TX) was used for all statistical analyses.

Results

Characteristics of the population analyzed are shown in Table 1. Family history of CRC, high BMI, high intake of energy, alcohol, red meat and processed meat were more frequent among cases (Chi^2 p values <0.05). The amount of water intake was also higher among cases (t test p values <0.05). Compared with the excluded, the subjects analyzed showed a higher proportion of controls, were younger, with lower physical activity, more frequent use of NSAIDs, and had lower (≤5 mg/L) or higher (≥10 mg/L) residential nitrate levels (Supporting Information Table 2).

On average (mean ± SD), this population had 3.3 ± 1.6 residences in adult life, and the time living in the most recent residence was 29.3 ± 14.9 years. The number of years (mean ± SD) with nitrate measurements available ranged from 4.0 ± 1.7 to 13.4 ± 1.5, among study areas. Nitrate measurements were available for 19% of the main exposure

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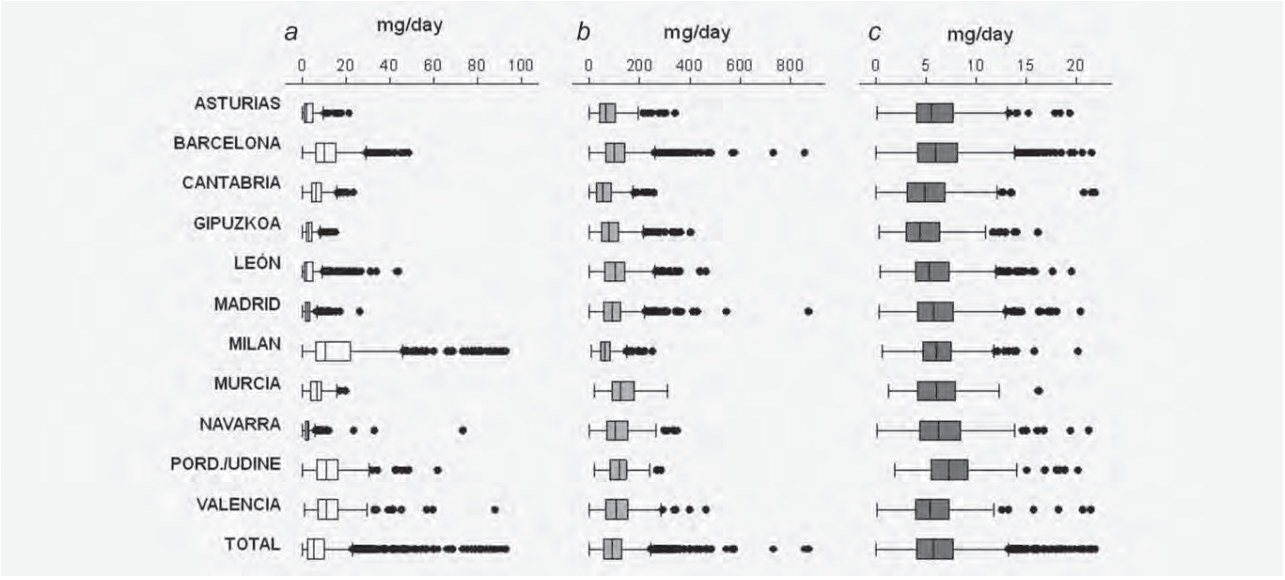

Figure 1. Average nitrate exposure levels among study areas. (*A*) Waterborne intake in the main exposure period (excluding intakes >105.8 mg/day, $n = 5$). (*B*) Dietary intake from vegetable sources (excluding intakes >1,000 mg/day, $n = 2$). (*C*) Dietary intake from animal sources (excluding intakes >22 mg/day, $n = 16$).

period (from 30 to 2 years before the interview), on average. Municipal water consumption was longer than bottled or well water consumption (19.2 ± 12.6 *vs.* 10.5 ± 16.5, and 0.8 ± 4.2 years, respectively), with differences among regions (Supporting Information Table 1).

Figure 1 shows average nitrate exposure levels through drinking water and diet during the main exposure period (from 30 to 2 years before the interview). Waterborne ingestion (mean ± SD) ranged from 3.4 ± 3.3 to 19.7 ± 22.6 mg/day, and residential levels ranged from 1.6 ± 0.9 to 30.0 ± 4.4 mg/L, among areas. The levels were similar in other exposure periods (results not shown). A high correlation was found between waterborne nitrate ingestion during the main exposure period and alternative exposure periods (*Spearman* correlation coefficients $r = 0.98$ with levels in adult life, and 0.91 with levels in early adult life). Dietary nitrate intake (mean ± SD) was 118 ± 72 mg/day (102 ± 70.5 mg/day from vegetables and 6.2 ± 3.3 mg/day from animal sources).

Table 2 shows the risk of CRC associated with waterborne ingested nitrate, overall and stratified by sex, for colon and rectum cancers sites. Adjusted ORs (95%CIs) of CRC for >10 versus ≤5 mg/day were 1.49 (1.24–1.78) overall, 1.50 (1.21–1.87) among men and 1.41 (1.04–1.91) among women. Interaction by sex was statistically significant for colorectal and colon, but not for rectal cancer. Results differed moderately by cancer site. The analyses of the alternative exposure periods led similar results, as well as the sensitivity analyses excluding subjects with low reliable score, or the subjects with less reliable interviews. Stratified analyses by time living in the current residence (≤15 years, >15–30 years and >30 years) also led similar results (not shown in tables). The ORs decreased slightly with additional adjustment for chloroform levels, while slightly increased after adjustment for brominated THMs (see Supporting Information Table 3).

Average residential nitrate levels were also associated with increased CRC (see Supporting Information Table 4), although the ORs were higher than those observed with waterborne ingested nitrate. These variables were moderately correlated, overall (*Spearman* correlation coefficient $r = 0.66$), but with wide differences among areas (*e.g.*, −0.04 in Madrid to 0.39 in León). In sensitivity analyses, areas with more than 10% of cases (Barcelona, León and Madrid) and Italian areas were alternatively excluded from the models. The ORs (95%CI) for the highest exposure category (>10 *vs.* <5 mg/L) decreased mostly after excluding Barcelona and Italian areas, but remained statistically significant. The ORs were higher among men versus women (interaction p values <0.001), and slightly higher for colon versus rectum tumors.

Figure 2 shows the GAMs for waterborne ingested nitrate. A small increase in CRC risk was found at ingested levels between 10 and 30 mg/day, among men and overall. At higher levels, the exposure-response curve was flat, with wide CIs. Area-specific GAMs showed heterogeneous exposure-response curves between areas (Supporting Information Fig. 1).

Table 3 shows stratified analyses by dietary endogenous nitrosation factors and fiber intake, overall and by cancer site. High ORs (95%CI) were found in the groups with highest waterborne ingested nitrate and highest red meat intake, particularly among men: 1.71 (1.30, 2.26) (see results by sex in Supporting Information Table 5). Results for processed meat were similar to results for red meat, overall (not shown in tables). Inverse ORs (95%CI) of CRC were found among the groups with low ingested nitrate and high vitamin E

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Table 2. Colorectal cancer risk associated with waterborne nitrate ingestion during the main exposure period in all population ($n = 5{,}399$) and stratified by cancer site and sex

Mean nitrate ingestion	≤5 mg/day			>5–10 mg/day			>10 mg/day		
	Cases	Contr.	OR[1] (95%CI)	Cases	Contr.	OR[1] (95%CI)	Cases	Contr.	OR[1] (95%CI)
Cancer site									
Colorectal[2]									
All	778	1,899	1.00 (ref.)	447	803	1.17 (0.98, 1.38)	644	828	1.49 (1.24, 1.78)
Men	498	918	1.00 (ref.)	289	454	1.16 (0.94, 1.44)	397	468	1.50 (1.21, 1.87)
Women	280	981	1.00 (ref.)	158	349	1.20 (0.90, 1.58)	247	360	1.41 (1.04, 1.91)
Colon[2]									
All	527	1,899	1.00 (ref.)	324	803	1.28 (1.06, 1.55)	434	828	1.52 (1.24, 1.86)
Men	322	918	1.00 (ref.)	202	454	1.26 (0.99, 1.61)	260	468	1.51 (1.17, 1.94)
Women	205	981	1.00 (ref.)	122	349	1.33 (0.97, 1.80)	174	360	1.46 (1.04, 2.05)
Rectum[2]									
All	244	1,899	1.00 (ref.)	110	803	0.93 (0.70, 1.23)	203	828	1.62 (1.23, 2.14)
Men	169	918	1.00 (ref.)	80	454	0.94 (0.68, 1.28)	133	468	1.55 (1.16, 2.08)
Women	75	981	1.00 (ref.)	30	349	0.87 (0.52, 1.45)	70	360	1.49 (0.89, 2.48)

[1]Odds ratios (OR) and 95% confidence intervals (CI). Results of mixed models with "area" as random effect, adjusted for: sex, age, education, body mass index, physical activity, non-steroidal anti-inflammatories use, family history of colorectal cancer and intake of energy. Analyses for women were also adjusted for oral contraceptives use.
[2]Interaction *p values* by sex = *0.01* for colorectal, *0.05* for colon and *0.15* for rectal cancer.

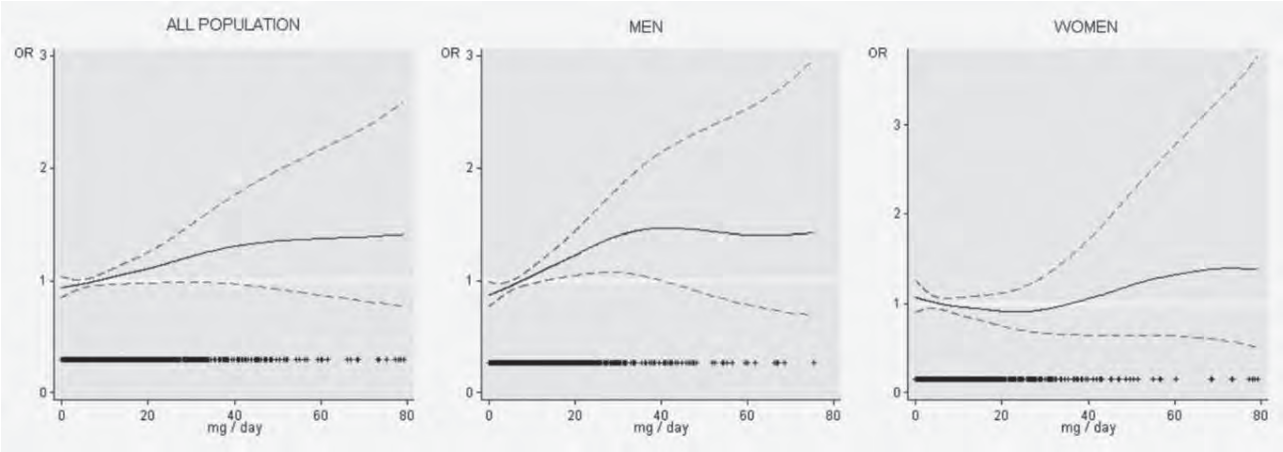

Figure 2. Exposure-response relationship between average waterborne ingested nitrate (mg/day) during the main exposure period and colorectal cancer risk. Generalized additive models (GAMs) adjusted for study area, sex, age, education, physical activity, body mass index, use of non-steroidal anti-inflammatory drugs, family history of colorectal cancer and energy intake. Subjects with ingestion levels >80 mg/day ($n = 21$) were excluded from these analyses.

(0.73, 0.59–0.89), and high fiber intake (0.65, 0.53–0.80). Results by cancer site showed similar results for colon cancer, but inverse ORs with vitamin C and fiber were found for rectum cancer. Stratified results did not differ by diabetes diagnosis, or smoking (not shown).

Table 4 shows the risk of CRC (overall and by cancer site) associated with dietary ingested nitrate. An association (OR, 95%CI) with nitrate intake from animal sources was found for rectal cancer (1.55, 1.17–2.05) while no association was observed for colon cancer (1.06, 0.87–1.30). Ingestion from total diet or vegetables led to null or inverse associations with CIs around the null value for both cancer sites. Waterborne and dietary ingested nitrate were poorly correlated (*Spearman* correlation coefficient for nitrate from total diet: 0.07, vegetables: 0.06 and animal sources: 0.07). The adjustment of waterborne ingested nitrate analyses' for dietary nitrate intake (through different sources) did not change the main results (results not shown).

Discussion

Results of this large case–control study suggest a positive association between CRC risk and long-term exposure to nitrate in drinking water, at levels below 50 mg/L of NO_3^-, particularly in subgroups of the population, such as men and

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Table 3. Colorectal cancer risk associated with waterborne ingested nitrate levels in the main exposure period. Joint effect with endogenous nitrosation factors and other dietary covariables in all population and by cancer site

Covariable Intake	Nitrate intake mg/day	Colorectal cancer ($n = 4{,}858$[1])		Colon cancer ($n = 4{,}326$[1])		Rectal cancer ($n = 3{,}680$[1])		Controls
		Cases	OR[2] (95%CI)	Cases	OR[2] (95%CI)	Cases	OR[2] (95%CI)	
Red meat								
≤29 g/day	≤4.4	296	1.00 (ref.)	209	1.00 (ref.)	85	1.00 (ref.)	842
	>4.4	380	1.09 (0.88–1.35)	265	1.12 (0.88, 1.44)	107	1.08 (0.76, 1.55)	744
>29 g/day	≤4.4	349	1.24 (1.02–1.51)	221	1.17 (0.93, 1.47)	124	1.49 (1.09, 2.02)	742
	>4.4	660	1.56 (1.26–1.94)	458	1.66 (1.30, 2.12)	191	1.57 (1.11, 2.21)	845
Interaction p values			0.27		0.12		0.90	
Vitamin C								
≤137 mg/day	≤4.4	343	1.00 (ref.)	218	1.00 (ref.)	121	1.00 (ref.)	766
	>4.4	589	1.20 (0.98–1.47)	409	1.36 (1.08, 1.71)	168	0.99 (0.73, 1.36)	820
>137 mg/day	≤4.4	302	0.83 (0.68–1.01)	212	0.92 (0.73, 1.15)	88	0.67 (0.49, 0.91)	818
	>4.4	451	0.95 (0.77–1.18)	314	1.09 (0.86, 1.38)	130	0.77 (0.56, 1.07)	769
Interaction p values			0.73		0.35		0.45	
Vitamin E								
≤10 mg/day	≤4.4	355	1.00 (ref.)	238	1.00 (ref.)	112	1.00 (ref.)	806
	>4.4	531	1.15 (0.94, 1.42)	373	1.26 (1.00, 1.59)	149	1.03 (0.75, 1.43)	780
>10 mg/day	≤4.4	290	0.73 (0.59, 0.89)	192	0.73 (0.57, 0.93)	97	0.75 (0.54, 1.04)	778
	>4.4	509	0.87 (0.70, 1.09)	350	0.94 (0.73, 1.21)	149	0.81 (0.57, 1.15)	809
Interaction p values			0.74		0.89		0.85	
Fiber								
≤20 g/day	≤4.4	344	1.00 (ref.)	224	1.00 (ref.)	115	1.00 (ref.)	741
	>4.4	595	1.13 (0.92–1.38)	422	1.28 (1.01, 1.61)	159	0.90 (0.66, 1.24)	845
>20 g/day	≤4.4	301	0.65 (0.53–0.80)	206	0.71 (0.56, 0.89)	94	0.55 (0.40, 0.76)	843
	>4.4	445	0.84 (0.68–1.04)	301	0.92 (0.73, 1.18)	139	0.72 (0.52, 1.00)	744
Interaction p values			0.32		0.88		0.07	

[1]Numbers do not add 5,399 due to missing values in dietary variables and cancer site.
[2]Odds ratios (OR) and 95% confidence intervals (CI). Results of mixed models with "area" as random effect adjusted for: sex, age, education, physical activity, non-steroidal anti-inflammatory drugs use, family history of colorectal cancer and energy intake.

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Table 4. Dietary ingested nitrate and colorectal cancer risk stratified by cancer site among population with available dietary information ($n = 4,858$)

Ingested nitrate from:	Median intake (mg/day)	Colorectal cancer		Colon cancer		Rectal cancer		Controls
		Cases[1]	OR[2] (95% CI)	Cases	OR[2] (95% CI)	Cases	OR[2] (95% CI)	
Animal sources								
<4.5 mg/day	3.1	473	1.00 (ref.)	352	1.00 (ref.)	112	1.00 (ref.)	1,058
4.5–6.8 mg/day	5.6	578	1.15 (0.98, 1.35)	378	1.03 (0.86, 1.24)	191	1.59 (1.22, 2.06)	1,058
>6.8 mg/day	9.4	634	1.16 (0.98, 1.38)	423	1.06 (0.87, 1.30)	204	1.55 (1.17, 2.05)	1,057
Continuous			1.03 (1.01, 1.05)		1.02 (1.00, 1.04)		1.04 (1.01, 1.07)	
Vegetable sources[3]								
<68 mg/day	42	597	1.00 (ref.)	392	1.00 (ref.)	194	1.00 (ref.)	1,058
68–118 mg/day	92	575	0.99 (0.85, 1.16)	397	1.04 (0.87, 1.24)	169	0.91 (0.71, 1.16)	1,058
>118 mg/day	179	513	0.83 (0.70, 0.99)	364	0.89 (0.73, 1.08)	144	0.75 (0.57, 0.99)	1,057
Continuous			1.00 (0.99, 1.00)		1.00 (0.99, 1.00)		1.00 (0.99, 1.00)	
Total diet[3]								
<83 mg/day	59	594	1.00 (ref.)	388	1.00 (ref.)	195	1.00 (ref.)	1,058
83–133 mg/day	108	564	0.97 (0.83, 1.14)	394	1.04 (0.87, 1.24)	161	0.85 (0.66, 1.08)	1,058
>133 mg/day	176	527	0.84 (0.70, 1.00)	371	0.90 (0.74, 1.10)	151	0.76 (0.58, 1.00)	1,057
Continuous			1.00 (0.99, 1.00)		1.00 (0.99, 1.00)		1.00 (0.99, 1.00)	

[1]This column does not add to total number of cancer cases since 46 were undefined site.
[2]Odds ratios (OR) and 95% confidence intervals (CI). Results of mixed models with "area" as random effect adjusted for sex, age, education, physical activity, non-steroidal anti-inflammatory drugs use, family history of colorectal cancer, body mass index and intake energy.
[3]Results are also adjusted for fiber intake.

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Cancer Epidemiology

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subjects with high red meat intake. The associations slightly differed for colon and rectal cancer. A positive association was found between rectal cancer risk and nitrate intake from animal sources, but an inverse association is suggested with intake from vegetables.

This is one of the few studies evaluating CRC risk and nitrate exposure through drinking water. Our results are comparable to previous case–control studies from the United States, although those studies evaluated residential, but not ingested nitrate, at higher levels than those observed in our study. A 2.9-fold increased risk of proximal colon cancer for NO_3-N residential levels $\geq$10 mg/L (44 mg/L of NO_3^-) versus $<$0.5 mg/L has been reported.[30] Increased risk of colon cancer was found among subjects with residential NO_3-N levels $>$5 mg/L for $>$10 years and low vitamin C intake or high meat intake.[16] Other available studies had ecologic design or ignored endogenous nitrosation factors and individual water consumption data,[31,32] thus are not totally comparable to our study.

Dietary ingested nitrate levels in this study were similar to those observed in other western countries.[33] Our results are consistent with a cohort study[15] that found higher colon cancer risk with ingested nitrate from animal sources. Results from other studies on CRC and dietary nitrate, nitrite or NOCs are heterogeneous,[5,6,13,14] and most of them did not evaluate ingestion from different dietary sources. In contrast to results for animal-derived nitrate, inverse associations were found for high nitrate intake from vegetables. These results may not be confounded by the protective effect of fiber, since the analyses were adjusted for this variable. The presence of endogenous nitrosation inhibitors in vegetables and hypothesized beneficial effects of nitrate from vegetables[34] may partly explain these findings.

Our results suggest an interaction between waterborne nitrate exposure and sex for CRC and colon cancer, but not for rectal cancer. The associations were higher among men, similarly to other exposures such as dietary factors.[35] This may partly be attributed to the protective effect of estrogens and other hormonal factors.[36] We found higher associations in groups with high red meat intake. These results were consistent with previous studies that evaluated other cancer types associated with nitrate or nitrite exposure.[33,37] Although the interaction with red meat was not statistically significant, is plausible, because red meat contains amines, amides, and heme iron which may increase endogenous formation of NOCs.[38] Information on heme iron intake was not available in this study, but should be accounted to evaluate the interaction with red meat in future analysis.[39] In contrast, inverse associations were found in groups of high vitamin E or fiber intake. Vitamins E and C inhibit endogenous nitrosation, and a protective effect is biologically plausible. The combined intake of vitamins C and E showed similar effects to those shown for each vitamin. The protective effect of fiber was also expected, based on previous evidence on fiber intake and CRC risk.[40] Apart from endogenous nitrosation, changes in gastrointestinal microbiota,[41] and genetic variants of CYP2E1 (involved in NOCs' bio-activation),[14] may also play a role in carcinogenesis of ingested nitrate and should be explored in future analyses.

Confounding by other water contaminants such as THMs[42] was a concern. In this study, estimates of THMs intake were available, and were evaluated as potential confounders. Associations decreased slightly after adjusting for chloroform, and increased slightly after adjusting for brominated THMs or total THMs, but the differences were not statistically significant. The potential interaction of these frequent water contaminants requires further evaluation, since contradictory effects are suggested for chlorinated versus brominated THMs. Other water contaminants showed levels around or below the QL in our study areas,[23] and are not likely to be relevant confounders in the context of this study.

Although different response rates between study areas and relatively low rates among controls may be a limitation, nonparticipation is unlikely related to nitrate exposure. Potential exposure measurement error is a limitation, since nitrate measurements in drinking water were only available in recent years. Missing historical levels were estimated based on recent measurements and were assumed to remain stable over time, depending on groundwater percentages. This assumption may introduce measurement error, particularly for long-term periods (*e.g.*, adult life). Nitrate levels may differ widely between groundwater sources according to the depth of wells, and may change in time according to factors other than water source (*e.g.*, agricultural practices). Such information was not collected, since the questionnaire was not originally designed to estimate historical nitrate levels, and was not available in official reports. However, we analyzed the municipalities with longest nitrate records: Llíria (Valencia) and Donostia (Gipuzkoa), and no significant changes were found in nitrate levels over 17 years. The levels estimated for a 30-year period would be sufficient to evaluate the association with CRC risk, among this population. Additionally, we applied several strategies to address the potential exposure measurement error: we analyzed only the population with exposure information available for $\geq$70% of the main exposure period (30 to 2 years before the interview). We performed sensitivity analyses excluding less reliable exposure estimates, obtaining similar results to those shown in Table 2. We analyzed three different exposure periods, but results for adult life and early adult life are limited because are based on estimates with low reliability. In addition, nitrate estimates from different exposure periods were highly correlated. Studies in other settings, with larger availability of historical environmental data, are needed to increase the current evidence on waterborne nitrate exposure and CRC risk.

Since dietary information was collected with a FFQ, recall bias may not be totally ruled out in the analyses for dietary nitrate. The results for dietary nitrate intake may not be extrapolated for long-term periods, since dietary information corresponded to the last 2 years previous to recruitment. Estimates of dietary nitrate are prone to measurement error since we used the same nitrate contents in food products,

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regardless of potential country-specific levels. However, the database used is valid for all European countries, and includes specific Spanish and Italian measurements.[4] Data on relevant vegetable sources of nitrate was not completely available, and data on storage and processing (*i.e.*, washing, peeling and cooking) was not collected, which also may introduce error in calculations of nitrate intake from vegetables. Finally, dietary nitrite intake was not available, but this would not be a major limitation since the main exposure route expected is through endogenous nitrate reduction.[8]

The wide differences on nitrate levels between study areas, and the low variability within areas hampered the statistical analyses. We applied different approaches for all-area combined analyses, including unconditional logistic regression, GAMs, and meta-smoothing analyses[43] (previously used in multicentric studies on air pollution). Mixed models, with area as random effect were finally applied given the heterogeneity of results between study areas. This heterogeneity is a limitation, and is probably related to other environmental or individual factors that were not evaluated in this study. The results of mixed models differed slightly from results of the GAMs, particularly among women. Results among women may be less robust due to the smaller sample size, compared with men. Results of meta-smoothing analyses are not shown, because were equivalent to results of the GAMs.

A main strength of this study was the availability of detailed individual information, allowing the assessment of several potential confounders and effect modifiers, including other frequent water contaminants (THMs) and endogenous nitrosation factors. In addition, the FFQ information enabled us to assess nitrate exposure through different dietary sources. Nitrate measurements in non municipal water (wells) were measured and included in the exposure assessment for the area with the highest consumption of this water type (León). Finally, the main results were robust, as were replicated using different approaches for statistical analysis.

Conclusions

Overall, effects of nitrate exposure differed by exposure source (water, vegetables and animal dietary sources). A positive association is suggested between CRC risk and long-term exposure to nitrate in drinking water at levels below the European regulatory limit, particularly among subjects with other risk factors. Dietary nitrate from animal sources increased rectal cancer risk, but high intake from vegetables seems to decrease it. Further research is required to confirm these findings.

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References

1. Ward MH. Too much of a good thing? Nitrate from nitrogen fertilizers and cancer. *Rev Environ Health* 2009;24:357–63.
2. Wakida F, Lerner D. Non-agricultural sources of groundwater nitrate: a review and case study. *Water Res* 2005;39:3–16.
3. WHO. Nitrate and nitrite. In: Guidelines for drinking water quality incorporating 1st and 2nd addenda recommendations, 3rd edn., Geneva: World Health Organization, 2008.
4. EFSA. Opinion of the scientific panel on contaminants in the food chain on a request from the European Commission to perform a scientific risk assessment on nitrate in vegetables. *EFSA J* 2008;689:1–79.
5. Ward MH, deKok TM, Levallois P, et al. Workgroup report: drinking-water nitrate and health–recent findings and research needs. *Environ Health Perspect* 2005;113: 1607–14.
6. Jakszyn P, Agudo A, Berenguer A, et al. Intake and food sources of nitrites and N-nitrosodimethylamine in Spain. *Public Health Nutr* 2006;9:785–91.
7. Lijinsky W. Life-span and cancer: the induction time of tumors in diverse animal species treated with nitrosodiethylamine. *Carcinogenesis* 1993;14: 2373–5.
8. IARC. Working Group on the Evaluation of Carcinogenic Risks to Humans. IARC monographs on the evaluation of carcinogenic risks to humans. Ingested nitrate and nitrite, and cyanobacterial peptide toxins. *IARC Monogr Eval Carcinog Risks Hum* 2010;94: 1–412.
9. Ferlay J, Steliarova-Foucher E, Lortet-Tieulent J, et al. Cancer incidence and mortality patterns in Europe: estimates for 40 countries in 2012. *Eur J Cancer* 2013;49:1374–403.
10. Bouvard V, Loomis D, Guyton KZ, et al. Carcinogenicity of consumption of red and processed meat. *Lancet Oncol* 2015;16:1599–600.
11. Stewart B, Wild CP. World cancer report 2014. Lyon, France: International Agency for Research on Cancer, 2014.
12. Cross A, Ferrucci L, Risch A, et al. A large prospective study of meat consumption and colorectal cancer risk: an investigation of potential mechanisms underlying this association. *Cancer Res* 2010;70:2406–14.
13. Loh Y, Jakszyn P, Luben R, et al. N-Nitroso compounds and cancer incidence: the European Prospective Investigation into Cancer and Nutrition (EPIC)-Norfolk Study. *Am J Clin Nutr* 2011;93: 1053–61.
14. Zhu Y, Wang P, Zhao J, et al. Dietary N-nitroso compounds and risk of colorectal cancer: a case-control study in Newfoundland and Labrador and Ontario, Canada. *Br J Nutr* 2014;111:1109–17.
15. Dellavalle C, Xiao Q, Yang G, *et al.* Dietary nitrate and nitrite intake and risk of colorectal cancer in the Shanghai Women's Health Study. *Int J Cancer* 2014;134:2917–26.
16. De Roos A, Ward M, Lynch C, *et al.* Nitrate in public water supplies and the risk of colon and rectum cancers. *Epidemiology* 2003;14:640–9.
17. EU. Directive 98/83/EC on the quality of water intended for human consumption. *CELEX-EUR Off J* 1998;330:32–54.
18. Castaño-Vinyals G, Aragonés N, Pérez-Gómez B, et al. Population-based multicase-control study in common tumors in Spain (MCC-Spain): rationale and study design. *Gac Sanit* 2015;29:308–15.
19. Nieuwenhuijsen M, Smith R, Golfinopoulos S, et al. Health impacts of long-term exposure to disinfection by-products in drinking water in Europe: HIWATE. *J Water Health* 2009;7:185–207.
20. Castaño-Vinyals G, Nieuwenhuijsen M, Moreno V, *et al.* Participation rates in the selection of population controls in a case-control study of colorectal cancer using two recruitment methods. *Gac Sanit* 2011;25:353–6.
21. Decarli A, Franceschi S, Ferraroni M, *et al.* Validation of a food-frequency questionnaire to assess dietary intakes in cancer studies in Italy. Results for specific nutrients. *Ann Epidemiol* 1996;6:110–8.
22. Martin-Moreno J, Boyle P, Gorgojo L, *et al.* Development and validation of a food frequency questionnaire in Spain. *Int J Epidemiol* 1993;22: 512–9.

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23. Espejo-Herrera N, Kogevinas M, Castaño-Vinyals G, et al. Nitrate and trace elements in municipal and bottled water in Spain. *Gac Sanit* 2013;27: 156–60.
24. D'Alessandro W, Bellomo S, Parello F, *et al.* Nitrate, sulphate and chloride contents in public drinking water supplies in Sicily, Italy. *Environ Monit Assess* 2012;184:2845–55.
25. Burkart M, Stoner J. Nitrate in aquifers beneath agricultural systems. *Water Sci Technol* 2007;56: 59–69.
26. Farran A, Zamora R, Cervera P. Tablas de composición de alimentos del Centre d'Ensenyament Superior de Nutrició i Dietètica (CESNID), 2nd edn. Barcelona: McGraw-Hill/Interamericana Spain S. A., 2008.
27. Gnagnarella P, Parpinel M, Salvini S, *et al.* The update of the Italian Food Composition Database. *J Food Compos Anal* 2004;17:509–22.
28. Griesenbeck J, Steck M, Huber JJ, *et al.* Development of estimates of dietary nitrates, nitrites, and nitrosamines for use with the Short Willet Food Frequency Questionnaire. *Nutr J* 2009;8:16.
29. Jakszyn P, Agudo A, Ibáñez R, *et al.* Development of a food database of nitrosamines, heterocyclic amines, and polycyclic aromatic hydrocarbons. *J Nutr* 2004;134:2011–4.
30. McElroy J, Trentham-Dietz A, Gangnon R, *et al.* Nitrogen-nitrate exposure from drinking water and colorectal cancer risk for rural women in Wisconsin, USA. *J Water Health* 2008;6:399–409.
31. Gulis G, Czompolyova M, Cerhan J. An ecologic study of nitrate in municipal drinking water and cancer incidence in Trnava District, Slovakia. *Environ Res* 2002;88:182–7.
32. Weyer P, Cerhan J, Kross B, *et al.* Municipal drinking water nitrate level and cancer risk in older women: the Iowa Women's Health Study. *Epidemiology* 2001;12:327–38.
33. Ward M, Cerhan J, Colt J, Hartge P. Risk of non-Hodgkin lymphoma and nitrate and nitrite from drinking water and diet. *Epidemiology* 2006; 17:375–82.
34. Hord N, Tang Y, Bryan N. Food sources of nitrates and nitrites: the physiologic context for potential health benefits. *Am J Clin Nutr* 2009;90: 1–10.
35. Kim S, Paik H, Yoon H, *et al.* Sex- and gender-specific disparities in colorectal cancer risk. *World J Gastroenterol* 2015;21:5167–75.
36. Fernandez E, La Vecchia C, Balducci A, *et al.* Oral contraceptives and colorectal cancer risk: a meta-analysis. *Br J Cancer* 2001;84:722–7.
37. Ward MH, Rusiecki JA, Lynch CF, *et al.* Nitrate in public water supplies and the risk of renal cell carcinoma. *Cancer Causes Control* 2007;18: 1141–51.
38. Bingham S, Hughes R, Cross A. Effect of white versus red meat on endogenous N-nitrosation in the human colon and further evidence of a dose response. *J Nutr* 2002;132:3522S–5S.
39. Bastide N, Pierre F, Corpet D. Heme iron from meat and risk of colorectal cancer: a meta-analysis and a review of the mechanisms involved. *Cancer Prev Res (Phila)* 2011;4: 177–84.
40. Bradbury K, Appleby P, Key T. Fruit, vegetable, and fiber intake in relation to cancer risk: findings from the European Prospective Investigation into Cancer and Nutrition (EPIC). *Am J Clin Nutr* 2014;100:394S–8S.
41. Azcárate-Peril M, Sikes M, Bruno-Bárcena J. The intestinal microbiota, gastrointestinal environment and colorectal cancer: a putative role for probiotics in prevention of colorectal cancer? *Am J Physiol Gastrointest Liver Physiol* 2011;301: G401–24.
42. Rahman M, Driscoll T, Cowie C, *et al.* Disinfection by-products in drinking water and colorectal cancer: a meta-analysis. *Int J Epidemiol* 2010;39: 733–45.
43. Schwartz J, Zanobetti A. Using meta-smoothing to estimate dose-response trends across multiple studies, with application to air pollution and daily death. *Epidemiology* 2000;11:666–72.

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Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study

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Nitrate in drinking water may increase risk of colorectal cancer due to endogenous transformation into carcinogenic *N*-nitroso compounds. Epidemiological studies are few and often challenged by their limited ability of estimating long-term exposure on a detailed individual level. We exploited population-based health register data, linked in time and space with longitudinal drinking water quality data, on an individual level to study the association between long-term drinking water nitrate exposure and colorectal cancer (CRC) risk. Individual nitrate exposure was calculated for 2.7 million adults based on drinking water quality analyses at public waterworks and private wells between 1978 and 2011. For the main analyses, 1.7 million individuals with highest exposure assessment quality were included. Follow-up started at age 35. We identified 5,944 incident CRC cases during 23 million person-years at risk. We used Cox proportional hazards models to estimate hazard ratios (HRs) of nitrate exposure on the risk of CRC, colon and rectal cancer. Persons exposed to the highest level of drinking water nitrate had an HR of 1.16 (95% CI: 1.08–1.25) for CRC compared with persons exposed to the lowest level. We found statistically significant increased risks at drinking water levels above 3.87 mg/L, well below the current drinking water standard of 50 mg/L. Our results add to the existing evidence suggesting increased CRC risk at drinking water nitrate concentrations below the current drinking water standard. A discussion on the adequacy of the drinking water standard in regards to chronic effects is warranted.

Cancer Epidemiology

Nitrate is leached to the aquatic environment, originating mainly from human activities, especially the use of fertilizers in intensive agriculture, and is a frequent drinking water pollutant.[1–3] Denmark is among the countries with the most intensive agriculture with two-thirds of its area under cultivation, resulting in pronounced nitrate pollution of groundwater.[4] The Danish drinking water structure is decentralized and based exclusively on groundwater.[5] The drinking water standard of 50 mg/L as nitrate ion was established to protect infants from the acute condition methemoglobinemia.[1] This standard is almost equivalent to the United States Environmental Protection Agency's maximum contaminant level of 10 mg/L as nitrogen.

However, physiological pathways of possible chronic effects have been suggested, due to endogenous transformation of nitrate into genotoxic *N*-nitroso compounds.[6] Most *N*-nitroso compounds are animal carcinogens,[7] and nitrate has been classified as probably carcinogenic to humans under conditions that favor endogenous nitrosation.[8] Colorectal cancer (CRC) is the third most frequent cancer worldwide,[9] with an age-standardized incidence rate of 43.6 (males) and 33.8 (females) per 100,000 persons per year in Denmark.[10]

Previous epidemiological studies on the association between nitrate in drinking water and CRC are few and yielded inconsistent results.[6] An ecologic study in Slovakia found a positive association between nitrate levels in drinking water and cancers in all digestive organs and CRC in particular.[11] A case–control study in Iowa showed an increased colon cancer risk at elevated nitrate levels in drinking water among susceptible subgroups with elevated endogenous nitrosation, that is, low vitamin C and high red meat intake.[12] A prospective cohort study of women carried out in the same area with a similar exposure assessment found no significant association between colon cancer and the quartile exposed to

Key words: nitrate, drinking water, colorectal cancer, Denmark, cohort studies

Abbreviations: CRC: colorectal cancer; CI: confidence interval; HR: hazard ratio

Additional Supporting Information may be found in the online version of this article.

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What's new?

Nitrate is considered a probable carcinogen in humans owing to its potential for endogenous transformation into genotoxic *N*-nitroso compounds. Cancer risk related to nitrate pollution in drinking water, as a consequence of intensive agriculture using fertilizers, is of particular concern. Here, analyses of water quality data and health registry data with a high spatiotemporal resolution for 2.7 million people in Denmark reveal an increased risk of colorectal cancer (CRC) in association with nitrate exposure. CRC risk was elevated at nitrate concentrations below the current drinking water standard.

the highest concentrations, while the second and third quartiles showed increased risks, and an inverse association was observed for rectal cancer.[13] A case–control study of women in Wisconsin found no overall association with colon or rectal cancer, but an increased risk of proximal colon cancer at nitrate levels around the drinking water standard.[14] A recent case–control study from Spain and Italy showed the higher the intake of nitrate from drinking water, the higher the risk of colon and rectal cancer, also at levels well below the drinking water standard.[15]

A common limitation of previous studies is the limited ability to access historical nitrate exposure for study subjects. To identify potentially small chronic effects, long-term follow-up of a large population is necessary. Large studies with well-characterized long-term exposures and inclusion of private well users were called for[6] assessing populations with large exposure contrast, even if concentrations are below the drinking water standard.[16]

We addressed these limitations by using the rich population-based Danish registers including longitudinal health and residential information,[17] linked in time and space with the likewise longitudinal information on drinking water quality with high spatial and temporal resolution, covering the entire country from 1978 onward.[5,18] The link of these unique nationwide and longitudinal data sources enabled us to study the association between nitrate in drinking water and CRC on an individual level.

Methods

We followed all Danish residents for development of CRC considering nitrate in drinking water as the exposure of interest. Details are described in the following sections.

Study design and population

The unique personal identification number, which is assigned to all Danish residents, was used as key identifier to accurately link data from several registers. Prospectively collected and continuously updated information on date of birth, sex, residential history and vital status were retrieved from the Danish Civil Registration System.[17] The study period was January 1, 1978 to December 31, 2011, as residential history was geocoded for this period. We defined the cohort as all residents of Denmark, alive on their 35th birthday. We followed each individual from their 35th birthday until the onset of colon or rectal cancer, the end of study (31 December 2011), death, emigration or disappearance. Diagnoses of colon cancer (ICD-10 codes C18 and C19), rectal cancer (C20) and all other cancers were retrieved from the Danish Cancer Registry, which has a high validity and degree of completeness.[19]

Exposure assessment

The approach of assigning each household to its annual nitrate concentration is described in detail elsewhere.[18] In brief, we assigned annual average drinking water nitrate concentrations, registered at waterworks level, to the 2,852 public water supply areas and the 2,382,445 publicly supplied households within these. Privately supplied households (81,663) were identified and assigned nitrate concentrations of their private well. In total, 208,706 drinking water samples with precise sampling date and location were used in this study. We interpolated concentrations for years without available nitrate measurements at household level. An exposure assessment quality level based on the number of years to the closest nitrate sample was calculated for each household and year (for detailed explanation of the levels, see results from sensitivity analyses in Table 2).

We calculated each individual's average nitrate exposure between their 20th and 35th birthday by linking their residential history from 1978 onward in time and space to the longitudinal drinking water nitrate concentration data at the Danish households. To be able to calculate an individual's exposure, their exposure window had to overlap with the study period, that is, their 35th birthday had to be after the beginning of study (January 1, 1978) and before the end of study (December 31, 2011). For the main analyses, we included only individuals with a high exposure assessment quality, having lived at least 75% of the time at households with an associated nitrate sample taken within 1 year.

Covariates

Covariates were selected *a priori*. Socioeconomic status was based on the *highest attained education* of each individual from the educational registers and included in four categories: (*i*) primary school only, (*ii*) shorter education (high school and short vocational training), (*iii*) medium long education (vocational training and bachelors) and (*iv*) long education (academics).[20] We included information on any *previous cancer*

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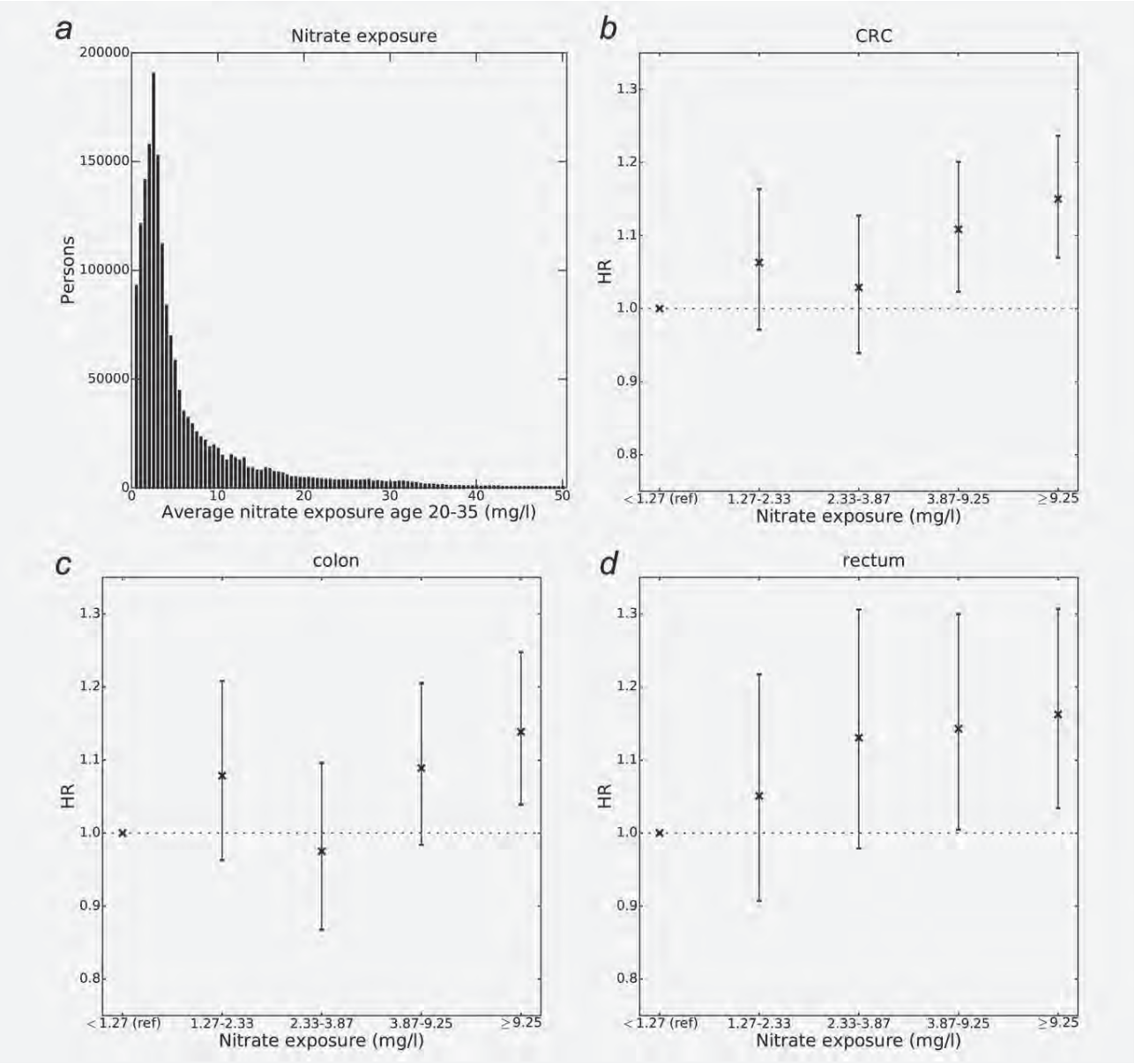

Figure 1. (*a*) Average drinking water nitrate exposure between age 20 and 35 of the study population (subjects exposed to > 50 mg/l [0.58%] not shown here). Hazard ratios (HR) and 95% CIs of nitrate exposure quintiles for (*b*) colorectal, (*c*) colon and (*d*) rectal cancer. Base adjustment.

diagnosis other than the outcome of interest, and *year of birth* in two-year bands to address birth cohort effects.

Statistical analyses

We assessed the association between drinking water nitrate and colon and rectal cancer as separate outcomes, and the combined outcome CRC. We used Cox proportional hazards models to estimate hazard ratios (HRs) using age as the underlying time scale while stratifying the baseline by sex. We included nitrate exposure as quintiles according to the distribution of nitrate exposure in the total population. The base adjustment controlled for age, sex, year of birth and previous cancer diagnosis. Additionally, we adjusted for highest attained education (2nd adjustment). We calculated a summary trend estimate, measuring the effect on a person exposed to the highest decile of nitrate concentrations in drinking water (≥16.75 mg/L) compared with a person exposed to the lowest decile of nitrate concentrations in drinking water (<0.69 mg/L), utilizing data from the in-between deciles (nominal scoring of deciles). Results are reported with 95% confidence intervals (CIs). We checked the validity of the proportional hazards assumption by assessing the null hypothesis of a zero slope of the Schoenfeld residuals on time. Analyses were done in STATA 13.1.

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Table 1. Adjusted hazard ratios (95% CIs) associated with high levels of nitrate exposure compared with low levels (trend estimate). Incident cases and study population size (*N*)

Cancer site	*N*[1]	Cases[1]	Base adjustment[2]	Second adjustment[3]
Colorectal	1,742,093	5,944	1.16 (1.08–1.25)	1.14 (1.06–1.23)
Colon	1,742,156	3,700	1.15 (1.05–1.26)	1.14 (1.04–1.26)
Rectum	1,742,255	2,308	1.17 (1.04–1.32)	1.13 (1.00–1.27)

[1]Incident cases for colon and rectal cancer are not mutually exclusive.
[2]Age, sex, year of birth and previous cancer diagnosis.
[3]Base and highest attained education.

Sensitivity analyses

Using the trend estimate, we assessed the robustness of our results considering potential bias due to private well users and quality, length and period of each individual's exposure assessment. We excluded persons with a previous cancer diagnosis other than the outcome of interest and residents of the Capital Region.

Ethical considerations

In keeping with Danish legislation, the Danish Data Protection Agency, the Danish Health Data Authority and Statistics Denmark approved this study.

Results

Of the 2,833,825 Danish residents whose exposure window concurred with the study period, 1,742,321 (61%) met the high exposure assessment quality criterion and were included in the main analyses. Persons who had a diagnosis before initiation of follow-up were excluded (CRC: 228; colon: 165; rectum: 66). The distribution of the average nitrate exposure between age 20 and 35 for this study population is shown in Figure 1a. During the 23 million person-years of follow-up, 5,944 persons were diagnosed with CRC, 3,700 with colon cancer and 2,308 with rectal cancer (Table 1 and Supporting Information, Table 1).

Figure 1 shows the HRs of the nitrate concentration exposure quintiles for (b) CRC, (c) colon and (d) rectal cancer. For both CRC and rectal cancer alone, the two highest exposure quintiles (>3.87 mg/L) showed statistically significant increased HRs. For colon cancer alone, only the highest exposure quintile (≥9.25 mg/L) was associated with a statistically significant increased HR. In the following, we focus on the trend estimate.

Individuals exposed to the highest level of drinking water nitrate (≥16.75 mg/L) had an increased risk of CRC [HR: 1.16 (95% CI: 1.08–1.25)] compared with individuals exposed to the lowest exposure level (<0.69 mg/L; see Table 1, base adjustment). Additional adjustment for education had only limited influence. Similar results were obtained when considering colon and rectal cancer as separate outcomes. Effect modification by sex was not observed (CRC: $p = 0.49$; colon: $p = 0.44$; rectum: $p = 0.99$; second adjustment). Stepwise reincluding individuals with a lower exposure assessment quality increased the study population to ultimately 2,692,508 individuals, followed for ∼44 million person-years (Table 2). As exposure assessment quality decreased, the observed effect sizes decreased as well.

Additional sensitivity analyses yielded robust results (Table 3). The proportional hazards assumption was not violated in any of the presented models. A previous cancer diagnosis other than the outcome of interest was associated with increased HRs for all outcomes, and a protective effect of increasing levels of education was observed (results not shown).

Discussion

This is the first nationwide population-based study using a historical longitudinal assessment of long-term drinking water nitrate exposure to assess the associated risk of CRC. Our results showed the higher the level of nitrate in drinking water, the higher the risk of CRC. Considering colon and rectal cancer as separate outcomes, we found similar results. Results for CRC combined and rectal cancer alone showed statistically significant increased HRs in the two highest quintiles of exposure (>3.87 mg/L). For colon cancer, this was only seen in the highest quintile (≥9.25 mg/L), still at concentrations substantially below the current drinking water standard of 50 mg/L. This suggests a need of lowering the drinking water standard to adequately protect the public against chronic adverse health effects of nitrate in drinking water.

From Figure 1, a dose–response relationship is suggested, which is supported by the results for the trend estimate of 1.14 (95% CI: 1.06–1.23) for CRC, 1.14 (1.04–1.26) for colon cancer alone and 1.13 (1.00–1.27) for rectal cancer alone in the full adjustment. Hazard ratios were similar in all adjustments, indicating little influence of the included covariates and sensitivity analyses showed stable and robust results. Interestingly, the higher the exposure assessment quality, the higher effect sizes were observed (Table 2). Lower exposure assessment quality levels were due to interpolation of nitrate concentrations for years with no sample taken at the respective waterworks. Consequently, effect sizes were expected to attenuate with increasing levels of misclassification.[21]

Our results showed a statistically significant positive association between nitrate in drinking water and CRC at levels well below the current drinking water standard, which is in agreement with the findings of a recent case–control study.[15] Espejo-Herrera *et al.* found an increased risk for colon cancer from 5 mg/d waterborne nitrate intake (corresponding to drinking water concentrations of ∼4.3 mg/L), and for CRC and rectal cancer from ∼8.6 mg/L. Espejo-Herrera *et al.* had individual-level data on endogenous nitrosation factors, diet, lifestyle and water consumption, allowing controlling for established CRC risk factors and additional covariates. They observed higher effect sizes in groups with high red meat intake, in agreement with a previous study.[12]

Table 2. Stepwise reinclusion of individuals with at least 75% of their exposure window at given, or higher, exposure assessment quality level. Trend estimate: hazard ratios (95% CIs), study population size (*N*) and number of cases for colon and rectal cancer. Second adjustment (age, sex, year of birth, previous cancer diagnosis and highest attained education)

Exposure assessment quality	Explanation	*N*[1]	Colon	Rectum
High (main analyses)	At least one nitrate sample taken within 1 year at waterworks supplying the residence[2]	1,742,156	1.14 (1.04–1.26)	1.13 (1.00–1.27)
		Cases	3,700	2,308
Medium high	At least one nitrate sample taken within 5 years at waterworks supplying the residence[2]	2,139,124	1.11 (1.03–1.19)	1.10 (1.01–1.21)
		Cases	6,025	3,764
Medium	At least one nitrate sample taken within 10 years at waterworks supplying the residence[2]	2,299,309	1.08 (1.01–1.16)	1.10 (1.01–1.19)
		Cases	6,966	4,384
Medium low	At least one nitrate sample taken outside time window of 10 years at waterworks supplying the residence[2]	2,615,138	1.09 (1.02–1.16)	1.08 (0.99–1.16)
		Cases	8,652	5,495
Low	No nitrate sample taken at waterworks supplying the residence[2]	2,692,508	1.09 (1.03–1.15)	1.07 (0.99–1.15)
		Cases	8,844	5,618

[1]Study population *N* for colon cancer analyses.
[2]Residence: longitudinal data refers to exposure assessment quality of each individual's residence at any point in time during the exposure window.

Table 3. Sensitivity analyses: hazard ratios (95% CIs) of trend estimate and study size *N*. Full adjustment: age, sex, year of birth, previous cancer diagnosis and education

Scenario	*N*[1]	Colon	Rectum
Main analysis (Table 1)	1,742,156	1.14 (1.04–1.26)	1.13 (1.00–1.27)
Excluding private well users	1,684,944	1.14 (1.04–1.25)	1.13 (1.00–1.27)
At least 5 years of exposure data	1,562,072	1.15 (1.01–1.31)	1.07 (0.90–1.26)
At least 10 years of exposure data	1,351,232	1.18 (0.98–1.41)	1.06 (0.84–1.33)
Only individuals with colon/rectum cancer as first cancer diagnosis	1,681,694	1.13 (1.02–1.25)	1.11 (0.98–1.26)
New exposure window: age 30–40	1,798,350	1.13 (1.05–1.21)	1.07 (0.98–1.18)
Excluding capital region	1,195,094	1.18 (1.06–1.31)	1.09 (0.95–1.25)

[1]Study population *N* for colon cancer analyses.

While we could not include individual-level data on diet and lifestyle, the strength of our study lies in its large population size and the comprehensive long-term exposure assessment. By including the entire population (up to 2.7 million persons followed for up to 34 years), we avoided selection bias. Register data used in this study are deemed to be of very high validity and completeness.[17,19] All administrative, health and drinking water quality data were prospectively collected, thereby eliminating bias due to differential recall and loss to follow-up.

In contrast to previous studies, our exposure assessment was based on exhaustive longitudinal drinking water quality data, registered in one nationwide database. We did not need to model historical nitrate concentrations at the waterworks, but could rely on the actual measurements of nitrate concentrations in drinking water samples taken and analyzed by certified laboratories.[22] We used the physical drinking water supply areas to assign nitrate concentrations to each household and knew the precise residential history of all study participants. Here, our exposure assessment is superior to earlier studies that needed to model historical exposure both spatially and temporally, or estimated exposure by nitrate concentrations at a given location at a single point in time.

Estimating waterborne nitrate intake from residential tap water is reasonable in the Danish context; the annual bottled water consumption is the lowest in Europe with 26 L per person.[23] Furthermore, it has been shown that nitrate levels do not change within a given distribution system and that seasonal variations in drinking water nitrate levels at public supplies are negligible in Denmark.[24] Groundwater abstracted

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for drinking water production has a typical age (time since recharge) of 10–60 years.[24] We do not have adequate data to assess seasonal variability in private wells. However, seasonal variability in shallow wells has been observed in other locations.[25] Private wells are often shallower than public supply wells; therefore, we cannot exclude seasonal variability in private wells. Since Danish waterworks abstain from using chemical disinfection, confounding by disinfection by-products was not a concern in this study.[26] Water samples used in this study were taken after all treatment steps at the waterworks. The use of in-home water treatment installations to reduce nitrate concentrations is uncommon in Denmark and authorities have been restrictive in giving permission to use such installations at private wells.[27]

The possibility of including information on private wells is another strength of our work. It was earlier shown that the drinking water sampling frequency for private wells is much lower compared to public supplies.[5,18] Therefore, residing a long time at a privately supplied household decreased an individual's exposure assessment quality level. The stepwise inclusion of lower exposure assessment quality levels into the model was therefore crucial to include those who lived many years with private well supply. Even though we could only retrieve nitrate concentrations of approximately half of the 55,752 private wells that we identified,[18] we knew the location of the remaining wells and could therefore exclude their users in our sensitivity analyses.

Given our study design, we were limited to include only covariates available in nationwide registers. We could for example not control for individual-level information on lifestyle and diet. A study on the dietary intake of nitrate in the Danish population estimated an average nitrate intake of 61 mg/d for adults.[28] Therefore, at elevated levels as seen in parts of the Danish population (Figure 1a), drinking water will be a major source of nitrate exposure. As diet (e.g., red meat), alcohol intake, smoking and lifestyle factors such as physical inactivity are established CRC risk factors that we could not include in our analyses, the possibility of confounding our results needs to be considered. To address this issue, we adjusted our analyses for highest attained education, an especially appropriate proxy for lifestyle, smoking and diet in the Danish population.[29] Furthermore, studies suggest that dietary nitrate intake is not associated with CRC, or even has a protective effect, because of antioxidants and nitrosation inhibitors in nitrate-containing foods.[6] Nevertheless, any observational study of human health, including the present, cannot exclude the possibility of residual confounding by unobserved factors.

Another limitation is the omission of drinking water nitrite levels in our models. Nitrite is an intermediate in the endogenous transformation of nitrate into genotoxic *N*-nitroso compounds. Nitrite occurs in groundwater in the anoxic nitrate reducing zone but can also be formed at the waterworks due to oxidation of ammonium. Drinking water samples are historically not measured for nitrite to the same extent as nitrate. The restrictive drinking water standard of 0.01 mg/L nitrite is complied with at the large waterworks[30]; however, little is known for smaller waterworks and private wells. An earlier study showed that even though nitrite is taken up through drinking water and food, up to 77% of the total exposure to nitrite is due to the reduction of nitrate *in vivo*.[31] Furthermore, nitrate in drinking water could also be a proxy for additional agricultural pollutants, such as pesticides, which we did not consider here.

We used the average nitrate concentration an individual was exposed to between their 20th and 35th birthdays as the exposure estimate. We assumed that this exposure period was representative of the relevant relationship between exposure and outcome. As geocoded residences were available from 1978 onward, our main analyses included the early cases of CRC only, with an age at diagnosis below 69, before incidence rates peak. Shifting the exposure window to age 30–40, we could include more cases (until age 74), however, at the expense of moving the exposure closer to the time of disease onset. We observed a high agreement between the estimated nitrate exposures in the two competing exposure models. Changing the exposure window to age 30–40 did not substantially change the associated HRs.

In conclusion, our study adds to the growing body of evidence that suggests an increased risk of CRC at nitrate levels in drinking water below the current drinking water standard. Several studies carried out in different locations with different designs and each of their strengths and limitations imply this association. While our study contributed with a large study population, the resulting statistical power, and a detailed exposure assessment, other studies' strengths lay in the inclusion of a number of additional covariates. Considering all evidence, not only in the light of the precautionary principle, a discussion about a reduction of the drinking water standard is warranted.

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References

1. WHO. *Nitrate and nitrite in drinking-water: background document for development of WHO guidelines for drinking-water quality*. Geneva: World Health Organization, 2011.
2. Galloway JN, Aber JD, Erisman JW, et al. The nitrogen cascade. *Bioscience* 2010; 53:341–56.
3. Ward MH. Too much of a good thing? Nitrate from nitrogen fertilizers and cancer: president's cancer panel - October 21, 2008. *Rev Environ Health* 2009; 24:357–63.
4. Hansen B, Thorling L, Dalgaard T, et al. Trend reversal of nitrate in Danish groundwater - a

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10970215, 2018, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/ijc.31306, Wiley Online Library on [05/07/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

reflection of agricultural practices and nitrogen surpluses since 1950. *Environ Sci Technol* 2011; 45:228–34.
5. Schullehner J, Hansen B. Nitrate exposure from drinking water in Denmark over the last 35 years. *Environ Res Lett* 2014; 9:095001.
6. Ward MH, deKok TM, Levallois P, et al. Workgroup report: drinking-water nitrate and health—recent findings and research needs. *Environ Health Perspect* 2005; 113:1607–14.
7. Tricker AR, Preussmann R. Carcinogenic N-nitrosamines in the diet: occurrence, formation, mechanisms and carcinogenic potential. *Mutat Res* 1991; 259:277–89.
8. IARC. *IARC monographs on the evaluation of carcinogenic risks to humans. Volume 94 - ingested nitrate and nitrite, and cyanobacterial peptide toxins*. Lyon: World Health Organization, International Agency for Research on Cancer, 2010.
9. Steward BW, Wild C. *World cancer report 2014*. Lyon: World Health Organization, International Agency for Research on Cancer, 2014.
10. Engholm G, Ferlay J, Christensen N, et al. NORDCAN: cancer incidence, mortality, prevalence and survival in the Nordic countries, version 7.3 (08.07.2016). Assoc. Nord. Cancer Regist. Danish Cancer Soc. 2017. Available from http://www.ancr.nu
11. Gulis G, Czompolyova M, Cerhan JR. An ecologic study of nitrate in municipal drinking water and cancer incidence in Trnava District, Slovakia. *Environ Res* 2002; 88:182–7.
12. De Roos AJ, Ward MH, Lynch CF, et al. Nitrate in public water supplies and the risk of colon and rectum cancers. *Epidemiology* 2003; 14:640–9.
13. Weyer PJ, Cerhan JR, Kross BC, et al. Municipal drinking water nitrate level and cancer risk in older women: the Iowa Women's Health Study. *Epidemiology* 2001; 12:327–38.
14. McElroy JA, Trentham-Dietz A, Gangnon RE, et al. Nitrogen-nitrate exposure from drinking water and colorectal cancer risk for rural women in Wisconsin, USA. *J Water Health* 2008; 6:399–409.
15. Espejo-Herrera N, Gràcia-Lavedan E, Boldo E, et al. Colorectal cancer risk and nitrate exposure through drinking water and diet. *Int J Cancer* 2016; 139:334–46.
16. Villanueva CM, Kogevinas M, Cordier S, et al. Assessing exposure and health consequences of chemicals in drinking water: current state of knowledge and research needs. *Environ Health Perspect* 2013; 122:213–21.
17. Pedersen CB. The Danish civil registration system. *Scand J Public Health* 2011; 39: 22–5.
18. Schullehner J, Jensen NL, Thygesen M, et al. Drinking water nitrate estimation at household-level in Danish population-based long-term epidemiologic studies. *J Geochemical Explor* 2017; 183:178–86.
19. Gjerstorff ML. The Danish cancer registry. *Scand J Public Health*. 39: 42–5.
20. Jensen VM, Rasmussen AW. Danish education registers. *Scand J Public Health* 2011; 39: 91–4.
21. Greenland S, Rothman KJ. *Modern epidemiology*. Philadelphia, PA: Lippincott-Raven, 1998.
22. Hansen M, Pjetursson B. Free, online Danish shallow geological data. *Geol Surv Denmark Greenl Bull* 2011; 23:53–6.
23. Rygaard M, Arvin E, Binning PJ. The valuation of water quality: effects of mixing different drinking water qualities. *Water Res* 2009; 43:1207–18.
24. Schullehner J, Stayner L, Hansen B. Nitrate, nitrite, and ammonium variability in drinking water distribution systems. *Int J Environ Res Public Health* 2017; 14:276.
25. Montgomery E, Coyne MS, Thomas GW. Denitrification can cause variable NO-3 concentrations in shallow groundwater. *Soil Sci* 1997; 162:148–56.
26. Rahman MB, Driscoll T, Cowie C, et al. Disinfection by-products in drinking water and colorectal cancer: a meta-analysis. *Int J Epidemiol* 2010; 39: 733–45.
27. Villumsen B, Christensen JJ, Jacobsen A. *Erfaringer Med Rensning Af Drikkevandet i Små Vandforsyningsanlæg (Experience with treatment of drinking water in small water supplies, in Danish)*. Copenhagen: Ministry of the Environment, 2006.
28. Petersen A, Stoltze S. Nitrate and nitrite in vegetables on the Danish market: content and intake. *Food Addit Contam* 1999; 16:291–9.
29. Pedersen AN, Christensen T, Matthiessen J, et al. *Dietary habits in Denmark 2011–2013. Main results*. Søborg: DTU National Food Institute, 2015.
30. Danish Nature Agency. *Kvaliteten Af Det Danske Drikkevand for Perioden 2011–2013 (Quality of the Danish drinking water for the period 2011–2013, in Danish)*. Copenhagen: Ministry of the Environment, 2014.
31. White JW. Relative significance of dietary sources of nitrate and nitrite. Correction. *J Agric Food Chem* 1976; 24:202.

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Review

Drinking Water Nitrate and Human Health: An Updated Review

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Abstract: Nitrate levels in our water resources have increased in many areas of the world largely due to applications of inorganic fertilizer and animal manure in agricultural areas. The regulatory limit for nitrate in public drinking water supplies was set to protect against infant methemoglobinemia, but other health effects were not considered. Risk of specific cancers and birth defects may be increased when nitrate is ingested under conditions that increase formation of *N*-nitroso compounds. We previously reviewed epidemiologic studies before 2005 of nitrate intake from drinking water and cancer, adverse reproductive outcomes and other health effects. Since that review, more than 30 epidemiologic studies have evaluated drinking water nitrate and these outcomes. The most common endpoints studied were colorectal cancer, bladder, and breast cancer (three studies each), and thyroid disease (four studies). Considering all studies, the strongest evidence for a relationship between drinking water nitrate ingestion and adverse health outcomes (besides methemoglobinemia) is for colorectal cancer, thyroid disease, and neural tube defects. Many studies observed increased risk with ingestion of water nitrate levels that were below regulatory limits. Future studies of these and other health outcomes should include improved exposure assessment and accurate characterization of individual factors that affect endogenous nitrosation.

Keywords: drinking water; nitrate; cancer; adverse reproductive outcomes; methemoglobinemia; thyroid disease; endogenous nitrosation; *N*-nitroso compounds

1. Introduction

Since the mid-1920s, humans have doubled the natural rate at which nitrogen is deposited onto land through the production and application of nitrogen fertilizers (inorganic and manure),

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the combustion of fossil fuels, and replacement of natural vegetation with nitrogen-fixing crops such as soybeans [1,2]. The major anthropogenic source of nitrogen in the environment is nitrogen fertilizer, the application of which increased exponentially after the development of the Haber–Bosch process in the 1920s. Most synthetic fertilizer applications to agricultural land occurred after 1980 [3]. Since approximately half of all applied nitrogen drains from agricultural fields to contaminate surface and groundwater, nitrate concentrations in our water resources have also increased [1].

The maximum contaminant level (MCL) for nitrate in public drinking water supplies in the United States (U.S.) is 10 mg/L as nitrate-nitrogen (NO_3-N). This concentration is approximately equivalent to the World Health Organization (WHO) guideline of 50 mg/L as NO_3 or 11.3 mg/L NO_3-N (multiply NO_3 mg/L by 0.2258). The MCL was set to protect against infant methemoglobinemia; however other health effects including cancer and adverse reproductive outcomes were not considered [4]. Through endogenous nitrosation, nitrate is a precursor in the formation of *N*-nitroso compounds (NOC); most NOC are carcinogens and teratogens. Thus, exposure to NOC formed after ingestion of nitrate from drinking water and dietary sources may result in cancer, birth defects, or other adverse health effects. Nitrate is found in many foods, with the highest levels occurring in some green leafy and root vegetables [5,6]. Average daily intakes from food are in the range of 30–130 mg/day as NO_3 (7–29 mg/day NO_3-N) [5]. Because NOC formation is inhibited by ascorbic acid, polyphenols, and other compounds present at high levels in most vegetables, dietary nitrate intake may not result in substantial endogenous NOC formation [5,7].

Studies of health effects related to nitrate exposure from drinking water were previously reviewed through early 2004 [8]. Further, an International Agency for Research on Cancer (IARC) Working Group reviewed human, animal, and mechanistic studies of cancer through mid-2006 and concluded that ingested nitrate and nitrite, under conditions that result in endogenous nitrosation, are probably carcinogenic [5]. Here, our objective is to provide updated information on human exposure and to review mechanistic and health effects studies since 2004. We summarize how the additional studies contribute to the overall evidence for health effects and we discuss what future research may be most informative.

2. Drinking Water Nitrate Exposures in the United States and Europe

Approximately 45 million people in the U.S. (about 14% of the population) had self-supplied water at their residence in 2010 [9]. Almost all (98%) were private wells, which are not regulated by the U.S. Environmental Protection Agency (EPA). The rest of the population was served by public water supplies, which use groundwater, surface water, or both. The U.S. Geological Survey's National Water Quality Assessment (USGS-NAWQA) Project [10] sampled principal groundwater aquifers used as U.S. public and private drinking water supplies in 1988–2015. Nitrate levels in groundwater under agricultural land were about three times the national background level of 1 mg/L NO_3-N (Figure 1) [11]. The mixed land use category mostly had nitrate concentrations below background levels reflecting levels in deeper private and public water supply wells. Based on the NAWQA study, it was estimated that 2% of public-supply wells and 6% of private wells exceeded the MCL; whereas, in agricultural areas, 21% of private wells exceeded the MCL [10]. The USGS-NAWQA study also revealed significant decadal-scale changes in groundwater nitrate concentrations among wells sampled first in 1988–2000 and again in 2001–2010 for agricultural, urban, and mixed land uses [12]. More sampling networks had increases in median nitrate concentration than had decreases.

A study of U.S. public water supplies (PWS) using data from EPA's Safe Drinking Water Information System estimated that the percentage of PWS violating the MCL increased from 0.28 to 0.42% during 1994–2009; most increases were for small to medium PWS (<10,000 population served) using groundwater [13]. As a result of increasing nitrate levels, some PWS have incurred expensive upgrades to their treatment systems to comply with the regulatory level [14–16].

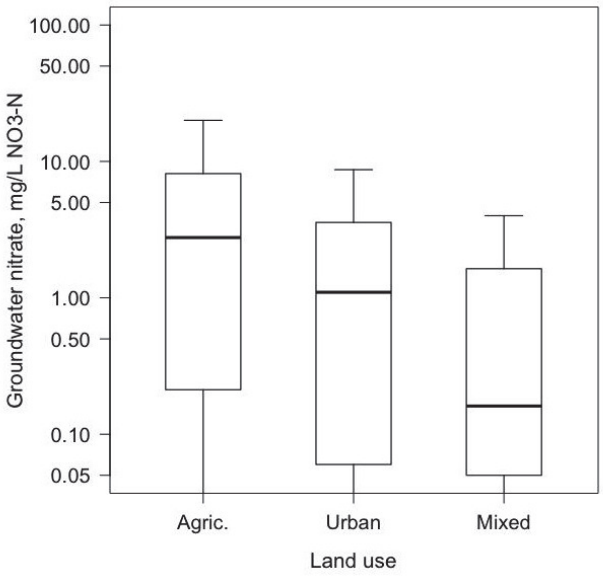

Figure 1. Boxplots of nitrate concentrations in shallow groundwater beneath agricultural and urban land uses, and at depths of private and public drinking water supplies beneath mixed land use. The number of sampled wells were 1573 (agricultural land), 1054 (urban), and 3417 (mixed). The agricultural and urban wells were sampled to assess land use effects, whereas the mixed category wells were sampled at depths of private and public supplies. Median depths of wells in the agricultural, urban, and mixed categories were 34, 32, and 200 feet, respectively. The height of the upper bar is 1.5 times the length of the box, and the lower bound was truncated at the nitrate detection limit of 0.05 mg/L NO_3-N.

In Europe, the Nitrates Directive was set in 1991 [17,18] to reduce or prevent nitrate pollution from agriculture. Areas most affected by nitrate pollution are designated as 'nitrate vulnerable zones' and are subject to mandatory Codes of Good Agricultural Practice [18]. The results of compliance with this directive have been reflected in the time trends of nitrate in some countries. For example, nitrate levels in groundwater in Denmark increased in 1950–1980 and decreased since the 1990s [19]. Average nitrate levels in groundwater in most other European countries have been stable at around 17.5 mg/L NO_3 (4 mg/L NO_3-N) across Europe over a 20-year period (1992–2012), with some differences between countries both in trends and concentrations. Average concentrations are lowest in Finland (around 1 mg/L NO_3 in 1992–2012) and highest in Malta (58.1 mg/L in 2000–2012) [20]. Average annual nitrate concentrations at river monitoring stations in Europe showed a steady decline from 2.7 NO_3-N in 1992 to 2.1 mg/L in 2012 [20], with the lowest average levels in Norway (0.2 mg/L NO_3-N in 2012) and highest in Greece (6.6 mg/L NO_3-N in 2012).

Levels in finished public drinking water have been published only for a few European countries. Trends of nitrate in drinking water supplies from 1976 to 2012 in Denmark showed a decline in public supplies but not in private wells [21]. In Spain, median concentrations were 3.5 mg/L NO_3 (range: 0.4−66.8) in 108 municipalities in 2012 [22], and 4.2 mg/L (range: <1−29) in 11 provinces in 2010 [23]. Levels in other countries included a median of 0.18 mg/L (range: <0.02−7.9) in Iceland in 2001−2012 [24], a mean of 16.1 mg/L (range: 0.05−296 mg/L) in Sicily, Italy in 2004−2005 [25] and a range from undetected to 63.3 mg/L in Deux-Sèvres, France in in 2005−2009 [26].

Nitrate levels in bottled water have been measured in a few areas of the EU and the U.S. and have been found to be below the MCL. In Sicily, the mean level was 15.2 mg/L NO_3(range: 1.2−31.8 mg/L) in 16 brands [25] and in Spain, the median level was 5.2 mg/L NO_3 (range: <1.0−29.0 mg/L) in 9 brands [23]. In the U.S., a survey of bottle water sold in 42 Iowa and 32 Texas communities found

varying but generally low nitrate levels. Nitrate concentrations ranged from below the limit of detection (0.1 mg/L NO_3-N) to 4.9 mg/L NO_3-N for U.S. domestic spring water purchased in Texas.

There are few published studies of nitrate concentrations in drinking water outside the U.S. and Europe. Nitrate concentrations in groundwater were reported for Morocco, Niger, Nigeria, Senegal, India-Pakistan, Japan, Lebanon, Philippines and Turkey with maximum levels in Senegal (median 42.9 mg/L NO_3-N) [5]. In India, nitrate in drinking water supplies is particularly high in rural areas, where average levels have been reported to be 45.7 mg/L NO_3 [27,28] and 66.6 mg/L NO_3 [28]; maximum levels in drinking water exceeded 100 mg/L NO_3 in several regions [27,29]. Extremely high levels of nitrate have been reported in The Gaza Strip, where nitrate reached concentrations of 500 mg/L NO_3 in some areas, and more than 50% of public-supply wells had nitrate concentrations above 45 mg/L NO_3 [30].

3. Exposure Assessment in Epidemiologic Studies

With the implementation of the Safe Drinking Water Act in 1974, more than 40 years of monitoring data for public water supplies in the U.S. provide a framework of measurements to support exposure assessments. Historical data for Europe are more limited, but a quadrennial nitrate reporting requirement was implemented as part of the EU Nitrates Directive [17,18]. In the U.S., the frequency of sampling for nitrate in community water systems is stipulated by their sources (ground versus surface waters) and whether concentrations are below the MCL, and historically, by the size of the population served and vulnerability to nitrate contamination. Therefore, the exposure assessment for study participants who report using a public drinking water source may be based on a variable number of measurements, raising concerns about exposure misclassification. In a study of bladder cancer risk in Iowa, associations were stronger in sensitivity analyses based on more comprehensive measurement data [31]. Other studies have restricted analyses to subgroups with more complete or recent measurements [32–35], with implications for study power and possible selection biases. Sampling frequency also limits the extent to which temporal variation in exposure can be represented within a study population, such as the monthly or trimester-based estimates of exposure most relevant for etiologic investigations of adverse reproductive outcomes. In Denmark, limited seasonal variation in nitrate monitoring data suggested these data would sufficiently capture temporal variation for long-term exposure estimates [36]. Studies have often combined regulatory measurements with questionnaire and ancillary data to better characterize individual variation in nitrate exposure, such as to capture changes in water supply characteristics over time or a participant's duration at a drinking water source [31,33,37,38]. Most case-control studies of drinking water nitrate and cancer obtained lifetime residence and drinking water source histories, whereas cohort studies typically have collected only the current water source. Many studies lacked information about study participants' water consumption, which may be an important determinant of exposure to drinking water contaminants [39].

Due to sparse measurement data, exposures for individuals served by private wells are more difficult to estimate than exposures for those on public water supplies. However, advances in geographic-based modeling efforts that incorporate available measurements, nitrogen inputs, aquifer characteristics, and other data hold promise for this purpose. These models include predictor variables describing land use, nitrogen inputs (fertilizer applications, animal feeding operations), soils, geology, climate, management practices, and other factors at the scale of interest. Nolan and Hitt [40] and Messier et al. [41] used nonlinear regression models with terms representing nitrogen inputs at the land surface, transport in soils and groundwater, and nitrate removal by processes such as denitrification, to predict groundwater nitrate concentration at the national scale and for North Carolina, respectively. Predictor variables in the models included N fertilizer and manure, agricultural or forested land use, soils, and, in Nolan and Hitt [40], water-use practices and major geology. Nolan and Hitt [40] reported a training R^2 values of 0.77 for a model of groundwater used mainly for private supplies and Messier, Kane, Bolich and Serre [41] reported a cross-validation testing R^2 value of 0.33 for a point-level

private well model. These and earlier regression approaches for groundwater nitrate [42–46] relied on predictor variables describing surficial soils and activities at the land surface, because conditions at depth in the aquifer typically are unknown. Redox conditions in the aquifer and the time since water entered the subsurface (i.e., groundwater age) are two of the most important factors affecting groundwater nitrate, but redox constituents typically are not analyzed, and age is difficult to measure. Even if a well has sufficient data to estimate these conditions, the data must be available for all wells in order to predict water quality in unsampled areas. In most of the above studies, well depth was used as a proxy for age and redox and set to average private or public-supply well depth for prediction.

Recent advances in groundwater nitrate exposure modeling have involved machine-learning methods such as random forest (RF) and boosted regression trees (BRT), along with improved characterization of aquifer conditions at the depth of the well screen (the perforated portion of the well where groundwater intake occurs). Tree-based models do not require data transformation, can fit nonlinear relations, and automatically incorporate interactions among predictors [47]. Wheeler et al. [48] used RF to estimate private well nitrate levels in Iowa. In addition to land use and soil variables, predictor variables included aquifer characteristics at the depth of the well screen, such as total thickness of fine-grained glacial deposits above the well screen, average and minimum thicknesses of glacial deposits near sampled wells, and horizontal and vertical hydraulic conductivities near the wells. Well depth, landscape features, nitrogen sources, and aquifer characteristics ranked highly in the final model, which explained 77% and 38% of the variation in training and hold-out nitrate data, respectively.

Ransom et al. [49] used BRT to predict nitrate concentration at the depths of private and public-supply wells for the Central Valley, California. The model used as input estimates of groundwater age at the depth of the well screen (from MODFLOW/MODPATH models) and depth-related reducing conditions in the groundwater. These estimates were generated by separate models and were available throughout the aquifer. Other MODFLOW-based predictor variables comprised depth to groundwater, and vertical water fluxes and the percent coarse material in the uppermost part of the aquifer where groundwater flow was simulated by MODFLOW. Redox variables were top-ranked in the final BRT model, which also included land use-based N leaching flux, precipitation, soil characteristics, and the MODFLOW-based variables described above. The final model retained 25 of an initial 145 predictor variables considered, had training and hold-out R^2 values of 0.83 and 0.44 respectively, and was used to produce a 3D visualization of nitrate in the aquifer. These studies show that modeling advances and improved characterization of aquifer conditions at depth are increasing our ability to predict nitrate exposure from drinking water supplied by private wells.

4. Nitrate Intake and Endogenous Formation of *N*-Nitroso Compounds

Drinking water nitrate is readily absorbed in the upper gastrointestinal tract and distributed in the human body. When it reaches the salivary glands, it is actively transported from blood into saliva and levels may be up to 20 times higher than in the plasma [50–53]. In the oral cavity 6–7% of the total nitrate can be reduced to nitrite, predominantly by nitrate-reducing bacteria [52,54,55]. The secreted nitrate as well as the nitrite generated in the oral cavity re-enter the gastrointestinal tract when swallowed.

Under acidic conditions in the stomach, nitrite can be protonated to nitrous acid (HNO_2), and subsequently yield dinitrogen trioxide (N_2O_3), nitric oxide (NO), and nitrogen dioxide (NO_2). Since the discovery of endogenous NO formation, it has become clear that NO is involved in a wide range of NO-mediated physiological effects. These comprise the regulation of blood pressure and blood flow by mediating vasodilation [56–58], the maintenance of blood vessel tonus [59], the inhibition of platelet adhesion and aggregation [60,61], modulation of mitochondrial function [62] and several other processes [63–66].

On the other hand, various nitrate and nitrite derived metabolites such as nitrous acid (HNO_2) are powerful nitrosating agents and known to drive the formation of NOC, which are

suggested to be the causal agents in many of the nitrate-associated adverse health outcomes. NOC comprise *N*-nitrosamines and *N*-nitrosamides, and may be formed when nitrosating agents encounter *N*-nitrosatable amino acids, which are also from dietary origin. The nitrosation process depends on the reaction mechanisms involved, on the concentration of the compounds involved, the pH of the reaction environment, and further modifying factors, including the presence of catalysts or inhibitors of *N*-nitrosation [66–69].

Endogenous nitrosation can also be inhibited, for instance by dietary compounds like vitamin C, which has the capacity to reduce HNO_2 to NO; and alpha-tocopherol or polyphenols, which can reduce nitrite to NO [54,70–72]. Inhibitory effects on nitrosation have also been described for dietary flavonoids such as quercetin, ferulic and caffeic acid, betel nut extracts, garlic, coffee, and green tea polyphenols [73,74]. Earlier studies showed that the intake of 250 mg or 1 g ascorbic acid per day substantially inhibited *N*-nitrosodimethylamine (NDMA) excretion in 25 women consuming a fish meal rich in amines (nitrosatable precursors) for seven days, in combination with drinking water containing nitrate at the acceptable daily intake (ADI) [75]. In addition, strawberries, garlic juice, and kale juice were shown to inhibit NDMA excretion in humans [76]. The effect of these fruits and vegetables is unlikely to be due solely to ascorbic acid. Using the *N*-nitrosoproline (NPRO) test, Helser et al. [77] found that ascorbic acid only inhibited nitrosamine formation by 24% compared with 41–63% following ingestion of juices (100 mL) made of green pepper, pineapple, strawberry or carrot containing an equal total amount of ascorbic acid.

The protective potential of such dietary inhibitors depends not only on the reaction rates of *N*-nitrosatable precursors and nitrosation inhibitors, but also on their biokinetics, since an effective inhibitor needs to follow gastrointestinal circulation kinetics similar to nitrate [78]. It has been argued that consumption of some vegetables with high nitrate content, can at least partially inhibit the formation of NOC [79–81]. This might apply for green leafy vegetables such as spinach and rocket salad, celery or kale [77] as well as other vegetables rich in both nitrate and natural nitrosation inhibitors. Preliminary data show that daily consumption of one bottle of beetroot juice containing 400 mg nitrate (the minimal amount advised for athletes to increase their sports performances) for one day and seven days by 29 young individuals results in an increased urinary excretion of apparent total nitroso compounds (ATNC), an effect that can only be partially inhibited by vitamin C supplements (1 g per day) [82].

Also, the amount of nitrosatable precursors is a key factor in the formation of NOC. Dietary intakes of red and processed meat are of particular importance [83–87] as increased consumption of red meat (600 vs. 60 g/day), but not white meat, was found to cause a three-fold increase in fecal NOC levels [85]. It was demonstrated that heme iron stimulated endogenous nitrosation [84], thereby providing a possible explanation for the differences in colon cancer risk between red and white meat consumption [88]. The link between meat consumption and colon cancer risk is even stronger for nitrite-preserved processed meat than for fresh meat leading an IARC review to conclude that processed meat is carcinogenic to humans [89].

In a human feeding study [90], the replacement of nitrite in processed meat products by natural antioxidants and the impact of drinking water nitrate ingestion is being evaluated in relation to fecal excretion of NOC, accounting for intakes of meat and dietary vitamin C. A pilot study demonstrated that fecal excretion of ATNC increased after participants switched from ingesting drinking water with low nitrate levels to drinking water with nitrate levels at the acceptable daily intake level of 3.7 mg/kg. The 20 volunteers were assigned to a group consuming either 3.75 g/kg body weight (maximum 300 g per day) red processed meat or fresh (unprocessed) white meat. Comparison of the two dietary groups showed that the most pronounced effect of drinking water nitrate was observed in the red processed meat group. No inhibitory effect of vitamin C intake on ATNC levels in feces was found (unpublished results).

5. Methemoglobinemia

The physiologic processes that can lead to methemoglobinemia in infants under six months of age have been described in detail previously [8,91]. Ingested nitrate is reduced to nitrite by bacteria in the mouth and in the infant stomach, which is less acidic than adults. Nitrite binds to hemoglobin to form methemoglobin, which interferes with the oxygen carrying capacity of the blood. Methemoglobinemia is a life-threatening condition that occurs when methemoglobin levels exceed about 10% [8,91]. Risk factors for infant methemoglobinemia include formula made with water containing high nitrate levels, foods and medications that have high nitrate levels [91,92], and enteric infections [93]. Methemoglobinemia related to high nitrate levels in drinking water used to make infant formula was first reported in 1945 [94]. The U.S. EPA limit of 10 mg/L NO_3-N was set as about one-half the level at which there were no observed cases [95]. The most recent U.S. cases related to nitrate in drinking water were reported by Knobeloch and colleagues in the late 1990s in Wisconsin [96] and were not described in our prior review. Nitrate concentrations in the private wells were about two-times the MCL and bacterial contamination was not a factor. They also summarize another U.S. case in 1999 related to nitrate contamination of a private well and six infant deaths attributed to methemoglobinemia in the U.S. between 1979–1999 only one of which was reported in the literature [96,97]. High incidence of infant methemoglobinemia in eastern Europe has also been described previously [98,99]. A 2002 WHO report on water and health [100] noted that there were 41 cases in Hungary annually, 2913 cases in Romania from 1985–1996 and 46 cases in Albania in 1996.

Results of several epidemiologic studies conducted before 2005 that examined the relationship between nitrate in drinking water and levels of methemoglobin or methemoglobinemia in infants have been described previously [8]. Briefly, nitrate levels >10 mg/L NO_3-N were usually associated with increased methemoglobin levels but clinical methemoglobinemia was not always present. Since our last review, a cross-sectional study conducted in Gaza found elevated methemoglobin levels in infants on supplemental feeding with formula made from well water in an area with the highest mean nitrate concentration of 195 mg/L NO_3 (range: 18–440) compared to an area with lower nitrate concentration (mean: 119 mg/L NO_3; range 18–244) [101]. A cross-sectional study in Morocco found a 22% increased risk of methemoglobinemia in infants in an area with drinking water nitrate >50 mg/L (>11 as NO_3-N) compared to infants in an area with nitrate levels <50 mg/L nitrate [102]. A retrospective cohort study in Iowa of persons (aged 1–60 years) consuming private well water with nitrate levels <10 mg/L NO_3-N found a positive relationship between methemoglobin levels in the blood and the amount of nitrate ingestion [103]. Among pregnant women in rural Minnesota with drinking water supplies that were mostly $\leq$3 mg/L NO_3-N, there was no relationship between water nitrate intake and women's methemoglobin levels around 36 weeks' gestation [104].

6. Adverse Pregnancy Outcomes

Maternal drinking water nitrate intake during pregnancy has been investigated as a risk factor for a range of pregnancy outcomes, including spontaneous abortion, fetal deaths, prematurity, intrauterine growth retardation, low birth weight, congenital malformations, and neonatal deaths. The relation between drinking water nitrate and congenital malformations in offspring has been the most extensively studied, most likely because of the availability of birth defect surveillance systems around the world.

Our earlier review focused on studies of drinking water nitrate and adverse pregnancy outcomes published before 2005 [8]. In that review, we cited several studies on the relation between maternal exposure to drinking water nitrate and spontaneous abortion including a cluster investigation that suggested a positive association [105] and a case-control study that found no association [106]. These studies were published over 20 years ago. In the present review, we were unable to identify any recently published studies on this outcome. In Table 1, we describe the findings of studies published since 2004 on the relation between drinking water nitrate and prematurity, low birthweight, and congenital malformations. We report results for nitrate in the units (mg/L NO_3 or NO_3-N) that

were reported in the publications. In a historic cohort study conducted in the Deux-Sèvres district (France), Migeot et al. [26] linked maternal addresses from birth records to community water system measurements of nitrate, atrazine, and other pesticides. Exposure to the second tertile of nitrate (14–27 mg/L NO_3) without detectable atrazine metabolites was associated with small-for-gestational age births (Odds Ratio (OR) 1.74, 95% CI 1.1, 2.8), but without a monotonic increase in risk with exposures. There was no association with nitrate among those with atrazine detected in their drinking water supplies. Within the same cohort, Albouy-Llaty and colleagues did not observe any association between higher water nitrate concentrations (with or without the presence of atrazine) and preterm birth [107].

Stayner and colleagues also investigated the relation between atrazine and nitrate in drinking water and rates of low birth weight and preterm birth in 46 counties in four Midwestern U.S. states that were required by EPA to measure nitrate and atrazine monthly due to prior atrazine MCL violations [108]. The investigators developed county-level population-weighted metrics of average monthly nitrate concentrations in public drinking water supplies. When analyses were restricted to counties with less than 20% private well usage (to reduce misclassification due to unknown nitrate levels), average nitrate concentrations during the pregnancy were associated with increased rates of very low birth weight (<1.5 kg Rate Ratio $(RR)_{per\ 1\ ppm}$ = 1.17, 95% CI 1.08, 1.25) and very preterm births (<32 weeks $RR_{per\ 1\ ppm}$ = 1.08, 95% CI 1.02, 1.15) but not with low birth weight or preterm birth overall.

In record-based prevalence study in Perth Australia, Joyce et al. mapped births to their water distribution zone and noted positive associations between increasing tertiles of nitrate levels and prevalence of term premature rupture of membranes (PROM) adjusted for smoking and socioeconomic status [109]. Nitrate concentrations were low; the upper tertile cut point was 0.350 mg/L and the maximum concentration was 1.80 mg/L NO_3-N. Preterm PROM was not associated with nitrate concentrations.

Among studies of drinking water nitrate and congenital malformations, few before 2005 included birth defects other than central nervous system defects [8]. More recently, Mattix et al. [110] noted higher rates of abdominal wall defects (AWD) in Indiana compared to U.S. rates for specific years during the period 1990–2002. They observed a positive correlation between monthly AWD rates and monthly atrazine concentrations in surface waters but no correlation with nitrate levels. Water quality data were obtained from the USGS-NAWQA project that monitors agricultural chemicals in streams and shallow groundwater that are mostly not used as drinking water sources. A case-control study of gastroschisis (one of the two major types of AWD), in Washington State [111] also used USGS-NAWQA measurements of nitrate and pesticides in surface water and determined the distance between maternal residences (zip code centroids) and the closest monitoring site with concentrations above the MCL for nitrate, nitrite, and atrazine. Gastrochisis was not associated with maternal proximity to surface water above the MCL for nitrate (>10 mg/L NO_3-N) or nitrite (>1 mg/L NO_2-N) but there was a positive relationship with proximity to sites with atrazine concentrations above the MCL. In a USA-wide study, Winchester et al. [112] linked the USGS-NAWQA monthly surface water nitrate and pesticide concentrations computed for the month of the last menstrual period with monthly rates of 22 types of birth defects in 1996–2002. Rates of birth defects among women who were estimated to have conceived during April through July were higher than rates among women conceiving in other months. In multivariable models that included nitrate, atrazine, and other pesticides, atrazine (but not nitrate or other pesticides) was associated with several types of anomalies. Nitrate was associated with birth defects in the category of "other congenital anomalies" (OR 1.18, 95% CI 1.14, 1.21); the authors did not specify what defects were included in this category. None of these three studies included local or regional data to support the assumption that surface water nitrate and pesticide concentrations correlated with drinking water exposures to these contaminants.

Using a more refined exposure assessment than the aforementioned studies, Holtby et al. [113] conducted a case-control study of congenital anomalies in an agricultural county in Nova Scotia,

Canada. They linked maternal addresses at delivery to municipal water supply median nitrate concentrations and used kriging of monthly measurements from a network of 140 private wells to estimate drinking water nitrate concentrations in private wells. They observed no associations between drinking water nitrate and all birth defects combined for conceptions during 1987–1997. However, the prevalence of all birth defects occurring during 1998–2006 was associated with drinking water nitrate concentrations of 1–5.56 mg/L NO_3-N (OR 2.44, 95% CI 1.05, 5.66) and $\geq$5.56 mg/L (OR 2.25, 95% CI 0.92, 5.52).

None of the studies of congenital anomalies accounted for maternal consumption of bottled water or the quantity of water consumed during the first trimester, the most critical period of organ/structural morphogenesis. Attempting to overcome some of these limitations, Brender, Weyer, and colleagues [38,114] conducted a population-based, case-control study in the states of Iowa and Texas where they: (1) linked maternal addresses during the first trimester to public water utilities and respective nitrate measurements; (2) estimated nitrate intake from bottled water based on a survey of products consumed and measurement of nitrate in the major products; (3) predicted drinking water nitrate from private wells through modeling (Texas only); and (4) estimated daily nitrate ingestion from women's drinking water sources and daily consumption of water. The study populations were participants of the U.S. National Birth Defects Prevention Study [115]. Compared to the lowest tertile of nitrate ingestion from drinking water (<0.91 mg/day NO_3), mothers of babies with spina bifida were twice as likely (95% CI 1.3, 3.2) to ingest $\geq$5 mg/day NO_3 from drinking water than control mothers. Mothers of babies with limb deficiencies, cleft palate, and cleft lip were, respectively, 1.8 (95% CI 1.1, 3.1), 1.9 (95% CI 1.2, 3.1), and 1.8 (95% CI 1.1, 3.1) times more likely to ingest $\geq$5.4 mg/day of water NO_3 than controls. Women were also classified by their nitrosatable drug exposure during the first trimester [116] and by their daily nitrate and nitrite intake based on a food frequency questionnaire [117]. Higher ingestion of drinking water nitrate did not strengthen associations between maternal nitrosatable drug exposure and birth defects in offspring [38]. However, a pattern was observed of stronger associations between nitrosatable drug exposure and selected birth defects for women in the upper two tertiles of total nitrite ingestion that included contributions from drinking water nitrate and dietary intakes of nitrate and nitrite compared to women in the lowest tertile. Higher intake of food nitrate/nitrite was found to also modify the associations of nitrosatable drug exposure and birth defects in this study [118,119] as well as in an earlier study of neural tube defects conducted in south Texas [120]. Multiplicative interactions were observed between higher food nitrate/nitrite and nitrosatable drug exposures for conotruncal heart, limb deficiency, and oral cleft defects [118].

In summary, five out of six studies, conducted since the 1980s of drinking water nitrate and central nervous system defects, found positive associations between higher drinking water nitrate exposure during pregnancy and neural tube defects or central nervous system defects combined [38,120–123]. The sixth study, which did not find a relationship, did not include measures of association, but compared average drinking water nitrate concentrations between mothers with and without neural tube defect-affected births, which were comparable [124].

Table 1. Studies of drinking water nitrate [a] and adverse pregnancy outcomes published January 2005–March 2018.

First Author, Year, Country	Study Design Regional Description	Years of Outcome Ascertainment	Exposure Description	Pregnancy Outcome	Summary of Findings
Albouy-Llaty, 2016 France [107]	Historic cohort study Deux-Sèvres	2005–2010	Measurements of atrazine metabolites and NO_3 in community water systems (263 municipalities) were linked to birth addresses	Preterm birth	No association for >26.99 mg/L vs. <14.13 mg/L NO_3 in community water systems with or without atrazine detections, adjusted for neighborhood deprivation
Brender, 2013 Weyer, 2014 USA [38]	Population-based case-control study Iowa and Texas	1997–2005	Maternal addresses during the first trimester linked to public water utility nitrate measurements; nitrate intake from bottled water estimated with survey and laboratory testing; nitrate from private wells predicted through modeling; nitrate ingestion (NO_3) estimated from reported water consumption	Congenital heart defects Limb deficiencies Neural tube defects Oral cleft defects	≥5 vs. <0.91 mg/day NO_3 from drinking water spina bifida OR = 2.0 (95% CI: 1.3, 3.2) ≥5.42 vs. <1.0 mg/day NO_3 from water: limb deficiencies OR = 1.8 (CI: 1.1, 3.1); cleft palate OR = 1.9 (CI: 1.2, 3.1) cleft lip OR = 1.8 (CI: 1.1, 3.1)
Holtby, 2014 Canada [113]	Population-based case-control study Kings County, Nova Scotia	1988–2006	Maternal addresses at delivery linked to municipal water supply median nitrate (NO_3-N) concentrations; nitrate in rural private wells estimated from historic sampling and kriging	Congenital malformations combined into one group	Conceptions in 1987–1997: no association with nitrate concentrations Conceptions in 1998–2006: 1–5.56 mg/L NO_3-N (vs. <1 mg/L) OR = 2.44 (CI: 1.05, 5.66); ≥5.56 mg/L OR = 2.25 (CI: 0.92, 5.52)
Joyce, 2008 Australia [109]	Record-based prevalence study Perth	2002–2004	Linked birth residences to 24 water distribution zones; computed average NO_3-N mg/L from historical measurements; independent sampling conducted for 6 zones as part of exposure validation; also evaluated trihalomethanes (THM)	Premature rupture of membranes at term (PROM) (37 weeks' gestation or later)	ORs for tertiles (vs. <0.125 mg/L NO_3-N): 0.125–0.350 mg/L OR = 1.23 (CI: 1.03, 1.52); >0.350 mg/L OR = 1.47 (CI: 1.20, 1.79) No association with THM levels
Mattix, 2007 USA [110]	Ecologic study Indiana	1990–2002	Monthly abdominal wall defect rates linked to monthly surface water nitrate and atrazine concentrations (USGS-NAWQA monitoring data [b])	Abdominal wall birth defects	No correlation observed between nitrate levels in surface water and monthly abdominal wall defects Positive correlation with atrazine levels

Table 1. *Cont.*

First Author, Year, Country	Study Design Regional Description	Years of Outcome Ascertainment	Exposure Description	Pregnancy Outcome	Summary of Findings
Migeot, 2013 France [26]	Historic cohort study Deux-Sèvres	2005–2009	Measurements of atrazine metabolites and NO_3 in community water systems (263 municipalities) were linked to birth addresses	Small-for-gestational age (SGA) births	ORs for tertiles (vs. <14.13 mg/L NO_3) in community water systems with no atrazine detections: 14–27 mg/L OR = 1.74 (CI: 1.10, 2.75); >27 mg/L OR = OR 1.51 (CI: 0.96, 2.4); no association with nitrate when atrazine was detected
Stayner, 2017 USA [108]	Ecologic study 46 counties in Indiana, Iowa, Missouri, and Ohio	2004–2008	Counties had one or more water utility in EPA's atrazine monitoring program; excluded counties with >20% of population on private wells and >300,000 population. Computed county-specific monthly weighted averages of NO_3-N in finished drinking water; exposure metric was average 9 months prior to birth	Preterm birth Low birth weight	Average nitrate not associated with low birth weight and preterm birth Very low birth weight: RR for 1 ppm increase in NO_3-N = 1.17 (CI: 1.08, 1.25); Very preterm birth RR for 1 ppm increase = 1.08 (CI: 1.02, 1.15)
Waller, 2010 USA [111]	Population-based case-control study Washington State	1987–2006	Calculated distance between maternal residence and closest stream monitoring site with concentrations >MCL for NO_3-N, NO_2-N, or atrazine in surface water (USGS-NAWQA data [b])	Gastroschisis	Gastroschisis was not associated with maternal residential proximity to surface water with elevated nitrate (>10 mg/L) or nitrite (>1 mg/L)
Winchester, 2009 USA [112]	Ecologic study USA-wide	1996–2002	Rates of combined and specific birth defects (computed by month of last menstrual period) linked to monthly surface water nitrate concentrations (USGS-NAWQA data [b]); also evaluated atrazine and other pesticides (combined)	Birth defects categorized into 22 groups	Birth defect category "other congenital anomalies": OR for continuous log nitrate = 1.15 (CI: 1.12, 1.18); adjusted for atrazine and other pesticides: OR = 1.18, CI: 1.14, 1.21); No association with other birth defects

Abbreviations: CI, 95% CI confidence interval; OR, odds ratio; RR, rate ratio; USGS-NAWQA, U. S. Geological Survey National Water Quality Assessment; [a] nitrate units are specified as reported in publications. NO_3 can be converted to NO_3-N by multiplying by 0.2258; [b] USGS-NAWQA data for 186 streams in 51 hydrological study areas; streams were not drinking water sources.

7. Cancer

Most early epidemiologic studies of cancer were ecologic studies of stomach cancer mortality that used exposure estimates concurrent with the time of death. Results were mixed, with some studies showing positive associations, many showing no association, and a few showing inverse associations. The results of ecologic studies through 1995 were reviewed by Cantor [125]. Our previous review included ecologic studies of the brain, esophagus, stomach, kidney, ovary, and non-Hodgkin lymphoma (NHL) published between 1999 and 2003 that were largely null [8]. We did not include ecologic studies or mortality case-control studies in this review due to the limitations of these study designs, especially their inability to assess individual-level exposure and dietary factors that influence the endogenous formation of NOC.

Since our review of drinking water nitrate and health in 2005 [8], eight case-control studies and eight analyses in three cohorts have evaluated historical nitrate levels in PWS in relation to several cancers. Nitrate levels were largely below 10 mg/L NO_3-N. Most of these studies evaluated potential confounders and factors affecting nitrosation. Table 2 shows the study designs and results of studies published from 2005 through 2018, including findings from periodic follow-ups of a cohort study of postmenopausal women in Iowa (USA) [31,37,126–129]. In the first analysis of drinking water nitrate in the Iowa cohort with follow-up through 1998, Weyer and colleagues [130] reported that ovarian and bladder cancers were positively associated with the long-term average PWS nitrate levels prior to enrollment (highest quartile average 1955–1988: >2.46 mg/L NO_3-N). They observed inverse associations for uterine and rectal cancer, but no associations with cancers of the breast, colon, rectum, pancreas, kidney, lung, melanoma, non-Hodgkin lymphoma (NHL), or leukemia. Analyses of PWS nitrate concentrations and cancers of the thyroid, breast, ovary, bladder, and kidney were published after additional follow-up of the cohort. The exposure assessment was improved by: (a) the computation of average nitrate levels and years of exposure at or above 5 mg/L NO_3-N, based on time in residence (vs. one long-term PWS average nitrate estimate used by Weyer and colleagues); and (b) by estimation of total trihalomethanes (TTHM) and dietary nitrite intake.

Thyroid cancer was evaluated for the first time after follow-up of the cohort through 2004. A total of 40 cases were identified [37]. Among women with >10 years on PWS with levels exceeding 5 mg/L NO_3-N for five years or more, thyroid cancer risk was 2.6 times higher than that of women whose supplies never exceeded 5 mg/L. With follow-up through 2010, the risk of ovarian cancer remained increased among women in the highest quartile of average nitrate in PWS [129]. Ovarian cancer risk among private well users was also elevated compared to the lowest PWS nitrate quartile. Associations were stronger when vitamin C intake was below median levels with a significant interaction for users of private wells. Overall, breast cancer risk was not associated with water nitrate levels with follow-up through 2008 [128]. Among women with folate intake $\geq$ 400 µg/day, risk was increased for those in the highest average nitrate quintile (Hazard Ratio (HR) = 1.40; 95% CI: = 1.05–1.87) and among private well users (HR = 1.38; 95% CI: = 1.05–1.82), compared to those with the lowest average nitrate quintile. There was no association with nitrate exposure among women with lower folate intake. With follow-up through 2010, there were 130 bladder cancer cases among women who had used PWS >10 years. Risk remained elevated among women with the highest average nitrate levels and was 1.6 times higher among women whose drinking water concentration exceeded 5 mg/L NO_3-N for at least four years [31]. Risk estimates were not changed by adjustment for TTHM, which are suspected bladder cancer risk factors. Smoking, but not vitamin C intake, modified the association with nitrate in water; increased risk was apparent only in current smokers (p-interaction <0.03). With follow-up through 2010, there were 125 kidney cancer cases among women using PWS; risk was increased among those in the 95th percentile of average nitrate (>5.0 mg/L NO_3-N) compared with the lowest quartile (HR = 2.2, 95% CI: 1.2–4.2) [127]. There was no positive trend with the average nitrate level and no increased risk for women using private wells, compared to those with low average nitrate in their public supply. An investigation of pancreatic cancer in the same population (follow-up through 2011)

found no association with average water nitrate levels in public supplies and no association among women on private wells [126].

In contrast to the positive findings for bladder cancer among the cohort of Iowa women, a cohort study of men and women aged 55–69 in the Netherlands with lower nitrate levels in PWS found no association between water nitrate ingestion (median in top quintile = 2.4 mg/day NO_3-N) and bladder cancer risk [131]. Dietary intake of vitamins C and E and history of cigarette smoking did not modify the association. A hospital-based case-control study of bladder cancer in multiple areas of Spain [33] assessed lifetime water sources and usual intake of tap water. Nitrate levels in PWS were low, with almost all average levels below 2 mg/L NO_3-N. Risk of bladder cancer was not associated with the nitrate level in drinking water or with estimated nitrate ingestion from drinking water, and there was no evidence of interaction with factors affecting endogenous nitrosation.

Several case-control studies conducted in the Midwestern U.S. obtained lifetime histories of drinking water sources and estimated exposure for PWS users. In contrast to findings of an increased risk of NHL associated with nitrate levels in Nebraska PWS in an earlier study [132], there was no association with similar concentrations in public water sources in a case-control study of NHL in Iowa [35]. A study of renal cell carcinoma in Iowa [34] found no association with the level of nitrate in PWS, including the number of years that levels exceeded 5 or 10 mg/L NO_3-N. However, higher nitrate levels in PWS increased risk among subgroups who reported above the median intake of red meat intake or below the median intake of vitamin C (p-interaction <0.05). A small case-control study of adenocarcinoma of the stomach and esophagus among men and women in Nebraska [133] estimated nitrate levels among long-term users of PWS and found no association between average nitrate levels and risk.

A case-control study of colorectal cancer among rural women in Wisconsin estimated nitrate levels in private wells using spatial interpolation of nitrate concentrations from a 1994 water quality survey and found increased risk of proximal colon cancer among women estimated to have nitrate levels >10 mg/L NO_3-N compared to levels < 0.5 mg/L. Risk of distal colon cancer and rectal cancer were not associated with nitrate levels [134]. Water nitrate ingestion from public supplies, bottled water, and private wells and springs over the adult lifetime was estimated in analyses that pooled case-control studies of colorectal cancer in Spain and Italy [135]. Risk of colorectal cancer was increased among those with >2.3 mg/day NO_3-N (vs. <1.1 mg/day). There were no interactions with red meat, vitamins C and E, and fiber except for a borderline interaction (p-interaction = 0.07) for rectum cancer with fiber intake. A small hospital-based case-control study in Indonesia found that drinking water nitrate levels above the WHO standard (>11.3 mg/L as NO_3-N) was associated with colorectal cancer [136]. A national registry-based cohort study in Denmark [32] evaluated average nitrate concentrations in PWS and private wells in relation to colorectal cancer incidence among those whose 35th birthday occurred during 1978–2011. The average nitrate level was computed over residential water supplies from age 20 to 35. Increased risks for colon and rectum cancer were observed in association with average nitrate levels ≥9.25 mg/L NO_3 (≥2.1 as NO_3-N) and ≥3.87 mg/L NO_3 (>0.87 as NO_3-N), respectively, with a significant positive trend. Because the study did not interview individuals, it could not evaluate individual-level risk factors that might influence endogenous nitrosation.

A case-control study of breast cancer in Cape Cod, Massachusetts (US) [137] estimated nitrate concentrations in PWS over approximately 20 years as an historical proxy for wastewater contamination and potential exposure to endocrine disruption compounds. Average exposures >1.2 mg/L NO_3-N (vs. <0.3 mg/L) were not associated with risk. A hospital-based case-control study in Spain found no association between water nitrate ingestion and pre- and post-menopausal breast cancers [138].

Table 2. Case-control and cohort studies of drinking water nitrate and cancer (January 2004–March 2018) by cancer site.

First Author (Year) Country	Study Design, Years Regional Description	Exposure Description	Cancer Sites Included	Summary of Drinking-Water Findings [a,b]	Evaluation of Effect Modification [c]
Zeegers, 2006 Netherlands [131]	Cohort Incidence, 1986–1995 204 municipal registries across the Netherlands	1986 nitrate level in 364 pumping stations, exposure data available for 871 cases, 4359 members of the subcohort	Bladder	Highest vs. lowest quintile intake from water (≥1.7 mg/day NO_3-N [median 2.4 mg/day] vs. <0.20) RR = 1.11 (CI: 0.87–1.41; *p*-trend = 0.14)	No interaction with vitamin C, E, smoking
Espejo-Herrera, 2015 Spain [33]	Hospital-based multi-center case-control Incidence, 1998–2001 Asturias, Alicante, Barcelona, Vallès-Bages, Tenerife provinces	Nitrate levels in PWS (1979–2010) and bottled water (measurements of brands with highest consumption based on a Spanish survey); analyses limited to those with ≥70% of residential history with nitrate estimate (531 cases, 556 controls)	Bladder	Highest vs. lowest quartile average level (age 18-interview) (≥2.26 vs. 1.13 mg/L NO_3-N) OR = 1.04 (CI: 0.60–1.81) Years >2.15 mg/L NO_3-N (75th percentile) (>20 vs. 0 years) OR = 1.41 (CI: 0.89–2.24)	No interaction with vitamin C, E, red meat, processed meat, average THM level
Jones, 2016 USA [31]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2010 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence with nitrate and trihalomethane estimates (20,945 women; 170 bladder cases); no measurements for private wells Adjusted for total trihalomethanes (TTHM)	Bladder	Highest vs. lowest quartile PWS average (≥2.98 vs. <0.47 mg/L NO_3-N) HR = 1.47 (CI: 0.91–2.38; *p*-trend = 0.11) Years >5 mg/L (≥4 years vs. 0) HR = 1.61 (CI: 1.05–2.47; *p*-trend = 0.03) Private well users (vs. <0.47 mg/L NO_3-N on PWS) HR = 1.53 (CI: 0.93–2.54)	Interaction with smoking (*p*-interaction = 0.03); HR = 3.67 (CI: 1.43–9.38) among current smokers/≥2.98 mg/L vs. non-smokers/<0.47 mg/L NO_3-N); No interaction with vitamin C, TTHM levels
Mueller, 2004 USA, Canada, France, Italy, Spain [139]	Pooled case-control studies Incidence among children <15 years (USA <20 years) 7 regions of 5 countries	Water source during pregnancy and first year of child's life (836 cases, 1485 controls); nitrate test strip measurements of nitrate and nitrite for pregnancy home (except Italy) (283 cases, 537 controls; excluding bottled water users: 207 cases, 400 controls)	Brain, childhood	Private well use versus PWS associated with increased risk in 2 regions and decreased risk in one; No association with nitrate levels in water supplies Astrocytomas (excludes bottled water users): ≥1.5 vs. <0.3 mg/L NO_2-N OR = 5.7 (CI: 1.2–27.2)	Not described
Brody, 2006 USA [137]	Case-control Incidence, 1988–1995 Cape Cod, Massachusetts	Nitrate levels in public water supplies (PWS) since 1972 was used as an indicator of wastewater contamination and potential mammary carcinogens and endocrine disrupting compounds; excluded women on private wells	Breast	Average ≥1.2 mg/L NO_3-N vs. <0.3 OR = 1.8, (CI: 0.6–5.0); summed annual NO_3-N ≥ 10 vs. 1–< 10 mg/L OR = 0.9, CI: 0.6–1.5); number of years >1 mg/L NO_3-N ≥8 vs. 0 years OR = 0.9 (CI: 0.5–1.5)	Not described

Table 2. *Cont.*

First Author (Year) Country	Study Design, Years Regional Description	Exposure Description	Cancer Sites Included	Summary of Drinking-Water Findings [a,b]	Evaluation of Effect Modification [c]
Inoue-Choi, 2012 USA [128]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2008 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence (20,147 women; 1751 breast cases); no measurements for private wells	Breast	Highest vs. lowest quintile PWS average (≥3.8 vs. ≤0.32 mg/L NO_3-N) HR = 1.14 (CI: 0.95–1.36; *p*-trend = 0.11); Private well (vs. ≤ 0.32 mg/L NO_3-N) HR = 1.14 (CI: 0.97–1.34); Private well (vs. ≤0.32 mg/L NO_3-N on PWS) HR = 1.38 (CI: 1.05–1.82); No association among those with low folate <400 µg/day	Interaction with folate for PWS (*p*-interaction = 0.06). Folate ≥400 µg/d: (≥3.8 vs. ≤0.32 mg/L NO_3-N) HR = 1.40 (CI: 1.05–1.87; *p*-trend = 0.04)
Espejo-Herrera, 2016 Spain [138]	Hospital-based multi-center case-control Incidence, 2008–2013 Spain (8 provinces)	Nitrate levels in PWS (2004–2010), bottled water measurements and private wells and springs (2013 measurements in 21 municipalities in León, Spain, the area with highest non-PWS use) Analyses include women with ≥70% of period from age 18 to 2 years before interview (1245 cases, 1520 controls)	Breast	Water nitrate intake based on average nitrate levels (age 18 to 2 years prior to interview) and water intake (L/day). Post-menopausal women: >2.0 vs. 0.5 mg/day NO_3-N OR = 1.32 (0.93–1.86); Premenopausal women: >1.4 vs. 0.4 mg/day NO_3-N OR = 1.14 (0.67–1.94)	No interaction with red meat, processed meat, vitamin C, E, smoking for pre- and post-menopausal women
McElroy, 2008 USA [134]	Population-based case-control, women Incidence, 1990–1992 and 1999–2001 Wisconsin	Limited to women in rural areas with no public water system (475 cases, 1447 controls); nitrate levels at residence (presumed to be private wells) estimated by kriging using data from a 1994 representative sample of 289 private wells	Colorectal	All colon cancers: Private wells ≥10.0 mg/L NO_3-N vs. <0.5 OR = 1.52 (CI: 0.95–2.44); Proximal colon cancer: OR = 2.91 (CI: 1.52–5.56)	Not described
Espejo-Herrera, 2016 Spain, Italy [135]	Multi-center case-control study Incidence, 2008–2013 Spain (9 provinces) and population-based controls; Italy (two provinces) and hospital-based controls	Nitrate levels in PWS (2004–2010) for 349 water supply zones, bottled water (measured brands with highest consumption), and private wells and springs (measurements in 2013 in 21 municipalities in León, Spain, the area with highest non-PWS use) Analyses include those with nitrate estimates for ≥70% of period 30 years before interview (1869 cases, 3530 controls)	Colorectal	Water nitrate intake based on average nitrate levels (estimated 30 to 2 years prior to interview) and water intake (L/day) Highest vs. lowest exposure quintiles (≥2.3 vs. <1.1 mg /day NO_3-N) OR = 1.49 (CI:1.24–1.78); Colon OR = 1.52 (CI: 1.24–1.86), Rectum OR = 1.62 (CI: 1.23–2.14)	Interaction with fiber for rectum (*p*-interaction = 0.07); >20 g/day fiber + >1.0 mg/L NO_3-N vs. <20 g/day + ≤1.0 mg/L HR = 0.72 (CI: 0.52–1.00). No interaction with red meat, vitamin C, E

Table 2. *Cont.*

First Author (Year) Country	Study Design, Years Regional Description	Exposure Description	Cancer Sites Included	Summary of Drinking-Water Findings [a,b]	Evaluation of Effect Modification [c]
Fathmawati, 2017 Indonesia [136]	Hospital-based case-control Incidence, 2014–2016 Indonesia (3 provinces)	Nitrate levels in well water collected during the raining season (Feb-March 2016) and classified based on >11.3 or ≤11.3 mg/L as NO_3-N and duration of exposure >10 and ≤10 years Analyses included participants who reported drinking well water (75 cases, 75 controls)	Colorectal	Water nitrate > WHO standard vs. below (> 11.3 vs. ≤11.3 mg/L NO_3-N) OR = 2.82 (CI: 1.08–7.40); > 10 years: 4.31 (CI: 11.32–14.10); ≤10 years: 1.41 (CI: 0.14–13.68)	Not described
Schullehner, 2018 Denmark [32]	Population-based record-linkage cohort of men and women ages 35 and older, 1978–2011 Denmark	Nitrate levels in PWS and private wells among 1,742,321 who met exposure assessment criteria (5944 colorectal cancer cases, including 3700 with colon and 2308 with rectal cancer)	Colorectal	Annual average nitrate exposure between ages 20–35 among those who lived ≥75% of study period at homes with a water sample within 1 year (61% of Danish population). Highest vs. lowest exposure quintile (≥2.1 vs. 0.16 mg/L NO_3-N); Colorectal: HR = 1.16 (CI: 1.08–1.25); colon: 1.15 (CI: 1.05–1.26); rectum: 1.17 (CI: 1.04–1.32)	No information on dietary intakes or smoking
Ward, 2007 USA [34]	Population-based case control Incidence, 1986–1989 Iowa	Nitrate levels in PWS among those with nitrate estimates for ≥70% of person-years ≥1960 (201 cases, 1244 controls)	Kidney (renal cell carcinomas)	Highest vs. lowest quartile PWS average (≥2.8 mg/L NO_3-N vs. <0.62) OR = 0.89 (CI 0.57–1.39); Years >5mg/L NO_3-N 11+ vs. 0 OR = 1.03 (CI: 0.66–1.60)	Interaction with red meat intake (p-interaction = 0.01); OR = 1.91 (CI 1.04–3.51) among 11+ years >5 mg/L NO_3-N and red meat ≥1.2 servings/day. Interaction with vitamin C showed similar pattern (p-interaction = 0.13)
Jones, 2017 USA [127]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2010 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence. PWS measurements for nitrate and TTHM; no measurements for private wells (20,945 women; 163 kidney cases)	Kidney	Nitrate and TTHM metrics computed for duration at water source (11+ years) 95th percentile vs. lowest quartile PWS average (≥5.00 vs. <0.47 mg/L NO_3-N) HR = 2.23 (CI: 1.19–4.17; p-trend = 0.35) Years >5 mg/L (≥4 years vs. 0) HR = 1.54 (CI: 0.97–2.44; p-trend = 0.09) Private well users (vs. <0.47 mg/L NO_3-N in PWS) HR = 0.96 (CI: 0.59–1.58)	No interaction with smoking, vitamin C
Ward, 2006 USA [35]	Population-based case-control Incidence, 1998–2000 Iowa	Nitrate levels in PWS among those with nitrate estimates for ≥70% of person-years ≥1960 (181 case, 142 controls); nitrate measurements for private well users at time of interviews (1998–2000; 54 cases, 44 controls)	Non-Hodgkin lymphoma	Private wells: >5.0 mg/L NO_3-N vs. ND OR = 0.8 (CI 0.2–2.5) PWS average: ≥2.9 mg/L NO_3-N vs. <0.63 OR = 1.2 (CI 0.6–2.2) Years ≥5mg/L NO3-N: 10+ vs. 0 OR = 1.4 (CI: 0.7–2.9)	No interaction with vitamin C, smoking

Table 2. *Cont.*

First Author (Year) Country	Study Design, Years Regional Description	Exposure Description	Cancer Sites Included	Summary of Drinking-Water Findings [a,b]	Evaluation of Effect Modification [c]
Inoue-Choi, 2015 USA [129]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2010 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence; PWS measurements for nitrate and TTHM; no measurements for private wells (17,216 women; 190 ovarian cases)	Ovary	Nitrate and TTHM metrics computed for reported duration at water source (11+ years) Highest vs. lowest quartile PWS average (≥2.98 mg/L vs. <0.47 mg/L NO_3-N) HR = 2.03 (CI = 1.22–3.38; *p*-trend = 0.003) Years >5 mg/L (≥4 years vs. 0) HR = 1.52 (CI: 1.00–2.31; *p*-trend = 0.05) Private well users (vs. <0.47 mg/L NO_3-N in PWS) HR = 1.53 (CI: 0.93–2.54)	No interaction with vitamin C, red meat intake, smoking for PWS nitrate Interaction with private well use and vitamin C intake (*p*-interaction = 0.01)
Quist, 2018 USA [126]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2011 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence; nitrate and TTHM estimates for PWS (20,945 women; 189 pancreas cases); no measurements for private wells Adjusted for TTHM (1955–1988), measured levels in 1980s, prior year levels estimated by expert)	Pancreas	Nitrate and TTHM metrics computed for reported duration at water source (11+ years) 95th percentile vs. lowest quartile PWS average (≥5.69 vs. <0.47 mg/L NO_3-N) HR = 1.16 (CI: 0.51–2.64; *p*-trend = 0.97) Years >5 mg/L (≥4 years vs. 0) HR = 0.90 (CI: 0.55–1.48; *p*-trend = 0.62) Private well users (vs. <0.47 mg/L NO_3-N) HR = 0.92 (CI: 0.55–1.52)	No interaction with smoking, vitamin C
Ward, 2008 USA [133]	Population-based case control Incidence, 1988–1993 Nebraska	Controls from prior study of lymphohematopoetic cases and controls interviewed in 1992–1994; Proxy interviews for 80%, 76%, 61% of stomach, esophagus, controls, respectively. Nitrate levels (1965–1985) in PWS for ≥70% of person-years (79 distal stomach, 84, esophagus, 321 controls); Private well users sampling at interview (15 stomach, 22 esophagus, 44 controls)	Stomach and esophagus (adenocarcinomas)	Highest vs. lowest quartile PWS average (>4.32 vs. <2.45 mg/L NO_3-N): stomach OR = 1.2 (CI 0.5–2.7); esophagus OR = 1.3 (CI: 0.6–3.1); Years >10 mg/L NO_3-N (9+ vs. 0): stomach OR = 1.1 (CI: 0.5–2.3); esophagus OR = 1.2 (CI: 0.6–2.7) Private well users (>4.5 mg/L NO_3-N vs. <0.5) stomach OR = 5.1 (CI: 0.5–52; 4 cases, 13 controls); esophagus OR = 0.5 (CI: 0.1–2.9; 8 cases; 13 controls)	No interaction with vitamin C, processed meat, or red meat for either cancer
Ward, 2010 USA [37]	Population-based cohort of postmenopausal women ages 55–69 Incidence, 1986–2004 Iowa	Nitrate levels in PWS (1955–1988) and private well use among women >10 years at enrollment residence (21,977 women; 40 thyroid cases); no measurements for private wells	Thyroid	Highest vs. lowest quartile PWS average (>2.46 vs. <0.36 mg/L NO_3-N) HR = 2.18 (CI: 0.83–5.76; *p*-trend = 0.02) Years >5 mg/L (≥5 years vs. 0) HR = 2.59 (CI: 1.09–6.19; *p*-trend = 0.04); Private well (vs. <0.36 mg/L NO_3-N on PWS) HR = 1.13 (CI: 0.83–3.66) Dietary nitrate intake quartiles positively associated with risk (*p*-trend = 0.05)	No interaction with smoking, vitamin C, body mass index, education, residence location (farm/rural vs. urban)

ND = not detected; PWS = public water supplies; [a] nitrate or nitrite levels presented in the publications as mg/L of the ion were converted to mg/L as NO_3-N or NO_2-N; [b] Odds ratios (OR) for case-control studies, incidence rate ratios (RR) and hazard ratios (HR) for cohort studies, and 95% confidence intervals (CI); [c] Factors evaluated are noted. Interaction refers to reported $p \leq 0.10$ from test of heterogeneity.

Animal studies demonstrate that in utero exposure to nitrosamides can cause brain tumors in the exposed offspring. Water nitrate and nitrite intake during pregnancy was estimated in a multi-center case-control study of childhood brain tumors in five countries based on the maternal residential water source [139]. Results for the California and Washington State sites were reported in our previous review [8,140]. Nitrate/nitrite levels in water supplies were measured using a nitrate test strip method in four countries including these U.S. sites; most of these measurements occurred many years after the pregnancy. Measured nitrate concentrations were not associated with risk of childhood brain tumors. However, higher nitrite levels (>1.5 mg/L NO_2-N) in the drinking water were associated with increased risk of astrocytomas.

8. Thyroid Disease

Animal studies demonstrate that ingestion of nitrate at high doses can competitively inhibit iodine uptake and induce hypertrophy of the thyroid gland [141]. An early study of women in the Netherlands consuming water with nitrate levels at or above the MCL, found increased prevalence of thyroid hypertrophy [142]. Since the last review, five studies have evaluated nitrate ingestion from drinking water (the Iowa cohort study also assessed diet) and prevalence of thyroid disease. A study of school-age children in Slovakia found increased prevalence of subclinical hypothyroidism among children in an area with high nitrate levels (51–274 mg/L NO_3) in water supplies compared with children ingesting water with nitrate $\leq$50 mg/L (11 mg/L NO_3-N). In Bulgarian villages with high nitrate levels (75 mg/L NO_3) and low nitrate levels (8 mg/L), clinical examinations of the thyroids of pregnant women and school children revealed an approximately four- and three-fold increased prevalence of goiter, respectively, in the high nitrate village [143,144]. The iodine status of the populations in both studies was adequate. Self-reported hypothyroidism and hyperthyroidism among a cohort of post-menopausal women in Iowa was not associated with average nitrate concentrations in PWS [37]. However, dietary nitrate, the predominant source of intake, was associated with increased prevalence of hypothyroidism but not hyperthyroidism. Modeled estimates of nitrate concentrations in private wells among a cohort of Old Order Amish in Pennsylvania (USA) were associated with increased prevalence of subclinical hypothyroidism as determined by thyroid stimulating hormone measurements, among women but not men [145].

9. Other Health Effects

Associations between nitrate in drinking water and other non-cancer health effects, including type 1 childhood diabetes (T1D), blood pressure, and acute respiratory tract infections in children were previously reviewed [8]. Since 2004, a small number of studies have contributed additional mixed evidence for these associations. Animal studies indicate that NOC may play a role in the pathology of T1D through damage to pancreatic beta cells [146]. A registry-based study in Finland [147] found a positive trend in T1D incidence with levels of nitrate in drinking water. In contrast, an ecological analysis in Italy showed an inverse correlation with water nitrate levels and T1D rates [148]. A small T1D case-control study in Canada with 57 cases showed no association between T1D and estimated intake of nitrate from drinking water (highest quartile >2.7 mg/day NO_3-N) [149]. Concentrations of nitrate in drinking water (median ~2.1 mg/L NO_3-N) were not associated with progression to T1D in a German nested case-control study of islet autoantibody-positive children, who may be at increased risk of the disease [150].

In a prospective, population-based cohort study in Wisconsin (USA), increased incidence of early and late age-related macular degeneration was positively associated with higher nitrate levels ($\geq$5 mg/L vs. <5 mg/L NO_3-N) in rural private drinking water supplies [151]. The authors suggested several possible mechanisms, including methemoglobin-induced lipid peroxidation in the retina.

Potential benefits of nitrate ingestion include lowering of blood pressure due to production of nitric oxide in the acidic stomach and subsequent vasodilation, antithrombotic, and immunoregulatory effects [152]. Experimental studies in animals and controlled feeding studies in humans have

demonstrated mixed evidence of these effects and on other cardiovascular endpoints such as vascular hypertrophy, heart failure, and myocardial infarction (e.g., [152–154]). Ingested nitrite from diet has also been associated with increased blood flow in certain parts of the brain [155]. Epidemiologic studies of these effects are limited to estimation of dietary exposures or biomarkers that integrate exposures from nitrate from diet and drinking water. Recent findings in the Framingham Offspring Study suggested that plasma nitrate was associated with increased overall risk of death that attenuated when adjusted for glomerular function (HR: 1.16, 95% CI: 1.0–1.35) but no association was observed for incident cardiovascular disease [156]. No epidemiologic studies have specifically evaluated nitrate ingested from drinking water in relation to these outcomes. Another potential beneficial effect of nitrate is protection against bacterial infections via its reduction to nitrite by enteric bacteria. In an experimental inflammatory bowel disease mouse model, nitrite in drinking water was associated with both preventive and therapeutic effects [157]. However, there is limited epidemiologic evidence for a reduced risk of gastrointestinal disease in populations with high drinking water nitrate intake. One small, cross-sectional study in Iran found no association between nitrate levels in public water supplies with mean levels of ~5.6 mg/L NO_3-N and gastrointestinal disease [158].

10. Discussion

Since our last review of studies through 2004 [8], more than 30 epidemiologic studies have evaluated drinking water nitrate and risk of cancer, adverse reproductive outcomes, or thyroid disease. However, the number of studies of any one outcome was not large and there are still too few studies to allow firm conclusions about risk. The most common endpoints studied were colorectal cancer, bladder, and breast cancer (three studies each) and thyroid disease (four studies). Considering all studies to date, the strongest evidence for a relationship between drinking water nitrate ingestion and adverse health outcomes (besides methemoglobinemia) is for colorectal cancer, thyroid disease, and neural tube defects. Four of the five published studies of colorectal cancer found evidence of an increased risk of colorectal cancer or colon cancer associated with water nitrate levels that were mostly below the respective regulatory limits [32,134,135,159]. In one of the four positive studies [159], increased risk was only observed in subgroups likely to have increased nitrosation. Four of the five studies of thyroid disease found evidence for an increased prevalence of subclinical hypothyroidism with higher ingestion of drinking water nitrate among children, pregnant women, or women only [37,144,145,160]. Positive associations with drinking water nitrate were observed at nitrate concentrations close to or above the MCL. The fifth study, a cohort of post-menopausal women in Iowa, had lower drinking water nitrate exposure but observed a positive association with dietary nitrate [37]. To date, five of six studies of neural tube defects showed increased risk with exposure to drinking water nitrate below the MCL. Thus, the evidence continues to accumulate that higher nitrate intake during the pregnancy is a risk factor for this group of birth defects.

All but one of the 17 cancer studies conducted since 2004 were in the U.S. or Europe, the majority of which were investigations of nitrate in regulated public drinking water. Thyroid cancer was studied for the first time [37] with a positive finding that should be evaluated in future studies. Bladder cancer, a site for which other drinking water contaminants (arsenic, disinfection by-products [DBPs]) are established or suspected risk factors, was not associated with drinking water nitrate in three of the four studies. Most of the cancer studies since 2004 evaluated effect modification by factors known to influence endogenous nitrosation, although few observed evidence for these effects. Several studies of adverse reproductive outcomes since 2004 have indicated a positive association between maternal prenatal exposure to nitrate concentrations below the MCL and low birth weight and small for gestational age births. However, most studies did not account for co-exposure to other water contaminants, nor did they adjust for potential risk factors. The relation between drinking water nitrate and spontaneous abortion continues to be understudied. Few cases of methemoglobinemia, the health concern that lead to the regulation of nitrate in public water supplies, have been reported in the U.S. since the 1990s. However, as described by Knobeloch et al. [96], cases may be underreported

and only a small proportion of cases are thoroughly investigated and described in the literature. Based on published reports, [100] areas of the world of particular concern include several eastern European countries, Gaza, and Morocco, where high nitrate concentrations in water supplies have been linked to high levels of methemoglobin in children. Therefore, continued surveillance and education of physicians and parents will be important. Biological plausibility exists for relationships between nitrate ingestion from drinking water and a few other health outcomes including diabetes and beneficial effects on the cardiovascular system, but there have been only a limited number of epidemiologic studies.

Assessment of drinking water nitrate exposures in future studies should be improved by obtaining drinking water sources at home and at work, estimating the amount of water consumed from each source, and collecting information on water filtration systems that may impact exposure. These efforts are important for reducing misclassification of exposure. Since our last review, an additional decade of PWS monitoring data are available in the U.S. and European countries, which has allowed assessment of exposure over a substantial proportion of participants' lifetimes in recent studies. Future studies should estimate exposure to multiple water contaminants as has been done in recent cancer studies [31,33,127,129]. For instance, nitrate and atrazine frequently occur together in drinking water in agricultural areas [161] and animal studies have found this mixture to be teratogenic [162]. Regulatory monitoring data for pesticides in PWS has been available for over 20 years in the U.S.; therefore, it is now feasible to evaluate co-exposure to these contaminants. Additionally, water supplies in agricultural areas that rely on alluvial aquifers or surface water often have elevated levels of both DBPs and nitrate. Under this exposure scenario, there is the possibility of formation of the nitrogenated DBPs including the carcinogenic NDMA, especially if chloramination treatment is used for disinfection [163,164]. Studies of health effects in countries outside the U.S. and Europe are also needed.

A comprehensive assessment of nitrate and nitrite from drinking water and dietary sources as well as estimation of intakes of antioxidants and other inhibitors of endogenous nitrosation including dietary polyphenols and flavonoids is needed in future studies. Heme iron from red meat, which increases fecal NOC in human feeding studies, should also be assessed as a potential effect modifier of risk from nitrate ingestion. More research is needed on the potential interaction of nitrate ingestion and nitrosatable drugs (those with secondary and tertiary amines or amides). Evidence from several studies of birth defects [38,118–120] implicates nitrosatable drug intake during pregnancy as a risk factor for specific congenital anomalies especially in combination with nitrate. Drugs with nitrosatable groups include many over-the-counter and prescription drugs. Future studies with electronic medical records and record-linkage studies in countries like Denmark with national pharmacy data may provide opportunities for evaluation of these exposures.

Populations with the highest exposure to nitrate from their drinking water are those living in agricultural regions, especially those drinking water from shallow wells near nitrogen sources (e.g., crop fields, animal feeding operations). Estimating exposure for private well users is important because it allows assessment of risk over a greater range of nitrate exposures compared to studies focusing solely on populations using PWS. Future health studies should focus on these populations, many of which may have been exposed to elevated nitrate in drinking water from early childhood into adulthood. A major challenge in conducting studies in these regions is the high prevalence of private well use with limited nitrate measurement data for exposure assessment. Recent efforts to model nitrate concentrations in private wells have shown that it is feasible to develop predictive models where sufficient measurement data are available [41,48,49]. However, predictive models from one area are not likely to be directly translatable to other geographic regions with different aquifers, soils, and nitrogen inputs.

Controlled human feeding studies have demonstrated that endogenous nitrosation occurs after ingestion of drinking water with nitrate concentrations above the MCL of 10 mg/L NO_3-N (~44 mg/L as NO_3). However, the extent of NOC formation after ingestion of drinking water with nitrate

concentrations below the MCL has not been well characterized. Increased risks of specific cancers and central nervous system birth defects in study populations consuming nitrate below the MCL is indirect evidence that nitrate ingestion at these levels may be a risk factor under some conditions. However, confounding by other exposures or risk factors can be difficult to rule out in many studies. Controlled human studies to evaluate endogenous nitrosation at levels below the MCL are needed to understand interindividual variability and factors that affect endogenous nitrosation at drinking water nitrate levels below the MCL.

A key step in the endogenous formation of NOC is the reduction of nitrate, which has been transported from the bloodstream into the saliva, to nitrite by the nitrate-reducing bacteria that are located primarily in the crypts on the back of the tongue [165–167]. Tools for measuring bacterial DNA and characterizing the oral microbiome are now available and are currently being incorporated into epidemiologic studies [168,169]. Buccal cell samples that have been collected in epidemiologic studies can be used to characterize the oral microbiome and to determine the relative abundance of the nitrate-reducing bacteria. Studies are needed to characterize the stability of the nitrate-reducing capacity of the oral microbiome over time and to determine factors that may modify this capacity such as diet, oral hygiene, and periodontal disease. Interindividual variability in the oral nitrate-reducing bacteria may play an important role in modifying endogenous NOC formation. The quantification of an individual's nitrate-reducing bacteria in future epidemiologic studies is likely to improve our ability to classify participants by their intrinsic capacity for endogenous nitrosation.

In addition to characterizing the oral microbiome, future epidemiologic studies should incorporate biomarkers of NOC (e.g., urinary or fecal NOC), markers of genetic damage, and determine genetic variability in NOC metabolism. As many NOC require α-hydroxylation by CYP2E1 for bioactivation and for formation of DNA adducts, it is important to investigate the influence of polymorphisms in the gene encoding for this enzyme. Studies are also needed among populations with medical conditions that increase nitrosation such as patients with inflammatory bowel disease and periodontal disease [8]. Because NOC exposures induce characteristic gene expression profiles [170,171], further studies linking drinking water intake to NOC excretion and gene expression responses are relevant to our understanding of health risks associated with drinking water nitrate. The field of 'Exposome-research' [172,173] generates large numbers of genomics profiles in human population studies for which dietary exposures and biobank materials are also available. These studies provide opportunities to measure urinary levels of nitrate and NOC that could be associated with molecular markers of exposure and disease risk.

Nitrate concentrations in global water supplies are likely to increase in the future due to population growth, increases in nitrogen fertilizer use, and increasing intensity and concentration of animal agriculture. Even with increased inputs, mitigation of nitrate concentrations in water resources is possible through local, national, and global efforts. Examples of the latter are the International Nitrogen Initiative [174] and the EU Nitrates Directive [17,18], which aim to quantify human effects on the nitrogen cycle and to validate and promote methods for sustainable nitrogen management. Evidence for the effectiveness of these efforts, which include the identification of vulnerable areas, establishment of codes of good agricultural practices, and national monitoring and reporting are indicated by decreasing trends in groundwater nitrate concentrations in some European countries after the implementation of the EU Nitrates Directive [19]. However, the effect of this initiative was variable across the EU. In the U.S., nitrogen applications to crop fields are not regulated and efforts to reduce nitrogen runoff are voluntary. Although strategies such as appropriate timing of fertilizer applications, diversified crop rotations, planting of cover crops, and reduced tillage can be effective [175], concentrations in U.S. ground and surface water have continued to increase in most areas [10]. Climate change is expected to affect nitrogen in aquatic ecosystems and groundwater through alterations of the hydrological cycle [176]. Climatic factors that affect nitrate in groundwater include the amount, intensity, and timing of precipitation. Increasing rainfall intensity, especially in

the winter and spring, can lead to increases in nitrogen runoff from agricultural fields and leaching to groundwater.

11. Conclusions

In summary, most adverse health effects related to drinking water nitrate are likely due to a combination of high nitrate ingestion and factors that increase endogenous nitrosation. Some of the recent studies of cancer and some birth defects have been able to identify subgroups of the population likely to have greater potential for endogenous nitrosation. However, direct methods of assessing these individuals are needed. New methods for quantifying the nitrate-reducing bacteria in the oral microbiome and characterizing genetic variation in NOC metabolism hold promise for identifying high risk groups in epidemiologic studies.

To date, the number of well-designed studies of individual health outcomes is still too few to draw firm conclusions about risk from drinking water nitrate ingestion. Additional studies that incorporate improved exposure assessment for populations on PWS, measured or predicted exposure for private well users, quantification of nitrate-reducing bacteria, and estimates of dietary and other factors affecting nitrosation are needed. Studies of colorectal cancer, thyroid disease, and central nervous system birth defects, which show the most consistent associations with water nitrate ingestion, will be particularly useful for clarifying these risks. Future studies of other health effects with more limited evidence of increased risk are also needed including cancers of the thyroid, ovary, and kidney, and the adverse reproductive outcomes of spontaneous abortion, preterm birth, and small for gestational age births.

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References

1. Davidson, E.A.; David, M.B.; Galloway, J.N.; Goodale, C.L.; Haeuber, R.; Harrison, J.A.; Howarth, R.W.; Jaynes, D.B.; Lowrance, R.R.; Nolan, B.T.; et al. Excess nitrogen in the U.S. environment: Trends, risks, and solutions. In *Issues in Ecology*; Ecological Society of America: Washington, DC, USA, 2012.
2. Vitousek, P.M.; Aber, J.D.; Howarth, R.W.; Likens, G.E.; Matson, P.A.; Schindler, D.W.; Schlesinger, W.H.; Tilman, D. Human alteration of the global nitrogen cycle: Sources and consequences. *Ecol. Appl.* **1997**, *7*, 737–750. [CrossRef]
3. Howarth, R.W. Coastal nitrogen pollution: A review of sources and trends globally and regionally. *Harmful Algae* **2008**, *8*, 14–20. [CrossRef]
4. USEPA. Regulated Drinking Water Contaminants: Inorganic Chemicals. Available online: https://www.epa.gov/ground-water-and-drinking-water/table-regulated-drinking-water-contaminants (accessed on 23 September 2017).
5. International Agency for Research on Cancer (IARC). *IARC Monographs on the Evaluation of Carcionogenic Risks to Humans: Ingested Nitrate and Nitrite and Cyanobacterial Peptide Toxins*; IARC: Lyon, France, 2010.
6. National Research Council (NRC). *The Health Effects of Nitrate, Nitrite, and N-Nitroso Compounds*; NRC: Washington, DC, USA, 1981.
7. Mirvish, S.S. Role of N-nitroso compounds (NOC) and N-nitrosation in etiology of gastric, esophageal, nasopharyngeal and bladder cancer and contribution to cancer of known exposures to NOC. *Cancer Lett.* **1995**, *93*, 17–48. [CrossRef]

8. Ward, M.H.; deKok, T.M.; Levallois, P.; Brender, J.; Gulis, G.; Nolan, B.T.; VanDerslice, J. Workgroup report: Drinking-water nitrate and health-recent findings and research needs. *Environ. Health Perspect.* **2005**, *113*, 1607–1614. [CrossRef] [PubMed]
9. Maupin, M.A.; Kenny, J.F.; Hutson, S.S.; Lovelace, J.K.; Barber, N.L.; Linsey, K.S. *Estimated Use of Water in the United States in 2010*; US Geological Survey: Reston, VA, USA, 2014; p. 56.
10. U.S. Geological Survey. USGS Water Data for the Nation. Available online: https://waterdata.usgs.gov/nwis (accessed on 1 January 2018).
11. Dubrovsky, N.M.; Burow, K.R.; Clark, G.M.; Gronberg, J.M.; Hamilton, P.A.; Hitt, K.J.; Mueller, D.K.; Munn, M.D.; Nolan, B.T.; Puckett, L.J.; et al. *The Quality of Our Nation's Waters—Nutrients in the Nation's Streams and Groundwater, 1992–2004*; U.S. Geological Survey: Reston, VA, USA, 2010; p. 174.
12. Lindsey, B.D.; Rupert, M.G. *Methods for Evaluating Temporal Groundwater Quality Data and Results of Decadal-Scale Changes in Chloride, Dissolved Solids, and Nitrate Concentrations in Groundwater in the United States, 1988–2010*; U.S. Geological Survey Scientific Investigations Report: 2012–5049; U.S. Geological Survey: Reston, VA, USA, 2012; p. 46.
13. Pennino, M.J.; Compton, J.E.; Leibowitz, S.G. Trends in Drinking Water Nitrate Violations across the United States. *Environ. Sci. Technol.* **2017**, *51*, 13450–13460. [CrossRef] [PubMed]
14. Van Grinsven, H.J.M.; Tiktak, A.; Rougoor, C.W. Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. *NJAS-Wagening. J. Life Sci.* **2016**, *78*, 69–84. [CrossRef]
15. Vock, D.C. Iowa Farmers Won a Water Pollution Lawsuit, But at What Cost? Available online: http://www.governing.com/topics/transportation-infrastructure/gov-des-moines-water-utility-lawsuit-farmers.html (accessed on 10 February 2018).
16. Des Moines Water Works. On Earth Day, Des Moines Water Works Reflects on Resources Spent to Manage Agrotoxins in Source Waters. Available online: http://www.dmww.com/about-us/news-releases/on-earth-day-des-moines-water-works-reflects-on-resources-spent-to-manage-agrotoxins-in-source-water.aspx (accessed on 10 February 2018).
17. European Commission. The Nitrates Directive. Available online: http://ec.europa.eu/environment/water/water-nitrates/index_en.html (accessed on 10 May 2018).
18. European Union (EU). *Council Directive 91/676/EEC of 12 December 1991 Concerning the Protection of Waters against Pollution Caused by Nitrates from Agricultural Sources*; European Union (EU): Brussels, Belgium, 1991.
19. Hansen, B.; Thorling, L.; Dalgaard, T.; Erlandsen, M. Trend Reversal of Nitrate in Danish Groundwater—A Reflection of Agricultural Practices and Nitrogen Surpluses since 1950. *Environ. Sci. Technol.* **2011**, *45*, 228–234. [CrossRef] [PubMed]
20. European Environment Agency (EEA). Groundwater Nitrate. Available online: https://www.eea.europa.eu/data-and-maps/daviz/groundwater-nitrate#tab-chart_1_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_country%22%3A%5B%22Slovenia%22%5D%7D%7D (accessed on 10 February 2018).
21. Schullehner, J.; Hansen, B. Nitrate exposure from drinking water in Denmark over the last 35 years. *Environ. Res. Lett.* **2014**, *9*, 095001. [CrossRef]
22. Vitoria, I.; Maraver, F.; Sanchez-Valverde, F.; Armijo, F. Nitrate concentrations in tap water in Spain. *Gac. Sanit.* **2015**, *29*, 217–220. [CrossRef] [PubMed]
23. Espejo-Herrera, N.; Kogevinas, M.; Castano-Vinyals, G.; Aragones, N.; Boldo, E.; Ardanaz, E.; Azpiroz, L.; Ulibarrena, E.; Tardon, A.; Molina, A.J.; et al. Nitrate and trace elements in municipal and bottled water in Spain. *Gac. Sanit.* **2013**, *27*, 156–160. [CrossRef] [PubMed]
24. Gunnarsdottir, M.J.; Gardarsson, S.M.; Jonsson, G.S.; Bartram, J. Chemical quality and regulatory compliance of drinking water in Iceland. *Int. J. Hyg. Environ. Health* **2016**, *219*, 724–733. [CrossRef] [PubMed]
25. D'Alessandro, W.; Bellomo, S.; Parello, F.; Bonfanti, P.; Brusca, L.; Longo, M.; Maugeri, R. Nitrate, sulphate and chloride contents in public drinking water supplies in Sicily, Italy. *Environ. Monit. Assess.* **2012**, *184*, 2845–2855. [CrossRef] [PubMed]
26. Migeot, V.; Albouy-Llaty, M.; Carles, C.; Limousi, F.; Strezlec, S.; Dupuis, A.; Rabouan, S. Drinking-water exposure to a mixture of nitrate and low-dose atrazine metabolites and small-for-gestational age (SGA) babies: A historic cohort study. *Environ. Res.* **2013**, *122*, 58–64. [CrossRef] [PubMed]

27. Taneja, P.; Labhasetwar, P.; Nagarnaik, P.; Ensink, J.H.J. The risk of cancer as a result of elevated levels of nitrate in drinking water and vegetables in Central India. *J. Water Health* **2017**, *15*, 602–614. [CrossRef] [PubMed]
28. Suthar, S.; Bishnoi, P.; Singh, S.; Mutiyar, P.K.; Nema, A.K.; Patil, N.S. Nitrate contamination in groundwater of some rural areas of Rajasthan, India. *J. Hazard. Mater.* **2009**, *171*, 189–199. [CrossRef] [PubMed]
29. Gupta, I.; Salunkhe, A.; Rohra, N.; Kumar, R. Groundwater quality in Maharashtra, India: Focus on nitrate pollution. *J. Environ. Sci. Eng.* **2011**, *53*, 453–462. [PubMed]
30. Weinthal, E.; Vengosh, A.; Marei, A.; Kloppmann, W. The water crisis in the Gaza strip: Prospects for resolution. *Ground Water* **2005**, *43*, 653–660. [CrossRef] [PubMed]
31. Jones, R.R.; Weyer, P.J.; DellaValle, C.T.; Inoue-Choi, M.; Anderson, K.E.; Cantor, K.P.; Krasner, S.; Robien, K.; Freeman, L.E.B.; Silverman, D.T.; et al. Nitrate from drinking water and diet and bladder cancer among postmenopausal women in Iowa. *Environ. Health Perspect.* **2016**, *124*, 1751–1758. [CrossRef] [PubMed]
32. Schullehner, J.; Hansen, B.; Thygesen, M.; Pedersen, C.B.; Sigsgaard, T. Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study. *Int. J. Cancer* **2018**, *1*, 73–79. [CrossRef] [PubMed]
33. Espejo-Herrera, N.; Cantor, K.P.; Malats, N.; Silverman, D.T.; Tardon, A.; Garcia-Closas, R.; Serra, C.; Kogevinas, M.; Villanueva, C.M. Nitrate in drinking water and bladder cancer risk in Spain. *Environ. Res.* **2015**, *137*, 299–307. [CrossRef] [PubMed]
34. Ward, M.H.; Rusiecki, J.A.; Lynch, C.F.; Cantor, K.P. Nitrate in public water supplies and the risk of renal cell carcinoma. *Cancer Causes Control* **2007**, *18*, 1141–1151. [CrossRef] [PubMed]
35. Ward, M.H.; Cerhan, J.R.; Colt, J.S.; Hartge, P. Risk of non-Hodgkin lymphoma and nitrate and nitrite from drinking water and diet. *Epidemiology* **2006**, *17*, 375–382. [CrossRef] [PubMed]
36. Schullehner, J.; Stayner, L.; Hansen, B. Nitrate, Nitrite, and Ammonium Variability in Drinking Water Distribution Systems. *Int. J. Environ. Res. Public Health* **2017**, *14*, 276. [CrossRef] [PubMed]
37. Ward, M.H.; Kilfoy, B.A.; Weyer, P.J.; Anderson, K.E.; Folsom, A.R.; Cerhan, J.R. Nitrate intake and the risk of thyroid cancer and thyroid disease. *Epidemiology* **2010**, *21*, 389–395. [CrossRef] [PubMed]
38. Brender, J.D.; Weyer, P.J.; Romitti, P.A.; Mohanty, B.P.; Shinde, M.U.; Vuong, A.M.; Sharkey, J.R.; Dwivedi, D.; Horel, S.A.; Kantamneni, J.; et al. Prenatal nitrate intake from drinking water and selected birth defects in offspring of participants in the national birth defects prevention study. *Environ. Health Perspect.* **2013**, *121*, 1083–1089. [CrossRef] [PubMed]
39. Baris, D.; Waddell, R.; Beane Freeman, L.E.; Schwenn, M.; Colt, J.S.; Ayotte, J.D.; Ward, M.H.; Nuckols, J.; Schned, A.; Jackson, B.; et al. Elevated Bladder Cancer in Northern New England: The Role of Drinking Water and Arsenic. *J. Natl. Cancer Inst.* **2016**, *108*. [CrossRef] [PubMed]
40. Nolan, B.T.; Hitt, K.J. Vulnerability of shallow groundwater and drinking-water wells to nitrate in the United States. *Environ. Sci. Technol.* **2006**, *40*, 7834–7840. [CrossRef] [PubMed]
41. Messier, K.P.; Kane, E.; Bolich, R.; Serre, M.L. Nitrate variability in groundwater of North Carolina using monitoring and private well data models. *Environ. Sci. Technol.* **2014**, *48*, 10804–10812. [CrossRef] [PubMed]
42. Eckhardt, D.A.V.; Stackelberg, P.E. Relation of ground-water quality to land use on Long Island, New York. *Ground Water* **1995**, *33*, 1019–1033. [CrossRef]
43. Nolan, B.T.; Hitt, K.J.; Ruddy, B.C. Probability of nitrate contamination of recently recharged groundwaters in the conterminous United States. *Environ. Sci. Technol.* **2002**, *36*, 2138–2145. [CrossRef] [PubMed]
44. Rupert, M.G. *Probability of Detecting Atrazine/Desethyl-Atrazine and Elevated Concentrations of Nitrate in Ground Water in Colorado*; Water-Resources Investigations Report 02-4269; U.S. Geological Survey: Denver, CO, USA, 2003; p. 35.
45. Tesoriero, A.J.; Voss, F.D. Predicting the probability of elevated nitrate concentrations in the Puget Sound Basin: Implications for aquifer susceptibility and vulnerability. *Ground Water* **1997**, *35*, 1029–1039. [CrossRef]
46. Warner, K.L.; Arnold, T.L. *Relations that Affect the Probability and Prediction of Nitrate Concentration in Private Wells in the Glacial Aquifer System in the United States*; U.S. Geological Survey Scientific Investigations Report 2010–5100; U.S. Geological Survey: Reston, VA, USA, 2010; p. 55.
47. Elith, J.; Leathwick, J.R.; Hastie, T. A working guide to boosted regression trees. *J. Anim. Ecol.* **2008**, *77*, 802–813. [CrossRef] [PubMed]
48. Wheeler, D.C.; Nolan, B.T.; Flory, A.R.; DellaValle, C.T.; Ward, M.H. Modeling groundwater nitrate concentrations in private wells in Iowa. *Sci. Total Environ.* **2015**, *536*, 481–488. [CrossRef] [PubMed]

49. Ransom, K.M.; Nolan, B.T.; Traum, J.A.; Faunt, C.C.; Bell, A.M.; Gronberg, J.A.M.; Wheeler, D.C.; Rosecrans, C.Z.; Jurgens, B.; Schwarz, G.E.; et al. A hybrid machine learning model to predict and visualize nitrate concentration throughout the Central Valley aquifer, California, USA. *Sci. Total Environ.* **2017**, *601–602*, 1160–1172. [CrossRef] [PubMed]
50. Leach, S.A.; Thompson, M.; Hill, M. Bacterially catalyzed *N*-nitrosation reactions and their relative importance in the human stomach. *Carcinogenesis* **1987**, *8*, 1907–1912. [CrossRef] [PubMed]
51. Lv, J.; Neal, B.; Ehteshami, P.; Ninomiya, T.; Woodward, M.; Rodgers, A.; Wang, H.; MacMahon, S.; Turnbull, F.; Hillis, G.; et al. Effects of intensive blood pressure lowering on cardiovascular and renal outcomes: A systematic review and meta-analysis. *PLoS Med.* **2012**, *9*, e1001293. [CrossRef] [PubMed]
52. Spiegelhalder, B.; Eisenbrand, G.; Preussmann, R. Influence of dietary nitrate on nitrite content of human saliva: Possible relevance to in vivo formation of *N*-nitroso compounds. *Food Cosmet. Toxicol.* **1976**, *14*, 545–548. [CrossRef]
53. Tricker, A.R.; Kalble, T.; Preussmann, R. Increased urinary nitrosamine excretion in patients with urinary diversions. *Carcinogenesis* **1989**, *10*, 2379–2382. [CrossRef] [PubMed]
54. Eisenbrand, G.; Spiegelhalder, B.; Preussmann, R. Nitrate and nitrite in saliva. *Oncology* **1980**, *37*, 227–231. [CrossRef] [PubMed]
55. Eisenbrand, G. *The Significance of N-Nitrosation of Drugs*; Nicolai, H.V., Eisenbrand, G., Bozler, G., Eds.; Gustav Fischer Verlag, Stuttgart: New York, NY, USA, 1990; pp. 47–69.
56. Ceccatelli, S.; Lundberg, J.M.; Fahrenkrug, J.; Bredt, D.S.; Snyder, S.H.; Hokfelt, T. Evidence for involvement of nitric oxide in the regulation of hypothalamic portal blood flow. *Neuroscience* **1992**, *51*, 769–772. [CrossRef]
57. Moncada, S.; Palmer, R.M.J.; Higgs, E.A. Nitric oxide: Physiology, pathophysiology, and pharmacology. *Pharmacol. Rev.* **1991**, *43*, 109–142. [PubMed]
58. Rees, D.D.; Palmer, R.M.; Moncada, S. Role of endothelium-derived nitric oxide in the regulation of blood pressure. *Proc. Natl. Acad. Sci. USA* **1989**, *86*, 3375–3378. [CrossRef] [PubMed]
59. Palmer, R.M.; Ferrige, A.G.; Moncada, S. Nitric oxide release accounts for the biological activity of endothelium-derived relaxing factor. *Nature* **1987**, *327*, 524–526. [CrossRef] [PubMed]
60. Radomski, M.W.; Palmer, R.M.; Moncada, S. Endogenous nitric oxide inhibits human platelet adhesion to vascular endothelium. *Lancet* **1987**, *2*, 1057–1058. [CrossRef]
61. Radomski, M.W.; Palmer, R.M.J.; Moncada, S. The Anti-Aggregating Properties of Vascular Endothelium—Interactions between Prostacyclin and Nitric-Oxide. *Br. J. Pharmacol.* **1987**, *92*, 639–646. [CrossRef] [PubMed]
62. Larsen, F.J.; Schiffer, T.A.; Weitzberg, E.; Lundberg, J.O. Regulation of mitochondrial function and energetics by reactive nitrogen oxides. *Free Radic. Biol. Med.* **2012**, *53*, 1919–1928. [CrossRef] [PubMed]
63. Ceccatelli, S.; Hulting, A.L.; Zhang, X.; Gustafsson, L.; Villar, M.; Hokfelt, T. Nitric oxide synthase in the rat anterior pituitary gland and the role of nitric oxide in regulation of luteinizing hormone secretion. *Proc. Natl. Acad. Sci. USA* **1993**, *90*, 11292–11296. [CrossRef] [PubMed]
64. Green, S.J.; Scheller, L.F.; Marletta, M.A.; Seguin, M.C.; Klotz, F.W.; Slayter, M.; Nelson, B.J.; Nacy, C.A. Nitric oxide: Cytokine-regulation of nitric oxide in host resistance to intracellular pathogens. *Immunol. Lett.* **1994**, *43*, 87–94. [CrossRef]
65. Langrehr, J.M.; Hoffman, R.A.; Lancaster, J.R.; Simmons, R.L. Nitric oxide—A new endogenous immunomodulator. *Transplantation* **1993**, *55*, 1205–1212. [CrossRef] [PubMed]
66. Wei, X.Q.; Charles, I.G.; Smith, A.; Ure, J.; Feng, G.J.; Huang, F.P.; Xu, D.; Muller, W.; Moncada, S.; Liew, F.Y. Altered immune responses in mice lacking inducible nitric oxide synthase. *Nature* **1995**, *375*, 408–411. [CrossRef] [PubMed]
67. D'Ischia, M.; Napolitano, A.; Manini, P.; Panzella, L. Secondary Targets of Nitrite-Derived Reactive Nitrogen Species: Nitrosation/Nitration Pathways, Antioxidant Defense Mechanisms and Toxicological Implications. *Chem. Res. Toxicol.* **2011**, *24*, 2071–2092. [CrossRef] [PubMed]
68. Mirvish, S.S. Formation of N-nitroso compounds: Chemistry, kinetics, and in vivo occurrence. *Toxicol. Appl. Pharmacol.* **1975**, *31*, 325–351. [CrossRef]
69. Ridd, J.H. Nitrosation, diazotisation, and deamination. *Q. Rev.* **1961**, *15*, 418–441. [CrossRef]
70. Akuta, T.; Zaki, M.H.; Yoshitake, J.; Okamoto, T.; Akaike, T. Nitrative stress through formation of 8-nitroguanosine: Insights into microbial pathogenesis. *Nitric Oxide* **2006**, *14*, 101–108. [CrossRef] [PubMed]

71. Loeppky, R.N.; Bao, Y.T.; Bae, J.Y.; Yu, L.; Shevlin, G. Blocking nitrosamine formation—Understanding the chemistry of rapid nitrosation. In *Nitrosamines and Related N-Nitroso Compounds: Chemistry and Biochemistry*; Loeppky, R.N., Michejda, C.J., Eds.; American Chemical Society: Washington, DC, USA, 1994; Volume 553, pp. 52–65.
72. Qin, L.Z.; Liu, X.B.; Sun, Q.F.; Fan, Z.P.; Xia, D.S.; Ding, G.; Ong, H.L.; Adams, D.; Gahl, W.A.; Zheng, C.Y.; et al. Sialin (SLC17A5) functions as a nitrate transporter in the plasma membrane. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 13434–13439. [CrossRef] [PubMed]
73. Stich, H.F.; Dunn, B.P.; Pignatelli, B.; Ohshima, H.; Bartsch, H. *Dietary Phenolics and Betel Nut Extracts as Modifiers of n Nitrosation in Rat and Man*; IARC Scientific Publications: Lyon, France, 1984; pp. 213–222.
74. Vermeer, I.T.; Moonen, E.J.; Dallinga, J.W.; Kleinjans, J.C.; van Maanen, J.M. Effect of ascorbic acid and green tea on endogenous formation of N-nitrosodimethylamine and *N*-nitrosopiperidine in humans. *Mutat. Res.* **1999**, *428*, 353–361. [CrossRef]
75. Vermeer, I.T.; Pachen, D.M.; Dallinga, J.W.; Kleinjans, J.C.; van Maanen, J.M. Volatile N-nitrosamine formation after intake of nitrate at the ADI level in combination with an amine-rich diet. *Environ. Health Perspect.* **1998**, *106*, 459–463. [PubMed]
76. Chung, M.J.; Lee, S.H.; Sung, N.J. Inhibitory effect of whole strawberries, garlic juice or kale juice on endogenous formation of *N*-nitrosodimethylamine in humans. *Cancer Lett.* **2002**, *182*, 1–10. [CrossRef]
77. Helser, M.A.; Hotchkiss, J.H.; Roe, D.A. Influence of fruit and vegetable juices on the endogenous formation of N-nitrosoproline and *N*-nitrosothiazolidine-4-carboxylic acid in humans on controlled diets. *Carcinogenesis* **1992**, *13*, 2277–2280. [CrossRef] [PubMed]
78. Zeilmaker, M.J.; Bakker, M.I.; Schothorst, R.; Slob, W. Risk assessment of *N*-nitrosodimethylamine formed endogenously after fish-with-vegetable meals. *Toxicol. Sci.* **2010**, *116*, 323–335. [CrossRef] [PubMed]
79. Khandelwal, N.; Abraham, S.K. Intake of anthocyanidins pelargonidin and cyanidin reduces genotoxic stress in mice induced by diepoxybutane, urethane and endogenous nitrosation. *Environ. Toxicol. Pharmacol.* **2014**, *37*, 837–843. [CrossRef] [PubMed]
80. Conforti, F.; Menichini, F. Phenolic Compounds from Plants as Nitric Oxide Production Inhibitors. *Curr. Med. Chem.* **2011**, *18*, 1137–1145. [CrossRef] [PubMed]
81. Abraham, S.K.; Khandelwal, N. Ascorbic acid and dietary polyphenol combinations protect against genotoxic damage induced in mice by endogenous nitrosation. *Mutat. Res.* **2013**, *757*, 167–172. [CrossRef] [PubMed]
82. De Kok, T.M.; (Maastricht, The Netherlands). Unpublished work. 2018.
83. Haorah, J.; Zhou, L.; Wang, X.J.; Xu, G.P.; Mirvish, S.S. Determination of total *N*-nitroso compounds and their precursors in frankfurters, fresh meat, dried salted fish, sauces, tobacco, and tobacco smoke particulates. *J. Agric. Food Chem.* **2001**, *49*, 6068–6078. [CrossRef] [PubMed]
84. Cross, A.J.; Pollock, J.R.; Bingham, S.A. Haem, not protein or inorganic iron, is responsible for endogenous intestinal N-nitrosation arising from red meat. *Cancer Res.* **2003**, *63*, 2358–2360. [PubMed]
85. Bingham, S.A.; Pignatelli, B.; Pollock, J.R.A.; Ellul, A.; Malaveille, C.; Gross, G.; Runswick, S.; Cummings, J.H.; O'Neill, I.K. Does increased endogenous formation of *N*-nitroso compounds in the human colon explain the association between red meat and colon cancer? *Carcinogenesis* **1996**, *17*, 515–523. [CrossRef] [PubMed]
86. Bingham, S.A.; Hughes, R.; Cross, A.J. Effect of white versus red meat on endogenous *N*-nitrosation in the human colon and further evidence of a dose response. *J. Nutr.* **2002**, *132*, 3522s–3525s. [CrossRef] [PubMed]
87. Bingham, S.A. High-meat diets and cancer risk. *Proc. Nutr. Soc.* **1999**, *58*, 243–248. [CrossRef] [PubMed]
88. Bouvard, V.; Loomis, D.; Guyton, K.Z.; Grosse, Y.; Ghissassi, F.E.; Benbrahim-Tallaa, L.; Guha, N.; Mattock, H.; Straif, K. International Agency for Research on Cancer Monograph Working, G. Carcinogenicity of consumption of red and processed meat. *Lancet Oncol.* **2015**, *16*, 1599–1600. [CrossRef]
89. International Agency for Research on Cancer (IARC). *IARC Monographs on the Evaluation of Carcionogenic Risks to Humans: Red Meat and Processed Meat*; IARC: Lyon, France, 2018.
90. Phytochemicals to Reduce Nitrite in Meat Products (PHYTOME). Available online: www.phytome.eu (accessed on 3 May 2018).
91. Greer, F.R.; Shannon, M. American Academy of Pediatrics Committee on Nutrition and the Committee on Environmental Health. Infant methemoglobinemia: The role of dietary nitrate in food and water. *Pediatrics* **2005**, *116*, 784–786. [CrossRef] [PubMed]
92. Sanchez-Echaniz, J.; Benito-Fernandez, J.; Mintegui-Raso, S. Methemoglobinemia and consumption of vegetables in infants. *Pediatrics* **2001**, *107*, 1024–1028. [CrossRef] [PubMed]

93. Charmandari, E.; Meadows, N.; Patel, M.; Johnston, A.; Benjamin, N. Plasma nitrate concentrations in children with infectious and noninfectious diarrhea. *J. Pediatr. Gastroenterol. Nutr.* **2001**, *32*, 423–427. [CrossRef] [PubMed]
94. Comly, H.H. Landmark article 8 September 1945: Cyanosis in infants caused by nitrates in well-water. By Hunter H. Comly. *JAMA* **1987**, *257*, 2788–2792. [CrossRef] [PubMed]
95. Walton, G. Survey of literature relating to infant methemoglobinemia due to nitrate-contaminated water. *Am. J. Public Health Nation's Health* **1951**, *41*, 986–996. [CrossRef]
96. Knobeloch, L.; Salna, B.; Hogan, A.; Postle, J.; Anderson, H. Blue babies and nitrate-contaminated well water. *Environ. Health Perspect.* **2000**, *108*, 675–678. [CrossRef] [PubMed]
97. Johnson, C.J.; Bonrud, P.A.; Dosch, T.L.; Kilness, A.W.; Senger, K.A.; Busch, D.C.; Meyer, M.R. Fatal outcome of methemoglobinemia in an infant. *JAMA* **1987**, *257*, 2796–2797. [CrossRef] [PubMed]
98. Lutynski, R.; Steczek-Wojdyla, M.; Wojdyla, Z.; Kroch, S. The concentrations of nitrates and nitrites in food products and environment and the occurrence of acute toxic methemoglobinemias. *Prz. Lek.* **1996**, *53*, 351–355. [PubMed]
99. Ayebo, A.; Kross, B.C.; Vlad, M.; Sinca, A. Infant Methemoglobinemia in the Transylvania Region of Romania. *Int. J. Occup. Environ. Health* **1997**, *3*, 20–29. [CrossRef] [PubMed]
100. World Health Organization. *Water and Health in Europe*; World Health Organization: Geneva, Switzerland, 2002.
101. Abu Naser, A.A.; Ghbn, N.; Khoudary, R. Relation of nitrate contamination of groundwater with methaemoglobin level among infants in Gaza. *East Mediterr. Health J.* **2007**, *13*, 994–1004. [CrossRef] [PubMed]
102. Sadeq, M.; Moe, C.L.; Attarassi, B.; Cherkaoui, I.; ElAouad, R.; Idrissi, L. Drinking water nitrate and prevalence of methemoglobinemia among infants and children aged 1–7 years in Moroccan areas. *Int. J. Hyg. Environ. Health* **2008**, *211*, 546–554. [CrossRef] [PubMed]
103. Zeman, C.; Beltz, L.; Linda, M.; Maddux, J.; Depken, D.; Orr, J.; Theran, P. New Questions and Insights into Nitrate/Nitrite and Human Health Effects: A Retrospective Cohort Study of Private Well Users' Immunological and Wellness Status. *J. Environ. Health* **2011**, *74*, 8–18. [PubMed]
104. Manassaram, D.M.; Backer, L.C.; Messing, R.; Fleming, L.E.; Luke, B.; Monteilh, C.P. Nitrates in drinking water and methemoglobin levels in pregnancy: A longitudinal study. *Environ. Health* **2010**, *9*, 60. [CrossRef] [PubMed]
105. Grant, W.; Steele, G.; Isiorho, S.A. Spontaneous abortions possibly related to ingestion of nitrate-contaminated well water: LaGrange County, Indiana, 1991–1994. *Morb. Mortal. Wkly. Rep.* **1996**, *45*, 569–572.
106. Aschengrau, A.; Zierler, S.; Cohen, A. Quality of community drinking water and the occurrence of spontaneous abortion. *Arch Environ. Health* **1989**, *44*, 283–290. [CrossRef] [PubMed]
107. Albouy-Llaty, M.; Limousi, F.; Carles, C.; Dupuis, A.; Rabouan, S.; Migeot, V. Association between Exposure to Endocrine Disruptors in Drinking Water and Preterm Birth, Taking Neighborhood Deprivation into Account: A Historic Cohort Study. *Int. J. Environ. Res. Public Health* **2016**, *13*, 796. [CrossRef] [PubMed]
108. Stayner, L.T.; Almberg, K.; Jones, R.; Graber, J.; Pedersen, M.; Turyk, M. Atrazine and nitrate in drinking water and the risk of preterm delivery and low birth weight in four Midwestern states. *Environ. Res.* **2017**, *152*, 294–303. [CrossRef] [PubMed]
109. Joyce, S.J.; Cook, A.; Newnham, J.; Brenters, M.; Ferguson, C.; Weinstein, P. Water disinfection by-products and prelabor rupture of membranes. *Am. J. Epidemiol.* **2008**, *168*, 514–521. [CrossRef] [PubMed]
110. Mattix, K.D.; Winchester, P.D.; Scherer, L.R. Incidence of abdominal wait defects is related to surface water atrazine and nitrate levels. *J. Pediatr. Surg.* **2007**, *42*, 947–949. [CrossRef] [PubMed]
111. Waller, S.A.; Paul, K.; Peterson, S.E.; Hitti, J.E. Agricultural-related chemical exposures, season of conception, and risk of gastroschisis in Washington State. *Am. J. Obstet. Gynecol.* **2010**, *202*, e241–e246. [CrossRef] [PubMed]
112. Winchester, P.D.; Huskins, J.; Ying, J. Agrichemicals in surface water and birth defects in the United States. *Acta Paediatr.* **2009**, *98*, 664–669. [CrossRef] [PubMed]
113. Holtby, C.E.; Guernsey, J.R.; Allen, A.C.; VanLeeuwen, J.A.; Allen, V.M.; Gordon, R.J. A Population-Based Case-Control Study of Drinking-Water Nitrate and Congenital Anomalies Using Geographic Information Systems (GIS) to Develop Individual-Level Exposure Estimates. *Int. J. Environ. Res. Public Health* **2014**, *11*, 1803–1823. [CrossRef] [PubMed]

114. Weyer, P.J.; Brender, J.D.; Romitti, P.A.; Kantamneni, J.R.; Crawford, D.; Sharkey, J.R.; Shinde, M.; Horel, S.A.; Vuong, A.M.; Langlois, P.H. Assessing bottled water nitrate concentrations to evaluate total drinking water nitrate exposure and risk of birth defects. *J. Water Health* **2014**, *12*, 755–762. [CrossRef] [PubMed]
115. Yoon, P.W.; Rasmussen, S.A.; Lynberg, M.C.; Moore, C.A.; Anderka, M.; Carmichael, S.L.; Costa, P.; Druschel, C.; Hobbs, C.A.; Romitti, P.A.; et al. The National Birth Defects Prevention Study. *Public Health Rep.* **2001**, *116* (Suppl. 1), 32–40. [CrossRef] [PubMed]
116. Brender, J.D.; Kelley, K.E.; Werler, M.M.; Langlois, P.H.; Suarez, L.; Canfield, M.A. National Birth Defects Prevention Study. Prevalence and Patterns of Nitrosatable Drug Use among U.S. Women during Early Pregnancy. *Birth Defects Res. A* **2011**, *91*, 258–264. [CrossRef] [PubMed]
117. Griesenbeck, J.S.; Brender, J.D.; Sharkey, J.R.; Steck, M.D.; Huber, J.C., Jr.; Rene, A.A.; McDonald, T.J.; Romitti, P.A.; Canfield, M.A.; Langlois, P.H.; et al. Maternal characteristics associated with the dietary intake of nitrates, nitrites, and nitrosamines in women of child-bearing age: A cross-sectional study. *Environ. Health* **2010**, *9*, 10. [CrossRef] [PubMed]
118. Brender, J.D.; Werler, M.M.; Shinde, M.U.; Vuong, A.M.; Kelley, K.E.; Huber, J.C., Jr.; Sharkey, J.R.; Griesenbeck, J.S.; Romitti, P.A.; Malik, S.; et al. Nitrosatable drug exposure during the first trimester of pregnancy and selected congenital malformations. *Birth Defects Res. A* **2012**, *94*, 701–713. [CrossRef] [PubMed]
119. Brender, J.D.; Werler, M.M.; Kelley, K.E.; Vuong, A.M.; Shinde, M.U.; Zheng, Q.; Huber, J.C., Jr.; Sharkey, J.R.; Griesenbeck, J.S.; Romitti, P.A.; et al. Nitrosatable drug exposure during early pregnancy and neural tube defects in offspring: National Birth Defects Prevention Study. *Am. J. Epidemiol.* **2011**, *174*, 1286–1295. [CrossRef] [PubMed]
120. Brender, J.D.; Olive, J.M.; Felkner, M.; Suarez, L.; Marckwardt, W.; Hendricks, K.A. Dietary nitrites and nitrates, nitrosatable drugs, and neural tube defects. *Epidemiology* **2004**, *15*, 330–336. [CrossRef] [PubMed]
121. Dorsch, M.M.; Scragg, R.K.; McMichael, A.J.; Baghurst, P.A.; Dyer, K.F. Congenital malformations and maternal drinking water supply in rural South Australia: A case-control study. *Am. J. Epidemiol.* **1984**, *119*, 473–486. [CrossRef] [PubMed]
122. Croen, L.A.; Todoroff, K.; Shaw, G.M. Maternal exposure to nitrate from drinking water and diet and risk for neural tube defects. *Am. J. Epidemiol.* **2001**, *153*, 325–331. [CrossRef] [PubMed]
123. Arbuckle, T.E.; Sherman, G.J.; Corey, P.N.; Walters, D.; Lo, B. Water nitrates and CNS birth defects: A population-based case-control study. *Arch Environ. Health* **1988**, *43*, 162–167. [CrossRef] [PubMed]
124. Ericson, A.; Kallen, B.; Lofkvist, E. Environmental factors in the etiology of neural tube defects: A negative study. *Environ. Res.* **1988**, *45*, 38–47. [CrossRef]
125. Cantor, K.P. Drinking water and cancer. *Cancer Causes Control* **1997**, *8*, 292–308. [CrossRef] [PubMed]
126. Quist, A.J.L.; Inoue-Choi, M.; Weyer, P.J.; Anderson, K.E.; Cantor, K.P.; Krasner, S.; Freeman, L.E.B.; Ward, M.H.; Jones, R.R. Ingested nitrate and nitrite, disinfection by-products, and pancreatic cancer risk in postmenopausal women. *Int. J. Cancer* **2018**, *142*, 251–261. [CrossRef] [PubMed]
127. Jones, R.R.; Weyer, P.J.; DellaValle, C.T.; Robien, K.; Cantor, K.P.; Krasner, S.; Freeman, L.E.B.; Ward, M.H. Ingested nitrate, disinfection by-products, and kidney cancer risk in older women. *Epidemiology* **2017**, *28*, 703–711. [CrossRef] [PubMed]
128. Inoue-Choi, M.; Ward, M.H.; Cerhan, J.R.; Weyer, P.J.; Anderson, K.E.; Robien, K. Interaction of nitrate and folate on the risk of breast cancer among postmenopausal women. *Nutr. Cancer* **2012**, *64*, 685–694. [CrossRef] [PubMed]
129. Inoue-Choi, M.; Jones, R.R.; Anderson, K.E.; Cantor, K.P.; Cerhan, J.R.; Krasner, S.; Robien, K.; Weyer, P.J.; Ward, M.H. Nitrate and nitrite ingestion and risk of ovarian cancer among postmenopausal women in Iowa. *Int. J. Cancer* **2015**, *137*, 173–182. [CrossRef] [PubMed]
130. Weyer, P.J.; Cerhan, J.R.; Kross, B.C.; Hallberg, G.R.; Kantamneni, J.; Breuer, G.; Jones, M.P.; Zheng, W.; Lynch, C.F. Municipal drinking water nitrate level and cancer risk in older women: The Iowa Women's Health Study. *Epidemiology* **2001**, *12*, 327–338. [CrossRef] [PubMed]
131. Zeegers, M.P.; Selen, R.F.; Kleinjans, J.C.; Goldbohm, R.A.; van den Brandt, P.A. Nitrate intake does not influence bladder cancer risk: The Netherlands cohort study. *Environ. Health Perspect.* **2006**, *114*, 1527–1531. [CrossRef] [PubMed]
132. Ward, M.H.; Mark, S.D.; Cantor, K.P.; Weisenburger, D.D.; Correa-Villasenor, A.; Zahm, S.H. Drinking water nitrate and the risk of non-Hodgkin's lymphoma. *Epidemiology* **1996**, *7*, 465–471. [CrossRef] [PubMed]

133. Ward, M.H.; Heineman, E.F.; Markin, R.S.; Weisenburger, D.D. Adenocarcinoma of the stomach and esophagus and drinking water and dietary sources of nitrate and nitrite. *Int. J. Occup. Environ. Health* **2008**, *14*, 193–197. [CrossRef] [PubMed]
134. McElroy, J.A.; Trentham-Dietz, A.; Gangnon, R.E.; Hampton, J.M.; Bersch, A.J.; Kanarek, M.S.; Newcomb, P.A. Nitrogen-nitrate exposure from drinking water and colorectal cancer risk for rural women in Wisconsin, USA. *J. Water Health* **2008**, *6*, 399–409. [CrossRef] [PubMed]
135. Espejo-Herrera, N.; Gracia-Lavedan, E.; Boldo, E.; Aragones, N.; Perez-Gomez, B.; Pollan, M.; Molina, A.J.; Fernandez, T.; Martin, V.; La Vecchia, C.; et al. Colorectal cancer risk and nitrate exposure through drinking water and diet. *Int. J. Cancer* **2016**, *139*, 334–346. [CrossRef] [PubMed]
136. Fathmawati; Fachiroh, J.; Gravitiani, E.; Sarto; Husodo, A.H. Nitrate in drinking water and risk of colorectal cancer in Yogyakarta, Indonesia. *J. Toxicol. Environ. Health Part A* **2017**, *80*, 120–128. [CrossRef] [PubMed]
137. Brody, J.G.; Aschengrau, A.; McKelvey, W.; Swartz, C.H.; Kennedy, T.; Rudel, R.A. Breast cancer risk and drinking water contaminated by wastewater: A case control study. *Environ. Health-Glob.* **2006**, *5*, 28. [CrossRef] [PubMed]
138. Espejo-Herrera, N.; Gracia-Lavedan, E.; Pollan, M.; Aragones, N.; Boldo, E.; Perez-Gomez, B.; Altzibar, J.M.; Amiano, P.; Zabala, A.J.; Ardanaz, E.; et al. Ingested Nitrate and Breast Cancer in the Spanish Multicase-Control Study on Cancer (MCC-Spain). *Environ. Health Perspect.* **2016**, *124*, 1042–1049. [CrossRef] [PubMed]
139. Mueller, B.A.; Nielsen, S.S.; Preston-Martin, S.; Holly, E.A.; Cordier, S.; Filippini, G.; Peris-Bonet, R.; Choi, N.W. Household water source and the risk of childhood brain tumours: Results of the SEARCH International Brain Tumor Study. *Int. J. Epidemiol.* **2004**, *33*, 1209–1216. [CrossRef] [PubMed]
140. Mueller, B.A.; Newton, K.; Holly, E.A.; Preston-Martin, S. Residential water source and the risk of childhood brain tumors. *Environ. Health Perspect.* **2001**, *109*, 551–556. [CrossRef] [PubMed]
141. De Groef, B.; Decallonne, B.R.; Van der Geyten, S.; Darras, V.M.; Bouillon, R. Perchlorate versus other environmental sodium/iodide symporter inhibitors: Potential thyroid-related health effects. *Eur. J. Endocrinol.* **2006**, *155*, 17–25. [CrossRef] [PubMed]
142. Van Maanen, J.M.; Welle, I.J.; Hageman, G.; Dallinga, J.W.; Mertens, P.L.; Kleinjans, J.C. Nitrate contamination of drinking water: Relationship with HPRT variant frequency in lymphocyte DNA and urinary excretion of N-nitrosamines. *Environ. Health Perspect.* **1996**, *104*, 522–528. [CrossRef] [PubMed]
143. Radikova, Z.; Tajtakova, M.; Kocan, A.; Trnovec, T.; Sebokova, E.; Klimes, I.; Langer, P. Possible effects of environmental nitrates and toxic organochlorines on human thyroid in highly polluted areas in Slovakia. *Thyroid Off. J. Am. Thyroid Assoc.* **2008**, *18*, 353–362. [CrossRef] [PubMed]
144. Tajtakova, M.; Semanova, Z.; Tomkova, Z.; Szokeova, E.; Majoros, J.; Radikova, Z.; Sebokova, E.; Klimes, I.; Langer, P. Increased thyroid volume and frequency of thyroid disorders signs in schoolchildren from nitrate polluted area. *Chemosphere* **2006**, *62*, 559–564. [CrossRef] [PubMed]
145. Aschebrook-Kilfoy, B.; Heltshe, S.L.; Nuckols, J.R.; Sabra, M.M.; Shuldiner, A.R.; Mitchell, B.D.; Airola, M.; Holford, T.R.; Zhang, Y.; Ward, M.H. Modeled nitrate levels in well water supplies and prevalence of abnormal thyroid conditions among the Old Order Amish in Pennsylvania. *Environ. Health* **2012**, *11*, 6. [CrossRef] [PubMed]
146. Longnecker, M.P.; Daniels, J.L. Environmental contaminants as etiologic factors for diabetes. *Environ. Health Perspect.* **2001**, *109* (Suppl. 6), 871–876. [CrossRef] [PubMed]
147. Moltchanova, E.; Rytkonen, M.; Kousa, A.; Taskinen, O.; Tuomilehto, J.; Karvonen, M.; Spat Study, G. Finnish Childhood Diabetes Registry, G. Zinc and nitrate in the ground water and the incidence of Type 1 diabetes in Finland. *Diabet. Med.* **2004**, *21*, 256–261. [CrossRef] [PubMed]
148. Muntoni, S.; Cocco, P.; Muntoni, S.; Aru, G. Nitrate in community water supplies and risk of childhood type 1 diabetes in Sardinia, Italy. *Eur. J. Epidemiol.* **2006**, *21*, 245–247. [CrossRef] [PubMed]
149. Benson, V.S.; Vanleeuwen, J.A.; Taylor, J.; Somers, G.S.; McKinney, P.A.; Van Til, L. Type 1 diabetes mellitus and components in drinking water and diet: A population-based, case-control study in Prince Edward Island, Canada. *J. Am. Coll. Nutr.* **2010**, *29*, 612–624. [CrossRef] [PubMed]
150. Winkler, C.; Mollenhauer, U.; Hummel, S.; Bonifacio, E.; Ziegler, A.G. Exposure to environmental factors in drinking water: Risk of islet autoimmunity and type 1 diabetes—The BABYDIAB study. *Horm. Metab. Res.* **2008**, *40*, 566–571. [CrossRef] [PubMed]

151. Klein, B.E.K.; McElroy, J.A.; Klein, R.; Howard, K.P.; Lee, K.E. Nitrate-nitrogen levels in rural drinking water: Is there an association with age-related macular degeneration? *J. Environ. Sci. Health Part A* **2013**, *48*, 1757–1763. [CrossRef] [PubMed]
152. Ahluwalia, A.; Gladwin, M.; Coleman, G.D.; Hord, N.; Howard, G.; Kim-Shapiro, D.B.; Lajous, M.; Larsen, F.J.; Lefer, D.J.; McClure, L.A.; et al. Dietary Nitrate and the Epidemiology of Cardiovascular Disease: Report From a National Heart, Lung, and Blood Institute Workshop. *J. Am. Heart Assoc.* **2016**, *5*, e003402. [CrossRef] [PubMed]
153. Kapil, V.; Khambata, R.S.; Robertson, A.; Caulfield, M.J.; Ahluwalia, A. Dietary nitrate provides sustained blood pressure lowering in hypertensive patients: A randomized, phase 2, double-blind, placebo-controlled study. *Hypertension* **2015**, *65*, 320–327. [CrossRef] [PubMed]
154. Omar, S.A.; Webb, A.J.; Lundberg, J.O.; Weitzberg, E. Therapeutic effects of inorganic nitrate and nitrite in cardiovascular and metabolic diseases. *J. Intern. Med.* **2016**, *279*, 315–336. [CrossRef] [PubMed]
155. Presley, T.D.; Morgan, A.R.; Bechtold, E.; Clodfelter, W.; Dove, R.W.; Jennings, J.M.; Kraft, R.A.; King, S.B.; Laurienti, P.J.; Rejeski, W.J.; et al. Acute effect of a high nitrate diet on brain perfusion in older adults. *Nitric Oxide* **2011**, *24*, 34–42. [CrossRef] [PubMed]
156. Maas, R.; Schwedhelm, E.; Kahl, L.; Li, H.; Benndorf, R.; Luneburg, N.; Forstermann, U.; Boger, R.H. Simultaneous assessment of endothelial function, nitric oxide synthase activity, nitric oxide-mediated signaling, and oxidative stress in individuals with and without hypercholesterolemia. *Clin. Chem.* **2008**, *54*, 292–300. [CrossRef] [PubMed]
157. Jadert, C.; Phillipson, M.; Holm, L.; Lundberg, J.O.; Borniquel, S. Preventive and therapeutic effects of nitrite supplementation in experimental inflammatory bowel disease. *Redox Biol.* **2014**, *2*, 73–81. [CrossRef] [PubMed]
158. Khademikia, S.; Rafiee, Z.; Amin, M.M.; Poursafa, P.; Mansourian, M.; Modaberi, A. Association of nitrate, nitrite, and total organic carbon (TOC) in drinking water and gastrointestinal disease. *J. Environ. Public Health* **2013**, *2013*, 603468. [CrossRef] [PubMed]
159. De Roos, A.J.; Ward, M.H.; Lynch, C.F.; Cantor, K.P. Nitrate in public water supplies and the risk of colon and rectum cancers. *Epidemiology* **2003**, *14*, 640–649. [CrossRef] [PubMed]
160. Gatseva, P.D.; Argirova, M.D. High-nitrate levels in drinking water may be a risk factor for thyroid dysfunction in children and pregnant women living in rural Bulgarian areas. *Int. J. Hyg. Environ. Health* **2008**, *211*, 555–559. [CrossRef] [PubMed]
161. Toccalino, P.L.; Norman, J.E.; Scott, J.C. Chemical mixtures in untreated water from public-supply wells in the U.S.—Occurrence, composition, and potential toxicity. *Sci. Total Environ.* **2012**, *431*, 262–270. [CrossRef] [PubMed]
162. Joshi, N.; Rhoades, M.G.; Bennett, G.D.; Wells, S.M.; Mirvish, S.S.; Breitbach, M.J.; Shea, P.J. Developmental abnormalities in chicken embryos exposed to *N*-nitrosoatrazine. *J. Toxicol. Environ. Health Part A* **2013**, *76*, 1015–1022. [CrossRef] [PubMed]
163. Mitch, W.A.; Sharp, J.O.; Rhoades Trussell, R.; Valentine, R.L.; Alvarez-Cohen, L.; DSedlak, D.L. *N*-Nitrosodimethylamine (NDMA) as a Drinking Water Contaminant: A Review. *Environ. Eng. Sci.* **2003**, *20*, 389–404. [CrossRef]
164. Krasner, S.W. The formation and control of emerging disinfection by-products of health concern. *Philos. Trans.* **2009**, *367*, 4077–4095. [CrossRef] [PubMed]
165. Hezel, M.P.; Weitzberg, E. The oral microbiome and nitric oxide homoeostasis. *Oral Dis.* **2015**, *21*, 7–16. [CrossRef] [PubMed]
166. Hyde, E.R.; Andrade, F.; Vaksman, Z.; Parthasarathy, K.; Jiang, H.; Parthasarathy, D.K.; Torregrossa, A.C.; Tribble, G.; Kaplan, H.B.; Petrosino, J.F.; et al. Metagenomic analysis of nitrate-reducing bacteria in the oral cavity: Implications for nitric oxide homeostasis. *PLoS ONE* **2014**, *9*, e88645. [CrossRef] [PubMed]
167. Burleigh, M.C.; Liddle, L.; Monaghan, C.; Muggeridge, D.J.; Sculthorpe, N.; Butcher, J.P.; Henriquez, F.L.; Allen, J.D.; Easton, C. Salivary nitrite production is elevated in individuals with a higher abundance of oral nitrate-reducing bacteria. *Free Radic. Biol. Med.* **2018**, *120*, 80–88. [CrossRef] [PubMed]
168. Vogtmann, E.; Chen, J.; Amir, A.; Shi, J.; Abnet, C.C.; Nelson, H.; Knight, R.; Chia, N.; Sinha, R. Comparison of Collection Methods for Fecal Samples in Microbiome Studies. *Am. J. Epidemiol.* **2017**, *185*, 115–123. [CrossRef] [PubMed]

169. Sinha, R.; Abu-Ali, G.; Vogtmann, E.; Fodor, A.A.; Ren, B.; Amir, A.; Schwager, E.; Crabtree, J.; Ma, S.; The Microbiome Quality Control Project Consortium; et al. Assessment of variation in microbial community amplicon sequencing by the Microbiome Quality Control (MBQC) project consortium. *Nat. Biotechnol.* **2017**, *35*, 1077–1086. [PubMed]
170. Hebels, D.G.; Jennen, D.G.; van Herwijnen, M.H.; Moonen, E.J.; Pedersen, M.; Knudsen, L.E.; Kleinjans, J.C.; de Kok, T.M. Whole-genome gene expression modifications associated with nitrosamine exposure and micronucleus frequency in human blood cells. *Mutagenesis* **2011**, *26*, 753–761. [CrossRef] [PubMed]
171. Hebels, D.G.; Jennen, D.G.; Kleinjans, J.C.; de Kok, T.M. Molecular signatures of N-nitroso compounds in Caco-2 cells: Implications for colon carcinogenesis. *Toxicol. Sci.* **2009**, *108*, 290–300. [CrossRef] [PubMed]
172. Vineis, P.; Chadeau-Hyam, M.; Gmuender, H.; Gulliver, J.; Herceg, Z.; Kleinjans, J.; Kogevinas, M.; Kyrtopoulos, S.; Nieuwenhuijsen, M.; Phillips, D.H.; et al. The exposome in practice: Design of the EXPOsOMICS project. *Int. J. Hyg. Environ. Health* **2017**, *220*, 142–151. [CrossRef] [PubMed]
173. Hebels, D.G.; Georgiadis, P.; Keun, H.C.; Athersuch, T.J.; Vineis, P.; Vermeulen, R.; Portengen, L.; Bergdahl, I.A.; Hallmans, G.; Palli, D.; et al. Performance in omics analyses of blood samples in long-term storage: Opportunities for the exploitation of existing biobanks in environmental health research. *Environ. Health Perspect.* **2013**, *121*, 480–487. [CrossRef] [PubMed]
174. International Nitrogen Initiative. Available online: http://www.initrogen.org/ (accessed on 22 April 2018).
175. Dinnes, D.L.; Karlen, D.L.; Jaynes, D.B.; Kaspar, T.C.; Hatfield, J.L.; Colvin, T.S.; Cambardella, C.A. Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. *Agron. J.* **2002**, *94*, 153–171. [CrossRef]
176. Baron, J.S.; Hall, E.K.; Nolan, B.T.; Finlay, J.C.; Bernhardt, E.S.; Harrison, J.A.; Chan, F.; Boyer, E.W. The interactive effects of excess reactive nitrogen and climate change on aquatic ecosystems and water resources of the United States. *Biogeochemistry* **2013**, *114*, 71–92. [CrossRef]



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Nitrate and nitrite ingestion and risk of ovarian cancer among postmenopausal women in Iowa

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Nitrate and nitrite are precursors in the endogenous formation of *N*-nitroso compounds (NOC), potential human carcinogens. We evaluated the association of nitrate and nitrite ingestion with postmenopausal ovarian cancer risk in the Iowa Women's Health Study. Among 28,555 postmenopausal women, we identified 315 incident epithelial ovarian cancers from 1986 to 2010. Dietary nitrate and nitrite intakes were assessed at baseline using food frequency questionnaire data. Drinking water source at home was obtained in a 1989 follow-up survey. Nitrate-nitrogen (NO_3-N) and total trihalomethane (TTHM) levels for Iowa public water utilities were linked to residences and average levels were computed based on each woman's duration at the residence. We computed multivariable-adjusted hazard ratios (HR) and 95% confidence intervals (CI) using Cox proportional hazards regression. We tested interactions of nitrate with TTHMs and dietary factors known to influence NOC formation. Ovarian cancer risk was 2.03 times higher (CI = 1.22–3.38, $p_{trend} = 0.003$) in the highest quartile ($\geq$2.98 mg/L) compared with the lowest quartile ($\leq$0.47 mg/L; reference) of NO_3-N in public water, regardless of TTHM levels. Risk among private well users was also elevated (HR = 1.53, CI = 0.93–2.54) compared with the same reference group. Associations were stronger when vitamin C intake was <median ($p_{interaction} = 0.01$ and 0.33 for private well and public supplies, respectively). Dietary nitrate was inversely associated with ovarian cancer risk ($p_{trend} = 0.02$); whereas, dietary nitrite from processed meats was positively associated with the risk ($p_{trend} = 0.04$). Our findings indicate that high nitrate levels in public drinking water and private well use may increase ovarian cancer risk among postmenopausal women.

Ovarian cancer has the highest mortality rate among all cancers of the female reproductive system.[1] Given its poor prognosis, identifying risk factors is critical to decrease mortality from ovarian cancer. However, the etiology of this malignancy is poorly understood. A large variation in ovarian cancer incidence among countries[2] and the increased risk of ovarian cancer among immigrants to the United States from other countries with low ovarian cancer incidence such as Japan[3,4] suggest a role of environmental factors, including diet. However, few modifiable risk factors have been identified to date.

Nitrate is a common contaminant of drinking water. Nitrogen from nitrogen fertilizer applications and animal and

Key words: nitrate, nitrite, ovarian cancer, diet, drinking water, disinfection byproducts

Abbreviations: BMI: body mass index; CI: confidence interval; CSFII: Continuing Survey of Food Intake by Individuals; DBP: disinfection byproduct; FFQ: food frequency questionnaire; HAA: haloacetic acid; HR: hazard ratio; IWHS: Iowa Women's Health Study; MCL: maximum contaminant level; NOC: *N*-nitroso compounds; RDI: recommended daily intake; TTHM: total trihalomethane.

Additional Supporting Information may be found in the online version of this article.

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MCEA Ex. 4

What's new?

While environmental factors such as diet are thought to have a role in ovarian cancer, few such factors have been identified. In the present study, the ingestion of nitrate and nitrite was investigated for possible involvement in ovarian cancer. Among postmenopausal women, risk of ovarian cancer was found to be positively associated with elevated nitrate levels in public drinking water supplies and with nitrite intake from processed meats. Elevated nitrate levels in private well water was linked to increased ovarian cancer risk among women with reduced vitamin C intake.

human waste can contaminate surface and groundwater drinking water sources. The maximum contaminant level (MCL) for public water supplies in the United States is 10 mg/L nitrate-nitrogen (NO_3-N) and is based on preventing methemoglobinemia or blue-baby syndrome in infants.[5] However, the long-term effects of chronic intake of moderately high levels (*i.e.*, $\geq$5 mg/L) of nitrate from drinking water on cancer risk are still not clear.[6,7] Nitrate is also a natural component of plants and is found at high levels in certain vegetables.[7] Nitrate and nitrite salts are also added as preservatives to processed meats such as bacons and hot dogs to prevent bacterial growth and to add color and flavor.[7]

About 5% of ingested nitrate is endogenously reduced to nitrite by bacteria in the oral cavity.[7] Under the acidic conditions in the stomach, nitrite is converted to nitrous acid, which can then be converted to nitrosating agents. Once formed, nitrosating agents can react with amines and amides to form nitrosamines and nitrosamides (collectively called *N*-nitroso compounds [NOCs]). Most NOCs are potent animal carcinogens[8] and ingested nitrate and nitrite are considered probable human carcinogens (2A) under conditions that result in endogenous nitrosation.[7] Nitrosamides directly alkylate DNA and may induce tumors in many organs, whereas nitrosamines must be activated by specific cytochrome P450 enzymes to be carcinogenic.[7] The organ specificity of tumor induction may therefore stem from tissue-specific cytochrome P450 enzymes, which vary in level across organs and species. Cytochrome P450 enzymes have been found in ovarian epithelial tissue of animals.[9,10] Certain nutrients are known to influence endogenous NOC formation in the stomach. Antioxidants, especially vitamin C, reduce the endogenous NOC formation in humans.[7] In contrast, heme iron, which is found mostly in red meats, has been shown to enhance total NOC formation.[11] However, epidemiologic evidence of such interactions on cancer risk is still evolving.

The Iowa Women's Health Study (IWHS) is a large ongoing prospective cohort study started in 1986. In prior analyses, we observed an increased risk of ovarian cancer among women who reported drinking public water with elevated nitrate levels; however, the association was not statistically significant based on a relatively small number of cases ($n = 82$).[12] With an additional 12 years of follow-up, we evaluated whether nitrate and nitrite intake from diet and drinking water (public supplies and private wells) were associated with ovarian cancer risk. We further evaluated whether the association between nitrate and nitrite intake and ovarian cancer risk was modified by dietary factors that may inhibit (vitamin C and E) or enhance (red meats) endogenous NOC formation and by levels of disinfection byproducts (DBPs) in drinking water.

Materials and Methods

The Iowa Women's Health Study (IWHS)

The study design of the IWHS has been described in detail.[13] In brief, a self-administered questionnaire was mailed to 99,826 women, aged 55–69 years, randomly selected from the Iowa State's driver's license list in 1986. Of these women, 41,836 (42%) completed the baseline questionnaire assessing a study participant's demographics, anthropometry, lifestyle, familial history of cancer, medical and reproductive histories, and dietary intake. Respondents and non-respondents were comparable in terms of baseline characteristics.[14] Five follow-up questionnaires (1987, 1989, 1992, 1998 and 2004) have been administered *via* mail. The IWHS was approved by the Institutional Review Boards of the University of Minnesota and the University of Iowa. Return of the completed questionnaire was considered as a subject's consent to study participation.

Dietary intake assessment

Dietary intake at baseline was assessed using the Harvard food frequency questionnaire (FFQ). Study participants were asked their usual intake frequency of 126 food items and the use of dietary supplements over the previous 12 months. The FFQ has been shown to have good validity and reproducibility for major macro- and micronutrients in the IWHS.[15] Nutrient intakes were computed by multiplying the frequency of consumption of each food by the nutrient content. Total intakes of vitamin C and E were calculated by combining intake from foods and dietary supplements.

The nitrate and nitrite contents of foods were determined from a literature review focusing on published reports for U.S. or Canadian populations as previously described.[16,17] We computed means of nitrate and nitrite values for foods weighted by the number of samples and accounting for preparation (raw, cooked and canned) when possible. Nitrate and nitrite contents of FFQ line items were computed by weighting the food-specific values by sex-specific intake amounts from the 1994–1996 Continuing Survey of Food Intake by Individuals (CSFII).[18] For each study participant, we

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computed nitrate and nitrite intake overall and from plant and animal sources separately, including from processed meats only.

Water nitrate and DBP estimation

Information on drinking water was collected in a follow-up questionnaire mailed in 1989. Participants were asked the main source of drinking water at their current residence (municipal water system, rural water system, bottled water, private well water, other) and how long they had been drinking water from the indicated water source (<1, 1–5, 6–10, 11–20, >20 years). Of the 36,127 women completing the questionnaire (89% response rate), 27,409 (78%) reported public (municipal or rural) water and 6,634 (19%) reported private well water. Of the 27,409 women reporting public water, 22,375 (82%) reported using their water source for ≥11 years and 19,282 (70%) used it for >20 years. Of the 6,634 private well water drinkers, 5,862 (88%) used their water source for ≥11 years and 4,953 (75%) used it for >20 years. Information on tap water consumption at home and work was not collected.

We estimated nitrate and DBP levels in drinking water supplies using an historical municipal water supply monitoring database for Iowa. The database included NO_3-N measurements from finished water samples (1955–1988). NO_3-N levels in water samples were analyzed at the University of Iowa Hygienic Laboratory using standard methods.[19,20] Total trihalomethanes (TTHMs) and the sum of five haloacetic acids (HAA5) are the regulated DBPs.[21] TTHMs are the sum of four trihalomethanes (chloroform, bromoform, bromodichloromethane and dibromochloromethane). HAA5 is the sum of monochloro-, dichloro-, trichloro-, monobromo- and dibromoacetic acids.

A detailed description of the exposure assessment of DBPs in drinking water, developed in the context of another study, may be found elsewhere.[22] Routine monitoring of TTHMs started in the mid-1980s, and HAA5 in the mid-1990s. Annual average estimates for each DBP before these time periods were based on expert assessments, which considered measured TTHMs and HAA5 concentrations available in databases and historical information on water source, disinfection (pre-, intermediate and/or post-treatment; use of chlorine and/or chloramines) and other water treatment practices (*e.g.*, filtration, coagulation, sedimentation, softening), as well as selected water quality parameters.[22,23] Of the 356 Iowa public water utilities that served ≥ 1,000 persons at the time of estimation, we selected 34 that represented six categories of source water (surface water, shallow groundwater with high levels of brominated THMs, shallow groundwater with low levels of brominated THMs, nonalluvial groundwater with high levels of brominated THMs, nonalluvial groundwater with low levels of brominated THMs, and mixed surface/groundwater systems). We estimated DBP levels for these 34 utilities, considering measured data, changes in source water and/or treatment/disinfection practices over time, and water quality data. Whenever a utility significantly changed its historical treatment/disinfection process or source water, new DBP estimates were made. These annual estimates of 34 representative utilities were assigned to other utilities that used the same water source and similar water treatment and disinfection scheme.

Our study participants included in the water contaminant analyses lived in a total of 473 cities. We estimated the median duration of reported drinking water source categories (1–5, 6–10, 11–20, >20 years) as 4, 8, 16 and 40 years, respectively, based on complete water source history data from female controls of comparable ages in population-based case–control studies conducted during the same time period in Iowa.[24] For each median duration, we computed the means for NO_3-N and DBPs and the number of years in the time period for which the annual estimates exceeded half the MCL (5 mg/L and 40 μg/L for NO_3-N and TTHMs, respectively). In the previous analysis,[12] average NO_3-N levels (1955–1988) were assigned to each participant regardless of duration at their water source. In this study, we assigned average NO_3-N levels depending on their residential cities as well as the duration of using the reported water source. The NO_3-N estimates for each woman in the current study were highly correlated with our previous estimates (Spearman correlation coefficient, $r = 0.94$).

Statistical analysis

We excluded women who met the following criteria at baseline (numbers of subjects are not exclusive): (1) previous cancer diagnosis ($n = 3,830$); (2) premenopausal at baseline ($n = 569$); (3) history of bilateral oophorectomy ($n = 8,064$); and (4) an incomplete FFQ (left ≥ 30 items blank) or implausible energy intake (<600 or >5,000 kcal/day) ($n = 3,102$). In addition, we excluded ovarian cancers other than common epithelial cancers, including cancers of germ cell, sex-cord-stromal and others ($n = 27$), resulting in 28,555 women in the analysis for dietary nitrate and nitrite. We further limited drinking water analyses to women who provided drinking water information and reported using their water source for ≥11 years. In addition, we excluded women who lived in cities with public water systems that derived <75% from the same water source. The latter exclusion should increase the validity of the exposure measurement, as contaminant levels can vary between surface and groundwater sources as well as by depth of groundwater sources.[12] As a result, 17,216 women (13,051 drinking public water and 4,164 drinking private well water) remained in the drinking water analyses.

Incident common epithelial ovarian cancers (1986–2010) were identified *via* the annual linkage with the State Health Registry of Iowa's cancer registry, which is part of the Surveillance, Epidemiology and End Results program of the National Cancer Institute. Diagnosis date, type, stage and morphology of each incident cancer were obtained. Vital status (the date and cause of death) is annually identified through the linkage with the State Health Registry of Iowa, supplemented with the National Death Index. Person-years

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were computed from the date of return of the baseline questionnaire to the date of first ovarian cancer diagnosis, bilateral oophorectomy (self-reported), emigration from Iowa (<0.5% annually), death or December 31, 2010, whichever came first.

Pair-wise correlations among NO_3-N and eight DBPs were evaluated using Spearman correlation coefficients (r). The eight DBPs were highly correlated ($r = 0.67$–0.98; Supporting Information Table S1) and we used TTHMs, the sum of the most prevalent DBP class measured, as a surrogate for total halogenated DBPs. Categorical variables were generated for water NO_3-N and TTHM levels (quartiles) and dietary nitrate and nitrite intake (quintiles). Because the range of nitrite intake from processed meats was narrow, we created a 4-level categorical variable (0, >0–0.09, 0.1–0.19, ≥0.2 mg/d) based on its distribution. We compared selected baseline characteristics by NO_3-N levels in public water and private well water use. Hazard ratios (HR) and 95% confidence intervals (CI) were computed using Cox proportional hazards regression as the measure of association with the lowest level as a reference group. We selected *a priori* several baseline characteristics that are risk or protective factors for ovarian cancer as covariates in the multivariable-adjusted model. These covariates included age (continuous), body mass index (BMI, continuous), familial history of ovarian cancer, number of live births (nulliparous, 1–2, 3–4, ≥5), age at menarche (≤ or >12), age at menopause (<45, 45–49, 50–54, ≥55), age at first live birth (<20, 20–24, 25–29, ≥30), oral contraceptive use (never, ever), estrogen use (never, ever) and history of unilateral oophorectomy. In the drinking water analyses, we mutually adjusted for NO_3-N and TTHMs levels (continuous) to evaluate the independent effect of each contaminant. Dietary nitrate and nitrite analyses were additionally adjusted for total energy intake and dietary factors (continuous) that were associated with ovarian cancer risk and were moderately correlated with dietary nitrate or nitrite intake in our study population (cruciferous vegetables, $r = 0.53$ and red meat, $r = 0.48$). Logarithmically transformed values were used for NO_3-N and TTHM levels and dietary factors as covariates, as their distributions were markedly skewed. We tested trends for associations across exposure levels using the median in each category as continuous variables. Because NO_3-N measurements in private well water were not available, ovarian cancer risk among private well water drinkers was compared with the risk among women in the lowest quartile of nitrate in public water. We tested interactions between water NO_3-N and TTHM levels as well as between nitrate (from drinking water or diet) and total vitamin C, E and red meat intake by stratified analyses (≤ or > median) and by including interaction terms (*i.e.*, cross products of dichotomous variables for vitamin C, E and red meats and median in nitrate or nitrite quartile or quintile as continuous variables) in regression models. We performed sensitivity analyses limited to women who reported using the same water source for >20 years. Statistical significance for all analyses was defined as $p < 0.05$.

Results

Mean age of study participants at baseline was 61.6 years (standard deviation, SD = 4.2 years). During the follow-up, 315 incident common epithelial ovarian cancers were identified. Of these, 190 ovarian cancers were included in water nitrate analysis (145 using public water supplies and 45 using private wells). Mean (SD) age at diagnosis was 73.2 (7.7) years. Higher risk for ovarian cancer was observed among women with a familial history of ovarian cancer, no history of unilateral oophorectomy, who were nulliparous and had fewer live births. Oral contraceptive use and ages at menarche and menopause were not associated with ovarian cancer risk; nor were demographic and lifestyle factors such as farm residence, age, BMI, cigarette smoking, physical activity, or alcohol intake. Median NO_3-N and TTHM levels for women drinking from public water supplies were 1.08 mg/L (range: 0.01–25.34 mg/L) and 4.59 μg/L (range: 0–200.88 μg/L), respectively. NO_3-N levels were not correlated with TTHMs or other DBP estimates ($r = -0.03$-0.29) (Supporting Information Table S1). A history of unilateral oophorectomy was slightly more prevalent among women with elevated NO_3-N levels in public water (Table 1). Other factors and dietary intake were not different across NO_3-N levels in public water. More than 90% of women who reported drinking private well water lived on a farm (72%) or in non-farm rural areas (19%) while about 95% of public water drinkers lived in towns. Compared with public water drinkers, more women on private well water had lower education levels, never smoked, had no history of unilateral oophorectomy and never used estrogens or oral contraceptives. Intakes of total calories and red meats (energy-adjusted) were higher among private well water drinkers than public water drinkers. In contrast, total vitamin C intake and energy-adjusted intakes of dietary nitrate and fruits and vegetables were slightly lower among private well users than public water drinkers.

Women who consumed water containing elevated NO_3-N levels were at higher risk for ovarian cancer ($HR_{Q4\ vs.Q1} = 2.14$, CI = 1.30–3.54, $p_{trend} = 0.002$; Table 2). This association did not change substantially by adjusting for TTHM levels. Longer duration of exposure to NO_3-N at levels exceeding half the MCL (5 mg/L) was associated with higher risk for ovarian cancer ($p_{trend} = 0.02$). Women who had ingested water with NO_3-N exceeding 5 mg/L for ≥4 years were at 1.6 times higher risk for ovarian cancer compared with women with no exposure to NO_3-N exceeding 5 mg/L (CI = 1.06–2.41). In contrast, neither average TTHM levels in public water nor years of exposure to TTHM levels exceeding half the MCL (40 μg/L) were associated with ovarian cancer risk. When stratified by low or high TTHM levels (≤ or >median, 4.60 μg/L), there was no evidence of interaction of NO_3-N with TTHMs (data not shown). None of the individual DBPs was associated with ovarian cancer risk (Supporting Information Table S2). Although not statistically significant, ovarian cancer risk was higher among private well users compared with those with the lowest NO_3-N levels in public water (HR = 1.53, CI = 0.93–2.54). Similar

Epidemiology

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Table 1. Demographic, lifestyle, reproductive and dietary factors among 17,216 women and by mean nitrate levels in public water and private well water use

		Mean nitrate (mg/L nitrate–nitrogen) levels in public water				
	All	0.01–0.472	0.473–1.08	1.09–2.97	2.98–25.34	Private well water
N	17,216	3,263	3,269	3,504	3,015	4,165
Age, years (mean ± SD)	61.6 ± 4.2	61.8 ± 4.2	61.7 ± 4.2	61.7 ± 4.2	61.7 ± 4.2	61.2 ± 4.1
BMI, kg/m^2 (mean ± SD)	26.9 ± 5.0	26.8 ± 5.0	26.7 ± 4.9	26.6 ± 5.0	26.8 ± 5.0	27.4 ± 5.1
Education, ≥ high school (%)	83.8	83.7	84.3	83.5	86.1	81.8
Residence location (%)						
Farm	19.6	3.3	3.3	2.1	2.5	71.9
Rural area (not farm)	6.2	1.7	2.3	1.4	3.0	19.1
Town	74.2	95.0	94.4	96.5	94.5	9.0
Smoking, ever (%)	34.3	37.2	38.9	40.3	37.2	21.3
Physical activity, low (%)	47.3	46.6	47.0	47.8	47.1	47.8
Unilateral oophorectomy (%)	9.8	11.3	10.2	9.8	9.7	8.7
Estrogen use, ever (%)	31.8	33.3	32.4	33.6	33.3	27.6
Oral contraceptive use (%)	19.8	20.7	21.0	19.5	19.0	19.1
Age at menarche ≥ 13 years (%)	57.4	58.4	57.4	56.7	56.6	58.0
Age at menopause ≥ 50 years (%)	53.8	51.9	53.2	52.5	53.0	57.3
Number of live births (mean ± SD)	3.1 ± 1.9	3.1 ± 2.0	3.0 ± 1.9	2.9 ± 1.8	2.9 ± 1.8	3.5 ± 2.0
Age at first live births, years (mean ± SD)	21.0 ± 7.7	20.7 ± 8.0	20.8 ± 7.8	20.7 ± 8.1	21.0 ± 7.8	21.5 ± 6.8
Total calorie intake, kcal (median)	1,731	1,699	1,693	1,702	1,694	1,839
Total vitamin C intake, mg/d (median)	188	189	189	188	192	186
Total vitamin E intake, mg/d (median)	9.5	9.5	9.5	9.5	9.5	9.5
Energy-adjusted intake[1] (median)						
Nitrate, mg/d	60.8	61.0	61.1	61.7	61.5	59.2
Fruits and vegetables, servings/wk	23.6	23.5	23.9	23.9	23.8	23.0
Red meat, servings/wk	3.0	2.9	1.9	2.9	2.8	3.5
Processed meat, servings/wk	0.7	0.7	0.7	0.7	0.7	0.7

[1]Intake adjusted for 1,000 kcal/d of total energy intake.

elevated risks were observed among private well drinkers who lived on a farm (HR = 1.49, CI = 0.87–2.55) or in rural areas or towns (HR = 1.64, 95% CI = 0.83–3.24). These associations remained unchanged after adjusting for dietary nitrate and nitrite intake. When limiting analyses to women who reported using the same water source for >20 years, all observed associations became slightly stronger.

The association between higher nitrate levels in public water and ovarian cancer was stronger among women with low vitamin C intake (≤ median, 190 mg/d, $p_{trend} = 0.005$) compared with those with high intake (> median, $p_{trend} = 0.12$); however, the interaction was not statistically significant ($p_{interaction} = 0.33$, Table 3). The elevated risk among private well water drinkers was observed only among women with low vitamin C intake (HR = 3.30, CI = 1.44–7.56, $p_{interaction} = 0.01$). We also attempted to use different cutpoints for total vitamin C intake including the recommended daily intake (RDI) for non-smoking adult women (=70 mg/d) and the first quartile of total vitamin C intake in our study population (=125 mg/d). Similar stronger positive associations between water nitrate and ovarian cancer risk were observed among women with lower vitamin C intake (data not shown); however, CIs in the low vitamin C intake group were wide due to small numbers of ovarian cancer cases. A stronger association between NO_3-N levels in public water or private well use and ovarian cancer risk was observed among women with high *vs.* low red meat intake although the interaction was not statistically significant.

Mean (SD) dietary nitrate and nitrite intakes were 123.3 mg/d (83.4 mg/d) and 1.2 mg/d (0.5 mg/d), respectively. Total dietary nitrate intake and nitrate intake from plants (*e.g.*, high nitrate vegetables such as lettuce, celery, beets, spinach and broccoli) were highly correlated ($r = 0.99$). On average, about 38% of dietary nitrite intake came from

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Table 2. Exposures to nitrate–nitrogen (NO_3–N) and total trihalomethanes (TTHMs) in public water and ovarian cancer risk

				HR (95% CI)		
	Median	*N*	Cases	Age-adjusted	Model 1[1]	Model 2[2]
NO_3-N (mg/L)						
0.01–0.472	0.31	3,263	23	1.0	1.0	1.0
0.473–1.08	0.75	3,269	32	1.41 (0.82–2.41)	1.36 (0.80–2.34)	1.27 (0.73–2.21)
1.09–2.97	1.68	3,504	41	1.66 (1.00–2.76)	1.55 (0.92–2.59)	1.45 (0.85–2.44)
2.98–25.34	3.81	3,015	49	2.34 (1.42–3.84)	2.14 (1.30–3.54)	2.03 (1.22–3.38)
p_{trend}				0.0005	0.002	0.003
Private well water	–	4,165	45	1.50 (0.91––2.49)	1.53 (0.93–2.54)	–
Years of NO_3-N >5 mg/L[3]						
0	0	9,206	91	1.0	1.0	1.0
1–3	1	1,871	22	1.20 (0.75–1.91)	1.05 (0.64–1.72)	1.08 (0.65–1.77)
≥ 4[4]	8	1,974	32	1.66 (1.11–2.49)	1.60 (1.06–2.41)	1.52 (1.00–2.31)
p_{trend}				0.01	0.02	0.05
TTHMs (μg/L)						
0–0.89	0.47	3,112	27	1.0	1.0	1.0
0.90–4.59	1.95	3,612	33	1.07 (0.64–1.78)	1.10 (0.65–1.86)	1.08 (0.64–1.82)
4.77–14.31	10.67	3,524	55	1.82 (1.15–2.89)	1.86 (1.146– 3.00)	1.64 (1.00–2.70)
14.50–200.88	76.32	2,803	30	1.27 (0.76–2.14)	1.31 (0.77–2.24)	1.24 (0.73–2.13)
p_{trend}				0.78	0.74	0.80
Years of TTHMs >40 μg/L[3]						
0	0	9,838	110	1.0	1.0	1.0
> 0–35	3	1,442	17	1.05 (0.63–1.76)	1.00 (0.59–1.70)	0.99 (0.59–1.68)
≥ 36[4]	40	1,771	18	0.93 (0.56–1.53)	0.90 (0.54–1.50)	0.91 (0.55–1.52)
p_{trend}				0.84	0.69	0.72

[1]Adjusted for age, BMI, family history of ovarian cancer, number of live births (0, 1–2, 3–4, ≥ 5), age at menarche (≤ or >12), age at menopause (< 45, 45–49, 50–54, ≥ 55), age at first live birth (< 20, 20–24, 25–29, ≥ 30), oral contraceptive use (never, ever), estrogen use (never, ever) and history of unilateral oophorectomy.
[2]Additionally mutually adjusted for logarithmically transformed values of NO_3–N or TTHMs levels in public water.
[3]Half the maximum contaminant level (MCL) determined by the U.S. Environmental Protection Agency.
[4]The median years of exposures to a half of MCL among women who exposed during the reported duration of exposure.

animal sources and 15% came from processed meats. Higher dietary nitrate intake was observed among IWHS participants reporting higher age, BMI, education level, alcohol intake, physical activity level and estrogen use.[25] Women reporting higher dietary nitrate intake also reported higher intake of total calories, cruciferous vegetables, red meats and vitamins C and E. Higher dietary nitrate intake was associated with lower ovarian cancer risk ($HR_{Q5\ vs.Q1} = 0.61$, CI = 0.40–0.95; $p_{trend} = 0.02$, Table 4). Dietary nitrite intake was not associated with ovarian cancer risk. Similarly, neither dietary nitrite intake from plant nor animal sources was associated with ovarian cancer risk. However, higher nitrite intake from processed meats was marginally associated with higher ovarian cancer risk after adjusting for confounders ($p_{trend} = 0.04$). On a continuous scale, the risk was 12% (CI = 4–20%) higher with each 0.1 mg increment in nitrite intake from processed meats. These associations did not change by additional adjustment for total vitamin C and E intakes. There was no interaction between dietary nitrate or nitrite intake and total vitamin C, E or red meat intakes.

Discussion

We found higher risk for epithelial ovarian cancer among women drinking water from public supplies with higher nitrate levels, regardless of TTHM levels. Ovarian cancer risk also appeared higher among women drinking private well water compared with the lowest $NO\text{-}N_3$ quartile in public water supplies, and we observed a statistically significant interaction with vitamin C intake. Higher dietary nitrate intake was associated with lower risk for ovarian cancer, whereas higher nitrite intake from processed meats was associated with higher risk.

Epidemiologic studies of dietary nitrate intake have predominantly evaluated stomach cancer and many studies reported null associations or inverse trends.[7,26] One explanation for these findings is the potential interaction between

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Table 3. Ovarian cancer risk in relation to nitrate–nitrogen (NO_3-N) levels in drinking water stratified by high or low total vitamin C and red meat intakes

	Vitamin C ≤190 mg/d				Vitamin C >190 mg/d				
	N	Cases	HR (95% CI)[1]	p_{trend}	*N*	Cases	HR (95% CI)[1]	p_{trend}	$p_{interaction}$
NO_3-N (mg/L)									
0.01–0.472	1,625	7	1.0	0.005	1,638	16	1.0	0.12	0.33
0.473–1.08	1,629	14	1.85 (0.74–4.65)		1,640	18	1.16 (0.59–2.29)		
1.09–2.97	1,762	26	3.17 (1.37–7.32)		1,742	15	0.83 (0.40–1.70)		
2.98–25.34	1,467	24	3.39 (1.45–7.95)		1,548	25	1.60 (0.85–3.02)		
Private well water[2]	2,125	29	3.30 (1.44–7.56)	–	2,040	16	0.77 (0.38–1.54)	–	0.01
	Red meats ≤5 servings/wk				Red meats >5 servings/wk				
	N	Cases	HR (95% CI)[1]	p_{trend}	*N*	Cases	HR (95% CI)[1]	p_{trend}	$p_{interaction}$
NO_3-N (mg/L)									
0.01–0.472	1,812	13	1.0	0.18	1,451	10	1.0	0.002	0.14
0.473–1.08	1,853	21	1.61 (0.81–3.22)		1,416	11	1.04 (0.43–2.50)		
1.09–2.97	2,032	26	1.69 (0.86–3.30)		1,472	15	1.36 (0.60–3.06)		
2.98–25.34	1,788	25	1.82 (0.93–3.57)		1,227	24	2.59 (1.23–5.48)		
Private well water[2]	1,629	15	1.34 (0.64–2.82)	–	2,536	30	1.68 (0.82–3.44)	–	0.63

[1]Adjusted for age, BMI, family history of ovarian cancer, number of live births (0, 1–2, 3–4, ≥5), age at menarche (≤ or >12), age at menopause (< 45, 45–49, 50–54, ≥55), age at first live birth (< 20, 20–24, 25–29, ≥30), oral contraceptive use (never, ever), estrogen use (never, ever) and a history of unilateral oophorectomy.
[2]HR and 95% CI were computed with the lowest quartile of nitrate among public water drinkers as a reference group.

nitrate and antioxidants, which are abundant in major dietary sources of nitrate such as green leafy and root vegetables.[27,28] Antioxidants, such as vitamins C and E, inhibit NOC formation by reducing nitrite to nitric oxides, and thus decreasing the level of NOCs and NOC-induced DNA adducts.[29,30] Therefore, a potentially carcinogenic effect of dietary nitrate intake may be reduced or eliminated by the protective effects of high antioxidant intake from fruits and vegetables. Indeed, dietary nitrate intake was highly correlated with total vegetable intake ($r = 0.84$), and moderately correlated with antioxidant intakes ($r = 0.36$–0.46) in our study.

Carcinogenic effects of NOCs in the ovary have been shown in animal studies.[9,10] However, to date, NOCs and their precursors nitrate and nitrite have been evaluated in relation to ovarian cancer risk in only a few epidemiologic studies. Ovarian cancer risk was evaluated in relation to dietary nitrate intake in two prospective cohort studies and these studies found no associations.[12,31] Dietary nitrite intake and ovarian cancer was assessed in only one prior cohort study.[31] In that study, total nitrite intake and nitrite intake from plant sources were not associated with epithelial ovarian cancer risk, but higher nitrite intake from animal sources was associated with higher risk ($HR_{Q5\ vs.\ Q1} = 1.34$, CI = 1.05–1.69, $p_{trend} = 0.02$). Processed meats contain added nitrate and nitrite as well as high amounts of amines and amides, precursors of NOCs. Ingestion of nitrate in combination with nitrosatable precursors has been shown to increase the formation of NOCs.[32] Furthermore, red and processed meats contain heme iron, a component of myoglobin, which promotes the formation of NOCs.[11] Therefore, nitrate and nitrite added to processed meats may result in exogenous and endogenous NOC formation. Three large prospective cohort studies have found statistically non-significant trends towards positive associations between processed meat intake and ovarian cancer.[33–35] Meta-analysis of four prospective cohort studies found a borderline positive exposure response between processed meat intake and ovarian cancer risk (HR = 1.05, CI = 0.98–1.14 for an intake increment of 100 g per week).[36]

Unlike dietary nitrate, nitrate from drinking water is not accompanied by micronutrients that could inhibit endogenous nitrosation. Therefore, nitrate from drinking water could result in more endogenously formed NOCs than nitrate from foods. Previous epidemiologic studies, including our study,[12] have shown associations between nitrate levels in public water and the risk of cancer, including bladder,[12] stomach and colorectal cancers.[6,7] However, ovarian cancer has been assessed in relation to nitrate in public water only in our previous analysis in the IWHS, as one of multiple cancer outcomes.[12] In our previous analysis including 82 incident ovarian cancers, we observed a positive association between higher nitrate levels in public water supplies and the risk of ovarian cancer ($HR_{Q4\ vs.\ Q1} = 1.86$, CI = 0.82–4.26); however, this association did not reach statistical significance level. In the current study, we found a statistically significant more than two-fold risk for ovarian cancer among women in the highest (median = 3.81 mg/L) compared in the lowest (median = 0.31 mg/L) NO_3-N quartiles in public water supplies.

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Table 4. Dietary nitrate and nitrite intake and ovarian cancer risk among 28,555 women

				HR (95% CI)	
	Median	*N*	Cases	Model 1[1]	Model 2[2]
Nitrate (mg/d)					
Total intake					
Q1: 3.87–65.43	49.5	5,711	59	1.0	1.0
Q2: 65.44–92.04	78.9	5,711	73	1.18 (0.83–1.68)	1.05 (0.73–1.50)
Q3: 92.05–121.96	106.2	5,711	54	0.86 (0.58–1.26)	0.72 (0.48–1.06)
Q4: 121.97–165.48	140.2	5,711	74	1.21 (0.84–1.74)	0.96 (0.66–1.41)
Q5: 165.54–2,083.52	209.2	5,711	55	0.85 (0.56–1.27)	0.61 (0.40–0.95)
p_{trend}				0.37	0.02
Per 10 mg/d	–	–	–	0.99 (0.98–1.01)	0.98 (0.96–1.00)
Nitrite (mg/d)					
Total intake					
Q1: 0.11–0.80	0.7	5,709	62	1.0	1.0
Q2: 0.81–1.02	0.9	5,716	52	0.84 (0.56–1.26)	0.80 (0.53–1.21)
Q3: 1.021–1.23	1.1	5,716	65	1.12 (0.73–1.72)	1.04 (0.68–1.59)
Q4: 1.239–1.53	1.4	5,703	70	1.26 (0.79–2.02)	1.14 (0.71–1.82)
Q5: 1.537–7.13	1.8	5,711	66	1.20 (0.68–2.12)	1.03 (0.58–1.84)
p_{trend}				0.24	0.50
Per 0.1 mg/d	–	–	–	1.00 (0.97–1.04)	0.99 (0.95–1.03)
Animal sources					
Q1: 0–0.26	0.2	5,638	63	1.0	1.0
Q2: 0.26–0.36	0.3	5,689	44	0.68 (0.45–1.02)	0.72 (0.48–1.08)
Q3: 0.36–0.47	0.4	5,597	83	1.29 (0.89–1.88)	1.39 (0.96–2.02)
Q4: 0.47–0.61	0.5	5,668	59	0.89 (0.59–1.37)	0.98 (0.64–1.50)
Q5: 0.61–3.47	0.7	5,648	66	1.04 (0.64–1.67)	1.18 (0.72–1.91)
p_{trend}				0.45	0.25
Per 0.1 mg/d	–	–	–	1.04 (0.98–1.11)	1.06 (1.00–1.13)
Processed meats					
0	0	4,872	54	1.0	1.0
> 0–0.09	0.04	19,770	212	0.94 (0.69–1.28)	1.01 (0.74–1.38)
0.1 – 0.19	0.13	2,537	32	1.15 (0.73–1.82)	1.27 (0.80–2.01)
≥ 0.2	0.26	1,135	17	1.46 (0.82–2.58)	1.65 (0.93–2.94)
p_{trend}				0.10	0.04
Per 0.1 mg/d	–	–	–	1.10 (1.03–1.19)	1.12 (1.04–1.20)
Plant sources					
Q1: 0.04–0.47	0.4	5,701	64	1.0	1.0
Q2: 0.47–0.61	0.5	5,717	62	0.88 (0.61–1.28)	0.82 (0.56–1.19)
Q3: 0.61–0.76	0.7	5,712	57	0.87 (0.59–1.28)	0.77 (0.52–1.14)
Q4: 0.76–0.98	0.9	5,721	67	1.01 (0.67–1.51)	0.86 (0.57–1.29)
Q5: 0.98–6.39	1.2	5,704	65	0.96 (0.60–1.52)	0.77 (0.48–1.24)
p_{trend}				0.79	0.54
Per 0.1 mg/d	–	–	–	0.99 (0.95–1.03)	0.97 (0.92–1.01)

[1]Adjusted for age, BMI, family history of ovarian cancer, number of live births (0, 1–2, 3–4, ≥ 5), age at menarche (≤ or >12), age at menopause (< 45, 45–49, 50–54, ≥ 55), age at first live birth (< 20, 20–24, 25–29, ≥ 30), oral contraceptive use (never, ever), estrogen use (never, ever), history of unilateral oophorectomy and total energy intake (logarithmically transformed).
[2]Additionally adjusted for logarithmically transformed values of cruciferous vegetable and red meat intake.

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For the first time, we found evidence suggesting a higher risk for ovarian cancer among women who were private well water drinkers. In Iowa, agricultural application of nitrogen is the major source of environmental nitrate contamination. Nitrate levels can be high in private wells in agricultural areas because of their location close to crop fields treated with nitrogen fertilizer and livestock manure, and because private wells are not regulated and may not be routinely monitored. In the United States, the average NO_3-N levels in streams and groundwater in agricultural areas are over 3 mg/L whereas average levels in urban areas and areas with mixed land use are about 1.5 mg/L and 1 mg/L, respectively.[6] About 22% of private wells in agricultural areas in the United States exceed the nitrate MCL (10 mg/L NO_3-N).[6] A survey of rural private wells in Iowa in 1988–1989 found that 18% of wells exceeded the MCL for nitrate. In addition, 37% of these rural private wells had levels greater than 3 mg/L, typically considered indicative of anthropogenic pollution.[37] We observed similarly elevated risk of ovarian cancers among private well users in farm and non-farm areas. Most of Iowa land is used for agriculture with row crops and grasslands covering 90% and urban areas accounting for only 1% of the state surface area.[38] Therefore, private wells located in non-farm rural areas or towns are likely to be in close proximity to farms and thus impacted by the agricultural use of nitrogen fertilizers. Nitrate levels in private well water are determined by many factors including geological characteristics and agricultural practices.[37] Well depth is the best predictor of well-water nitrate contamination with higher nitrate levels found in shallower wells. NO_3-N levels in 35% of private wells less than 15 m deep exceeded the MCL (about 28% of private wells in Iowa are less than 15 m deep).[37,39] Unfortunately, information on well depth was not collected in our study.

It should be noted that elevated nitrate levels may be an indicator of contamination with other chemicals or bacteria.[40] In agricultural areas, wells with elevated nitrate levels may also have elevated levels of herbicides, some of which are suspected carcinogens. For example, atrazine, a triazine herbicide, is one the most frequently detected pesticides in Iowa groundwater, and occupational exposure is a hypothesized risk factor for ovarian cancer.[41,42] Exposures to pesticides *via* drinking water are likely to be substantially lower than occupational exposures but few studies have been conducted. Atrazine and its metabolites have been detected in Iowa public water supplies, although levels are usually below the MCL and detections are not as frequent as for nitrate.[43] The 1988–1989 state-wide survey revealed that pesticides were present in about 5% of private wells in Iowa.[37] DBPs in drinking water have been associated with higher risk for bladder cancer and possibly other sites.[44] We evaluated, for the first time, DBPs in drinking water in relation to ovarian cancer and found only non-significant, uneven elevations of risk for the DBP metrics in our analysis. Evaluation in other populations would be valuable.

Ovarian cancer is a relatively rare cancer, but a large sample size as well as a long follow-up period enabled us to study 190 cases in relation to water contaminants. Emigration from Iowa rarely occurred in our cohort (<0.5% annually), enabling a nearly complete follow-up of the cohort and likely detection of most incident ovarian cancers. The attainment of water nitrate and DBP data through a linkage with a historical public water monitoring database is another strength of our study. In addition, reported duration of water source use enabled us to estimate the length of exposure to water contaminants, which is a key factor in exposure assessment. The majority of our cohort participants lived in the same address for more than 10 years at the post-enrollment drinking water data collection, which enabled us to estimate long-term exposures to nitrate and DBPs in drinking water. Our study has limitations as well. Dietary intake was assessed at cohort baseline and may have changed during the long follow-up period. However, dietary intakes assessed at cohort baseline and at the 2004 follow-up survey were reasonably correlated (*e.g.*, $r = 0.44$ for total calorie, 0.39–0.42 for macronutrients, 0.36 for total vegetables and 0.24 for processed meat products) and earlier exposures are likely to be the most relevant for cancer risk. Potential misclassification of dietary intake assessed using a FFQ is also probable. Furthermore, dietary intake assessment by a FFQ cannot capture important information related to the nitrate content and NOC formation such as food storage and cooking methods. Because information on study participants' daily water consumption was not available, patterns in individuals' water consumption such as the amount and timing as well as water consumption outside of their home (*e.g.*, work) was not taken into account in our exposure assessment. In addition, we did not have information on other factors that may influence nitrate metabolism to include in our analyses. For example, factors that affect the number of nitrate-reducing bacteria in saliva, such as mouthwash use and oral hygiene, may alter the rate of nitrate–nitrite conversion by saliva.[7] Similarly, proton-pump inhibitor use increases the pH in the stomach and may increase NOC formation.[45] Finally, study included only postmenopausal white women; therefore, interpretation of our results is limited to this population, and future studies should evaluate these exposures among all women including premenopausal women and other ethnic groups with ovarian cancer.

In conclusion, this study indicates that nitrate from public drinking water may be associated with higher risk of ovarian cancer among postmenopausal women. Our results suggest that postmenopausal women who drink private well water may be at higher risk for ovarian cancer, especially with low vitamin C intake. Our findings also support the hypothesis that dietary nitrite intake from processed meats increases ovarian cancer risk. Additional confirmatory studies with a larger number of ovarian cancer cases are warranted and could result in a novel target for ovarian cancer risk reduction.

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References

1. ACS. *Cancer Facts & Figures 2014*. Atlanta, Georgia: American Cancer Society, 2014.
2. IARC. Cancer Incidence in Five Continents Vol. VIII. Lyon: International Agency for Research on Cancer, 2002.
3. Haenszel W, Kurihara M. Studies of Japanese migrants. I. Mortality from cancer and other diseases among Japanese in the United States. *J Natl Cancer Inst* 1968;40:43–68.
4. Dunn JE. Cancer epidemiology in populations of the United States—with emphasis on Hawaii and California and Japan. *Cancer Res* 1975;35(11 Pt. 2):3240–5.
5. EPA. U.S. Environmental Protection Agency (EPA): National Primary Drinking Water Regulations. EPA 816-F-09–2004: U.S. Environmental Protection Agency; 2009. Available at: http://water.epa.gov/drink/contaminants/upload/mcl-2.pdf, April 26, 2013.
6. Ward MH, deKok TM, Levallois P, et al. Workgroup report: drinking-water nitrate and health—recent findings and research needs. *Environ Health Perspect* 2005;113:1607–14.
7. IARC. IARC monographs on the evaluation of carcinogenic risks to humans; v. 94. Ingested nitrate and nitrite, and cyanobacterial peptide toxins. Lyon: IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2010.
8. Bogovski P, Bogovski S. Animal Species in which N-nitroso compounds induce cancer. *Int J Cancer* 1981;27:471–4.
9. Diaz Gomez MI, Tamayo D, Castro JA. Nitrosodimethylamine metabolism in rat ovaries. Interactions of its metabolites with nucleic acids and proteins. *Cancer Lett* 1988;41:257–63.
10. Arai M, Aoki Y, Nakanishi K, et al. Long-term experiment of maximal non-carcinogenic dose of dimethylnitrosamine for carcinogenesis in rats. *Gann* 1979;70:549–58.
11. Cross AJ, Pollock JR, Bingham SA. Haem, not protein or inorganic iron, is responsible for endogenous intestinal N-nitrosation arising from red meat. *Cancer Res* 2003;63:2358–60.
12. Weyer PJ, Cerhan JR, Kross BC, et al. Municipal drinking water nitrate level and cancer risk in older women: the Iowa Women's Health Study. *Epidemiology* 2001;12:327–38.
13. Folsom AR, Kaye SA, Potter JD, Prineas RJ. Association of incident carcinoma of the endometrium with body weight and fat distribution in older women: early findings of the Iowa Women's Health Study. *Cancer Res* 1989;49:6828–31.
14. Bisgard KM, Folsom AR, Hong CP, Sellers TA. Mortality and cancer rates in nonrespondents to a prospective study of older women: 5-year follow-up. *Am J Epidemiol* 1994;139:990–1000.
15. Munger RG, Folsom AR, Kushi LH, et al. Dietary assessment of older Iowa women with a food frequency questionnaire: nutrient intake, reproducibility, and comparison with 24-hour dietary recall interviews. *Am J Eepidemiol* 1992;136:192–200.
16. Ward MH, Cantor KP, Riley D, et al. Nitrate in public water supplies and risk of bladder cancer. *Epidemiology* 2003;14:183–90.
17. Ward MH, Cerhan JR, Colt JS, Hartge P. Risk of non-Hodgkin lymphoma and nitrate and nitrite from drinking water and diet. *Epidemiology* 2006;17:375–82.
18. Subar AF, Midthune D, Kulldorff M, et al. Evaluation of alternative approaches to assign nutrient values to food groups in food frequency questionnaires. *Am J Epidemiol* 2000;152:279–86.
19. APHA. Standard methods for the examination of water and wastewater, 13rd edn. MJ T, ed. New York: American Public Health Association and American Water Works Association, 1971.
20. APHA. Standard Methods for the Examination of Water and Wastewater, 14th ed. New York: American Public Health Association, 1976.
21. USEPA. 40 CFR Parts 9, 141, and 142. National Primary Drinking Water Regulations: stage 2 Disinfectants and Dosinfection Byproducts Rule; Final Rule. U.S. Environmental Protection Agency, 2006.
22. Amy G, Graziano N, Craun G, et al. Improved Exposure Assessment on Existing Cancer Studies. Denver, CO: AWWA Research Foundation, 2005.
23. CHEEC. Historical community water supply and treatment data for the State of Iowa, 6th ed. Iowa City, IA: Center for Health Effects of Environmental Contamination, University of Iowa, 2013.
24. Cantor KP, Lynch CF, Hildesheim ME, et al. Drinking water source and chlorination byproducts. I. Risk of bladder cancer. *Epidemiology* 1998;9:21–8.
25. Inoue-Choi M, Ward MH, Cerhan JR, et al. Interaction of nitrate and folate on the risk of breast cancer among postmenopausal women. *Nutr Cancer* 2012;64.
26. Bryan NS, Alexander DD, Coughlin JR, et al. Ingested nitrate and nitrite and stomach cancer risk: an updated review. *Food Chem Toxicol* 2012;50:3646–65.
27. Dellavalle CT, Xiao Q, Yang G, et al. Dietary nitrate and nitrite intake and risk of colorectal cancer in the Shanghai Women's Health Study. *Int J Cancer* 2014;132:2917–26.
28. Kim HJ, Lee SS, Choi BY, Kim MK. Nitrate intake relative to antioxidant vitamin intake affects gastric cancer risk: a case-control study in Korea. *Nutr Cancer* 2007;59:185–91.
29. Mirvish SS. Effects of vitamins C and E on N-nitroso compound formation, carcinogenesis, and cancer. *Cancer* 1986;58(8 Suppl):1842–50.
30. Das M, Khan WA, Asokan P, et al. Inhibition of polycyclic aromatic hydrocarbon-DNA adduct formation in epidermis and lungs of SENCAR mice by naturally occurring plant phenols. *Cancer Res* 1987;47:767–73.
31. Aschebrook-Kilfoy B, Ward MH, Gierach GL, et al. Epithelial ovarian cancer and exposure to dietary nitrate and nitrite in the NIH-AARP Diet and Health Study. *Eur J Cancer Prev* 2012;21:65–72.
32. Vermeer IT, Pachen DM, Dallinga JW, et al. Volatile N-nitrosamine formation after intake of nitrate at the ADI level in combination with an amine-rich diet. *Environ Health Perspect* 1998;106:459–63.
33. Cross AJ, Leitzmann MF, Gail MH, et al. A prospective study of red and processed meat intake in relation to cancer risk. *PLoS Med* 2007;4:e325.
34. Schulz M, Nothlings U, Allen N, et al. No association of consumption of animal foods with risk of ovarian cancer. *Cancer Epidemiol Biomarker Prev* 2007;16:852–5.
35. Larsson SC, Wolk A. No association of meat, fish, and egg consumption with ovarian cancer risk. *Cancer Epidemiol Biomarker Prev* 2005;14:1024–5.
36. Wallin A, Orsini N, Wolk A. Red and processed meat consumption and risk of ovarian cancer: a dose-response meta-analysis of prospective studies. *Br J Cancer* 2011;104:1196–201.
37. Kross BC, Hallberg GR, Bruner DR, et al. The nitrate contamination of private well water in Iowa. *Am J Public Health* 1993;83:270–2.
38. IowaDNR. Iowa Geological & Water Survey. Iowa's Statewide Land Cover Inventory. Iowa Department of Natural Resources: Iowa Department of Natural Resources. Available at: http://www.igsb.uiowa.edu/Browse/landcvr/landcvr.htm, accessed February 5, 2014.
39. Kross BC, Hallberg GR, Bruner DR, et al. *The Iowa state-wise rural well-water survey: water-quality data: initial analysis*. Iowa City, Iowa: Iowa Department of Natural Resources, Geological Survey Bruau, Technical Information Series 19, 1990.
40. Brody JG, Aschengrau A, McKelvey W, et al. Breast cancer risk and drinking water contaminated by wastewater: a case control study. *Environ Health* 2006;5:28.
41. Donna A, Crosignani P, Robutti F, et al. Triazine herbicides and ovarian epithelial neoplasms. *Scand J Work Environ Health* 1989;15:47–53.
42. Koutros S, Alavanja MC, Lubin JH, et al. An update of cancer incidence in the Agricultural Health Study. *J Occup Environ Med* 2010;52:1098–105.
43. .EPA. U.S. Environmental Protection Agency (EPA). Summary of 2003–2005 AMP Results, August 2006. Available at: http://www.epa.gov/oppsrrd1/reregistration/atrazine/amp_2003_2005_sum.pdf.
44. Cantor KP, Ward MH, Moore LE, Lubin JH. Water contaminants. In: Schottenfeld D, Fraumeni JF, eds. Cancer epidemiology and prevention, 3rd edn. New York: Oxford University Press, 2006.
45. McColl KE. Effect of proton pump inhibitors on vitamins and iron. *Am J Gastroenterol* 2009;104 Suppl 2:S5–9.

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Early prenatal nitrate exposure and birth outcomes: A study of Iowa's public drinking water (1970–1988)

Jason Semprini

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Abstract

Despite the biological mechanisms linking prenatal nitrate exposure to birth outcomes, epidemiological research has been inconclusive. The evidence-base has been limited by where and how nitrate exposure was measured, and the spurious correlation between geotemporal nitrate heterogeneity and unmeasurable factors contributing to gestational age and birth weight. We linked Iowa water quality data and birth records to estimate the independent association between early prenatal nitrate exposure and birth outcomes. Accessing Community Water Supply Quality Data, we calculated the median nitrate (mg/L) level for each county-date. With birth certificate microdata from the National Center for Health Statistics, we linked every Iowa birth (1970–1988) to a county-level nitrate measure within thirty days of conception. The outcomes were gestational age (weeks), preterm birth (< 37 weeks), birth weight (g), and low birth weight (< 2500 g). Nitrate exposure was first measured as a "dose-response" continuous variable, then as four binary variables (>10 mg/L, > 5 mg/L, > 0.1 mg/L, > 0.0 mg/L). We constructed linear regression models which controlled for maternal and paternal characteristics, and county-year and year-month fixed-effects to account for unobservable annual variation between counties and longitudinal variation within all counties. Among 357,741 births, mean nitrate exposure was 4.2 mg/L. Early prenatal exposure to >0.1 mg/L nitrate was associated preterm birth (Est. = +0.66%-points; C.I. = 0.31, 1.01). Early prenatal exposure to 5 mg/L nitrate was associated with low birth weight (Est. = +0.33%-points; C.I. = 0.03, 0.63). The associations between elevated exposure to nitrate and any birth outcomes did not differ from lower levels of exposure. Prenatal exposure to nitrate below the > 10 mg/L standard may cause harm. Since establishing this standard in 1992, groundwater nitrate levels have risen. Our results warrant greater scholarly and policymaking attention to understand and combat the adverse effects of nitrate.

Author summary

Rising levels of nitrate in our drinking water pose a threat to public health. Emerging evidence suggests a possible association between early prenatal exposure to nitrate in drinking water and adverse birth outcomes. Understanding this association has proved challenging, as there is currently no regulatory guidance on safe levels of nitrate during the early prenatal period and many factors contribute to adverse birth outcomes. Focusing on Iowa, a state with some of the highest levels of ground water nitrate in the country, this study linked public water quality data to more than 350,000 birth records. During the study period (1970–1988), nitrate levels increased 8% annually. Mean nitrate levels were 4.2 mg/L, well below the 10 mg/L regulatory threshold. Interestingly, exposure to nitrate above the 10 mg/L threshold had no association with birth outcomes. Rather, the study showed that prenatal exposure to lower levels of nitrate were adversely associated with gestational age and low birthweight. These results suggest that current regulatory standards, which have not been updated since 1992, may be inadequate.

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Data Availability: For this study, the public water quality data was obtained from the University of Iowa's Center for Health Effects of Environmental Contamination. The data included all public water quality sample measures of nitrate levels (mg/L) reported between January 1, 1970 to December 31, 1988. In addition to the nitrate level measures, the water quality data included measurement dates, names, and geocodes of the public water systems. While this data was shared by CHEEC to the authors of this current study, the authors of this current study were not given explicit permission to share the data. The two key contacts for data requests are David Cwiertny (David-cwiertny@uiowa.edu) and Darrin Thompson (darrin-thompson-1@uiowa.edu). These two faculty hold appointments at CHEEC and are acknowledged in the manuscript under the acknowledgements section. Additionally, the public website for CHEEC is found here: https://cheec.uiowa.edu/ (E-Mail: cheec@uiowa.edu). In addition, the repository which holds the analytic code can be accessed with the following link: (https://github.com/jsemprini/Iowa-Water-Nitrate-Births7088).

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MCEA Ex. 5

Introduction

Nitrate is a naturally occurring compound needed by plants and animals, increasingly used in inorganic fertilizers [1]. Once consumed by humans, most frequently through drinking water via agricultural runoff into groundwater, nitrates could interfere with the blood's capacity to carry oxygen [1,2]. This interference is especially concerning for children, possibly fatal [3]. The Environmental Protection Agency (EPA) explicitly identifies the risk from drinking water with elevated nitrate levels in infants [4]. Given the risk, in 1992 the EPA set a maximum contaminant level for water-based nitrate at 10 mg/L [5]. Researchers have since identified biological mechanisms and potentially adverse effects of maternal transfer of nitrate compounds in utero [6]. Prenatal nitrate exposure could also induce thyroid disfunction and oxidative stress [7,8]. Yet, still today the EPA does not identify adverse birth outcomes as a risk from consuming water-based nitrate [9].

Biological mechanisms suggest that early prenatal nitrate exposure could increase the risk of fetal death, malformation, and growth defects [6,9]. After the fourth month in utero, the placenta protects against maternal transfer of nitrate compounds [10]. Thus, nitrate exposure poses the greatest risk during the perinatal period just before or after conception [10,11]. Yet, despite the plausible biological mechanisms linking early prenatal exposure to nitrate on adverse birth outcomes, epidemiological research has been inconclusive [10,12–14]. A large study in Denmark, which linked birth records to water quality at the household level, found that even low measures of nitrate exposure were associated with birthweight and body size but found no association between elevated levels of nitrate and low birthweight outcomes [15]. Three recent studies have reviewed the epidemiological literature evaluating the association between nitrate exposure and birth outcomes [12–14]. All three revealed that the evidence-based, spanning over thirty years, remains inconsistent. However, three reviews revealed some important consistencies. One common theme was the limited population-based research conducted in the U.S. Of the 16 studies in Lin's review, only three were U.S. population-based studies [12,16–18]. Clemmensen's review of 13 studies included three additional U.S. population-based studies [13,19–21]. Taken together, these six U.S. studies in six states (CA, IA, IN, MO, OH, TX) described a clear association between prenatal exposure to nitrates and increased risk of fetal malformation and preterm birth, but less evidence on birth weight [16–21]. Two of these studies, both in California, found adverse effects from nitrate exposure under the EPA standard of 10 mg/L [17,18]. However, while most of the U.S. population-based studies showed consistent adverse effects of exposure, methodological concerns related to timing of exposure, unit of analysis, and design may pose threats to internal validity [12–14]. One study, however, implemented a research design to overcome potential confounding between maternal health and exposure to elevated nitrates [18]. The Sherris study found that exposure to > 5 mg/L nitrate was associated with higher odds of preterm birth in California (2000–2011). Unfortunately, no other individual-level, population based U.S. research has implemented designs aiming to overcome unobserved confounding, leaving a major evidence gap for residents in states with higher levels of groundwater nitrate.

Objectives

To continue advancing the evidence evaluating the potential effect of early prenatal exposure to nitrate on birth outcomes, we aimed to analyze population-based data in a state with high levels of nitrate using a research design equipped to overcome threats to internal validity and unobserved confounding. To achieve this aim, we linked Iowa water quality data with historic birth records. Implementing a two-way fixed-effects research design to account for unobserved county, annual, and monthly heterogeneity, we tested the following hypotheses: 1) Exposure to nitrate (mg/L) within thirty days of conception has a linear "dose-response" relationship with birth outcomes; 2) Exposure to different thresholds of nitrate (>10 mg/L, > 5 mg/L, > 0.1 mg/L, > 0.0 mg/L) within thirty days of conception are associated with birth outcomes; 3) Compared with exposure to less than 0.1 mg/L, the association between nitrate exposure and birth outcomes varies across levels of nitrate exposure (>10 mg/L vs. > 5 mg/L to 10 mg/L vs. > 0.1 mg/L to 5 mg/L).

Methods

Data

Water data.

Public drinking water data for this study came from Community Water Supply Quality Data, which was obtained from the University of Iowa's Center for Health Effects of Environmental Contamination [22]. Specifically, we analyzed nitrate levels (mg/L) for all public water service measurements reported between January 1, 1970 to December 31, 1988. In addition to the nitrate level measures, the water quality data included measurement dates, names, and geocodes of the public water systems.

The original water quality file included 14,262 measurements. 815 measurements were exact duplicates. Using public water system's latitude-longitude, we used Open Street Map data and Nominatim reverse geocoding API to identify the county of each public water system [23,24]. Given that the consistently most granular level of the birth record data was the county, we calculated a median nitrate level for all counties with multiple measures on the same date. The resulting water quality file included 10,124 county-level nitrate measurements.

Birth data.

Iowa birth outcomes were derived from vital records birth certificate microdata, created by the National Center for Health Statistics and made available by the National Bureau of Economic Research [25,26]. Variables which were consistent across all years (1970–1988) were retained. During this period, all birth records included maternal county of residence. Subtracting the birth date by gestational age, we created a 'date of conception' variable. In total, there were 725,756 birth certificates with known gestational age and known birth weight. We also excluded birth records which did not report the education status of the mother (867 births) and births without an attendant (1,253 births).

Linkage.

To determine early prenatal exposure to nitrate, we created an algorithm which linked each birth record to a water quality measure in the same county near the date of conception. The algorithm worked as follows. For each birth, we first identified the county of residence. Then we matched the birth's county of residence to the county in the water quality data. Next, within this county, we searched for the nitrate measurement date nearest the conception date. We then calculated the distance (in days) from conception to the nearest measurement date. We then excluded all births where the nearest measure was > 30 days from conception (387,418 births) [10]. The resulting datafile included 357,741 births linked to a nitrate measure within thirty-days of conception.

Collection and analysis of birth record data complied with terms and conditions outlined by the NCHS.

Statistical analysis and design

To estimate the independent association between early prenatal nitrate exposure and birth outcomes, we constructed a series of two-way fixed effect linear regression models [27]. For continuous outcomes (gestational age, birth weight), we used normal linear regression models. For binary outcomes (preterm birth, low birth weight), we used linear probability regression models. For inference, we estimated standard errors robust to heteroskedasticity and autocorrelation, clustered within each county [28].

Our first model estimated a "dose-response" association, measuring nitrate exposure as a continuous variable (mg/L). We then created four binary exposure measures, which we first each modelled separately. The binary exposures included 1) elevated exposure as defined by the EPA standard (Nitrate > 10 mg/L) compared to a reference value (Nitrate <= 10 mg/L), 2) high exposure (> 5 mg/L) compared to a reference value (Nitrate <= 5 mg/L), 3) 1% of the EPA standard (Nitrate > 0.1 mg/L) compared to a reference value (Nitrate <= 0.1 mg/L), 4) and any exposure (Nitrate > 0 mg/L) compared to a reference value (Nitrate == 0 mg/L). For the binary outcomes (preterm birth, low birth weight), we also estimated a model with three levels of exposure simultaneously (0.1-5 mg/L, > 5–10 mg/L, > 10 mg/L) and calculated Wald statistics to test for differences across levels of exposure compared to a reference value (Nitrate <0.1 mg/L).

In addition to adjusting for maternal and paternal characteristics (Table 1), the birth weight models included gestational age as a categorical control variable. We also accounted for unobserved heterogeneity with county, year, and month-level fixed effects. Specifically, all models included a county-year interaction fixed-effect which accounted for all unobserved factors differentially associated with birth outcomes between counties each year. Additionally, all models included month-year fixed effects, which accounted for temporal and seasonal variation in birth outcomes consistent across all counties. This design effectively rules out unobserved confounding between nitrate exposure and birth outcomes between counties in a given year, and unobserved confounding between nitrate exposure and birth outcomes over time within the entire state.

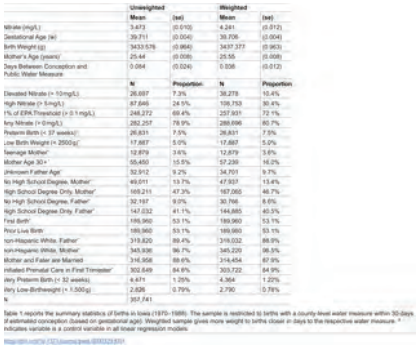

	Unweighted		Weighted	
	Mean	(se)	Mean	(se)
Nitrate (mg/L)	3.473	(0.010)	4.241	(0.012)
Gestational Age (w)	39.711	(0.004)	39.706	(0.004)
Birth Weight (g)	3433.576	(0.964)	3437.377	(0.963)
Mother's Age (years)	25.44	(0.008)	25.55	(0.008)
Days Between Conception and Public Water Measure	0.064	(0.024)	0.036	(0.012)
	N	Proportion	N	Proportion
Elevated Nitrate (> 10 mg/L)	26,697	7.3%	38,278	10.4%
High Nitrate (> 5 mg/L)	87,646	24.5%	108,753	30.4%
1% of EPA Threshold (> 0.1 mg/L)	248,272	69.4%	257,931	72.1%
Any Nitrate (> 0 mg/L)	282,257	78.9%	289,696	80.7%
Preterm Birth (< 37 weeks)	26,831	7.5%	26,831	7.5%
Low Birth Weight (< 2500 g)	17,887	5.0%	17,887	5.0%
Teenage Mother	12,879	3.6%	12,879	3.6%
Mother Age 30 +	55,450	15.5%	57,230	16.0%
Unknown Father Age	32,912	9.2%	34,701	9.7%
No High School Degree, Mother	49,011	13.7%	47,937	13.4%
High School Degree Only, Mother	169,211	47.3%	167,065	46.7%
No High School Degree, Father	32,197	9.0%	30,766	8.6%
High School Degree Only, Father	147,032	41.1%	144,885	40.5%
First Birth	189,960	53.1%	189,960	53.1%
Prior Live Birth	189,960	53.1%	189,960	53.1%
non-Hispanic White, Father	319,820	89.4%	318,032	88.9%
non-Hispanic White, Mother	345,936	96.7%	345,220	96.5%
Mother and Faker are Married	316,958	88.6%	316,454	87.9%
Initiated Prenatal Care in First Trimester	302,649	84.6%	303,722	84.9%
Very Preterm Birth (< 32 weeks)	4,471	1.25%	4,364	1.22%
Very Low-Birthweight (< 1,500 g)	2,826	0.79%	2,790	0.78%
N	357,741			

Table 1 reports the summary statistics of births in Iowa (1970–1988). The sample is restricted to births with a county-level water measure within 30-days of estimated conception (based on gestational age). Weighted sample gives more weight to births closer in days to the respective water measure. * indicates variable is a control variable in all linear regression models.

Table 1. Sample Summary Statistics.
https://doi.org/10.1371/journal.pwat.0000329.t001

The only possible remaining bias from unobserved confounding would be the presence of dynamic seasonal heterogeneity between counties systematically correlated with both nitrate exposure and birth outcomes.

Our primary models were weighted by the inverse of the difference between date of conception and date of nearest public water system measurement. Secondary models did not include any weights. To assess the validity of our research design and statistical analysis, we included a falsification test where we replicated our unweighted models with primary outcomes, but restricted the sample to observations where the nearest public water system measurement was at least 90 days before the date of conception.

Sensitivity checks and exploratory outcomes

Although recent empirical evidence suggests linearity is no longer a requirement for unbiased estimation of Ordinary Least Squares, traditional theory suggested that our linear regression model specification would be biased if the linearity assumption was violated [29]. To assess whether our linear regression estimates for continuously measured birth outcomes, were sensitive to model specification, we estimated linear models with 1) natural log transformed exposure variable, 2) natural log transformed outcome variable, and 3) a log-log model where both outcome and exposure variables were transformed.

For binary outcomes, we did not compute a logistic regression model, given the computational intensity and likelihood of bias from calculating nonlinear high-dimensional fixed-effects [30]. The linear probability model served as our preferred, primary specification for two reasons [31,32]. First, our design relied on adjusting for annual differences between counties and seasonal variation over time. To model these adjustments, each regression includes a large number of fixed-effect parameters (99 counties x 19 years + 12

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months x 19 years = 2,109 fixed-effects. Analytically and computationally, 2,109 fixed-effects is no problem for a linear probability model but could pose a problem for a non-linear logistic regression model [33,34]. Specifically, estimates from a logistic regression models may be biased and unreliable when with increasing fixed-effects due to the 'Incidental parameter problem' intrinsic to many common non-linear models [30,35]. Second, estimates from a logistic regression model can be difficult to interpret and even more challenging to compare across tests [35–37]. However, to assess whether our primary estimates were sensitive to model specification, we re-estimated each binary model as a logistic regression and reported the marginal effect estimates [36,38].

Finally, to explore how various levels of nitrate exposure were associated with rare birth outcomes, we added two exploratory outcomes: 1) very low birthweight (< 1,500 g) and 2) very preterm birth (< 32 w) [39,40].

The collection of data, and all statistical analysis and programming techniques complied with the terms and conditions of the source of data.

Results

Summary statistics

The analytic sample included 357,741 births. The average difference between date of conception and date of public water system measurement in the weighted sample was 0.038 days. The median difference was zero days. The mean nitrate exposure at conception was 4.2 mg/L (Table 1). Between 1970–1988, nitrate levels increased 8% each year (Fig 1). Nitrate levels varied considerably across the state (Fig 2; S1 Table). 10.4% of births were exposed to elevated nitrate levels (> 10mg/L) and 80.7% of births were exposed to any level of nitrate in public drinking water. Five percent of the births were low birth weight (<2,500 g) and 7.5% were preterm (<37 weeks).

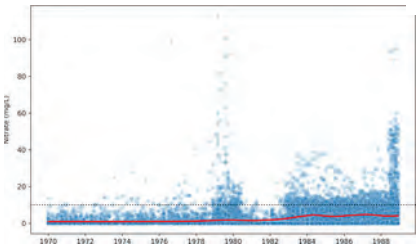

Fig 1. Longitudinal Nitrate Measures in Public Water: Iowa (1970-1988).
Figure 1 reports the median nitrate level in each month-year of all reported public water measures in Iowa (1970-1988). Each blue point is a nitrate measure (mg/L). The red line represents the average, based on the locally weighting smoothing technique. The dotted black line at 10 mg/L represents the maximum contaminant level set by the EPA.
https://doi.org/10.1371/journal.pwat.0000329.g001

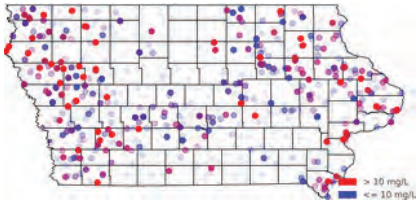

Fig 2. Map of Nitrate Measures in Public Water: Iowa (1970-1988).
Figure 2 reports the median nitrate level in each month-year of all reported public water measures in Iowa (1970-1988). Each blue point is a nitrate measure (mg/L) <=10 mg/L (the maximum contaminant level set by the EPA). Each red point is a nitrate measure >10 mg/L. Points are shaded by nitrate measure on a continuous scale.
https://doi.org/10.1371/journal.pwat.0000329.g002

Fig 3 visualizes birth weight and nitrate exposure by preterm birth status. S2 Table reports the weighted sample statistics, average nitrate measures, and birth outcomes for each of Iowa's ninety-nine counties.

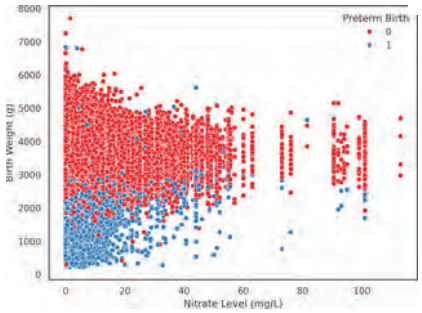

Fig 3. Nitrate Level, Birth Weight, and Pre-Term Birth Status.
Figure 3 visualizes birth outcomes and nitrate levels in Iowa (1970-1988). The y-axis measures birth weight (g). The x-axis measures nitrate levels (mg/L) for each respective birth based on the closest within-county measurement in the first trimester. Preterm Birth (0 - Red) = >=37 weeks gestation. Preterm Birth (1 - Blue) = < 37 weeks gestation.
https://doi.org/10.1371/journal.pwat.0000329.g003

Estimated association of nitrate exposure on gestational age

There was no estimated "dose-response" association between early prenatal exposure to nitrates (measured as a continuous variable) and gestational age (weeks) or on the probability of preterm birth (Table 2). However, the unweighted models found that each mg/L increase in nitrate was associated with increasing the probability of preterm birth by 0.02%-points (S3 Table). For context, this would indicate that early prenatal exposure to > 10 mg/L nitrate would have a 0.2%-point higher risk of preterm birth than no exposure.

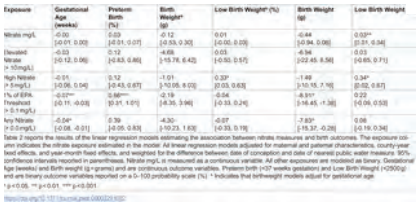

Table 2. Estimated Association Between Prenatal Nitrate Exposure and Birth Outcomes.
https://doi.org/10.1371/journal.pwat.0000329.t002

Across multiple specifications, weighted and unweighted, we found that lower gestational age was associated with early prenatal exposure to any nitrate (Est. = -0.04, C.I. = -0.08, 0.01) and exposure to 1% of the EPA's standard level of nitrate (Est. = -0.07, C.I. = -0.11, -0.03) (Table 2). These estimates represent an association of -0.25 to -0.5 days, or 0.1% of baseline gestational age in weeks. There was no association between high or elevated exposure to nitrates and gestational age.

We also estimated that exposure to at least 1% of the EPA standard nitrate level (>0.1 mg/L) was associated with increasing the probability of preterm birth by 0.66%-points (C.I. = 0.31, 1.01). This association represented a 9% relative difference from average preterm birth rates. Again, there was no association between high or elevated exposure to nitrates. In the falsification tests, however, we found that exposure to > 5mg/L nitrates more than 90 days before conception was associated with significantly lower probability of preterm birth (S4 Table). This specific falsification test result may indicate that the statistically insignificant association between early prenatal exposure to >5 mg/L nitrate and preterm birth may be due to mean regression or selection bias.

Fig 4 visualizes the association between early prenatal exposure at various thresholds on the probability of preterm birth, relative to <0.1 mg/L exposure. While the only statistically significant estimate was exposure to nitrate >0.1-5 mg/L, we failed to reject the null hypothesis that the association on preterm birth does not vary by level of exposure (p = 0.9087). We did reject the null hypothesis that the association from all three levels of nitrate exposure equal zero (p = 0.0022).

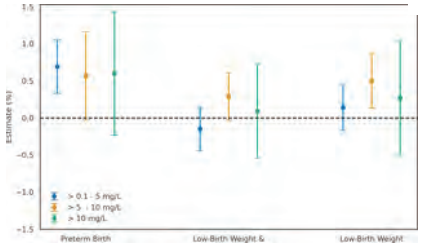

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Fig 4. Estimated Association Between Nitrate Exposure and Birth Outcomes.
Figure 4 visualizes the results of the linear regression models simultaneously estimating the association between nitrate measures and birth outcomes at various levels of exposure. Each estimate corresponds to a change in birth outcomes, relative to exposure to <0.1 mg/L nitrate. All linear regression models adjusted for maternal and paternal characteristics, county-year fixed effects, and year-month fixed effects, and weighted for the difference between date of conception and date of nearest public water measure. 95% confidence intervals are represented by error bars. The two binary outcomes, preterm birth (<37 weeks gestation) and Low Birth Weight (<2500 g), were estimated separately and reported on a 0-100 probability scale (%). & Indicates that birthweight models adjust for gestational age. For summary data used to create Figure 4, see S8 Table.
https://doi.org/10.1371/journal.pwat.0000329.g004

Estimated association of nitrate exposure on birth weight

Across all model specifications where we adjusted for gestational age, there was no statistically significant "dose-response" association between early prenatal exposure to nitrate and birth weight (g) (Table 2). When removing gestational age as a control variable, we observed a statistically significant "dose-response" association between nitrate exposure and the probability of low birth weight (Est. = 0.03%-points; Table 2). For context, this would suggest that compared to zero exposure, early prenatal exposure to > 10 mg/L was associated with increasing the risk of low birth weight by 0.3%-points.

For all thresholds of nitrate exposure, we also found no association between early prenatal exposure to nitrates and birth weight. However, we did estimate that early prenatal exposure to high levels of nitrate (> 5 mg/L) was associated with increasing the probability of low birth weight by 0.33%-points (C.I. = 0.03, 0.63). This association represents a 7% relative difference from average low birth weight rates. The estimated association between >0.1 mg/L and any exposure to nitrates on birth weight were statistically significant when removing gestational age from the regression models. All falsification tests for birth weight outcomes were near zero and statistically not significant (S4 Table).

Fig 4 visualizes the association between early prenatal exposure at various thresholds on the probability of low birth weight, relative to <0.1 mg/L exposure. The only marginally statistically significant estimate was exposure to nitrate >5 mg/L. Here, however, we rejected the null hypothesis that the association with low birth weight does not vary by level of exposure ($p = 0.0088$). We also rejected the null hypothesis that the association from all three levels of nitrate exposure equals zero ($p = 0.0224$).

Sensitivity checks and exploratory outcomes

Log-transformed exposure.

S5 Table reports the sensitivity checks of the primary continuous gestational age (weeks) and birthweight (g) outcomes and nitrate exposure variable (mg/L), as well as the alternative log-transformed models. For gestational age, the results of the log-transformed exposure variable are statistically significantly associated with reduced gestational age. To interpret the coefficient (Est. = -0.0185), a 10% increase in nitrate was associated with a 0.00185 week reduction in gestational age. To interpret the coefficient (Est. = -0.0005) when gestational age is log-transformed, a 10% increase in nitrate was associated with a 0.005% reduction in gestational age. Neither of these estimates, although statistically significant, are clinically meaningful. In the models which adjust for gestational age, the log-transformed estimates are consistent with the primary specification in terms of direction and inference. However, in the models which do not adjust for gestational age, the log-transformed exposure variable was found to be statistically significantly associated with reduced birthweight and log-transformed birthweight. If ignoring gestational age from the model, the coefficient (Est. = -2.4837) suggests that a 10% increase in nitrate exposure was associated with reducing birthweight by 0.25 g. Again, although statistically significant, these sensitivity check results are not clinically meaningful or different than the primary results suggesting there is no association between nitrate measured as a continuous variable and birthweight (g) or gestational age (weeks).

Comparing linear probability model and logistic model estimates.

S6 Table reports the primary estimates for the binary outcomes and binary measure of nitrate exposure, compared to the logistic regression specification. In summary, each estimate from the primary specification and the logistic regression were consistent in terms of direction of the association and statistical inference. However, the magnitude of the statistically significant associations are quite different and substantially larger in the logistic regression specifications. These inflated estimates in the logistic regression are likely due to poor performance of a non-linear model with high-dimensional fixed effects.

Exploratory birth outcomes.

When exploring rare outcomes, we found no association between any level of nitrate exposure and the probability of very preterm birth (S7 Table). The association did not differ between elevated levels compared to the association with lower levels of nitrate exposure (Fig 5). We did find marginally significant evidence that elevated exposure (> 10 mg/L) to nitrate, when adjusting for gestational age, was associated with 0.14%-point increase in the probability of being born at very low-birth weight (C.I. = -.02, 0.30; $p = 0.096$). Using the confidence interval, this estimate reflects a -1.6% to 24.0% relative change from baseline very low-birthweight rates. Still, there was no statistically significant difference between the association from elevated exposure and the association from lower levels of exposure (Fig 5).

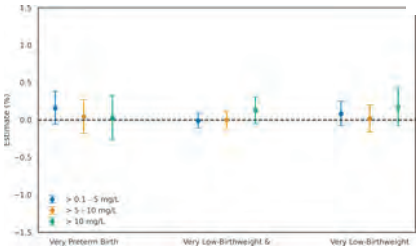

Fig 5. Estimated Association Between Nitrate Exposure and Rare Birth Outcomes (Exploratory).
Figure 5 visualizes the results of the linear regression models simultaneously estimating the association between nitrate measures and rare birth outcomes at various levels of exposure. Each estimate corresponds to a change in birth outcomes, relative to exposure to <0.1 mg/L nitrate. All linear regression models adjusted for maternal and paternal characteristics, county-year fixed effects, and year-month fixed effects, and weighted for the difference between date of conception and date of nearest public water measure. 95% confidence intervals are represented by error bars. The two binary outcomes, Very Preterm Birth (<32 weeks gestation) and Very Low-Birthweight (<1,500 g), were estimated separately and reported on a 0-100 probability scale (%). & Indicates that birthweight models adjust for gestational age. For summary data used to create Figure 5, see S9 Table.
https://doi.org/10.1371/journal.pwat.0000329.g005

Discussion

Consistent with the existing population-based research studying nitrate exposure on birth outcomes in the U.S., we found evidence that early prenatal exposure to nitrate in public drinking water was associated with adverse birth outcomes [18–20]. Our first contributions were the results suggesting that early prenatal exposure to any or low levels of nitrate were associated with gestational age and preterm birth [18]. Second, we also found that early prenatal exposure to high nitrate levels (> 5 mg/L) was associated with increasing the probability of a low birth weight (< 2500 g), reaffirming existing evidence on the risk of exposure to nitrate below the EPA standard [19].

In conclusion, our results suggest that early prenatal exposure to low levels of nitrate are associated with the probability of preterm birth, which serves as a potential mechanism linking low levels of nitrate exposure to birth weight. Additionally, independent of nitrate's association with gestational age, we found that exposure to > 5 mg/L nitrate in early prenatal periods was associated with increased risk of low birth weight. We found no evidence that exposure to elevated levels, as defined by the EPA (> 10 mg/L) poses any additional risk on birth outcomes than lower levels of exposure. This standard has not been updated since 1992 [4]. Meanwhile, nitrate levels in America's water has risen substantially [41].

Iowa is a state with among the highest levels of groundwater nitrate in the world [42]. The data in this study, although over 35 years old, revealed that nitrate levels were increasing annually [42]. In Iowa, and most of the midwestern United States, nitrate levels in public water systems were lower in the 70's and 80's than nitrate levels today [41,42]. While our work in this current study contributed new evidence reaffirming the potential negative impact of prenatal exposure to nitrates on birth outcomes, the extent to which our results generalize across time should be explored further given the persistent rise in nitrate levels. Research with more contemporary U.S. data, likely via access to restricted vital statistic microdata, could quantify how the risk from early prenatal exposure to nitrates has changed over time. More granular and nuanced birth record data within rural, agricultural states like Iowa could also be used to analyze public and private well water. Such research could have tremendous value for improving rural maternal and infant outcomes, given that rural Americans who source their water from private wells face exceptional risk of exposure to nitrate [43,44].

Across federal, state, and local government, we conclude with several policy recommendations. At the federal level, as evidence continues to mount showing the adverse association between prenatal exposure to nitrate and birth outcomes, the EPA must update their regulatory language to identify this potential risk. Additionally, our work also adds to the evidence-base that the current regulatory threshold (> 10 mg/L) may be insufficient for protecting the in utero transmission of water-based nitrate during the first trimester of pregnancy [18]. Delaying the EPA's plan to reevaluate nitrate's maximum contaminant level only delays the public's ability to respond to rising levels of nitrate in our groundwater. Regardless of the EPA's progress towards updating regulatory guidance, states also have considerable power for monitoring and enforcing regulatory compliance. Greater oversight and transparency not only promotes research, but compliance with meeting minimum standards of water quality. But, to exceed minimum water quality standards needed to improve birth outcomes, we hope these results empower municipal policymakers to explore innovative approaches. In cities, large and small, across the country, municipal policymakers have implemented or piloted programs to reduce nitrate contamination in water [45]. These innovative solutions, however, can often be expensive. Policies aiming to improve water quality to improve birth outcomes cannot ignore the reality of cost. Rather, policymakers must conduct rigorous cost-benefit analyses of not only water quality improvement but nitrate reduction strategies. Only with such quantifiable evidence can the public advocate for policies reversing the decade-long trend of rising nitrate levels in our drinking water.

Many factors contribute to birth weight and gestational age, two rare but important markers for infant health and early child development [46–49]. This study reaffirms that nitrate exposure, even in low doses, during early prenatal periods may be a critical factor for preterm births and that exposure to higher levels, but below the EPA maximum contaminant level, may contribute to low birth weight [17–19]. The magnitude of the association between early prenatal exposure to nitrate with preterm birth and low birth weight were.66%-points and 0.33%-points, respectively. For context, nitrate's association pales in comparison with the respective effect of smoking on each birth outcome [50,51]. Interpreted causally, the effect of early prenatal exposure to nitrate on birth outcomes is only 15% of the effect of smoking on birth outcomes. Although this comparison may be changing given the rising nitrate levels and declining maternal smoking rates over the past thirty years, we do not, introduce this comparison to minimize the

results of our study. Rather, we introduce the comparison to highlight a potential incongruence between research, policy, and practice. If the harm from exposure to nitrate exhibits 15% of the harm from smoking, why doesn't exposure to nitrates garner an equivalent 15% of our attention?

Limitations

This study is not without limitations. First, although nitrate reporting is required by federal law, the water quality data is based on self-reports and may not constitute a representative sample. Still these data are considered best available, gold-standard for measuring exposure to environmental health effects. Second, the birth record data, as mentioned above, is outdated (1970–1988). To analyze more recent data, however, investigators would need access to restricted data as, beginning in 1989 birth record microdata began suppressing county identifiers with population under 100,000. This study is also limited in scope, focusing only on one state. Despite Iowa being a leading state in groundwater nitrate exposure, the results may not generalize beyond its borders. While adding more states could improve external validity and increase statistical Power, such an endeavor would be much more computationally intensive given the size of the data. More problematic, also, would be how to link birth records to water quality exposure given that most states, unlike Iowa, do not have counties of consistent size and shape. Adding information on private well water could also improve this study, but that would require private well data and birth records identifying that the mother resided in an unincorporated area. Next, the birth record data does not include specific variables which could potentially be correlated with impact of exposure to nitrates and birthweight. These variables include co-occurring environmental exposures in air or water or maternal health status (i.e., obesity, weight gain). Later releases of birth record data include more variables on maternal and pregnancy health outcomes but as mentioned these later datafiles suppress geographic identifiers of small population areas. Future research with novel data linkages could enhance the findings of this current study, potentially identifying how co-occurring exposures or maternal health status could mediate the associations between exposure to nitrate and birth outcomes. Related to outcomes in this study, future research could also improve assessing how to disentangle the potential confounding between nitrate exposure, gestational age, and birth weight. Moreover, while evidence continues to show that lower levels of nitrate exposure may adversely impact birth outcomes, less is known about how the duration of various levels of exposure influence these negative effects. Finally, the last limitation relates to design. We made every effort to avoid using causal language when describing this study, given the likely sources of bias related to unobserved confounding between exposure to nitrates and birth outcomes for both the mother (i.e., maternal health correlated with nitrate exposure) and county (time-variant changes in socioeconomic conditions correlated with nitrate exposure). Our design adjusted for observable contributors to birth outcomes and accounted for unobserved baseline and annual differences by county, as well as unobserved longitudinal heterogeneity. Yet, our design could still be biased if early prenatal nitrate exposure was systematically correlated with birth, maternal, or socioeconomic conditions across counties differently within each year (i.e., seasonal differences across counties within each year). Our falsification test helps support the primary findings, but not completely as exposure >90-days from conception may be correlated with exposure near conception. We encourage future researchers to assess the validity of instrumental variable methods (i.e., rain as an instrument for nitrate levels) and within-mother designs (i.e., matched birth records) to replicate and build upon the findings of our current study. Such work has been carried out, utilizing not only novel linkages but innovative approaches to measuring pollution as an index rather than point-measures of specific contaminants [52]. To continue advancing the evidence base, however, will require greater collaboration between academic researchers and public policymakers. We hope our study here facilitates such partnerships as we collectively pursue initiatives to improve birth outcomes across the United States.

Conclusions

Despite unambiguous biological pathways between nitrate in drinking water and adverse birth outcomes most population-based research in humans has been mixed. By creating a novel linkage between public drinking water data and historic birth records for a state with high levels of groundwater nitrate, we advanced the evidence base by 1) focusing on early prenatal exposure to nitrate 2) modelled at various thresholds 3) with a design accounting for geotemporal confounding. Analyzing 357,741 births, we found that early prenatal exposure to low (>0.1 mg/L) levels of nitrate were associated gestational age and preterm birth. Early prenatal exposure to 5 mg/L nitrate was associated with low birth weight. The associations between elevated exposure, as defined by the EPA, and any birth outcomes did not differ from the associations at lower nitrate levels. The > 10 mg/L standard set by the EPA has not changed since 1992. Meanwhile, groundwater nitrate levels continue to increase in the U.S. Given the importance of gestational age and birth weight for healthy infants and early child development, our evidence should motivate greater scholarly and policymaking attention for understanding and mitigating the potential adverse effects of exposure to nitrate in our drinking water.

Supporting information

S1 Table. Iowa Nitrate Measures (mg/L).
S1 Table shows the distribution of weighted and unweighted nitrate measures in Iowa public water for the entire study period and for each year (1970–1988).
https://doi.org/10.1371/journal.pwat.0000329.s001
(XLSX)

S2 Table. County Summary Statistics.
S2 Table shows the summary statistics of births in each county. Outcomes included nitrate measure thresholds, birthweight outcomes, and gestational age outcomes.
https://doi.org/10.1371/journal.pwat.0000329.s002
(XLSX)

S3 Table. Unweighted Estimates.
S3 Table shows the unweighted estimate results of the linear regression models estimating the association between nitrate measures and birth outcomes. The exposure column indicates the nitrate exposure estimated in the model. All linear regression models adjusted for maternal and paternal characteristics, county-year fixed effects, and year-month fixed effects. Standard errors reported in parentheses. Nitrate mg/L is measured as a continuous variable. All other exposures are modeled as binary. Gestational

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Age (weeks) and Birth weight (g = grams) and are continuous outcome variables. Preterm birth (<37 weeks gestation) and Low Birth Weight (<2500 g) and are binary outcome variables reported on a 0–100 probability scale (%). & Indicates that birthweight models adjust for gestational age. ^ Reported on a binary (0–1) scale. * p < 0.05.
https://doi.org/10.1371/journal.pwat.0000329.s003
(XLSX)

S4 Table. Falsification Tests (Nitrate Measure 90+ Before Conception).
S4 Table shows the results of a falsification test, using a placebo exposure to nitrate based on a measure taken 90+ before conception. *** p < 0.001. ^ Reported on a binary (0–1) scale.
https://doi.org/10.1371/journal.pwat.0000329.s004
(XLSX)

S5 Table. Sensitivity Checks, Continuous Birthweight Outcomes - Linear and Log-Transformed Models.
S5 Table shows the results of sensitivity checks related to log-transformations of dependent and independent continuous variables. * p < 0.05, ** p < 0.01, *** p < 0.001. & Model adjusts for gestational age.
https://doi.org/10.1371/journal.pwat.0000329.s005
(XLSX)

S6 Table. Linear Probability Model and Logistic Regression Model Estimates - Sensitivity Check.
S6 Table shows the results of sensitivity checks comparing primary linear probability model (LPM) and logistic regression model with marginal analysis. * p < 0.05, ** p < 0.01, *** p < 0.001. & Model adjusts for gestational age. ^ Reported on a percentage (%) (0–100) scale.
https://doi.org/10.1371/journal.pwat.0000329.s006
(XLSX)

S7 Table. Exploratory Outcomes.
S7 Table reports the exploratory results of the linear regression models estimating the association between nitrate measures and birth outcomes. The exposure column indicates the nitrate exposure estimated in the model. All linear regression models adjusted for maternal and paternal characteristics, county-year fixed effects, and year-month fixed effects, and weighted for the difference between date of conception and date of nearest public water measure. Standard errors reported in parentheses. All exposures are modeled as binary. Gestational Age (weeks) and Birth weight (g = grams) and are continuous outcome variables. & Indicates that birthweight models adjust for gestational age. ^ Reported on a binary (0–1) scale. & Adjusts for gestational age. # p = 0.096.
https://doi.org/10.1371/journal.pwat.0000329.s007
(XLSX)

S8 Table. Primary Binary Outcomes - Fig 4.
S8 reports the data for Fig 4. Est. = Estimated association between exposure and birth outcome. SE = Standard Error. Lower = Lower bound of 95% confidence interval. Upper = Upper bound of 95% confidence.
https://doi.org/10.1371/journal.pwat.0000329.s008
(XLSX)

S9 Table. Exploratory Binary Outcomes - Fig 5.
S9 reports the data for Fig 4. Est. = Estimated association between exposure and exploratory outcome. SE = Standard Error. Lower = Lower bound of 95% confidence interval. Upper = Upper bound of 95% confidence.
https://doi.org/10.1371/journal.pwat.0000329.s009
(XLSX)

S1 File. Response_PlosWater-Nitrate.
https://doi.org/10.1371/journal.pwat.0000329.s010
(DOCX)

S2 File. Review Iowa Study.
https://doi.org/10.1371/journal.pwat.0000329.s011
(DOCX)

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References

1. Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for Nitrate and Nitrite [Internet]. DHHS, PHS; 2017 [cited 2024 Oct 1.]. Available from: https://wwwn.cdc.gov/TSP/ToxProfiles/ToxProfiles.aspx?id=1452&tid=258

2. Miodovnik A. The biochemistry, diagnosis, and treatment of nitrate toxicity. AMA Journal of Ethics. 2009;11(6):451–5. pmid:23199355
View Article • PubMed/NCBI • Google Scholar

3. Knobeloch L, Salna B, Hogan A, Postle J, Anderson H. Blue babies and nitrate-contaminated well water. Environ Health Perspect. 2000;108(7):675–8. pmid:10903623
View Article • PubMed/NCBI • Google Scholar

MCEA Ex. 5

4. EPA. National Primary Drinking Water Regulations [Internet]. 2024 [cited 2024 Oct 1.]. Available from: https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations
View Article • Google Scholar

5. EPA. Chemical Contaminant Rules [Internet]. 2023 Nov [cited 2024 Oct 1.]. Available from: https://www.epa.gov/dwreginfo/chemical-contaminant-rules
View Article • Google Scholar

6. Bruning-Fann CS, Kaneene JB. The effects of nitrate, nitrite and N-nitroso compounds on human health: a review. Vet Hum Toxicol. 1993;35(6):521–38.
View Article • Google Scholar

7. Moore TA, Ahmad IM, Zimmerman MC. Oxidative Stress and Preterm Birth: An Integrative Review. Biol Res Nurs. 2018;20(5):497–512.
View Article • Google Scholar

8. van MJ, van DA, M K, de BM, M PC, van der HD, et al. Consumption of drinking water with high nitrate levels causes hypertrophy of the thyroid. Toxicology Letters [Internet]. 1994;72(1–3). [cited 2024 Oct 1.]. Available from: https://pubmed.ncbi.nlm.nih.gov/8202954/
View Article • Google Scholar

9. Agency for Toxic Substances and Disease Registry (ATSDR). Nitrate/Nitrite Toxicity: What Are the Health Effects from Exposure to Nitrates and Nitrites? [Internet]. CDC; 2023 May [cited 2024 Oct 1.]. Available from: https://www.atsdr.cdc.gov/csem/nitrate-nitrite/health_effects.html

10. Manassaram DM, Backer LC, Moll DM. A Review of Nitrates in Drinking Water: Maternal Exposure and Adverse Reproductive and Developmental Outcomes. Environ Health Perspect. 2006;114(3):320–7.
View Article • Google Scholar

11. Scragg RKR, McMichael AJ, Baghurst PA, Dorsch MM. Birth defects and household water supply Epidemiological studies in the Mount Gambier region of South Australia. Medical Journal of Australia. 1982;2(12–13):577–9.
View Article • Google Scholar

12. Lin L, St Clair S, Gamble GD, Crowther CA, Dixon L, Bloomfield FH. Nitrate contamination in drinking water and adverse reproductive and birth outcomes: a systematic review and meta-analysis. Sci Rep. 2023;13(1):563.
View Article • Google Scholar

13. Clemmensen PJ, Schullehner J, Brix N, Sigsgaard T, Stayner LT, Kolstad HA, et al. Prenatal Exposure to Nitrate in Drinking Water and Adverse Health Outcomes in the Offspring: a Review of Current Epidemiological Research. Curr Envir Health Rpt. 2023;10(3):250–63.
View Article • Google Scholar

14. Royal H, 't Mannetje A, Hales S, Douwes J, Berry M, Chambers T. Nitrate in drinking water and pregnancy outcomes: A narrative review of epidemiological evidence and proposed biological mechanisms. PLOS Water. 2024;3(1):e0000214.
View Article • Google Scholar

15. Coffman VR, Jensen AS, Trabjerg BB, Pedersen CB, Hansen B, Sigsgaard T, et al. Prenatal Exposure to Nitrate from Drinking Water and Markers of Fetal Growth Restriction: A Population-Based Study of Nearly One Million Danish-Born Children. Environ Health Perspect. 2021 Feb;129(2):27002.
View Article • Google Scholar

16. Croen LA, Todoroff K, Shaw GM. Maternal exposure to nitrate from drinking water and diet and risk for neural tube defects. Am J Epidemiol. 2001;153(4):325–31. pmid:11207149
View Article • PubMed/NCBI • Google Scholar

17. Brender JD, Weyer PJ, Romitti PA, Mohanty BP, Shinde MU, Vuong AM, et al. Prenatal nitrate intake from drinking water and selected birth defects in offspring of participants in the national birth defects prevention study. Environ Health Perspect. 2013;121(9):1083–9. pmid:23771435
View Article • PubMed/NCBI • Google Scholar

18. Sherris AR, Baiocchi M, Fendorf S, Luby SP, Yang W, Shaw GM. Nitrate in Drinking Water during Pregnancy and Spontaneous Preterm Birth: A Retrospective Within-Mother Analysis in California. Environ Health Perspect. 2021;129(5):57001. pmid:33949893
View Article • PubMed/NCBI • Google Scholar

19. Stayner LT, Almberg K, Jones R, Graber J, Pedersen M, Turyk M. Atrazine and nitrate in drinking water and the risk of preterm delivery and low birth weight in four Midwestern states. Environ Res. 2017;152:294–303.
View Article • Google Scholar

20. Huang H, Woodruff TJ, Baer RJ, Bangia K, August LM, Jellife-Palowski LL. Investigation of association between environmental and socioeconomic factors and preterm birth in California. Environ Int. 2018;121(Pt 2):1066–78.
View Article • Google Scholar

21. Blaisdell J, Turyk ME, Almberg KS, Jones RM, Stayner LT. Prenatal exposure to nitrate in drinking water and the risk of congenital anomalies. Environ Res. 2019;176:108553.
View Article • Google Scholar

22. Center for Health Effects of Environmental Contamination. Environmental Databases [Internet]. 2024 [cited 2024 Oct 1.]. Available from: https://cheec.uiowa.edu/data/environmental-databases
View Article • Google Scholar

23. OpenStreetMap Foundation. Nominatim [Internet]. 2016 [cited 2024 Oct 1.]. Available from: https://nominatim.org/
View Article • Google Scholar

24. OpenStreetMap Foundation. OpenStreetMap [Internet]. 2024 [cited 2024 Oct 1.]. Available from: https://www.openstreetmap.org/
View Article • Google Scholar

25. NCHS. Birth Data Files - Vital Statistics Online [Internet]. 2024 [cited 2024 Oct 1.]. Available from: https://www.cdc.gov/nchs/data_access/vitalstatsonline.htm
View Article • Google Scholar

26. NBER. Vital Statistics Natality Birth Data [Internet]. 2023 [cited 2024 Oct 1.]. Available from: https://www.nber.org/research/data/vital-statistics-natality-birth-data
View Article • Google Scholar

27. Imai K, Kim IS. On the Use of Two-Way Fixed Effects Regression Models for Causal Inference with Panel Data. Polit Anal. 2020;29(3):405–15.
View Article • Google Scholar

28. Abadie A, Athey S, Imbens GW, Wooldridge JM. When Should You Adjust Standard Errors for Clustering? The Quarterly Journal of Economics. 2023;138(1):1–35.
View Article • Google Scholar

29. Hansen BE. A Modern Gauss–Markov Theorem. Econometrica. 2022;90(3):1283–94.
View Article • Google Scholar

30. Lancaster T. The incidental parameter problem since 1948. Journal of Econometrics. 2000;95(2):391–413.
View Article • Google Scholar

31. Lee M j a e, Lee G, Choi J y o u n g. Linear probability model revisited: why it works and how it should be specified. Sociological Methods & Research. 2025;54(1):173–86.
View Article • Google Scholar

32. Battey HS, Cox DR, Jackson MV. On the linear in probability model for binary data. R Soc open sci. 2019;6(5):190067.
View Article • Google Scholar

33. Timoneda JC. Estimating group fixed effects in panel data with a binary dependent variable: How the LPM outperforms logistic regression in rare events data. Soc Sci Res. 2021;93:102486.
View Article • Google Scholar

34. Lewis RM, Battey HS. On inference in high-dimensional logistic regression models with separated data. Biometrika. 2024;111(3):989–1011.
View Article • Google Scholar

35. Norton EC, Dowd BE, Garrido MM, Maciejewski ML. Requiem for odds ratios. Health Serv Res. 2024;59(4):e14337. pmid:38822737
View Article • PubMed/NCBI • Google Scholar

36. Norton EC, Dowd BE. Log Odds and the Interpretation of Logit Models. Health Serv Res. 2018;53(2):859–78. pmid:28560732
View Article • PubMed/NCBI • Google Scholar

37. Tajeu GS, Sen B, Allison DB, Menachemi N. Misuse of odds ratios in obesity literature: an empirical analysis of published studies. Obesity (Silver Spring). 2012;20(8):1726–31. pmid:22436842
View Article • PubMed/NCBI • Google Scholar

38. Williams R. Using the Margins Command to Estimate and Interpret Adjusted Predictions and Marginal Effects. The Stata Journal: Promoting communications on statistics and Stata. 2012;12(2):308–31.
View Article • Google Scholar

MCEA Ex. 5

39. Cutland CL, Lackritz EM, Mallett-Moore T, Bardají A, Chandrasekaran R, Lahariya C. Low birth weight: Case definition & guidelines for data collection, analysis, and presentation of maternal immunization safety data. Vaccine. 2017;35(48 Part A):6492–500.
View Article • Google Scholar

40. Barfield WD. Public Health Implications of Very Preterm Birth. Clin Perinatol. 2018;45(3):565–77.
View Article • Google Scholar

41. DeSimone LA, McMahon PB, Rosen MR. The quality of our Nation's waters: Water quality in principal aquifers of the United States, 1991-2010 [Internet]. Circular. U.S. Geological Survey; 2015 [cited 2024 Oct 1.]. Report No.: 1360. Available from: https://pubs.usgs.gov/publication/cir1360

42. EWG. EWG Investigation: Across Farm Country, Nitrate Pollution of Drinking Water for More Than 20 Million Americans Is Getting Worse [Internet]. 2024 Jun [cited 2024 Oct 1.]. Available from: http://www.ewg.org/interactive-maps/2020-nitrate-pollution-of-drinking-water-for-more-than-20-million-americans-is-getting-worse/ia/
View Article • Google Scholar

43. Skalaban TG, Thompson DA, Madrigal JM, Blount BC, Espinosa MM, Kolpin DW. Nitrate exposure from drinking water and dietary sources among Iowa farmers using private wells. Sci Total Environ. 2024;919:170922.
View Article • Google Scholar

44. Kross BC, Hallberg GR, Bruner DR, Cherryholmes K, Johnson JK. The nitrate contamination of private well water in Iowa. Am J Public Health. 1993;83(2):270–2. pmid:8427340
View Article • PubMed/NCBI • Google Scholar

45. US EPA O. Addressing Nitrates in Drinking Water with the DWSRF [Internet]. 2021 [cited 2025 Jan 29.]. Available from: https://www.epa.gov/dwsrf/addressing-nitrates-drinking-water-dwsrf
View Article • Google Scholar

46. K C A, Basel PL, Singh S. Low birth weight and its associated risk factors: Health facility-based case-control study. PLoS One. 2020;15(6):e0234907. pmid:32569281
View Article • PubMed/NCBI • Google Scholar

47. Crump C. An overview of adult health outcomes after preterm birth. Early Human Development. 2020;150:105187.
View Article • Google Scholar

48. Institute of Medicine (US) Roundtable on Environmental Health Sciences R, Mattison DR, Wilson S, Coussens C, Gilbert D. Preterm Birth and Its Consequences. In: The Role of Environmental Hazards in Premature Birth: Workshop Summary [Internet]. National Academies Press (US); 2003 [cited 2024 Oct 1.]. Available from: https://www.ncbi.nlm.nih.gov/books/NBK216221

49. Committee to Study the Prevention of Low Birthweight; Division of Health Promotion and Disease Prevention. The Significance of Low Birthweight. In: Preventing Low Birthweight [Internet]. National Academies Press (US); 1985 [cited 2024 Oct 1.]. Available from: https://www.ncbi.nlm.nih.gov/books/NBK214473/

50. Liu B, Xu G, Sun Y, Qiu X, Ryckman KK, Yu Y, et al. Maternal cigarette smoking before and during pregnancy and the risk of preterm birth: A dose-response analysis of 25 million mother-infant pairs. PLoS Med. 2020;17(8):e1003158. pmid:32810187
View Article • PubMed/NCBI • Google Scholar

51. Zheng W, Suzuki K, Tanaka T, Kohama M, Yamagata Z, Okinawa Child Health Study Group. Association between Maternal Smoking during Pregnancy and Low Birthweight: Effects by Maternal Age. PLoS One. 2016;11(1):e0146241. pmid:26795494
View Article • PubMed/NCBI • Google Scholar

52. DiSalvo RW, Hill EL. Drinking Water Contaminant Concentrations and Birth Outcomes. J Policy Anal Manage. 2024;43(2):368–99. pmid:38983462
View Article • PubMed/NCBI • Google Scholar

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Guidelines for manure application rates

Quick facts

- Manure nutrient management planning is important for maximizing crop productivity while protecting water quality
- Guidelines for manure application rates vary depending on crop and cropping history
- Manure application rates should consider all nutrient sources that will be or have been applied to a field. For example, if commercial, inorganic fertilizers will be applied or if manure was applied in the previous two years, take credit!

Animal manure is a good source of nutrients for crops, including nitrogen (N), phosphorus (P), and potassium (K). The proportion of the nutrients in manure are typically not the same as needed by the crops, however. Manure application based on one nutrient may over- or under apply other required crop nutrients. Nitrogen is required in the largest quantities by non-legume crops. Applying manure to meet crop N needs will likely overapply P, and possibly K, for a crop such as corn. On the other hand, using manure to meet P needs of the crop will likely result in a lower application rate and will underapply N and possibly K. Commercial fertilizers will then be needed to balance out N and K needs. Consider the pros and cons of these two options when choosing a manure application rate.



Credit: MPCA

Nutrients in manure are not 100% available in the first year. First-year plant-available N (PAN) will depend on animal species and how the manure is applied. Plant-available P (PAP) is assumed to be 80% of the total P applied in the first year. You can learn more about calculating PAN and PAP, including first-year PAN and PAP, from our "calculating manure application rates" recommendations. The guidelines for manure application rates below are based on PAN or PAP, not total N and P.

Nitrogen guidelines for manure

The rates below are the maximum amounts of N that should be applied when manure is used, whether it is all manure or a combination of manure and inorganic commercial fertilizers. Lower rates may be considered based on the productivity of the soils in your fields, economics, or environmental concerns. In all cases, all sources of N should be taken into consideration when estimating how much N to apply, including:

- N from irrigation water.
- Credits from manure, or other organic N sources, that was applied in the past 2 years.
- Credits from legumes like edible beans, red clover, etc.

Why is that? Research across the US Midwest has shown that applications of N above the economically optimum N rate (EONR) for a crop significantly increase the potential for N losses. For example, once N leaches past the plant root zone into the ground water, it becomes a concern for drinking water and will eventually end up in lakes, rivers, and streams. On the other hand, excess N that is not taken up by crops can also be lost as a gas through denitrification. When manure N becomes plant available, it behaves exactly the same in the environment as N from commercial inorganic fertilizer, so it is important that all forms of N applied to the soil are taken into consideration. Don't waste your manure!

Non-irrigated corn

The maximum rate of plant-available nitrogen (PAN) that should be applied with manure to non-irrigated corn, depending on the crops prior to corn, can be found in the table below.

Crop prior to corn ▸	Crop 2 years prior to corn ▸	Maximum lbs of PAN to apply ▸
Corn (or other non-legume crop)	Not applicable	195
Corn	Alfalfa (1-year-old stand)	120
Corn	Alfalfa (>2-year-old stand)	80
Soybean	Not applicable	150

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Crop prior to corn ▸	Crop 2 years prior to corn ▸	Maximum lbs of PAN to apply ▸
Alfalfa (1-year-old stand)	Not applicable	80
Alfalfa (>2-year-old stand)	Not applicable	40

Irrigated corn grown on sandy soils

Corn grown under irrigation is a special case because it is usually done on coarse-textured (or sandy) soils. Under these conditions, there is a higher risk of N loss due to the high leaching potential of these types of soils. With manure, there are other nutrients to consider that could potentially also be lost through leaching. Because of this, we suggest applying a lower rate of manure (as an example, see the section on "Phosphorus Guidelines for Manure" below), then supplement with commercial N fertilizers to meet total N needs. See the table below for the total N rate guidelines.

A good rule of thumb is to apply a lower rate of manure (195 lbs of plant-available N [PAN] or lower), then add the remaining N as commercial fertilizer.

Crop prior to corn ▸	Pounds of nitrogen to apply ▸
Soybean	205
Other crops	235

Other non-legume crops

The maximum amount of PAN you should apply to non-legume crops with manure should follow University of Minnesota guidelines for nitrogen fertilizers.

Details for each crop:

- Barley
- Buckwheat
- Canola
- Grasses
- Grass-legume mixtures
- Oat
- Potato (irrigated)
- Rye
- Sugarbeet

- Sunflower
- Wheat

Legume crops

If manure is applied to a legume crop, you can apply as much PAN as the crop will likely take up in the harvested portion. You can find out how much N will be taken up per harvestable unit in the table below Multiply this number by the amount of yield you expect from that field to get your application rate.

Crop ▸	Yield unit ▸	Crop N removal (lbs per yield unit)▸
Alfalfa	Tons (air dry)	50.4
Red clover	Tons (air dry)	45.1
Soybean	Bushels	3.5

Example: Assume that field conditions have been poor, so you need to apply manure in the fall to a field where soybean will be planted the following spring because it is the only dry field you have. You expect the soybean yield to be about 60 bushels per acre (this is the typical yield you get from this field). If you multiply 60 bushels per acre by 3.5 lbs of N per bushel, you will find that the crop will take up 210 lbs of N. This means you can apply a manure rate of 210 lbs of PAN per acre.

Phosphorus guidelines for manure

In cases where manure is readily available frequently, using a P-based manure application rate may make the most long-term, economic sense because the crops will use nutrients more efficiently. For manure, it is recommended to apply as much plant-available phosphorus (PAP) as the crop will use.

Amount of phosphorus removed per unit of harvested yield

See the table below for crop P removal rates in the harvested portion (the units are in P_2O_5 to make it comparable to what you would apply with commercial fertilizer). Multiply this number by the amount of yield you expect from that field to get your PAP application rate.

Note that soil testing should be conducted regularly in your fields where manure will be applied. If the soil P test level is very high (over 21 ppm Bray-P or over 16 ppm Olsen-P), you are not likely to see a yield benefit from the additional P in the manure. Instead, consider using the manure in a field where P applications will help improve yields.

If soil test P levels are excessively high (over 50 ppm Bray-P or over 30 ppm Olsen P), do not apply manure, especially near water bodies, because building soil test P levels further will increase the risk for soluble P losses from the soil.

Once you determine your P-based application rate, remember to credit the manure for the nitrogen that will be applied. Balance the remaining N needs of the crop with commercial fertilizers.

Crop ▸	Yield units ▸	Crop P_2O_5 removal (lbs per yield unit) ▸
Alfalfa	Tons (air dry)	10.8
Barley (grain)	Tons (air dry)	0.41
Barley (grain and straw)	Bushels	0.55
Canola	Cwt.	1.3
Corn (grain)	Bushels	0.28
Corn (silage)	Tons (as fed)	3.8
Edible beans	Pounds	0.01
Grass or hay pasture	Tons (air dry)	8.9
Grass/legume	Tons (air dry)	11.2
Oats (grain)	Bushels	0.25
Oats (grain and straw)	Bushels	0.32
Peas	Pounds	0.01

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Crop ▸	Yield units ▸	Crop P_2O_5 removal (lbs per yield unit) ▸
Potatoes	Cwt.	0.14
Red clover	Tons (air dry)	10.8
Rye (grain)	Bushels	0.44
Rye (grain and straw)	Bushels	0.59
Soybeans	Bushels	0.82
Sugarbeets	Fresh Tons	0.73
Sunflower	Pounds	0.01
Sweet corn	Tons	11
Wheat (grain)	Bushels	0.53
Wheat (grain and straw)	Bushels	0.64

Where do our guidelines come from?

Inorganic commercial fertilizers are often used to figure out crop nutrient needs in experiments across Minnesota. These fertilizers are designed to release 100% of the N and P in the first year, so it makes it easier to determine how much to apply to get the optimized yields. As an example, N guidelines for corn are based on 170+ experiments across the state, most of which occurred in the past five years. As new experiments are completed, the data on optimal N needed are added to the overall database, and N guidelines are adjusted accordingly.

With manure, we can calculate the estimated plant-available nutrients that will be available in a given year. Once nutrients from manure are plant-available, they behave in the environment exactly the same as a nutrient from a commercial fertilizer. Thus, our guidelines for manure application are

based on optimal nutrient rates needed, which is known from fertilizer experiments, and how much plant-available nutrient will be available in the first year after application.

Guidelines for Manure Application Rates (printable PDF, 2022)

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Reviewed in 2022

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Fertilizing corn in Minnesota

In Minnesota, corn is grown on more acres than any other crop. Nationally, Minnesota ranks among the top five states in corn production. Average corn yields have improved steadily over the past several decades.



While general fertilizer use contributed substantially to yield increases in the past, total fertilizer management, which optimizes nutrient efficiency, will be needed to increase future production and profitability.

Nitrogen guidelines

Minnesota corn growers receive a substantial return for money invested in nitrogen (N) fertilizers. For many situations, the most profitable yield cannot be achieved unless N fertilizers are used.

There are many management decisions involved in the use of N fertilizers. The most important decision is the selection of an N rate that will produce maximum profit while limiting the potential for environmental degradation. The choice of an appropriate rate of fertilizer N is not easy because of the transient nature of N in soils.

Standard N guidelines

The consideration of soil productivity, price/value ratio and previous crop are used to arrive at the fertilizer N guidelines for corn. This represents a significant change compared to previous approaches. This process has been in place since 2005 and is the product of a multi-state effort to use a similar philosophy/approach for determining N rate guidelines for corn.

Because of technology improvements in corn production practices such as weed and pest control, expected yield is not as important of a factor in determining N rate as it has been in the past.

Soil productivity has become a better indicator of N need. A majority of Minnesota soils are highly productive and have generally produced maximum economic corn yield with similar N rates over the last 15 years.

Some soils have a reduced yield potential due to erosion, reduced water holding capacity caused by lower organic matter content, sandy soil texture, poor drainage and restricted root growth. The fluctuation in fertilizer price affects the economic optimum N rate. To account for this change, the ratio of the price of N per pound to the value of a bushel of corn has been added to the N rate decision.

An example calculation of the price/value ratio is if N fertilizer costs $0.40 per lb N (or $656 per ton of anhydrous ammonia), and corn is valued at $4.00 per bushel, the ratio would be 0.40/4.00 = 0.10.

The maximum return to N value (MRTN) shown in Table 1 is the N rate that maximizes profit to the producer based on the large number of Minnesota experiments supporting these guidelines. Once the soil productivity and price/value ratio have been determined, a producer's attitude towards risk must be factored into the process.

A producer who is risk-averse and cannot tolerate risk associated with less-than-maximum yields in some years, even though economic return to N may not always be highly profitable, may want to use the N rates near the high end of the acceptable range shown in Table 1.

On the other hand, if corn is grown on medium or fine-textured soils considered to be of low or medium productivity and/or localized N response data support lower N rates, producers may choose N rates near the low end of the acceptable range in Table 1 if they are willing to accept the possibility of less-than-maximum yield in some years without sacrificing profit.

The acceptable range gives the producer flexibility in arriving at an acceptable and profitable N rate that is calculated as the rate +/- $1 from the MRTN rate.

Prior crop ▸	N price/Crop value ratio ▸	MRTN (lbs N/acre) ▸	Acceptable range (lbs N/acre) ▸
Corn	0.075	200	180-220
Corn	0.100	185	170-200
Corn	0.125	175	160-190
Corn	0.150	165	150-175
Soybeans	0.075	155	145-170
Soybeans	0.100	150	135-160

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Prior crop ▸	N price/Crop value ratio ▸	MRTN (lbs N/acre) ▸	Acceptable range (lbs N/acre) ▸
Soybeans	0.125	140	130-155
Soybeans	0.150	135	125-145

The N rate guidelines in Table 1 are used if corn is grown in rotation with soybean or following corn when NOT irrigated. Corn grown on sandy soils deserves special consideration.

If irrigated, the guidelines listed in Table 2 are appropriate when corn is grown in rotation with corn. If corn is grown following soybean on irrigated sandy soils, a credit of 30 lbs of N per acre should be taken from the suggestions given in Table 2.

N price/Crop value ratio ▸	MRTN (lbs N/acre) ▸	Acceptable range (lbs N/acre) ▸
0.05	235	210-255
0.1	210	190-225
0.15	190	175-210
0.2	180	165-190

For non-irrigated corn grown on soils with a loamy fine sand texture and less than 3% organic matter, use the guidelines provided in Table 3.

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Soils considered medium productivity in the past were given special consideration. More recent data has not shown strong support for a separate suggested application rate of N for medium-productivity soils.

The rate of N can be adjusted based on the acceptable range if a soil is considered to be medium productivity and has shown to be more or less responsive to fertilizer N.

N price/Crop value ratio ▸	Corn/Corn (lbs N/acre) ▸	Soybean/Corn (lbs N/acre) ▸
0.05	100	70
0.1	90	60
0.15	80	50
0.2	70	40

Nitrogen management for first and second-year corn following alfalfa

Alfalfa, which includes pure stands of alfalfa and alfalfa-grass mixtures with at least 50% alfalfa in the stand, can eliminate or greatly reduce the need for N from fertilizer or manure during the two subsequent years if corn is grown.

Past guidelines assigned N credits to corn based on alfalfa stand density, but analyses of field trials from across Minnesota and the Midwest indicate that the frequency and level of yield response to N in first and second-year corn following alfalfa are more closely associated with soil texture, age of alfalfa at termination, alfalfa termination timing and weather conditions.

It is well established that first-year corn following alfalfa rarely responds to N except on sandy soils, on fine-textured soils when there are prolonged wet early-season conditions and on medium-textured soils when following very young alfalfa stands or in some cases when following spring-terminated alfalfa.

In past field trials from across Minnesota and the Midwest, yield of second-year corn following alfalfa did not respond to N in half of the fields studied.

Suggested rates of N for first and second-year corn following alfalfa are in Table 4. In some cases, the optimal rate of N can vary greatly due to weather-related variability in soil N mineralization. In such cases, limit the amount of N from fertilizer and manure applied before and near corn planting and apply additional N to corn during the growing season if necessary based on weather and crop conditions.

Soil texture[b] ▸	Irrigated or non-irrigated ▸	Alfalfa age[c] ▸	Alfalfa termination time ▸	First-year corn following alfalfa (lbs N/acre) ▸	Second-year corn following alfalfa (lbs N/acre) ▸
Coarse	Irrigated	1 year	Fall or spring	140-170	140-170?
Coarse	Irrigated	2 or more years	Fall or spring	70-150	70-150
Coarse	Non-irrigated	1 year	Fall or spring	40-80[d]	80-120[d]
Coarse	Non-irrigated	2 or more years	Fall or spring	0-20	0-80
Medium	Both	1 year	Fall or spring	40-80[d]	80-120[d]
Medium	Both	2 or more years	Fall	0-20	0-80
Medium	Both	2 or more years	Spring	0-40	0-80
Fine	Both	1 year	Fall or spring	40-80[d]	80-120[d]

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Soil texture[b] ▸	Irrigated or non-irrigated ▸	Alfalfa age[c] ▸	Alfalfa termination time ▸	First-year corn following alfalfa (lbs N/acre) ▸	Second-year corn following alfalfa (lbs N/acre) ▸
Fine	Both	2 or more years	Fall	0-20[d]	0-80[d]
Fine	Both	2 or more years	Spring	0-40[d]	0-80[d]

[a]Includes pure stands of alfalfa and alfalfa-grass mixtures with at least 50% alfalfa in the stand.
[b] Coarse = sands and sandy loams; medium = loams and silt loams; fine = clays, clay loams and silty clay loams.
[c]Alfalfa age at termination, including the establishment year if alfalfa was direct-seeded without a small grain companion crop.
[d]An additional 30 to 40 lbs N/acre can be applied to corn during the growing season if necessary, based on the Corn calculator for supplemental nitrogen

Nitrogen credits from other previous crops

To arrive at a guideline following other crops, an adjustment (credit) is made to the corn following corn guidelines. The adjustments can be found in Table 5.

In Table 5, several crops are divided into Group 1 and Group 2. The crops for each group are listed in Table 6.

Previous crop ▸	1st year N credit (lbs N/acre) ▸
Group 1 crops	75
Group 2 crops	0

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Previous crop ▸	1st year N credit (lbs N/acre) ▸
Edible beans	20
Field peas	20

The N rates listed in Tables 1 and 2 define the total amount of fertilizer N that should be applied. All N applied should be accounted for in the calculation, including N in starter fertilizer, weed and feed program, DAP (di-ammonium phosphate) or MAP (mono-ammonium phosphate) applied late fall (after 4" average soil temperatures stabilize at 50ϑF) on non-sandy soils or for all soil types in spring, and with sulfur.

It is generally accepted that legume crops provide N to the next crop in the rotation. Some forage legumes provide some N in the second year after the legume was grown.

Red clover is the only crop other than alfalfa that may provide a second-year N credit. If red clover was grown two years before the current crop, 35 lbs of N per acre should be subtracted from the N rate when corn follows the crops listed in Group 2, Table 5.

Crop ▸	Group number ▸
Alsike clover	1
Birdsfoot trefoil	1
Grass/legume hay	1
Grass/legume pasture	1
Fallow	1
Red clover	1
Barley	2
Buckwheat	2
Canola	2

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Crop ▸	Group number ▸
Corn	2
Grass hay	2
Grass pasture	2
Oats	2
Potatoes	2
Rye	2
Sorghum-sudan	2
Sugar beet	2
Sunflower	2
Sweet corn	2
Vegetables	2
Wheat	2

Using manure as a nitrogen source

The use of manure as a fertilizer source can raise questions about adequate nitrogen rates. The economics of manure application are not straightforward when on-farm sources are used in corn production.

Manure presents challenges as not all of the nutrients are 100% available to crops in the first year of application. Plant available N (PAN) is a term used when applying manure to identify the amount of N applied that is plant available in any given year and may be less than the total N applied.

Suggestions for N application when manure is the primary nutrient source are given in Table 7. If commercial fertilizer is used along with manure, the suggested rates in Table 7 should not be exceeded. Lower application rates similar to the 0.10 price ratio may be considered based on the

productivity of the soils in your fields, economics or environmental concerns.

Crop grown prior to corn ▸	Field irrigated? ▸	Suggested PAN to apply (lbs N/acre) ▸
Corn	No	195
Corn	Yes	235
Corn (after 1 year old stand of alfalfa; 2 years prior to corn)	No	n/a
Corn (after 2 or more year old stand of alfalfa; 2 years prior to corn)	No	80
Soybean	No	150
Soybean	Yes	205
Alfalfa (1 year old stand)	No	80
Alfalfa (2 or more year old stand)	No	40

Use of a soil nitrate test encouraged

The pre-plant soil nitrate test (PPNT) can be a useful tool for assessing situations where residual soil nitrate can be credited to the corn crop. The PPNT should not be used when commercial fertilizer or manure was applied in the previous fall or in the spring before the sample is taken.

Western Minnesota

The use of the fall or spring PPNT is a key management tool for corn producers in western Minnesota. The suggestion that residual N in the fall can impact the need for nitrogen is contingent on the fact that evapotranspiration of water has historically exceeded precipitation in this area of the state.

The use of the fall PPNT is appropriate in the maroon-colored counties shown on the map. The PPNT is particularly useful for conditions where elevated residual nitrate-N is suspected.

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The decision tree indicates situations where the nitrate-N soil test would be especially useful.

For the PPNT, soil should be collected from a depth of 6 to 24 inches, in addition to the 0 to 6-inch sample used to test for pH, phosphorus, and potassium.

Corn growers in western Minnesota also have the option of collecting soil samples from 0 to 24 inches and analyzing them for nitrate-nitrogen (NO_3-N). This 0 to 24-inch sample should not be analyzed for pH, phosphorus and potassium because the results cannot be used to predict lime needs or rates of phosphate and potash fertilizer needed.

When using the spring or fall PPNT, the amount of fertilizer N required is determined from the following equation:

NG = (Table 1 value for corn/corn) - (0.60 x STN(0-24in.))

- NG = Amount of fertilizer N needed (lbs N/acre)
- Table 1 value = the amount of fertilizer needed to be adjusted for soil potential, value ratio and risk
- STN(0-24 inch) = Amount of nitrate-N measured by using the fall PPNT (lbs N/acre)

The fall pre-plant nitrate test is appropriate for the maroon-shaded counties.

Decision tree for determining the probability of having significant residual nitrate-nitrogen in the soil following specific crops and situations where manure has been applied in a field within two to three cropping years before soil sample collection.

South-central, southeastern, and east-central Minnesota

Research has led to the inclusion of a spring PPNT to adjust fertilizer N guidelines in south-central, southeastern and east-central Minnesota (gray counties on the map).

Soil nitrate-N, measured in the spring before planting from a two-foot sampling depth, is an option that can be used to estimate residual N.

In implementing this test, the user should first evaluate whether conditions exist for residual N to accumulate. Factors such as previous crop, soil texture, manure history and preceding rainfall can have a significant effect on the accumulation of residual N.

A crop rotation that has corn following corn generally provides the greatest potential for significant residual N accumulation. In contrast, when soybean is the previous crop, much less residual N has been measured. The PPNT should not be used following alfalfa.

The spring PPNT works best on medium and fine-textured soils derived from loess or glacial till. The use of the soil N test on coarse-textured soils derived from glacial outwash is generally not worthwhile because these soils consistently have low amounts of residual nitrate-nitrogen.

The amount of residual nitrate-nitrogen in the soil is also dependent on the rainfall received the previous year. In a year following a widespread drought (2012, for example), a majority of fields will have significant residual nitrate. However, following relatively wet years, little residual nitrate can be expected.

Nitrogen fertilizer guidelines for corn can be made with or without the soil N test. The University of Minnesota's N guidelines (Table 1) are still the starting point. We recommend a five-step process when considering the soil nitrate-nitrogen test.

1. Determine the N rate guideline using Table 1 using soil productivity, price/value ratio, and previous crop for the specific field. The prescribed rate assumes that best management practices (BMPs) will be followed for the specific conditions.
2. Determine whether conditions are such that residual nitrate-nitrogen may be appreciable. The decision tree, which includes factors such as previous crop, manure history, and previous fall rainfall, can provide insight into the applicability of testing for nitrate-nitrogen. If the probability of residual nitrate is small and soil testing for nitrate is not recommended, use the N guideline derived in Step 1.
3. If conditions suggest that a soil nitrate test is warranted, collect a pre-plant soil sample from 0 to 2 feet deep, taking enough soil cores from the field so that the sample is representative of the entire field. The sample should be sent to a laboratory and analyzed for nitrate-nitrogen.
4. Determine residual N credit based on the measured soil nitrate-nitrogen concentrations. Use Table 8 to determine this credit.
5. Calculate the final N rate by subtracting the residual N credit (Step 4) from the previously determined N guideline (Step 1). The resulting fertilizer N rate can then be applied either pre-plant or as a side-dress application.

Soil nitrate-N ▸	Residual N credit ▸
0.0-6.0 (ppm)	0 (lbs N/acre)

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Soil nitrate-N ▸	Residual N credit ▸
6.1-9.0	35
9.1-12.0	65
12.1-15.0	95
15.1-18.0	125
Over 18.0	155

Best management practices for nitrogen

Because of the diversity of soils, climate and crops in Minnesota, there are no uniform statewide guidelines for the selection of a source of fertilizer N, placement of the N fertilizer and use of a nitrification inhibitor.

In order to accurately address this diversity, Minnesota has been divided into five regions and BMPs for N use in each region have been identified and described. The listing of these management practices for all regions is not appropriate for this publication, but they are available at the Minnesota Department of Agriculture

Currently, the use of these BMPs is voluntary. Corn growers should implement BMPs to optimize N use efficiency, profit and protect against increased losses of nitrate-nitrogen to the environment.

Phosphate and potash guidelines

Phosphorus and potassium rate tables

When needed, phosphate and/or potassium (potash) fertilizer can produce profitable increases in corn yields. Soil test categories represent the probability the soil will supply all the needed crop nutrients.

Table 9 shows field research data summarizing the expected percent of time when a measurable response to P fertilizer will occur and the percentage of maximum yield produced when no fertilizer is applied.

The chance of a yield response to P and the increase in yield is greatest when soil P tests very low and decreases as soil test P increases. Corn yield may still be increased by P at high and very high soil tests but the net return to P may not be profitable.

Bray-P1 or Olsen soil test P category ▸	Expected time P fertilizer will increase corn grain yield ▸	Expected yield without P fertilizer ▸
Very low	87%	87%
Low	83%	90%
Medium	27%	98%
High	13%	99%
Very high	7%	99%

Table 10: Broadcast (Bdcst) and band phosphate guidelines for corn production i Minnesota*

Expected yield ▸	Broadcast/band ▸	P soil test: 0-5 parts per million (ppm) Bray and 0-3 ppm Olsen ▸	P soil test: 6-10 ppm Bray and 4-7 ppm Olsen ▸	P soil test: 11-15 ppm Bray and 8-11 ppm Olsen ▸	P soil test: 16-20 ppm Bray and 12-15 ppm Olsen ▸	P soil t 21 + pp Bray a 16 + pp Olsen
151-175 (bu/acre)	Broadcast	90 (lbs P2O5/acre)	60 (lbs P2O5/acre)	35 (lbs P2O5/acre)	10 (lbs P2O5/acre)	0 (lbs P2O5/a
151-175	Band	45	35	25	10-15	10-15
176-200	Broadcast	110	75	45	15	0
176-200	Band	55	40	30	10-15	10-15

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Expected yield ▸	Broadcast/band ▸	P soil test: 0-5 parts per million (ppm) Bray and 0-3 ppm Olsen ▸	P soil test: 6-10 ppm Bray and 4-7 ppm Olsen ▸	P soil test: 11-15 ppm Bray and 8-11 ppm Olsen ▸	P soil test: 16-20 ppm Bray and 12-15 ppm Olsen ▸	P soil t 21 + pp Bray a 16 + pp Olsen
201-225	Broadcast	130	90	55	20	0
201-225	Band	65	45	30	10-15	10-15
226-250	Broadcast	145	100	60	20	0
226-250	Band	75	50	30	10-15	10-15
250 +	Broadcast	160	115	70	25	0
250 +	Band	80	60	35	10-15	10-15

* Use one of the following equations if a P_2O_5 guideline for a specific soil test value and a specific expected yield is desired.

$P_2O_{5suggestions}$ = [0.700 - .035 (Bray P ppm)] (expected yield)

$P_2O_{5suggestions}$ = [0.700 - (.044 (Olsen P ppm)] (expected yield)

No phosphate fertilizer is suggested if the soil test for P is greater than 25 ppm (Bray) or 20 ppm (Olsen).

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Expected yield ▸	Broadcast/band ▸	K soil test: 0-50 ppm ▸	K soil test: 51-100 ppm ▸	K soil test: 101-150 ppm ▸	K soil test: 151-200 ppm ▸	K soil test: 200 + ppm ▸
151-175 (bu/acre)	Broadcast	160 (lbs K2O/acre)	115 (lbs K2O/acre)	70 (lbs K2O/acre)	20 (lbs K2O/acre)	0 (lbs K2O/acre)
151-175	Band	75	60	45	10-15	10-15
176-200	Broadcast	185	135	80	25	0
176-200	Band	90	70	50	10-15	10-15
201-225	Broadcast	210	155	90	30	0
201-225	Band	105	80	55	10-15	10-15
226-250	Broadcast	235	165	100	35	0
226-250	Band	120	85	60	10-15	10-15
250 +	Broadcast	255	180	110	40	0
250 +	Band	130	90	65	15-20	10-15

* Use one of the following equations if a K_2O guideline for a specific soil test value and a specific expected yield is desired.

$K_2O_{suggested}$ = [1.12 - 0.0056 (Soil Test K, ppm)] (expected yield)<

No potash fertilizer is suggested if the soil test for K is 200 ppm or greater.

Rate changes with placement

In general, the results of the Olsen test should be used if the soil pH is 7.4 or greater. There are some situations where the results of the Bray test are greater than the results of the Olsen test when soil pH values are greater than 7.4. For these cases, the amount of phosphate suggested should be based on the soil test value that is the higher of the two.

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Measurement of P by the Mehlich III procedure is not suggested for use in Minnesota. However, some soil testing laboratories analyze P with this analytical test. For these situations, use the guidelines appropriate for the results of the Bray procedure.

The definition of categories is the same for both the Bray and Mehlich III analytical procedures when P is determined colorimetrically. If the soil pH is greater than 7.4, use of the Mehlich III test is not suggested as the results may not correlate to the Olsen P test.

A combination of band and broadcast applications is suggested if the soil test for P is very low (0-5 ppm for Bray; 0-3 ppm for Olsen). For fields with very low P soil test values, plan on using the suggested band rate at planting then subtract the amount of P banded from the suggested broadcast P rate, then broadcast and incorporate the remainder of P before planting.

Phosphate fertilizer can be applied as either a broadcast application or in a band fertilizer if the soil test value for P is in the low (6-10 ppm for Bray; 4-7 ppm for Olsen) or medium (11-15 ppm for Bray; 8-11 ppm for Olsen) ranges. Broadcast applications of phosphate fertilizer have a low probability of increasing corn yields when the soil test for P is in the high range (16-20 ppm for Bray; 12-15 ppm for Olsen). The use of phosphate in a banded fertilizer is suggested for these situations.

No phosphate fertilizer is suggested for either broadcast or banded application if the soil test is greater than 25 ppm (Bray), or 20 ppm (Olsen), and conventional tillage systems are used.

As with phosphate, the suggested rates of potash vary with the soil test for potassium (K), expected yield and placement Table 11. A combination of broadcast and band applications is suggested when the soil test for K is in the range of 0-40 ppm.

For fields with these values, plan on using the suggested rate in the band at planting, subtract this amount from the suggested broadcast rate, then broadcast and incorporate the remainder needed before planting. The grower can choose either broadcast or band placement if the soil test for K is in the low (41-80 ppm) or medium (81-120 ppm) range. Applying potash in a band is emphasized if the soil test for K is in the high range (121-160 ppm).

Maintenance based P and K strategies

Many growers would prefer to maintain soil test values for P and K in the medium to high range to reduce the risk of yield loss due to insufficient P or K. This is especially true if they own, rather than rent, the land.

There is justified concern that soil test levels for either P or K will drop substantially if low rates of phosphate or potash fertilizers are applied year after year and soils are not tested frequently enough to make adjustments for decreasing soil test values. In these circumstances, the application of P and K based on crop removal may be warranted.

Median rates of P and K removed per bushel of corn grain are listed in Table 12. High rates of P or K applied for maintenance will typically result in a less return in crop value per pound of nutrient applied.

The most economical use of P and K fertilizer is to only apply what is needed year to year. Recent research suggests that crop removal based on a proven yield (5-10 year yield average) can be economical for soils testing in the medium to high soil test categories.

For very high testing soils, a small starter rate of P or K is typically sufficient to achieve maximum crop yield in situations where corn will respond to applied fertilizer. Application of 50% or less of crop removal is suggested for soils testing very high in available nutrients to allow soil tests to gradually draw down to the high STP classification.

Nutrient ▸	Median (lbs/bushel) ▸	Range (lbs/bushel) ▸
Phosphate (P_2O_5)	0.28	0.25-0.33
Potash (K_2O)	0.19	0.18-0.22

Strict crop removal of P and K may not provide sufficient nutrients for soils that test very low or low for either nutrient. Extra P can be applied to build some soils to the medium or high soil test category.

A general rule is that 16-18 lbs P_2O_5 and 7-10 lbs K_2O are required to increase the Bray-P1 or ammonium acetate K tests by 1 ppm, respectively. Rapid buildup of soil test P or K is not suggested. Research has shown that the rates of P suggested for the very low and low STP categories will slowly build STP to the medium classification for neutral to acid soils.

The amount of P or K needed to build the soil test greatly depends on soil chemical properties. For soils in western Minnesota where the Olsen P test is used, aggressively building soil test P values will not be cost-effective due to the reaction of ortho-phosphate with calcium. Under these circumstances, applying only what the crop needs to maximize yield potential is suggested.

Excessive building of P can lead to increased risk for P loss to the environment. The strategy outlined in Table 13 shows the STP range which is optimal for maintenance within the medium to high STP categories and suggests drawing STP down using P application based on partial crop removal in order to maintain STP in a more profitable zone. Soil test P ranges are not given for the Olsen P test as it may not be possible to build and maintain some high pH soils.

The example in Table 13 could be used for K. However, research has demonstrated increased seasonal variability in the soil K test. Collecting samples at the same time is critical to best evaluate maintenance-based strategies for K.

Bray-P1 test ▸	Suggested rate ranges ▸
0-10 (ppm)	See table 9
10-20	100% (crop removal)
20-30	25-50%
30-40	0-20%
40-50	0-10%
50 +	No P fertilizer suggested

Impact of cation exchange on corn K guidelines

Potassium fertilizer guidelines for corn have been revised based on recent research on medium - and fine-textured soils in Minnesota. Currently, these guideline rates are not adjusted based on a soil's ability to hold potassium on cation exchange sites of clays.

Coarse-textured soils, such as sands and loamy sands, have very little clay and low cation exchange capacity (CEC). Potassium can leach from low CEC soils, potentially wasting K fertilizer and reducing economic return to fertilizer.

Research in Minnesota is ongoing to determine if K guidelines need to vary based on soil CEC. Recent research on sandy soils with a CEC of around 5 meq per 100 grams has shown that sandy soils require less potassium fertilizer than medium - and fine-textured soils with the same soil test K level and have a lower critical soil test level.

Due to K's leaching potential and a lower critical level of low CEC soils, it is not recommended to build soil test K greater than 120 ppm. Until more research data are available, K fertilizer can be applied to low CEC soils using the equation below.

However, use of this equation will reduce K fertilizer application rates on low CEC soils and should be done on a trial basis to ensure K is not limiting yield on irrigated corn grown on low CEC sandy soils.

$K_2O_{suggested}$ = [1.08 - 0.0084 (Soil Test K, ppm)] (expected yield)

Special considerations

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Because of the diversity of Minnesota's soils and climate, rental and lease arrangements for land and goals of individual growers, the phosphate and potash suggestions listed in Tables 10 and 11 cannot be rigid across the entire state. There are some special situations where rates might be changed. Some, but not all, of these situations are described in the following paragraphs.

East-central Minnesota soils

This region of the state usually has high native levels of soil test P and strict interpretation of the guidelines suggests that no phosphate is needed in a fertilizer program. However, many corn growers have observed responses to phosphate when applied in a band at planting.

Soils in this region are frequently cool and wet in the spring and these conditions can lead to a requirement for phosphate fertilizer early in the growing season. Therefore, a rate of 15-20 lbs phosphate per acre is suggested for use in a banded fertilizer placed close to the seed at planting for corn production in these situations, regardless of soil test level for P.

Broadcasting low rates

Some of the suggested rates for phosphate and potash listed in Tables 10 and 11 are small and fertilizer spreaders cannot be adjusted to apply these low rates. The suggested broadcast rate of phosphate can be blended with the suggested broadcast rate of potash and the mixture could then be applied with available equipment.

In other situations, broadcast applications of low rates of only phosphate or potash may be suggested. For these fields, it may be more practical to double the suggested broadcast rate and apply on alternate years.

Changes in P and K soil test values

Research in Minnesota has shown that soil test levels for P and K should not change rapidly with time. Yearly decreases have been small for situations where no phosphate or potash fertilizer has been applied but can vary from year to year depending on environmental conditions. Always use long-term soil test trends over five years when assessing changes in soil test values using maintenance-based strategies.

A small decrease in soil test levels for P and K can be expected when phosphate and potash are used repeatedly in a banded fertilizer. Likewise, some reduction can be expected when low rates of phosphate and potash are used year after year.

When soil test values drop, broadcast applications of higher rates of phosphate and/or potash fertilizers are justified if profitability and cash flow is favorable and the grower wants to maintain soil test values in the medium or high range.

Unless long-term leases or rental arrangements are in place, the use of a banded placement for phosphate and/or potash may be the most profitable management system for rented land. It is difficult to economically justify the use of high rates of phosphate and/or potash to build soil test

levels on rented acres.

Adjusting for manure use

Animal manure is an excellent source of plant nutrients. When using manure, first determine the amount of plant-available nutrients it will provide in the first year (80% of P and 90% of K).

Adjust the fertilizer program to make up the difference between what was applied and what is needed according to the fertilizer guidelines. Extension resources that describe in detail the use of manure are listed at the end of this publication.

Using a banded fertilizer

The use of a banded fertilizer at planting is an excellent management tool for corn production in Minnesota, especially when soils are cold and wet at planting. Yield increases are not always guaranteed when using a starter, especially if soil test values are in the very high range or when recommended rates of broadcast P or K are applied.

The rate of fertilizer that can be applied in a band directly on the seed at planting varies by fertilizer source and soil texture. See a summary of appropriate rates for Banding fertilizer on the corn seed

Applying fertilizer two inches beside and below the seed row presents a very low risk for reduced germination, and higher rates of nutrients can be applied when there is one or more inches between the fertilizer and seed placement. All nutrients applied in starter fertilizer should be accounted for in the total fertilizer program.

> CAUTION! Do not apply urea, ammonium thiosulfate (12-0-0-26), potassium thiosulfate, or fertilizer containing boron in contact with the seed.

Sulfur, magnesium and micronutrient needs

Sulfur guidelines

The addition of sulfur (S) to a fertilizer program for corn should be a major consideration based on soil texture, crop rotation, soil drainage and soil organic matter concentration in the top six inches. Suggested sulfur application rates as sulfate-sulfur forms are given in Table 14.

Banding sulfur fertilizer can increase effectiveness and reduce the required application rate by as much as one-half. Keep in mind that ammonium or potassium thiosulfate should not be placed in contact with the seed. Thiosulfate will not harm germination or emergence if there is at least one inch of soil between seed and fertilizer.

Crop rotation ▸	Drainage ▸	0-2% ▸	2-4% ▸	4+% ▸
Soybean/wheat-corn	Well	10-25	10-15	0
Soybean/wheat-corn	Poor	15-25	10-15	5-15
Corn-corn	All	15-25	10-15	5-15
Course/sandy soils	n/a	25	25	15-25

Visual sulfur deficiency symptoms early in the growing season are common in Minnesota due to limited mineralization and uptake of S early in the growing season. Some of these symptoms may be temporary and will go away as the soil warms.

If a deficiency of S is suspected, recent data have shown that fertilizer S can be applied when corn is 12 inches tall or less without a reduction in yield potential. Plant-available sulfur in the sulfate form is an anion and is susceptible to leaching loss.

Recent data suggests that sulfate can carry over from one year to the next. Total corn uptake of S can range from 20-25 lbs of S per year. Application in excess of this amount will not result in increased grain yield but S not used by the current corn crop may be carried over to the next year, reducing the need for S application for the following crop.

There are several materials that can be used to supply S. Any fertilizer that supplies S in the sulfate (SO_4^{2-}S) form is preferred.

Fertilizer sources containing elemental sulfur are commonly sold in Minnesota. Elemental sulfur must be oxidized to sulfate sulfur before it can be taken up by the plant. If elemental S is used, sulfate S may be required to ensure adequate availability of S early in the growing season and the application rate of elemental S should be 20 lbs S per acre or greater or double the amount of S suggested in Table 14.

Liquid S is commonly sold as thiosulfate products. The thiosulfate ion contains half of the S in sulfate and half in the elemental S form. Research has shown a greater availability of S from the elemental S fraction in thiosulfate fertilizers.

Magnesium guidelines

Most Minnesota soils are well-supplied with magnesium (Mg), and this nutrient is typically not required in a fertilizer program. There are some exceptions. The very acidic soils of east-central Minnesota may require magnesium.

There should be no need for the addition of Mg if dolomitic limestone has been applied for legume crops in the rotation or when soils are irrigated and the water source used contains a high concentration of Mg.

A soil test can be used to predict the need for this nutrient. The suggestions for using Mg in a fertilizer program are summarized in Table 15.

Magnesium soil test ▸	Relative level ▸	Row ▸	Broadcast ▸
0-50 (ppm)	Low	10-20 (lbs/acre)	50-100 (lbs/acre)
51-100	Medium	Trial*	0
101 +	Adequate	0	0

* Apply 10-20 lbs. Mg per acre in a band only if a Mg deficiency is suspected or if a deficiency has been confirmed by plant analysis.

Micronutrient needs

Plants take up less than one pound of micronutrients per acre, with only a few ounces required for optimal plant production. While micronutrients are needed for optimal plant growth, they may not need to be applied.

Zinc

Research trials conducted throughout Minnesota indicate that zinc (Zn) is the only micronutrient that may be needed in a fertilizer program for corn. This nutrient, however, is not required in all fields.

The DTPA soil test for zinc is highly reliable and accurately predicts the needs for this essential nutrient. The suggestions for Zn are summarized in Table 16.

Zinc soil test* ▸	Band (lbs/acre) ▸	Broadcast (lbs/acre) ▸
0.0-0.25 (ppm)	2	10

MCEA Ex. 7

Zinc soil test* ▸	Band (lbs/acre) ▸	Broadcast (lbs/acre) ▸
0.26-0.50	2	10
0.51-0.75	1	5
0.76-1.00	0	0
1.01 +	0	0

* Zinc extracted by the DTPA procedure.

Because corn is the only agronomic crop that will consistently respond to Zn fertilization, the use of Zn in a banded fertilizer is suggested. However, carryover to succeeding years will be better with broadcast applications.

There are several fertilizer products that can be used to supply Zn. Except for large particles of zinc oxide, all are equally effective. Cost should be a major consideration in product selection.

Chelated zinc is commonly used when liquid starter fertilizer is applied directly on the corn seed. Chelated Zn can increase the availability of Zn by preventing the precipitation of low-solubility Zn compounds, but these products typically cost more per lb of Zn applied.

Zinc fully chelated with EDTA has been shown to provide the greatest stability of zinc across a range in soil pH values. Using chelated Zn does not increase the potential for a yield response for soils testing 0.75 ppm or greater in soil test Zn and should be targeted to soils where a response to Zn is expected.

Boron

Recent research has shown that boron (B) is not likely to increase yield of corn across a variety of soils across Minnesota. Boron availability in soils is affected by soil organic matter concentration and soil moisture.

There is a small chance of a response to B on sandy soils with SOM less than 1.0% and boron soil tests of 0.08 ppm or less. If a deficiency to boron is suspected, the application of boron should not exceed 1-2 lbs per acre of B broadcast applied on a trial basis. There are no guidelines for foliar-applied boron as low rates of B applied to foliage do present a risk for boron toxicity.

Other micronutrients

The use of iron (Fe), copper (Cu), and manganese (Mn) is not suggested for corn fertilizer programs in Minnesota.

You can download a print version of this page (PDF).

Additional resources

- U of M nutrient management
- Managing the rotation from alfalfa to corn
- Corn supplemental N rate calculator
- Regional corn N rate calculator
- Manure land application
- Using banded fertilizer for corn production

Authors: Daniel Kaiser, Fabian Fernandez and Melissa Wilson, Extension nutrient management specialists; Jeffrey Coulter, Extension corn agronomist; and Keith Piotrowski, director of the soil testing laboratory

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Please scan the above QR code to visit the live webpage for links.

https://extension.umn.edu/crop-specific-needs/fertilizing-corn-minnesota

MCEA Ex. 7

Sources and Risk Factors for Nitrate and Microbial Contamination of Private Household Wells in the Fractured Dolomite Aquifer of Northeastern Wisconsin

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See "Quantitative Microbial Risk Assessment for Contaminated Private Wells in the Fractured Dolomite Aquifer of Kewaunee County, Wisconsin" in volume 129, 067003.
See "Farm to Faucet? Agricultural Waste and Private Well Contamination in Kewaunee County, Wisconsin" in volume 129, 114001.
Go to:

Abstract

Background:

Groundwater quality in the Silurian dolomite aquifer in northeastern Wisconsin, USA, has become contentious as dairy farms and exurban development expand.

Objectives:

We investigated private household wells in the region, determining the extent, sources, and risk factors of nitrate and microbial contamination.

Methods:

Total coliforms, *Escherichia coli*, and nitrate were evaluated by synoptic sampling during groundwater recharge and no-recharge periods. Additional seasonal sampling measured genetic markers of human and bovine fecal-associated microbes and enteric zoonotic pathogens. We constructed multivariable regression models of detection probability (log-binomial) and concentration (gamma) for each contaminant to identify risk factors related to land use, precipitation, hydrogeology, and well construction.

Results:

Total coliforms and nitrate were strongly associated with depth-to-bedrock at well sites and nearby agricultural land use, but not septic systems. Both human wastewater and cattle manure contributed to well contamination. Rotavirus group A, *Cryptosporidium*, and *Salmonella* were the most frequently detected pathogens. Wells positive for human fecal markers were associated with depth-to-groundwater and number of septic system drainfield within 229m. Manure-contaminated wells were associated with groundwater recharge and the area size of nearby agricultural land. Wells positive for any fecal-associated microbe, regardless of source, were associated with septic system density and manure storage proximity modified by bedrock depth. Well construction was generally not related to contamination, indicating land use, groundwater recharge, and bedrock depth were the most important risk factors.

Discussion:

These findings may inform policies to minimize contamination of the Silurian dolomite aquifer, a major water supply for the U.S. and Canadian Great Lakes region. https://doi.org/10.1289/EHP7813 Go to:

Introduction

The paradox presented to the 13.1 million households in the United States that rely on private wells for supplying their drinking water (NGWA 2020) is that the household owns the well and the land on which the well is constructed, but it does not control the source, movement, and quality of the pumped groundwater. Anthropogenic disturbances on neighboring properties, such as changes in land cover, building development, agricultural practices, septic systems, and groundwater withdrawals, can alter the supply and quality of groundwater on which the household depends. Thus, as a shared natural resource, groundwater is susceptible to the “tragedy of open access” (Bromley and Cernea 1989), where without appropriate institutional safeguards the resource (i.e., groundwater) can become diminished and degraded.

This tension of having competing land uses affect the shared groundwater resource is particularly noteworthy in northeastern Wisconsin, where both dairy farms and exurban development have expanded atop the underlying Silurian dolomite aquifer. The aquifer is the water source for at least 85% of private wells in the region (K. Bradbury, Wisconsin State Geologist, personal communication). In the region’s four main agricultural counties, Brown, Calumet, Kewaunee, and Manitowoc, the number of milking dairy cows increased from 132,558 to 180,860 between 2002 and 2017, a 36% increase (USDA NASS 2002, 2017). This number of milking cows produces approximately 5.9×109 kg of excrement (manure and urine) per year (Nennich 2005), which in northeastern Wisconsin is all applied to the landscape (Erb et al. 2015). Population growth in the four-county region between 1950 and 2000 increased exurbanization by as much as 60% (Brown et al. 2005). Dairy farms and exurban homes are in greater proximity than years ago, each land use potentially contributing to the degradation of the common groundwater resource on which they depend.

Compounding the effects of more intensive land use on groundwater quality is the highly vulnerable nature of the Silurian dolomite aquifer, which is an important water supply for the region (Figure 1). The dolomite bedrock is densely fractured in both horizontal and vertical directions, and in many regions the surficial sediment overlying the bedrock is thin, i.e., 6m or less (Sherrill 1978). Groundwater recharge is extremely rapid because soil macropores and the extensive vertical fracture network allow rain and snowmelt water to infiltrate easily (Muldoon and Bradbury 2010). Infiltrating water carries contaminants originating at the land surface to the water table, after which groundwater flow in horizontal fractures can be rapid, providing little attenuation to contaminant transport (Bradbury and Muldoon 1992; Muldoon et al. 2001).

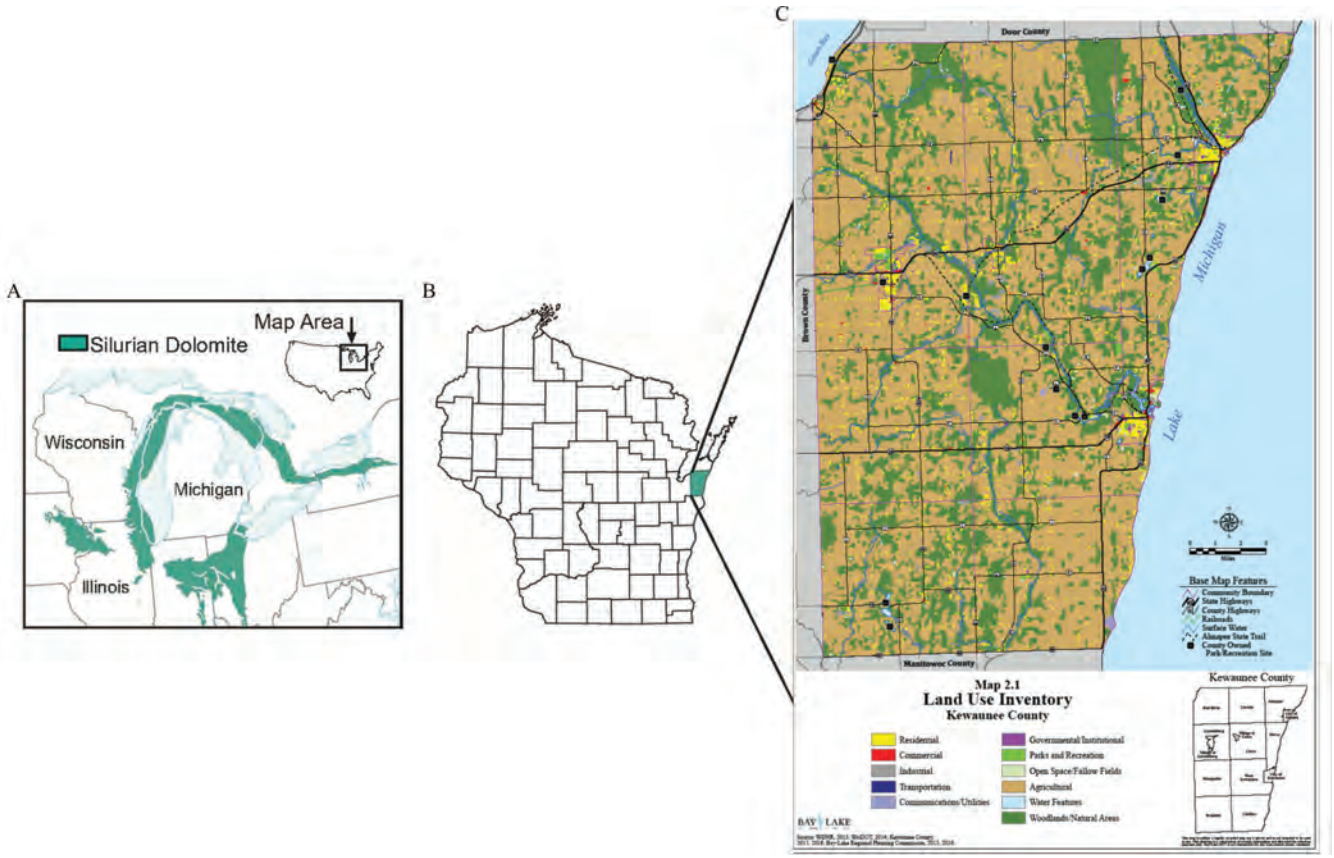

Figure 1.
Location of study site including (A) map of generalized Silurian dolomite subcrop shown as shaded area (modified from Shaver et al. 1978); (B) location of Kewaunee County, Wisconsin, United States; and (C) map of land use within the county. Land use map reprinted with permission from Bay Lake Regional Planning Commission, Green Bay, Wisconsin.

Contamination of private household wells open to the Silurian dolomite aquifer has been evaluated primarily by standard indicator bacteria for water sanitary quality (i.e., total coliform bacteria and *Escherichia coli*) and nitrate–nitrogen (NO−3-N) In the five-county region where the aquifer is most vulnerable (Brown, Calumet, Door, Kewaunee, and Manitowoc Counties), 14% of 7,521 samples from private wells exceeded the U.S. Environmental Protection Agency (U.S. EPA) health advisory of 10mg/L for NO−3-N for public water supplies (U.S. EPA 2020). Twenty-three percent of 6,739

samples tested positive for total coliforms, and 2% of 6,583 samples were positive for *E. coli* (Center for Watershed Science and Education Wisconsin 2018). Although these analyses may indicate the extent of contamination, they do not provide information on the source of contamination.

The most obvious contamination events happen when manure enters the aquifer and is pumped from a household well into indoor taps as odoriferous brown water (Figure 2). Manure-containing brown water incidents are more likely during groundwater recharge when snow is melting and after dairy manure is applied to agricultural fields (Erb et al. 2015). Erb et al. (2015) documented 25 brown water incidents between 2008 and 2014 in domestic wells located in Brown, Calumet, Kewaunee, and Manitowoc counties, and these incidents can present a health risk (Wisconsin Department of Health Services n.d.).



Figure 2.
“Brown water” event at a Kewanee County household with a private well. Note: Photo provided and permission granted by Chuck Wagner.

As the “tragedy of open access” of the groundwater resource in northeast Wisconsin was unfolding, public debate centered on two questions: *a*) what is the true extent of groundwater contamination? and *b*) what are the sources of contamination, septic systems or dairy manure? Through interactions

with stakeholders, we learned that historical total coliform and nitrate data were considered biased by some because it was believed samples were submitted only from problem wells that were not representative of groundwater conditions. As for the source question, opposing sides generally took positions without having data in hand, because the technology of microbial source tracking (MST) to identify fecal sources has rarely been applied to household wells. To help resolve these questions and bring information to bear on potential solutions, we proposed three study objectives: *a*) conduct random sampling of private wells, stratified by depth-to-bedrock, for indicator bacteria and nitrate; *b*) from the subset of wells in Objective 1 that were positive for total coliform bacteria or had NO−3-N>10mg/L, conduct random sampling for enteric pathogens and MST markers indicating whether fecal contamination was from septic systems or dairy manure; and *c*) perform statistical analyses to identify land use, weather, hydrogeology, and well construction risk factors that were associated with private well contamination.

Go to:

Methods

Study Area

The study area was Kewaunee County located in northeast Wisconsin, USA (Figure 1). The county's population is 20,600, of which 11,300 (55%) live in 4,900 rural homes served by septic systems and private wells (Bay Lake Regional Planning Commission 2016). Land cover in the 2808-km2 county is predominantly agriculture (63%), natural areas (29%), and residential (3%) (Bay Lake Regional Planning Commission 2016). Dairy farming and associated crop production are the primary agricultural activities. Cattle and calves number approximately 107,000 on 306 farms (USDA NASS 2017). The climate is continental, modified by the proximity of Lake Michigan, with precipitation (rain and snow) of 78cm water per year (NOAA n.d.). Soils are medium- to fine-textured, underlain by Pleistocene glacial deposits; unconsolidated sediments vary in thickness from several centimeters to more than 30m over the bedrock (Erb et al. 2015). Karst features such as open fractures are present, albeit many are covered with soil (Erb et al. 2015).

Indicator Bacteria and Nitrate

Private household wells were selected by stratified random sampling for tests of total coliforms (hereafter coliforms), *E. coli*, and nitrate. Candidate wells were identified from a list of property parcels that *a*) were not served by municipal water systems and *b*) had improvement values greater than USD $30,000, which indicated that a residence (and therefore private well) was likely present (n=4,896). Parcels with mailing and property addresses that did not match were excluded to prevent confusion regarding sample location (n=948).

Water sampling was conducted during two synoptic events, 13–14 November 2015 and 29–30 July 2016. Strata were defined by depth-to-bedrock (i.e., the depth of unconsolidated sediment overlying bedrock at the well site) because earlier work suggested this parameter influenced groundwater contamination (Final Report of the Northeast Wisconsin Karst Task Force 2007). Using ArcMap software (version 10.3.1; ESRI), candidate wells were grouped into three strata based on an existing

depth-to-bedrock map (Sherrill 1979): <1.5m (n=269), 1.5–6.1m (n=473), and >6.1m (n=3,206). (Depth-to-bedrock data were not available for individual wells at the time of well selection.) Letters inviting participation were mailed, and all willing well owners (approximately 50% of invitees) received a sampling kit. After accounting for unreturned kits, 323 and 401 private well samples were submitted for the fall and summer sampling events, respectively. Some wells (103) were sampled in both events (see Figure S1 for well recruitment, exclusion, and dropout). All study wells were completed in the Silurian dolomite or overlying sediment.

Samples were collected by well owners following written instructions to sterilize the sample tap with a flame for 15 s or by alcohol swab and run the water run for at least 5 min prior to filling two polypropylene bottles provided in the sampling kit. The 60-mL nitrate bottle contained 160μL of 96% sulfuric acid for preservation. Samples were collected on the scheduled dates and on the same day delivered to designated receiving locations in the county where they were transported that day on ice to the laboratory. Coliforms and *E. coli* were analyzed by Colilert Quanti-Trays (IDEXX) within 48 h of sample collection. Nitrate was measured on an AQ1 Discrete Analyzer (SEAL Analytical) by cadmium reduction and reaction with sulfanilamide in conjunction with N-(1-naphthylethylenediamine) dihydrochloride (Method 4500-NO−3F; American Public Health Association 1995).

Microbial Source Tracking and Pathogen Occurrence

Wells positive for coliforms or with NO−3-N>10mg/L were eligible for additional sampling to assess sources of fecal contamination and the occurrence of enteric pathogens. From this group, wells were selected for five sampling events: 18–22 April, 1–3 August, and 31 October–2 November in 2016 and 23–24 January and 27–29 March in 2017. For each event, selection was randomized and stratified by the three depth-to-bedrock categories. We sampled 22 to 30 wells during each event, resulting in 138 samples from 131 wells; seven wells were sampled in two events.

Sampling was conducted by trained staff using dead-end ultrafiltration (Smith and Hill 2009) with Hemodialyzer Rexeed-25s ultrafilters (Asahi Kasei Medical MT Corp.). Water taps were flame-sterilized before ultrafilter attachment; all ultrafilter tubing and fittings were new for each sample. Well water was collected prior to softening or other treatment systems. Mean sample volume was 839L (range: 522–1,517L, n=138). Ultrafilters were bagged, placed on ice, and back-flushed in the laboratory within 72 h.

Ultrafilters were back-flushed using a 500-mL solution containing 0.01% sodium polyphosphate (NaPP), 0.5% Tween 80, and 0.001% antifoam Y-30 (Smith and Hill 2009). Bacto beef extract (ThermoFisher Scientific Catalog No. 211520) was added to the back-flushed eluate at a 1% weight to volume ratio (typically 6.5g of beef extract into 650mL of eluate) to provide an organic matrix for sample archival at −80°C and to aid flocculation of the secondary concentration step by polyethylene glycol (PEG) flocculation (Lambertini et al. 2008). Briefly, samples were incubated overnight at 4°C following addition of 8% PEG 8,000 and 0.2M NaCl. Samples were centrifuged for 45 min at 4,700×g at 4°C, and the pellet was resuspended in TE buffer to a final concentrated sample volume (FCSV) of 3–26mL (4mL average). FCSVs were stored at −80°C until extraction of nucleic acids. Nucleic acids were extracted from 280μL of final concentrated sample volume with the

QIAamp DNA blood mini kit and buffer AVL using a QIAcube® (Qiagen). Final volume of the nucleic acid suspension was 140µL. Three extractions were performed per sample to produce sufficient template for all gene markers assayed.

Virus RNA was reverse-transcribed (RT) by adding 25.8µL nuclease-free water and 2.1µL random hexamers (ProMega) to 25.8µL of the extracted nucleic acids. This mixture was heated for 5 min at 95°C and then mixed with 96.3µL RT master mix consisting of the following components reported as final concentrations in the 150µL total reaction volume: 50 mM Tris-HCl (pH 8.3), 75 mM KCl, 3 mM MgCl2, 0.6 mM dithiothreitol, 70µM of each deoxynucleoside triphosphate (ProMega), 1U/µL RNasin® (ProMega), 0.5U/µL SuperScript® III reverse transcriptase (Invitrogen Life Technologies). Reaction incubation was 42°C for 60 min followed by 5 min at 95°C and then held at 4°C until polymerase chain reaction (PCR) amplification.

Samples were analyzed by quantitative real-time polymerase chain reaction (qPCR) for 33 gene markers specific to 30 microbial taxa or groups (see Table S1). The microbes tested were all fecal-associated and, based on the biology of the microbe or validation studies reported in the scientific literature, placed in one of three host-specificity categories: human-specific, bovine- or ruminant-specific, and no host specificity. qPCR was performed with a LightCycler® 480 instrument (Roche Diagnostics) using the LightCycler 480 Probes Master kit for all markers except for human *Bacteroides*, which used TaqMan Environmental Master Mix 2.0® (Applied Biosystems). Six µL extracted DNA or cDNA from reverse transcription was added to 14µL of master mix, producing a 20-µL reaction volume. Primers and hydrolysis probes (Integrated DNA Technology), and their concentrations are reported in Table S1. For all markers except human *Bacteroides*, thermocycling began at 95°C for 5 min followed by 45 cycles of 10 s at 95°C and 1 min at 60°C with ramp rates of 4.4 and 2.2°C per second, respectively. Thermocycling for human *Bacteroides* began at 95°C for 10 min followed by 45 cycles of 30 s at 95°C, 2 min at 56°C, and 1 min at 72°C with ramp rates of 2.2, 1.1, and 2.2°C per second, respectively. Two qPCR technical replicates were performed per marker. If both replicates were negative the result is reported as 0. If only one was positive, that concentration is reported. If both replicates were positive, the average concentration is reported.

To ensure laboratory contamination was absent (i.e., no false positives), we performed negative controls (i.e., no-template controls) of every gene marker for the extraction, reverse transcription, and qPCR steps for every batch of these process steps, and we tested for every marker in every batch of ultrafilter backflush solution. All tests had to be negative [i.e., no cycle quantification (Cq) value] for sample data to be accepted.

Inhibition was evaluated following the approach of Gibson et al. (2012), using as controls Hepatitis G virus RNA oligonucleotide (IDT) and G-lambda DNA (New England Biolabs) for reverse transcription and qPCR inhibition, respectively. Samples with Cq values of controls that increased two or more were considered inhibited. Twelve of 138 samples were qPCR-inhibited, requiring dilution with AE buffer (Qiagen).

Extraction positive controls were bovine herpes virus vaccine for DNA and bovine respiratory syncytial virus vaccine for RNA (both vaccines from Zoetis Inc.), the latter serving also as the reverse transcription positive control. qPCR positive controls were gBlocks® or Ultramers® (IDT) of

each marker, with sequences modified to distinguish from wild type while maintaining the same guanine and cytosine content.

Standard curves were generated by serially diluting the positive controls in AE buffer with 0.02% bovine serum albumin, creating a concentration range of 1 to 106 gene copies (gc)/reaction. Quantification cycle (Cq) values were calculated using the second derivative maximum method and regressed against the decimal logarithm of marker concentration using the nonlinear function provided by the LightCycler® 480 software. Standard curve parameters and 95% limits of detection are reported in Table S2 and Table S3, respectively.

Samples positive by qPCR for rotavirus group A were further analyzed following the methods of Iturriza-Gómara et al. (2004) and Madadgar et al. (2015) to determine human and bovine G and P genotypes using seminested PCR assays targeting the *VP7* and *VP4* structural viral protein genes. In brief, nucleic acid extraction and reverse transcription were performed as described above. The first PCR amplified the *VP7* or *VP4* gene using VP7-F/VP7-R or Con-3/Con-2 primers, respectively. The 20-μL reaction contained 6μL of cDNA from reverse transcription, 14μL of Roche LightCycler 480 master mix, and 200 nM of each primer. A separate seminested reaction was run for each human and bovine G- and P-type (19 type-specific reactions). For all seminested reactions, 2μL of amplicon from the first reaction were added to 18μL of master mix containing one of the initial primers and a type-specific primer at 200 nM each for a final reaction volume of 20μL. (See Table S4 for all primers and their concentrations and Table S5 for thermocycling conditions for each reaction.)

PCR products (20μL) were visualized by gel electrophoresis on 1.5% agarose gel (100 V for 90 min). A negative control and two positive controls [RotaTeq® vaccine-positive human fecal specimen and bovine CalfGuard® vaccine (Zoetis)] were included in each analysis batch along with the DNA ladder (ProMega). Gel bands matching specific genotypes were purified with illustra™ GFX PCR DNA and Gel Band Purification Kit (GE Healthcare), and identity was confirmed by sequencing. Direct sequencing of the amplicons was performed in both directions using the seminested reaction primers (see Table S4). We used the BigDye® Terminator V3.1 Cycle Sequencing Kit (Applied Biosystems) for the sequencing reaction, and the University of Wisconsin–Madison Biotechnology Center performed the reads on an ABI 3730xl DNA Analyzer. Consensus sequences were constructed with Lasergene (DNAStar) and submitted for identification using BLAST (National Center for Biotechnology Information, Bethesda, MD). Genotypes were used to classify all rotavirus group A detections as human or bovine for inclusion in human and bovine-specific outcome measures: G1P[8] and G10P[11] were considered human- and bovine-specific genotypes, respectively (Pitzer et al. 2011; Papp et al. 2013).

Samples positive for human-specific *Bacteroides* (HF183/BacR287; Green et al. 2014) or ruminant-specific *Bacteroides* (Rum-2-Bac; Mieszkin et al. 2010) were reanalyzed by PCR (676 bp amplicon) and sequencing, following the method of Bernhard and Field (2000), to confirm *Bacteroides* identity. *Bacteroides* DNA was extracted by the method described above and 6μL DNA extract was added to 14μL LightCycler 480 Probes Master including 500 nM of primers Bac32F and Bac708R (Bernhard and Field 2000). PCR commenced at 94°C for 5 min followed by 35 cycles consisting of 94°C for 30 s, 53°C for 1 min, and 72°C for 2 min, followed by a final 6-min extension at 72°C. PCR product (10μL) was visualized on 1.5% agarose gel. If the amplicon band was absent or faint, sensitivity was

increased by reamplifying 1–6μL of amplicon under the same thermocycling conditions. Product purification from the gel, the sequencing reaction, and analyses were performed as described above for rotavirus A genotyping. Direct sequencing of the amplicons was performed in both directions using primers 32F and 708R.

Risk Factor Variables

Well construction variables were obtained from well driller reports filed at the Wisconsin Geological and Natural History Survey or Wisconsin Department of Natural Resources. Reports were available for 65% of sampled wells. As described above, initial well selection was stratified using existing depth-to-bedrock maps. However, for the statistical analyses, the exact depth-to-bedrock value for each well was obtained from its construction report. When a report was not available (n=116 and 135 for fall and summer sampling events, respectively), bedrock depth was estimated by interpolation from reports of nearby wells. Well elevation was obtained from the county digital elevation model.

Groundwater depth was measured continuously in U.S. Geological Survey monitoring well KW-183 (USGS 443535087345401 KW-25/24E/34-0183) and data are available in the USGS National Water Information System (USGS 2020). The well is located in Kewaunee County near an agricultural field. Relative to the ground surface, depth-to-bedrock is $2.1\mathrm{m}$, borehole depth is $9.14\mathrm{m}$, and casing depth is $3.05\mathrm{m}$ (Muldoon and Bradbury 2010).

Groundwater recharge was estimated by the water table fluctuation method (Healy and Cook 2002), using graphical extrapolation of the antecedent recession curve and a specific yield of 0.04 based on previous assessments of recharge in the fractured rock in this area (Bradbury and Muldoon 1992). Cumulative recharge was obtained by summing individual recharge events for the 2-, 7-, 14-, and 21-d periods preceding sample collection.

Quantitative precipitation estimates (QPE) for each sampled well location (in 4-km grids) were provided by the North Central River Forecast Center of the U.S. National Weather Service. Because QPE values include snow, and frozen snow will not infiltrate soils, we excluded precipitation measurements for all well locations for days when snow without rain was recorded at the nearby National Weather Service station in Green Bay, Wisconsin. Cumulative precipitation was calculated by summing hourly QPE values over 2, 7, 14, and 21 d prior to sampling. Precipitation was not included in analyses of coliform and nitrate data because the synoptic design precluded variation in precipitation over the short time samples were collected.

Geographic Information System (GIS) data layers maintained by the Kewaunee County government reported locations of septic systems, agricultural fields, manure storages, and surface bedrock features. Agricultural field data included whether the field had a nutrient management plan (NMP) and therefore likely received manure applications.

Septic systems were divided into three categories for analysis: *a*) septic systems, included active systems of all types; *b*) drainfield, included inspected and uninspected systems that are designed to release effluent to the subsurface (i.e., excludes holding tanks); and *c*) not inspected, included only

those systems that had not been inspected by county staff. Systems not in use were excluded from all three categories. The risk factor “distance to nearest septic system” excluded the system on the same property as the well, whereas counts of septic systems included the system on the same property.

Using ArcMap and Python script, fecal contamination sources and bedrock features were enumerated for each study well in two forms: *a*) distance from the well to the nearest contamination source or bedrock feature; and *b*) the count or areal size of the source or feature within three circular areas surrounding the well. The circular areas were defined by three radii from the well: 229, 457, and 914m (equal to 750, 1,500, and 3,000 ft, respectively), corresponding to 16, 66, and 262 ha (approximately 40, 160, and 640 acres). These area sizes were selected prior to data analysis based on an earlier study of septic system counts in similar-sized areas that were associated with childhood infectious diarrhea (Borchardt et al. 2003a).

Statistical Analyses

Stratified random sampling was employed to generate estimated contamination rates of coliforms, *E. coli*, and nitrate. Sampling strata were defined by depth-to-bedrock (<1.5, 1.5–6.1, and >6.1m). Smaller strata were oversampled relative to a simple random sample. This approach, in conjunction with the use of corresponding analytic weights and finite population correction factors in the analyses, resulted in more precise estimates for the smaller depth-to-bedrock strata without sacrificing the ability to estimate a countywide contamination rate. The analytic weight was defined as the product of the inverse of the sampling probability and the inverse of the response rate (i.e., the proportion of sampled well owners who agreed to participate in the study) within the appropriate depth-to-bedrock stratum. Rao-Scott likelihood ratio chi-square tests (Lohr 2010) were used to test associations between contamination rates and depth-to-bedrock as well as compare fall 2015 (groundwater recharge period) and summer 2016 (no recharge period) estimated contamination rates, both overall and within depth-to-bedrock strata. Statistical computations accounted for the complex sampling design.

Risk factors for well contamination were evaluated for independent variables relating to land use, precipitation, hydrogeology, bedrock, and well construction. Variables were tested for association with *a*) well contaminant detection and *b*) well contaminant concentration (among wells where contaminants were detected). Five contaminants (or contaminant groups) were tested for associations with risk factors: coliform bacteria, nitrate, human fecal markers, bovine fecal markers, and any fecal marker. Tests for coliform bacteria and nitrate associations were performed for each sampling period, groundwater recharge and no recharge.

For dichotomous (detect/nondetect) dependent variables, univariable screening for inclusion in the multivariable modeling process was performed using logistic regression. Each independent variable was represented as a linear (in the logit) term in the models. For independent variables with >10% zero values, a dichotomous (zero vs. greater than zero) term was included in the screening model in addition to the linear term. A plot of the estimated detection probability across the observed range of values for the independent variable being evaluated was also generated as part of the screening process. The same univariable screening process was performed for the well contaminant

concentration dependent variables except that gamma regression with a natural log link function was used (Garson 2013), the model terms were linear in the log, and plots of estimated mean concentrations were generated.

For both univariable and multivariable analyses, outliers were excluded from the models for some of the concentration dependent variables. Specifically, 4 and 11 outliers were excluded from the analyses of coliform concentration for groundwater recharge and no recharge periods, respectively. And one, two, and four outliers were excluded for human, bovine, and any fecal marker concentration models, respectively. The criterion for excluding data points from the analyses was that their inclusion in the model caused the fitted curve to deviate meaningfully from the pattern exhibited by the remaining data. Concentration values for outliers were generally orders of magnitude larger than those in the remaining data points.

To be included in the multivariable model for a particular dependent variable, risk factors had to meet several criteria: *a*) strength of association (i.e., p≤0.15); *b*) plausibility, the association had to be biologically or physically possible; and *c*) internal consistency, where variables of the same measurement but at different levels (e.g., count of septic system drainfields within 229, 457, or 914m of a well) had similar directions of association (positive or negative) and strengths of association. When two variables of different measurements (e.g., well elevation and depth to bedrock) were correlated, the variable that most satisfied criteria 1, 2, and 3 was selected.

Additional screening was applied for inclusion in multivariable modeling when risk factors of the same measurement but at different levels were all associated with well contamination. Levels could differ in time (2, 7, 14, or 21 d) or area (within 229, 457, or 914m from a well). Under this situation, the risk factor with the greatest strength of association was selected. For example, 2-, 7-, and 14-d cumulative precipitation variables were all strongly associated with well contamination of human-specific markers. However, the 2-d cumulative precipitation variable had the largest regression coefficient and lowest *p*-value, so it was selected for inclusion.

Once the independent variables for a given multivariable model were identified, a screening process for interaction terms among these variables was undertaken. Only interactions deemed plausible and relevant were assessed. A screening model contained a term for the interaction and main effect terms for the individual risk factors comprising the interaction. As with the univariable screening of main effects, the independent variables comprising the interaction were represented as linear terms in the models; an interaction term was included in the multivariable model when its *p*-value was ≤0.15.

For multivariable analyses, the same procedure was used for both well contaminant detection and well contaminant concentration. Gamma regression was employed for all multivariable analyses of well contaminant concentration. Prior to performing multivariable regression analyses, each independent variable retained after the screening process was reassessed at the univariable level to establish whether a more complex representation than linear (e.g., quadratic or spline) would be appropriate in the multivariable model. To decide on an appropriate representation, a plot of the logit of the detection probability (log of the mean concentration) across the observed range of values for the independent variable was generated and examined, with the independent variable represented

as a natural cubic spline (Hastie et al. 2001) in the corresponding logistic (or gamma) regression model. If a more complex representation was deemed appropriate, it was used in both main effect and interaction terms in the multivariable models.

All risk factors and interaction terms retained after the above screening processes were included in each final multivariable model. We did this in order that the independent effects of each risk factor could be evaluated in the presence of (i.e., adjusting for) the other model terms.

The final multivariable models were fit using log-binomial (or gamma) regression to facilitate interpretation of the results (McNutt et al. 2003). These models permit direct estimation of ratios of detection probabilities (or mean concentrations). This is in contrast to logistic regression models, which estimate ratios of odds rather than probabilities. When presence of the dependent variable is not rare (roughly <10%), which is typical in studies of well contaminant detection, the odds ratio does not closely approximate the corresponding ratio of detection probabilities and must be interpreted with caution.

For each multivariable model, procedures specific to generalized linear models were used to determine whether the information matrix was ill-conditioned (http://support.sas.com/kb/32/471.html). This approach entailed examining whether collinearity in the weighted risk factors was present, where the weights were determined by the model fitting algorithm.

Separate multivariable models for well construction risk factors were created because a number of wells were missing well construction reports. Had all risk factors been combined into a single model, only those wells without missing construction data would have been included, reducing statistical power to evaluate the other risk factors.

SAS version 9.4 was used to conduct all analyses (SAS Institute Inc.).
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Results and Discussion

Groundwater Levels during Sampling

Groundwater levels during the first study year followed the pattern typical for the upper Midwest with rising levels in the fall and spring and falling levels in the summer and winter (Figure 3). However, there was a prolonged recharge period from fall 2016 to spring 2017 (Figure 3). In January 2017, snowmelt raised groundwater levels during a long warm period (NOAA n.d.). Coliform and nitrate sampling corresponded with fall recharge (hereafter “recharge”) and with the summer decline when groundwater was at nearly its deepest level (hereafter “no recharge”). Sampling for microbial source tracking occurred during recharge (3 events) and no-recharge (2 events) periods.

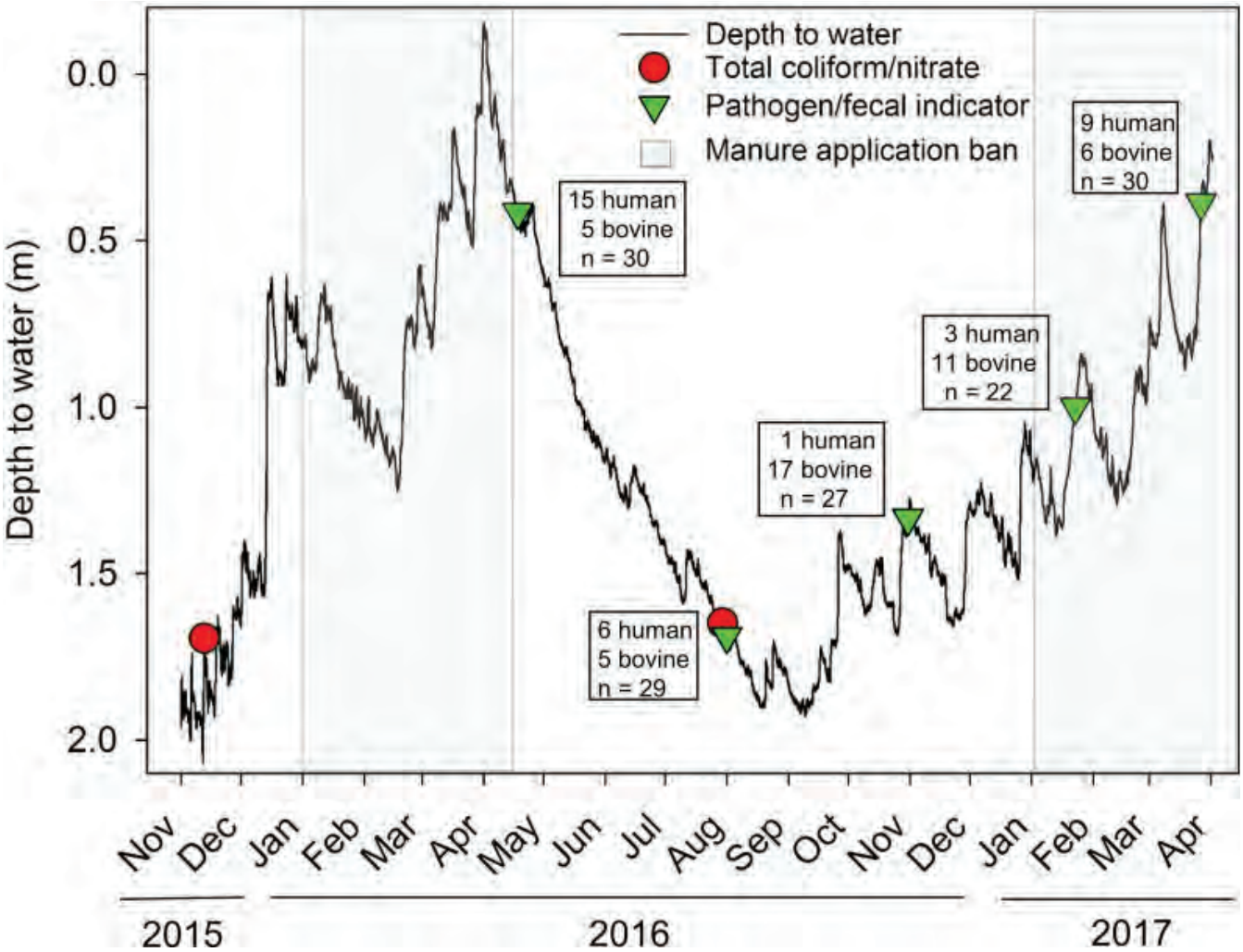

Figure 3.
Sampling periods in relation to groundwater level in Kewaunee County monitoring well KW-183 (USGS 443535087345401; USGS 2020). Sampling times indicated by red circles (total coliforms and nitrate) and green triangles (pathogens and fecal indicators). Boxes indicate the number of wells positive for human-specific or bovine-specific markers; $n = \text{total number of wells sampled}$. Gray shaded areas designate seasonal manure application ban for fields with bedrock depths $< 6.1\text{m}$.

Bacteria and Nitrate Contamination Rates

The countywide private well contamination rates for coliforms, *E. coli*, and NO−3-N>10mg/L were similar to the average rates for the state of Wisconsin (Table 1). However, for wells in the two shallowest bedrock depth strata (<1.5m and 1.5–6.1m), contamination rates were generally greater than the statewide averages, and rates were consistently greater than rates for wells in the deepest stratum (>6.1m to bedrock). The greater the bedrock depth and transport distance through surficial sediments, the less likely these contaminants will reach bedrock fractures that allow rapid transport (Final Report of the Northeast Wisconsin Karst Task Force 2007; Rasmuson et al. 2020).

Table 1

Estimated contamination rates (percent positive wells) for total coliform bacteria, *Escherichia coli*, or nitrate-N>10mg/L.

Sampling period or reference data	Region or depth-to-bedrock category[a]	Number of wells sampled	Percent positive wells (95% confidence interval)			
			Total coliforms	*E. coli*	Nitrate-N>10mg/L	Total coliforms or nitrate-N>10mg/L
Groundwater recharge	<1.5m to bedrock	26	46 (30, 63)	4 (0, 9)	7 (0, 15)	50 (34, 66)
	1.5–6.1m to bedrock	120	28 (18, 37)	1 (0, 2)	20 (7, 33)	42 (28, 55)
	>6.1m to bedrock	167	19 (11, 26)	0.3 (0, 0.6)	6 (1, 10)	23 (15, 31)
	Kewaunee County	313[b,c] 316[c,d]	21 (14, 27)	0.4 (0.1, 0.7)	7 (3, 11)	26 (19, 34)
No groundwater recharge	<1.5m to bedrock	24	23 (6, 39)	7 (0, 15)	10 (0, 20)	33 (12, 53)
	1.5–6.1m to bedrock	122	29 (16, 41)	1 (0, 3)	19 (9, 28)	40 (28, 53)
	>6.1m to bedrock	252	21 (15, 27)	26 (19, 32)		
	Kewaunee County	396[b,c] 400[c,d]	22 (17, 28)	1 (0.1, 2)	7 (4, 10)	28 (22, 33)
Reference data	Wisconsin[e]	534	23	3	7	—
	Wisconsin[f]	3,838	18	—	10	—

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Note: —, no data available. Estimates and corresponding 95% confidence intervals account for the stratified random sampling design employed in the study.

[a]The estimated number of wells in each bedrock depth category are 76, 575, and 4,156 wells at <1.5, 1.5–6.1, and >6.1m, respectively, totaling 4,807 wells in Kewaunee County. Our final estimates of the number of wells in each bedrock depth category are different than the initial estimates at the study beginning using the bedrock map created by Sherrill (1979).
[b]*n* for coliforms and *E. coli*.

[c]The *n*'s do not equal the number of samples analyzed (see Figure S1) because some wells had missing depth-to-bedrock values (six wells for the groundwater recharge period and one well for the no recharge period) for which analytic weights could not be generated.

[d]*n* for nitrate.

[e]Data for private wells; U.S. General Accounting Office 1997.
[f]Knobeloch et al. 2013.
Groundwater recharge and no-recharge periods did not have significantly different contamination rates, regardless of contaminant type or level of data aggregation (Table 1). There was one exception; coliform contamination during recharge was greater than the no-recharge period for wells with bedrock depths <1.5m (p=0.042).

Table 2 reports descriptive statistics for coliforms, *E. coli*, and nitrate-N concentrations of positive samples. In both recharge and no-recharge periods, 25% of wells positive for nitrate-N had concentrations greater than 9mg/L.

Table 2

Descriptive statistics of coliform bacteria, *Escherichia coli*, and nitrate concentrations.

Sampling period	Measurement	Number of positive samples	Number of non-detects	Concentration of positive samples[a]					
				Mean	Median	Minimum	25th percentile	75th percentile	Maximum[b]
Groundwater recharge	Coliforms	87	232	73.2	5.2	1.0	2.0	17.3	>2,419.6
	E. coli	5	314	5.0	2.0	1.0	2.0	4.1	16.1
	Nitrate-N	203	119	6.3	4.7	0.2	1.6	9.0	29.7
No groundwater recharge	Coliforms	87	310	116.8	6.2	1.0	2.0	55.4	>2,419.6
	E. coli	10	387	105.0	3.1	1.0	1.3	8.8	1011.2
	Nitrate-N	205	196	6.5	5.2	0.2	2.1	9.1	33.3

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Note: MPN, most probable number.

[a]Coliforms and *E. coli*, MPN/100mL; nitrate-N, mg/L.

[b]2,419.6 MPN/100mL was the upper limit of quantification.

Coliforms, although nonpathogenic, are the standard indicator of drinking-water sanitary quality in the United States. Studies of coliform-positive private wells have observed (DeFelice et al. 2016) and not observed (Strauss et al. 2001) associations with acute gastrointestinal illness. High nitrate in drinking water can cause methemoglobinemia, and in some studies it has been linked with colorectal cancer, thyroid disease, and central nervous system birth defects (Ward et al. 2018). The U.S. National Primary Drinking Water Standards apply only to public water systems, not private wells. Nonetheless, the U.S. drinking water Maximum Contaminant Level Goals (MCLG) for coliforms and nitrate-N provide public health benchmarks, which are zero and 10mg/L, respectively (U.S. EPA 2020). Multiplying the MCLG exceedance rates for coliforms or nitrate-N (Table 1) by the estimated number of wells in each bedrock depth category in Kewaunee County [76, 575, and 4,156 wells at <1.5, 1.5–6.1, and >6.1m, respectively (Borchardt et al. 2019)], we estimate approximately 1,300 wells (27%) during the study period did not meet U.S. EPA public health goals for safe drinking water.

Calculating well contamination rates by county, state, or other governmental units has the advantage of matching policy-making jurisdictions. However, aggregating data in this manner can overlook factors underlying contamination “hotspots,” in this case, bedrock depth. For example, the statewide averages for coliform and nitrate MCLG exceedances in Wisconsin, irrespective of bedrock depth, are 18% and 10%, respectively (Knobeloch et al. 2013). Using the multivariable models for coliforms and nitrate for recharge and no-recharge periods, respectively (see below and Figures 4B and and4C),4C), the statewide percentages are equivalent to detection probabilities at bedrock depths of 10m (coliforms) and 14m (nitrate) in Kewaunee County. We estimate the number of wells with shallower bedrock depths, and therefore higher detection probabilities than the statewide averages, to be 1,562 (coliforms) and 2,464 (nitrate), which is 32% and 50% of the county’s private wells. This assessment is consistent with the high rates of coliform and nitrate exceedances for carbonate aquifers (e.g., Silurian dolomite) and agricultural areas observed in private well data nationally (DiSimone 2009).

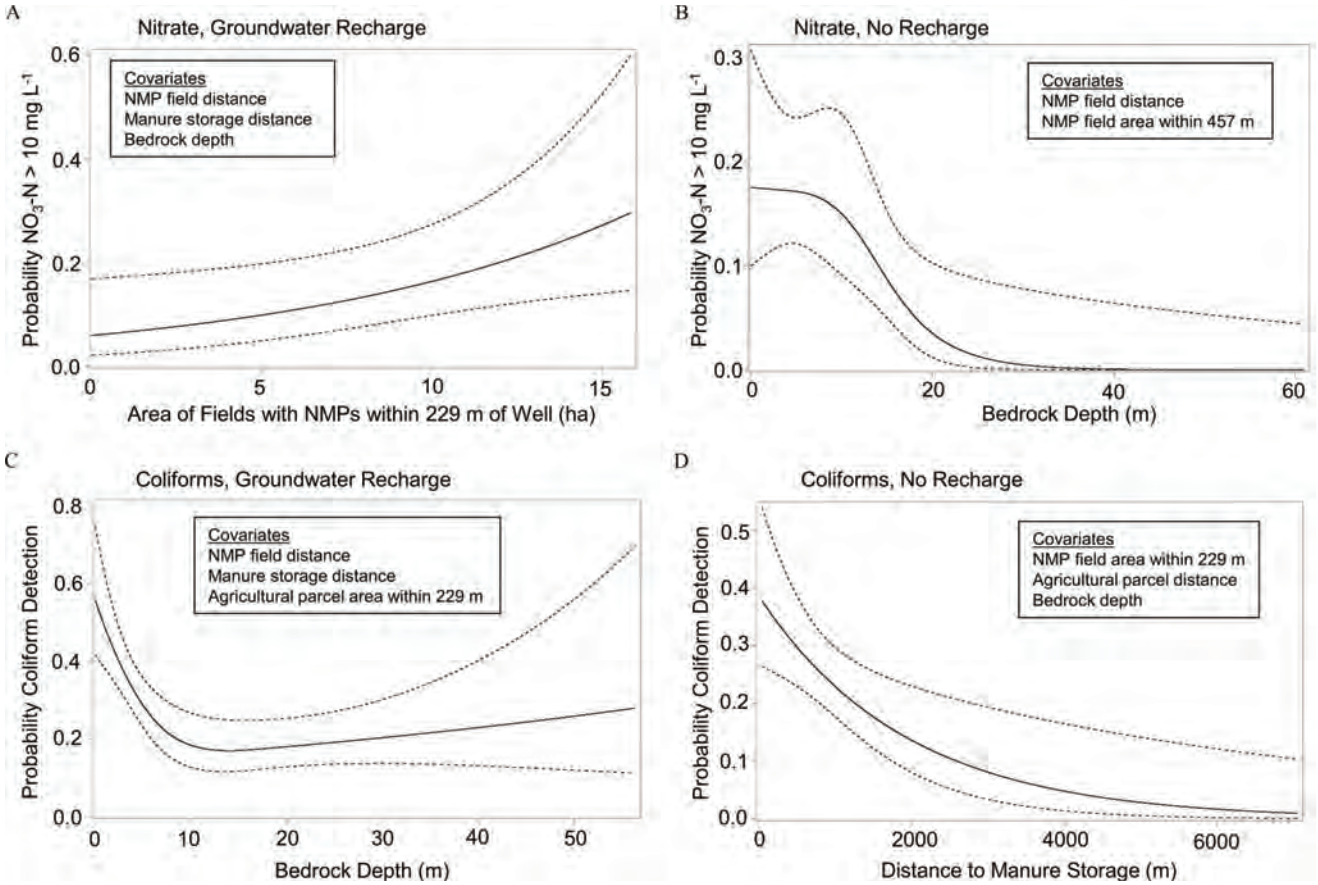

Figure 4.

Detection probabilities for NO3-N>10mg/L and coliform bacteria in private wells regressed (log-binomial) on key risk factors during groundwater recharge and no recharge periods. Coefficients and *p*-values are reported in Table 4. Black line: estimated probability of detection. Dashed lines: 95% pointwise confidence limits. Covariates in the multivariable models were fixed at their median values for the purpose of plotting. Fields with NMPs likely receive manure and inorganic fertilizer inputs. Note: NMP, nutrient management plan.

Microbial Source Tracking and Pathogen Occurrence

Of 138 samples from 131 wells, 82 samples (59%) from 79 wells (60%) were positive for markers of fecal-associated microbes (Table 3). Among the 79 wells with fecal contamination, 32 wells had markers for pathogens that could infect humans (human-specific and zoonotic pathogens without host specificity). Seventy wells were positive for two or more markers. Well water concentrations of fecal-associated markers were generally low; *Bacteroidales*-like CowM2 and *Bacteroidales*-like CowM3 had the highest median concentrations (Table 3).

Table 3

Gene markers of fecal-associated microbes detected in samples (n=138) from private household wells (n=131).

Host specificity	Microbe[a]	Gene marker[b]	Number of positive wells[c]	Number of positive samples[c]	Concentration of positive samples (gene copies/L)	
					Median	Range
Human-specific	*Bacteroidales*-like Hum M2	Glycosyl hydrolase family 92	7	8	4	<1–1,050
	Human *Bacteroides*	16s rRNA (HF183/BacR287)	27	28	<1	<1–34
	Cryptosporidium hominis	18s rRNA	1	1	<1	<1
	Adenovirus A	hexon	1	1	1	1
	Rotavirus group A, G1 P[8]	*NSP3*	7	7	<1	<1–3
	Rotavirus group A, G1 P[8]	*VP1*	3	3	1	<1–22
	Any human marker	—	33	34	<1	<1–1,050
Bovine- or ruminant-specific	*Bacteroidales*-like Cow M2	DHIG domain protein	2	2	472	29–915
	Bacteroidales-like Cow M3	HD super family hydrolase	4	4	174	3–49,818
	Ruminant *Bacteroides*	16s rRNA (Rum-2-Bac)	36	36	1	<1–42,398
	Bovine polyomavirus	*VP1*	8	8	4	<1–451
	Bovine enterovirus	5’ non-coding region	1	1	2	2
	Rotavirus group A, G10 P[11]	*NSP3*	12	12	12	2–4,481
	Rotavirus group A, G10 P[11]	*VP1*	5	5	23	<1–732
	Any bovine or ruminant marker	—	44	44	3	<1–49,818

Host specificity	Microbe[a]	Gene marker[b]	Number of positive wells[c]	Number of positive samples[c]	Concentration of positive samples (gene copies/L)	
					Median	Range
No host specificity	Pepper mild mottle virus	replication-associated protein	13	14	14	2–3,811
	Cryptosporidium spp.	18s rRNA	2	2	<1	<1–1
	Cryptosporidium parvum	18s rRNA	13	13	<1	<1−14
	Giardia duodenalis group B	β-giardin	2	2	<1	<1
	Campylobacter jejuni	*mapA*	1	1	<1	<1
	Salmonella spp.	*invA*	3	3	6	<1–13
	Salmonella spp.	*ttr*	5	5	10	5–59
	E. coli (pathogenic)	*eae*	1	1	4	4
	Shiga toxin producing bacteria	*stx1*	1	1	16	16
	Shiga toxin producing bacteria	*stx2*	1	1	1	1
	Rotavirus group C	*VP6*	3	3	50	45–1,301
	Any nonspecific marker	—	37	46	5	<1–3,811
All	Any fecal marker	—	79	82	2	<1–49,818

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Note: —, Any of the gene markers within the specified group.

[a]Microbial markers analyzed but not detected: human adenovirus groups B, C, D, and F; human enterovirus; human norovirus genogroups I and II; human polyomavirus; *Cryptosporidium bovis*; bovine adenovirus; bovine coronavirus; and bovine viral diarrhea virus types 1 and 2.

MCEA Ex. 8

[b]Primers, probes, and references for qPCR assays are reported in Table S1.

[c]Totals are less than the sum of individual markers because some wells and samples were positive for more than one marker.
The 60% fecal contamination rate could be an overestimate because we limited well selection to those wells previously positive for coliforms or with nitrate-N concentrations >10mg/L to favor successful completion of the study objective, that is, identify fecal sources of contamination. On the other hand, 60% could be an underestimate, because 95% of the wells were sampled only once, and detection probability was shown to increase the more frequently a well was sampled in one study (Atherholt et al. 2015).

Comparing the fecal contamination rate of our study wells with rates from other studies is confounded by differences in hydrogeological setting, well type, sampling season, the number of wells, the number of samples per well, and the types and number of fecal microorganisms tested. Five studies approximate our study design, setting, or type and number of fecal microbes and can provide some context. Among 50 private wells in seven hydrogeological districts of Wisconsin, 8% were positive for human enteric viruses (Borchardt et al. 2003b). Private wells completed in fractured Silurian dolomite in Ontario, Canada (11 wells), and fractured bedrock in Pennsylvania, USA (5 wells), had microbes of fecal origin in 45% and 100%, respectively (Allen et al. 2017; Murphy et al. 2020). Ninety-six percent of public wells tested in Minnesota, USA, for similar types and number of fecal organisms were positive (Stokdyk et al. 2020), and, as in the present study, *Cryptosporidium* was the most frequently detected pathogen, suggesting it is more common in groundwater than previously thought (Stokdyk et al. 2019). Last, in a comprehensive review of groundwater studies conducted in Canada and the United States, Hynds et al. (2014a) reported that of 12,616 public and private wells tested, at least one enteric pathogen was detected in 15%. Although comparisons among studies are abstruse, the weight of evidence suggests fecal contamination of drinking water wells is not uncommon.

Fecal contamination stemmed from both human wastewater and bovine manure sources. Human wastewater was present in 33 wells, and bovine manure was present in 44 wells (Table 3). Nine wells were contaminated by both fecal sources, human and bovine. Of the 37 wells (46 samples) positive for nonspecific markers, 11 wells (13 samples) did not have coincident detections for human- or bovine-specific markers, indicating that for these wells and samples the fecal source was unknown.

Previous studies have found human-specific and bovine-specific *Bacteroidales* genetic markers detected together in the same private wells (Krolik et al. 2014; Felleiter et al. 2020) and wells and springs (Diston et al. 2015). Nine private wells completed in the dolomite aquifer of six Wisconsin counties were positive for *Bacteroidales* markers specific to human, bovine, or swine fecal material (Zhang et al. 2014).

Identifying which fecal source, human or bovine, was the greatest contributor to groundwater fecal contamination in the county is not possible from our MST data. The proportion of samples positive for human or bovine markers varied by sampling period, which is to say by season, groundwater level, and timing of manure applications (Figure 3). Beginning 1 January 2016, Kewaunee County

banned manure applications during the 1 January–15 April period on all fields with bedrock depths <6.1m. The proportion of wells positive for bovine-specific markers likely depends on the timing and location of well sampling relative to the ban regulations. Groundwater recharge is also important (see below). Therefore, both human and bovine fecal sources contribute to contamination, and the fecal source that appears to bear the most responsibility for contamination depends on sample timing.

Human-specific HF183 *Bacteroides* (28 samples) and ruminant *Bacteroides* (36 samples) were the most common fecal markers, and all samples positive for these were successfully sequenced to confirm *Bacteroides* host identities (see Table S6, Table S7). The Rum-2-Bac marker is specific to ruminants, not cattle alone. However, two lines of evidence suggest the detected Rum-2-Bac markers were indeed from dairy manure: *a*) All amplicons (676 bp) from Rum-2-Bac-positive samples matched *Bacteroidales* or *Bacteroides* species from cattle feces with percent identities greater than 98% and E-scores of zero; and *b*) The only other abundant ruminants in Kewaunee County are approximately 16,000 white tail deer (Wisconsin Department of Natural Resources 2018). Deer excrete 261g/d fecal material (McCullough 1982), which for the Kewaunee County landscape equals 1.3×106 kg/y. In comparison, the land-applied cattle manure in the county is 1.76×109 kg/y (see Supplemental Material, Cattle Manure Volume Produced Annually in Kewaunee County), more than 1,000 times greater than that of deer, suggesting the more probable groundwater contaminant is cattle manure.

Rotavirus group A subtyping was successful for distinguishing human from bovine fecal sources in our study, but that may not always be possible. The human rotavirus vaccine, RotaTeq, contains five human–bovine reassortment strains (Matthijnssens et al. 2010), and because the G6 (bovine) strain can be shed in human stool after oral vaccination (Higashimoto et al. 2018), the fecal source cannot be distinguished when that strain is detected (i.e., vaccine shed into septic systems or G6 wild type in dairy manure). However, our study wells were not positive for the G6 strain, because subtyping analysis revealed rotavirus G1 [P8], which is typically associated with human rotavirus infection (Pitzer et al. 2011), or G10 [P11], a subtype associated with rotavirus infections in cattle (Papp et al. 2013). (Two wells were positive for both subtypes.) Whether the G1 [P8] rotavirus we detected is wild type or vaccine is uncertain, but it indicates a human fecal source regardless.

The human pathogens we detected in private wells have been previously reported in groundwater, except rotavirus group C. Rotavirus group C is zoonotic (unlike group A) and has been found in American cattle and children (Tsunemitsu et al. 1992; Jiang et al. 1995). One-third of young adults in the United States may experience infection in their lifetimes (Riepenhoff-Talty et al. 1997). Twenty wells (15%) were positive for rotaviruses (groups A and C), and rotavirus group C and bovine-related rotavirus group A had the highest concentrations (Table 3), suggesting groundwater in northeastern Wisconsin may be a common reservoir for the sharing and possible reassortment of rotavirus strains among people and cattle.

Risk Factors for Private Well Contamination–Univariable Association Tests

All univariable association tests between private well contamination outcomes and risk factors are reported in Tables S8–S13. Summary statistics of risk factor values are reported in Tables S14–S16.

Sinkholes and rock ledges were associated with well contamination of all five investigated contaminants (coliforms, nitrate, human-specific, bovine-specific, and any fecal markers), but these risk factors were excluded from multivariable analyses for several reasons: *a*) sinkholes and rock ledges were highly correlated with bedrock depth; *b*) sinkhole and ledge locations were determined by field inspections by county staff, and 20% of fields had not been inspected; and *c*) inspections did not include residential properties, biasing the data toward agricultural fields.

Risk Factors for Well Contamination with Nitrate or Coliforms

All land use risk factors eligible for multivariable modeling of nitrate and coliform contamination were related to agriculture (Table 4), suggesting agricultural activities were the primary sources for these contaminants. Septic system density in univariable tests was, at times, associated with coliform and nitrate contamination (see Tables S8 and S9). However, the associations were negative (i.e., implausible and therefore not eligible for model inclusion), likely because more land with housing and septic systems meant there was less land nearby with agricultural activities. Rayne et al. (2019) made a similar observation, showing that when an agricultural field near Madison, Wisconsin, was developed into a housing subdivision with septic systems, the number of monitoring wells with NO−3-N>10mg/L declined.

Table 4

Multivariable modeling of land use and bedrock risk factors as related to detection probabilities and concentrations of coliforms and nitrate in private wells.

Sampling period	Contaminant and outcome measurement[a] (*n*)[b]	Risk factor	Univariable model p-value	Multivariable model			
				Risk factor median[c]	Risk factor range[c]	Coefficient or trend[d,e]	p-value[f]
Groundwater recharge	Coliforms detection (315)	Bedrock depth	0.0090	7.6	0–56.4	Negative	0.0001
		NMP field distance[g]	0.036	42	0–723	−0.002	0.20
		Manure storage distance	0.14	899	46–3,728	−0.00008	0.63
		Agricultural field area within 229m	0.072	12.7	0–16.4	−0.008	0.77
	NO−3-N>10mg/L detection (318)	NMP field area within 229m	0.0013	7.1	0–15.9	0.1	0.024
		NMP field distance	0.14	42	0–724	0.002	0.38
		Manure storage distance	0.082	928	46–3,728	−0.0002	0.49
		Bedrock depth	0.0028	7.6	0–56.4	Negative	0.082
	NO−3-N concentration (200)	NMP field area within 914m	0.071	141.7	10.2–235.7	Positive	0.29
		Bedrock depth	0.0063	5.0	0–56.4	Negative	0.0065

Sampling period	Contaminant and outcome measurement[a] (*n*)[b]	Risk factor	Univariable model p-value	Multivariable model			
				Risk factor median[c]	Risk factor range[c]	Coefficient or trend[d,e]	p-value[f]
No groundwater recharge	Coliforms detection (395)	Manure storage distance	0.0014	878	48–7,054	−0.0005	0.0062
		Agricultural field distance, dichotomous	0.15	NA	NA	0.3	0.24
		Agricultural field distance, continuous	0.081	24	0–805	−0.003	0.34
		NMP field area within 229m	0.059	7.4	0–15.6	0.008	0.75
		Bedrock depth	0.12	12.2	0–61	−0.006	0.42
	Coliforms concentration (76)	NMP field distance	0.0026	36	0–554	Negative	0.0050
	NO−3-N>10mg/L detection (399)	Bedrock depth	<0.0001	12.2	0–61	Negative	0.021
		NMP field area within 457m	0.014	33.3	0–62.4	0.008	0.48
		NMP field distance	0.082	40	0–836	−0.001	0.66

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Note: NA, Not applicable; NMP, nutrient management plan. Univariable model *p*-values used for selecting risk factors are included for reference; complete univariable statistics are provided in Tables S8 and S9. Risk factor eligibility for inclusion in multivariable models is described in statistical methods.

[a]Univariable analyses for: *a*) coliform concentration, groundwater recharge; and *b*) nitrate concentration, no recharge, showed no eligible variables for multivariable modeling; therefore, these models are missing from the table.

[b]n=number of samples in multivariable model.

[c]Units for distance and depth are meters; area is hectares.

[d]In lieu of reporting multiple coefficients for spline-represented variables, we report the overall trend (positive or negative).

[e]Interpretation of coefficient linear terms: change in ln(detection probability) or change in ln(concentration) for a unit change in the risk factor.

[f]The composite *p*-value is reported for spline-represented variables.

[g]Fields with NMPs likely receive manure and inorganic fertilizer inputs.
The area of fields with NMPs within 229m was positively associated with having a well with NO−3-N>10mg/L during groundwater recharge. This association was adjusted for three other risk factors: distance to manure storage, distance to NMP field, and bedrock depth (Table 4). For instance, wells surrounded by 15 ha of NMP fields within 229m, compared with zero hectares, had a 458% increase in the probability of having NO−3-N concentrations >10mg/L (27.2% vs. 5.9%) (Figure 4A). Approximately 80% of the agricultural field area in Kewaunee County follows NMPs (D. Bonness, Kewaunee County Land and Water Conservation Director, personal communication). Because we did not have data on manure and inorganic fertilizer applications, we used county records of NMPs to identify fields likely receiving these inputs.

During the no-recharge period, bedrock depth had the strongest association with the detection of wells with NO−3-N>10mg/L (adjusted for distance to NMP field and area of NMP fields within 457m). Wells with bedrock depths ≥40m had nearly 0% probability of NO−3-N>10mg/L compared with 18% probability for wells with bedrock depths of zero (Figure 4B). Bedrock depth was also a significant risk factor for nitrate concentrations in wells during recharge (Table 4).

In a U.S. nationwide study of nitrate in 1,230 wells, Nolan (2001) identified risk factors within 500-m radii encircling wells and tested associations by multivariable logistic regression, an approach similar to ours. Significant risk factors were nitrogen fertilizer loading, percent cropland, population density, percent well-drained soils, depth to the seasonally high water table, and rock fractures within an aquifer. Our results are consistent with other studies that have associated groundwater nitrate contamination with agricultural-related risk factors, including agricultural land use (Eckhardt and Stackelberg 1995; Lichtenberg and Shapiro 1997; Nolan and Hitt 2006; Lockhart et al. 2013; Zirkle et al. 2016), animal feeding operations (Toetz 2006; Wheeler et al. 2015), dairy manure lagoons (Lockhart et al. 2013), and swine manure lagoons (Messier et al. 2014), but contrast with studies that associated nitrate with septic systems (Lichtenberg and Shapiro 1997; Gardner and Vogel 2005). Our study differs from previous nitrate work in that we dichotomized the nitrate outcome for log-binomial regression using the U.S. EPA health-based MCLG as the threshold; other studies used much lower thresholds, 4mg/L or lower (Eckhardt and Stackelberg 1995; Nolan 2001; Gardner and Vogel 2005).

Coliforms multivariable modeling showed the primary risk factors for detection were bedrock depth during groundwater recharge and distance to the nearest manure storage during the no-recharge period (Table 4). The concentration of coliforms was associated with only one risk factor: distance to the nearest NMP field (Table 4).

Coliform detection in wells during recharge became less likely the deeper the bedrock to depths of 10m (Figure 4C). Wells in locations with 10-m bedrock depth were 67% less likely to have coliform detections in comparison with wells with bedrock at the land surface (18.3% vs. 55.6%).

During the no-recharge period, coliform detection decreased with increasing distance between private wells and manure storage sites (Figure 4D). For example, in comparison with wells located 48m from manure storage (the minimum distance observed), the coliform detection probability for wells 4,000m distant decreased 87% (37.8% vs. 4.8%). Distance to manure storage was also a covariate in the multivariable models for coliform detection and nitrate detection during groundwater recharge (Table 4).

According to records maintained by the Kewaunee County Land and Water Conservation Department, there are 277 manure storage structures in the county, mostly lagoons ranging in size from 0.01 to 2.06 ha and typically 3.7m deep. Lagoon design specifications allow bottom leakage rates of 47,000L/ha/d (NRCS 313), equivalent to 3.4×107L/y for a 2-ha lagoon. Coliform concentrations in dairy manure are on the order of 106 CFU/g wet manure (Blaustein et al. 2015). Groundwater velocities in the Silurian dolomite fractures have been measured as high as 115 to 600m/d (Bradbury and Muldoon 1992; Bradbury et al. 2001), suggesting leaked manure could deliver coliforms to private wells 1,600m distant (1 mi) in 3 to 14 d.

However, one confounder to consider is a possible negative association between manure storage distance and land-applied manure volume. Transporting manure by tanker truck for land application is costly and time-consuming. More distant fields may receive less land-applied manure. Data on manure application volumes and locations in Kewaunee County are sparse, so discriminating between mechanisms (lagoon leakage vs. applied manure volume) is not possible.

Although we cannot identify the mechanism underlying the association between coliform contamination and manure storage, the relationship is consistent with previous studies (Li et al. 2015; Yessis et al. 1996). Previous studies have also linked the occurrence of coliforms and other indicator bacteria in wells to other agriculture-related factors, including proximity to farm animal operations (Allevi et al. 2013) or agricultural point sources (e.g., farmyards, animal holding facilities, manure storage) (Hynds et al. 2014b; Fennell 2017; Goss et al. 1998; Li et al. 2015) and the density of livestock (Invik et al. 2019; O'Dwyer et al. 2018). Moreover, Óhaiseadha et al. (2017) showed that laboratory-confirmed verotoxigenic *E. coli* infections in Ireland were positively associated with private well usage and cattle density. Our study differed from previous work in that we used GIS to measure continuous-scaled (i.e., not dichotomous or ordinal) "distance to" and "area of" agricultural activities with respect to study well locations.

Risk Factors for Well Contamination with Human Fecal Markers

Human fecal contamination of private wells was modeled with four variables, of which the median groundwater depth 14 d prior to sampling had the strongest association with contamination (Table 5). For example, the detection probability for human fecal contamination increased to 35% from 11%, with a 1.4-m decrease in median groundwater depth 14 d prior to sampling. Density of neighboring septic system drainfields was another risk factor. These two risk factors are in agreement with the fact that septic systems are the primary source of human fecal wastes on the rural county landscape, and that shallower groundwater depth gives microbes shorter travel distance from the bottom of septic drainfields to the top of the groundwater table. Likewise, bedrock depth, which reflects the distance microbes must travel to reach the fractured bedrock, was associated with the concentration of human markers (Table 5).

Table 5

Multivariable modeling of land use and bedrock risk factors as related to detection probabilities and concentrations of genetic markers of host-specific and fecal-associated microbes in private wells.

Fecal marker source and outcome measurement (n)[a]	Risk factor	Univariable model p-value	Multivariable model			
			Risk factor median[b]	Risk factor range[b]	Coefficient or trend[c,d]	p-value[e]
Human marker detection (137)	Drainfield septic systems, count within 229m	0.038	2	0–10	0.09	0.11
	Groundwater depth, 14-d antecedent, median	0.0003	1.2	0.3–1.6	−0.9	0.011
	Rainfall, 2-d antecedent, cumulative	0.0093	14	0–37	Positive	0.69
	Bedrock depth	0.051	6.1	0–46.6	Negative	0.13
Human marker concentration (33)	Bedrock depth	0.011	4.3	0.3–36.6	Negative	0.011
Bovine marker detection (138)	Groundwater recharge, 7-d antecedent, cumulative	0.0041	50	0–60	Positive	0.0092

Fecal marker source and outcome measurement (n)[a]	Risk factor	Univariable model p-value	Multivariable model			
			Risk factor median[b]	Risk factor range[b]	Coefficient or trend[c,d]	p-value[e]
Bovine marker concentration (41)	Agricultural field area within 229m	0.029	11.6	3.7–16.4	Positive	0.024
	Bedrock depth	0.0019	5.2	0–29	−0.1	0.0006
Any fecal marker[f] detection (137)	Drainfield septic systems, count within 229m	0.0036	2	0–10	Positive	0.036
	Rainfall, 2-d antecedent, cumulative	0.12	14	0–37	Positive	0.19
	Manure storage distance[g]	0.94	687	71–3,728	−0.0004	0.036
	Bedrock depth	0.027	6.1	0–46.6	−0.06	0.0058
	Manure storage distance times bedrock depth interaction	0.045	NA	NA	Negative	0.024
Any fecal marker concentration (77)	Agricultural field area within 229m	0.035	12.7	1.1–16.4	Positive	0.097
	Manure storage distance	0.083	762	113–3,728	−0.0001	0.76
	Bedrock depth	0.0003	4.6	0–36.6	−0.08	0.002

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Note: NA, Not applicable. Univariable model *p*-values used for selecting risk factors are included for reference; complete univariable statistics are provided in Table S10. Risk factor eligibility for inclusion in multivariable models is described in statistical methods.

[a]n=number of samples in multivariable model.

[b]Units for distance and depth are meters; rainfall and recharge are millimeters; area is hectares.

[c]In lieu of reporting multiple coefficients for spline-represented variables we report the overall trend (positive or negative).

[d]Interpretation of coefficient linear terms: change in ln(detection probability) or change in ln(concentration) for a unit change in the risk factor.

[e]The composite *p*-value is reported for spline-represented variables.

[f]"Any fecal marker" includes all microorganisms regardless of host specificity.

[g]Included in multivariable model because of its significant interaction with bedrock depth.
One other possible human fecal source was septage (i.e., wastewater pumped from septic tanks) land-applied to approved agricultural fields. Tests of association between septage-applied fields and well contamination were ambiguous, suggesting septage was not an important risk factor (see Supplemental Material, Septage Land-Applied Fields—Univariable Associations). County records show during the study period only 10 fields equaling 110 ha received 2.57×106L septage. In contrast, septic systems are located throughout the county and the volume of untreated effluent released to the subsurface was calculated to be 6.79×108L per year (see Supplemental Material, Septic System Effluent Volume Released Annually in Kewaunee County).

Septic system effluent contamination of groundwater with fecal indicator bacteria and pathogenic viruses and bacteria is well documented in the literature (Hagedorn et al. 1981; Yates 1985: Nicosia et al. 2001; Katz et al. 2010; Hynds et al. 2012; Lusk et al. 2017). In one study, vaccine poliovirus was introduced into the tank of a new conventional septic system, and the virus was cultured in multiple samples over time in a monitoring well 6m down-gradient from the edge of the drainfield (Alhajjar et al. 1988). More recently, detection in groundwater of the human-specific markers HF183 and HumM2 has been linked with septic system effluent (Schneeberger et al. 2015; Murphy et al. 2020). Groundwater-borne disease outbreaks (Yates 1985; Beller et al. 1997; Borchardt et al. 2011) and endemic diarrheal illness (Borchardt et al. 2003a) have also been associated with septic systems.

As early as 1977 the U.S. EPA recommended that to minimize groundwater contamination septic system density should not exceed 40 systems per square mile (1 system/6.5 ha or 0.15 systems/ha) (U.S. EPA 1977). Three subsequent studies have suggested septic system density should not exceed 5, 1–2.5, and 3.5–6 systems/ha (Reneau 1979; Gardner et al. 1997; Morrissey et al. 2015). In the fractured dolomite aquifer of our study, as the number of septic drainfields within 229m of private wells increased from zero to 10, the probability of human fecal contamination increased 2.5 times, from 13% to 33% (Figure 5A), with the upper limit (10 septic drainfields) equivalent to 0.6 systems/ha. This relationship was adjusted for groundwater depth, rainfall, and bedrock depth (Table 5). (In Figure 5A the count of one drainfield represents the well contamination probability from a household's own drainfield, 14%.)

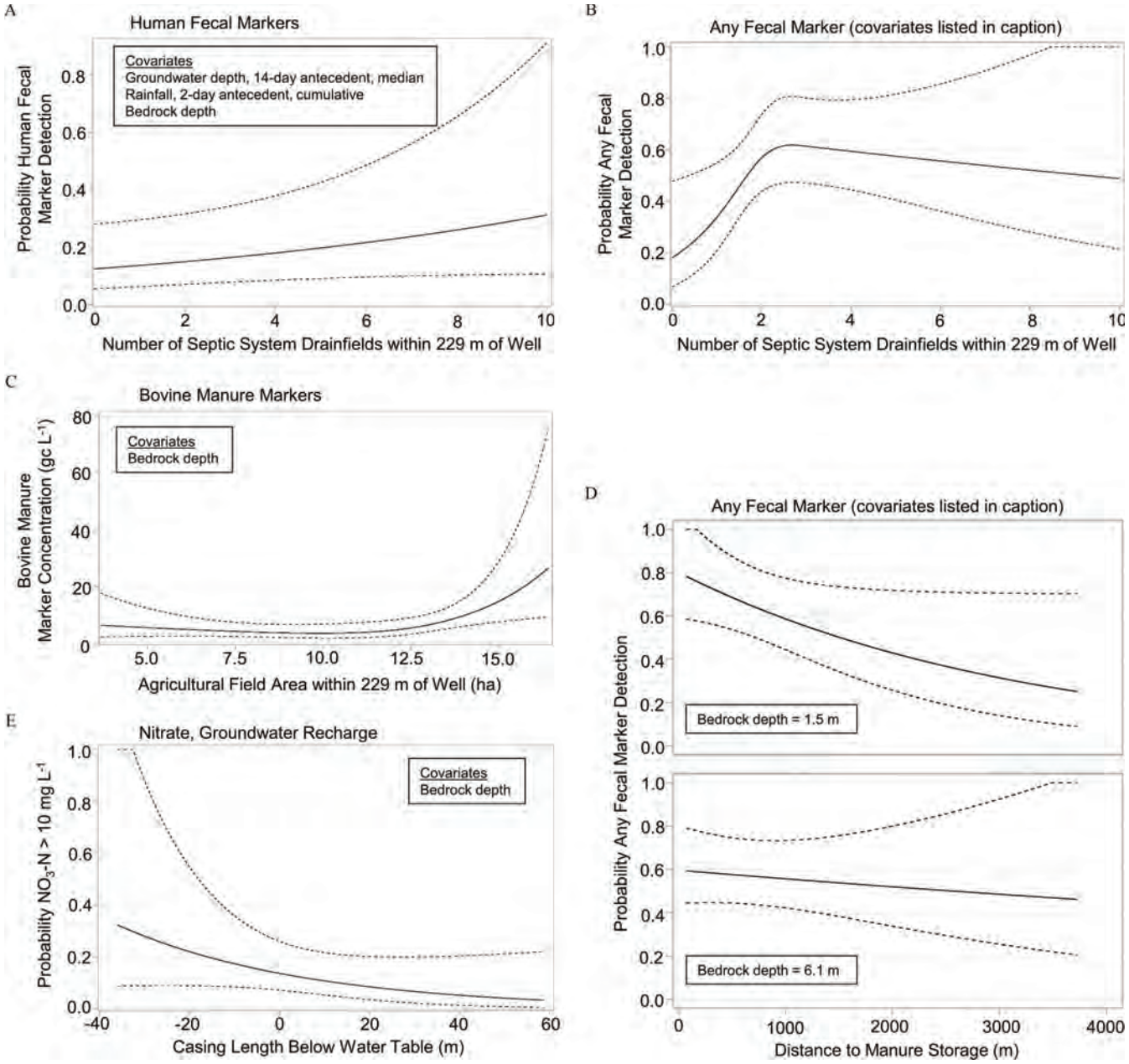

Figure 5.

Key risk factors regressed on private well contamination probability (log-binomial regression) or concentration (gamma regression): (A) detection probability for human-specific markers; (B) detection probability for any fecal marker; covariates: manure storage distance, bedrock depth, manure storage distance times bedrock depth interaction, rainfall 2-d antecedent cumulative; (C) estimated bovine-specific marker concentration (mean sum); (D) interaction between manure storage distance and bedrock depth for any fecal marker detection probability; covariates: septic system drainfields within 229m of well, rainfall 2-d antecedent cumulative; (E) detection probability of NO−3-N>10mg/L. Black line: regression estimates. Dashed lines: 95% pointwise confidence limits. Coefficients and *p*-values are reported in Table 5. Covariates in the multivariable models were fixed at their median values for the purpose of plotting.

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Considering other vulnerable aquifers, Blaschke et al. (2016) estimated the distance between septic systems and private wells needed for 12-log10 virus removal to achieve a risk of 10−4 infections/person/y, and their lower setback distance estimates for gravel and coarse gravel aquifers were 66m and 1,000m, respectively (equivalent to densities of 0.7 and 0.003 systems/ha). For limestone aquifers similar to our study site, Morrissey et al. (2015) derived a recommendation of 3.5 systems/ha from groundwater flow modeling of indicator bacteria and nitrate, and Masciopinto et al. (2008) estimated the setback required for 7-log10 virus reduction from municipal wastewater injected into sinkholes was 8,000m. Although previous work was based on indicators and nitrate or log removal of viruses, our model is based on the probability of contamination by fecal waste specific to humans.

Risk Factors for Well Contamination with Bovine Manure Markers

The detection probability of bovine-specific markers increased during periods of groundwater recharge (Table 5), as infiltrating precipitation and snowmelt carried manure from the surface to the water table. An increase from 0 to 40 millimeters cumulative recharge 7 d prior to sampling increased the detection probability of bovine markers from 13% to 50%.

Agricultural risk factors were not associated with the detection probability of bovine markers but were associated with those markers' *concentrations* (see Table S10), and of these the area of agricultural fields within 229m of wells had the strongest association. When the area exceeded 13 ha, bovine marker concentration increased (Figure 5C).

The reason we found associations between fecal sources and detection probability of human markers but not bovine markers likely stem from differences in release patterns between septic systems and manure. Septic system locations are fixed and known with certainty; the systems operate every day, continually releasing household wastewater to the subsurface. In contrast, manure applications vary in location, timing, and volume; manure could be applied near a well on one day and then not again that year. Unlike manure field applications, manure storages are like septic systems: The locations are fixed and known, meaning our distance measurements between manure storages and study wells had minimal error. This may have contributed to our finding that the "distance to manure storage" risk factor was relevant in five multivariable models.

Because manure application records were incomplete (only large farms are required to report applications), we assumed all agricultural fields near wells were potential sources of manure at the time of sampling, which was likely true for only some fields, resulting in misclassification. However, when the model was restricted to only bovine-positive samples, this restriction removed any chance of misclassification (i.e., positivity indubitably showed manure must be near the well), which likely explains why we were able to link agricultural field area to bovine marker concentration. The impact of misclassification of manured sites may have been lessened for contaminant detection models constructed with more positive samples (i.e., greater statistical power). These models (coliforms, nitrate-N, and any fecal marker) did indeed identify agricultural risk factors.

Risk Factors for Well Contamination with Markers for Any Fecal Microbe

The any fecal marker category included the 82 samples (79 wells) positive for any of the 24 microbial markers found in the fecal material of humans, bovines and ruminants, or other vertebrate hosts (Table 3). Multivariable modeling showed detection of any marker in this category was associated with well proximity to locations of both human and bovine fecal material, namely septic drainfields and manure storages. The model included two other risk factors: rainfall and bedrock depth (Table 5). Similar findings were reported by O'Dwyer et al. (2018), who showed septic system density, cattle density, rainfall, and karst bedrock in Ireland were associated with private well contamination with *E. coli*.

Any fecal marker detection probability increased by a factor of three when septic drainfields increased from zero to two within 229m of wells; additional drainfields did not further increase the detection probability (Figure 5B). Manure storage distance from wells was associated with fecal contamination after accounting for its interaction with bedrock depth; for wells closer to manure storage, the probability of detecting any fecal marker increased more steeply at shallow bedrock depth (Figure 5D).

To model the concentration outcome of any fecal marker, only positive samples were included, reducing statistical power compared to the detection outcome model. Nonetheless, bedrock depth was strongly associated with fecal marker concentration after adjusting for manure storage distance and the area of agricultural fields within 229m of wells (Table 5).

The multivariable models for any fecal marker encapsulate the key study finding: Fecal contamination in the county's private wells stems from both septic systems and manure, and contamination is exacerbated by shallow bedrock depth and elevated rainfall. Both fecal sources release untreated wastes to the landscape at noteworthy volumes. Septic system drainfields in the county are estimated to release into the subsurface 6.79×108 L of household wastewater per year, and the county's cattle population produces approximately 1.74×109 L manure (fecal and urine combined) per year (see Supplemental Material, "Septic System Effluent Volume Released Annually in Kewaunee County, Cattle Manure Volume Produced Annually in Kewaunee County").

Precipitation as a Risk Factor for Private Well Contamination

There is ample evidence showing precipitation favors microbial contamination of private wells. Precipitation quantity in the period preceding sampling was positively associated with the occurrence in private wells of indicator bacteria (Hynds et al. 2012; O'Dwyer et al. 2014; Procopio et al. 2017; Invik 2019) human enteric viruses (Allen et al. 2017) and the human-specific *Bacteroides* marker HF183 (Murphy et al. 2020). The antecedent precipitation periods associated with contamination varied between 30 (Invik et al. 2019) and 5 d (Hynds et al. 2012), and even shorter periods of rainfall (24 h) may be associated with contamination of vulnerable aquifers (Morrissey et al. 2015). In our study 2-d antecedent cumulative rainfall was more strongly associated than 7- or 14-d periods with detection of any fecal marker and markers specific to humans (see Table S10). However, when rainfall was included in multivariable models it was not as strongly associated to contamination as the other risk factors (Table 5).

Well Construction Risk Factors Related to Contamination

Well construction risk factor modeling did not identify a single overriding factor. Of 14 possible multivariable models (combinations of contaminant type, recharge, and outcome measurement) only six had any variables that met the univariable screening criteria (Table 6; and see Tables S11, S12, and S13). Four of the six models involved nitrate, suggesting well construction was more related to nitrate than microbial contamination. Statistical power may have been an issue, particularly for human and bovine markers, as construction data on file with the state government were not available for 35% of study wells. Nevertheless, the quality of the well construction data was good. Our data were derived from bona fide construction records instead of relying on well-owner recall. Summary statistics for all well construction data are reported in Tables S14–S16.

Table 6

Multivariable modeling of well construction risk factors as related to detection probabilities and concentrations of coliforms, any fecal-associated marker, and nitrate in private wells.

			Multivariable model			
Contaminant and outcome measurement (n)[a]	**Risk factor**	**Univariable model p-value**	**Risk factor median[b]**	**Risk factor range[b]**	**Coefficient or trend[c,d]**	**p-value[e]**
Any fecal marker[f] detection (83)	Casing depth	0.15	17.7	12.2–48.2	Negative	0.31
	Open interval length	0.13	29.0	2.1–79.6	Positive	0.24
	Bedrock depth	0.027	4.6	0–46.6	−0.02	0.26
Coliforms concentration, recharge (47)	Well depth	0.047	48.8	18.3–100.6	Negative	0.59
	Casing depth	0.057	18.9	12.2–80.2	None	0.91
	Groundwater depth at construction	0.0004	12.2	1.8–36.6	Negative	0.0038
	Well age	0.0042	24	5–49	0.04	0.016
NO−3-N>10mg/L detection, recharge (201)	Casing length below water table	0.040	8.5	–36–58.8	−0.02	0.13
	Bedrock depth	0.0028	6.4	0–55.2	Negative	0.28

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			Multivariable model			
Contaminant and outcome measurement (n)[a]	**Risk factor**	**Univariable model p-value**	**Risk factor median[b]**	**Risk factor range[b]**	**Coefficient or trend[c,d]**	**p-value[e]**
NO−3-N concentration, recharge (124)	Well age	0.15	22	2–80	Positive	0.16
	Bedrock depth	0.0063	4.7	0–31.4	Negative	0.11
NO−3-N>10mg/L detection, no-recharge (251)	Casing depth	0.12	18.9	6.1–126.5	0.01	0.65
	Casing length below water table	0.02	8.8	–36–117.3	−0.02	0.33
	Bedrock depth	<0.0001	10.1	0.3–54.3	Negative	0.07
NO−3-N concentration, no-recharge (127)	Casing depth	0.043	18.0	6.1–126.5	−0.008	0.57
	Casing length below water table	0.054	5.5	–19.8–117.3	Negative	0.74
	Bedrock depth	0.0019	6.7	0.3–49.4	Negative	0.0088

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Note: Univariable model p-values used for selecting risk factors are included for reference; complete univariable statistics are provided in Tables S11, S12, and S13. Risk factor eligibility for inclusion in multivariable models is described in statistical methods.

[a]n=number of samples in multivariable model.

[b]Units for length and depth are meters; age is in years.

[c]In lieu of reporting multiple coefficients for spline-represented variables we report the overall trend (positive or negative).

[d]Interpretation of coefficient linear terms: change in ln(detection probability) or change in ln(concentration) for a unit change in the risk factor.

[e]The composite p-value is reported for spline-represented variables.

[f]"Any fecal marker" includes all microorganisms regardless of host specificity.

Casing depth was included in more multivariable well construction models than any other variable; minimum depths specified in well construction codes are believed to prevent contamination. However, its independent effect in the presence of other risk factors in the well construction models was equivocal; associations were weak, and trends were inconsistent (positive, negative, and none)

(Table 6). Casing length below water table was the second most frequently included risk factor, and its trends were consistent; longer casing into the aquifer reduced NO−3-N contamination. For example, increasing casing length from 36m above to 59m below the water table decreased the probability of NO−3-N contamination >10mg/L during recharge by 90% (Figure 5E). Placing the casing bottom deeper into the aquifer likely results in nitrate that is infiltrating from the land surface to be further diluted before it enters the well. Of 453 study wells that had data on casing length below water table, 77 wells (17%) had casings that ended above the water table, providing no dilution benefit.

Older wells tend to have greater nitrate and bacterial contamination (Yessis et al. 1996; Goss et al. 1998), but in our study, of the 14 possible multivariable models, well age was associated only with coliforms concentration during recharge (Table 6). Changes in State code in 1988 improved well construction reporting, so our construction data skewed toward newer wells (median age approximately 20 y) that comply with recent construction regulations (e.g., only one well had casing depth less than the State minimum of 12.2m.)

Well depth is frequently identified in groundwater studies as an important factor affecting nitrate and microbial contamination. Deeper wells have less nitrate (Glanville et al. 1997; Lichtenberg and Shapiro 1997; Goss et al. 1998; Allevi et al. 2013; Swistock et al. 2013; Lockhart et al. 2013; Warner and Arnold 2010), coliforms (Gonzales 2008; Goss et al. 1998; Allevi et al. 2013), *E. coli* (O'Dwyer et al. 2018), and human viruses (Allen et al. 2017). Warner and Arnold (2010) found that nitrate concentrations among 378 private wells in the glacial aquifer system in the United States (of which Kewaunee County is part) had less spatial and temporal variation than the variation contributed by well depth. They suggest deeper wells have older groundwater with lower dissolved oxygen favoring denitrification. Well depth was not associated with nitrate contamination in our study wells, likely because the aquifer is oxic at least to 70m (Bradbury and Muldoon 1992).

Hynds et al. (2012) showed that well design and construction were more important than septic systems, geological setting, or precipitation in explaining the variability of thermotolerant coliform contamination in private wells in Ireland. Our findings differ. Overall, well construction was not strongly associated with nitrate and microbial contamination of private wells in the Silurian dolomite aquifer of northeastern Wisconsin. Nor are our findings unique. In a study of 180 randomly selected private wells in northeastern Ohio, well age and well depth determined from construction records were not associated with coliform contamination (Won et al. 2013). Many studies that have investigated the link between well construction and contamination included dug wells and sand points (Yessis et al. 1996; Goss et al. 1998) or wells that lacked adequate sealing between the casing and well annulus, a condition that would allow direct ingress of surface contaminants (Hynds et al. 2012; Fennell 2017). In contrast, for our study wells that have construction data, all were drilled, none were dug, and all were sealed with grout. For wells such as these, in this hydrogeological setting, it appears differences in construction have less impact on contamination than other factors.

Utility and Generalizability of Findings

We have shown private household wells open to the Silurian dolomite aquifer in Kewaunee County, Wisconsin, were contaminated with nitrate, coliform bacteria, and diverse taxa of fecal-associated microbes, some of which were pathogenic. Contamination rates depended on bedrock depth, land use, groundwater recharge, rainfall, and to a lesser extent factors related to well construction. Our examination of risk factors was comprehensive, and multivariable modeling allowed each risk factor to be evaluated for its independent effects in the presence of other factors. In addition, risk factors were analyzed as continuous-scaled variables, which aids interpretation and is amenable for policymaking, for example, establishing setback distances between private wells and agricultural fields, allowable septic system densities, or minimum bedrock depths for manure applications.

Our findings likely apply to other regions that depend on the Silurian dolomite aquifer and where agricultural and exurban land uses affect groundwater quality. The aquifer is regionally extensive and an important water supply for public, domestic, and commercial uses in six U.S. states: Wisconsin, Illinois, Iowa, Michigan, Indiana, and Ohio (USGS 2016). The Silurian dolomite aquifer in Canada extends from Lake Huron to Niagara Falls and supplies water to nearly 800,000 people in southern Ontario (Allen et al. 2017). In northeast Wisconsin the aquifer is emblematic of an open-access resource and the “tragedies” that can result when the resource becomes degraded by competing interests. Understanding how the aquifer is contaminated—the sources, extent, and factors involved—may contribute to the broader appreciation that this essential resource is shared among all who depend on it.

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Acknowledgments

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References

- Alhajjar BJ, Stramer SL, Cliver DO, Harkin JM. 1988. Transport modelling of biological tracers from septic systems. Water Res 22(7):907–915, 10.1016/0043-1354(88)90028-0. [CrossRef] [Google Scholar]
- Allen AS, Borchardt MA, Kieke BA Jr., Dunfield KE, Parker BL. 2017. Virus occurrence in private and public wells in a fractured dolostone aquifer in Canada. Hydrogeol J 25(4):1117–1136, 10.1007/s10040-017-1557-5. [CrossRef] [Google Scholar]
- Allevi RP, Krometis L-AH, Hagedorn C, Benham B, Lawrence AH, Ling EJ, et al.. 2013. Quantitative analysis of microbial contamination in private drinking water supply systems. J Water Health 11(2):244–255, PMID: 23708572, 10.2166/wh.2013.152. [PubMed] [CrossRef] [Google Scholar]
- American Public Health Association. 1995. Standard Methods for the Examination of Water and Wastewater, 19th ed. Washington, DC: American Public Health Association. [Google Scholar]
- Atherholt TB, Korn LR, Louis JB, Procopio NA. 2015. Repeat sampling and coliform bacteria detection rates in New Jersey domestic wells. Groundwater Monit R 35(2):70–80. 10.1111/j.1745-6584.2012.00997.x, 10.1111/gwmr.12094. [CrossRef] [CrossRef] [Google Scholar]
- Bay Lake Regional Planning Commission. 2016. Kewaunee County 20-Year Comprehensive Plan Update. http://media.baylakerpc.org/media/51229/kewaunee%20county%20comp%20plan_farm%20preservation%20plan%20full%20document-%2001182017.pdf [accessed 10 September 2019].
- Blaschke AP, Derx J, Zessner M, Kirnbauer R, Kavka G, Strelec H, et al.. 2016. Setback distances between small biological wastewater treatment systems and drinking water wells against virus contamination in alluvial aquifers. Sci Total Environ 573:278–289, PMID: 27570196, 10.1016/j.scitotenv.2016.08.075. [PubMed] [CrossRef] [Google Scholar]
- Blaustein RA, Pachepsky YA, Hill RL, Shelton DR. 2015. Solid manure as a source of fecal indicator microorganisms: release under simulated rainfall. Environ Sci Technol 49(13):7860–7869, PMID: 26011817, 10.1021/acs.est.5b01095. [PubMed] [CrossRef] [Google Scholar]
- Borchardt MA, Bradbury KR, Alexander EC, Archer J, Braatz L, Forest B, et al.. 2011. Norovirus outbreak caused by a new septic system in a dolomite aquifer. Ground Water 49(1):85–97, PMID: 20199588, 10.1111/j.1745-6584.2010.00686.x. [PubMed] [CrossRef] [Google Scholar]
- Borchardt MA, Muldoon MA, Hunt RJ, Bonness DE, Firnstahl AD, Kieke BA, et al.. 2019. Assessing Groundwater Quality in Kewaunee County, Wisconsin and Characterizing the Timing and Variability of Enteric Pathogen Contamination Within the Dolomite Aquifer in Northeastern Wisconsin. DNR Project Number 227, Final Report. Wisconsin Geology and Natural History Survey, Open-File Report 2019-05, 2019.
- Bradbury KR, Muldoon MA. 1992. Hydrogeology and groundwater monitoring of fractured dolomite in the Upper Door Priority Watershed, Door County, Wisconsin. Wisconsin Geological and Natural History Survey Open File Report, WOFR 1992-2, https://wgnhs.wisc.edu/catalog/publication/000776/resource/wofr199202 [accessed 22 June 2019].

- Bradbury KR, Rayne TW, Muldoon MA. 2001. Field verification of capture zones for municipal wells at Sturgeon Bay, Wisconsin. Final Report to the Wisconsin Department of Natural Resources. https://wgnhs.uwex.edu/pubs/000823/ [accessed 22 June 2019].
- Bromley DW, Cernea MM. 1989. The Management of Common Property Natural Resources: Some Conceptual and Operational Fallacies (English). World Bank Discussion Papers; No. WDP 57. Washington, DC: World Bank Group, http://documents.worldbank.org/curated/en/548811468740174575/The-management-of-common-property-natural-resources-some-conceptual-and-operational-fallacies [accessed 15 March 2018]. [Google Scholar]
- Center for Watershed Science and Education Wisconsin. 2018. Well Water Viewer: Private Well Data for Wisconsin. University of Wisconsin – Stevens Point. https://www.uwsp.edu/cnr-ap/watershed/Pages/WellWaterViewer.aspx [accessed 29 March 2018].
- DiSimone LA. 2009. Quality of Water from Domestic Wells in Principal Aquifers of the United States, 1991-2004. U.S. Geological Survey Scientific Investigations Report 2008–5227. http://pubs.usgs.gov/sir/2008/5227 [accessed 21 November 2019].
- Diston D, Sinreich M, Zimmermann S, Baumgartner A, Felleisen R. 2015. Evaluation of molecular- and culture-dependent MST markers to detect fecal contamination and indicate viral presence in good quality groundwater. Environ Sci Technol 49(12):7142–7151, PMID: 25871525, 10.1021/acs.est.5b00515. [PubMed] [CrossRef] [Google Scholar]
- Eckhardt DAV, Stackelberg PE. 1995. Relation of ground-water quality to land use on Long Island, New York. Groundwater 33(6):1019–1033, 10.1111/j.1745-6584.1995.tb00047.x. [CrossRef] [Google Scholar]
- Erb K, Ronk E, Koundinya V, Luczaj J. 2015. Groundwater quality changes in a karst aquifer of northeastern Wisconsin, USA: reductions of brown water incidence and bacterial contamination resulting from implementation of regional task force recommendations. Resources 4(3):655–672, 10.3390/resources4030655. [CrossRef] [Google Scholar]
- Final Report of the Northeast Wisconsin Karst Task Force. 2007. Erb K, Steiglitz R, eds. https://cdn.shopify.com/s/files/1/0145/8808/4272/files/G3836.pdf [accessed 12 February 2020].
- Felleiter S, McDermott K, Hall G, Sheth P, Majury A. 2020. Exploring private water wells for fecal sources and evidence of pathogen presence in the context of current testing practices for potability in Ontario. Water Qual Res J Can 55(1):93–105, 10.2166/wqrj.2019.035. [CrossRef] [Google Scholar]
- Fennell C. 2017. The impact of domestic wastewater treatment system effluent on private water wells: an evaluation of contamination fingerprinting techniques. Thesis. University of Dublin, Trinity College, Dublin. [Google Scholar]
- Gardner KK, Vogel RM. 2005. Predicting ground water nitrate concentration from land use. Ground Water 43(3):343–352, PMID: 15882326, 10.1111/j.1745-6584.2005.0031.x. [PubMed] [CrossRef] [Google Scholar]
- Gardner TED, Geary P, Gordon IAN. 1997. Ecological sustainability and on-site effluent treatment systems. Australas J Environ Manag 4(2):144–156, 10.1080/14486563.1997.10648378. [CrossRef] [Google Scholar]
- Garson GD. 2013. Generalized Linear Models/Generalized Estimating Equations, 2013 Edition. Asheboro, NC: Statistical Associates Publishers. [Google Scholar]

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- Gibson KE, Schwab KJ, Spencer SK, Borchardt MA. 2012. Measuring and mitigating inhibition during quantitative real time PCR analysis of viral nucleic acid extracts from large-volume environmental samples. Water Res 46(13):4281–4291, PMID: 22673345, 10.1016/j.watres.2012.04.030. [PubMed] [CrossRef] [Google Scholar]
- Glanville TD, Baker JL, Newman JK. 1997. Statistical analysis of rural well contamination and effects of well construction. Trans ASAE 40(2):363–370, 10.13031/2013.21281. [CrossRef] [Google Scholar]
- Goss MJ, Barry DAJ, Rudolph DL. 1998. Contamination in Ontario farmstead domestic wells and its association with agriculture: 1. Results from drinking water wells. J Contam Hydrol 32(3–4):267–293, 10.1016/S0169-7722(98)00054-0. [CrossRef] [Google Scholar]
- Hagedorn C, Mc Coy EL, Rahe TM. 1981. The potential for ground water contamination from septic effluents. J Environ Qual 10(1):1–8, 10.2134/jeq1981.00472425001000010001x. [CrossRef] [Google Scholar]
- Hastie TJ, Tibshirani RJ, Friedman JH. 2001. The Elements of Statistical Learning: Data Mining, Inference, and Prediction. New York: Springer-Verlag. [Google Scholar]
- Healy RW, Cook PG. 2002. Using groundwater levels to estimate recharge. Hydrogeol J 10(1):91–109, 10.1007/s10040-001-0178-0. [CrossRef] [Google Scholar]
- Hynds PD, Misstear BD, Gill LW. 2012. Development of a microbial contamination susceptibility model for private domestic groundwater sources. Water Resour Res 48:W12504, 10.1029/2012WR012492. [CrossRef] [Google Scholar]
- Hynds P, Misstear BD, Gill LW, Murphy HM. 2014b. Groundwater source contamination mechanisms: physicochemical profile clustering, risk factor analysis and multivariate modeling. J Contam Hydrol 159:47–56, PMID: 24583518, 10.1016/j.jconhyd.2014.02.001. [PubMed] [CrossRef] [Google Scholar]
- Invik J, Barkema HW, Massolo A, Neumann NF, Cey E, Checkley S. 2019. Escherichia coli contamination of rural well water in Alberta, Canada is associated with soil properties, density of livestock and precipitation. Can Water Resour J 44(3):248–262, 10.1080/07011784.2019.1595157. [CrossRef] [Google Scholar]
- Iturriza-Gómara M, Kang G, Gray J. 2004. Rotavirus genotyping: keeping up with an evolving population of human rotaviruses. J Clin Virol 31(4):259–265, PMID: 15494266, 10.1016/j.jcv.2004.04.009. [PubMed] [CrossRef] [Google Scholar]
- Jiang B, Dennehy PH, Spangenberger S, Gentsch JR, Glass RI. 1995. First detection of group C rotavirus in fecal specimens of children with diarrhea in the United States. J Infect Dis 172(1):45–50, PMID: 7797945, 10.1093/infdis/172.1.45. [PubMed] [CrossRef] [Google Scholar]
- Katz BG, Griffin DW, McMahon PB, Harden HS, Wade E, Hicks RW, et al.. 2010. Fate of effluent-borne contaminants beneath septic tank drainfields overlying a karst aquifer. J Environ Qual 39(4):1181–1195, PMID: 20830905, 10.2134/jeq2009.0244. [PubMed] [CrossRef] [Google Scholar]
- Krolik J, Evans G, Belanger P, Maier A, Hall G, Joyce A, et al.. 2014. Microbial source tracking and spatial analysis of *E. coli* contaminated private well waters in southeastern Ontario. J Water Health 12(2):348–356, PMID: 24937229, 10.2166/wh.2013.192. [PubMed] [CrossRef] [Google Scholar]

- Li X, Atwill ER, Antaki E, Applegate O, Bergamaschi B, Bond RF, et al.. 2015. Fecal indicator and pathogenic bacteria and their antibiotic resistance in alluvial groundwater of an irrigated agricultural region with dairies. J Environ Qual 44(5):1435–1447, PMID: 26436261, 10.2134/jeq2015.03.0139. [PubMed] [CrossRef] [Google Scholar]
- Lichtenberg E, Shapiro LK. 1997. Agriculture and nitrate concentrations in Maryland community water system wells. J Environ Qual 26(1):145–153, 10.2134/jeq1997.00472425002600010022x. [CrossRef] [Google Scholar]
- Lockhart KM, King AM, Harter T. 2013. Identifying sources of groundwater nitrate contamination in a large alluvial groundwater basin with highly diversified intensive agricultural production. J Contam Hydrol 151:140–154, PMID: 23800783, 10.1016/j.jconhyd.2013.05.008. [PubMed] [CrossRef] [Google Scholar]
- Lohr SL. 2010. Sampling: Design and Analysis. 2nd ed. Boston, MA: Brooks/Cole. [Google Scholar]
- Lusk MG, Toor GS, Yang Y-Y, Mechtensimer S, De M, Obreza TA. 2017. A review of the fate and transport of nitrogen, phosphorus, pathogens, and trace organic chemicals in septic systems. Crit Rev Environ Sci Technol 47(7):455–541, 10.1080/10643389.2017.1327787. [CrossRef] [Google Scholar]
- Madadgar O, Nazaktabar A, Keivanfar H, Zahraei Salehi T, Lotfollah Zadeh S. 2015. Genotyping and determining the distribution of prevalent G and P types of group a bovine rotaviruses between 2010 and 2012 in Iran. Vet Microbiol 179(3–4):190–196, PMID: 26072368, 10.1016/j.vetmic.2015.04.024. [PubMed] [CrossRef] [Google Scholar]
- Masciopinto C, La Mantia R, Chrysikopoulos CV. 2008. Fate and transport of pathogens in a fractured aquifer in the Salento area, Italy. Water Resour Res 44:W01404, 10.1029/2006WR005643. [CrossRef] [Google Scholar]
- Matthijnssens J, Joelsson DB, Warakomski DJ, Zhou T, Mathis PK, van Maanen MH, et al.. 2010. Molecular and biological characterization of the 5 human-bovine rotavirus (WC3)-based reassortant strains of the pentavalent rotavirus vaccine, RotaTeq. Virology 403(2):111–127, PMID: 20451234, 10.1016/j.virol.2010.04.004. [PubMed] [CrossRef] [Google Scholar]
- McNutt LA, Wu C, Xue X, Hafner JP. 2003. Estimating the relative risk in cohort studies and clinical trials of common outcomes. Am J Epidemiol 157(10):940–943, PMID: 12746247, 10.1093/aje/kwg074. [PubMed] [CrossRef] [Google Scholar]
- Mieszkin S, Yala JF, Joubrel R, Gourmelon M. 2010. Phylogenetic analysis of *Bacteroidales* 16S rRNA gene sequences from human and animal effluents and assessment of ruminant faecal pollution by real-time PCR. J Appl Microbiol 108(3):974–984, PMID: 19735325, 10.1111/j.1365-2672.2009.04499.x. [PubMed] [CrossRef] [Google Scholar]
- Morrissey PJ, Johnston PM, Gill LW. 2015. The impact of on-site wastewater from high density cluster developments on groundwater quality. J Contam Hydrol 182:36–50, PMID: 26331764, 10.1016/j.jconhyd.2015.07.008. [PubMed] [CrossRef] [Google Scholar]
- Muldoon MA, Bradbury KR. 2010. Assessing seasonal variations in recharge and water quality in the silurian aquifer in areas with thicker soil cover. Wisconsin groundwater management practice monitoring project, DNR-198. http://digital.library.wisc.edu/1711.dl/EcoNatRes.MuldoonAssess [accessed 22 June 2019].

- Muldoon MA, Simo JA, Bradbury KR. 2001. Correlation of high-permeability zones with stratigraphy in a fractured-dolomite aquifer, Door County, Wisconsin. Hydrogeol J 9(6):570–583, 10.1007/s10040-001-0165-5. [CrossRef] [Google Scholar]
- Murphy HM, McGinnis S, Blunt R, Stokdyk J, Wu J, Cagle A, et al.. 2020. Septic systems and rainfall influence human fecal marker and indicator organism occurrence in private wells in southeastern Pennsylvania. Environ Sci Technol 54(6):3159–3168, PMID: 32073835, 10.1021/acs.est.9b05405. [PubMed] [CrossRef] [Google Scholar]
- Nennich TD, Harrison JH, VanWieringen LM, Meyer D, Heinrichs AJ, Weiss WP, et al.. 2005. Prediction of manure and nutrient excretion from dairy cattle. J Dairy Sci 88(10):3721–3733, PMID: 16162547, 10.3168/jds.S0022-0302(05)73058-7. [PubMed] [CrossRef] [Google Scholar]
- NGWA (National Groundwater Association). 2020. Groundwater Use in the United States of America. NGWA USA Groundwater Use Factsheet 01-13-2020. https://www.ngwa.org/docs/default-source/default-document-library/groundwater/usa-groundwater-use-fact-sheet.pdf?sfvrsn=5c7a0db8_4 [accessed 1July 2020].
- Nicosia LA, Rose JB, Stark L, Stewart MT. 2001. A field study of virus removal in septic tank drainfields. J Environ Qual 30(6):1933–1939, PMID: 11789999, 10.2134/jeq2001.1933. [PubMed] [CrossRef] [Google Scholar]
- NOAA (National Oceanic and Atmospheric Administration/National Centers for Environmental Information). n.d.. Climate at a Glance: Global Mapping. https://www.ncdc.noaa.gov/cag/ [accessed 18 March 2021].
- Nolan BT, Hitt KJ. 2006. Vulnerability of shallow groundwater and drinking-water wells to nitrate in the United States. Environ Sci Technol 40(24):7834–7840, PMID: 17256535, 10.1021/es060911u. [PubMed] [CrossRef] [Google Scholar]
- Nolan BT. 2001. Relating nitrogen sources and aquifer susceptibility to nitrate in shallow ground waters of the United States. Groundwater 39(2):290–299, 10.1111/j.1745-6584.2001.tb02311.x. [PubMed] [CrossRef] [Google Scholar]
- NRCS 313 (Natural Resources Conservation Service Conservation Practice Standard 313). Waste Storage Facility, Wisconsin Natural Resources Conservation Service, Madison, WI, January 2014.
- O'Dwyer J, Dowling A, Adley CC. 2014. Microbiological assessment of private groundwater-derived potable water supplies in the Mid-West Region of Ireland. J Water Health 12(2):310–317, PMID: 24937225, 10.2166/wh.2014.178. [PubMed] [CrossRef] [Google Scholar]
- O'Dwyer J, Hynds PD, Byrne KA, Ryan MP, Adley CC. 2018. Development of a hierarchical model for predicting microbiological contamination of private groundwater supplies in a geologically heterogeneous region. Environ Pollut 237:329–338, PMID: 29499576, 10.1016/j.envpol.2018.02.052. [PubMed] [CrossRef] [Google Scholar]
- Procopio NA, Atherholt TB, Goodrow SM, Lester LA. 2017. The likelihood of coliform bacteria in NJ domestic wells based on precipitation and other factors. Ground Water 55(5):722–735, PMID: 28369797, 10.1111/gwat.12518. [PubMed] [CrossRef] [Google Scholar]

- Rasmuson A, Erickson B, Borchardt M, Muldoon M, Johnson WP. 2020. Pathogen prevalence in fractured versus granular aquifers and the role of forward flow stagnation zones on pore-scale delivery to surfaces. Environ Sci Technol 54(1):137–145, PMID: 31770489, 10.1021/acs.est.9b03274. [PubMed] [CrossRef] [Google Scholar]
- Rayne TW, Bradbury KR, Krause JJ. 2019. Impacts of a rural subdivision on groundwater quality: results of long-term monitoring. Ground Water 57(2):279–291, PMID: 29603208, 10.1111/gwat.12666. [PubMed] [CrossRef] [Google Scholar]
- Reneau RB Jr. 1979. Changes in concentrations of selected chemical pollutants in wet, tile-drained soil systems as influenced by disposal of septic tank effluents. J Environ Qual 8(2):189–196, 10.2134/jeq1979.00472425000800020011x. [CrossRef] [Google Scholar]
- Shaver RH, Ault CH, Ausich WI, Droste JB, Horowitz AS, James WC, et al.. 1978. The Search for a Silurian Reef Model, Great Lakes Area: Indiana Department of Natural Resources Geological Survey Special Report 15. https://igws.indiana.edu/bookstore/details.cfm?Pub_Num=SR15 [accessed 29 June 2019].
- Sherrill MG. 1979. Contamination Potential in the Silurian Dolomite Aquifer, Eastern Wisconsin. USGS Water-Resources Investigations Open-File Report, 78–108. Reston, VA: USGS, 10.3133/wri78108 [accessed 1 October 2018]. [CrossRef] [Google Scholar]
- Sherrill MG. 1978. Geology and ground Water in Door County, Wisconsin, with Emphasis on Contamination Potential in the Silurian Dolomite. U.S. Geological Survey Water-Supply Paper 2047. Reston, VA: USGS. [Google Scholar]
- Stokdyk J, Spencer SK, Walsh J, de Lambert J, Firnstahl AD, Anderson A, et al.. 2019. *Cryptosporidium* incidence and surface water influence of groundwater supplying public water systems in Minnesota, USA. Environ Sci Technol 53(7):3391–3398, PMID: 30895775, 10.1021/acs.est.8b05446. [PubMed] [CrossRef] [Google Scholar]
- Stokdyk JP, Firnstahl AD, Walsh JF, Spencer SK, de Lambert JR, Anderson AC, et al.. 2020. Viral, bacterial, and protozoan pathogens and fecal markers in wells supplying groundwater to public water systems in Minnesota, USA. Water Res 178:115814, PMID: 32325219, 10.1016/j.watres.2020.115814. [PubMed] [CrossRef] [Google Scholar]
- Toetz D. 2006. Nitrate in ground and surface waters in the vicinity of a concentrated animal feeding operation. Arch Hydrobiol 166(1):67–77, 10.1127/0003-9136/2006/0166-0067. [CrossRef] [Google Scholar]
- U.S. EPA. (United States Environmental Protection Agency). 1977. The Report to Congress–Waste Disposal Practices and Their Effects on Ground Water. CgD-78-120: B-166506. Washington, DC: U.S. Environmental Protection Agency. [Google Scholar]
- U.S. EPA. 2020. National Primary Drinking Water Regulations. 40 CFR Part 141 https://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr141_main_02.tpl [accessed 16 April 2020].
- U.S. General Accounting Office. 1997. Information on the Quality of Water Found at Community Water Systems and Private Wells. United States GAO/RCED-97-123.. Washington, DC: U.S. Government Accounting Office. [Google Scholar]
- USDA NASS (U.S. Department of Agriculture National Agricultural Statistics Service). 2002. Census of Agriculture. http://agcensus.mannlib.cornell.edu/AgCensus/getVolumeOnePart.do?year=2002&part_id=1015&number=49&title=Wisconsin [accessed 2 November 2018].

- USDA NASS. 2017. Census of Agriculture. www.nass.usda.gov/AgCensus [accessed 8 December 2020].
- USGS (U.S. Geological Survey). 2016. U.S. Geological Survey Ground Water Atlas of the United States, https://pubs.usgs.gov/ha/ha730/ Page last modified 30-Nov-2016 [accessed 27 May 2020].
- USGS (U.S. Geological Survey). 2020. USGS Water Data for the Nation: U.S. Geological Survey National Water Information System Database. 10.5066/F7P55KJN [accessed 15 September 2018]. [CrossRef]
- Warner KL, Arnold TL. 2010. Relations that Affect the Probability and Prediction of Nitrate Concentration in Private Wells in the Glacial Aquifer System in the United States. U.S. Geological Survey Scientific Investigations Report 2010–5100, https://pubs.usgs.gov/sir/2010/5100/ [accessed 1 April 2020].
- Wisconsin Department of Health Services. n.d. Drinking Water: Manure in Private Wells. https://www.dhs.wisconsin.gov/water/manure.htm [accessed 10 May 2021].
- Wisconsin Department of Natural Resources. 2018. Deer Abundance and Densities in Wisconsin Deer Management Units. https://dnr.wi.gov/topic/hunt/maps.html/falldeerperdr.pdf [accessed 12 May 2021].
- Won G, Gill A, LeJeune JT. 2013. Microbial quality and bacteria pathogens in private wells used for drinking water in northeastern Ohio. J Water Health 11(3):555–562, PMID: 23981882, 10.2166/wh.2013.247. [PubMed] [CrossRef] [Google Scholar]
- Yates MV. 1985. Septic tank density and ground-water contamination. Groundwater 23(5):586–591, 10.1111/j.1745-6584.1985.tb01506.x. [CrossRef] [Google Scholar]
- Yessis J, McColl RS, Seliske P. 1996. Methodological aspects of monitoring for microbial contamination of drinking water from private wells: the water quality program of the region of waterloo. Can Water Resour J 21(3):221–228, 10.4296/cwrj2103221. [CrossRef] [Google Scholar]
- Zhang Y, Kelly W, Panno SV, Liu W-T. 2014. Tracing fecal pollution sources in karst groundwater by Bacteriodales genetic biomarkers, bacterial indicators, and environmental variables. Sci Total Environ 490:1082–1090, PMID: 24922611, 10.1016/j.scitotenv.2014.05.086. [PubMed] [CrossRef] [Google Scholar]

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Confronting our Agricultural Nonpoint Source Control Policy Problem

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Research Impact Statement: Reform of agricultural nonpoint source pollution policies is necessary to make progress in achieving water quality goals.

Abstract

Federal and state agricultural and environmental agencies have spent enormous sums since the 1990s to reduce nonpoint source (NPS) water pollution from agriculture. Yet, water quality problems are pervasive, and agriculture is a major cause. The lack of progress is often attributed to insufficient funding for pollution control practices relative to the scale of the problem. However, we attribute the lack of progress to shortcomings in agricultural NPS pollution control policy. We illustrate our argument after considering nearly four decades of federal, state, and local efforts to reduce agricultural NPS pollution to the Chesapeake Bay. Additional funding for current programs, absent fundamental program reform, is unlikely to produce reductions from agriculture needed to achieve desired water quality outcomes.

INTRODUCTION

The 1972 Federal Clean Water Act ushered in a new era of state and federal regulation, supported by enormous public and private spending directed at restoring, in the words of the Act "the physical, biological and chemical integrity of the nation's waters." Now, 50 years later,

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States (U.S.) rivers and streams are in poor biological condition, 25% are in fair condition, and only 28% are in good condition (USEPA 2017). Agricultural nonpoint source (NPS) pollution is often a principal cause of water quality impairments. The 2017 USEPA National Water Quality Inventory lists agricultural NPS pollution as the leading cause of water quality impairments in rivers and streams, the third-largest cause for lakes, the second largest for wetlands, and a major contributor to contamination of estuaries and groundwater (USEPA 2017). Agriculture is the largest source of nutrients contributing to the eutrophication of the Gulf of Mexico, the Chesapeake Bay, and the Great Lakes (Goolsby et al. 1999; Howarth 2008).

Policies and programs to reduce agricultural NPS pollution rely primarily on agricultural producers voluntarily implementing pollution control practices, encouraged by technical and financial assistance from federal and state programs. These programs have achieved only limited successes in reducing agricultural NPS loads (Sprague et al. 2011; Shortle et al. 2012; Ator et al. 2020). This widely acknowledged gap between NPS reductions achieved and the amount needed to meet water quality goals often is attributed to insufficient funding for existing technical and financial assistance programs (DeGood 2020).

We argue that increased funding is not enough. The limited success of NPS programs is embedded in the structure of the programs, and how these programs guide and direct choices; choices made by agricultural producers, technical assistance providers who advise producers, and water quality program managers. We illustrate our argument with the Chesapeake Bay Program (CBP) and conclude that fundamental policy reforms will be needed for achieving substantial reductions in agricultural NPS loads.

EXISTING APPROACHES TO ADDRESS AGRICULTURAL NPS POLLUTION

Programs to encourage agricultural NPS load reductions can take a variety of forms (Segerson 2013; OECD 2017; Shortle 2017; Pannell and Classen 2020; Shortle et al. 2021). With some exceptions, [1] conventional agricultural NPS policy in the U.S. rests on the premise that agricultural producers voluntarily decide how to manage their operations and whether or how to reduce to NPS pollution. To encourage producers to implement NPS pollution control practices, information programs inform them of the best management practices (BMPs) intended to improve water quality, and points them to government funding and sometimes private funding available for implementing the practices. Because BMPs can be costly, and in many cases reduce producers' net income, programs typically encourage implementation by sharing implementation costs (Shortle et al. 2021). Federal and state technical assistance

Environmental Quality Incentives Program and there are state programs that also cost-share BMP implementation. Cost sharing is typically for a portion of the cost of BMP installation and in limited circumstances some annual operation and maintenance costs (Ribaudo and Shortle **2019**; Ribaudo **2001**).

The Limited Success of NPS Programs: Illustration from the Chesapeake Bay

The CBP illustrates the current agricultural NPS pollution policy conundrum. Since the 1980s, nitrogen and phosphorus were identified as the primary pollutants limiting attainment of desired Bay water quality outcomes and agricultural NPS was identified early on as a major contributor of nutrient loads. In 1990, nutrient reduction targets for meeting water quality goals were set, these targets were revised in the 2000s, and brought under federally mandated nutrient limits in 2010.[2] Through all these years, policymakers understood that without agricultural NPS load reductions nutrient reduction targets and desired water quality outcomes would be unattainable.

For over three decades, federal and state governments have been committed to funding the types of conventional technical and financial cost share programs described above, hoping to encourage BMP implementation and meet agricultural NPS reduction targets. In fact, the CBP has been successful in increasing federal and state funding to support these programs, including securing a special federal appropriation of $256 million for the NRCS Chesapeake Bay Watershed Initiative (Natural Resource Conservation Service **2021**). Recently, there have been renewed efforts to increase NPS program funding, arguing that more funding for these conventional programs will finally secure Bay water quality goals (Northey **2021**).

Also of note is that the CBP has invested substantial resources to build a state-of-the-art model to evaluate and inform water quality managers decision-making (Hood et al. **2021**). With respect to NPS pollution, the CBP watershed model is the basis for prioritizing BMP implementation and for crediting progress toward meeting NPS load reduction targets. As BMP implementation is reported, the CBP model credits NPS reductions by multiplying model-based estimates of nutrient runoff (pounds per acre) by an assigned BMP removal efficiency and the number of acres treated by the BMP. The model calculates nutrient runoff as an average over a relatively large area (~20,000 acres) for different land use types (crop, hay, etc.). The BMP pollutant removal efficiencies are generally a single number (e.g., 30% N removal for a riparian buffer) applied across the watershed. In the CBP model, these removal efficiencies are usually generated by expert judgment from a group of subject matter authorities (Stephenson et al. **2018**).

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the CBP model estimates, all pollution controls (implemented since 1985) have reduced nitrogen (N) loads by nearly 100 million pounds and phosphorus loads 14 million pounds per year. Over three-quarters of N reductions have come from wastewater treatment plants and from reductions in atmospheric deposition (CBP **2021**). Point sources have reduced P loadings about 80% since 1985, which represents about 70% of the estimated P reductions achieved since 1985. The CBP identifies a need for another 50 million pounds of N reductions by 2025 to meet water quality standards, noting that these reductions must come primarily from agricultural NPS.

Meanwhile, statistical analyses of monitoring data suggest that the CBP model may be overestimating the nutrient reductions achieved by the cumulative impact of agricultural BMPs. Ator et al. (**2019**) found little evidence that agricultural NPS loads declined between 1992 and 2012. Another statistical analysis of monitoring data found that while P loads are declining in some regions of the Bay watershed, those improvements were offset by increases in agricultural P sources in other areas (Fanelli et al. **2019**; Kleinman et al. **2019**; Ator et al. **2020**). While the limited response in observed pollutant reductions could be due the time that is required for NPS reductions to produce ambient water quality outcomes, the so-called "lag times," evidence suggests that another cause is at play: our agricultural NPS programs are not as effective as expected. The CBP is not alone in confronting this NPS challenge. Reductions from BMP implementation predicted by models routinely over estimate measured reductions (Osmond et al. **2012**; Lintern et al. **2020**). The challenge of measuring reductions in NPS loads in response to BMP adoption is one of the most fundamental and common challenges confronting large-scale water quality programs (Osmond et al. **2012**; Boesch **2019**; Lintern et al. **2020**).

CHALLENGES WITH AGRICULTURAL NPS INCENTIVES

The continued failure to meet agricultural NPS reduction goals is not simply due to a lack of funding or a lack of effort. To a significant degree, the problem lies with the incentives inherent in conventional program design. These incentives influence choices made by producers and technical service providers that often limit the implementation of cost-effective BMPs in the locations that produce the greatest NPS loads. The following illustrations of NPS incentive challenges are drawn from the CBP, but these challenges are common across most large-scale water quality programs.

Agricultural Producers Face Limited Financial Incentives to Address NPS Pollution

sharing for practices is unlikely to result in producers and technical service providers seeking to identify water quality problem areas, and then implementing the most effective BMPs. Consider a BMP that produces little agronomic benefit to a producer's operation, promises significant low-cost nutrient reductions but requires substantial upfront capital investment and ongoing operation and maintenance expenditures. BMPs such as stream buffers, denitrifying bioreactors, stream fencing, and manure storage/treatment can generate substantial nutrient reductions at relatively low costs (Price et al. **2021**; Stephenson et al. **2021**). From a strictly financial perspective, agricultural producers will not install and operate a technology with few on-farm benefits and that costs them money (even if cost-shared). The structure of our cost-share programs does not directly pay producers for what is needed: pollutant reductions.

Program Managers Have Limited Ability and Incentives to Target NPS Hotspots

Many studies demonstrate that relatively small portions of the agricultural landscape produce most of the agricultural load. The way NPS loads are counted and reductions are credited is a disincentive for program managers to identify and treat these high loss areas. Suppose that 80% of nutrient losses on a 250-acre farm is coming from only 25 acres. The CBP crediting system and technical assistance programs provide few incentives for technical service providers and producers to focus on those 25 acres. If the 250 acres is in the same land use (say corn), CBP crediting gives the same reduction credit whether the BMP is placed on any of the 225 low loss acres, or the 25 high loss acres. Furthermore, conventional programs typically require that agricultural producers develop conservation plans for the entire farm operation to be eligible for program benefits. A producer willing to aggressively treat only the 25 high loss acres might not want or need a whole farm plan and, under current program guidelines, the producer would be ineligible for financial assistance without a plan that covers the entire farm.

Technical Service Providers Are Not Rewarded for Loads Reduced

Technical service providers serve as the conduit between the entity funding BMP implementation and producers, providing engineering, installation, and maintenance assistance to producers, and facilitating financial assistance. This structure, the technical service provider as a liaison, provides no direct incentive for a service provider to prioritize reductions from difficult and often high loading areas. Suppose a service provider can work with two neighboring producers. One producer has low nutrient losses and willingly adopts conservation practices. The other producer has high nutrient losses and is reluctant to participate in government programs. Such diversity of producer behavior is real and can be substantial (Ribaudo **2015**). One recent study in a portion of the Chesapeake Bay watershed

as measured by contracts processed. When programs, as in the CBP, credit nutrient reductions by BMPs installed, the same NPS reduction credit applies to both producers. Spending time with a reluctant, but high nutrient loss producer is a poor investment of the service providers time when the measure of success is participants enrolled and BMPs installed.

Technical Service Providers and Water Quality Managers cannot "Go Big"

Cost-share programs typically cap the amount of assistance that can be received by an individual agricultural producer. While distributing funding over more participants helps engage more producers in the conservation program, such funding limitations restrict what water quality managers and technical service providers can do to address larger scale NPS issues. For example, at a regional level, nutrient losses tend to be highest in areas with nutrient mass imbalances, where nutrient imports, in the form of fertilizers and animal feed, exceed the ability of the local cropping system to utilize the nutrients. The use of conventional BMPs, most of which do not address excessive nutrient mass imbalances, offers limited potential to reduce NPS loads. Regional animal waste management systems (manure conversion, waste to energy projects, transport) offer opportunities to address regional nutrient mass imbalances, but given the large upfront and ongoing maintenance and operation cost, and lack of on farm benefits associated with such systems limit their uptake.

Barriers to Innovation Exist in Current Program Structure

Incentives for innovation in NPS technologies and management are weak. Under conventional cost-share programs, entrepreneurs face limited profit opportunities to develop innovative NPS control practices because conventional agricultural cost-share programs create no buyers for such products. Producers have no incentive to pay for these technologies (unless there are on-farm benefits) and water quality managers have no means to pay for them given the requirement that costs must be shared.

Water quality managers, agricultural producers, and technical service providers have few incentives to invest in actions that produce more certain load reductions. Consider a producer who wants to implement a BMP where pollutant removal can be more readily measured or observed, for example in situ nutrient extraction (measurement of aquatic biomass harvest), direct treatment of runoff or water (influent and effluent from bioreactors), or manure conversion technologies, among others (Rose et al. **2015**; Stephenson and Shabman **2017**; Stephenson et al. **2018**). Consider another example of a producer who is willing to demonstrate intermediate outcomes from conservation activities, such as changes in soil nutrient levels or

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POLICY REFORM IS NEEDED TO MAKE PROGRESS IN ADDRESSING NPS POLLUTION

Conventional NPS program designs create limited incentives for program managers, technical service providers, or producers to care about whether BMPs provide the expected NPS load reductions. As a result, it is unlikely that significant progress will be made on NPS load reduction without fundamental policy and programmatic change (Shortle et al. 2012, 2021; Ribaudo and Shortle 2019). The most fundamental change would replace the current program premise that producers decide both whether and how to control their pollution, with a new premise that a producer or group of producers is obligated to limit their pollution but has discretion and flexibility in deciding how that limit is met.

Whatever the program premise, first, reform must shift the focus from practices to outcomes. Incentive systems that reward quantifiable nutrient reductions or observable water quality outcomes, such as “pay-for-performance” (“pay-for-success”) systems, may better motivate agricultural producers to seek out and implement practices that result in the largest NPS reductions. Payment for performance programs can be designed in a variety of ways, but all should require that technical service providers also be able and willing to evaluate all NPS reduction options and develop plans for reducing pollutants.[3]

Second, the focus on outcomes through a “pay-for-performance” (“pay-for-success”) system will require establishing acceptable practices for quantifying either pollutant reduction or changes in water quality conditions. Outcomes can be documented by direct measurement, by indirect, but observable, indicators of pollutant loss potential (e.g. soil nutrient levels), or by using more sophisticated field-scale models to predict site-specific reductions from implemented BMPs. Measured outcomes can be used for determining when the producers would be paid under the pay for performance system or for determining if the limits are being met. Measured outcomes allow technical service providers to be rewarded for working with high loss producers and for targeting high loss areas, and measured outcomes mean water quality managers' report progress as quantified load reductions, or improvement in ambient water quality conditions.

A shift toward outcome-based program design should involve experimentation with innovative combinations of incentive systems and outcome-based measurement (Shabman et al. 2011). As one example, producer-led watershed cooperatives could be created with the assistance of technical service providers to achieve measurable water quality. Such organizations would be incentivized to achieve specific quantifiable, independently verified, water quality outcomes, for instance, at the outlet of small watersheds by offering reward or bonus payments made to the

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producers to identify and direct cost-share funds received from the NPS programs to the investments that yield the most effective, more certain pollutant reductions (Maille et al. 2009).

Third, as noted above, reform may require shifting away from the premise of conventional programs that producers decide based on financial or personal adoption benefits whether to limit NPS pollution, to program designs that obligate producers to limit their NPS pollution. Such mandatory limits must be structured to recognize the diversity in agriculture across scales and across production systems. Consider large regional nutrient mass imbalances from high concentrations of intensive livestock operations. In vertically integrated production systems, such as poultry and swine, manure ownership and management requirements could be assigned to the integrator, rather than individual producers working under contract with the integrator. The integrator would be responsible for meeting manure disposal requirements but would be allowed the flexibility and technical expertise to find cost-effective solutions for the treatment, transport, and use of the manure.

Reform may mean that some agricultural producers accept more responsibilities for delivering pollutant reductions. Reform can mean more funding to existing programs given that funding requests often exceed available program funds, but new funding must be dedicated to paying for outcomes. Reform must mean that water quality managers rely more on measured outcomes, rather than tallying BMPs installed when determining progress. Reform must mean that agencies invest in training technical service providers in new skills needed to execute new program designs and embrace changes to familiar program and reward systems.

The challenges to making this transition are many and transition will not come easily. Reform will meet resistance. Acknowledging the need for change is the first step, and that will require accepting that we cannot simply buy our way out of the problem by spending more money on conventional, voluntary programs.

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AUTHOR CONTRIBUTIONS

Kurt Stephenson: Conceptualization; writing – original draft. Leonard Shabman: Conceptualization; writing – original draft. James Shortle: Conceptualization; writing – review and editing. Zachary Easton: Conceptualization; writing – original draft.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

LITERATURE CITED

Ator, S.W., J.D. Blomquist, J.S. Webber, and J.G. Chanat. 2020. "Factors Driving Nutrient Trends in Streams of the Chesapeake Bay Watershed." *Journal of Environmental Quality*. https://doi.org/10.1002/jeq2.20101.

PubMed | Web of Science® | Google Scholar

Ator, S.W., A.M. Garcia, G.E. Schwarz, J.D. Blomquist, and A.J. Sekellick. 2019. "Toward Explaining Nitrogen and Phosphorus Trends in Chesapeake Bay Tributaries, 1992–2012." *Journal of the American Water Resources Association* **55** (5): 1149–68.

CAS | Web of Science® | Google Scholar

Boesch, D. 2019. "Barriers and Bridges in Abating Coastal Eutrophication." *Frontiers in Marine Science* **6**. https://doi.org/10.3389/fmars.2019.00123.

Web of Science® | Google Scholar

CBP (Chesapeake Bay Program). 2021. " Chesapeake Progress: Modeled Nitrogen and Phosphorus Loads to the Chesapeake Bay." https://www.chesapeakeprogress.com/clean-water/watershed-implementation-plans.

Google Scholar

DeGood, K. 2020. *A Call to Action on Combating Nonpoint Source and Stormwater Pollution*. Center for American Progress. https://www.americanprogress.org/issues/economy/reports/2020/10/27/492149/call-action-combating-nonpoint-source-stormwater-pollution/
.

Google Scholar

Back

Fanelli, R.M., J.D. Blomquist, and R.M. Hirsch. 2019. "Point Sources and Agricultural Practices Control Spatial–Temporal Patterns of Orthophosphate in Tributaries to Chesapeake Bay." *Science of the Total Environment* **652**: 422–33.

PubMed | Web of Science® | Google Scholar

Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.R. Hooper, D.R. Keeney, and G.J. Stensland. 1999. " Flux and Sources of Nutrients in the Mississippi Atchafalaya River Basin Topic 3 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico: Silver Spring, MD, NOAA Coastal Ocean Office, NOAA Coastal Ocean Program Decision Analysis Series No. 17." 130 pp.

Google Scholar

Hood, R.R., G.W. Shenk, R.L. Dixon, S.M.C. Smith, W.P. Ball, J.O. Bash, R. Batiuk, et al. 2021. "The Chesapeake Bay Program Modeling System: Overview and Recommendations for Future Development." *Ecological Modeling* **456**: 109635.

Web of Science® | Google Scholar

Howarth, R.W. 2008. "Coastal Nitrogen Pollution: A Review of Sources and Trends Globally and Regionally." *Harmful Algae* **8** (1): 14–20.

CAS | Web of Science® | Google Scholar

Keiser, D.A., and J.S. Shapiro. 2019. "Consequences of the Clean Water Act and the Demand for Water Quality." *Quarterly Journal of Economics* **134** (1): 349–96.

Web of Science® | Google Scholar

Kleinman, P., R. Fanelli, B. Hirsch, A.R. Buda, Z.M. Easton, L. Wainger, C. Brosch, et al. 2019. "Phosphorus and the Chesapeake Bay — Lingering Issues and Emerging Concerns for Agriculture." *Journal of Environmental Quality* **48**: 1191–203.

CAS | PubMed | Web of Science® | Google Scholar

Kling, C.L. 2013. "State Level Efforts to Regulate Agricultural Nonpoint Sources of Water Quality Impairment." *Choices* **28** (3): 1–4.

Google Scholar

MCEA Ex. 9

Back

Science & Technology. https://doi.org/10.1021/acs.est.9b07511.

PubMed | Web of Science® | Google Scholar

Maille, P., A.R. Collins, and N. Gillies. 2009. "Performance-Based Payments for Water Quality: Experiences from a Field Experiment." *Journal of Soil and Water Conservation* **64** (3): 85A–87A.

Web of Science® | Google Scholar

Natural Resource Conservation Service. 2021. " Chesapeake Bay Watershed Initiative." https://www.nrcs.usda.gov/Internet/NRCS_RCA/reports/fb08_cp_cbwi.html https://www.nrcs.usda.gov/Internet/NRCS_RCA/reports/cp_nat.html.

Google Scholar

Northey, H. 2021. " Chesapeake Bay Farmers Facing Cleanup Deadline Seek USDA Boost." *E&E News*, September 20.

Google Scholar

OECD. 2017. *Diffuse Pollution, Degraded Waters: Emerging Policy Solutions*. Paris: OECD Studies on Water, OECD Publishing. https://doi.org/10.1787/9789264269064-en.

Google Scholar

Osmond, D., D. Meals, D. Hoag, M. Arabi, A. Luloff, G. Jennings, M. McFarland, J. Spooner, A. Sharpley, and D. Line. 2012. "Improving Conservation Practices Programming to Protect Water Quality in Agricultural Watersheds: Lessons Learned from the National Institute of Food and Agriculture–Conservation Effects Assessment Project." *Journal of Soil and Water Conservation* **67** (5): 122A–27A.

Web of Science® | Google Scholar

Pannell, D.J., and R. Classen. 2020. "The Roles of Adoption and Behavior Change in Agricultural Policy." *Applied Economic Perspectives and Policy* **42** (1): 31–41.

Web of Science® | Google Scholar

Back

of Environmental Quality. https://doi.org/10.2134/jeq2008.0...

Web of Science® Google Scholar

Price, E., T. H. Fleming, and L. Wainger. 2021. " Cost Analysis of Stormwater and Agricultural Practices for Reducing Nitrogen and Phosphorus Runoff in Maryland." Maryland Center for Environmental Science, Report number: TS-772-21. https://doi.org/10.13140/RG.2.2.28896.74246/1.

Google Scholar

Ribaudo, M. 2001. " Non-Point Source Pollution Control Policy in the USA." In *Environmental Policies for Agricultural Pollution Control*, edited by J.S. Shortle and D. Abler, 123–50. New York: CABI Publishing.

Google Scholar

Ribaudo, M. 2015. "The Limits to Voluntary Conservation Programs." *Choices* **30** (2): 1–5.

Google Scholar

Ribaudo, M., and J. Shortle. 2019. "Reflections on 40 Years of Applied Economics Research on Agriculture and Water Quality." *Agricultural and Resource Economics Review* **48** (3): 519–30.

Web of Science® Google Scholar

Rose, J., S. Bricker, S. Deonarine, J.G. Ferreira, T. Getchis, J. Grant, J.K. Kim, et al. 2015. *Nutrient Bioextraction*. New York: Encyclopedia of Sustainability Science and Technology, Springer.

Google Scholar

Segerson, K. 2013. "When is Reliance on Voluntary Approaches in Agriculture Likely to Be Effective?" *Applied Economic Perspectives and Policy* **35** (4): 565–92.

Web of Science® Google Scholar

Shabman, L., B. Rose, and K. Stephenson. 2011. "Environmental Services Programs for the Chesapeake Bay." *Choices* **26** (3).

Google Scholar

Back

Web of Science® Google Scholar

Shortle, J.S., M. Ollikainen, and A. Iho. 2021. *Water Quality and Agriculture: Economics and Policy for Agricultural Nonpoint Source Water Pollution*. Cham: Springer Nature.

Google Scholar

Shortle, J.S., M. Ribaudo, R.D. Horan, and D. Blandford. 2012. "Reforming Agricultural Nonpoint Pollution Policy in an Increasingly Budget-Constrained Environment." *Environmental Science & Technology* **46** (3): 1316–25.

CAS PubMed Web of Science® Google Scholar

Sprague, L.A., R.M. Hirsch, and B.T. Aulenbach. 2011. "Nitrate in the Mississippi River and its Tributaries, 1980 to 2008: Are we Making Progress?" *Environmental Science and Technology* **45** (17): 7209–16.

CAS PubMed Web of Science® Google Scholar

Stephenson, K., W. Ferris, E. Bock, and Z. Easton. 2021. "Treatment of Legacy Nitrogen as a Compliance Option to Meet Chesapeake Bay TMDL Requirements." *Environmental Science and Technology* **55** (20): 13593–601.

CAS PubMed Web of Science® Google Scholar

Stephenson, K., C. Hershner, B. Benham, Z.M. Easton, J. Hanson, S. Julius, and E. Hinrichs. 2018. " Consideration of BMP Performance Uncertainty in Chesapeake bay Program Implementation." STAC Publication Number 18-003, Edgewater, MD, 33 pp.

Google Scholar

Stephenson, K., and L. Shabman. 2017. "Nutrient Assimilation Services for Water Quality Credit Trading Programs: A Comparative Analysis with Nonpoint Source Credits." *Coastal Management* **45** (1): 24–43.

Web of Science® Google Scholar

USEPA (U.S. Environmental Protection Agency). 2017. " National Water Quality Inventory: Report to Congress." EPA 841-R-16-011.

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BEFORE THE
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Petition for Emergency Action Pursuant to the Safe Drinking Water Act, 42 U.S.C. § 300i, to Protect the Citizens of the Karst Region of Minnesota from Imminent and Substantial Endangerment to Public Health Caused By Nitrate Contamination of Underground Sources of Drinking Water.

EPA Docket No. _____
April 24, 2023

Submitted on Behalf of Petitioners
Minnesota Center for Environmental Advocacy,
Environmental Working Group,
Minnesota Well Owners Organization,
Center for Food Safety,
Clean Up the River Environment,
Food & Water Watch,
Friends of the Mississippi River,
Izaak Walton League Minnesota Division
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I. Introduction

Petitioners respectfully petition the U.S. Environmental Protection Agency (EPA) to exercise its emergency powers established in Section 1431 of the Safe Drinking Water Act (SDWA), 42 U.S.C. § 300i, to address groundwater contamination that presents an imminent and substantial endangerment to the health of residents in southeastern Minnesota. Like many other parts of the Nation plagued by pollution from industrial agriculture, the residents in southeastern Minnesota are suffering from drinking water contamination. As detailed in this Petition, this region has an extensive and well-documented history of nitrate contamination in its underground sources of drinking water, which continues to put the health of residents at risk. The EPA must act now to address this too-long ignored health crisis and ensure clean drinking water for Minnesotans.

Southeastern Minnesota is particularly vulnerable to groundwater pollution due to its karst geography. According to the Minnesota Pollution Control Agency (MPCA):

> Southeastern Minnesota is characterized by an unusual type of geography called karst. It features rolling hills, hollows, caves, sinkholes, and dramatic bluffs and valleys. In karst landscapes, the distinction between groundwater and surface water is blurry. . . . [C]ontaminated surface water can easily become groundwater pollution, and pose a health risk to those using it for drinking.[1]

The "karst region" of southeastern Minnesota is depicted in Figure 1 below.[2]

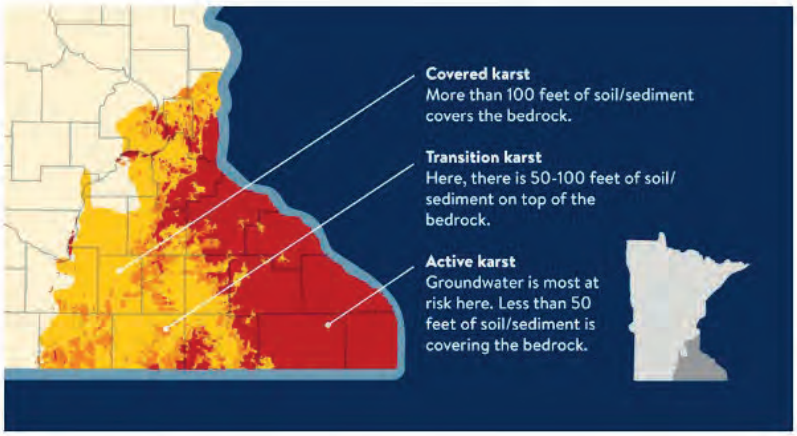

Figure 1: Minnesota's Karst Region
Based on a map created by E. Calvin Alexander, Jr., Yongli Gao, and Jeff Green

[1] *Protecting water in karst regions*, MINN. POLLUTION CONTROL AGENCY, https://www.pca.state.mn.us/air-water-land-climate/protecting-water-in-karst-regions (last visited Apr. 13, 2023).
[2] *Id.*

The karst region[3] is a predominantly rural area of the State where many people rely on private wells, rather than public water supplies, for their drinking water.[4] All drinking water in this region—public and private—comes from groundwater aquifers. The population of the eight counties comprising this region is 380,513.[5] About 300,000 people in this area rely on community water systems while the remaining 80,000 use wells.[6] It is important to note that the populations more likely to be affected by nitrate contamination are people living in small towns, who are dependent on community water systems and private wells and who are also more likely to be of lower income.[7] The karst region of Minnesota is a community overburdened by pollution. The Administrator has called on EPA to strengthen the enforcement of cornerstone environmental statutes in these communities.[8]

This Petition is based on data that have been compiled by the Minnesota Department of Agriculture (MDA), the Minnesota Department of Health (MDH), the Minnesota Pollution Control Agency (MPCA), the Minnesota Department of Natural Resources (MDNR), Petitioner Minnesota Well Owners Organization, and Petitioner Environmental Working Group. The data demonstrate that nitrate concentrations in

[3] The karst region does not follow county lines, but for purposes of data analysis, this Petition uses the eight counties of Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Wabasha, and Winona as a substitute. These counties are all fully within what is considered the karst region.

[4] For information on community water systems in Minnesota that rely on groundwater *see Interactive Map: Community Water Systems*, MINN. DEP'T OF HEALTH, https://mndatamaps.web.health.state.mn.us/interactive/cwss.html (last visited Apr. 13, 2023). For further data on private wells in Minnesota, *see Minnesota Well Index*, MINN. DEP'T OF HEALTH, https://mnwellindex.web.health.state.mn.us/# (last visited Apr. 13, 2023).

[5] *See Minnesota Demographics*, CUBIT PLANNING, https://www.minnesota-demographics.com/counties_by_population (last visited Apr. 13, 2023).

[6] The population served by each community water system in the eight-county region system can be determined by clicking on MDH's water system map, *see Interactive Map: Community Water Systems*, MINN. DEP'T OF HEALTH, https://mndatamaps.web.health.state.mn.us/interactive/cwss.html (last visited Apr. 13, 2023).

[7] *Tap Water for 500,000 Minnesotans Contaminated With Elevated Levels of Nitrate*, ENV'T WORKING GRP. (Jan. 14, 2020), https://www.ewg.org/interactive-maps/2020_nitrate_in_minnesota_drinking_water_from_groundwater_sources/ [hereinafter EWG Tap Water Report]; *see also Interactive Maps: Poverty in Minnesota counties*, MINN. DEP'T OF HEALTH, https://mndatamaps.web.health.state.mn.us/interactive/poverty.html (last visited Apr. 14, 2023).

[8] Memorandum from Lawrence E. Starfield, Acting Assistant Adm'r of U.S. EPA, on Strengthening Enf't in Communities with Env't Just. Concerns to Office of Enf't and Compliance Assurance (Apr. 30, 2021), https://www.epa.gov/sites/default/files/2021-04/documents/strengtheningenforcementincommunitieswithejconcerns.pdf.

public water systems and underground sources of drinking water routinely exceed federal and state drinking water standards, putting the health of area residents at serious risk.

As explained in this Petition, the well-documented nitrate contamination of drinking water in the karst region necessitates prompt and decisive EPA emergency action under the SDWA. Elevated levels of nitrate in drinking water are known to increase the risk of a wide range of very serious health problems, including birth defects, blue-baby syndrome, various cancers, thyroid disease, and other maladies. This contamination poses an imminent and substantial threat to human health, and the problem is not getting any better.

Despite Minnesota applying for and being granted "primacy" under the SDWA, state and local officials have failed to do what is needed to correct the pervasive threat to human health. The data confirm that past voluntary measures employed by the State have been unsuccessful at reducing nitrate concentrations in crucial drinking water sources to below federal and state standards. EPA is fully empowered under the SDWA to take emergency action to protect human health in the karst region of Minnesota given present circumstances.

Because of its landscape features, groundwater quality in the karst region is largely driven by land use practices, and land use in this region is dominated by industrial row crop agriculture and feedlots. Petitioners request that EPA act to protect human health and effectuate the goals of the SDWA in the karst region of Minnesota through an investigation focused on the agricultural land uses that are most likely driving the contamination of drinking water resources. Specifically, Petitioners request that EPA issue orders, as necessary, to protect the health of people who use the drinking water, including, at a minimum, orders that require responsible contaminators to provide a free and safe alternative source of drinking water for impacted communities; orders that prohibit concentrated animal feeding operations (CAFOs) from expanding or constructing new operations until nitrate concentrations fall below unsafe levels; public notice of potential contamination events, such as manure land applications; an investigation to determine the specific entities and land use practices causing the contamination; a survey to identify public water systems, private supply wells, or ground water monitoring wells near potentially contaminated areas; monitoring of contaminants; control of the source of contaminants; and cleanup of contaminated soils endangering underground sources of drinking water. Petitioners further request that EPA seek injunctions through civil actions, as needed, to return the area's underground aquifers to a safe and drinkable condition.

II. Interests of Petitioners

Minnesota Center for Environmental Advocacy (MCEA) is a nonprofit environmental advocacy organization with offices in St. Paul and Duluth, Minnesota.

Since 1974, MCEA has defended Minnesota's natural resources, water, air and climate, and the health and welfare of Minnesotans. MCEA is driven by the principle that everyone has a right to a clean and healthy environment, and that decisions must be based on fact, science, and the law.

Environmental Working Group (EWG) is a nonprofit, nonpartisan organization that empowers people to live healthier lives in a healthier environment. For 30 years, EWG has harnessed its signature blend of research, advocacy, and unique educational tools to drive consumer choice and inspire civic action.

Minnesota Well Owners Organization (MNWOO) is a statewide nonprofit with a mission to help ensure safe drinking for Minnesota private well users who depend on groundwater for their private water systems and wells. MNWOO works with well users and partners with other non-governmental organizations, and local and state government units to build individual and community values for the protection, enhancement, and restoration of Minnesota groundwater through outreach, education, and advocacy. MNWOO's goal is to conduct free water quality screening clinics and provide professional help to connect and activate the community of well owners, land managers, water managers, and policy makers who steward Minnesota's groundwater. MNWOO seeks to remove the threats to safe drinking water on a foundation of accurate, up-to-date, and practical information that addresses the personal, community, economic, technical, legal, and policy barriers faced by private well owners seeking safe drinking water. MNWOO works to motivate private well owners and decision makers to take the individual and collective steps necessary to assure safe drinking water from all private wells for future generations.

Center for Food Safety (CFS) is a nonprofit environmental advocacy organization that aims to empower people and protect the environment from the harmful effects of industrial agriculture, including groundwater contamination from the concentration of industrial animal operations and their waste. CFS represents over a million members and supporters across the country, including over 9,000 members in Minnesota. CFS uses education, science-based advocacy, and litigation to address the negative environmental and public health effects of industrial agriculture.

Clean Up the River Environment (CURE) is a rural Minnesota nonprofit organization headquartered in the Minnesota River valley. CURE's mission is to protect and restore resilient rural landscapes and build vibrant, just, and equitable rural communities. CURE embodies three core practices: (1) awakening people's bonds with the natural world around them; (2) inclusively, strategically, and dialectically exploring issues and actions; and (3) systematically building communities of change at critical intersections of ecological and social wellbeing. Among CURE's values and guiding principles are that the capacity of communities to flourish is directly connected to the condition of the landscapes that embrace them; a moral responsibility to future generations to be good stewards of the ecosystems in which they live; and the human use

of natural resources can be regenerative and a sustainable force. CURE, with its rural roots, is aware that the Dakota and Ojibwe Nations and other rural communities, already culturally, socially, and politically marginalized, are often most impacted by climate change, clean water scarcity, and environmental degradation. While local control is important to CURE, it is equally important that there is accountability to all Minnesotans and to future generations. Because rural communities are frontline communities when it comes to pollution from industrial agriculture, CURE requests that EPA exercise its broad emergency powers, per the SDWA, to address groundwater contamination in southeastern Minnesota. Too often industrial agriculture is given a pass on protections for our land and water, putting profits over people. CURE asks EPA to step in and be a voice for those communities impacted by groundwater contamination.

Food & Water Watch (FWW) is a national, nonprofit membership organization that mobilizes regular people to build political power to move bold and uncompromised solutions to the most pressing food, water, and climate problems of our time. FWW uses grassroots organizing, media outreach, public education, research, policy analysis, and litigation to protect people's health, communities, and democracy from the growing destructive power of the most powerful economic interests. FWW has long advocated for stronger regulation of factory farm pollution and industrial agribusiness to protect farmers, rural communities, and the environment.

Friends of the Mississippi River (FMR) engages people to protect, restore and enhance the Mississippi River and its watershed in the Twin Cities region. FMR's water quality and drinking water protection work focuses on addressing agricultural contamination of surface water and groundwater with a goal of ensuring all Minnesotans have access to clean, safe, and healthy waters.

For over 100 years, the Izaak Walton League has fought for clean air and water, healthy fish and wildlife habitat, and conserving special places for future generations. It was the first conservation organization with a mass membership. Today, the League plays a unique role in supporting citizens locally and shaping conservation policy nationwide. The League is a grass roots member organization that has led efforts for clean water legislation achieving initial success with the passage of federal water pollution acts in 1948, 1956 and finally the Clean Water Act of 1972. The League continues to advocate for preserving wetlands, protecting wilderness, and promoting soil and water conservation. Its Save Our Streams (SOS) program involves activists in all fifty states in monitoring water quality. The Minnesota Division of the Izaak Walton League of America is composed of 16 chapters located throughout the state of Minnesota. The League's broader mission is to conserve, restore, and promote the sustainable use and enjoyment of our natural resources, including soil, air, woods, waters, and wildlife. More specifically in regard to groundwater, by a resolution passed at the 1988 Annual Meeting, the Division went on record pointing out the need for better protection and management of the state's groundwater. While some protections have been put in place at the state

level, it is clear that these have been inadequate. Greater federal protections are urgently needed.

Land Stewardship Project (LSP) is a private, nonprofit organization founded in 1982 to foster an ethic of stewardship for farmland, to promote sustainable agriculture, and to develop healthy communities. LSP is dedicated to creating transformational change in our food and farming system. LSP's work has a broad and deep impact, from new farmer training and local organizing to federal policy and community-based food systems development. At the core of all of LSP's work are the values of stewardship, justice, and democracy.

Minnesota Trout Unlimited (MNTU) is a nonprofit, nonpartisan conservation organization working to protect, restore, and sustain the watersheds and groundwater sources that support coldwater fisheries. For more than 60 years our members have advocated for clean water, both for recreational benefits and drinking. Minnesota trout streams are protected as Class 1 drinking water sources due to their close connection to groundwater. Nitrate contamination of southeast Minnesota groundwater and trout streams not only harms humans, but also the aquatic organisms on which these ecosystems depend. MNTU's several thousand Minnesota members regularly fish southeast streams and drink the water drawn from area aquifers.

Public Health Law Center (PHLC) is a nonprofit law and policy organization working to advance equitable public health policies through the power of law. For over 20 years, PHLC has fought to regulate and eliminate commercial tobacco, promote healthy food, support physical activity, and improve environmental health as a means of reducing chronic disease. PHLC partners with Tribal health leaders, federal agencies, health advocacy organizations, state and local governments, and many others to combat systems of institutional racism and create healthier communities across the country.

III. Legal Background

A. Safe Drinking Water Act

Congress enacted the SDWA as a powerful tool for protecting drinking water resources throughout the United States. Under the Act, EPA may delegate duties to state authorities to develop policies, regulations, and programs to ensure access to safe drinking water. On the federal level, the SDWA "requires EPA to protect the public from . . . drinking water contaminants."[9]

[9] *City of Portland v. Env't Prot. Agency*, 507 F.3d 706, 709 (D.C. Cir. 2007).

States may apply for, and EPA may delegate, "primacy" to states, which shifts significant authority and responsibility to state officials to implement the SDWA.[10] To assume primacy, the state is supposed to adopt regulations at least as stringent as EPA's national requirements, develop adequate procedures for enforcement and levying penalties, conduct inventories of water systems, maintain records and compliance data, and develop a plan for providing safe drinking water under emergency conditions.[11] While a state granted primacy has responsibility to implement the SDWA's provisions in that state, EPA retains emergency powers under Section 1431 of the SDWA to take actions necessary to abate imminent and substantial endangerment to the health of persons caused by drinking water contamination when state officials have failed to effectively do so on their own.

B. EPA's Emergency Powers

For EPA to exercise its Section 1431 authority, two conditions must be met. First, EPA must have received "information that a contaminant which is present in or likely to enter a public water system or an underground source of drinking water . . . may present an imminent and substantial endangerment to the health of persons."[12] Second, EPA must have received information that "appropriate State and local authorities have not acted to protect the health of such persons" in a timely and effective manner.[13]

1. Contaminant

The SDWA defines a contaminant as "any physical, chemical, biological, or radiological substance or matter in water."[14] While this broad definition does not require a substance to be regulated under the Act in order to be classified as a "contaminant," nitrate is listed as a contaminant with an established maximum contaminate level (MCL) of 10 mg/L.[15] An MCL is the "maximum permissible level of a contaminant in water which is delivered to any user of a public water system."[16] MCLs are promulgated after a determination by EPA based on the best available, peer-reviewed science and data that the regulation of the contaminant will reduce a threat to public health.[17] Establishing

[10] 42 U.S.C. § 300g-2; 40 C.F.R. §§ 142.10–142.19 (primacy enforcement responsibility).
[11] ELENA H. HUMPHREYS & MARY TIEMANN, CONG. RES. SERV., RL31243, SAFE DRINKING WATER ACT (SDWA): A SUMMARY OF THE ACT & ITS MAJOR REQUIREMENTS 7 (2021), https://sgp.fas.org/crs/misc/RL31243.pdf.
[12] 42 U.S.C. § 300i; *see also* U.S. ENV'T PROT. AGENCY, UPDATED GUIDANCE ON EMERGENCY AUTHORITY UNDER SECTION 1431 OF THE SDWA 8 (2018) [hereinafter EMERGENCY AUTHORITY GUIDANCE].
[13] 42 U.S.C. § 300i; *see also* EMERGENCY AUTHORITY GUIDANCE, *supra* note 12, at 12-13.
[14] 42 U.S.C. § 300f(6).
[15] 40 C.F.R. § 141.62(b).
[16] 42 U.S.C. § 300f(3).
[17] 42 U.S.C. §§ 300g-l(b)(1)(A), (b)(3)(A).

nationwide, health-based MCLs is central to EPA's role in protecting drinking water under the SDWA.[18]

The MCL for nitrate was set at 10 mg/L to protect against blue-baby syndrome; however, recent studies have shown that even lower levels of nitrate can cause other health effects, including cancer and reproductive harm.[19] For example, recent studies have found statistically significant increased risks of colorectal cancer at drinking water levels far below the current MCL of 10 mg/L.[20]

2. Imminent & Substantial Endangerment

An endangerment from a contaminant is "imminent" if conditions that give rise to it are present, even if the actual harm may not be realized for years.[21] Courts have established that an "imminent hazard" may be declared at any point in a chain of events that may ultimately result in harm to the public.[22] Information presented to EPA need not demonstrate that residents are actually drinking contaminated water and becoming ill to warrant EPA exercising its Section 1431 emergency authority.[23] In other words, an actual injury need not have occurred for EPA to act, and to wait for such actual injury to befall the public would be counter to the precautionary intent behind the SDWA. Thus, while the threat or risk of harm must be "imminent" for EPA to act, actual and documented harm itself need not be.[24] While endangerments are readily determined to be imminent where MCL violations expose sensitive populations to a contaminant, contaminants that lead to chronic health effects may also cause "imminent endangerment."[25] In such cases, it is appropriate to consider the length of time a population has been or could be exposed to a contaminant.[26]

An endangerment is "substantial" "if there is a reasonable cause for concern that someone may be exposed to a risk of harm."[27] For instance, Congress has deemed an

[18] 42 U.S.C. § 300g-1(b)(4)(B).
[19] *See, e.g.,* Mary. H. Ward et al., *Drinking Water Nitrate and Human Health: An Updated Review*, 15 INT'L J. ENV'T RSCH. & PUB. HEALTH 1557 (2018); Alexis Temkin et al., *Exposure-Based Assessment and Economic Valuation of Adverse Birth Outcomes and Cancer Risk Due to Nitrate in United States Drinking Water*, 176 ENV'T RSCH. 108442 (2019).
[20] *See, e.g.,* Jorg Schullehner et al., *Nitrate in Drinking Water and Colorectal Cancer Risk: A Nationwide Population-Based Cohort Study*, 143 INT'L J. CANCER 73 (2018).
[21] EMERGENCY AUTHORITY GUIDANCE, *supra* note 12, at 8 (citing *United States v. Conservation Chem. Co.*, 619 F. Supp. 162, 193-94 (W.D. Mo. 1985)).
[22] *Id.* n.15 (citing cases).
[23] *See Trinity Am. Corp. v. Env't Prot. Agency*, 150 F.3d 389, 399 (4th Cir. 1998).
[24] EMERGENCY AUTHORITY GUIDANCE, *supra* note 12, at 8.
[25] *Id.*
[26] *Id.*
[27] *Id.* at 11.

endangerment sufficiently substantial where a substantial likelihood exists that contaminants capable of causing adverse health effects will be ingested by consumers if preventative action is not taken.[28] As with imminence, EPA has made clear that actual reports of human illness resulting from contaminated drinking water are not necessary to establish substantial endangerment.[29]

C. Minnesota's Authority

Minnesota has several state agencies with jurisdiction over the quality of underground sources of drinking water: MDH, MDA, and MPCA are the primary ones. The graphic below shows the differing roles of these agencies.[30]

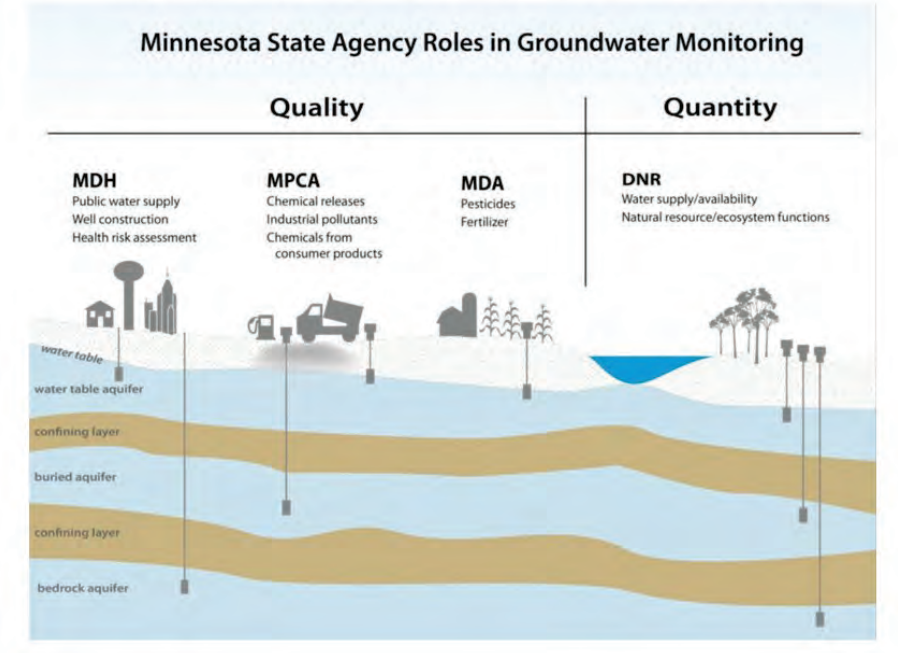

Figure 2: Agency Roles in Groundwater

[28] *See* H.R. REP. NO. 93-1185, at 35-36 (1974).

[29] *See* EMERGENCY AUTHORITY GUIDANCE, *supra* note 12, at 11 (citing *United States v. North Adams*, 777 F. Supp. 61, 84 (D. Mass. 1991)).

[30] SHARON KROENING & SOPHIA VAUGHAN, MINN. POLLUTION CONTROL AGENCY, CONDITIONS OF MINNESOTA'S GROUNDWATER QUALITY 2013-2017, 4 (2019), https://www.pca.state.mn.us/sites/default/files/wq-am1-10.pdf [hereinafter MPCA GROUNDWATER QUALITY 2013-2017]. The graphic also depicts the MDNR, which controls water appropriation and has a role in agricultural drainage projects that affect public waters. MDNR also conducts some groundwater monitoring as part of is County Geologic Atlas program.

The MDH administers the Minnesota Well Code for the construction of new wells and borings[31] and Minnesota's SDWA.[32] EPA granted Minnesota primacy under the federal SDWA in 1976.[33] Although the SDWA allows states to set higher standards than the federal minimum, Minnesota state law sets the drinking water quality standard for nitrate at the same level as the federal standard: 10 mg/L.[34] Public water systems with nitrate levels over 10 mg/L must notify people who receive water from them.[35]

The MPCA's authority extends to discharges from point sources under its water pollution control laws.[36] Point sources include animal feeding operations, which, as discussed below, are a significant contributor of nitrate pollution to groundwater in the karst region. The MPCA regulates animal feeding operations with more than 1,000 animal units through the issuance of National Pollution Discharge Elimination System (NPDES) permits,[37] but smaller farms are unregulated. Finally, the MDA has statutory authority under the Minnesota Groundwater Protection Rule to regulate the use of pesticides and commercial fertilizer.[38]

D. EPA's Authority in Minnesota

Despite Minnesota's primacy under the SDWA, EPA retains emergency powers to abate present or likely contamination of public water systems (PWS) or underground sources of drinking water (USDW) when such contamination poses an imminent and substantial threat to human health and the state "ha[s] not acted to protect the health of [endangered] persons."[39]

EPA's Section 1431 authority extends to contaminated USDW and PWS that pose a threat to human health,[40] including sources that supply private wells.[41] EPA defines USDW as an aquifer or part of an aquifer "(1) [w]hich supplies any public water systems; or (2) which contains a sufficient quantity of ground water to supply a public water system; and (i) currently supplies drinking water for human consumption."[42] PWS are

[31] MINN. R. 4725.0500–4725.7605.
[32] MINN. STAT. §§ 144.381–144.387.
[33] MINN. DEP'T OF HEALTH, MINNESOTA DRINKING WATER ANNUAL REPORT FOR 2021 2 (2022), https://www.health.state.mn.us/communities/environment/water/docs/report21.pdf.
[34] MINN. R. 4720.0350 (adopting national standards by reference).
[35] MINN. STAT. § 144.385.
[36] MINN. STAT. § 115.03.
[37] MINN. R. 7020.2003, subp. 2(B).
[38] MINN. STAT. § 103H.275; MINN. R. 1573.0010–1573.0090.
[39] 42 U.S.C. § 300i(a).
[40] *Id.*
[41] EMERGENCY AUTHORITY GUIDANCE, *supra* note 12, at 7-8.
[42] 40 C.F.R. § 144.3.

aquifers that provide water for human consumption and "ha[ve] at least fifteen service connections or regularly serve[] at least twenty-five individuals."[43] The drinking water for the hundreds of thousands of residents of the karst region of Minnesota comes from either private or community wells that rely on groundwater. The underground aquifers that supply these wells therefore qualify as USDW and PWS within the purview of the SDWA.

To abate endangerment to human health that arises despite a state's efforts to curtail it, Congress authorized EPA to, among other things, issue "such orders as may be necessary to protect the health of persons who are or may be users of" the affected drinking water supplies and to commence civil enforcement actions against entities causing threats to public health by contaminating drinking water supplies.[44] Petitioners ask EPA to use that authority here.

IV. Drinking Water Contamination in the Karst Region Constitutes an Endangerment under the SDWA and Necessitates Emergency Action by EPA

Nitrate contamination in Minnesota's karst region is a widespread issue that has stubbornly persisted through decades as state officials continuously fail to effectively address the problem. "Nitrate contamination of surface water and groundwater is a long-standing issue in the region. Impacts to municipal and private drinking water supplies by nitrate are widespread and well-documented."[45] According to MPCA, "[t]rends from the past 10, 20, and 40 years show that statewide . . . nitrate concentrations have generally been increasing."[46] Figure 3 is a MPCA graphic which shows that there are no areas of the state where nitrate trends in surface water have decreased between 2008 and 2017.[47] The main contributors to this problem are large-scale animal agriculture facilities and industrial row-crop agriculture which dominate land use within the area and that are not effectively addressed by existing regulations and policies promoting voluntary actions.

[43] 42 U.S.C. § 300f(4)(A).
[44] EMERGENCY AUTHORITY GUIDANCE, *supra* note 12, at Attach. 2.
[45] ANTHONY C. RUNKEL ET AL., GEOLOGIC CONTROLS ON GROUNDWATER AND SURFACE WATER FLOW IN SOUTHEASTERN MINNESOTA AND ITS IMPACT ON NITRATE CONCENTRATIONS IN STREAMS, MINN. GEOLOGIC SURV., 4 (2013) [hereinafter RUNKEL 2013].
[46] DAVE WALL ET AL., MINN. POLLUTION CONTROL AGENCY, 5-YEAR PROGRESS REPORT ON MINNESOTA'S NUTRIENT REDUCTION STRATEGY 17 (2020), https://www.lrl.mn.gov/docs/2021/other/210420.pdf [hereinafter 5-YEAR PROGRESS REPORT].
[47] *Id.*

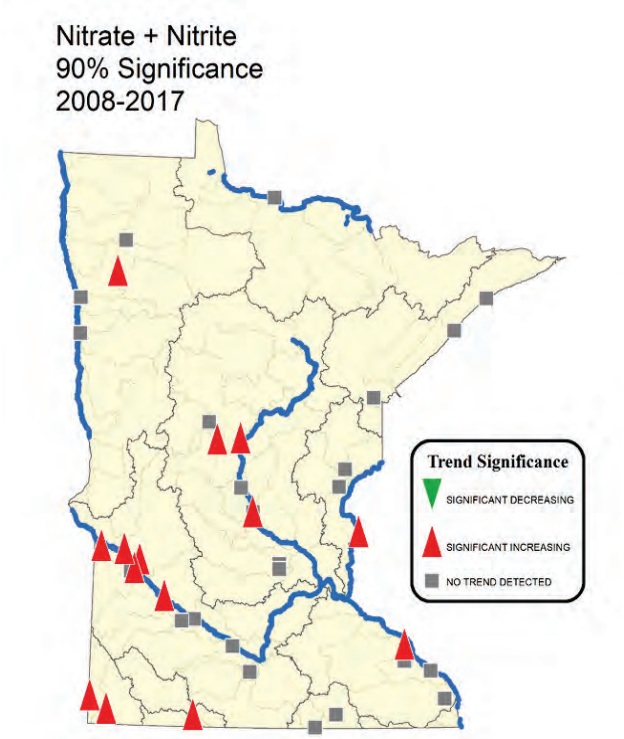

Figure 3: 5-year Progress on Nitrate

Emergency action by EPA is necessary to address the dangerous levels of nitrate in the karst region because the contamination poses an imminent and substantial risk to the health of more than 380,000 residents who rely on groundwater, and because Minnesota officials have failed to improve drinking water quality, despite knowing about the problem, for over 40 years.[48]

A. The Karst Region is Particularly Susceptible to Nitrate Pollution

Groundwater in the karst region is vulnerable to contamination because of the fluid interaction between groundwater and surface water. The rapid movement of water in and out of the ground in this region leaves a blurry distinction between groundwater and surface water that is compounded by Minnesota's multi-agency approach to drinking water policies, regulation, and funding. Specific karst features such as stream sinks and sinkholes that inject water into the ground and the springs that discharge groundwater to the surface are depicted in Figure 4.[49] "[N]ot only does karst aquifer groundwater flow rapidly (flows have been measured in miles per day versus the inches, or feet, per year common to sandstones), but contaminants in the groundwater are not

[48] 5-YEAR PROGRESS REPORT, *supra* note 46, at 17.
[49] RUNKEL 2013, *supra* note 45, at Fig. 3.

readily filtered out. As a result, contaminants can reach domestic wells located miles from the source of contamination."[50]

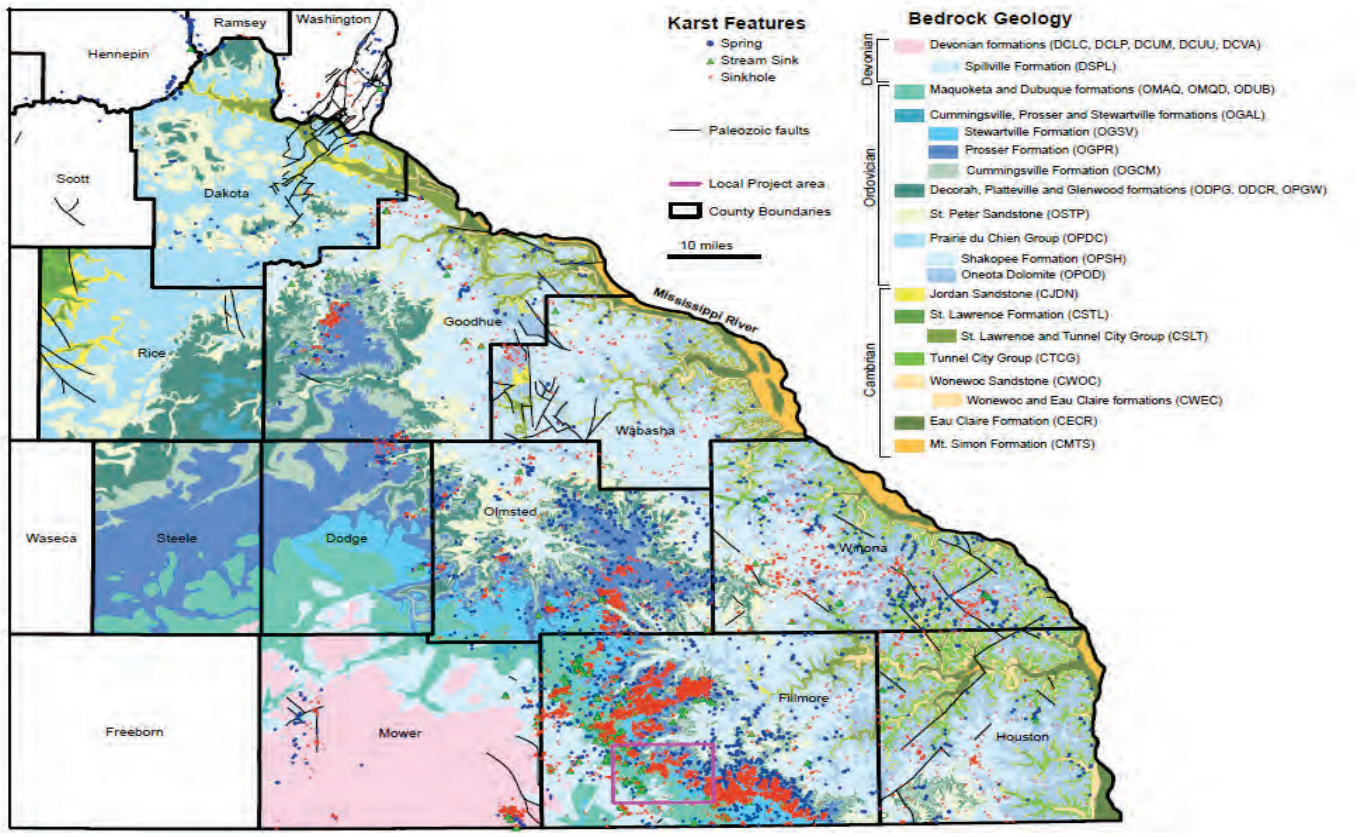

Figure 4: Karst Features

Nitrate pollution is particularly troublesome because nitrate is mobile in groundwater.[51] Nitrate mobility in karst regions can be largely determined by rainfall frequency and intensity.

Recent research indicates that up to 80% of nitrate loading in karst regions can be traced to fertilizers that are quickly flushed from soils into the karst and groundwater

[50] JEFFREY ST. ORES ET AL., GROUNDWATER POLLUTION PREVENTION IN SOUTHEAST MINNESOTA'S KARST REGION, 465 UNIV. OF MINN. EXTENSION BULL. 6 (1982), https://conservancy.umn.edu/bitstream/handle/11299/169069/mn_2000_eb_465.pdf?sequence=1 [hereinafter ORES 1982].

[51] MINN. POLLUTION CONTROL AGENCY, EFFECTS OF LIQUID MANURE STORAGE SYSTEM ON GROUNDWATER QUALITY 3 (2001), https://www.pca.state.mn.us/sites/default/files/rpt-liquidmanurestorage.pdf.

systems during rain events.[52] Water carries the excess nitrogen from fertilizers on the surface through the soil column and into the fractured karst bedrock, where oxygenated conditions facilitate conversion of nitrogen to nitrate.[53] Combining nitrogen intensive land uses with the karst region's heightened vulnerability to nitrate contamination is a major hazard.

As a result, "[g]roundwater in uppermost bedrock units, especially on the karstic plateaus that dominate the landscape of southeastern Minnesota, is typically nitrate-enriched, with concentrations commonly between 5-15 ppm."[54] Rural communities are particularly at risk since private wells are more likely to draw from shallow aquifers than public water systems, which can pull water from deeper wells and multiple sources.[55]

Minnesota officials have been aware of the vulnerability of this region for at least 80 years. "S.P. Kingston, a former Minnesota health official, noted in 1943 that the regional groundwater system in southeast Minnesota is particularly vulnerable to contamination from many sources."[56] And nitrate was identified as one of the contaminants of concern as early as 1982: "Many shallow wells in southeast Minnesota contain coliform bacteria and high nitrate levels—both indicators of possible contamination."[57] The evidence of nitrate contamination in the groundwater of this region is robust.

B. The Karst Region Has a Documented History of Nitrate Contamination

The karst region has an extensive history with nitrate contamination in groundwater aquifers. Although nitrate is a naturally occurring substance, the presence of nitrate in groundwater at concentrations above 3 parts per million or milligrams per liter is not natural and indicates an anthropogenic source of the nitrate.[58]

[52] Fu-Jun Yue et al., *Rainfall and Conduit Drainage Combine to Accelerate Nitrate Loss from a Karst Agroecosystem: Insights from a Stable Isotope Tracing and High-Frequency Nitrate Sensing*, 186 WATER RSCH. 116388 (2020), https://doi.org/10.1016/j.watres.2020.116388.
[53] PHILIP MONSON, MINN. POLLUTION CONTROL AGENCY, AQUATIC LIFE WATER QUALITY STANDARDS DRAFT TECHNICAL SUPPORT DOCUMENT FOR NITRATE 1 (2022), https://www.pca.state.mn.us/sites/default/files/wq-s6-13.pdf.
[54] RUNKEL 2013, *supra* note 45, at 59.
[55] *Learn About Private Water Wells*, ENV'T PROT. AGENCY (Mar. 1, 2023), https://www.epa.gov/privatewells/learn-about-private-water-wells.
[56] ORES 1982, *supra* note 50, at 3.
[57] *Id.*
[58] *Nitrate in Drinking Water*, MINN. DEP'T OF HEALTH (DEC. 8, 2022), https://www.health.state.mn.us/communities/environment/water/contaminants/nitrate.html.

Regular sampling of wells to detect nitrate began over 30 years ago. Fifty-five wells in Winona County were first sampled in 1990 and 1991.[59] Twenty-five of the well samples were taken from the shallower Prairie du Chien aquifer and 30 were from the deeper Jordan aquifer. "Nitrate concentrations exceeded the 10 mg/l drinking water standard in 48 percent of Prairie du Chien wells and 3.2 percent of Jordan wells."[60] Fifteen to thirty years later, nothing had improved: testing data from wells sampled between 2005 to 2017 revealed that 49% of wells in agricultural areas of the state, installed near the water table, exceeded the MCL for nitrate.[61]

Petitioners present a compilation of data in this Petition that shows nitrate contamination in private wells in the karst region. The data were compiled by Petitioners EWG and MNWOO. In 2020, EWG used data from the Township Testing Program[62] conducted by MDA, a Volunteer Nitrate Monitoring Network,[63] and new well tests required by MDH since the Well Code was adopted in 1975.[64] EWG used the data to create an interactive map showing nitrate contamination by township.[65] The Township Testing Program sampled and analyzed over 32,000 private wells between 2017 and 2020. The Volunteer Nitrate Monitoring Network in the karst region began in 2008 with a network of 675 private drinking water wells. "Between February 2008 and August 2018, 13 sampling events occurred representing 5,421 samples."[66] And MDH provided EWG with location data and test results for each of the 45,598 wells sampled between 2009 and 2018.[67] Finally, MNWOO hosts well testing clinics that allow homeowners to test their

[59] David B. Wall & Charles P. Regan, *Water Quality and Sensitivity of the Prairie du Chien-Jordan Aquifer in West-Central Winona County*, MINN. POLLUTION CONTROL AGENCY, ES1 (1991).
[60] *Id*.
[61] MPCA GROUNDWATER QUALITY 2013-2017, *supra* note 30, at 2, 15.
[62] MINN. DEP'T AGRIC., TOWNSHIP TESTING PROGRAM UPDATE - MAY 2022 (2022), https://www.mda.state.mn.us/sites/default/files/docs/2022-05/ttpupdate2022_05.pdf (hereinafter TOWNSHIP TESTING UPDATE 2022).
[63] MINN. DEP'T OF HEALTH, VOLUNTEER NITRATE MONITORING NETWORK: METHODS AND RESULTS (2012), https://www.health.state.mn.us/communities/environment/water/docs/swp/no3methods.pdf.
[64] MINN. R. 4725.0500–4725.7605.
[65] *Interactive Map: Nitrate in Minnesota Private Drinking Water from Groundwater Sources (2009-2018)*, ENV'T WORKING GRP., https://www.ewg.org/interactive-maps/2020_nitrate_in_minnesota_private_drinking_water_from_groundwater_sources/map/ (last visited Apr. 17, 2023).
[66] KIM KAISER ET AL., MINN. DEP'T OF AGRIC., NITRATE RESULTS AND TRENDS IN PRIVATE WELL MONITORING NETWORKS 2008-2018 2 (2019), https://wrl.mnpals.net/islandora/object/WRLrepository%3A3395/datastream/PDF/view.
[67] EWG Tap Water Report, *supra* note 7, at Methodology.

well water for nitrates and chlorides at no cost. MNWOO provided data from 119 different wells, from at least 24 townships from five counties in the karst region. To date, these data points do not appear in any other public record. The karst-region-specific data from these combined sources are depicted in Figure 5.

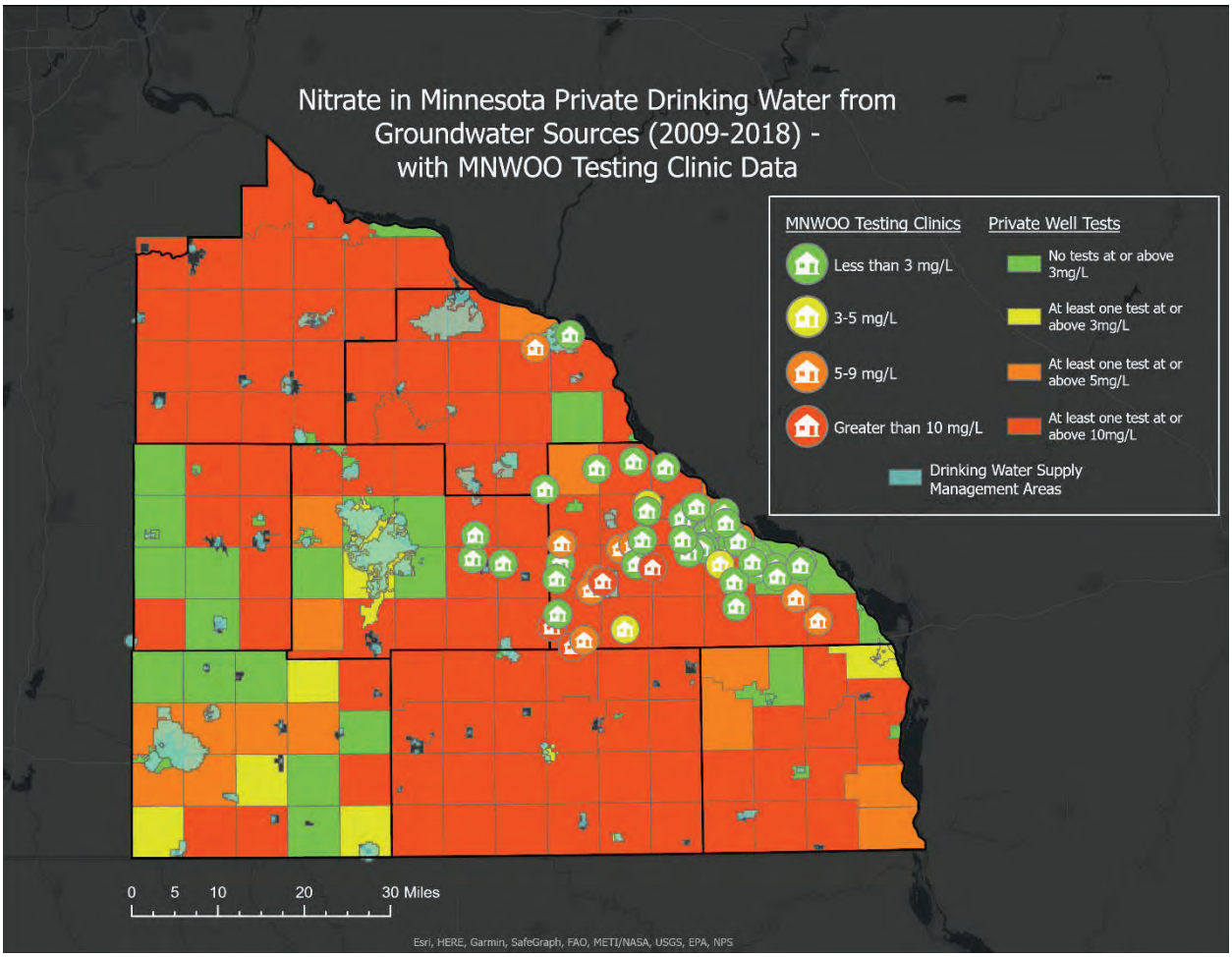

Figure 5: Private Well Contamination
Data from Township Testing Program, Southeast Volunteer Monitoring Network, MDH Well Index, and MNWOO clinic

Approximately 9% of the wells tested during the initial round of the Township Testing Program were found to have samples that exceeded the MCL for nitrate of 10mg/l. The multiple rounds of sampling and analysis also found a maximum nitrate concentration of 69.8 mg/L. The percentage of wells tested between 2008 and 2018 in the Volunteer Nitrate Monitoring Network (VNMN) above 10 mg/l ranged from a low of 7.5% in 2012 to a high of 14.6% in 2008. More recent data from the VNMN show that (among continuing participants) nitrate contamination continues: In 2019, 9% of wells

tested above 10 mg/l, in 2020 it was 9.4% and in 2021 it was 8.5%.[68] The MNWOO clinic conducted in the karst region in February 2023 showed a 6% rate of nitrate contamination above 10 mg/L.

Figure 5 also depicts the location of the wells in comparison to the Drinking Water Supply Management Areas (DWSMAs). DWSMAs are defined geographic areas around public water supply wells that represent a 10-year travel time for water to reach the well. These areas are used by MDH and local communities in developing Well Head Protection Areas and are the geographic limitation for MDA's ability to protect groundwater under the Groundwater Protection Rule from commercial fertilizers and pesticides. As figure 5 demonstrates, many of the private wells in this region fall outside of a protected DWSMA. EPA needs to step in to afford private well owners protection against nitrate contamination.

It is also important to note that despite the additional protection available to protect PWS, many community water supplies with 25 or more connections to a well and many transient community water supplies like churches, campgrounds, and businesses in the area, are also affected by nitrate contamination. Petitioner EWG has also compiled Minnesota well testing data into an interactive map for public water systems,[69] and presents a karst-specific version of that map in Figure 6.

[68] *Southeast Minnesota Volunteer Monitoring Network*, MINN. DEP'T OF AGRIC., https://www.mda.state.mn.us/southeast-minnesota-volunteer-nitrate-monitoring-network (last visited Apr. 17, 2023).

[69] *Interactive Map: Nitrate in Minnesota Public Drinking Water from Groundwater Sources (2009-2018)*, ENV'T WORKING GRP., https://www.ewg.org/interactive-maps/2020_nitrate_in_minnesota_public_drinking_water_from_groundwater_sources/map/ (last visited Apr. 17, 2023).

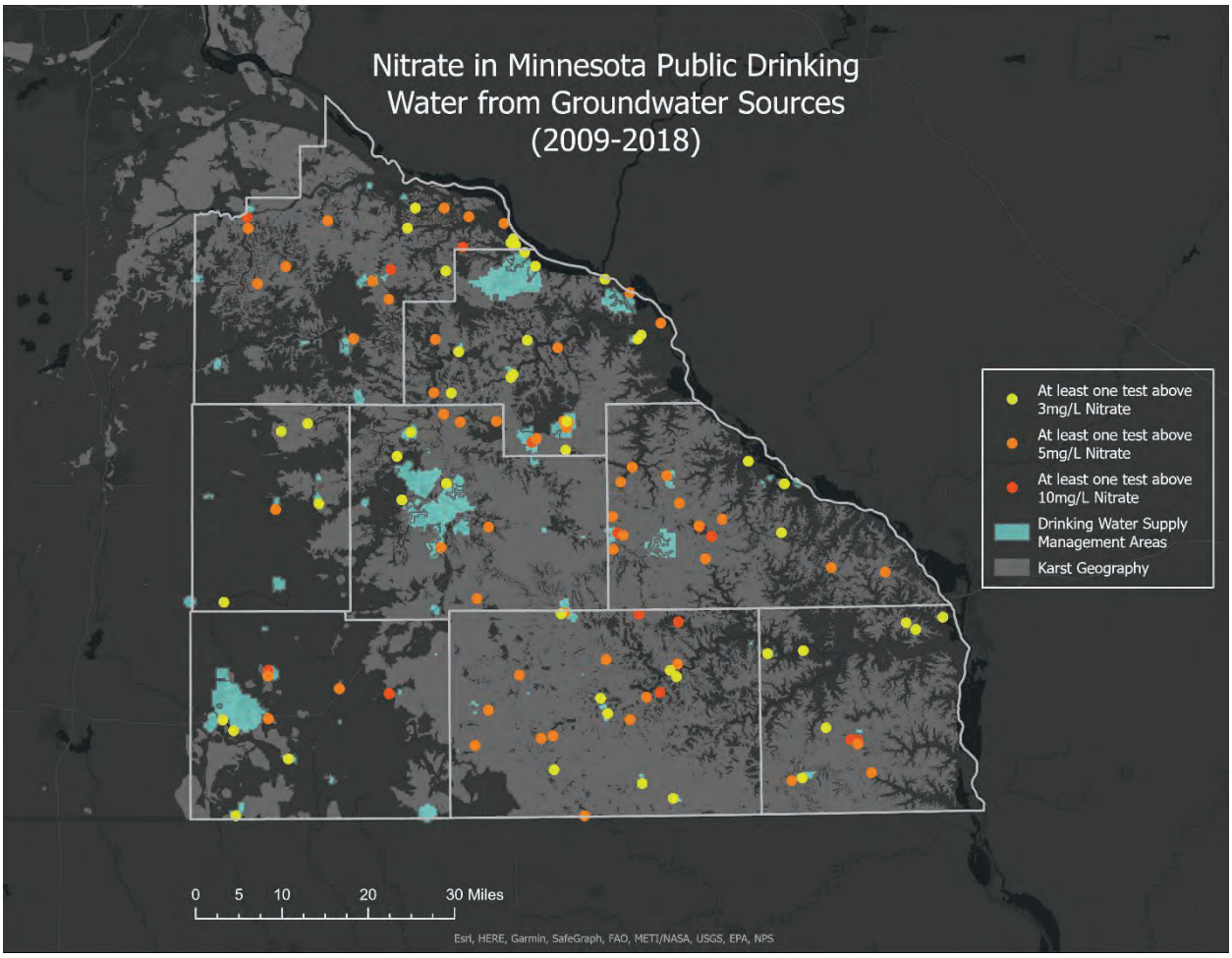

Figure 6: Public Drinking Water Contamination

In its 2020 analysis, EWG determined that groundwater-derived drinking water for an estimated 150,000 Minnesotans is contaminated with nitrate at levels over the legal limit. For 4,178 Minnesotans, the level is more than double the legal limit.[70] Cities in the karst region have long struggled with high nitrate concentrations in their drinking water. For example, the city of Lewiston has dug multiple deeper wells to try to eradicate nitrate from the city's water at a cost of approximately $1 million per well.[71] Had the city pursued a treatment system, the cost would have risen to $3.1 million, and doubled water rates for residents.[72]

[70] EWG Tap Water Report, *supra* note 7.
[71] Elizabeth Baier, *Even in Region with Abundant Water, Residents Turn to Bottles and Try to Conserve*, MPR NEWS (Mar. 20, 2014), https://www.mprnews.org/story/2014/03/20/ground-level-beneath-the-surface-southeast-minnesota.
[72] *Id.*

As another example, the city of Utica has two city wells, but as shown in the graph below, one well has been exceeding the 10 mg/L MCL since 2003 and is now for emergency use only. The other well, drilled in the late 1970s, began with a nitrate concentration of 3.9 mg/L, but that concentration has been steadily increasing and was as high as 8.6 mg/l in 2019.

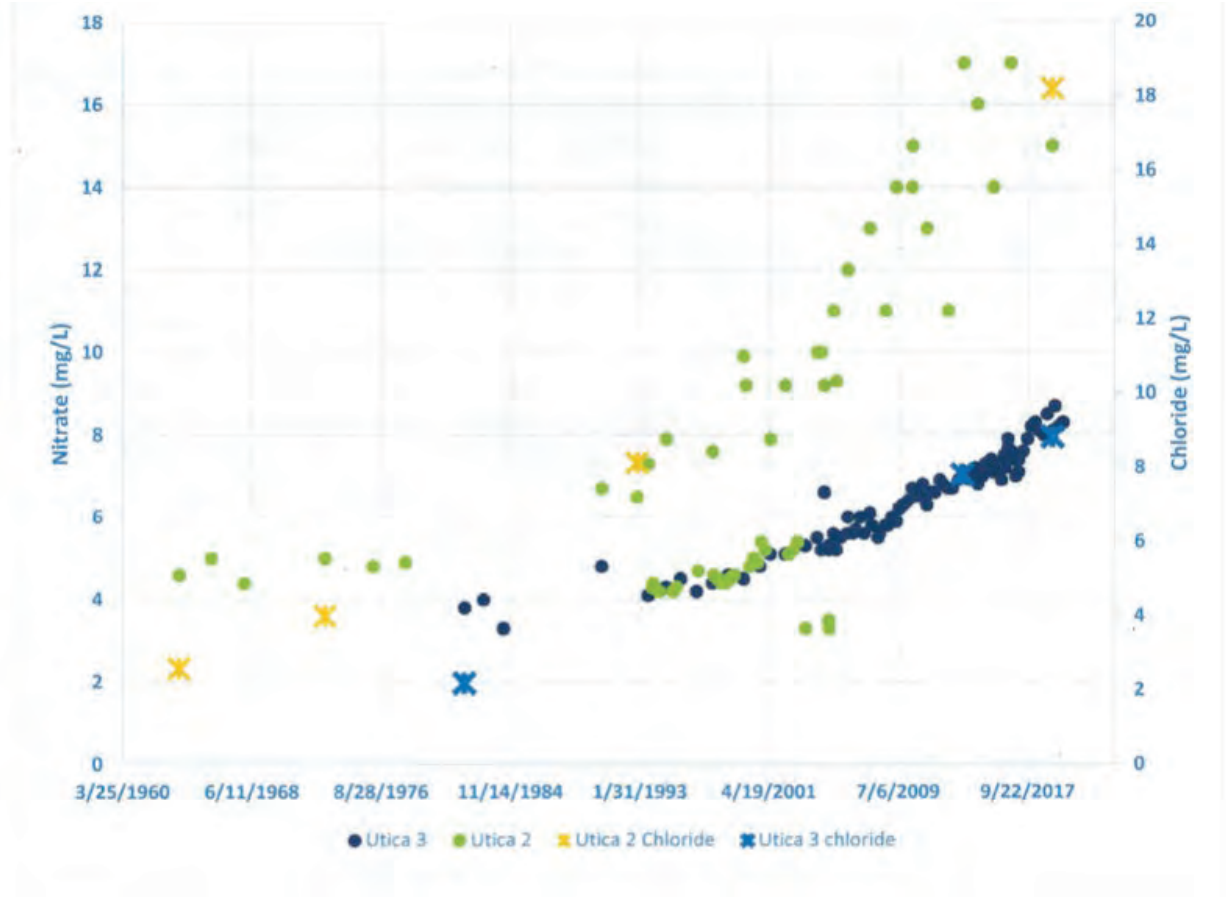

Figure 7: Utica City Well Contamination
Data from Minnesota Geological Survey

C. Under-Regulated Animal Feeding Operations and Industrial Row Crop Agriculture Are Dominant Land Use Activities and the Predominant Causes of Nitrate Contamination in the Karst Region

Most nitrate contamination in the karst region is caused by harmful agricultural practices on groundwater recharge areas that are not sufficiently addressed by Minnesota regulators. Despite evidence of adverse impacts on groundwater and public health caused by manure storage, the excessive or poorly timed application of manure, and animal feeding operations under MPCA, industrial row-crop agriculture under MDA, or the wellhead protections under MDH, Minnesota has had inadequate state and local regulation for decades, resulting in a public health crisis that requires emergency action

from EPA. The root cause of this pollution is public policy that makes polluting actions cheaper and easier than sustainable practices. The vast majority of farmers care deeply about stewardship of the land, but our policies do not reflect that same stewardship.

1. Animal Agriculture

Within the boundaries of Houston, Fillmore, Mower, Dodge, Olmsted, Wabasha, Winona, and Goodhue counties, there are currently approximately 3,170 animal feedlot operations that are required to register with MPCA's Feedlot program, with more added every year.[73] In addition, as depicted in the map below, many more feedlots are located in this area that fall below the number of animal units that require a permit or registration.

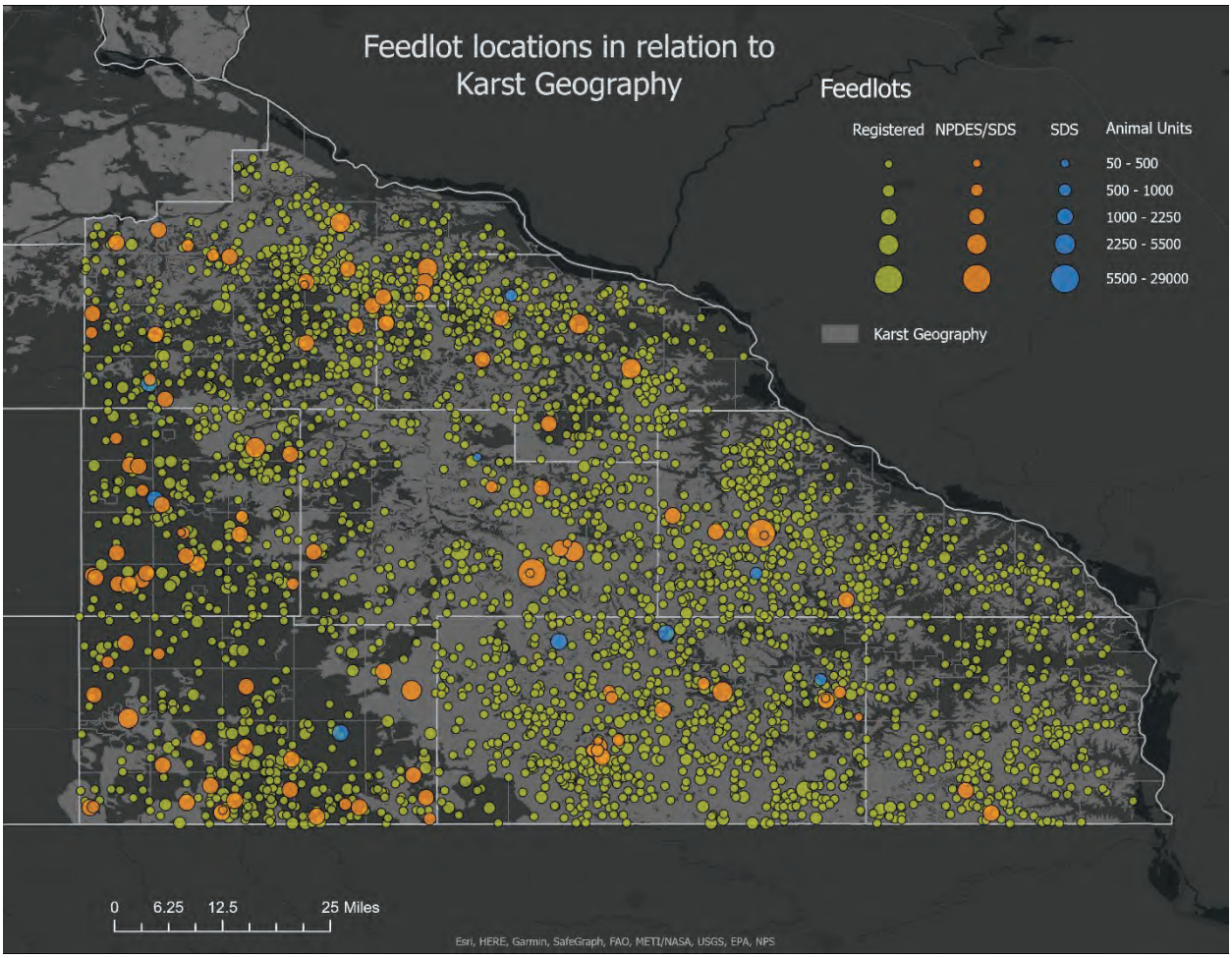

Figure 8: Karst Region Feedlots
Data from MPCA's Feedlots in Minnesota Database

[73] *Counties Delegated to Administer the MPCA Feedlot Program,* MINN. POLLUTION CONTROL AGENCY (Apr. 2022), https://www.pca.state.mn.us/sites/default/files/wq-f1-12.pdf.

The counties that are subject to this Petition house approximately 500,000 dairy cow and cattle animal units and another 260,000 swine units.[74] And the number of feeding operations statewide is on the rise.[75] Current feeding operations also continue to grow: in February 2023, the Fillmore County Board of Commissioners voted unanimously to increase the county's animal unit cap from 2,000 to 4,000 animal units per feedlot.[76] Moreover, almost 65% of the cattle units and over 37% of the swine units are located within landscapes designated as prone to surface karst feature development by MDNR. Those numbers jump to 96% and 69% respectively if we look at facilities within one mile of areas prone to the development of surface karst features.[77]

The storage structures designed to contain millions of gallons of liquid manure, manure piles, and feedlot runoff, can also be significant sources of nitrogen to groundwater in this area.[78] Manure storage structures that are constructed in compliance with National Resource Conservation Service (NRCS) standards are actually designed to leak. According to the NRCS handbook, "properly" constructed lagoons can leak up to 5,000 gallons of manure wastewater per acre per day.[79] In one study conducted by MPCA, "[t]here was evidence of shallow ground water contamination down-gradient of manure storage areas at each [feedlot operation]."[80]

[74] *Feedlots in Minnesota*, MINN. GEOSPATIAL COMMONS, https://gisdata.mn.gov/dataset/env-feedlots (last visited Apr. 17, 2023).
[75] Sarah Porter & Craig Cox, *Manure Overload: Manure Plus Fertilizer Overwhelms Minnesota's Land and Water*, ENV'T WORKING GRP. (May 28, 2020), https://www.ewg.org/interactive-maps/2020-manure-overload/ [hereinafter *Manure Overload*].
[76] Brian Todd, *Fillmore County doubles its animal unit cap for feedlots*, AGWEEK (Mar. 1, 2023), https://www.agweek.com/news/policy/fillmore-county-doubles-its-animal-unit-cap-for-feedlots.
[77] *Minnesota Regions Prone to Surface Karst Feature Development*, MINN. GEOSPATIAL COMMONS, https://gisdata.mn.gov/dataset/geos-surface-karst-feature-devel (last visited Apr. 17, 2023).
[78] MINN. POLLUTION CONTROL AGENCY, EFFECTS OF LIQUID MANURE STORAGE SYSTEMS ON GROUND WATER QUALITY–SUMMARY REPORT (2001), https://www.pca.state.mn.us/sites/default/files/rpt-liquidmanurestorage-summary.pdf.
[79] U.S. DEP'T OF AGRIC. NAT. RES. CONSERVATION SERV., AGRICULTURAL WASTE MANAGEMENT FIELD HANDBOOK, CHAPTER 10: AGRICULTURAL WASTE MANAGEMENT SYSTEM COMPONENT DESIGN App. 10D-16 (2009), https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=31529.wba ("NRCS guidance considers an acceptable initial seepage rate to be 5,000 gallons per acre per day.").
[80] MINN. POLLUTION CONTROL AGENCY, EFFECTS OF LIQUID MANURE STORAGE SYSTEMS ON GROUND WATER QUALITY–SUMMARY REPORT 2 (2001), https://www.pca.state.mn.us/sites/default/files/rpt-liquidmanurestorage-summary.pdf.

In addition to the manure storage structures themselves, manure from livestock operations in the karst region is commonly used as fertilizer for row crops in the area. When liquified manure storage systems reach capacity, operators must empty them, often by disposing of the liquified manure and process wastewater onto nearby agricultural fields, regardless of the season. These land applications of manure are one of the largest sources of nitrogen from animal feeding operations.[81]

The karst region includes a number of townships, such as Utica and Fremont, that have sandy soils derived from sandstone bedrock. Applications of manure to sandy soils at high agronomic rates leave nitrogen in the soil after the growing season, which then leaches into the groundwater as nitrate, endangering public health.[82] The townships with the highest percentages of private wells exceeding 10 mg/L nitrate concentration have sandy soils or thin soils over karst.

2. Industrial Agriculture

Another major contributor to the nitrate contamination is widespread industrial agriculture in the region. In the eight-county area, 73% of land cover is devoted to agriculture—60% is cropland and 13% is hay or pastureland.[83] This is a high concentration of agriculture for a sensitive karst landscape with a high sensitivity to groundwater contamination. In comparison, only 51% of Minnesota's land cover is devoted to agriculture statewide.[84] A significant portion of this southeastern Minnesota land is related to the animal agriculture in the region: it is used to grow feed crops for

[81] *Estimated Animal Agriculture Nitrogen and Phosphorus from Manure*, ENV'T PROT. AGENCY (Jan. 11, 2023), https://www.epa.gov/nutrient-policy-data/estimated-animal-agriculture-nitrogen-and-phosphorus-manure.

[82] Michael J. Goss et al., *Chapter Five–A Review of the Use of Organic Amendments and the Risk to Human Health*, 120 ADVANCES IN AGRONOMY 275 (2013), https://doi.org/10.1016/B978-0-12-407686-0.00005-1 ("Spreading manure on the land in fall or winter results in smaller recovery of applied nitrogen by the crops, while the risk of surface runoff, leaching and denitrification is greater.") ("Leaching losses of labeled N from the manure application were considerably greater than those from the original fertilizer application in all years.").

[83] These percentages were calculated using the Multi-Resolution Land Characteristics National Land Cover Database Enhanced Visualization Analysis Tool, *see MRLC NLCD EVA Tool*, MRLC, https://www.mrlc.gov/eva/ (last visited Apr. 17, 2023).

[84] *Agricultural Lands*, MINN. BOARD OF WATER AND SOIL RES., https://bwsr.state.mn.us/agricultural-lands (last visited Apr. 17, 2023).

animals[85] and/or receives the application of manure and waste from the nearby CAFOs as fertilizer.

But much of this fertilizer is over-applied. EWG's modeling found that in 69 of Minnesota's 72 agricultural counties, nitrogen from manure combined with nitrogen in fertilizer exceeded the recommended agronomic rates of MPCA and the University of Minnesota.[86] EWG identified 13 counties in Minnesota where the percent of Nitrogen, from fertilizer and manure combined, was more than 150% of the recommended amount needed to maximize crop yields.[87] Five of these 13 counties are in the karst region.[88] The total estimated nitrogen overload in these five counties is 26,424 tons per year.[89]

The image below shows the coverage of corn and soybeans in the karst region along with average nitrate concentrations at areas near designated trout streams.[90]

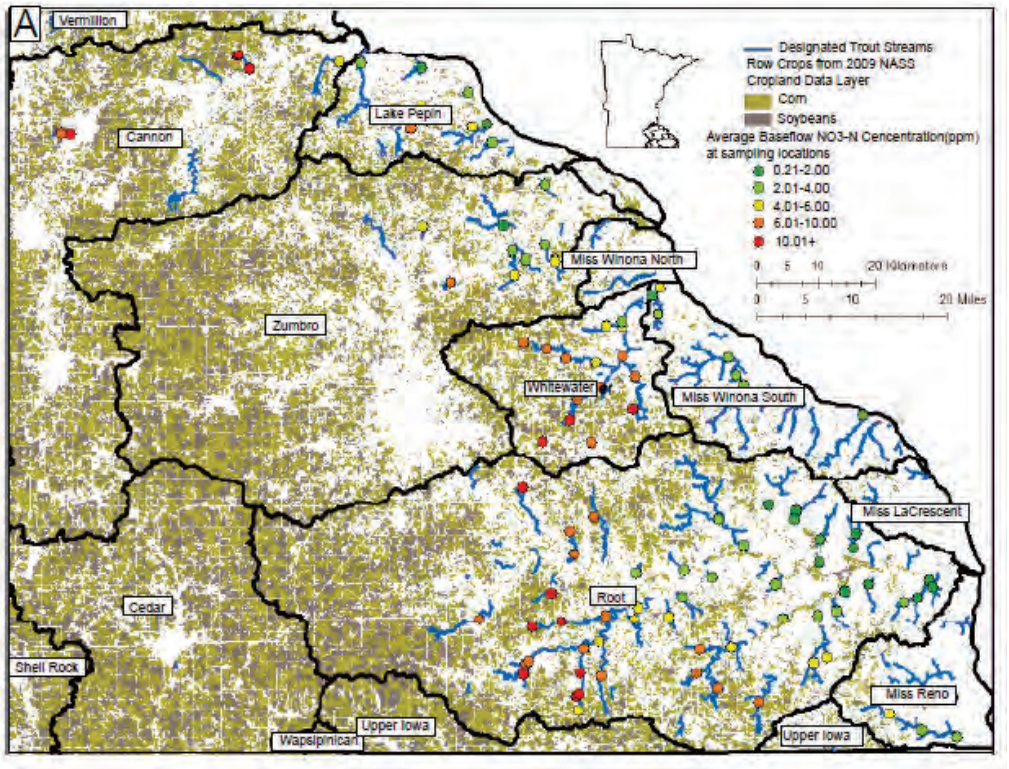

Figure 9: Industrial Agriculture and Nitrate-Contaminated Trout Streams

[85] Up to 40% of domestic corn use is allocated to livestock feed. *See Feed Grains Sector at a Glance*, U.S. DEP'T OF AGRIC., https://www.ers.usda.gov/topics/crops/corn-and-other-feed-grains/feed-grains-sector-at-a-glance/ (last visited Apr. 17, 2023).
[86] *Manure Overload*, *supra* note 75.
[87] *Id.*
[88] *Id.*
[89] *Id.*
[90] RUNKEL 2013, *supra* note 45, at Fig. 37.

The correlation between land used to grow exclusively corn and soybeans and nitrate pollution is well documented. In a 2020 report, researchers at MDA found that the mean nitrate concentration of lysimeters placed on cropland that was in a constant corn or corn-soybean rotation was 22.3 mg/L.[91] The figure below compares this to other land uses.

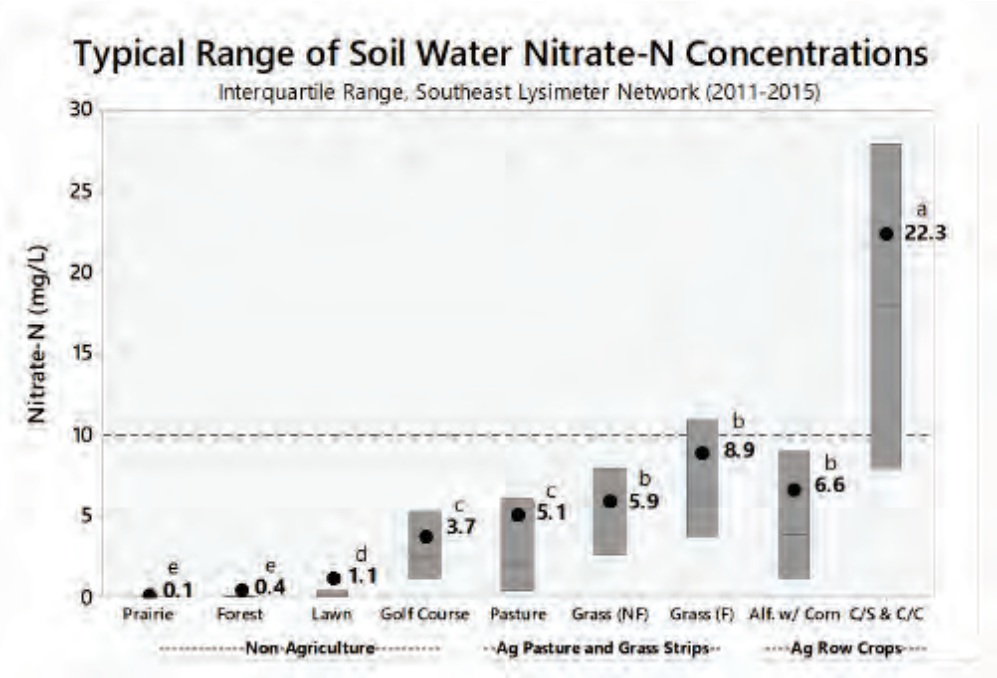

Figure 10: Land Cover and Nitrate Contamination

As Figure 10 demonstrates, industrial agricultural land suffers from significantly more contamination than other types of land uses generating a risk to both surface and groundwater.

D. Conditions in the Karst Region Constitute an Imminent and Substantial Endangerment to Human Health Under the SDWA

The current levels of nitrate in drinking water in the karst region present an imminent and substantial endangerment to human health because consumption of drinking water that is contaminated with nitrate is known to cause serious health risks. Given the thousands of individuals who rely on either contaminated private wells or

[91] KEVIN KUEHNER ET AL., MINN. DEP'T OF AGRIC., EXAMINATION OF SOIL WATER NITRATE-N CONCENTRATIONS FROM COMMON LAND COVERS AND CROPPING SYSTEMS IN SOUTHEAST MINNESOTA KARST 14 (2020), https://wrl.mnpals.net/islandora/object/WRLrepository%3A3654/datastream/PDF/view.

contaminated PWS for drinking water in this region, there is reasonable cause for concern that individuals are, and will be, exposed to this risk at unhealthy concentrations.

Nitrate is plainly an endangerment to public health under the SDWA because EPA not only categorizes it as a "contaminant,"[92] but as an "acute contaminant" known to pose significant health risks. According to EPA, "[n]itrate is an acute contaminant, meaning that one exposure can affect a person's health. Too much nitrate in your body makes it harder for red blood cells to carry oxygen."[93] EPA previously found that nitrate levels above the MCL of 10 mg/L present an imminent and substantial endangerment to human health.[94]

Nitrate is a particularly insidious contaminant because it is colorless, odorless, and tasteless, meaning that people do not have a way of identifying its presence in their drinking water without testing.[95] MNWOO reports that at their testing clinics across the state, many of the people with high nitrate tests were unaware of the contamination and reported that they liked the taste of their well water.

Additionally, boiling nitrate-laden drinking water, as is often done in preparation of baby formula, increases the nitrate concentration of the water because nitrates do not evaporate and become more concentrated in the formula.[96] Shallower aquifers are both more likely to be used for private wells and are more contaminated. For example, in the karst region, the Prairie du Chien aquifer is shallower and much more nitrate contaminated than the deeper Jordan aquifer.[97] But deep wells can also be contaminated. For example, the well on the farm of one of MNWOO's directors is a multi-aquifer well with a total depth of 400 feet, but the water from that well has exceed 13 mg/L nitrates for over 20 years.[98]

[92] 40 C.F.R. § 141.62(b).
[93] *Frequently Asked Questions About Nitrates & Drinking Water*, ENV'T PROT. AGENCY (Sept. 2012), https://nepis.epa.gov/Exe/ZyPDF.cgi/P10150PM.PDF?Dockey=P10150PM.PDF.
[94] *See, e.g.,* Administrative Order on Consent, *In the Matter of Yakima Valley Dairies*, SDWA-10-2013-0080, at 7 (Mar. 19, 2013) (finding that "above the concentration of 10 mg/L in drinking water, nitrate may present an imminent and substantial endangerment to the health of persons"), https://www.epa.gov/sites/default/files/2017-12/documents/lower-yakima-valley-groundwater-consent-order-2013.pdf.
[95] *Nitrate in Drinking Water*, MINN. DEP'T OF HEALTH (Dec. 8, 2022), https://www.health.state.mn.us/communities/environment/water/contaminants/nitrate.html.
[96] *Frequently Asked Questions About Nitrates and Drinking Water*, ENV'T PROT. AGENCY (Sept. 2012), https://nepis.epa.gov/Exe/ZyPDF.cgi/P10150PM.PDF?Dockey=P10150PM.PDF.
[97] RUNKEL 2013, *supra* note 45, at 45.
[98] Jeffrey S. Broberg, MNWOO founder and board member, personal communication.

Drinking water contaminated with nitrate has well-documented adverse health risks including a variety of cancers, "blue-baby syndrome," and reproductive problems.[99] Childhood brain cancer has been linked to high nitrate levels in drinking water.[100] MDH also reports other potential health effects such as "increased heart rate, nausea, headaches, and abdominal cramps."[101] Nitrate in water supplies has also been linked to spontaneous miscarriages and birth defects.[102]

The numerous studies demonstrating that a contaminant known to cause disease and illness is present at unsafe levels in wells used by tens of thousands of residents proves an unambiguous SDWA "endangerment."

Because the present contamination of the region's drinking water and risk of significant adverse health effects from drinking contaminated water are both thoroughly documented, endangerment is clearly imminent. As explained above, endangerment is "imminent" if conditions that give rise to it are present, even if actual harm has not already been documented in the contaminated area. Unsafe levels of nitrate contamination in the karst region drinking water supply were first identified over 30 years ago,[103] and recent data trends indicate that nitrate contamination is continuing at a persistent—and harmful—level.[104]

[99] *Nitrate in Drinking Water*, MINN. DEP'T OF HEALTH (DEC. 8, 2022), https://www.health.state.mn.us/communities/environment/water/contaminants/nitrate.html; N. BEAUDET ET AL., NITRATES, BLUE BABY SYNDROME, AND DRINKING WATER: A FACTSHEET FOR FAMILIES, PEDIATRIC ENV'T HEALTH SPECIALTY UNITS (2014), https://ldh.la.gov/assets/oph/Center-EH/envepi/PWI/Documents/PEHSU_Nitrates_Consumer_1.20.15FINAL.pdf; Roberto Picetti et al., *Nitrate and Nitrate Contamination in Drinking Water and Cancer Risk: A Systematic Review with Meta-Analysis*, 210 ENV'T RSCH. 112988 (2022), https://www.sciencedirect.com/science/article/pii/S0013935122003152#bib109.

[100] A. Zumel-Marne et al., *Environmental Factors and the Risk of Brain Tumours in Young People: A Systematic Review*, 53 NEUROEPIDEMIOLOGY 121 (2019), https://www.karger.com/Article/Fulltext/500601?utm_source=external&utm_medium=referral&utm_campaign=getFTR; *see also*, Yanqi Xu, *Nebraska's Dirty Water,* THE READER (Oct. 28, 2022), https://thereader.com/2022/10/28/nebraskas-dirty-water/ ("Areas of the state that have higher pediatric cancer rates and birth defect rates also have higher nitrate levels, researchers say.").

[101] *Nitrate in Drinking Water*, MINN. DEP'T OF HEALTH (DEC. 8, 2022), https://www.health.state.mn.us/communities/environment/water/contaminants/nitrate.html.

[102] Allison R. Sherris et al., *Nitrate in Drinking Water during Pregnancy and Spontaneous Preterm Birth: A Retrospective Within-Mother Analysis in California*, 129 ENV'T HEALTH PERSPECTIVES, (2021), https://ehp.niehs.nih.gov/doi/full/10.1289/EHP8205.

[103] ORES 1982, *supra* note 50.

[104] TOWNSHIP TESTING UPDATE 2022, *supra* note 62.

The public health risks associated with nitrate contamination in the karst region constitute a "substantial" endangerment under the SDWA. According to EPA's updated guidance on SDWA emergency authority, an example of substantial endangerment is "a substantial likelihood that contaminants capable of causing adverse health effects will be ingested by consumers if preventative action is not taken."[105] Well sampling has consistently shown elevated nitrate levels in residential drinking water wells across the karst region. Thus, residents of the karst region have been, and continue to be, ingesting this contaminant. This alone demonstrates that the endangerment is substantial.

V. Minnesota Officials Have Failed to Achieve Safe Drinking Water Quality Despite Decades of Attempting to Implement Mitigation Plans

EPA should exercise its emergency authority under Section 1431 of the SDWA because users of USDW and PWSs in the karst region face imminent and substantial endangerment and actions by Minnesota officials have been ineffective. The chronology below describes state agencies' recognition of, and attempts to address, the substantial and imminent endangerment posed by nitrate pollution. The persistent contamination despite these efforts demonstrates their ineffectiveness.

Minnesota enacted the Groundwater Protection Act in 1989. It was based on a growing recognition of the vulnerability of Minnesota's groundwater resources.[106] In part, in was based on groundwater testing in the 1980s that showed nitrate levels exceeding the health limits in 40% of private wells tested and 7% of public wells.[107] It was followed closely by the development of the Nitrogen Fertilizer Management Plan by MDA in 1990.[108] Neither of these initiatives resulted in effective protection of Minnesota's groundwater resources from nitrate pollution, as evidenced by the persistent contamination of private and public water supplies at or above the health risk limit.[109] In 2010, MDA began the process of revising the Nitrogen Fertilizer Management Plan.[110] The updated Nitrogen Fertilizer Management Plan was finalized by MDA in 2015 and led to the Township Testing Program discussed above. One of the objectives for the Township Testing Program was to better grasp the extent and severity of the nitrate

[105] EMERGENCY AUTHORITY GUIDANCE, *supra* note 12, at 11 (explaining that an endangerment is substantial "if there is a reasonable cause of concern that someone may be exposed to a risk of harm").
[106] JOHN HELLAND, MINN. H.R. RSCH. DEP'T, A SURVEY OF THE GROUNDWATER ACT OF 1989, (2001), https://www.house.mn.gov/hrd/pubs/gdwtract.pdf.
[107] *Id*.
[108] MINN. DEP'T OF AGRIC., NITROGEN FERTILIZER MANAGEMENT PLAN (2015, addended July 2019), https://www.mda.state.mn.us/sites/default/files/2019-08/nfmp2015addendedada_0.pdf [hereinafter NITROGEN FERTILIZER MANAGEMENT PLAN].
[109] JOHN HELLAND, MINN. H.R. RSCH. DEP'T, A SURVEY OF THE GROUNDWATER ACT OF 1989, (2001), https://www.house.mn.gov/hrd/pubs/gdwtract.pdf.
[110] NITROGEN FERTILIZER MANAGEMENT PLAN, *supra* note 108, at ix.

contamination problem—which it did. These data were used to inform the development of the Groundwater Protection Rule, which was passed in 2019 but falls short of the regulatory response needed to address the issue for the reasons documented below.

Also in 2010, the Minnesota Legislature approved funds for MPCA to develop aquatic life water quality standards for nitrate, in recognition of the need to protect Minnesota's aquatic life from the toxic effects of high nitrate. In response, MPCA issued its Aquatic Life Water Quality Standards Technical Support Document for Nitrate, which recommended a chronic nitrate standard of 3.1 mg/L to be protective of aquatic life.[111] The MPCA did not adopt water quality standards for nitrate, however, and has continued to defer to that 2010 legislative mandate to this day.

In 2013, MPCA published a report titled "Nitrogen in Minnesota Surface Waters." The report documents the widespread extent of nitrate contamination in Minnesota's waters, noting that in southeastern Minnesota, there are several streams where "groundwater baseflow provides a continuous supply of high nitrate water to streams throughout the year."[112] In other words, MPCA recognized that the groundwater in this area is so polluted, it is polluting the surface water.

In 2014, eleven Minnesota organizations jointly published a Nutrient Reduction Strategy for nitrogen and phosphorous pollution, led by MPCA.[113] The goal was to ultimately reach Minnesota's state water quality goals and downstream impacts like eutrophication in the Gulf of Mexico. In 2020, MPCA issued its 5-year progress report, considering whether the 2014 Nutrient Reduction Strategy was successful. The progress report shows that while phosphorous concentration trends in Minnesota waterways have generally decreased over the past 10-20 years, nitrate concentration trends have increased—in some major rivers by 20-60%. The Progress Report identifies row crop agriculture as the largest source of nitrogen.

Even with overwhelming data and analysis showing the trends and the reasons for concern, more recent strategies have been similarly ineffective. In 2019, MDA finalized

[111] PHIL MONSON, MINN. POLLUTION CONTROL AGENCY, AQUATIC LIFE WATER QUALITY STANDARDS TECHNICAL SUPPORT DOCUMENT FOR NITRATE (2010), https://wrl.mnpals.net/islandora/object/WRLrepository%3A77. Although MPCA's regulatory focus has been on surface water, in the karst region the connection between surface and groundwater is so immediate, that surface water quality standards are highly relevant to protecting groundwater quality.

[112] MINN. POLLUTION CONTROL AGENCY, NITROGEN IN MINNESOTA SURFACE WATERS 3 (2013), https://www.pca.state.mn.us/sites/default/files/wq-s6-26a.pdf.

[113] MINN. POLLUTION CONTROL AGENCY, THE MINNESOTA NUTRIENT REDUCTION STRATEGY (2014), https://www.pca.state.mn.us/sites/default/files/wq-s1-80.pdf.

the Groundwater Protection Rule, which has several deficiencies.[114] For example, although fall application of commercial fertilizer is restricted in the karst region, as well as in identified DWSMAs, fall application of manure is not. There are other significant flaws in the rule that fail to adequately protect USDWs. First, the regulatory scope of the rule is limited to DWSMAs for community wells and provides no direct assessment or protection of private wells that fall inside a DWSMA and no assessment or protection for those outside of a DWSMA (see Figure 5 above). As both MCEA and MDH noted in comments on the Groundwater Protection Rule, the Rule should include a mitigation process for private wells and non-community public water supply wells that is equivalent to what it establishes for public water supplies.[115] Without this equitable approach, MDH notes that the rule "does not serve the public health needs of rural Minnesotans, many of whom already suffer inequities relative to public health outcomes."[116] Second, there can be a significant lag time from days to years from the initial contamination of groundwater or surface water from sources of nitrogen and the necessary action taken by the state agencies to address the source. The MDA has the general authority to issue penalties for violations of its rules through Minnesota Statutes 18D, but the Groundwater Protection Rule requires a monitoring period that can last decades before enforcement actions are taken.[117] Lastly, the rule only requires best management practices to be used once a water source reaches mitigation level 3 or 4 contamination and even then, MDA cannot require application rates below that recommended by the University of Minnesota's Extension Services. Since the Groundwater Protection Rule went into effect, none of the DWSMAs with elevated nitrates have been classified at mitigation level 3 or 4, and thirteen mitigation level decisions have been "delayed for good cause."[118] This means that thus far, the Rule continues to rely on voluntary approaches that have not remedied the problem over the last several decades.

[114] Attached to this Petition as Exhibit A is Petitioner MCEA's Comment to MDA, which explains the deficiencies of the rule in greater detail.

[115] Ex. A; *see also* Minn. Dep't of Health Comment Letter on Proposed Minnesota Department of Agriculture Rules Governing Groundwater Protection, Add. 1 (Aug. 14, 2018), https://speakup-us-production.s3.amazonaws.com/uploads/attachment/file/5b746f627d79656b8800e3cb/MDH_GW_ProtRuleComments.pdf.

[116] Minn. Dep't of Health Comment Letter on Proposed Minnesota Department of Agriculture Rules Governing Groundwater Protection, at 2 (Aug. 14, 2018), https://speakup-us-production.s3.amazonaws.com/uploads/attachment/file/5b746f627d79656b8800e3cb/MDH_GW_ProtRuleComments.pdf.

[117] MINN. DEP'T OF AGRIC., STATEMENT OF NEED AND REASONABLENESS IN THE MATTER OF PROPOSED PERMANENT RULES RELATING TO GROUNDWATER PROTECTION 131-133 (2018).

[118] *Delayed for Good Cause: Drinking Water Supply Management Area Mitigation Level Determination*, MINN. DEP'T OF AGRIC., https://www.mda.state.mn.us/delayed-good-cause (last visited Apr. 21, 2023).

In 2021, MPCA released the final General NPDES Permit for CAFOs, which also has several deficiencies.[119] First, there is no monitoring required to ensure that nitrate is not leaching from storage lagoons into groundwater or whether the land application practices are causing or contributing to water quality problems. Both of these practices are known to contribute nitrate to Minnesota's waters, and all NPDES permits are required to have conditions that assure compliance with applicable limitations.[120] Second, there is no prohibition on fall application of manure, and winter application of solid manure is allowed in December and January. There are also no controls on summertime application of manure on hayfields without incorporation into the sensitive soils of the karst region. Third, there is no required pre-plant testing for nitrate to ensure that farmers properly account for residual nitrates that remain from manure applied in previous years when they calculate expected crop nitrogen needs.[121]

The Minnesota Department of Health is charged with insuring that public water supplies meet drinking water standards and implementing wellhead protection measures.[122] In a March 2021 report, MDH stated that "currently, there are approximately 400,000 acres in vulnerable groundwater Drinking Water Supply Management Areas," and that MDH's Source Water Protection Program "has a goal to protect vulnerable land in DWSMAs statewide by 2034."[123] However, the implementation of land use changes in Source Water Protection Plans is largely voluntary and does not protect underground sources of drinking water supply for private well owners who live outside of DWSMA boundaries. Finally, under the Minnesota Well Code MDH regulates private well construction and initial testing for nitrate and other pollutants like total coliform. However, "private drinking water testing and monitoring are otherwise unregulated and voluntary, with no formal tracking of water quality over time."[124]

Most recently, in 2022, MPCA stated that it was still not going to develop water quality standards for nitrate pollution in surface waters used for recreation and aquatic

[119] Attached to this Petition as Exhibit B is Petitioner MCEA's Comment to MPCA, which explains the deficiencies of the CAFO General Permit in greater detail.
[120] 33 U.S.C. § 1342(a)(2); *see also* 40 C.F.R. § 122.48(b), Minn. R. 7001.0150 subp.2B.
[121] Ex. B at 22-23.
[122] James Lundy et al., *Minnesota's 1989 Ground Water Protection Act: Legacy and Future Directions*, 5 MINN. GROUNDWATER ASSOC. (2022).
[123] *Protecting Vulnerable Drinking Water Sources*, MINN. DEP'T OF HEALTH (March 23, 2021), https://www.health.state.mn.us/communities/environment/water/docs/cwf/vulnacres.pdf.
[124] James Lundy et al., *Minnesota's 1989 Ground Water Protection Act: Legacy and Future Directions*, 5 MINN. GROUNDWATER ASSOC. 34 (2022).

life, despite the recognition that such a standard is necessary.[125] The State's repeated failures to mitigate nitrate levels in drinking water put more and more people at risk of drinking contaminated water. Allowing agricultural practices to continue in the karst region without meaningful changes to commercial fertilizer application, manure management, and manure disposal practices, will perpetuate the imminent and substantial endangerment to residents' health in direct violation of the SDWA. Although Minnesota officials have clear authority to adopt the mandatory regulations necessary to resolve the imminent and substantial endangerment, they have consistently refused to act. EPA must not let Minnesota officials continue to sit on the sidelines for another decade as the threat to the health of Minnesota citizens grows ever more severe.

VI. Requested Emergency Action to Abate Ongoing and Ever-Increasing Endangerment to Human Health from Nitrate Contamination

As discussed in detail above, the statutory prerequisites for emergency action under 42 U.S.C. § 300i are satisfied here. First, nitrate, which is a "contaminant" under the SDWA, is present in and continues to leach into USDW in the karst region. Second, the presence of nitrate contamination in groundwater is causing an imminent and substantial endangerment to public health; an alarming number of karst region residents rely on USDW that have been identified as carrying substantial nitrate risks for users. Finally, the State of Minnesota has not taken timely or effective action to abate the public health endangerment.

EPA has broad authority to investigate and remediate threats to public health under the SDWA. "Once EPA determines that action under Section 1431 is needed, a very broad range of options is available" as necessary to protect users of USDW.[126] The tools available to EPA include conducting studies, halting the disposal of contaminants that may be contributing to the endangerment, and issuing orders such as mandatory changes to manure generation, handling, and land application practices. In fact, "EPA may take such actions notwithstanding any exemption, variance, permit, license, regulation, order, or other requirement that would otherwise apply."[127]

EPA should prioritize investigating and abating nitrate contamination in the karst region. Specifically, Petitioners respectfully request EPA take at least the following measures under its SDWA Section 1431 emergency powers, either by administrative order or through civil action:

[125] PHIL MONSON, MINN. POLLUTION CONTROL AGENCY, AQUATIC LIFE WATER QUALITY STANDARDS TECHNICAL SUPPORT DOCUMENT FOR NITRATE (2010), https://www.pca.state.mn.us/sites/default/files/wq-s6-13.pdf.
[126] EMERGENCY AUTHORITY GUIDANCE, *supra* note 12, at 14.
[127] *Id.* at 9.

Investigation and Risk Assessment:

- Conduct investigation and monitoring throughout the karst region to more accurately trace the sources and quantities of nitrogen pollution, and to identify which sources are causing nitrate contamination;
- Investigate MPCA's CAFO permit requirements and MDA's and MPCA's best management practices for nutrient management to determine why they have been unsuccessful at protecting groundwater in the karst region;

Engagement and Communication:

- Work with MDH to notify the public of the existing nitrate hazards and provide public updates throughout the process of returning drinking water to a safe condition;

Planning:

- Determine what enforcement measures should be implemented to effectively reduce nitrogen pollution from CAFO and industrial agriculture sources;
- Provide a timetable for implementing a remedy to abate nitrate contamination from identified contaminators;

Assistance:

- Order the parties responsible for the nitrate contamination to supply free water testing and ensure a free source of clean drinking water to residents of the karst region whose private wells or PWSs exceed safe limits for nitrate to prevent blue-baby syndrome, cancer, and other adverse health effects;
- Provide assistance to private well owners to engage in effective private well management practices;

Regulation:

- Prohibit CAFOs from opening, expanding, or modifying operations in the karst region unless and until nitrate concentrations in wells with historically high levels of nitrate consistently fall below the MCL of 10 mg/L;
- Require CAFOs and agricultural operators land-applying CAFO waste or other nitrogen fertilizers to modify their practices so that these operations will cease overburdening the area with nitrogen pollution via lagoon leakage, land application of manure, and/or spills and leaks.

The threat to public health in the karst region from nitrate pollution of groundwater is present and pervasive, and all signs indicate a continuation and exacerbation of dangerous contamination levels absent EPA action. Therefore, the

undersigned Petitioners respectfully request that EPA use its emergency powers under the SDWA to take the actions necessary to abate the sources of contamination that increasingly place the public at substantial risk and provide other forms of relief within its authority as long as the endangerment persists.

VII. Conclusion

In conclusion, for the reasons stated above, the undersigned Petitioners respectfully request that EPA invoke its emergency authority under Section 1431 of the Safe Drinking Water Act to urgently address the imminent and substantial endangerment to public health within the karst region of Minnesota caused by ongoing and increasing nitrate contamination. Please contact the undersigned for more information regarding this Petition.

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Exhibit A

Minnesota Center for Environmental Advocacy

Using law, science, and research to protect Minnesota's environment, its natural resources, and the health of its people.

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August 15, 2018

VIA ELECTRONIC SUBMISSION

Administrative Law Judge Jessica Palmer-Denig

Re: Proposed Rules Governing Groundwater Protection, Minnesota Rules, 1573;
Revisor's ID Number RD4337,
OAH Docket No. 71-9024-35205

Dear Administrative Law Judge Palmer-Denig:

This letter includes the comments of the Minnesota Center for Environmental Advocacy (MCEA) on the Minnesota Department of Agriculture's (MDA) Proposed Rules Relating to Water Resource Protection Requirements. MCEA is a Minnesota nonprofit environmental organization whose mission is to use law, science and research to preserve and protect Minnesota's wildlife, natural resources, and the health of its people. MCEA has statewide membership. MCEA is concerned about the impacts of agricultural pollution on Minnesota's waters and has been engaged with MDA on issues related to nitrogen fertilizer management for a number of years, including commenting on MDA's 2017 rule proposal.[1]

MCEA has supported its comments with references with numerous published documents which are provided as exhibits to this letter.

I. INTRODUCTION AND SUMMARY OF POSITION

MCEA agrees that a rule to protect groundwater from nitrate contamination is needed: indeed, it is long overdue.[2] Documentation in the record supplied by the Minnesota Department of Agriculture ("MDA") establishes that the voluntary best management practices ("BMPs") have failed to reduce or stabilize nitrate concentrations in groundwater in many areas of the state, and that those

[1] A copy of MCEA's 2017 comment letter is included as an attachment.
[2] Chapter 103H was enacted in 1989, with the goal of preventing degradation of the groundwater by human activities. Where prevention is practicable, it is intended that it be achieved. Minn. Laws 1989, ch. 326, art. 1, section 1.

concentrations continue to grow. Even where fully adopted, the BMPs are not enough to reduce excessive nitrate levels where they already exist.[3] More is needed.

MCEA supports the proposed fall and frozen soils application ban in "vulnerable areas" and in drinking water system management areas ("DWSMAs") where N has exceeded 5.4 mg/L at any time in the past 10 years. However, the fall application ban part of the rule as proposed is riddled with convoluted and unsupported exclusions and exceptions which will make the fall application ban difficult to implement. Most importantly, the record shows that simply restricting the timing of nitrogen fertilizer application will not meet the statutory goals in those areas that are vulnerable to contamination. In fact, restricting the timing of application is one of the least effective of the University of Minnesota nitrogen fertilizer application recommendations.[4] At the very minimum, the record shows that in these vulnerable areas of the state, all the University of Minnesota "recommended" practices, including rate, timing, source, and placement, must be mandated to have a significant impact on excessive nitrate levels, with a particular focus on the "right rate" of nitrogen fertilizer.[5] And likely more actions must be required in order to prevent exceedances of the nitrate Health Risk Limit ("HRL") in these areas.[6]

MCEA supports the issuance of Water Resource Protection Requirement orders ("WRPRs") by the commissioner, but believes that the proposed rule too narrowly restricts the use of such WRPRs to public water supply system protection areas. Protection is also needed for people who drink well water. MCEA also believes that the proposed rule fails to provide adequate due process when a WRPR is issued: both "responsible parties," and people who drink groundwater, must have the right to challenge the order.

Below, MCEA has provided alternatives that are supported by the record and that will not result in a substantially different rule within the meaning of Minn. Stat. § 14.05, subd. 2, but which will result in a rule that is in compliance with Minn. Stat. § 103H.275, subd. 1(c), by requiring water resources protection requirements that are "designed to prevent and minimize the pollution to the extent practicable" and, most importantly, are "designed to prevent the pollution from exceeding the health risk limits."

The main issues with the rule are as follows.

A. The Proposed Rule Fails To Comply With Statutory Authority And Is Arbitrary Because It Does Not Protect People Who Drink From Private Wells

Persons who use water supplied by municipal or rural water supply providers are protected against drinking high nitrate levels by existing regulations requiring testing and which ensure a

[3] This is not surprising because, while helpful in controlling nitrogen fertilizer-related pollution, the BMPs were developed from research based on yield optimization and the production economics of corn and not specifically on water quality indices. Randall, *Nitrogen BMP's for Corn in Minnesota* (provided in the exhibits).
[4] Wall, *Nitrogen in Minnesota Surface Waters*, Minnesota Pollution Control Agency (June 2013). *See also* comments filed by Dr. Gyles Randall, August 1, 2018.
[5] *Id.*
[6] *Id.*

healthy water supply.[7] When a community water supply well becomes contaminated, community water supplies typically have various options to deal with it.[8] In contrast, people drinking from a private well may not test on a regular basis[9] and suffer the same costs[10]—but with fewer options—when their water becomes contaminated. Despite these facts, the rule as proposed only protects persons who use water supplied by municipal or rural water supply providers.[11] The proposed rule should be amended to require mandatory requirements and WRPRs in township areas where excessive nitrate levels are present based on available test results. This change is supported by the record. Indeed, the MDA notes that it initially considered implementing regulatory actions "on the township level" in 2017, and further admits that in at least twenty townships more than 10% of the people who voluntarily sampled their wells are drinking water that exceeds the health risk limit for nitrate.[12] The only reason offered as to why townships with significant private well contamination levels were not included in the published rule is the lack of resources and a preference on the part of affected responsible parties to have the program stay voluntary.[13] These reasons do not provide an adequate basis for the decision to abandon private well users and this decision is inconsistent with the MDA's duty under Minn. Stat. § 103H.275, subd. 1(c)(1) and (2). Furthermore, the MDA has undermined its "limited resources" argument by noting that "the MDA will implement the voluntary parts of the 2015 NFMP in townships up to level 2, including forming [Local Advisory Teams] and conducting groundwater

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[7] The federal Safe Drinking Water Act standards apply to community water systems in Minnesota. *See* 42 U.S.C. § 300f et seq. The Safe Drinking Water Act standards are enforced by the Minnesota Department of Health. *See* https://data.web.health.state.mn.us/drinkingwater.

[8] As noted by the Department of Health, community water systems can take a high nitrate well and reclassify it to only be used in case of emergency, remove the well from service, or seal the well so that it cannot be used again. While these strategies may appear to be more economical than adding a treatment process, there are still costs associated with each strategy - locating a new well site, drilling a new well, or treating for a different contaminant. *See* 2017 Annual Report at 15, available at http://www.health.state.mn.us/divs/eh/water/com/dwar/report2016.pdf.

[9] According to the Minnesota MDA of Health, "Twenty-one percent of Minnesotans (1.2 million people) get their drinking water from a private well. Private well users are not afforded the same water quality safeguards as people who get their water from public water systems. While public water systems make sure water is safe for the end-user, private well users are responsible for making sure their water is safe for everyone in the household to drink." http://www.health.state.mn.us/divs/eh/cwl/wells/index.html.

[10] In 2008, average remediation costs were $190 y-1 to buy bottled water, $800 to buy a NO3 removal system plus $100 y -1 for maintenance, and $7,200 to install a new well. Lewandowski, A. M., Montgomery, B. R., Rosen, C. J., & Moncrief, J. F. (2008*). Groundwater nitrate contamination costs: A survey of private well owners*. Compare to increased public water supply costs cited in http://www.house.leg.state.mn.us/comm/docs/CostofNitrateContaminationtoPublicSuppliers2007.pdf.

[11] The attached map demonstrates how little area is *potentially* covered by the proposed rule (the black circled areas), as opposed to the areas where townships have already tested as having more than 5 percent wells above the HRLs.

[12] Statement of Need and Reasonableness dated April 30, 2018 ("SONAR") p. 110.

[13] *Id*.

monitoring."[14] It is unreasonable for MDA to prioritize its limited resources to require action to reduce nitrate contamination for public water supply users who are already guaranteed clean water over private wells owners who do not have such a guarantee. Moreover, if resources are limited, the MDA has non-arbitrary means for deciding how to allocate these resources, such as phasing in a program based on priorities, which this rule already identifies.[15] MDA's decision to abandon private well owners from the protections of the rule is arbitrary for the same reasons that the Minnesota Department of Labor and Industry was found to have acted arbitrarily in *Builders Ass'n of Twin Cities v. Minnesota Dept. of Labor and Industry*, 872, N.W.2d 263 (Minn. App. 2015). In that case, the Court of Appeals concluded that it was unreasonable for the Minnesota Department of Labor to adopt a building code that failed to require smaller homes to be protected by sprinkler systems where the record supported the potential for a phase-in of sprinkler requirement. MDA has not provided a reasonable basis for making WRPR protection available to only some of the millions of Minnesota residents who use drinking water as their major source of water – the nearly 30% of those residents excluded from these protections are those most in need. Private well users must be included; fundamental fairness compels nothing less.[16]

The following chart reflects a reasonable system to protect private well users from nitrogen fertilizer-related pollution which could be adopted as part of this rule in addition to the current provision protecting those who consume water from community drinking water sources:

Mitigation Level ("ML")	Criteria	Required actions for the commissioner and responsible parties[17]	Transition to higher level
1	At least 3 to less than 5% of private wells tested exceed the HRL within a township	Commissioner provides education and compliance resource information to all responsible parties within the township; Commissioner provides notice of opportunity to form a local advisory team ("LAT"). All responsible parties required to maintain and produce (on request) nitrogen fertilizer application records.	Exceed criteria for ML1.

[14] SONAR p. 111.
[15] *See* proposed 1573.0050, subp. 1, Item D (prioritization criteria for WRPRs).
[16] MCEA refers MDA to the petition filed as a separate comment today, signed by close to 200 individuals, that asks MDA to protect the drinking water of individual well owners contaminated by nitrates, not just city water supplies.
[17] MCEA also proposes, as discussed below, that the designation of a mitigation level area include certain reasonable actions that can be taken by responsible parties prior to the issuance of a WRPR. The actions shown in this chart are the same as those proposed by MCEA for the equivalent DWSMA mitigation level areas, creating a level playing field for responsible parties in DWSMA areas and township areas.

2	At least 5 to less than 10% of private wells tested exceed the HRL within a township	ML 1 actions; Responsible parties: • comply with no-risk nitrogen BMPs; • obtain yearly subsoil nitrogen samples (Nebraska program) and produce upon request.	Exceed criteria for ML2.
3	Greater than 10% of private wells tested exceed the HRL within a township	ML2 actions; Responsible parties: • develop and implement a nutrient management plan; • comply with all other actions required by the commissioner in a WRPR.	Exceed criteria for ML3.
4	Greater than 15% of private wells tested exceed the HRL within a township	ML3 actions; Responsible parties comply with all other actions required by the commissioner in a WRPR.	

B. The Rule Arbitrarily Prolongs Reliance On Voluntary Best Management Practices To Reduce Nitrates In Groundwater Despite Evidence That The Best Management Practices Have Not Succeeded In Controlling Nitrate Levels. Further, The Rule Allows The Voluntary Compliance To Continue For An Indeterminate Period Of Time

Initially, the rule allows the commissioner to establish only Mitigation Level ("ML") 1 and 2 areas. In these areas, there are no mandatory requirements and WRPRs cannot be issued, despite the fact that in ML2 areas the water is predicted to exceed the health risk limit ("HRL") in 10 years or has already had a reading in excess of the HRL. In the ML1 and 2 areas, MDA proposes only to try—again—to get responsible parties to use the nitrogen BMPs to control nitrate levels. This is manifestly unreasonable because the MDA has admitted in the SONAR that the existing nitrogen use BMPs have not proven to be a successful means for reducing nitrate levels, particularly due to adoption failure.[18] Worse, the proposed rule prohibits the commissioner from evaluating the impact of the nitrogen use BMPs for "at least three growing seasons" or the "lag time," whichever is longer. Lag times can be decades. The phrase "at least" is not limiting. As a result, the proposed rule unreasonably and arbitrarily allows the commissioner to prolong this monitoring period, potentially for decades, regardless of whether the nitrogen use BMPs have been implemented and regardless of whether nitrate levels continue to increase in the subsoil.[19] Thus, voluntary activities can be continued for an endless period of time, regardless of result.

[18] SONAR part IV, pp. 49-59.

[19] Proposed rule 1575.0040, subp. 7, Items G and H allow the commissioner, with unfettered discretion, to postpone mandatory actions for an additional 3 or more growing seasons if the commissioner determines that the "responsible parties…have demonstrated progress in

The MDA cannot have it both ways. The MDA cannot continue to rely on voluntary BMP compliance while admitting that voluntary compliance has not been effective. If the MDA believes one last voluntary period is justified, then that period must be carefully limited by the rule and not be subject to extension. The commissioner should react to the data—not BMP compliance—to determine when more action is needed.[20]

Further, MCEA believes that the record supports a decision to require responsible persons in all areas where elevated nitrate levels are detected (both for public and private wells) to require compliance with certain reasonable requirements such as recordkeeping *before* a site specific WRPR is issued, in particular in areas where exceedance of the health risk limit is statistically likely to occur.

The following table shows reasonable criteria for establishing mitigation levels for areas served by public wells and private wells. This table also shows reasonable actions that MDA could require responsible parties to take prior to WRPR issuance. MCEA believes these actions are needed and reasonable to ensure that the goal of the Groundwater Protection Act—to *prevent* groundwater from exceeding HRLs—is met.

Mitigation Level ("ML")	Criteria	Required Actions for Commissioner and Responsible Parties	Transition to higher level
1	One reading of 3.0 mg/L or greater in a public water supply well(s) At least 3 to less than 5% of private wells tested exceed the HRL within a township	• Commissioner provides education and compliance resource information.[21] • Commissioner provides notice of opportunity to form a local advisory team ("LAT"). • All responsible parties required to maintain and produce (on request) nitrogen fertilizer application records.	ML 1 stays a ML1 so long as it does not meet the criteria for a ML2.

addressing nitrates…" or if there is a "significant change in land use in a drinking water supply management area." Neither "demonstrated progress" nor "significant change" are defined in any manner that would allow a party to determine with any certainty what these statements mean. The lack of enforceability of these rule provisions contravenes the statutory goals and is unsupported by the record.

[20] Although MDA suggests that is it is required by statute to "evaluate" BMP adoption before it can issue a WRPR, Minn. Stat. § 103H.275 says nothing about evaluation of BMP adoption before a WRPR can be issued. Instead, the statute indicates that the contents of a WRPR—the requirements in the WRPR—must be based on "the use and effectiveness of best management practices." The BMPs already exist. If the BMPs have been effective, they can be included in the WRPR. If they have not been effective, they should not be included in the WRPR. But in any event, BMP adoption levels are not mandated as a pre-condition for issuance of a WRPR.

[21] This would include providing the recommended BMPs for the area.

2	One reading of 5.4 mg/L or greater in a public water supply well(s). At least 5 to less than 10% of private wells tested exceed the HRL within a township	All ML1 activities plus: • All responsible persons required to obtain yearly subsoil nitrogen samples (Nebraska program) and produce upon request.	ML2 becomes a ML3 if statistics show HRL will be exceeded in 10 years.
3	One reading of 7.0 mg/L or greater in a public water supply well(s). Greater than 10% of private wells tested exceed the HRL within a township	All ML 2 activities plus: • The No-risk Nitrogen Fertilizer Use BMPs. • Compliance with a Nutrient Management Plan. • [Commissioner issues WRPR based on priority criteria.]	ML3 becomes an ML4 if the health risk limit is exceeded.
4	One reading of 8.0 mg/L or greater in a public water supply well(s). Greater than 15% of private wells tested exceed the HRL within a township	All ML 3 activities plus: Commissioner issues a WRPR based on priority criteria that must include AMTs.	

Neither recordkeeping[22] nor subsoil sampling are presently included in the rule as actions that responsible parties should take at lower mitigation levels, yet these actions would provide the commissioner information that the commissioner could use to determine whether BMPs are being complied with and are being effective, and would not be costly.[23] The sampling is reasonable because it is currently conducted by Nebraska producers and others.[24] Recordkeeping is reasonable because compliance with the BMPs requires recordkeeping, and any producer applying nitrogen fertilizer (or their agent or consultant) would be required to have such records.[25] The requirement for responsible parties in ML3 areas to comply with nitrogen fertilizer BMPs and nutrient management plans immediately upon triggering the ML3 designation is reasonable because these actions will not significantly increase costs for the

[22] Recordkeeping is only required after a WRPR is issued. *See* 1573.0060, Item A(1).
[23] In fact, many Minnesota producers are already keeping such records and taking such samples. *See* testimony of Zach Johnson and Richard Syverson, July 25, 2018.
[24] *See Id.*; SONAR p. 122.
[25] *See* http://www.mda.state.mn.us/nitrogenbmps.

responsible parties,[26] and it may take some time for the commissioner to develop and issue a WRPR. In the interim, because the health risk limit may shortly be exceeded, it is reasonable to require the responsible parties to take immediate actions to better document and control nitrogen fertilizer use.

C. The Rule Lacks Adequate Due Process When The Commissioner Issues A WRPR Order, And Limits The Commissioner's Discretion To Include Effective Conditions

Although the rule requires notice to be given to affected persons prior to issuance of a WRPR as required by statute, only "responsible persons" subject to the order can seek review, which is unfair to the affected persons drinking the water. All persons impacted by the WRPR must be provided an opportunity for administrative and judicial review. Further, no standard is stated in the rule against which the commissioner's decision will be judged to determine whether it meets the standards of the statute. The rule should—at a minimum—require that a WRPR "prevent and minimize the pollution to the extent practicable" and be "designed to prevent the pollution from exceeding the health risk limits."[27] Finally, the review process lacks basic standards necessary to limit frivolous appeals, and appears to confuse "contested case hearings" with "public hearings."

D. The Rule Unreasonably Limits The Commissioner's Discretion To Require Actions That Would Reduce Nitrogen Concentrations Where Necessary To Ensure That The Health Risk Limit For Nitrate Is Not Exceeded

The proposed rule fails to require the commissioner to include certain basic content that should be required in the WRPR, including monitoring, record-keeping, reporting, and the like. But more importantly, the proposed rule limits the commissioner's authority to require certain actions in a WRPR that are immediately effective to reduce nitrogen—alternative management tools—just because the alternative management tool might cost money to implement. Similarly, the proposed rule limits the commissioner's authority to require any changes to the "primary crop" and limits the use of nitrogen fertilizer to levels below rates the University of Minnesota has identified as the most profitable. Although undefined, it would appear that this provision would limit the commissioner's ability to require, for any area for any time, a different crop to be grown (say alfalfa as part of a rotation on a particular field), as part of a WRPR. These limitations are unreasonable and unsupported by the record and do not meet the goals stated in Minn. Stat. § 103H.275. Instead, if there is a particular requirement that would cause hardship for a responsible party to implement, the commissioner should have the authority to enter into a two-year schedule of compliance that would allow a regulated party to make the necessary adjustments to come into compliance.

E. The Rule Contains Many Provisions That Provide The commissioner Too Much Discretion, As Further Described Below

The rule uses the phrase "as determined by the commissioner" in four places and the phrase "if the commissioner determines" in seven places. This language does not meet the standard for a

[26] Throughout this record it is noted that compliance with nitrogen BMPs may save producers money.
[27] Minn. Stat. § 103H.275, subd. 1(c)(1)(2).

rule, because it vests the decision in the commissioner without establishing a standard or a process. For example, all areas where "exclusions" can be established from the ban on fall nitrate fertilizer application are "as determined by the commissioner." This fails to meet the standard for administrative rules, which cannot allow excessive and unfettered discretion such that a party is unable to determine how the rule will be applied. The Administrative Law Judge must reject a rule if it "is not a "rule" as defined in Minnesota Statutes, section 14.02, subdivision 4, or by its own terms cannot have the force and effect of law."[28] This rule cannot be determined by its own terms, because it relies on decisions by the commissioner based on unstated criteria in many provisions. In fact, this lack of standards for WRPRs makes it extremely difficult to determine whether the rule will have any positive impact – the commissioner could rely on exclusions and issue WRPRs that include very minimal requirements (there is no stated standard for the commissioner's WRPR order, just a list of potential options that could be included in a WRPR), and implement the rule in a manner that contradicts the goals of the Groundwater Protection Act.

F. The Rule Contains Many Provisions That Are Fatally Vague, As Further Described Below

For example, the proposed rule does not establish a deadline in part 1573.0040, subpart 2, for the commissioner to designate a DWSMA as a mitigation level 1 or 2 following receipt of information from the Department of Health ("MDH") that a public well has exceeded a trigger level as set forth in subpart 3. To be enforceable, the rule must establish a deadline for the commissioner to act, i.e., within 60 days of receipt of information from MDH.

In addition to the above, the rule contains numerous provisions that are poorly drafted and should be fixed to ensure that the rule can be enforced.

II. FACTUAL AND LEGAL BACKGROUND

A. Nitrogen Fertilizer Use And Nitrate Contamination In Minnesota

The following are the underlying facts pertaining to these proposed rules that must be taken into consideration in evaluating whether the proposed rule meets the statutory standard.

Despite MDA's years of promoting compliance with the University of Minnesota nitrogen fertilizer use recommendations, nitrogen fertilizer sales in Minnesota skyrocketed by nearly 200,000 tons/year from 1990 to 2016, including a 15% increase over the past 5 years.[29] In addition the acreage of crops that "leak" nitrogen fertilizer into groundwater, corn and soybeans, are consistently expanding, with over 4 million more leaky acres today than in 1990.[30]

The result is widespread nitrate contamination of groundwater in Minnesota's agricultural landscapes. Nearly half of the wells in MDA's shallow groundwater monitoring network exceed

[28] Minn. R. 1400.2100 (g).
[29] MDA Draft Nitrogen Fertilizer Rule Presentation, at slide 24, found at http://www.mda.state.mn.us/~/media/Files/chemicals/nfmp/nfrpresentation.pdf (last visited Aug. 14, 2018).
[30] *Id.* at slide 25.

the nitrate Health Risk Limit ("HRL") of 10 mg/L.[31] Where shallow wells are contaminated, deeper wells also are likely contaminated.[32]

The Minnesota Department of Health reviewed data for 2014 – 2015 from Minnesota's public water supply wells across the state and found that 537 of 10,519 (5.11 percent) had nitrate levels above 3 mg/L. These include wells for both communities and for businesses, schools, and organizations that provide water to the public.[33]

The Minnesota Department of Agriculture's Township Testing Program ("TTP") provides testing for nitrate to homeowners who have wells in vulnerable areas of the state where groundwater used for drinking water can be affected by agricultural production. As of March 2018, 242 vulnerable townships from 24 counties participated in the TTP from 2013 to 2017. In the 242 townships tested, 113 (47%) have 10% or more of the wells over the HRL for Nitrate-N. Overall, 10.1% (2,583) of the 25,652 wells voluntarily tested exceeded the HRL for Nitrate-N.[34]

And these numbers are expected to rise: changes to cropping practices can be expected to result in an increased risk of nitrogen loading.[35]

B. Statutory Requirement For WRPRs

The Groundwater Protection Act of 1989 has the goal of preventing groundwater degradation.[36] For agricultural chemicals and practices, including the use of nitrogen fertilizer, the statute is implemented by the MDA, and requires MDA to evaluate the detection of agricultural pollutants in the state's groundwater;[37] monitor groundwater for pollutants found to be of "common detection" as the result of normal use of a product or practice;[13] develop voluntary, practicable measures that are capable of preventing and minimizing degradation of groundwater from agricultural chemicals and practices, called BMPs;[38] and promote and evaluate the use and effectiveness of these BMPs.[39]

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[31] *Id.* at 2-83.
[32] In 2010, MDA installed eight new wells in the Central Sands Region, approximately 10-15 feet deeper than existing shallow well sites. Id. at 2-75. 75% of these wells exceeded the Health Risk Limit. *Id.* at 2-83.
[33] *Minnesota Drinking Water 2017*, Annual Report for 2016, Minnesota Department of Health Environmental Health Division Section of Drinking Water Protection, available at http://www.health.state.mn.us/divs/eh/water/com/dwar/report2016.pdf
[34] http://www.mda.state.mn.us/~/media/Files/chemicals/nfmp/ttpudate201806.pdf
[35] Keeler and Gourevitch et al, *The Social Costs of Nitrogen*, Sci. Adv. 2016, at 6. The mechanisms are graphically explained at http://www.bwsr.state.mn.us/practices/farm-bill/FBAP_Winter_Meeting/2015/Estimating_the_External_Costs_of_Nitrogen_Fertilizer_in_MN.pdf.
[36] Minn. Stat. § 103H.001.
[37] Minn. Stat. § 103H.251, subd. 1. 13 Minn. Stat. §§ 103H.251, subd. 1(b) and 103H.005, subd. 5.
[38] Minn. Stat. §§ 103H.151, subd. 2 and 103H.005, subd. 4.
[39] Minn. Stat. §§ 103H.151, subd. 3 and 103H.275, subd. 1.

If implementation of BMPs proves ineffective, the Act provides MDA with the authority to adopt mandatory water resource protection requirements (WRPRs) that include "design criteria, standards, operation and maintenance procedures, practices to prevent releases, spills, leaks, and incidents, restrictions on use and practices, and treatment requirements."[40] WRPRs may be statewide or targeted, but those that are not statewide become effective only in areas designated by order of the MDA Commissioner.[41] WRPRs must be intended to prevent and minimize groundwater pollution to the extent practicable; be designed to "prevent the pollution from exceeding the health risk limits;"[42] and be based on "the use and effectiveness of best management practices, the product use and practices contributing to the pollution detected, economic factors, availability, technical feasibility, implementability, and effectiveness."[43] Although economic factors can be considered in decisions, these factors do not trump the overall goals established for the Act and cannot be paramount in view of overarching state policy in support of maintaining the resources of the state for the use of future generations.[44] Further, economic considerations cannot be limited to just those related to the cost to the responsible party; MDA must consider the cost of not acting on the affected public, who must pay to replace contaminated water supplies, as noted above.

Where this rule does not meet the intent of Groundwater Protection Act, MCEA requests that the Administrative Law Judge recommend changes to the rule that will ensure that it meets the minimum goals of the Groundwater Protection Act, in particular that the actions "prevent the pollution from exceeding the health risk limits" rather than allowing the status quo to continue, as that status quo has not succeeded in reducing impacts from nitrogen fertilizer to the groundwater as required by law.

III. MDA'S PROPOSED RULE: DETAILED PART BY PART ANALYSIS

MCEA provides detailed comments on the proposed rule below. In addition, MCEA has prepared a separate redline document of the proposed rule (attached). The proposed redline language addresses the problems identified in the proposed rule language and includes MCEA's proposed language.

A. DEFINITIONS (1573.0010):

1573.0010, subp. 2. Alternative management tools ("AMTs") are "specific practices and solutions described in part 1573.0090, subpart 1. . .that are approved by the commissioner to address groundwater nitrate problems," but in fact no specific practices are described in the referenced part. Instead, the referenced subpart merely indicates that the commissioner will post a list. Based on the SONAR, the AMTs are intended to "go beyond the nitrogen fertilizer BMPs" and could be identified by the local advisory teams, and could include a variety of management

[40] Minn. Stat. § 103H.005, subd. 15.
[41] Minn. Stat. § 103H.275, subd. 2(c).
[42] Minn. Stat. § 103H.275, subds. 1-2.
[43] Minn. Stat. § 103H.275, subd. 2(a).
[44] In addition to the Act, Minn. Stat. § 116D.02 makes clear that economic impacts are not more important than the value of preserving natural resources for future generations.

practices. Because the commissioner may allow these practices to substitute for nitrogen fertilizer best management practices,[45] the rule must define all the practices that would be approvable AMTs and establish a standard for new practices that might not be currently known. As currently drafted, the rule is too vague and provides too much unfettered discretion to the commissioner in allowing the unknown AMTs to substitute for mandated best management practices.

Needed definition: Health Risk Limit or HRL. The definitions should reference the particular health risk limit at Minn. Stat. § 103H.201 because this term is used throughout the rule and has a particular meaning.

Needed definition: Interested Person. To simplify references to public notice procedures, MCEA recommends that the commissioner define "interested persons" as those who have registered with the department to receive public notices concerning actions of the commissioner under the rule.

1573.0010, subp. 12. The definition of lag time is limited to areas "being monitored." The definition is too restrictive. Areas that have been monitored in the past will have an established lag time. It is unclear who is performing the monitoring referenced in this definition. Lag time should be defined to include all areas where data is adequate to support a determination of how long it takes for nitrogen fertilizer applied at the surface to enter the groundwater.

1573.0010, subp. 14. The rule must establish a process by which members of a "local advisory team" ("LAT") are "approved" by the commissioner and the definition should reference that process, or the rule should establish that the LAT must have a certain constitution, but does not require "approval" by the commissioner. The rule must better define the role of the LAT.

1573.0010, subp. 17. For the purpose of this rule, it does not make sense to use additional concepts from Minn. Stat. § 18C.215, which is a chapter designed for the regulation and control of the manufacture, distribution, and sale of fertilizer in this state. The intent of this rule is to ensure that the MDA can regulate agricultural practices that are leading to excess nitrate levels, and the definition of nitrogen fertilizer must reflect all fertilizers that are applied to supply nitrogen. The MDA should amend this definition to simply reference the statutory definition.

1573.0010, subp. 18. Subpart 18 defines a "public well" as a "community water system" which includes permanent (but not necessarily municipal) water supplies. MCEA supports this definition, but notes that the definitions of municipal public water supply well, and public well, as used in the rule, create confusion. The rule should cover all drinking water supply management areas that have been established to protect public water supplies, whether municipal or non-municipal. There is no basis under this rule for a distinction.

1573.0010, subp. 19. It is unclear why this definition restricts soil tests to those conducted by or under the direction of the commissioner within a drinking water supply management area. Residual soil nitrate tests should include any tests conducted under appropriate controls in any area by any person. MCEA recommends striking the phrase "conducted by or under the direction

[45] *See* Minn. R. 7040.0040, subp. 6 (evaluation of BMP adoption as part of determination of whether a "level 2" mitigation area continued).

of the commissioner" from this definition. The phrase "that are representative" will prevent non-standard test results from being considered. MCEA recommends that MDA reference a standard method of obtaining results from soil testing.

B. FALL AND FROZEN SOILS VULNERABLE AREAS BAN (1573.0030):

This part of the rule establishes a ban on application of nitrogen in areas with vulnerable soils in the fall and when there are frozen soil conditions. However, part 1573.0030, subp. 2 and subp. 3 establishes numerous exclusions and exceptions that undermine the intent of the ban. MCEA supports the ban, but does not agree with the language that allows the commissioner excessive discretion.

1573.0030, subp. 1. The proposed provision contains an odd wording. A DWSMA is not "from" a municipal public water supply well. The rule should state that the water supply management area is "established for" a public water supply well. Item A (3)(b) needs to worded in a similar fashion, i.e., reference that it is a drinking water supply management area established for a public water supply well with (or "which has had") nitrate-nitrogen levels greater than or equal to 5.4 mg/L at any point in the previous ten years. DWSMAs are established for public wells that are not municipal. MCEA believes that all public wells should be included.

1573.0030, subp. 1, Item C. Item C indicates that a responsible party in charge of cropland depicted on the commissioner's map is subject to the prohibition on fall application that is stated in part A. This sets up a potential conflict between the criteria in part A and duty to comply with the map in part C. It is important that the map not undermine the prohibition in part 1573.0030, Subp. 1, Item A. If Item A says "a responsible person shall not," then Item C, which states that "any responsible person is subject to Item A," is not needed.

1573.0030, subp. 2. Exclusions.

In general, this section of the proposed rule is drafted in a convoluted manner that makes it difficult to understand. However, closely read, the "exclusion" section appears to remove a significant portion of the vulnerable and DWSMA areas[46] subject to the prohibition on fall application based on certain broad soil ("leaching index") and climactic ("frost-free") assumptions. In Item G, the proposed rule also authorizes the commissioner to allow, based on unstated criteria and without any process whatsoever, fall applications in areas within a high-reading DWSMA if the commissioner believes "that the area is not contributing significantly to the contamination of the well" in the drinking water supply management area. Thus, the overall impact of Subpart 2 is to undermine the protection provided by prohibiting fall application of nitrogen fertilizer in vulnerable areas and threatened drinking water supply management areas.

The "exclusions" allow fall application of nitrogen fertilizer based on frost-free dates "in the county or a portion of the county" and a "leaching index" of various levels.[47] Later, however, the proposed rules state (Item B) that the exclusion applies to the entire county if a condition is represented on 50 percent or more of the land area of the county, but (Item C) commissioner can

[46] MCEA notes that MDA has proposed to correct this section to include DWSMA areas.
[47] The proposed rule states that the "leaching index" is "determined by the commissioner," but the definition of "leaching index" references the gridMet dataset for 1981-2010.

also subdivide a county by geographical boundary "if there is a clear change in conditions represented in a specific area of the county," but there is no description of what this "clear change in conditions" might be, or how the commissioner will make this determination or announce this determination. Finally, as noted above, the proposed rule appears to limit the exclusions to areas that are not drinking water supply management areas "with nitrate-nitrogen levels greater than or equal to 5.4 mg/L."[48] It is unclear whether these areas are the same as the areas subject to the fall application prohibition, which are stated to be those with a well having "nitrate-nitrogen levels greater than or equal to 5.4 mg/L at any point in the previous 10 years." Even so, as previously noted, this "exception to the exclusion" is undermined by Item G, which broadly allows the commissioner to exclude high-reading DWSMAs without any particular criteria for such an exclusion being set forth, nor any process by which the commissioner will exercise this authority.

The SONAR demonstrates that the MDA has proposed these exclusions based on the notion that cooler spring soils, combined with lower leaching indices, would result in reduced risk of groundwater contamination. However, although the MDA documents that it "heard many concerns from farmers in the western and northern parts of the state about the importance of fall nitrogen applications because of the short application window in the spring,"[49] there is little evidence of *scientific support* for the theory advanced by the MDA cited in the SONAR. No peer-reviewed or published articles are cited as support for the two-factor theory. One can only conclude that the MDA put the exclusions into this rule not on the basis of science, but instead because "there are logistical problems such as with an insufficient numbers (sic) tender trucks and spreaders to complete all fertilizer applications in this compressed spring period."[50]

If the MDA's theory that cooler spring temperatures and a reduced leaching index is scientifically based, MCEA would support removing areas that have these characteristics from the fall application ban area. However, the language creating the exclusion areas must be clear and not subject to the discretion of the commissioner, as detailed below.

1573.0030, subp. 2, item E. This Item appears intended to exclude non-agricultural counties, but references the wrong "Item A." The exclusion should be for *subpart 1,* Item A.[51]

1573.0030, subp. 2, items F and G. These are both problematic because they are vague. In Item F, what does it mean for a point source to be "a significant source" of N contamination? In Item G, the rule fails to specify the criteria that the commissioner will use to determine that the area is "not contributing significantly" to the N problem. Both of these exclusions are too vague to be enforceable unless amended. They both allow the commissioner free-rein to determine that an area will not be subject to the fall nitrogen prohibition, without any possibility of review. And

[48] As above, it is assumed that this reference is to the wells in the drinking water supply management areas.
[49] SONAR p. 97.
[50] SONAR p. 98.
[51] MDA has identified this as a needed change in an errata document published on the MDA website.

such discretion is unnecessary: state law already provides a variance procedure that a person needing relief can use if the application of the rule is unreasonable as applied to the person.[52]

1573.0030, subp. 3. Exceptions.

The MDA asserts that these exceptions are needed because they are a "necessary agricultural practice."[53] MCEA supports the requirement that the fall application allowed by the rules must be consistent with the BMPs or the rates in the Fertilizer Guidelines published by the University of Minnesota Extension.[54] However, in a number of cases, the information presented in the SONAR undermines the assertion that the exceptions are needed as a necessary agricultural practice.

For example, for item 2, the SONAR states that, for pasture fertilization, "an early spring nitrogen application is the recommended timing." The fall application exception is only necessary, apparently, if the producer is seeking a "high yield system," and then only ¼ of the application is to occur in the fall, a limit which is not reflected in the exception.[55] As a result, a reasonable "exception" would be "when nitrogen fertilizer is required for a high yield pasture, provided that only ¼ of the yearly application is made in the fall." Similarly, for item 4, grass seed production, the cited reference indicates that "either a fall application or very early spring application is recommended."[56] As a result, fall application is not a necessary practice. Where fall application is a necessary practice, it should be done by October 1 to get plant root uptake of the nitrogen.

Item C is arbitrary as drafted. The SONAR notes that when farmers are adding phosphorus to fields, it generally is formulated with up to 40 pounds per acre of nitrogen and applied in the fall for use over two seasons. The Item states that "notwithstanding subpart 1" and "in addition to item A" (it is assumed that rule intended to reference *Subpart 2,* Item A), fall application is allowed so long as the applied N rate does not exceed an average of 40 pounds per acre in a field. However, without explanation, the rule then allows more than 40 pounds per acre (without any upper limit whatsoever), if a soil analysis demonstrates that the fields have "low to very low phosphorus levels." Although the SONAR argues that this exception will be temporary, the language in the rule does not reflect any temporal limit. No scientific information is provided to explain what the impact of this exception would be on soil nitrate levels. Because (as noted in the SONAR), there are other methods to increase P where needed, this exception is arbitrary and

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[52] *See* Minn. Stat. §§14.055-.056. For example, a farmer who applies nitrogen in the fall using techniques and equipment that ensure that leaching does not occur might be able to apply to the commissioner for a variance from the fall application ban, on the ground that it is unreasonable under the unique site conditions and techniques being used. The commissioner, in granting such a variance, could agree so long as the farmer continued to use the techniques and documents the results.

[53] SONAR p. 102.

[54] Proposed rule, 1573.0030, Subpart 3, Item B. It would appear that this document is no longer available on the internet, making it difficult to check the references.

[55] SONAR p. 103.

[56] *Id.*

undermines the intent of the rule. Only the first part of the phosphorus-related exception is justified.

C. DRINKING WATER SUPPLY MANAGEMENT AREA; MITIGATION LEVEL DESIGNATION (1573.0040).

This part of the rule establishes the preconditions for the issuance of "water resource protection orders" or "WRPRs." This part provides various duties for the commissioner: establishing mitigation level areas ("MLs"); "determining" BMPs; monitoring; and evaluating. The rule requires no actions by responsible parties until WRPRs are issued. The rule is unreasonable and will not meet the goals of the Groundwater Protection Act where it continues voluntary actions in areas where nitrate levels threaten to exceed the HRL. The rule is defective because it fails to establish a clear deadline for an ML2 to move to a ML3, a level at which the commissioner could issue a WRPR. In particular, MCEA believes that the current rule language, which allows unlimited "evaluation time" for a ML2, is unreasonable and not supported by the record.

MDA has the authority to require, by rule, statewide actions applicable to areas where specific evidence exists of the threat of public (and private) well contamination and should use this authority to establish reasonable conditions, such as recordkeeping, sampling, and nutrient management planning, that apply where a threat has been documented and a "mitigation area" established, *prior to a WRPR being issued.*

It is not reasonable for all sites—even sites where statistical evidence suggests that the HRL will be exceeded—to be classified in the "voluntary" ML1 and ML2 categories. More serious sites—where the HRL has been exceeded or is statistically likely to be exceeded or where a significant number of private wells already exceed the HRLs—must immediately be prioritized for WRPRs. Under Minn. Stat. § 103H.275, the commissioner is required to ensure that the water source protection requirements are "designed to prevent the pollution from exceeding the health risk limits." As currently drafted, this rule fails to meet this standard.

1573.0040, subp. 1.[57] Although subpart 1 notes that the application of the part is "to responsible parties in drinking water supply management area," it would be more accurate to state that this part establishes the procedures that the *commissioner* will use to establish and evaluate mitigation level areas prior to issuance of a water resource protection requirement order. MCEA proposes that requirements for responsible parties in designated mitigation areas prior to the issuance of a WRPR also be included in this section of the rule.

1573.0040, subp. 2. This states that the commissioner will use public well nitrate-nitrogen concentration data provided by the commissioner of health to designate a DWSMA with a "mitigation level." While there is no problem with using data provided by the Department of

[57] As noted above, MCEA finds no support in the record for the commissioner's decision to limit the designation of mitigation levels to DWSMAs, because the decision arbitrarily leaves persons depending on private wells—persons who are more vulnerable to health impacts from nitrate levels with fewer options for addressing the exceedance—without regulatory protection.

Health (and indeed, the MDA should defer to the Minnesota Department of Health), this rule subpart cannot be enforced because it does not provide a deadline for the commissioner to act on the data provided. To address this issue, the rule must provide an action deadline, i.e., 60 days from the date that the Department of Health provides the necessary data.

1573.0040, subp. 3. This section establishes the criteria for "being designated" by the commissioner at a particular "mitigation level."

A ML2 is where, within a rolling 10-year period, (a) based on a "statistical analysis[58]. . .the groundwater. . .is projected to exceed the health risk limit in the next ten years; or (b) a reading has been 8 mg/L or greater. It is unreasonable to classify an area as an ML2 if it is statistically likely to exceed the HRL, or has in fact documented an exceedance of an HRL. Immediate mandatory actions are needed for such sites, i.e., a WRPR, if the statutory goal of Minn. Stat. § 103H.175 to prevent exceedance of the health risk limit is to be achieved. Under the rule as currently proposed, a public well could have had a reading of 12 mg/L nitrate, but still have its associated DWSMA characterized as a "voluntary only" mitigation level 2. This approach is not supported by the record, and does not comply with the Minn. Stat. § 103H.275.

Having established these "voluntary only" mitigation levels, the rule provides that the commissioner can, nevertheless, exclude portions of the affected DWSMA from the ML area. Subpart 3, item B provides that the commissioner "may make exceptions for increasing a mitigation level" for a "nonmunicipal" public supply well based on "significant change" in land use, and "the severity of nitrate" in "other wells" and the "population affected" and "other factors."[59] Item C provides that the commissioner "may exclude" an area if there is a point source "that is…significant" and item D provides that the commissioner "may exclude" a part of a DWSMA from the mitigation level if the commissioner determines that the area is not contributing "significantly" to the contamination. These exclusions are all purely subject to the discretion of the commissioner and fatally vague, and must be eliminated from the proposed rule or amended to remove the vague language and excessive discretion.

1573.0040, subp. 4. Subpart 4 requires the commissioner to "determine" the nitrogen fertilizer BMPs for the affected DWSMA, but this is unnecessary because the BMPs for various areas of the state are well-established.

1573.0040, subp. 5. In subpart 5, the commissioner is required to conduct some form of monitoring, but that monitoring may only be to obtain data from the public well. As the commissioner is already obtaining data from the public well, this part fails to define any new mandated monitoring activities and therefore fails to protect the public. To the extent that this provision was written because of limited resources for monitoring, MCEA proposes that the monitoring criteria include priorities for monitoring.

[58] The method should be described in the rule.

[59] This provision suffers from the same "substantive due process" defect as the decision to abandon private wells from protection under the rule: it provides lesser protection to smaller public well user groups based on the argument that MDA needs to prioritize work in other areas.

1573.0040, subp. 6. In subpart 6, the commissioner is required to conduct an evaluation of the ML2 to determine whether the BMPs have been implemented. There is no time limit on the commissioner to conclude this evaluation, but only a minimum time (3 years) that the commissioner must allow for evaluation. In general, voluntary implementation of BMPs has not protected the groundwater from nitrate contamination, and should not be continued under this rule. MCEA believes that BMP implementation is not a valid criterion on which to base continuous voluntary action, particularly when a significant percentage (20 percent) of responsible parties are not counted, the criteria for determining BMP compliance are not clearly stated, and the time and resources needed to accomplish this survey has not been justified. At any rate, it is manifestly unreasonable for the rule to allow evaluation of compliance for an unlimited period of time. The rule must establish a firm limit for the time that the commissioner can take to evaluate BMP compliance. Given the prolonged period of time that BMPs have been the subject of outreach to agricultural communities, this time should be short.

1573.0040, subp. 7. Subpart 7 is important, because it describes how the commissioner can redesignate a ML2 (where nothing is required) to a ML3 (where a WRPR can be issued).

Item A. This item suffers from the same defect as subpart 6: no limit is put on the time during which the commissioner will evaluate ML2 designation. The length of the allowed evaluation period is "no fewer than three growing seasons" or "the lag time"—whichever is longer.[60] This means that the commissioner could "evaluate" for an unlimited amount of time. If BMP compliance is maintained as part of this rule, it must be changed to provide a firm end-date for the evaluation period, such as 3 years. This period should be adequate for the commissioner to determine whether the BMPs have been implemented, and whether they are having an impact.

Item B. MCEA does not support item B, which allows a ML2 to become and ML1. Once the criteria for an ML2 have been met, the ML2 should not be redesignated as a lower-priority ML1, as that may allow the conditions under which the nitrate contamination developed to re-occur. MCEA supports adding mandated actions for responsible parties once a ML has been designated. For example, at a ML2, MCEA believes that responsible parties should conduct soil sampling. This soil testing requirement is reasonable because it has been implemented in Nebraska for many years, is not burdensome and is likely in use where a crop consultant is employed, and (where manure is used) can be combined with required testing under MPCA's rules. It is reasonable for the responsible parties and the commissioner to collect this data to ensure that actions that are being taken are having a positive effect, and to be able to better determine where additional resources and actions may be necessary.[61] The SONAR also notes that "Canadian researchers have used nationwide residual soil nitrate information from shallow sampling over time to make policy decision related to fertilizer use efficiencies and groundwater implications (Yang et al., 2007; Drur et al., 2007)." *Id.* The SONAR rejects the idea of requiring testing on the basis of unstated "cost" and because "this testing requires access to a large number of acres."[62]

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[60] MCEA notes that the proposed rule also states that, "however," if residual soil nitrate testing is conduced, the review period shall not be less than three growing seasons. As the word "however" seems to be wrong in this context because nothing is changed, MCEA wonders if MDA meant to propose that the review period would "not be *more* than three growing seasons."
[61] *See* SONAR pp. 122-4
[62] *Id.*

However, if the producers are doing the testing themselves, no access is needed. The unstated cost cannot be unreasonable given that the requirement is one of longstanding in Nebraska. Other state rules require regular soil testing without compensation.[63] The BMPs recommend use of soil nitrate tests in a number of cases.[64] Testimony at the St. Cloud rulemaking hearing supports that producers are testing their soils voluntarily. Similarly, responsible parties in an ML3 area should prepare nutrient management plans in accordance with National Resources Conservation Service Practice Nutrient Management guidelines.[65]

Items C-E. Items C-E establish criteria for moving a well from a ML2 to a ML3. MCEA does not support item C, which appears to allow the area to remain a ML2 so long as 80 percent of the responsible parties are in compliance with the BMPs, even if the statistical analysis still demonstrates that exceedance of the HRL is probable. Item D provides that the commissioner "shall" move to a ML3 if the net residual nitrate in soil below the root zone is increasing "after not less than 3 growing seasons." MCEA cannot support this criterion, because there is no limit on the number of growing seasons that could be considered, but could support this criterion if the evaluation was required after 3 years. Item E provides that the commissioner "shall" move to a ML3 "if the statistical analysis indicates the nitrate-nitrogen concentration is increasing for the public well or groundwater monitoring network." MCEA supports this criterion, provided this evaluation is not viewed as being limited by the time criterion stated in Item A.

Item G. This item allows the commissioner to "grant a onetime exemption" from the move to ML3 on the vague criteria that "responsible parties...have demonstrated progress." Because there are no criteria for "demonstrating progress," MCEA does not support granting the commissioner this authority.

Item H. MCEA does support item H, which allows the commissioner to "make exceptions for increasing a mitigation level designation if there has been a significant change in land use." Because what is "significant" is not defined, this criterion is fatally vague and should be eliminated.

1573.0040, subp. 8. Subpart 8 suffers from many of the same defects as subpart 7, in particular the language allowing the commissioner an unlimited period in which to evaluate whether a ML3 should be redesignated as a ML4. MCEA refers the ALJ to its comments on subpart 7.

1573.0040, subp. 9. Subpart 9 describes how ML4 area can be redesignated as a ML 3 area, if the water will not exceed the HRL in 10 years based on statistical analysis, and no three samples have reached or exceeded 9.0 mg/L. As noted above, MCEA does not believe that it is appropriate for an area that has demonstrated the potential to exceed the HRL to "drop back" to a level of lessor protection that may allow the prior conditions to re-occur.

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[63] *See* Minn. R. 7020.2225, Subp. 3, Item C (phosphorus).
[64] *See*, e.g., sugarbeet production.
[65] Available at https://www.nrcs.usda.gov/wps/portal/nrcs/detail/mn/technical/ecoscience/nutrient/?cid=nrcseprd1369002 (last visited August 14, 2018).

1573.0040, subp. 10. MCEA does not support the artificial and unsupported limit stated in Subpart 10, which limits the move to one ML. If an area should suffer a sudden increase in nitrate levels, there is no reason for the rule to limit the authority of the commissioner not to take action as required by the Groundwater Protection Act.

D. WATER RESOURCE PROTECTION ORDER PROCESS (1573.0050):

Part 1573.0050 establishes the requirement for the commissioner to issue a WRPR, but does not provide adequate due process or standards for WRPR development.

1573.0050, subp. 1 requires the commissioner to issue a WRPR to responsible parties in ML3 and ML4 areas, but does not establish any deadline or any standard that must be met. As a result, there is no stated basis on which the order can be challenged or reviewed, except broadly as not meeting the requirements of the statute.

Item A. Item A notes that the commissioner will issue WRPRs based on the monitoring in part 1573.0040, subp. 5, but, as discussed above, this provision does not require the commissioner to do any monitoring as currently drafted.

Item B. Item B requires the WRPR to apply to the "entire" DWSMA—but only if a groundwater monitoring well network is installed or residual soil nitrate testing is conducted. As noted above, such testing is not mandated. As a result, the commissioner's authority to issue a WRPR to the entire DWSMA is likely quite limited and will not achieve the statutory mandate of Minn. Stat. § 103H.275 to prevent exceedances of the health risk limit.

Item C. This item includes another unnecessary and complicating limitation on the scope of the WRPR that can be issued. If the commissioner has not installed a groundwater monitoring network,[66] subpart 1, item C, limits the scope of the WRPR based on estimated lag time and travel time.[67] Again, the WRPR will not necessarily apply even to the whole DWSMA established by the Commissioner of Health. MCEA objects to this unreasonable limitation on the commissioner's authority.

Item D. This item prioritizes the issuance of WRPRs. It is reasonable for the commissioner to establish criteria for prioritization, but these criteria could be expanded.

Item E. Item D states what must be included in a WRPR, but isn't specific other than including "the water resource protection requirements."[68] For a meaningful order, there needs to be

[66] Although the commissioner is required by part 1573.0040, Subp. 5 to monitor a DWSMA, the commissioner is **not** required to install a groundwater monitoring network. Thus, it is impossible to predict how many DWSMAs will be fully subject to the WRPR, once issued.

[67] The process by which the commissioner will make the determination is vaguely described in part 1573.0050, Subp. 1, Item C. As a DWSMA is generally based on the 10-year travel time to the protected well, it is unclear why the commissioner here would choose a different area to protect, and this provision therefore introduces unnecessary complication into the process. *See* Minn. R. 4720.5510.

[68] These requirements are evidently intended to be the requirements in part 1573.0060, but those requirements are only to maintain and provide upon request the field-specific records documenting nitrogen fertilizer use, to comply with the already applicable fall application and

language (at a minimum) such as "the commissioner's order must include water resource protection requirements that are necessary to ensure that pollution is minimized to the extent practicable and to prevent the pollution from exceeding the health risk limits." Even better, MDA should establish that each WRPR must include basic items, such as mandated practices, monitoring, recordkeeping, and reporting requirements, to be adequate.

Item F. Item F is unnecessary and redundant with Item A.

Item G. Item G is vague and cannot be enforced because no standards are established under which the commissioner will determine than an "area is not contributing significantly to the contamination in the well or that it is not practicable to include that part." As a result, it should simply be eliminated from the proposed rule.

1573.0050, subp. 2. This subpart addresses notice that will be given regarding the WRPR, but lacks properly articulated due process.

Item A. This item requires the commissioner to hold "at least one" public information meeting in the county affected by the proposed MRPR before it is published. Normally, a proposed permit, environmental review document, or other administrative action would first be published so that the public attending the meeting have an opportunity to review and raise questions that are meaningful. Subpart 2 should be amended to require the public informational meeting(s) to be held during the public comment period following publication of the proposed WRPR notice. The rules should specify how the commissioner will conduct the public informational meeting, particularly if the commissioner decides to use the public informational meeting as a forum for receipt of comments on the rule in lieu of or in addition to the right to request a contested case hearing under the Minnesota Administrative Procedures Act. The rule should provide that the commissioner must include a record of comments and responses to all substantive comments received during the public informational meeting when the final WRPR is issued as part of the findings on the WPRP.

Item B. This item deals with notice. It should be amended to specify that the commissioner must provide a copy of the proposed order, proposed findings, and a technical support document explaining its terms and conditions, to the "affected parties" who must include persons who are drinking the water that is threatened with nitrate contamination. This is reasonable because other agencies (i.e., the MPCA) typically provide fact sheets or technical support documents in support of their proposed actions.[69]

1573.0050, subp. 3 addresses contested case hearings.

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frozen soils prohibitions, and "comply with any water resource management requirements orders that apply to the drinking water supply management area governing the cropland over which the responsible party has control" which adds nothing and is circular in the extreme. In proposed part 1573.0070, the rule lists only content that the commissioner "shall consider." Alternative management practices can only be mandated if they are "funded" meaning that a responsible party does not bear the cost of compliance.

[69] *See, e.g.,* Minn. R. 7001.0100.

Item A. This item should be amended to provide that "any person or entity subject to the water resources protection requirements order *or affected by the water resource protection requirements order*" can petition for a contested case hearing. It is necessary to include affected persons (i.e., persons who depend on the water supply) to ensure that the persons who are supposed to be protected by the rule can exercise their rights if the commissioner's order is deficient.

Item C. This item requires the commissioner to order a "public hearing" if one is requested. A "public hearing" is not the same as a "contested case hearing." In the SONAR, MDA states that the process that it intends to follow was based on that used to create the "public waters inventory." It is unlikely that MDA has correctly selected the necessary due process, because the public waters inventory did not create any new requirements on the owners of the listed waters. The public waters inventory simply created a record of which waters were or were not public waters based on existing statutory criteria, and did not impose new requirements.[70] Furthermore, the proposed rule does not, in fact, set forth or follow the procedures that were used to adopt the public waters inventory, which involved county review and approval and special hearing teams.[71]

MCEA recommends that the commissioner create a "two option" process for receiving comments and recommendations on the proposed WRPR. The first process would be informal: holding a public informational meeting where members of the public could testify before department representatives who would then have to draft a formal "response to comments" document as part of the WRPR findings. The second process would be formal: holding a contesting case hearing under chapter 14 rules if the criteria for requesting a formal hearing are met.[72] Minn. Stat. § 14.57 provides that, unless otherwise provided by law, "an agency shall decide a contested case only in accordance with the contested case procedures of the Administrative Procedure Act." As there is no other law establishing a separate procedure, MDA must order any "contested cases" as provided under Chapter 14.

1573.0050, subp. 5. This subpart appears to allow amendments to the WRPR just with notice and comment. MCEA does not object to this process, provided that the final amended order is subject to judicial review as a final agency order. MCEA proposes that the commissioner have the duty to review and amend issued WRPRs on a 5 year basis to ensure that the terms are having the desired impact on nitrogen levels.

1573.0050, subp. 6. This subpart allows "any person subject to a final . . .order or amended order to seek judicial review." This provision suffers from the defect that it limits review only to those persons "subject to" orders, which (MCEA assumes) means that only the responsible person can appeal. Minn. Stat. § 103H.275 does not limit rights to persons "subject to" orders,

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[70] *See* Minn. Laws 1979, ch. 199, § 7 (required DNR publication, county board review, DNR notice to counties of accepting or rejecting county recommendations, publication of final listings, process by which "any person" or county could challenge the designation of specific waters as public waters, publication of final listing).

[71] *Id.*

[72] MCEA recommends that MDA use the criteria employed by other state agencies for ordering contested case hearings. *See, e.g.,* Minn. R. 7000.1900 (MPCA); Minn. Stat. § 93.483, subd. 3 (DNR mining permit).

but instead refers to "persons affected by the rule and order of the commissioner."[73] The rule must be clarified to ensure that any affected party (i.e., party that can establish standing and who has participated in administrative proceedings) can appeal an order. The rule also fails to specify how a party can obtain judicial review. Is the judicial review provided under the Minnesota Administrative Procedures Act for a "contested case" (Minn. Stat. § 14.63), which provides that an appeal must be filed in 30 days, or would review be provided under the "generic" certiorari statute, Minn. Stat. ch. 606, which provides for 60 days in which to seek review? If MDA intends that review be under the Minnesota Administrative Procedures Act, then a hearing under that act must be offered.

1573.0050, subp. 7. This provision requires the commissioner to record all final WRPRs. MCEA respectfully suggests that MDA ascertain whether this is possible, and what the effect of a "blanket" recording would be.

E. REQUIREMENTS FOR RESPONSIBLE PARTIES SUBJECT TO WRPRs (1573.0060-90).

In this part, the proposed rule establishes certain requirements for responsible parties subject to WRPRs, such as recordkeeping. Above, MCEA has proposed to include certain of these requirements (such as recordkeeping) when mitigation levels are established, and does not agree with limiting these requirements to parties that are subject to a WRPR. If MCEA's proposal is accepted, this part is needed only to specify what records must be kept and for how long, and to provide conditions on access consistent with MDA's statutory authority.

1573.0060. This provision requires a responsible party in a mitigation level 3 or 4 area to maintain field-specific records "starting with the effective date of the water resource protection requirements order." As noted above, it is unreasonable to wait to require such record-keeping until a WRPR is issued as this is a low-impact requirement that producers should be using under the BMPs to monitor their nutrient use. Item A(3) requires compliance with the fall application prohibition, but this would already be required for these producers if the DWSMA protected well has had a reading over 5.4 mg/L, which would be the case for ML3 and 4 areas receiving a WRPR, so it adds nothing and could be confusing, causing persons subject to the "part 1" fall application ban to believe that nothing is required until a WRPR is issued.

1573.0070, subp. 1. This section requires the commissioner "to consider" including the listed requirements in a WRPR. As a result, the content of the order is not cabined in any way by this rule. Under these circumstances, only the due process related to the draft order will allow parties to challenge the content of the order, but this due process is deficient as noted above. MCEA supports making certain of these content requirements mandatory with any order, i.e., field testing, monitoring, crediting of all nutrient sources, nutrient management plans, and the use of alternative management tools that the commissioners specifically finds are necessary to reduce soil nitrogen-nitrate levels in the area subject to the WRPR.

[73] Minn. Stat. § 103H.275, subd. 2(d).

MCEA is deeply troubled by the limit posed by subpart 1, item B. Item B limits the commissioner's ability to impose alternative management tools by stated that such tools can only be mandated as part of an order "provided a source of funding for increased costs related to the implementation of the alternative management tool is available to responsible parties." This is arbitrary and will thwart achievement of the goals of the Groundwater Protection Act. Other parties required to protect public resources (for example, those who are regulated under air, water or solid waste permits issued by the MPCA) must internalize the cost of compliance, and are not allowed to avoid compliance unless government money pays for it. In other regulatory programs, if a regulated party finds that the cost of compliance is unreasonable, the regulated party has the burden of seeking relief.[74] The same process should be applied to agricultural producers, especially where there are numerous sources of public funds available to defray the cost of compliance.[75] Compliance should not be limited to funded activities unless the cost of compliance would present a hardship, and then only if reasonable conditions are established in a schedule of compliance to ensure that any damage caused by the delay is limited. The proposed rule does not require any showing of hardship, and therefore is unreasonable. The prohibition on requiring AMTs, the very practices that the MDA has acknowledged will be necessary to achieve the HRL in vulnerable areas, unless funding is provided, must be removed from the rule because it is contrary to the goals of the Groundwater Protection Act. If MDA wants to provide some limited time for a responsible party to obtain funding necessary to comply with the AMTs, a schedule of compliance process could be included in the part of the rule addressing WPRPs, limited to agreements with the commissioner lasting no longer than two years. This should be adequate to address temporary situations resulting from weather events and temporary financial situations affecting a particular responsible party.[76]

1573.0070, subp. 2. This subpart addresses requirements for mitigation level 4. In the SONAR, the MDA states that in mitigation level 4, "alternative management practices that meet the requirements listed under Minn. Stat. § 103H.275, subd. 2(a) shall be considered for inclusion in a water resource protection requirements order regardless of whether or not funding is available" but this authority is not found in the rule. If ML4 area regulated parties can be mandated in a WRPR to use alternative management tools, it should be expressly stated. The cost of compliance should not be the deciding factor in determining whether a management practice should be imposed. Cost is but one factor that should be considered under the statute.[77] Item B in this section limits the commissioner's authority to require fertilizer application rates that are less than the recommended rate set by the University of Minnesota. Fertilizer application rates are set to ensure the maximum harvest level, not to protect groundwater. As the purpose of the WRPR is to protect groundwater, the commissioner must have the authority to require application rates

[74] *See, e.g.,* Minn. R. 7000.7000.
[75] The various funding opportunities are listed on MDA's website and the website of the Board of Water and Soil Resources.
[76] For other parts of the rule, MCEA notes that state law already contains a variance process, which could be utilized by responsible parties. The proposed rule might be amended to include a reference to that process. See Minn. Stat. §§ 14.055-.056.
[77] Minn. Stat. § 103H.275, subd. 2.

that are less than recommended if the particular circumstances of the situation make such reduced rates reasonable.

1573.0070, subp. 2, item C. Subpart 2, item C, prohibits the commissioner from restricting the selection of the "primary crop." The term "primary crop" is undefined. It is unclear whether this term means that the commissioner is prohibited from requiring, as an alternative management tool, the inclusion of a nitrogen-reducing crop in a rotation, and thus is fatally vague. To achieve the goal of the Act, the commissioner must have the authority to require, if circumstances demand, that extremely vulnerable acres not be planted with crops that contaminate drinking water supplies, or that a different crop be added into a crop rotation, such as alfalfa or grasses, that would quickly reduce soil nitrate levels.[78] To eliminate the commissioner's authority to require a technique that is well-established as a method to reduce soil nitrogen-nitrate levels is arbitrary.

1573.0070, subp. 3. Subpart 3 provides the commissioner, with unlimited discretion, the authority to provide exemptions to a WRPR "on a site-specific basis." There is no description whatsoever of how this process would be made public or controlled. As a result, this provision is fatally vague. Instead, the commissioner should establish a fair temporary schedule of compliance process whereby particular conditions that create hardship, on a site-specific basis, can be fairly evaluated and addressed in a controlled fashion.

1573.0080. This rule provides that a responsible party who is certified through the Minnesota Agricultural Water Quality Certification Program ("MAWQCP") is "deemed to be in compliance" with this chapter. MDA's rule proposal requires the Department to presume that land certified under the MAWQCP is cropland where the nitrogen fertilizer use recommendations have been fully implemented. However, the MAWQCP does not require certified farms to either meet these recommendations, or implement any other practices that reduce nitrate contamination in groundwater.[79] Unless MDA provides evidence that a certified farm has implemented the nitrogen fertilizer use recommendations, this presumption is not justified.

1573.0090. subp. 1. This subpart requires the commissioner to maintain a list of alternative management tools ("AMT") on the MDA website, and to note if the tool can be substituted for a nitrogen fertilizer best management practice. No standard is provided for when this substitution is to be authorized, making this rule fatally vague. The commissioner should, *in this rule*, list the alternative management tools and which AMTs can be substituted for specific BMPs or amend the rule to provide a more functional definition of AMT.

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[78] *See* De Haan et al*, Residual soil nitrate content and profitability of five cropping systems in northwest Iowa*, PLOS One, March 1, 2017; 12(3); e0171994, available at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5332022/. *See also* Comment of Dr. Gyles Randall, August 1, 2018.

[79] *See Minnesota Agricultural Certainty Program: Is It Working for Water Quality, An Assessment of Minnesota's Agricultural Water Quality Certification Program*, MCEA, December 2015.

Item C. Item C allows a responsible party subject to a WRPR to implement an AMT if the commissioner's list allows it, subject only to keeping records of all AMTs used "and the specific water resource protection requirements order that allows the alternative management tool to be used." This is reasonable if the only time an AMT is allowed to substitute for a BMP is under the control of a WRPR, but the rule is not clear.

1573.0090, subp. 2. This subpart allows a person who is subject to a WRPR to apply to the commissioner for an alternative protection requirement pursuant to statute. However, the rule fails to establish any due process concerning how such a substitution will be approved, and is therefore deficient. MCEA suggests requiring such alternative protection requirements to be proposed during the comment period on the WRPR.

IV. CONCLUSION

MCEA supports the need for a rule to prevent and mitigate nitrate pollution in groundwater. The instant rule falls short of what is needed and what Minn. Stat. § 103H.275 demands, in particular because it offers little protection to persons who get their drinking water from private wells, and because it continues to lean on BMPs to reduce nitrate levels despite the fact that BMPs have not succeeded in reducing nitrate levels to date. In order to be approved, the rule must be amended to eliminate vague and unenforceable language and the rule must ensure that groundwater is protected and that the HRL is not exceeded. Finally, where the rule is to be used as the basis for issuance of an order, it must include adequate standards and procedures to ensure that all affected parties have an opportunity to seek meaningful relief, and should not prevent the commissioner from requiring reasonable agricultural practices that reduce soil nitrate/nitrogen levels.

Sincerely,

/s/Ann Cohen
Ann Cohen
Staff Attorney
Minnesota Center for Environmental Advocacy

Exhibit B

Clean Water Organizations'
Comments on the Proposed 2021 NPDES General Permit
for Concentrated Animal Feeding Operations

July 23, 2020

INTRODUCTION

Nitrate pollution from manure and commercial fertilizer is a serious problem in Minnesota. Despite laws intended to limit manure application, nitrate pollution from excess manure continues to contaminate drinking water and degrade aquatic habitats. Minnesota Center for Environmental Advocacy,[1] Friends of the Mississippi River,[2] Minnesota Well Owners Organization,[3] and Sierra Club North Star Chapter[4] (collectively, "Clean Water Organizations") have concluded that the

[1] Minnesota Center for Environmental Advocacy ("MCEA") is a Minnesota non-profit organization that defends every aspect of Minnesota's environment, relying upon facts, science, and the law. For nearly half a century, MCEA has worked with community members, decision makers, and other partners to protect Minnesota's natural resources and the health and wellbeing of all the state's citizens. As a public interest organization, MCEA works to ensure that Minnesota's bedrock environmental laws are enforced and defended. It has a particular interest in water quality, and it has engaged in legislative and administrative advocacy, rulemaking and permitting proceedings, and litigation to protect Minnesota's water quality.

[2] Friends of the Mississippi River ("FMR") is a nonprofit established in 1993 to engage Minnesotans to protect, restore, and enhance the Mississippi River and its watershed in the Twin Cities Metro area. As part of its efforts to protect and preserve a clean Mississippi River, FMR works with 2,500 members, 2,000 advocates, and over 5,000 volunteers yearly. A major part of FMR's work is focused on watershed protection for the Mississippi River, including preserving water quality by advocating for land use policies and practices that will lead to cleaner water throughout the entire watershed.

[3] Minnesota Well Owners Organization ("MNWOO") is a nonprofit organization for private well owners that works to preserve, protect, and restore Minnesota's water resources and to ensure the safety of those who use private wells for drinking water. MNWOO also provides education, technical and legal services, and advocacy for private well owners. MNWOO works to protect the water quality of the 1.2 million private wells in Minnesota, more than 10% of which are contaminated at levels above allowed health risk limits. This includes many private wells with elevated levels of nitrates.

[4] The Sierra Club North Star Chapter ("SCNS") is a nonprofit organization that is the Minnesota branch of the national Sierra Club, America's oldest, largest, and most influential grassroots environmental organization. SCNS works through grassroots political action, including its 80,000 members, to strategically address Minnesotans' most pressing environmental issues. One of SCNS's priorities in its water program is fighting agricultural pollution in Minnesota, including nitrate pollution.

newly proposed National Pollutant Discharge Elimination System ("NPDES") General Permit for Concentrated Animal Feeding Operations ("Proposed General Permit") drafted by the Minnesota Pollution Control Agency ("MPCA") does not effectively address this problem or follow Minnesota's laws regarding land application of manure. Unless MPCA revises the Proposed General Permit to better reflect the protective standards of the law, Minnesota's water quality is likely to worsen during the permit's tenure.

Since the MPCA issued the 2016 NPDES General Permit for Concentrated Animal Feeding Operations ("2016 General Permit"), Minnesota's nitrate pollution problem has intensified. The drinking water for nearly half a million Minnesotans is now tainted with elevated levels of nitrates, which can cause cancers and other diseases. Now, MPCA has an opportunity to provide better protections for Minnesota's waters, while ensuring farmers can meet their crops' nitrogen needs, through the Proposed General Permit. Yet, the Proposed General Permit perpetuates the same problems that exist in the 2016 General Permit, which will lead to continued contamination of water needed for drinking, recreation, wildlife, and aquatic habitat. Accordingly, the Clean Water Organizations suggest changes to the Proposed General Permit to ensure the protection of water quality and compliance with Minnesota laws regarding manure application.

Most importantly, the Clean Water Organizations propose that the MPCA revise the Proposed General Permit to limit manure application rates to truly reflect expected crop nitrogen needs. As it did in the 2016 General Permit, the MPCA has referenced recommendations for manure application based on maximizing the economic return for farmers, not on the actual plant needs for nitrogen. These recommendations are inconsistent with the governing rules for land application of manure and have led to over-application by many farmers. MPCA must amend the Proposed General Permit to ensure that the referenced recommendations are consistent with the

rule's requirements. In addition, the Clean Water Organizations request that the MPCA revise Proposed General Permit to restore the section from the 2016 General Permit regarding pre-plant testing for nitrates, provide clearer requirements to farmers about determining soil temperatures prior to manure application, strengthen October restrictions on manure application, prohibit application of solid manure in December and January, and require geographic-information-system ("GIS") identification of fields in manure management plans. The Clean Water Organizations ask that MPCA revise the permit to make these changes or grant a contested case hearing so that material issues of fact can be heard by a neutral administrative law judge who can develop the record and present a recommendation to the MPCA.

I. MINNESOTA'S DRINKING WATER AND AQUATIC HABITATS ARE ALREADY POLLUTED WITH DANGEROUS LEVELS OF NITRATES

Minnesota takes great pride in its water. Minnesotans depend on their lakes, rivers, and groundwater as sources of clean, drinkable water and habitats for wildlife. While the "Land of 10,000 Lakes" claims the headwaters of the Mississippi River and other historical, cultural, and economically significant waterways, increasing levels of nitrates, which have profound impacts on aquatic and human life, are threatening the health of many of Minnesota's great waters.

A. Minnesota's Nitrate Pollution Is Worsening.

Nitrate contamination in Minnesota's drinking water systems is getting worse. Data collected by the U.S. Environmental Protection Agency ("EPA") showed that between 1995 and 2018, 63% of Minnesota's 115 community wells experienced growing nitrate contamination, with the southern part of the state experiencing the largest increases.[5] As one example, in the Rock County Rural Water System, located in southwestern corner of the state, 24 of the 107 tests

[5] Envtl. Working Grp., *Nitrate Trends in Minnesota Drinking Water*, https://www.ewg.org/interactive-maps/2020-in-minnesotas-farm-country-nitrate-pollution-of-drinking-water-getting-worse/map/ (last visited July 17, 2020).

collected during this time frame revealed nitrate levels exceeding 10 milligrams per liter ("mg/l"), the "safe for consumption" threshold set by the EPA in 1962.[6] Across the state in Winona County, nitrates in the Utica water system surged between 2016 and 2018.[7] Nitrates also threaten metropolitan area community water supplies. EPA tests collected from the Kjellberg system in Wright County, which serves approximately 1,000 people, revealed nitrate levels greater than 3 m/l in more than half of the 204 tests obtained during the study period.[8] In Hastings, 217 out of 313 tests of its groundwater supply, which serves over 22,000 Minnesotans, showed nitrate concentrations exceeding 5 mg/l.[9]

The Minnesota Department of Health's ("MDH") testing also shows troubling trends for private wells. Prior to 2011, less than 1% of MDH private well tests showed nitrate contamination exceeding 10 mg/l.[10] However, with the exception of 2016, beginning in 2011 and every year thereafter, more than 1% of tested private wells were contaminated with nitrate levels exceeding the federal safe consumption limit.[11]

MPCA data confirms that nitrate levels in Minnesota's surface waters are also increasing. Data collected between 1976 and 2010 reveal that 22 of Minnesota's 32 major rivers shows a statistically significant upward trend in overall nitrate concentrations.[12] These rivers showed increases in nitrate concentrations as much as an astonishing 268% during the 30 to 35 year study

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[6] *Id.*
[7] *Id.*
[8] *Id.*
[9] *Id.*
[10] Minn. Dep't of Health, *Nitrate in Private Wells*, https://data.web.health.state.mn.us/nitrate_wells (last visited July 17, 2020), attached as Ex. 3.
[11] *Id.*
[12] Minn. Pollution Control Agency, *Nitrogen in Minnesota Surface Waters* 150 (2013), *available at* https://www.pca.state.mn.us/sites/default/files/wq-s6-26a.pdf, [hereinafter "Nitrogen in Surface Waters].

period.[13] Most of MPCA's regularly monitored testing sites along the Mississippi River have recorded an explosive growth of nitrate concentrations, with MPCA noting that, except for two specific sites, "nitrate concentrations [in the Mississippi River] have been increasing everywhere downstream of Clearwater at a rate of 1% to 4% per year" in recent years.[14] MPCA monitoring sites on the St. Croix River reflected a 49% growth in nitrate concentration between 1976 and 2004.[15] MPCA data collected from major tributaries similarly shows nitrate concentrations increased in the majority of sampled waterways during the study period, with the greatest recorded growth reaching 207%.[16] And the contaminated Rock County Rural Water System discussed above is a surface water source of drinking water.[17]

B. Nitrate Pollution Poses Dangers For People And Aquatic Life.

This increase in nitrate pollution is a serious problem for Minnesotans, as elevated nitrate levels are hazardous to human health and wreak havoc on aquatic life. Increasing nitrate contamination threatens the health of the nearly 75% of Minnesotans who rely on groundwater for their drinking water.[18] Consuming water contaminated with nitrates is associated with adverse birth outcomes, thyroid disease, neural tube defects, and several cancers.[19] Elevated nitrate levels in drinking water are especially dangerous for infants, pregnant women, and people with certain

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[13] *Id.* at 151.
[14] *Id.* at 398.
[15] *Id.* at 177.
[16] *Id.* at 150-51, 53.
[17] Envtl. Working Grp., *supra* note 2.
[18] Minn. Dep't of Agric., *Minnesota Nitrogen Fertilizer Management Plan* 20 (2019), *available at* https://www.mda.state.mn.us/sites/default/files/2019-08/nfmp2015addendedada_0.pdf, attached as Ex. 4.
[19] Alexis Temkin et al., *Exposure-Based Assessment and Economic Valuation of Adverse Birth Outcomes and Cancer Risk Due to Nitrate in United States Drinking Water*, 176 ENVIRONMENTAL RESEARCH 1-2 (2019), *available at* https://www.sciencedirect.com/science/article/pii/S001393511930218X, attached as Ex. 5.

blood disorders, who are at risk of methemoglobinemia, or "blue-baby syndrome," which causes severe oxygen deficiency that, without medical treatment, can lead to death.[20]

The EPA set the current health standard for nitrate in water at 10 mg/l in 1962 largely to protect against blue-baby syndrome. New studies strongly suggest that the current standard does not reflect the present understanding of nitrate associated health risks.[21] According to a recent study by Environmental Working Group ("EWG"), lower levels, even below 5 mg/l, are associated with higher risks of certain cancers and adverse birth outcomes.[22] EWG concluded that nitrate pollution of drinking water at levels far below the legal limit may cause up to 12,594 cases of cancer each year in the United States.[23] This tracks large-scale studies in Spain and Italy, published in 2016, and Denmark, published in 2018, which found statistically significant increases of colorectal cancer risks associated with nitrate levels below 2 mg/l.[24] Minnesota regulators should be exceedingly concerned by these new studies because hundreds of thousands of Minnesotans currently access public water systems contaminated with nitrates exceeding 3 mg/l.[25] Even worse, the data shows that over 150,000 Minnesotans accessed public water systems with nitrate contamination levels exceeding Minnesota's health standard of 10 mg/l.[26] Nitrates also plague private water supplies. Minnesota Department of Agriculture data collected pursuant to its Nitrate Clinic Outreach Program shows that 7.7% of 2,063 private well tests reported nitrate levels

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[20] Minn. Dep't of Agric., *supra* note 15, at 7-8.
[21] Minn. Dep't of Health, *Nitrate in Well Water*, https://www.health.state.mn.us/communities/environment/water/wells/waterquality/nitrate.html#:~:text=Safe%20Level,water%20for%20public%20water%20supplies (last visited July 17, 2020), attached as Ex. 6; Sarah Porter & Anne Weir Schechinger, Envtl. Working Grp., *Tap Water for 500,000 Minnesotans Contaminated with Elevated Levels of Nitrate* (Jan. 14, 2020), attached as Ex. 7.
[22] Temkin et al., *supra* note 16, at 11; Porter & Schechinger, *supra* note 18.
[23] Porter & Schechinger, *supra* note 18.
[24] *Id.*
[25] Minn. Dep't of Health, *supra* note 18.
[26] Porter & Schechinger, *supra* note 18.

exceeding 10 mg/l.[27] The 2012 data shows an increase in the percentage of private wells exceeding the current standard from samples tested in 2011, suggesting nitrate infiltration into well water supplies throughout Minnesota is an increasing problem.[28] In fact, due to a lack of testing, the number of contaminated wells in Minnesota may actually be much greater.[29]

In addition to impairing drinking water, elevated nitrate concentrations in Minnesota's waterways are significant contributors to aquatic habitat destruction. High nitrate levels in surface waters directly contribute to eutrophication, which stimulates excessive plant growth and depletes oxygen levels in the water, causing harm or death to fish.[30] Nitrate also is directly toxic to fish and other aquatic organisms, causing heart and liver problems, electrolyte imbalance, and increased vulnerability to bacterial and parasitic diseases.[31] Due to nitrate's solubility in water, its ultimate intrusion into the Mississippi River is in part to blame for the hypoxic "dead zone" in the Gulf of Mexico.[32] One study estimates that the 158 million pounds of nitrate that leave Minnesota annually via the Mississippi River has caused nearly $2.4 billion in annual damages to fish stocks and habitat for more than 30 years.[33]

C. Much Of Minnesota's Nitrate Problem Is Caused By Agriculture.

Agriculture is Minnesota's largest contributor to nitrate pollution—specifically, nitrate runoff or leaching from farmland from commercial nitrogen fertilizer or manure. According to the

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[27] Minn. Dep't of Agric., *2012 Nitrate Clinic Outreach Summary Report* 2 (2012), *available at* https://www.mda.state.mn.us/sites/default/files/inline-files/2012nitrateclinic.ashx.pdf.
[28] *Id.*
[29] Jennifer Bjorhus, *One in Eight Minnesotans Drink Nitrate-Tainted Tap Water, Report Says*, STAR TRIBUNE (Jan. 14, 2020), *available at* https://www.startribune.com/one-in-eight-minnesotans-drink-nitrate-tainted-water/566960262/.]
[30] Nitrogen in Surface Waters, *supra* note 9, at 43.
[31] *Id.*
[32] *Id.* at 36, 46.
[33] Rebecca Boehm, Union of Concerned Scientists, *Reviving the Dead Zone* 3 (2020), *available at* https://www.ucsusa.org/sites/default/files/2020-06/reviving-the-dead-zone.pdf.

Minnesota Department of Agriculture, approximately 2.7 million tons of inorganic nitrogen are added to Minnesota soils each year, and 80% of that nitrogen is attributable to agriculture.[34] Unfortunately, a significant portion of that nitrogen reaches state waters. In its 2013 study, MPCA estimated that cropland sources account for almost 73% of the statewide nitrate load to streams and lakes in an average year.[35] A "significant" part of this comes from applied manure.[36] Notably, MPCA found that the largest increases in nitrate pollution are clustered in the southern third of the state, where most of Minnesota's confined animal feeding operations are located.[37]

This is unsurprising. Domestic and international studies have long confirmed an association between livestock concentration and a documented degradation in water quality. For example, Iowa watersheds with the highest livestock density had some of the highest stream concentrations of nitrates in the state.[38] In the Chesapeake Bay watershed, for example, land application of manure contributes to elevated ground water nitrate concentrations and suffocating algae blooms.[39] This connection is not new. In the 1960s, nutrient runoff from the Danube River seriously degraded the northwestern Black Sea.[40] Conditions rapidly improved after the fall of communist regimes in the late 1980s precipitated the closure of many large animal farms.[41]

The ease with which nitrate escapes the fields is largely to blame. A significant amount of nitrogen from applied manure is lost through volatilization, runoff, and leaching. The University of Minnesota Extension Service ("Extension Service") estimates that up to 50% of the nitrogen

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[34] Minn. Dep't of Agric., *supra* note 15, at 33-34.
[35] Nitrogen in Surface Waters, *supra* note 9, at 205.
[36] *Id.* at 219.
[37] *Id*. at 295; Minn. Pollution Control Agency, https://resources.gisdata.mn.gov/pub/gdrs/data/pub/us_mn_state_pca/env_feedlots/preview/preview.jpg (last visited July 17, 2020).
[38] Dr. Christopher Jones, *Expert Report* 6 (2020), attached as Ex. 1.
[39] *Id.*
[40] *Id.*
[41] *Id.*

from manure may be lost through these processes.[42] University of Minnesota research indicates that applications of nitrate above the economically optimum nitrogen rate for a specific crop significantly increase the potential for nitrate losses.[43]

Partly to blame for the nitrogen losses is the way manure is applied by farmers and how it is used by plants. Manure contains both organic and inorganic forms of nitrogen.[44] While inorganic nitrogen—in the form of nitrate or ammonium—is available to be used by plants for growth immediately, the organic form is not.[45] Before plants can take up organic nitrogen, it must first be mineralized by microorganisms in the soil to inorganic forms.[46] After this conversion process, however, the inorganic form ammonium can be easily converted into gas and lost into the atmosphere through volatilization, only to cause water pollution when it dissolves in rain and returns to earth.[47] But more significantly, since inorganic nitrates are soluble, they are prone to leaching.[48] Thus, the converted nitrate is highly susceptible to filtering through the soil profile and into the groundwater.[49]

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[42] Univ. of Minn. Extension, *Manure Application Methods and Nitrogen Losses*, (2018), https://extension.umn.edu/manure-land-application/manure-application-methods-and-nitrogen-losses, [hereinafter "Manure Application Methods"], attached as Ex. 8.

[43] Melissa Wilson, Univ. of Minn. Extension, *Guidelines for Manure Application Rates*, https://extension.umn.edu/manure-land-application/manure-application-rates (last visited July 17, 2020), [hereinafter "Guidelines for Manure Application"], attached as Ex. 9.

[44] Melissa Wilson, Univ. of Minn. Extension, *Manure Characteristics*, https://extension.umn.edu/manure-land-application/manure-characteristics (last visited July 17, 2020), [hereinafter "Manure Characteristics"], attached as Ex. 10.

[45] *Id.*; Manure Application Methods, *supra* note 39.

[46] Manure Characteristics, *supra* note 41; Ron Wiederholt, N.D. State Univ. Extension Serv., *Environmental Implications of Excess Fertilizer and Manure on Water Quality* (2017) https://www.ag.ndsu.edu/publications/ environment-natural-resources/environmental-implications-of-excess-fertilizer-and-manure-on-water-quality, attached as Ex. 11.

[47] *Id.*

[48] Scott C. Killpack & Daryl Bucholz, Univ. of Mo. Extension, *Nitrogen in the Environment: Leaching*, https://extension2.missouri.edu/wq262 (last visited July 17, 2020).

[49] Wiederholt, *supra* note 43.

In addition, if a farmer applies manure incorrectly—in too large of quantities, on vulnerable soils, or at improper times—leaching or runoff is more likely. If too much manure is applied, plants do not take it up, allowing nitrates to leach away.[50] If manure is applied to coarse-textured soils, nitrates can sink past plant roots and into groundwater.[51] If manure is applied early in the fall on ground that is too warm, it will quickly convert to into nitrate and likely be lost before spring planting; but if manure is applied in the winter on frozen soils, it is unlikely to be incorporated into the soil and instead runs off during melts or spring rains.[52]

In addition, multiple factors make manure challenging to manage as fertilizer and encourage over-application. First, the nutrient concentration in manure is far lower and much more uncertain than commercial fertilizer.[53] Time windows for effective manure application are narrower than with commercial fertilizer, and farm implements designed to distribute manure to fields can apply material non-uniformly.[54] Nitrogen loss to the atmosphere through volatilization can be significant and difficult to predict.[55] And insufficient storage capacity for manure may lead to farmers applying manure at ineffective times, when it is more likely that nutrients will run off or leach into the water and be lost to plants.[56] These uncertainties may lead farmers to over-apply manure in their eagerness to ensure that plants have abundant sources of nitrogen to use as they grow—or may even cause them to apply manure in the fall followed by commercial fertilizer in

[50] Guidelines for Manure Application, *supra* note 43.
[51] *Id.*
[52] Melissa Wilson, Univ. of Minn. Extension, *Manure Timing*, https://extension.umn.edu/ manure-land-application/manure-timing (last visited July 17, 2020), [hereinafter "Manure Timing'], attached as Exhibit 12.
[53] Jones, *supra* note 35, at 6.
[54] *Id.*
[55] *Id.*
[56] *Id.*

the spring.[57] These factors "frequently result in manured land receiving larger amounts of nutrient than those that receive only commercial N [fertilizer]."[58]

This is not necessarily a problem for the farmer, however. Unlike commercial fertilizer, which must be purchased, farmers with large livestock operations have access to free, always available manure in ample quantities. In some scenarios, research has found maximizing nitrogen loss to the environment is more profitable than attempting to use all of the nutrients from the manure.[59] For these farmers, manure is a waste product, and squandering its nutrients is not necessarily economically wasteful.[60] In fact, because of the costs of hauling manure, farmers may find it more profitable to concentrate manure applications on the fields closest to the animal confinements and buy commercial fertilizer—with its higher, uniform, and known nitrogen content—for the remaining fields.[61]

Overall, for farmers, the economic risk of under-applying manure is far greater than that of over-applying.[62] When a farmer under-applies nitrogen, the farmer takes on a considerable economic risk: that crop growth will not be maximized, leading to lower yields and less product to sell.[63] But when a farmer over-applies nitrogen, the farmer is only taking on the risk of the cost of the additional manure—which in many cases costs nothing at all—while increasing the opportunity to maximize crop yields and product for sale.[64] While the economic risk to the *farmer* of over-application is small, however, the *environmental* risk of over-application is severe.[65] Any

[57] *Id.*
[58] *Id.*
[59] *Id.* at 6.
[60] *Id.*
[61] *Id.*
[62] *Id.* at 8.
[63] *Id.*
[64] *Id.*
[65] *Id.*

excess nitrate not taken up by crops is vulnerable to loss to the atmosphere, aquifers, lakes, and streams.[66] This increases the costs to the public, which takes on the burden of addressing pollution, but does not increase costs to the farmer.[67] Accordingly, over-application of nitrogen "transfers the economic and natural risks associated with nitrogen application from the individual farmer to the public." [68]

Preventing nitrate from reaching water is vital to successfully addressing the growing nitrate pollution problem. Prevention is far less costly than treatment of contaminated water—when treatment is even possible.[69] Accordingly, controlling manure application to prevent nitrate runoff and leaching is critical to protecting public health from still worse increases in nitrate pollution. MPCA must ensure that the Proposed General Permit imposes restrictions that will adequately limit nitrate pollution to protect the people and aquatic habitats of Minnesota.

II. MINNESOTA LAW PLACES LIMITS ON LAND APPLICATION OF MANURE

Because of the harm posed by the threat of nitrate pollution, and the economic incentive of farmers to over-apply nitrogen, MPCA adopted a rule—Minn. R. 7020.2225, subp. 3 ("Land Application Rule")—that imposes limits on the amount of manure that can be applied to fields as fertilizer. The Proposed General Permit must include those limitations.[70]

The Land Application Rule requires that manure application be "limited" so that "the estimated plant available nitrogen from all nitrogen sources does not exceed *expected crop nitrogen needs* for nonlegume crops and *expected nitrogen removal* for legumes."[71] In other words,

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[66] *Id.* at 2.
[67] *Id.* at 8.
[68] *Id.*
[69] Minn. Dep't of Agric., *supra* note 15, at 18, 68.
[70] Minn. R. 7001.1080, subp. 1 (stating that any NPDES permit issued by the MPCA must "contain conditions necessary for the permittee to achieve compliance with all Minnesota or federal statutes or rules").
[71] Minn. R. 7020.2225, subp. 3(A) (emphasis added).

farmers must determine how much nitrogen their crops are expected to need or remove from the soil, how much nitrogen is available to their crops from all sources, and how much manure is needed to make up the difference between the needed nitrogen and available nitrogen. Then farmers must limit their manure application to ensure the application does not provide more nitrogen than the crops "need" or "remove."

To perform this calculation, farmers must first determine "expected crop nitrogen needs," "crop nitrogen removal rates," and "estimated plant available nitrogen." According to the rule, these variables "must be based on the most recent published recommendations of the University of Minnesota Extension Service or of another land grant college in a contiguous state."[72] Farmers must also identify all sources of nitrogen available to their crops, including "commercial fertilizer nitrogen, soil organic matter, irrigation water, legumes grown during previous years, biosolids, process wastewater, and manure applied for the current year and previous years."[73]

The rule provides some flexibility for farmers, however. Once the manure application calculation has been performed, farmers may deviate up to 20% from the Extension Service recommendations "where site nutrient management history, soil conditions, or cool weather warrant additional nitrogen application."[74] And if crop nitrogen deficiencies are "visible" or "measured," farmers may be able to apply even more nitrogen than the extra 20%.[75]

III. THE PROPOSED GENERAL PERMIT SHOULD BE REVISED TO PROTECT WATER QUALITY AND COMPLY WITH MINNESOTA RULES

While the Proposed General Permit includes some positive changes, the draft does not go far enough to protect Minnesota's water quality or comply with the Land Application Rule. Unless

[72] *Id.*, subp. 3(A)(1).
[73] *Id.*, subp. 3(A)(3).
[74] *Id.*, subp. 3(A)(2).
[75] *Id.*

MPCA makes changes, nitrate pollution in Minnesota is likely to worsen during the five-year tenure of the Proposed General Permit. Accordingly, the Clean Water Organizations request MPCA make the following changes to the Proposed General Permit.

A. Section 13.3: Limitation Of Manure Application Rates

First, MPCA must revise the Proposed General Permit to limit rates of manure application so that application is truly restricted to the amount of nitrogen the crop needs, as required by the Land Application Rule. As written, the Proposed General Permit references recommendations from the Extension Service and the MPCA for plant nitrogen needs that are based on economic risk and cost factors that are unrelated to the amount of nitrogen a typical crop will actually need or remove. This is called the Maximum Return to Nitrogen, or MRTN, system. Based on analysis by experts Dr. Gyles Randall, professor emeritus at the University of Minnesota's Department of Soil, Water, and Climate, who has conducted numerous studies relating to plant nitrogen needs and removal; and Dr. Christopher Jones, research engineer at Iowa State University, the MPCA's referenced recommendations are not consistent with the standard established by the Land Application Rule.

1. MRTN is not a measure of expected crop nitrogen needs or expected nitrogen removal.

Under the Land Application Rule, farmers must "limit[]" manure application so that the plant available nitrogen in the soil from all nitrogen sources is no more than "expected crop nitrogen needs" for nonlegumes and "expected nitrogen removal" for legumes.[76] The Land Application Rule states that the "expected crop nitrogen needs" and "expected nitrogen removal" must be based on the most recent published recommendations from the Extension Service (or of

[76] *Id.*, subp. 3(A).

another land grant college in a contiguous state).[77] The Proposed General Permit, accordingly, identifies recommendations from the Extension Service and specifically two fact sheets from MPCA to use in determining "expected crop nitrogen needs" and "expected nitrogen removal."[78] These fact sheets direct users to an Extension Service website, entitled "Calculating Manure Application Rates," which directs users to first "find the nutrient needs of the crop."[79] To do so, users are directed to another Extension Service website, called "Guidelines for Manure Application Rates." This website provides recommendations based on the MRTN system, for example, 195 pounds of nitrogen per acre for corn following corn and 150 pounds of nitrogen per acre for corn following soybeans.[80]

The MRTN referred to in these documents is based on three variables: expected crop price, expected nitrogen source cost, and expected crop production in response to the amount of fertilizer

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[77] *Id.*, subp. (3)(A)(1).

[78] Minn. Pollution Control Agency, Proposed General Permit § 13.3 (2020) [hereinafter "Proposed General Permit"] (directing permit holders to "the most recent recommendations of the Extension Service and the MPCA fact sheets '*Manure Nitrogen Rates For Corn Production (wq-f8-18)*' and '*Manure Management For Corn On Irrigated Sandy Soils (wq-f8-52)*'" (emphasis added)); *see also* Minn. Pollution Control Agency, *Manure Nitrogen Rates for Corn Production (wq-f8-18)* (2019) [hereinafter "Manure Nitrogen Rates for Corn"], attached as Ex. 13; Minn. Pollution Control Agency, *Manure Management For Corn On Irrigated Sandy Soils (wq-f8-52)* (2016), attached as Ex. 14.

[79] Melissa Wilson, Univ. of Minn. Extension, *Calculating Manure Application Rates* (2019), https://extension.umn.edu/manure-land-application/calculating-manure-application-rates, attached as Ex. 15.

[80] Guidelines for Manure Application, *supra* note 40. Concerningly, the MRTN recommendations under the current Extension Service documents are much higher than under previous versions of the recommendations. For example, the 2011 recommendations from Extension Service identify the MRTN at the 0.05 ratio as 155 lb. N/acre for corn after corn, and 120 lb. N/acre for corn after soybeans (and are even lower for less productive soils). It is unclear to MCEA why the recommendations have risen by 25% in both cases: 40 lb. N/acre for corn after corn and 30 lb. N/acre for corn after soybeans. This is a substantial and unexplained change that is almost certain to have significant environmental effects. *See* Univ. of Minn. Extension, *Fertilizer Guidelines for Agronomic Crops in Minnesota* 15 (2011), available at https://conservancy.umn.edu/bitstream/handle/11299/198924/Fertilizer%20Guidelines%20for%20Agronomic%20Crops%20in%20Minnesota.pdf?sequence=1&isAllowed=y.

applied.[81] While the expected crop production is based on research into plant nitrogen needs, the other variables can significantly change the recommended amount of nitrogen farmers should apply.[82] Accordingly, recommendations based on the MRTN system are intended to maximize economic performance for farmers, not simply to provide the crop with the nitrogen it needs to grow.[83]

Specifically, the MRTN calculates a ratio of the cost of commercial nitrogen fertilizer to the expected sale price for that crop. For example, if anhydrous ammonia fertilizer is being sold for $0.30/lb.-N, and the price of corn is $3.00 per bushel, the ratio will be 0.10.[84] This ratio is then used to determine how much nitrogen should be applied to a field to achieve the most *cost-effective* outcome.[85] Plants can only use a certain amount of nitrogen—at some point, plants stop taking in nitrogen from the soil and further application will produce no additional plant growth. However, at a certain point before plants reach this maximum growth, the incremental increase of nitrogen applied to the crop will produce a diminishing return in terms of crop yield.[86] Thus, the cost of adding that extra fertilizer to achieve the smaller potential growth becomes less cost-effective for the farmer.[87] The MRTN identifies the crucial point that produces the *maximum economic return for the farmer*. Beyond that point, the revenue generated from the additional bushels produced by additional fertilizer will (in theory) be less than the cost of the extra fertilizer applied to produce those bushels.[88] But if fertilizer is cheap, the MRTN system recommends additional applications

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[81] *See* Iowa State Univ. Agronomy Extension & Outreach, *Corn Nitrogen Rate Calculator* (2020) [hereinafter "Corn Nitrogen Calculator"], available at http://cnrc.agron.iastate.edu/.
[82] *See id*.
[83] *See* Manure Nitrogen Rates for Corn, *supra* note 75, at 1.
[84] Jones, *supra* note 35, at 5-6.
[85] Corn Nitrogen Rate Calculator, *supra* note 78.
[86] Jones, *supra* note 35, at 5.
[87] *Id.*
[88] *Id.* at 6.

in the hope that additional grain yields will occur, even if plants are unlikely to need the additional nitrogen and nitrogen loss to groundwater is highly likely. For this reason, the MRTN does not strictly focus on the magnitude of the grain yield or the crop needs for nitrogen, but instead on the economic return to the farmer.[89]

The recommendations generated by the MRTN system do not align with the Land Application Rule's requirement that manure application be limited to "expected crop nitrogen needs" for nonlegumes or "expected nitrogen removal" for legumes.[90] Contrary to the rule's language, the recommendations identified by the Proposed General Permit do not in fact define "expected crop nitrogen needs" or "expected nitrogen removal." Instead, they define the *maximum economic return to nitrogen* for farmers. The growth needs of a plant are not the same as a farmer's desire to maximize economic return. Actual crop nitrogen needs are dependent on a number of variables, including the timing, intensity, and total amount of precipitation; amount of sunshine; insect, weed, and disease pressures; other nutrient deficiencies (such as phosphorus, potassium, and sulfur); the amount of soil organic matter (which breaks organic nitrogen down into a form plants can use); and soil type and texture.[91] The MRTN system includes no variables for these factors. Instead the MRTN recommendations are explicitly based on *fertilizer and crop price*, not *crop needs,* and accordingly these recommendations allow manure applications that likely exceed crop needs if it appears the farmer may economically profit.

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[89] *Id.* at 6.
[90] Minn. R. 7020.2225, subp. 3(A).
[91] Jones, *supra* note 35, at 3. Notably, the MPCA fact sheet recognizes that some fields can be highly productive without applying the maximum MRTN, based on different conditions. *See* Manure Nitrogen Rates for Corn, *supra* note 75, at 1. For example, the fact sheet acknowledges that fields in southeastern Minnesota with loess soils need less nitrogen to maximize yields. *Id.* But MPCA provides no recommendation for what the nitrogen level should be in these situations.

Because the section of the Proposed General Permit that identifies the MPCA fact sheets and Extension Service websites is based on the MRTN, the Proposed General Permit is inconsistent with the requirements of the Land Application Rule. The MPCA must adjust the recommendation to reflect the rule's requirement that the application rate must be strictly based on expected crop nitrogen needs and expected nitrogen removal. The Clean Water Organizations therefore propose that Section 13.3 be revised as follows:

> The Permittee shall ~~control~~ limit manure application rates so the estimated nitrogen available to crops from all nitrogen sources (including commercial fertilizer) does not exceed expected annual crop nitrogen needs for non-legumes and expected nitrogen removal for legumes. Expected crop nitrogen needs, crop nitrogen removal rates, and estimated plant available nitrogen from manure and legumes must be based on the most recent published recommendations of the University of Minnesota Extension Service, but must not be based on recommendations incorporating cost-factors for nitrogen fertilizer (i.e., MRTN system).. ~~based on the most recent recommendations of the MES and the MPCA fact sheets "*Manure Nitrogen Rates For Corn Production (wq-f8-18)*" and "*Manure Management For Corn On Irrigated Sandy Soils (wq-f8-52)*".~~ The Permittee may use recommendations for annual crop nitrogen needs from another land grant college in a contiguous state ~~may be utilized~~ in the MMP provided the field and climate conditions at the land application site are similar to those within the contiguous state, and do not incorporate cost-factors as set forth above. [Minn. R. 7020.2225]

2. The MRTN for manure should not be calculated using a lower cost ratio than that used for commercial nitrogen fertilizer.

The manure application rates identified by Extension Service are also improper and inconsistent with the Land Application Rule because the rates are formulated based on the cost of commercial nitrogen fertilizer and often produce excessive results when used for manure. If MPCA uses the MRTN recommendations, at a minimum those recommendations should be the same for manure as for commercial fertilizer. After all, expected crop nitrogen needs should not change based on whether the farmer applies commercial fertilizer or manure.

As explained above, the MRTN is calculated based on the ratio of the cost of *commercial nitrogen fertilizer* to the expected sale price of the crop. Minnesota's recommendations for the

MRTN for commercial fertilizer include calculations that use ratios of 0.05, 0.10, 0.15, and 0.20 to account for price fluctuations in fertilizer and corn.[92] However, because the ratio of the prices of fertilizer to corn has remained approximately the same, the 0.10 ratio usually been used for commercial fertilizer recommendations in Minnesota.[93]

For manure, considerations are different. Often, the farmer owns or manages livestock and may obtain manure without paying for it.[94] Presumably to account for that fact that manure is cheaper than fertilizer, the Extension Service recommendations identified in the Proposed General Permit do not use the 0.10 ratio that would be used for commercial fertilizer. Instead, the recommendations use the 0.05 ratio.[95]

This leads to a significantly larger nitrogen recommendation for manure application than for commercial fertilizer, Dr. Jones explains. As an example, using the 0.10 ratio for corn grown after soybeans produces a recommended MRTN of 131 lb. N/acre, with a profitable range of 118–144 lb. N/acre.[96] Using the 0.05 ratio, by contrast, increases the MRTN Rate to 150 lb. N/acre and the profitable range to 135–169 lb. N/acre.[97] Thus, under the Extension Service recommendations, for the same field, a farmer could add 19 lb. N/acre when applying manure instead of commercial fertilizer. These two examples are shown below in Figure 1:

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[92] Daniel Kaiser, et al., Univ. of Minn. Extension, *Fertilizing Corn in Minnesota* (2020), https://extension.umn.edu/crop-specific-needs/fertilizing-corn-minnesota#standard-n-guidelines-2237060, attached as Ex. 17.
[93] Dr. Gyles Randall, *Expert Report* 1 (2020), attached as Ex. 2.
[94] Jones, *supra* note 35, at 7.
[95] Manure Nitrogen Rates for Corn, *supra* note 75; Guidelines for Manure Application, *supra* note 40.
[96] Jones, *supra* note 35, at 7.
[97] *Id.*

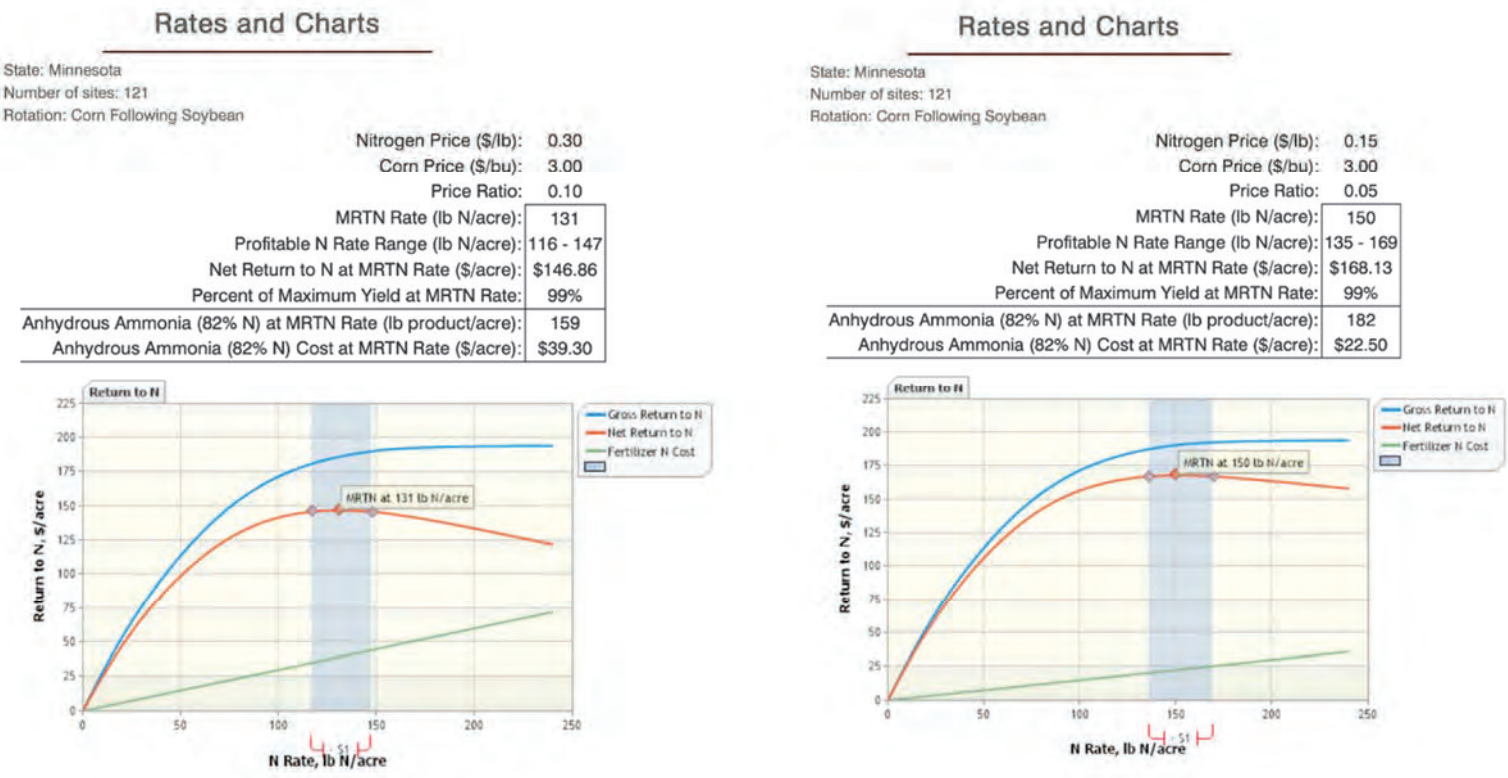

Figure 1. Two scenarios using the MRTN Calculator for commercial anhydrous ammonia (left) and manure (right), at current prices for N fertilizer and corn, using the Proposed General Permit's guidelines for manure application rate at 0.05 MRTN.[98]

Importantly, the orange line's downward slope to the right of the MRTN shows that a farmer who uses commercial fertilizer beyond the MRTN will incur an economic penalty.[99] By contrast, as Dr. Jones explains, "there is almost no economic consequence for the farmer to keep applying manure far beyond the MRTN rate, which is already 19 lbs./acre higher than the recommended rate using commercial nitrogen."[100] In addition, the difference between the total net return to the farmer for commercial fertilizer and manure is notable. When using commercial fertilizer at the 0.10 MRTN rate, the farmer achieves a net return of $146.86/acre. When using

[98] *Id.* at 7.
[99] *Id.*
[100] *Id.*

manure, the farmer could achieve that same net return using an application rate far below the 0.05 MRTN rate—about 80 lbs./acre in this example.[101] Clearly, the farmer using manure can achieve economic parity with the farmer using commercial fertilizer, even while applying manure at a rate far below the Extension Service recommendations.[102] But, according to Dr. Jones, "the Extension Service guidelines do quite the opposite—they encourage application of [nitrogen] far beyond that threshold."[103]

For this additional reason, the Extension Service's recommendations, which are referenced in the Proposed General Permit, do not comply with the Land Application Rule requirement that limits manure application to "expected crop nitrogen needs" or "nitrogen removal rates." The actual crop needs for nitrogen do not change based on whether a farmer applies commercial nitrogen fertilizer or manure, or based on a change in the cost of fertilizer. Accordingly, if the MPCA elects to use the MRTN, it is unreasonable and inconsistent with the Land Application Rule to use a different MRTN for commercial fertilizer than for manure.[104] If the 0.10 MRTN rate provides sufficient nitrogen for plant growth when commercial fertilizer is used, that same rate will provide sufficient nitrogen to meet the expected crop nitrogen needs or nitrogen removal rates when manure is used.[105]

Accordingly, if the MPCA determines that the recommended rate should remain the MRTN, the Clean Water Organizations propose that Section 13.3 be revised as follows:

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[101] *Id.*
[102] *Id.*
[103] *Id.*
[104] Notably, one of the original MRTN developers has stated that the price of commercial nitrogen fertilizer *should* be used to calculate the MRTN ratio for manure, instead of the lower rate indicating that manure is less expensive. Randall, *supra* note 90, at 1.
[105] Maximizing the amount of manure to apply is particularly inappropriate when the Land Application Rule already allows farmers to deviate up to 20% in excess of recommendations when needed under the circumstances. Minn. R. 7020.2225, subp. 3(A)(2).

The Permittee shall ~~control~~ limit manure application rates so the estimated nitrogen available to crops from all nitrogen sources (including commercial fertilizer) does not exceed expected annual crop nitrogen needs for non-legumes and expected nitrogen removal for legumes. Expected crop nitrogen needs, crop nitrogen removal rates, and estimated plant available nitrogen from manure and legumes must be based on the most recent published recommendations of the University of Minnesota Extension Service, but must not be based on recommendations incorporating cost-factors for nitrogen fertilizer (i.e., MRTN system) unless the MRTN recommendation used is based on a cost factor of at least 0.10. ~~based on the most recent recommendations of the MES and the MPCA fact sheets "*Manure Nitrogen Rates For Corn Production (wq-f8-18)*" and "*Manure Management For Corn On Irrigated Sandy Soils (wq-f8-52)*".~~ The Permittee may use recommendations for annual crop nitrogen needs from another land grant college in a contiguous state ~~may be utilized~~ in the MMP provided the field and climate conditions at the land application site are similar to those within the contiguous state, and if the recommendations are based on the MRTN, they use a cost factor of at least 0.10. [Minn. R. 7020.2225]

B. Section 13.3(a): Pre-Plant Testing For Nitrate.

Next, the Clean Water Organizations request that MPCA add back into the Proposed General Permit a section relating to pre-plant testing for nitrate. MPCA included such a section in the 2016 General Permit, and it is needed to comply with the Minnesota Rules and to ensure that farmers are not over-applying manure that will cause water pollution.

The Land Application Rule requires that manure management plans include "plans for soil nitrate testing in accordance with University of Minnesota Extension Service recommendations."[106] Under the rules, any required testing must be sufficient to yield representative data to determine whether a permittee is complying with the conditions of the permit and state rules.[107] In this case, the Land Application Rule and the Proposed General Permit require farmers to limit manure applications to "expected crop nitrogen needs" or "nitrogen removal rates." The Land Application Rule and the Proposed General Permit also require that in calculating these amounts, farmers consider *all* sources of nitrogen available to their crops, including

[106] *Id*., subp. 4(D)(12).
[107] Minn. R. 7001.0150, subp. 2(B).

"commercial fertilizer nitrogen, soil organic matter, irrigation water, legumes grown during previous years, biosolids, process wastewater, and manure applied for the current year and previous years."[108] Accordingly, nitrate testing is needed to ensure that farmers properly account for all nitrogen sources, and that farmers do not apply nitrogen in excess of expected crop nitrogen needs. In short, farmers cannot limit their application to the crop's expected nitrogen needs if they do not know how much nitrogen is already in the soil, and they cannot know how much nitrogen is in the soil without testing.

Determining how much nitrogen farmers should credit from previous years is not an easy task without testing. Many factors affect how much residual nitrogen remains in the soil, including the previous crop grown, the soil texture, and historic rainfall.[109] One of the most important factors—with the most difficult-to-predict effects—is the amount of residual nitrates that remain from manure applied in previous years.[110] As the Extension Service explains, microbes require several years to mineralize organic forms of nitrogen in manure into nitrate that can be used by plants, and the length of the process depends on soil moisture and temperature conditions.[111] Accordingly, manure applied in one growing season will continue to provide nitrate to plants for several growing seasons.[112] The amount of residual nitrogen, however, can vary greatly, is difficult to predict, and can have substantial effects on the amount of preplant nitrogen that should be added to the soil.[113] As Dr. Randall explains, a soil test of 13 sites where manure had been applied in the

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[108] Minn. R. 7020.2225, subps. 3(A)(1), (A)(3)
[109] Univ. of Minn. Extension, *Soil Testing for Corn Nitrogen Recommendations* (2018), https://extension.umn.edu/nitrogen/soil-testing-corn-nitrogen-recommendations, [hereinafter "Soil Testing for Corn"], attached as Ex. 18.
[110] *Id.*
[111] Manure Characteristics, *supra* note 41, at 6.
[112] *Id.*
[113] *Id.*; *see also* Randall, *supra* note 90, at 2.

previous five years showed that the amount of nitrogen to be applied should be reduced by an average of 43 lb. N/acre based on the residual nitrogen.[114] For several sites, the recommended rate of nitrogen to be applied was reduced by 70 lb. N/acre, and for others it was reduced by only 19 lb. N/acre, showing the wide range of results that manure application can have at different fields.[115]

Accounting for nitrates released from manure over time can be done using a "credit" for manure from the previous two years.[116] But the crediting system cannot precisely account for the actual amount of nitrates, and in some cases may result in excessive fertilizer recommendations.[117] Measuring nitrates in the soil is more reliable than other methods of estimating the need for additional nitrogen application.[118] As the Iowa State University Extension Service explains, using a late-spring test for soil nitrate "should help corn producers manage N to increase their profits while reducing environmental degradation."[119]

Currently, the Proposed General Permit does not include any requirement for soil testing for nitrogen, although it does require soil testing for phosphorus.[120] The 2016 General Permit, however, *does* require soil nitrate testing "according to the method and frequency recommended by the most recent MES-published guidelines."[121] It is unclear why MPCA removed this requirement in the Proposed General Permit. To comply with the requirements of the Land

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[114] Randall, *supra* note 94, at 2.
[115] *Id.*
[116] Manure Characteristics, *supra* note 41, at 4.
[117] Soil Testing for Corn, *supra* note 106, at 4 (explaining that using the standard manure nitrogen crediting system without a soil test when manure was applied in October or November "may result in high fertilizer recommendations if significant residual nitrogen was present before the manure was applied.")
[118] A.M. Blackmer et al., Iowa State Univ. Extension Serv., *Nitrogen Fertilizer Recommendations for Corn in Iowa* 4 (1997), attached as Ex. 19.
[119] *Id.* at 1.
[120] *See* Proposed General Permit, *supra* note 75, § 12.6.
[121] Minn. Pollution Control Agency, *NPDES General Permit for Concentrated Animal Feeding Operations* § 4.5.4 (2016).

Application Rule and ensure farmers are able to accurately determine the proper amount of manure they should apply, the Clean Water Organizations propose that the following language be added to the Proposed General Permit:

> The Permittee shall ensure that fields receiving manure are sampled and tested for soil nitrates according to the method and frequency recommended by the most recent MES-published guidelines. The Permittee shall use the results of the sample in calculating a residual N credit. [Minn. R.7020.2225, subp. 3.A(3)].

C. Section 14.6: October Restrictions On Manure Application.

The Clean Water Organizations also request changes to the section regarding October Restrictions on Manure Application to better guard against nitrate pollution. The Clean Water Organizations appreciate that the Proposed General Permit now requires best management practices ("BMPs") for any manure application in October, but believes that those requirements should be strengthened to further protect water quality.

First, with regard to the soil temperature, the proposed language provides no direction about how to determine soil temperature. This is important, because fall manure application when temperatures exceed 50º F is highly likely to cause nitrate pollution. In such cases, the organic nitrogen will be mineralized to inorganic nitrate at a time when the crops are not growing.[122] Then, the nitrate will remain in the soil until the crop takes it up, possibly not until the following June.[123] The longer the nitrate remains in the soil, the more likely it is to leach into the groundwater—particularly during heavy rains in the fall or early spring.[124] Accordingly, ensuring that soil temperatures prior to manure application are below 50º F, and are likely to *remain* that way until spring, is critical. Allowing farmers to apply manure as soon as their area has one 50º F soil

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[122] Fred Madison et al., Univ. of Wis. Extension Serv., *Guidelines for Applying Manure to Cropland and Pasture in Wisconsin* 11 (2014), https://soilsextension.webhosting.cals.wisc.edu/wp-content/uploads /sites/68/2014/02/A3392.pdf, attached as Ex. 20.
[123] Randall, *supra* note 90, at 2.
[124] *Id.* at 2; Madison, *supra* note 119, at 11.

temperature reading will not prevent nitrate leaching, as mineralization to nitrate will begin again if the soil temperatures rise after manure application. To ensure consistency, Dr. Randall recommends that soil temperature readings be taken at a depth of six inches and be less than 50 degrees for three consecutive days before farmers apply manure.[125]

Second, with regard to cover crops, the Proposed General Permit indicates manure may be applied in October if a cover crop "is established in accordance with the requirements of this Permit for June, July, August, or September applications." But the likelihood that a cover crop can be established drops quickly after the first half of September, particularly in the northern half of the state.[126] After October 1, establishing a cover crop would be very difficult even in southern Minnesota and extremely unlikely in northern Minnesota.[127] To effectively prevent nitrate pollution, a cover crop must not merely be germinated—it must be well-established and sufficiently robust to take up a substantial amount of nitrate from the manure.[128] This means the crop must be well-grown—perhaps six to eight inches tall—by mid-to-late October.[129] A cover crop planted in October is extremely unlikely to fulfill its intended function as a temporary fixer of nitrates.[130] But the Proposed General Permit would allow a farmer to seed a cover crop in October within 10 days of manure application and hope for the best—and there would be no way to remove the manure if the cover crop does not sprout. Any manure applied under these circumstances is very likely to mineralize to nitrate and leach into the groundwater.[131] If, however,

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[125] Randall, *supra* note 90, at 3. For the same reason, this standard—three consecutive days of temperatures below 50 degrees, measured at a soil depth of six inches below the surface—also should be added to section 14.4, relating to manure application on coarse-textured soils.
[126] Randall, *supra* note 90, at 3.
[127] *Id.*
[128] *Id.*
[129] *Id.*
[130] *Id.*
[131] *Id.*

a cover crop has already been established prior to October, application of manure through an injector into the growing cover crop could be a potential BMP.[132] Therefore, the Proposed General Permit should be revised to indicate that cover crops may be used as a BMP for October manure application only if the cover crop has been planted in a previous month and already established before the October application.

Third, for the split application of nitrogen, the Proposed General Permit does not indicate when the second half of the nitrogen could be applied. Applying the second half of the manure soon after the first half—in early November, for example—would negate the effectiveness of splitting the nitrogen application. And manure application during the winter months, to frozen or snow-covered soils, is prohibited or subject to strict conditions under the terms of the permit.[133] Even under those conditions, winter manure application is risky and likely to lead to runoff, as explained in the next section. Under no circumstances should applying manure during winter months be considered a BMP. Accordingly, the Proposed General Permit should specify that the second half of the split application of nitrogen should be applied only in the spring, when the ground is no longer frozen.

Finally, the Proposed General Permit does not require implementation of BMPs during an "emergency" manure application, perhaps on the assumption that BMPs would not be feasible. But in some cases, farmers may in fact be able to implement these BMPs despite an emergency. For example, a nitrogen stabilizing agent potentially could be added to the manure before spreading, despite poor weather conditions or equipment failure that prevented an earlier manure

[132] *Id.*
[133] *See* Proposed General Permit, *supra* note 75, §§ 14.8, 14.10.

application.[134] In such cases, when following the BMPs remains feasible, farmers should not be excused from following the BMPs intended to prevent nitrate pollution.

Accordingly, to better protect water quality, the Clean Water Organizations propose the following revisions to Section 14.6:

> October Restrictions - The Permittee shall not apply manure in October to harvested fields unless at least one of the following nitrogen BMPs are implemented:
>
> a) Soil temperature ~~is~~ has been below 50 degrees for three consecutive days at the time of manure application based on temperatures taken six inches below the soil surface;
>
> b) A nitrogen stabilizing agent/product is added at the recommended inclusion rates;
>
> c) A cover crop ~~is~~ has been established prior to October in accordance with the requirements of this Permit for June, July, August, or September manure applications; or
>
> d) A split application of nitrogen is used where no more than 1/2 of the recommended nitrogen rate is applied before October 31 and the remainder is applied after April 1 or after the soil is no longer frozen or snow-covered, whichever is later.
>
> ~~Alternatives developed by a land grant University can be used if approved by the MPCA and included as part of the approved MMP.~~
>
> Nitrogen BMP implementation is ~~not~~ required for emergency manure application, as defined by this Permit, unless implementation of BMPs is infeasible due to the emergency conditions necessitating the application. [Minn. R. 7001.0150]

D. Section 14.8: Winter Application Of Solid Manure.

Similarly, while the Clean Water Organizations appreciate MPCA's efforts to strengthen the Proposed General Permit's section on winter application of solid manure, a broader prohibition could make this section even stronger. Prohibiting application of solid manure in December and January, along with February and March, will provide even better protection against nitrate pollution.

[134] *See id.* § 30.19 (defining "emergency manure application").

When farmers apply manure to snow-covered or frozen soil, nutrients cannot soak into the soil, and the potential for nitrate loss is "extremely high."[135] When farmers apply manure during the winter months, the majority of the inorganic nitrogen is likely to be lost to the air through volatilization.[136] And winter-applied manure is very likely to be "carried off to lakes and streams during thaws or during winter or early spring rains."[137] For these reasons, the Proposed General Permit contains a prohibition on applying solid manure during February and March. However, these same considerations apply with equal force to December and January, when the ground is also likely to be frozen or snow-covered.[138] Accordingly, the Clean Water Organizations propose the following revision:

> Winter application of solid manure - Winter application of solid manure during the months of December, January, February and March is prohibited. When allowed, winter application must comply with all of the following:
>
> a) Manure is applied on fields identified in the MPCA approved MMP for winter application;
>
> b) Manure is applied more than 300 feet from sensitive features including lakes, streams, open tile inlets, sinkholes, water supply wells, mines and quarries, intermittent streams, un-bermed drainage ditches, or public water wetlands;
>
> c) Air temperatures are less than 40 degrees Fahrenheit during, and for at least 24 hours from the end of, the application process when two or more inches of snow are on the field;
>
> d) Less than a 50% probability of rainfall in excess of 0.25 inches predicted by the National Weather Service within 24 hours of the end of the application period;
>
> e) Slopes are less than or equal to six percent on the entire portion of the field where manure is land applied;

---

[135] Manure Timing, *supra* note 52. This Extension Service publication recommends, unless there is an emergency, "Do not apply in winter." *Id*.
[136] Soil Testing for Corn, *supra* note 106, at 4.
[137] Madison et al., *supra* note 119, at 15.
[138] If the ground is not frozen or snow-covered in December or January, then the application would not qualify as a "winter manure application" under the Proposed General Permit definition and therefore would not be prohibited. *See* Proposed General Permit, *supra* note 75, § 30.53.

f) Water or ice do not occupy tillage furrows to the extent that additional snowmelt or precipitation cannot be contained between furrows or in other depressions within the field; and

g) Fields used for land application meet a total phosphorus loss risk index number of two or less (low to very low relative risk) as calculated according to the Minnesota Phosphorus Index.

In the event of significant snow accumulation within animal holding areas, the Permittee may obtain approval from the MPCA for winter application of the snow and manure-snow mix during December, January, February and March. If approved, the application fields must, at a minimum, meet the requirements above. Additional measures/practices may be required by the MPCA. [Minn. R. 7001.0150]

E. Section 11.4: Review Of Manure Management Plan.

Finally, revising Section 11.4 to require farmers to identify fields in manure management plans ("MMP") using GIS information will assist MPCA staff. Using GIS information will make it easier for MPCA to determine whether any fields receive double applications of manure because they are identified in more than one MMP and receiving manure from more than one farmer.

Pursuant to the Land Application Rule, MMPs "must include acreage available for manure and process wastewater application including maps or aerial photos showing field locations and areas within the fields that are suitable for manure or process wastewater application."[139] The rule, accordingly, requires farmers to specifically identify fields in the MMPs. Identification through GIS information will make descriptions on MMPs more readily comparable for MPCA staff. Under the current system, two applicants could describe the same field using different descriptors, and determining whether there is overlap between two plans is cumbersome for MPCA staff, who must compare different maps or aerial photographs to determine whether the same field has been identified in more than one MMP. Using GIS information would standardize descriptions of fields

[139] Minn. R. 7020.2226, subp. 4(D)(3).

in the MMPs, making it clear to both MPCA staff and applicants which fields are being referred to in the MMP.

Accordingly, the Clean Water Organizations propose the following revision to Section 11.4:

> The Permittee shall annually review and update the approved MMP to ensure that it meets all applicable requirements. The annual review and update shall include information for each field where manure will be applied during the following growing season. The permittee shall provide an area delineation of each manure application site in a GIS polygon geospatial file format (.kml, .shp, .json, etc.) with detailed coordinate system information, including a description of the site. Annual updates to the MMP do not require a modification of coverage under this Permit provided the updates are consistent with the methodology of the approved MMP. [Minn. R. 7001.0190, Minn. R. 7020.2225]

IV. THE CLEAN WATER ORGANIZATIONS REQUEST A CONTESTED CASE HEARING

The Clean Water Organizations request a contested case hearing on the issue of whether the recommendation MPCA has referenced in Section 13.3 of the Proposed General Permit is consistent with "expected crop nitrogen needs, crop nitrogen removal rates, and estimated plant available nitrogen from manure and legumes" as required by the Land Application Rule.

The information required by Minn. R. 7000.1800 is provided below.

1. Statement of reasons or proposed findings supporting an MPCA decision to hold a contested case hearing.

(A) There is a material issue of fact in dispute concerning this matter.

As noted in the Clean Water Organizations' comments above in section V.A, the Proposed General Permit references recommendations from the University of Minnesota that incorporate economic risk and cost factors unrelated to the amount of nitrogen a typical crop[140] will actually need or remove to support plant growth. As a result, these recommendations are inconsistent with

[140] MCEA notes that Minn. R. 7020.2225, subp. 3 already provides for increased nitrogen application if conditions particular to the crop or field require additional applications to secure the crop.

what the Land Application Rule requires and will allow permittees to apply manure at rates resulting in excess loss of nitrate to the groundwater, exacerbating the issues the Clean Water Organizations describe in section II.B above. Whether the recommendations conform to the objective requirement of the rule is a factual issue that can be resolved with expert testimony.[141] This expert testimony will identify the results of research into "expected crop nitrogen needs, crop nitrogen removal rates, and estimated plant available nitrogen from manure and legumes," why the economic components incorporated into the current recommendation result in applications not supported by the scientific data, and why the recommendations will lead to excess application inconsistent with the text and intent of MPCA's land application rule.

(B) The MPCA has the jurisdiction to make a determination on this issue.

In the proposed general permit, MPCA has referenced a particular recommendation of the Extension Service. If MPCA agrees with the Clean Water Organizations that the recommendation it references is not consistent with the standard established by the Land Application Rule, MPCA could ask the Extension Service to modify its recommendation, or MPCA could modify the Proposed General Permit to ensure that a modified version of the Extension Service's recommendations are referenced in the Proposed General Permit. As a result, this issue is within MPCA's jurisdiction.

(C) There is a reasonable basis underlying the disputed material issue of fact or facts such that the holding of a contested case hearing would allow the introduction of information that would aid the MPCA in resolving the disputed facts in making a final decision on the matter.

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[141] *See In re City of Owatonna's NPDES/SDS Proposed Permit Reissuance for the Discharge of Treated Wastewater*, 672 N.W.2d 921, 928 (Minn. Ct. App. 2004) (finding a fact issue supporting a contested case hearing request existed when relator submitted expert affidavits and a report challenging MPCA's interpretation of its modeling and explaining, "When experts disagree, a fact question arises.")

The Clean Water Organizations support this request with two expert reports, by Dr. Christopher Jones, research engineer at Iowa State University (attached as Exhibit 1) and Dr. Gyles Randall, professor emeritus at the University of Minnesota (attached as Exhibit 2).[142] These experts will testify that the recommendation currently included in the Proposed General Permit is not consistent with the standard established by the Land Application Rule.[143] These experts will base their testimony on research conducted in Minnesota and Iowa. These experts will demonstrate that the economic factors incorporated into the current recommendations, particularly as applied to manure, result in excess application inconsistent with "expected crop nitrogen needs, crop nitrogen removal rates, and estimated plant available nitrogen from manure and legumes" and that this excess application can be predicted to lead to enhances nitrogen loss to the groundwater.

2. A statement of the issues proposed to be addressed by a contested case hearing and the specific relief requested or resolution of the matter.

The issue to be addressed by a contested case hearing is whether the recommendation referenced in the Proposed General Permit conforms to the standard established by the Land Application Rule. The relief requested is amendment of the Proposed General Permit to include a recommendation that will result manure application rates consistent with plant needs established by scientific research, as required by the Land Application Rule.

Clean Water Organization has identified two changes that MPCA could make to the Proposed General Permit to address this issue, in section V.A, above. First, MPCA could request the Extension Service to prepare a recommendation that does not include the economic factors on which the current MRTN recommendation is based. Second, MPCA could request the Extension

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[142] *See* Jones, *supra* note 35; and Randall, *supra* note 90.

[143] *See City of Owatonna,* 672 N.W.2d at 929 (explaining that relator had sufficiently supported the requested for a contested case hearing when it submitted affidavits of experts who challenged MPCA's methodology and interpretation of the modeling at issue).

Service to prepare a recommendation specific to manure that utilizes the MRTN, but includes a higher cost factor ratio similar to the one used for commercial fertilizer, which is less likely to result in over-application of manure.

3. Witnesses, exhibits, and estimate of time.

At a contested case hearing, the Clean Water Organizations would intend to present the following witnesses: Dr. Christopher Jones and Dr. Gyles Randall. Proposed exhibits would include all exhibits attached to this comment or referenced herein. The estimated time for the contested case hearing would be a half-day. The Clean Water Organizations reserve the right to introduce other witnesses or exhibits in accordance with Minn. R. 7000.1800, subp. 2(C). The Clean Water Organizations note that MCEA has been seeking a meeting with MPCA and Extension Service representatives to discuss the use of MRTN recommendations, which could lead to changes that would resolve this issue without a contested case hearing.

CONCLUSION

While the Clean Water Organizations appreciate that the Proposed General Permit makes some incremental changes that are likely to help improve water quality, the Clean Water Organizations' position is that the Proposed General Permit will allow the continued pollution of Minnesota's water, endangering drinking water and aquatic life. Already, hundreds of thousands of Minnesotans are drinking water with elevated levels of nitrates, which will increase their risks of cancers and other health problems. If farmers are allowed to continue to apply manure to their fields in excess of crop nitrogen needs, and at times and using methods that pose high risk of nitrate leaching and runoff, dangerous nitrate pollution will continue to increase across Minnesota. Accordingly, the Clean Water Organizations respectfully request that MPCA revise the Proposed General Permit as follows:

(1) revise Section 13.3 to limit manure application rates to "expected crop nitrogen needs" or "expected nitrogen removal"; or in the alternative, to ensure that the MRTN uses a cost factor of at least 0.10;

(2) add Section 13.3(a) to require pre-plant testing for nitrate according to Extension Service recommendations;

(3) revise Section 14.4 to require soil temperature measurements below 50 degrees for three consecutive days, measured at a soil depth of six inches below the surface;

(4) revise Section 14.6 to strengthen October restrictions on manure application;

(5) revise Section 14.8 to prohibit application of solid manure in December and January; and

(6) revise Section 11.4 to require GIS field identification in MMPs.

Respectfully submitted,

MINNESOTA CENTER FOR ENVIRONMENTAL ADVOCACY

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'Manure is complicated': 5 reasons you need a manure management plan

blog-crop-news.extension.umn.edu/2023/06/manure-is-complicated-5-reasons-you.html

By: Chryseis Modderman, Extension manure management educator

When applying manure, the main goals are to apply at an accurate rate and to avoid nutrient pollution. But this isn't always easy because manure, in general, is complicated. There are five main factors that make manure complicated; often, more complicated than commercial fertilizer. Following a manure management plan will help combat these challenges. Read on for the five challenging factors.

Overall nutrient content is low

Total nutrient content of manure is low – rarely above 10 percent – whereas commercial fertilizers have a much higher nutrient concentration by weight. The low nutrient content of manure is a potential problem because you need a lot more volume of manure than commercial fertilizer to achieve the same nutrient application rates. This increases time and transportation cost, making it more economical to apply to the field nearest the barn. Over time, repeated over-application to the same field can lead to nutrient build up and subsequent pollution. It is quite common to see fields nearest a livestock operation with very high soil test phosphorus levels.

Nutrient ratio is fixed

Unlike commercial fertilizers that can be mixed and adjusted to reach desired nutrient balance, manure nutrients are fixed. It is what it is. Let's do some quick math to illustrate this. Let's say you have turkey manure with 30 pounds of plant-available nitrogen and 40 pounds of plant-available phosphorus per ton, and your agronomist says to apply 180 pounds of nitrogen per acre for your corn crop. You'd need to apply manure at six tons per acre (180 / 30 = 6).

Does this application rate pose a risk for nutrient pollution? Yes. At 6 tons/acre, you will apply 240 lbs P/acre (40*6=240). Corn only uses 0.29 lbs P per yield unit. So, even a really high yield of 250 bu/ac corn would only require 72.5 lbs P/acre; and that's including what is already in the soil. Adding 240 lbs of P is way too much! Over-application of phosphorus can lead to phosphorus buildup, which can lead to pollution.

Nutrient availability is difficult to estimate

Nutrient availability, especially the availability of nitrogen, can be challenging to accurately estimate. Manure supplies two forms of nitrogen: inorganic and organic nitrogen. The inorganic nitrogen is immediately available to the plant; while the organic nitrogen is not. Organic nitrogen can become inorganic nitrogen over time through a process called mineralization. The challenge is estimating how much organic nitrogen will become inorganic nitrogen, and how fast. This can be tricky because mineralization is a microbial process, meaning that how fast or slow it processes organic nitrogen depends heavily on the environment. And we know how fickle the environment can be!

Nutrient content is not uniform

Unlike commercial fertilizers that are fairly uniform throughout, manure uniformity varies spatially and over time. This can make accurate rate calculations tricky. To meet this challenge, it is very important to take a good representative manure sample for testing. But even then, it is likely that slight over- or under-application can occur.

Nutrient timing may not be ideal

In a perfect world, manure would only be applied when the nutrients are necessary and when it poses the least risk to the environment. Unfortunately, we don't live in a perfect world. Often, manure application timing is driven by storage limitations and working around wet weather, harvest, or planting rather than when it is best for the crop and environment. Nutrient loss from manure is higher when application occurs in late winter, around the time of snowmelt.

How to meet these challenges

While we may never be 100 percent perfect with manure management, there are ways to minimize these challenges. The most significant is to have a manure management plan which encompasses best management practices such as accurate rate calculations, sampling, setbacks and buffers, spreader calibration and more!

This post was originally published by Manure Manager and has been republished here with permission.

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United States Environmental Protection Agency
Region 10
1200 Sixth Avenue, Suite 155
Seattle, Washington 98101-3188

Authorization to Discharge under the
National Pollutant Discharge Elimination System

In compliance with the provisions of the Clean Water Act (CWA), 33 U.S.C. § 1251 *et seq.*, as amended by the Water Quality Act of 1987, P.L. 100-4, the "Act",

Concentrated Animal Feeding Operations (CAFOs) in Idaho as defined in Section I of this permit

are authorized to discharge in accordance with discharge point(s), effluent limitations, monitoring requirements, and other conditions set forth herein.

This permit shall become effective: June 15, 2020

This permit and the authorization to discharge shall expire at midnight: June 14, 2025

The permittee shall reapply for a permit reissuance on or before December 16, 2024, 180 days before the expiration of this permit if the permittee intends to continue operations and discharges at the facility beyond the term of this permit.

/s/

Daniel D. Opalski, Director
Water Division

The general permit was modified to includes new and revised conditions to address the Ninth Circuit Court of Appeal's Order and Opinion filed on December 16, 2021 (*Food & Water Watch et al. v. U.S. Environmental Protection Agency* (No. 20-71554). See 2023 and 2024 permit modification fact sheets and the response to comments document for details.

SUSAN POULSOM

Digitally signed by SUSAN POULSOM
Date: 2024.12.12 09:26:24 -08'00'

Susan Poulsom
Acting Branch Manager
Permitting, Drinking Water and Infrastructure

b) Alternative practices compliance alternative. As a compliance alternative, the CAFO may demonstrate that a setback or buffer is not necessary because implementation of alternative conservation practices or field-specific conditions will provide pollutant reductions equivalent or better than the reductions that would be achieved by the 100-foot setback. Alternative conservation practices can include practices that are designed in consultation with a Professional Engineer licensed in the state of Idaho. Alternatively, an adequate demonstration may include the use of site-specific data using a tool such as the Idaho NRCS Water Quality Technical Note #6, Idaho Nutrient Transport Risk Assessment (INTRA) (Appendix D) or the Idaho Phosphorus Site Index (Appendix H) and associated implementation of alternative conservation practices recommended as a result of these tools.

9. No Dry Weather Discharge. There shall be no dry weather discharge of manure, litter, or process wastewater to a water of the United States from a CAFO as a result of the application of manure, litter or process wastewater to land areas under the control of the CAFO. This prohibition includes discharges to waters of the United States through tile drains, ditches or other conveyances, and irrigation return.

   a) During any land application of manure, litter, or process wastewater to a land application area, a visual inspection of the downgradient edge of the field and any other potential discharge locations (e.g., tile drains, ditches, or other conveyances) must be conducted during the land application event and after the land application event to check for field runoff and discharges. This also applies where a land application setback or compliance alternative is required pursuant to Section II.B.8 of this permit, to confirm that the land application setback or compliance alternative is being maintained and functioning as intended, and to determine if there are any discharges. In the event of a discharge, the monitoring requirements of Section IV.E.1 must be implemented.

10. Prohibition on Land Application to Frozen, Snow-Covered and Saturated Soils. The land application of manure, litter, or process wastewater must not occur when the land application area is:

   a) Frozen and/or snow-covered soils, or

   b) When the top two inches of soil are saturated from rainfall, snow melt, irrigation, or when current or predicted weather is capable of producing such conditions.

III. SPECIAL CONDITIONS

A. Nutrient Management Plan

The permittee shall develop, submit, and implement a site-specific Nutrient Management Plan (NMP). The NMP shall identify and describe practices that will be implemented to ensure compliance with the effluent limitations and special conditions of this permit (Sections II and III). Unless otherwise stated in this permit, the NMP must be developed in accordance with Section III.A.2 below.

1. Schedule. The completed NMP must be submitted to EPA with a NOI for CAFOs seeking coverage under this permit. The permittee shall implement its NMP upon authorization under this permit.

2. NMP Content. The NMP must include site-specific practices and procedures necessary to implement the applicable effluent limitations and standards. In addition, the NMP must:

   a) Ensure adequate storage of manure, litter, and process wastewater including procedures to ensure proper operation and maintenance of the wastewater and manure storage structures. All wastewater and manure storage structures shall be designed, constructed, operated, and maintained in accordance with the requirements specified in Section II.A.1 of this permit.

      (i) The permittee must determine if existing or planned wastewater and manure storage structures are adequately sized in accordance with Section II.A.1 by evaluating each wastewater or manure storage structure. The permittee may use the Idaho Animal Waste Management (IDAWM) Software, Version 4, December 2000 (Appendix C) and accompanying spreadsheet, the NRCS Animal Waste Management Software, or demonstrate that the facility is designed with adequate storage capacity as determined by runoff and design calculations followed by an as-built survey conducted by a Professional Engineer licensed in the state of Idaho. If the evaluation determines that the existing wastewater or manure storage structures have a storage capacity less than the minimum capacity requirements specified in Section II.A.1, the NMP must include measures the permittee will take to ensure that the storage capacity specified in Section II.A.1 is met. The NMP must include in the evaluation the results of the wastewater and manure storage structure evaluations, including any corrective and interim measures, and a schedule for implementation.

      (ii) The permittee must ensure the proper operation and maintenance of each wastewater and manure storage structure by evaluating compliance with NRCS Appendix 10D and IDAPA 02.04.14.030.01. If the evaluation of the wastewater or manure storage structures identifies deficiencies in the operation or maintenance of the structures, the permittee must identify measures to address those deficiencies in its NMP. This evaluation must be completed by a Professional Engineer, geologist, hydrogeologist, or another qualified individual, and the NMP must include the results of the evaluation. (See Appendices I and J for optional guidance)

      (iii) The permittee must include a subsurface discharge monitoring plan to identify and monitor any functionally equivalent subsurface discharges to Waters of the United States from each wastewater or manure storage structure in accordance with the specifications in Section IV.D.6. The NMP must include the subsurface discharge monitoring plan and the results of all subsurface monitoring from each wastewater and manure storage structure.

The permittee must develop a subsurface discharge monitoring plan as part of the NMP unless the exceptions in (a) or (b) below are met:

(a) Each wastewater or manure storage structure must be evaluated by a Professional Engineer, geologist, hydrogeologist or another qualified individual documenting that each wastewater or manure storage structure does not have a subsurface discharge to Waters of the United States.

(b) Confirm, and maintain documentation in NMP, that each wastewater and manure storage structure is constructed of concrete or steel, or with a double-layer synthetic liner with leak detection, and is properly operated and maintained in accordance with III.A.2.a.ii.

b) Ensure proper management of mortalities (i.e., dead animals) to ensure that they are not disposed of in a liquid manure, storm water, or process wastewater storage or treatment system that is not specifically designed to treat animal mortalities. Mortality handling practices must be in accordance with all applicable Federal, State, and local regulatory requirements.

The permittee must include information in its NMP that addresses both typical and catastrophic mortalities. At a minimum, the NMP must identify the following:

(i) Schedules for collecting, storing, and disposing of carcasses;

(ii) Description of on-site storage before disposal;

(iii) Description of final disposal method;

(iv) Additional management practices to protect waters of the United States for on-site disposal including composting or burial; and

(v) Contingency plans for mass mortalities.

c) Ensure that clean water is diverted, as appropriate, from the production area. Any clean water that is not diverted and comes into contact with raw materials, products, or byproducts including manure, litter, process wastewater, feed, milk, eggs, or bedding is subject to the effluent limitations specified in Section II.A of this permit. Where clean water is not diverted from the production area, the wastewater or manure storage structure shall include adequate storage capacity for the additional clean water. Clean water includes, but is not limited to, snow melt and/or rain falling on the roofs of facilities and runoff from adjacent land. The NMP must identify the BMPs or engineering controls, existing or needed, to exclude clean water from the production area. The NMP must include operation and maintenance procedures required to maintain the existing BMPs or engineering controls or the timing for the construction of needed BMPs or engineering controls.

d) Prevent the direct contact of animals confined or stabled at the facility with waters of the United States. Animals confined at the CAFO must not come into direct

contact with waters of the United States. At a minimum, the NMP must describe the BMPs or engineering controls the CAFO will use to prevent animals in the production area from coming into contact with waters of the United States.

e) Ensure that chemicals and other contaminants handled on-site are not disposed of in any manure, litter, process wastewater, or storm water storage or treatment system unless specifically designed to treat such chemicals or contaminants. All wastes from dipping vats, pest and parasite control units, and other facilities utilized for the management of potentially hazardous or toxic chemicals shall be handled and disposed of in a manner sufficient to prevent pollutants from entering the manure, litter, or process wastewater storage structure or waters of the United States. The NMP must include references to any applicable chemical storage and handling protocols and incorporate specific BMPs and actions that will be taken to prevent the improper disposal of chemicals and other contaminants into any manure, litter, process wastewater, or storm water storage or treatment system. The NMP should also consider chemical handling plans for the protection of wells, water supplies, and any drainage ways that are close to chemical storage and handling areas.

f) Identify appropriate site-specific conservation practices to be implemented on the land application areas, including as appropriate buffers or equivalent practices as stipulated in Section II.B.8, to control runoff of pollutants to waters of the United States. The NMP must include appropriate conservation practices identified by evaluating each land application area using the Idaho NRCS Water Quality Technical Note #6, Idaho Nutrient Transport Risk Assessment (INTRA) (Appendix D). CAFOs may opt to utilize the Idaho Phosphorus Site Index (P Index) (Appendix H). The NMP must include the results of the INTRA or P Index evaluations. All CAFOs must follow guidance provided by INTRA and the P Index. If the site-specific conservation practices are NRCS conservation practice standards, the NMP must include provisions to operate and maintain those site-specific conservation practices according to the specific NRCS conservation practices standard. If the owner/operator proposes alternative practice or performance standards, the NMP must describe and cite those standards so that EPA can perform an adequate review. In addition, the NMP must include a schedule for implementation of site-specific conservation practices and proper operation and maintenance procedures.

g) Protocols for appropriate testing of manure, litter, process wastewater, and soil.

   (i) Manure must be analyzed at least once annually for nitrogen and phosphorus content in accordance with the University of Idaho Manure and Wastewater Sampling CIS 1139 (Appendix E). The results of these analyses must be included in the NMP and be used in determining application rates for manure, litter, and process wastewater as described in Section III.A.2.h).

   (ii) Soil samples must be taken from every field to which manure, litter and process wastewater will be applied. Soil must be analyzed annually in accordance with University of Idaho Bulletin 704 (Appendix F). At a minimum, soil samples must be analyzed for the following constituents: pH,

soil organic matter (SOM), Nitrate- Nitrogen (NO_3-N), Ammonium-Nitrate (NH_4-N), and phosphorus (P). The results of these analyses must be included in the NMP and used in determining application rates for manure, litter, and process wastewater as described in Section III.A.2.h).

(iii) Soil samples must be analyzed by a laboratory certified by the North American Proficiency Testing Program (NAPT). Manure samples must be analyzed by a certified Manure Analysis Proficiency Laboratory.

h) Establish protocols to land apply manure, litter, or process wastewater in accordance with site specific nutrient management practices that ensure appropriate agricultural utilization of the nutrients in the manure, litter, or process wastewater

Annual nutrient budgets must be generated to determine land application rates for each field where manure, litter, or process wastewater is applied. The annual budget must be included in the NMP and be developed in accordance with the University of Idaho Fertilizer Guides or related University of Idaho Crop Production Guide. In the absence of an appropriate University of Idaho Fertilizer or Crop Production Guide, a fertilizer or production guide from a Pacific Northwest Land Grant University may be used (i.e., Oregon State University or Washington State University). In the absence of specific Land Grant University fertilizer or production guides, the NMP must identify and include the best available data used to determine specific land application rates for the crop. The NMP must express land application rates of nutrients in pounds per acre, and volume of manure, litter, and process wastewater in tons, gallons or cubic feet. Ensuring accurate application rates reduces probability of off-site transport. The NMP developed to meet the requirements of this permit, and submitted to the permitting authority for review, must include all necessary calculations. Thereafter, for the remainder of the permit term, application rates may be calculated annually, or immediately prior to land application, if all data and calculations are appropriately documented in the NMP.

i) Identify and maintain site specific records to document the implementation and management of the minimum elements described in Sections III.A.2.a-h and in compliance with the permit.

3. Signatory. The NMP shall be signed by the owner/operator or other signatory authority in accordance with Section V.C.5 (Signatory Requirements) of this permit.

4. NMP Availability. A current copy of the NMP shall be kept on site at the permitted facility in accordance with Section IV.A of this permit and provided to the permitting authority upon request.

5. Changes to the NMP

a) When a permittee makes changes to the CAFO's NMP previously submitted to EPA, the CAFO owner or operator must provide EPA with the most current version of the CAFO's NMP and identify changes from the previous version.

b) When changes to a NMP are submitted to EPA, EPA will review the revised NMP to ensure that it meets the requirements of Section II and Section III.A.2. If EPA determines that the changes to the NMP necessitate revision to the terms of the NMP incorporated into the permit issued to the CAFO, EPA will determine whether such changes are substantial as defined by 40 CFR 122.42(e)(6). Substantial changes to the terms of a NMP incorporated as terms and conditions of a permit include, but are not limited to:

   (i) Addition of new land application areas not previously included in the CAFO's NMP;

   (ii) Changes to the maximum amounts of nitrogen and phosphorus derived from all sources for each crop;

   (iii) Addition of any crop or other uses not included in the terms of the CAFO's NMP; and

   (iv) Changes to site specific components of the CAFO's NMP, where such changes are likely to increase the risk of nitrogen and phosphorus transport to waters of the United States.

c) If EPA determines that the changes to the terms of the NMP are not substantial, EPA will make the revised NMP publicly available and include it in the permit file, revise the terms of the NMP incorporated into the permit, and notify the permittee and the public of any changes to the terms of the NMP that are incorporated into the permit.

d) If EPA determines that the changes to the terms of the NMP are substantial, EPA will provide the public with the opportunity to comment upon the changes to the NMP and the information submitted by the CAFO owner or operator as set forth in Section III.A.2. of this permit. EPA will respond to all significant comments received during the comment period. The process for public comments, hearing requests and the hearing process, if a hearing is held, will follow the procedures set forth in 40 CFR 124.11 through 124.13.

   EPA may require the permittee to further revise the NMP, if necessary. Once EPA incorporates the revised terms of the NMP into the permit, EPA will notify the permittee of the revised terms and conditions of the permit.

B. Lagoon Liner Requirements

Liner Requirements: CAFOs constructing new wastewater or manure storage structures or modifying existing wastewater or manure storage structures shall have a liner that is constructed and maintained in accordance with Idaho NRCS practice standards. Any damage to the liner must be evaluated by a Professional Engineer and corrected within thirty (30) days of the damage, unless the Permitting Authority approves an alternative schedule. The permittee must submit the request within thirty (30) days of the damage, and it must include the Professional Engineer's evaluation of the risks of pollutant releases if the liner is not repaired immediately. All documentation of liner maintenance shall be kept with the NMP.

C. Facility Closure

The following conditions shall apply to the closure of lagoons and other earthen or synthetic lined basins and other manure, litter, or process wastewater storage and handling structures:

1. Closure of Lagoons and Other Surface Impoundments

   a) No lagoon or other earthen or synthetic lined basin shall be permanently abandoned.

   b) Lagoons and other earthen or synthetic lined basins shall be maintained at all times until closed in compliance with this section.

   c) All lagoons and other earthen or synthetic lined basins that are no longer needed as a part of a waste management system and are to be permanently decommissioned or converted for another use must be properly closed consistent with the Idaho NRCS Practice Standard Code 360 contained in Natural Resources Conservation Service Field Office Technical Guide (Appendix B). Consistent with this standard the permittee shall remove all waste materials to the maximum extent practicable and dispose of them in accordance with the permittee's NMP, unless otherwise authorized by EPA.

   d) For any lagoon or other earthen or synthetic lined basin that is not in use for a period of twelve (12) consecutive months but will not be permanently decommissioned or converted to another use, the permittee shall:

      (i) Maintain the structure as though it were actively in use in order to prevent compromise of structural integrity.

      (ii) The permittee shall notify EPA, in writing, of the action taken, and shall conduct routine inspections, maintenance, and record keeping as though the structure were in use. Prior to restoration of use of the structure, the permittee shall notify EPA, in writing, and provide the opportunity for inspection. The permittee shall properly handle and dispose of the water used to preserve the integrity synthetic or earthen liner during periods of non-use in accordance with the NMP.

   e) Unless otherwise authorized by EPA, completion of closure for lagoons and other earthen or synthetic lined basins shall occur as promptly as practicable after the permittee ceases to operate or, if the permittee has not ceased operations, twelve (12) months from the date on which the use of the structure ceased, unless the lagoons or basins are being maintained for possible future use in accordance with the requirements above.

2. Closure Procedures for Other Manure, Litter, or Process Wastewater Storage and Handling Structure

   No other manure, litter, or process wastewater storage and handling structure shall be abandoned. Closure of all such structures shall occur as promptly as practicable within twelve (12) months after the date on which the use of the structure ceased, unless the lagoons or basins are being maintained for possible future use in

accordance with the requirements above. To close a manure, litter, or process wastewater storage and handling structure, the permittee shall remove all manure, litter, or process wastewater and dispose of it in accordance with the permittee's NMP, or document its transfer from the permitted facility in accordance with off-site transfer requirements specified in this permit Section III.D, unless otherwise authorized by EPA.

D. Requirements for the Transfer of Manure, Litter, and Process Wastewater

1. In cases where CAFO-generated manure, litter, or process wastewater is sold or given away, the permittee must comply with the following conditions:

   a) Maintain records showing the date and amount of manure, litter, and/or process wastewater that leaves the permitted facility;

   b) Record the name and address of the recipient;

   c) Provide the recipient(s) with representative information on the nutrient content of the manure, litter, and/or process wastewater analyzed in accordance with Section III.A.2.g)(i); and

   d) Retain the records on-site, for a period of five years, and submit the records to EPA, upon request.

IV. Records, Reporting, Monitoring, and Notification

A. Records Management

1. Record Keeping Requirements for the Production Area

   The permittee must maintain on-site for a period of five (5) years from the date they are created a complete copy of the NOI, the NMP, records to document the implementation and management of Section II.A and Section III.A.2.a-e, Section IV.D and Section IV.A.1.a-i below. The permittee must make these records available to EPA upon request.

   a) Records documenting the inspections of all storage, containment and treatment structures as required under Section II.A.2.a. and Section III.A.2.a;

   b) Weekly records of the depth of the manure and process wastewater in storage, containment and/or treatment structure(s), as applicable, as indicated by the depth marker under Section II.A.2.b);

   c) Documentation of whether or not the wastewater level in all liquid waste storage structures is below the level required to maintain capacity to store the runoff and precipitation from a 25-year, 24-hour storm under Section II.A.2.b);

   d) Records documenting the inspections of all stormwater diversion and channel structures under Section III.A.2.c);

   e) Records documenting the inspections of all water line inspections, including drinking and cooling water lines and whether or not leaks were discovered;

f) For all structures in Section II.A.2.a)(i)-iii, records documenting any actions taken to correct deficiencies required under Section II.A.2.c). Deficiencies not corrected with thirty (30) days must be accompanied by an explanation of the factors preventing immediate correction;

g) Records of mortalities management and practices used by the permittee to meet the requirements of Section II.A.2.d) and Section III.A.2.b);

h) Records documenting the current design of any wastewater or manure storage structure to meet the requirements of Section II.A.1.b). including volume for solids accumulation, design treatment volume, total design volume, and approximate number of days of storage capacity; and

i) Records of the date, time, and estimated volume of any overflow and additional requirements of Section IV.D.

2. Record Keeping Requirements for the Land Application Area

Each permittee must maintain on-site for a period of five (5) years from the date they are created, a complete copy of the information required by Section II.B and Section III.A.2.f)-i, and the records specified in Section IV.A.2.a)-g below. The permittee must make these records available to EPA upon request. For every field, provide the following information associated with the same unique field identification used in the NMP:

a) The date(s) manure, litter, or process waste water application was begun for each field, for each land application event and all methods associated with the application of the manure, litter or process wastewater, including application method, incorporation method, soil surface conditions, weather conditions, number of acres utilized, amounts of manure, litter and process wastewater, and total amounts of nitrogen and phosphorus applied under Sections II.B.2, 3 and 5 and Section III.A.2.h);

b) Documentation of all manure, litter or process wastewater sample collection and analysis protocols under Section II.B.6 and Section III.A.2.g)(i);

c) Documentation of all soil sample collection and analysis protocols under Section II.B.6 and Section III.A.2.g)(ii);

d) Documentation that all required setbacks, buffers or approved alternatives and conservation practices identified in the NMP were observed and/or implemented, and an explanation for any deviation from these practices under Section II.B.4 and Section II.B.8;

e) The date that the equipment used for the land application event was last inspected under Section II.B.7; and

f) Documentation for all requirements for manure, litter and process wastewater transfers under Section III.D.

g) Documentation of visual inspections of potential land application area discharge locations and land application setback(s) or compliance alternative(s) specified in Sections II.B.9.a)

B. Annual Reporting Requirements

1. The permittee shall submit an annual report by March 1st of each year. Prior to December 20, 2020, reports must be submitted electronically or in hard copy to EPA, the appropriate IDEQ district office and Idaho State Department of Agriculture. Hard copies may be submitted to the addresses below.

   U.S. EPA Region 10
   Attn: ICIS Data Entry Team
   1200 6th Avenue, Suite 155 ECAD-101
   Seattle, Washington 98101-3188

   Idaho State Department of Agriculture
   Division of Animal Industries
   P.O. Box 790
   Boise, Idaho 83701

   After December 20, 2020, annual reports must be submitted *electronically only* to IDEQ. Annual Reports must continue also be submitted to the Idaho State Department of Agriculture.

2. The permittee may seek an electronic reporting waiver by submitting a request. Prior to July 1, 2020, this request must be submitted to EPA. Beginning July 1, 2020, this request must be submitted to IDEQ. This waiver request should contain the following details: facility name; NPDES permit number; facility address; name, address and contact information for the owner, operator, or duly authorized facility representative; and a brief written statement regarding the basis for claiming such a temporary waiver. The request will be either approved or denied within 120 days. The duration of the temporary waiver will not exceed 5 years.

3. The annual report must include all of the information detailed in the Annual Report Template in Appendix G. The permittee may use the fillable pdf template provided or may compile all of the required information in a separate document. Completion and electronic submittal of the Annual Report template shall fulfill the electronic reporting requirements.

C. Notification of Unauthorized Discharges Resulting from Manure, Litter, and Process Wastewater Storage, Handling, On-site Transport and Application

1. If, for any reason, there is an unauthorized discharge of pollutants to a water of the United States, the permittee is required to make immediate oral notification within 24-hours to the EPA Region 10, NPDES Compliance Section, Enforcement and Compliance Assurance Division, Seattle, WA at 206-553-1846 and notify ISDA, the appropriate IDEQ regional office, and the appropriate county authorities in writing, within five (5) working days of the discharge of pollutants to a water of the United States from the facility. In addition, the permittee shall keep a copy of the notification submitted to EPA and ISDA together with the other records required by this permit. The discharge notification shall include the following information:

a) A description of the discharge and its cause, including a description of the flow path to the receiving water body and an estimate of the flow and volume discharged; and

b) The period of non-compliance, including exact dates and times, the anticipated time it is expected to continue, and steps taken or planned to reduce, eliminate and prevent recurrence of the discharge.

D. Monitoring Requirements for All Discharges from Wastewater or Manure Storage Structures

1. In the event of any overflow or other discharge, including any subsurface discharges, of pollutants to waters of the United States from a manure or wastewater storage structure, whether or not authorized by this permit the following actions shall be taken:

   a) All discharges from wastewater or manure storage structures to waters of the United States shall be sampled and analyzed. Samples must, at a minimum, be analyzed for the following parameters: total nitrogen, nitrate nitrogen, ammonia nitrogen, total phosphorus, *E. coli*, five-day biochemical oxygen demand (BOD5), total suspended solids, pH, and temperature. The discharge must be analyzed in accordance with approved EPA methods for water analysis listed in 40 CFR Part 136;

   b) For any overflow or other discharge, including any subsurface discharge, subject to monitoring under paragraph 1, if the duration of the discharge event exceeds 24 hours, the discharge shall be monitored daily until the discharge ceases.

2. Record an estimate of the volume of the release and the date and time;

3. Samples shall consist of grab samples collected from the point of overflow or discharge from the waste impoundment or production area. Subsurface discharges shall be sampled at the point of discharge to the receiving water. If the point of discharge to the receiving water is inaccessible, samples of subsurface discharges shall be collected at a point that provides a sample that is representative of the discharge to the receiving water. A minimum of one sample shall be collected within 30 minutes of the detection of the overflow or discharge and the sample(s) of the overflow or discharge must be collected and analyzed in accordance with EPA approved methods for water analysis listed in 40 CFR Part 136. The sample(s) collected from the overflow or discharge must be representative of the overflow or discharge;

4. If conditions are not safe for sampling, the permittee must provide documentation of why samples could not be collected and analyzed. For example, the permittee may be unable to collect samples during dangerous weather conditions (such as local flooding, high winds, hurricane, tornadoes, electrical storms, etc.). However, once dangerous conditions have passed, the permittee shall collect a sample from the wastewater or manure storage structure from which the discharge occurred;

5. The analytical results of the representative sample(s) taken from the overflow or discharge must be submitted to EPA Region 10, Enforcement and Compliance Assurance Division, within thirty (30) days of the overflow or discharge. Copies of the analytical results shall also be submitted to ISDA and the IDEQ state and appropriate regional office at the addresses listed in Section I.B.3 of this permit; and

6. Subsurface Discharge Monitoring Plan. For those CAFOs required to include a subsurface discharge monitoring plan in the NMP, pursuant to Section III.A.2.a. of this permit, the plan that is included in the CAFO's NMP must include site-specific information and procedures that will be implemented to address the following:

   a) Identification of the structures and/or locations to be monitored;

   b) Routine periodic monitoring adequate to identify leaks, damage, and other issues that could cause a functionally equivalent subsurface discharge, including the frequency of monitoring and the specific technology or protocols that will be used;

   c) Criteria or protocols that will be used to determine whether a functionally equivalent subsurface discharge has occurred; and

   d) Site specific protocols for monitoring subsurface discharges in accordance with the requirements in Section IV.D.

E. Monitoring Requirements for Discharges from Land Application Areas

1. In the event of any runoff or discharge from a CAFO's land application area to a water of the United States, the actions specified below must be taken. Discharges subject to monitoring requirements include, but are not limited to, (1) dry weather discharges resulting from land application of manure, litter, or process wastewater, including discharges through tile drains, ditches, or other conveyances, and irrigation return, and (2) stormwater or snowmelt runoff or discharges of manure, litter, or process wastewater that has not been applied in accordance with site specific nutrient management practices that ensure appropriate agricultural utilization of the nutrients in the manure, litter or process wastewater as provided in 33 U.S.C. § 1362(14) and 40 CFR § 122.23(e).

   a) All discharges that meet either of the two criteria specified in Section E.1 above from land application areas to waters of the United States shall be sampled and analyzed as follows.

      (i) Grab samples of the discharge must be collected at a location prior to mixing with the receiving waters, that will provide for a representative sample of the discharge. The specific sampling location(s) must be documented.

      (ii) Samples shall be collected in accordance with the protocols described in Section 3 of EPA's Industrial Stormwater Monitoring and Sampling Guide (EPA 832-B-09-003, April 2021). For sheet flow discharges that are too shallow to collect with a sample bottle, the protocols in the Industrial Stormwater Monitoring and Sampling Guide may be supplemented with

procedures for installing a temporary barrier device or similar structure to intercept runoff flow.

(iii) Samples must, at a minimum, be analyzed for the following parameters: total Kjeldahl nitrogen (TKN), nitrate nitrogen, nitrite nitrogen, total phosphorus, E. coli, fecal coliform, and five-day biochemical oxygen demand (BOD_5).

(iv) The discharge samples must be analyzed in accordance with approved EPA methods for water analysis listed in 40 CFR Part 136.

b) Samples of the receiving water shall be collected upstream and downstream of the point of discharge to the receiving stream as follows.

(i) Upstream samples must be collected at a location that provides a representative sample of the water quality immediately upstream of the discharge, prior to mixing with the discharge. Downstream samples must be collected at a location that provides a representative sample of the water quality after mixing with the discharge and prior to the introduction of other pollutant sources. The specific sampling locations must be documented.

(ii) Samples shall be collected in accordance with EPA Region 4's Surface Water Sampling procedures (LSASDPROC-201-R5, December 2021).

(iii) Grab samples of ambient receiving waters must, at a minimum, be analyzed for the following parameters: total Kjeldahl nitrogen (TKN), nitrate nitrogen, nitrite nitrogen, total phosphorus, E. coli, fecal coliform, and five-day biochemical oxygen demand (BOD_5).

(iv) The receiving water samples must be analyzed in accordance with approved EPA methods for water analysis listed in 40 CFR Part 136.

c) A log shall be kept of the receiving water conditions throughout the reach bounded by the upstream and downstream sampling locations during the discharge event. The log must document any discoloration; bottom deposits; condition of any aquatic life observed; presence of visible films, sheens or coatings; fungi, slimes or objectionable growths; and potential nuisance conditions.

d) For any discharge subject to monitoring under Section E.1, if the duration of the discharge event exceeds 24 hours, the discharge and receiving water shall be monitored daily until the discharge ceases.

e) An estimate of the volume of the discharge and the date and time must be recorded;

f) If conditions are not safe for sampling, the permittee must provide documentation of why samples could not be collected and analyzed. For example, the permittee may be unable to collect samples during dangerous weather conditions (such as local flooding, high winds, hurricane, tornadoes, electrical storms, etc.). However, once dangerous conditions have passed, the permittee shall collect a sample of the discharge. If the discharge stops before dangerous conditions have passed, and therefore cannot be sampled, the permittee shall record the estimated time,

duration, and volume of the discharge, and the reason the sample could not be collected, and include this information in the Notification of Unauthorized Discharge submitted in accordance with Section IV.C of this permit.

g) The analytical results of the representative sample(s) taken from the discharge and receiving water must be submitted to EPA Region 10, Enforcement and Compliance Assurance Division, within thirty (30) days of the discharge. Copies of the analytical results shall also be submitted to ISDA and the IDEQ state and appropriate regional office at the addresses listed in Section I.B.3 of this permit.

F. Spills / Releases in Excess of Reportable Quantities

1. This permit does not relieve the permittee of the federal reporting requirements of 40 CFR §§ 110, 117 and 302 relating to spills or other releases of oils or hazardous substances.

   Where a release containing a hazardous substance or oil in an amount equal to or in excess of a reportable quantity established under either 40 CFR § 110, 40 CFR § 117 or 40 CFR § 302, occurs during a 24-hour period:

   a) The permittee must provide notice to the National Response Center (NRC) (800–424–8802; in the Washington, DC, metropolitan area, call 202–267– 2675) in accordance with the requirements of 40 CFR §§ 110, 117 and 302 as soon as site staff have knowledge of the discharge; and

   b) The permittee must, within 7 calendar days of knowledge of the release, provide a description of the release, the circumstances leading to the release, and the date of the release. The permittee must also implement measures to prevent the reoccurrence of such releases and to respond to such releases.

2. Any spill of hazardous material must be immediately reported to the appropriate IDEQ regional office (see table below). Spills of petroleum products that exceed 25 gallons or that cause a visible sheen on nearby surface waters should be reported to IDEQ within 24-hours. Petroleum product spills of less than 25 gallons that do not cause a sheen on nearby surface waters shall only be reported to IDEQ if clean-up cannot be accomplished within 24-hours.

   IDEQ Regional Office contact information for reporting spills

Regional Office	Phone #	Regional Office	Phone #
Boise	(208) 373-0550	Lewiston	(208) 799-4370
Coeur d'Alene	(208) 769-1422	Pocatello	(208) 236-6160
Idaho Falls	(208) 528-2650	Twin Falls	(208) 736-2190

Outside of regular business hours, qualified spills should be reported to the IDEQ 24-hour reporting hotline at 1-833-IPDES24.

Taking soil samples for nitrogen analysis could pay big this year

blog-crop-news.extension.umn.edu/2022/03/taking-soil-samples-for-nitrogen.html



By: Brad Carlson, Extension educator

Record high nitrogen (N) fertilizer prices have received plenty of attention over the past several months. While farmers are scratching their heads trying to keep input costs down, an unusual opportunity is presenting itself this spring. Last year's exceptionally dry weather may have led to a nitrogen carryover credit that is not normally there.

The 2021 drought and soil nitrate levels

The nitrogen cycle naturally converts nitrogen in soil to the nitrate form. The nitrate ion is negatively charged, like soil particles, and therefore is not bound to the soil. Nitrate moves readily with water beyond the rooting zone or it can be lost via "denitrification" to the atmosphere if the soil stays saturated for long periods of time. Some nitrate naturally accumulates in the soil after the crop matures but before the soil cools down. This accumulated nitrate, together with any leftover fertilizer from the previous growing season, is usually lost during the spring before the next year's crop can take it up. It is for this reason that N fertilizer recommendations do not consider a nitrogen credit for this late season accumulated nitrate under normal circumstances. However, when there is enough of a water deficit in the soil profile that melting snow and spring rains do not

saturate the soil, there is less risk of N loss, meaning you may be able to take an N credit. Historical records show that nitrate concentration in surface water spikes in years following drought or excessively dry conditions. After the soil finally saturates, this accumulated soil nitrate flushes into surface water. It is anticipated that this may be the case at some point either this year or next year following the dry conditions experienced in much of the state in 2021.

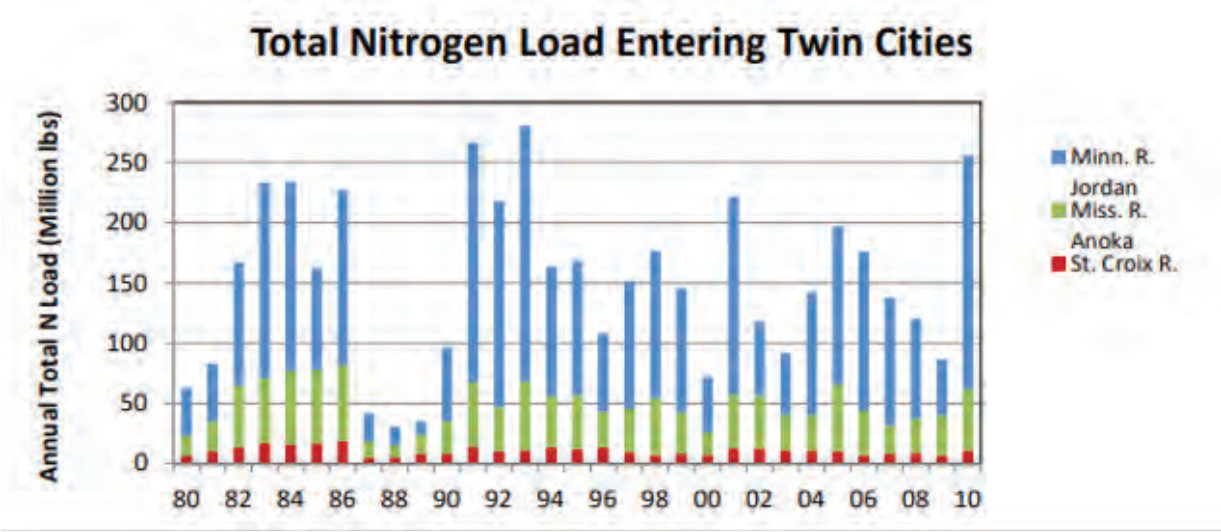

This chart shows how nitrogen loads in Minnesota's rivers spiked following the drought of the late 1980s (MPCA 2013). A similar situation could unfold this year or next year if residual soil nitrate levels aren't accounted for and N fertilizer is overapplied.

Clues from last fall

Minnesota Valley Testing Labs conducted soil nitrate tests last fall and generously shared their data with us. Over 70% of the nearly 240 samples analyzed had an N credit of at least 35 pounds. Nearly 30% of the samples had N credits of 155 pounds or more. It should be noted that this is not a random sampling of sites, but rather an indication of soil N status where a carryover is suspected on the western side of the state where a fall test is considered acceptable. Data provided by Centrol Crop Consulting for tests run in advance of planting sugar beets shows a much smaller prevalence of N credits, with less than 5% showing a credit following soybeans, and about one third of samples indicating a credit following corn. However, there are some fundamental differences between the pre-sugar beet test and the pre-plant soil nitrate test (PPNT) for corn, and the samples were from the Red River Valley in northwest Minnesota where conditions were not nearly as dry as the southern third of the state.

Table 1. *Fall 2021 MVTL soil nitrate test results (239 samples, 0-24 inch samples)*

Nitrate level (ppm)	% of samples	N credit (lbs./ac)
0-6	28%	0
6-9	14%	35
9-12	10%	65
12-15	10%	95
15-18	5%	125
18+	28%	155

Pre-plant soil nitrate test (PPNT) tips

University of Minnesota research going back to the early 1990s resulted in the recommendation to use a soil nitrate test to measure this effect and credit residual N against the next year's fertilizer inputs under certain circumstances. The situations where a credit is likely are:

1. Fields that have a long-term manure history
2. Continuous corn following a drought

It should be noted that the test will work on any field where corn is going to be grown this year; it is just less likely that you will find an N credit in other circumstances, so it may not be worth the cost of testing. Also, it is important to note that portions of western and northern Minnesota received enough precipitation toward the end of, or after, the growing season to bring soils to field capacity, meaning you are less likely to find an N credit.

Minnesota's PPNT recommendations call for taking samples two feet deep to capture any nitrate that has already moved but still within the rooting zone. With the ability to variable-rate apply, it makes sense to break a field into management zones where there are likely to be differences (like one would do for any soil test). Be sure to take enough cores to ensure a good average, mix thoroughly, and dry quickly. Our research has shown that, in this case, more is always better. We suggest a minimum of 10 cores in a composite sample for the test results to be representative of the portion of the field or area of interest.

There are a few points to keep in mind if you are going to use the PPNT. Since nitrate is subject to leaching or denitrification loss, you want to take the sample as late as possible to ensure that what is measured is still there at the time the plants need it.

Furthermore, if it becomes extremely wet after a sample is collected, the credit may disappear, so be prepared to compensate for this with additional sidedress N.

If you're growing corn this year, remember to request and use the PPNT, which gives results in ppm nitrate, and not the pre-sugar beet test, which gives results in pounds per acre. The interpretation of the results for corn are only calibrated for the PPNT, not the pre-sugar beet test. For similar reasons, you should not use recommendations from out-of-state, as the interpretation of the test results may not be correlated to the test protocol used in Minnesota.

Another point to remember is that the test only finds nitrate, so it will not accurately measure any fertilizer already applied or available N from a manure application. And lastly, Do not confuse the PPNT with the pre-sidedress nitrate test (PSNT), which is taken in-season and is most useful for fields with substantial potential for mineralization because of previous manure applications or where alfalfa was terminated.

More detailed instructions for taking the PPNT, as well as a chart to interpret results, can be found in our corn fertilizer guidelines.

For the latest nutrient management information, subscribe to the Minnesota Crop News email newsletter, like UMN Extension Nutrient Management on Facebook, follow us on Twitter, and visit our website.

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Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage

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Cost effectiveness

ABSTRACT

Much work has been invested in the development of practices and technologies that reduce nitrate losses from agricultural drainage in the US Midwest. While each individual practice can be valuable, the effectiveness will be site specific and the acceptability of each approach will differ between producers. To enhance decision making in terms of water quality practices, this work created average cost effectiveness parameters for seven nitrate management strategies (controlled drainage, wetlands, denitrification bioreactors, nitrogen management rate and timing, cover crops, and crop rotation). For each practice, available published cost information was used to develop a farm-level financial model that assessed establishment and maintenance costs as well as examined financial effects of potential yield impacts. Then, each practice's cost values were combined with literature review of N reduction (% N load reduction), which allowed comparison of these seven practices in terms of cost effectiveness (dollars per kg N removed). At −$14 and −$1.60 kg N^{-1} yr^{-1}, springtime nitrogen application and nitrogen application rate reduction were the most cost effective practices. The in-field vegetative practices of cover crop and crop rotation were the least cost effective (means: $55 and $43 kg N^{-1} yr^{-1}, respectively). With means of less than $3 kg N^{-1} yr^{-1}, controlled drainage, wetlands, and bioreactors were fairly comparable with each other. While no individual technology or management approach will be capable of addressing

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drainage water quality concerns in entirety, this analysis provides measures of average cost effectiveness across these seven strategies that allows direct comparison.

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1. Introduction

Artificial subsurface drainage systems in the Midwestern "Corn Belt" region have allowed for increased productivity over the past century [1], but nitrate (NO_3^-) losses in drainage have caused significant multi-scale environmental concerns [2,3]. Much work has been done developing and advancing practices to reduce NO_3^- losses in subsurface agricultural drainage. Dinnes et al. [1] provide a comprehensive review of NO_3^- reducing technologies for the Midwest including in-field "preventative" N strategies (e.g., N management, cover crops, diversified rotations) and "remedial" strategies for N removal from drainage (e.g., controlled drainage, bioreactors, wetlands). While each strategy and individual practice can be valuable, the NO_3^- removal effectiveness will be site specific and the acceptability of each individual approach will differ between producers. Nevertheless, no individual technology or management approach will be capable of addressing drainage water quality concerns in entirety [1,4]; as such, a suite of approaches used across these landscapes will be required [5].

On an individual farmer basis, adoption of environmental management practices designed to mitigate or prevent issues such as NO_3^- losses through drainage to surface waters are motivationally different from production innovations largely because short-term economic advantages of adopting a mitigation technology are rare [6,7]. Farm level action involving use of technology is in large part influenced by owner and operator beliefs and attitudes (i.e., regarding environmental and financial risk) in combination with personal environmental goals and knowledge about technology [8]. Perceptions of a technology in turn are shaped by external factors such as cost, overall complexity and effectiveness of the available technology, and available technical/financial support [9,10]. As such, crop producers require comprehensive information about water quality technologies with regard to the context for use, operational parameters, performance efficacy, and the full range of financial parameters (e.g., upfront and long-term costs). Of particular and universal concern for farmers is the financial feasibility of a particular technology in the context of their production system, as well as comparative advantage across technology-based management options. Moreover, comprehensive financial information is needed to calibrate agricultural conservation cost-share programming and targeting and to better guide federal and state technical service provision at county levels [4].

To enhance land-use decision making, this work investigates and makes transparent the financial parameters of seven NO_3^- management strategies; three are remedial N strategies: controlled drainage, wetlands, denitrification bioreactors and four are preventative N strategies: N rate reduction, spring N application, cover crops, and crop rotation. It bears to note early-on; however, that the Midwest is a heterogeneous region where not every abatement strategy will be equally appropriate (i.e., costly or effective) in any given situation. Suitability, in addition to NO_3^- reduction effectiveness, can vary by soil type, topography, landscape position, and microclimate (e.g., rainfall patterns, winter severity) for each of the seven distinct practices investigated here. For example, winter cover crops may be more difficult to establish in northern Minnesota vs. southern Indiana, and controlled drainage will be most cost effective on flatter topographies. The assumed baseline cropping system for this work was a corn/soybean rotation, reflective of the Midwestern agricultural landscape [11], and because tillage generally has a relatively small impact upon tile drainage NO_3^- export [12], it was not included as a variable here.

Controlled drainage (also known as drainage water management) is a strategy that addresses agricultural NO_3^- loading through the use of a series of structures installed in drainage pipes or drainage ditches that allow control of the water table depth [13,14]. Though this practice can be used to achieve agronomic and/or environmental objectives [14], a major limitation is that controlled drainage becomes more expensive on slopes greater than 0.5–1% [1,15]. The second practice under

consideration here, denitrification or woodchip bioreactors, uses control structures to regulate drainage water flowing through an excavation (typically >30 m long, >1 m wide) filled with a carbon source allowing enhanced denitrification of the NO_3^- in the drainage water [16,17]. These systems have been tested for treating drainage from "field-sized" areas of approximately 20 ha and usually require very little to no land to be removed from production by fitting in grassed edge-of-field areas [17]. The third of the remedial strategies, constructed wetlands, is a long-term NO_3^- reduction strategy intended for watershed-scale treatment [18,19]. A key consideration for N removal in wetlands is the wetland to treatment area ratio with increased N removal possible at increased wetland: watershed area ratios [18,20–22].

Regarding in-field, preventative practices, N fertilizer management, here in terms of rate and timing, is one of the farm operator-controlled factors to reduce N losses in agricultural drainage [1,12,23,24]. Water quality benefits of reduced application rates will be a function of the original and the modified rate [25,26]. Lawlor et al. [27] proposed that a corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) rotations can be described with:

$$\text{N Concentration in Drainage} = 5.72 + 1.33e^{(0.0104 \times N\ Rate)} \quad (1)$$

where N concentration is in mg N L^{-1} and rate is in kg N applied ha^{-1} [27]. Spring N application in the U.S. Midwest more closely synchronizes the application with plant uptake [28,29], an outcome that is preferable from both water quality and agronomic perspectives [24]. Nevertheless, fall N applications are a way to manage risk associated with uncertain spring weather and spring-time field activities [30].

The "preventative" strategy of winter cover crops such as rye, oat, winter wheat, brassica, or winter-hardy legumes, utilizes plant uptake as the major water quality improvement mechanism [31,32]. Benefits of cover crops (as well as several of the other practices) extend beyond drainage water NO_3^- reduction (e.g., erosion control, pest control, enhancement of soil productivity) [29,33] but were not included here as this analysis focuses solely on NO_3^- reduction; see Table 1 for abbreviated comments and Christianson et al. [34] for a broad discussion of ecosystem services associated with the use of any of these seven practices. The main limitations of winter cover crops are that they need to grow well under non-ideal conditions [1,32], some need to be killed before planting the main crop, and a corn yield reduction following certain covers is possible [31,32]. The final practice, crop rotations that include perennials, similarly provides water quality benefits via N and water uptake [1,35] and additional benefits to the soil [36]. Although the main limitations for this sort of rotation include access to markets, crop storage, and additional machinery requirements, Dinnes [29] reported diversifying cropping systems in Iowa has the most potential to reduce NO_3^- loadings compared to any other best management practice.

The objectives of this exploratory financial assessment are two-fold: (1) characterize and quantify the financial (cost) parameters of the seven NO_3^- reduction strategies; and (2) explore and compare the average cost efficiency of each strategy (dollars per kg N removed) using published measures of N reduction effectiveness. The primary motivation of this work is that while cost assessment of this type is fairly straight-forward, cost comparison analysis across various agricultural best management practices is invariably challenged [37] by (1) limited availability of published cost information, (2) variable methodology in published financial assessments, (3) limited methodological transparency in published cost assessments, (4) variable discount rates, (5) inconsistent analysis horizons due to variable life spans or management horizons, and (6) many costs are often site specific and therefore can exhibit significant ranges. This analysis is therefore an attempt to make transparent the structure and timing of cost parameters associated with using any of these NO_3^- management strategies, and to develop comparable measures of average cost effectiveness across these seven NO_3^- management strategies. Nevertheless, we recognize an inherent limitation of this work arises from the site-specific nature of the practices being compared; their application at different sites and under different conditions will necessarily confound a comparison of their effectiveness in reducing N loads and hence their calculated cost efficiencies.

Table 1
Description of the scenarios, uncertainty ranges for the Total Present Value Costs, and the additional benefits and costs that were not quantified for seven nitrogen reduction practices for agricultural drainage; see Christianson et al. [34] for more specific discussion of ecosystem services of these practices.

Practice	Practicable lifespan (yr)	Specific scenario	Uncertainty of ranges for TPVC	Unquantified costs and benefits
Controlled drainage	40	1 structure per 4 ha–8 ha	Low uncertainty	Potential yield impacts Potential increase in soil erosion, soil compaction, or surface runoff
Bioreactor	40	20.2 ha field treated with a 0.1 ha bioreactor	Low uncertainty	None
Wetland	50	405 ha treated by a 4 ha wetland plus buffer	Moderate uncertainty due to predominance of land cost and the variability of this factor	Additional ecosystem services including pollination, wood fuel, ornamental resources, natural hazard regulation, and recreation
N rate reduction	1	168 kg N ha^{-1}–140 kg N ha^{-1}	Large uncertainty due to yield impact variability	Probabilistic variability of yields
N spring application	1	Apply N in spring instead of fall	Large uncertainty due to unquantified risk and yield impact variability	Cost of infrastructure potentially required for fertilizer storage, handling, etc. Probabilistic variability of yields Potential loss of yield by a delayed planting date
Cover crop	4	Rye drilled	Large uncertainty as this practice is primarily implemented for reasons other than N reduction and due to yield impact variability	Additional ecosystem services including pollination and erosion and pest regulation; Potential future yield enhancement due to cover crop-induced soil quality and organic matter enhancement
Rotation	10	3 years alfalfa, 2 years corn	Very large uncertainty due to rotation complexity and the variability of alfalfa-induced yield increase	Additional ecosystem services including pollination and erosion and pest regulation; Potential future yield enhancement due to perennial-induced soil quality and organic matter enhancement

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2. Materials and methods

There is limited availability of published cost information regarding drainage NO_3^- reduction strategies, and the variable methodology and limited transparency for the studies that have been done in this area make comparison between published analyses difficult. The timing of costs particularly complicates comparisons of water quality practices. For example, controlled drainage, bioreactors, and wetlands all have large initial capital outlays and intermittent management costs, while N management, cover crops, and crop rotations largely involve variable annual costs. Cost assessments have been carefully constructed for all seven practices with itemized cost parameters and unit cost data for each strategy collected from various secondary sources (e.g., published literature, published custom rate surveys, and when necessary personal communication with knowledgeable individuals). Total present value costs (TPVCs) were assessed with a discounted cost model that aggregates total fixed and variable costs.

$$\mathrm{TPVC}_{\mathrm{practice}} = C_{\mathrm{est,practice}} \text{ in year } 1 + C_{\mathrm{main}} \text{ occuring over n years} \tag{2}$$

where $\mathrm{TPVC}_{\mathrm{Practice}}$ is the total present value of the cost of a practice, $C_{\mathrm{est,Practice}}$ is the full establishment cost, and C_{main} involves all annual and/or periodic maintenance costs of the practice applicable for and discounted over n years. The specific variations of this general model for each individual technology are presented in Supplemental material.

To develop a range of costs for each practice, minimum and maximum values for each individual cost category were summed to develop a minimum and maximum TPVC, respectively (Tables 2–7). If only a single value (i.e., mean) was available for a cost, this value was used in both the minimum and maximum TPVC calculation for that practice. As is appropriate for this type of cost comparison assessment (e.g., [38–41]), the minimum and maximum TPVCs for each practice were then used to develop a range of equal annual costs (EACs) for the strategies (Table 9). The EAC approach involves determining the equal annual payment (in present value terms) that would be made at the end of each year to fully cover costs over a planning horizon, and allows for the direct comparison of total present value costs from practices that have different practicable life spans [42]. More pragmatically, the EAC format allows farm-level decision makers to consider environmental best management practice costs essentially on a similar basis that they consider typical farm-level production costs [43].

Following Burdick et al. [44] and Tyndall and Grala [45], conversion to EACs was done using a capital recovery factor (CRF):

$$\mathrm{EAC} = \mathrm{TPVC} \times \mathrm{CRF} \tag{3}$$

where TPVC is the total present value of the cost of the practice and the CRF is calculated using:

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{4}$$

where i is the annual real discount rate and n is the number of years in the evaluation (i.e., planning horizon). The analysis was carried out using a 4% real discount rate, and the n was set to each practice's individual practicable lifespan (Table 1). A 4% discount rate represented the average real interest rate on Iowa farmland loans during 2008–2010 and was very similar to the 2011 rate for federal water projects (4.125%) [46].

Calculated EACs were combined with published measures of NO_3^- removal efficacy (% load reduction; Table 8) to develop an average efficiency parameter of dollars per kg N removed. This literature review-based approach (as opposed to a more site-specific modeling approach, which was outside the scope of this financial parameterization work) allowed capture of some inherent variability as the literature contains observations across sites and conditions. Dividing the EAC of each strategy by the amount of NO_3^--N removed is a standard way to present total costs per unit e.g., [44,47]. To do so, a Midwestern-representative load of 31.4 kg N ha^{-1} was developed from an average of Jaynes et al. [48] tile and drain N loads and Lawlor et al. [49] drainage N loads at their 168 kg N ha^{-1} application rate. Then, the minimum and maximum EAC for each practice were each applied to that practices' range for N load reduction (mean, median, 25th, and 75th percentiles from Table 8 and Fig. 1

Table 2
Itemized costs and Total Present Value Costs for controlled drainage in the U.S. Midwest at real discount rate of 4 % and analysis horizon of 40 years.

Item	Cost timing (yr)	Minimum cost ($ ha^{-1})	Mean cost ($ ha^{-1})	Maximum cost ($ ha^{-1})	Notes and assumptions	Reference
Structure cost	1	$61.78		$247.11	New drainage system: 1 structure per 8 ha at $500–$2000 per ea.	[15]
	1	$123.55		$494.21	Existing drainage system: 1 structure per 4 ha at $500–$2000 per ea.	
Transport structures	–				Assumed included above	Assumption
Design cost	1		$80.63		For new drainage systems but also included as design cost of existing	[100]
Contractor fees	1	$4.32	$9.47	$15.44	Structure installation: Back hoeing at $35.00 h^{-1}, $76.65 h^{-1}, $125.00 h^{-1} for 8 h to treat 65 ha	[81]
Total cost of establishment		**$146.73**		**$343.18**	**New (TPVC)**	
		$208.51		**$590.29**	**Existing (TPVC)**	
Time to raise/lower	$1-n$	$0.99		$4.94	Four hours × two to four times a year; labor at $8–$20 h^{-1}, 65 ha treatment area	[81]
Stop log/gate replacement	8, 16, 24, …	$17.67		$35.34	Summation of single sum TPV every eight years for 5 gates per structure at original cost of $14.17–$15.32 per ea. for 15 cm structures, 1 structure per 4 (Existing) or 8.1 (New) ha	[101]
Total cost of establishment, maintenance, and replacement		**$183.96**		**$723.44**	**TPVC**	

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Table 3
Itemized costs and Total Present Value Costs for a denitrification bioreactor in the U.S. Midwest at real discount rate of 4 % and analysis horizon of 40 years.

Item	Cost timing (yr)	Minimum cost ($ ha^{-1})	Mean cost ($ ha^{-1})	Maximum cost ($ ha^{-1})	Notes	Reference
Both control structures	1	$49.42		$197.68	Two control structures at $500–$2000 ea.; 20.2 ha treatment area	[101]
Structure transport	–				Assumed included above	Assumption
Woodchip cost	1		$116.14		Two semi loads at $975 chips+$200 transport ea.; 20.2 ha treatment area	[102]
Woodchip transport to farm	–				Included above	
Design cost	1	$0.00		$31.63	Assumed: $40 h^{-1} for 2 days of work or NRCS service provider; 20.2 ha treatment	Assumption
Contractor fees	1	$27.68	$60.61	$98.84	Back hoeing at $35.00 h^{-1}, $76.65 h^{-1}, $125.00 h^{-1} for 16 h to treat 20.2 ha	[81]; Assumptions
Seeding bioreactor surface	1	$0.05	$0.11	$0.15	Seeding grass, broadcast with tractor; for 20.2 ha treatment and 0.10 ha bioreactor at $9.88, $22.61, and $29.65 h^{-1}	[81]
Seed cost	1		$1.11		Seed costs from dealer: $222.27 ha^{-1} for CRP Mix (CP23) Diversified mix; bioreactor surface 0.005 of treatment area	[82]
Misc. materials	1		$8.80		6″ tile $890 per 305 m(1000 ft); Assume 61 m needed for control structure connections for 20.20 ha treatment area	[101]
Total cost of establishment		**$203.19**		**$454.35**	**TPVC**	
Time to raise/lower	$1-n$	$1.19		$2.97	Three hours per yr with farm labor wages at $8–$20 h^{-1}, 20.2 ha treatment area	[81]; Assumption
Mowing/maintenance	$1-n$	$0.12		$0.62	Spot mowing bioreactor at $24.71–$123.55 ha^{-1} for 20.2 ha treatment	[83]
Replacement year 20	20	$65.66		$98.18	Single sum TPVC at 20 years: woodchips, contractor, seeding	Assumption
Gate replacement	8, 16, 24,…		$14.14		Summation of single sum TPV every eight years for 5 gates per structure ($14.17–$15.32 per ea. for 15 cm structure) 2 structures per 20.2 ha	[101]
Total cost of establishment, maintenance, and replacement		**$308.91**		**$637.59**	**TPVC**	

Table 4
Itemized costs and Total Present Value Costs for a wetland in the U.S. Midwest at real discount rate of 4 % and analysis horizon of 50 years.

Item	Cost timing (yr)	Minimum cost ($ ha^{-1})	Mean cost ($ ha^{-1})	Maximum cost ($ ha^{-1})	Notes	Reference
Design cost	1		$71.17		Assumed: $40 h^{-1} for 90 days of work (8 h d^{-1}) for 405 ha site	Assumption
Contractor fees	1	$28.17	$34.43	$41.51	Building ponds at 8 h d^{-1} for 15 days with Custom Rate Survey $ h^{-1} for 405 ha wetland , not including seeding time	[81]
Seeding buffer	1	$0.35	$0.79	$1.04	Tractor broadcasting at $9.88, $22.61, or $29.65 ha^{-1} for 14 ha wetland buffer for 405 ha treatment	[81]
Seed cost	1	$7.43		$95.38	Seed costs from dealer: $212.39 ha^{-1} for CRP wetland program mix to $162.09 kg^{-1} for "wetland seed mix" at needed 16.8 kg ha^{-1}	[82,84]
Weir plate	1		$14.83		$30 per sq ft. for 40 ft width × 5 ft sheet pile plate, for 405 ha site	Assumption
Control structure	1	$3.26		$7.25	One large control structure ($1320–$2935 per ea.), for 405 ha site	[101]
Land acquisition	1	$529.08		$679.31	$11,757–$15,095 ha^{-1} for 4 ha wetland plus 14 ha buffer treating 405 ha; 2010 state-wide Iowa average for high and medium grade lands	[85]
Total cost of establishment		**$654.28**		**$910.48**	**TPVC**	
Time to manage	1 – *n*	$0.09		$0.43	Spot mowing 10% of buffer area at $24.71–$123.55 ha^{-1}	[83]
Control structure and weir replacement	40	$4.55		$5.75	Single sum TPVC at year 40 includes costs of a new structure and weir and 16 hrs of earth work	Assumption
Total cost of establishment, maintenance, and replacement		**$660.69**		**$925.52**	**TPVC**	

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Table 5
Itemized costs and Total Present Value Costs for N management for corn in the U.S. Midwest at real discount rate of 4 % and analysis horizon of 1 year.

Item	Cost timing (yr)	Minimum cost ($ ha^{-1})	Mean cost ($ ha^{-1})	Maximum cost ($ ha^{-1})	Notes	Reference
Fertilizer application	1 – *n*	$14.83	$24.09	$42.01	Anhydrous-injecting, w/tool bar	[81]
Diesel for equipment	–				Included above	
Fertilizer cost	1 – *n*		$156.40		North Central US mean 2008–2010 anhydrous ammonia price paid: $762.80 metric ton^{-1}; 168 kg N ha^{-1}; AA:82-0-0 (82%)	[56]
Total cost of establishment for baseline application		$171.23		$198.41	Using Fertilizer cost: $156.40 ha^{-1} considering application of 168 kg N ha^{-1} in Fall	[56]
Total cost of establishment at a lower rate (from 168 kg N ha^{-1} to 140 kg N ha^{-1})		**$145.16**		**$172.34**	Using Fertilizer cost: $130.33 ha^{-1} for application of 140 kg N ha^{-1} rather than $156.40 ha^{-1} for 168 kg N ha^{-1}	[56]
Total cost of establishment of Spring application		**$178.42**		**$205.60**	Spring price of $798 metric ton^{-1} at 168 kg N ha^{-1} application rate ($163.59 ha^{-1})	[56,58]
Annual baseline revenue	1 – *n*		$1850.12		Iowa mean 2008–2010 yield of 10.84 metric ton ha^{-1} and 2008–2010 mean corn price received of $0.17 kg^{-1}; at 99% yield for 168 kg N ha^{-1}	[55,56]
Annual revenue from changed yields due to N management (Lower rate)	1 – *n*		$1831.44		Iowa mean 2008–2010 yield of 10.84 metric ton ha^{-1} and 2008–2010 mean corn price received of $0.17 kg^{-1}; at 98% yield for 140 kg N ha^{-1}	[55,56]
Annual revenue from changed yields due to N management (Spring application)	1 – *n*		$1947.30		Iowa mean 2008–2010 yield of 10.84 metric ton ha^{-1} and 2008–2010 mean corn price received of $0.17 kg^{-1}; with 4.2% yield boost for spring application	[56]
Total cost of establishment and revenue impacts for baseline application		−$1614.32		−$1588.19	TPVC (negative represents a revenue)	
Total cost of establishment and revenue impacts at a lower application rate		**−$1621.42**		**−$1595.28**	**TPVC (negative represents a revenue)**	
Total cost of establishment and revenue impacts for Spring application		**−$1700.85**		**−$1674.71**	**TPVC (negative represents a revenue)**	
N Rate Marginal Cost		**−$7.09**		**−$7.09**	**Marginal TPVC**	
Spring N Marginal Cost		**−$86.52**		**−$86.52**	**Marginal TPVC**	

Table 6
Itemized costs and Total Present Value Costs for a cover crop in the U.S. Midwest at real discount rate of 4 % and analysis horizon of 4 years.

Item	Cost timing (yr)	Minimum cost ($ ha^{-1})	Mean cost ($ ha^{-1})	Maximum cost ($ ha^{-1})	Notes	Reference
Seed costs	$1-n$	$14.83		$29.65	Planted at 63 kg ha^{-1}; cereal rye	[32,103]
Planting Drill	$1-n$	$18.53	$32.12	$49.42	Custom cost to have small grains drilled	[81]
Diesel for equipment	–				Included above	
Spraying	$1-n$	$11.12	$15.07	$21.99	Ground, broadcast, tractor	[81]
Herbicide cost	$1-n$		$14.09		Herbicides, Glyphosate, 480 kg m^{-3}, Price paid, US Total, 2010: $6023 m^{-3} ; 0.0023 m^3 ha^{-1}	[32,56]
Total cost of establishment		**$58.56**		**$115.15**	**TPVC**	
Annual baseline revenue (no cover crop)	$1-n$		$1868.81		Iowa mean 2008–2010 yield of 10.84 metric ton ha^{-1} and 2008–2010 mean corn price received of $0.17 kg^{-1}; at 100% yield	[56]
Annual revenue from changed yields due to cover crop	$1-n$		$1752.95		Iowa mean 2008–2010 yield of 10.84 metric ton ha^{-1} and 2008–2010 mean corn price received of $0.17 kg^{-1}; at 6.2% yield reduction for corn following rye	[56]
Difference in annual revenue from baseline			$115.87		Considered a cost of cover crop with corn grown in every other year	
Total cost of establishment and revenue impacts		**$594.98**		**$800.39**	**TPVC**	

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Table 7
Itemized costs and Total Present Value Costs for a diversified crop rotation in the U.S. Midwest at real discount rate of 4 % and analysis horizon of 10 years.

Item	Cost timing (yr)	Minimum cost ($ ha^{-1})	Mean cost ($ ha^{-1})	Maximum cost ($ ha^{-1})	Notes	Reference
Seed costs	Year 3 of every 5	$101.19		$140.48	Legume, alfalfa, public and common seed or proprietary seed, price paid, National, 2010: $273–$379 cwt^{-1}; planted 16.8 kg ha^{-1}	[56]
Planting drill	Year 3 of every 5	$18.53	$32.12	$49.42	Custom cost to have small grains drilled	[81]
Diesel for equipment	—				Included above	Assumption
Soil preparation	Year 3 of every 5		$34.10		Disking, harrow: Default values from ISU Ag Decision Maker	[72] (alfalfa)
Herbicide	Year 3 of every 5		$37.81		Default values from ISU Ag Decision Maker (machinery and chemical)	[72] (alfalfa)
Labor	3–5 of every 5		$81.54		Pre-harvest labor: 7.4 h ha^{-1} at $11.00 h^{-1}	[72] (alfalfa)
Fertilizer	3–5 of every 5	$307.15		$481.36	Default values from ISU Ag Decision Maker for establishment year (min) and production year (max); machinery and chemical	[72] (alfalfa)
Harvesting – mowing	3–5 of every 5	$19.77	$30.64	$37.07	Mowing/conditioning	[81]
Harvesting – baling	3–5 of every 5	$74.13	$123.55	$172.97	Haying baling - small square: $0.30–$0.70 bale^{-1}; 12.4 ton ha^{-1} at 45.4 kg bale^{-1}	[81]; Assumption
Total cost of alfalfa establishment	Year 3 of every 5	**$674.23**		**$860.55**		
Total cost of alfalfa maintenance	Year 4 and 5	$656.81		$772.95	Labor, fertilizer and harvesting costs from above	
Corn in year 1	YEAR 1 of 5		$1183.64		Cost of corn establishment (corn following soybean to be more accurate for years 6, etc.); land rent removed, 10.84 metric ton ha^{-1} yield	[72] (corn following soybean)
Corn in year 2	Year 2 of 5		$1312.13		Cost of corn establishment (corn following corn); land rent removed, 10.84 metric ton ha^{-1}	[72] (corn following corn); [49]
Total costs for five year diversified rotation		**$4214.00**		**$4588.79**	**TPVC: Corn in years 1 and 2 with alfalfa establishment in year 3 and alfalfa maintenance in years 4–5**	
Alfalfa revenue	4–5 of every 5		$1511.46		Alfalfa average yield 12.4 ton ha^{-1} (assuming 3 cuttings); Iowa mean 2008–2010 alfalfa hay price received: $134.85 metric ton^{-1}	[56,72]
Corn revenue			$1868.81			[56]

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	1–2 of every 5				Iowa mean 2008–20109 corn yield: 10.84 metric ton ha^{-1} and 2008–2010 mean corn price received of \$0.17 kg^{-1}	
Total revenue for five year diversified rotation			**\$6850.51**		**TPV: Corn revenue in year 1 plus 4.5% yield boost, corn revenue in year 2, alfalfa revenue divided by 3 (only 1 cutting) in alfalfa establishment year, and alfalfa revenue in year 4–5**	[73]
Total costs and revenue for diversified crop rotation for 10 yr horizon		**−\$10,456.91**		**−\$8970.43**	**TPVC (negative represents a revenue)**	
Cost of corn and soybean five year rotation			\$4469.53		TPVC: Five year cost of corn soybean rotation; starting with corn (ISU Decision Maker, corn following soy, yield 10.8 metric ton ha^{-1}); soybean cost: \$637.53 ha^{-1} ISU Ag Decision Maker for herbicide tolerant soybeans following corn, yield 3.33 metric ton^{-1}; land rent removed	[72]
Revenue of corn and soybean five year rotation			\$7564.77		TPV: Five year revenue of corn soybean rotation, starting with corn; corn revenue described above; soybean revenue: Iowa mean 2008–2010 yield of 3.33 metric ton ha^{-1} and mean price \$0.38 kg^{-1} yields \$1281.05 ha^{-1}	[56]
Total costs and revenue for corn and soybean rotation for 10 yr horizon			**−\$12,276.31**		**TPVC (negative represents a revenue)**	
Marginal cost		**\$1819.40**		**\$3305.87**	**Marginal TPVC**	

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Table 8
Review of nitrogen load reduction effectiveness for seven drainage water quality practices in the U.S. Midwest.

Practices and references	N load reduction			Notes
	Minimum (%)	Mean (%)	Maximum (%)	
Controlled drainage				
[86]	30		40	Overview of this N management practice
[15]	15		75	Controlled drainage factsheet
[87]	48	75	100	Load reduction for mean loads from six months of free drainage vs. controlled water tables at 0.25 m and 0.5 m above the drain; Ontario, Canada
[14]		30		Overview of this N management practice
[13]	10		20	An original paper on drainage control
[88]		43		Controlled drainage/sub-irrigation system, Canada
[29]	0		50	N technology comparison
[89]	31	44	51	Simulation of Midwestern region with Root Zone Water Quality Model-Decision Support System for Agrotechnology Transfer (RZWQM –DSSAT)
[90]		26		Mean of DRAINMOD-NII simulated N losses for drain spacing 18 m–36 m for conventional vs. controlled drainage; Waseca, Minnesota
Bioreactor				
[76]	11		13	Bioreactor in Iowa
[76]	47		57	Bioreactor in Iowa
[76]	27		33	Bioreactor in Iowa
[91]	40	55	65	Denitrification trenches surrounding tile drain, Iowa
[92]	23	33	50	Bioreactor in Illinois
[93]		47		Bioreactor in Illinois, slug of NO_3^- injected
[94]	18		47	Bioreactor in Minnesota
[94]	35		36	Bioreactor in Minnesota
Wetland				
[21]	25		78	Review table
[18]	33	40	55	Annual N load reduction for three wetlands, three years of data; Champaign County, Illinois
[95]		33		Wetland in Illinois
[20]	9		15	Mean N load reduction for two years from wetland with area treatment ratio of 1046:1; Iowa
[20]	34		44	Mean N load reduction for two years from wetland with area treatment ratio of 349:1; Iowa
[20]	55		74	Mean N load reduction for two years from wetland with area treatment ratio of 116:1; Iowa
[29]	20		40	N technology comparison
[54]	40		90	Summary of CREP wetlands in Iowa
Spring N application				
[96]	−67	6.4	44	Load difference between fall and spring (corn phase)
[97]	0	27	41	Load difference between fall and spring (corn phase)
[23]	24		30	6-yr period at Waseca, Minnesota

[29]	−10		30	N technology comparison
[59]	14	35	52	Simulation with Environmental Policy Integrated Climate (EPIC) for central Illinois; Fall vs. spring application at five rates ranging from 112 kg N ha^{-1} to 224 kg N ha^{-1} for Drummer soil
[49]	−62	−23	7.4	N load difference between spring and fall applied at 168 and 252 kg N ha^{-1}; Iowa
N rate reduction				
[23]	21		28	6-yr period at Waseca, Minnesota; 134 kg ha^{-1} vs. 202 kg ha^{-1} application
[29]	20		70	N technology comparison
[98]	17		40	Central Iowa; loadings of 48 kg N ha^{-1}, 35 kg N ha^{-1}, and 29 kg N ha^{-1} for high, medium and low N application rates, respectively
Cover crops				
[66]		13		Southwestern Minnesota, three year study
[100]		40		Based on review
[71]	−13.5	−3.3	7.6	Four year loads and mean for corn treatment vs. corn with rye cover; Gilmore City, Iowa
[31]		61		Four year average; Boone County, Iowa
[29]	10		70	N technology comparison
Crop rotation				
[36]	14		77	Review
[99]	11		14	Six year average losses from corn/soybean or soybean/corn vs. rotation with three years alfalfa followed by corn, soybean, oats; Nashua, Iowa
[35]	18	48	80	Conversion from alfalfa pasture; three year study, compared with corn and soybean and continuous corn rotations; Lamberton, Minnesota
[29]	−50		95	N technology comparison

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Table 9
Nitrogen load reduction effectiveness and Equal Annual Costs in terms of treatment area or nitrogen removal for seven drainage water quality practices in the U.S. Midwest (without government payments).

	EAC (area-based)		Load reduction from Fig. 2				EAC (N-based)			
	Minimum ($ ha^{-1} yr^{-1})	Maximum ($ ha^{-1} yr^{-1})	25th (%)	75th (%)	Mean (%)	Median (%)	Mean (Standard Deviation, $ kg N removed^{-1} yr^{-1})	Median ($ kg N removed^{-1} yr^{-1})	Minimum [a] ($ kg N removed^{-1} yr^{-1})	Maximum [a] ($ kg N removed^{-1} yr^{-1})
Controlled Drainage	$9.30	$37.00	26.0	50.0	40.5	40.0	$2.00 ($1.40)	$1.70	$0.60	$4.50
Bioreactors	$16.00	$32.00	27.0	47.0	37.5	36.0	$2.10 ($0.90)	$2.00	$1.10	$3.80
Wetland	$31.00	$43.00	30.9	55.0	42.8	40.0	$2.90 ($0.80)	$2.80	$1.80	$4.40
N rate reduction	−$7.40	−$7.40	—	—	14.5	—	−$1.60 ($0.00)	−$1.60	−$1.60	−$1.60
Spring N application [b]	−$90.00	−$90.00	−2.5	31.3	9.3	19.0	−$14.00 ($12.00)	−$12.00	−$31.00	−$0.07
Cover crop	$164.00	$221.00	4.9	45.3	23.1	11.5	$55.00 ($48.00)	$38.00	$12.00	$144.00
Crop rotation	$224.00	$408.00	14.0	77.0	34.1	18.0	$43.00 ($29.00)	$39.00	$9.30	$93.00

[a] Minimum and maximum calculated using the minimum EAC and the 75th percentile load reduction and the maximum EAC and the 25th percentile load reduction, respectively.
[b] Due to confounding effects of negative EAC and negative 25th percentile load reduction (indicating a contribution to the N load), the maximum value for Spring N application was calculated using the marginal increase to the baseline load based on the 25th percentile and the minimum value was calculated from the mean load reduction.

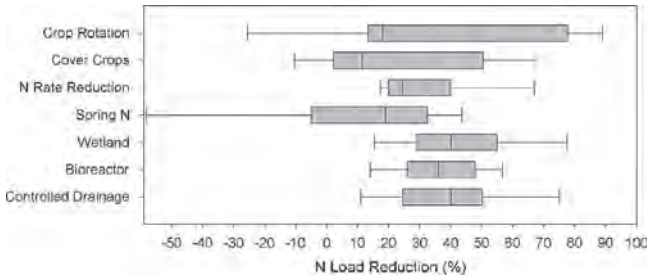

Fig. 1. Comparison of nitrogen load reductions obtained from literature for seven water quality improvement strategies in the U.S. Midwest; the box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dotted line represents the mean, and the whiskers show the 10th and 90th percentiles.

are shown in Table 9).

$$\frac{\text{EAC \$}}{\text{kg N yr}} = \frac{\text{minimum or maximum EAC \$}}{ha\ yr} \div \left(\frac{\text{31.4 kg N lost baseline}}{\text{ha}} \times \text{Load removal percentage mean, median, 25th, or 75th}\right) \quad (5)$$

In the case of modified N application rate, rather than use load reduction values from literature, a correlation from Lawlor et al. [27] was used (Eq. (1)). For this practice, literature values proved to be too variable as they were not for the specific rates used in this comparison. After drainage NO_3^-–N concentrations were developed via Eq. (1) for the two application rates, a constant drainage volume was assumed to develop a percent N load reduction. While, Eq. (1) was specifically applicable to the database and site from which it was developed (northwestern Iowa), and does not account for other factors that affect N leaching losses (e.g., soil mineralizable N, the time of N application relative to crop N uptake, soil moisture content, weather conditions), it provided a straight forward approach to estimate approximate concentrations based upon N fertilizer application rates.

Finally, because cost-share has been shown to be an important incentive for operators to make environmental mitigation decisions, the impact of existing government cost-share and incentive programming was assessed. In Iowa, USDA environmental quality incentive program (EQIP) payments were available for each of the practices evaluated here except for modification of fertilizer rate [50] (Table 10). EQIP cost rates used were standard rate, not the higher rates available for historically underserved groups. Incentives for controlled drainage, bioreactors, wetlands, and N management were treated as one time, present value payments (year 1), while the others occurred in years $1-n$ with time limits set by EQIP payment schedules. Though EQIP funding is available for wetlands, cost share payments from the Iowa Department of Agriculture and Land Stewardship's Conservation Reserve Enhancement Program (IDALS CREP) are more appropriate because the wetland in this analysis was sized based upon Iowa CREP guidelines. For a CREP 30 year easement agreement, compensation included 15 annual rental payments of 150% the soil rental rate, cost-share for 100% of the wetland installation (90% federal, 10% state), and a one-time incentive payment ($247 ha^{-1}) [19,51]. The soil rental rate was assumed to be the average cash rental rate for 2008–2010 for the state of Iowa ($447 ha^{-1}) [52].

2.1. Controlled drainage

The major cost of controlled drainage is the capital expense of the structures and their installation. Because of this expense, land slope limitations are an important factor as more structures are needed at steeper sites. Another important consideration is the cost difference between implementing controlled drainage in existing vs. newly designed drainage systems [14].

For this evaluation of controlled drainage, the costs to retrofit an existing drainage system and the cost to implement a new drainage system designed for controlled drainage are considered. To reflect

Table 10
Environmental Quality Incentives Program (EQIP) payment schedule rates for Iowa for seven nitrogen reduction practices [50] and calculated total present value ($TPVC_{Govt}$) of this government cost-share for this evaluation.

	EQIP practice name	Practice code	Payment schedule cost	Payment unit	Minimum life (yr)	Year of payment	Payment ($ ha treated $^{-1}$)	$TPVC_{Govt}$ ($ ha^{-1})
Controlled drainage [a]	Drainage water management	554	$364.08	Per number of water control zones	1	1	$44.98	$44.98
Bioreactors [b]	Denitrifying bioreactor	747	$3999.50	Per bioreactor	10	1	$197.66	$197.66
Wetland [c]	Wetland creation	658	$680.00	Per acre	15	1	$16.80	$16.80
N rate reduction [d]	—	—	—	—	—	—	$0.00	$0.00
Spring N application [d, f]	Nutrient management	590	$11.00	Per acre	1	1	$27.18	$27.18
Cover crop [e, f]	Cover crop (and green manure)	340	$53.26	Per acre	1	1–3	$131.61	$379.83
Crop rotation [f]	Conservation crop Rotation	328	$52.00	Per acre	1	1–3	$128.50	$370.85

[a] Used scenario of 65 ha, requiring eight zones.
[b] EQIP specifies treatment of drainage from 12.1 ha which was less than the treatment area assumed here of 20.2 ha; EQIP cost-share was not used in replacement years for bioreactors or controlled drainage.
[c] Based on CREP 30 yr contract incentives rather than EQIP cost share shown here (see Section 2).
[d] Based on a mid-range payment rate requiring only two additional enhancement practices.
[e] Based on "cover crop winter hardy" rate for a winter cover of rye.
[f] EQIP funding for N management, cover crop and crop rotation practices has three year payment time limits; payments for cover crop and crop rotation were assumed to happen in the first three years of the analysis period and because N management had a planning horizon of $n=1$, only 1 year of EQIP was included.

the marginal cost of water quality improvement and not just the cost of new drainage systems, contractor tiling and materials expenses for new systems are not included. Full cost components are described in Table 2. Regarding more long-term costs, the cost of maintenance for this practice includes landowner time to manipulate the control structures; this would vary based on the number of structures, distance between them, and management intensity a landowner chose. The control structure stop logs/gates need to be replaced every eight years. Because the structures themselves would need to be replaced in year 40, this determined the practicable lifespan of this practice ($n=40$).

2.2. Bioreactors

As with controlled drainage, bioreactor establishment costs include design, contractor and structure fees. However, unlike controlled drainage, bioreactor treatment area differs from the surface area of the technology. Here, the $\$\,ha^{-1}$ values referred to the treatment area not the bioreactor surface footprint. On an itemized basis, a maximum value for engineering fees of $\$40\,h^{-1}$ for 16 h of work is assumed, though if the bioreactor is designed by a technical service provider, these fees may not apply. Although no land is typically removed from production for bioreactors, seeding the surface is important to prevent erosion of the soil cap. Bioreactors are typically less than 0.5% of the drainage treatment area, so this area ratio is used for the seeding and mowing costs. Bioreactor full cost components are described in Table 3.

Farmer time for adjusting the control structures is minimal compared to the controlled drainage practice due to fewer structures here. In addition to annual maintenance, the bioreactor material is replaced once in year 20 (involving costs associated with new woodchips, seeding and contractor fees) before the structures' lifespan is exhausted in year 40 (bioreactor practicable lifetime, $n=40$). Similar to controlled drainage, the stop logs/gates are replaced every eight years.

2.3. Wetlands

Wetlands are unique in that their capital expense can be very high, but they are capable of treating drainage from far larger areas than the other strategies considered here. Design and construction are important components of wetland establishment but the largest single expense is the land acquisition cost. Longer-term economic considerations sometimes include the opportunity cost of lost crop income (e.g., Prato et al. [53] and Crumpton et al. [22]), as well as maintenance and mowing expense and potential income streams.

For the purposes of this comparison, a 405 ha treatment area is assumed with a wetland occupying 1% of this area (4 ha) consistent with the conservation reserve enhancement program (CREP) guidelines for Iowa which specify a wetland size of 0.5–2% of the treatment area (not including associated wetland buffer) [19,54]. Accordingly, in addition to the wetland basin, a grass buffer is required. The wetland buffer has a 3.5:1 area ratio with the wetland (i.e., 3.5% of the treatment area in buffer, 14 ha) (Iowa Department of Ag. and Land Stewardship, personal communication, 2011). Because land acquisition costs are the largest portion of CREP wetland expense, this is included here; however, land for the other practices (e.g., edge-of-field area for the bioreactor or fields for the in-field practices) is assumed to be owned. Alternatively, forgone annual land rent would be another way to account for land costs. The cost per area for this practice reflected the area treated, not the area of the wetland and associated buffer. Wetland cost components are shown in Table 4.

Structural components include a water control structure and a weir plate, which are used to control wetland flow. The annual maintenance cost involves mowing 10% of the buffer area. Replacement costs of the control structure and sheet pile weir in year 40 are included within the 50 year wetland planning horizon ($n=50$). Also, over the life of a wetland, sediment removal and earthwork maintenance would be required, though those costs are not incorporated in this analysis because their timing would be difficult to estimate and may occur at greater than the 50 year planning horizon.

2.4. N rate reduction (168–140 kg N ha^{-1})

The establishment costs for both N management practices (rate reduction and timing) are similar and include custom rates for application machinery usage and fertilizer costs as described in Table 5. Because an N management practice is an annual occurrence, there are no long-term maintenance costs but, rather, establishment cost and revenue impacts occur every year (practicable lifespan, $n=1$). For these N management strategies, a baseline scenario of fall applied 168 kg N ha^{-1} is developed for comparison. The marginal difference in TPVC between the baseline and the rate/timing alternative is used in the analysis rather than the absolute value of the rate/timing TPVC themselves. Using these marginal costs of the lower rate practice and of the spring timing practice allows evaluation of their cost solely due to water quality improvement.

Financial analysis of lowering the N application rate consists of less fertilizer expense in addition to the cost of potential yield loss depending upon the initial and final application rates [25]. This analysis is complicated by the variability of the impacts of initial and revised fertilizer rates. In practice, challenges to N fertilizer rate reduction include the fact that the optimum rate is indeterminable at application time (though soil testing can help) and is highly variable year to year. Sawyer and Randall [25] provide a detailed explanation of these variable negative and positive returns based on initial and final fertilizer rates.

In analyzing the costs of reduced fertilizer rate here, "establishment" cost consists of less fertilizer purchased (i.e., a cost savings) as well as the effect of potentially reduced yield. The Iowa State University N-Rate Calculator [55] is used to estimate the yield impact from changing the fertilizer rate. Using a three-yr average (2008–2010) anhydrous ammonia price of \$763 metric ton^{-1} [56] and a three-yr average (2008–2010) Iowa corn price of \$0.17 kg^{-1} [56], the calculated percent of maximum yield is 99% at an N application rate of 168 kg N ha^{-1} and is approximately 98% at 140 kg N ha^{-1} (corn following soybean rotation). However, it is worth noting that shifting to this lower rate permanently may not be sustainable over long periods if soil N pools become depleted [57].

2.5. Spring N application

The cost of shifting application from the fall to the spring is affected by differences in both fall/spring fertilizer price and yield. Because current fall vs. spring fertilizer prices are no longer published by USDA, the average historical difference in the fall and spring fertilizer prices, on a percentage basis, is used to calculate the average increase in expense for spring anhydrous application. Between 1960 and 1994, the average prices for September/October were \$184 metric ton^{-1} and for April/May were \$193 metric ton^{-1} [58], thus an increase of 4.6% over the average 2008–2010 anhydrous price of \$763 metric ton^{-1} is used for spring (spring: \$798 metric ton^{-1}).

Multiple authors have reported lower drainage NO_3^- loadings with corresponding higher corn yields for spring vs. fall N applications [23,59,60]. Spring N fertilizer applications may increase yield by 8–14% compared to fall applications [23,60], though this may not always be the case. For example, there was no corn yield difference between fall and spring applications at two different application rates during a study in Iowa [49]. Despite this variability, an overall 4.2% corn yield boost is included for the practice of spring application (site year average from Refs. [49,61–64]).

2.6. Cover crops (cereal rye)

For the purposes of this evaluation, cereal rye (*Secale cereale* L.) is studied as a cover crop because this crop has good potential to improve water quality in cool Midwestern climates [31] and is popular in this region [65]. First year costs of a cover crop (Table 6) (assuming a no-till system in this analysis) include planting as well as herbicide application because cereal rye overwinters [32]. Cover cropping is an annual practice, thus there are no long-term maintenance costs but rather annual establishment costs. A yield reduction for corn following rye is also an important part of the analysis. A 6.2% corn yield reduction is assumed compared to a baseline where no cover crop was used (site year average from Refs. [31,66–71]). This corn revenue reduction is assumed to occur every other year during the

planning horizon (i.e., a corn/soybean rotation; cover crop practice period, $t=2$; cover crop planning horizon, $n=4$).

2.7. Crop rotation (multiple years of alfalfa)

The number of possible rotation combinations is quite large, and to simplify this work, a multi-year incorporation of alfalfa (*Medicago sativa* L.) into a corn rotation is investigated. Only one year of alfalfa in a rotation may not be as beneficial as several years considering high seed cost and potential low alfalfa yield in the establishment year [36]. Therefore, this diversified crop rotation consists of two years of corn (years 1–2) followed by three years of alfalfa (years 3–5). The major costs for such a crop rotation are the seed, planting, and harvesting. The cost components of this rotation are shown in Table 7, with the rotation practice period (t) equal to five years and the planning horizon, n, equal to 10 years.

Within the rotation, enterprise budget information published by Iowa State University is used to specifically estimate the costs of corn following soybean (for years 1, 6, etc.; most applicable for corn following alfalfa) and for corn following corn (in years 2, 7, etc.) [72]. Default Iowa State University Ag Decision Maker [72] values were used after removing land rent costs (i.e., assumed land owned) and substitution of average Iowa 2010 corn yield from USDA NASS [56].

A multiple year alfalfa rotation may provide monetary benefit via reduced fertilizer requirements, reduced tillage and other field trips, and revenue from the alfalfa harvest. Here only direct revenue streams are considered with alfalfa revenue in years 3–5 and corn revenue in years 1–2. The establishment year of alfalfa is assumed to only have one cutting rather than the three as in the maintenance years (i.e., establishment years had one third of the yield experienced in maintenance years). Corn following alfalfa may have an increased yield of 19–84% compared to corn after corn according to a review by Olmstead and Brummer [36], but Liebman et al. [73] showed more moderate corn yield increases averaging 4.5% which was used here for the first year of corn.

Additionally, the TPVCs for this crop rotation scenario are compared against TPVCs for traditional corn/soybean rotations. Similarly to the N management practices, this allowed evaluation of the cost of this water quality practice (i.e., marginal cost of the practice). The corn/soybean baseline scenario is evaluated using the same five year framework as the extended rotation with cost values taken from ISU Ag Decision maker for corn following soybeans and herbicide tolerant soybeans following corn with default values except for removal of land rent costs and use of average yields (2008–2010, USDA NASS data) (Table 7) [72].

3. Results and discussion

3.1. Equal annualized costs

The TPVCs from the seven practices ranged from a cost savings of approximately \$90 ha^{-1} for spring applied N fertilizer to a cost of \$3306 ha^{-1} for a diversified crop rotation (Tables 2–7), and the resulting EACs ranged from $-$\$90 ha^{-1} yr^{-1} (Spring N, representing cost savings) to \$408 ha^{-1} yr^{-1} (crop rotation) (Table 9). The highest EACs were associated with the two in-field vegetated practices, cover crops and crop rotations, and the lowest were associated with the N management strategies. However, the high EACs developed for the cover and diversified cropping practices were associated with large uncertainties (Tables 1 and 9).

With regard to spring N applications, Randall and Sawyer [24] also noted long-term economic gains of \$46–\$126 ha^{-1} yr^{-1} (seven and fifteen year averages). However, a complete shift from fall fertilization could be expensive for individual producers in terms of both additional infrastructure required for spring applications (storage, equipment, labor, handling, application, etc.) and in the potential loss of yield by a delayed planting date [74]. Additionally, when lower N rates are applied, the risk of a yield loss is increased compared to higher application rates if it is a year where corn is more responsive to N inputs (depending upon the soil mineralizable N). In these years, the probability

of obtaining a certain yield percentage declines when lower rates are applied; this probabilistic variability was not reflected here. Any such potential increased risk for either of these N management practices is an important factor in terms of producer decision-making.

Along with the relatively high EACs for the rye cover crop ($164–$221 ha^{-1} yr^{-1}; Table 9), several comments should be noted. First, costs to kill the cover are contingent upon producer actions. For example, in a no-till system as assumed here, an early burn-down application of herbicide may be done regardless if a cover crop was present; likewise, in a tilled system, a producer may do a second tillage pass in the spring regardless of a cover crop. Second, rye cover crop implementation costs can be $10–$15 ha^{-1} lower if a landowner chooses not to use a custom operator [75]. Next, potential negative yield impacts will likely be reduced or minimized through several years of experience with cover crop management. This increased experience also likely means a more effective cover, though returns to farm management can improve under highly skilled managers regardless of the production practice. Finally, some of the N taken up by a cover crop will be returned to future crops. It is difficult to place an economic value on this, but it is worth noting the multiple benefits to the soil provided by cover crops [33]. Because cover crops are typically done for reasons other than drainage water quality improvement, it has been suggested that only a portion of the cost should be attributed to N. However, because this work was solely focused on N reduction cost effectiveness, see Table 1 or Christianson et al. [34] for discussion of the ecosystem services provided by these practices.

The EAC for the diversified rotation was $224–$408 ha^{-1} yr^{-1} (Table 9). The values developed here were contrary to values from Olmstead and Brummer [36] who showed a diversified rotation was more profitable than a conventional rotation. One major caveat worth noting is the potential for large scale market effects if this rotation were done by a large numbers of producers in a limited area; if this practice became widespread, the alfalfa price could markedly decline.

The two field-scale constructed practices, controlled drainage and bioreactors, had similar EAC ranges at $9.30–$37 ha^{-1} yr^{-1} (spanning both existing and new drainage systems) and $16–$32 ha^{-1} yr^{-1}, respectively. For reference of installation costs, bioreactor TPVC estimates (Table 3) were within the range of five bioreactor installations in Iowa (total costs of $4400–$11,800 to treat drainage from 12 ha to over 40 ha [76]), and overall TPVCs estimated for constructed wetlands ($661–$926 ha^{-1}, Table 4) compared well with cost assessments from IDALS CREP wetlands constructed in Iowa. CREP wetlands average approximately $880 ha^{-1} including land acquisition ($513 ha^{-1}), establishment and maintenance costs ($297 ha^{-1}), and engineering costs ($69 ha^{-1}). As of 2011, 72 wetlands had been installed under the CREP wetland program in Iowa with an average treatment area of 505 ha (Iowa Department of Ag. and Land Stewardship, personal communication, 2011).

3.2. Comparative average cost effectiveness of nitrogen mitigation

In addition to variation between practices in TPVCs and EACs, the practices also varied widely in terms of N removal effectiveness (Fig. 1). For example, modification of fertilizer timing had comparatively low N removal, ranging notably into the potential for negative water quality impacts, while the constructed practices tended to have relatively better water quality performance. Bioreactors had the smallest range of N load reduction between the 25th and 75th percentiles with mean and median values above 35% load reduction. The other two constructed practices, controlled drainage and wetlands, had similarly high load reduction potential (means and medians $\geq 40\%$). Note, because the 25th percentile for spring N application was a negative value (-2.5%), indicating a contribution to the N load, the resulting marginal increase to the baseline load was used to calculate the $ kg N^{-1} yr^{-1} for this value.

When these N removal performances were combined with the cost data, spring N application timing was the most cost effective option for removing N from drainage (mean $14 kg N^{-1} yr^{-1} cost savings or revenue) and cover crop the least (mean $55 kg N^{-1} yr^{-1}) (Table 9, Fig. 2). Both N management practices yielded negative average cost efficiencies indicating a savings or increased profitability. However, it's important to note nutrient management practices alone may not be sufficient to meet all N water quality goals in the Midwestern Region. In addition to the highest mean

values, the cover crop and the diversified rotation had the largest standard deviations (pre-government payment), which highlighted the variability of these two in-field vegetative practices both in terms of costs and N removal potential. The more constructed practices of controlled drainage, bioreactors and wetlands had fairly comparable average cost efficiencies with mean values between \$2 and \$3 kg N^{-1} yr^{-1} (Table 9, Fig. 2).

To put these average cost efficiencies in context of other reported values is difficult in light of the variable methodology and limited transparency of other assessments. Nevertheless several practices were in the range of literature, while others were distinctly different. For example, the cost efficiency of controlled drainage in this analysis was \$2.00 ± \$1.40 kg N^{-1} yr^{-1}, which was similar to reports which are often in the range of \$2–\$4 kg N^{-1} [77,78]. Moreover, the average cost efficiency of wetlands is often reported at approximately \$3–\$4 kg N^{-1} [51,54,77,79]; the value reported in our study was \$2.90 ± \$0.80 kg N^{-1} yr^{-1}. Only one report was available for bioreactors; in a multi-year cost analysis of a theoretical denitrification system, Schipper et al. [80] calculated costs of \$2.39–\$15.17 kg N^{-1}. This range was higher than what was estimated for a bioreactor in our study (\$2.10 ± \$0.90 kg N^{-1} yr^{-1}). Finally, cover crops have been reported to be less expensive per kg N removed than calculated in this analysis (mean \$55 ± \$48 kg N^{-1} yr^{-1}). Values from cover crop literature have ranged from \$1.26 kg N^{-1} to \$11.06 kg N^{-1} [32,75,77], though these previous reports may not have included corn yield impacts.

Inclusion of EQIP or CREP payments generally increased the average cost effectiveness of the practices from a farmer's perspective (Table 9 vs. Table 11) with the largest percentage change

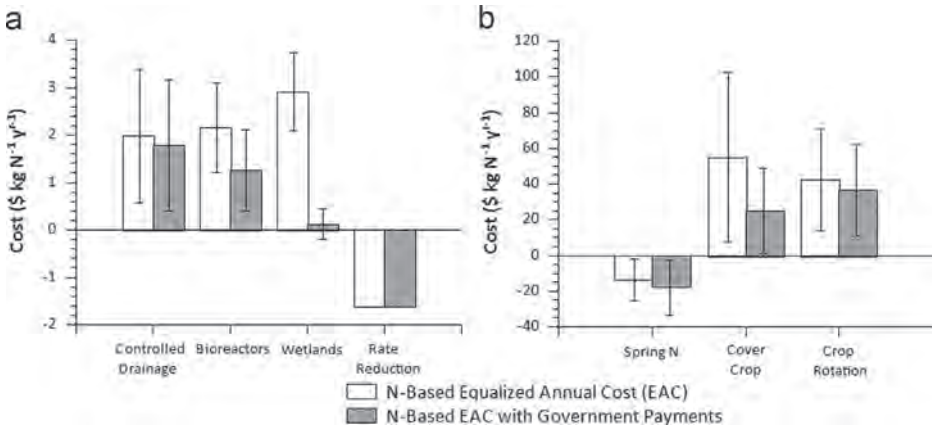

Fig. 2. Equal Annual Costs (\$ kg N^{-1} yr^{-1}) on a nitrogen removal basis for seven agricultural practices in the U.S. Midwest with and without government payments at real discount rate of 4% and analysis horizons of practicable lifespans by practice; note y-axis scales differ for figure parts (a) and (b).

Table 11
Nitrogen removal-based Equal Annual Costs for seven drainage water quality practices in the U.S. Midwest including government payments and additional revenue at real discount rate of 4 % and analysis horizons of practicable lifespan by practice.

	Equal annual costs	
	Mean (standard deviation, \$ kg N^{-1} yr^{-1})	Median (\$ kg N^{-1} yr^{-1})
Controlled drainage	\$1.80 (\$1.40)	\$1.50
Bioreactors	\$1.30 (\$0.86)	\$1.10
Wetland	\$0.12 (\$0.32)	\$0.09
N rate reduction	−\$1.60 (\$0.00)	−\$1.60
Spring N application	−\$18.00 (\$16.00)	−\$16.00
Cover crop	\$25.00 (\$24.00)	\$16.00
Crop rotation	\$36.00 (\$26.00)	\$33.00

occurring for the wetland practice. Without government payments, the practices in order of average cost effectiveness were (based on mean value): Spring N application, N application rate reduction, controlled drainage, bioreactors, wetlands, crop rotation and cover crops. When government payments were included, wetlands and bioreactors became the third and fourth most cost effective practices, respectively, and diversified crop rotations became the least cost effective (from the farmer's perspective) (Fig. 2).

4. Conclusions

Each drainage N reduction strategy provides landowners an additional distinct option for drainage water quality improvement and different strategies or combinations of such will be applicable in different locations. In this work, the N management practices were the most cost effective as both lowering the application rate (from 168 to 140 kg N ha^{-1}) and moving applications to spring resulted in negative costs. Of course, the scenarios here were limited in scope, and there is a wide range of N management and application possibilities that could yield different results. Importantly, a complete ban of fall fertilization could have large-scale economic effects, which were not investigated in this farm-level analysis. The least cost effective practices were the in-field vegetative practices of cover crop and crop rotation though these average cost efficiencies had wide standard deviations. Moreover, benefits like soil productivity, erosion protection, and management or reduction of multiple contaminants were not quantified. The three constructed practices were comparable in terms of pre-cost share \$ kg N^{-1} yr^{-1} although wetlands were very cost effective when CREP incentives were included. A final important note is that while this study focused on water quality NO_3^- mitigation, several of these practices provide significant additional ecosystem services not quantified here.

In an applied sense, these average cost efficencies need to be considered in context of the multiple agricultural and environmental objectives that will differ for each farm and for each farmer. Though the N management practices had the most attractive cost efficiencies, sole focus on N management either on farm or in policies will likely be insufficient to meet water quality goals in entirety. And while improved N management may be “low hanging fruit” for farmers aiming to improve water quality, there are important large scale impacts (e.g., infrastructure requirements for a complete fall fertilizer ban) that were not investgated in this farm level study. At the other end of the cost efficiency spectrum, the in-field vegetative practices were the least attractive in this analysis. However, with this work defined narrowly by reduction of N in drainage water, several potential additional agronomic and environmental benefits of these practices were excluded. Reduction of erosion and improved soil qualities potentially provided by these practices may be important considerations for farm decision makers. These strategies should certainly not be overlooked as Dinnes [29] reported that diversifying cropping systems in Iowa has the most potential to reduce NO_3^- loadings compared with any other best management practice.

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Appendix A. Supplementary information

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References

[1] D.L. Dinnes, D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, C.A. Cambardella, Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils, Agronomy Journal 94 (2002) 153–171.

[2] United States Geological Survey, Nitrogen in the Mississippi Basin—Estimating Sources and Predicting Flux to the Gulf of Mexico. ⟨http://ks.water.usgs.gov/pubs/fact-sheets/fs.135-00.pdf⟩, 2000 (accessed 08.08.12).

[3] J.A. Delgado, R.F. Follett, Advances in nitrogen management for water quality, Journal of Soil and Water Conservation 66 (2011) 25A–26A.

[4] D.W. Lemke, D.P. McKenna, Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop, ASABE, St. Joseph, MI vii–ix.

[5] L. Christianson, J. Tyndall, Seeking a dialog: a targeted technology for sustainable agricultural systems in the US Corn Belt, Sustainability: Science Practice and Policy 7 (2011) 70–77.

[6] R.D. Battel, D.E. Krueger, Barriers to change: farmers' willingness to adopt sustainable manure management practices, Journal of Extension 43 (2005). ⟨http://www.joe.org/joe/2005august/a7.shtml⟩.

[7] J.M Gillespie, S.A. Kim, K. Paudel, Why don't producers adopt best management practices? An analysis of the beef cattle industry, Agricultural Economics 36 (2007) 89–102.

[8] R.L. McCown, New thinking about farmer decision makers, in: J.L. Hatfield (Ed.), The Farmer's Decision, Soil and Water Conservation Society, Ankeny, Iowa 2005, pp. 11–44.

[9] L.S. Prokopy, K. Floress, D. Klotthor-Weinkauf, A. Baumgart-Getz, Determinants of agricultural best management practice adoption: evidence from the literature, Journal of Soil and Water Conservation 63 (2008) 300–311.

[10] A.M. Lemke, T.T. Lindenbaum, W.L. Perry, M.E. Herbert, T.H. Tear, J.R. Herkert, Effects of outreach on the awareness and adoption of conservation practices by farmers in two agricultural watersheds of the Mackinaw River, Illinois, Journal of Soil and Water Conservation 65 (2010) 304–315.

[11] USDA ARMS, Agricultural Resource Management Survey USDA. ⟨http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/tailored-reports.aspx#.Ua3Y9EC1GCk⟩, 2012 (accessed 05.06.13).

[12] G.W. Randall, M.J. Goss, Nitrate losses to surface water through subsurface, tile drainage, in: R.F. Follett, J.L. Hatfield (Eds.), Nitrogen in the Environment: Sources, Problems, and Management, Elsevier Science, 2001. (Chapter 5).

[13] J.W. Gilliam, R.W. Skaggs, S.B. Weed, Drainage control to diminish nitrate loss from agricultural fields, Journal of Environmental Quality 8 (1979) 137–142.

[14] R.A. Cooke, G.R. Sands, L.C. Brown, Drainage Water Management: A Practice for Reducing Nitrate Loads from Subsurface Drainage Systems. http://water.epa.gov/type/watersheds/named/msbasin/upload/2006_8_24_msbasin_symposia_ia_session2.pdf, (accessed 08.08.12).

[15] J. Frankenberger, E. Kladivko, G. Sands, D. Jaynes, N. Fausey, M. Helmers, R. Cooke, J. Strock, K. Nelson, L. Brown, Drainage Water Management for the Midwest: Questions and Answers About Drainage Water Management for the Midwest, Purdue Agriculture. ⟨http://www.extension.purdue.edu/extmedia/wq/wq-44.pdf⟩, 2006 (accessed 08.08.12).

[16] R.A. Cooke, A.M. Doheny, M.C. Hirschi, Bio-reactors for Edge of Field Treatment of Tile Outflow, Paper Number 012018, in: Proceedings of the 2001 ASAE Annual International Meeting, ASABE, St. Joseph, MI, 2001.

[17] L. Christianson, A. Bhandari, M. Helmers, Emerging technology: denitrification bioreactors for nitrate reduction in agricultural waters, Journal of Soil and Water Conservation 64 (2009) 139A–141A.

[18] D.A. Kovacic, M.B. David, L.E. Gentry, K.M. Starks, R.A. Cooke, Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage, Journal of Environmental Quality 29 (2000) 1262–1274.

[19] Iowa Department of Agriculture & Land Stewardship, ⟨http://www.agriculture.state.ia.us/waterResources/pdf/LandownerGuide.pdf⟩, (accessed 08.08.12).

[20] J.L. Baker, W.G. Crumpton, Use of Constructed/Reconstructed Wetlands to Reduce Nitrate–Nitrogen Transported with Subsurface Drainage, in: Proceedings of the 1st Agricultural Drainage Field Day, Lamberton, MN, 2002. ⟨http://swroc.cfans.umn.edu/prod/groups/cfans/@pub/@cfans/@swroc/documents/content/cfans_content_290197.pdf⟩, (accessed 08.08.12).

[21] W.G. Crumpton, G.A. Stenback, B.A. Miller, M.J. Helmers, Potential Benefits of Wetland Filters for Tile Drainage Systems: Impact on Nitrate Loads to Mississippi River Subbasins, Final Project Report to U.S. (Proj. No. IOW06682), Department of Agriculture, 2006 ⟨http://www.fsa.usda.gov/Internet/FSA_File/fsa_final_report_crumpton_rhd.pdf⟩ (accessed 08.08.12).

[22] W.G. Crumpton, D.A. Kovacic, D.L. Hey, J.A. Kostel, Potential of Restored and Constructed Wetlands to Reduce Nutrient Export from Agricultural Watersheds in the Corn Belt, in: Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop, ASABE, St. Joseph, MI29–42 (Chapter 3).

[23] G.W. Randall, D.J. Mulla, Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices, Journal of Environmental Quality 30 (2001) 337–344.

[24] G.W. Randall, J.E. Sawyer, Nitrogen Application Timing, Forms, and Additives, in: Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop, ASABE, St. Joseph, MI73–85 (Chapter 6).

[25] J.E. Sawyer, G.W. Randall, Nitrogen Rates, in: Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop, ASABE, St. Joseph, MI59–72 (Chapter 5).

[26] M.J. Helmers, J.L. Baker, Strategies for Nitrate Reduction: The Cedar River case study, in: Proceedings of 22st Annual Integrated Crop Management Conference, Iowa State University, Ames, IA, 2010.

[27] P.A. Lawlor, M.J. Helmers, J.L. Baker, S.W. Melvin, D.W. Lemke, Nitrogen application rate effect on nitrate-nitrogen concentration and loss in subsurface drainage for a corn-soybean rotation, Transactions of the ASABE 51 (2008) 83–94.

[28] K.G. Cassman, A. Dobermann, D.T. Walters, Agroecosystems, nitrogen-use efficiency, and nitrogen management, Ambio 31 (2002) 132–140.

[29] D.L. Dinnes, Assessments of Practices to Reduce Nitrogen and Phosphorus Nonpoint Source Pollution of Iowa's Surface Waters, Report for the Iowa, Department of Natural Resources in cooperation with the USDA-ARS National Soil Tilth Laboratory, 2004 ⟨http://www.iowadnr.gov/portals/idnr/uploads/water/nutrients/files/nps_assessments.pdf⟩ (accessed 08.08.12).

[30] United States Department of Agriculture Economic Research Service, Agricultural Resources and Environmental Indicators Publication, 4.5 Nutrient Management, 1997. ⟨http://www.ers.usda.gov/publications/arei/ah712/AH7124-5.PDF⟩, (accessed 08.08.12).

[31] T.C. Kaspar, D.B. Jaynes, T.B. Parkin, T.B. Moorman, Rye cover crop and gamagrass strip effects on NO_3 concentration and load in tile drainage, Journal of Environmental Quality 36 (2007) 1503–1511.
[32] T.C. Kaspar, E.J. Kladivko, J.W. Singer, S. Morse, D. Mutch, Potential and Limitations of Cover Crops, Living Mulches, and Perennials to Reduce Nutrient Losses to Water Sources from Agricultural Fields, in: Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop, ASABE, St. Joseph, MI129–147 (Chapter 10).
[33] T.C. Kaspar, J.W. Singer, The use of cover crops to manage soil, in: J.L. Hatfield, T.J. Sauer (Eds.), Soil Management: Building a Stable Base for Agriculture, American Society of Agronomy and Soil Science Society of America, Madison, WI 2011, pp. 321–337.
[34] L. Christianson, T. Knoot, D. Larsen, J. Tyndall, M. Helmers, Adoption potential of nitrate mitigation practices: an ecosystem services approach, International Journal of Agricultural Sustainability (2013)http://dx.doi.org/ 10.1080/14735903.2013.835604. in press.
[35] D.R. Huggins, G.W. Randall, M.P. Russelle, Subsurface drain losses of water and nitrate following conversion of perennials to row crops, Agronomy Journal 93 (2001) 477–486.
[36] J. Olmstead, E.C. Brummer, Benefits and barriers to perennial forage crops in Iowa corn and soybean rotations, Renewable Agriculture andFood Systems 23 (2008) 97–107.
[37] V. Afari-Sefa, E.K. Yiridoe, R. Gordon, D. Hebb, Decision considerations and cost analysis of Beneficial Management Practice implementation in Thomas Brook Watershed, Nova Scotia, Journal of International Farm Management 4 (2008) 1–32.
[38] N.S. Rao, Z.M. Easton, D.R. Lee, T.S. Steenhuis, Economic analysis of best management practices to reduce watershed phosphorus losses, Journal of Environmental Quality 41 (2012) 855–864.
[39] Y. Yuan, S.M. Dabney, R.L. Bingner, Cost effectiveness of agricultural BMPs for sediment reduction in the Mississippi Delta, Journal of Soil and Water Conservation 57 (2002) 259–267.
[40] X. Zhou, M.J. Helmers, M. Al-Kaisi, H.M. Hanna, Cost-effectiveness and cost-benefit analysis of conservation management practices for sediment reduction in an Iowa agricultural watershed, Journal of Soil and Water Conservation 64 (2009) 314–323.
[41] J.R. Williams, P.M. Clark, P.G. Balch, Streambank stabilization: An economic analysis from the landowner's perspective, Journal of Soil and Water Conservation 59 (2004) 252–259.
[42] J. Canada, W. Sullivan, D. Kulonda, J. White, Capital Investment Analysis for Engineering and Management, 3rd ed., Prentice Hall, New Jersey624.
[43] R.D. Kay, W.M. Edwards, P.A. Duffy, Investment Analysis, in: Farm Management, McGraw-Hill, New York, NY 308–329 (Chapter 17).
[44] C.R. Burdick, D.R. Refling, H.D. Stensel, Advanced biological treatment to achieve nutrient removal, Journal of the Water Pollution Control Fed 54 (1982) 1078–1086.
[45] J.C. Tyndall, R.C. Grala, Financial feasibility of using shelterbelts for swine odor mitigation, Agroforestry Systems 76 (2009) 237–250.
[46] United States Department of Agriculture Natural Resources Conservation Service, Rate for federal water projects. ⟨http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/econ/references/?&cid=nrcs143_009685⟩, 2012 (accessed 08.08.12).
[47] R.H. Van Note, P.V. Hebert, R.M. Patel, C. Chupek, L. Feldman, A Guide to the Selection of Cost-effective Wastewater Treatment System. ⟨http://nepis.epa.gov⟩, 1975 (accessed 08.08.12).
[48] D.B. Jaynes, J.L. Hatfield, D.W. Meek, Water quality in Walnut Creek Watershed: herbicides and nitrate in surface waters, Journal of Environmental Quality 28 (1999) 45–59.
[49] P.A. Lawlor, M.J. Helmers, J.L. Baker, S.W. Melvin, D.W. Lemke, Comparison of liquid swine manure and ammonia nitrogen application timing on subsurface drainage water quality in Iowa, Transactions of the ASABE 54 (2011) 973–981.
[50] United States Department of Agriculture Natural Resources Conservation Service (Iowa), Iowa Environmental Quality Incentives Program (EQIP) list of eligible practices and payment schedule FY2011. ⟨http://www.ia.nrcs.usda.gov/programs/eqip/FY2011%20Iowa%20EQIP%20Practice%20Descriptions%20and%20Payment%20Rates.pdf⟩, 2010 (accessed 08.08.12).
[51] S. Hyberg, Economics of CREP/CRP Treatment Wetlands for the Tile Drained Cropland in the Corn Belt. ⟨http://www.fsa.usda.gov/Internet/FSA_File/hyberg_iowa_wetlands.pdf⟩, 2007 (accessed 08.08.12).
[52] Iowa State University Extension, Cash rental rates for Iowa 2012 Survey File C2-10. http://www.extension.iastate.edu/agdm/wholefarm/pdf/c2-10.pdf, 2012 (accessed 08.08.12).
[53] T. Prato, Y. Wang, T. Haithcoat, C. Barnett, C. Fulcher, Converting hydric cropland to wetland in Missouri: a geoeconomic analysis, Journal of Soil and Water Conservation 50 (1995) 101–106.
[54] R. Iovanna, S. Hyberg, W. Crumpton, Treatment wetlands: cost-effective practice for intercepting nitrate before it reaches and adversely impacts surface waters, Journal of Soil and Water Conservation 63 (2008) 14A–15A.
[55] J. Sawyer, E. Nafziger, G. Randall, L. Bundy, G. Rehm, B. Joern, 2006. Concepts and Rationale for Regional Nitrogen Rate Guidelines for Corn (PM 2015), Iowa State University Extension.
[56] United States Department of Agriculture National Agricultural Statistics Service, Quick Stats 2.0. ⟨http://quickstats.nass.usda.gov/⟩, 2011 (accessed 08.08.12).
[57] D.B. Jaynes, D. Karlen, Sustaining Soil Resources While Managing Nutrients, in: Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop, ASABE, St. Joseph, MI149–158 (Chapter 11).
[58] United States Department of Agriculture Economic Research Service, Data Sets: Fertilizer use and Price. ⟨http://www.ers.usda.gov/Data/FertilizerUse/⟩, 2012 (accessed 08.08.12).
[59] R.M. Rejesus, R.H. Hornbaker, Economic and environmental evaluation of alternative pollution-reducing nitrogen management practices in central Illinois, Agriculture, Ecosystems and Environment 75 (1999) 41–53.
[60] G. Randall, 2008. Managing Nitrogen for Optimum Profit and Minimum Environmental Loss, in: Proceedings of Annual Integrated Crop Management Conference, Iowa State University, Ames, IA.
[61] G.W. Randall, J.A. Vetsch, J.R. Huffman, Corn production on a subsurface-drained mollisol as affected by time of nitrogen application and Nitrapyrin, Agronomy Journal 95 (2003) 1213–1219.
[62] J.A. Vetsch, G.W. Randall, Corn production as affected by nitrogen application timing and tillage, Agronomy Journal 96 (2004) 502–509.

[63] M.W. Clover, Impact of nitrogen management on corn grain yield and nitrogen loss on a tile drained field (M.S. thesis), University of Illinois at Urbana-Champaign, Urbana-Champaign, IL, 2005.
[64] G.W. Randall, J.A. Vetsch, Corn production on a subsurface-drained mollisol as affected by fall versus spring application of nitrogen and Nitrapyrin, Agronomy Journal 97 (2005) 472–478.
[65] J.W. Singer, Corn Belt assessment of cover crop management and preferences, Agronomy Journal 100 (2008) 1670–1672.
[66] J.S. Strock, P.M. Porter, M.P. Russelle, Cover cropping to reduce nitrate loss through subsurface drainage in the Northern U. S. Corn Belt, Journal of Environmental Quality 33 (2004) 1010–1016.
[67] J. Sawyer, J. Pantoja, D. Barker, Nitrogen fertilization of corn grown with a cover crop, Iowa State University Research Farm Report, , 2009 ⟨http://www.agronext.iastate.edu/soilfertility/info/2009CoverCrop-NFertilization.pdf⟩ (accessed 08.08.12).
[68] C. Pederson, R. Kanwar, M. Helmers, A. Mallarino, Impact of liquid swine manure application and cover crops on ground water quality, Iowa State University Northeast Research and Demonstration Farm Annual Report (RFR-A10111), 2010 ⟨http://www.ag.iastate.edu/farms/10reports/Northeast/ImpactLiquidSwine.pdf⟩ (accessed 08.08.12).
[69] J. Sawyer, J. Pantoja, D. Barker, Nitrogen fertilization of corn grown with a cover crop, Iowa State University Research Farm Report (RFR-A1064), 2010 ⟨http://www.ag.iastate.edu/farms/10reports/Northeast/ImpactLiquidSwine.pdf⟩ (accessed 08.08.12).
[70] Practical Farmers of Iowa, Cover Crop Effect on Cash Crop Yield: Year 2. ⟨http://www.practicalfarmers.org/assets/files/field_crops/cropping-systems/Cover_Crop_Effect_on_Yield.pdf⟩, 2011 (accessed 08.08.12).
[71] Z. Qi, M.J. Helmers, R.D. Christianson, C.H. Pederson, Nitrate-Nitrogen losses through subsurface drainage under various agricultural land covers, Journal of Environmental Quality 40 (2011) 1578–1585.
[72] Iowa State University Extension, Estimated costs of crop production in Iowa—2011 (including corn following corn, corn following soybeans, herbicide tolerant soybeans following corn, and alfalfa or alfalfa-grass hay). http://www.extension.iastate.edu/agdm/crops/html/a1-20.html, 2011 (accessed October 2011).
[73] M. Liebman, L.R. Gibson, D.N. Sundberg, A.H. Heggenstaller, P.R. Westerman, C.A. Chase, R.G. Hartzler, F.D. Menalled, A. S. Davis, P.M. Dixon, Agronomic and economic performance characteristics of conventional and low-external-input cropping systems in the central Corn Belt, Agronomy Journal 100 (2008) 600–610.
[74] D. Otto, Economic impacts of fall commercial nutrient regulation, Iowa State University Department of Economics. ⟨https://www.econ.iastate.edu/sites/default/files/publications/papers/p11215-2008-03-01.pdf⟩, 2008 (accessed 08.08.12).
[75] A. Saleh, E. Osei, D.B. Jaynes, B. Du, J.G. Arnold, Economic and environmental impacts of LSNT and cover crops for nitrate-nitrogen reduction in Walnut Creek watershed, Iowa, using FEM and enhanced SWAT models, Transactions of the ASABE 50 (2007) 1251–1259.
[76] L. Christianson, Design and performance of denitrification bioreactors for agricultural drainage (Ph.D. dissertation), Iowa State University, Ames, IA, 2011.
[77] J. Baker, 2009. The UMRSHNC Workshop: the Basis for the Cedar River Watershed Case Study, in: Proceedings of the Science to Solutions: Reducing Nutrient Export to the Gulf of Mexico, a Workshop for Managers, Policy Makers, and Scientists, Soil and Water Conservation Society, Ankeny, IA.
[78] D.B. Jaynes, K.R. Thorp, D.E. James, 2010. Potential Water Quality Impact of Drainage Water Management in the Midwest USA, Paper Number IDS-CSBE100084, in: Proceedings of the 9th International Drainage Symposium of the ASABE, ASABE, St. Joseph, MI.
[79] M.O. Ribaudo, R. Heimlich, R. Claassen, M. Peters, Least-cost management of nonpoint source pollution: source reduction versus interception strategies for controlling nitrogen loss in the Mississippi Basin, Ecological Economics 37 (2001) 183–197.
[80] L.A. Schipper, W.D. Robertson, A.J. Gold, D.B. Jaynes, S.C. Cameron, Denitrifying bioreactors—an approach for reducing nitrate loads to receiving waters, Ecological Engineering 36 (2010) 1532–1543.
[81] Iowa State University Extension, 2010 Iowa Farm Custom Rate Survey Ag Decision Maker. ⟨http://www.extension.iastate.edu/publications/fm1698.pdf⟩, 2010 (accessed October 2011).
[82] Prairie Land Management, CRP Mix—Seed Mix Pricing. http://www.habitatnow.com/store/shop/shop.php?pn_selected_category=37, 2005 (accessed 08.08.12).
[83] Iowa State University Extension, Natural Resources Custom Rate Survey Ag Decision Maker. http://www.extension.iastate.edu/agdm/crops/pdf/a3-11.pdf, 2009 (accessed 08.08.12).
[84] Ernst Conservation Seed, Seed mixes. ⟨http://www.ernstseed.com/seed-mixes/⟩, 2011 (accessed October 2011).
[85] Iowa State University Extension, 2010 Farmland value survey. ⟨http://www.extension.iastate.edu/agdm/wholefarm/html/c2-70.html⟩, 2011 (accessed October 2011).
[86] R.A. Cooke, G.R. Sands, L.C. Brown, Drainage water management: A practice for reducing nitrate loads from subsurface drainage systems, in: Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop, ASABE, St. Joseph, MI 19–28 (Chapter 2).
[87] V. Lalonde, C.A. Madramootoo, L. Trenholm, R.S. Broughton, Effects of controlled drainage on nitrate concentrations in subsurface drain discharge, Ag, Water Management 29 (1996) 187–199.
[88] C.F. Drury, C.S. Tan, J.D. Gaynor, T.O. Oloya, T.W. Welacky, Influence of controlled drainage-subirrigation on surface and tile drainage nitrate loss, Journal of Environmental Quality 25 (1996) 317–324.
[89] K.R. Thorp, D.B. Jaynes, R.W. Malone, Simulating the long-term performance of drainage water management across the Midwestern United States, Transactions of the ASABE 51 (2008) 961–976.
[90] W. Luo, G.R. Sands, M. Youssef, J.S. Strock, I. Song, D. Canelon, Modeling the impact of alternative drainage practices in the northern Corn-belt with DRAINMOD-NII, Ag, Water Management 97 (2010) 389–398.
[91] D.B. Jaynes, T.C. Kaspar, T.B. Moorman, T.B. Parkin, In situ bioreactors and deep drain-pipe installation to reduce nitrate losses in artificially drained fields, Journal of Environmental Quality 37 (2008) 429–436.
[92] K.P. Woli, M.B. David, R.A. Cooke, G.F. McIsaac, C.A. Mitchell, Nitrogen balance in and export from agricultural fields associated with controlled drainage systems and denitrifying bioreactors, Ecological Engineering 36 (2010) 1558–1566.
[93] J.A. Chun, R.A. Cooke, J.W. Eheart, J. Cho, Estimation of flow and transport parameters for woodchip-based bioreactors: II. field-scale bioreactor, Biosystems Engineering 105 (2010) 95–102.

[94] A. Ranaivoson, J. Moncrief, R. Venterea, M. Dittrich, Y. Chander, P. Rice, Bioreactor Performance In Minnesota. ⟨http://www.extension.umn.edu/AgDrainage/components/Ranaivoson.pdf⟩, 2010 (accessed 08.08.12).
[95] P.S. Miller, J.K. Mitchell, R.A. Cooke, B.A. Engel, A wetland to improve agricultural subsurface drainage water quality, Transactions of the ASAE 45 (2002) 1305–1317.
[96] G.W. Randall, J.A. Vetsch, J.R. Huffman, Nitrate losses in subsurface drainage from a corn–soybean rotation as affected by time of nitrogen application and use of Nitrapyrin, Journal of Environmental Quality 32 (2003) 1764–1772.
[97] G.W. Randall, J.A. Vetsch, Nitrate losses in subsurface drainage from a corn–soybean rotation as affected by fall and spring application of nitrogen and Nitrapyrin,, Journal of Environmental Quality 34 (2005) 590–597.
[98] D.B. Jaynes, T.S. Colvin, D.L. Karlen, C.A. Cambardella, D.W. Meek, Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate, Journal of Environmental Quality 30 (2001) 1305–1314.
[99] R.S. Kanwar, R.M. Cruse, M. Ghaffarzadeh, A. Bakhsh, D.L. Karlen, T.B. Bailey, Corn-soybean and alternative cropping systems effects on NO_3–N leaching losses in subsurface drainage water, Applied Engineering in Agriculture 21 (2005) 181–188.
[100] D.B. Jaynes, Personal communication, USDA ARS National Laboratory for Agriculture and the Environment, Ames, IA, USA (2011).
[101] Agri Drain Corp., Personal communication, Adair, IA, USA (2011).
[102] Iowa Soybean Association, Personal communication, Ankeny, IA, USA (2011).
[103] T. Kaspar, Personal communication, USDA ARS National Laboratory for Agriculture and the Environment, Ames, IA, USA (2011).

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Reductions in soil water nitrate beneath a perennial grain crop compared to an annual crop rotation on sandy soil

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Nitrate (NO_3^--N) leaching into groundwater as a result of high nitrogen (N) fertilizer rates to annual crops presents human health risks and high costs associated with water treatment. Leaching is a particularly serious concern on sandy soils overlying porous bedrock. Intermediate wheatgrass (IWG) [*Thinopyrum intermedium* (Host.) Barkw. & D.R. Dewey], is a perennial grass that is being bred to produce agronomically and economically viable grain, which is commercially available as Kernza®. Intermediate wheatgrass is a low-input crop has the potential to produce profitable grain and biomass yields while reducing NO_3^--N leaching on sandy soils compared with common annual row crop rotations in the Upper Midwest. We compared grain yields, biomass yields, soil solution NO_3^--N concentration, soil extractable NO_3^--N, soil water content, and root biomass under IWG and a conventionally managed corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation for 3 years on a Verndale sandy loam in Central Minnesota. Mean soil solution NO_3^--N was 77–96% lower under IWG than the annual crop rotation. Soil water content was greater under annuals compared to IWG early in the growing season, suggesting greater water use by IWG during this time. Interactions between crop treatments and depth were observed for soil water content in Year 3. Root biomass from 0 to 60 cm below the soil surface was five times greater beneath IWG compared to soybean, which may explain differences in soil extractable and solution NO_3^--N among crops. With irrigation on coarse structured soils, IWG grain yields were 854, 434, and 222 kg ha^{-1} for Years 1–3 and vegetative biomass averaged 4.65 Mg ha^{-1} yr^{-1}; comparable to other reports on heavier soils in the region. Annual crop grain yields were consistent with local averages. These results confirm that IWG effectively reduces soil solution NO_3^--N concentrations even on sandy soils, supporting its potential for broader adoption on land vulnerable to NO_3^--N leaching.

KEYWORDS

intermediate wheatgrass, nitrate, leaching, Kernza, groundwater, perennial grains

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Introduction

Water quality in the Upper Midwest is threatened by the intensive management practices used in annual cropping systems, including tillage and fertilizer application that lead to nutrient losses and water contamination through leaching and runoff (Randall and Mulla, 2001; Dinnes et al., 2002; Feyereisen et al., 2006; Erisman et al., 2013). While annual commodity crops like corn provide the potential for high economic return, nutrient losses cause eutrophication and hypoxia in surface waters and contamination of groundwater, posing significant risks to human health (Ward et al., 2010, 2018; Brender et al., 2013). Impacts are often high where shallow aquifers and sandy soils make drinking water sources vulnerable to contamination. This leads to additional water treatment costs of over $5 million for some counties (Keeler et al., 2016). In Southeast Minnesota, for example, conversion of grassland to agriculture is expected to cause a 45% increase in private wells exceeding 10 ppm NO_3^--N, resulting in between $700,000 and $12,000,000 in associated costs over a 20-year period (Keeler and Polasky, 2014). New alternative cropping systems that provide economic returns comparable to those of annual systems and which effectively reduce nutrient losses will be essential for protecting drinking water sources in the future.

Replacing annual crops with perennials has the potential to help reduce NO_3^- leaching to groundwater and provide other ecosystem services (Asbjornsen et al., 2014; Ferchaud and Mary, 2016). Cropping systems that include perennial grasses for conservation, forage, and biofuel production have lower NO_3^- leaching losses than corn-soybean systems, largely because perennial grasses have greater root biomass that extends deeper into the soil, increasing N recovery and reducing leaching (Culman et al., 2013b; Pugesgaard et al., 2015; Ferchaud and Mary, 2016). Deep roots may be particularly important in reducing NO_3^- leaching since they can expand the total volume of soil from which NO_3^--N is taken up, and because NO_3^- is highly mobile and more prone to leaching from deep soil horizons (Maeght et al., 2013). NO_3^- losses in the subsurface drainage water for a corn-soybean system were about 37 times higher than from a Conservation Reserve Program (CRP) planting dominated by perennial grasses (Randall et al., 1997). This reduction was attributed to the greater season-long evapotranspiration (ET) that resulted in less drainage and greater uptake and/or immobilization of N. In that study, average NO_3^- concentrations in the water during the flow period were 24 mg/L for the corn-soybean rotation and 2 mg/L for the perennial grass CRP (Randall et al., 1997). Although plantings that include perennial grasses are effective at reducing NO_3^- leaching, a lack of economic return has prevented their large-scale adoption in Midwestern agricultural landscapes.

Intermediate wheatgrass (IWG), [*Thinopyrum intermedium* (Host.) Barkw. & D.R. Dewey] is a perennial cool-season grass being domesticated to produce a grain marketed as Kernza® (DeHaan et al., 2018) with the first commercial variety, "MN-Clearwater," released in 2020 (Bajgain et al., 2020). The crop has potential to provide economic return for producers (Hunter et al., 2020a,b; Law et al., 2022) while reducing NO_3^- leaching compared to corn (Jungers et al., 2019). Intermediate wheatgrass initiates growth earlier in the season than warm-season forage and bioenergy grasses and is thus better able to reduce NO_3^--N losses early in the season (Jungers et al., 2019) when losses are typically the highest in the Upper Midwest (Randall and Mulla, 2001; Crews and Peoples, 2005). Vegetative regrowth following IWG grain harvest helps reduce post-harvest nitrate losses and erosion late into the fall.

One potential mechanism by which IWG can reduce NO_3^- leaching compared to annual crops is related to water demand. Although total growing season ET and drainage were similar between IWG and corn, soil water content was lower under IWG compared to corn and switchgrass at 50 and 100 cm depths (Jungers et al., 2019), suggesting that soil moisture may be stored in other regions of the soil profile. Compared to annual wheat (*Triticum aestivum* L.), IWG had lower soil moisture up to a depth of 70–100 cm, which was associated with NO_3^--N leaching reductions of up to 86% (Culman et al., 2013b). The distribution of IWG root biomass and its effects on soil water content throughout the soil profile are largely unknown.

Reductions in NO_3^- leaching beneath IWG compared to annual crops can also be related to differences in nitrogen fertilization regimes and associated losses of N in the form of soluble NO_3^--N in the soil water. Soil solution NO_3^- increased from 0.1 to 0.3 mg L^{-1} when IWG was fertilized with 120 kg N ha^{-1} compared to an unfertilized control, yet this was still lower than the 24.0 mg L^{-1} measured beneath corn fertilized at 160 kg ha^{-1} (Jungers et al., 2019). Integrating legumes such as soybean into annual crop rotations can limit N fertilizing needs, yet the effects of legume crops in rotation on NO_3^--N leaching compared to IWG are unknown.

Our objective was to assess the potential of IWG grain production to reduce NO_3^--N leaching compared to an annual soybean-corn-soybean rotation on irrigated sandy soil by measuring soil solution NO_3^--N concentration and soil water content. We hypothesized that soil water NO_3^--N concentrations and soil water content would be lower under IWG, and that this would be related to increased root biomass and rooting depth of IWG compared to corn and soybean. Crop yields and vegetative biomass were measured to assess potential profitability.

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TABLE 1 Average air temperature, precipitation, irrigation, and 30-year averages for each month of the growing season in Staples, MN.

	Mean monthly air temperature (°C)				Monthly and season total precipitation (P) and irrigation (I) (mm)						
	2018	2019	2020	30-year avg.	2018		2019		2020		30-year avg.
					P	I	P	I	P	I	P
April	2	5	3	5	4.6	0	25.7	0	22.4	0	36.8
May	17	11	12	12	62.8	0	62.5	0	33.8	0	72.9
June	20	18	21	18	78.3	12.7	68.4	12.7	57.2	25.4	117.3
July	21	21	22	20	62.5	38.1	103.2	63.5	102.7	38.1	99.1
Aug.	19	18	20	19	66.6	38.1	93.8	12.7	158.6	38.1	74.4
Sept.	14	15	14	15	73.7	0	106.3	0	16	0	71.1
Oct.	4	5	3	7	80.0	0	92.3	0	10.9	0	56.6
					428.5	88.9	552.2	88.9	401.6	101.6	528.2

Methods

Site description

Field research was conducted from 2018 to 2020 at the Central Lakes Community College in Staples, MN, USA (lat. 46.38, long. −94.80). The soil type was a Verndale sandy loam (Typic Argiudoll). The soil contains 1–1.7% organic matter, is excessively well-drained, and is considered low fertility potential (USDA-NRCS, 2021). Local climate data are reported in Table 1. Plots had previously been planted to a corn-soybean rotation followed by barley fertilized with 40 kg N ha^{-1} applied in spring prior to IWG planting in 2017. Baseline soil samples from 0 to 30 cm were collected by block in the fall of 2017. Soil extractable nitrogen was 10.0 mg kg $soil^{-1}$ for NO_3^--N and 3.9 mg kg $soil^{-1}$ for ammonium (NH_4^+-N). Soil phosphorus (P) and potassium (K) concentrations were 9.13 and 72.21 ppm, respectively.

Experimental design

Treatments were applied in a randomized block design with two cropping systems replicated once in each of six blocks for a total of twelve plots. Plots were 4.11 by 9.14 m (13.5 by 30 ft.). The annual cropping system was a soybean-corn-soybean rotation. The perennial system was IWG. Soybeans were planted as the first phase of the soybean-corn rotation in May 2018, followed by corn in May 2019 and soybean again as the third phase in June 2020. Corn and soybeans were seeded in 75 cm rows at rates of 346,000 and 84,000 seeds ha^{-1}, respectively, with four rows per plot. The corn variety was Organic Viking O.84-95UP Seed Corn and the soybean was Organic MN0810CN.

An improved population of IWG bred for increased grain yield was used in this study. The population came from the fourth cycle of selection by Land Institute (Salina, KS) and was seeded at a rate of 15 kg ha^{-1}. The IWG was seeded in 15-cm rows with 20 rows per plot on 20 August 2017. Intermediate wheatgrass was fertilized with urea at rates of 80, 100, and 100 kg N ha^{-1} in May 2018, 2019, and 2020, respectively. Urea was split-applied to corn at 140 and 80 kg Nha^{-1} in May and June 2019. Soybean was not fertilized. Weed pressure was low and when present, weeds were manually removed in all plots. The experiment was irrigated with a linear irrigation system with events based on ET estimates and water demand for the annual crop. The fields received 89 mm of irrigation water over five events in 2018, 89 mm over seven events in 2019, and 102 mm over eight events in 2020. Dates of irrigation events are in Figure 1. Each individual irrigation event resulted in an application of 13 mm of water with the exception of 7/16/2018 and 8/22/2018, which received 25 mm.

Soil fertility and extractable N

Soil was sampled at four depth intervals (0–15, 15–30, 30–45, and 45–60 cm) in June 2019 and October 2020 and analyzed for organic matter, K, P, pH, and extractable NO_3^--N and NH_4^+-N. Samples were taken from eight cores in each plot and aggregated by depth, stored in a cooler when transported, and kept refrigerated until analyzed or processed for shipping. All soil analyses except extractable N were conducted by Agvise Laboratories (Benson, MN; www.agvise.com). Agvise samples were oven-dried prior to shipping. Soil extractable N was determined by extraction with a 2 M KCl solution, where 40 ml solution was added to 10 g fresh soil followed by 1 h shaking (Culman et al., 2013a). Extractions were performed within 48 h of field collection. NO_3^--N and NH_4^+ analyses of the extractions were performed at the UMN Research Analytical Lab. Method details can be found at http://ral.cfans.umn.edu/tests-analysis/soil-analysis.

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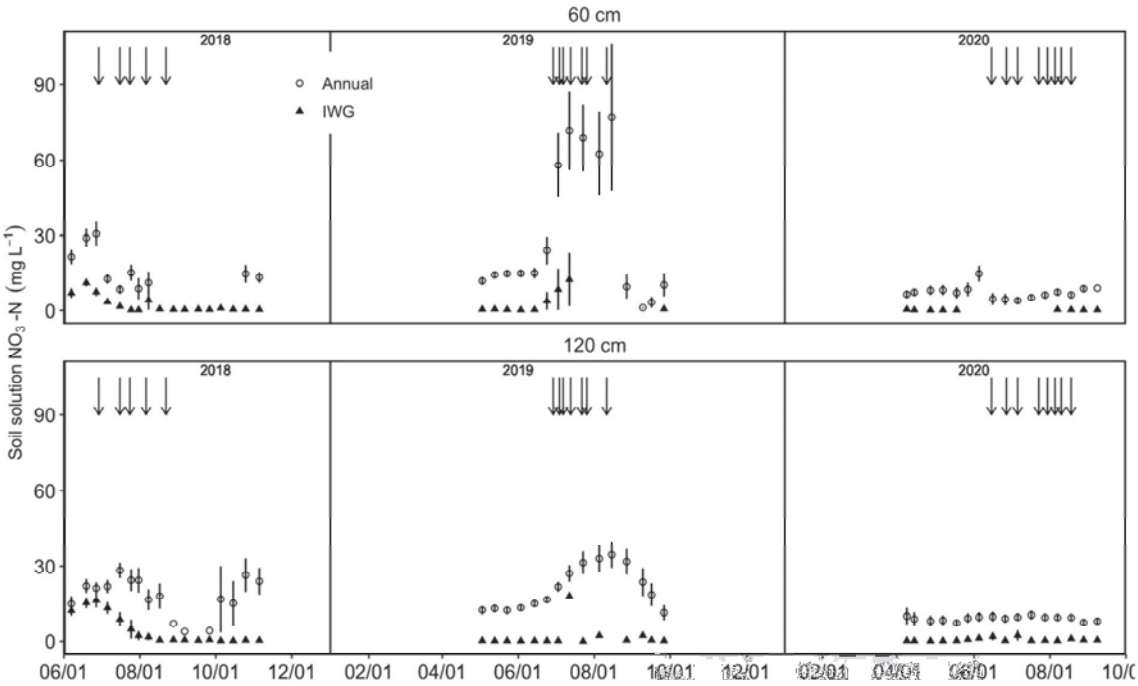

FIGURE 1
Mean soil solution NO_3^--N from lysimeters 60 and 120 cm below annual crops (soybean in 2018 and 2020, corn in 2019) and intermediate wheatgrass (IWG) sampled during the growing season in 2018, 2019, and 2020. Points are means from two lysimeters per treatment replicate and six replicates ($n = 12$), while error bars indicate standard error of the mean. Arrows indicate dates of irrigation events.

Crop yields

Crop yields were estimated each year from 2018 to 2020. Samples were taken in August of each year when the IWG had reached physiological maturity from two 76 by 76 cm quadrats with a total area of 0.58 m^2. Seed heads were removed from all IWG plants within the quadrat by cutting approximately 2 cm below the basal spikelet. After seed heads were removed, all remaining IWG biomass was harvested to an 8 cm stubble height. The remaining biomass was mechanically harvested and removed from the plots following quadrat sampling.

Biomass and seed heads were dried at 35°C for 72 h or until constant mass before being weighed. Grain was removed from spikes using a Wintersteiger LD 350 laboratory thresher (Wintersteiger; www.wintersteiger.com/us/Plant-Breeding-and-Research). Grain was separated from the chaff and other debris by hand-sieving and with a fractionating aspirator (Carter-Day International, Inc.; http://www.carterday.com).

Corn and soybean yields were determined by harvesting a subsection of the middle two rows of each plot. For corn, two 2-m sections of rows were cut from each corn plot. The number of corn stalks cut was recorded for each plot. All ears from the cut stalks were collected, dried (35°C for 72 h), shelled, and both cobs and kernels were weighed. Three stalks from each row section were randomly selected, dried, and weighed to estimate stover mass. Soybean yields were determined by harvesting whole plants from two 1-m sections of rows from each plot, followed by drying, threshing, and weighing. Following harvest for yield measurement, the remaining corn and soybean plants were mechanically harvested and removed from the plots.

Root biomass

Root biomass samples were taken in September 2020 with two 5-cm diameter manual push cores per plot at depths of 0–15, 15–30, 30–45, and 45–60 cm. Roots were separated from soil and debris using a hydropneumatic elutriation system (Smucker et al., 1982), then removed manually from sieves using tweezers. Due to the difficulty of distinguishing live from dead roots, no effort was made to separate them. Roots were dried at 35°C for 72 h. Samples were checked after drying for any remaining sand and debris, which was removed before weighing.

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Soil solution NO_3^--N concentration

Soil solution NO_3^--N concentrations were determined by collecting soil solution samples with suction lysimeters. Lysimeters consisted of a porous ceramic end cap, a PVC tube, and an airtight rubber stopper (Jungers et al., 2019). Two pairs of 60 and 120 cm lysimeters were installed in each plot. Samples were collected every 7–10 days from April to October each year and analyzed by depth for soil solution NO_3^--N concentration using a colorimetric assay with a HACH DR 6000 spectrophotometer (Hach, https://www.hach.com).

Soil water content

Soil water content was measured on four dates in 2019 (June 17, July 19, August 21, October 31) and six dates in 2020 (May 12, June 23, July 15, August 5, September 1, and September 25) at 10, 20, 30, 40, 60, and 100 cm using a Delta-T Devices PR2/6 Probe (Delta-T Devices, 2021).

Statistical analysis

Analysis of variance (ANOVA) was conducted using mixed effects models to explain variation in soil water NO_3^--N concentration, soil water content, soil extractable NO_3^--N, root biomass, and crop yields. Predictor variables for the ANOVA were cropping system, depth (for soil variables), and their interaction. Years were analyzed separately because the annual crop varied. Cropping system was treated as a categorical variable; depth was treated as a categorical variable for root biomass and soil extractable NO_3^--N. Soil solution NO_3^--N concentrations from the 60 and 120 cm depths were not statistically different, based on preliminary statistics, and thus were averaged for the analysis. The treatment applied to the nearest neighboring plot was included in the model as a covariate to account for possible lateral movement of N applied to the neighboring plot. Data were analyzed with block as a random effect. For the soil solution NO_3^--N, which included two pairs of lysimeters per plot, plot was nested within block in the random effects structure. An autoregressive 1 correlation structure was fit to the model to account for temporal correlation in sample results within each plot. Analysis of variance was used to explain variation in soil water content for each sampling date, with a model including treatment, depth, and their interaction. Total water content from 0 to 100 cm was calculated for each plot and date using trapezoidal integration (Hupet et al., 2004) and compared among treatments using ANOVA. Mean comparisons using Tukey's adjusted *P*-value were used to generate estimated means for effects. Statistical analysis was carried out using statistical software program R (Version 3.5.2 GUI 1.70) including *emmeans* and *nlme* packages (R Core Team, 2018; Length, 2019; Pinheiro et al., 2019).

Results

Soil solution NO_3^--N concentration

Annual average soil solution NO_3^--N concentration differed by cropping system treatment in 2018 ($P < 0.001$), 2019 ($P = 0.004$), and 2020 ($P = 0.003$; Table 2; Figure 1), but did not vary by sampling depth or show an interaction effect in any year ($P > 0.05$). The average soil solution NO_3^--N concentration was 77%, 96%, and 96% lower in the perennial system than the annual system in Years 1–3, respectively (Table 2).

Throughout the seasons, both intra- and inter-annual variation was observed (Figure 1). Soil solution NO_3^--N concentrations under IWG initially had mean values between 10 and 20 mg L^{-1} in Year 1 but declined to nearly zero by the end of July 2018 and remained at those levels for all 3 years except for occasional deviations. In 2018, soil solution NO_3^--N concentrations under soybean were initially high at levels above 20 mg L^{-1}, declining to near zero in mid-September, but increasing to early season levels after harvest. In 2019, however, soil solution NO_3^--N concentrations under corn were between 10 and 20 mg L^{-1} but spiked to levels over twice that between late June and late August. Concentrations slowly declined over the remainder of the year. In 2020, mean soil solution NO_3^--N concentrations under soybean were consistently around 10 mg L^{-1}.

Soil extractable NO_3^--N

There was an effect of cropping system treatment, depth, and a depth by treatment interaction (*p*-values < 0.001) on soil extractable NO_3^--N measured at the end of the study in 2020 (Table 3). Soil NO_3^--N was greater in the annual cropping system compared to IWG at 0–15, 15–30, and 30–45 cm depths at the end of the study ($P < 0.001$), but extractable NO_3^--N levels were similar among treatments at the 45–60 cm depth. Soil extractable NO_3^--N was greatest at the 0–15 cm depth below the annual crops and decreased with each depth interval until 45–60 cm, which was similar to the 30–45 cm depth interval. There was no difference in soil extractable NO_3^--N across depths beneath the IWG.

Root biomass

Root biomass collected at the end of the study in 2020 was affected by treatment ($P = 0.006$), depth ($P < 0.001$), and a treatment by depth interaction ($P < 0.001$). Root biomass was

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TABLE 2 Average soil solution NO_3^--N, grain, and biomass yields in the annual and IWG systems in 2018, 2019, and 2020.

	2018		2019		2020	
	Annual	IWG	Annual	IWG	Annual	IWG
Soil solution NO_3^--N (mg L^{-1})	19.0a	4.3b	22.1a	0.8b	7.8a	0.3b
Grain yield (Mg ha^{-1})	3.05a	0.85b	7.33a	0.43b	1.98a	0.22b
Biomass yield (Mg ha^{-1})	2.43b	4.12a	5.85	5.41	2.86b	4.41a

Crops in the annual system were soybean, corn and soybean in 2018, 2019, and 2020, respectively. Soil solution NO_3^--N were averaged across depths. Lower-case letters denote statistical significance between treatments at $P < 0.05$ within each year.

TABLE 3 Mean root biomass and soil extractable nitrate (mg NO_3^--N kg $soil^{-1}$) at four depth intervals from 0 to 60 cm at the end of the study in 2020.

	Root biomass (Mg ha^{-1})		Soil extractable nitrate (mg NO_3^--N kg $soil^{-1}$)	
	Annual	IWG	Annual	IWG
0–15	1.69b	8.57aA	2.77aA	0.17b
15–30	0.42b	2.82aB	1.38aB	0.00b
30–45	0.25	1.30B	0.48aC	0.00b
45–60	0.17	1.03B	0.25C	0.00

Letters denote statistical significance at $P < 0.05$; lower-case indicates difference between treatments; upper-case indicates difference between depths.

greater under IWG compared to the annual cropping system at all depths (Table 3). Soybean root biomass was 80%, 85%, 81%, and 83% lower than IWG root biomass at 0–15, 15–30, 30–45, and 45–60 cm, respectively. Summed over all the depths, total IWG root biomass was 13.73 Mg ha^{-1} while soybean root biomass was 2.54 Mg ha^{-1}, 82% lower ($P < 0.001$).

Crop yield

Grain yield was higher for the annual crops than for IWG in all years ($P < 0.001$, Table 2). Intermediate wheatgrass vegetative biomass yields (Table 2) were higher than soybean in 2018 ($P = 0.001$) and 2020 ($P = 0.009$) but similar to corn in 2019 ($P = 0.322$).

Soil water content

Of the four dates when soil water content was measured in 2019, there were very few effects of treatment, depth, or an interaction. Dates had a significant treatment by depth interaction. There was a main effect of cropping system treatment on soil water content on July 19 and October 31 ($P < 0.001$), in which soil water content was greater beneath the annual cropping system (0.09 m m^{-3}) compared to the perennial (0.03 m m^{-3}) on July 19 but lower in the annual (0.04 m m^{-3}) compared to the perennial (0.05 m m^{-3}) on October 31, 2019. In 2020, soil water content varied by treatment on June 23 ($P < 0.001$), in which soil water content was greater beneath the annual compared to the perennial. There was a significant interaction between treatment and depth on three other dates in 2020. Soil water content by treatment and depth is shown in Figure 2 to illustrate the interaction.

Discussion

Soil solution NO_3^--N concentration

Consistent with previous findings, we observed drastically lower concentrations of soil solution NO_3^--N beneath IWG compared to the annual cropping system (Figure 1). Concentrations under IWG were initially between 10 and 20 mg L^{-1} during June and July of 2018, the first spring after seeding, but approached zero by August and remained very low for the duration of the experiment. A previous study in Minnesota found that soil solution NO_3^--N beneath IWG averaged 0.09–0.3 mg L^{-1} when fertilized with 80 kg N ha^{-1} (Jungers et al., 2019). Despite only receiving 20 kg N ha^{-1} more fertilizer annually in this study, annual average soil solution NO_3^--N concentrations ranged from 4.3 mg L^{-1} in the first-year to 0.3 mg L^{-1} at the end of the study. Higher NO_3^--N concentrations found in this study compared to previous finding in Minnesota could be related to the potentially higher drainage rate associated with coarse structured soil at our study. These relatively higher soil solution NO_3^--N levels observed in the first-year of our study were also likely attributable to lower root biomass during stand establishment and thus reduced ability to capture and assimilate soil solution NO_3^--N. In line with this thinking, our results were similar to a study on sandy soil in

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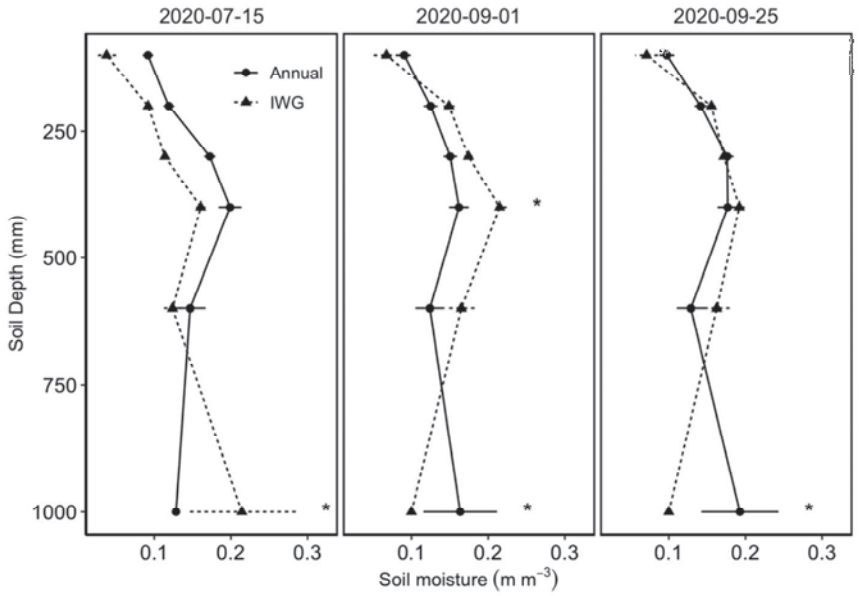

FIGURE 2
Soil water content beneath soybean (annual) and intermediate wheatgrass (IWG) on days when there was a significant interaction between cropping system treatment and depth. Asterisks indicate depths for which soil water content differed significantly between cropping systems.

Michigan during stand establishment (Culman et al., 2013b). Despite the slightly higher soil solution NO_3^--N concentrations observed in Year 1 here and on other sandy soils, values were comparable to mixtures of perennial grasses and forbs found in CRP plantings (Randall et al., 1997) and consistently below the EPA safe drinking standard of 10 mg L^{-1}.

Average annual soil solution NO_3^--N concentrations beneath the annual crops were similar to or slightly lower than those reported by other studies in Minnesota. During the corn phase of the annual rotation, our annual soil solution NO_3^--N of 22.1 mg L^{-1} was similar to findings by Ochsner et al. (2017), who reported an average soil solution NO_3^--N of 21.2 mg L^{-1} beneath a corn-soybean rotation with corn phases fertilized at 146 kg N ha^{-1} as urea annually. In another study also conducted on coarse-structured soils in Minnesota, Struffert et al. (2016) reported an average annual soil solution NO_3^--N concentration of 18.8 mg L^{-1} beneath soybean, and determined that soil solution NO_3^--N during the soybean phase was not affected by N fertilizer rates applied to corn the previous year.

This is also among the first studies to compare soil solution NO_3^--N levels of fertilized IWG to an unfertilized legume crop. Despite applying 100 kg N ha^{-1} of urea annually to the IWG, lower soil solution NO_3^--N concentration were observed in the IWG compared to the unfertilized soybean. Biologically fixed N may have been mineralized after exudation or sloughing of soybean roots, which may have contributed to higher soil solution NO_3^--N levels compared to IWG. The elevated soil solution NO_3^--N in the soybean could also have originated from N fertilizer applied during the previous crops. However, as previously mentioned, N fertilizer rates applied to a previous corn crop did not affect soil solution NO_3^--N beneath subsequent soybean (Struffert et al., 2016). Significant N demand by IWG may have also contributed to the large difference in soil solution NO_3^--N.

Soil extractable NO_3^--N

In addition to lower soil solution NO_3^--N concentration, we also found less extractable NO_3^--N in the soil after 3 years of IWG production compared to the annual rotation system. This suggests that the IWG assimilated NO_3^- more thoroughly from the soil than the annual rotation system, especially because the Year 3 crop was unfertilized soybean. Extractable NO_3^--N remaining in the soil is a major factor determining the concentration of dissolved NO_3^--N in soil solution, which in turn determines total leaching loads (Randall and Mulla, 2001; Culman et al., 2013a; Jungers et al., 2019).

The low levels of extractable NO_3^--N under IWG also suggest that the plants may have been N-limited, despite being fertilized at the high end of optimal rates (Jungers et al., 2017). Nitrogen removal during IWG grain and biomass harvest can exceed 150 kg N ha^{-1} in the first-year of production (Crews

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et al., 2022; Tautges et al., 2018). Intermediate wheatgrass tissue N concentrations at the time of grain harvest in Minnesota peaked above 10 g N kg^{-1} biomass and declined with stand age (Jungers et al., 2017). If tissue N concentrations were similar to previous studies in MN, removal rates could have been between 46 and 58 kg N ha^{-1} $year^{-1}$, thus less than the N applied as fertilizer (100 kg N ha^{-1}). However, total N demand may have been greater to support root biomass production. If root tissue N was similar to previously reported estimates between 9 and 11 g N kg^{-1} (Dobbratz, 2019), then there would be another pool of nearly 130 kg N ha^{-1} in belowground root tissues. It is not known what fraction of root N is recycled during root death and mineralization of root biomass from year to year in an IWG system, but our results suggest that the N fertilizer applied was needed to support above and belowground IWG biomass and that little N was likely lost *via* leaching or left in the soil.

Root biomass

Root biomass is considered an important trait of perennial crops for providing ecosystem services such as reduced nitrate leaching to groundwater. Intermediate wheatgrass root biomass averaged 13.7 Mg ha^{-1} after the third-year of production, while soybean root biomass was 2.5 Mg ha^{-1} when sampled from 0 to 60 cm. These values are similar to other reported values for these crops. For example, Intermediate wheatgrass fertilized at 80 kg N ha^{-1} had root biomass of 4.10, 7.32, and 9.51 Mg ha^{-1} (0–60 cm depth) in Years 1–3 of a 3-year study, while a soybean-corn-soybean rotation had root biomass of 2.22, 2.93, and 2.30 Mg ha^{-1} in Years 1–3 (Bergquist, 2019). Root biomass accumulation over time allows IWG to more effectively capture NO_3^--N before it reaches depths below the rooting zone where it is subject to leaching to groundwater. Nearly 63% of the IWG root biomass was found in the top 0–15 cm depth. Previous work has reported IWG belowground biomass to be 3.28 Mg ha^{-1} in the first 10 cm, on average, in Minnesota and Wisconsin (Sakiroglu et al., 2020). In an intra-annual study of root biomass beneath IWG, total root biomass from 0 to 20 cm peaked between 3.5 and 4 Mg ha^{-1} in June and July before declining to 1 Mg ha^{-1} at the end of the growing season (Pugliese et al., 2019). This concentration of root biomass at shallow depths also likely increases NO_3^--N capture and consequently reduce soil solution NO_3^--N below the rooting zone.

Soil water content

We found inconsistent differences in soil water content between annual crops and IWG. In the second-year of the study, soil water content was greater beneath the corn compared to the IWG in July, perhaps because IWG biomass would have been approaching peak biomass and thus been demanding more water than corn. A similar early-season pattern was found in Year 3 when soil water content was greater beneath the soybean compared to the IWG when measured in June. By the end of Year 2 (October), soil water content was greater in IWG compared to corn. Only in Year 3 did we observe any differences in soil water content by depth across treatments (Figure 2). In July, soil water content was greater beneath IWG compared to soybean at the deepest measured depth of 1,000 mm. This treatment effect was opposite at the 1,000 mm depth in September, where soil moisture content was greater for the soybean compared to IWG. Our results do match those from previous studies. In one comparison of perennial and annual systems, soil water content beneath *Miscanthus* and switchgrass was lower than a corn-soybean rotation earlier in the season, but the treatment effect flipped later in the season when switchgrass had higher soil water content (McIsaac et al., 2010). It has also been observed that soil water content tended to be higher under annuals than semi-perennials, and that there was less drainage from semi-perennials and perennials than annuals (Ferchaud and Mary, 2016). In studies with IWG, researchers have reported less in soil water content under IWG compared to annual wheat (Culman et al., 2013b) and corn (Jungers et al., 2019).

Soil water content can be used to make inferences on transpiration and drainage, the latter being an important component of nitrate leaching. The timing and frequency of our soil water content measurements precluded us from determining if both treatments had similar ET and drainage rates. Irrigation at our experiment could also have minimized our ability to detect differences in soil water content from plant ET. It is also established that greater root biomass increases water and nutrient uptake, which could reduce soil water content (Ehdaie et al., 2010; Matsunami et al., 2012; Carvalho et al., 2014). In our study, the similar soil moisture contents observed in the perennial and annual treatments may have been a function of the low water holding capacity of the sandy soil, which may have promoted drainage regardless of root biomass.

Grain and biomass yields

Intermediate wheatgrass grain yields at our sandy site were comparable to previous reports from sites with higher soil fertility levels. Under similar fertilizer treatments, reported first-year values range from 763 kg ha^{-1} (Zimbric et al., 2020) to 1,089 kg ha^{-1} at sites in Wisconsin (Favre et al., 2019) and from 893 kg ha^{-1} (Jungers et al., 2017) to 1,150 kg ha^{-1} (Fernandez et al., 2020) in Minnesota. Second- and third-year yields tend to be much lower, typically ranging from 150 kg ha^{-1} (Fernandez et al., 2020) to 630 kg ha^{-1} (Sakiroglu et al., 2020) in Year 2 and from 153 kg ha^{-1} (Jungers et al., 2017) to 371 kg ha^{-1} (Zimbric et al., 2020) in Year 3. Our yields suggest that this soil type and climate is appropriate for IWG grain and biomass production with irrigation.

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Forage production is important for profitable IWG systems, since a major challenge of IWG grain production is the substantial yield declines in later years of production (Jungers et al., 2017; Pugliese et al., 2019; Hunter et al., 2020a). Intermediate wheatgrass biomass yields in this study included the stems and leaves that were remaining after grain harvest soon after peak productivity. Biomass harvested at this time, after physiological maturity, is relatively low in terms of forage quality compared to IWG biomass harvested at vegetative stages, but high compared to annual small grain biomass after grain harvest (Hunter et al., 2020b). Intermediate wheatgrass biomass yields were similar to those of other reports in Minnesota, though they were at the lower end of the range. Reported summer aboveground biomass values include 5,130 kg ha^{-1} in the second-year and 5,850 kg ha^{-1} in the third-year for IWG fertilized at 90 and 134 kg ha^{-1} in Wisconsin and 10,600 kg ha^{-1} for third-year stands in Minnesota (Sakiroglu et al., 2020). Similarly, summer yields of approximately 6,200 kg ha^{-1} were reported for first-year monocultures fertilized at 100 kg N ha^{-1} as urea (Favre et al., 2019). Biomass yields averaged 13,400 to 14,320 kg ha^{-1} for control treatments in a management study fertilized at 56 kg ha^{-1} the previous year (Pinto et al., 2021). Our results support that understanding that post-grain harvest biomass yields can be high enough for growers to consider harvesting for used as feed or straw on the farm or marketed for an additional revenue stream.

Conclusion

We found that soil solution NO_3^--N concentrations were 77–96% lower under IWG than the annual corn-soybean rotation, even in the unfertilized soybean phase of rotation, but soil water content was similar. This suggests that the IWG captured and utilized a greater proportion of soil solution NO_3^--N, which is also demonstrated by very low residual soil extractable NO_3^--N levels at the end of the experiment relative to the annual crops. The lower NO_3^--N concentrations in soil solution would be expected to translate to reductions in total leaching load of a similar magnitude. The increased uptake of N by IWG was likely facilitated by its greater root biomass, which was 5.4 times higher than that under the annual system. Despite the challenges associated with production of IWG on low-fertility sandy soils, grain yields were comparable to other locations and the system would likely be profitable in the first-year for grain alone. Biomass yields would support additional revenue streams in subsequent years to improve economic viability, and together our study provides evidence that IWG could be a good option for coarse textured soils that are prone to nitrate pollution.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ER: collected data, analyzed data, wrote the first draft of the manuscript, and contributed to the final draft of the manuscript. JG: oversaw soil sample processing and contributed to the final draft of the manuscript. CS: designed the field experiment and contributed to the final draft of the manuscript. JJ: acquired funding, designed the field experiment, oversaw field sampling and data collection, data visualization, and contributed to the final draft of the manuscript. All authors contributed to data interpretation, manuscript writing, and revision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Asbjornsen, H., Hernandez-Santana, V., Liebman, M., Bayala, J., Chen, J., Helmers, M., et al. (2014). Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renew. Agric. Food Syst.* 29, 101–125. doi: 10.1017/S1742170512000385

Bajgain, P., Zhang, X., Jungers, J. M., DeHaan, L. R., Heim, B., Sheaffer, C. C., et al. (2020). 'MN-Clearwater', the first food-grade intermediate wheatgrass (Kernza perennial grain) cultivar. *J. Plant Regist.* 14, 288–297. doi: 10.1002/plr2.20042

Bergquist, G. (2019). Biomass Yield and Soil Microbial Response to Management of Perennial Intermediate Wheatgrass (Thinopyrum *intermedium*) as Grain Crop and Carbon Sink. Master's Theses, University of Minnesota.

Brender, J. D., Weyer, P. J., Romitti, P. A., Mohanty, B. P., Shinde, M. U., Vuong, A. M., et al. (2013). Prenatal nitrate intake from drinking water and selected birth defects in offspring of participants in the national birth defects prevention study. *Environ. Health Perspect.* 121, 1083–1089. doi: 10.1289/ehp.1206249

Carvalho, P., Azam-Ali, S., and Foulkes, M. J. (2014). Quantifying relationships between rooting traits and water uptake under drought in Mediterranean barley and durum wheat: root traits and water uptake. *J. Integr. Plant Biol.* 56, 455–469. doi: 10.1111/jipb.12109

Crews, T. E., Kemp, L., Bowden, J. H., and Murrell, E. G. (2022). How the nitrogen economy of a perennial cereal-legume intercrop affects productivity: can synchrony be achieved? *Front. Sustain. Food Syst.* 6:755548. doi: 10.3389/fsufs.2022.755548

Crews, T. E., and Peoples, M. B. (2005). Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review. *Nutr. Cycl. Agroecosystems* 72, 101–120. doi: 10.1007/s10705-004-6480-1

Culman, S. W., Snapp, S. S., Green, J. M., and Gentry, L. E. (2013a). Short- and long-term labile soil carbon and nitrogen dynamics reflect management and predict corn agronomic performance. *Agron. J.* 105, 493–502. doi: 10.2134/agronj2012.0382

Culman, S. W., Snapp, S. S., Ollenburger, M., Basso, B., and DeHaan, L. R. (2013b). Soil and water quality rapidly responds to the perennial grain Kernza wheatgrass. *Agron. J.* 105, 735–744. doi: 10.2134/agronj2012.0273

DeHaan, L., Christians, M., Crain, J., and Poland, J. (2018). Development and evolution of an intermediate wheatgrass domestication program. *Sustainability* 10:1499. doi: 10.3390/su10051499

Delta-T Devices (2021). *PR2 Profile Probe - Analogue Version*. Cambridge, UK. Available online at: www.delta-t.co.uk/product/pr2/

Dinnes, D. L., Karlen, D. L., Jaynes, D. B., Kaspar, T. C., Hatfield, J. L., Colvin, T. S., et al. (2002). Review and interpretation: nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron. J.* 94, 153–171. doi: 10.2134/agronj2002.1530

Dobbratz, M. (2019). *Perennial fuel, feed, and cereal: High diversity perennials for biofuel and intermediate wheatgrass for grain and forage.* PhD Dissertation retrieved from University of Minnesota Digital Conservancy. Available online at: https://hdl.handle.net/11299/211748

Ehdaie, B., Merhaut, D. J., Ahmadian, S., Hoops, A. C., Khuong, T., Layne, A. P., et al. (2010). Root system size influences water-nutrient uptake and nitrate leaching potential in wheat: root system and nutrient uptake in wheat. *J. Agron. Crop Sci.* 196, 455–466. doi: 10.1111/j.1439-037X.2010.00433.x

Erisman, J. W., Galloway, J. N., Seitzinger, S., Bleeker, A., Dise, N. B., Petrescu, A. M. R., et al. (2013). Consequences of human modification of the global nitrogen cycle. *Philos. Trans. R. Soc. B Biol. Sci.* 368, 20130116. doi: 10.1098/rstb.2013.0116

Favre, J. R., Castiblanco, T. M., Combs, D. K., Wattiaux, M. A., and Picasso, V. D. (2019). Forage nutritive value and predicted fiber digestibility of Kernza intermediate wheatgrass in monoculture and in mixture with red clover during the first production year. *Anim. Feed Sci. Technol.* 258, 114298. doi: 10.1016/j.anifeedsci.2019.114298

Ferchaud, F., and Mary, B. (2016). Drainage and nitrate leaching assessed during 7 years under perennial and annual bioenergy crops. *Bioenergy Res.* 9, 656–670. doi: 10.1007/s12155-015-9710-2

Fernandez, C. W., Ehlke, N., Sheaffer, C. C., and Jungers, J. M. (2020). Effects of nitrogen fertilization and planting density on intermediate wheatgrass yield. *Agron. J.* 112, 4159–4170. doi: 10.1002/agj2.20351

Feyereisen, G. W., Wilson, B. N., Sands, G. R., Strock, J. S., and Porter, P. M. (2006). Potential for a rye cover crop to reduce nitrate loss in Southwestern Minnesota. *Agron. J.* 98, 1416–1426. doi: 10.2134/agronj2005.0134

Hunter, M. C., Sheaffer, C. C., Culman, S. W., and Jungers, J. M. (2020a). Effects of defoliation and row spacing on intermediate wheatgrass I: Grain production. *Agron. J.* 112, 1748–1763. doi: 10.1002/agj2.20128

Hunter, M. C., Sheaffer, C. C., Culman, S. W., Lazarus, W. F., and Jungers, J. M. (2020b). Effects of defoliation and row spacing on intermediate wheatgrass II: forage yield and economics. *Agron. J.* 112, 1862–1880. doi: 10.1002/agj2.20124

Hupet, F., Bogaert, P., and Vanclooster, M. (2004). Quantifying the local-scale uncertainty of estimated actual evapotranspiration. *Hydrol. Process.* 18, 3415–3434. doi: 10.1002/hyp.1504

Jungers, J. M., DeHaan, L. H., Mulla, D. J., Sheaffer, C. C., and Wyse, D. L. (2019). Reduced nitrate leaching in a perennial grain crop compared to maize in the Upper Midwest, USA. *Agric. Ecosyst. Environ.* 272, 63–73. doi: 10.1016/j.agee.2018.11.007

Jungers, J. M., DeHaan, L. R., Betts, K. J., Sheaffer, C. C., and Wyse, D. L. (2017). Intermediate wheatgrass grain and forage yield responses to nitrogen fertilization. *Agron. J.* 109, 462–472. doi: 10.2134/agronj2016.07.0438

Keeler, B. L., Gourevitch, J. D., Polasky, S., Isbell, F., Tessum, C. W., Hill, J. D., et al. (2016). The social costs of nitrogen. *Sci. Adv.* 2, e1600219. doi: 10.1126/sciadv.1600219

Keeler, B. L., and Polasky, S. (2014). Land-use change and costs to rural households: a case study in groundwater nitrate contamination. *Environ. Res. Lett.* 9, 074002. doi: 10.1088/1748-9326/9/7/074002

Law, E. P., Wayman, S., Pelzer, C. J., Culman, S. W., Gómez, M. I., DiTommaso, A., et al. (2022). Multi-criteria assessment of the economic and environmental sustainability characteristics of intermediate wheatgrass grown as a dual-purpose grain and forage crop. *Sustainability.* 14, 3548. doi: 10.3390/su14063548

Length, R. (2019). *emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.3.3.* Available online at: https://CRAN.R-project.org/package=emmeans

Maeght, J.-L., Rewald, B., and Pierret, A. (2013). How to study deep roots—and why it matters. *Front. Plant Sci.* 4:299. doi: 10.3389/fpls.2013.00299

Matsunami, M., Matsunami, T., Ogawa, A., Toyofuku, K., Kodama, I., and Kokubun, M. (2012). Genotypic variation in biomass production at the early vegetative stage among rice cultivars subjected to deficient soil moisture regimes and its association with water uptake capacity. *Plant Prod. Sci.* 15, 82–91. doi: 10.1626/pps.15.82

McIsaac, G. F., David, M. B., and Mitchell, C. A. (2010). *Miscanthus* and switchgrass production in Central Illinois: impacts on hydrology and inorganic nitrogen leaching. *J. Environ. Qual.* 39, 1790–1799. doi: 10.2134/jeq2009.0497

Ochsner, T. E., Schumacher, T. W., Venterea, R. T., Feyereisen, G. W., and Baker, J. M. (2017). Soil water dynamics and nitrate leaching under corn–soybean rotation, continuous corn, and kura clover. *Vadose Zone J.* 17, 1–11. doi: 10.2136/vzj2017.01.0028

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., and and, R., Core Team (2019). *nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-139,.* Available online at: https://CRAN.R-project.org/package=nlme

Pinto, P., De Haan, L., and Picasso, V. (2021). Post-harvest management practices impact on light penetration and Kernza intermediate wheatgrass yield components. *Agronomy* 11, 442. doi: 10.3390/agronomy11030442

Pugesgaard, S., Schelde, K., Larsen, S. U., Laerke, P. E., and Jørgensen, U. (2015). Comparing annual and perennial crops for bioenergy production - influence on nitrate leaching and energy balance. *GCB Bioenergy* 7, 1136–1149. doi: 10.1111/gcbb.12215

Pugliese, J. Y., Culman, S. W., and Sprunger, C. D. (2019). Harvesting forage of the perennial grain crop Kernza (*Thinopyrum intermedium*) increases root biomass and soil nitrogen cycling. *Plant Soil* 437, 241–254. doi: 10.1007/s11104-019-03974-6

R Core Team (2018). *R: A Language and Environment for Statistical Computing.* Vienna: R Foundation for Statistical Computing Available online at: https://www.R-project.org/

Randall, G. W., Huggins, D. R., Russelle, M. P., Fuchs, D. J., Nelson, W. W., and Anderson, J. L. (1997). Nitrate losses through subsurface tile drainage in Conservation Reserve Program, Alfalfa, and row crop systems. *J. Environ. Qual.* 26, 1240–1247. doi: 10.2134/jeq1997.00472425002600050007x

Randall, G. W., and Mulla, D. J. (2001). Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. *J. Environ. Qual.* 30, 337–344. doi: 10.2134/jeq2001.302337x

Sakiroglu, M., Dong, C., Hall, M. B., Jungers, J., and Picasso, V. (2020). How does nitrogen and forage harvest affect belowground biomass and nonstructural carbohydrates in dual-use Kernza intermediate wheatgrass? *Crop Sci.* 60, 2562–2573. doi: 10.1002/csc2.20239

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Smucker, A. J. M., McBurney, S. L., and Srivastava, A. K. (1982). Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. *Agron. J.* 74, 500–503. doi: 10.2134/agronj1982.00021962007400030023x

Struffert, A. M., Rubin, J. C., Fernández, F. G., and Lamb, J. A. (2016). Nitrogen management for corn and groundwater quality in Upper Midwest irrigated sands. *J. Environ. Qual.* 45.1557–1564. doi: 10.2134/jeq2016.03.0105

Tautges, N. E., Jungers, J. M., DeHaan, L. R., Wyse, D. L., and Sheaffer, C. C. (2018). Maintaining grain yields of the perennial cereal intermediate wheatgrass in monoculture v. bi-culture with alfalfa in the Upper Midwestern USA. *J. Agric. Sci.* 156, 758–773. doi: 10.1017/S0021859618000680

USDA–NRCS (2021). *Web Soil Survey. USDA – Natural Resources Conservation Service*. Available online at: https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

Ward, M., Jones, R., Brender, J., de Kok, T., Weyer, P., Nolan, B., et al. (2018). Drinking water nitrate and human health: an updated review. *Int. J. Environ. Res. Public Health* 15, 1557. doi: 10.3390/ijerph15071557

Ward, M. H., Kilfoy, B. A., Weyer, P. J., Anderson, K. E., Folsom, A. R., and Cerhan, J. R. (2010). Nitrate intake and the risk of thyroid cancer and thyroid disease. *Epidemiology* 21, 389–395. doi: 10.1097/EDE.0b013e3181d6201d

Zimbric, J. W., Stoltenberg, D. E., and Picasso, V. D. (2020). Effective weed suppression in dual-use intermediate wheatgrass systems. *Agron. J.* 112, 2164–2175. doi: 10.1002/agj2.20194

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SOIL MANAGEMENT

Subsurface Drain Losses of Water and Nitrate following Conversion of Perennials to Row Crops

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ABSTRACT

Nitrate losses through subsurface drains in agricultural fields pose a serious threat to surface water quality. Substantial reductions in drainage losses of NO_3–N can occur with alfalfa (*Medicago sativa* L.) or perennial grasses as used in Conservation Reserve Program (CRP) plantings. Conversion of perennials to annual row crops, however, could have rapid, adverse affects on water quality. We evaluated water and N use efficiency of row crops following perennials, and losses of water and NO_3–N to subsurface drains. Four cropping systems: continuous corn (*Zea mays* L.), a corn–soybean [*Glycine max* (L.) Merr.] rotation, alfalfa (ALF), and CRP, were established in 1988. The ALF and CRP were converted to a corn–corn–soybean sequence from 1994 through 1996 while continuous corn (C-C) and corn–soybean (C-S) rotations were maintained. Following CRP, corn yield was 14% and water use efficiency (WUE) 20% greater as compared with C-C. Yield was 19% and WUE 21% greater for soybean following corn in CRP and ALF as compared with C-S. Residual soil NO_3–N (RSN) increased 125% in first year corn following CRP and was 32% greater than C-C by 1996. High N uptake efficiencies of corn following alfalfa slowed the buildup of RSN, but levels were equal to row crop systems after 2 yr. Nitrate losses in drainage water remained low during the initial year of conversion, but were similar to row crop systems during the subsequent 2 yr. Beneficial effects of perennials on subsurface drainage characteristics were largely negated following 1 to 2 yr of corn.

Production of annual row crops on large areas of poorly drained soils in the Upper Midwest requires artificial drainage to improve timeliness of field operations and suitability of the soil environment for annual crop growth (Wheaton, 1977). Adverse environmental consequences of intensive row-crop production with artificial drainage, however, are well documented and include sediment, nutrient (N, P), and pesticide delivery to surface waters via subsurface drain lines (Gast et al., 1978; Logan et al., 1980, 1993; Kladivko et al., 1991; Buhler et al., 1993; Randall et al., 1997). Recently, river-borne nutrients, mainly NO_3–N from farmland in the Upper Midwest, have been implicated in the spread of hypoxic bottom waters in the Gulf of Mexico near the mouth of the Mississippi River (Antweiler et al., 1995; Burkhart and James, 1999). A major source of NO_3–N found in the upper Mississippi River is from agricultural fields that are artificially drained (Goolsby, 1999). The contamination of surface and ground waters from sediment and land-applied agri-chemicals (CAST, 1985) combined with spreading hypoxia in the Gulf of Mexico raises concerns about the sustainability of annual row-crop production in the Upper Midwest.

Crop rotation can have a substantial effect on the quantity and quality of water entering subsurface drains. Most investigations in the Midwest have evaluated the influence of annual row-crop (e.g., corn and soybean) production on nutrient loss via subsurface drains (Gast et al., 1978; Logan et al., 1980, 1993; Baker and Johnson, 1981; Kladivko et al., 1991; Randall and Iragavarapu, 1995; Randall et al., 1997). These studies concluded that: (i) annual losses of NO_3–N through subsurface tile drains are substantial, ranging up to 120 kg N ha^{-1}; (ii) NO_3–N concentrations of drainage water often exceed the USEPA drinking water standard of 10 mg L^{-1}; and (iii) NO_3–N losses in row-crop systems are dependent on drain flow volumes and fertilizer N management. In contrast to annual crops, perennial crops such as alfalfa and grass can reduce NO_3–N concentrations in the soil profile (Mathers et al., 1975; MacLean, 1977; Russelle and Hargrove, 1989; Randall et al., 1997), decrease NO_3–N concentrations and flux in drainage waters, and

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Abbreviations: CRP, Conservation Reserve Program; RSN, residual soil NO_3–N; C, corn; S, soybean; ALF, alfalfa; NUE, nitrogen use efficiency; PVC, polyvinyl chloride; WUE, water use efficiency; ET, evapotranspiration.

lower drainage volumes (Bolton et al., 1970; Logan et al., 1980; Bergstrom, 1987; Owens, 1990; Randall et al., 1997). In a comparison of four rotations—continuous corn (C-C), corn–soybean (C-S), alfalfa (ALF), and alfalfa–grass mixture (CRP)—Randall et al. (1997) reported average NO_3–N concentrations from subsurface drains of 32 mg L^{-1} for C-C, and 24 mg L^{-1} for C-S, but only 3 mg L^{-1} for ALF and 2 mg L^{-1} for CRP. In addition, drainage from the row-crop systems exceeded that from perennial crops by up to fivefold. Greater drain flows and NO_3–N concentrations in C-C and C-S rotations (Randall et al., 1997) produced annual losses of NO_3–N that were 35 times (avg. loss of 53 kg N ha^{-1}) greater than NO_3–N losses in the perennial systems (avg. loss of 1.5 kg N ha^{-1}).

The Conservation Reserve Program (CRP) was initiated in 1985 and was designed to assist landowners in conserving and improving soil and water resources of highly erodible and environmentally sensitive land (Cubbage, 1992; Osborn, 1993). The CRP reached 16.2 million ha by 1993, with 14.7 million ha in grassland and 1.5 million ha in forestland (Osborn, 1993). By 1999, total area in the CRP was reduced slightly to 12.7 million ha. Historically, states in the Corn Belt have had significant participation in the CRP accounting for 13% of the national CRP-land area (USDA, 1999).

The conversion of land from intensive annual crop production to permanent vegetative cover under CRP has resulted in substantial benefits to soil quality (Gebhart et al., 1994; Huggins et al., 1997; Staben et al., 1997; Karlen et al., 1999) and water quality (Randall et al., 1997). These benefits, however, can be short-lived as CRP contracts expire after only 10 to 15 yr and if post-CRP management includes a return to annual cropping. Management strategies for returning CRP-land to crop production should consider options that attempt to maintain environmental benefits gained by the CRP. Improvements in soil aggregation, structural stability, C sequestration, and water infiltration on CRP-land can largely be maintained through conservation tillage practices, notably no-tillage (Lindstrom et al., 1994; Huggins et al., 1997). The effects of CRP land conversion on water quality are largely unknown and take on further significance as riparian buffer areas are included in the CRP or in the Wetlands Reserve Program (WRP).

Conversion of CRP-land to row crops will likely result in a return to pre-CRP water flow volumes and NO_3–N concentrations in subsurface drains. How long water quality benefits might persist following CRP-land conversion to row crops, and what management strategies may extend those benefits were the over-riding questions of our research. Specifically, our objectives were to determine the effects of converting perennial cropping systems (e.g., alfalfa and CRP plantings) to annual row-crop systems (corn and soybean) on (i) aboveground biomass and N accumulation, (ii) water and N use efficiency, and (iii) water and NO_3–N losses to subsurface drains. Furthermore, we expected this evaluation to provide (i) insights into the persistence of crop and water quality benefits acquired from perennial cropping systems including CRP-land; and (ii) a basis for devising crop rotation and CRP-land conversion strategies that would optimize water and N use.

MATERIALS AND METHODS

Site Description and Experimental Design

The study was conducted on a long-established subsurface drainage site at the University of Minnesota Southwest Research and Outreach Center near Lamberton, MN. In 1972, perforated PVC subsurface drains (10-cm diam.) were installed 1.2-m deep on 15 plots, 13.7 by 15.3 m, to simulate 28-m spacing on a Normania clay loam (fine-loamy, mixed, mesic Aquic Haplustolls). Previous studies have examined N rate effects on drain nitrate losses (Gast et al., 1978), perennial vs. annual row crop effects on nitrate losses through drains (Randall et al., 1997), and modeling of water quality with DRAINMOD-N (Zhao et al., 2000). Further details on the establishment of the subsurface drainage plots, soil characteristics, past management, and previous research findings can be obtained from these studies.

In the spring of 1988, four cropping systems—continuous corn (C-C), corn after soybean (S-C), soybean after corn (C-S), alfalfa (ALF), and a perennial grass–alfalfa mixture (CRP) representing CRP-land—were established in 15 subsurface drainage plots in a randomized complete-block design with three replications. The C-S and S-C treatments were included to allow representation of each crop every year in the 2-yr corn–soybean rotation. The first phase of the experiment was completed in the fall of 1993 after six cropping seasons (Randall et al., 1997). Phase two of the study was initiated in the fall of 1993 when the ALF and CRP treatments were moldboard plowed and rotated to corn in 1994 and 1995, and then to soybean in 1996 (ALF-C-C-S and CRP-C-C-S, respectively). The C-C, S-C, and C-S cropping system treatments were continued as established in 1988 through the fall of 1996 when phase two was completed.

Field and Laboratory Procedures

Annual experimental procedures for each cropping system are given in Table 1. Tillage following corn consisted of fall moldboard plowing and spring cultivation before planting and row cultivation (one operation) after planting. The soil was left untilled in the fall following soybean and plots were spring cultivated before corn planting. Best management practices (BMPs) were used for N fertilization of corn (Rehm and Schmitt, 1989). Nitrogen was side-dressed at application rates based on spring soil NO_3–N (0–1.2 m), previous crop (corn, soybean, alfalfa, CRP-perennial grass), and a corn yield goal of 8.8 Mg ha^{-1}. Starter fertilizer was applied during corn planting, and urea was surface side-dressed and immediately incorporated with row cultivation (Table 1). No fertilizers were applied to soybean.

Corn and soybean grain yields were measured with a plot combine following physiological maturity from two 12.2-m row subsamples. Corn stover biomass was determined from the dry-weight ratio of grain to stover of 10 plants hand-sampled just before harvest, and applied to the overall grain yield from the larger plot harvest. Soybean stover biomass was assessed by collecting all leaves, petioles, and stems within a wire-caged, 1-m length of row in each plot.

Detailed methods for the collection and analysis of subsurface drainage water and nitrate flux are given in Randall et al. (1997). Briefly, drain flow rates were determined daily, except Saturday and Sunday unless precipitation occurred. Water samples for NO_3–N analysis were collected manually

Table 1. Management procedures for corn and soybean in each of the cropping systems (1994–1996). Underlined crops denote specific crop within crop sequence that information refers to.

Cropping system	Procedure	Year		
		1994	1995	1996
Corn†	Pioneer hybrid	3 563	3 531	3 531
	Planting rate, seeds ha^{-1}	71 630	74 100	74 100
	Planting date	4 May	4 May	16 May
	Starter, kg ha^{-1}, N–P–K	17–15–18	17–15–18	17–15–18
	Urea appl. date	6 June	7 June	24 June
	Cultivation date	6 June	7 June	24 June
	Harvest date	19 Oct.	9 Oct.	9 Oct.
Continuous corn	Urea, kg N ha^{-1}	148	143	112
Soybean-Corn‡	Urea, kg N ha^{-1}	95	91	67
Alfalfa-Corn-Corn§	Urea, kg N ha^{-1}	0	60	n.a.¶
CRP-Corn-Corn#	Urea, kg N ha^{-1}	160	132	n.a.
Soybean††	Variety	Parker	Parker	Parker
	Planting date	4 May	17 May	20 May
	Cultivation date	13 June	7 June	24 June
	Harvest date	19 Oct.	15 Oct.	1 Oct.
All crops	Sampling for soil water and NO_3–N	18 April 1 Nov.	17 May 17 Oct.	1 May 15 Oct.

† Procedures used for all corn plots.
‡ Corn following a previous crop of soybean.
§ Corn following alfalfa in 1994 and corn in 1995 (soybean grown in 1996).
¶ n.a. = not applicable (soybean grown in 1996).
# Corn following the Conservation Reserve Program (CRP) in 1994 and corn in 1995 (soybean grown in 1996).
†† Procedures used for all soybean plots.

in 250-mL plastic bottles three times per week (Monday, Wednesday, Friday) and frozen until analyzed. Nitrate-N was determined colorimetrically by Cd-reduction and levels of NO_2–N were assumed to be negligible. Nitrate-N levels were linearly interpolated for days when samples were not taken. Total flux of NO_3–N through drains was calculated by multiplying sample NO_3–N concentration by total water flow for the same time period. Flow-weighted average NO_3–N concentrations were calculated by dividing total NO_3–N flux by total water flow for the same time period.

Nitrogen concentration of aboveground biomass (grain and stover) of corn and soybean was determined by grinding subsamples to pass a 1-mm sieve and analyzing for total N (Technicon Industrial Method no. 325-74W Sept. 1974; Ammoniacal Nitrogen/BD Acid Digests; Technicon Industrial Systems, Tarrytown, NY).[1]

Nitrogen content of aboveground biomass was expressed on an area basis using grain and stover values from harvested biomass of corn and soybean. Following harvest, two soil cores (4.1-cm diam.) were collected from each plot to a depth of 3.0 m with a hydraulic probe and composited in 30-cm increments. Gravimetric water content was determined after oven drying (105°C) and NO_3–N was measured on air-dried samples ground to pass a 2-mm sieve, extracted with 2 *M* KCl, and analyzed colorimetrically using Cd-reduction. Soil NO_3–N and water were expressed on a volume basis using soil bulk densities determined in 1994.

Calculation of Nitrogen and Water Use Efficiency

Components of N use efficiency (NUE) were based on major plant physiological processes (Huggins and Pan, 1993). Nitrogen use efficiency was defined as grain production (G_w) per unit of N supply (N_s), where N_s is the sum of all sources of available N. In turn, two primary factors of NUE were defined as (i) N uptake efficiency (N_t/N_s), the amount of aboveground plant N (N_t) at maturity per unit of N_s; and (ii) N utilization efficiency (G_w/N_t), the amount of grain production per unit of N_t. In this study, N_s and net mineralized N (N_m) were estimated using the following equations:

$$N_s = N_r + N_f + N_m \quad [1]$$

$$N_m = (N_t + N_h + N_{sd}) - (N_r + N_f) \quad [2]$$

where N_r is residual soil NO_3–N (0–1.5 m) from the fall of the previous year, N_f is applied fertilizer N, N_m is net mineralized N, N_t is aboveground plant N, N_h is soil NO_3–N (0–1.5 m) following harvest, and N_{sd} is NO_3–N loss through subsurface drains. These calculations do not consider losses of N due to denitrification, volatilization, or leaching below 1.5 m, and therefore underestimate N_m and N_s.

Components of water use efficiency (WUE) were based on a similar analysis where WUE was defined as grain production (G_w) per unit of water supply (W_s). Two primary factors of WUE were defined as (i) water uptake efficiency (ET/W_s), the amount of evapotranspiration (ET) per unit of W_s; and (ii) water utilization efficiency (G_w/ET), the amount of grain production per unit of evapotranspiration. In this study, W_s and ET were estimated using the following two equations:

$$W_s = W_r + W_p \quad [3]$$

$$ET = W_d + W_p - W_{sd} \quad [4]$$

where W_r is residual soil water from the previous fall (0–3 m), W_p is hydrologic year precipitation (October–September), W_d is soil water depletion (Residual soil water from previous fall − Residual soil water after harvest, 0–3 m), and W_{sd} is loss of water through subsurface drainage. The calculation of ET is slightly overestimated because losses of water below 3 m are not considered. Estimates of annual water flow to groundwater are relatively small; however, <3 cm (Baker et al., 1979). Runoff is negligible from this site as slopes are <1%.

Statistical Analyses

Analysis of variance (ANOVA) was used to determine significant (0.05 probability level) cropping system effects for

[1] Names are necessary to report factually on available date; however, the USDA and the Univ. of Minnesota neither guarantee nor warrant the standard of the product, and the use of the name by the USDA and the Univ. of Minnesota implies no approval of the product to the exclusion of others that may be suitable.

Table 2. Cropping system effects on corn and soybean grain yield and stover biomass (1994–1996).

Cropping system†	1994		1995		1996	
	Grain	Stover	Grain	Stover	Grain	Stover
	dry matter, kg ha^{-1}					
C-C	8 709	6 842	5 713	8 180	(6 573)	(5 642)
C-S	9 126	7 313	7 050	11 653	(6 553)	(5 874)
S-C	(2 932)	(3 501)	(2 210)	(2 421)	2 210	2 930
ALF-C-C-S‡	9 031	7 788	5 829	10 436	2 621	3 761
CRP-C-C-S	9 386	7 647	7 097	12 089	2 630	3 684
LSD (0.05)	*423**	*1 221*	*896**	*2 432**	*167**	*438**

* Significant differences occurred according to Fischer's least significant difference (LSD) test (0.05 level of probability). Mean comparisons exclude values in parentheses in each column. Therefore, the LSD's for grain and stover are for corn sequences in 1994 and 1995, and soybean sequences in 1996.
† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ C-C-S signifies corn in 1994, corn in 1995, and soybean in 1996.

each year of the study (SAS Inst., 1996). A multiple mean comparison of cropping system effects was performed using Fischer's least significant difference (LSD) test (0.05 probability level). Fischer's LSD tests are reported for all variables as a measure of variance; however, LSD tests are indicated as significant only when the ANOVA had significant F ratios for cropping system effects. Least squares regression analysis was used to relate subsurface drainage to water supply and the coefficient of determination (r^2) calculated (SAS Inst., 1996).

RESULTS AND DISCUSSION

Grain Yield and Stover Biomass

Corn grain yields in 1994 were 8% greater following 6 yr of CRP compared with continuous corn, whereas yields following alfalfa (6 yr), soybean, or continuous corn were not significantly different (Table 2). These data contrast with our expectations that beneficial rotation effects on yield would be greater for corn following alfalfa compared with grass (Porter et al., 1997a). Both grain yield reductions and increases, however, have been reported for corn grown after either alfalfa or grass. Soil water deficits created by high water use crops such as alfalfa and perennial grasses can negatively impact subsequent crop growth and yield (Shrader and Pierre, 1966; Grecu et al., 1988). Precipitation was 166% of normal during the 1993 growing season, which recharged soil water deficits in CRP and ALF, and resulted in nearly equivalent residual soil water levels across cropping systems in the fall of 1993 (Randall et al., 1997). Despite high precipitation in 1993, W_s was still 5% greater in C-C compared with ALF-C (Table 3) for 1994, which may have depressed beneficial rotation effects expected when corn follows alfalfa. When minimal differences in soil water occur and adequate nutrient levels are supplied, increased yields of corn following alfalfa or hay crops compared with continuous corn have been reported (Barber, 1972; Hesterman et al., 1986). Overall, corn yields in 1994 were greater than yield goals as a result of favorable in-season growing conditions. Beneficial rotation effects of alfalfa and CRP on subsequent corn yields would be expected to be less pronounced under a high yielding environment (Barber, 1972; Roder et al., 1989; Porter et al., 1997b).

In 1995, overall corn yields were less than those of 1994, below yield goals, and differences in yield among the cropping systems were more pronounced (Table 2). Corn yields were 20% greater in S-C and CRP-C-C-S rotations than in C-C and ALF-C-C-S.[2] Differences in cropping system W_s were not significant in 1995 (Table 3); however, insufficient available N may have reduced second-year corn yields following alfalfa as N uptake efficiencies were similar but N_s was reduced in ALF-C-C-S compared with CRP-C-C-S and S-C (Table 4).

Soybean grain yields in 1996 were 19% and stover production 25% greater in CRP-C-C-S and ALF-C-C-S sequences compared with C-S (Table 2). These data support the conclusion of Porter et al. (1997b), that the C-S rotation does not maximize rotation benefits for soybean yield. Soybean had not been grown on this site for >25 yr, and the 19% yield increase is greater than the 6% yield increase reported by Porter et al. (1997b) for soybean following 5 yr of C-C compared with a C-S rotation. Management strategies for initial conversion of CRP to annual row-crops in the Midwest should consider soybean, as crop rotation effects on yield will likely be greater than for corn.

Water Use and Subsurface Drain Flow

During phase one, the average annual W_s for alfalfa and CRP (1989–1993) was lower than for row crops (Table 5). This occurred as greater ET in alfalfa and CRP depleted quantities of residual water in the upper 3 m of soil (Randall et al., 1997). In phase two, W_s was still greater in the C-C sequence compared with ALF-C-C-S in 1994, but W_s was similar in 1995 and 1996 (Table 3). No differences in residual soil water occurred among the cropping systems in the 0- to 1.5-m depth by the fall of 1994, whereas levels of soil water in the 1.5- to 3.0-m depths were slightly elevated in C-C compared with ALF-C-C-S (Table 6). Differences in fall residual soil water were not significant in 1995 and only marginally different in 1996 (Table 6). Although the magnitude of ET changed from year to year, no differences occurred in ET among crops or cropping systems from 1994 through 1996 (Table 3). These results agree with those of Copeland et al. (1993), who found that ET estimates for corn and soybean did not differ significantly among rotation sequences at the Lamberton site.

Subsurface drain flow was directly related to annual

[2] Underlined letter denotes specific crop within crop sequence that information refers to.

Table 3. Cropping system effects on water supply, losses, and use (1994–1996).

Cropping system†	Precip.‡	W_s§	Subsurface drainage	ET¶	G_w/W_s#	ET/W_s††	G_w/ET‡‡
	cm				kg cm^{-1}	cm cm^{-1}	kg cm^{-1}
1994	70.6						
C-C		169.0	12.7	59.9	51.5	0.35	145.9
C-S		162.7	13.3	56.1	56.1	0.34	162.8
S-C		164.5	14.0	58.1	(17.8)	0.35	(50.5)
ALF-C		161.0	10.3	59.9	56.1	0.37	151.1
CRP-C		163.9	11.6	61.1	57.3	0.37	154.6
LSD (0.05)		*7.0**	*4.0*	*6.8*	*2.6**	*0.04*	*20.2*
1995	72.8						
C-C		169.2	19.7	55.1	33.8	0.33	105.1
C-S		165.2	23.1	48.8	42.7	0.29	145.6
S-C		166.1	19.9	52.7	(13.3)	0.32	(42.3)
ALF-C-C		163.6	17.5	56.0	35.7	0.34	104.3
CRP-C-C		164.0	21.2	51.0	43.3	0.31	139.2
LSD (0.05)		*6.5*	*6.0**	*9.4*	*6.0**	*0.05*	*35.6**
1996	75.0						
C-C		169.5	17.9	62.6	(38.8)	0.37	(105.5)
C-S		168.5	16.1	62.5	(38.9)	0.37	(105.1)
S-C		168.2	17.5	62.3	13.1	0.37	35.4
ALF-C-C-S		165.2	13.3	61.6	15.9	0.37	42.6
CRP-C-C-S		166.9	15.2	61.1	15.9	0.37	43.2
LSD (0.05)		*7.0*	*3.9**	*7.5*	*1.1**	*0.04*	*3.6**

* Significant differences occurred according to Fischer's least significant difference (LSD) test (0.05 level of probability). The LSD's for G_w/W_s and G_w/ET are for corn sequences in 1994 and 1995, and soybean sequences in 1996; therefore, mean comparisons exclude values in parentheses in each of these columns.
† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ Precip. = hydrologic year precipitation (October–September).
§ W_s = water supply.
¶ ET = evapotranspiration.
# G_w/W_s = water use efficiency.
†† ET/W_s = water uptake efficiency.
‡‡ G_w/ET = water utilization efficiency.

W_s for both phase one and phase two studies (Fig. 1). Calculated W_s includes the soil water depletion effects of the previous crop(s) as well as precipitation (Eq. [3]). Soil water deficits created by alfalfa and CRP reduced W_s compared with annual row crops (Table 5). Low cropping system W_s is an indication of greater consump-

Table 4. Cropping system effects on nitrogen uptake, losses, and use efficiency (1994–1996).

Cropping system†	Grain N	Stover N	Drain N	N_s‡	N_m§	G_w/N_s¶	N_t/N_s#	G_w/N_t††
	kg N ha^{-1}					kg kg^{-1}		
1994								
C-C	87	29	15	211	−18	42.6	0.57	75.0
C-S	87	29	13	174	7	52.7	0.68	78.3
S-C	(121)	(34)	13	n.c.‡‡	n.c.	n.c.	n.c.	n.c.
ALF-C	82	25	3	137	95	65.7	0.78	84.6
CRP-C	99	34	1	188	−10	51.6	0.71	71.4
LSD (0.05)	*10**	*13*	*6**	*76*	*76**	*17.3**	*0.19**	*11.1**
1995								
C-C	69	40	22	248	8	23.1	0.44	52.4
C-S	72	64	25	260	97	27.1	0.52	52.1
S-C	(88)	(25)	17	n.c.	n.c.	n.c.	n.c.	n.c.
ALF-C-C	57	44	14	203	98	28.8	0.50	57.7
CRP-C-C	86	75	17	312	108	22.9	0.52	44.0
LSD (0.05)	*14**	*13**	*9**	*45**	*39**	*3.3**	*0.06**	*5.8**
1996								
C-C	(38)	(76)	13	179	−66	37.0	0.64	57.6
C-S	(36)	(77)	9	171	−12	38.3	0.66	58.4
S-C	105	49	10	n.c.	n.c.	n.c.	n.c.	n.c.
ALF-C-C-S	136	78	7	n.c.	n.c.	n.c.	n.c.	n.c.
CRP-C-C-S	133	76	11	n.c.	n.c.	n.c.	n.c.	n.c.
LSD (0.05)	*12**	*34*	*4**	*16*	*47**	*6.4*	*0.19*	*6.5*

* Significant differences occurred according to Fischer's least significant difference (LSD) test (0.05 level of probability). The LSD's for grain N and stover N are for corn sequences in 1994 and 1995, and soybean sequences in 1996; therefore, mean comparisons exclude values in parentheses in each of these columns.
† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ N_s = nitrogen supply.
§ N_m = net nitrogen mineralization.
¶ G_w/N_s = nitrogen use efficiency.
# N_t/N_s = nitrogen uptake efficiency.
†† G_w/N_s = nitrogen utilization efficiency.
‡‡ n.c. = not calculated.

Table 5. Previous cropping system effects on annual water use (avg. of 1989–1993).

Cropping system†	Precip.‡	W_s§	Subsurface drainage	ET¶	ET/W_s#
	cm				cm cm^{-1}
	71.5				
C-C		161.5	15.4	53.1	0.33
C-S		160.9	18.1	52.3	0.33
S-C		160.6	18.0	53.1	0.32
ALF		144.9	8.3	59.1	0.41
CRP		149.8	12.8	55.2	0.37

† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ Precip. = hydrologic year precipitation (October–September).
§ W_s = water supply.
¶ ET = evapotranspiration.
# ET/W_s = water uptake efficiency.

tive use, resulting in lower quantities of water that contribute to saturated flow. In this case, annual W_s <143 cm resulted in no drain flow, whereas overall, each cm greater than 143 increased subsurface drainage by 0.85 cm (Fig. 1).

Conversion of CRP and alfalfa to row crops increased W_s and consequently, subsurface drainage (Fig. 1). Drainage was not significantly different among cropping systems in 1994 and 1995, but treatments formerly in alfalfa averaged 20% less drain flow than continuous annual cropping throughout the study period (Table 3). These data show that cropping systems can readily impact drain flows and confirm that perennial crops are able to reduce quantities of gravitational water that would otherwise be lost via subsurface drains under annual row cropping. These data are also an example of cropping system feedbacks that occur when W_s and crop water use are not well matched. The C-C and C-S rotations do not effectively use available water resources in this environment, leaving relatively high residual levels of soil water. Subsurface drainage becomes necessary to remove water so that management operations can proceed on a timely basis and grain yield can be optimized (Zhao et al., 2000). Employing crop rotations where water demand is more suitably matched to available water can reduce tile flows and potential adverse effects to surface waters. In this environment, a rotation of

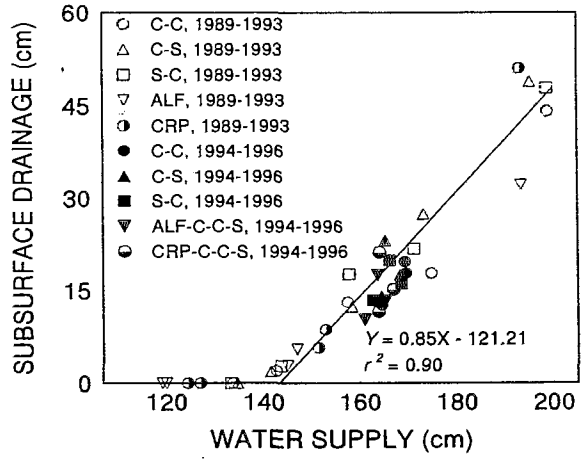

Fig. 1. Relationship between water supply (W_s) and subsurface drainage (W_{sd}) for cropping systems in phase one (1989–1993) and after conversion of CRP and ALF in phase two (1994–1996).

perennial and annual crops is likely necessary to achieve this goal.

One consequence of the rotation effect is reported to be enhanced crop water uptake and utilization (Copeland et al., 1993), although causal mechanisms remain elusive. In 1994, WUE (G_w/W_s) was 10% greater in CRP-C-C-S, ALF-C-C-S, and S-C than in C-C (Table 3). Greater yields in CRP-C-C-S compared with C-C contributed to differences in WUE, but neither W_s nor ET were significantly different in 1994, 1995, or 1996. Greater water uptake efficiency (ET/W_s) suggests that the crop had improved root function, but ET/W_s was not significantly different among cropping systems in this study. Water utilization efficiency (G_w/ET) of corn tended to be different among the cropping systems in 1994 and significant differences occurred in 1995 (Table 3). These data suggest that rotation benefits arose from factors other than increased efficiency of water uptake. Pierce and Rice (1988) hypothesized that increases in WUE may lead to reduced leaching losses; however, gains in WUE achieved through greater G_w/ET rather than ET/W_s are unlikely to affect water losses through subsurface tile lines.

Table 6. Cropping system effects on residual fall soil water and NO_3–N (1994–1996).

Cropping system†	1994 Depth, m		1995 Depth, m		1996 Depth, m	
	0–1.5	1.5–3.0	0–1.5	1.5–3.0	0–1.5	1.5–3.0
	Soil water, cm					
C-C	42.0	54.4	43.1	51.3	38.4	50.6
C-S	40.9	51.4	42.0	51.1	39.2	49.2
S-C	42.3	50.9	43.1	50.3	40.1	49.8
ALF-C-C-S‡	41.4	49.4	41.3	48.8	42.0	48.3
CRP-C-C-S	41.0	50.2	42.0	49.8	40.9	49.6
LSD (0.05)	*4.2*	*4.4**	*4.7*	*3.2*	*2.2**	*1.9**
	Soil NO_3–N, kg ha^{-1}					
C-C	80	105	116	185	52	102
C-S	45	70	99	131	50	87
S-C	55	56	99	121	59	76
ALF-C-C-S‡	27	14	87	95	54	36
CRP-C-C-S	54	10	133	98	69	50
LSD (0.05)	*44**	*44**	*33**	*14**	*16**	*29**

* Significant differences occurred among cropping systems according to Fischer's least significant difference (LSD) test (0.05 level of probability).
† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ C-C-S signifies corn in 1994, corn in 1995, and soybean in 1996.

Residual Soil Nitrate, Nitrogen Use, and Losses through Tile Drainage

In the fall of 1993, after the conclusion of phase one, residual soil NO_3–N (RSN) (0- to 3-m profile) was markedly greater in C-C (168 kg N ha^{-1}) and C-S (119 kg N ha^{-1}) than in alfalfa (51 kg N ha^{-1}) and CRP (47 kg N ha^{-1}) (Randall et al., 1997). A greater proportion of the difference in RSN occurred in the 1.5- to 3.0-m profile, an indication of excess N leaching below the row-crop rooting depth. High levels of RSN are typically found with continuous corn rotations in southwestern Minnesota, even when soil test values and realistic yield goals are used to formulate optimal N rates and time of application (Nelson and MacGregor, 1973; Gast et al., 1974; Randall et al., 1997). On conversion of alfalfa and CRP to corn, RSN began to increase in the upper portion of the soil profile (Table 6, Fig. 2). The increase in RSN was particularly evident with CRP-C-C-S, where by 1996, NO_3–N had risen to levels greater than C-C in the 0- to 1.5-m profile (Table 6). Increases in RSN following conversion of alfalfa were less rapid but by 1996 no significant differences in RSN (0- to 1.5-m) occurred between ALF-C-C-S and other cropping sequences.

Residual effects of alfalfa and CRP on RSN below the root zone of row crops (1.5- to 3.0-m) persisted throughout the 3 yr (Table 6, Fig. 2). Here, accumulation of RSN in the 1.5- to 3.0-m profile of ALF-C-C-S and CRP-C-C-S occurred more slowly than in the upper profile and RSN remained relatively low, particularly with ALF-C-C-S compared with C-C and C-S. In 1996, RSN below the root zone was lower than in 1995, likely due to a shift from corn to unfertilized soybean. Under the environmental conditions of the study, >3 yr was required for row crops to negate perennial system depletion of deep RSN.

Nitrogen supply ranged from a low of 137 kg N ha^{-1} for ALF-C to 211 kg N ha^{-1} for C-C in 1994, but no significant differences were detected among cropping systems (Table 4). In 1995, N_s for the second year of corn in ALF-C-C-S was 203 kg N ha^{-1}, significantly lower than the other cropping systems, which ranged up to 312 kg N ha^{-1} for CRP-C-C-S. Adjustments in N fertilizer recommendations for corn following alfalfa (N credit) have been as large as 180 kg N ha^{-1} (Kurtz et al., 1984). In southwest Minnesota, N credits for first-year harvested alfalfa range from 45 to 168 kg N ha^{-1}, depending on stand characteristics (Rehm et al., 1994). Nitrogen credits for the second year following alfalfa are 50% of first-year credits. Our estimates of net mineralized N (N_m) following alfalfa were consistent for 1994 and 1995, averaging just under 100 kg N ha^{-1} (Table 4). Net N_m contributed 69% of N_s in 1994, when only 17 kg N ha^{-1} was applied, and 48% of N_s in 1995 when 77 kg N ha^{-1} was applied (Table 1). These N_m values were significantly greater than N_m for C-C, which averaged −5 kg N ha^{-1} for 1994 and 1995 (Table 4). The N credit is based on comparisons with C-C; therefore, the 2-yr N_m total was close to expected values. But unexpectedly, the distribution was nearly equal during the 2 yr and indicates that N credits following alfalfa can be difficult to predict. This uncertainty often results in over-applications of N by farmers (Lory et al., 1995).

The adequacy of N for optimal yields depends not only on N_s but also on N uptake efficiency. In 1994, calculated efficiency of N uptake was very high in ALF-C-C-S (78%) compared with C-C (57%), whereas CRP-C-C-S (71%) and S-C (68%) were intermediate in value but not significantly different than the other treatments (Table 4). Fertilizer N uptake efficiency usually ranges from 30 to 80% (Stanford, 1973; Hesterman et al., 1987; Jokela and Randall, 1989) and is reported to be greater than uptake efficiencies of N derived from residues of previous legumes (Hesterman et al., 1987). This occurs, in part, from the relatively low availability of first-year N from legume residues (10–48%) (Ladd et al., 1981, 1983; Hesterman et al., 1987) compared with

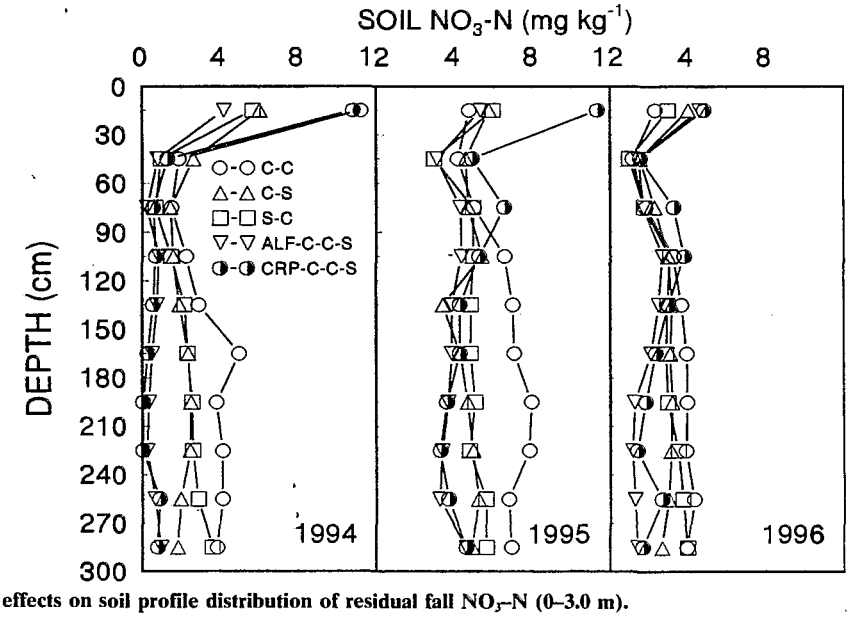

Fig. 2. Cropping system effects on soil profile distribution of residual fall NO_3–N (0–3.0 m).

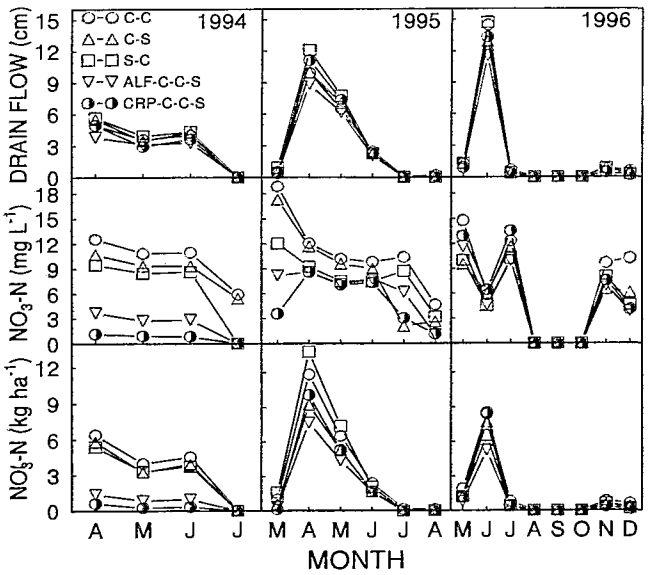

Fig. 3. Cropping system effects on flow volumes, flow-weighted NO_3–N concentrations, and NO_3–N losses through subsurface drains. Data are reported for only those months when subsurface drainage occurred.

fertilizer-derived N. The N uptake efficiencies of 78% achieved with ALF-C-C-S are contrary to this conclusion and demonstrate that under environments that favor N mineralization and subsequent N uptake, corn following alfalfa can approach upper N efficiency limits. Nitrogen uptake efficiency usually decreases with greater N_s (Kurtz et al., 1984; Pierce and Rice, 1988; Huggins and Pan, 1993). Equal N_s is difficult to achieve in studies with varying cropping system treatments and the lower N uptake efficiencies of C-C are in part due to the tendency of greater N_s under C-C compared with ALF-C-C-S. Rotation effects on crop yields can be divided into two effects: one from legume N supply, and an additional effect observed when N is not limiting (Baldock et al., 1981). The high N uptake efficiencies found with ALF-C-C-S, CRP-C-C-S, and C-S in 1994 indicate that rotation effects increased efficiency of N use, regardless of whether or not N_s was limiting. Corn N uptake efficiencies were markedly lower in 1995 than in 1994, averaging about 50% for S-C, CRP-C-C-S, and ALF-C-C-S and 44% for C-C (Table 4). In ALF-C-C-S, low N_s and N uptake efficiencies likely limited grain yield in 1995 as N_s was significantly less than greater yielding CRP-C-C-S and S-C.

The ALF-C-C-S and CRP-C-C-S rotations had contrasting N_s, N_m, and NUE. In 1994 and 1995, a total of 326 kg N ha^{-1} was applied to corn in CRP-C-C-S compared with 94 kg N ha^{-1} in ALF-C-C-S. Net N immobilization (10 kg N ha^{-1}) following CRP (predominantly perennial grasses) contrasted with net mineralization (95 kg N ha^{-1}) following alfalfa in 1994. However, N uptake efficiency was high in both cases and grain N was 21% greater for first-year corn after CRP compared with alfalfa (Table 4). In 1995, N_m was about 100 kg N ha^{-1} for both sequences. The net mineralization during the second year of corn following CRP was 100 kg N ha^{-1} greater than found under C-C (8 kg N ha^{-1}), often considered an equivalent cropping sequence with respect to N fertility management of corn. The large mineralization of N following CRP is due to the buildup of labile forms of organic C and N that occur under CRP (Huggins et al., 1997). Rapid turnover of labile organic C and N pools likely occurred following conversion of CRP resulting in net N immobilization during the first growing season followed by net N mineralization during the second season. Because in-season N mineralization must be anticipated (N credit) and cannot be accounted for through spring soil testing, overapplication of fertilizer N occurred in second-year corn following CRP and resulted in 26% greater N_s than under C-C. One consequence of N overfertilization was the rapid buildup of RSN under CRP-C-C-S (Fig. 2, Table 6). These data indicate that N fertilizer recommendations for second-year corn following CRP or perennial grasses need to be modified to consider available N contributions from delayed effects of N mineralization.

Greater N uptake efficiencies in 1994 with ALF-C-C-S compensated for low N_s, and grain and stover N were not significantly different than C-C or S-C (Table 4). In contrast, the relatively low N uptake efficiencies of 1995 contributed to low grain yields and N accumulation of ALF-C-C-S compared with CRP-C-C-S and S-C, despite 48% greater N_s than in the previous year. The largest grain and stover N accumulations occurred in CRP-C-C-S in 1994 and 1995 as a result of high N_s and N uptake efficiencies (Table 4).

Losses of NO_3–N through subsurface drains in 1994 were 4 to 5 times greater in C-S, S-C and C-C than in ALF-C-C-S, and 13 to 15 times greater than in CRP-C-C-S (Fig. 3, Table 4). In addition, concentrations of NO_3–N were <5 mg L^{-1} in ALF-C-C-S and CRP-C-C-S compared with concentrations >9 mg L^{-1} for most of the season under C-S, S-C, and C-C (Fig. 3). High N uptake efficiencies of CRP-C-C-S and ALF-C-C-S combined with low RSN limited NO_3–N loss through drains (Table 4). By 1995, early season (March) losses and concentrations of NO_3–N in drain flows were still significantly lower in ALF-C-C-S and CRP-C-C-S (Fig. 3); however, total seasonal NO_3–N losses were only less for ALF-C-C-S compared with S-C. Nearly equivalent losses and concentrations of NO_3–N occurred in drains across cropping systems by 1996, although ALF-C-C-S still had significantly lower losses than C-C (Fig. 3, Table 4). Thus, the benefits of CRP and alfalfa in reducing concentrations and losses of NO_3–N through subsurface drainage had essentially ceased following the second year of corn. This occurred as RSN in the root zone (0–1.5 m) rapidly increased following conversion to 2 yr of corn. Benefits likely remained, however, to improved ground water quality as quantities and concentrations of NO_3–N in the subroot zone (1.5–3.0 m) were still lower in ALF-C-C-S and CRP-C-C-S compared with C-S, S-C and C-C (Fig. 2, Table 6).

Strategies for Optimizing Crop Rotation and Conservation Reserve Program Conversion for Water and Nitrogen Use Efficiency

Although our data are limited, they do indicate some potential rotation strategies for CRP–land conversion

to row-crops. Corn yielded well after CRP; however, these yields benefitted from abnormally high precipitation in 1993 that recharged depleted soil water. If moisture deficits had persisted into the 1994 season, corn grain yields may have been reduced (as likely was the case with ALF-C-C-S). Soybean may be a better crop option than corn following CRP, because effects of water deficits and N immobilization (Table 4) can be comparatively reduced and positive rotation benefits on grain yield realized (Table 2). The buildup of RSN would also be slowed because no fertilizer N is applied to soybean and benefits to subsurface drainage water quality could be extended. Following soybean with corn in the subsequent year of CRP takeout could capture additional rotation benefits, including greater NUE and water utilization efficiency, compared with a second year of corn. In addition, a CRP-S-C sequence may position corn to be synchronized with the availability of large quantities of N mineralization from decomposing CRP grass residues (Table 4). If CRP benefits to water quality are to be extended by maintaining low RSN, N fertilizer strategies for corn must be developed to efficiently use this release of mineralized N from CRP. Lower RSN and reduced losses of NO_3–N to tile drainage are likely to be prolonged with CRP followed by a S-C rotation compared with an initial sequence of C-C that rapidly rebuilds RSN.

Although not evaluated, tillage practices are fundamental to the development of strategies for converting perennials to row crops. The use of conservation tillage to convert CRP and alfalfa to row crops would likely have slowed N mineralization rates and changed N use efficiency, buildup of RSN, and losses of water and NO_3–N to subsurface drains.

In conclusion, adding perennial grasses and legumes to cropping systems can have substantial effects on the water quality of artificial subsurface drainage by lowering flow volumes, and NO_3–N concentrations and losses. Devising crop sequences to convert perennials back to row crops may have an initial effect on delaying increases in RSN and reducing NO_3–N losses to subsurface drains. But despite these strategies, continued row-cropping that consists of corn and soybean sequences will soon develop high RSN, W_s, and drain flow volumes that combine to give high drain NO_3–N concentrations and losses. If NO_3–N losses to subsurface drainage are to be significantly reduced and maintained at low concentrations, improvements are needed in water and N use efficiency. Adjusting N fertilizer recommendations to include second-year credits for N mineralization following perennial grass conversion to row crops could improve N use efficiency and reduce losses. Currently, the only cropping sequences that achieve sufficient efficiencies in water and N use in the Upper Midwest include perennial crops in rotation with annual row crops.

REFERENCES

Antweiler, R.C., D.A. Goolsby, and H.E. Taylor. 1995. Nutrients in the Mississippi River. p. 73–82. *In* R.H. Meade (ed.) Contaminants in the Mississippi River. U.S. Geol. Surv. Circ. 1133.

Baker, D.G., W.W. Nelson, and E.L. Kuehnast. 1979. Climate of Minnesota: XII. The hydrologic cycle and soil water. Minn. Agric. Exp. Stn. Tech. Bull. 322.

Baker, J.L., and H.P. Johnson. 1981. Nitrate-nitrogen in tile drainage as affected by fertilization. J. Environ. Qual. 10:519–522.

Baldock, J.O., R.L. Higgs, W.H. Paulson, J.A. Jackobs, and W.D. Shrader. 1981. Legume and mineral fertilizer effects on crop yields of several crop sequences in the Upper Mississippi Valley. Agron. J. 73:885–890.

Barber, S.A. 1972. Relations of weather to the influence of hay crops on subsequent corn yields on a Chalmers silt loam. Agron. J. 64:8–10.

Bergstrom, L. 1987. Nitrate leaching and drainage from annual and perennial crops in tile-drained plots and lysimeters. J. Environ. Qual. 16:11–18.

Bolton, E.F., J.W. Aylesworth, and R.F. Hore. 1970. Nutrient losses through tile drains under three cropping sytems and two fertility levels on a Brookside clay loam. Can. J. Soil Sci. 50:275–279.

Buhler, D.D., G.W. Randall, W.C. Koskinen, and D.L. Wyse. 1993. Atrazine and alachlor losses from subsurface tile drainage of a clay loam soil. J. Environ. Qual. 22:583–588.

Burkhart, M.R., and D.E. James. 1999. Agricultural-nitrogen contributions to hypoxia in the Gulf of Mexico. J. Environ. Qual. 28:850–859.

Copeland, P.J., R.R. Allmaras, R.K. Crookston, and W.W. Nelson. 1993. Corn–soybean rotation effects on soil water depletion. Agron. J. 85:203–210.

Council for Agricultural Science and Technology. 1985. Agriculture and water quality. Rep. 103. CAST, Ames, IA.

Cubbage, F.C. 1992. Federal land conversion programs. p. 177–194. *In* R.N. Sampson and D. Hairs (ed.) Forest and global change. Vol. 1. Opportunities for increasing forest cover. American Forests, Washington, DC.

Gast, R.G., W.W. Nelson, and J.M. MacGregor. 1974. Nitrate and chloride accumulation and distribution in fertilized tile-drained soils. J. Environ. Qual. 3:209–213.

Gast, R.G., W.W. Nelson, and G.W. Randall. 1978. Nitrate accumulation in soils and loss in tile drainage following nitrogen application to continuous corn. J. Environ. Qual. 7:258–262.

Gebhart, D.L., H.B. Johnson, H.S. Mayeux, and H.W. Polley. 1994. The CRP increases soil organic carbon. J. Soil Water Conserv. 49:488–492.

Goolsby, D. 1999. Hypoxia in the Gulf of Mexico [Online]. Available at http://www.rcolka.cr.usgs.gov/midconherb/hypoxia.html (verified 24 Jan. 2001).

Grecu, S.J., M.B. Kirkham, E.T. Kanemasu, D.W. Sweeney, L.R. Stone, and G.A. Milliken. 1988. Root growth in a claypan with a perennial-annual rotation. Soil Sci. Soc. Am. J. 52:488–494.

Hesterman, O.B., M.P. Russelle, C.C. Sheaffer, and G.H. Heichel. 1987. Nitrogen utilization from fertilizer and legume residues in legume–corn rotations. Agron. J. 79:726–731.

Hesterman, O.B., C.C. Sheaffer, D.K. Barnes, W.E. Lueschen, and J.H. Ford. 1986. Alfalfa dry matter and nitrogen production, and fertilizer nitrogen response in legume–corn rotations. Agron. J. 78:19–23.

Huggins, D.R., D.L. Allan, J.C. Gardner, D.L. Karlen, D.F. Bezdicek, M.J. Rosek, M.J. Alms, M. Flock, B.S. Miller, and M.L. Staben. 1997. Enhancing carbon sequestration in CRP-managed land. p. 323–334. *In* R. Lal et al. (ed.) Management of carbon sequestration in soil. CRC Press, Boca Raton, FL.

Huggins, D.R., and W.L. Pan. 1993. Nitrogen efficiency component analysis: An evaluation of cropping system differences in productivity. Agron. J. 85:898–905.

Jokela, W.E., and G.W. Randall. 1989. Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. 81:720–726.

Karlen, D.L., M.J. Rosek, J.C. Gardner, D.L. Allan, M.J. Alms, D.F. Bezdicek, M. Flock, D.R. Huggins, B.S. Miller, and M.L. Staben. 1999. Conservation Reserve Program effects on soil quality indicators. J. Soil Water Conserv. 54:439–444.

Kladivko, E.J., G.E. Van Scoyoc, E.J. Monke, K.M. Oates, and W. Pask. 1991. Pesticide and nutrient movement into subsurface tile drains on a silt loam in Indiana. J. Environ. Qual. 20:264–270.

Kurtz, L.T., L.V. Boone, T.R. Peck, and R.G. Hoeft. 1984. Crop

rotations for effecient nitrogen use. p. 295–306. *In* R.D. Hauck (ed.) Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, WI.

Ladd, J.N., M. Amoto, R.B. Jackson, and J.H.A. Butler. 1983. Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. Soil Biol. Biochem. 13:231–238.

Ladd, J.N., J.M. Oades, and M. Amoto. 1981. Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. Soil Biol. Biochem. 13:251–256.

Lindstrom, M.J., T.E. Schumacher, and M.L. Blecha. 1994. Management considerations for returning CRP lands to crop production. J. Soil Water Conserv. 49:420–425.

Logan, T.J., D.J. Eckert, and D.G. Beak. 1993. Tillage, crop and climate effects on runoff and tile drainage losses of nitrate and four herbicides. Soil Tillage Res. 30:75–103.

Logan, T.J., G.W. Randall, and D.R. Timmons. 1980. Nutrient content of tile drainage from cropland in the North Central Region. North Central Reg. Res. Publ. 268. OARDC Res. Bull. 1119. OARDC, Wooster, OH.

Lory, J.A., G.W. Randall, and M.P. Russelle. 1995. Crop sequence effects on response of corn and soil inorganic nitrogen to fertilizer and manure nitrogen. Agron. J. 87:876–883.

MacLean, A.J. 1977. Movement of nitrate nitrogen with different cropping systems in two soils. Can. J. Soil Sci. 57:27–33.

Mathers, A.C., B.A. Stewart, and B. Blair. 1975. Nitrate-nitrogen removal from soil profiles by alfalfa. J. Environ. Qual. 4:403–405.

Nelson, W.W., and J.M. MacGregor. 1973. Twelve years of continuous corn fertilization with ammonium nitrate or urea nitrogen. Soil Sci. Soc. Am. Proc. 37:583–586.

Osborn, T. 1993. The Conservation Reserve Program: Status, future, and policy options. J. Soil Water Conserv. 48:272–279.

Owens, L.B. 1990. Nitrate-nitrogen concentrations in percolate from lysimeters planted to a legume–grass mixture. J. Environ. Qual. 19:131–135.

Pierce, F.J., and C.W. Rice. 1988. Crop rotation and its impact on efficiency of water and nitrogen use. p. 21–42. *In* W.L. Hargrove (ed.) Cropping strategies for efficient use of water and nitrogen. ASA Spec. Publ. 51. ASA, CSSA, and SSSA, Madison, WI.

Porter, P.M., R.K. Crookston, J.H. Ford, D.R. Huggins, and W.E. Lueschen. 1997a. Interrupting yield depression in monoculture corn: Comparative effectiveness of grasses and dicots. Agron. J. 89:247–250.

Porter, P.M., J.G. Lauer, W.E. Lueschen, J.H. Ford, T.R. Hoverstad, E.S. Oplinger, and R.K. Crookston. 1997b. Environment affects the corn and soybean rotation effect. Agron. J. 89:441–448.

Randall, G.W., D.R. Huggins, M.P. Russelle, D.J. Fuchs, W.W. Nelson, and J.L. Anderson. 1997. Nitrate losses through subsurface tile drainage in Conservation Reserve Program, alfalfa, and row crop systems. J. Environ. Qual. 26:1240–1247.

Randall, G.W., and T.K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. J. Environ. Qual. 24:360–366.

Rehm, G.W., and M.A. Schmitt. 1989. Fertilizing corn in Minnesota. Univ. of Minnesota Ext. Serv. AG-FO-3790. Univ. of Minnesota, St. Paul, MN.

Rehm, G., M. Schmitt, and R. Munter. 1994. Fertilizer recomendations for agronomic crops in Minnesota. Univ. of Minnesota Ext. Serv. BU-6240-E. Univ. of Minnesota, St. Paul, MN.

Roder, W., S.C. Mason, M.D. Clegg, and K.R. Kniep. 1989. Yield-soil water relationships in sorghum–soybean cropping systems with different fertilizer regimes. Agron. J. 81:470–475.

Russelle, M.P., and W.L. Hargrove. 1989. Cropping systems: Ecology and management. p. 227–317. *In* R.F. Follett (ed.) Nitrogen management and groundwater protection. Dev. Agric. Managed Forest Ecol. 21. Elsevier, Amsterdam.

SAS Institute. 1996. Proprietary Software Release 6.12. SAS Inst., Cary, NC.

Shrader, W.D., and J.J. Pierre. 1966. Soil suitability and cropping systems. *In* W.H. Pierre et al. (ed.) Advances in corn production: Principles and practices. Iowa State Univ. Press, Ames, IA.

Staben, M.L., D.F. Bezdicek, J.L. Smith, and M.F. Fauci. 1997. Assessment of soil quality in Conservation Reserve Program and wheat fallow soils. Soil Sci. Soc. Am. J. 61:124–130.

Stanford, G. 1973. Rationale for optimum nitrogen fertilization in corn production. J. Environ. Qual. 2:159–166.

U.S. Department of Agriculture. 1999. The Conservation Reserve Program [Online]. Available at http://www.fsa.usda.gov/DAFP/cepd/18thcrp/18thBookletFinal.PDF (verified 24 Jan. 2001).

Wheaton, R.Z. 1977. Drainage needs of the Upper Midwest. ASAE Pap. 77-2086. ASAE, St. Joseph, MI.

Zhao, S.L., S.C. Gupta, D.R. Huggins, and J.F. Moncrief. 2000. Predicting subsurface drainage, corn yield, and nitrate nitrogen losses with DRAINMOD-N. J. Environ. Qual. 29:817–825.

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Best Management Practices to Use on Karst and Silurian Soil

Written by CHRISTINE ANNE CLARK and LAURA PALETTA

This article is part 2 of a 2 part series explaining Karst and Silurian Bedrock

The terms karst topography and Silurian bedrock are related geological and hydrologic features. However, they can have different focuses and contexts. Karst pertains to unique landforms, such as sinkholes and rock outcropping, while Silurian refers to a specific area of shallow bedrock located in the eastern part of Wisconsin.

Water quality is an important issue to consider on landscapes with these features because having a thin soil layer means that precipitation water drains through the soil without much filtering. In these areas, fertile soils can look parched between rainfall events, even if the amount of rainfall is adequate. When water hits the fractured bedrock, it quickly moves to the groundwater aquifer. Groundwater contamination from sources such as septic systems, agricultural wastes, pesticides, and herbicides is a higher risk in karst areas because underground filtering is minimal.

State standards targeted to sensitive areas

Consistent with Wisconsin state statutes, NR 151 is a rule that directs the Department of Natural Resources to use performance standards to meet runoff and water quality standards. NR 151 includes a performance standard to address spreading manure on soils in sensitive areas of the state (NR 151.075), where depth to bedrock is shallow and the bedrock is fractured (also described as karst topography or Silurian bedrock).

There are 1.6 million acres of cropland on Silurian bedrock. Of that, 17.6% or 283,795 acres, have less than 20 feet of topsoil that will be subject to restrictions under NR 151.075.

Valuable Tool = Nutrient Management Plan

A nutrient management plan is a very useful tool to use when farming in sensitive areas. Nutrient management planning can protect farm profitability, water quality (surface &

groundwater), and soil erosion. The completed plan provides setbacks and considerations for nutrient application rates, timing and approved methods of fertilizing near water bodies, shows conduits to groundwater and where sensitive landscape features exist, as well as lists specific NR 151 standards that need to be met for each field.

In Wisconsin, farmers can develop a nutrient management plan using the free SnapPlus nutrient management planning software. The program alerts farmers when soil loss may cause nutrients to run off the field during or immediately after fertilizer or manure application. The nutrient management plan includes information to help surface and groundwater protection, such as meeting tolerable soil loss (T), maintaining a 5 foot setback from surface water, and preventing runoff from feedlots to enter into water bodies, to name a few.

Agricultural Best Management Practices to Follow

Verify the depth to bedrock on your land so you can manage for production and water quality.

Karst regions often have shallow soils with some being less than 36" deep. A thin layer of soil does not provide much filtering capacity for nutrients and water contaminants. In order to determine depth to bedrock on your property, you can start with SnapPlus. The program has a few layers that indicate shallow soil. These are labeled, "karst features," and "Silurian Dolomite areas." For further investigation to make sure the map is correct for your area, you may verify depth yourself using this protocol:
VerifOfDepthToBedrockStandardDATCP01.pdf (wi.gov)
(https://datcp.wi.gov/Documents2/VerifOfDepthToBedrockStandardDATCP01.pdf)

Know where the runoff from your field goes.

Take an in depth walk around your field or use online maps to learn where water moves after precipitation or snowmelt. A field investigation to identify sinkholes and karst features should extend a quarter of a mile or more surrounding each field. Rainfall and runoff events could carry nutrients to vulnerable areas on or near your property. Installing a grassed buffer or grassed waterway would also help reduce nutrients from entering into water bodies or vulnerable areas such as sinkholes.

Follow Silurian bedrock standards.

If you farm in an area with Silurian Bedrock (map to right), you must follow the NR151 regulations listed here: **Wisconsin Legislature: NR 151.075(11)(c)** (https://docs.legis.wisconsin.gov/code/admin_code/nr/100/151/ii/075/11/c) . This **DATCP NR151.075 Presentation** (https://datcp.wi.gov/Documents2/Mtg1Silurian_Presentation.pdf) is a helpful guide to understand the new regulations.



If you farm in this area, a few of the biggest rules to follow are:

- You must create and follow a nutrient management plan each year
- You may not spread manure if soil is 2 feet or less.
- You cannot spread manure within 250 feet of a private well, 1000 feet of a community well, or 300 feet upslope or 100 feet downslope of a direct conduit to groundwater (sinkhole, outcrop).

Continue to focus on soil conservation practices.

Practices that reduce soil and nutrient losses, such as grass buffer strips, cover crops, and reduced tillage are important in sensitive areas such as karst topography and Silurian bedrock. Less nutrients running off fields will help limit the contamination of surface and groundwater.

MCEA Ex. 17

Utilizing precision agriculture techniques and applying nutrients to crops close to nutrient uptake (split applications) can also help keep nutrients in the soil and readily available for plant uptake.

Avoid spreading manure when clay soil is excessively dry.

If you farm on clay soil and there are dry conditions, avoid spreading manure. When clay soil dries, it often creates large cracks. If manure is applied on these cracks, it has the potential to flow directly to tile drains, bedrock, or groundwater. This issue is perpetuated even more in areas with shallow soils where manure only has a few feet to travel to hit bedrock. In addition to contaminating groundwater, the nutrients in the manure are not held by the soil and lost below the root zone.

If spreading cannot be avoided in dry clay soil conditions, use tillage to disrupt the cracks. When spreading, apply in smaller volumes and monitor field drainage tiles for several days afterwards. Have spill containment and respond material ready in case manure is found in the tile drain.

Key Takeaways

Karst topography and Silurian bedrock are areas that are more susceptible to water contamination due to shallow soils and increased number direct conduits to groundwater, such as sinkholes. When farming in these areas, and especially spreading manure, it is important to follow all rules and regulations. Being aware and choosing better management practices for the most sensitive spots on your farm can aid in reducing nutrient losses and can help positively impact water quality. Follow a nutrient management plan, utilize soil conservation practices, and comply with NR 151 standards to lessen the impact these sensitive areas can have on water quality.

View Part 1 of this article series: Wisconsin's Unique Landscapes: Karst Formation and Silurian Bedrock Explained (https://cropsandsoils.extension.wisc.edu/articles/wisconsins-unique-landscapes-karst-formation-and-silurian-bedrock-explained/)

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MCEA Ex. 17

Reducing Water Quality Impacts from Manure

extension.umn.edu/manure-management/reduce-water-quality-issues

Reduce water quality issues from manure

Minnesotans know how precious clean surface and groundwater is to recreation and wildlife habitat in the state. Access to clean water is something that many take for granted, but protecting it from harm needs to be a top priority.

Pollution from towns and farms harm both surface and groundwater. Nitrogen, phosphorus, and pathogens are the most common water pollutants from manure on farms.

Nitrogen

Nitrogen – in the form of nitrate – is of most concern in groundwater since that is where 3 out of 4 Minnesotans get their drinking water.

- The nitrate threshold for safe drinking water is only 10 ppm. Above that level, infants may develop a condition that limits the supply of oxygen to the blood.
- Nitrates that leave Minnesota through the Mississippi River add to the Gulf of Mexico dead zone. Added nitrates cause an excess of ocean plants and algae to grow.

- When the plants and algae die, they are decomposed by bacteria that use up dissolved oxygen. This causes areas of low oxygen to form where ocean plants and animals cannot live.

Phosphorus

Phosphorus is a major concern because it causes excessive plant and algae growth in lakes and rivers. This causes an oxygen-depleting reaction similar to what happens in the Gulf of Mexico dead zone.

Fish kills and loss of habitat are caused by the decreased oxygen content. Certain types of algae growth caused by phosphorus (called harmful algal blooms) can harm the health of humans and animals that come in contact with them.

Pathogens

Pathogens such as harmful bacteria and viruses in manure become an issue when they enter waterways and groundwater.

E. coli, Cryptosporidium, and Giardia are just a few pathogens that can cause serious health problems in people and animals that come in contact with contaminated water.

Tips to reduce water quality impacts of manure:

Though farms are not the only source of water contamination, farmers still have the responsibility to do their part in protecting water quality. These recommendations can help farmers manage manure to reduce the amount of pollutants leaving their farm or field.

1. Manage runoff and leaching from stockpiled manure. Stacking solid manure on a concrete pad will reduce leaching of nutrients through the soil. Also, placing the stockpile in an open-sided shed, on a level surface, and above the seasonal high-water table will reduce runoff risk. A catch basin can also be placed nearby to hold any runoff before it reaches a waterway.
2. Manage runoff and leaching from open lots. Catch basins and grass buffer strips can be used to hold and filter runoff from open lots before it reaches a waterway.
3. Manage leaching from storage pits. Impermeable concrete, synthetic, or clay soil liners should be used in manure pits to keep nutrients from leaching downward. Pits should also be monitored closely and pumped before overflowing.
4. Use clean-water diversion system. Berms, ditches, and gutters can be used to divert upslope and rain water from areas with manure so that it does not carry nutrients and pathogens to waterways.

5. Use correct manure application techniques on fields. Apply nutrients only as needed in accordance with the University of Minnesota and Minnesota Pollution Control Agency's guidelines. Whenever possible, incorporate manure into the soil to reduce risk of surface runoff. Do not apply on saturated or frozen soils as this will increase runoff.

Chryseis Modderman, Extension educator
Reviewed in 2020

Manure applied on frozen soil or snow - what will happen to my nitrogen?

blog-crop-news.extension.umn.edu/2019/01/manure-applied-on-frozen-soil-or-snow.html



By Melissa Wilson, manure management and water quality Extension specialist

It was a tough fall for manure application. In many places of the state it was wet and harvest was delayed. On top of that, winter arrived earlier than it has in the past couple of years. Many people were forced to apply manure on top of frozen soils or even snow. We've gotten a lot of questions about how the nitrogen in the manure will be impacted.

When manure is applied on the surface of frozen soils or on top of snow, we have two concerns. First, it cannot seep into the ground, so if there is any runoff in your fields, it can carry the manure to low spots or away from the field entirely which may cause environmental issues. We have already seen widespread rain in December across southern Minnesota and snow melt in January in many parts of the state. Fields with higher amounts of residue are less likely to have as much runoff as fields with low residue, so this problem may be worse in some fields and not others.

The second problem we have to consider is the ammonia losses. Remember that manure has two main forms of nitrogen: organic-nitrogen and ammonium-nitrogen. When ammonium-nitrogen is on the soil surface instead of being mixed in with the soil, it can volatilize and be lost as ammonia gas. This is mainly driven by chemical and physical factors. While the freezing temperatures slow the reaction down, research suggests it doesn't stop it entirely. Plus, with the freeze thaw cycles we have seen this year, it is difficult to pinpoint how much will be lost as the manure sitting on the surface freezes and thaws, too. This problem is likely to impact all manure types, but especially swine manure since the total nitrogen content is roughly 60 to 80 percent ammonium-nitrogen when applied.

The good news is that with the cooler temperatures, the conversion of ammonium-nitrogen in manure to nitrate-nitrogen form is minimal. We do not expect nitrate leaching or denitrification to be increased because of the conditions in which manure was applied this year. This is because bacteria are responsible for the conversion, and the freezing temperatures minimize their activity in the winter. This could change depending on the kind of spring we have, however.

Unfortunately, we cannot predict exactly how much nitrogen was lost this year if it was applied on frozen soil or snow. Manure nutrient release can vary depending on specific circumstances. Our best guess is to use our guidelines in Table 1. This will help determine the percent of nitrogen available the first year when broadcasting manure with no incorporation (see the second column). The actual amount available may be more or less, however.

My best advice is to keep an eye on your crop this upcoming year and be prepared to sidedress additional nitrogen if the crop is looking deficient. The Minnesota Pollution Control Agency says you can apply an additional 20 percent of total crop N needs above UMN nitrogen guidelines (PDF) if soil conditions or cool weather warrants additional nitrogen application.

Table 1. Nitrogen availability and loss as affected by method of manure application and animal type.

Percent of total nitrogen available for first year crop after application

Animal type	Broadcast incorporated later than 96 hours or not incorporated	Broadcast incorporated in 12-96 hours	Broadcast incorporated in less than 12 hours	Inject - sweep	Inject - knife
Beef	25%	45%	60%	60%	50%
Dairy	20%	40%	55%	55%	50%
Swine	35%	55%	75%	80%	70%
Poultry	45%	55%	70%	--	--

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RESEARCH ARTICLE

Livestock manure driving stream nitrate

Christopher S. Jones, Chad W. Drake, Claire E. Hruby, Keith E. Schilling, Calvin F. Wolter

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Abstract Growth and consolidation in the livestock industry in the past 30 years have resulted in more total farm animals being raised on fewer Iowa farms. The effects of this on stream water quality at the landscape scale have largely gone unexplored. The main objective of this work was to quantify the effects on stream nitrate levels of livestock concentration in two western Iowa watersheds relative to seven other nearby watersheds. To achieve this objective, we used data on high-frequency nitrate concentration and stream discharge, commercial nitrogen fertilizer use, and manure-generated nitrogen in each watershed. Our analysis shows much higher stream nitrate in the two watersheds where livestock concentration has been greatest, and little difference in commercial fertilizer inputs with the widespread availability of manure N. Reducing N inputs and better management of manure N, including analysis of crop N availability in soil and manure, can reduce uncertainty regarding fertilization while improving water quality.

Keywords Concentrated livestock · Commercial fertilizer · Flow weighted average · Manure · Nitrate-nitrogen

INTRODUCTION

The state of Iowa, located in the U.S. Midwest, has long been one of the country's leading producers of hogs, cattle, poultry, and eggs. Currently Iowa exceeds all other states in egg and pork production and is fourth in production of feeder cattle (USDA 2018). Iowa has also been a leading producer of both corn (*Zea mays* L.) and soybeans (*Glycine max* [L.] Merr.), frequently topping all other U.S. states in harvested totals of these commodities (Jones et al. 2018a). Co-locating crop production and livestock within the state has created efficiencies of production, transportation, and fertilization.

High yield agriculture, such as that conducted on nearly 70% of Iowa's area (USDA 2018), depends on addition of nitrogen fertilizers. Various forms of fertilizer nitrogen are used throughout the state to enhance crop yields, especially those of corn. Most of this nitrogen is applied as formulations of ammonia/ammonium (NH_3/NH_4^+) and nitrate (NO_3–N) generated from industrial processes, but also animal manures where available. The use of industrially produced nitrogen fertilizers emerged as an important component of U.S. and Iowa agriculture following World War II (Commoner 1977). Before 1945, nearly all nitrogen inputs used to fertilize Iowa corn fields came from legumes such as alfalfa and clovers, and animal waste. However, after this time, the use of inorganic nitrogen fertilizers increased 13-fold from 1945 to 1972 as they quickly became affordable and widely available (Commoner 1977). Livestock, especially cattle, consumed the alfalfa and clover, but commercial fertilizer allowed farmers to forgo hay crops and cattle. This enabled many Iowa farmers to specialize on corn and soybean production (Hendrickson and James 2005). The demand for animal protein, however, continued to increase with world population and increased income levels (Delgado et al. 2001). With fewer farmers wanting or needing livestock, those that continued with livestock production were able to greatly enlarge their operations. This is especially evident in Iowa with hog production. In 1980, 65 000 Iowa farmers raised a total of 13 million hogs; by 2002, the number of hog farmers had dwindled to 10 000, but total hog numbers increased to 14 million (Herriges et al. 2005). This dramatic shift in production resulted in many hogs being concentrated in certain areas of the state and a geographical alignment with

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buyers, packing houses, feed and equipment suppliers, and haulers (Honeyman and Duffy 2006). Similar scenarios have also played out with cattle and poultry. This agricultural specialization that has occurred in Iowa is consistent with changes that are still occurring worldwide (Liu et al. 2017).

This transition from diverse, multi-species farms to ones specializing in corn and soybean production with a subset of the latter raising concentrated livestock has produced both efficiencies and negative environmental consequences. It has long been known that nitrogen fertilization correlates with stream nitrate in the U.S. Cornbelt (Klepper 1974) with impacts on municipal water supply (Hatfield et al. 2009) and Gulf of Mexico Hypoxia (Rabalais et al. 2002). However, because nitrogen inputs cycle through plant biomass and into and out of soil organic matter (Jackson et al. 2000), and because of the time lag of pollutant transport to streams via groundwater pathways (Van Meter et al. 2017), it is nearly impossible to trace stream nitrate back to commercial fertilizer, animal manure, legumes, or soil organic matter. Hence, many have attempted to gain insights on nitrate sources and pathways using nitrogen budgeting (David et al. 1997; Libra et al. 2004; Jones et al. 2016).

The intensity of crop and livestock production in Iowa has made the state a major contributor to Mississippi River basin nitrate loads (David et al. 2010; Jones et al. 2018a, b). Nitrate loading from Iowa appears to be increasing (Jones et al. 2018a), especially in the Missouri River and its Iowa tributaries (Sprague et al. 2011; Li et al. 2013), and Iowa contributes up to 89% of the annual Missouri River nitrate load even though Iowa areas draining to the Missouri comprise only 3% of the total watershed area (Jones et al. 2018a). Northwest Iowa, which drains to the Missouri River, is an area where livestock production has been concentrated in recent years (Andersen and Pepple 2017). The overall objective of our research was to assess whether the manure generated from high animal densities drives stream nitrate levels in the region. Using high-frequency river monitoring data collected from nine western Iowa watersheds draining to the Missouri River, two of which have a much larger animal density than the others, and comparing the water quality data to crop area, fertilization, and livestock populations, we show that river nitrate levels are linked to agricultural and livestock management.

MATERIALS AND METHODS

Study area

The nine western Iowa watersheds selected for study are shown in Fig. 1 and Table 1. These nine watersheds were selected because they all drain to the Missouri River and were instrumented with real-time, continuous nitrate sensors co-located with a discharge measurement station. Areas upstream of the water quality and discharge monitoring locations constitute 23% of Iowa's area and 74% of the state's area that drains to the Missouri River. Agricultural land use dominates each catchment and large point source discharges are absent, with no cities greater than 10 000 population draining into any of the watersheds.

Agricultural data

County-level data for the latest available (2012) commercial nitrogen fertilizer were obtained from the US Geological Survey National Water Quality Assessment project (Gronberg and Spahr 2012). County-level manure data were obtained from Gronberg and Arnold (2017). There is reason to believe that the 2012 commercial fertilizer data are relevant in the present day because changes in crop areas from 2012 to 2017 were small in the nine watersheds, e.g., − 6.2, + 5.4, and − 1.3% for corn, soybean, and total corn plus soybean, respectively, and statewide commercial fertilization rates have not changed appreciably since 1990 (Hatfield et al. 2009).

Data for animal populations were collected from two sources. Recent (2018) data for animal numbers were obtained from the Iowa Department of Natural Resources (IDNR) Animal Feeding Operations (AFO) database (IDNR 2018a). The IDNR's database is mostly limited to regulated facilities; therefore, numbers obtained from this source are likely to represent less than the actual number of animals raised in these areas. When calculating total animal units (AU) in a watershed, the population of a species is multiplied by the equivalence factor shown in Table 2 (IAC 2018). Historical county-level hog (1980–2012) and cattle (2002–2012) population data were obtained from USDA (2018) and adjusted to each watershed area based on the portion of the county that lies within the individual watershed. Watershed-level hog and cattle populations for 2018 were obtained from IDNR (2018a). The county-level areas planted with corn and soybeans in 2012 and 2017 were obtained from USDA (2018) and adjusted to the county's area portion within each watershed.

For the purposes of constructing a rough agronomic N budget for each watershed, inputs included commercial N (CN), N generated by manure (MN), fixation N (FN) from the previous year's soybean crop while outputs included N harvested in the grain (GN) (Eq. 1).

$$\mathrm{CN} + \mathrm{MN} + \mathrm{FN} - \mathrm{GN} = \text{N surplus or deficit.} \quad (1)$$

Biological N fixation of soybean in 2016 was calculated according to Barry et al. (1993) using county-level crop areas and soybean yields adjusted to the area portion lying

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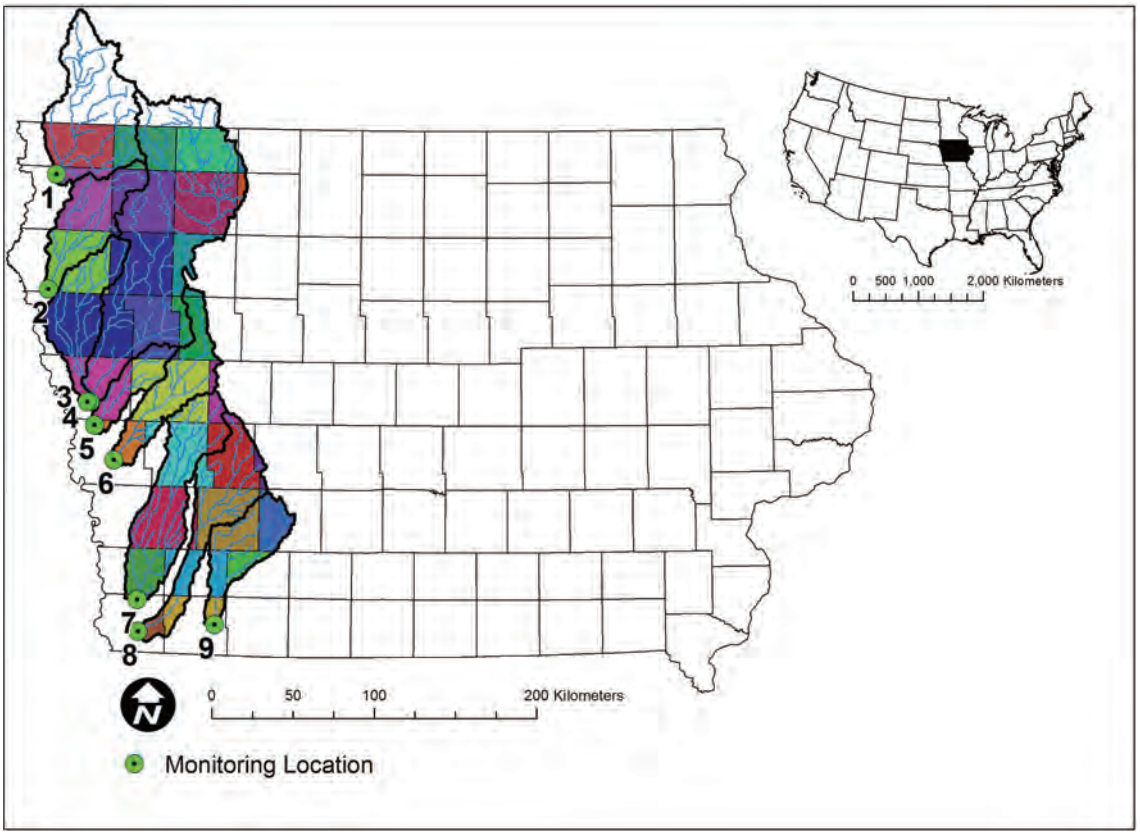

Fig. 1 Nine western Iowa watersheds are evaluated here. The number corresponds to the watershed number shown in Table 1. The green circle designates monitoring location near the outlet

within each watershed. Nitrogen harvested in corn grain was calculated using watershed crop yields and the measured average for Iowa corn reported by Blesh and Drinkwater (2013). Export of N in the harvested soybeans was calculated assuming 6.4% N in soybean seeds according to the USDA protocols using the Crop Nutrient Tool (2009).

Hydrology

Watershed precipitation totals for 2017 were estimated based on data collected at 22 stations within the individual watersheds and averaging data from each watershed location. These data were obtained from the Iowa State University Mesonet network (2017). Discharge data for all the sites were generated by the U.S. Geological Survey (USGS 2018). These 15-min interval data were aggregated into daily averages and the water yield was calculated by dividing total annual discharge by watershed area.

Water quality

High frequency (15 min) 2017 NO_3–N concentration data were obtained from the University of Iowa's Water Quality Information System (Jones et al. 2018b). This network of real-time water quality sensors measures NO_3–N concentrations at about 65 sites throughout Iowa including those shown in Fig. 1. Data quality for the network is governed by a QA/QC plan adopted from USEPA and USGS protocols. Basic QA protocols include systematic monitoring of incoming water quality data, remote monitoring of field sensor/system health (e.g., battery voltage and signal strength), automatic data review through the use of data thresholds and limits, and use of data descriptors for denoting state of data review. Measurements are generated by the Hach Nitratax sc plus (Loveland, CO, US) nitrate sensor and accuracy is verified through regular collection of grab samples that are lab-analyzed. Extensive details about measurement and quality control protocols can be found at Jones et al. (2018b). Data from the IDNR ambient monitoring program were used (IDNR 2018b) for periods when high-frequency data were missing (i.e., equipment malfunction and Dec–Feb). Linear interpolation was used to estimate NO_3–N concentrations on days with no NO_3–N data. Daily average NO_3–N concentrations were multiplied by daily average discharges and then summed to obtain annual NO_3–N loads and yields (load per watershed area). Flow weighted average (FWA) NO_3–N concentrations

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Table 1 Watersheds in the study area along with crop area, livestock densities, commercial N fertilizer application rates, and nitrogen generated from animal manure

Figure 1 Map No.	Name	Iowa area (km^2)	Area fractions						Animal Units (AU) ha^{-1} 2017	kg ha^{-1}			
			2012			2017				Corn + soybean area			Corn area only
			Corn	Soybean	Total corn–soybean	Corn	Soybean	Total corn–Soybean		Commercial N application rate (2012)	Manure N generated	Commercial N + generated manure N	Commercial N + generated manure N
1	Rock River	1748	0.50	0.33	0.81	0.44	0.34	0.78	5.00	116	111	227	369
2	Floyd River	2295	0.48	0.34	0.82	0.47	0.35	0.82	3.53	112	117	229	379
3	Monona-Harrison Ditch	2331	0.42	0.31	0.73	0.38	0.33	0.71	1.31	122	37	159	261
4	Little Sioux R.	8350	0.45	0.34	0.79	0.42	0.35	0.77	1.04	119	40	159	262
5	Soldier River	1049	0.46	0.31	0.76	0.42	0.33	0.75	0.76	128	22	150	240
6	Boyer River	2202	0.49	0.31	0.81	0.45	0.34	0.79	1.13	138	38	176	235
7	W. Nishnabotna R.	3434	0.44	0.32	0.76	0.40	0.35	0.75	0.68	121	23	144	241
8	E. Nishnabotna R.	2862	0.39	0.31	0.69	0.36	0.33	0.69	0.53	106	32	138	233
9	W. Nodaway R.	1974	0.33	0.29	0.63	0.32	0.32	0.64	0.45	91	24	115	201

Table 2 Factors used to calculate total animal units (AU). Populations are multiplied by the factors shown to quantify total AU

Animal species	Factor
Horses	2.0
Mature dairy cattle	1.4
Slaughter or feeder cattle	1.0
Immature dairy cattle	1.0
Hogs > 25 kg	0.4
Hogs 7–25 kg	0.1
Turkeys > 3 kg	0.018
Chickens > 1.4 kg	0.01
Turkeys < 3 kg	0.0085
Chickens < 1.4 kg	0.0025
Fish	0.001

were calculated by dividing total load by total discharge. Minnesota areas draining to the Rock and Little Sioux Rivers were used when calculating yields.

RESULTS

Agricultural

Current density of animals ranged from 0.45 (West Nodaway) to 5.00 AU ha^{-1} (Table 1). The Floyd (3.53 AU ha^{-1}) and Rock (5.00 AU ha^{-1}) watersheds had much higher animal densities than the other seven watersheds (average 0.84 AU ha^{-1}). Cattle and hogs are by far the largest contributors to AU units in all watersheds, and historical data for these species are shown in Fig. 2, illustrating how the concentration of hogs has risen since 1980 and cattle since 2002. Hog densities have increased since 1980 in the Rock, Floyd, Monona-Harrison Ditch, and Little Sioux watersheds and declined in the others, with the decline especially pronounced in the West Nodaway (− 80%) and increases largest in the Floyd (+ 126%) and Rock watersheds (+ 269%). Overall, hog populations increased 41% since 1980, but when the Floyd and Rock watersheds are excluded, the increase is only 4.2%. The Floyd and Rock watersheds also have the highest current cattle densities at 1.14 and 1.70 per ha, respectively. Since 2002, the average cattle population grew by 37%, but increased only 0.01% when the Rock and Floyd watersheds are excluded. Large declines in cattle populations occurred in the Soldier (− 46%) and West Nodaway (− 74%) watersheds.

Areas planted with corn and soybean were obtained for 2012 and 2017 (Table 1) for comparison with available fertilization and water quality data. Overall in the nine watersheds, the total corn–soybean area was 1.3% lower in

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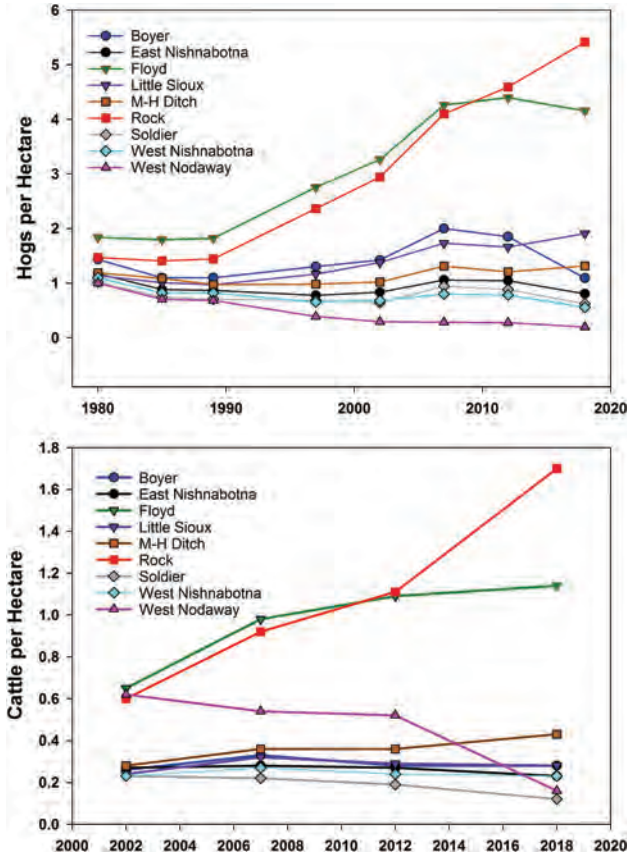

Fig. 2 Hog and cattle densities in the nine studied watersheds

2017 compared to 2012, with 6.2% less corn area and 5.4% more soybean area. Between watersheds, the biggest increase from 2012 to 2017 was in the West Nodaway (+ 1.6%) while the largest decrease was in the Monona-Harrison Ditch watershed (− 2.7%). Total corn–soybean area declined from 2012 to 2017 in all watersheds except the Floyd and West Nodaway. The cropped portion of each watershed ranged from 0.64 (West Nodaway) to 0.82 (Floyd) with an overall average of 0.74 in 2017.

The latest available fertilization data are from 2012 and are listed in Table 1. The commercial rates plus generated manure are based on 2012 crop areas and vary from 115 (West Nodaway) to 229 kg ha^{-1} of combined corn and soybean area. However, soybeans usually do not receive much nitrogen fertilizer in Iowa, with a statewide average of 15.7 kg ha^{-1} (Jones et al. 2016). Considering this, amounts per corn area alone ranged from 201 kg ha^{-1} (West Nodaway) to 379 kg ha^{-1} (Floyd) and averaged 269 kg ha^{-1} across all watersheds. Interestingly, the commercial N rates in the Rock watershed (116 kg ha^{-1} to all corn–soybean area) and the Floyd watershed (112 kg ha^{-1}) were similar to the nine-watershed average (117 kg ha^{-1}), this even with abundance of manure N generated by livestock (111 and 117 kg ha^{-1}, respectively). The commercial N rates in the West Nodaway watershed (91 kg ha^{-1} to all corn–soybean area) were lowest of the nine watersheds, even though the generated manure N was also quite low at 24 kg ha^{-1}, second lowest of the group.

Water quality and hydrology

The annual nitrate (NO_3–N), precipitation, and discharge data for 2017 are shown in Table 3. The precipitation recorded in the Rock (804 mm) and Floyd (759 mm) watersheds was substantially less than the other seven watersheds where the average was 917 mm. Despite lower amounts of rainfall, the Rock and Floyd each had the highest annual NO_3–N yields (24.7 and 30.5 kg ha^{-1}, respectively) and FWA NO_3–N concentration (11.5 and 16.2 mg L^{-1}, respectively) (Fig. 3). The averages for the other seven watersheds were 20.0 kg ha^{-1} (yield) and 7.3 mg L^{-1} (FWA concentration). The Monona-Harrison Ditch watershed had the lowest yield of NO_3-N (11.1 kg ha^{-1}) and the West Nodaway River had the lowest FWA concentration (4.9 mg L^{-1}).

Nitrogen budget

An estimated 2017 nitrogen budget was constructed assuming the fertilization rates from 2012 were relevant to 2017, using commercial N and manure data, crop yield data from 2017, and soybean area and yield from 2016 to calculate contributions from nitrogen fixation. This is shown in Table 4 along with the FWA NO_3–N concentrations for comparison. The surplus nitrogen, i.e., the amount applied as commercial fertilizer plus the amount generated by livestock plus the amount fixed by soybeans the previous year minus the amount harvested in the grain, ranged from 55 kg ha^{-1} (West Nodaway) to 161 kg ha^{-1} (Floyd) and averaged 99 kg ha^{-1} across the nine watersheds. The watersheds with the three largest surplus N values (Floyd, Rock, and Boyer) also had the three highest FWA concentrations while the watersheds with the two smallest surpluses also had the two smallest FWA concentrations. The average surplus for the Rock and Floyd (155 kg ha^{-1}) was nearly double the average of the other seven watersheds (83 kg ha^{-1}).

The FWA concentrations were well correlated with fertilization and crop area (Fig. 4). These concentrations correlated significantly ($p < 0.01$) with surplus nitrogen (fertilizer + manure + fixation-grain N), commercial + manure + fixation N, commercial + manure N, and manure N, and less significantly with area portion in corn and soybean ($p < 0.05$). The FWA concentrations did not correlate with commercial N ($p > 0.10$).

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Table 3 2017 hydrology and stream NO_3–N data

Watershed	Annual precipitation (mm)	Discharge[a]	NO_3–N measurement days (N)	NO_3–N yield (kg ha^{-1})	NO_3–N yield/precipitation (g ha^{-1} mm^{-1})	FWA[b] NO_3–N (mg L^{-1})
Rock River	804	215	115	24.7	30.7	11.5
Floyd River	759	188	284	30.5	40.2	16.2
Monona-Harrison Ditch	942	172	171	11.1	11.8	7.2
Little Sioux River	816	241	181	17.1	20.9	7.1
Soldier River	846	259	233	21.9	25.9	8.5
Boyer River	1056	312	249	27.1	25.7	8.7
West Nishnabotna River	846	291	293	23.9	28.3	8.2
East Nishnabotna River	974	430	193	23.7	24.3	5.5
West Nodaway River	963	282	288	13.9	14.4	4.9
Average	890	266	223	21.5	24.7	8.6

[a]Discharge calculated by dividing total discharge volume at the outlet by watershed area draining to the site

[b]FWA is Flow Weighted Average concentration, which is obtained by dividing total river NO_3–N load by total discharge

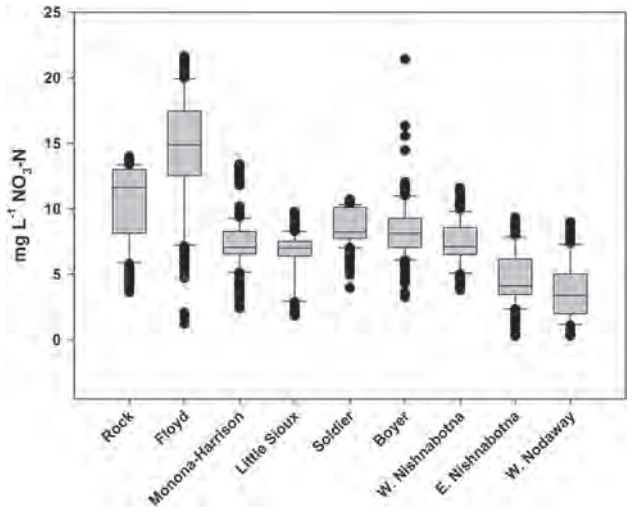

Fig. 3 Box plots of 2017 daily average NO_3–N concentrations. The boxes bracket the 25th–75th percentiles; the line in the box indicates the median; the whiskers the 10th and 90th percentiles, and the dots are data points less than (greater than) the 10th (90th) percentiles

DISCUSSION

Iowa State University (ISU) Extension guidelines for N application rates (kg ha^{-1}) range from 135 to 165 (average 150) for corn following soybean, and 193–221 (average 206) for corn following corn under the current price structure for commercial nitrogen fertilizer and corn grain (Sawyer 2016). When we adjust for statewide N rates to soybeans (15.7 kg ha^{-1}, Jones et al. 2016), commercial fertilizer data for 2012 show average annual commercial N rate to corn in these nine watersheds is 189 kg ha^{-1}, generally in-line-to-slightly-above ISU guidelines. However, these rates do not account for the substantial amounts of manure N generated in the nine watersheds, and especially in the Floyd and Rock watersheds, where the generated manure N is roughly equivalent to commercial N sales. After the generated manure N is added to commercial N, then the amount of N per corn-hectare exceeds ISU guidelines in all watersheds except the West Nodaway, where coincidentally the lowest FWA NO_3-N was recorded in 2017. In the Floyd and Rock watersheds, the commercial N plus N generated from manure sources is $\sim$ 370–380 kg ha^{-1} of corn (accounting for average N application to soybean), which is about double ISU recommendations. In these two watersheds, the "surplus" N (i.e., commercial + manure + fixation − grain) actually exceeds the ISU recommendations for corn grown after soybeans. It should be pointed out that this is based on 2012 animal populations and that hog and cattle numbers increased substantially in the Rock watershed since then (Fig. 2). The fate of all manure N applied to agricultural fields is not well understood. Some amount of the N in fresh animal manure is lost to volatilization (Kirchmann and Witter 1989) and never becomes available for crop uptake. There is evidence, however, that much of this volatilized N is deposited within 1 km of the confinement (Loubet et al. 2009) and McGinn et al. (2016) reported a 50% decline in deposition 200 m from a cattle confinement. Thus, much of this volatilized N is not lost from the watershed. Additionally, some portion of manure N is often in organic forms and not immediately available to plants after field application, a condition informed by testing the manure and soil for available N (NO_3–N and NH_4–N) (Paul and Beauchamp 1993). This organic N must eventually become available to crops and/or leach into the stream

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Table 4 Estimated 2017 nitrogen budget for using commercial N rates, generated livestock manure, soybean fixation from previous year, N harvested in the grain, and stream NO_3–N for comparison

Watershed	Commercial N + generated manure N (Kg NO_3–N ha^{-1} $year^{-1}$)	Fixation from 2016 soybean crop	Fixation from 2016 soybean crop	Commercial N + manure N + fixation N-grain N	FWA NO_3–N (mg L^{-1})
Rock River	226	100	178	148	11.5
Floyd River	229	107	175	161	16.2
Monona-Harrison Ditch	159	110	169	100	7.2
Little Sioux River	158	111	172	97	7.1
Soldier River	150	96	171	74	8.5
Boyer River	176	98	171	103	8.7
West Nishnabotna River	145	97	159	83	8.2
East Nishnabotna River	138	95	163	70	5.5
West Nodaway River	115	98	159	55	4.9

network, and thus it must be considered in watershed N budgets. Finally, it is likely some of the generated manures are being transported beyond watershed boundaries for application elsewhere. Long-range hauling (more than ~ 8 km), however, becomes economically problematic (Fleming et al. 1998) and there is evidence that farmers tend to apply manure on fields nearby confinements (Innes 2000; Jackson et al. 2000). Thus, the majority of manure generated within watersheds of the size studied here is likely to remain in that watershed. All things considered, the amount of purchased (commercial) N plus the amount of N generated by manure is far beyond crop nutrient requirements in some of these watersheds, and this surplus N will accumulate as decaying plant matter, soil organic matter and organisms, and soil water NO_3–N, creating a growing pool of mobile N (Jackson et al. 2000).

When 2017 water quality data are considered alongside these estimates of fertilization and generated manure, the Floyd and Rock watersheds stand out not only for their level of fertilization, but also for stream NO_3–N concentration levels. Despite the relative dryness in these two watersheds compared to the others, their FWA NO_3–N concentrations are nearly double those of the other seven when considered in aggregate (13.9 vs. 7.3 mg L^{-1}). Likewise, the commercial plus manure N in the West Nodaway and East Nishnabotna watersheds is only 60% of that in the Rock and Floyd, and this is reflected in stream water quality where NO_3–N concentrations are only 37% as high as in the Rock and Floyd watersheds. Howarth et al. (2012) estimated when net anthropogenic N inputs (NANI), similar to the surplus N described here, exceeded 1070 kg N km^{-2} $year^{-1}$, 25% of this amount on average was exported to rivers worldwide. The average surplus N for our nine watersheds was 4489 kg N km^{-2} during 2017, and an all-watershed average of 33% of this amount exited in the stream network. Our simple N budgets, which do not incorporate pathways such as atmospheric deposition of N and N returned to livestock in animal feed, still produce a value not that different from the Howarth et al. (2012) analysis, and our stream export values could be expected to exceed those of Howarth et al. (2012) because our surplus N is 4 times as large as the threshold in that study.

It is notable that the Rock watershed, with higher livestock densities than the Floyd watershed (Fig. 2), actually has lower levels of stream NO_3–N (Fig. 3). It is important to note that 58% of the Rock River watershed lies outside of the state of Iowa in Minnesota. The state of Minnesota Pollution Control Agency (MPCA) conducts NO_3–N water monitoring on the Rock River at a site about 18 stream-km north of the Iowa border (MPCA 2018). In 2017, six samples were collected by MPCA from April 26 to September 27 and averaged 8.48 mg L^{-1} NO_3–N. The concentrations downstream at Rock Valley, Iowa, the site of the monitoring conducted for this study, were 10.04 mg L^{-1} during that period. Thus, we suspect that lower concentrations of NO_3–N in water from Minnesota are diluting higher concentrations of NO_3–N in water contributed by Iowa portions of the Rock watershed.

Recently, the metric NO_3–N yield per unit of precipitation (g NO_3–N ha^{-1} mm P^{-1}) was used to compare NO_3–N delivery in seven Iowa watersheds (Jones et al. 2018c). In the second 15 years of that study (2002–2016), an average of 22 g NO_3–N ha^{-1} was mobilized to streams per mm of precipitation. For the 2017 water quality and hydrology data presented here, the nitrogen yield from the Floyd (40.2 g NO_3–N ha^{-1} mm P^{-1}) and Rock (30.7 g NO_3–N ha^{-1} mm P^{-1}) watersheds were considerably higher than the other seven, where the aggregated average was 22.0. The West Nodaway watershed received 204 mm more precipitation than the Floyd (27% more) but the NO_3–N yields were less than half, a clear indicator that the

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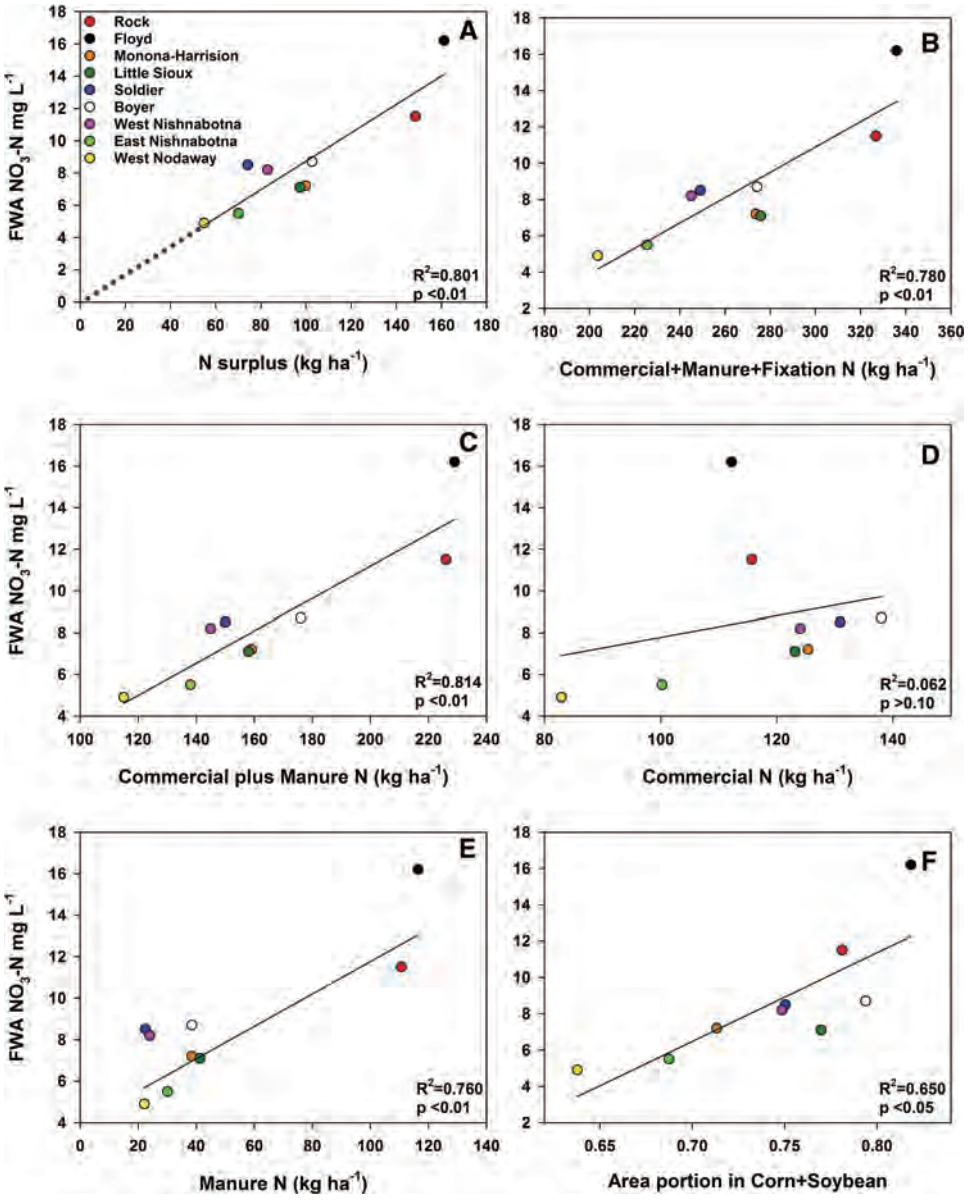

Fig. 4 Correlations of 2017 watershed Flow Weighted Average (FWA) NO_3–N concentrations with N surplus (**a**), sum of commercial, manure and fixation nitrogen (**b**), sum of commercial and manure nitrogen (**c**), commercial nitrogen (**d**), generated manure nitrogen (**e**), and area portion in corn and soybean (**f**). The dotted portion of the regression line in **a** is an extrapolation backward to a zero surplus condition. FWA is defined as total NO_3–N load divided by total discharge for 2017

supply of loss-vulnerable N was far higher in the Floyd watershed compared to the West Nodaway.

Li et al. (2013) evaluated NO_3–N concentrations and trends for Iowa streams from 1998 to 2012. Of the 48 Iowa streams in that study that had sufficiently long data records for trend analysis, the Rock and Floyd Rivers had the largest positive trends for NO_3–N concentration (0.33 and 0.29 mg L^{-1} $year^{-1}$, respectively) during a time when hog and cattle populations in the two watersheds were doubling (Fig. 2). The statistical significance of those trends was strong ($p < 0.01$). The other sites in that study that were also evaluated here included the West Nodaway River (increasing trend of 0.17 mg L^{-1} $year^{-1}$), Boyer River (0.16 mg L^{-1} $year^{-1}$), West Nishnabotna River (0.06 mg L^{-1} $year^{-1}$), Soldier River (0.03 mg L^{-1} - $year^{-1}$), and Little Sioux River (0.03 mg L^{-1} $year^{-1}$). Without detailed information about manure nitrogen quantities, Li et al. (2013) speculated that manure applications associated with increasing hog populations were a driving factor for the upward NO_3–N trends in western Iowa, and we believe the data presented herein are consistent with that.

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There are examples in the literature linking livestock concentration with surplus stream nutrients and degraded water quality in other parts of the world. For example, the northwestern Black Sea was seriously degraded from the 1960s to the 1980s by nutrient runoff from the Danube River, but rapidly improved after 1989 with the closure of many large animal farms as a result of the fall of communist regimes (Mee 2006). Considering that the average animal unit density in our study was 1.60 ha^{-1}, the average magnitude of N surplus we report (99 kg ha^{-1}) is consistent with research from other agricultural regions. For example, Wang et al. (2018) reported average N surpluses of 75-306 kg ha^{-1} when AU density exceeded 1 ha^{-1} for several countries in Europe, Asia, and the Americas. Oenema et al. (2007) reported highest levels of NO_3–N leaching in Europe to be in the northwest where livestock densities were highest. Leaching rates 20 to over 50 kg ha^{-1} were reported in that study, compared to 30.5 and 24.7 kg ha^{-1} for the Floyd and Rock watersheds, the two highest-density livestock watersheds of the nine assessed here. When considering the NO_3–N transported by these streams, and especially the Rock and Floyd Rivers, it is relevant to consider how this pollutant links to various processes that control stream amounts. At the landscape scale in the U.S. cornbelt, the NO_3–N loading is clearly transport-limited (Sprague et al. 2011; Jones et al. 2017). However, there are years within individual watersheds where supply limitations are controlling (Jones et al. 2017). Furthermore, fertilizer nitrogen has been shown to be a strong predictor and regulator of stream NO_3–N concentrations (David et al. 2010; Li et al. 2013). The Floyd and Rock were the two driest watersheds evaluated here, but still had by far the highest NO_3–N delivery of these nine western Iowa basins. The fact that in the Floyd and Rock watersheds, the commercial N inputs combined with generated manure N were nearly double the other watersheds illustrates the importance of N supply management for water quality improvement. There is ample evidence that U.S. Cornbelt farmers over-apply nitrogen, often in manure forms (Yadav et al. 1997; Jackson et al. 2000; Sheriff 2005; Khanal et al. 2014). This is not necessarily wasteful; rather, the economics of nitrogen can make it more profitable for farmers to concentrate manure applications on nearby fields and purchase chemical fertilizer for the rest of the farm (Letson et al. 1998). In fact, Jackson et al. (2000) concluded that in some scenarios it makes clear economic sense for large livestock confinements to maximize N volatilization losses. In these circumstances, manure becomes a waste product and the practice of squandering manure nutrients itself is not necessarily economically wasteful (Fleming et al. 1998; Sheriff 2005), i.e., the farmer may benefit financially by not fully taking advantage of the fertility benefits available in the generated manure. Many farmers may also manage manure application rates based not on N, but rather phosphorus and/or potassium. Farmers also may apply manure in the fall, followed by commercial fertilizer applications the following spring.

Interestingly, the N inputs in the West Nodaway watershed are in line with ISU recommendations for corn cultivation, and the FWA NO_3–N concentration was a relatively modest 4.9 mg L^{-1} and the daily concentration never exceeded the safe drinking water standard of 10 mg L^{-1}. This watershed illustrates the obvious opportunity for farmers and policy makers to make progress towards Iowa's water quality goal of a 45% NO_3–N load reduction (Iowa Nutrient Reduction Strategy 2013). Figure 4a indicates that reducing surplus N by better balancing inputs relative to expected crop needs would reduce stream NO_3–N levels. When considering Fig. 4a, extrapolating the regression backward to a zero surplus N condition results in a FWA NO_3–N concentration of < 1 mg L^{-1}. We acknowledge that legacy N (Van Meter et al. 2017) may elevate stream NO_3–N for prolonged periods after inputs are balanced with crop requirements and that the extrapolation in 4(A) is somewhat speculative. Nonetheless, it is apparent that better management and accounting of manure inputs could generate significant and rapid progress towards Iowa's water quality objective for stream N. The surplus N relates much more strongly to generated manure N ($R^2 = 0.83$) than commercial N inputs ($R^2 = 0.14$) among the nine watersheds and therefore this suggests a starting place when assessing inputs on the watershed scale. These findings are consistent with Khanal et al. (2014), who determined that manure-fertilized rotations had a higher net N (i.e., difference between inflows and outflows) statewide in Iowa. While the amount of N generated in livestock manure is not a precise estimate of what will be available to the receiving crop, methods exist to help reduce this uncertainty (Paul and Beauchamp 1993) and integration of commercial fertilizer and manure recommendation systems that account for soil fertility, crop needs, and availability of manure N is needed (Liu et al. 2017). With commercial fertilizer sales seemingly unrelated to the availability of manure N in these watersheds, refinements in planning and manure management hold great potential for producing water quality improvement in areas where livestock has been concentrated. Several policy recommendations were proposed by Jackson et al. (2000) to address similar issues in Central Iowa. These included alternative livestock housing, increased regulatory scrutiny of manure management plans, modification of land zoning rules, and incentivizing extended crop rotations that include small grains and forage legumes. Although now nearly 20 years old, we wish to emphasize that while these recommendations have mostly gone unheeded, they

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continue to hold potential for more efficient nitrogen use and water quality improvement.

CONCLUSIONS

While commercial fertilizer nitrogen input rates are similar among these nine western Iowa watersheds, generated manure N is far higher in two, the Floyd and Rock River watersheds, and the FWA NO_3–N concentrations at the outlets of these watersheds are approximately double that of the other seven. The commercial N inputs plus the generated manure N in these two watersheds total 370-380 kg corn ha^{-1}, which is about double the recommended application rates. The FWA NO_3–N concentration was significantly correlated with total N inputs and generated manure but not with commercial N fertilizer amounts. The only watershed where commercial fertilizer N inputs plus generated manure was consistent with the rate recommendations was the West Nodaway watershed, where the FWA NO_3–N concentrations were lowest and never exceeded 10 mg L^{-1}. Overall, the results from this study strongly suggest that better management of manure holds promise for producing significant water quality improvements at a watershed scale.

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REFERENCES

Andersen, D.S., and L.M. Pepple. 2017. A County-Level Assessment of Manure Nutrient Availability Relative to Crop Nutrient Capacity in Iowa: Spatial and Temporal Trends. *Transactions of the ASABE* 60: 1669–1680.

Barry, D.A.J., D. Goorahoo, and M.J. Goss. 1993. Estimation of Nitrate Concentrations in Groundwater Using a Whole Farm Nitrogen Budget. *Journal of Environmental Quality* 22: 767–775.

Blesh, J., and L.E. Drinkwater. 2013. The Impact of Nitrogen Source and Crop Rotation on Nitrogen Mass Balances in the Mississippi River Basin. *Ecological Applications* 23: 1017–1035.

Commoner, B. 1977. Cost-Risk-Benefit Analysis of Nitrogen Fertilization: A Case History. *Ambio* 6: 157–161.

David, M.B., L.E. Drinkwater, and G.F. McIsaac. 2010. Sources of Nitrate Yields in the Mississippi River Basin. *Journal of Environmental Quality* 39: 1657–1667.

David, M.B., L.E. Gentry, D.A. Kovacic, and K.M. Smith. 1997. Nitrogen Balance in and Export from an Agricultural Watershed. *Journal of Environmental Quality* 26: 1038–1048.

Delgado, C., M. Rosegrant, H. Steinfeld, S. Ehui, and C. Courbois. 2001. Livestock to 2020: The Next Food Revolution. *Outlook on Agriculture* 30: 27–29.

Fleming, R.A., B. Babcock, and E. Wang. 1998. Resource or Waste? The Economics of Swine Manure Storage and Management. *Review of Agricultural Economics* 20: 96–113.

Gronberg, J.M., and N.E. Spahr. 2012. County-level estimates of nitrogen and phosphorus from commercial fertilizer for the Conterminous United States, 1987–2006: U.S. Geological Survey Scientific Investigations Report 2012-5207. https://pubs.usgs.gov/sir/2012/5207/.

Gronberg, J.M., and T.L. Arnold. 2017. County-level estimates of nitrogen and phosphorus from animal manure for the conterminous United States, 2007 and 2012, U.S. Geological Survey Open-File Report 2017-1021, https://doi.org/10.3133/ofr20171021.

Hatfield, J.L., L.D. McMullen, and C.S. Jones. 2009. Nitrate–Nitrogen Patterns in the Raccoon River Basin Related to Agricultural Practices. *Journal of Soil and Water Conservation* 64: 190–199.

Hendrickson, M.K., and H.S. James. 2005. The Ethics of Constrained Choice: How the Industrialization of Agriculture Impacts Farming and Farmer Behavior. *Journal of Agricultural and Environmental Ethics* 18: 269–291.

Herriges, J.A., S. Secchi, and B.A. Babcock. 2005. Living with Hogs in Iowa: The Impact of Livestock Facilities on Rural Residential Property Values. *Land Economics* 81: 530–545.

Honeyman, M.S., and M.D. Duffy. 2006. Iowa's Changing Swine Industry. *Animal Industry Report* 652: 64.

Howarth, R., D. Swaney, G. Billen, J. Garnier, B. Hong, C. Humborg, P. Johnes, C.M. Mörth, and R. Marino. 2012. Nitrogen Fluxes from the Landscape are Controlled by Net Anthropogenic Nitrogen Inputs and by Climate. *Frontiers in Ecology and the Environment* 10: 37–43.

IAC (Iowa Administrative Code) 2018. Chapter 65.1. https://www.legis.iowa.gov/docs/iac/rule/11-09-2016.567.65.1.pdf.

IDNR, Iowa Department of Natural Resources, 2018a. Iowa DNR Animal Feeding Operation Database. https://programs.iowadnr.gov/animalfeedingoperations/.

Innes, R. 2000. The Economics of Livestock Waste and Its Regulation. *American Journal of Agricultural Economics* 82: 97–117.

Iowa DNR, Iowa Department of Natural Resources 2018b. Iowa's Ambient Water Quality Monitoring and Assessment Program. http://www.iowadnr.gov/Environmental-Protection/Water-Quality/Water-Monitoring.

Iowa Nutrient Reduction Strategy. 2013. A Science-and Technology-Based Framework to Assess and Reduce Nutrients to Iowa Waters and the Gulf of Mexico. http://publications.iowa.gov/23225/.

Iowa State University, College of Agriculture, Department of Agronomy. 2017. Iowa Environmental Mesonet, IEM Climodat Reports. From: http://mesonet.agron.iastate.edu/climodat/index.phtml.

Jackson, L.L., D.R. Keeney, and E.M. Gilbert. 2000. Swine Manure Management Plans in North-central Iowa: Nutrient Loading and Policy Implications. *Journal of Soil and Water Conservation* 55: 205–212.

Jones, C.S., C.A. Davis, C.W. Drake, K.E. Schilling, S.H. Debionne, D.W. Gilles, I. Demir, and L.J. Weber. 2018a. Iowa Statewide Stream Nitrate Load Calculated Using In Situ Sensor Network. *JAWRA Journal of the American Water Resources Association* 54: 471–486.

Jones, C.S., K.E. Schilling, I.M. Simpson, and C.F. Wolter. 2018b. Iowa stream nitrate, discharge and precipitation: 30 year perspective. *Environmental Management*. https://doi.org/10.1007/s00267-018-1074-x.

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Jones, C.S., J.K. Nielsen, K.E. Schilling, and L.J. Weber. 2018c. Iowa Stream Nitrate and the Gulf of Mexico. *PLoS ONE* 13: e0195930.

Jones, C.S., A. Seeman, P.M. Kyveryga, K.E. Schilling, A. Kiel, K.-S. Chan, and C.F. Wolter. 2016. Crop Rotation and Raccoon River Nitrate. *Journal of Soil and Water Conservation* 71: 206–219.

Jones, C.S., B. Wang, K.E. Schilling, and K.S. Chan. 2017. Nitrate Transport and Supply Limitations Quantified Using High-Frequency Stream Monitoring and Turning Point Analysis. *Journal of Hydrology* 549: 581–591.

Khanal, S., R.P. Anex, B.K. Gelder, and C.F. Wolter. 2014. Nitrogen Balance in Iowa and the Implications of Corn-Stover Harvesting. *Agriculture, Ecosystems & Environment* 183: 21–30.

Kirchmann, H., and E. Witter. 1989. Ammonia Volatilization During Aerobic and Anaerobic Manure Decomposition. *Plant and Soil* 115: 35–41.

Klepper, R., 1974. Fertilizer application rates and nitrate concentrations in Illinois surface waters. National Agricultural Library. http://agris.fao.org/agris-search/search.do?recordID=US201300533223.

Letson, D., N. Gollehon, C. Kascak, V. Breneman, and C. Mose. 1998. Confined Animal Production and Groundwater Protection. *Review of Agricultural Economics* 20: 348–364.

Li, D., K.-S. Chan, and K.E. Schilling. 2013. Nitrate Concentration Trends in Iowa's Rivers, 1998 to 2012: What Challenges Await Nutrient Reduction Initiatives? *Journal of Environmental Quality* 42: 1822–1828.

Libra, R.D., C.F. Wolter, and R.J. Langel. 2004. Nitrogen and phosphorus budgets for Iowa and Iowa watersheds. https://ir.uiowa.edu/cgi/viewcontent.cgi?article=1046&context=igs_tis.

Liu, Q., J. Wang, Z. Bai, L. Ma, and O. Oenema. 2017. Global Animal Production and Nitrogen and Phosphorus Flows. *Soil Research* 55: 451–462.

Loubet, B., W.A. Asman, M.R. Theobald, O. Hertel, Y.S. Tang, P. Robin, M. Hassouna, U. Dämmgen, S. Genermont, P. Cellier, and M.A. Sutton. 2009. Ammonia deposition near hot spots: processes, models and monitoring methods. *Atmospheric Ammonia*, 205–267. Dordrecht: Springer.

McGinn, S.M., H.H. Janzen, T.W. Coates, K.A. Beauchemin, and T.K. Flesch. 2016. Ammonia Emission from a Beef Cattle Feedlot and Its Local Dry Deposition and Re-emission. *Journal of Environmental Quality* 45: 1178–1185.

Mee, L. 2006. Reviving Dead Zones. *Scientific American* 295: 78–85.

MPCA, Minnesota Pollution Control Agency, Environmental Data Access. 2018. https://cf.pca.state.mn.us/eda/stationInfo.php?ID=S000-687&ORG=MNPCA&wdip=2.

Oenema, O., D. Oudendag, and G.L. Velthof. 2007. Nutrient Losses from Manure Management in the European Union. *Livestock Science* 112: 261–272.

Paul, J.W., and E.G. Beauchamp. 1993. Nitrogen Availability for Corn in Soils Amended with Urea, Cattle Slurry, and Solid and Composted Manures. *Canadian Journal of Soil Science* 73: 253–266.

Rabalais, N.N., R.E. Turner, and W.J. Wiseman Jr. 2002. Gulf of Mexico Hypoxia, Aka "The dead zone". *Annual Review of Ecology and Systematics* 33: 235–263.

Sawyer, J.E., 2016. Iowa State University, Extension and Outreach Publications 5-2016. Nitrogen use in Iowa corn production. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1081&context=extension_pubs.

Sheriff, G. 2005. Efficient Waste? Why Farmers Over-apply Nutrients and the Implications for Policy Design. *Review of Agricultural Economics* 27: 542–557.

Sprague, L.A., R.M. Hirsch, and B.T. Aulenbach. 2011. Nitrate in the Mississippi River and Its Tributaries, 1980 to 2008: Are We Making Progress? *Environmental Science and Technology* 45: 7209–7216.

USDA, 2009. Natural Resources Conservation Service, Crop Nutrient Tool, Plants Database. A tool for calculating the approximate amount of nitrogen, phosphorus, and potassium that is removed by the harvest of agricultural crops. https://plants.usda.gov/npk/main.

USDA. National agricultural statistics service quick stats. 2018. https://quickstats.nass.usda.gov/.

USGS, 2018. National Water Information System, Web Interface, Current Conditions for Iowa: Streamflow. https://waterdata.usgs.gov/ia/nwis/current/?type=flow.

Van Meter, K.J., N.B. Basu, and P. Van Cappellen. 2017. Two Centuries of Nitrogen Dynamics: Legacy Sources and Sinks in the Mississippi and Susquehanna River Basins. *Global Biogeochemical Cycles* 31: 2–23.

Wang, J., Q. Liu, Y. Hou, W. Qin, J.P. Lesschen, F. Zhang, and O. Oenema. 2018. International Trade of Animal Feed: Its Relationships with Livestock Density and N and P Balances at Country Level. *Nutrient Cycling in Agroecosystems* 110: 197–211.

Yadav, S.N., W. Peterson, and K.W. Easter. 1997. Do Farmers Overuse Nitrogen Fertilizer to the Detriment of the Environment? *Environmental & Resource Economics* 93: 323–340.

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Report on Nitrogen Surplus in Minnesota Driftless

Christopher S. Jones, Ph.D.

2025

I. Introduction

Geologists have observed a lack of glacial 'drift', the material deposited on the landscape by glaciers and glacial meltwater, in areas of Southeast Minnesota, Northeast Iowa, Southwest Wisconsin, and Northwest Illinois since the since the middle of the 19th century. Often known as the "Driftless Area" to residents of the four states, it is now known that only areas east of the Mississippi River are completely without drift, and glaciers even advanced east of the present-day Mississippi in some places (1). Thus, Driftless Area as a technical term attached to the physiography of the area has been mostly abandoned by scientists in recent decades. The term still, however, retains important cultural significance for the region's residents and is often referred to in policy discussions concerning these areas.

The glaciated and unglaciated portions do share similar topography and the same ecological systems, i.e. transition areas from eastern hardwood forest to savanna and tallgrass prairie. While evidence of glacial drift and other glacial features such as moraines and erratic granitic boulders are present in the Iowa and Minnesota areas, the landscape-shaping forces of glaciation were far less dramatic than in the rest of those two states. To accommodate the glacial evidence west of the Mississippi River, the region has also been referred to as the Upper Mississippi River Hill Country (2) and the Paleozoic Plateau (3). The commonly recognized term Driftless Area will be used here going forward for the purposes of simplicity.

Despite the lack of glacial drift in the Iowa (IA) and Minnesota (MN) portions of The Driftless, the underlying bedrock geology characteristic of the Paleozoic Period (541-242 million years BP) is consistent with that in the Wisconsin (WI) and Illinois (IL) portions. IA and MN Driftless topography is similar to WI and IL because the erosional forces shaping the area occurred relatively recently in geological time, i.e. the Pleistocene (2.5 million to 12,000 years BP) and Holocene (12,000 BP to now) periods. So, while patchy glacial deposits exist, especially on the stream divides in MN and IA, the effect of water erosion was largely the same in all four states.

It's noteworthy that streams flow into the Driftless Area, but only in a very few circumstances flow out of the region. The watershed divides separating the Driftless and non-Driftless areas are around 1200-1300' elevation while the receiving Mississippi River is around 650', creating a steep drop of ~600' in 150 miles (or less) and an overall slope of 4'/mile for major rivers like the Cannon, Upper Iowa, and Root Rivers, far greater than what exists in the non-Driftless areas of the four states. The increased stream energy associated with this slope created the dramatic relief characteristic of the region.

The enhanced erosional condition left the region with thin topsoils (compared to much of the rest of the four states) and steep hillslopes. As a result, the suitability of the region for agriculture, especially row crop agriculture requiring tillage, is diminished except in the flatter upland areas. The underlying limestone and dolomite bedrock, relatively close to the earth's surface, exhibits extensive Karst development through the dissolving action of water on the carbonate materials. Karst characteristics include topographic forms such as sinkholes and springs at the land surface and development of cavern systems beneath the surface (3). Rainwater infiltrates through the surface to the bedrock and then travels through fracture traces in the rock, transporting contaminants from the surface in addition to dissolving soluble salts within the bedrock. This action helps characterize the composition of groundwater resources (i.e. aquifers) in the region. Thus, while water infiltration is usually considered an overall good in a farmed landscape because it reduces surface runoff and soil erosion, it can in fact lead to aquifers severely contaminated with agricultural and other anthropomorphic pollution (4,5,6,7,8). As a result, many private and public water supply wells in the Driftless Area have been contaminated with nitrate and other contaminants (4,9,10,11,12,13).

The Driftless Area was recognized for its great natural beauty by indigenous people and the earliest European settlers. The steep wooded hills, green vales (coulees), clear streams teeming with trout, and the stunning vistas of the bisecting Upper Mississippi River Bluff Country have inspired some to say it is one of the most beautiful landscapes on earth (2). But as Stanley Trimble, the pre-eminent geological expert on the region noted, "in the early 20th century, the region went through a dark and desperate period of soil erosion, stream sedimentation, and flooding. In a real sense, the landscape was out of control (2)." The nightmare scenarios caused by agriculture-driven erosion are mostly a thing of the past, thanks to soil conservation measures developed in the 1930s and implemented since then and right up to the present day. But over the past 50 years, the region's agriculture has been transitioning from one featuring bucolic farms characterized by diverse and integrated crop-livestock systems to that of intense corn-soybean rotations with animals concentrated in huge numbers on a subset of farms. Agriculture lying within this geological oddity is increasingly inspired to emulate the agricultural systems and practices of the surrounding cornbelt, with one apparent outcome being a new "dark and desperate period", not of soil erosion but of groundwater contamination.

II. Minnesota Driftless

All or parts of eight southeastern Minnesota counties are located within the Driftless Area: Dodge, Fillmore Goodhue, Houston, Mower, Olmstead, Wabasha and Winona (Fig. 2). Table 1 below illustrates the largest city in each county, the county's population, and the population change since 1980. Figure 3 illustrates population change in each county.

Table 1: Population trends of 8 Southeast Minnesota Counties

county	Largest City	1980	1990	2000	2010	2020	1980-2020 change	% change
DODGE	Kasson	14,773	15,731	17,731	20,087	20,987	6214	42.1
FILLMORE	Spring Valley	21,930	20,777	21,122	20,866	21,135	-795	-3.6
GOODHUE	Red Wing	38,749	40,690	44,127	46,183	46,318	7569	19.5
HOUSTON	Caledonia	18,382	18,497	19,718	19,027	18,632	250	1.4
MOWER	Austin	40,390	37,385	38,603	39,163	40,150	-240	-0.6
OLMSTED	Rochester	92,006	106,470	124,277	144,248	159,300	67294	73.1
WABASHA	Lake City	19,335	19,744	21,610	21,676	21,642	2307	11.9
WINONA	Winona	46,256	47,828	49,985	51,461	50,485	4229	9.1
TOTAL	Rochester	291,821	307,122	337,173	362,711	378,649	86828	29.8

As shown in Table 1, total population in the Minnesota 'Driftless' area has increased about 30% since 1980. Minnesota population as whole has increased 40% during that time, while US population has increased 46%. Olmstead County, the most populated of the eight counties, accounts for 73% of the Minnesota Driftless population growth, and Olmstead, Goodhue, and Dodge Counties account for 93%. Fillmore and Mower counties were both less populated in 2020 than in 1980, although the population of Mower County has been growing slowly but steadily since 1990. It's likely that growth in Olmstead County has also driven some population growth in surrounding counties.

III. Drinking Water in the Eight Driftless Counties

Groundwater obtained from both municipal supply wells and privately-owned wells provides virtually all the water needed by the counties' residents. Even communities such as Red Wing, Lake City and Winona that have access to a suitable surface water source—the Mississippi River—use groundwater for municipal supply. This is because groundwater quality is less dynamic and thus more predictable, simplifying water treatment and reducing infrastructure costs, especially for small communities.

Southeast Minnesota has reliable bedrock aquifers whose aesthetic quality (hardness, iron, odor, taste, etc.) is exceptional in most circumstances. These bedrock aquifers reside within laterally extensive sequences of sandstone, siltstone, and sedimentary

limestone and dolomite. Water resides in granular pore spaces, partings, joints, fractures, and dissolution features. Karst (e.g., sinkholes, solution conduits, fracture-flow, caves) is common and water availability from it is usually suitable to very good, but water quality is easily impacted by human activity on the surface (13). Some communities do use shallow wells lying within the water table that would be considered to have a different set of vulnerabilities and contaminant pathways than wells drawing from Karstic formations. For example, Lake City, which lies on the banks of the Mississippi River, uses four 'Water Table' wells all less than 163 feet deep. The City of Wabasha also uses similar shallow wells. Deep bedrock aquifers in the region include the Jordan, St. Peter, Mount Simon, Fond du Lac, and Prairie du Chien aquifers. Private wells across the eight counties can vary greatly in depth, formation, age, and maintained condition, all of which affect their vulnerability to surface pollution and their subsequent water quality.

It's well known that many water supply wells in the southern half of Minnesota are contaminated with nitrate at levels that present a health risk (14). Nitrate is the fully oxidized fate of nitrogen released to the environment and comprises the vast majority of nitrogen in most streams, lakes and aquifers. The EPA drinking water standard for the contaminant in municipal supply is 10 mg/L as Nitrogen (N). Community water supplies delivering water above this limit are considered out-of-compliance with drinking water regulations. The 10 mg/L limit dates to the first days of the Safe Drinking Water Act (1974) and was intended to be protective of infants that may consume baby formula prepared with such water. High nitrate water is a cause of methemoglobinemia (blue baby syndrome) in children less than 6 months of age because of an undeveloped assemblage of intestinal organisms that otherwise would metabolize the nitrate, rendering it harmless to the baby. Emerging evidence has shown that levels of nitrate-N less than 5 mg/L may present health risks to adults consuming this water over several years or a lifetime (15,16,17,18,19) and prenatal effects to infants and mothers (20). About 4% of Minnesota wells have tested above 3 mg/L (level indicating human contamination) and about 1% of monitored wells test above 10 mg/L every year (14) (Fig. 4). The Minnesota Department of Agriculture (MDA) Township Testing Program found that over 40 percent of the private wells sampled in some townships in Southeastern Minnesota contain nitrate-N above 10 mg/L (14). In total, 12.1% (1058) of the tested wells exceeded 10 mg/L in the region.

The most recent data compiled by the Minnesota Pollution Control Agency (MPCA) from the Township Testing Program and additional state databases show that 11.9% of the 5533 tested wells and springs exceeded 10 mg/L nitrate-N (or nitrate-nitrite-N) for the period 2014-2018. From 2018-2022, the same dataset shows 16.1% of the 1651 tested

wells and springs exceed 10 mg/L nitrate-N. Nearly all Southeast Minnesota is considered to be in moderate to high risk for groundwater nitrate contamination (Fig. 5).

IV. Causes of Nitrate Pollution

The corn-soybean system that predominates in the US Midwest has long been known to 'leak' nitrogen to the surrounding environment (21,22,23,24,25,29), and the loss of nitrate and other agricultural pollutants from corn/soy systems is an ongoing local, regional and national problem resulting in impairment of surface and groundwater resources (21,22,23,24,25).

The fundamental issue with this is that fertilizer (commercial formulations and manure nutrients) applications almost by necessity are not synchronized with crop (especially corn) nutrient needs, and thus it's intuitive that some inputs will be lost before crop uptake. As a result, farmers are often motivated to apply more nutrient (in this case N) than what will be removed in the crop. A significant amount of N inputs is applied in the Autumn months and since corn nutrient needs become most robust in the month of June, that applied material must remain in place for eight months in some circumstances, a colossal challenge considering weather conditions in US Midwest can be extreme and dynamic due to its mid-continental location.

Midwestern soils commonly contain high levels of organic matter (30,31) and this is one factor in why much of the land is suitable for row crop agriculture. Much of this organic matter is comprised of amino acids and other N-containing compounds. These forms of nitrogen are not 'plant available' but the N becomes available as biological processes 'mineralize' the organic N to plant available forms, i.e. nitrate and ammonia primarily. Depending on the soil, which can vary significantly both within a field and across a region, a significant portion of the nitrogen used by the crop can be sourced to these processes. In the native ecosystems of the region (i.e. prairie, wetland, savanna) this process was in sync with the nutrient needs of the native perennial plant species. Corn and soybean, however, are non-native annual plants and the timing of their nutrient needs are unaligned with this process in some years. Thus, some of the N lost to streams, lakes, and aquifers can be sourced to soil organic matter but is a result of landscape decisions made by cornbelt farmers. The amount of N used by a corn crop that can be sourced to these processes is variable but well known (32).

Countless researchers have investigated strategies to reduce N loss from corn-soybean systems over the past 50 years. These strategies can be classified as either in-field or edge-of-field practices. In field practices require modification of farmer decisions and methods of production. Edge-of-field practices trap some portion of the N-laden water

leaving the field in ways that allow biological processes to consume the N. Constructed wetlands are an example. Many strategies of both types exist and financial assistance for farmer adoption is available through publicly funded state and federal conservation programs. This approach to conservation, which relies on voluntary adoption of conservation by cornbelt farmers, has mostly failed to stem N pollution at both the local and regional scale (33,34,35,36,37). The reason for the failure is three-fold: 1) far less conservation adoption than what is needed to affect water quality improvements at the landscape scale; 2) continued expansion of drivers of the pollution (more crop acres, more fertilizer, more livestock and manure, and more agricultural drainage tile which increases surface water N pollution and 3) a recalcitrance to aligning N inputs with crop N needs. As to point 3), this system fundamentally has what is known as a mass balance problem, i.e. more N is applied to fields than what is removed in the grain harvest. This surplus N can be sequestered in the farmed soils through a process known as immobilization, but much of it enters the surrounding environment, i.e. lakes, streams, aquifers, atmosphere. Land grant universities in Midwest states including Minnesota have attempted to address this imbalance with an 'N Rate Calculator' (38) that uses corn and N prices to recommend application rates that will optimize economic return without wasting N to the environment, but this tool has not substantially corrected the mass imbalance of N on the landscape.

What follows in subsequent sections is an analysis of the N budget for the eight counties of the Minnesota Driftless Area, and a discussion about possible solutions to the N pollution going forward.

V. Southeast Minnesota Crops

The region has been farmed using techniques common to Western agriculture since the earliest days of European settlement. While much of the land is considered of lesser quality for agriculture compared to the rest of the Cornbelt, weather is very suitable for a variety of crops and irrigation, while present, is not considered necessary for most crop production scenarios. Steep hillslopes and thinner topsoils (compared to areas of Minnesota lying to the west) limit crop production in many areas, with topographical relief increasing with decreasing distance to the Mississippi River and major tributaries. Surface runoff from steep slopes is a strong driver of soil erosion while water infiltration in the more level (and more frequently cropped) areas can transport nitrate and other contaminants to aquifers through Karstic features like sinkholes and bedrock fractures. Thus, while yields of corn and soybeans can be quite high from cropped acres in MN Driftless counties, groundwater vulnerability is disproportionately high in this area due to its peculiar geological features.

Prior to 1990, Southeast Minnesota farms featured a diverse assemblage of cash and forage crops including corn, soybean, and oats along with alfalfa and other hay/haylage crops. Beginning around 1986, however, increased soybean acreage began to displace oats and alfalfa (Fig. 6), requiring an increased reliance on commercial nitrogen fertilizers for many farmers as livestock were concentrated on fewer and fewer farms. This specialization and especially the loss of crop diversity has been shown to be a strong driver of nitrate loss to the surrounding environment (21). In the present day, corn and soybean crops dominate in Southeast Minnesota (Table 2).

Table 2: Total, corn and soybean area in the 8 Driftless Counties. Areas are in acres. Data source: USDA-NASS Quickstats.

County	Total County Area	Average Corn Area, 2010-20	Average Soybean Area, 2010-20	% of Land in Corn and Soy Production
Dodge	280,960	121,000	84,964	73
Fillmore	551,040	181,227	89,718	49
Goodhue	484,480	157,227	92,555	52
Houston	353,280	60,109	28,322	25
Mower	455,040	200,182	147,700	76
Olmstead	417,920	118,864	70,670	45
Wabasha	334,720	94,018	38,678	40
Winona	400,640	83,691	29,120	28

The data in Table 2 illustrate the effect of slope on cropped area. As topographical relief (i.e. hilliness) increases from west to east toward the Mississippi River, the proportion of land that can be cropped decreases in the counties bordering the Mississippi (Houston and Winona, for example).

Nitrogen is removed in the crop harvest and the N content of corn and soybean grain is well known (39). By obtaining the corn and soy yields for the counties from the USDA-NASS database (41) and applying the crop areas (41) shown in Table 2, the harvested N is shown in Table 3. Also shown in Table 3 is the amount of N that could be expected to be available to the next year's corn crop by soybean fixation, based on the recommendation of the University of Minnesota (average 38 pounds per acre) (40). It's important to recognize that the amount N actually fixed by a soybean crop is far larger than 38 pounds per acre (42), but since the University of Minnesota Extension value is conservative from a policy and agronomic standpoint, it is used here.

Table 3: Corn and soybean area, harvest, grain nitrogen, and soybean N fixation in the 8 MN Driftless Counties, 2010-20.

year	corn acres	soy acres	corn bushels	soybean bushels	N removed in corn (lbs)	N removed in soybean (lbs)	total N removed in grain (lbs)	Common soybean Credit (38 lbs/ac)
2010	981,000	603,000	174,242,000	31,426,000	117,090,624	120,675,840	237,766,464	23297890
2011	1,059,900	569,000	178,350,000	27,007,000	119,851,200	103,706,880	223,558,080	22,914,000
2012	1,107,800	534,600	191,969,632	29,995,589	129,003,593	115,183,062	244,186,654	21,622,000
2013	830,500	481,400	129,180,000	21,697,000	86,808,960	83,316,480	170,125,440	20,314,800
2014	1,100,800	553,600	183,077,000	28,044,000	123,027,744	107,688,960	230,716,704	18,293,200
2015	1,012,000	554,500	180,584,000	31,730,000	121,352,448	121,843,200	243,195,648	21,036,800
2016	1,050,700	582,700	192,590,000	34,253,000	129,420,480	131,531,520	260,952,000	21,071,000
2017	991,300	649,200	203,002,474	34,521,122	136,417,662	132,561,107	268,978,769	22,142,600
2018	1,003,300	563,100	180,634,000	31,202,000	121,386,048	119,815,680	241,201,728	24,669,600
2019	1,035,300	465,400	176,732,000	23,580,000	118,763,904	90,547,200	209,311,104	21,397,800
2020	1,006,900	461,000	182,305,000	26,252,000	122,508,960	100,807,680	223,316,640	17,685,200

VI. Fertilization With Commercially Available Products

Sales of commercial fertilizer are tracked by the Minnesota Department of Agriculture at the county scale (43). Several different N-containing products are sold, all containing different percentages of nitrogen. Using sales data for these products and the N content, the amount of commercial N applied to cropped fields in the eight Minnesota Driftless Counties was estimated. It stands to reason that some material is used in a county different from where it was purchased. But this works both ways—commercial fertilizer both leaves and enters the county, and for this analysis, it is safely assumed that these amounts are approximately equal. The amount of commercial fertilizer for the eight counties is shown in Table 4 below.

Table 4: Nitrogen (N) contained within commercial fertilizer products sold/applied in the eight MN Driftless Counties. Data source: MN Department of Agriculture.

year	commercial N lbs (2)
2010	127,146,000
2011	159,368,000
2012	162,070,000
2013	133,776,000
2014	181,806,000
2015	163,332,000
2016	163,480,000
2017	176,126,000
2018	172,110,000
2019	180,300,000
2020	188,726,000

The amount of commercial fertilizer applied shown in table 4 added to the soybean credit (38 lbs/ac) in table 3, aligns fairly well with, but is about 18% less, than the amount of nitrogen removed in the grain, as a long term average. This is shown in table 5.

Table 5: Comparison of Commercial N sold plus Soybean N Credit versus N harvested in the grain.

year	commercial N (lbs)	N from soybean credit (lbs)	commercial N + Soybean Credit (lbs)	N removed in corn and soy grain (lbs)	Balance (lbs)	% Deficit	Deficit per corn acre (lbs)
2011	159,368,000	22,914,000	182,282,000	223,558,080	-41,276,080	-18.5	-38.9
2012	162,070,000	21,622,000	183,692,000	244,186,654	-60,494,654	-24.8	-54.6
2013	133,776,000	20,314,800	154,090,800	170,125,440	-16,034,640	-9.4	-19.3
2014	181,806,000	18,293,200	200,099,200	230,716,704	-30,617,504	-13.3	-27.8
2015	163,332,000	21,036,800	184,368,800	243,195,648	-58,826,848	-24.2	-58.1
2016	163,480,000	21,071,000	184,551,000	260,952,000	-76,401,000	-29.3	-72.7
2017	176,126,000	22,142,600	198,268,600	268,978,769	-70,710,169	-26.3	-71.3
2018	172,110,000	24,669,600	196,779,600	241,201,728	-44,422,128	-18.4	-44.3
2019	180,300,000	21,397,800	201,697,800	209,311,104	-7,613,304	-3.6	-7.4
2020	188,726,000	17,685,200	206,411,200	223,316,640	-16,905,440	-7.6	-16.8

It's clear that the gap between the amount of N sold plus the soybean N credit and the amount removed in the grain narrowed in the most recent years. Overall, that gap varied from 73 lbs/ac (2016) to 7 lbs/ac (2019). A relevant question is whether the narrowing of the gap is due to increased fertilizer application or increased grain yields, which would concomitantly increase N harvested in the grain. In this case, it's clear the narrowing of the gap is due to increased sales of N fertilizer. Since N is typically only applied to corn and not soybeans, the amount of N sold is going to be highly dependent on the number of acres planted to corn. Other factors can also contribute, namely, the price of both N and corn. Figure 6 illustrates that there is a clear trend of increased commercial N fertilizer application, while the amount of N removed at harvest in the grain is static.

To summarize this section, commercial fertilizer sales coupled with the soybean N credit are on average 18% and 41.5 pounds per corn acre less than what is being removed in the corn and soybean harvested grain. The total deficit when only fertilizer and the soybean N credit are considered (i.e., not including N from manure sources) averages 42.3 million pounds per year. Sales of commercial fertilizer N are trending up while the amount of N removed in the grain is static.

VII. Livestock Production and its excretion of nitrogen in Southeast Minnesota

Livestock production for animal protein is common in much of the southern half of Minnesota, and this includes the eight southeastern counties. For this report, Animal Unit data was obtained from the compiled information assembled in the Minnesota

Pollution Control Agency Livestock/Feedlot database (26) (MPCA). Since the amount of waste an animal excretes is dependent upon the species of the animal and its stage of life, the use of the term 'animal unit' (AU) helps normalize the amount of waste to a single reference point. For example, a mature beef cow has an animal unit value of 1.0; a feeder hog, 0.4. The nitrogen excretion rates for the different species and life stages were obtained from the USDA-Agricultural Research Service (ARS) in St. Paul, MN (27).

Because the livestock operations in the MPCA database cannot be considered at 100% of the permitted capacity, USDA-ARS uses estimated average capacities. Using the MPCA AU database and the ARS protocols described above, the amount of nitrogen excreted by livestock in the eight counties is summarized in Table 6 below. The amount of nitrogen excreted by the human population in the eight counties is also included, using the population data from Table 1 and the reference value of 11.8 lbs of N per person (excreted plus industrial) per year (28).

Feeder hogs (Swine > 55 pounds) and dairy cattle > 1000 pounds account for a little more than half of the excreted N in the eight-county region. Beef cattle of various sizes account for 17% while dairy heifers, turkeys, and human beings each account for about 4%. The total amount of N excreted from animals (excluding wildlife) is about 101 million pounds per year.

It's interesting to consider how the total amount of manure N is sourced to the different sizes of operations. Of the animal categories shown in table 6, ten contribute at least 1% of the total. How the N is sourced to operations of >1000 au, 300-999 au, and >299 au for these 10 animal categories is shown in Table 7. Within swine operations, the largest feedlots or CAFOs (above 1,000 animal units) account for approximately 32% of the N excreted in manure, while midsize AFOs (300-999 AUs) account for 58.5%. For dairy cattle operations, the largest operations account for approximately 27% of the N excreted in manure, while mid-size AFOs (300-999 AUs) account for 38%.

Almost all manure from animals is applied to crop ground, especially land to be planted to corn. Not all (or even most, some in cases) of the excreted N is conserved from moment of excretion to field application. Depending upon how the manure is managed (lagoon, pit, etc.) N in various forms can be lost to the atmosphere. Much of this off-gassed N, however, has been shown to be deposited within a short distance (< 1 km) from the livestock operation (44) and McGinn et al. (45) reported a 50% decline in deposition only 200 m from a cattle confinement, indicating approximately half was deposited within 200 m. Thus, much of this volatilized N is not lost from the region or even the farm where it was generated and must be considered when assessing N budgets and pollution and the environmental impact of livestock production.

There are also agronomic concerns about manure N availability to plants since much of the manure N may be in organic forms. Plants typically need N to be mineralized in the nitrate (NO_3^-) or ammonium (NH_4^+) forms before it can be used for their life processes. As such, many if not most livestock farmers fail to take credit for unavailable forms, even though such N eventually will be mineralized and used by plants, leached to aquifers, washed away to streams and lakes, immobilized in the soil organic matter, denitrified (a biological process whereby NO_3^- is converted to N_2 gas), or off-gassed to the atmosphere in other various forms. Thus, like manure N lost to atmosphere prior to

Table 6: Nitrogen excreted by animals in the 8 MN Driftless Counties.

animal	wt (lbs)	N excreted per AU per year	Animal Units in 8 Driftless Counties	Total Excreted N (lbs)	UMN/NASS feedlot capacity correction factor	Total excreted N after correction	% of Total excreted N
Dairy cattle> 1000 pounds	1400	238	167754	39,925,357	0.64	25,552,228	25
Dairy cattle<1000 pounds	1000	238	6920	1,646,960	0.64	1,054,054	1
Dairy cattle – heifers	750	112	48661	5,450,032	0.64	3,488,020	3
Dairy cattle – calves	250	146	8315	1,214,019	0.64	776,972	1
Veal calves	200	44	352	15,488	0.64	9,912	0
Beef cattle - slaughter/stock	1000	131	93415	12,237,365	0.56	6,852,924	7
Beef cattle - feeder/heifer	800	128	61810	7,911,680	0.56	4,430,541	4
Beef cattle - cow/calf pairs	1300	128	83804	10,726,912	0.56	6,007,071	6
Beef cattle – calves	200	162	3577	579,474	0.56	324,505	0
Beef – mature bull	1000	131	432	56,592	0.56	31,692	0
Swine>300 pounds	300	61	31868	1,943,948	0.83	1,613,477	2
Swine 55-300 pounds	170	219	206294	45,178,342	0.83	37,498,024	37
Swine<55 pounds	25	292	14516	4,238,584	0.83	3,518,025	3
Chickens - liquid manure	3	316	78	24,648	0.51	12,570	0
Chickens – broilers>5 pounds	6	383	37	14,171	0.51	7,227	0
Chickens – broilers<5 pounds	2	383	573	219,459	0.51	111,924	0

Chickens – layers>5 pounds	7	316	46	14,536	0.51	7,413	0
Chickens – layers<5 pounds	3	316	240	75,840	0.51	38,678	0
Turkeys>5 pounds	10	285	22157	6,314,745	0.7	4,420,322	4
Turkeys<5 pounds	1	285	2355	671,175	0.7	469,823	0
Human Being	175	12	378,649	4,543,788	NA	4,543,788	4
total						100,769,190	100

field application, these 'unavailable' forms must be considered when assessing N budgets and pollution resulting from livestock production.

When only commercial N, the soybean N credit, and the N harvested in corn and soybean grain is considered, the eight-county area has an average N deficit (input N < harvested N) of 42.3 million pounds per year. But after the N excreted by animals is accounted for, the region has an N surplus of approximately 60 million pounds per year. This is an amount of nitrogen that could conceivably contaminate 2.7 trillion liters (722 billion gallons) of water to a level exceeding the EPA safe drinking water standard. Thus, it is clear that N inputs are misaligned with crop N removal in the region.

Table 7: Percentage of manure N excreted by animals from different sizes of livestock operations in the 8 SE MN counties.

Animal Category	**Total Amount of N Excreted**	**% excreted from different sized operations**		
		>1000 au	**300-999 au**	**<300 au**
Swine 55-300 pounds	45,178,342	31.9	58.5	9.7
Dairy cattle greater than 1000 pounds	39,925,357	26.9	38.3	34.8
Beef cattle - slaughter/stock	12,237,365	16.2	14.5	69.3
Beef cattle - cow/calf pairs	10,726,912	14.3	1.4	84.2
Beef cattle - feeder/heifer	7,911,680	15.9	3.2	81.0
Turkeys greater than 5 pounds	6,314,745	17.6	75.2	7.2
Dairy cattle – heifers	5,450,032	0.0	21.1	78.9
Swine less than 55 pounds	4,238,584	0.0	50.2	49.8
Swine greater than 300 pounds	1,943,948	51.2	30.1	18.7
Dairy cattle less than 1000 pounds	1,646,960	0	11	89

Emphasis in the agricultural community on the availability and off-gassing of manure N are clearly important for agronomic considerations but should also be seen as what amounts to an admission of the N loss that results in aquifer and other pollution. Thus, farmer concerns related to "recoverability" of excreted manure nutrients must be considered within the context of how their responses to these concerns in fact drive much of the pollution.

USDA-ARS draft documents (27) have estimated manure nutrient recoverability for Minnesota based on average expected nitrogen losses from storage, application and plant availability of applied nutrients, based on Kellogg et al. (46). These values are different for the various animal categories and for liquid and solid manure. Here we use those recoverability values to calculate best and worst-case scenarios for the 8 county SE MN region.

Scenario 1: Cattle and hog manure 100% liquid, poultry manure 100% solid

Scenario 2: Cattle and poultry manure 100% solid, hog manure 100% liquid

Note: Hog manure is nearly always stored as a liquid; poultry manure as a solid.

Table 8 below shows the excreted livestock nitrogen corrected for the average percentage feedlot capacity in Minnesota (from Table 6, column 7) adjusted using recoverability factors developed by Minnesota ARS staff. Since some N is not in plant usable forms in the year of application, some amount can be expected to carry over to the second year; this is illustrated in Table 8. The total year 1 plus year 2 amount could be expected to be available to the crop if approximately the same amount of manure is being applied in the region every year.

Table 8: Available Manure N when availability/recoverability factors are considered.

animal category		Recoverability Factor				Million lbs N available scenario 1			Million lbs N available scenario 2		
	Excreted N corrected for average % feedlot capacity	Yr 1 liquid	Yr 2 liquid	Yr 1 solid	Yr 2 solid	Yr 1	Yr 2	Yr 1-2 Total	Yr 1	Yr 2	Yr 1-2 Total
Dairy cattle > 1000 lbs	25.55	0.5	0.25	0.3	0.25	12.78	6.39	19.16	7.67	6.39	14.05
Dairy cattle < 1000 lbs	1.05	0.5	0.25	0.3	0.25	0.53	0.26	0.79	0.32	0.26	0.58
Dairy cattle – heifers	3.49	0.5	0.25	0.3	0.25	1.74	0.87	2.62	1.05	0.87	1.92
Dairy cattle – calves	0.78	0.5	0.25	0.3	0.25	0.39	0.19	0.58	0.23	0.19	0.43
Veal calves	0.01	0.5	0.25	0.3	0.25	0.00	0.00	0.01	0.00	0.00	0.01
Beef cattle - slaughter/stock	6.85	0.55	0.25	0.35	0.25	3.77	1.71	5.48	2.40	1.71	4.11
Beef cattle - feeder/heifer	4.43	0.55	0.25	0.35	0.25	2.44	1.11	3.54	1.55	1.11	2.66
Beef cattle - cow/calf pairs	6.01	0.55	0.25	0.35	0.25	3.30	1.50	4.81	2.10	1.50	3.60
Beef cattle – calves	0.32	0.55	0.25	0.35	0.25	0.18	0.08	0.26	0.11	0.08	0.19
Beef – mature bull	0.03	0.55	0.25	0.35	0.25	0.02	0.01	0.03	0.01	0.01	0.02
Swine > 300 lbs	1.61	0.7	0.15			1.13	0.24	1.37	1.13	0.00	1.13
Swine 55-300 lbs	37.50	0.7	0.15			26.25	5.62	31.87	26.25	0.00	26.25
Swine < 55 lbs	3.52	0.7	0.15			2.46	0.53	2.99	2.46	0.00	2.46
Chick. - liquid manure	0.01	0.35	0.25			0.00	0.00	0.01	0.00	0.00	0.00
Chick. - broilers>5 lbs	0.01			0.55	0.25	0.00	0.00	0.01	0.00	0.00	0.01
Chick. - broilers< 5lbs	0.11			0.55	0.25	0.06	0.03	0.09	0.06	0.03	0.09
Chick.- layers > 5 lbs	0.01			0.55	0.25	0.00	0.00	0.01	0.00	0.00	0.01
Chick. layers < 5 lbs	0.04			0.55	0.25	0.02	0.01	0.03	0.02	0.01	0.03
Turkeys > 5 lbs	4.42			0.55	0.25	2.43	1.11	3.54	2.43	1.11	3.54
Turkeys < 5 lbs	0.47			0.55	0.25	0.26	0.12	0.38	0.26	0.12	0.38
total	**96.2**					57.77	19.79	**77.57**	48.07	13.40	**61.46**

When availability/recoverability factors are considered, the total manure N is reduced between 19.4 and 36.1%, illustrated by the bolded numbers in Table 8. This reduction lowers the total N inputs (commercial N + soybean credit + manure N) between 6.1 and 11.5%, and still leaves N total inputs in the 260 to 280 pounds per corn acre range for the 8-county region. Thus, while it can't be emphasized enough that the unrecoverable or unavailable manure N is a pollutant entering the surrounding environment, including aquifers, **accounting for storage and availability factors still leaves total inputs far above the nitrogen needs of the corn crop**.

VIII. Recommendations

a. Summary of problem

It's apparent that groundwater contamination in the MN Driftless area can be sourced back to an imbalance of agronomic inputs and outputs. This imbalance is known to be present throughout many places in the US cornbelt and indeed other places in Minnesota. However, the unique vulnerabilities of the water supply wells located within Karstic geology make the problem in Southeast Minnesota more dire and more urgent to protect human health.

The fundamental problem is an overapplication of N. Using the N rate calculator at today's N and corn prices ($0.48/lb for anhydrous ammonia-N, $4.14 for bushel of corn), the N rate recommended by the University of Minnesota is 139 pounds per acre for corn grown in rotation with soybeans. Using the livestock excretion data, and commercial N sales from 2020 and the soybean N credit, the average N from these sources totals nearly 300 pounds per corn acre in the 8-county region. While it must be acknowledged that much of the manure N is lost before and during field application, there can be no doubt that Southeast Minnesota groundwater contamination can be sourced back to this imbalance.

Many in government and the ag industry want to focus on strategies that try to avoid N loss without addressing the N mass imbalance. This includes modifying the timing and form of nitrogen to be applied and co-applying inhibitors that slow the conversion of N fertilizer to soluble nitrate. Indeed, there are some intuitive practices that farmers can embrace to reduce N loss. This includes soil N testing to help guide rate decisions, postponing application until soil temperatures are below 50° (F) and taking credit for the previous year's soybean N fixation. But there must be a mechanism to drive farmers into this mindset.

It is foolhardy and results in a waste of taxpayer resources to not consider the N rate component and the landscape scale surplus of N as drivers of groundwater contamination. Nonetheless, many would like to promote taxpayer-funded edge of field strategies that require nothing of the farmer other than to provide contractor access to the site where the practice will be installed. Asking the taxpayer to fund edge of field mitigation of the farmer's pollution while still giving the farmer license to do whatever they wish with N inputs is perverse policy.

Clearly, aggressive regulation of N inputs provides the quickest and surest pathway to reducing the imbalance-caused pollution. This can include additional restrictions on N application rates, timing of fertilizer application, laws that constrict or reduce the size of the livestock industry and limiting the number of animals on farms or within watersheds. The best use of taxpayer funds is very likely assistance for farmers to transition to more diverse and integrated crop and livestock systems that effectively reduce the acreage of the most polluting crops (i.e. corn and soybean) and disperse animals such that they are raised in a more dispersed manner and perhaps by more individual farmers. Taxation of both N inputs and/or pollution resulting from crop and livestock production also presents an alternative or additional mechanism to regulating inputs.

Barring a coordinated move to more sustainable production systems, Minnesota citizens should be able to have an expectation that the polluting system is being robustly managed by regulation and enforcement of farm practices. As such, we provide the following recommendations.

b. Recommendation Group 1: **Better align N inputs with expected crop removal of nutrient utilizing existing tools.** Zero N loss is a not a reasonable expectation in the current corn/soy/CAFO production system. It's abundantly clear, however, that many if not most SE MN farmers are ignoring tools available to them that would minimize this loss. This includes use of the N rate calculator to guide the decisions on N input amounts, split application of nutrients (multiple and incremental applications of commercial fertilizer and manure over wider time windows) and use of soil nitrogen testing to guide fertility decisions.

   Failure to embrace these strategies is often assigned to a lack of awareness or education about them. This must be viewed within the backdrop that conservation professionals have been advocating for them through various outreach programs for decades. At this late date, any purported lack of

farmer awareness must be viewed as either willful ignorance and/or abject failure of the voluntary approach endorsed by longstanding government policy. Contrastingly, the industry and its practitioners seem hyper-aware of N loss that occurs through phenomena such as volatilization of N from manure and denitrification in anaerobic soils, and ironically, they use these loss pathways to justify above-recommended application rates. It's just this sort of logic that has polluted groundwater aquifers in region over the past several decades.

It's noteworthy that the industry and many in the conservation community advocate the use of N inhibitors to reduce N loss from farm fields to the environment. These products slow the conversion of ammonia and other forms of nitrogen into the more loss-vulnerable nitrate. There is no evidence inhibitors improve water quality at scale but, importantly, they 1) provide revenue for ag retailers and 2) allow the farmer to continue with their present fertilization scheme unchanged. This is illustrative of industry mindset.

The solution here is self-evident: society must be allowed an expectation that nutrients will be managed at the watershed scale. What this means is that inputs must controlled in ways that align with expected crop needs and minimization of loss to the environment, **at scale**. It's within our power to establish environmentally responsible animal populations and fertilizer inputs within the context of desired environmental outcomes. But to do this **at the scale** that prevents regional contamination of aquifers and the stream network will require government intervention. Thus, governmental bodies must have the power over decisions like siting/permitting of livestock facilities where water resources that have already been contaminated with nutrient pollution. Requirements that farmers also adopt known loss-minimization practices or incur penalties for not doing so are also reasonable.

c. **Recommendation Group 2: Create regulatory frameworks that recognize the unique geological vulnerabilities of the SE MN Karst region.** It's well known that corn belt agriculture degrades water quality throughout the entire region. While the four-state driftless region can be thought to lie within the cornbelt, its unique geological features and vulnerabilities to modern agriculture make it distinct, and policy must recognize this if desired environmental outcomes are to be realized.

Because of these vulnerabilities, a broad range of feedlot sizes (and not just large operations > 1000 animal units) must be considered going forward. The 8-county karst region houses a large number of livestock animals (especially cattle) in small operations (Table 7) and it stands to reason that these smaller operations contribute to the pollution problem. **Desirable environmental outcomes cannot be achieved by only focusing on large operations when determining land application requirements for manure.**

The geological vulnerabilities linked to Karst are not evenly dispersed across a farmed field and some locations are especially vulnerable. This includes sinkholes which can be seen as direct conduits for surface contaminants to aquifers important to public health. Current Minnesota law bans land application of manure and process wastewater within 50 feet of an active or inactive water supply well, sinkhole, mine, or quarry, and manure must be incorporated within 24 hours of surface application when applied to land that slopes toward a sinkhole and is less than 300 feet from the sinkhole. No setback incorporation is required where diversions prevent manure-contaminated runoff from entering the sinkhole. We strongly believe the scientific basis of these setbacks either be examined for adequacy or the setback distances be extended to account for worst case scenarios, considering the already demonstrated public health implications in Minnesota. There is evidence that larger setbacks would be appropriate: the state of New York requires a 100' setback from water supply wells in Karst areas (47) and Missouri 300' (48). Can we propose a stricter setback requirement for both manure AND fertilizer applications near sinkholes?

We also assert that in a region where drinking water supply is contaminated with nitrate—a substance sourced to **both** manure and commercial fertilizer, that setbacks restrict application of **both** manure and commercial fertilizer. This would be an intuitive step toward making nutrient management more robust within the context of protection of public health. A nitrate molecule sourced back to commercial fertilizer is equally injurious to the public health as one sourced back to livestock manure. Minnesota policy should reflect this.

While the focus of this document is on the eight SE MN counties, it's important to recognize that the state of Minnesota defines vulnerable groundwater as such: An area with vulnerable groundwater is an area where nitrate can move easily through soil and into groundwater, contaminating

drinking water sources. Vulnerable areas are defined as coarse textured soils, shallow bedrock, and karst geology (49). Areas that fall into this description are shown in Figure 2 and 5. The types of restrictions proposed here for SE MN are appropriate for all areas with coarse textured soils and shallow bedrock based on USDA NRCS soils maps, as well as karst geology based on Minnesota DNR determinations.

In summary, let us emphasize that requiring these production systems be managed in a more environmentally-sound manner merely adds protections to the public health without wholescale changes in the production system that require alternative crops, organic production, or banning of CAFOs. And let us also emphasize that requiring farmers to manage nitrogen inputs according to well-established protocols can actually improve farmers' economic outcomes **while producing benefits for all Minnesotans**, and not just production agriculture.

IX. Figures

Figure 1: Map showing the extent of the 'true' Driftless Area and adjacent areas with similar Karstic geology and Driftless topography. Image credit: Phil Kerr, Iowa Geological Survey.

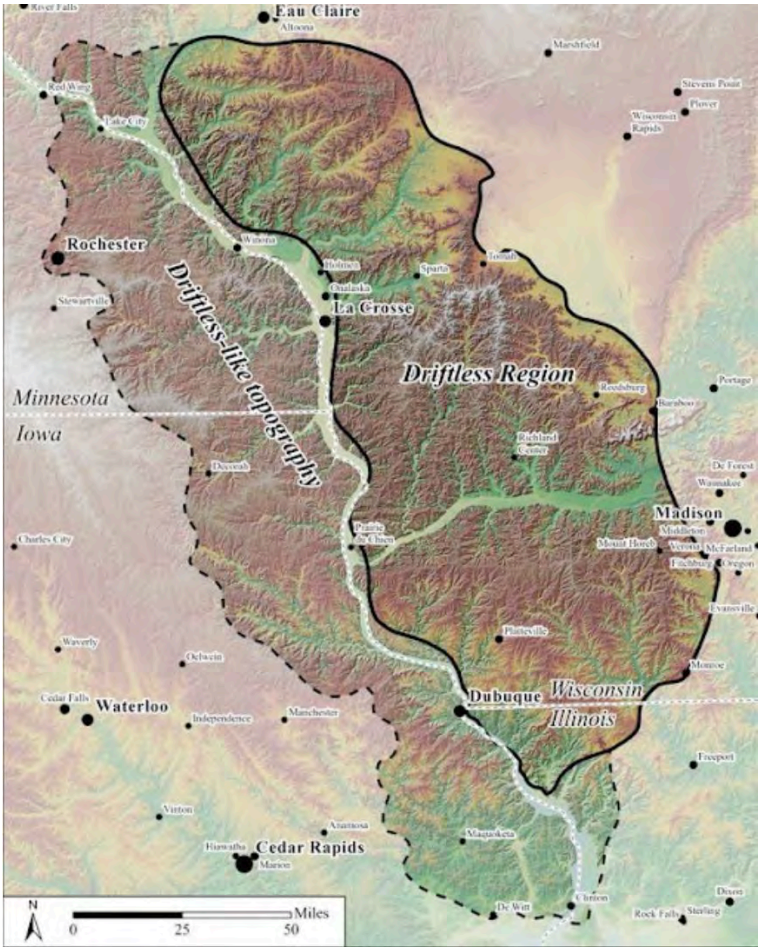

Figure 2: Minnesota counties lying with the state's portion of the Driftless Area. Counties denoted with a star are the focus of this report. Image taken from: Tipping, R., Rantala, M., Alexander Jr, E.C., Gao, Y. and Green, J., 2015. History and future of the Minnesota Karst feature database.

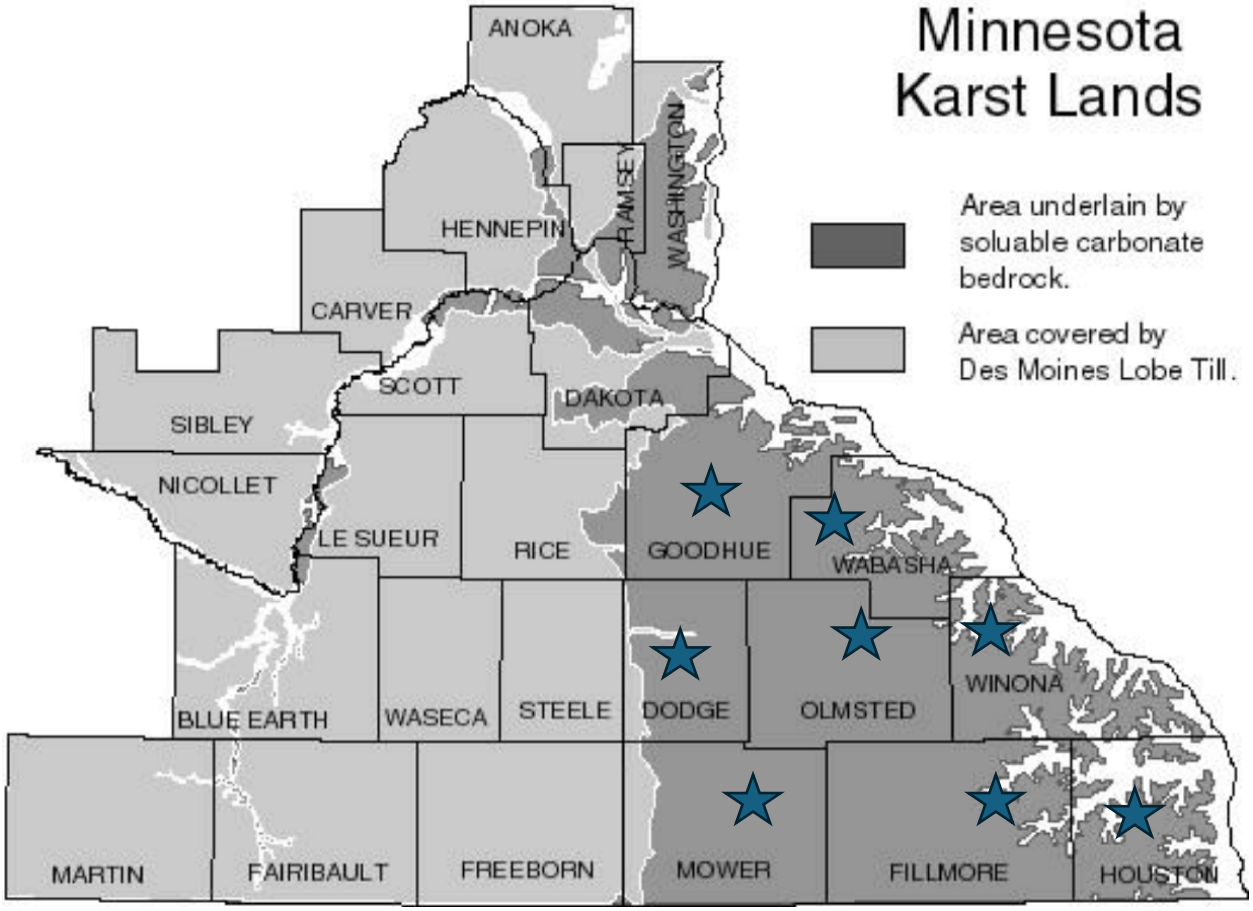

Figure 3: Population trends of the eight counties.

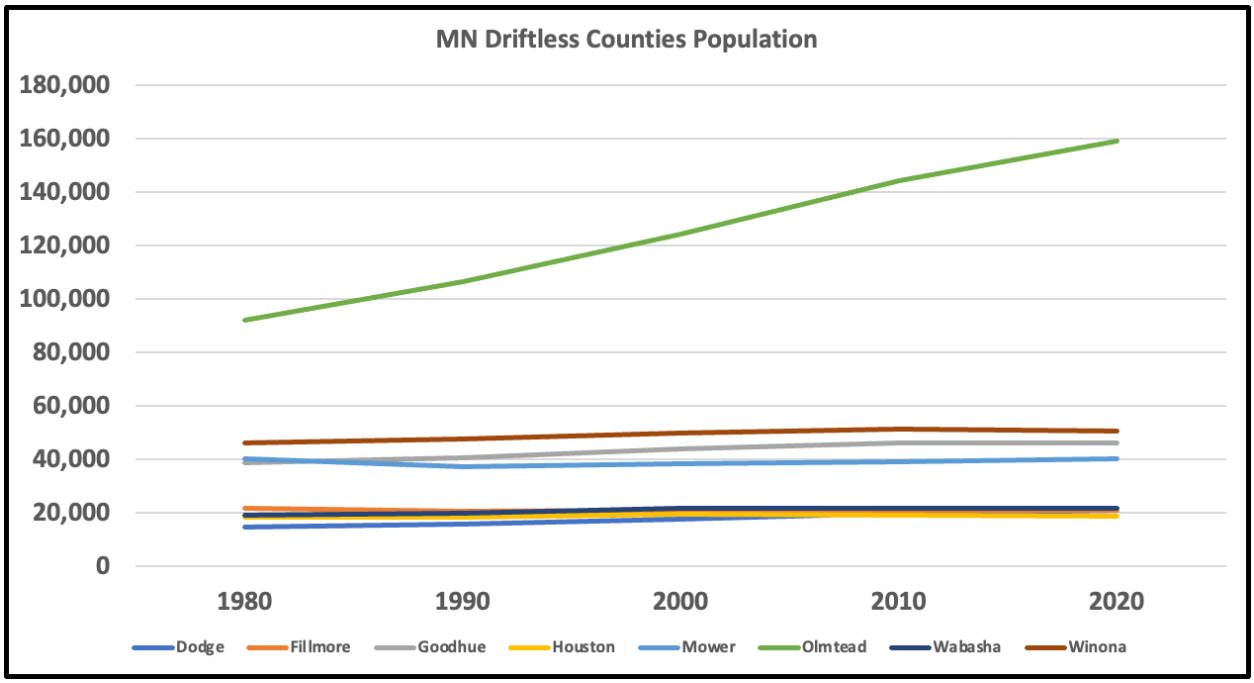

Figure 4: Nitrate-N in Minnesota Private Wells. Source: Minnesota DNR.

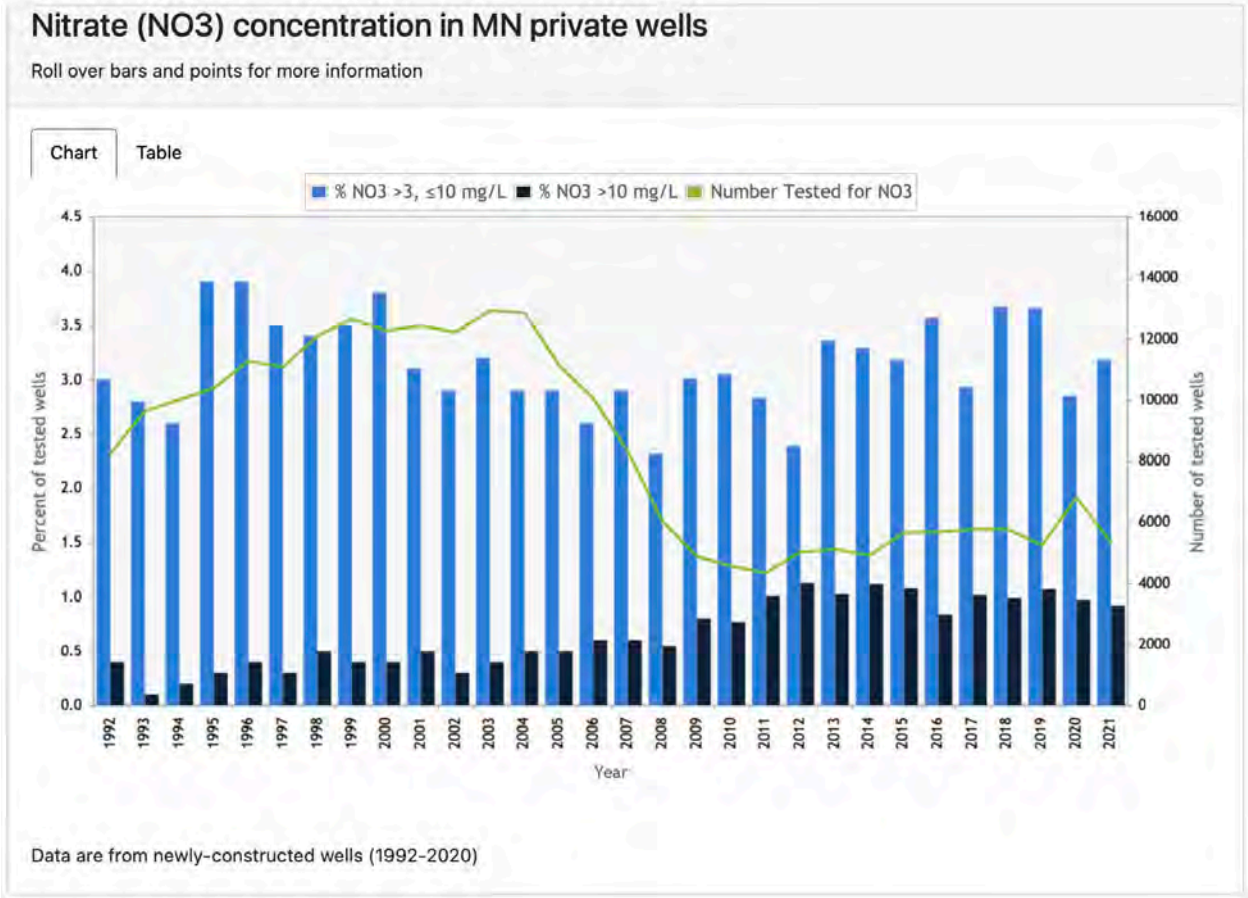

Figure 5: Nitrate risk for Southeast Minnesota Aquifers. Source: Minnesota Department of Health.

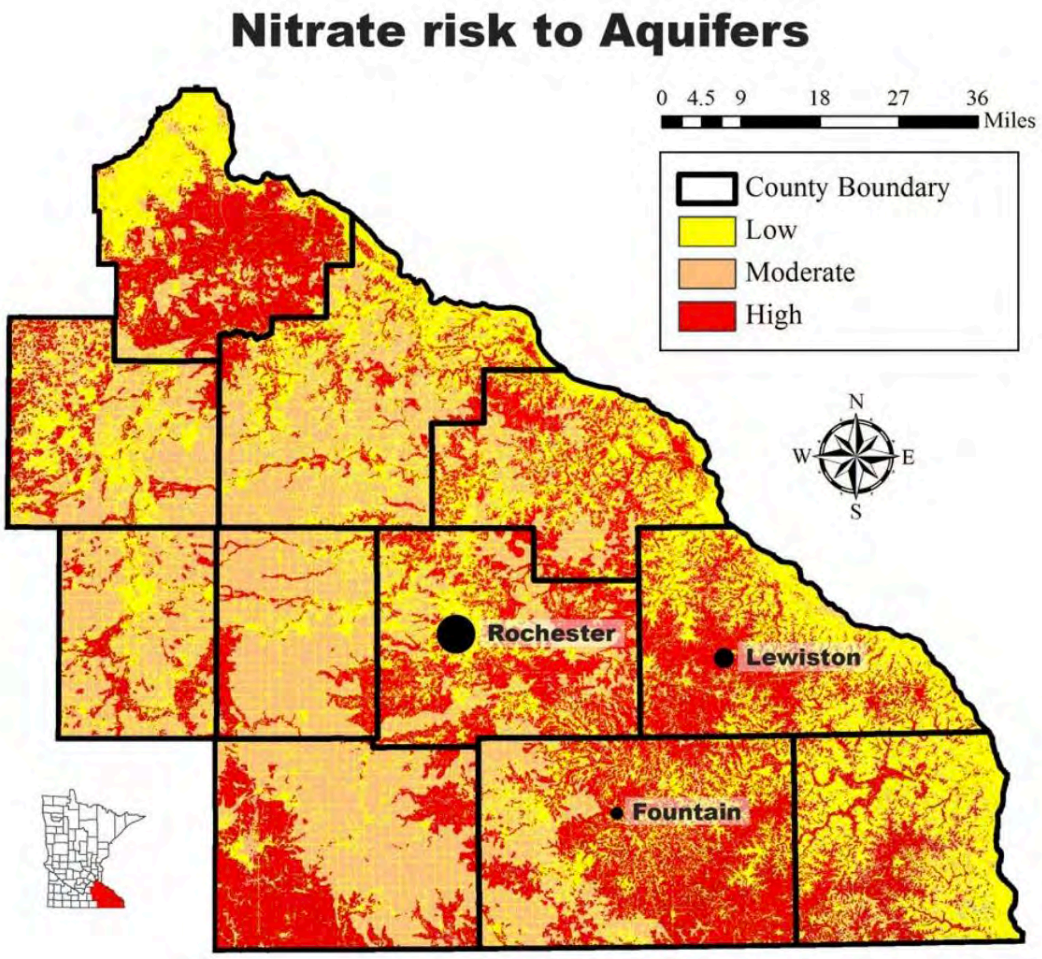

Figure 6: Crop acres in SE Minnesota crop district, 1972-2018. Data Source: USDA-NASS Quickstats.

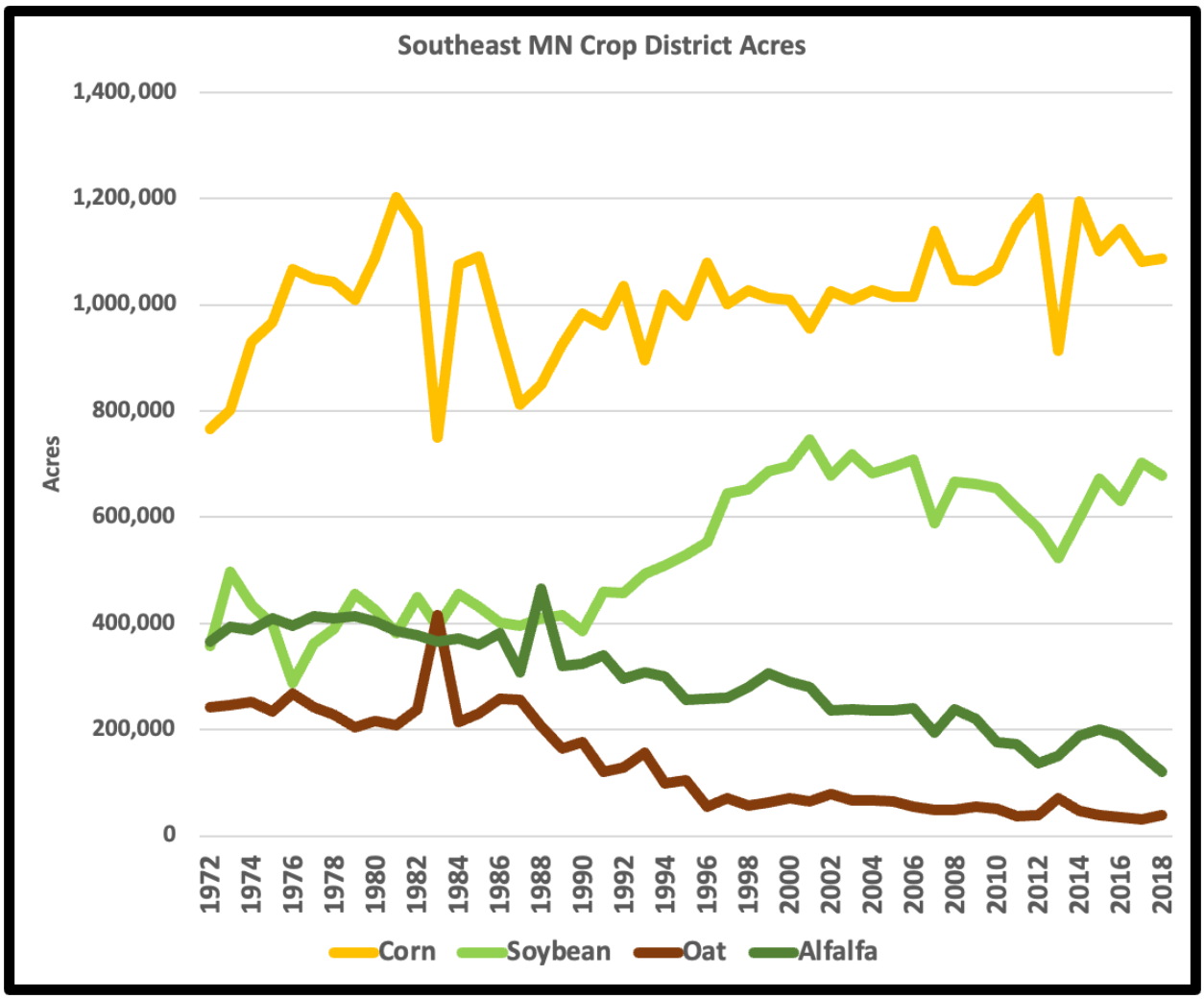

Figure 6: Commercial N sold in the 8 MN Driftless along with the amount of N removed in the corn and soybean crops at harvest.

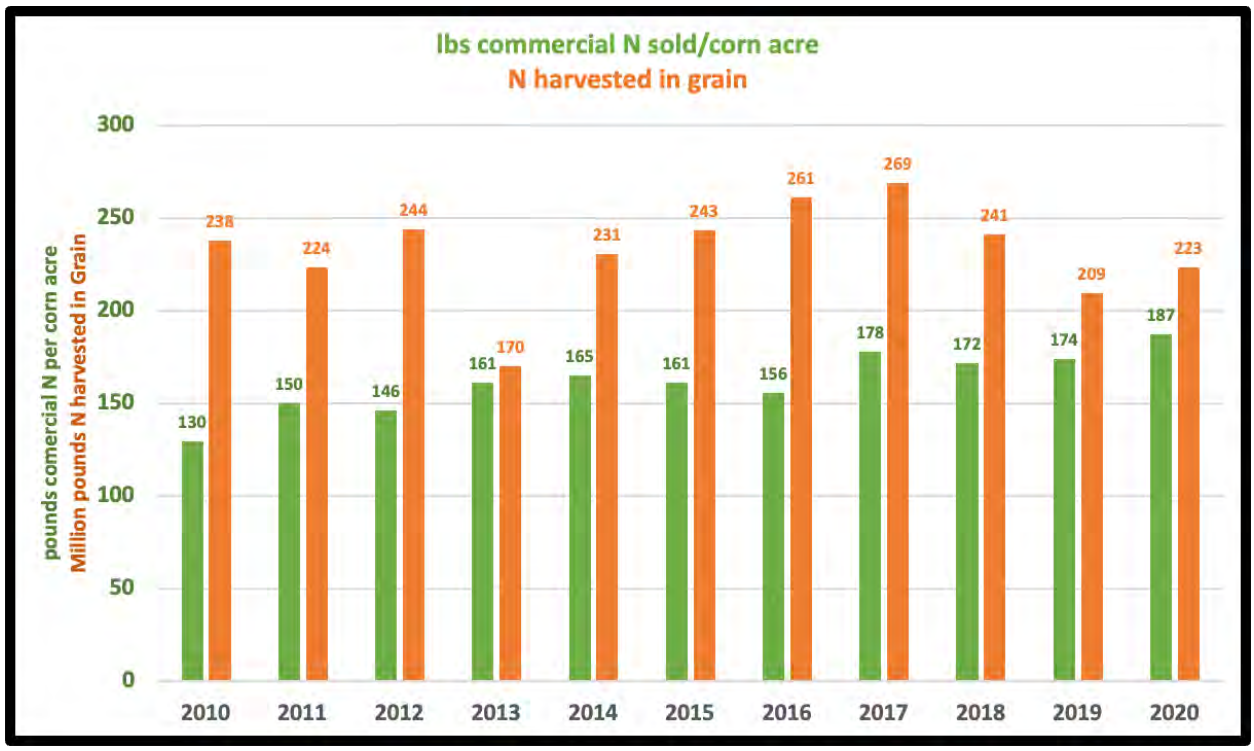

Figure 7: Areas of coarse textured soil, shallow bedrock and karst geology in Minnesota. Source: Minnesota Department of Agriculture.

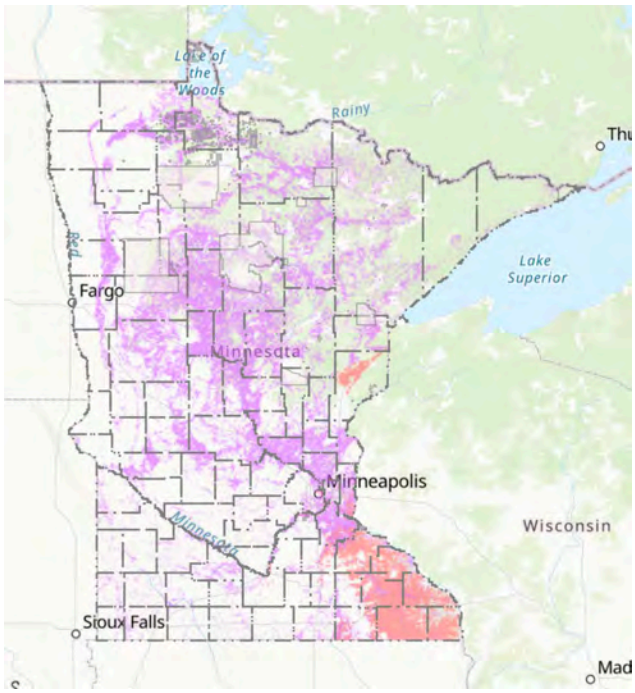

X. Citations

1) Carson et al., 2023. The Driftless Area: The Extent of Unglaciated and Similar Terrains in Wisconsin, Illinois, Iowa, and Minnesota. Wisconsin Geological and Natural History Survey, Educational Series 057.
2) Trimble, S.W., 2012. *Historical agriculture and soil erosion in the Upper Mississippi Valley Hill Country*. CRC Press.
3) Hallberg, G.R., Bettis III, E.A. and Prior, J.C., 1984. Geologic overview of the Paleozoic Plateau region of northeastern Iowa. In *Proceedings of the Iowa academy of science* (Vol. 91, No. 1, pp. 5-11).
4) Schilling, K.E., Jones, C.S., Clark, R.J., Libra, R.D., Liang, X. and You-Kuan, Z., 2019. Contrasting NO 3-N concentration patterns at two karst springs in Iowa (USA): insights on aquifer nitrogen storage and delivery. *Hydrogeology journal*, *27*(4), pp.1389-1400.
5) Hallberg, G.R., Libra, R.D. and Hoyer, B.E., 1985, May. Nonpoint source contamination of groundwater in karst-carbonate aquifers in Iowa. In *Perspectives on Nonpoint Source Pollution, Proceedings of a National Conference, Kansas City, Mo* (pp. 109-114).
6) St Ores, J., Alexander Jr, E.C. and Halsey, C.F., 1982. Groundwater pollution prevention in Southeast Minnesota's karst region.
7) Alexander, E.C. and Brick, G.A., 2021. Minnesota caves and karst. *Caves and Karst of the Upper Midwest, USA: Minnesota, Iowa, Illinois, Wisconsin*, pp.37-114.
8) Zhang, Y., Kelly, W.R., Panno, S.V. and Liu, W.T., 2014. Tracing fecal pollution sources in karst groundwater by Bacteroidales genetic biomarkers, bacterial indicators, and environmental variables. *Science of the Total Environment*, *490*, pp.1082-1090.
9) Panno, S.V. and Kelly, W.R., 2015. Driftless Area Karst of Northwestern Illinois and its Effects on Groundwater Quality.
10) Moser, R. Drinking water in 8 Minnesota counties found to have unsafe levels of nitrate. WCCO News, November 10, 2023.
11) Mahron, K. Southeast Minnesota struggles for common ground on nitrate pollution as health worries rise. Minnesota Public Radio, October 31, 2023.
12) Schneider, K. US regulators order Minnesota to clean up nitrate contaminated water. Investigate Midwest, November 13, 2023.
13) Minnesota Department of Natural Resources. Minnesota Groundwater Provinces.
14) Minnesota Department of Public Health. Nitrate in Drinking Water. 2024.

15) Weyer, P.J., Cerhan, J.R., Kross, B.C., Hallberg, G.R., Kantamneni, J., Breuer, G., Jones, M.P., Zheng, W. and Lynch, C.F., 2001. Municipal drinking water nitrate level and cancer risk in older women: the Iowa Women's Health Study. *Epidemiology*, pp.327-338.
16) Jones, R.R., Weyer, P.J., DellaValle, C.T., Inoue-Choi, M., Anderson, K.E., Cantor, K.P., Krasner, S., Robien, K., Freeman, L.E.B., Silverman, D.T. and Ward, M.H., 2016. Nitrate from drinking water and diet and bladder cancer among postmenopausal women in Iowa. *Environmental health perspectives*, *124*(11), pp.1751-1758.
17) Inoue-Choi, M., Jones, R.R., Anderson, K.E., Cantor, K.P., Cerhan, J.R., Krasner, S., Robien, K., Weyer, P.J. and Ward, M.H., 2015. Nitrate and nitrite ingestion and risk of ovarian cancer among postmenopausal women in Iowa. *International Journal of Cancer*, *137*(1), pp.173-182.
18) Ward MH, Kilfoy BK, Weyer P, Wang A. Cerhan JR. Nitrate intake and the risk of thyroid cancer and thyroid disease. *Epidemiology* 2010; **21**: 389–95.
19) Mathewson, P.D., Evans, S., Byrnes, T., Joos, A. and Naidenko, O.V., 2020. Health and economic impact of nitrate pollution in drinking water: a Wisconsin case study. *Environmental Monitoring and Assessment*, *192*(11), p.724.
20) Brender, J.D., Weyer, P.J., Romitti, P.A., Mohanty, B.P., Shinde, M.U., Vuong, A.M., Sharkey, J.R., Dwivedi, D., Horel, S.A., Kantamneni, J. and Huber Jr, J.C., 2013. Prenatal nitrate intake from drinking water and selected birth defects in offspring of participants in the national birth defects prevention study. *Environmental health perspectives*, *121*(9), pp.1083-1089.
21) Hatfield, J.L., McMullen, L.D. and Jones, C.S., 2009. Nitrate-nitrogen patterns in the Raccoon River Basin related to agricultural practices. Journal of soil and water conservation, 64(3), pp.190-199.
22) Piske, J.T. and Peterson, E.W., 2020. The role of corn and soybean cultivation on nitrate export from Midwestern US agricultural watersheds. Environmental Earth Sciences, 79, pp.1-14.
23) Burkart, M.R. and James, D.E., 1999. Agricultural-nitrogen contributions to hypoxia in the Gulf of Mexico (Vol. 28, No. 3, pp. 850-859). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.
24) McLellan, E., Robertson, D., Schilling, K., Tomer, M., Kostel, J., Smith, D. and King, K., 2015. Reducing nitrogen export from the Corn Belt to the Gulf of Mexico: Agricultural strategies for remediating hypoxia. JAWRA Journal of the American Water Resources Association, 51(1), pp.263-289.
25) Jones, C.S., Nielsen, J.K., Schilling, K.E. and Weber, L.J., 2018. Iowa stream nitrate and the Gulf of Mexico. PloS one, 13(4), p.e0195930.
26) Minnesota Pollution Control Agency. Feedlots. 2024. https://www.pca.state.mn.us/business-with-us/feedlots.

27) Sara Porter, USDA-Agricultural Research Service, personal communication, January 17, 2024.
28) Libra, R.D., Wolter, C.F. and Langel, R.J., 2004. Nitrogen and phosphorus budgets for Iowa and Iowa watersheds.
29) Gentry, L.E., David, M.B., Smith, K.M. and Kovacic, D.A., 1998. Nitrogen cycling and tile drainage nitrate loss in a corn/soybean watershed. Agriculture, ecosystems & environment, 68(1-2), pp.85-97.
30) Jones, C.S. and Schilling, K.E., 2013. Carbon export from the Raccoon River, Iowa: patterns, processes, and opportunities. Journal of environmental quality, 42(1), pp.155-163.
31) Jones, C.S., Schilling, K.E. and Seeman, A., 2019. Relating carbon and nitrogen transport from constructed farm drainage. Agricultural water management, 213, pp.12-23.
32) Christianson, L., M. Castellano, and M. Helmers. 2012. Nitrogen and phosphorous balances in Iowa cropping systems: Sustaining Iowa's soil resource. Des Moines, IA: Iowa State University and The Iowa Department of Agriculture and Land Stewardship.
33) Ribaudo, M., 2015. The limits of voluntary conservation programs. Choices, 30(2), pp.1-5.
34) Savage, J. and Ribaudo, M., 2016. Improving the efficiency of voluntary water quality conservation programs. Land Economics, 92(1), pp.148-166.
35) Segerson, K., 2013. When is reliance on voluntary approaches in agriculture likely to be effective? Applied economic perspectives and policy, 35(4), pp.565-592.
36) Read, D.J. and Wainger, L., 2023. Assessing intervention effectiveness at promoting voluntary conservation practice adoption in agrienvironments. Conservation Biology, 37(1), p.e14009.
37) Secchi, S., 2023. The role of conservation in United States' agricultural policy from the Dust Bowl to today: A critical assessment. Ambio, pp.1-14.
38) Ransom, C.J., Kitchen, N.R., Camberato, J.J., Carter, P.R., Ferguson, R.B., Fernández, F.G., Franzen, D.W., Laboski, C.A., Nafziger, E.D., Sawyer, J.E. and Scharf, P.C., 2020. Corn nitrogen rate recommendation tools' performance across eight US midwest corn belt states. Agronomy Journal, 112(1), pp.470-492.
39) Blesh, J., and L.E. Drinkwater. 2013.The impact of nitrogen source and crop rotation on nitrogen mass balances in the Mississippi River Basin. Ecological Applications 23(5):1017-1035.
40) University of Minnesota, 2018. Why Do We Need a Soybean Nitrogen Credit? Minnesota Crop News, University of Minnesota Extension, April 2, 2018.
41) USDA, NASS-Quickstats. https://quickstats.nass.usda.gov.
42) Barry, D.A.J., Goorahoo, D. and Goss, M.J., 1993. Estimation of nitrate concentrations in groundwater using a whole farm nitrogen budget (Vol. 22, No. 4, pp. 767-775). American Society of Agronomy, Crop Science.

43) Minnesota Department of Agriculture, 2024. Fertilizer Use and Sales Data. https://www.mda.state.mn.us/pesticide-fertilizer/fertilizer-use-sales-data.
44) Loubet, B., Asman, W.A., Theobald, M.R., Hertel, O., Tang, Y.S., Robin, P., Hassouna, M., Dämmgen, U., Genermont, S., Cellier, P. and Sutton, M.A., 2009. Ammonia deposition near hot spots: processes, models and monitoring methods. Atmospheric ammonia: detecting emission changes and environmental impacts, pp.205-267.
45) McGinn, S.M., Janzen, H.H., Coates, T.W., Beauchemin, K.A. and Flesch, T.K., 2016. Ammonia emission from a beef cattle feedlot and its local dry deposition and re-emission. Journal of Environmental Quality, 45(4), pp.1178-1185.
46) Kellogg, R.L., Moffit, D.C., and Gollehon, N.R. Estimates of Recoverable and Non-Recoverable Manure Nutrients Based on the Census of Agriculture. USDA-NRCS, September 2014.
47) Czymmek et al. Manure Management Guidelines for Limestone Bedrock/Karst Areas of Genesse County, New York: Practices for Risk Reduction. Cornell University Animal Science Publication Series No. 240.
48) University of Missouri Extension, Setback Distances for Land Application of Manure. University of Missouri Extension.
49) Minnesota Department of Agriculture. Vulnerable Groundwater Area Map. https://www.mda.state.mn.us/chemicals/fertilizers/nutrient-mgmt/nitrogenplan/mitigation/wrpr/wrprpart1/vulnerableareamap#:~:text=An%20area%20with%20vulnerable%20groundwater%20is%20an%20area,areas%20are%20not%20subject%20to%20the%20fall%20restriction.

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Use of manure nutrients from concentrated animal feeding operations

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CAFO
Phosphorus
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ABSTRACT

Over the past few decades, there has been a nationwide trend away from small livestock farms and toward large Concentrated Animal Feeding Operations (CAFOs). This shift results in concentrated manure production and introduces potential problems associated with its disposal. We analyzed data from 13 permitted CAFOs in southeastern Michigan, including 1187 occurrences of manure application from 12 of the CAFOs with available field-level data. CAFOs applied excess manure nutrients to cropland by applying to fields with soil phosphorus test levels >50 ppm (42% of all cases), applying to soybeans (7% of all cases), over-estimating crop yields in calculating plant nutrient requirements (67% of all cases), and applying beyond what is allowed by state permits (26% of all cases). This represents significant potential for redistribution of manure nutrients. The total amount of manure from all instances of over-application could be redistributed to fertilize over 4775 ha (11,800 acres) per year. Significant barriers to redistribution of manure exist, however, including cost, land availability, crop and soil need, transport logistics, and farmers' reluctance to use manure instead of inorganic fertilizer due to its variable composition. These findings are relevant to the harmful algal bloom and hypoxia issues in Lake Erie, which are driven by excess nutrients, and can be used to better inform science, modeling, and policy in the region.
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Introduction

Over the past few decades, there has been a nationwide trend toward large animal operations and away from small farms (Kellogg et al., 2000; Gollehon et al., 2001). While the total number of livestock has remained relatively stable, the number of livestock farms has decreased, resulting in more livestock kept in larger operations and in confinement. Concentrated Animal Feeding Operations (CAFOs) are defined by the United States Environmental Protection Agency (EPA) as operations that confine animals for >45 days a year and either meet a certain size threshold (e.g., 1000 beef cattle, 700 dairy cows, 2500 swine weighing >55 pounds) or discharge manure or wastewater directly into a waterway (USEPA, 2008). The shift from traditional smaller farms to CAFOs results in concentrated manure production and introduces potential problems associated with its disposal. There has been growing public concern about the environmental effects of CAFOs, particularly regarding potential contamination of surface water and groundwater with nitrogen (N) and phosphorus (P), the primary nutrients in manure. Excess inputs of N and P can lead to eutrophication of surface water, resulting in harmful algal blooms (HABs) and depleted dissolved oxygen concentration (hypoxia). The Clean Water Act and other federal and state laws regulate CAFOs to minimize environmental impacts, but uncertainty remains regarding the effect of CAFOs on nutrient inputs to surface water and the success of policies designed to protect against water contamination.

The manure produced in CAFOs can be used to fertilize cropland, but there may be agronomical, logistical, and economic constraints on these large operations because there may not be enough nearby cropland in need of nutrients to receive all of the manure. In these cases, manure may be applied far from CAFO barns or transferred to another operation (both of which can be expensive), stored on site, or potentially over-applied on nearby cropland. Nutrients applied above crop requirements can accumulate in the soil (especially P), denitrify (in the case of N), or wash off fields and then contaminate surface water. Studies have suggested that the amount of land needed to use CAFO manure nutrients is often underestimated (Kellogg et al., 2000; Jackson et al., 2000; Gollehon et al., 2001; Ribaudo et al., 2003a), so there is an opportunity to spread manure on more land, and potentially reduce inorganic fertilizer applications. Those studies, however, use literature-based manure nutrient composition and assumed application rates and do not consider the effect of inorganic fertilizer applications at CAFOs. Herein, we address these shortcomings by using detailed, field-level manure application data reported by CAFOs to further understanding of manure management at these operations.

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We analyzed data from 13 southeastern Michigan CAFOs that are within a 15 km (9.3 mi) radius of each other in the River Raisin and Maumee River watersheds, both of which discharge to western Lake Erie (Fig. 1). This includes six of the seven CAFOs in the River Raisin Watershed and seven of about 80 CAFOs in the Maumee River Watershed, which has most of its land area and CAFOs in Ohio and Indiana (IDEM, 2017; MDEQ, 2017; OEPA, 2017b). While this area is relatively dense with CAFOs compared to the rest of the Maumee River Watershed, it is not unique. There are over 30 CAFOs within a 30 km (18.6 mi) radius in southern Mercer County, Ohio, and CAFOs in other areas throughout mid-Michigan are even more dense. In recent years, harmful algal blooms and hypoxia in Lake Erie have increased in extent and intensity due to elevated P loadings from watersheds that drain to the lake, particularly from the Maumee River watershed. Farm fertilizers and manure are primary sources of the Maumee River's P load (Scavia et al., 2014, 2017), and it has been estimated that about 12% of phosphorus applied to cultivated cropland throughout western Lake Erie basin (WLEB) watersheds is from manure (USDA, 2017a). Policymakers have set a goal of reducing the P input to Lake Erie by 40% (GLWQA, 2012), and meeting the goal will require a better understanding of the relative contributions and the spatial distribution of nutrient sources, including manure. While a majority of the critical WLEB watershed area is in Ohio, only Michigan has publicly-available, detailed field-level data on CAFO manure nutrient application. We chose our study area because we can address key questions about CAFO practices in this region using the data provided publicly by Michigan. Our primary objectives were to 1) develop a baseline understanding of manure produced and applied at CAFOs in a critical watershed area and 2) examine agronomic and logistic potential for redistributing manure nutrients to land with greater nutrient needs.

Methods

CAFO data and manure application records

The state of Michigan requires all CAFOs to submit to the Michigan Department of Environmental Quality (MDEQ) Comprehensive Nutrient Management Plans (CNMPs) and Annual Reports that include field-level manure application records. These data are available through Michigan's MiWaters online database (MDEQ, 2017). We compiled the most recent CNMPs and three years (2013–2015) of annual reports for 11 dairy CAFOs and two swine CAFOs in southeastern Michigan (Fig. 1). The annual reports have two main components: general operation data and field-level manure application data. The general data include average and maximum number of animals confined, estimated total waste generated, estimated total waste transferred off-site to another operation, total number of acres available for land application, and total number of acres used for land application for each calendar year. The field-level application data include field size, soil P level, date of soil test, planted crop, yield goal, actual yield, manure application rate, manure N application rate, available N, N credit, manure P application rate, fertilizer N application rate, fertilizer P application rate, total N, total P, and the basis for rate calculation (e.g., N-based, 1 year P-based, 2 year P-based) for every field to which manure was applied during the crop year. Fields must be 40 acres or smaller. Data are not provided for fields that received only inorganic fertilizer or were not fertilized. After omitting the field-level information from one CAFO due to reporting errors (R. Burns, MDEQ, pers. comm., February 13, 2017), we compiled a database of 1187 manure application records from the remaining 12 CAFOs. The annual reports' general data described above were retained and analyzed for all 13 CAFOs.

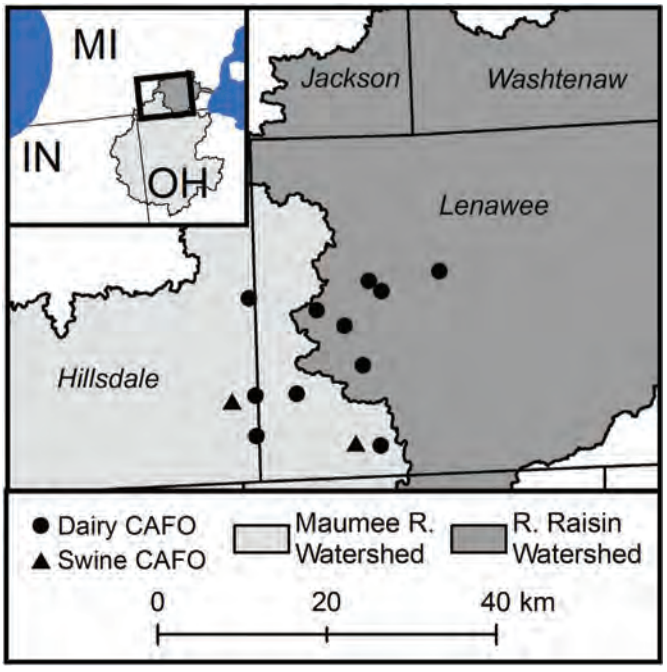

Fig. 1. Locations of CAFOs included in this study.

Missing data and data calculations

There were some inconsistencies in reporting among CAFOs, and records were occasionally missing information. When a field's size was not reported (8% of records), we used the average size of all other fields fertilized with manure by the given operation in calculations. Other cases of missing data are described below when relevant. The CAFO permits require that soil P tests use the Bray P1 method unless an alternate method is approved (MDEQ, 2015). Because no exceptions were noted on any reports, we assumed Bray P1 tests were used in all cases. When applicable, units for P application were converted from P to P_2O_5 and units for soil P test levels were converted from lb./acre to ppm using conversion factors from Warncke et al. (2004) and assuming a 16.96 cm (6.67 in) soil depth. All other data were used as reported. Herein, "P_2O_5" (phosphate) is used instead of "P" for discussion of phosphorus application rates and manure composition in accordance with U.S. agricultural convention. Unless otherwise noted, manure N refers to first-year plant-available N, which can be less than total manure N applied, as this is what is reported as the final rate in the CAFOs' annual reports.

Total liquid and solid manures applied by each CAFO each year were calculated by multiplying application rates by field areas. Total manure accounted for was this amount plus manure transferred off site. Manure N and P_2O_5 contents for each reported field application were calculated by dividing the total manure N and P_2O_5 application rates by rates of total manure applied.

Recommended and allowed application rates

The maximum allowed manure nutrient application rates for CAFOs in Michigan are based partially on Tri-State Fertilizer Standards established in 1995 by Michigan, Ohio, and Indiana (Warncke et al., 2004). P_2O_5 recommendations are based on soil P level and yield goal, and it is recommended to apply no P_2O_5 when soil P levels are >40 ppm (for corn and soybeans) or 50 ppm (for wheat and alfalfa). In Michigan, CAFOs are allowed to apply at 1, 2, or 4 times the Tri-State recommended P_2O_5 rate, depending on soil P levels, and application is allowed on soils with P levels up to 150 ppm (MDEQ, 2015). The MDEQ allowances follow the Tri-State N recommendations, which are based on previous crop and yield goal, except they allow application on soybeans and alfalfa, which the Tri-State Standards do not recommend.

We compared the reported CAFOs' N and P_2O_5 application rates to the Tri-State Standard recommended rates and to MDEQ-allowed

rates. The MDEQ-allowed rates were calculated using equations from the Tri-State Standards bulletin (Warncke et al., 2004) and the MDEQ allowance guidelines (MDEQ, 2015), and the rates were confirmed when possible using annual report reviews completed by MDEQ staff and available on MiWaters (MDEQ, 2017). Of the 1187 compiled records of manure application, allowed P_2O_5 rates were calculated for 1109 (93%) and N rates were calculated for 1123 (95%). The omitted records either had a crop other than corn, wheat, soybeans, or alfalfa; were planted with a combination of crops; or lacked reported soil P level or yield goal. In cases where alfalfa was reported without specifying hay or haylage, we assumed hay if the yield goal was ≤11.2 tonnes/ha (5 tons/acre) and haylage if the yield goal was ≥13.5 tonnes/ha (6 tons/acre). In addition to calculating the maximum allowed rates using the CAFOs' reported yield goals, we calculated maximum allowed rates using each CAFOs' own actual average crop yields as yield goals.

Spatial data and land use

To examine the distribution of manure application relative to CAFO barn locations, we digitized field boundaries reported in the CNMPs in ArcGIS for all CAFO-managed fields that are used to spread manure. The MDEQ also provided ArcGIS field maps to supplement and confirm the digitized boundaries. The National Landcover Dataset (NLCD) (Homer et al., 2015) was used to determine area of cropland when considering potential redistribution of manure.

Results

Livestock totals, total manure, and annual manure utilization

The total number of cattle in the 11 dairy CAFOs increased from 15,478 to 23,524 between 2013 and 2015, with the majority in Lenawee County (14,310 in 2013 and 19,345 in 2015). The National Agricultural Statistics Service reported 32,114 cattle in Lenawee County in 2012 (USDA, 2012), suggesting that about 50% are in the county's eight dairy CAFOs. The swine CAFO in Lenawee County reported 4000 animals each year; in 2012, there were 6016 hogs and pigs in 35 farms in the county, suggesting that the one swine CAFO in the county contained approximately 66% of its swine. Out of about 70,000 swine in 48 farms in Hillsdale County, the swine CAFO averaged 7000 swine per year (10% of total county swine). These percentages suggest that a substantial portion of the manure nutrients applied to cropland in this area may be from CAFOs.

Over the study period, 314 to 644 million liters (83 to 170 million gallons) of liquid waste and 64 to 335 thousand tonnes (71 to 369 thousand tons) of solid waste were generated by the 13 CAFOs annually. These totals include water added to liquid manure and bedding and compost added to solid manure. Approximately 20% of the liquid manure was transferred to other operations, but it was only reported as transferred in 18 out of the 33 annual reports when it was produced. When liquid manure was transferred to other operations, an average of 30% of the generated waste was transferred, ranging from <10% to 80%. Approximately 12% of all solid manure was transferred to other operations, but in the 11 transfers of solid manure reported (out of 26 reported instances when solids were produced), about 35% of what was generated was transferred, ranging from <5% to 100%. The CAFO reports did not indicate how far transferred manure traveled or how it was subsequently managed and applied. Manure that was not transferred is assumed to be kept on site and either applied to cropland managed by the CAFO or kept in storage.

It has generally been assumed in studies of land available for manure application (e.g., Jackson et al., 2000; Ribaudo et al., 2003a; Kaplan et al., 2004) and in watershed models studies (e.g., Han et al., 2012; Luscz et al., 2015; Scavia et al., 2017) that all of the manure generated at a CAFO is applied on site each year. However, over our study period, there were five CAFOs where the amount of liquid manure applied and transferred was less than the amount generated each year, suggesting some was stored for more than three years. Conversely, there were 12 occurrences at seven CAFOs where more manure was applied and/or transferred than was generated, suggesting stored manure was applied to fields at those CAFOs. While over time these deficits and excesses may balance, this year-to-year variability may be important when analyzing or modeling dynamic manure application.

Manure composition

Michigan CAFOs' CNMPs include annual animal nutrient production based on published "book values" from the MidWest Plan Service (Lorimor et al., 2004) for as-excreted manure. The CAFOs are also required to test their stored manure annually to determine its nutrient content. The composition of manure as applied to fields varied greatly among the CAFOs, as well as within individual CAFOs (Fig. 2). On average, the applied liquid dairy manure had only 0.72 g P_2O_5/L and 1.15 g N/L (6.0 lb. P_2O_5 and 9.6 lb. N per 1000 gal), compared to as-excreted book values of 1.88 g P_2O_5/L and 4.23 g N/L (15.7 lb. P_2O_5 and 35.3 lb. N per 1000 gal) for milking cows and 0.97 g P_2O_5/L and 2.41 g N/L (8.1 lb. P_2O_5 and 20.1 lb. N per 1000 gal) for heifers (Lorimor et al., 2004; James et al., 2006). In contrast, applied solid dairy manure often contained more nutrients than as-excreted manure, averaging 2.90 g P_2O_5/kg and 4.00 g N/kg (5.8 lb. P_2O_5 and 8.0 lb. N per ton), compared to as-excreted book values of 2.20 g P_2O_5/kg and 4.95 g N/kg (4.4 lb. P_2O_5 and 9.9 lb. N per ton) for milking cows and only 1.10 g P_2O_5/kg and 2.65 g N/kg (2.2 lb. P_2O_5 and 5.3 lb. N per ton) for heifers.

As-applied swine manure generally had less P_2O_5 than as-excreted book values, averaging 2.3 g P_2O_5/L (19.3 lb./1000 gal) compared to as-excreted values of 4.5 g P_2O_5/L (37.9 lb./1000 gal). N content of applied swine manure was similar to the content of as-excreted manure, averaging 5.2 g N/L (43.1 lb./1000 gal), compared to as-excreted book values of 5.5 g N/L (45.5 lb./ton).

Land area and field distribution for manure application

The 13 CAFOs are located within a 15 km (9.3 mi) radius, and together they reported between 10,623 and 13,615 ha (26,249 and 33,643 ac) available for manure application in 2013–2015, with between 3918 and 5792 ha (9682 and 14,313 ac) (37% to 43%) used each year. Although the CAFOs are near a watershed boundary (Fig. 1), 94% of fields used for manure application were within the same watershed as their CAFO. Approximately 25% of field acreage used for manure application was within 2 km (1.2 mi) of CAFO barns, 51% was within 5 km (3.1 mi), and 95% was within 15 km (9.3 mi). The median distance to a field from the CAFO barns was 5.7 km (3.5 mi), and the maximum distance was 33 km (20 mi). These distances are for on-site application of manure; distances traveled in transfers off-site were not reported.

Actual nutrient application rates vs. recommended and allowed rates

On average, total P_2O_5 application rates at CAFOs were similar to the Tri-State recommendations for all crops (Fig. 3), although there was substantial variability with several extreme outliers. The mean reported total N rates were lower than the Tri-State recommended rates for corn but higher for wheat, alfalfa, and soybeans. The Tri-State Standards recommend no N be applied to soybeans or alfalfa and no P be applied to soils where the soil P level is >40 or 50 ppm, depending on the crop. Between 2013 and 2015, there were only 80 occurrences (7% of all records) of manure applied to soybeans, but 495 occurrences (42% of all records) of manure applied when the soil P test was >50 ppm. Assuming an average rate of 34 kg P_2O_5/ha (30 lb./ac), manure applied to soybeans could have been redistributed to fertilize an average of 730 ha (1800 ac) per year, and the manure applied to fields with soil P levels >50 ppm could have fertilized an average of over 4025 ha (9945 ac)

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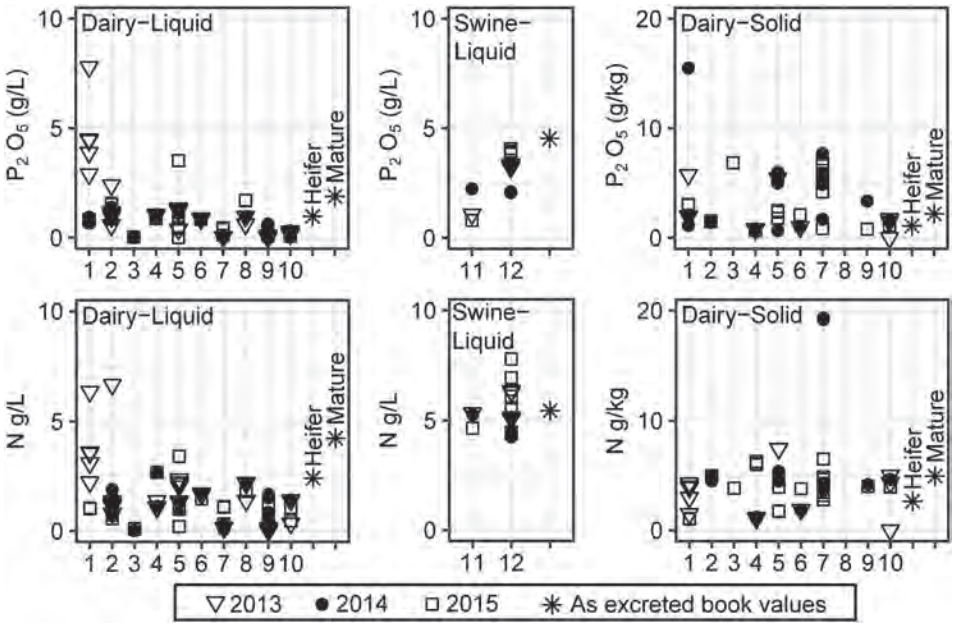

Fig. 2. Reported P (top row) and N (bottom row) content of as-applied liquid dairy manure (first column), liquid swine manure (second column), and solid dairy manure (third column) from 12 CAFOs over three years. Asterisks represent book values of nutrient content of as-excreted manure for heifers, mature dairy cows, and swine (Lorimor et al., 2004; James et al., 2006).

per year (Fig. 4). Using application rates based on N needs would cover less land because of the low N:P ratio in manure.

Because the MDEQ allowed rates are higher than the Tri-State recommendations, Tri-State exceedances described above were often within MDEQ permitted limits. Over the three-year period, there were 256 exceedances (23% of all records) of the MDEQ allowed N rates and 111 exceedances (10%) of allowed P_2O_5 rates on fields fertilized with manure (Fig. 5). Assuming an average rate of 34 kg P_2O_5/ha (30 lb./ac), the excess manure nutrients from these cases could be redistributed to fertilize an average of over 481 ha (1190 ac) of additional cropland every year (Fig. 4). Many of these exceedances were due to application of supplemental inorganic fertilizer (Fig. 5), which is further discussed below.

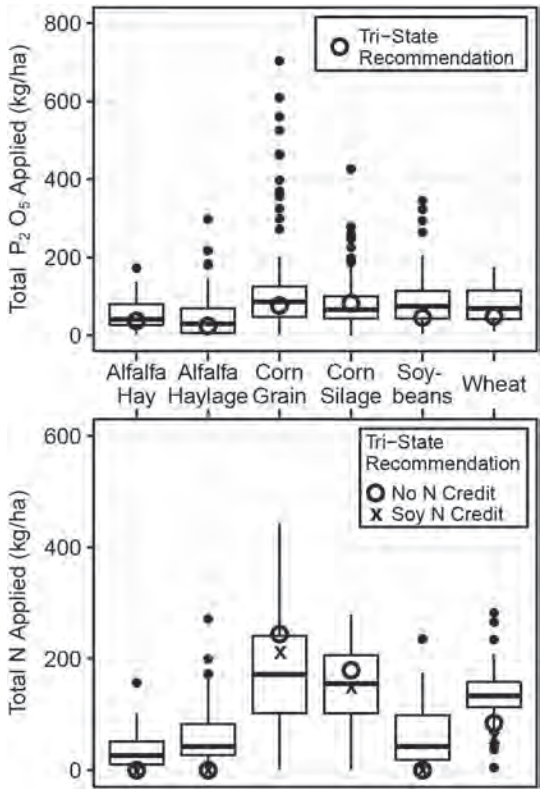

Fig. 3. Total nutrient application rates reported by CAFOs for different crops compared to Tri-State standard recommended rates. Reported rates are total N and P including manure and inorganic fertilizer. Tri-State rates assume maintenance soil P levels and average yields across all CAFOs in our dataset for yield goals.

There is broad interest in knowing if the nutrient exceedances are systemic or if only select operations are in violation. Not all CAFOs in this study violated MDEQ allowance limits. Considering both manure and supplemental inorganic fertilizer applications, four CAFOs exceeded the MDEQ N allowance on fewer than five field applications over three years; four of them averaged six or seven exceedances per year; three averaged 11 or 12 exceedances per year; and one averaged 20 exceedances per year (29% of all their applications) (Electronic Supplementary material (ESM) Table S1; see ESM Table S2 for exceedances summarized by crop). P_2O_5 exceedances were less frequent. Three CAFOs never exceeded P_2O_5 allowances, and six had fewer than 10 total exceedances over three years. But one had 40 P_2O_5 exceedances (19% of all their applications) (ESM Table S1).

Crop yield goals

Recommended application rates for both N and P_2O_5 are based on crop yield goals. A higher yield goal allows for a higher nutrient application rate, and CAFO operators set their own yield goals. We found that the stated yield goals were higher than actual yields 67% of the time. For alfalfa hay, wheat, and soybeans, yield goals were not met in 85%, 58%, and 57% of cases, respectively (Fig. 6). Conversely, actual yields were greater than goals in 72% of cases for alfalfa haylage and in 61% of cases for corn silage. Corn grain yields were above and below goals in roughly equal proportions. We determined the average actual yield for each crop at each CAFO and calculated the MDEQ's allowed N and P_2O_5 application rates using those as yield goals instead of the CAFOs' stated yield goals. In cases where the application rate exceeded the recommended rate calculated using average yields as goals, using the lower rate would have made available enough manure to fertilize an additional 438 ha (1083 ac) every year at an average rate of 34 kg P_2O_5/ha

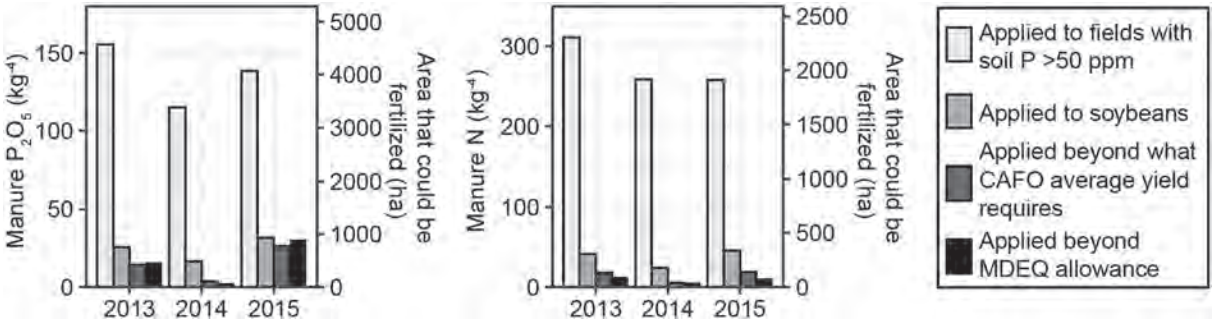

Fig. 4. Thousands of kilograms of excess manure P_2O_5 and N applied by CAFOs (left Y axis), and area which those nutrients could fertilize (right Y axis). Each bar represents one way that nutrients were under-utilized. Bars are not cumulative (e.g., the same field may have had both soil P >50 ppm and be in soybeans). N amounts applied beyond MDEQ allowances and beyond average yield requirements represent only first-year plant-available manure N, as this is how exceedances are determined in those cases; total manure N could be much greater. Areas are calculated based on application rates of 34 kg P_2O_5/ha and 135 kg N/ha.

(30 lb./ac) (Fig. 4). While many factors affect yields, some CAFOs consistently used yield goals that they did not achieve; seven of 12 CAFOs achieved yield goals <50% of the time. This finding is consistent with Jackson et al. (2000) who found that CAFOs in Iowa were underestimating the area required for manure application by projecting above-average crop yields.

Use of supplemental inorganic fertilizer

During our study period, 36% of fields received inorganic P_2O_5 fertilizer and 63% received inorganic N fertilizer in addition to manure. A majority of the exceedances for both N and P_2O_5 were on fields which received supplemental inorganic fertilizer (Fig. 5). We found that 23 of the 111 fields (21%) that exceeded the MDEQ P_2O_5 allowance and 197 of the 256 fields (77%) that exceeded the N allowance would have been below the allowed rates if inorganic fertilizer was not added. So, while we have considered only excess manure nutrients when calculating additional cropland areas that could be fertilized through redistribution (e.g. Fig. 4), recorded use of excess inorganic fertilizer would increase these amounts.

The average P_2O_5 application rate on fields that were fertilized with only manure was 64.8 kg/ha (57.8 lb./ac), while on fields that were

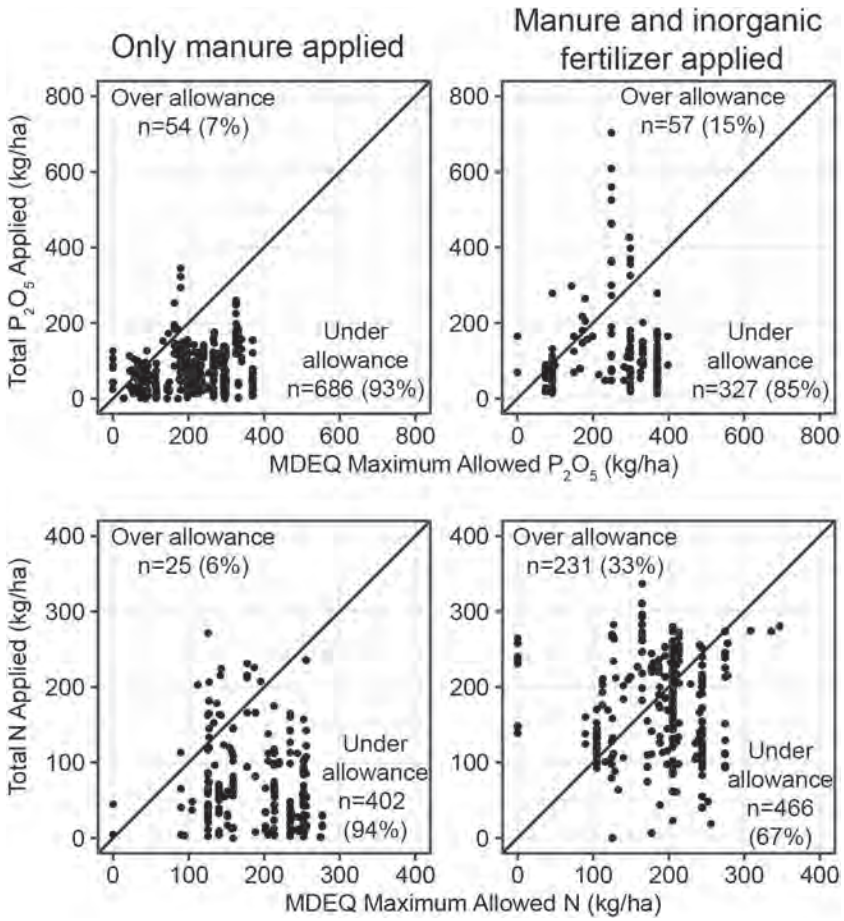

Fig. 5. Maximum P_2O_5 (top row) and N (bottom row) application rates allowed by the MDEQ compared to reported P_2O_5 and N application rates. Plots in the left column are for fields where only manure was used as fertilizer; plots in the right column are for fields where manure and additional inorganic fertilizer were used. Any point above the 1:1 line is an exceedance of the MDEQ allowed rate.

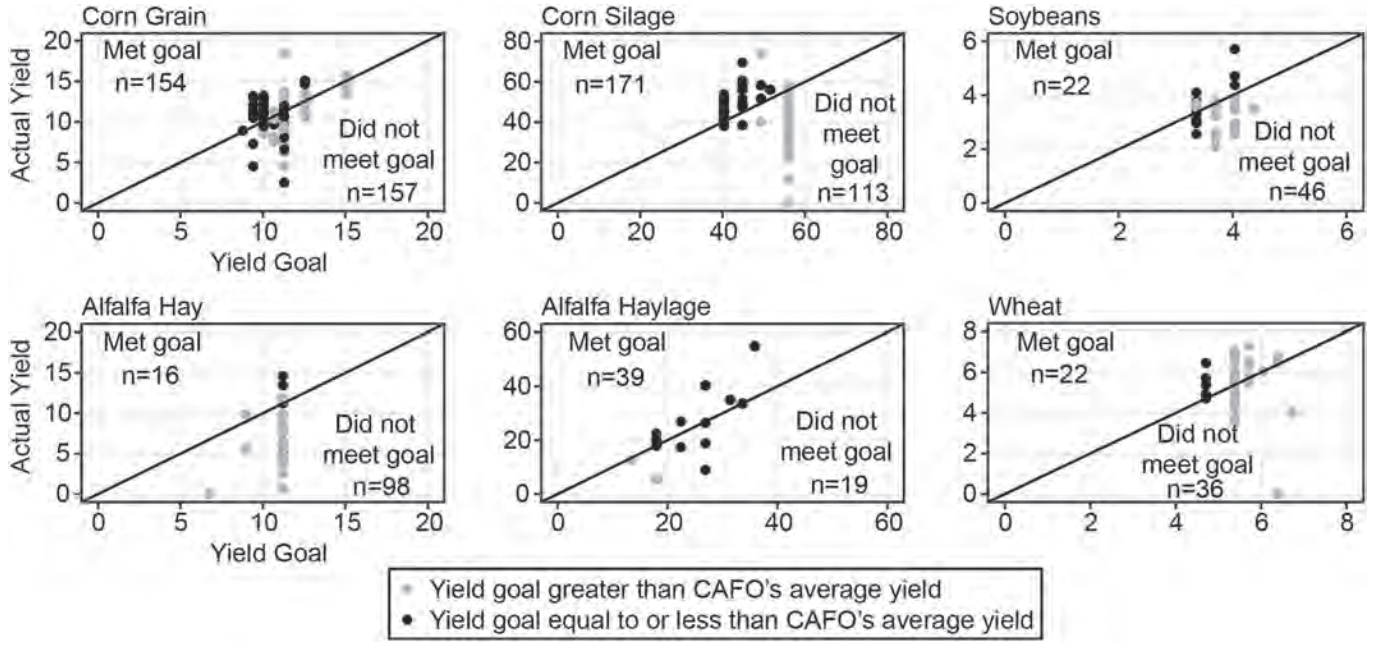

Fig. 6. Yield goals compared to actual crop yields for major crops at all CAFOs. Units are kg/ha for corn grain, wheat, and soybeans, and tonnes/ha for corn silage, alfalfa hay, and alfalfa haylage.

fertilized with both manure and inorganic fertilizer, the average total P_2O_5 application rate was 111.1 kg/ha (91.1 lb./ac), about 72% greater. The regional average total P_2O_5 application rate for fields to which manure is applied (with or without inorganic fertilizer as well) is 85.0 kg/ha (75.8 lb./ac) (USDA, 2017b). The rates at the CAFOs are higher than the regional average P_2O_5 application rates for fields to which only inorganic fertilizer applied, which is 50.1 kg/ha (44.7 lb./ac) (USDA, 2017b). As previously stated, no data were available for fields fertilized with only inorganic fertilizer at the CAFOs. It is worth noting that these regional rates are for most of MI, IN, IL, IA, WI, MN, and OH and parts of MO, SD, KS, NE, and OK, an area much larger than our study area.

Discussion

Manure composition and application rates

The wide range of manure nutrient content that we found is to be expected because different animal feeds, animal species, manure storages, storage duration, sampling techniques, and application methods all influence nutrient content (O'Dell et al., 1995; Petersen et al., 1998; Lorimor et al., 2004; Griffin et al., 2005). Our results emphasize the importance of using recent manure composition data because as-excreted literature values may lead to over- or under-estimation of nutrient availability (Fig. 2). As-applied liquid dairy manure often had lower nutrient content than as-excreted manure due to dilution and nutrient losses during storage. However, as-applied solid manure often had higher nutrient content than as-excreted manure, likely due to additions of compost materials and loss of water content. This wide range of nutrient composition also demonstrates that using published or average values to estimate nutrient loss (e.g., Kellogg et al., 2000) may still result in errors because the nutrient content is sensitive to many variables. The variability in manure composition may be one reason for nutrient exceedances.

Because more manure is generally produced by a CAFO than can easily be used, it is often treated as waste rather than as a valuable replacement for inorganic fertilizer (Hoag and Roka, 1995; Fleming et al., 1998). In 42% of records in our dataset, manure was applied to fields with soil P levels >50 ppm, even though the Tri-State Standard recommends no P_2O_5 application is needed in these cases. That amounted to 406,000 kg (895,000 lb.) of excess P_2O_5 and 818,000 kg (1,800,000 lb.) of excess N applied to over 5600 ha (13,800 ac) over three years. Thus, there are opportunities for better nutrient use, not only in southeastern Michigan, but potentially in other Midwestern states that have CAFOs and that allow nutrient application beyond what is recommended in the Tri-State Standards. Indiana allows CAFOs to apply manure on land with soil P levels up to 300 ppm (IDEM, 2014), reducing it to 200 ppm in 2018. In Ohio, CAFOs can apply manure to land with soil P levels up to 150 ppm. Adhering to the Tri-State Standard recommendations could result in improved nutrient use throughout the region and would also decrease the risk of nutrient runoff and contamination of surface water with excess N and P. The Tri-State recommendations are based on maintaining a soil P where crop yield will be 95–97% of maximum so that economic return on added nutrients is optimized (Warncke et al., 2004). So, adhering to Tri-State recommendations should not negatively impact yields and could be economically beneficial. While these data demonstrate the potential for improved manure use, there are barriers to manure redistribution, which are discussed in more detail in the next section.

Redistributing manure nutrients: How much is feasible?

Theoretically, it would be possible to redistribute manure to an average of >4775 ha/year (11,800 ac/year) from these CAFOs in southeastern Michigan, based on the amount of manure that was applied to soybeans or to land where soil P test level was >50 ppm, and at rates beyond what is allowed by the state or based on over-estimated crop yield goals. On average, manure produced by the 13 CAFOs in the study area is currently applied to about 5000 ha/year (12,350 acres/year), so this could potentially almost double the land used for application. The median distance from CAFO barns to fields that received manure was just over 5 km (3.1 mi), and there are 33,400 ha (82,500 ac) of cropland within 5 km of the CAFO barns, so applying to an additional 4775 ha seems feasible.

However, there are barriers to redistribution. For example, not all land near the CAFOs could require manure application, and nearby land managed by others may not need additional fertilizer. Other limitations include hauling cost, asynchrony between timing of manure availability and off-site need, public concern about odor and potential public

health risks, and farmers' reluctance to substitute manure for inorganic fertilizer due to inconsistencies in manure nutrient content (Risse et al., 2006; Kleinman et al., 2012). More frequent or on-site testing could reduce uncertainty in nutrient content, but additional incentives and changes in insurance programs are likely needed to help address other barriers. The USDA's Environmental Quality Incentives Program (EQIP) can provide financial assistance to CAFOs for storage, treatment, and use of manure, which can lead to more effective on-site use, but it does not address off-site transfer (Ribaudo et al., 2004; USDA, 2017c). Improvements in the integration between the commercial fertilizer industry and manure management agencies could increase substitution of manure for inorganic fertilizer (Kleinman et al., 2012).

In many cases, cost remains a barrier to redistribution because it is expensive to haul manure long distances. This is in addition to potential increased costs associated with application, obtaining more land, and additional tests for soil and manure nutrient content. For example, Ribaudo et al. (2003b) found that production costs for large dairy farms in the northern US would increase by up to 3% to meet a P-based standard of applying P at rates not greater than removal rates. They note, however, that there is a relative abundance of cropland available for manure application in Michigan, Ohio, and Indiana, a finding consistent with our analysis. Willingness of other operators to accept manure greatly influences the cost of distribution (Ribaudo et al., 2003b); addressing uncertainty in manure nutrient content, as discussed above, may increase their acceptance. Models exist to estimate the cost of transporting manure in specific cases (e.g., Fleming et al., 1998; Ribaudo et al., 2003b), and developing them for this region could provide additional valuable information to guide manure management.

Data needs and potential improvements for CAFO reporting

While CAFO data reporting in Michigan is relatively comprehensive, additional information would help improve our understanding of existing manure management. For example, it would be useful to know where CAFOs transfer manure, especially for operations that generate large amounts of solid manure, because hauling this low moisture manure is less expensive and therefore more likely to occur. Without knowing where transferred manure goes, how far it travels, and how it is subsequently managed, it is difficult to complete a comprehensive assessment of the impact that CAFOs have on nutrient loads in a watershed, as noted by Steeves (2002). It would also be useful to know when and how manure is applied, because proper timing and method of application are both critical for reducing nutrient losses (Kleinman et al., 2002).

Despite these shortcomings, the quality and availability of data in Michigan exceeds that in many other Midwestern states. Most states are authorized by the EPA to implement their own CAFO regulatory and permitting programs, and thus program requirements differ among states. All CAFOs are required to obtain NPDES permits in Michigan. In Ohio and Indiana, only CAFOs that discharge manure or wastewater are required to obtain those permits, and field-level reporting is not as detailed as in Michigan (IDEM, 2014; OEPA, 2017a). Uniformity among state reporting systems would be helpful when assessing watersheds that cross state lines, such as the Maumee River watershed that crosses three states and contains over 80 CAFOs (IDEM, 2017; MDEQ, 2017; OEPA, 2017b).

Applications for watershed modeling

Lake Erie watershed models have successfully quantified nutrient sources and delivery rates, but in doing so, broad assumptions had to be made about manure compositions and application rates and locations (Kleinman et al., 2002). Such assumptions likely impact estimates of critical nutrient source areas and perhaps overall nutrient loss rates. Incorporating more precise manure data, as summarized here, will likely improve those estimates. The field-level information described here can also improve models in any region where dairy and swine CAFOs are prevalent. For example, where CAFOs are prevalent, it is more appropriate to assume manure is applied within 15 km (9.3 mi) of CAFOs, to use nutrient compositions reflective of manure that has been stored (e.g., Luscz et al., 2015), and to consider that fields receiving nutrients from manure may also be applied with inorganic fertilizers.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2018.01.006.

References

Fleming, R.A., Babcock, B.A., Wang, E., 1998. Resource or waste? The economics of swine manure storage and management. Rev. Agric. Econ. 20 (1), 96–113.
GLWQA (Great Lakes Water Quality Agreement), 2012. The 2012 Great Lakes Water Quality Agreement.Available at. https://binational.net/glwqa-aqegl/ (verified 6 June 2017).
Gollehon, N.R., Caswell, M., Ribaudo, M., Kellogg, R.L., Lander, C., Letson, D., 2001. Confined Animal Production and Manure Nutrients. United States Department of Agriculture, Economic Research Service.
Griffin, T.S., He, Z., Honeycutt, C.W., 2005. Manure composition affects net transformation of nitrogen from dairy manures. Plant Soil 273 (1–2), 29–38.
Han, H., Allan, J.D., Bosch, N.S., 2012. Historical pattern of phosphorus loading to Lake Erie watersheds. J. Great Lakes Res. 38 (2), 289–298.
Hoag, D.L., Roka, F.M., 1995. Environmental policy and swine manure management: waste not or want not? Am. J. Agric. Econ. 10 (4), 163–166.
Homer, C.G., Dewitz, A.J., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., Megown, K., 2015. Completion of the 2011 National Land Cover Database for the conterminous United States-representing a decade of land cover change information. Photogramm. Eng. Remote. Sens. 81 (5), 345–354.
IDEM (Indiana Department of Environmental Management), 2014. Guidance Manual for Indiana's Confined Feeding Program. Available at. http://www.in.gov/idem/cfo/files/guidance_manual_cfo_program.pdf.
IDEM (Indiana Department of Environmental Management), 2017. Virtual File Cabinet. Available at. http://www.in.gov/idem/legal/2363.htm (verified 13 July 2017).
Jackson, L.L., Keeney, D.R., Gilbert, E.M., 2000. Swine manure management plans in North-Central Iowa: nutrient loading and policy implications. J. Soil Water Conserv. 55 (2), 205–212.
James, R., Eastridge, M.L., Brown, L.C., Elder, K.H., Foster, S.S., Hoorman, J.J., Joyce, M.J., Keener, H.M., Mancl, K., Monnin, M.J., Rausch, J.N., Smith, J.M., Tuovinen, O., Watson, M.E., Wicks, M.H., Widman, N., Zhao, L., 2006. Ohio Livestock Manure Management Guide. Ohio State University Extension, Columbus, Ohio, USA.
Kaplan, J.D., Johansson, R.C., Peters, M., 2004. The manure hits the land: economic and environmental implications when land application of nutrients is constrained. Am. J. Agric. Econ. 86 (3), 688–700.
Kellogg, R.L., Lander, C.H., Moffitt, D.C., Gollehon, N., 2000. Manure nutrients relative to the capacity of cropland and pastureland to assimilate nutrients: spatial and temporal trends for the United States. Proc. Water Environ. Fed. 2000 (16), 18–157.
Kleinman, P.J.A., Sharpley, A.N., Moyer, B.G., Elwinger, G.F., 2002. Effect of mineral and manure phosphorus sources on runoff phosphorus. J. Environ. Qual. 31 (6), 2026–2033.
Kleinman, P., Blunk, K.S., Bryant, R., Saporito, L., Beegle, D., Czymmek, K., Ketterings, Q., Sims, T., Shortle, J., McGrath, J., Coale, F., Dubin, M., Dostie, D., Maguire, R., Meinen, R., Allen, A., O'Neill, K., Garber, L., Davis, M., Clark, B., Sellner, K., Smith, M., 2012. Managing manure for sustainable livestock production in the Chesapeake Bay Watershed. J. Soil Water Conserv. 67 (2), 54A–61A.
Lorimor, J., Powers, W., Sutton, A., 2004. Manure Characteristics. MidWest Plan Service, Iowa State University, Ames, Iowa.
Luscz, E.C., Kendall, A.D., Hyndman, D.W., 2015. High resolution spatially explicit nutrient source models for the Lower Peninsula of Michigan. J. Great Lakes Res. 41 (2), 618–629.
MDEQ (Michigan Department of Environmental Quality), 2015. National Pollutant Discharge Elimination System Wastewater Discharge General Permit for Concentrated Animal Feeding Operations. Permit No. MIG01000. Available at. http://www.michigan.gov/documents/deq/wrd-npdes-cafo-GP_2015_488595_7.pdf.
MDEQ (Michigan Department of Environmental Quality), 2017. MiWaters.Available at. https://miwaters.deq.state.mi.us/miwaters/#/external/home (verified 30 May 2017).

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O'Dell, J.D., Essington, M.E., Howard, D.D., 1995. Surface application of liquid swine manure: chemical variability. Commun. Soil Sci. Plant Anal. (USA) 26 (19–20), 3113–3120.

OEPA (Ohio Environmental Protection Agency), 2017a. DSW: concentrated animal feeding operation map.Available at. http://wwwapp.epa.ohio.gov/dsw/gis/cafo/ (verified 13 July 2017).

OEPA (Ohio Environmental Protection Agency), 2017b. Concentrated animal feeding operations.Available at. http://www.epa.ohio.gov/dsw/cafo/index.aspx (verified 13 July 2017).

Petersen, S.O., Lind, A.-M., Sommer, S.G., 1998. Nitrogen and organic matter losses during storage of cattle and pig manure. J. Agric. Sci. 130 (1), 69–79.

Ribaudo, M.O., Gollehon, N.R., Agapoff, J., 2003a. Land application of manure by animal feeding operations: is more land needed? J. Soil Water Conserv. 58 (1), 30–38.

Ribaudo, M., Kaplan, J., Christensen, L.A., Gollehon, N., Johansson, R., Breneman, V.E., Aillery, M., Agapoff, J., Peters, M., 2003b. Manure Management for Water Quality Costs to Animal Feeding Operations of Applying Manure Nutrients to Land. Social Science Research Network, Rochester, NY.

Ribaudo, M., Cattaneo, A., Agapoff, J., 2004. Cost of meeting manure nutrient application standards in hog production: the roles of EQIP and fertilizer offsets. Rev. Agric. Econ. 26 (4), 430–444.

Risse, L.M., Cabrera, M.L., Franzluebbers, A.J., Gaskin, J.W., Gilley, J.E., Killorn, R., Radcliffe, D.E., Tollner, W.E., Zhang, H., 2006. Land application of manure for beneficial reuse. National Center for Manure and Animal Waste Management White Papers (913C0306), pp. 283–316.

Scavia, D., Kalcic, M., Muenich, R.L., Aloysius, N., Boles, C., Confesor, R., DePinto, J., Gildow, M., Martin, J., Read, J., Redder, T., Sowa, S., Wang, Y.-C., Yen, H., 2014. Informing Lake Erie Agriculture Nutrient Management via Scenario Analysis. University of Michigan Water Center.

Scavia, D., Kalcic, M., Muenich, R.L., Read, J., Aloysius, N., Bertani, I., Boles, C., Confesor, R., DePinto, J., Gildow, M., Martin, J., Redder, T., Robertson, D., Sowa, S., Wang, Y.-C., Yen, H., 2017. Multiple models guide strategies for agricultural nutrient reductions. Front. Ecol. Environ. 15 (3), 126–132.

Steeves, M., 2002. The EPA's proposed CAFO regulations fall short of ensuring the integrity of our nation's waters. J. Land Resour Environ. Law 22 (2), 367–398.

USDA, 2012. National Agriculture Statistics Survey. Census of Agriculture.

USDA, Natural Resources Conservation Service, 2017a. Conservation Practice Adoption on Cultivated Cropland Acres: Effects on Instream Nutrient and Sediment Dynamics and Delivery in Western Lake Erie Basin, 2003–06 and 2012.

USDA, Natural Resources Conservation Service, 2017b. Effects of Conservation Practices on Phosphorus Loss from Farm Fields: A National Assessment Based on the 2003–06 CEAP Survey and APEX Modeling Databases.

USDA, 2017c. Natural Resources Conservation Service, Michigan, Environmental Quality Incentives Program.Available at. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/mi/programs/financial/eqip/?cid=stelprdb1270324 (verified 10 July 2017).

USEPA, 2008. The Clean Water Act, 33 U.S.C. 1251 §122.23. Available at. https://www.epa.gov/sites/production/files/2015-08/documents/cafo_final_rule2008_comp.pdf.

Warncke, D., Dahl, J., Jacobs, J., Laboski, C., 2004. Nutrient Recommendations for Field Crops in Michigan. Michigan State University Extension, East Lansing, Michigan.

KNOW YOUR ENVIRONMENT. PROTECT YOUR HEALTH.

Five years after EWG's first analysis, manure still overloads Minnesota

By **Ethan Bahe** (/who-we-are/our-team/ethan-bahe) (EWG)

MAY 15, 2025



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generated almost 49 million tons of manure in 2024, a new EWG analysis finds.

It's a long-running problem that EWG highlighted in **a 2020 investigation** (https://www.ewg.org/research/manure-overload). Five years after that report, this new analysis finds only a slight downtick in the number of animal facilities, from 23,725 in 2019 to 23,503 in 2024, and a similarly small decrease in the amount of manure they produce. The waste they generate is equivalent to almost 8.5 tons of manure yearly for every Minnesotan.

But cattle production has become more concentrated at the largest facilities, which have increased in number by over 12 percent. Many meat and animal products sold in the U.S. come from livestock raised in animal facilities, which produce hundreds or thousands of hogs, poultry or cattle in concentrated barns or feedlots.

The enormous amounts of manure these facilities generate are often applied to nearby farm fields as a fertilizer, since the nitrogen and phosphorus it contains are nutrients that feed crops. But manure and its components can wash off farm fields, leach through soil into drainage systems that empty into nearby streams, or get into groundwater.

Nitrogen can form in drinking water as nitrate, and consuming this water can **increase the risk of birth defects and cancer** (https://ehsrc.public-health.uiowa.edu/wp-content/uploads/2024/09/Nitrate-Environmental-Health-and-Cancer-Fact-Sheet.pdf). Manure runoff can also create potentially toxic algae blooms in recreational waters when nutrients are applied in excess of crops' uptake capacity. EWG has **previously reported** (https://www.ewg.org/research/more-monitoring-needed-keep-people-safe-algae-toxins-iowa-minnesota-and-wisconsin) on algae toxins in bodies of water throughout Minnesota.

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practices for animal feeding operations, or AFOs. These practices include waste storage facilities and covers for manure pits, which encourage more production and waste.

At the state level, Minnesota could more strictly regulate AFOs to reduce the risk of animal manure polluting water. One option is to regulate facilities that fall below the Environmental Protection Agency's threshold for Clean Water Act discharge permits.

Risk of nitrogen overload

At the largest livestock facilities, known as concentrated animal feeding operations, or CAFOs, the risk of over-application increases. That's because there is limited cropland nearby, and transporting the waste elsewhere is often difficult and expensive.

EWG also analyzed which fields near AFOs likely received manure in 2024. Analysis found hot spots – areas most at risk for overapplication of manure.

The analysis found nine counties that are hot spots for nitrogen overload. This happens when nitrogen from manure, combined with nitrogen in fertilizer sold in the county, exceeds crop recommendations by more than 40 percent.

Nitrogen overload can be a particular problem in "**vulnerable groundwater areas** (https://www.mda.state.mn.us/chemicals/fertilizers/nutrient-mgmt/nitrogenplan/mitigation/wrpr/wrprpart1/vulnerableareamap)," as defined by the Minnesota Pollution Control Agency, or MPCA. In these areas, nitrate applied to farm fields through fertilizer or manure can easily get through soil and pollute groundwater. In 2024, 6,480 animal feeding operations were located within a vulnerable groundwater area. (See Figure 1.)

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Figure 1. Minnesota counties and vulnerable groundwater areas at risk of nitrogen overload

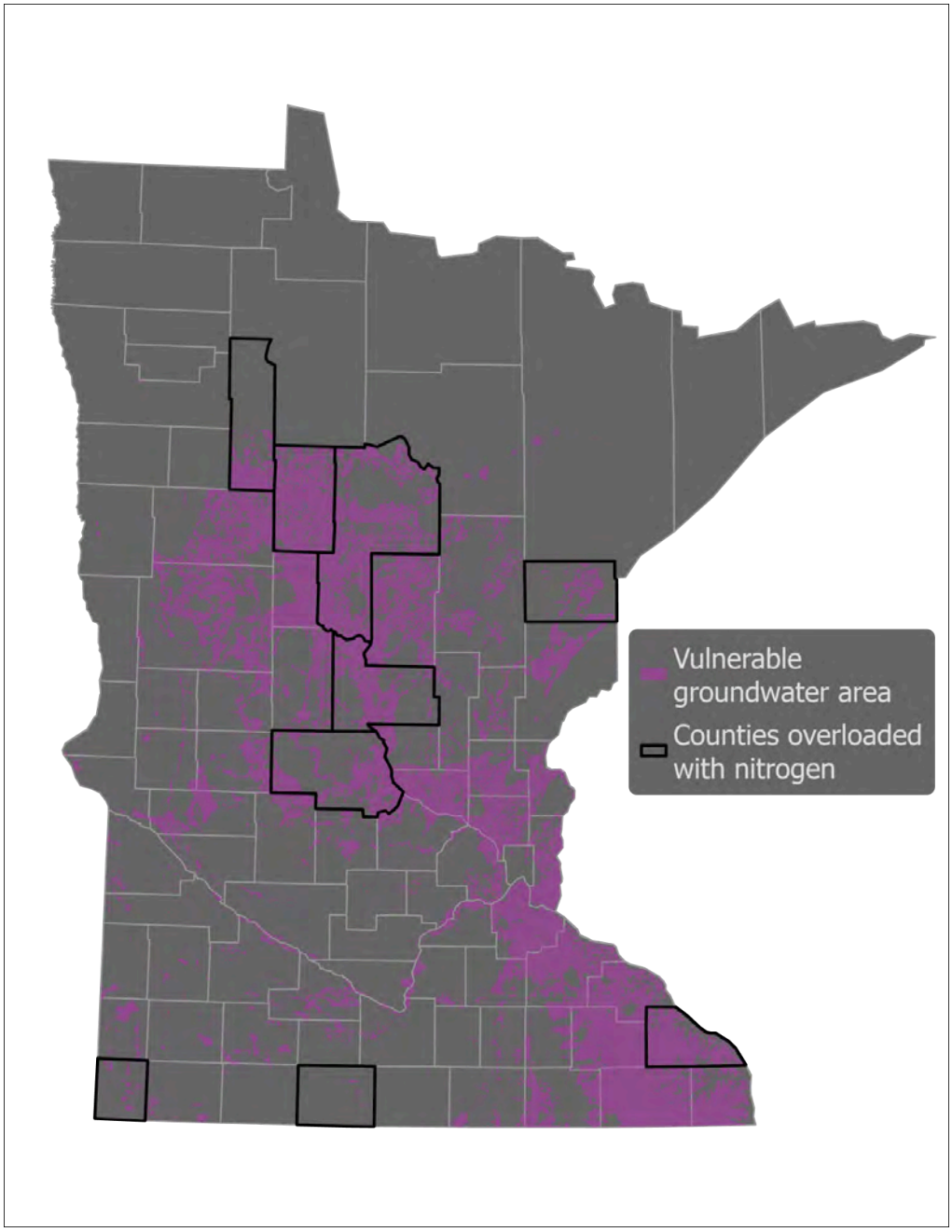

Source: EWG, from MPCA vulnerable groundwater area dataset

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Water contamination threatens Minnesota's drinking water, recreational water and public health. Consolidating animal production in large CAFOs intensifies that risk.

Huge amounts of manure

EWG's analysis finds that Minnesota had 23,503 animal feeding operations in 2024. These facilities house up to 1.03 million dairy cattle, 1.6 million beef cattle, 10.8 million hogs and 58.7 million turkeys and chickens, which together produced over 48.9 million tons of manure that year.

Cattle make up most operations in the state and account for over 64 percent of manure, while swine are 27 percent and poultry 8 percent. (See Figure 2.)

Figure 2. Cattle operations produce most of the manure in Minnesota

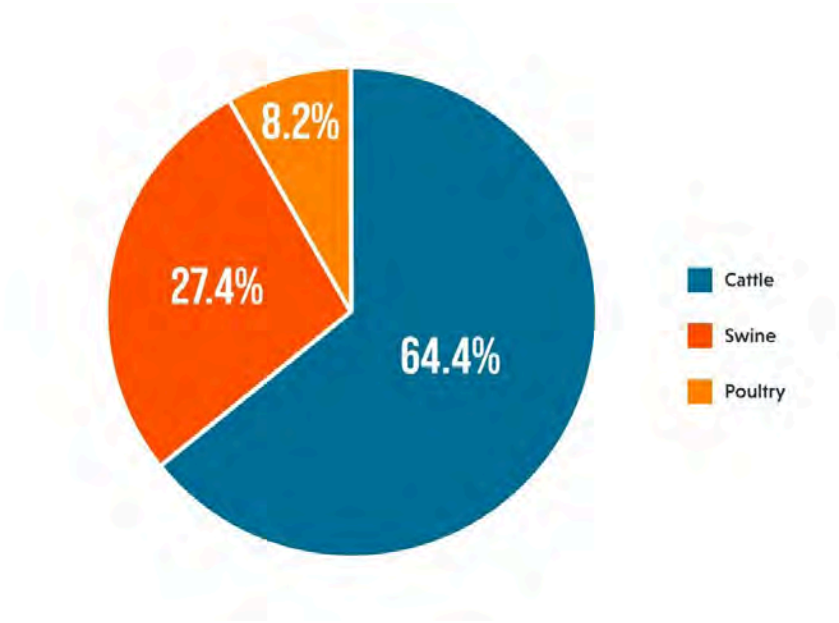

Source: EWG, from Manure Characteristics Midwest Plan Service, or MWPS, 18 Section 1, 2004, Second Edition

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Stearns, Todd, Goodhue, Fillmore and Winona counties (in order of most to least) had the most animal feeding operations in 2024, representing 25 percent of all facilities in the state. (See Figure 3.)

Most livestock facilities in the state are small, but the large facilities produce a disproportionate amount of manure. We used **the EPA's CAFO definitions** (https://www3.epa.gov/npdes/pubs/sector_table.pdf) for this report. Small facilities have fewer than 300 animal units, medium facilities have between 300 and 999, and large have 1,000 or more animal units.

An "animal unit" is defined as an animal equivalent to 1,000 pounds live weight. For example, a single animal unit would be one beef cattle, 2.5 hogs or 125 chickens. So large facilities, or CAFOs, have at least 1,000 beef cattle, 2,500 hogs or 125,000 chickens.

While 78 percent of facilities were small, they produced just 24 percent of manure. Medium facilities made up only 18 percent of all operations but produced the largest share of manure, at 43 percent. Four percent of facilities were large but generated 33 percent of manure.

Figure 3. Map of Minnesota's animal feeding operations in 2024 by animal type and county

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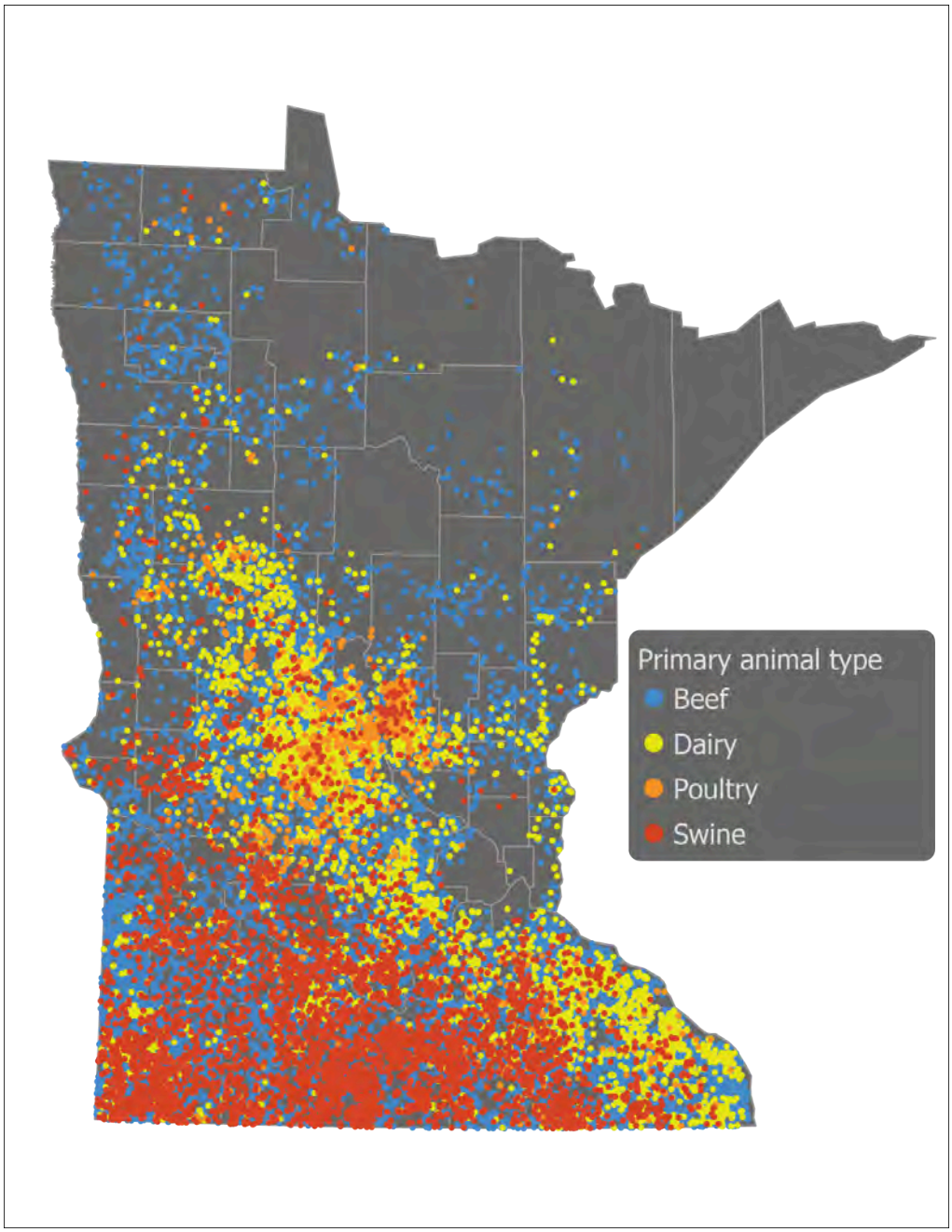

Source: EWG, from MPCA feedlot dataset

Cattle production is getting more concentrated in the largest facilities in Minnesota. There were 22 more large cattle facilities in 2024 than in 2019 – a 12 percent increase in CAFOs with 1,000 or more animal units. The number

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of large swine facilities stayed the same, while the number of large poultry facilities decreased slightly.

For both cattle and swine, the average number of animal units per facility also increased in 2024 for the largest facilities – some of the biggest CAFOs are getting even bigger. The average number of animal units per facility increased by 257 between 2019 and 2024 in the case of large cattle facilities. The average went up by 24 animal units per facility for large swine operations.

Regulation falling short

In Minnesota, large animal feeding operations must have either an EPA Clean Water Act **National Pollutant Discharge Elimination System** (https://www.epa.gov/npdes/animal-feeding-operations-npdes-cafo-permitting) permit or a state-based **State Disposal System** (https://www.pca.state.mn.us/business-with-us/npdes-and-sds-feedlot-permits) permit to operate.

The permits require these large operations to create and submit to the state a manure management plan showing which farm fields livestock operators plan to apply their manure to each year. Permitted facilities must also follow certain land application restrictions to protect vulnerable groundwater areas.

Management plans aim to prevent multiple facilities from applying manure to the same fields, applying manure above the agronomic rate, or both.

These plans are far from perfect and poorly enforced, which is why manure overapplication is still common near large facilities in many areas of the state. But manure management plans, along with the other regulations that apply to large facilities, do rein in some of the worst potential pollution.

Facilities that house between 300 and just under 1,000 animal units do not

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construction permit. So these medium-sized facilities are not subject to other rules that could protect water quality and public health, such as those that apply to large CAFOs.

In Minnesota, 983 facilities housed between 750 and 999 animal units – just a few hundred units under the 1,000 level that requires regulation. These facilities still produced a lot of manure, as they are 14 percent of all facilities in the state, but are barely regulated. And among these, there were 374 operations that were between 950 and 999 animal units - just 50 animal units short of the large CAFO designation. So almost 400 facilities are polluting at levels close to the amounts from large facilities, but are not regulated in the same way, though they should be.

Manure application hot spots

EWG simulated which individual fields could safely accept manure, based on their distance from the feedlot and the amount of nitrogen recommended for growing crops. Nitrogen rates were based on MPCA guidelines and University of Minnesota fertilizer recommendations.

In areas with a dense concentration of livestock, almost all crop fields are needed to achieve safe use of manure produced by nearby feedlots. In a few isolated areas, there is too much manure to dispose of within a reasonable distance.

EWG's simulation likely understates the risk of this overload, because we assumed every field within 5 miles of a cattle or hog feedlot and 25 miles of a poultry feedlot is available to take manure, while in most real situations, manure does not travel that far.

There are nine county hot spots for nitrogen overload, where nitrogen from

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crop recommendations by more than 40 percent. (See Table 1.)

Table 1. Counties with nitrogen overload

County	Percent nitrogen recommendation met by fertilizer sold	Percent nitrogen recommendation met by applied manure	Percent nitrogen recommendation met by manure and fertilizer combined
Cass	84.1	74.5	158.7
Carlton	84.1	72.1	156.2
Morrison	84.1	69.9	154.0
Martin	89.4	61.2	150.7
Winona	100.9	49.6	150.6
Hubbard	84.1	61.4	145.5
Rock	77.6	66.2	143.9
Clearwater	126.8	15.9	142.7
Stearns	84.1	57.6	141.7

Source: EWG, from Manure Characteristics MWPS-18 Section 1 Midwest Plan Service, 2004, Second Edition and MPCA feedlot dataset

Research shows that much of the nitrogen considered lost to the atmosphere during manure storage and application ends up redeposited on the land nearby, adding to the potential overload. The concentration of feedlots leaves little or no room to adapt to year-to-year changes in cropping patterns and fluctuating manure composition. It also increases the risk of overloading fields with phosphorus.

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Many counties with nitrogen overload, highlighted in Figure 4 below with black outlines, are within the Central Sands and Southeast regions of Minnesota. These two regions have a high percentage of land with the MPCA vulnerable groundwater area distinction.

Figure 4. Areas in Minnesota with nitrogen overload from manure

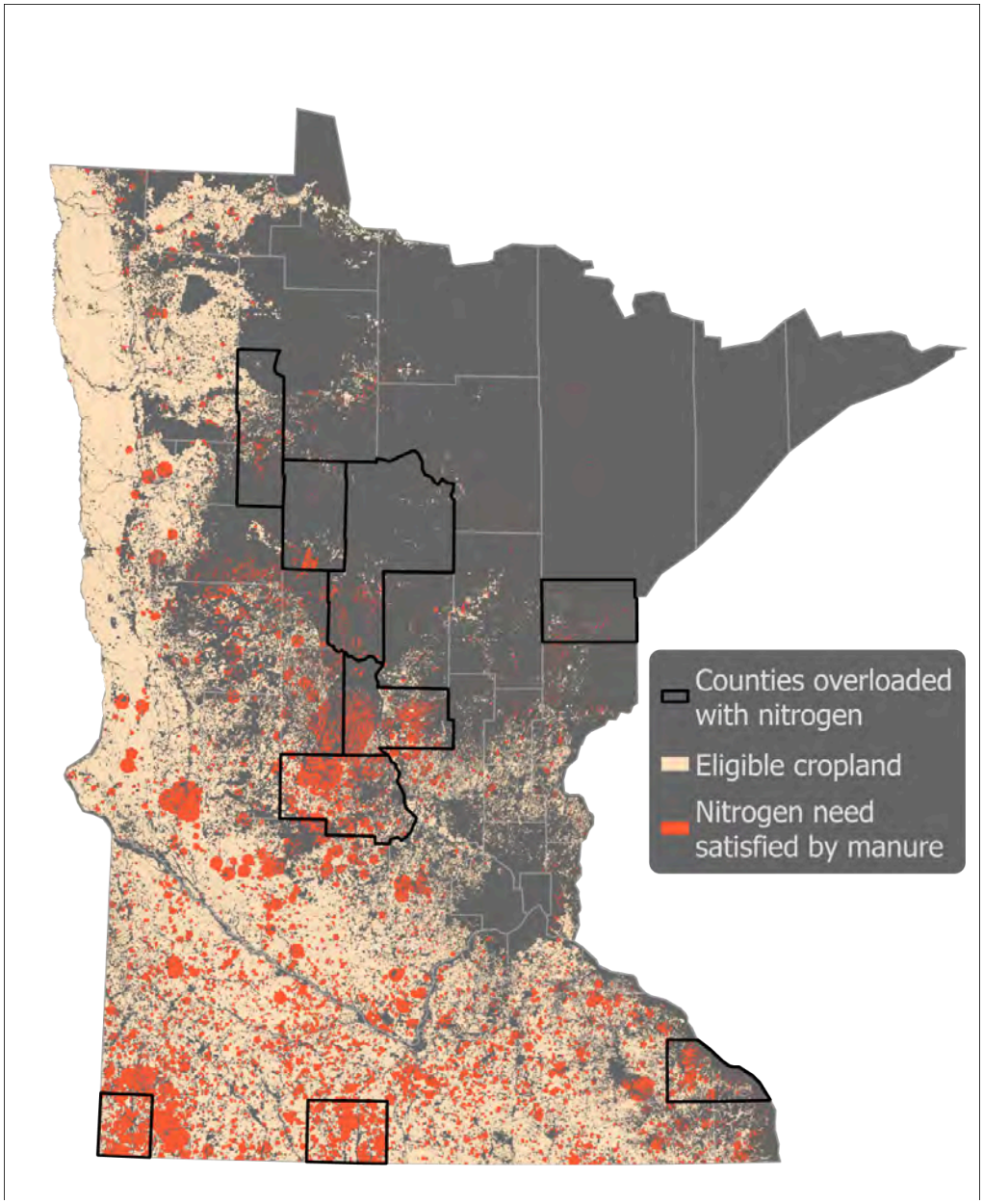

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Source: EWG, from MPCA feedlot dataset

When manure is applied to meet the nitrogen recommendation for crops, phosphorus is often overapplied. This nutrient imbalance is worse for poultry and cattle manure. Phosphorus overload in Minnesota is common – a problem since phosphorus is a major driver of toxic algae blooms.

Algae blooms in recreational water sources can pose a health hazard for humans and pets, not to mention the ecosystem harm. When applying manure at a nitrogen fertilizer rate, the phosphorous content of the manure often exceeds plant need.

The state's newly updated permitting regulations will determine when large facilities in vulnerable groundwater areas can apply manure to nearby fields. But out of the 6,480 operations in a vulnerable groundwater area, only 161 are above the 1,000 animal unit threshold.

Almost five times that number (791 facilities) fall into the medium category – with more than 300 animal units but fewer than 1,000 animal units. The rest of the facilities do not have rules about how much manure they can apply to vulnerable fields or when. And 53 of these facilities have slightly fewer than 1,000 animal units. So they produce a lot of manure in vulnerable groundwater areas without being subject to the large CAFO rules.

Reforms to help reduce pollution

Minnesota has long struggled with nitrate in drinking water, **especially** (https://www.mncenter.org/protecting-drinking-water-in-MNs-karst-region) in the Southeast portion of the state. This region has **karst soils** (https://stormwater.pca.state.mn.us/index.php/Karst) that water and contaminants can easily leach through, making groundwater more vulnerable to nitrate contamination. Private wells in the region and in other areas of

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Minnesota have levels of nitrate in their drinking water that are dangerous for the people who rely on them.

EWG joined the Minnesota Center for Environmental Advocacy in 2023 to petition the EPA to work toward fixing the groundwater nitrate contamination crisis in this region.

Livestock facilities also damage air quality, emitting pollutants like ammonia, hydrogen sulfide and particulate matter. This air pollution can cause **respiratory illnesses** (https://www.sciencedirect.com/science/article/pii/S0160412018320750#:~:text=Residential%20proximity%20to%20a%20CAFO%20was%20similarly%20associated%20with%20asthma,miles%20from%20a%20CAFO%20(Fig.) like asthma and bronchitis in people living nearby. And **studies** (https://pmc.ncbi.nlm.nih.gov/articles/PMC8530906/) show that people who live within a few miles of an AFO have increased rates of mortality from respiratory and cardiovascular problems.

Food production should not imperil water quality and public health.

Reform of federal conservation programs to reduce how much money goes to structural practices for animal feeding operations would be a good first step. The Department of Agriculture's Environmental Quality Incentives Program, or EQIP, is one of the largest federal conservation programs. This program requires half of all funding to go to farmers for livestock practices. It sent over $1.3 billion to farmers in 2024.

Reforms could include:

- Exempting states from the requirement that 50 percent of EQIP dollars go toward livestock production.
- Lowering the payment limit from $450,000 to $250,000 to prevent a few large producers from monopolizing EQIP funds.

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- Barring the largest CAFOs from receiving funding for upgrading or installing infrastructure equipment.

Additionally, the state of Minnesota should change how it regulates AFOs to reduce the risk of pollution of water with animal manure, adopting these policies:

- Permitted, large facilities should be required to monitor subsurface discharges to see how much nitrate ends up in water. There is currently no way to make sure these operations do not violate Minnesota's water quality standards.
- Facilities that are under 1,000 animal units but still produce huge amounts of manure, such as those between 750 and 999 animal units, should be required to get a State Disposal System permit.

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METHODOLOGY

Special thanks to Sarah Porter, previously with EWG

Introduction

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Adequately addressing water quality issues in Minnesota requires a better understanding of the relative contribution of the major nutrient sources and their distribution.

Consolidation of animal operations has created landscape scenarios in which large quantities of manure are produced in geographically clustered areas. Losses of nitrogen, or N, and phosphorus, or P, the two primary nutrients in manure, can contaminate surface water and groundwater. This leads to a wide range of environmental and economic consequences.

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REFERENCES

[1] Minnesota Pollution Control Agency. Feedlots in Minnesota; St. Paul, Minnesota, 2019. Available Online from the Minnesota Geospatial Commons: https://gisdata.Minnesota.gov/dataset/env-feedlots (https://gisdata.mn.gov/dataset/env-feedlots).

[2] Office of the Revisor of Statutes, State of Minnesota. Minnesota Administrative Rules; Chapter 7020, Animal Feedlots; Minnesota, 2019. Available Online: https://www.revisor.Minnesota.gov/rules/7020/ (https://www.revisor.mn.gov/rules/7020/).

[3] Porter, S.A.; James, D.E. Using a Spatially Explicit Distribution Model to Assess the Contribution of Animal Agriculture to Minnesota's Agricultural Nitrogen Budget. *Agronomy*. 2020, 10(4), 1–15.

[4] Lorimor, J.; Powers, W.; Sutton, A. Manure Characteristics; MWPS-18, Section 1; Midwest Plan Service: Ames, Iowa, 2004.

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In the Midwest, we're working to make agriculture sustainable. The way farmland is used and managed has profound effects on our health, through the water we drink and the food we eat. But with simple changes, farming can actually be part of the solution.



(/areas-focus/farming-agriculture/farm-pollution)



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Farm Pollution (/areas-focus/farming-agriculture/farm-pollution)

Conventional agriculture can pollute rivers, lakes and tap water with unsafe levels of toxic chemicals. EWG offers science-based information to learn more.

Farming & Agriculture (/areas-focus/farming-agriculture)

EWG works to find innovative ways to protect your health and environment while ensuring a sustainable future for America's working farmers.

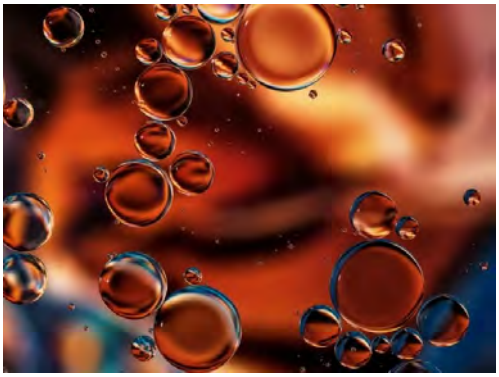

(/areas-focus/toxic-chemicals)



(/areas-focus/regional-issues)

Toxic Chemicals (/areas-focus/toxic-chemicals)

Chemical companies aren't required to test chemicals for safety before they go on the market. We offer resources to help you make better, safer decisions.

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EWG spotlights regional issues in California and the Midwest. We help raise awareness and hold industries accountable – for your health, for your environment.

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Rush Creek fish kill response — Winona County

Summary

Rush Creek is a cold-water trout stream that begins just south of the city of Lewiston in Winona County. It flows in a southerly direction into Fillmore County and eventually joins the Root River at the city of Rushford. Rush Creek is highly valued by trout anglers.



Rush Creek investigation map

On the evening of July 25, 2022, the Minnesota Duty Officer (MDO) received a report of several dead fish in Rush Creek. Local staff from the Minnesota Department of Natural Resources (MDNR) and Minnesota Pollution Control Agency (MPCA) began coordinating a response immediately. The field response began the following morning, July 26, and included staff from Winona County, the Minnesota Department of Agriculture (MDA), MDNR, and MPCA.

Fisheries staff from the MDNR estimated that more than 2,500 fish were killed, including at least 1,900 brown trout. The remaining species included white sucker and mottled sculpin. The responding agencies concluded that the fish kill likely happened after a significant runoff-producing local rainfall event on July 23, 2022 (1.5 inches to 2 inches that fell in a short period of time). Several factors may have contributed to the fish kill including warm temperatures, recent upstream applications of manure and pesticides, and low-flow conditions in the creek prior to the rainfall, resulting in limited dilution of the contaminated runoff.

Two branches of Rush Creek converge in the area of the fish kill; one from the north in the direction of Lewiston, the other from the west. Because no dead fish were observed in the branch from the north, it was concluded that the contaminated runoff came from the 10 square-mile area that drains to the western branch. This eliminated from consideration a wastewater discharge from the City of Lewiston.

First report, response, extent, and size of fish kill

Following the report to the Minnesota Duty Officer, local staff from DNR and MPCA began coordinating a response on the evening of July 25, 2022.

On July 26, MDNR Fisheries staff, MPCA feedlot staff and water monitoring staff, MDA pesticide monitoring staff, and Winona County feedlot staff were all on site. MDNR Fisheries staff walked the stream to determine the geographic extent of the fish kill and to document the type, size, and number of fish lost. MPCA and Winona County feedlot staff evaluated livestock facilities and a manure application field in the vicinity of the fish kill and began a broader survey of livestock facilities in the larger upstream drainage area. MPCA and MDA monitoring staff made visual observations, took field measurements, and collected water chemistry samples as well as macroinvertebrates at multiple locations on Rush Creek.



White sucker fish found in Rush Creek

MDNR Fisheries staff determined that the fish kill occurred over two miles of Rush Creek from just upstream of Winona County Road 29 to downstream of Interstate Highway 90. Their survey of 1,050 feet of Rush Creek collected 162 brown trout, 27 white sucker, and 23 mottled sculpin. The estimated total number of fish killed were 2,523 including 1,921 brown trout, 325 white sucker, and 277 mottled sculpin. *For information about fish by location, type, size, and quantity, see Tables 1-3 in the Appendices.*

On the morning of July 27, DNR Fisheries staff noticed after a second, smaller rainfall event, that the western branch of Rush Creek was cloudy and discolored as compared to the branch from the north. Fisheries staff collected water samples for analysis by MPCA and MDA.

In subsequent days, additional investigatory visits were made to the area, including a visit on August 4 that included a stream ecologist from Winona State University accompanying MDNR Fisheries staff surveying aquatic macroinvertebrates in Rush Creek.

Water sample results

MPCA and MDA staff coordinated water quality sampling on July 26 at multiple locations on Rush Creek. The samples were analyzed for 182 different pesticide analytes (including fungicides and insecticides) and 13 different general water chemistry analytes (*see Table 4 in Appendices*) typically measured during fish kills. None of the analytes were detected at elevated levels.

Additional samples were also taken on July 27, after a small rain event. This rain event produced observed runoff and stream response, so a sample was collected to gain information about potential sources that may have still been present in the watershed. Elevated levels of E. coli bacteria (an indicator of manure or sewage) and phosphorus were present in this sample, but the remaining general water quality parameters were not found at elevated levels. Compared to the July 26 sample, some

additional pesticides were detected, but not at elevated levels. The results showed organic pollution, which is common for a runoff event in this region. *See Table 5 for pesticide sample results.*

Organic pollution results from the decomposition of living organisms and their by-products. This includes decaying plant material, manure and human sewage, livestock feed, and waste products from the food processing industry. Organic pollution can be directly or indirectly toxic to fish and other aquatic life.

Typically, water quality impacts from fish kill events are difficult to capture unless samples are collected within a short period of time (i.e., ideally within 24 hours). Streams will often fall back to "normal" water chemistry levels very quickly after storms due to constant inflows of new groundwater. By the time water samples were taken on Rush Creek (two to three days after the storm event), the contamination that killed the fish had already moved downstream and/or was significantly diluted, making it difficult to detect in water quality samples.

Aquatic macroinvertebrate sample results

There were two primary purposes for the macroinvertebrate sampling conducted by a stream ecologist from Winona State University and MDNR Fisheries staff. The first purpose was to help understand whether there would be broader or lingering ecological impacts to Rush Creek beyond the fish that died at the end of July. Macroinvertebrates play a key role in a stream's food chain. In simple terms, they eat algae and other organic matter and become food for fish. While fish are highly mobile and can recolonize rapidly, it would take some time for macroinvertebrates to return to an area where they were severely impacted. The second purpose for the sampling was to provide clues to possible causes of the fish kill, as fish and macroinvertebrates have different susceptibilities to pollutants.

The intent of the macroinvertebrate sampling was to assess conditions at multiple locations in the fish kill zone, and to compare these results with a sample from the non-impacted north branch of Rush Creek. There was also a limited opportunity to compare with previous macroinvertebrate sampling on Rush Creek.

The macroinvertebrate sampling results indicate that whatever killed the fish in Rush Creek did not harm the macroinvertebrate community in an appreciable way. A comparison of the macroinvertebrate data collected on Rush Creek above and below the confluence with the South Tributary stream did not show any differences that suggest an impact to the macroinvertebrate community. Similarly, a comparison between the data collected in the South Tributary, to the data collected on the upstream and downstream reaches did not show any discernable differences. There were subtle differences in the data, but not more than would be expected to occur naturally.

Combined with the pesticide water sample results, the lack of impact to the macroinvertebrate community may suggest pesticides were less of a factor in the fish kill as compared to organic pollution.

Feedlot and pesticide use survey results

MPCA and Winona County staff conducted multiple feedlot inspections and in-field land application inspections in the area of the fish kill on July 26, July 27, and Dec 12, as well as a stockpile investigation on Aug 11. These inspections included feedlot facility inspections, review of land-application of manure records, and in-field land-application inspections. Winona County feedlot staff requested land application of manure records from all facilities located within the 10 square-mile watershed in the western branch of Rush Creek. Of the 100 landowners contacted regarding manure application and manure stockpiling activities, Winona County received more than 60 responses. Winona County determined that those who did not respond were not feedlot owners, were small feedlot owners who were not required to maintain land-application records or were small land/feedlot owners whose land

did not directly impact the stream (meaning the land was in the watershed, but any run-off from the land would flow overland across others property prior to making it into a Rush Creek).

The inspections and records review showed that two facilities within the watershed had inadequate or incomplete records, as well as setback violations from sinkholes and special protection areas. This resulted in notices of violation issued to these two facilities. However, during the course of the in-field land-application inspections, no evidence of direct discharge to Rush Creek was found. The MDA surveyed property owners in the vicinity of Rush Creek to identify potential pesticide applications in the area. During the MDA's investigation, they identified cropland that had received pesticide applications around the time of the rain event on July 23. After reviewing application records and applicator interviews, the MDA found no label violations associated with these applications.

Fish kill cause: Burst of rain; contaminated runoff; low creek flows

Responding state agencies concluded that contaminated runoff following a significant rainfall event on July 23 likely caused the fish kill. As discussed previously, several factors may have contributed to the fish kill including warm temperatures, recent upstream applications of manure and pesticides, and low-flow conditions in the creek prior to the rainfall, resulting in limited dilution of the contaminated runoff. It is difficult to determine how a mix of contaminants might interact to harm fish. Warm summer temperatures and lower flows may also elevate stream temperatures; this in turn may stress cold-water fish species and make them more susceptible to mortality, although there is no direct evidence that this was the case here.

Infectious disease may also be an important factor associated with fish kills in Minnesota, and opportunistic bacterial pathogens are implicated in multiple freshwater fish mortality events each year. However, infections disease was ruled out as a major contributing factor to the Rush Creek mortality event since standard pathological inspection (including parasite screening, viral and bacterial culture) did not uncover any infectious agents.

Fish community recovery

As we have observed in recent fish kills, fish will continue to return to the section of stream where the kill occurred, but it will take years to replace the larger fish that previously resided in this section of stream. Rush Creek is known for having abundant brown trout, is larger than most area streams, and is over 22 miles long. These are all factors that increase resiliency, but brown trout are a sensitive fish species. A fish kill of this magnitude will certainly disrupt the size structure, species diversity, and numbers of catchable size trout. If pollution events continue, there could be detrimental effects to the entire stream long-term.

Also, despite the apparent resiliency observed in Minnesota driftless-region trout streams so far, large scale mortality events are evidence of severe stressors that are concerning, including the possibility of increased frequency of extreme weather events. Minnesota waters are expected to continue their warming trends and be impacted by increased frequency of severe precipitation events. Thus, it is imperative to identify and work to mitigate stressors associated with large scale mortality events in these vulnerable fisheries.

Next steps

This is the fourth significant trout stream fish kill in this part of southeastern Minnesota since 2015. The other fish kills occurred on the South Fork of the Whitewater River, Garvin Brook, and Trout Valley Creek. Certain common conditions and risk factors have emerged. These include low stream flow, warm air temperature, elevated water temperatures, thunderstorms, and the presence of certain types of pollutants that are susceptible to runoff.

Unauthorized releases and permit violations that lead to fish kills are preventable and unacceptable. To mitigate the fish kill risk, the MPCA, MDNR, and MDA are working to summarize and proactively communicate these risk factors as part of an interagency effort. An emphasis of this communication effort will be on the use of weather and runoff forecasting tools to help plan the timing of manure and pesticide applications. Additional strategies include inspections of livestock facilities, including land application of manure records and field reviews, in areas where fish kills have occurred, and the precise identification of high-risk runoff pathways on agricultural fields in a part of Minnesota characterized by steep slopes and karst topography.

For more information

It is critical for anyone that observes a fish kill to report it immediately to increase the chances of identifying the cause or source for a fish kill. If you see something, contact the MDO at 800-422-0798. If there is an immediate threat to life or property, call 911 first.

There is more information on fish kills in Minnesota on the MPCA website. You can also learn more on the DNR website.

Appendices — Rush Creek fish kill

Table 1. Universal Transverse Mercator (UTMs) of stations on Rush Creek, July 26, 2022. Station 1 and 2 were counting dead fish and fish kill extent is the entire reach dead fish were observed (12,437 ft).

Station	Station length (feet)	Downstream UTMs (easting, northing)	Upstream UTMs (easting, northing)
Fish station 1	536	591071, 4865976	591017, 4866125
Fish station 2	514	591528, 4865304	591670, 4865369
Fish kill extent	12,437	592004, 4864755	590280, 4866074

Table 2. Species and length of dead fish collected in Station 1 and 2 (1,050 ft) on July 26, 2022.

Species	Length category	Number
Brown trout	3-5 inches	33
Brown trout	6-10 inches	112
Brown trout	11-15 inches	15
Brown trout	16-20 inches	2
White sucker	ALL	27
Mottled sculpin	ALL	23
	TOTAL	**212**

Table 3. Estimated numbers of dead fish in Rush Creek (12,437 ft).

Species	Estimated number	% of total
Brown trout	1,921	76%
White sucker	325	13%
Mottled sculpin	277	11%
TOTAL	**2,523**	

Table 4. General Water Chemistry Sample Results

	Water Sample Station			
	WC1	WC2	WC3	WC4
Date	7/26	7/26	7/26	7/27
	all values in mg/l			
Ammonia-N	0.10	<	<	0.06
Unionized ammonia	0.011*	na	na	na
Chloride	25.3	25.7	34.9	23.4
NO2/NO3	<	12.0	8.7	7.9
TSS	490	5.2	10	28
TSVS	100	<	3.2	9.0
TP	2.06	0.068	0.102	0.491
Ortho-P	1.42	0.059	0.089	0.301
TKN	9.07	<	<	1.04
CBOD (5-day)	25.7	0.78	0.99	na
Comments	Standing water near stream; 1L given to MDH for pesticides; some analyses not available	South (west) trib.	North trib.	South (west) trib.; repeat sample by DNR next day after 0.5 inches rain; preserved late.; E. coli out of hold - 24000 MPN/100ml

< = below reporting limit, non-detect

All field parameters (temperature, pH, dissolved oxygen, conductivity) taken were normal on 7/26

*Chronic WQ standard for unionized ammonia for cold-water streams (0.016 mg/L; 16 ug/L)

Table 5. Rush Creek Fish Kill Pesticide Samples

Analyte	P1 - CR 29 South Tributary		P2 - CR 5 North	P3 - CR 5 South	P4 - CR 25	Lowest available aquatic life fish benchmark or MN state standard
All results and reference values are in ng/L						
2022 Dates sampled	**7/26**	**7/27**	**7/26**	**7/26**	**7/26**	
2,4-D	< 8.3	9.15	22.6	16	18.4	79,200
Acetochlor ESA	31.8	162	98.3	96.6	99.5	> 90,000,000
Acetochlor OXA	< 33.3	296	98.6	96.6	< 33.3	No benchmark available
Alachlor ESA	< 41.6	< 41.6	178	165	595	> 52,000,000
Atrazine	32.2	60.7	33.9	< 30	46.4	3,400†
Azoxystrobin	< 10	36.7	< 10	< 10	< 10	147,000
Deethylcyanazine Acid	< 25	< 25	< 25	< 25	28.8	No benchmark available
Desethylatrazine	92.9	72.4	97.1	98.9	84.6	1,000,000*
Didealkylatrazine	155	151	206	199	151	> 50,000,000
Hydroxyatrazine	13.7	58.8	29.1	28.1	18.6	> 1,500,000
Metolachlor ESA	455	258	546	504	425	24,000,000
Metolachlor OXA	< 10	36.1	28.4	26.6	16.1	> 46,550,000
Propiconazole	< 10	25.6	< 10	< 10	< 10	15,000
Pydiflumetofen	< 10	49.0	< 10	< 10	< 10	42,000‡

† Class 1B, 2A and 2Bd waters; protected for cold water aquatic life and drinking water

* No fish benchmark available; used the non-vascular plant benchmark value for reference

‡ No fish benchmark available; MDA calculated an insect-based value based on toxicity data from the EPA Environmental Fate and Effects Division (EFED)

Reviving the Dead Zone

Solutions to Benefit Both Gulf Coast Fishers and Midwest Farmers



Union of Concerned Scientists

On the surface, nothing seems amiss in the waters of the Gulf of Mexico, just off the Louisiana coastline. Deep below, however, an invisible phenomenon threatens aquatic life forms for months on end, year after year.

For more than 30 years, scientists have investigated an area of deep water in the Gulf known as a "dead zone," which contains so little oxygen that fish and other marine life flee from it or die (Hazen et al. 2009). In the summer of 2017, it swelled to the size of New Jersey. The size of this area experiencing often fatally low levels of oxygen—what scientists call hypoxia—varies depending upon spring rains and snow melt. These carry large quantities of excess soil nutrients, largely nitrogen, down the Mississippi and Atchafalaya rivers to the Gulf. There, this polluted water sets off a chain reaction of ecological and economic consequences straining the resilience of diverse fishing operations and local communities that depend upon a healthy Gulf for their livelihoods.

EXCESS NITROGEN FUELS THE DEAD ZONE

Most of the nitrogen that contributes to the dead zone—between 60 and 80 percent—originates on farms and livestock operations in the Midwest, largely in the form of synthetic fertilizers that run off fields of corn and other crops. The significant expansion of agricultural production in some parts of the Midwest over the last many decades (Fausti 2015; Lin and Huang 2019) adds to this concern. The excess nitrogen in rivers can cause algae overgrowth and deplete the oxygen supply available to healthy marine life, creating vast dead zones that make it harder for the region's fishers to make a living. The challenge of the dead zone is made worse by other closely intertwined environmental stressors. Climate change is increasing the frequency of heavy rains and floods in the Midwest, which could wash even more nitrogen off farms and into rivers feeding the Gulf (Altieri and Gedan 2015). Ocean temperature changes are expected to exacerbate Gulf pollution effects, which will make shrinking the dead zone even more challenging in the years ahead (Laurent et al. 2018; Reidmiller et al. 2018). What is more, oil drilling in the Gulf of Mexico and the potential for oil spills—such as the 2010 British Petroleum Deepwater Horizon disaster—threaten the Gulf fishing industry as long as our economy stubbornly relies on fossil fuels.

> ***Climate change is increasing the frequency of heavy rains and floods in the Midwest, which could wash even more nitrogen off farms and into rivers feeding the Gulf.***

With all these challenges bearing down on the Gulf and the people who fish in it, straightforward solutions are needed. Reducing nitrogen losses from farms is such a solution—with the added bonus of many co-benefits for farmers and rural communities upstream—that could head off much more serious damage to Gulf ecosystems and fishing industries in the future. While many studies have estimated how much it would cost to reduce nitrogen losses from Midwest farms in order to meaningfully shrink the dead zone (Kling et al. 2014; Rabotyagov et al. 2014a), the potential economic *benefits* of such action have not yet been quantified. Gulf fisheries and marine habitat are the foundation for fishing and coastal industries. These industries in turn are important economic engines for the region. In 2016 alone, commercial fishing industries generated between $17 billion and $57 billion in economic impacts and 200,000 jobs for the region (NMFS 2016). Reducing nitrogen losses from farms could generate a large return on investment through healthier, more productive fisheries in the Gulf.

REDUCING NITROGEN FOR THE BENEFIT OF FARMERS AND FISHERS ALIKE

Fortunately, there are already ways to make this return on investment a reality. Farmers and scientists have developed a suite of agricultural practices that reduce synthetic nitrogen fertilizer use and keep what is applied to fields out of

Cover image: Billy Metcalf Photography/Creative Commons/Flickr

waterways. The resulting soils contain more living organic matter and are kept covered year-round to resist erosion and hold more water and nutrients. These practices can simultaneously reduce farmers' costs and make farmland more resilient to floods and droughts, while improving the long-term fertility of soil (Basche 2017; Basche and DeLonge 2019; Hunt, Hill, and Leibman 2019; Mulik 2017; Myers, Weber, and Tellatin 2019; Stillerman and DeLonge 2019). Thus, these two important food production and economic forces in our country—the Midwest farming industry and the Gulf Coast fishing industry—can jointly benefit from one set of practices.

To show how improved agricultural practices in the Midwest can offer economic benefits to the Gulf fishing industry, we used publicly available data to estimate how much avoidable nitrogen pollution has made its way from farm fields and into the two main rivers that feed the Gulf of Mexico. We next estimated in economic terms the damage that nitrogen pollution from farms, which fuels the dead zone, causes to the ecosystem services that fisheries and marine habitat provide for the Gulf of Mexico. We further explored the value of the damage costs that could be averted if nitrogen pollution and the dead zone were reduced through changes in agricultural practices upstream. Our analysis found that on average the equivalent of 3,100 standard-sized shipping containers per year of excess nitrogen has washed off Midwest cropland into the Mississippi and Atchafalaya rivers, and ultimately into the Gulf of Mexico. This nitrogen has contributed up to $2.4 billion in damages to ecosystem services generated by fisheries and marine habitat every year since 1980. We also found that significant economic benefits could be realized by reducing these damages through changes in agriculture upstream.

These benefits cannot be realized without policy support. We recommend policy actions that can help Gulf Coast fishing industries and communities while supporting a thriving, sustainable agricultural economy in the Midwest through science-based solutions that provide farmers with tools to build healthy, living soil.

Healthy Fisheries Are Economically Important to Diverse Gulf Coast Communities

Commercial fisheries, recreational fishing, and coastal tourism along the Gulf Coast play an important role in the region's economy. Gulf of Mexico fisheries have the second highest commercial landings—the quantity of fish caught and unloaded on shore—in the United States, just behind Alaska (NMFS 2018). In 2016, commercial fishing along the Gulf Coast generated at least $17 billion in economic impacts (Box 1, p. 4) and nearly 200,000 jobs (NMFS 2016). Recreational fishing together with coastal tourism along the Gulf Coast (which includes non-fishing recreational boating excursions) generated an additional $57 billion in economic impacts in sales and nearly 500,000 jobs in 2016 (Kosaka and Steinback 2018; NMFS 2018).[1]



Grant Heilman Photography/Alamy Stock Photo

Midwestern farmers rely heavily on nitrogen fertilizer, much of which escapes and flows downstream every year. While pairing fertilizer application with conservation tillage (as shown here) can help, US agriculture must do much more overall to reduce applications of nitrogen and keep more of it in the soil.

Yet some reporting indicates that commercial fish landings have declined in the Gulf (Karnauskas et al. 2017), and economic impact data show that commercial and recreational fishing industries in the Gulf have experienced little growth over the past decade (Figure 1, p. 5; Figure 2, p. 6). Additional challenges to the commercial fishing industries in the Gulf Coast region stem from both human-caused and environmental stressors (Chen 2017; Johnson 2019), such as competition from imported seafood (Karnauskas et al. 2017). While imports are affected by a variety of drivers, cleaning up the dead zone could make the region's fishing operations more competitive and present potential economic benefits.

The recreational fishing industry is also put at risk by the dead zone, as some tourists may be turned off by the thought of a "dead" ocean ruining a fishing trip, even if those concerns may be overstated or misunderstood (Felsher 2013). Consequently, reducing nitrogen loadings and hypoxia in the Gulf could be a way to boost the economic impact of both commercial and recreational fishing industries (see Box 1), bringing additional jobs and tax revenue to the region and making the commercial industry more competitive against imports.

The shrimp industry—which is particularly vulnerable to the formation of the dead zone—is an important economic and cultural feature of life along the Gulf Coast. In 2016, the total value of shrimp caught in the Gulf was estimated at $412 million, and shrimp is arguably the most valuable fishery in the region, bringing in nearly half the revenue of the top 10 commercial fishery catches in that year (NMFS 2018).

Commercial shrimp operations in the Gulf have caught nearly 200 million pounds of shrimp every year since the late 1990s. However, annual total catch has been decreasing steadily over this time period, partly due to increased pressure from inexpensive imported shrimp but also due to other human and environmental stressors (Tabarestani, Keithly, and Marzoughi-Ardakani 2017; Asche et al. 2012).

These challenges have made it increasingly difficult for Gulf shrimpers to remain profitable, and many are going out of business (Box 2, p. 7). In Texas, two-thirds of shrimper licenses have been repurchased by the state since the mid-1990s, and the number of shrimp boats going farther offshore in search of a viable catch has declined by one-fourth since 2010 (Subramanian 2018). Our analysis of commercial fishing and shrimping licenses issued by the Louisiana Department of Fish and Wildlife indicates a significant decline over a similar time period (LDWF 2019; see Appendix 1, online at www.ucsusa.org/resources/reviving-dead-zone).

From Big Rivers to Open Oceans: Excess Nitrogen Causes Great Harm

Nitrogen occurs naturally in waterways and is essential to healthy aquatic ecosystems (Gruber and Galloway 2008). However, large infusions of excess nitrogen from agriculture runoff alter an aquatic system's natural ecological balance and harms various species. In particular, excess nitrogen causes eutrophication—in which nutrient-rich waters cause excessive

BOX 1.

From Sea to Plate: Economic Ripple Effects of the Gulf Fishing Industry

A healthy Gulf ecosystem benefits many people, beyond just those who fish. Economic value generated by commercial fishing accrues to many other people and businesses in the Gulf region. Commercial fishers buy fuel, gear, and other supplies, and then they sell their catch to various buyers: wholesalers, seafood processors, restaurants, and retail stores. These transactions trigger additional economic activity, resulting in a wide network of business opportunities and jobs for local residents. The wages and income generated from these businesses multiply throughout the Gulf economy, as seafood restaurant owners and workers, for example, spend their paychecks on goods and services, and restaurants purchase equipment and supplies from other businesses in the region. Together, the economic transactions that originate from commercial fisheries sales generate direct, indirect, and induced economic impacts, illustrated in Figure 1.

Economic impacts from recreational fishing and coastal tourism flow through the region in a similar way. For-hire and private boating operations, as well as shore-fishing operations, purchase tackle and fuel from other businesses, which provides jobs and wages for residents. When tourists pay boat and shore-fishing operators for their services, they spend their income on rent, food, and other goods and services. Again, this spending ripples through the economy. The combined economic impacts (direct, indirect, and induced) of the recreational fishing industry are illustrated in Figure 2.

FIGURE 1. Total Economic Impacts of Gulf Coast Commercial Fishing Industries, with and without Seafood Imports, 2006–2016

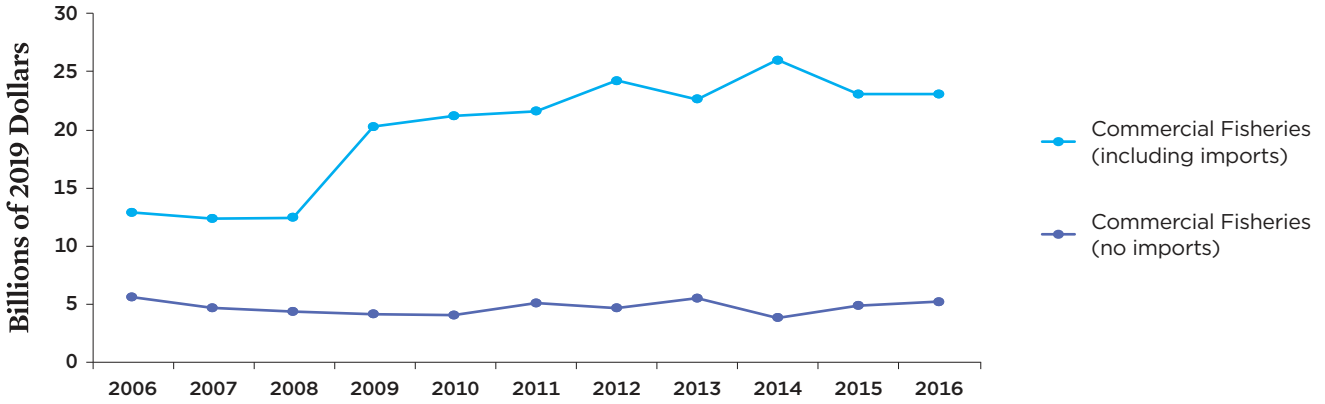

Imported seafood is responsible for an increasing amount of the economic impact of commercial fishing industries in the Gulf. Shrinking the dead zone could increase the economic impact of domestically caught commercial fish industries for the Gulf region.

Notes: Economic impacts include the dollar value of each industry's sales, the indirect economic effects of those sales on related business-to-business transactions, and the induced impacts resulting from consumer-to-business transactions. Impacts in the figure are for Alabama, Louisiana, Mississippi, Texas, and West Florida. Nominal dollar values were adjusted to 2019 dollars using the Consumer Price Index for all urban consumers residing in the South (BLS Consumer Price Index 2020).

SOURCES: ANNUAL EDITIONS OF "FISHERIES ECONOMICS OF THE UNITED STATES" FROM 2006 TO 2016 (SEE NMFS 2006–2016).

growth of algae—which when severe enough can cause hypoxia (Turner and Rabalais 1994). In freshwater environments such as the Mississippi River, excess nitrogen has been reported to reduce aquatic species diversity, cause skeletal deformities in fish and amphibians, and delay the hatching of fish and amphibian eggs (Camargo and Alonso 2006; Alabaster and Lloyd 1982; Morris, Taylor, and Brown 1989). Up and down the Mississippi River, concentrations of nitrate (a water-soluble nitrogen compound) have risen by as much as fivefold since the early 1900s (Box 3, p. 8) (Goolsby et al. 2000).

THE DEVELOPMENT OF HYPOXIA

Far beyond the ecosystems and communities in the Mississippi and Atchafalaya watersheds, the damage continues. Just beyond the shoreline and wetlands at the mouth of these river basins, excess nitrogen is flushed out into the shallow waters of the Louisiana continental shelf, causing a cascade of changes in these ecologically sensitive waters. Excess nitrogen ultimately leads to a proliferation of bacteria, which deplete the water's dissolved oxygen. The large amounts of nitrogen first increase the growth and reproduction of algae. Some of the algae die and sink to the ocean floor, where they are decomposed by bacteria. Other algae are consumed by microscopic aquatic animals known as zooplankton, whose fecal material also falls to the Gulf sea floor and is consumed by bacteria. Hypoxia is the result. In the Gulf, hypoxia has serious impacts on suitable habitat for commercially important fishes and crustaceans and on the abundance of small bottom-dwelling organisms that are the food for commercially important species (Coleman n.d.).

The shrimp industry is particularly vulnerable to the formation of the dead zone.

THE AGRICULTURAL ORIGINS OF NITROGEN LOADING IN THE GULF OF MEXICO

Between 60 and 80 percent of the nitrogen loading in the Gulf of Mexico has been traced back to farming and livestock production in the Mississippi and Atchafalaya watersheds (Figure 3, p. 9) (EPA 2017; Robertson and Saad 2013; White et al. 2014). Just over 40 percent of the total nitrogen loading comes from synthetic fertilizer used to grow crops, particularly corn. Ten percent comes from livestock manure produced by animal feeding operations, and 9 percent comes from legumes that fix nitrogen in the soil (Robertson and Saad 2013).[2]

FIGURE 2. Total Economic Impacts of Gulf Coast Recreational Fishing and Non-Fishing Recreational Industries, 2006–2016

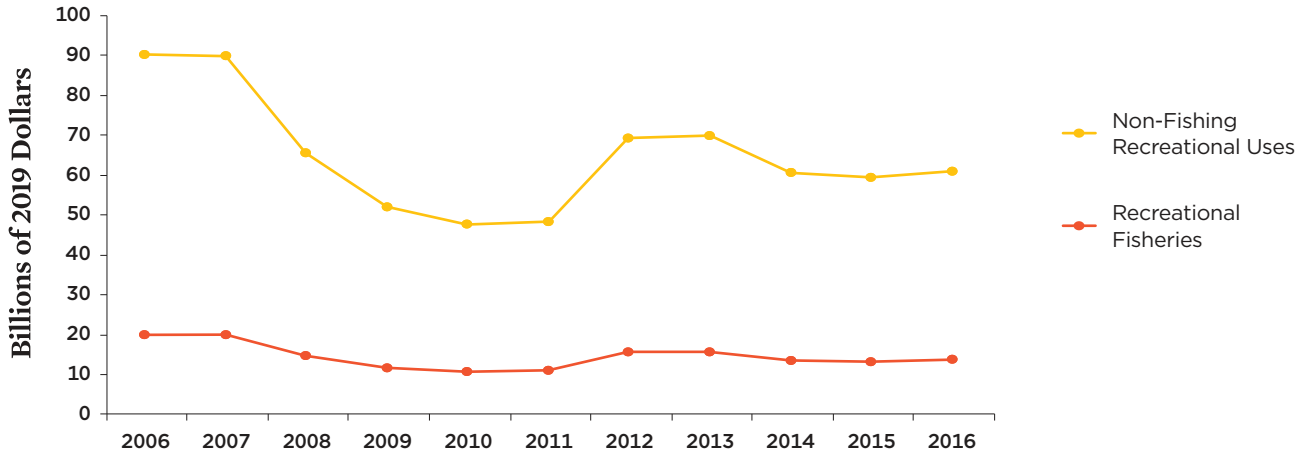

Over time, the economic impacts of both recreational and non-recreational fishing industries have either remained flat or declined. Shrinking the dead zone could potentially help increase these economic impacts.

Notes: Economic impacts include the dollar value of each industry's sales, the indirect economic effects of those sales on related business-to-business transactions, and the induced impacts resulting from consumer-to-business transactions. Impacts in the figure are for Alabama, West Florida, Mississippi, Louisiana, and Texas. Nominal dollar values were adjusted to 2019 dollars using the Consumer Price Index for all urban consumers residing in the South (BLS Consumer Price Index 2020).

SOURCES: ANNUAL EDITIONS OF "FISHERIES ECONOMICS OF THE UNITED STATES" FROM 2006 TO 2016 (SEE NMFS 2006–2016); KOSAKA AND STEINBACK 2018.

Today, most farmers in the Corn Belt[3]—in the heart of the Mississippi and Atchafalaya watersheds—apply nitrogen fertilizer to ensure maximum plant growth and crop yields.[4] Farmers typically use fertilizer generously because it is relatively inexpensive, representing a small share of their operating budgets, and it can act as a form of crop insurance for farmers (Ribaudo et al. 2011). Synthetic nitrogen fertilizer use became increasingly popular in US agriculture following World War II (Cao, Lu, and Yu 2018; Zhang et al. 2015). Between 1960 and 1980, when prices for synthetic nitrogen began to fall significantly, its use on US farms increased more dramatically than at any other time in history and continued to rise at a decreasing rate thereafter until the present time (Cao, Lu, and Yu 2018). The Corn Belt has the highest rates of total nitrogen use in the United States, and while many crops are fertilized with nitrogen in this region, the per-acre application rate is highest for corn (Cao, Lu, and Yu 2018).

Annual measures indicate that the Gulf dead zone typically peaks in the summer months, a result of springtime fertilizer applications on farms and peak river water flows in the Mississippi and Atchafalaya rivers, which coincides with increasing ocean temperatures and a reduction in the mixing of natural layers of ocean water (Rabalais et al. 1991). The largest dead zone on record occurred in 2017, when it was the size of New Jersey (Hypoxia Research Team n.d.). Since the tracking of the dead zone began in the mid-1980s, its areal extent (its size as measured from the bottom area) has not been meaningfully reduced, nor have nitrogen levels upstream in the month of May, which are strongly linked to the size and volume of the dead zone (Boesch 2019; Scavia et al. 2017; Scavia et al. 2019; Turner, Rabalais, and Justić 2008).

THE IMPACTS OF GULF HYPOXIA ON MARINE LIFE

Numerous studies have found a largely negative association between Gulf hypoxia and indicators of the health of fish, crustaceans, and other marine species, including their abundance and spatial distribution. Moderate to severe seasonally recurring hypoxia in the Gulf has reduced the abundance of species such as crustaceans, mollusks, sponges, and other species that occupy the sea floor (Diaz and Rosenberg 1995). Other research found that Atlantic croaker populations could decline by up to 25 percent in the future if hypoxia in the Gulf is not reduced significantly (Rose et al. 2018a; Rose et al. 2018b). The abundance of jellyfish, which can harm competing fish species in the same area, increased substantially between 1987 and 1997 in the waters adjacent to the discharge of the Mississippi and Atchafalaya rivers, which overlaps with the dead zone (Graham 2001). Bottom-dwelling fish and crustaceans have been

observed temporarily moving away from the dead zone during its summer peak and reoccupying the area in the fall (Craig et al. 2001; Rabalais, Harper, and Turner 2001; Rabalais and Turner 2001), and some species, such as flounder (a flatfish), avoid hypoxic areas in the Gulf even after the area recedes in the fall (Switzer, Chesney, and Baltz 2009). Fish that occupy waters closer to the surface have also been observed avoiding the area where the dead zone forms each year (Zhang et al. 2009). What is more, change in the spatial distribution of commercial species can increase the accidental catch of vulnerable species such as turtles and dolphins (Craig 2012; Craig and Bosman 2013; Purcell et al. 2017).

The Economic Impacts of Hypoxia on Gulf Fishing Operations

How the Gulf dead zone affects landings and catch rates, and other economic indicators of the fishing industry, is less clear. This is partly attributable to the fact that marine life can adapt by moving out of harm's way. One study found that shrimp catches increased despite the formation of the seasonal dead zone (Zimmerman, Nance, and Wiams 1996), although the same authors later found that that in years when hypoxia was extensive, some shrimp species could not migrate to offshore waters and instead came nearshore, which made them easier to catch (Zimmerman and Nance 2001). Other research has found that shrimp employ compensatory mechanisms in their respiratory capacity to survive hypoxia (Rosas et al. 1998). Newer research has found beneficial impacts on some fish catches from increased nitrogen loading in the Gulf, since relatively small amounts of additional nitrogen promotes growth of marine plants and species (de Mutsert et al. 2016; de Mutsert et al. 2017). But some studies have more definitively shown declines in fish catches due to Gulf hypoxia. In the early 1980s, shrimp and finfish catch rates were lower in the most severely hypoxic areas (Leming and Stuntz 1984; Renaud 1986). Later, an assessment by the National Oceanic and Atmospheric Administration found that brown shrimp catches declined significantly from 1992 to 1997, coinciding with a substantial decrease in dissolved oxygen concentrations in Gulf waters (Diaz and Solow

BOX 2.

Diverse Gulf Community Traditions and Livelihoods Are on the Line

Each May, some Cajun, Vietnamese, and other shrimpers in Plaquemines Parish, Louisiana, perform the "Blessing of the Fleet," a tradition to ensure a healthy brown shrimp season (Wist 2019). The importance of this annual celebration reflects just how heavily many communities rely on shrimp harvests for their incomes and way of life. For example, one-quarter of Louisiana's commercial shrimpers are Vietnamese refugees who brought a fishing tradition with them to this country and who still make their living from the sea (Fernandez Campbell, Whiteman, and *National Journal* 2014). But nitrogen pollution that fuels the dead zone, as well as climate change and other intertwined concerns, are putting these cultural traditions and the economic well-being of this and other communities at risk.

Kim Tran, a Vietnamese shrimper out of Texas and a leader of a local shrimper's association, told reporters in 2019 that increased water and pollution flowing into the Gulf caused by flooding in the Midwest forced shrimp and other marine life farther out to sea. Tran described how this in turn made some shrimp smaller and harder to catch, increasing fuel and other costs for many boats and causing many shrimper families to go hungry (Dick 2019). A shrimp processing business owner in the area, Trey Pearson, worried last year about the dead zone because of the risks it poses to his bottom line (Lee 2019). Dean Blanchard, who has been shrimping in the Gulf for nearly 40 years and is one of the nation's largest shrimp suppliers, explained in 2019 that "when the dead zone comes, it just kills everything." Even new equipment and technology, which few shrimpers can afford, have not sufficiently helped them overcome the challenge (Johnson 2019). Moreover, when shrimp harvests are bad, other regional businesses that process and sell shrimp also feel the impact (see Box 1).

Indigenous people who rely on Gulf waters for economic security and their cultural identity are also hurt by its degradation. For example, members of the United Houma Nation, which is composed of 17,000 tribal members along the southeastern Louisiana coast, have been catching and preparing shrimp and other seafood for generations (United Houma Nation 2019; Parker 2019). Shrimp file gumbo, a classic Cajun dish, originated from the Houma (McIntosh 2019). In the early 2010s, many Houma Nation and nearby Pointe-au-Chien Native American shrimpers were forced to shut down their operations due—in addition to competition from imported shrimp, the BP oil spill, and hurricane activity—to excess nitrogen in the Gulf that fuels the dead zone (Bayles 2011).

BOX 3.

Nitrogen Contaminates Drinking Water and Harms Health on Its Way Downstream

Up and down the Mississippi and Atchafalaya rivers, excess nitrogen has contaminated groundwater and drinking water supplies for many communities. Nitrogen in drinking water can cause acute health problems, such as blue baby syndrome in which oxygen is restricted in the blood supply of infants exposed to nitrate in water, leading to congenital heart defects and respiratory problems (Majumdar 2003). It can also cause chronic health conditions such as cancer and thyroid disease, as well as adverse pregnancy outcomes and birth defects (OWMB 2011; Ward et al. 2018). Remediating contaminated drinking water is very costly. In some Minnesota counties, for example, the cost to society due to nitrogen contamination in private domestic wells and public water supplies is estimated to be $5 million per year (Keeler et al. 2016). In Iowa, the Des Moines Water Works spent more than $500,000 to remove nitrates from drinking water in 2016 alone and is planning to expand its operation at a cost of $15 million (Cannon 2019).

1999). More recent studies have found that menhaden populations, for example, have shifted due to hypoxia, increasing the effort needed to catch them in the most severely hypoxic Gulf waters (Langseth et al. 2014; Langseth et al. 2016).

The biological complexity of the Gulf ocean ecosystem has made researching how the dead zone affects the fishing industry a major challenge for decades. Despite these challenges, the economic consequences of the dead zone for Gulf fisheries are beginning to emerge, largely due to increasingly interdisciplinary and sophisticated research efforts. Two studies stand out in this regard. In the first, Gulf hypoxia was found to be negatively correlated with the relative price of large and small brown shrimp catch (Smith et al. 2017). The study found that as the hypoxic zone reaches peak size, smaller shrimp migrate closer to shore to avoid it, making them easier to catch and, as a result, the price that shrimpers earn for them goes down and fewer shrimp are able to grow to larger and more valuable sizes. Another Gulf-based study found that shrimpers must exert more effort—defined as the amount and intensity of time spent catching shrimp—to catch shrimp when hypoxia occurs (Purcell et al. 2017).

Without doubt, more research detailing the economic consequences of Gulf hypoxia on the fishing and shrimping industries is needed. Yet studies of other hypoxic waters in the United States and globally provide additional insights about the economic dangers of the Gulf dead zone. For example, in North Carolina, seasonal hypoxia—due in large part to agricultural nitrogen losses—in the Neuse River and Pamlico Sound has resulted in a 13 percent annual decrease in brown shrimp landings from 1999 to 2005, while shifting the optimal shrimp harvest season to much earlier in the year (Huang, Smith, and Craig 2010; Huang and Smith 2011), disrupting normal fleet operations. When shrimp landings are down, imported shrimp make up the shortfall, further hurting shrimper revenues (Huang et al. 2012; Keithly and Poudel 2008). For North Carolina's blue crab fishers, research indicates that reducing hypoxia there could result in millions of dollars in economic benefits to it, while bringing additional co-benefits to recreational fisheries (Smith et al. 2007).

Research has also documented the harm caused by hypoxia on commercially important fisheries elsewhere. This includes the Chesapeake Bay and one of its main tributaries, the Patuxent River. Summer flounder catch rates there have been reduced by as much as 20 percent due to hypoxia, while striped bass fisher and blue crabber revenues have been collectively reduced by hundreds of thousands of dollars in a single year due to this problem (Lipton and Hicks 2003; Massey, Newbold, and Gentner 2006; Mistiaen, Strand, and Lipton 2003). Hypoxia's economic consequences have also been extensively studied in the Baltic Sea (Compton 2020). Researchers there have found that reducing eutrophication and related water quality problems could bring as much as $10 billion (1999 dollars) more in economic benefits than the costs of reducing nitrogen loads (Gren 2001; Gren, Jannke, and Elofsson 1997; Rabotyagov et al. 2014b; Turner et al. 1999).

Dollars at Stake: Shrinking the Dead Zone Can Help Gulf Coast Fisheries

In the fall of 1997, the Environmental Protection Agency established the Mississippi River/Gulf Hypoxia Task Force to better understand the impacts of nutrient pollution and hypoxia in the Gulf. This group—and the passage of the landmark federal law the Harmful Algal Bloom Research and Hypoxia Research

FIGURE 3. Total Nitrogen Load in the Mississippi and Atchafalaya Rivers from Farm Fertilizer, by State

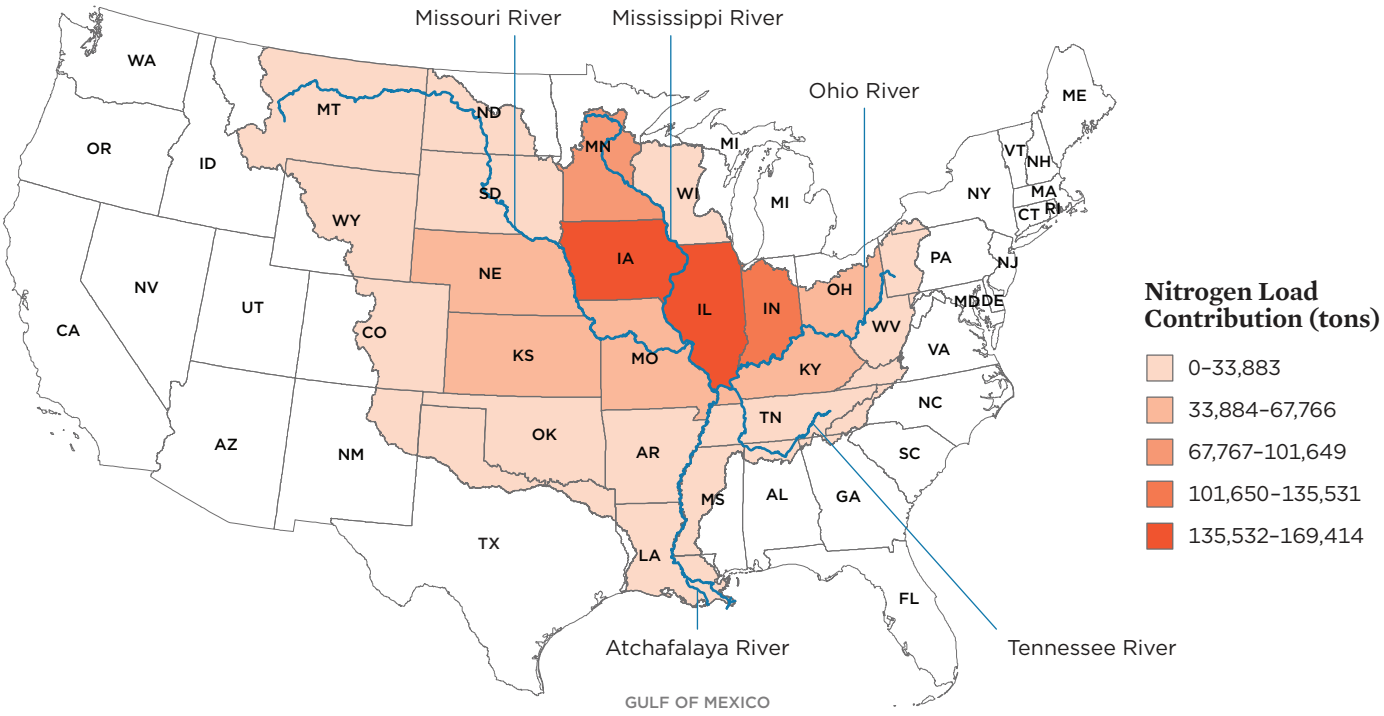

Fertilizer runoff flows to the Gulf via several major rivers (and smaller tributaries, not shown) that drain a vast expanse of the central United States. As this map shows, the highest concentrations of nitrogen loading come from states at the heart of the Corn Belt: Iowa, Illinois, and Indiana.

Note: State loading represents sum of incremental loads for each state and includes farm and non-farm sources of nitrogen. For more methodological details please see source. Loading data are based on nutrient inputs similar to 2002 and while dated Figure 4 in this report shows that inputs have not declined substantially since this time period.

SOURCE: DATA OBTAINED FROM USGS MISSISSIPPI-ATCHAFALAYA RIVER BASIN NUTRIENT LOADING MAP, USING THE SPARROW MODEL. AVAILABLE ONLINE AT HTTPS://SPARROW.WIM.USGS.GOV/MARB/.

and Control Act of 1998—stimulated research on the impacts of the Gulf dead zone, including many estimates of the costs of reducing its size through changes in agricultural practices across the Mississippi and Atchafalaya watersheds (Kling et al. 2014; NRCS 2012; Tallis et al. 2019). These studies have provided information that lawmakers need to implement policies and programs to cost-effectively reduce the dead zone by reducing nitrogen losses from agriculture upstream. Yet, to date, few studies have quantified economic benefits that Gulf Coast communities reliant on healthy oceans could realize if the dead zone were reduced. Quantifying these benefits in economic terms can help policymakers understand the potential return on investment from addressing this problem.

To date, few studies have quantified how Gulf Coast communities could benefit economically if the dead zone were reduced.

ESTIMATES OF AVOIDABLE NITROGEN

We used state-level data from the US Department of Agriculture on the application of fertilizer nitrogen in states that drain partially or exclusively into the Mississippi and Atchafalaya watersheds (NASS 2020). Based on our analysis, we estimate that since 1990, corn and soybean farmers in the Mississippi and Atchafalaya River basins have applied approximately 114 million tons of fertilizer nitrogen to their fields, at a total cost of $37 billion in 2018 dollars (see Appendix 2). Even with recent improvements in available methods for farmers to fine

tune nitrogen applications, the most recent estimates indicate that 34 percent of applied fertilizer nitrogen to crops in the United States is lost to the environment (Zhang et al. 2015). Some nitrogen loss is inevitable, including a small share that will be lost as nitrous oxide, a potent heat-trapping gas that contributes to climate change. On farms, however, a relatively large amount of nitrogen is easily carried away as water drains through and from agricultural fields (Rabotyagov et al. 2010; David, Drinkwater, and McIsaac 2010); nearly 75 percent of the nitrogen lost typically flows into surface water and groundwater (NRCS 2012).

Our analyses also reveal that over the same time period nearly 31 million tons of fertilizer nitrogen from corn and soybean farms flowed into surrounding rivers and streams that feed into the Gulf, fueling the dead zone (Figure 4). Based on historical nitrogen fertilizer prices over the last three decades (ERS 2019), we estimate that this lost nitrogen represents $12 billion (in 2018 dollars) in total nitrogen purchased for corn and soybean crops over three decades, an average of nearly $400 million per year (in 2018 dollars).

ESTIMATING COSTS TO FISHERIES AND MARINE HABITAT

Much of this nitrogen ultimately makes its way into the Gulf and fuels the dead zone, causing harm to the natural ecosystem and marine life. This damage has an economic cost, which we estimate here. Due to data and methodological limitations, our estimates of the economic cost do not directly include impacts to fisheries' landings, revenues, or other economic indicators. Rather, we have quantified the damage to ecosystem services on which Gulf fisheries depend, thus shining light indirectly on the economic impacts of the dead zone on these fisheries.

About 34 percent of applied fertilizer nitrogen to crops in the United States each year is lost to the environment.

Ecosystem services are defined as the benefits that the environment and wildlife provide to people. Specifically, we evaluated the damage caused to ecosystem services provided by fisheries and marine habitat due to annual peak Gulf nitrogen loadings attributable to agricultural nitrogen losses upstream.[5]

Quantifying the value of ecosystem services tells us how economically important they are to human populations. In turn, these economic values can be used by policymakers to make decisions about how to manage natural resources and other environmental amenities. In the case of the Gulf of Mexico, fisheries and marine habitat provide many ecosystem services.

FIGURE 4. Tons of Fertilizer Nitrogen Leaving Corn and Soybean Farms and Entering the Mississippi and Atchafalaya Watersheds, 1990–2018

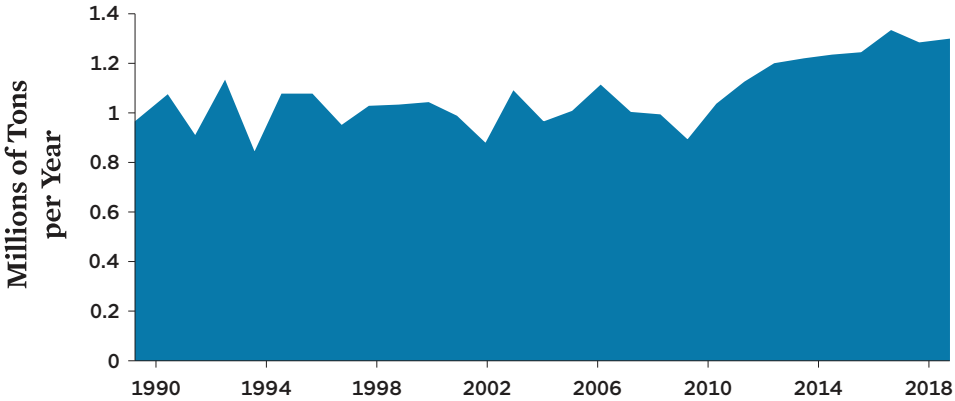

Estimated total fertilizer nitrogen applications have only increased in the watershed since 1990. The sharp increase after 2009 has been linked to an expansion of corn and soybean acreage following the enactment of the federal Renewable Fuel Standard (Lark, Salmon, and Gibbs 2015). (See Appendix 2 for methodological details.).

SOURCES: NITROGEN APPLICATION DATA WERE OBTAINED FROM THE US DEPARTMENT OF AGRICULTURE'S NATIONAL AGRICULTURAL STATISTICS SERVICE AGRICULTURAL RESOURCE MANAGEMENT CHEMICAL USE SURVEY PROGRAM FOR ANNUAL DATA FROM 1990 TO 2018.



gulfhypoxia.net

Scientists have studied the Gulf of Mexico dead zone for more than 30 years. Here, researchers from the Louisiana Universities Marine Consortium and the National Oceanic and Atmospheric Administration collect data on an annual expedition to map the dead zone's location and measure its size. In 2017, it was the size of New Jersey, the largest measurement on record.

For example, they help maintain the natural balance of nutrients and species and they produce food for human consumption (Barbier, 2017; Constanza et al. 1997). Economists have developed ways to calculate the value of these ecosystem goods and services even though they are not easily priced like regular goods and services that we typically buy. Our analysis relies on estimates of how much people are willing to pay for restoring ecosystem services derived from fisheries and marine habitats that have been lost due to excess nitrogen loading. We refer to the value of these lost ecosystem services as damage costs.

First, we estimated the damage to the ecosystem services that could be averted by reducing annual peak nitrogen loadings to levels that substantially shrink the Gulf dead zone. We then compared (1) the costs of achieving these nitrogen-loading reductions through changes in agricultural practices upstream, to (2) the economic benefits resulting from reduced damages to the ecosystem services provided by fisheries and marine habitat in the Gulf. This reflects our assumption that May nitrogen loading levels cause the greatest harm in the Gulf and that reducing this month's loadings would be the most effective way to reduce the dead zone and, consequently, damage to Gulf fisheries and marine habitat. To calculate damage costs, we compiled total Gulf of Mexico nitrogen loading data from the US Geological Survey from the month of May from 1980 to 2017 (Lee, Norman, and Reutter 2018). May nitrogen loading values are strongly correlated with annual peak river water flow, which naturally delivers the largest amounts of nitrogen to the Gulf over the course of a year (Scavia et al. 2017; Lee, Norman, and Reutter 2018). May nitrogen loadings are also highly correlated with the peak area and volume of the dead zone (Scavia et al. 2017; Turner, Rabalais, and Justić 2008). To estimate the amount attributable to fertilizer lost from croplands upstream, we multiplied the May nitrogen loading values by 41 percent (EPA 2015; Robertson and Saad 2013).

To estimate the damage costs to Gulf fisheries and marine habitat attributable to upstream fertilizer losses, we multiplied May nitrogen loading attributable to upstream crop production by nitrogen damage factors (Sobota et al. 2015). The nitrogen damage factors are obtained through previous surveys of people that ask them to quantify the amount they would be willing to pay to protect certain ecosystem services.[6] In the context of excess nitrogen loading in waterways, willingness to pay

studies are a standard economic methodology used to assess how much people would pay to resolve a particular environmental concern. In this case, increases in ecosystem services were assumed to be achieved by reductions in excess nitrogen loading, eutrophication, and hypoxia in ocean systems (Van Grinsven et al. 2013), and the estimated low, medium and high values were $6,236, $16,190, and $27,016 (2018 dollars) per ton of nitrogen, respectively. This range of values accounts for the variability and uncertainty inherent in estimating people's willingness to pay to protect ecosystem services.

We then estimated the proportion of these damage costs that could be averted by decreasing agricultural nitrogen losses upstream. Here we used a series of nitrogen loss reduction scenarios achieved through changes in agricultural practices, derived from four previously published studies. These studies all examined how widespread shifts in practices on cropland in the Mississippi and Atchafalaya watersheds influenced nitrogen loadings in the Gulf (Kling et al. 2014; NRCS 2012; Rabotyagov et al. 2014a; Tallis et al. 2019). The scenarios assumed different scales and scopes of changes to current agricultural practices, such as increased adoption of cover cropping, nutrient management, conservation tillage, riparian buffers, planting of perennials, and improved subsurface tile management to achieve reductions in nitrogen losses. In these scenarios, reductions in the May Gulf nitrogen loading due to shifts in agricultural practices upstream ranged from just over 5 percent to 45 percent.



Southern Foodways Alliance /Creative Commons (Flickr)

Nitrogen pollution from upstream farms imposes significant costs on Gulf coast industries and communities—we estimated annual costs between $552 million and $2.4 billion. Damage to fish habitat and stocks can make fishing less profitable, helping to drive some small fishers out of business.

We then calculated damage costs averted for each scenario by multiplying the percentage reduction in nitrogen loading by total damage costs to fisheries and marine habitat under current May nitrogen loading levels. (Additional methodological details and information about these scenarios can be found in Appendix 3.)

A SUBSTANTIAL RETURN ON INVESTMENT

Our results showed that, on average, May nitrogen loading in the Gulf attributable to agricultural losses upstream is estimated to be nearly 87,000 tons annually. To put this number in perspective, this amount of nitrogen would fit, measured in weight only, into approximately 3,100 standard 40-foot-long shipping containers.[7] Our findings show that nitrogen loading in the Gulf that is attributable to agricultural losses upstream caused between $552 million and $2.4 billion (2018 dollars) in damage to Gulf fisheries and marine habitat annually from 1980 to 2017. Based on the scenarios described above, we estimate that between $34.4 million and $990 million (2018 dollars) in damage costs to Gulf fisheries and marine habitat could have been averted every year from 1980 to 2017 through shifts in agricultural practices (see Appendix 3 for full scenarios) (Figure 5). Further, we found that scenarios that decreased May nitrogen loading by 20 percent or more could reduce the average size of the dead zone to levels recommended by the Environmental Protection Agency's Hypoxia Task Force.

The ways in which our estimates may under- or overestimate the actual value of damage costs due to May nitrogen loading in the Gulf are important to note. Our analysis could overstate the potential to avert damage costs based on our assumption that immediate reductions in Gulf nitrogen loading would result in immediate reductions in dead zone areal extent. Recent research has indicated that so much nitrogen has accumulated in the Mississippi River basin that it may take 30 years or more to reduce loads enough to meaningfully reduce the size of the Gulf dead zone (Ballard et al. 2019; Van Meter, Cappellen, and Basu 2018). And in several ways our analysis underestimates damage costs. First, our damage cost estimates only reflect harm to ecosystem services derived from fisheries and marine habitats most affected by the dead zone; other impacts of nitrogen loading in the Gulf have also been documented (Ren, Rabalais, and Turner 2020). Second, we did not evaluate how reduced damage costs to the ecosystem services provided by healthier fisheries and marine habitat would ripple through the many industries connected to Gulf fishing (see Box 1). Third, nitrogen pollution from agriculture upstream causes harm to waterways and the climate as it makes its way to the Gulf of Mexico (see Box 2). However, our damage cost estimates do not take into account the costs of this impaired groundwater, surface water, and drinking water. Nor do we

FIGURE 5. Potential Reductions in Damage Costs to Gulf Fisheries and Marine Habitat Made Possible from Reductions in Nitrogen Loading

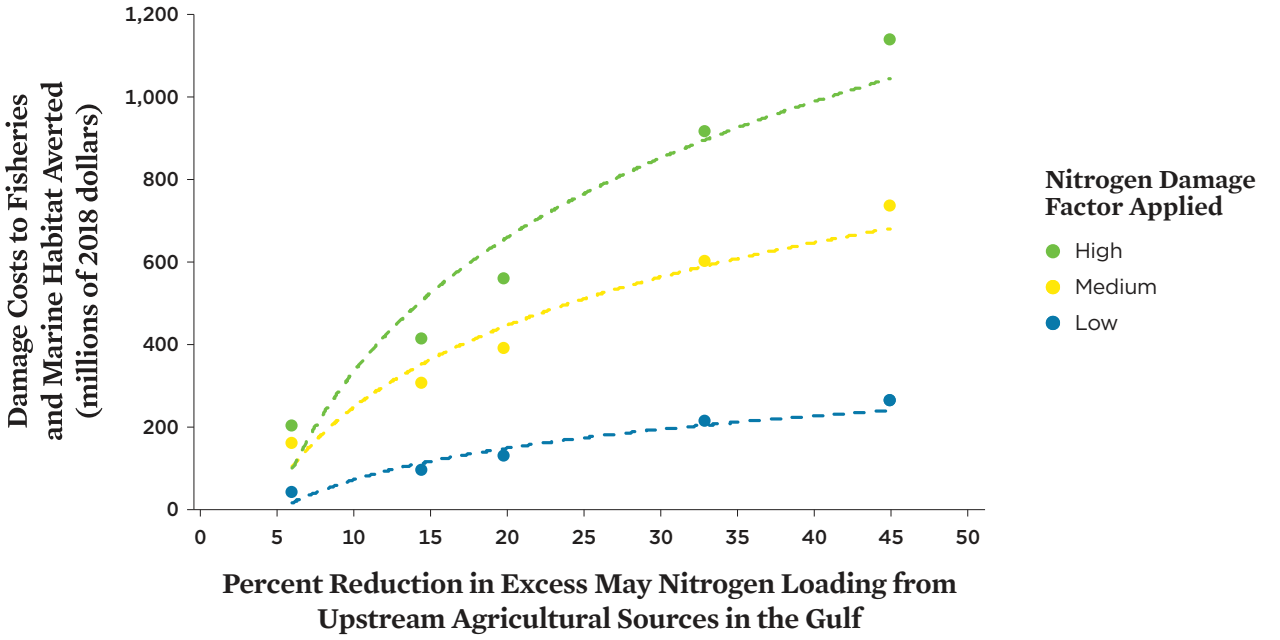

Estimated damage to fisheries and marine habitat ecosystem services caused by the nitrogen pollution that forms the dead zone ranges from $552 million to $2.4 billion (2018 dollars).

Note: Damage costs averted under three scenarios are based on high, medium, and low nitrogen damage factors applied and the percent reduction in nitrogen. Point estimates are fitted with logarithmic best fit lines to show trends in damage costs averted for each of the damage factors applied. Appendix 3 provides additional methodological details and data sources.

account for the economic value of decreased emission of nitrous oxide, a global warming gas. If these factors were able to be taken into consideration, estimates of damage costs would likely be much higher.

Of course, financial investments are needed to achieve these benefits. In the scenarios analyzed from previously published work, researchers estimated the increased adoption of agricultural practices that reduce nitrogen losses to the Gulf to cost between $705 million and $3.1 billion annually in 2018 dollars (Kling et al. 2014; NRCS 2012; Rabotyagov et al. 2014a; Tallis et al. 2019). By comparison, our analysis estimated benefits of a similar magnitude for the medium and high damage factor scenarios. Given that the costs and benefits in the medium and high scenarios are of similar magnitude, we conclude that there could be a major return on investment in adopting improved agricultural practices that can reduce nitrogen losses to the Gulf.

It is important to note that our analysis and comparisons here are not intended to be a complete accounting of all the costs and benefits associated with improvements to agriculture upstream and returns to the Gulf fishing industry. The costs associated with implementing improved agricultural practices to reduce nitrogen losses reflect only policy and program costs. The widespread shifts in agricultural practices in these scenarios could change production costs, individual farmer yields in the short term, or total land devoted to agricultural production. In turn, these shifts could affect crop prices and farmer incomes, with broader effects and unintended economic consequences for the agricultural industry (Marshall et al. 2018). Likewise, the present analysis does not fully account for all of the potential economic benefits from the adoption of the recommended practices that would accrue to the Gulf.

Policy Recommendations

Millions of tons of nitrogen continue to wash off Midwestern farmland each year, fueling the annual Gulf dead zone. This excess nitrogen, as we documented in this report, causes a range of serious problems for the fishing industry and people along the Gulf Coast who rely on healthy ocean waters for their livelihoods and cultural traditions. However, our analysis reveals that significant economic benefits could be realized

through reducing Gulf nitrogen loading attributable to agricultural losses upstream. The fishing industry stands to benefit from increased ecosystem services provided by healthier waters in the Gulf.

Hypoxia is being addressed successfully elsewhere in the United States. For example, efforts to reduce total daily loads of nitrogen in the Chesapeake Bay and thus reduce hypoxia have had a positive impact, providing up to an estimated $88 million in annual benefits to the commercial and recreational fishing industries in the region (Massey et al. 2017). However, for these benefits to materialize for the Gulf of Mexico, farmers in the Midwest need to adopt agricultural practices that reduce nitrogen losses. Such practices also benefit farmers, preserving agricultural soils and protecting the water supplies for countless communities. To achieve these benefits, we offer several policy recommendations that focus on expanding the adoption of these practices in Midwest agriculture and that bring greater awareness and understanding to the Gulf Coast fishing industry's need for healthy ocean waters.

INCREASE ADOPTION OF HEALTHY SOIL PRACTICES

We recommend increased funding to expand the adoption of agricultural practices that improve soil health and keep nutrients such as nitrogen out of our waterways. Large quantities of nitrogen have accumulated in the Mississippi River basin over the past three decades, and, as our analysis has shown, nitrogen continues to flow to the Gulf in large quantities. Consequently, action to reduce nitrogen levels in the Gulf are urgently needed. We stress that additional funding must be spent in ways that cause the largest and most immediate reductions to nitrogen flowing to the Gulf. The following federal policy changes are crucial:

Funding must be spent in ways that cause the largest and most immediate reductions to nitrogen flowing to the Gulf.

- **Establish performance-based standards or discounts within the federal crop insurance program to incentivize large-scale reduction in nitrogen losses from farming through improved soil management.** As this report has demonstrated, crop agriculture in the Midwest is the primary source of the nitrogen pollution that makes its way into the Gulf, fueling the dead zone. Conservation compliance programs have worked in the past to incentivize crop farmers to adopt practices that benefit soil and water quality (Claassen et al. 2017). As a result, we recommend that crop insurance programs incentivize the adoption of soil health–building practices that have proven to significantly reduce nitrogen losses. The US Department of Agriculture's Risk Management Agency should give a premium discount to farmers who use the following agricultural management practices: cover cropping, conservation tillage, riparian buffers, and perennial plantings.
- **Expand and speed up the reductions in nitrogen loss by increasing funding for and strengthening the Conservation Stewardship Program's (CSP) focus on soil health improvements.** This popular working-lands conservation program takes a holistic approach and incentivizes conservation practices based on national, state, and local priority resource concerns. However, participation in CSP is competitive, as farmer demand continues to outpace available funding (NSAC 2015). We recommend that CSP funding be expanded significantly to meet this demand. Further, to more effectively target its funding toward management practices that build soil health and reduce nitrogen losses, soil health improvement should be added to the list of criteria under which CSP contract offers are evaluated.



Lynn Betts/NRCS/SWCS

Planting perennial prairie plants in and around crop fields is one practice shown to cost-effectively reduce nitrogen runoff. When planted on just 10 percent of crop acres, prairie strips like those shown here can reduce nitrogen loss by 80 percent.

- **Further reduce nitrogen losses to the Gulf by expanding the number of focus area watersheds in the Mississippi River Basin Healthy Watersheds Initiative and increase overall funding.** Established in 2009, the Mississippi River Basin Healthy Watersheds Initiative draws funding from multiple farm bill conservation programs, focusing on individual watersheds within the Mississippi River basin to reduce nitrogen losses. Approximately 61 percent of these watersheds are in the Upper Mississippi and Ohio River basins, which have been identified as the basins which contribute the most nutrients to the Gulf (Marshall et al. 2018). However, the initiative fails to target all of the watersheds that have high levels of nitrogen losses (Rabotyagov et al. 2014a). The watersheds selected for inclusion in this program should be evaluated to ensure maximum reductions in nitrogen flowing to the Gulf.

ENSURE PROTECTION FOR GULF FISHING INDUSTRIES AFFECTED BY NITROGEN LOADING AND THE DEAD ZONE, AND ENSURE THEIR REPRESENTATION ON THE HYPOXIA TASK FORCE

As this report has shown, diverse fishing operations, including those operated by refugee, immigrant, and indigenous people, are harmed by nitrogen pollution and the Gulf dead zone. It is critical for them to be represented in efforts to address this problem. The following actions can accomplish this:

- **Investigate the feasibility of creating a new program to compensate Gulf fishing industries for losses they incur from the chronic occurrence of nitrogen pollution and the dead zone.** Under the Magnuson-Stevens Act, fishing operations and related coastal businesses can receive payments when natural or other disasters occur in US ocean waters. Just as hurricanes and oil spills cause acute damage, nitrogen pollution causes chronic, long-term damage to the Gulf ocean ecosystem and harms the fishing and shrimping industries. Policymakers should explore amending the Magnuson-Stevens Act to create a new program to compensate Gulf fishing or shrimping operations for losses they incur from the chronically recurring dead zone. Payments could be determined based on May nitrogen loadings in the Gulf measured by the US Geological Survey or the size of the dead zone as measured by the National Oceanic and Atmospheric Administration.
- **Instruct the Environmental Protection Agency's Office of the Inspector General to conduct an audit or investigation of the effectiveness of the Mississippi River/Gulf Hypoxia Task Force.** Established in 1997, this task force was charged with evaluating the causes and effects of eutrophication in the Gulf and coordinating efforts to reduce the size and severity of the dead zone (EPA 2015).



Eric Gay/AP Photo

The dead zone particularly affects the lucrative Gulf shrimp industry—valued at more than $400 million annually—and the people who work in it. This has particular equity implications, as many Gulf shrimpers are immigrants or people of color.

As this report has documented (see Figure 4), there has been little to no progress reducing the size of the dead zone or nutrient loads in the Gulf over this time. The audit or investigation should analyze why the task force is not making progress in reducing hypoxia in the Gulf and offer concrete recommendations on how its efficacy can be improved. Those concrete recommendations should include which actions, including regulatory action, could help achieve nitrogen reductions in the Gulf.

- **Update and amend the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force Charter to ensure that diverse voices and perspectives are in positions of power on the task force, including voices of those involved in the Gulf fishing industry.** The Hypoxia Task Force currently lacks representation from diverse voices within leadership positions, despite its most recent report to Congress stating that it would expand and build new partnerships (EPA 2017). There is only one nongovernmental

> ***Policymakers, researchers, and advocates need to act with immediacy to shrink the Gulf dead zone.***

member of the Hypoxia Task Force (a member of the National Tribal Water Council), and most of the members represent agricultural interests. While these voices are essential for addressing Gulf hypoxia, people who are affected by the dead zone must have greater representation on the task force. The charter should be amended to allow for increased representation of tribal communities, community-based businesses, and organizations in the Gulf that are most vulnerable to the impacts of the dead zone (see Box 2). For example, groups such as Coastal Communities Consulting in Gretna, Louisiana, provide assistance to underserved fishing communities and businesses, and should be considered for membership on the Hypoxia Task Force given their expertise and knowledge (Coastal Communities Consulting n.d.; Fernandez Campbell, Whiteman, and *National Journal* 2014).

INVEST IN INTEGRATED RESEARCH ON THE IMPACTS OF NITROGEN AND OTHER NUTRIENT POLLUTION IN THE GULF OF MEXICO ON INDUSTRIES RELIANT ON HEALTHY OCEAN WATERS

As this report shows, there needs to be additional research to understand the economic impacts of this problem on fishing industries and related businesses, especially those that rely on or operate in the waters that become hypoxic each year. For example, federal lawmakers can provide:

- **Support and additional funding for research by the Environmental Protection Agency, US Department of Agriculture, Department of Energy, National Science Foundation, and universities on the damage costs caused by nitrogen pollution to the environment and trends in farmer nitrogen applications and loss, and how such trends affect nitrogen loadings in the Gulf.** For our analysis of damage costs from nitrogen loading in the Gulf, we applied the nitrogen damage factors from Sobota et al. (2015); however, much more work is needed to better evaluate the environmental and social costs of nitrogen pollution in the Gulf. Further, the US Department of Agriculture's tracking of nitrogen applications only occurs every five years for select states and crops, and losses are not tracked in a systematic way at the federal level. While models exist to evaluate the linkages between nitrogen applications on farms and loadings in the Gulf of Mexico (e.g., Kling et al. 2014), there is a need to improve the data and accuracy of such modeling approaches. Interdisciplinary collaborations within and between these agencies will help improve nitrogen application monitoring and losses, while improving our understanding of how nitrogen applied on farms affects the Gulf of Mexico ecosystem.
- **Increased federal funding and prioritized integrated research on how nitrogen pollution and the dead zone in the Gulf of Mexico affects the economic vitality of commercial and recreational fishing industries.** The Gulf of Mexico is a complex biological system, and disturbances to its natural state cause dynamic human and socioeconomic responses and feedbacks. This has made research on the impacts of the dead zone on the fishing industries very challenging, as this report has demonstrated. Further, many environmental and economic stressors affect the region's fisheries. How these other stressors interact with nitrogen pollution and the dead zone impacts is not fully known, yet together they could have serious consequences for the viability of the region's coastal economy. Consequently, a top priority should be to substantially increase and guarantee funding for integrated and systems-oriented economic research through the National Oceanic and Atmospheric Administration, National Science Foundation, Environmental Protection Agency, and US Department of Agriculture. This type of research will provide information on interconnected economic, social, and environmental costs and benefits that policymakers need to consider when they develop solutions to address nitrogen pollution and the Gulf dead zone.

Conclusion

Policymakers, researchers, and advocates need to act with immediacy to shrink the Gulf dead zone. Fisheries face multiple environmental and economic stressors in addition to nitrogen pollution, from climate change and ocean acidification to overfishing and increased competition from imported seafood. Of this set of challenges, nitrogen pollution may be the most straightforward to address. The origins of excess nitrogen are known and, importantly, agricultural practices to reduce the downstream nitrogen pollution bring significant benefits to farmers, as well as to the many communities that rely on healthy rivers and streams for their drinking water.

This analysis reveals that addressing nitrogen pollution and the Gulf dead zone would reduce the damage to fisheries and marine habitat that provide ecological and economic benefits for Gulf fishing and coastal industries. These benefits

would likely have positive ripple effects for the region's wider economy. What is more, prior research has shown that farmers also stand to benefit in the short and long term when they adopt practices that reduce nitrogen losses and protect waterways, all while preserving and building up healthy soils. By adopting these practices, they can grow the food, fuel, and fiber that power our nation's economy while protecting fishing operations' revenue, regional jobs, and the diverse cultural traditions of Gulf Coast communities for generations to come.

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ENDNOTES

1 The National Oceanic and Atmospheric Administration defines commercial fishing as operations selling their catch for profit and recreational fishing operations as fishing for pleasure rather than for selling fish for profit or subsistence (NMFS 2018). Non-fishing recreational activities are defined as viewing or photographing the ocean, beachcombing, water sports, and other outdoor activities (Kosaka and Steinback 2018).

2 Another 14 percent of the nitrogen in the Gulf originates from urban runoff; discharges from wastewater treatment plants; and natural, agricultural, and urban atmospheric deposition (Robertson and Saad 2013). Atmospheric deposition is a process by which nitrogen gas in the air is transformed so that it can dissolve in water or penetrate soil (Paerl, Dennis, and Whitall 2002). Some of the nitrogen reaching the Gulf via atmospheric deposition originates from agricultural sources, but the exact amount is unknown.

3 States generally considered part of the Corn Belt include Illinois, Indiana, Iowa, Kansas, Missouri, Nebraska, South Dakota, and Ohio (Green et al. 2018).

4 A report by the US Department of Agriculture indicated that 97 percent of corn acres receive nitrogen, either synthetic fertilizer or nitrogen in animal manure used to fertilize farm fields (Ribaudo 2012).

5 We did not evaluate the damage costs associated with Gulf peak phosphorus loading because nitrogen loading has been found to be the primary driver of the dead zone (Scavia et al. 2017).

6 The European Nitrogen Assessment estimated willingness to pay to clean up eutrophication and other water quality concerns among European citizens living near oceans and other water bodies to calculate the damage costs of nitrogen in these ecosystems (Sutton et al. 2011). Because no US-based estimates of willingness to pay to reduce eutrophication or hypoxia exist, to our knowledge, we assumed for this analysis that the willingness to pay of US and European citizens would be similar. Additional US-focused studies are needed. A recent working paper has evaluated this topic, but it has not been published in a peer-reviewed journal, nor is the study focused on people living along the US Gulf Coast (Parthum and Ando 2019).

7 A standard 40-foot-long shipping container commonly transported by ships, trucks, or trains can hold approximately 28 tons. For simplicity, we did not convert fertilizer nitrogen for this analysis into a volume measurement.

REFERENCES

Alabaster, J. S., and R. Lloyd. 1982. "Finely Divided Solids." In *Water Quality Criteria for Freshwater Fish*, second edition, edited by J. S. Alabaster and R. Lloyd, 1–20. London, UK: Butterworth.

Altieri, Andrew H., and Keryn B. Gedan. 2015. "Climate Change and Dead Zones." *Global Change Biology* 21 (4): 1395–1406. https://doi.org/10.1111/gcb.12754

Asche, Frank, Lori S. Bennear, Atle Oglend, and Martin D. Smith. 2012. "US Shrimp Market Integration." *Marine Resource Economics* 27 (2): 181–192. https://doi.org/10.5950/0738-1360-27.2.181

Ballard, Tristan C., Anna M. Michalak, Gregory F. McIsaac, Nancy N. Rabalais, and R. Eugene Turner. 2019. "Comment on 'Legacy Nitrogen May Prevent Achievement of Water Quality Goals in the Gulf of Mexico.'" *Science* 365 (6455): eaau8401. https://doi.org/10.1126/science.aau8401

Barbier, Edward B. 2017. "Marine Ecosystem Services." *Current Biology* 27(11): R507–R510. https://doi.org/10.1016/j.cub.2017.03.020

Basche, Andrea. 2017. *Turning Soils into Sponges: How Farmers Can Fight Floods and Droughts*. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/resources/turning-soils-sponges

Basche, Andrea D., and Marcia S. DeLonge. 2019. "Comparing Infiltration Rates in Soils Managed with Conventional and Alternative Farming Methods: A Meta-Analysis." *PLoS ONE* 14 (9). https://doi.org/10.1371/journal.pone.0215702

Bayles, Cara. 2011. "American Indian Businesses in Decline." *Houma Today*, October 10, 2011. https://www.houmatoday.com/article/20111009/Business/608096164

BLS (Bureau of Labor Statistics) Consumer Price Index. 2020. Dataset for All Urban Consumers in the Southern United States; accessed April 2. https://www.bls.gov/cpi/data.htm

Boesch, Donald F. 2019. "Barriers and Bridges in Abating Coastal Eutrophication." *Frontiers in Marine Science* 6. https://doi.org/10.3389/fmars.2019.00123

Camargo, Julio A., and Álvaro Alonso. 2006. "Ecological and Toxicological Effects of Inorganic Nitrogen Pollution in Aquatic Ecosystems: A Global Assessment." *Environment International* 32 (6): 831–849. https://doi.org/10.1016/j.envint.2006.05.002

Cannon, Austin. 2019. "Des Moines Water Works Unveils Plans for Regional Water Utility." *Des Moines Register*, September 26, 2019. https://www.desmoinesregister.com/story/news/2019/09/26/des-moines-water-works-unveils-plans-for-regional-water-utility-in-ankeny-urbandale-west-des-moines/3777449002/

Cao, Peiyu, Chaoqun Lu, and Zhen Yu. 2018. "Historical Nitrogen Fertilizer Use in Agricultural Ecosystems of the Contiguous United States during 1850–2015: Application Rate, Timing, and Fertilizer Types." *Earth System Science Data* 10 (2): 969–984. https://doi.org/10.5194/essd-10-969-2018

Chen, Yong. 2017. "Fish Resources of the Gulf of Mexico." In *Habitats and Biota of the Gulf of Mexico: Before the Deepwater Horizon Oil Spill*, edited by C. Herb Ward, 869–1038. New York: Springer.

Claassen, Roger L., Maria Bowman, Vince Breneman, Tara Wade, Ryan Williams, Jacob Fooks, LeRoy Hansen, Rich Iovanna, and Chuck Loesch. 2017. *Conservation Compliance: How Farmer Incentives Are Changing in the Crop Insurance Era*. Washington, DC: US Department of Agriculture, Economic Research Service.

Coastal Communities Consulting. n.d. About CCC. Accessed February 1, 2020. http://ccc-nola.org/about-ccc

Coleman, Elizabeth. n.d. "What Is Hypoxia and How Does It Affect Fisheries?" Baton Rouge, LA: Louisiana Sea Grant Program, Louisiana State University. Accessed February 26, 2020. https://www.lsu.edu/seagrantfish/resources/factsheets/hypoxia.htm

Compton, Jana. 2020. Email communication with the author, January 16, 2020. Jana Compton is a research ecologist for the Environmental Protection Agency's Office of Research and Development.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, et al. 1997. "The Value of the World's Ecosystem Services and Natural Capital." *Nature* 387:253–260. https://doi.org/10.1038/387253a0

Craig, J. Kevin. 2012. "Aggregation on the Edge: Effects of Hypoxia Avoidance on the Spatial Distribution of Brown Shrimp and Demersal Fishes in the Northern Gulf of Mexico." *Marine Ecology Progress Series* 445:75–95.

Craig, J. Kevin, and Samantha H. Bosman. 2013. "Small Spatial Scale Variation in Fish Assemblage Structure in the Vicinity of the Northwestern Gulf of Mexico Hypoxic Zone." *Estuaries and Coasts* 36 (2): 268–285. https://doi.org/10.1007/s12237-012-9577-9

Craig, J. Kevin, Larry B. Crowder, Charlotte D. Gray, Carrie J. McDaniel, Tyrrell A. Henwood, and James G. Hanifen. 2001. "Ecological Effects of Hypoxia on Fish, Sea Turtles." *Coastal Hypoxia: Consequences for Living Resources and Ecosystems* 58:269.

David, Mark B., Laurie E. Drinkwater, and Gregory F. McIsaac. 2010. "Sources of Nitrate Yields in the Mississippi River Basin." *Journal of Environmental Quality* 39 (5): 1657–1667. https://doi.org/10.2134/jeq2010.0115

de Mutsert, Kim, Jeroen Steenbeek, James H. Cowan, and Villy Christensen. 2017. "Using Ecosystem Modeling to Determine Hypoxia Effects on Fish and Fisheries." In *Modeling Coastal Hypoxia*, edited by D. Justić, K. Rose, R. Hetland, and K. Fennel, 377–400. https://doi.org/10.1007/978-3-319-54571-4_14

de Mutsert, Kim, Jeroen Steenbeek, Kristy Lewis, Joe Buszowski, James H. Cowan, and Villy Christensen. 2016. "Exploring Effects of Hypoxia on Fish and Fisheries in the Northern Gulf of Mexico Using a Dynamic Spatially Explicit Ecosystem Model." In *Ecopath 30 Years: Modelling Ecosystem Dynamics; Beyond Boundaries with EwE*, edited by S. Villasante, F. Arreguín-Sánchez, S. J. J. Heymans, S. Libralato, C. Piroddi, and M. Coll. Special issue, *Ecological Modelling* 331 (July): 142–150. https://doi.org/10.1016/j.ecolmodel.2015.10.013

Diaz, Robert J., and Rutger Rosenberg. 1995. "Marine Benthic Hypoxia: A Review of Its Ecological Effects and the Behavioural Responses of Benthic Macrofauna." *Oceanography and Marine Biology: An Annual Review* 33:245–303.

———. 2008. "Spreading Dead Zones and Consequences for Marine Ecosystems." *Science* 321 (5891): 926–929.

Diaz, Robert J., and Andrew Solow. 1999. *Ecological and Economic Consequences of Hypoxia: Topic 2, Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico*. Silver Spring, MD: US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Coastal Ocean Program.

Dick, Jacob. 2019. "Looming Deluge Threatens Gulf Fisheries." *Beaumont Enterprise*, May 30, 2019. https://www.beaumontenterprise.com/news/article/Looming-deluge-threatens-Gulf-fisheries-13908395.php

EPA (Environmental Protection Agency). 2015. "Hypoxia Task Force Reports to Congress." Washington, DC. https://www.epa.gov/ms-htf/hypoxia-task-force-reports-congress

———. 2017. *Mississippi River/Gulf of Mexico Watershed Nutrient Task Force: 2017 Report to Congress*. Washington DC. https://www.epa.gov/sites/production/files/2017-11/documents/hypoxia_task_force_report_to_congress_2017_final.pdf

ERS (Economic Research Service). 2019. Fertilizer Use and Price Dataset. Washington, DC: US Department of Agriculture. Accessed December 10, 2019. https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx

Fausti, Scott W. 2015. "The Causes and Unintended Consequences of a Paradigm Shift in Corn Production Practices." *Environmental Science and Policy* 52 (October): 41–50. https://doi.org/10.1016/j.envsci.2015.04.017

Felsher, John N. 2013. "Catching Fish in the 'Dead Zone.'" *My New Orleans*, October 1, 2013. https://www.myneworleans.com/catching-fish-in-the-dead-zone/

Fernandez Campbell, Alexia, Mauro Whiteman, and *National Journal*. 2014. "Is This the End of the Line for Louisiana's Vietnamese Shrimpers?" *The Atlantic*, October 30, 2014. https://www.theatlantic.com/politics/archive/2014/10/is-this-the-end-of-the-line-for-louisianas-vietnamese-shrimpers/431418/

Goolsby, Donald A., William A. Battaglin, Brent T. Aulenbach, and Richard P. Hooper. 2000. "Nitrogen Flux and Sources in the Mississippi River Basin." *Science of The Total Environment* 248 (2): 75–86. https://doi.org/10.1016/S0048-9697(99)00532-X

Graham, W. M. 2001. "Numerical Increases and Distributional Shifts of *Chrysaora quinquecirrha* (Desor) and *Aurelia aurita* (Linné) (Cnidaria: Scyphozoa) in the Northern Gulf of Mexico." In *Jellyfish Blooms: Ecological and Societal Importance*, edited by J. E. Purcell, W. M. Graham, and H. J. Dumont. *Developments in Hydrobiology* 155:97–111. https://doi.org/10.1007/978-94-010-0722-1_9

Green, Timothy R., Holm Kipka, Olaf David, and Gregory S. McMaster. 2018. "Where is the USA Corn Belt, and How Is It Changing?" *Science of the Total Environment* 618:1613–1618.

Gren, Ing-Marie. 2001. "International Versus National Actions against Nitrogen Pollution of the Baltic Sea." *Environmental and Resource Economics* 20 (1): 41–59. https://doi.org/10.1023/A:1017512113454

Gren, Ing-Marie, Paul Jannke, and Katarina Elofsson. 1997. "Cost-Effective Nutrient Reductions to the Baltic Sea." *Environmental and Resource Economics* 10 (4): 341–362. https://doi.org/10.1023/A:1026497515871

Gruber, Nicolas, and James N. Galloway. 2008. "An Earth-System Perspective of the Global Nitrogen Cycle." *Nature* 451 (7176): 293–296. https://doi.org/10.1038/nature06592

Hazen, Elliott L., J. Kevin Craig, Caroline P. Good, and Larry B. Crowder. 2009. "Vertical Distribution of Fish Biomass in Hypoxic Waters on the Gulf of Mexico Shelf." *Marine Ecology Progress Series* 375 (January): 195–207. https://doi.org/10.3354/meps07791

Huang, Ling, Lauren A. B. Nichols, J. Kevin Craig, and Martin D. Smith. 2012. "Measuring Welfare Losses from Hypoxia: The Case of North Carolina Brown Shrimp." *Marine Resource Economics* 27 (1): 3–23. https://doi.org/10.5950/0738-1360-27.1.3

Huang, Ling, and Martin D. Smith. 2011. "Management of an Annual Fishery in the Presence of Ecological Stress: The Case of Shrimp and Hypoxia." *Ecological Economics* 70 (4): 688–697. https://doi.org/10.1016/j.ecolecon.2010.11.003

Huang, Ling, Martin D. Smith, and J. Kevin Craig. 2010. "Quantifying the Economic Effects of Hypoxia on a Fishery for Brown Shrimp *Farfantepenaeus aztecus*." *Marine and Coastal Fisheries* 2 (1): 232–248.

Hunt, Natalie Dawn, Jason D. Hill, and Matt Liebman. 2019. "Cropping System Diversity Effects on Nutrient Discharge, Soil Erosion, and Agronomic Performance." *Environmental Science and Technology* (January): 1344–1352. https://doi.org/10.1021/acs.est.8b02193

Hypoxia Research Team. n.d. "Shelfwide Cruises of the Gulf of Mexico to Measure Dead Zone Areal Extent." Chauvin, LA. Accessed April 15, 2020. https://gulfhypoxia.net/

Johnson, Spike. 2019. "Shrinking the Gulf Coast Dead Zone Part 1: Downriver." *The Lens*, September 6, 2019. https://thelensnola.org/2019/09/05/shrinking-the-gulf-coast-dead-zone-part-1-downriver/

Karnauskas, M., C. Kelble, S. Regan, C. Quenee, R. Allee, M. Jepson, A. Freitag, et al. 2017. "2017 Ecosystem Status Report Update for the Gulf of Mexico." NOAA Technical Memorandum NMFS-SEFSC-706. Miami, FL: US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southeast Fisheries Science Center. https://www.aoml.noaa.gov/ocd/ocdweb/ESR_GOMIEA/

Keeler, Bonnie L., Jesse D. Gourevitch, Stephen Polasky, Forest Isbell, Chris W. Tessum, Jason D. Hill, and Julian D. Marshall. 2016. "The Social Costs of Nitrogen." *Science Advances* 2 (10): e1600219. https://doi.org/10.1126/sciadv.1600219

Keithly, Walter R., and Pawan Poudel. 2008. "The Southeast U.S.A. Shrimp Industry: Issues Related to Trade and Antidumping Duties." *Marine Resource Economics* 23 (4): 459–483. https://doi.org/10.1086/mre.23.4.42629675

Kling, Catherine L., Yiannis Panagopoulos, Sergey S. Rabotyagov, Adriana M. Valcu, Philip W. Gassman, Todd Campbell, Michael J. White, et al. 2014. "LUMINATE: Linking Agricultural Land Use, Local Water Quality and Gulf of Mexico Hypoxia." *European Review of Agricultural Economics* 41 (3): 431–459. https://doi.org/10.1093/erae/jbu009

Kosaka, R., and S. Steinback. 2018. "2012 National Ocean Recreation Expenditure Survey." Washington DC: US Department of Commerce. https://repository.library.noaa.gov/view/noaa/19558

Langseth, Brian J., Kevin M. Purcell, J. Kevin Craig, Amy M. Schueller, Joseph W. Smith, Kyle W. Shertzer, Sean Creekmore, Kenneth A. Rose, and Katja Fennel. 2014. "Effect of Changes in Dissolved Oxygen Concentrations on the Spatial Dynamics of the Gulf Menhaden Fishery in the Northern Gulf of Mexico." *Marine and Coastal Fisheries* 6 (1): 223–234. https://doi.org/10.1080/19425120.2014.949017

Langseth, Brian J., Amy M. Schueller, Kyle W. Shertzer, J. Kevin Craig, and Joseph W. Smith. 2016. "Management Implications of Temporally and Spatially Varying Catchability for the Gulf of Mexico Menhaden Fishery." *Fisheries Research* 181 (September): 186–197. https://doi.org/10.1016/j.fishres.2016.04.013

Lark, Tyler J., J. Meghan Salmon, and Holly K. Gibbs. 2015. "Cropland Expansion Outpaces Agricultural and Biofuel Policies in the United States." *Environmental Research Letters* 10 (4): 044003. https://doi.org/10.1088/1748-9326/10/4/044003

Laurent, A., K. Fennel, D. S. Ko, and J. Lehrter. 2018. "Climate Change Projected to Exacerbate Impacts of Coastal Eutrophication in the Northern Gulf of Mexico." *Journal of Geophysical Research: Oceans* 123 (5): 3408–3426.

LDWF (Louisiana Department of Wildlife and Fishing). 2019. "Commercial Fishing License Sales." Baton Rouge, LA. https://www.wlf.louisiana.gov/resources/category/licenses-and-permits/1

Lee, C. J., J. E. Norman, and D. C. Reutter. 2018. "Nutrient and Pesticide Data Collected from the USGS National Water Quality Network and Previous Networks, 1963–2017." Washington, DC: US Geological Survey. https://doi.org/10.5066/P9TMSQFE

Lee, Elizabeth. 2019. "'Dead Zone' Threatens Livelihood of Gulf of Mexico Fishermen." Voice of America, June 24, 2019. https://www.voanews.com/usa/dead-zone-threatens-livelihood-gulf-mexico-fishermen

Leming, Thomas D., and Warren E. Stuntz. 1984. "Zones of Coastal Hypoxia Revealed by Satellite Scanning Have Implications for Strategic Fishing." *Nature* 310 (5973): 136–138. https://doi.org/10.1038/310136a0

Lin, Meimei, and Qiping Huang. 2019. "Exploring the Relationship between Agricultural Intensification and Changes in Cropland Areas in the US." *Agriculture, Ecosystems and Environment* 274 (March): 33–40. https://doi.org/10.1016/j.agee.2018.12.019

Lipton, Douglas, and Robert Hicks. 2003. "The Cost of Stress: Low Dissolved Oxygen and Economic Benefits of Recreational Striped Bass Fishing in the Patuxent River." *Estuaries* 26 (2): 310–315. https://doi.org/10.1007/BF02695969

Majumdar, Deepanjan. 2003. "The Blue Baby Syndrome." *Resonance* 8 (10): 20–30. https://doi.org/10.1007/BF02840703

Marshall, Elizabeth, Marcel Aillery, Marc Ribaudo, Nigel Key, Stacy Sneeringer, LeRoy Hansen, Scott Malcolm, and Anne Riddle. 2018. *Reducing Nutrient Losses From Cropland in the Mississippi/Atchafalaya River Basin: Cost Efficiency and Regional Distribution*. Washington DC: US Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/publications/pub-details/?pubid=90175

Massey, David M., Chris Moore, Stephen C. Newbold, and Howard Townsend. 2017. "Commercial Fishing and Outdoor Recreation Benefits of Water Quality Improvements in the Chesapeake Bay." Working paper. *AgEcon Search*. https://doi.org/10.22004/ag.econ.280937

Massey, D. Matthew, Stephen C. Newbold, and Brad Gentner. 2006. "Valuing Water Quality Changes Using a Bioeconomic Model of a Coastal Recreational Fishery." *Journal of Environmental Economics and Management* 52 (1): 482–500. https://doi.org/10.1016/j.jeem.2006.02.001

McIntosh, Laura. 2019. "Janie Luster of Houma Tribe Cooks Shrimp File Gumbo." Filmed on July 9, 2019, in Louisiana. *Bringing It Home with Laura McIntosh*. YouTube video, 4:02. Louisiana: Public Broadcasting Service. https://www.youtube.com/watch?v=EEJGk4M_vsA

Mistiaen, Johan A., Ivar E. Strand, and Douglas Lipton. 2003. "Effects of Environmental Stress on Blue Crab Harvests in Chesapeake Bay Tributaries." *Estuaries* 26 (2): 316–322. https://doi.org/10.1007/BF02695970

Morris, Ronald, E. W. Taylor, and J. A. Brown. 1989. *Acid Toxicity and Aquatic Animals*. Vol. 34. Cambridge, UK: Cambridge University Press.

Mulik, Kranti. 2017. *Rotating Crops, Turning Profit: How Diversified Farming Systems Can Help Farmers While Protecting Soil and Preventing Pollution*. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/resources/rotating-crops-turning-profits

Myers, Rob, Alan Weber, and Sami Tellatin. 2019. "Cover Crop Economics: Opportunities to Improve Your Bottom Line in Row Crops." Sustainable Agriculture Research and Extension Technical Bulletin. Washington DC: US Department of Agriculture. https://www.sare.org/Learning-Center/Bulletins/Cover-Crop-Economics

NASS (National Agricultural Statistics Service). 2020. "USDA Agricultural Resource Management Survey, Chemical Use Survey. 1990-2018 Corn, Peanuts, Soybeans." Washington, DC: US Department of Agriculture. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/index.php

NMFS (National Marine Fisheries Service). 2006–2016. "Fisheries Economics of the United States." Technical memorandum. Washington DC: US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Coastal Ocean Program. https://www.fisheries.noaa.gov/national/sustainable-fisheries/fisheries-economics-united-states

———. 2018. *Fisheries Economics of the United States 2016*. Technical Memorandum NMFS-F/SPO-187. Washington DC: US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service Coastal Ocean Program. https://www.fisheries.noaa.gov/resource/document/fisheries-economics-united-states-report-2016

NRCS (Natural Resources Conservation Service). 2012. "Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin." Washington, DC. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf

NSAC (National Sustainable Agriculture Coalition). 2015. "Farmers Guide to the Conservation Stewardship Program." Washington, DC. http://sustainableagriculture.net/wp-content/uploads/2015/02/CSP-Farmers-Guide-2015-final.pdf

OWMB (Office of Water Monitoring Branch). 2011. "Nitrogen and Phosphorus Pollution in the Mississippi River Basin: Findings of the Wadeable Streams Assessment." Washington DC: Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-03/documents/epa-marb-fact-sheet-112911_508.pdf

Paerl, Hans W., Robin L. Dennis, and David R. Whitall. 2002. "Atmospheric Deposition of Nitrogen: Implications for Nutrient Over-Enrichment of Coastal Waters." *Estuaries* 25 (4): 677–693. https://doi.org/10.1007/BF02804899

Parker, H. 2019. "'We Are Here': Local Tribes Celebrate First Indigenous Peoples' Day." *Houma Today*, October 14, 2019. https://www.houmatoday.com/news/20191014/we-are-here-local-tribes-celebrate-first-indigenous-peoples-day

Parthum, Bryan, and Amy W. Ando. 2019. "Local Benefits and Willingness to Pay to Reduce Hypoxia in the Gulf of Mexico." Working paper. https://bryanparthum.s3.us-east-2.amazonaws.com/Parthum_Ando_2019.pdf

Purcell, Kevin M., J. Kevin Craig, James M. Nance, Martin D. Smith, and Lori S. Bennear. 2017. "Fleet Behavior Is Responsive to a Large-Scale Environmental Disturbance: Hypoxia Effects on the Spatial Dynamics of the Northern Gulf of Mexico Shrimp Fishery." *PLoS ONE* 12 (8): e0183032. https://doi.org/10.1371/journal.pone.0183032

Rabalais, Nancy N., D. E. Harper, and R. Eugene Turner. 2001. "Responses of Nekton and Demersal and Benthic Fauna to Decreasing Oxygen Concentrations." *Coastal and Estuarine Studies* 58: 115–128.

Rabalais, N. N., and R. E. Turner. 2001. *Coastal Hypoxia: Consequences for Living Resources and Ecosystems. Coastal and Estuarine Studies*. Washington, DC: American Geophysical Union.

Rabalais, Nancy N., R. Eugene Turner, William J. Wiseman, and Donald F. Boesch. 1991. "A Brief Summary of Hypoxia on the Northern Gulf of Mexico Continental Shelf: 1985–1988." *Geological Society*, London, Special Publications 58 (1): 35–47. https://doi.org/10.1144/GSL.SP.1991.058.01.03

Rabotyagov, Sergey, Todd Campbell, Manoj Jha, Philip W. Gassman, Jeffrey Arnold, Lyubov Kurkalova, Silvia Secchi, Hongli Feng, and Catherine L. Kling. 2010. "Least-Cost Control of Agricultural Nutrient Contributions to the Gulf of Mexico Hypoxic Zone." *Ecological Applications* 20 (6): 1542–1555. https://doi.org/10.1890/08-0680.1

Rabotyagov, Sergey S., Todd D. Campbell, Michael White, Jeffrey G. Arnold, Jay Atwood, M. Lee Norfleet, Catherine L. Kling, et al. 2014a. "Cost-Effective Targeting of Conservation Investments to Reduce the Northern Gulf of Mexico Hypoxic Zone." *Proceedings of the National Academy of Sciences* 111 (52): 18530–18535. https://doi.org/10.1073/pnas.1405837111

Rabotyagov, S. S., C. L. Kling, P. W. Gassman, N. N. Rabalais, and R. E. Turner. 2014b. "The Economics of Dead Zones: Causes, Impacts, Policy Challenges, and a Model of the Gulf of Mexico Hypoxic Zone." *Review of Environmental Economics and Policy* 8 (1): 58–79. https://doi.org/10.1093/reep/ret024

Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L. M. Lewis, Thomas K. Maycock, and Brooke C. Stewart. 2018. *Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II*. Washington, DC: US Global Change Research Program. https://doi.org/10.7930/NCA4.2018

Ren, L., N. N. Rabalais, and R. E. Turner. 2020. "Effects of Mississippi River Water on Phytoplankton Growth and Composition in the Upper Barataria Estuary, Louisiana." *Hydrobiologia*, 1–20.

Renaud, Maurice L. 1986. "Hypoxia in Louisiana Coastal Waters during 1983: Implications for Fisheries." *Fishery Bulletin* 84 (1): 19–26.

Ribaudo, Marc. 2012. "Nitrogen Management in Corn Production Appears To Be Improving." Amber Waves, December. Washington, DC: US Department of Agriculture Economic Research Service. https://www.ers.usda.gov/amber-waves/2012/december/nitrogen-management-in-corn-production-appears-to-be-improving/

Ribaudo, Marc, Jorge Delgado, LeRoy Hansen, Mike Livingston, Roberto Mosheim, and James Williamson. 2011. "Nitrogen in Agricultural Systems: Implications for Conservation Policy." Working paper. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2115532

Robertson, Dale M., and David A. Saad. 2013. "SPARROW Models Used to Understand Nutrient Sources in the Mississippi/Atchafalaya River Basin." *Journal of Environmental Quality* 42 (5): 1422–1440. https://doi.org/10.2134/jeq2013.02.0066

Rosas, Carlos, Evenor Martinez, Gabriela Gaxiola, Roberto Brito, Eugenio Díaz-Iglesia, and Luis A. Soto. 1998. "Effect of Dissolved Oxygen on the Energy Balance and Survival of *Penaeus Setiferus* Juveniles." *Marine Ecology Progress Series* 174 (November): 67–75. https://doi.org/10.3354/meps174067

Rose, Kenneth A., Sean Creekmore, Dubravko Justić, Peter Thomas, J. Kevin Craig, Rachael Miller Neilan, Lixia Wang, Md Saydur Rahman, and David Kidwell. 2018a. "Modeling the Population Effects of Hypoxia on Atlantic Croaker in the Northwestern Gulf of Mexico: Part 2—Realistic Hypoxia and Eutrophication." *Estuaries and Coasts* 41 (1): 255–279. https://doi.org/10.1007/s12237-017-0267-5

Rose, Kenneth A., Sean Creekmore, Peter Thomas, J. Kevin Craig, Md Saydur Rahman, and Rachael Miller Neilan. 2018b. "Modeling the Population Effects of Hypoxia on Atlantic Croaker in the Northwestern Gulf of Mexico: Part 1—Model Description and Idealized Hypoxia." *Estuaries and Coasts* 41 (1): 233–254. https://doi.org/10.1007/s12237-017-0266-6

Scavia, Donald, Isabella Bertani, Daniel R. Obenour, R. Eugene Turner, David R. Forrest, and Alexey Katin. 2017. "Ensemble Modeling Informs Hypoxia Management in the Northern Gulf of Mexico." *Proceedings of the National Academy of Sciences* 114 (33): 8823–8828. https://doi.org/10.1073/pnas.1705293114

Scavia, Donald, Dubravko Justić, Daniel R. Obenour, J. Kevin Craig, and Lixia Wang. 2019. "Hypoxic Volume Is More Responsive than Hypoxic Area to Nutrient Load Reductions in the Northern Gulf of Mexico—and It Matters to Fish and Fisheries." *Environmental Research Letters* 14 (2): 024012. https://doi.org/10.1088/1748-9326/aaf938

Smith, Martin, Sumaila Ussif Rashid, Gordon R. Munro, and Jon G. Sutinen. 2007. "Generating Value in Habitat-Dependent Fisheries: The Importance of Fishery Management Institutions." *Land Economics* 83 (1): 59–73. https://doi.org/10.3368/le.83.1.59

Smith, Martin D., Atle Oglend, A. Justin Kirkpatrick, Frank Asche, Lori S. Bennear, J. Kevin Craig, and James M. Nance. 2017. "Seafood prices reveal impacts of a major ecological disturbance." *Proceedings of the National Academy of Sciences* 114.7 (2017): 1512-1517. https://doi.org/10.1073/pnas.1617948114

Sobota, Daniel J., Jana E. Compton, Michelle L. McCrackin, and Shweta Singh. 2015. "Cost of Reactive Nitrogen Release from Human Activities to the Environment in the United States." *Environmental Research Letters* 10 (2): 025006. https://doi.org/10.1088/1748-9326/10/2/025006

Stillerman, Karen Perry, and Marcia DeLonge. 2019. *Safeguarding Soil: A Smart Way to Protect Farmers, Taxpayers, and the Future of Our Food*. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/resources/safeguarding-soil

Subramanian, Meera. 2018. "It's 'Going to End with Me': The Fate of Gulf Fisheries in a Warming World." *InsideClimate News*, December 28, 2018. https://insideclimatenews.org/news/23122018/climate-change-shrimp-oysters-fisheries-gulf-global-warming-hurricanes

Sutton, M. A., C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, J. J. M. van Grinsven, and B. Grizzetti. 2011. *The European Nitrogen Assessment*. Cambridge, UK: Cambridge University Press. http://www.nine-esf.org/node/360/ENA-Book.html

Switzer, Theodore S., Edward J. Chesney, and Donald M. Baltz. 2009. "Habitat Selection by Flatfishes in the Northern Gulf of Mexico: Implications for Susceptibility to Hypoxia." In *Ecological Impacts of Hypoxia on Living Resources*, edited by A J. Lewitus, D. M. Kidwell, E. B. Jewett, S. Brandt, an d D. M. Mason. Special issue, *Journal of Experimental Marine Biology and Ecology* 381 (December): S51–S64. https://doi.org/10.1016/j.jembe.2009.07.011

Tabarestani, Maryam, Walter R. Keithly, and Hassan Marzoughi-Ardakani. 2017. "An Analysis of the US Shrimp Market: A Mixed Demand Approach." *Marine Resource Economics* 32 (4): 411–429. https://doi.org/10.1086/693360

Tallis, Heather, Stephen Polasky, Jessica Hellmann, Nathaniel P. Springer, Rich Biske, Dave DeGeus, Randal Dell, et al. 2019. "Five Financial Incentives to Revive the Gulf of Mexico Dead Zone and Mississippi Basin Soils." *Journal of Environmental Management* 233 (March): 30–38. https://doi.org/10.1016/j.jenvman.2018.11.140

Turner, R. Eugene, and Nancy N. Rabalais. 1994. "Coastal Eutrophication near the Mississippi River Delta." *Nature* 368 (6472): 619–621. https://doi.org/10.1038/368619a0

Turner, R. Eugene, Nancy N. Rabalais, and Dubravko Justić. 2008. "Gulf of Mexico Hypoxia: Alternate States and a Legacy." *Environmental Science and Technology* 42 (7): 2323–2327. https://doi.org/10.1021/es071617k

Turner, R. Kerry, Stavros Georgiou, Ing-Marie Gren, Fredric Wulff, Scott Barrett, Tore Söderqvist, Ian J. Bateman, et al. 1999. "Managing Nutrient Fluxes and Pollution in the Baltic: An Interdisciplinary Simulation Study." *Ecological Economics* 30 (2): 333–352. https://doi.org/10.1016/S0921-8009(99)00046-4

United Houma Nation. 2019. "About Houma Nation." Golden Meadow, LA. https://unitedhoumanation.org/about/

Van Grinsven, Hans J. M., Mike Holland, Brian H. Jacobsen, Zbigniew Klimont, Mark a. Sutton, and W. Jaap Willems. 2013. "Costs and Benefits of Nitrogen for Europe and Implications for Mitigation." *Environmental Science and Technology* 47 (8): 3571–3579. https://doi.org/10.1021/es303804g

Van Meter, K. J., P. Van Cappellen, and N. B. Basu. 2018. "Legacy Nitrogen May Prevent Achievement of Water Quality Goals in the Gulf of Mexico." *Science* 360 (6387): 427–430. https://doi.org/10.1126/science.aar4462

Ward, Mary H., Rena R. Jones, Jean D. Brender, Theo M. De Kok, Peter J. Weyer, Bernard T. Nolan, Cristina M. Villanueva, and Simone G. Van Breda. 2018. "Drinking Water Nitrate and Human Health: An Updated Review." *International Journal of Environmental Research and Public Health* 15 (7): 1557. https://doi.org/10.3390/ijerph15071557

White, M. J., C. Santhi, N. Kannan, J. G. Arnold, D. Harmel, L. Norfleet, P. Allen, et al. 2014. "Nutrient Delivery from the Mississippi River to the Gulf of Mexico and Effects of Cropland Conservation." *Journal of Soil and Water Conservation* 69 (1): 26–40. https://doi.org/10.2489/jswc.69.1.26

Wist, Allie. 2019. "How Louisiana's Vietnamese Shrimpers Are Adapting to Climate Change." *Saveur*, November 12, 2019. https://www.saveur.com/what-climate-change-means-for-vietnamese-shrimpers-in-new-orleans/

Zhang, Hongyan, Stuart A. Ludsin, Doran M. Mason, Aaron T. Adamack, Stephen B. Brandt, Xinsheng Zhang, David G. Kimmel, Michael R. Roman, and William C. Boicourt. 2009. "Hypoxia-Driven Changes in the Behavior and Spatial Distribution of Pelagic Fish and Mesozooplankton in the Northern Gulf of Mexico." *Journal of Experimental Marine Biology and Ecology* 381:S80–S91.

Zhang, Xin, Eric A. Davidson, Denise L. Mauzerall, Timothy D. Searchinger, Patrice Dumas, and Ye Shen. 2015. "Managing Nitrogen for Sustainable Development." *Nature* 528 (7580): 51–59. https://doi.org/10.1038/nature15743

Zimmerman, R. J., and J. M. Nance. 2001. "Effects of Hypoxia on the Shrimp Fishery of Louisiana and Texas." *Coastal Hypoxia: Consequences for Living Resources and Ecosystems* 58:293–310.

Zimmerman, R., J. Nance, and J. Wiams. 1996. "Trends in Shrimp Catch in the Hypoxic Area of the Northern Gulf of Mexico. Galveston Laboratory, National Marine Fisheries Service." In *Proceedings of the First Gulf of Mexico Hypoxia Management Conference*. EPA–55–R–97–001. Washington, DC: Environmental Protection Agency.

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Minnesota Department of Agriculture

Nitrate Results and Trends in Private Well Monitoring Networks 2008-2018

Central Sands Private Well Network and the Southeast Volunteer Nitrate Monitoring Network

June 2019

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Minnesota Private Well Networks

The Minnesota Department of Agriculture (MDA) has been working closely with other state and local agencies on developing regional private well nitrate-nitrogen (nitrate) networks. Homeowner volunteers are the cornerstone of the private well networks. Homeowners collect their own water sample and send it by mail to be tested by a laboratory or a county collaborator using MDA equipment at no cost to the homeowner. This method has been developed from years of collaboration with other state and local agencies through pilot projects testing different methods of collection and sample delivery. The MDA currently coordinates two volunteer nitrate monitoring networks with assistance from other state agency and local partners, the Southeast Minnesota Volunteer Nitrate Monitoring Network and the Central Sands Private Well Network. The two networks are discussed in greater detail below.

SOUTHEAST VOLUNTEER NITRATE MONITORING NETWORK 2008-2018

Drinking water quality is a concern across southeastern Minnesota where nitrate loading to the subsurface can be significant and hydrogeologic sensitivity is highly variable within short distances. In 2008, the Southeast Minnesota Water Resources Board (SEMNWRB) and several state agency partners (MPCA, MDA, MDH) began collecting samples and data from the Southeast Volunteer Nitrate Monitoring Network (VNMN). This region was selected as a pilot because of its vulnerable and complex geology.

This pilot began as a network of 675 private drinking water wells representing a stratified-random distribution across the nine counties (Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Rice, Wabasha and Winona) of southeastern Minnesota. The wells included in the network represent groundwater nitrate concentration data from several aquifers.

Before data collection began, well network coordinators (county staff) enrolled volunteers (well owners) into the program by collecting detailed information about well location, well construction, and nearby nitrate sources. Between February 2008 and August 2018, 13 sampling events occurred representing approximately 5,421 samples. During this period, the percentage of wells exceeding the Health Risk Limit (HRL) for each sampling event ranged between 7.5 and 14.6 percent (Table 1). The most recent sampling results from 2018 are presented in Figure 1.

Table 1. Summary of the 2008 through 2018 long- term Southeast VNMN results.

Year	Total Wells	50th Percentile (Median)	90th Percentile	% of Wells ≥10	% of Wells <10
		Nitrate-N (mg/L)			
2/1/2008	519	0.3	12.0	14.6%	85.4%
8/1/2008	510	0.3	11.0	11.4%	88.6%
2/1/2009	494	0.2	11.0	11.1%	88.9%
8/1/2009	471	0.3	11.5	11.0%	89.0%
8/1/2010	422	0.7	9.5	9.2%	90.8%
8/1/2011	428	0.6	10.0	10.3%	89.7%
8/1/2012	411	0.4	8.8	7.5%	92.5%
8/1/2013	315	0.1	8.8	8.3%	91.7%
8/1/2014	361	0.2	9.4	8.9%	91.1%
8/1/2015	373	0.2	9.4	8.8%	91.2%
8/2/2016	387	0.3	10.8	10.9%	89.1%
8/1/2017	341	<0.25	10.1	10.0%	90.0%
8/1/2018	389	0.3	9.5	9.0%	91.0%

The 2018 nitrate results by aquifer are presented in Table 2. The highest median and upper percentile concentrations were observed in wells open to the Quaternary water table aquifer followed by the Prairie du Chien-Jordan and the Prairie du Chien aquifers. The Quaternary aquifer consists of unconsolidated sediments and generally represents the shallowest aquifers in this study with a mean depth of 56 feet. The Prairie du Chien-Jordan and the Prairie du Chien aquifers are limestone and sandstone bedrock aquifers that are generally deeper with a mean well depth of 315 and 300 feet, respectively.

Table 2. Southeast VNMN nitrate concentrations by aquifer in 2018.

Aquifer	Number of Wells	Mean Depth (ft)	Values				Percentiles			
			Min	Max	Mean	Median	75th	90th	95th	99th
			Nitrate-N (mg/L)							
Not Available	83	NA	<0.03	29.4	3.9	0.74	7.0	11.8	16.8	26.5
Quaternary Water Table	11	56	<0.03	23.6	4.8	2.70	4.8	15.2	22.9	23.6
Quaternary Undifferentiated	8	84	<0.03	11.7	1.6	<0.03	0.6	8.5	11.7	11.7
Quaternary Buried	8	142	<0.03	0.90	0.2	<0.03	0.3	0.8	0.9	0.9
Cedar Valley Wapsipinicon	16	139	<0.03	7.24	0.8	<0.03	0.1	3.3	6.1	7.2
Spillville	11	149	<0.03	9.62	1.5	<0.03	1.9	6.6	9.4	9.6
Maquoketa-Dubuque	9	174	<0.03	4.59	1.6	0.34	4.1	4.5	4.6	4.6
Galena	22	148	<0.03	24.8	3.0	<0.03	4.8	8.9	16.6	24.8
St. Peter	29	237	<0.03	22.2	2.2	0.6	1.9	5.9	10.5	22.2
Prairie du Chien	78	300	<0.03	49	4.4	1.3	7.7	11.3	14.2	40.3
Prairie du Chien-Jordan	17	315	<0.03	20.6	6.1	6.6	9.1	14.8	19.0	20.6
Jordan	49	365	<0.03	24.9	3.3	0.2	6.4	8.3	13.0	24.9
Saint Lawrence-Tunnel City	5	320	0.066	10.4	3.6	2.7	6.2	10.4	10.4	10.4
Tunnel City-Lone Rock	25	373	<0.03	3.64	0.7	<0.03	0.5	3.5	3.6	3.6
Tunnel City-Wonewoc	6	410	<0.03	3.15	0.7	<0.03	1.0	2.9	3.2	3.2
Wonewoc-Eau Claire	12	338	<0.03	7.13	1.0	0.03	1.1	3.5	6.6	7.1
Total	389	269	<0.03	49	3.16	0.3	4.7	9.5	13.0	24.3

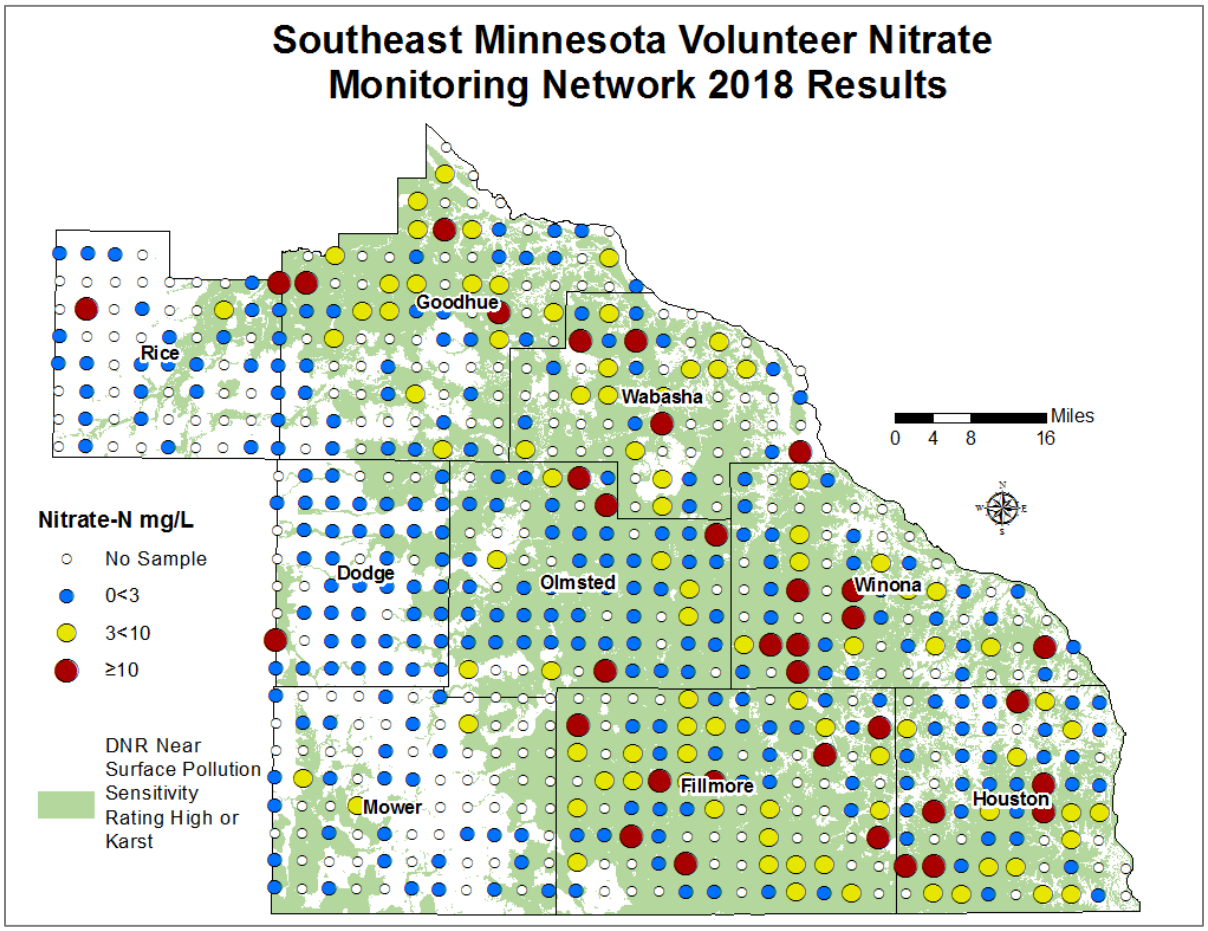

Figure 1. Southeast VNMN 2018 results by location.

As Table 1 indicates, the number of homeowners (wells) participating in the project is variable with time, ranging from 519 in 2008 to 389 in 2018. To investigate the possible impact of this change, a comparison of depth and age (Tables 3 and 4) was performed for the Southeast VNMN, for wells that had known information. The results suggest that, with respect to well characteristics, there did not appear to be large differences in the sampled wells over the years as the depths and ages did not change significantly (p value= 0.933 and 0.817 respectively). Therefore, it is reasonable to say that changes in water quality are not being strongly affected by the small changes in well characteristics of the network.

Table 3. Summary of well depth of submitted samples by year in Southeast VNMN.

Date Sampled	Number of Wells	Number of Wells with Depth	Number of Wells without Depth	% of Wells without Depth	Min Depth (ft)	Max Depth (ft)	Mean Depth (ft)	Median Depth (ft)
2/1/2008	519	451	68	13.1%	18	725	254	220
8/1/2008	510	455	55	10.8%	18	725	256	225
2/1/2009	494	442	52	10.5%	18	725	257	223
8/1/2009	471	423	48	10.2%	18	725	257	225
8/1/2010	422	394	28	6.6%	18	725	261	230
8/1/2011	428	393	35	8.2%	20	725	267	240
8/1/2012	411	368	43	10.5%	18	725	264	230
8/1/2013	315	291	24	7.6%	18	725	266	230
8/1/2014	361	328	33	9.1%	18	725	256	220
8/1/2015	373	338	35	9.4%	18	725	257	220
8/2/2016	387	347	40	10.3%	20	725	268	242
8/1/2017	341	293	48	14.1%	18	725	265	240
8/1/2018	389	341	48	12.3%	20	725	269	245

Table 4. Summary of well age of submitted samples by year in the Southeast VNMN.

Date Sampled	Number of Wells	Number of Wells with Dates	Number of Wells without Dates	% of Wells without Dates	Min Year	Max Year	Mean Year	Median Year
2/1/2008	519	415	104	20.0%	1870	2007	1969	1973
8/1/2008	510	418	92	18.0%	1870	2008	1969	1973
2/1/2009	494	406	88	17.8%	1870	2008	1970	1974
8/1/2009	471	388	83	17.6%	1870	2008	1970	1973
8/1/2010	422	363	59	14.0%	1870	2010	1970	1973
8/1/2011	428	361	67	15.7%	1870	2010	1970	1975
8/1/2012	411	337	74	18.0%	1870	2011	1970	1974
8/1/2013	315	273	42	13.3%	1870	2013	1971	1975
8/1/2014	361	304	57	15.8%	1870	2013	1970	1974
8/1/2015	373	315	58	15.5%	1870	2012	1970	1973
8/2/2016	387	320	67	17.3%	1880	2016	1971	1975
8/1/2017	341	268	73	21.4%	1900	2016	1973	1976
8/1/2018	389	308	81	20.8%	1870	2016	1973	1977

TREND ANALYSIS- SOUTHEAST VNMN

Groundwater nitrate concentration measurements are often not normally distributed data sets. Consequently, using parametric trend analysis is not appropriate. For this analysis, a nonparametric Mann-Kendal test for the time trend analysis (Helsel and Hirsh, 2002) was determined to be the most appropriate.

There were two sampling events early on in the network that occurred in February; otherwise, sampling occurred in August of each year. The February and August sampling events in 2008 and 2009 were evaluated to see if there were any differences between the events in these years. A boxplot was produced (Figure 2) and a nonparametric Kruskal-Wallis comparison test was performed (Table 5) to assist with this evaluation. It was found that there were no significant differences between the events in 2008 and 2009, so only the August event data from each year was utilized. This also permitted traditional trend testing, where time steps between the data being analyzed were consistent.

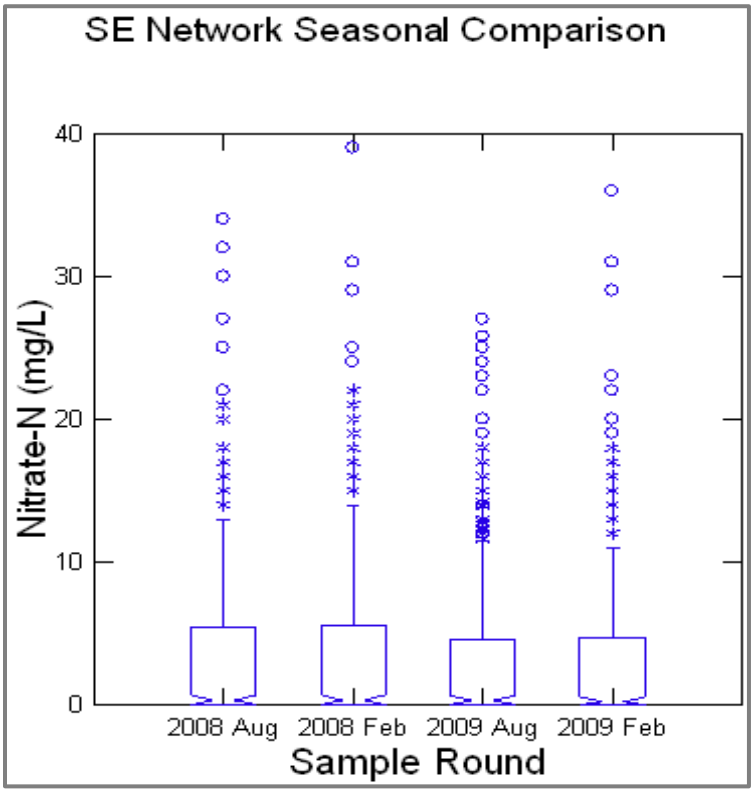

Figure 2. Boxplot of nitrate concentrations from the Southeast VNMN during the February and August sampling events in 2008 and 2009.

Table 5. Comparison test results for the Southeast VNMN data during the February and August sampling in 2008 and 2009.

Sample Events Tested	Kruskal-Wallis Test p-Value	Result
February 2008 & August 2008	0.875	No Difference
February 2009 & August 2009	0.658	No Difference

No statistically significant trend (H0: No Trend vs. H1: Two-Sided Trend or H0: No Trend vs H1 Downward Trend) was found for any of the percentile data (Table 6) for the period from 2008 through 2018. Figure 3 shows the percentiles for the nitrate concentration data over time plotted with binomial fit lines, which are used in nonparametric methods to illustrate the central tendency of data over time (Helsel and Hirsch, 2002).

Table 6. Trend analysis for the Southeast VNMN data.

Percentile	Mann-Kendal Test p-Value (95th confidence level)		Mann-Kendal Downward Trend p-Value (95th confidence level)	
50th	0.159	No Trend	0.079	No Trend
75th	0.39	No Trend	0.195	No Trend
90th	0.755	No Trend	0.378	No Trend

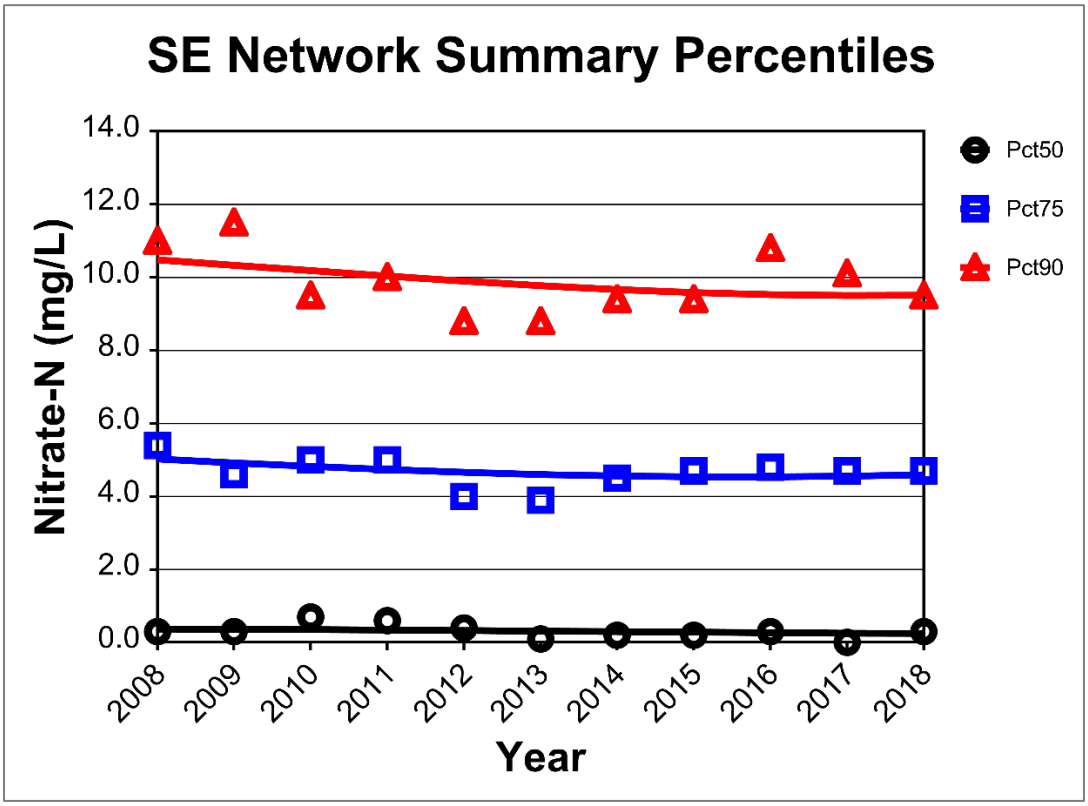

Figure 3. Binomial lines fit to nitrate percentile concentrations from the Southeast VNMN.

CENTRAL SANDS PRIVATE WELL MONITORING NETWORK 2011-2018

Due to the success of the Southeast VNMN, as well as the availability funding from the Clean Water Legacy Amendment, the MDA launched a similar project in the Central Sands area of Minnesota, which includes 14 counties, in 2011. The MDA determined that, because high levels of nitrate had been measured in MDA's Central Sands monitoring wells, it was important to expand nitrate monitoring to private drinking water wells to determine if the concentrations were similar to concentrations found in MDA's monitoring wells in this area. In the spring of 2011, the MDA began the Central Sands Private Well Monitoring Network (CSPWN). The goals of this project were to evaluate nitrate concentrations in private wells across the Central Sands region and assess nitrate concentration trends over time using a representative subset of this data.

The CSPWN was designed as an unaligned grid across the 14 county area. Homeowners from within the grids in agricultural areas were randomly invited to participate in the network. By July 1, 2011, the MDA had analyzed 1,555 samples for nitrate (MDA 2012). Over 88 percent of the wells sampled had concentrations below 3 mg/L nitrate-N, 6.8 percent of the wells ranged

from 3-10 mg/L of nitrate-N and 4.6 percent of the wells were greater than the nitrate-N HRL (Table 7). These results were similar to findings from a 2010 U. S. Geological Survey (USGS) report on nitrate concentrations in private wells in the glacial aquifer systems across the upper United States (Warner and Arnold 2010). The USGS report found that less than 5 percent of sampled private wells had concentrations greater than or equal to 10 mg/L nitrate-N. The 2011 CSPWN results indicated nitrate concentrations varied widely over relatively short distances. The USGS report on glacial aquifer systems indicated similar findings related to spatial variability in nitrate concentration.

Table 7. Summary of CSPWN 2011 nitrate data.

Number of Samples	Min (mg/L)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)	% ≤ 3 (mg/L)	% 3<10 (mg/L)	% ≥10 (mg/L)
1,555	<0.03	0.01	0.66	4.15	31.9	88.6%	6.8%	4.6%

Over 500 homeowners volunteered to participate in long-term annual sampling of their private wells. Participation in sampling decreased over time, similar to the Southeast VNMN; however, results from 2011 through 2018 have indicated minimal variation in nitrate concentration over time. The 2018 results indicate 3 percent of the wells had nitrate concentrations greater than or equal to 10 mg/L nitrate-N (Table 8). Overall, 95.5-97.8 percent of wells in the CSPWN have been below the 10 mg/L HRL for nitrate-N. The highest nitrate result was detected in a well with an unknown aquifer source, however, elevated concentrations can be found throughout the water table to the buried quaternary aquifers (Table 9). The most recent sampling results from 2018 are presented in Figure 4. For further information on this sampling project, see http://www.mda.state.mn.us/en/protecting/cleanwaterfund/gwdwprotection/characterizingnitrates.aspx

Table 8. CSPWN nitrate results summary 2011 through 2018.

Year	Total Wells	50th Percentile (Median)	90th Percentile	% of Wells ≥ 10	% of Wells < 10
		Nitrate-N (mg/L)			
2011	534	<0.03	3.3	3.9%	96.1%
2012	506	0.20	3.6	3.2%	96.8%
2013	487	0.20	3.6	2.7%	97.3%
2014	432	<0.03	3.2	3.5%	96.5%
2015	402	<0.03	3.5	4.5%	95.5%
2016	397	<0.03	3.0	3.5%	96.5%
2017	367	<0.03	3.3	2.2%	97.8%
2018	338	<0.03	3.0	3.0%	97.0%

Table 9. Nitrate results summary by aquifer in the CSPWN in 2018.

Aquifer	Total Wells	Mean Depth (ft)	Values				Percentiles			
			Min	Max	Mean	Median	75th	90th	95th	99th
			Nitrate-N (mg/L)							
NA	139	NA	<0.03	35.70	1.35	<0.03	0.84	4.31	6.50	23.95
Quaternary Water Table	26	66	<0.03	26.70	1.64	<0.03	0.06	1.35	14.94	26.70
Quaternary Buried Unconfined	7	77	<0.03	6.79	1.69	<0.03	3.42	6.29	6.79	6.79
Quaternary Buried Undifferentiated	1	133	<0.03	<0.03	<0.03	<0.03	NA	NA	NA	NA
Quaternary Undifferentiated	5	146	<0.03	0.11	0.02	<0.03	0.03	0.11	0.11	0.11
Quaternary Buried Artesian Aquifer	158	105	<0.03	33.70	0.88	<0.03	0.05	2.37	3.67	14.77
Hillman Tonalite	1	128	0.078	0.08	0.08	0.08	NA	NA	NA	NA
Precambrian Rock Undifferentiated	1	353	<0.03	<0.03	<0.03	<0.03	NA	NA	NA	NA
Total	338	102	<0.03	35.70	1.13	<0.03	0.16	3.05	6.10	23.00

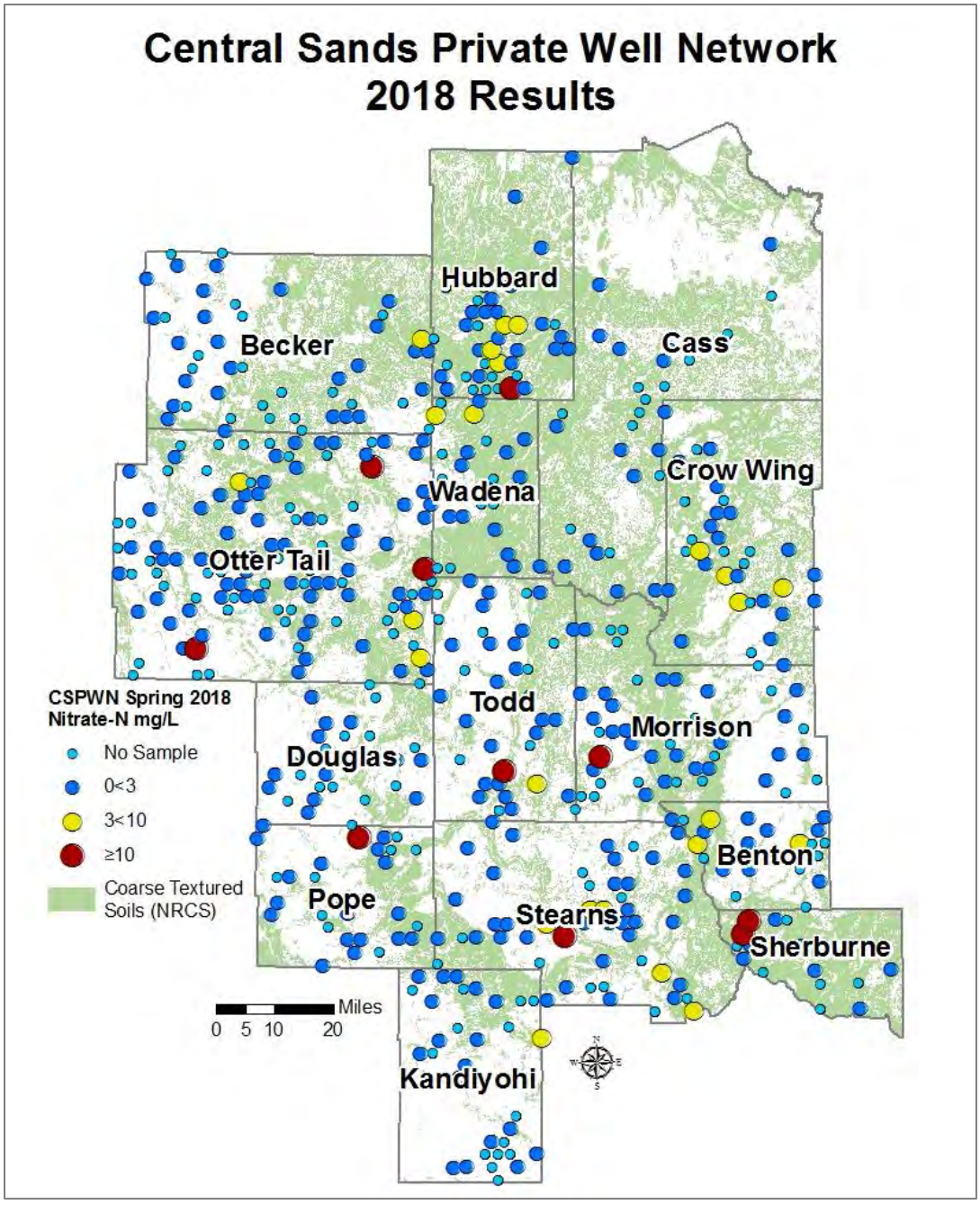

Figure 4. CSPWN 2018 Results.

As Table 8 indicates, the number of homeowners (wells) participating in the project is variable with time, ranging from 534 at its highest in 2011 to 338 at its lowest in 2018. To investigate the possible impact of this change, a summary comparison of well depth and age (Tables 10 and 11) was also performed for the CSPWN, for wells that had known information. The results suggest that, with respect to well characteristics, there did not appear to be large differences in the sampled wells over time as the depths and ages did not change significantly (p value= 0. 982

and 0.957 respectively). Therefore, it is reasonable to assume that changes in water quality are not being strongly affected by the changing network population overtime.

Table 10. Summary of well depths for submitted samples by year in the CSPWN.

Date Sampled	Number of Total Wells	Number of Wells with Depth	Number of Wells without Depth	% of Wells without Depth	Min Depth (ft)	Max Depth (ft)	Mean Depth (ft)	Median Depth (ft)
2011	534	306	228	43%	15	400	106	90
2012	506	294	212	42%	15	400	105	90
2013	487	283	204	42%	15	400	105	87
2014	432	258	174	40%	15	400	104	86
2015	402	243	159	40%	15	400	106	90
2016	397	237	160	40%	15	400	103	86
2017	367	210	157	43%	15	356	103	85
2018	338	199	139	41%	15	400	102	84

Table 11. Summary of well construction dates for submitted samples by year in the CSPWN.

Date Sampled	Number of Total Wells	Number of Wells with Dates	Number of wells without Dates	% of wells without Dates	Min Year	Max Year	Mean Year	Median Year
2011	534	305	229	43%	1966	2011	1997	1999
2012	506	293	213	42%	1966	2011	1997	1999
2013	487	282	205	42%	1966	2013	1997	1999
2014	432	257	175	41%	1966	2011	1997	1999
2015	402	242	160	40%	1966	2015	1997	1999
2016	397	236	161	41%	1966	2013	1997	1999
2017	367	210	157	43%	1966	2013	1997	1999
2018	338	198	140	41%	1972	2013	1998	1999

TREND ANALYSIS-CSPWN

The non-parametric time series analysis for the CSPWN indicates that there is not enough information to reject the null hypothesis (H0: No Trend vs. H1: Two-Sided Trend) that there is no statistically significant trend in the nitrate percentiles (50th, 75th, and 90th) through this test (Table 12). However, there is enough evidence for a downward trend in the 90th percentile (H0: No Trend vs. H1 Downward Trend) through the downward trend test. Figure 5 presents the percentiles for the nitrate concentrations plotted overtime with binomial fit lines, which indicate the central tendency of the data (Helsel and Hirsch, 2002).

Table 12. Trend analysis for the CSPWN 2011 through 2018.

Percentile	Mann-Kendal Trend (two-sided) p-Value (95th confidence level)		Mann-Kendal Downward Trend p-Value (95th confidence level)	
50th	0.362	No Trend	0.181	No Trend
75th	0.844	No Trend	0.422	No Trend
90th	0.097	No Trend	0.048	Downward Trend

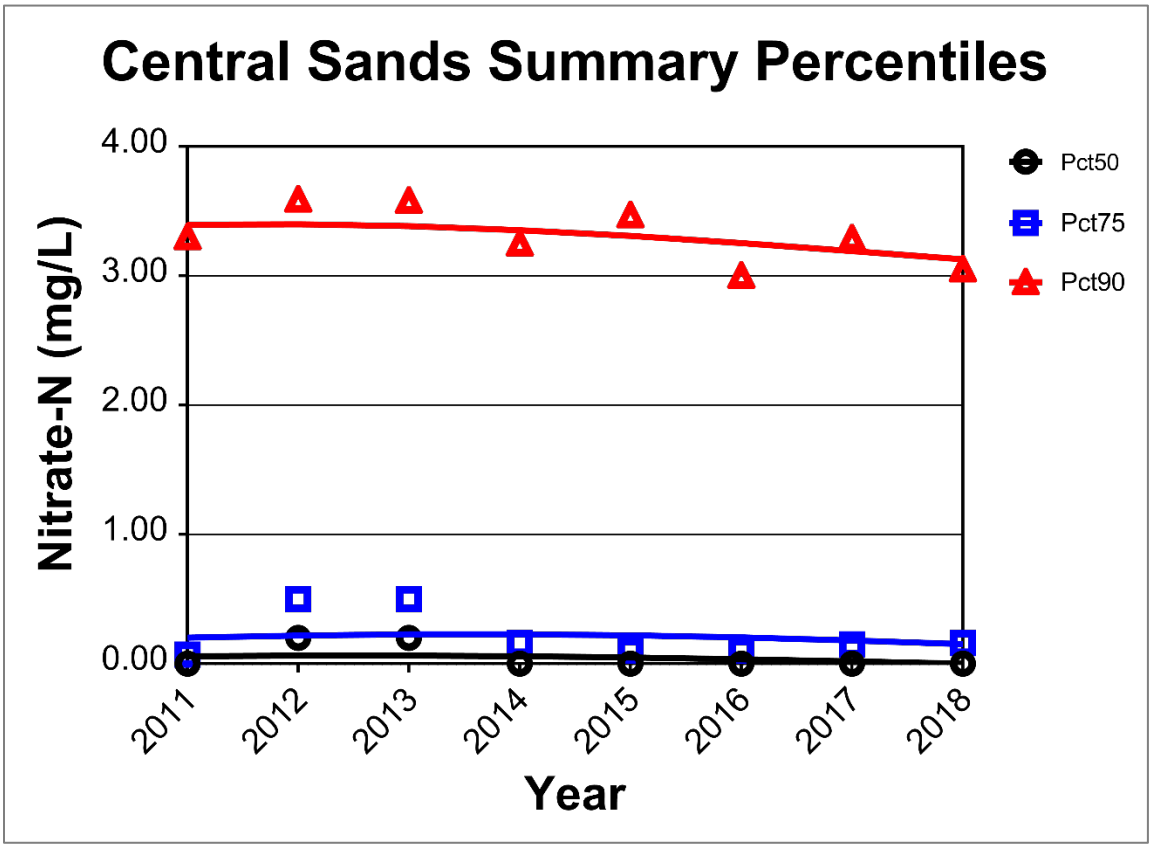

Figure 5. CSPWN binomial fit lines.

SUMMARY

Although there can be variability in the sampled population and nitrate concentration in individual wells from year to year, the regional data presented in this report is useful for evaluating long term trends. Analysis of the data from these private well monitoring networks indicates a concern for nitrate in groundwater from vulnerable aquifers in central and southeast Minnesota.

Nitrate concentration data from the Southeast Volunteer Nitrate Monitoring Network (2008-2018) and the Central Sands Private Well Network (2011-2018) were analyzed for statistical trend. In order to ensure all years were treated equally, the February sampling periods from years 2008 and 2009 were removed prior to the nitrate trend analysis in the Southeast Volunteer Nitrate Monitoring Network. The data from the August event sampling from each year (eleven years of monitoring) showed that there was no statistically significant trend for the 50th percentile (median), 75th or 90th percentile data in the Southeast Volunteer Nitrate Monitoring Network. Data from the Central Sands Private Well Network showed a slight statistically significant downward trend in the 90th percentile data based on eight years of monitoring in that network.

Over time network participation did decline in both networks, so additional analysis of well depths and ages was completed to evaluate the potential impact that these changes may have had on the sampled populations over time. Based on an analysis of wells with known characteristics (well depth and age) there were no significant differences in either network. Reasons volunteers leave the networks may include selling their home, apathy based on not seeing a change in nitrate results over time, replacing an old well with a new well, and homeowners are too busy. Future work will include emphasis on keeping volunteers engaged and participating in the network on an annual basis to keep the network consistent.

REFERENCES

Helsel and Hirsch. 2002. USGS Statistical Methods for Water Resources. TWRI 04-A3.

Minnesota Department of Agriculture. 2012. Central Sands Private Well Network 2011 Current Nitrate Conditions Summary. http://www.mda.state.mn.us/protecting/cleanwaterfund/gwdwprotection/~/media/Files/protecting/cwf/cspwnsummary.ashx (accessed November 10, 2016).

Warner, K.L., and T.L. Arnold. 2010. Relations that Affect the Probability and Prediction of Nitrate Concentrations in Private Wells in the Glacial Aquifer System in the United States: A USGS National Water Quality Assessment Program Scientific Investigations Report.



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Dear Dr. Cunningham, Mr. Peterson, and Ms. Kessler:

On April 24th, 2023, Petitioners[1] requested that the U. S. Environmental Protection Agency exercise its emergency powers under Section 1431 of the Safe Drinking Water Act (SDWA) to address groundwater nitrate contamination that presents a risk to the health of the residents in eight counties of the Southeast Karst Region[2] (Karst Region) of Minnesota. Section 1431 authorizes EPA to act upon receipt of information that a contaminant is present in or is likely to enter a public water system (PWS) or an underground source of drinking water (USDW), which may present an imminent and substantial endangerment to the health of persons, and that appropriate state and local authorities have not

[1] Petitioners: Minnesota Center for Environmental Advocacy, Environmental Working Group, Minnesota Well Owners Organization, Center for Food Safety, Clean Up the River Environment, Food & Water Watch, Friends of the Mississippi River, Izaak Walton League Minnesota Division, Land Stewardship Project, Minnesota Trout Unlimited, and Mitchell Hamline Public Health Law Center.

[2] Minnesota's Karst Region referenced in the petition consists of eight counties: Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Wabasha, and Winona county.

acted to protect the health of such persons. Approximately 390,682[3] people reside in the Karst Region; about 300,000 people are served by 93 PWSs and approximately 93,805[4] people rely on private wells as their primary source of drinking water. Based on the information currently available from past nitrate monitoring, it had been estimated that 9,218[5] residents in the Karst Region were or still are at risk of consuming water at or above the maximum contaminant level (MCL) for nitrate, with Minnesota Department of Agriculture reporting that 12.1% of the private wells tested (equating to 1,058 wells) exceeded the MCL of 10mg/L[6]. Several of the PWSs in the Karst Region have also been impacted by MCL exceedances resulting in additional treatment and/or having to drill deeper wells.

We appreciate the time that you and your staff have taken to meet with my staff on numerous occasions to share each agency's efforts to protect Minnesota's drinking water, including the information you shared in and after our meeting on August 28, 2023 (See Enclosure). While we appreciate the collective commitment to address nitrate contamination through state-administered programs, based on our discussions and current available drinking water data, there is an evident need for further actions to safeguard public health.

EPA's immediate priority is to protect human health by ensuring that residents impacted by nitrate contamination are: (1) identified; (2) provided notice in all applicable languages regarding their potential exposure to elevated nitrate concentrations and information regarding the associated health risks; and (3) provided the opportunity to obtain alternate drinking water until nitrate contamination in groundwater falls below the MCL for nitrate of 10 mg/L.

EPA expects state agencies to take timely actions to address the nitrate contamination, especially with respect to providing public notice and alternate water. To address these priorities, EPA requests that the Minnesota agencies develop a coordinated and comprehensive work plan to identify, contact, conduct drinking water testing and offer alternate water to all impacted persons in the Karst Region, as soon as possible, and to sustain these efforts for as long as nitrate concentrations in the groundwater of the Karst Region remain at or above the MCL. An adequate work plan to address immediate health concerns should include the following:

1. **Coordination** – The state should create a communication plan that identifies how information and responsibilities will be shared among the state agencies, local governments

[3] Calculated using the 2022 data, for each county, reported on the Minnesota State Demographic Center "PopFinder For Minnesota, Counties, & Regions". https://mn.gov/admin/demography/data-by-topic/population-data/our-estimates/pop-finder1.jsp

[4] Calculated using Minnesota Department of Health "Community Water Systems: MNPH Data Access" to determine population serviced by CWS's, then subtracted by the population in the region. https://mndatamaps.web.health.state.mn.us/interactive/cwss.html last updated 03/07/2023.

[5] Calculated using the Township Testing Program "Final Report" by adding up the estimated population at risk, reported in the "Estimates of Population at Risk" section of each report, for each county. Data used ranges from 2014 – 2019. https://www.mda.state.mn.us/township-testing-schedule-reports

[6] From the Township Testing Program county reports for this region.

(county, city, township), and any private businesses or local utilities that have volunteered or been required to act, so that each entity's efforts serve a singular and coordinated response.

2. **Identification of Impacted Residences** – The state should identify each residence that obtains drinking water from a private well within the Karst Region. This includes wells that were constructed prior to the adoption of Minnesota's Well Code.

3. **Education and Outreach** – The state should provide notice to newly and previously impacted residents and continue to provide notice as long as contamination persists at or above the MCL for nitrate. If notice has not been provided to those that were previously identified as having private drinking water wells at or above the MCL for nitrate, we expect the state to provide notice *immediately* to such residents.

Similarly, if notice has not been provided to customers served by regulated PWSs that had nitrate levels at or above the MCL, we expect the state or owner/operators to provide notice *immediately*. Public education and outreach should be conducted in a form and manner reasonably calculated to reach all impacted residents in all applicable languages.

The state should prioritize its education and outreach toward the most vulnerable populations for associated health risks (e.g., homes with infants, pregnant women), including efforts to work with health care facilities and daycares serving such populations.

In addition to public health information, clear instruction for private drinking water well users to request drinking water testing should be included in appropriate languages. Minnesota should measure its progress in contacting all private well users identified as part of outreach efforts. For those private well users that do not respond to public notices, Minnesota should attempt personal communications, such as visits to individual residences (e.g., Minnesota Water Stewards).

4. **Drinking Water Testing** – Responsible agencies should create and implement a plan to provide analysis of drinking water samples obtained from any private well users in the Karst Region that request testing. For any residents identified as having private drinking water wells at or above the MCL for nitrate, we expect the state to provide timely notice to such impacted residents.

5. **Provision of Alternate Water** – Alternate drinking water should be offered as soon as practicable to each residence where water tests show an exceedance of the MCL for nitrate in the private well. The state should prioritize provision of alternate water to particularly vulnerable populations (e.g., homes with infants, pregnant women). As part of your response to EPA, please provide a detailed plan for distribution (e.g., water made available to residents at centralized locations) and a timeline for provision of such water.

Alternate water should be provided as needed for drinking, cooking, and maintaining oral hygiene. This shall be at no cost to the resident and in a manner that minimizes the burden on the impacted resident to obtain safe drinking water, such as water distribution locations and/or delivery services, reverse osmosis treatment units, or connection to a public water system.

6. **Public Records** – Maintain and regularly publish records such that Minnesota residents and the general public can better understand the scope and severity of nitrate contamination in the Karst Region and measure Minnesota's progress in implementing its response plan including provision of alternate water, and to establish an effective way to communicate updates to the general public.

7. **Communication with EPA** – EPA requests that the Minnesota agencies provide progress reports quarterly to EPA that (a) describe actions taken during the previous quarter to address the immediate health impacts of nitrate contamination; (b) identify major accomplishments and issues that arose; (c) describe actions and timelines planned for the next quarter; and (d) describe any problems or delays encountered and the solutions implemented to address them.

While this letter is largely focused on addressing immediate health concerns regarding nitrate contamination in drinking water in the Karst Region, Minnesota must also develop and implement a long-term solution to achieve reductions in nitrate concentrations in drinking water supplies.

Developing a complete understanding of potential sources of nitrate contamination is an important immediate step for the state. A risk analysis of current and future nitrate contamination of the impacted groundwater will be critical for determining long-term solutions, and such analysis should incorporate the latest science and technologies.

Minnesota has tools to effect reductions in nitrate concentrations through the National Pollutant Discharge Elimination System (NPDES) and State Disposal System permit programs, including development and implementation of more protective NPDES/SDS CAFO permits.

In addition, Minnesota should consider adopting monitoring requirements in NPDES/SDS permits related to (1) subsurface discharges from manure, litter, and process wastewater storage, as well as (2) discharges from land application, similar to those proposed by EPA as modifications to the EPA-issued CAFO general permit for Idaho: https://www.epa.gov/npdes-permits/npdes-general-permit-concentrated-animal-feeding-operations-cafos-idaho. We also encourage Minnesota to consider modifications to the state's Technical Standards for Nutrient Management with regard to land application of manure, litter or process wastewater, and any Minnesota guidelines for land application of commercial fertilizer, specific to Karst areas.

EPA expects Minnesota to hold sources of nitrate accountable using all available tools to reduce the amount of nitrate they release to ground water. While the Agency appreciates the state agencies' engagement and past efforts in addressing groundwater contamination in the Karst Region, EPA will

continue to closely monitor this situation and consider exercising our independent emergency and enforcement authorities.

Given the urgency inherent in any situation involving drinking water contamination with known potential health risks, we respectfully request confirmation of your agencies' plan to provide "Education and Outreach" and "Provision of Alternate Water" as soon as possible. EPA expects a reply with respect to the elements noted above within 30 days, which must include the anticipated timeframe for submission of the agencies' work plan.

Sincerely,

DEBRA SHORE

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Debra Shore
Regional Administrator
& Great Lakes National Program Manager

Enclosure: Summary of Minnesota Efforts to Address Nitrate Contamination

EPA recognizes the Minnesota's past and current efforts to address nitrate contamination:
The Clean Water council (consisting of MDA, MPCA, and MDH representatives) was able to advise the Legislature to appropriate $100,000 of the state's Clean Water Fund to the "Tap In" initiative, which was carried out at the county level, including counties in the Karst Region. This initiative in 2021 assisted low-income private well owners with nitrate contamination that exceeds the MCL. The initial grant covered 186 tests, 7 reverse osmosis filters, 6 new wells, and one well repair.

MDA and MDH created a private well network for residents in which to participate in the Central Sands and Southeast Karst Region. The purpose of the Southeast Minnesota Volunteer Nitrate Monitoring Network was to monitor long term trends of nitrate concentrations in private drinking water wells throughout Southeastern Minnesota. Samples were collected from 2008 – 2012.

MDA and MDH provide technical assistance to CWSs when the nitrate level is detected above 3 mg/L. MDA had established Nitrate Testing Clinics, which has provided 50,000 well owners with testing services and educational outreach since 1993, and local partners with equipment to carry out nitrate analysis.

MDA provided free nitrate sampling to private well owners in vulnerable Townships throughout the state from 2013 to 2019 via the Township Testing Program. Of the 344 townships determined to be vulnerable statewide, 133 are in the Karst Region.

MDA was the initial partner in the *We are Water MN*, providing technical assistance, staff time, and financial investments.

MDA continues to develop and publish videos, infographics, and additional resources targeted for residents of the Karst Region.

MDA developed the Groundwater Protection Rule to support the 2015 Nitrogen Fertilizer Management Plan, which went into effect on June 28, 2019.

MDH established and enforces laws and rules for proper construction and sealing of wells and borings and provides guidance to private well owners. MDH assists and regulates public water systems by approving system construction and treatment plans in response to nitrate issues, as well as requiring PWSs to protect water sources from contamination and providing technical assistance and grants to do so. Since 1993, MDH has successfully returned 8 CWSs and 38 NCWSs back to compliance with SDWA's regulatory limits for nitrates.

MPCA created the state's Nutrient Reduction Strategy in 2014 to guide the state in reducing excess nutrients in water to meet state and downstream water quality goals.

MPCA had released the Groundwater Protection Recommendation Report in 2016 which states recommendations for preventing nitrate contamination in groundwater.

MPCA uses NPDES permits to (1) prevent manure, litter, and process wastewater discharge to surface water from Large CAFO production areas and (2) minimize nutrient movement to surface water from manure, litter, and process wastewater application to land under the control of Large CAFOs. State Disposal System-based conditions in these permits, and in SDS-only permits for Large CAFOs, are for the purpose of protecting ground water. In a July 22, 2021 letter from MPCA to EPA, MPCA underscored that it set conditions in its 2021 statewide NPDES/SDS general permit for Large CAFOs for the specific purpose of addressing existing elevated levels of nitrates in ground water (Peter Tester letter to Cheryl Newton, page one). For decades, Minnesota has operated a supplementary state law regulatory program for feedlots as small as 50 animal units (10 in shoreland).

In addition, we thank Minnesota staff for taking time to participate in recent calls and sharing information on your work to address nitrate contamination including calls with MDH on May 8, May 18, and June 20; MDA on May 18, MPCA on August 22, and a joint call with all three agencies on August 28.

Winona County: Final Overview of Nitrate Levels in Private Wells (2016-2017)

The Minnesota Department of Agriculture (MDA) determines current nitrate-nitrogen concentrations in private wells, on a township scale, through the Township Testing Program. The MDA has identified townships throughout the state that are vulnerable to groundwater contamination and have significant row crop production. The MDA plans to offer nitrate testing to more than 70,000 private well owners in over 300 townships by 2019.

Winona County Final Highlights

- Number of townships with 10% of wells over the HRL : **4**
- **209** (22%) wells removed from initial data set.

Each selected township is offered testing in two steps, the "initial" sampling and the "follow-up" sampling. In the initial sampling, all township homeowners using private wells are sent a nitrate test kit. If nitrate is detected in their initial sample, the homeowner is offered a follow-up nitrate test, pesticide test and well site visit. Trained MDA staff visit willing homeowners to resample the well and then conduct a site assessment. The assessment helps to identify possible non-fertilizer sources of nitrate and to see the condition of the well. A well with construction problems may be more susceptible to contamination.

The MDA and Winona County Environmental Services worked together to select townships and implement the nitrate testing project. The following townships were selected: **Elba, Fremont, Hart, Hillsdale, Mt. Vernon, Norton, Pleasant Hill, St. Charles, Saratoga, Utica, Warren, Wilson, and Wiscoy.** The initial sampling in Winona County started in 2016 and follow-up sampling ended in 2017.

Results

Two datasets, "Initial" and "Final", are used to evaluate nitrate in private wells. The initial dataset represents private well drinking water regardless of the potential source of nitrate. The final dataset was formed through an assessment process to evaluate wells. In the assessment, wells that had nitrate-nitrogen results over 5 mg/L were removed from the initial dataset to form the final dataset if a potential non-fertilizer source or well problem was identified, there was insufficient information on the construction or condition of the well, or for other reasons which are outlined in the full report (see Appendix E for details). The final dataset represents wells with nitrate attributed to the use of fertilizer. The initial dataset for Winona County contains 940 wells; the final dataset contains 731 wells. A total of 209 wells (22%) were removed.

The results from the initial and final well datasets are summarized in the following table and figures. In the initial dataset nine townships had more than 10% of the wells over the Health Risk Limit of 10 mg/L of nitrate-nitrogen (see map). In the final dataset four of the townships had more than 10%. The final percent of wells over the Health Risk Limit in each township ranged from 0% to 42.9%. The Winona County Final Report is available on the MDA website in 2019: www.mda.state.mn.us/townshiptesting.

Next steps

The MDA uses the TTP data and assessment process and prioritization guidelines in the Minnesota Nitrogen Fertilizer Management Plan (NFMP) to determine next steps. It is MDA's intent to implement the voluntary aspects of the NFMP in townships with elevated nitrate with the highest priority placed on areas with high sampling results. Find more information about the NFMP on the MDA website at www.mda.state.mn.us/nfmp.

Funding for this project is provided by the Clean Water, Land and Legacy Amendment

Table: Winona County Private Well Nitrate Results.

Township	Initial Well Dataset		Final Well Dataset	
	Total Wells*	Percent of Wells ≥10 mg/L Nitrate-Nitrogen	Total Wells	Percent of Wells ≥10 mg/L Nitrate-Nitrogen
Elba	62	16.1%	52	5.8%
Fremont	42	54.8%	28	42.9%
Hart	48	18.8%	31	6.5%
Hillsdale	52	1.9%	44	0.0%
Mt. Vernon	33	15.2%	24	0.0%
Norton	80	11.3%	62	4.8%
Pleasant Hill	58	8.6%	50	4.0%
St. Charles	85	34.1%	62	14.5%
Saratoga	56	19.6%	40	5.0%
Utica	86	46.5%	51	19.6%
Warren	92	28.3%	62	11.3%
Wilson	196	6.1%	179	1.7%
Wiscoy	50	0.0%	46	0.0%
Total	940	19.1%	731	7.1%

* All well types included.

In accordance with the Americans with Disabilities Act, this information is available in alternative forms of communication upon request by calling 651-201-6000. TTY users can call the Minnesota Relay Service at 711. The MDA is an equal opportunity employer and provider.

Figure: Winona County Final Well Dataset Map.

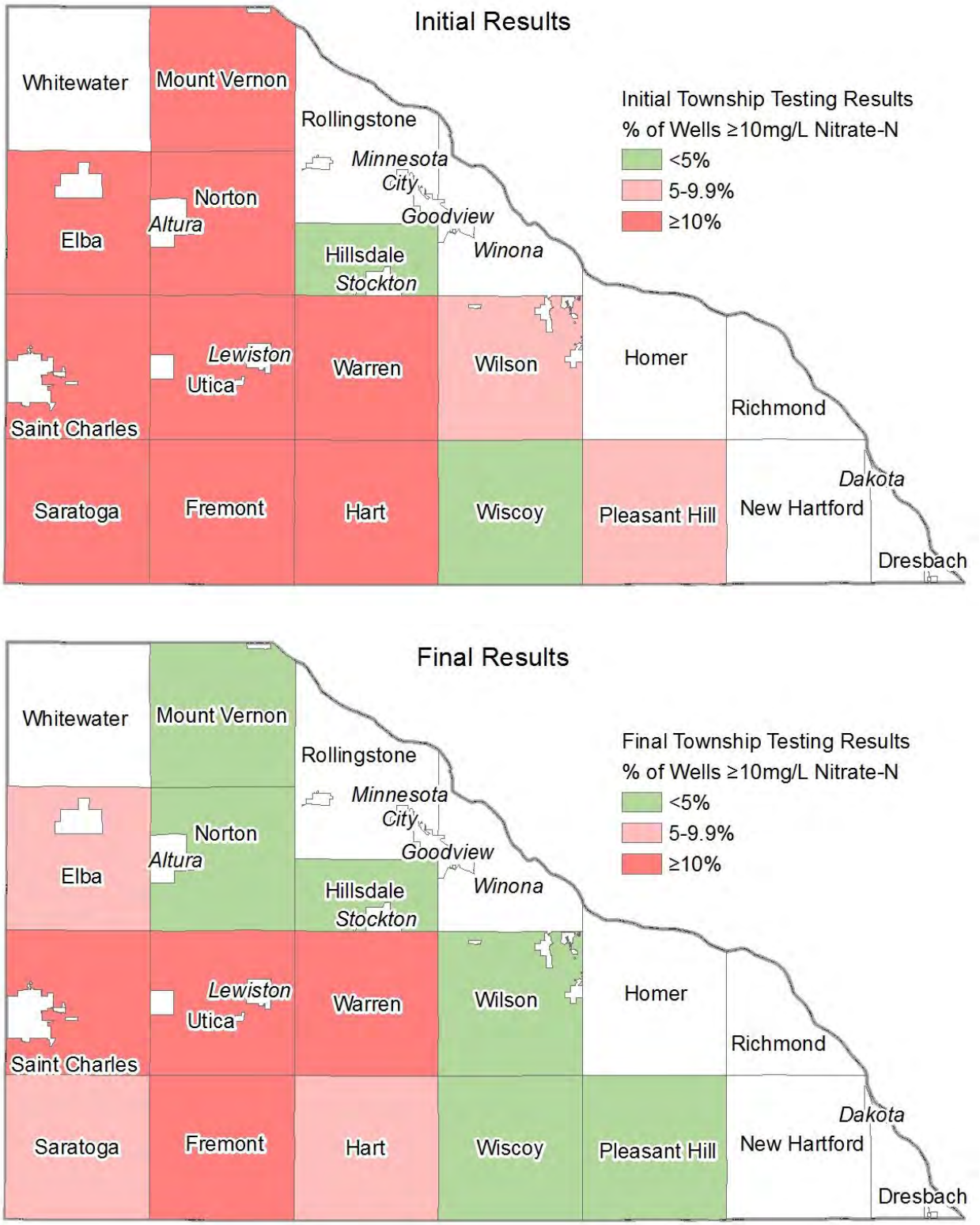

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SOUTHEAST MINNESOTA VOLUNTEER NITRATE MONITORING NETWORK 2023 RESULTS

DEPARTMENT OF AGRICULTURE

MCEA Ex. 29

The Southeast Minnesota Volunteer Nitrate Monitoring Network was developed in 2008 in order to determine nitrate trends in private wells in the region. Drinking water high in nitrate can cause serious health effects in infants. The state's Health Risk Limit (HRL) for nitrate-nitrogen is 10 mg/L.

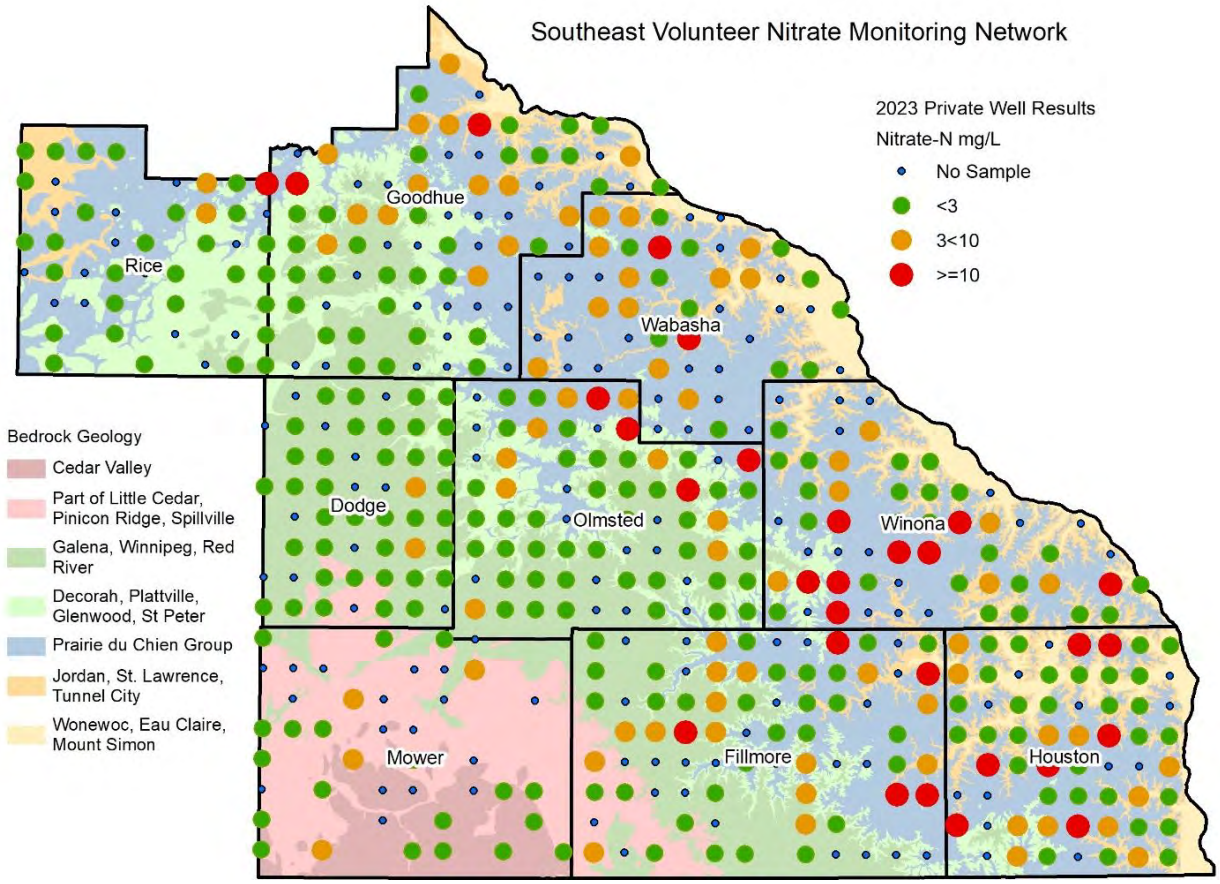

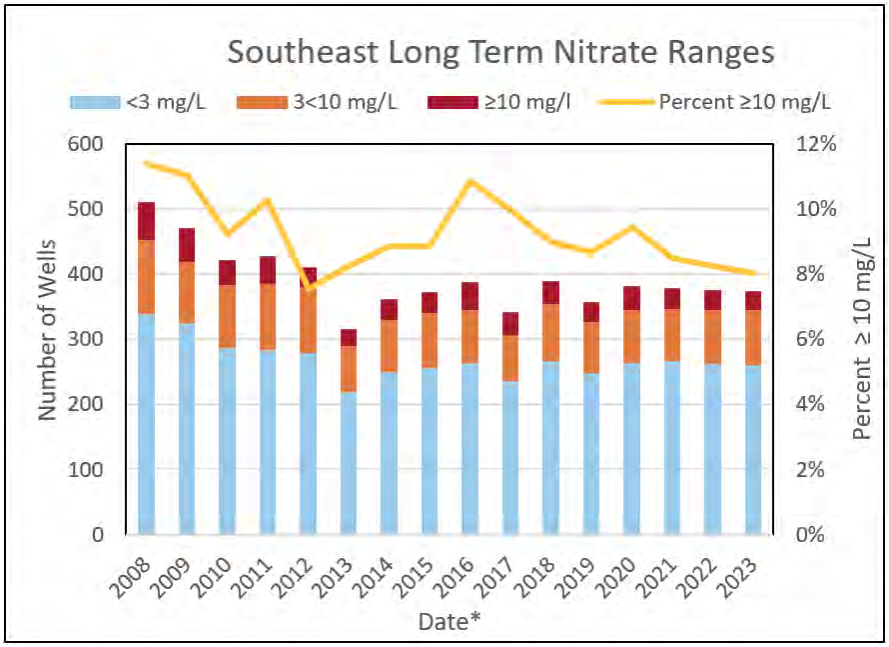

*In 2008 and 2009, 2 samples were taken per year. The fall sampling is represented for the purpose of consistency.

Southeastern Minnesota has karst geology that makes it vulnerable to groundwater contamination. The areas near the edge of the Decorah formation are especially vulnerable to nitrate contamination which is illustrated in the map.

In 2023, 374 private drinking water wells were sampled for nitrate. Thirty wells were over the nitrate HRL.

2023 Nitrate-N Results

- 69.5% of results <3 mg/L
- 22.5% of results were 3<10 mg/L
- 8.0% of results were ≥10 mg/L.

On a regional scale, 92.0% of participating wells have water that is below the nitrate HRL. There was a downward trend in the 50th percentile from 2008 to 2023. However, there were no significant trends from the 10-year time frame of 2014 to 2023.

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2023 NITRATE RESULTS BY COUNTY

County	Total Wells	Nitrate-N Min (mg/L)	Nitrate-N Max (mg/L)	Nitrate-N Mean (mg/L)	Nitrate-N Median (mg/L)	Nitrate-N 90th (mg/L)	% of wells <3 mg/L	% of wells 3<10 mg/L	% of wells ≥10 mg/L
Dodge	42	<0.25	4	0.19	<0.25	0.09	95.2%	4.8%	0.0%
Fillmore	51	<0.25	20.9	3.99	2.8	10.9	56.9%	31.4%	11.8%
Goodhue	49	<0.25	37.9	3.08	0.4	8.92	65.3%	30.6%	4.1%
Houston	52	<0.25	19.9	4.01	1.8	12.54	59.6%	26.9%	13.5%
Mower	24	<0.25	7.4	1.10	<0.25	5.18	83.3%	16.7%	0.0%
Olmsted	55	<0.25	16	2.18	0.4	8.9	76.4%	16.4%	7.3%
Rice	33	<0.25	11.6	0.62	<0.25	1.04	90.9%	6.1%	3.0%
Wabasha	28	<0.25	12.7	4.22	3.6	9.21	46.4%	46.4%	7.1%
Winona	40	<0.25	26.5	4.81	1.6	14.7	57.5%	22.5%	20.0%
Total	374	<0.25	37.9	2.80	0.15	9.12	69.5%	22.5%	8.0%

* The 90th percentile means that 90% of results are below this value.

Nitrate concentrations varied between counties in the Southeast Minnesota region. Winona County had the highest percentage of wells (20.0%) greater than 10 mg/L, followed by Houston (13.5%), and Fillmore (11.8%). Wells with nitrate results in the range of 3 to 10 mg/L are considered impacted by human activities on the land surface. The water in the impacted range is above natural levels of nitrate, but below the Health Risk Limit. Wabasha (46.4%), Fillmore County (31.4 %), and Goodhue County (30.6%) have the highest percentage of impacted wells.

The Minnesota Department of Agriculture will continue to offer free nitrate sampling kits to participating well owners on an annual basis. Olmsted County and Olmsted Soil and Water Conservation District, along with local well network coordinators, will continue to provide local coordination for the entire network. This coordinated effort will continue to engage well owners for continued participation.

Additional Programs to Protect Water Quality

Soil and Water Conservation Districts (SWCDs) in the area have cost share programs available to assist with sealing wells, installing water treatment systems, and new well construction on private property. Cost share is set at a 50 - 90% rate with a maximum amount per well. Be sure to contact your local SWCD about this cost share before work is done, as preapproval is required to qualify for the cost share. Private well water should also be tested annually for bacteria by a certified laboratory. Use the QR Code in the bottom right corner for more information and resources about recommended testing, funding, and maintenance of your well in SE Minnesota.

Thank you to the homeowner volunteers! Their participation makes this program possible and helps protect local groundwater. If you have any questions for MDA, please contact Nikol Ross at Nikol.Ross@state.mn.us, 651-392-5027 or contact Caitlin Meyer the Olmsted SWCD Water Resources Coordinator: 507-328-6396, Caitlin.Meyer@olmstedcounty.gov.

TAP-IN Safe Drinking Water Resources

Updated November 2024

DEPARTMENT OF AGRICULTURE

OLMSTED COUNTY MINNESOTA

CLEAN WATER LAND & LEGACY AMENDMENT

OLMSTED SOIL & WATER CONSERVATION DISTRICT



2014 Water Quality Monitoring Report

January – December 2014

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MINNESOTA DEPARTMENT
OF AGRICULTURE

MAU-15-101

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2.7 Statewide groundwater nitrate

There were 238 nitrate-nitrogen samples collected from shallow groundwater monitoring wells during 2014 (Table 22).

- 205 samples, or 86 percent of all samples analyzed, had detectable levels of nitrate-nitrogen.
- The highest concentration (67.40 mg/L) and highest median (15.55 mg/L) were found in PMR 4.
- Every PMR had at least 56 percent of samples with detectable levels of nitrate-nitrogen. Two PMRs (5 and 9) had 100 percent of samples with detectable levels of nitrate-nitrogen.

Table 22. Summary of nitrate-nitrogen results in groundwater samples for 2014.

PMR	Detections/Total Samples	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	8/14	57	0.57	2.81	18.14	20.30
4	83/86	97	15.55	23.90	36.74	67.40
5	16/16	100	8.27	16.65	21.92	30.80
6	9/16	56	0.61	3.46	27.03	37.20
7	8/14	57	6.56	14.80	22.34	29.00
8	17/28	61	1.00	10.45	20.78	35.90
9	64/64	100	7.79	10.15	12.82	14.20
All Samples	205/238	86	7.62	15.30	24.84	67.40

There are four categories when assessing nitrate-nitrogen sample results: no measurable levels (less than MDL), background (greater than MDL but less than 3.00 mg/L), impacted (3.01 mg/L or greater but less than 10.00 mg/L), and exceeding the health risk limit (greater than 10.00 mg/L; Table 23).

- It is common throughout Minnesota agricultural areas to have shallow groundwater exceed the MDH health risk limit for nitrate-nitrogen.
- PMRs 4 and 5 had the highest percent detection at concentrations exceeding the MDH health risk limit (59 and 44 percent, respectively).

Table 23. Summary of the percent of 2014 nitrate-nitrogen results in groundwater samples compared against MDH health risk limit categories.

PMR	MDH Health Risk Assessment Categories			
	< MDL (%)	MDL to 3.00 mg/L (%)	3.01 to 10.00 mg/L (%)	> 10.00 mg/L (%)
1	43	36	0	21
4	4	14	23	59
5	0	12	44	44
6	44	25	19	12
7	43	0	21	36
8	39	22	14	25
9	0	0	73	27
Total percent of samples	14	12	35	39

A summary of the nitrate-nitrogen results from the eight shallow and eight deep paired wells in PMR 4 sampled during 2014 can be found in Table 24.

- The shallow wells had higher nitrate concentrations than the deeper wells, with median concentrations of 21.75 mg/L and 17.25 mg/L, respectively.
- All samples from the shallow wells had detectable levels of nitrate-nitrogen, while 88 percent of the deep well samples had detections.
- The highest nitrate-nitrogen concentration (65.40 mg/L) was from a shallow well.
- A larger percentage of shallow well samples than deep well samples (94 percent versus 75 percent, respectively) exceeded the MDH health risk limit of 10.00 mg/L.

Table 24. Summary of nitrate-nitrogen results in paired shallow and deep wells in PMR 4.

Depth Type	Detections	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)	Percent Exceeding 10.00 mg/L Standard
Shallow	16/16	100	21.75	35.25	56.40	65.40	94
Deep	14/16	88	17.25	21.80	34.28	38.70	75

Time-trend graphics have been prepared using data available since 2000 and provide a historical perspective on nitrate-nitrogen concentrations in MDA's monitoring wells (Figures 40 and 41).

- PMRs 4 and 5 consistently have the highest median nitrate-nitrogen concentrations around 10.00 mg/L.
- Due to small annual sample counts and widely varying observed nitrate-nitrogen concentrations, the upper percentiles (75th and 90th) in PMRs 1, 5, 6, 7, and 8 exhibit wide fluctuations in values.

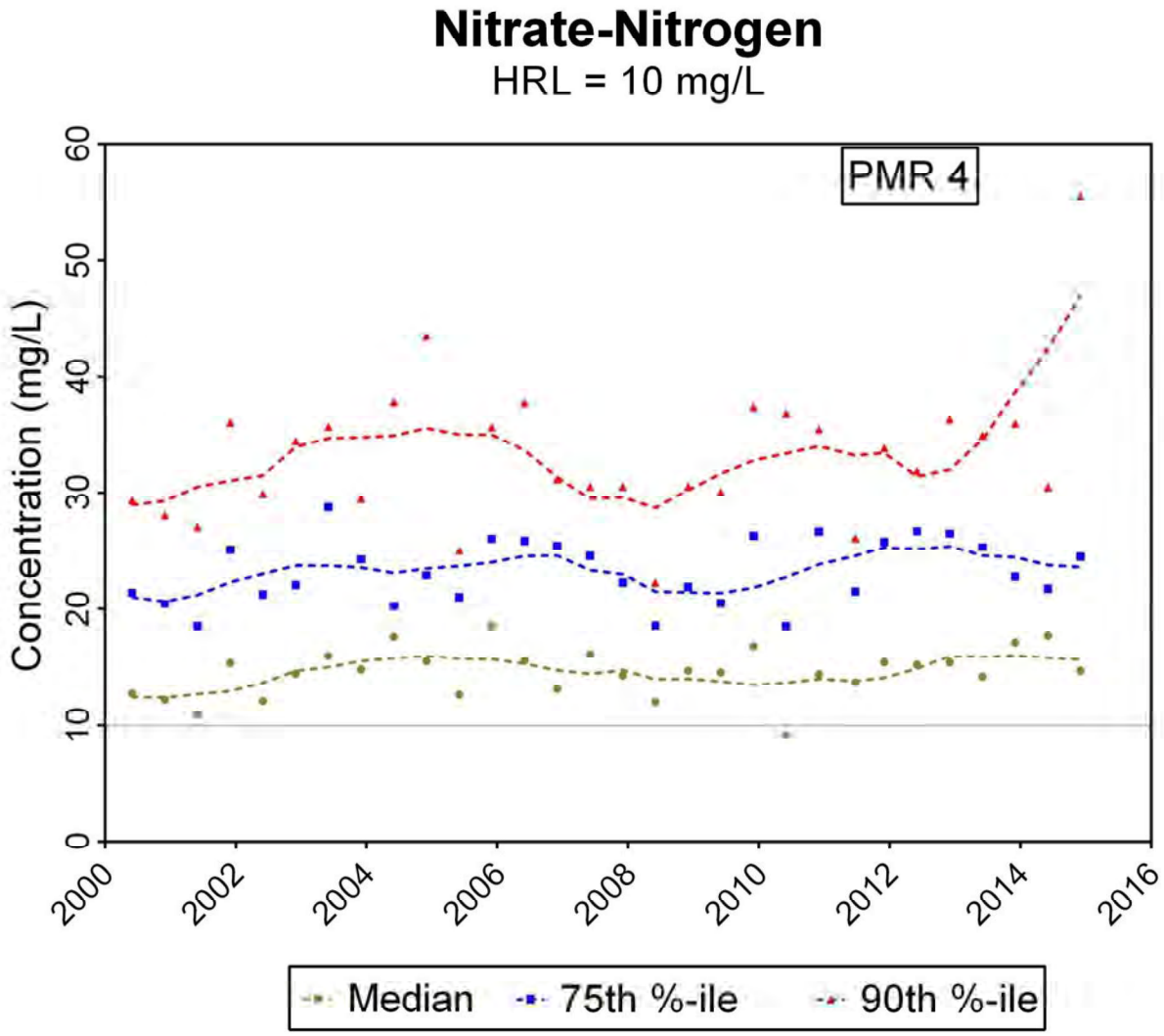

Figure 40. Nitrate-nitrogen analysis results over time for MDA PMR 4 groundwater samples.

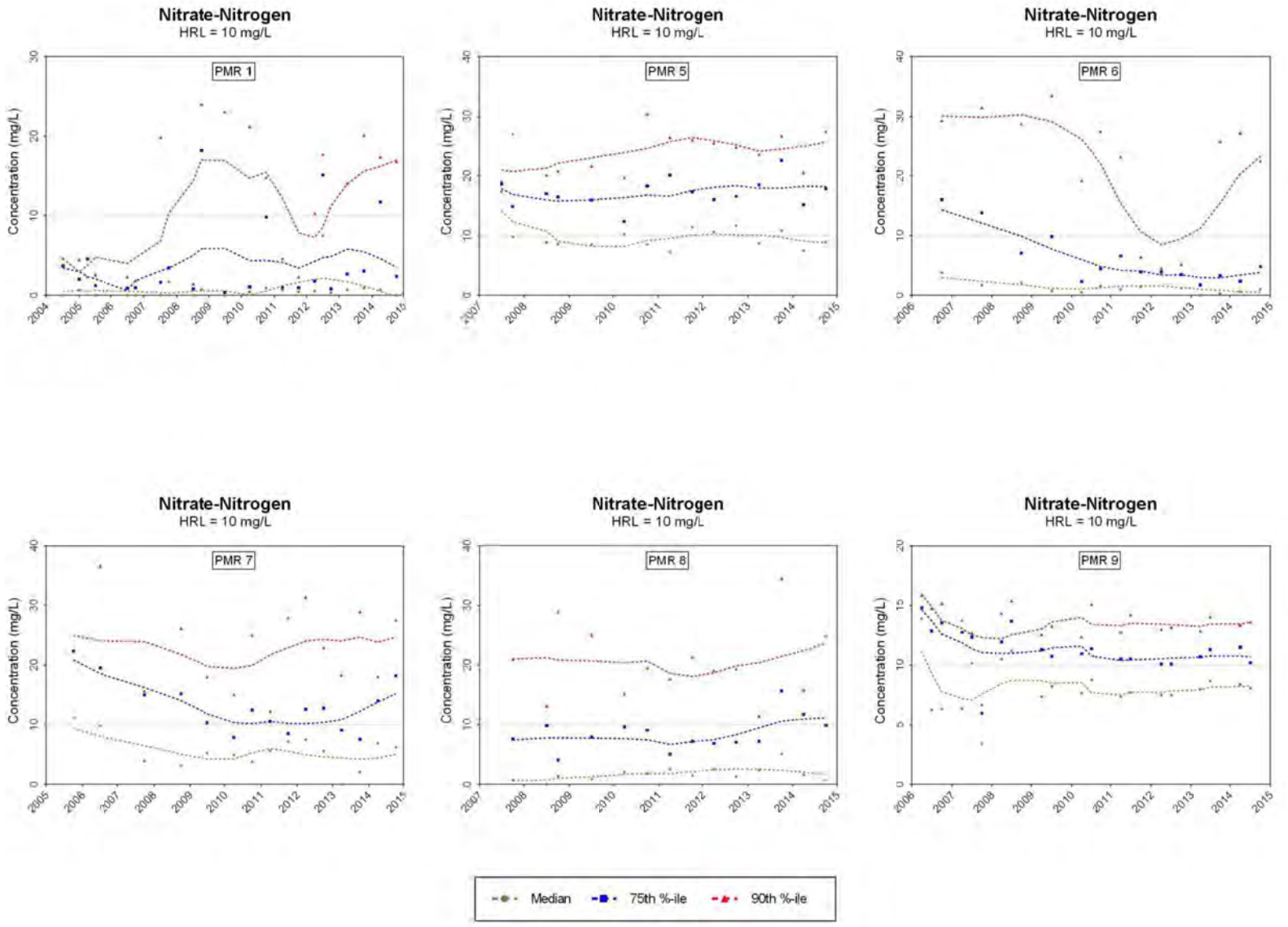

Figure 41. Nitrate-nitrogen analysis results over time for MDA PMRs 1, 5, 6, 7, 8, and 9 groundwater samples.



MINNESOTA DEPARTMENT
OF AGRICULTURE
PESTICIDE AND FERTILIZER MANAGEMENT

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2.8 STATEWIDE GROUNDWATER NITRATE

Nitrate-nitrogen (nitrate) is one of the most common chemicals found in Minnesota's groundwater. High levels of nitrate can pose health risks to infants. As part of the MDA's monitoring work, samples for nitrates are routinely collected at all of the MDA's monitoring wells. The HRL for nitrate is 10 mg/L.

In 2015, 211 nitrate samples were collected from shallow groundwater monitoring wells that are not used as drinking water sources (Table 2-19).

- 189 samples, or 89 percent of all samples analyzed statewide from the MDA monitoring network, had detectable levels of nitrate.
- The highest concentration (74.2 mg/L) was recorded in PMR 4, as well as the highest median concentration (16.4 mg/L).
- Every PMR had at least 63 percent of samples with detectable levels of nitrate. Three PMRs (4, 5, and 9) had 100 percent of samples with detectable levels of nitrate.

Table 2-19. Summary of nitrate-nitrogen results in groundwater samples for 2015.

PMR	Detections/Total Samples	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	10/14	71	1.05	4.49	18.9	28.6
4	86/86	100	16.4	31.7	39.4	74.2
5	16/16	100	8.26	17.5	22.4	25.7
6	10/16	63	1.28	2.89	18.4	35.9
7	10/14	71	8.79	13.2	26.9	44.9
8	19/28	68	2.95	10.1	30.2	60.5
9	38/38	100	7.53	10.0	13.1	17.1
All Samples	189/212	89	8.58	20.0	35.2	74.2

There is a general classification of nitrate levels which is used as guidance in Minnesota for evaluating human impact on nitrate concentrations in groundwater. These categories were developed by an Minnesota Department of Health (MDH) convened work group in 1998 and are used for evaluating the potential for impacts to human health based on the nitrate concentrations. The four categories are:

- No measurable levels (less than MRL),
- Background (greater than MRL, but less than 3.00 mg/L),
- Impacted (3.01 mg/L or greater, but less than 10.00 mg/L),

- Exceeding the health risk limit (greater than 10.00 mg/L).

Table 2-20 presents a summary of the nitrate results compared to the HRL.

- It is common throughout Minnesota agricultural areas to have shallow groundwater exceed the HRL for nitrate.
- PMR 4 had the highest detection frequency at concentrations exceeding the HRL (72 percent).

Table 2-20. Summary of nitrate-nitrogen results in groundwater samples for 2015 compared against MDH health risk limits.

PMR	< MRL (%)	MRL to 3.00 mg/L (%)	3.01 to 10.00 mg/L (%)	> 10.00 mg/L (%)
1	29	43	14	14
4	0	15	13	72
5	0	6	50	44
6	38	44	6	13
7	29	7	21	43
8	32	18	25	25
9	0	0	76	24
Statewide	11	16	28	45

A summary of the nitrate results from the eight shallow and eight deep paired wells in PMR 4 sampled during 2015 can be found in Table 2-21.

- The shallow wells had higher nitrate concentrations than the deeper wells, with median concentrations of 29.4 mg/L versus 17.2 mg/L.
- All of the samples from the shallow wells had detectable levels of nitrate, while 94 percent of the deep well samples had nitrate detections.
- The highest nitrate concentration (74.2 mg/L) was from a shallow well.
- All of the shallow well samples exceeded the HRL of 10.0 mg/L in 2015.

Table 2-21. Summary of nitrate-nitrogen results in paired shallow and deep wells in PMR 4.

Depth Type	Detections	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)	Percent Exceeding 10.00 mg/L Standard
Shallow	16	100	29.4	41.6	54.4	74.2	100
Deep	15	94	17.2	23.3	32.6	38.4	75

Time-trend graphics have been prepared using data available since 2000, which provide a historical perspective on nitrate concentrations from MDA's monitoring wells (Figures 2-44 and 2-45).

- PMRs 4 and 5 consistently had the highest median nitrate concentrations, around 10.00 mg/L.
- The majority of PMRs generally appear to have increasing or stable median nitrate concentrations.
- Due to small annual sample numbers and widely varying observed nitrate concentrations, the upper percentiles (75th and 90th) in PMRs 1, 6, 7, and 8 exhibit wide fluctuations in concentration.

2016 Water Quality Monitoring Report

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2.7 STATEWIDE GROUNDWATER NITRATE SAMPLING

Nitrate is one of the most common chemicals found in Minnesota's groundwater. High levels of nitrate can pose health risks to humans, particularly to infants. The MDA routinely collects nitrate samples, at all of the MDA's groundwater monitoring sites, whenever pesticide samples are collected. In the urban areas, the MPCA collects nitrate samples as part of their routine sampling.

2.7.1 2016 MDA NITRATE DATA

In 2016, 213 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells around the state (Table 2-18). The principal findings for nitrate from the 2016 data include:

- Nitrate was detected in 89 percent of samples statewide.
    - Detection frequencies ranged from 53 percent in PMR 6 to 100 percent in PMRs 4, 5, and 9.
- The highest concentration (91.6 mg/L) came from a well in PMR 8.
- The highest median concentration (18.4 mg/L) was in PMR 4.

Table 2-18. Summary of nitrate results in groundwater samples for 2016.

PMR	Detections/Total Samples	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	10/14	71	1.36	10.2	18.9	24.2
4	88/88	100	18.4	26.8	33.9	55.2
5	16/16	100	8.01	15.4	23.4	30.2
6	8/15	53	2.04	4.88	20.0	29.2
7	9/14	64	10.5	22.4	25.9	28.8
8	20/28	71	1.74	11.6	19.6	91.6
9	38/38	100	7.03	9.93	13.7	21.3
All Samples	189/213	89	9.21	20.2	28.2	91.6

2.7.2 EVAULATION OF MDA NITRATE DATA

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). These were modified slightly by the MDA, due to the nitrate MRL from the MDA Laboratory, and the four general classes are:

- Less than 0.4 mg/L – assumed to represent natural background concentration (ambient conditions without human impact).
- 0.4 to less than 3.0 mg/L – transitional concentrations that may or may not represent human influence.
- 3.0 to less than 10 mg/L – may indicate elevated concentrations resulting from human activities.
- 10 mg/L and higher – exceeds drinking water standards for public and private drinking water supplies.

The 2016 MDA nitrate data is presented at the PMR-level based on the general nitrate classification system (Table 2-19). The principal findings from the nitrate data were:

- Statewide, 28 percent of the nitrate samples were classified as elevated, and an additional 47 percent exceeded the health risk limit.
- In PMR 4, 72 percent of the samples exceeded the health risk limit.

Table 2-19. Summary of nitrate results in groundwater samples for 2016 compared against the general nitrate classification system.

PMR	< 0.4 mg/L (%)	> 0.4 - < 3.0 mg/L (%)	> = 3.0 - < 10 mg/L (%)	> = 10 mg/L (%)
1	29	29	13	29
4	0	14	14	72
5	0	13	50	37
6	47	20	20	13
7	36	7	7	50
8	29	25	17	29
9	0	0	74	26
Total	11	14	28	47

2.7.3 REVIEW OF NITRATE DATA FROM THE WELL NESTS IN PMR 4.

A summary of the nitrate results from the eight well nests in PMR 4 sampled during 2016 can be found in Table 2-20. The principal findings for the results from the well nests include:

- The shallow wells had higher nitrate concentrations than the deep wells, with median concentrations of 27.2 mg/L versus 22.3 mg/L.

- All of the samples from the shallow wells had detectable levels of nitrate, while 94 percent of the deep well samples had nitrate detections.
- The highest nitrate concentration (45.9 mg/L) was from a shallow well.
- All of the shallow well samples exceeded the HRL of 10 mg/L.
- These results are similar to historical data from these wells.

Table 2-20. Summary of nitrate results from well nests in PMR 4.

Depth Type	Detections	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)	Percent Exceeding 10 mg/L Standard
Shallow	16	100	27.2	30.6	39.7	45.9	100
Deep	15	94	22.3	26.4	32.9	35.9	75

2.7.4 MDA LONG-TERM NITRATE DATA REVIEW

Time-series graphics by PMR have been prepared using data available since 2000. These graphics provide a historical perspective on nitrate concentrations from the MDA's monitoring networks (Figures 2-43 and 2-44). The principal findings for the MDA long-term nitrate data include:

- PMRs 4 and 5 consistently had the highest median nitrate concentrations, around 10 mg/L.
- The majority of PMRs generally appear to have increasing or stable median nitrate concentrations.

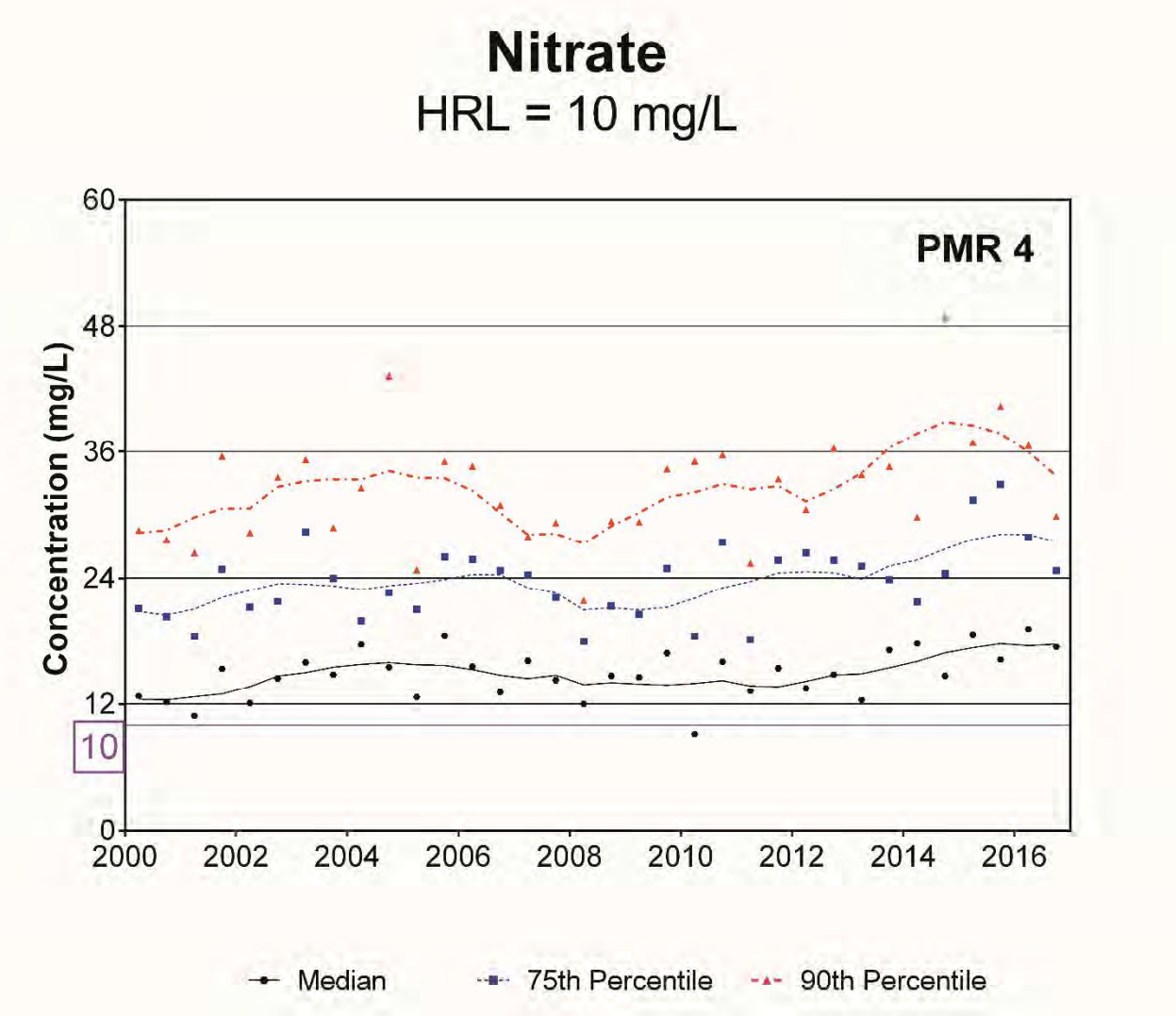

Figure 2-43. Nitrate analysis results from 2000 - 2016 for MDA PMR 4.

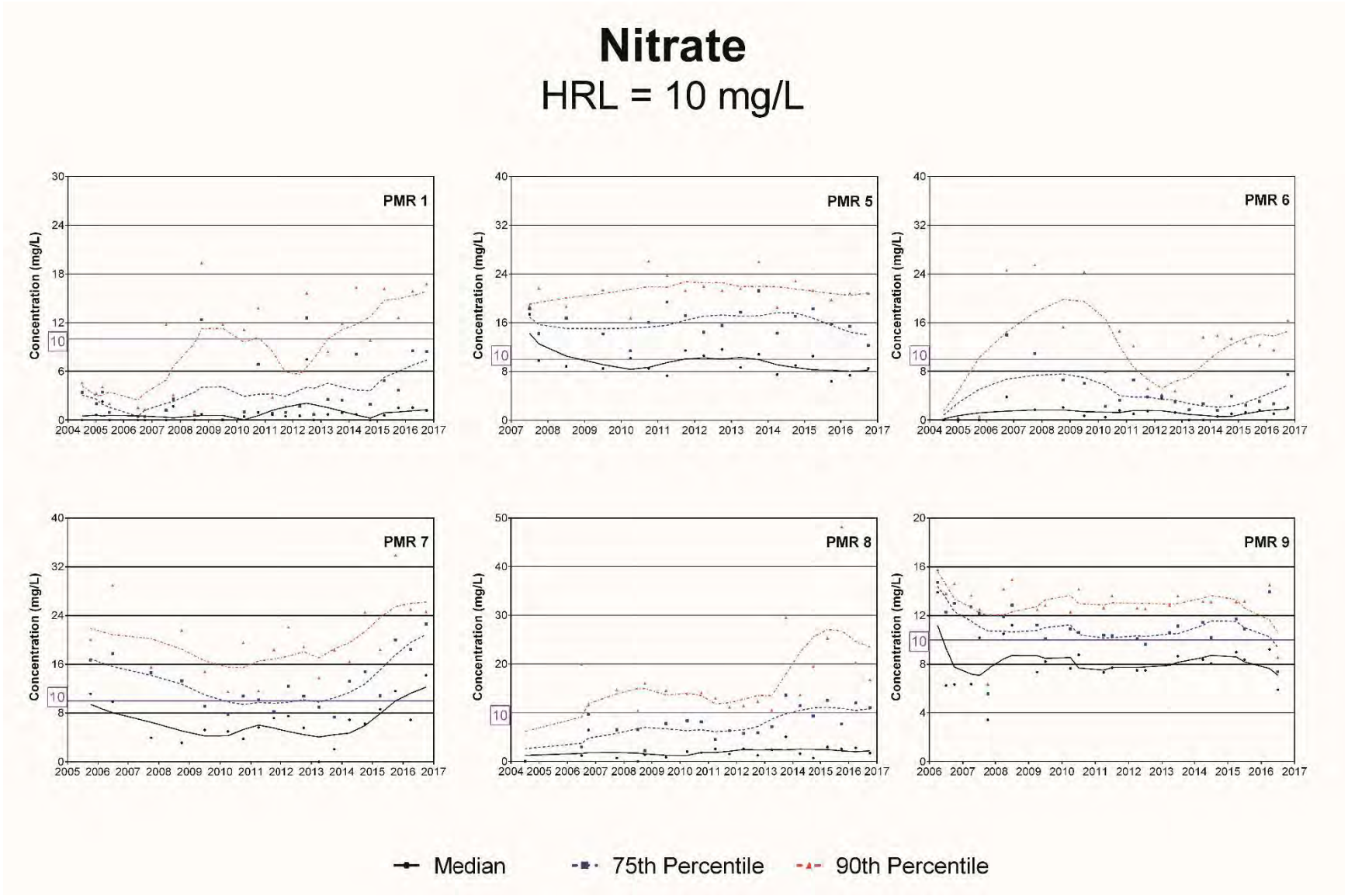

Figure 2-44. Nitrate analysis results over time for MDA PMRs 1 and 5 through 9.

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Section 5: Nutrient and Sediment Results

In conjunction with pesticide monitoring, the MDA collected nutrient and sediment samples at numerous sites to provide additional water quality information about the groundwater and surface water of Minnesota. The following section provides a summary of the nutrient and sediment results collected in 2017 from groundwater and streams by the MDA.

5.1 Statewide groundwater nitrate sampling

Nitrate is one of the most common chemicals found in Minnesota's groundwater. High concentrations of nitrate can pose health risks to humans, particularly to infants under six months old. The MDA collected nitrate samples at all of the MDA's groundwater monitoring sites whenever pesticide samples were collected. In the urban areas, the MPCA collected a nitrate sample along with the pesticide samples they collected for the MDA. The nitrate data collected by the MPCA is not included in this report.

5.1.1 2017 MDA nitrate data

In 2017, 213 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells around the state (Table 5-0). The principal findings for nitrate include:

- Nitrate was detected in 90% of samples statewide.
    - Detection frequencies ranged from 67% in PMR 6 to 100% in PMRs 5 and 9.
- The highest concentration (71.5 mg/L) occurred in a well in PMR 4.
- The highest median concentration (19.6 mg/L) measured in PMR 4.

Table 5-0. Summary of nitrate results in groundwater samples for 2017.

PMR	Detections/Total Samples	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	11/15	73	2.84	4.38	10.2	16.7
4	86/87	99	19.6	28.1	34.4	71.5
5	16/16	100	11.4	18.0	26.0	31.1
6	10/15	67	2.82	8.76	24.5	41.5
7	10/14	71	13.2	23.6	32.6	50.6
8	21/28	75	1.03	11.5	29.8	43.8
9	38/38	100	8.47	11.5	14.9	16.5
All Samples	192/213	90	9.99	21.0	31.8	71.5

5.1.2 Review of nitrate data from the well nests in PMR 4

A summary of the nitrate results from the eight well nests in PMR 4 sampled in 2017 can be found in Table 5-1. Time-trend graphics for the concentration and detection frequency of nitrate results from the shallow and deep wells are shown in Figure 5-0.

The principal findings for the results from the well nests include:

2017

- The shallow wells had higher nitrate concentrations than the deep wells, with a median concentration of 25.3 mg/L versus 22.3 mg/L.
- All of the samples from the shallow wells had detectable levels of nitrate, while 94% of the samples from the deep wells had nitrate detections.
- The highest nitrate concentration (58.3 mg/L) was measured in a shallow well.
- All of the shallow well samples exceeded the Health Risk Limit (HRL) of 10 mg/L.

2010-2017

- The annual detection frequency in the shallow wells has been 100% every year since monitoring began in the fall of 2010, while the detection frequency in the deep wells has been between 85-98%.
- Median nitrate concentrations from the shallow and deep wells have been above the HRL since sampling began.

Table 5-1. Summary of nitrate results from well nests in PMR 4 in 2017.

Depth Type	Detections	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)	Percent Exceeding 10 mg/L HRL
Shallow	16	100	25.3	32.0	43.3	58.3	100
Deep	15	94	22.3	26.7	37.3	48.4	75

Figure 5-0. Nitrate concentration and detection frequency over time in the shallow and deep wells in MDA PMR 4.

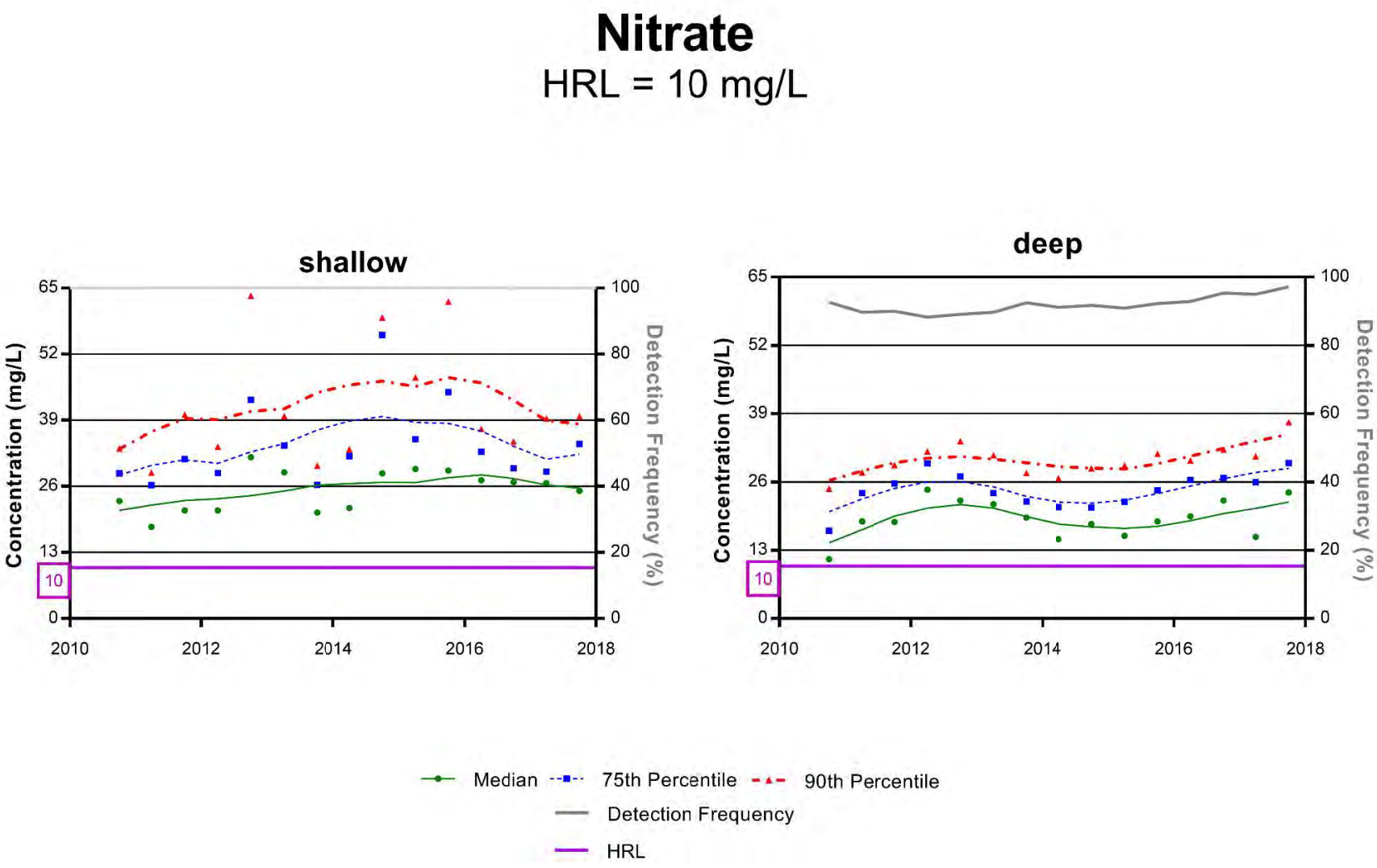

5.1.3 Evaluation of MDA nitrate data

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). The classification system was modified slightly by the MDA, due to the MDA laboratories analytical method. The four general classes are:

- Less than 0.4 mg/L – assumed to represent natural background concentration (ambient conditions without human impact).
- 0.4 to less than 3.0 mg/L – transitional concentrations that may or may not represent human influence.
- 3.0 to less than 10 mg/L – may indicate elevated concentrations resulting from human activities.
- 10 mg/L and higher – exceeds drinking water standards for public and private drinking water supplies.

The 2017 MDA nitrate data are presented at the PMR-level based on the modified MDA general nitrate classification system (Table 5-2). The nitrate data was censored to the highest historical MRL (0.4 mg/L), due to the MDA Laboratory lowering their MRL to 0.2 mg/L in 2017.

The principal findings from the nitrate data were:

- Statewide, 27% of the nitrate samples were classified as elevated, while 49% exceeded the HRL.
- In PMR 4, 68% of the samples exceeded the HRL.
- PMR 7 had the highest percentage of samples (71%) of samples that exceeded the HRL.
- All samples in PMR 9 had concentrations that were classified as elevated or exceeded the HRL.

Table 5-2. Summary of nitrate results in groundwater samples for 2017 compared against the general nitrate classification system.

PMR	<0.4 mg/L (%)	> 0.4 - <3.0 mg/L (%)	> = 3.0 - <10 mg/L (%)	> = 10 mg/L (%)
1	40	13	34	13
4	1	16	15	68
5	0	6	44	50
6	33	20	20	27
7	29	0	0	71
8	36	21	11	32
9	0	0	66	34
Statewide	12	12	27	49

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www.mda.state.mn.us

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Section 5: Nutrient and Total Suspended Solids Results

In conjunction with pesticide monitoring, the MDA collected nutrient and total suspended solids samples at numerous sites to provide additional water quality information about the groundwater and surface water of Minnesota. The following section provides a summary of the nutrient and total suspended solids results collected in 2018 from groundwater and streams by the MDA.

5.1 Statewide groundwater nitrate sampling

Nitrate is one of the most common chemicals found in Minnesota's groundwater. High concentrations of nitrate can pose health risks to humans, particularly to infants under six months old. The MDA collected nitrate samples at all of the MDA's groundwater monitoring sites whenever pesticide samples were collected. In the urban areas, the MPCA collected a nitrate sample along with the pesticide samples they collected for the MDA. The nitrate data collected by the MPCA is not included in this report.

5.1.1 2018 MDA nitrate data

In 2018, 232 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells around the state (Table 5-0). The principal findings for nitrate include:

- Nitrate was detected in 88% of samples statewide.
    - Detection frequencies ranged from 63% in PMRs 1 and 6, to 100% in PMRs 4, 5, and 9.
- The highest concentration (52.2 mg/L) occurred in a PMR 4 monitoring well.
- The highest median concentration (15.0 mg/L) was in PMR 4.

Table 5-0. Summary of nitrate results in groundwater samples for 2018.

PMR	Detections/Total Samples	Detection Frequency (%)	Median (mg/L)	75th Percentile (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	10/16	63	2.16	6.28	10.4	14.3
4	88/88	100	15.0	23.8	33.3	52.2
5	16/16	100	6.80	17.2	28.7	29.7
6	10/16	63	1.03	7.31	21.6	33.6
7	9/14	64	2.78	6.88	17.3	45.3
8	20/28	71	1.02	5.74	9.06	24.7
9	38/38	100	8.77	10.9	13.9	16.7
All Samples	191/216	88	7.55	16.0	26.9	52.2

5.1.2 Evaluation of MDA nitrate data

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). The classification system was modified slightly by the MDA, due to the MDA laboratories analytical method. The four general classes are:

- Less than 0.4 mg/L – assumed to represent natural background concentration (ambient conditions without human impact).
- 0.4 to less than 3.0 mg/L – transitional concentrations that may or may not represent human influence.
- 3.0 to less than 10 mg/L – may indicate elevated concentrations resulting from human activities.
- 10 mg/L and higher – exceeds drinking water standards for public and private drinking water supplies.

The 2018 MDA nitrate data are presented at the PMR-level based on the modified MDA general nitrate classification system (Table 5-1). The nitrate data were censored to the highest historical MRL (0.4 mg/L), due to the MDA Laboratory lowering their MRL to 0.2 mg/L in 2017.

The principal findings from the nitrate data were:

- Statewide, 30% of the nitrate samples were classified as elevated, while 41% exceeded the HRL.
- PMR 4 had the highest percentage of samples (66%) that exceeded the HRL.

Table 5-1. Summary of nitrate results in groundwater samples for 2018 compared against the general nitrate classification system.

PMR	<0.4 mg/L (%)	> =0.4 - <3.0 mg/L (%)	> = 3.0 - <10 mg/L (%)	> = 10 mg/L (%)
1	38	19	31	13
4	2	14	18	66
5	0	25	31	44
6	38	19	25	19
7	36	14	29	21
8	39	29	25	7
9	0	3	63	34
Statewide	14	15	30	41

5.1.3 MDA long-term nitrate data review

Time-series graphics by PMR have been prepared using data available since 2000. These graphics provide a historical perspective on nitrate concentrations and the detection frequency from the MDA's monitoring networks (Figure 5-0). The nitrate data were censored to the highest historical MRL (0.4 mg/L), due to the MDA Laboratory lowering their MRL to 0.2 mg/L in 2017.

The principal findings for the MDA long-term nitrate data include:

- PMRs 4 and 5 have consistently had the highest median nitrate concentrations.
- In 2018, the median concentration best fit line was at or above 10 mg/L in PMRs 4 and 5.
- The detection frequency best fit line has always been greater than 80% in PMRs 4 and 5 and 100% in PMR 9.

Figure 5-0. Long-term nitrate concentration results and detection frequencies for all monitored PMRs.

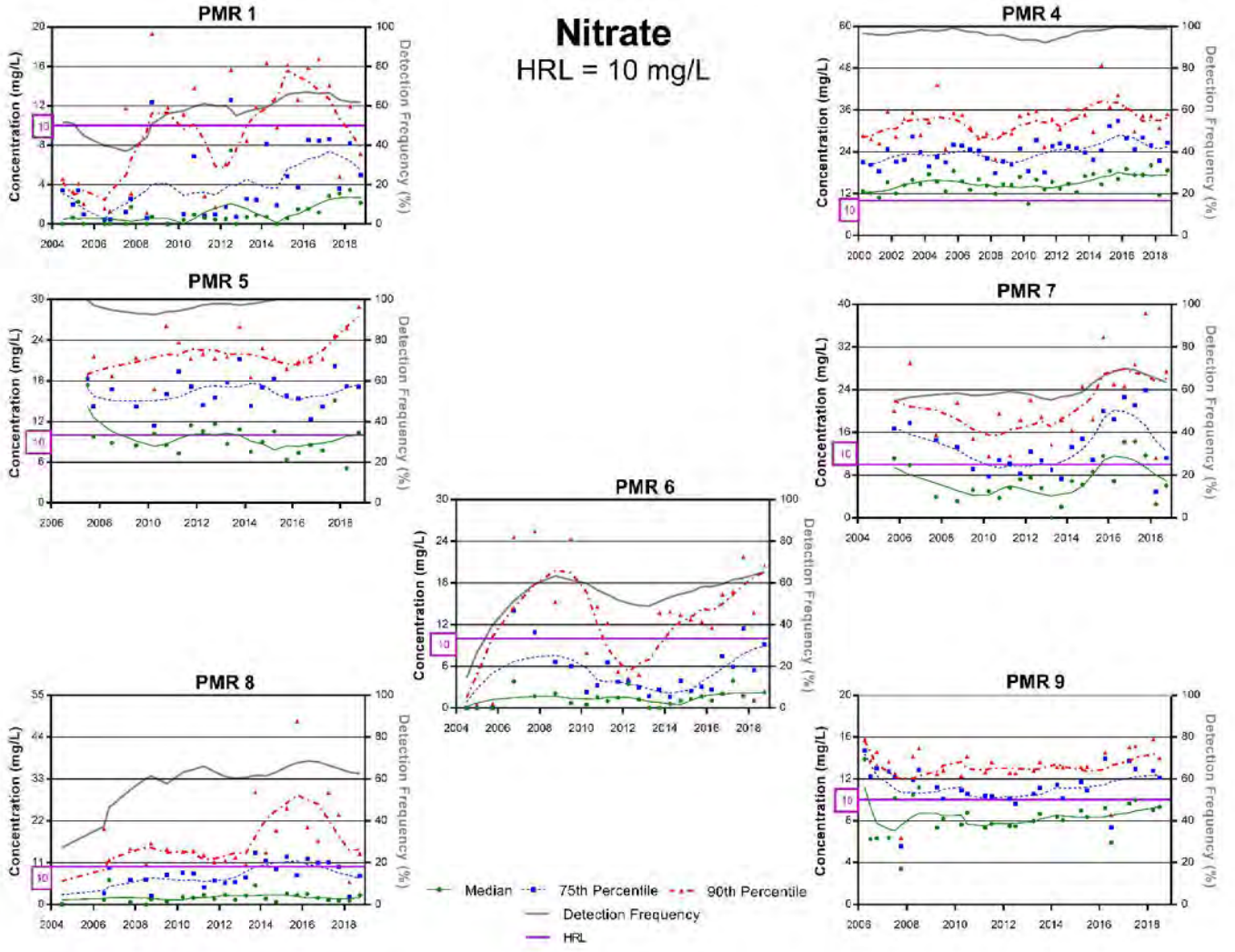

2019 Water Quality Monitoring Report

January – December 2019

Minnesota Department of Agriculture
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Section 6: Nutrient and Total Suspended Solids Results

In conjunction with pesticide monitoring, the MDA collected nutrient and total suspended solids samples at most locations to provide additional water quality information about the groundwater and surface water of Minnesota. The following section provides a summary of the nutrient and total suspended solids results collected in 2019 from groundwater and surface water by the MDA.

6.1 Statewide groundwater nitrate sampling

Nitrate is one of the most frequently detected chemical compounds in Minnesota's groundwater. High concentrations of nitrate pose health risks to humans, particularly to infants under six months old, and pregnant women. The MDA collected nitrate samples at all of the MDA's groundwater monitoring sites whenever pesticide samples were collected. In urban areas, the MPCA collected and analyzed nitrate samples with pesticide samples they collected for the MDA.

6.1.1 2019 MDA nitrate data

In 2019, 201 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells around the state (Table 6-0). Only the domestic wells (five percent of sites in the network) are directly used as a source of drinking water. The principal findings for nitrate include:

- Nitrate was detected in 89% of samples collected statewide.
    - Detection frequencies ranged from 57% in PMR 1 to 100% in PMRs 5 and 9.
- The highest concentration (39.8 mg/L) occurred in a PMR 4 monitoring well.
- The highest median concentration (13.8 mg/L) was in PMR 4.

Table 6-0. Summary of nitrate results in groundwater samples for 2019.

PMR	Samples Analyzed	Number of Detections	Detection Frequency (%)	Median (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	14	8	57	0.64	8.14	22.1
4	78	76	97	13.8	26.9	39.8
5	16	16	100	8.76	30.3	39.7
6	16	10	63	0.93	19.0	32.0
7	14	9	64	2.83	12.9	13.7
8	26	22	85	1.73	13.7	24.7
9	37	37	100	8.31	13.1	14.9
All Samples	201	178	89	7.08	22.5	39.8

6.1.2 Evaluation of MDA nitrate data

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). The classification system was modified slightly by the MDA, due to the MDA Laboratory's analytical MRL. The four general classes are:

- Less than 0.4 mg/L – assumed to represent natural background concentration (ambient conditions without human impact).
- 0.4 to less than 3.0 mg/L – transitional concentrations that may or may not represent human influence.
- 3.0 to less than 10 mg/L – may indicate elevated concentrations resulting from human activities.
- 10 mg/L and higher – exceeds drinking water standards (*i.e.* HRL) for public and private drinking water supplies.

The 2019 MDA nitrate data are presented at the PMR-level in Table 6-1, based on the modified MDA general nitrate classification system. The nitrate data were censored to the highest historical MRL (0.4 mg/L), due to the MDA Laboratory lowering their MRL to 0.2 mg/L in 2017.

The principal findings from the nitrate data were:

- Statewide, 32% of the nitrate samples were classified as elevated, while 37% exceeded the HRL.
- PMR 4 had the highest percentage of samples (58%) that exceeded the HRL.

Table 6-1. 2019 Detection frequency in groundwater samples compared against the general nitrate classification system.

PMR	<0.4 mg/L (%)	> =0.4 - <3.0 mg/L (%)	> = 3.0 - <10 mg/L (%)	> = 10 mg/L (%)
1	43	21	29	7
4	3	17	23	58
5	6	25	31	38
6	44	19	25	13
7	36	14	21	29
8	23	35	19	23
9	0	3	70	27
All Samples	13	17	32	37

6.1.3 MDA long-term nitrate data review

Time-series graphics by PMR have been prepared using long-term data available from the groundwater monitoring network, with the earliest data results back to 2000 (from PMR 4). These graphics provide a historical perspective on nitrate concentrations and the detection frequency from the MDA's monitoring networks (Figure 6-0). The nitrate data were censored to the highest historical MRL (0.4 mg/L), due to the MDA Laboratory lowering their MRL to 0.2 mg/L in 2017.

The principal findings for the MDA's long-term nitrate data include:

- PMR 4 has consistently had the highest median nitrate concentrations.
- The median concentration best fit line has consistently been at or above 10 mg/L in PMR 4.
- The detection frequency best fit line has always been greater than 80% in PMRs 4 and 5 and 100% in PMR 9.

Figure 6-0. Long-term nitrate concentration results and detection frequencies for all monitored PMRs.

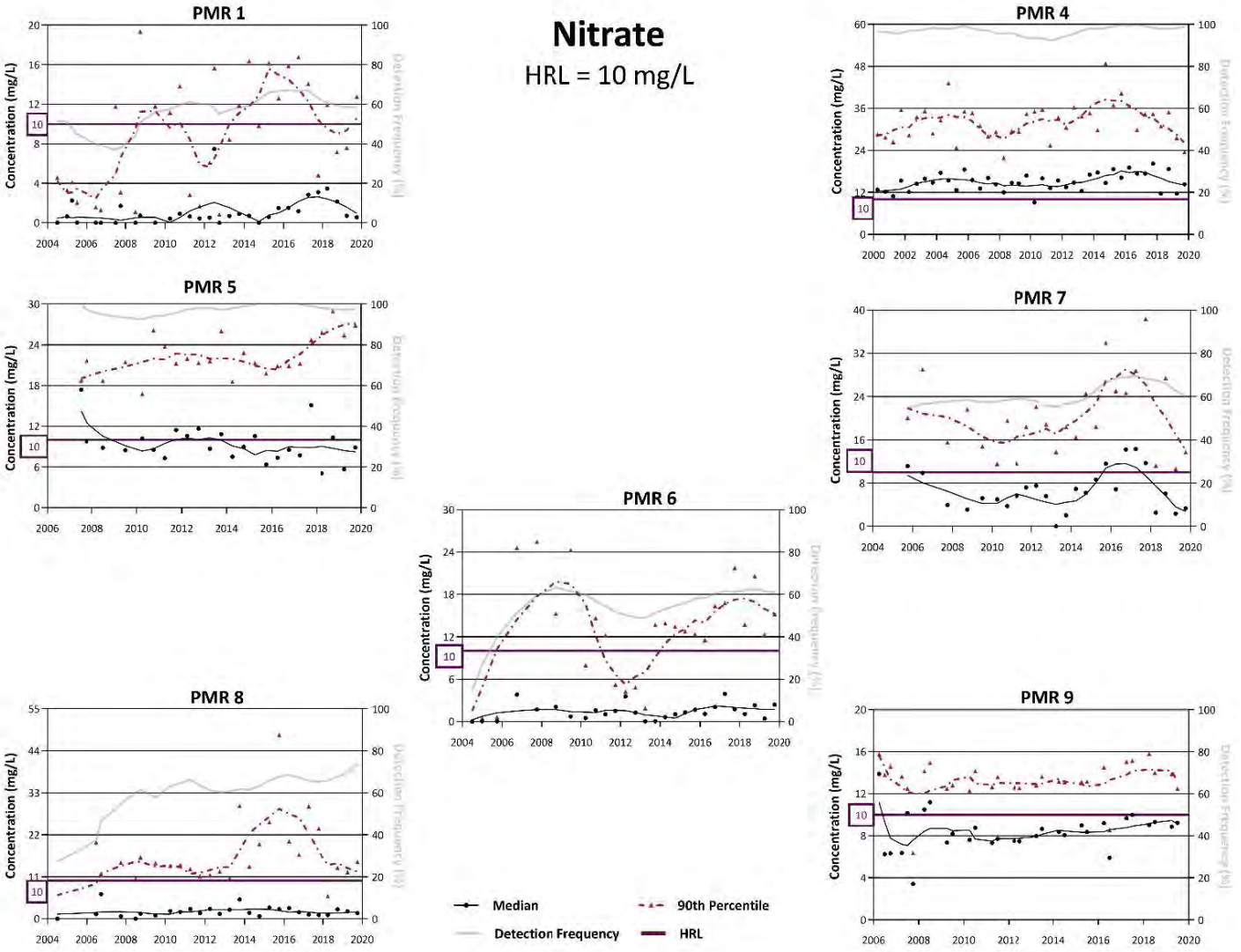

6.1.4 Review of nitrate data from the shallow and deep well nests in PMR 4

A summary of the 2019 nitrate results, from the eight well nests in PMR 4, is presented in Table 6-2. Time-trend graphics for nitrate concentration and detection frequency from the shallow and deep well wells are shown in Figure 6-1 (See Section 2.6 for further information about the shallow and deep well nests).

The principal findings for the results from the shallow and deep well nests include:

2019

- The deep wells had higher nitrate concentrations than the shallow wells, with median concentrations being 28.3 mg/L and 19.0 mg/L, respectively.
- All wells had detectable nitrate concentrations.
- The highest nitrate concentration (39.6 mg/L) was measured in a deep well, compared to the maximum concentration of 27.8 mg/L from a shallow well.
- Eighty-eight percent of the shallow and deep well samples exceeded the HRL of 10 mg/L.

2010-2019

- The annual detection frequency in the shallow wells has been 100% every year since monitoring began in the fall of 2010, while the detection frequency in the deep wells has ranged between 80-100%.
- Median nitrate concentrations from the shallow and deep wells have been above the HRL since sampling began.

Table 6-2. Summary of nitrate results from shallow and deep well nests in PMR 4 in 2019.

Depth Type	Samples Analyzed	Number of Detections	Detection Frequency (%)	Median (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)	Percent Exceeding 10 mg/L HRL
Shallow	8	8	100	19.0	27.4	27.8	88
Deep	8	8	100	28.3	36.2	39.6	88

DEPARTMENT OF AGRICULTURE

2020 Water Quality Monitoring Report

January through December 2020

June 15, 2021

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Section 6: Nutrient and Total Suspended Solids Results

In conjunction with pesticide monitoring, the MDA collected nutrient and total suspended solids (TSS) samples at most locations to provide additional water quality information about the groundwater and surface water of Minnesota. The following section provides a summary of the nutrient and TSS results collected in 2020 from groundwater and surface water by the MDA.

6.1 Statewide groundwater nitrate sampling

Nitrate is one of the most frequently detected chemical compounds in Minnesota's groundwater. High concentrations of nitrate pose health risks to humans, particularly to infants under six months old and pregnant women. The MDA collected nitrate samples at all of the MDA's groundwater monitoring sites whenever pesticide samples were collected. In urban areas, the MPCA collected and analyzed nitrate samples with pesticide samples they collected for the MDA. The nitrate samples collected by MPCA, which were analyzed by a different laboratory, are not included in this report.

6.1.1 2020 MDA nitrate data

In 2020, 203 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells around the state (Table 6-0). Only the domestic wells (five percent of sites in the network) were directly used as a source of drinking water. The principal findings for nitrate include:

- Nitrate was detected in 87% of samples collected statewide.
    - Detection frequencies ranged from 57% in PMR 1 to 100% in PMRs 5 and 9.
- The highest concentration (38.3 mg/L) occurred in a PMR 4 monitoring well.
- The highest median concentration (10.0 mg/L) was based on the results from PMR 4.

Table 6-0. Summary of nitrate results in groundwater samples collected in 2020.

PMR	Samples	Number of Detections	Detection Frequency (%)	Median (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	14	8	57	1.54	9.05	11.7
4	77	76	99	10.0	25.6	38.3
5	16	16	100	7.51	22.3	31.8
6	15	9	60	1.52	23.3	30.6
7	14	9	64	3.20	17.0	20.0
8	28	19	68	0.56	11.5	23.9
9	39	39	100	7.84	12.0	14.1
All Samples	203	176	87	6.86	18.9	38.3

6.1.2 Evaluation of MDA nitrate data

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). The classification system was modified slightly by the MDA, due to the MDA Laboratory's analytical MRL at that time. The four general classes are:

- Less than 0.40 mg/L – assumed to represent natural background concentration (ambient conditions without human impact).
- 0.40 to less than 3.00 mg/L – transitional concentrations that may or may not represent human influence.
- 3.00 to less than 10.0 mg/L – may indicate elevated concentrations resulting from human activities.
- 10.0 mg/L and higher – exceeds drinking water standards (*i.e*. HRL) for public and private drinking water supplies.

The 2020 MDA nitrate data are presented at the PMR level in Table 6-1, based on the modified MDA general nitrate classification system. The nitrate data were censored to the highest historical MRL (0.40 mg/L), due to the MDA Laboratory lowering their MRL to 0.20 mg/L in 2017.

The principal findings from the nitrate data evaluation were:

- As based on all of the nitrate sample results, 32% were classified as elevated while 35% exceeded the HRL.
- PMR 4 had the highest percentage of samples (51%) that exceeded the HRL.

Table 6-1. 2020 Detection frequency in groundwater samples compared against the general nitrate classification system.

PMR	Detection Frequency (%)			
	< 0.40 mg/L	≥0.40 - <3.00 mg/L	≥3.00 - <10.0 mg/L	≥10.0 mg/L
1	43	21	29	7
4	1	25	23	51
5	6	12	44	38
6	40	20	13	27
7	36	14	14	36
8	43	25	14	18
9	0	2	72	26
All Samples	15	18	32	35

6.1.3 MDA long-term nitrate data review

Time-series graphics by PMR have been prepared using long-term data available from the groundwater monitoring network, with data from PMR 4 going back to 2000. These graphics provide a historical perspective on nitrate concentrations and the detection frequency from the MDA's monitoring networks (Figure 6-0). All nitrate data were censored to the highest historical MRL (0.40 mg/L), due to the MDA Laboratory lowering their MRL to 0.20 mg/L in 2017.

The principal findings for the MDA's long-term nitrate data include:

- PMR 4 has consistently had the highest median nitrate concentrations.
- The median concentration best fit line had consistently been at or above 10 mg/L in PMR 4 until the fall of 2020.
- The detection frequency best fit line has always been greater than 80% in PMRs 4 and 5 and 100% in PMR 9.

Figure 6-0. Long-term nitrate concentration results and detection frequencies for all monitored PMRs.

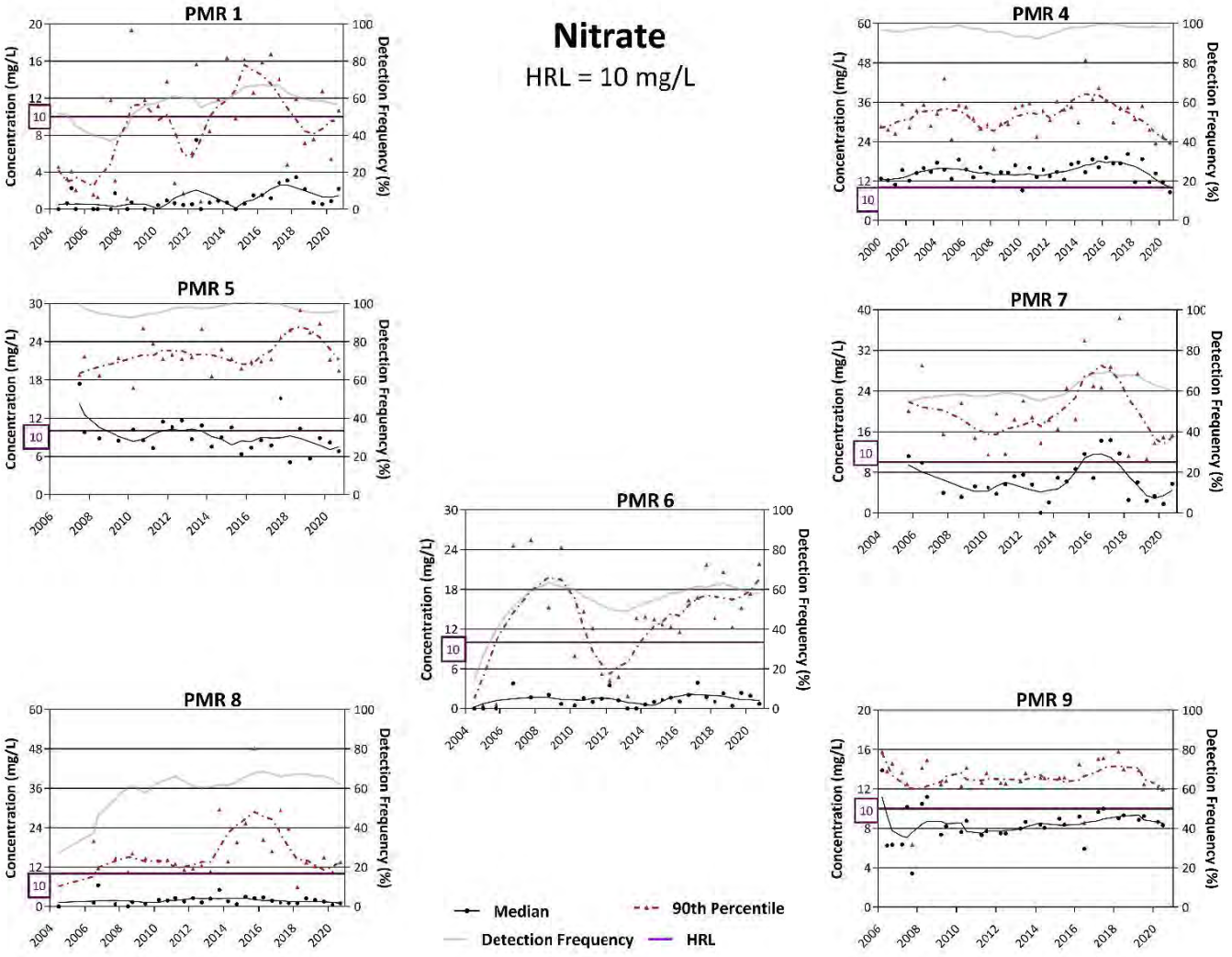

6.1.4 Review of nitrate data from the shallow and deep well nests in PMR 4

A summary of the 2020 nitrate results, from the eight well nests in PMR 4, is presented in Table 6-2. Time-trend graphics for nitrate concentration and detection frequency from the shallow and deep wells are shown in Figure 6-1 (See Section 2.6 for further information about the shallow and deep well nests).

The principal findings for the results from the shallow and deep well nests include:

2020

- The deep wells, as a group, had higher nitrate concentrations than the shallow wells, based upon median concentrations being 18.8 mg/L and 16.1 mg/L, respectively.
- All but one of the wells from the shallow and deep well nests had detectable nitrate concentrations.
- The highest nitrate concentration (35.7 mg/L) was measured in a deep well, compared to the maximum concentration of 26.2 mg/L from a shallow well.
- Seventy-five percent of the nested shallow and deep well samples exceeded the HRL of 10 mg/L.

2010-2020

- The annual detection frequency in the shallow wells has been 100% every year since monitoring began in the fall of 2010, while the detection frequency in the deep wells has ranged between 80-100%.
- Median nitrate concentrations from the shallow and deep wells have been above the HRL since sampling began.

Table 6-2. Summary of nitrate results from shallow and deep well nests in PMR 4 in 2020.

Depth Type	Samples	Number of Detections	Detection Frequency (%)	Median (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)	Percent Exceeding 10 mg/L HRL
Shallow	8	8	100	16.1	23.5	26.2	75
Deep	8	7	88	18.8	30.9	35.7	75

DEPARTMENT OF AGRICULTURE

CLEAN WATER LAND & LEGACY AMENDMENT

2021 Water Quality Monitoring Report

January through December 2021

June 15, 2022

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Section 6: Nutrient and Total Suspended Solids Results

In conjunction with pesticide monitoring, the MDA collected nutrient and total suspended solids (TSS) samples at most locations to provide additional water quality information about the groundwater and surface water of Minnesota. The following section provides a summary of the nutrient and TSS results collected in 2021 from groundwater and surface water by the MDA.

6.1 Statewide groundwater nitrate sampling

Nitrate is one of the most frequently detected chemical compounds in Minnesota's groundwater. High concentrations of nitrate pose health risks to humans, particularly to infants under six months old and pregnant women. The MDA collected nitrate samples at all of the MDA's groundwater monitoring sites whenever pesticide samples were collected. In urban areas, the MPCA collected and analyzed nitrate samples with pesticide samples they collected for the MDA. The nitrate samples collected by MPCA, which were analyzed by a different laboratory, are not included in this report.

6.1.1 2021 MDA nitrate data

In 2021, 202 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells around the state (Table 6-0). Only the domestic wells (eight percent of sites in the network) were directly used as a source of drinking water. The principal findings for nitrate include:

- Nitrate was detected in 84% of samples collected statewide.
    - Detection frequencies ranged from 54% in PMR 8 to 100% in PMR 9.
- The highest concentration (48.0 mg/L) occurred in a PMR 4 monitoring well.
- The highest median concentration (11.8 mg/L) was based on the results from PMR 4.

Table 6-0. Summary of nitrate results in groundwater samples collected in 2021.

PMR	Samples	Detections	Detection Frequency (%)	Median (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	14	8	57	4.84	14.3	29.8
4	74	73	99	11.8	31.1	48.0
5	16	14	88	5.65	22.5	28.6
6	15	9	60	0.61	23.3	31.1
7	14	10	71	5.26	11.0	16.3
8	28	15	54	0.35	9.85	17.1
9	41	41	100	8.85	11.5	13.9
All Samples	202	170	84	6.96	22.0	48.0

6.1.2 Evaluation of MDA nitrate data

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). The classification system was modified slightly by the MDA, due to the MDA Laboratory's analytical MRL at that time. The four general classes are:

- Less than 0.40 mg/L – assumed to represent natural background concentration (ambient conditions without human impact).
- 0.40 to less than 3.00 mg/L – transitional concentrations that may or may not represent human influence.
- 3.00 to less than 10.0 mg/L – may indicate elevated concentrations resulting from human activities.
- 10.0 mg/L and higher – exceeds drinking water standards (*i.e.*, HRL) for public and private drinking water supplies.

The 2021 MDA nitrate data are presented at the PMR level in Table 6-1, based on the modified MDA general nitrate classification system. The nitrate data were censored to the highest historical MRL (0.40 mg/L), due to the MDA Laboratory lowering their MRL to 0.20 mg/L in 2017.

The principal findings from the nitrate data evaluation were:

- As based on all the nitrate sample results, 31% were classified as elevated while 38% exceeded the HRL.
- PMR 4 had the highest percentage of samples (59%) that exceeded the HRL.

Table 6-1. 2021 detection frequency in groundwater samples compared against the general nitrate classification system.

PMR	Detection Frequency (%) < 0.40 mg/L	Detection Frequency (%) ≥0.40 - <3.00 mg/L	Detection Frequency (%) ≥3.00 - <10.0 mg/L	Detection Frequency (%) ≥10.0 mg/L
1	43	0	14	43
4	3	19	19	59
5	12	19	38	31
6	47	20	13	20
7	29	14	43	14
8	53	18	18	11
9	0	2	66	32
All Samples	18	14	31	37

6.1.3 MDA long-term nitrate data review

Time-series graphics by PMR have been prepared using long-term data available from the groundwater monitoring network, with data from PMR 4 going back to 2000. These graphics provide a historical perspective on nitrate concentrations and the detection frequency from the MDA's monitoring networks (Figure 6-0). All nitrate data were censored to the highest historical MRL (0.40 mg/L), due to the MDA Laboratory lowering their MRL to 0.20 mg/L in 2017.

The principal findings for the MDA's long-term nitrate data include:

- PMR 4 has consistently had the highest median nitrate concentrations.
- The median concentration best fit line has consistently been at or above 10 mg/L in PMR 4.
- The detection frequency best fit line has always been greater than 80% in PMRs 4 and 5 and 100% in PMR 9.

Figure 6-0. Long-term nitrate concentration results and detection frequencies for all monitored PMRs.

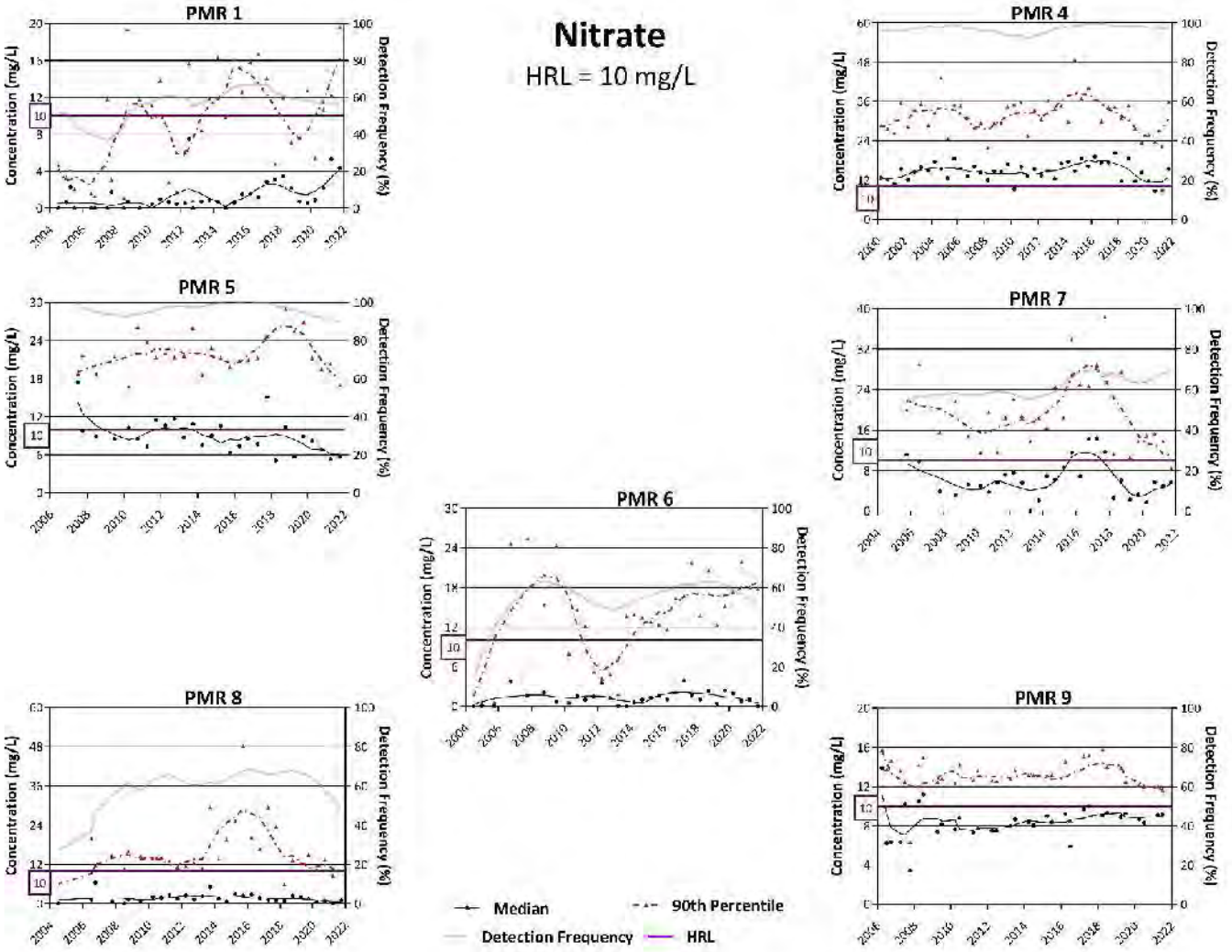

DEPARTMENT OF AGRICULTURE

CLEAN WATER LAND & LEGACY AMENDMENT

2022 Water Quality Monitoring Report

January through December 2022

June 1, 2023

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Section 6: Inorganic Analyte Results

In conjunction with pesticide monitoring, the MDA collected samples for select inorganic analytes at most locations to provide additional water quality information about the groundwater and surface water of Minnesota. The following section provides a summary of the 2022 inorganic analyte results.

6.1 Inorganic analyte monitoring in groundwater

The MDA analyzed groundwater samples for nitrate + nitrate nitrogen (nitrate) and chloride and select groundwater samples for bromide in 2022.

The MDA analyzed for nitrate during every groundwater sample collection event. Nitrate is one of the most frequently detected chemical compounds in Minnesota's groundwater. The Minnesota Department of Health (MDH) has established a nitrate health risk limit (HRL) of 10 mg/L. Concentrations of nitrate over the HRL may pose health risks to humans, particularly to infants under six months old and pregnant women.

The MDA analyzed for chloride during every groundwater sample collection event. Chloride is present naturally to some degree in Minnesota's groundwater. Overbo and Heger (2018) and the MPCA (2019) identified four primary chloride uses that are responsible for elevated chloride levels in the environment including road salt, fertilizer use, livestock excretion and household water softeners. The MDA began monitoring for chloride in shallow groundwater in agricultural regions in 2022 to provide more data on the potential mpacts of fertilizers, including potash, on groundwater resources.

The MDA analyzed for bromide once from each site in the MDA's groundwater network on the first sample collection visit in 2022. The MDA used the bromide result to calculate a chloride/bromide ratio to evaluate if the chloride concentration were natural occurring or caused by anthropogenic sources.

The MPCA collected samples at 19 urban wells for the MDA in 2022. The MDA laboratory analyzed the pesticide samples, and the MPCA analyzed for nitrate, chloride, and bromide at the MDH laboratory. These results are included in the tables to contrast the results from agricultural regions and are footnoted as "The urban samples were collected by the MPCA and analyzed at the MDH laboratory".

6.1.1 2022 MDA groundwater nitrate results

In 2022, 204 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells around the state (Figure 6-0 and Table 6-0) as part of the ambient groundwater monitoring network. Only the domestic wells (eight percent of sites in the network) were directly used as a source of drinking water. The principal findings for nitrate include:

- Nitrate was detected in 85% of samples collected statewide.
    - Detection frequencies ranged from 57% in PMRs 6 and 8 to 100% in PMRs 5 and 9.
- The highest concentration (46.0 mg/L) occurred in a PMR 4 monitoring well.
- The highest median concentration (9.63 mg/L) occurred in PMR 4.
- The lowest median concentration (0.51 mg/L) occurred in the urban network.

Table 6-0. Summary of 2022 nitrate concentrations and detection frequency results in groundwater samples.

PMR	Samples	Detections	Detection Frequency (%)	Median (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	14	9	64	2.59	5.17	10.5
4	77	73	95	9.63	26.7	46.0
5	16	16	100	4.83	14.9	16.9
6	14	8	57	0.77	23.3	30.4
7	14	10	71	3.11	8.96	12.0
8	28	16	57	0.65	11.8	16.3
9	41	41	100	8.59	11.8	23.2
PMR 1-9 Combined	204	173	85	5.47	21.3	46.0
Urban*	19	14	74	0.51	5.28	11.0

*The urban samples were collected by the MPCA and analyzed at the MDH laboratory. The MDH Laboratory has a 0.05 mg/L MRL for nitrate.

Figure 6-0. 2022 groundwater maximum nitrate concentrations.

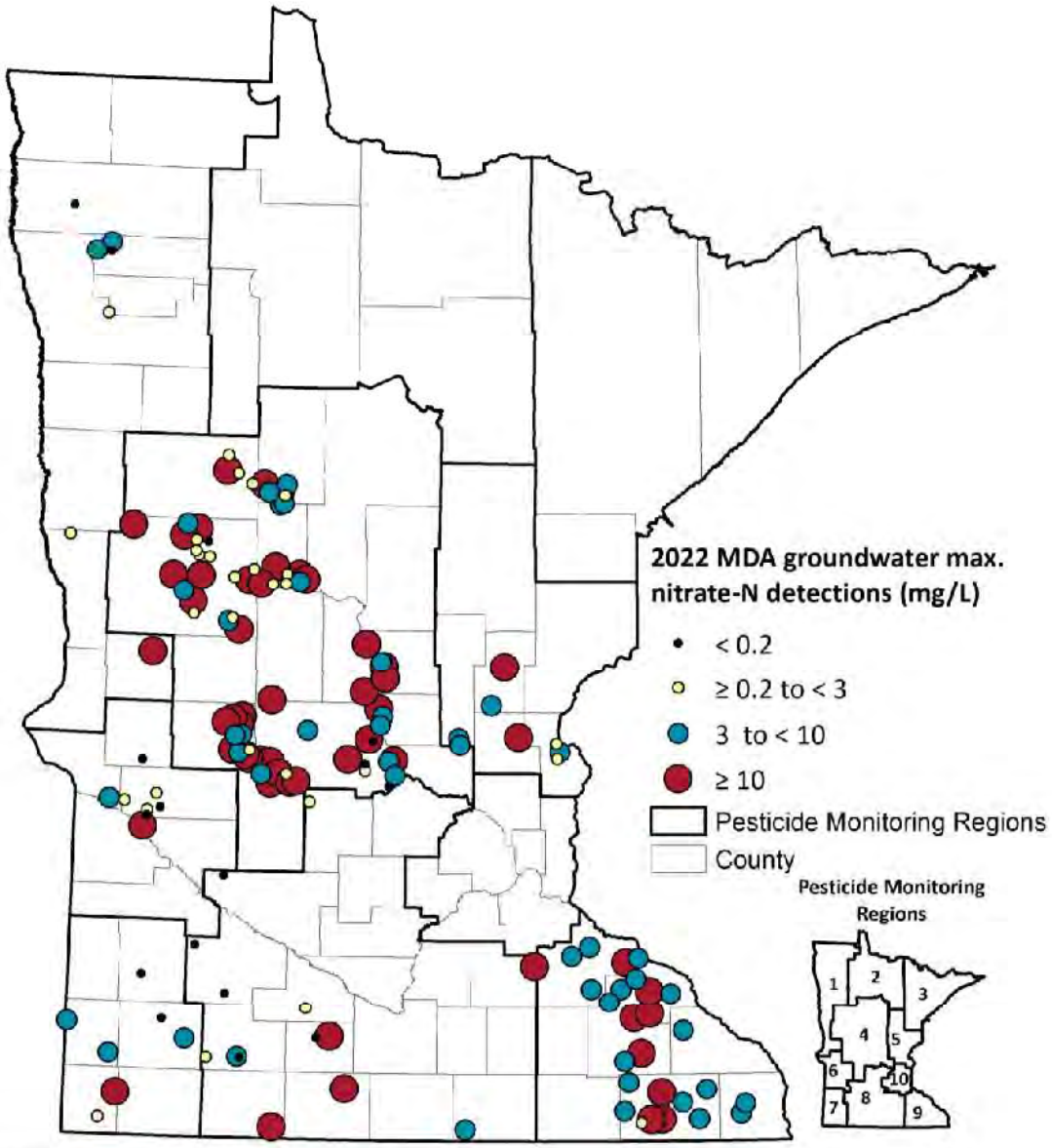

6.1.2 Evaluation of MDA groundwater nitrate data

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). This work group utilized and modified a classification system developed by Madison and Brunett with the lowest classification for nitrate concentration of 0.2 mg/L (Madison and Brunett, 1984). The MDH workgroup modified the classifications to begin with 1 mg/L as the lowest classification to account for different detection limits across laboratories. For this document, the lowest classification uses the 0.2 mg/L which matches the MDA Laboratory's 2022 nitrate MRL. The four general classes are:

- Less than 0.20 mg/L – assumed to represent natural ambient background concentration, without human impacts.
- 0.20 to less than 3.00 mg/L – transitional concentrations that may or may not represent human influence.
- 3.00 to less than 10.0 mg/L – may indicate elevated concentrations resulting from human activities.
- 10.0 mg/L and higher – exceeds drinking water standards (*i.e.*, HRL) for public and private drinking water supplies.

The 2022 MDA nitrate data are presented at the PMR level in Table 6-1, based on the MDH general nitrate classification system. The principal findings from the nitrate data evaluation were:

- Statewide, 34% of the nitrate sample results were classified as elevated, and 31% exceeded the HRL
- PMR 4 had the highest percentage of samples (48%) that exceeded the HRL.
- The urban wells had the lowest percentage of samples (5%) that exceeded the HRL

Table 6-1. 2022 detection frequency in groundwater samples compared against the general nitrate classification system.

PMR	Samples	Percentage of Samples in the Category (%)			
		< 0.20 mg/L	≥0.20 - <3.00 mg/L	≥3.00 - <10.0 mg/L	≥10.0 mg/L
1	14	43	21	29	7
4	77	9	20	23	48
5	16	0	37	38	25
6	14	50	22	14	14
7	14	29	21	43	7
8	28	50	7	25	18
9	41	0	3	63	34
PMR 1-9 Combined (%)	204	19	16	34	31
Urban*	19	42	32	21	5

*The urban samples were collected by the MPCA and analyzed at the MDH laboratory. The MDH Laboratory has a 0.05 mg/L MRL for nitrate.

6.1.3 MDA long-term groundwater nitrate data review

Time-series graphics by PMR have been prepared using long-term data available from the groundwater monitoring network, based on data from 2013 to 2022. These graphics provide a historical perspective on nitrate concentrations and the detection frequency from the MDA's monitoring networks (Figure 6-1). All nitrate

data were censored to the highest historical MRL (0.40 mg/L), The principal findings for the MDA's long-term nitrate data include:

- Compared to other PMRs, PMR 4 consistently had the highest annual median nitrate concentration.
- The detection frequency best fit line was consistently greater than 80% in PMRs 4 and 5, and 100% in PMR 9.

Figure 6-1. Nitrate concentration results and detection frequencies for all monitored PMRs, 2013-2022.

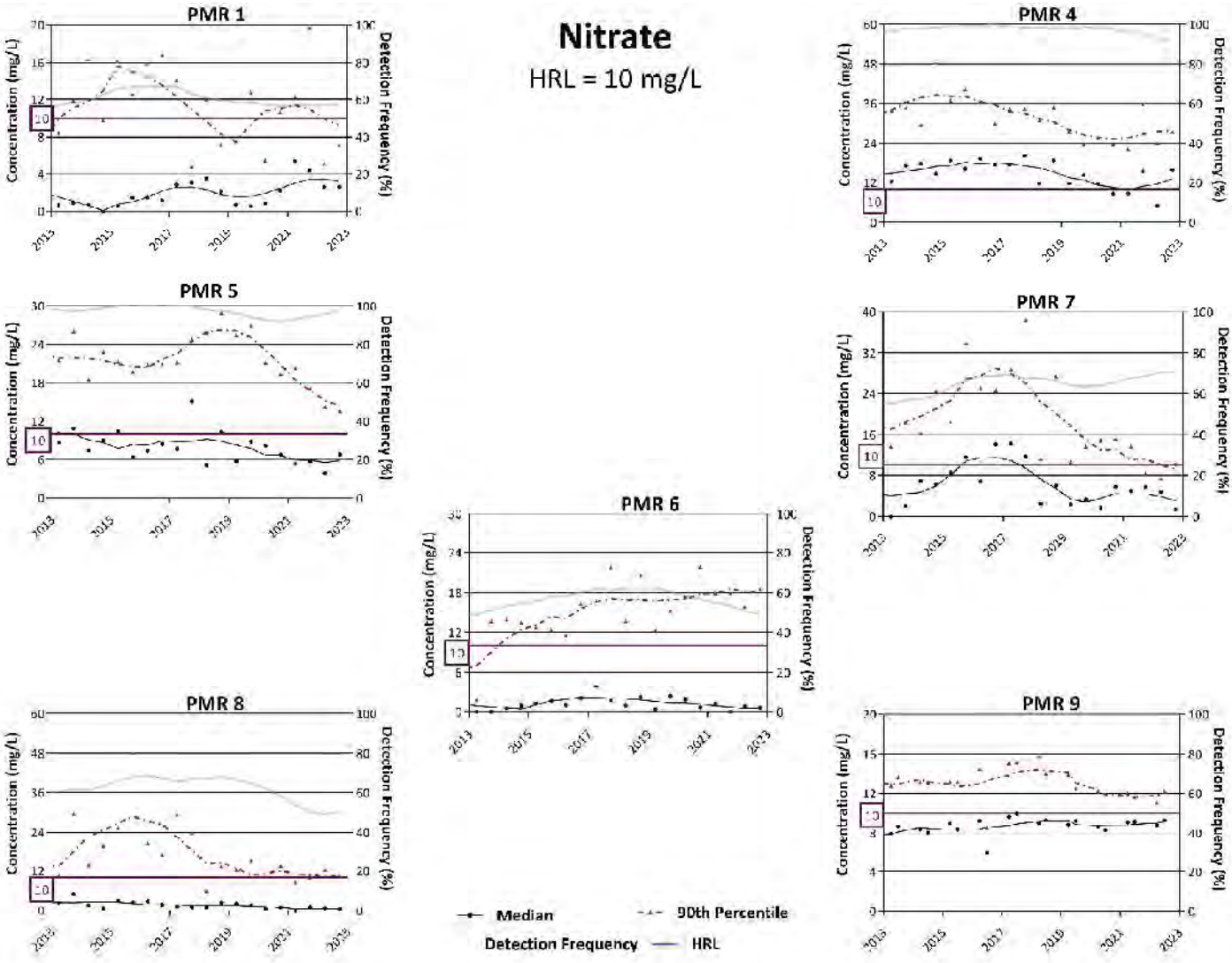

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CLEAN WATER LAND & LEGACY AMENDMENT

2023 Water Quality Monitoring Report

January through December 2023

June 1, 2024

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of the paired results. The summary statistics of the relative percent differences for these pairs were a median of 1.6% and a 90th percentile of 6.9%.

The MDA Laboratory also completed internal QA/QC measures that included sample blanks, spikes, and spike duplicates with each batch of samples analyzed and reviewed the data before the results were authorized. All QA/QC data were excluded from the data analysis of this report and are available by request.

6.1.2 2023 MDA groundwater nitrate results

In 2023, 204 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells (Figure 6-1 and Table 6-1) as part of the ambient groundwater monitoring network. Only the domestic wells (8% of sites in the network) were directly used as a source of drinking water. The principal findings for nitrate include:

- Nitrate was detected in 84% of samples collected in PMRs 1,4, 5, 6, 7, 8, and 9.
    - Detection frequencies ranged from 43% in Pesticide Monitoring Region (PMR 6) to 100% in PMR 9.
- Except for the urban wells, the maximum nitrate concentration in every monitored PMR was ≥10 mg/L.
    - The highest concentration (33.0 mg/L) occurred in a PMR 4 monitoring well.
- The median concentration of samples collected in PMRs 1,4, 5, 6, 7, 8, and 9 was 5.97 mg/L.
    - The lowest median concentration (<0.2 mg/L) occurred in the urban network.
    - The highest median concentration (10.2 mg/L) occurred in PMR 4.

Table 6-1. Summary of 2023 nitrate concentrations and detection frequency results in groundwater samples.

PMR	Samples	Detections	Detection Frequency (%)	Median (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	14	8	57	1.10	6.61	13.0
4	76	74	97	10.2	27.3	33.0
5	16	14	88	8.35	18.0	26.4
6	14	6	43	<0.20	22.9	29.9
7	14	10	71	1.36	7.08	12.9
8	28	17	61	1.10	7.42	13.3
9	42	42	100	8.40	12.0	17.0
PMR 1-9 Combined	204	171	84	5.97	19.9	33.0
Urban*	20	9	45	<0.20	5.37	8.20

*The urban samples were collected by the MPCA and analyzed at the MDH laboratory at a different Method Reporting Limit (MRL; 0.05 mg/L). The data was censored to the MDA laboratory MRL for nitrate (0.2 mg/L), to be consistent in evaluation between these datasets.

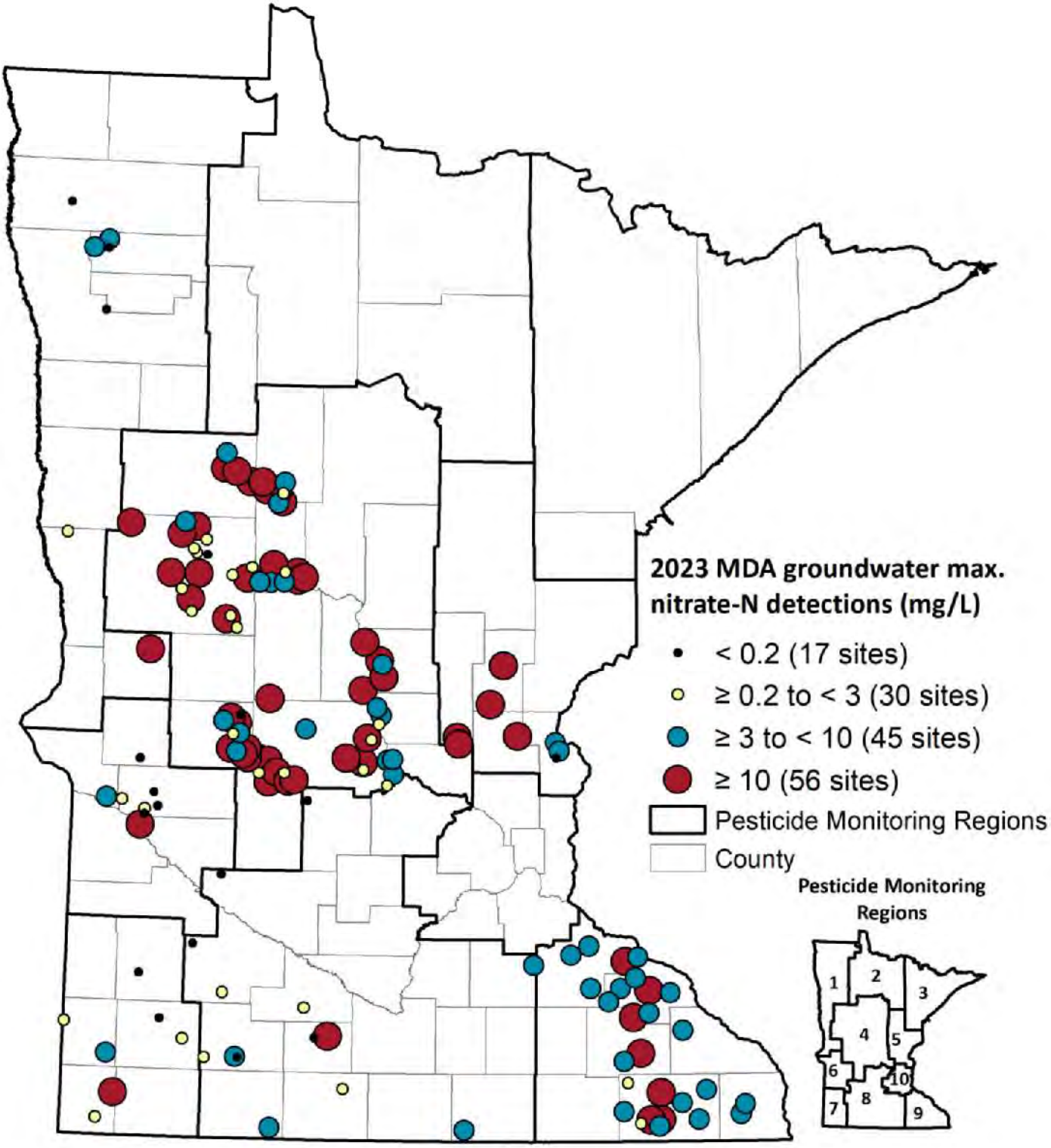

Figure 6-1. 2023 groundwater maximum nitrate concentrations.

6.1.3 Evaluation of the MDA groundwater nitrate data

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). This work group utilized and modified a classification system developed by Madison and Brunett, with the lowest classification for nitrate concentration of 0.2 mg/L (Madison and Brunett, 1984). The MDH workgroup modified the classifications to

begin with 1 mg/L as the lowest classification to account for different detection limits across laboratories. For this document, the lowest classification uses the 0.2 mg/L concentration, which matches the MDA Laboratory's 2023 nitrate MRL. The 4 general classes are:

- Less than 0.20 mg/L – assumed to represent natural ambient background concentration, without human impacts.
- 0.20 to less than 3.00 mg/L – transitional concentrations that may or may not represent human influence.
- 3.00 to less than 10.0 mg/L – may indicate elevated concentrations resulting from human activities.
- 10.0 mg/L and higher – exceeds drinking water standards (*i.e.*, HRL) for drinking water supplies.

The 2023 MDA nitrate data are presented at the PMR level in Table 6-2, based on the MDH general nitrate classification system. The principal findings from the nitrate data evaluation were:

- Statewide, 31% of the nitrate sample results were classified as elevated, and an additional 21% exceeded the HRL.
- PMR 4 had the highest percentage of samples (51%) that exceeded the HRL.
- No samples from urban wells exceeded the HRL.

Table 6-2. 2023 detection frequency in groundwater samples compared against the general nitrate classification system.

PMR	Samples	Percentage of Samples in the Category (%)			
		< 0.20 mg/L	≥0.20 - <3.00 mg/L	≥3.00 - <10.0 mg/L	≥10.0 mg/L
1	14	43	21	29	7
4	76	3	24	22	51
5	16	13	6	44	38
6	14	57	14	14	14
7	14	29	50	14	7
8	28	39	32	25	4
9	42	0	5	67	29
PMR 1-9 Combined (%)	204	26	22	31	21
Urban*	20	55	15	30	0

* The urban samples were collected by the MPCA and analyzed at the MDH laboratory at a different MRL level (0.05 mg/L).

6.1.4 MDA long-term groundwater nitrate data review

Time-series graphics by PMR have been prepared using long-term data available from the groundwater monitoring networks. These graphics provide a historical perspective on nitrate concentrations and detection frequencies from the MDA's monitoring network (Figure 6-3). All nitrate data were used for generating these graphics, and time periods are delineated in these figures based on the MRL at that time (0.40 mg/L through 2017; 0.20 mg/L since 2018). Figure 6-2 shows the regional nitrate trend analysis maps for the median concentration, 90th percentile concentration, and detection frequency statistics based on the most recent 10-year data period (from 2014-2023). The principal findings for the MDA's long-term nitrate data include:

- Compared to other regions, PMR 4 had the highest annual median nitrate concentration.
- The detection frequency was consistently greater than 80% in PMRs 4 and 5, and 100% in PMR 9.

- Declining regional nitrate trends (2014-2023) were observed for detection frequency (PMRs 1, 4, 5, and 6), median concentration (PMR 4) and 90th percentile concentration (PMRs 1, 4, 7, and 8).
- The only increasing regional nitrate trend statistic was for median concentration in PMR 9.
- All other regional nitrate trends showed no statistical trend.

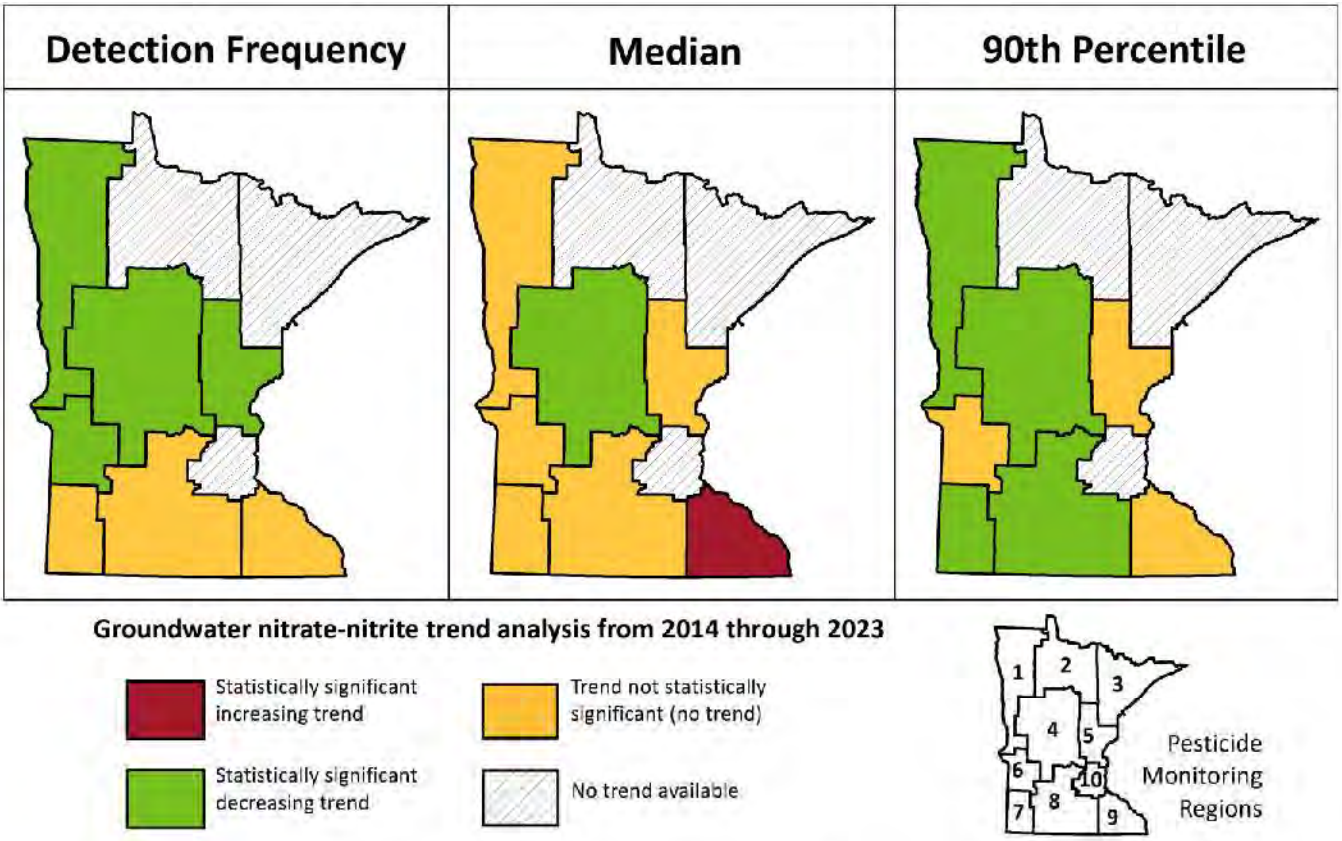

Figure 6-2. 2014 through 2023 nitrate median concentrations, 90th percentile concentrations, and detection frequency trend maps.

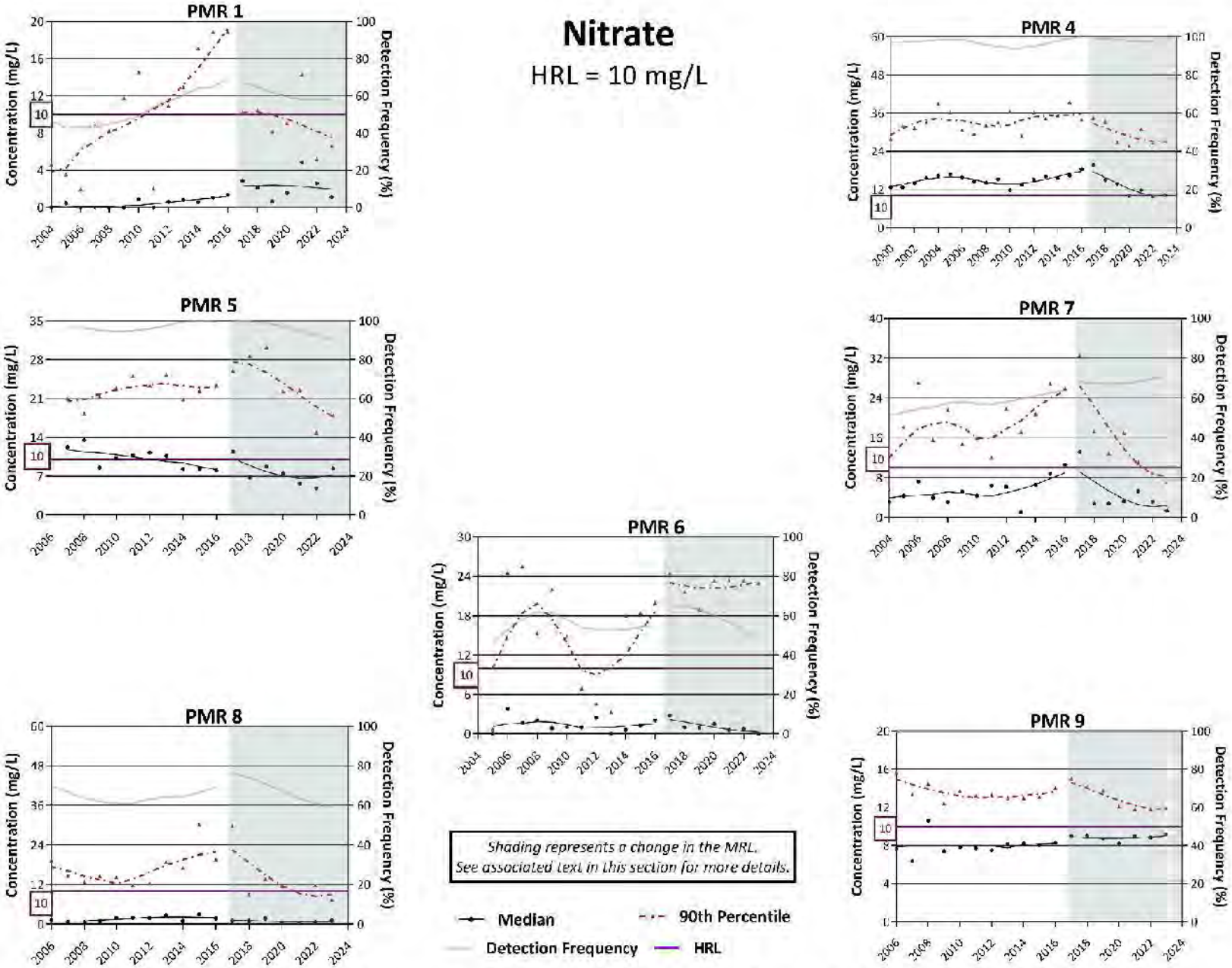

Figure 6-3. Long-term nitrate concentration results and detection frequencies for all monitored PMRs.

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The MDA Laboratory also completed internal QC measures that included sample blanks, spikes, and spike duplicates with each batch of samples analyzed and reviewed the data before the results were authorized. All QC data were excluded from the data analysis of this report and are available by request.

6.1.2 2024 MDA groundwater nitrate results

In 2024, 215 nitrate samples were collected from shallow groundwater monitoring wells, springs, or domestic wells (Figure 6-1 and Table 6-1) as part of the MDA ambient groundwater monitoring network. This also included samples from 10 monitoring wells in the southern portion of Pesticide Monitoring Region (PMR) 10 for the agricultural monitoring network (10A). Ten nitrate samples were collected by the MPCA from the PMR 10 urban monitoring network (10U). Only the domestic wells (8% of sites in the network) were directly used as a source of drinking water. The principal findings for nitrate include:

- Nitrate was detected in 84% of samples collected in PMRs 1, 4, 5, 6, 7, 8, 9, and 10A.
    - Detection frequencies ranged from 50% in PMR 6 to 100% in PMRs 5, 9, and 10A.
- The maximum nitrate concentration in every monitored PMR was ≥10 mg/L, except for PMR 7.
    - The highest concentration (81.2 mg/L) occurred in a PMR 4 monitoring well.
- The lowest median concentration (<0.2 mg/L) occurred in the PMR 10 urban network, while the highest median concentration (14.7 mg/L) occurred in PMR 4.

Table 6-1. Summary of nitrate concentrations and detection frequency results in groundwater samples, 2024.

PMR	Samples	Detections	Detection Frequency (%)	Median (mg/L)	90th Percentile (mg/L)	Maximum (mg/L)
1	14	8	57	1.43	9.67	10.4
4	77	73	95	14.7	28.0	81.2
5	16	16	100	9.26	16.5	18.5
6	14	7	50	0.27	17.3	29.7
7	14	9	64	1.54	6.09	7.10
8	28	16	57	1.04	12.2	25.0
9	43	43	100	8.54	12.2	18.8
10A	9	9	100	11.3	20.5	22.6
Ag Regions Combined	215	181	84	7.66	22.7	81.2
10U*	10	5	50	<0.2	8.03	11.0

*The urban samples were collected by the MPCA and analyzed at the MDH laboratory at a different MRL (0.05 mg/L). The data were censored to the MDA laboratory MRL for nitrate (0.2 mg/L), to be consistent in evaluation between these datasets.

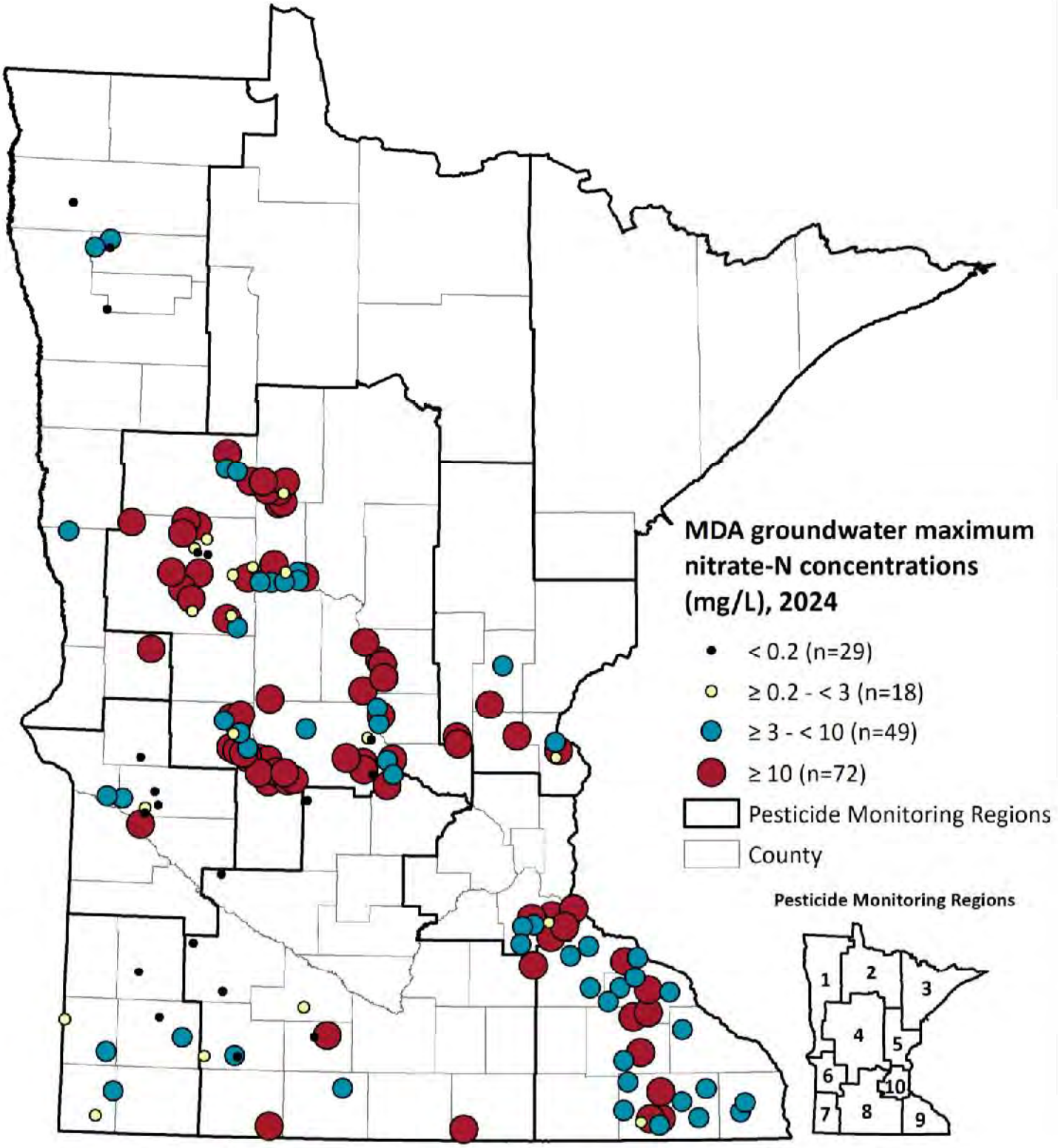

Figure 6-1. Groundwater maximum nitrate concentrations, 2024.

6.1.3 Evaluation of the MDA groundwater nitrate data

The MDH convened a work group in 1998 and developed a classification system that can be used for evaluating potential human impacts to groundwater based on nitrate concentrations (MDH, 1998). This work group utilized and modified a classification system developed by Madison and Brunett, with the lowest classification for nitrate concentration of 0.2 mg/L (Madison and Brunett, 1984). The MDH workgroup modified the classifications to begin with 1 mg/L as the lowest classification to account for different detection limits across laboratories. For this document, the lowest classification uses the 0.20 mg/L concentration, which matches the MDA Laboratory's 2024 nitrate MRL. The 4 general classes are:

- Less than 0.20 mg/L – assumed to represent natural ambient background concentration, without human impacts.
- 0.20 to less than 3.00 mg/L – transitional concentrations that may or may not represent human influence.
- 3.00 to less than 10.0 mg/L – may indicate elevated concentrations resulting from human activities.
- 10.0 mg/L and higher – exceeds drinking water standards (*i.e.*, HRL) for drinking water supplies.

The 2024 MDA nitrate data are presented at the PMR level in Table 6-2, based on the MDH general nitrate classification system. The principal findings from the nitrate data evaluation were:

- Statewide, from agricultural monitoring regions, 33% of the nitrate sample results were classified as elevated, and an additional 37% exceeded the HRL.
- PMR 4 had the highest percentage of samples (61%) that exceeded the HRL.

Table 6-2. Detection frequency in groundwater samples compared against the general nitrate classification system, 2024.

PMR	Samples	<0.20 mg/L (%)	0.20 <3.00 mg/L (%)	3.00 <10.0 mg/L (%)	≥10.0 mg/L (%)
1	14	43	14	36	7
4	77	5	13	21	61
5	16	0	19	38	44
6	14	50	14	21	14
7	14	36	36	29	0
8	28	43	21	18	18
9	43	0	2	70	28
10A	9	0	11	33	56
Ag Regions Combined	215	16	14	33	37
10U*	10	50	20	20	10

* The urban samples were collected by the MPCA and analyzed at the MDH laboratory at a different MRL (0.05 mg/L).

6.1.4 MDA long-term groundwater nitrate data review

Time-series graphics by PMR have been prepared using long-term data available from the groundwater monitoring networks. These graphics provide a historical perspective on nitrate concentrations and detection frequencies from the MDA's monitoring network (Figure 6-2). All nitrate data were used for generating these graphics, and time periods are delineated in these figures based on the MRL at that time (0.40 mg/L through 2017; 0.20 mg/L since 2018).

Table 6-3 shows the regional nitrate trend analysis results for the median concentration, 90th percentile concentration, and detection frequency statistics based on the most recent -10-year data period (from 2015-2024). The principal findings for the MDA's long-term nitrate data include:

- Compared to other regions, PMR 4 had the highest annual median nitrate concentration.
- Declining regional nitrate trends (2015-2024) were observed for detection frequency in PMRs 1, 4, 6, and 8.
- PMRs 4, 6, and 7 had decreasing trends in the median concentration.
- PMRs 1, 4, 7, 8, and 9 had decreasing trends in the 90th percentile concentration.
- The only increasing regional nitrate trend statistic was for the median concentration in PMR 9.
- All other regions showed no statistically significant trend for nitrate.

Table 6-3. Median concentration, 90th percentile concentration, and detection frequency trend analysis results for nitrate in groundwater, 2015 through 2024.

Note on table symbols: ↑ = statistically significant increasing trend, ↓ = statistically significant decreasing trend, ↔ = trend not statistically significant.

PMR	Nitrate – Median Concentration Trend	Nitrate – 90th percentile Concentration Trend	Nitrate – Detection Frequency Trend
1	↔	↓	↓
4	↓	↓	↓
5	↔	↔	↔
6	↓	↔	↓
7	↓	↓	↔
8	↔	↓	↓
9	↑	↓	↔

Nitrate

HRL = 10 mg/L

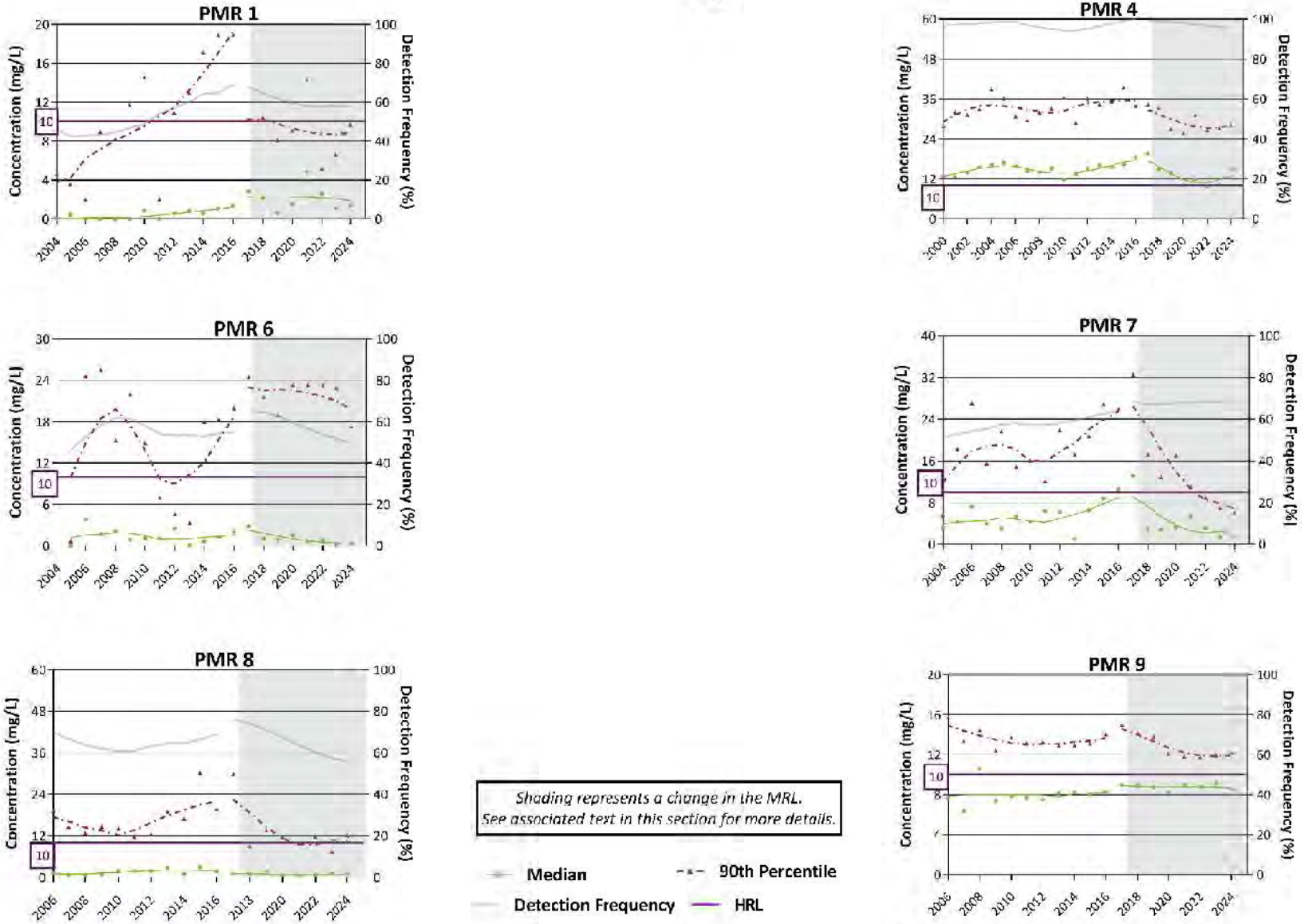

Figure 6-2. Long-term nitrate concentration results and detection frequencies for PMRs 1, 4, 6, 7, 8, and 9.

MCEA Ex. 31

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Understanding nitrogen in soils

What you should know

- Numerous nitrogen (N) sources exist. Consider these when evaluating the N budget.
- Soil type and climate greatly affect nitrogen loss from the soil system.
- Because Minnesota has such diverse soils and climate, N cycle interpretations should be site-specific.

Here, we'll cover how nitrogen behaves in Minnesota soil systems and how to manage it for more profitable and environmentally friendly crop production.

Basics of nitrogen

Why understand N

Environmental and economic issues have increased the need to better understand the role and fate of nitrogen (N) in crop production systems. Nitrogen is the nutrient most often deficient for crop production in Minnesota, and its use can result in substantial economic return for farmers.

However, when N inputs to the soil system exceed crop needs, there's a possibility that excessive amounts of nitrate (NO_3--N) may enter either ground or surface water.

Managing N inputs to achieve a balance between profitable crop production and environmentally tolerable levels of NO_3--N in water supplies should be every grower's goal. Nitrogen's behavior in the soil system is complex, yet understanding these basic processes is essential for a more efficient N management program.

Nitrogen cycle

Nitrogen exists in the soil system in many forms, and changes (transforms) very easily from one form to another. The route N follows in and out of the soil system is collectively called the nitrogen cycle (Figure 1).

The nitrogen cycle is biologically influenced. Biological processes, in turn, are influenced by prevailing climatic conditions along with a particular soil's physical and chemical properties. Both climate and soils vary greatly across Minnesota and affect N transformations for the different areas.

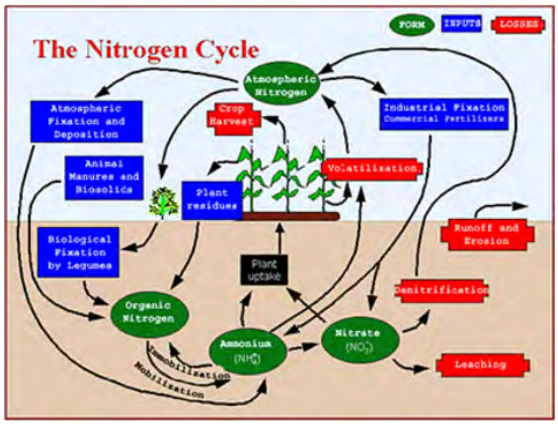

Figure 1: The nitrogen cycle, courtesy of the International Plant Nutrition Institute (IPNI).

Inputs of N for plant growth

The atmosphere

Atmospheric N is the major reservoir for N in the N cycle (air is 79 percent N2 gas).

Although unavailable to most plants, leguminous plants can use large amounts of N2 via biological N fixation. In this biological process, nodule-forming Rhizobium bacteria inhabit the roots of leguminous plants and, through a symbiotic relationship, convert atmospheric N2 to a form the plant can use.

Legumes can fix substantial amounts of N2 into usable N. An alfalfa crop, for example, has the potential to fix several hundred pounds of N per acre per year. Any legume crop that's left after harvest, including roots and nodules, can supply N to the soil system when the plant material is decomposed.

Several nonsymbiotic organisms fix N, but N additions from these organisms are quite low (1 to 5 pounds per acre per year). In addition, precipitation adds small amounts of N to the soil. In Minnesota, precipitation supplies an average of 5 to 10 pounds of N per acre per year.

Commercial fertilizers

Commercial N fertilizers are also derived from the atmospheric N pool. The major step is to combine N2 with hydrogen (H2) to form ammonia (NH3). Anhydrous ammonia is then used as a starting point in the manufacture of other nitrogen fertilizers.

Anhydrous ammonia or other N products derived from NH3 can then supplement other N sources for crop nutrition.

Organic N sources

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Nitrogen can also become available for plant use from organic N sources. Before these organic sources are available to plants, they must be converted to inorganic forms. Nitrogen is available to plants as either ammonium (NH4+-N) or nitrate (NO3--N).

Manures

Animal manures and other organic wastes can be important sources of N for plant growth. The amount of N supplied by manure will vary with the type of livestock, handling, rate applied and method of application. Because the N form and content of manures widely varies, a manure analysis is recommended to improve N management.

Crop residues

Crop residues from non-leguminous plants also contain N, but in relatively small amounts compared to legumes. Nitrogen exists in crop residues in complex organic forms and the residue must decay – a process that can take several years – before N becomes available for plant use.

Soil organic matter

Soil organic matter is also a major source of N used by crops. Organic matter is primarily composed of rather stable material called humus that has collected over a long period of time.

Easily decomposed portions of organic material disappear relatively quickly, leaving behind residues more resistant to decay. Soils contain approximately 2,000 pounds of N in organic forms for each percent of organic matter. This portion of organic matter decomposes at a rather slow rate and releases about 20 pounds of N per acre per year for each percent of organic matter.

Nitrogen transformations

Nitrogen, present or added to the soil, is subject to several changes, or transformations. These dictate the availability of N to plants and influence the potential movement of NO3--N to water supplies.

Causes and effects of N changes

Organic N that's present in soil organic matter, crop residues and manure is converted to inorganic N through the mineralization process. In this process, bacteria digest organic material and release NH_4^+-N.

Formation of NH_4^+-N increases as microbial activity increases. Bacterial growth is directly related to soil temperature and water content. The NH_4^+-N supplied from fertilizer is the same as the NH_4^+-N supplied from organic matter.

Ammonium-N has properties of practical importance for N management. Plants can absorb NH_4^+-N. Also, because ammonium has a positive charge, it's attracted or held by negatively charged soil and soil organic matter. This means that NH_4^+-N doesn't move downward in soils.

Nitrogen in the NH_4^+-N form that isn't taken up by plants is subject to other changes in the soil system. Nitrification is the conversion of NH_4^+-N to NO_3^--N.

Nitrification

Nitrification is a biological process. It rapidly proceeds in warm, moist, well-aerated soils, and slows at soil temperatures below 50 degrees Fahrenheit.

Nitrate-N is a negatively charged ion and isn't attracted to soil particles or soil organic matter like NH_4^+-N. Nitrate-N is water-soluble and can move below the crop rooting zone under certain conditions.

Denitrification

In denitrification, bacteria convert NO_3^--N to N gases that are lost to the atmosphere. Denitrifying bacteria use NO_3^--N instead of oxygen in the metabolic processes. The process takes place in waterlogged soil and with ample organic matter to provide energy for bacteria.

For these reasons, denitrification is generally limited to topsoil. Denitrification can rapidly proceed when soils are warm and become saturated for two or three days.

Immobilization

Immobilization, or the tie up of soil N, can temporarily reduce the amount of plant-available N. Bacteria that decompose high-carbon, low-N residues, such as corn stalks or small grain straw, need more N to digest the material than is present in the residue.

Immobilization occurs when the growing microbes use NO_3^--N and/or NH_4^+-N present in the soil to build proteins. The actively growing bacteria that immobilize some soil N also break down soil organic matter to release available N during the growing season.

There's often a net gain of N during the growing season because the additional N in the residue will be the net gain after immobilization-mineralization processes.

Nitrogen loss from the soil system

When developing N programs and evaluating environmental effects, consider nitrogen's mobility factor in the soil. Sandy soils may lose N through leaching, while heavy, poorly drained soils may lose N through denitrification.

Leaching

Unlike the previously described biological transformations, loss of nitrate by leaching is a physical event.

Leaching is the loss of soluble NO_3^--N as it moves with soil water, generally excess water, below the root zone. Nitrate-N that moves below the root zone has the potential to enter groundwater or surface water through tile drainage systems.

Coarse-textured soils have a lower water-holding capacity and, therefore, more potential to lose nitrate from leaching compared to fine-textured soils. Some sandy soils, for instance, may retain only a half inch of water per foot of soil while some silt loam or clay loam soils may retain up to 2 inches of water per foot.

Nitrate-N can be leached from any soil if rainfall or irrigation moves water through the root zone.

Denitrification

Denitrification can be a major loss mechanism of NO_3^--N when soils are saturated with water for two or three days. Nitrogen in the NH_4^+-N form isn't subject to this loss. Management alternatives are available if denitrification losses are a potential problem.

Volatilization

Significant losses from some surface-applied N sources can occur through the process of volatilization. In this process, N is lost as ammonia (NH_3) gas.

Manure and fertilizer products containing urea can cause nitrogen to be lost this way. Ammonia is an intermediate form of N during the process that transforms urea to NH_4^+-N. Incorporating these N sources will virtually eliminate volatilization losses.

Nitrogen loss from volatilization is greater when:

- Soil pH is higher than 7.3.
- Air temperature is high.
- The soil surface is moist.
- There's a lot of residue on the soil.

Crop removal

Substantial amounts of N are lost from the soil system through crop removal. A 250-bushel-per-acre corn crop, for example, removes approximately 175 pounds of N with the grain. Crop removal accounts for a majority of the N that leaves the soil system.

Soil erosion and runoff

Nitrogen can be lost from agricultural lands through soil erosion and runoff. Losses through these events normally don't account for a large portion of the soil N budget, but should be considered for surface water quality issues.

Incorporating or injecting manure and fertilizer can help protect against N loss through erosion or runoff. Where soils are highly erodible, conservation tillage can reduce soil erosion and runoff, resulting in less surface loss of N.

Key points for crop producers

Considering the many transformations and reactions of N in soils, there are some major points to keep in mind:

- Although you can add either organic or inorganic N forms to soil, plants only take up inorganic N (that is, NO_3^--N and NH_4^+-N).
- One form isn't more important than the other and all N sources can be converted to NO_3^--N. Commercial N fertilizers, legumes, manures and crop residues are all initial sources of NO_3^--N and NH_4^+-N.
- Once it's in the plant or water supply, it's impossible to identify the initial source.
- Nitrate is always present in the soil solution and will move with the soil water.
- Inhibiting the conversion of NH_4^+-N to NO_3^--N can result in less N loss and more plant uptake. While it's not possible to totally prevent the movement of some NO_3^--N to water supplies, sound management practices can keep losses within acceptable limits.

Fabian G. Fernandez, Extension nutrient management specialist and Daniel E. Kaiser, Extension nutrient management specialist

Reviewed in 2021

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https://extension.umn.edu/nitrogen/understanding-nitrogen-soils

Minnesota Department of Agriculture

Morrison County: Overview of Nitrate Levels in Private Wells (2013-2015)

The Minnesota Department of Agriculture (MDA) created the Township Testing Program to help identify where elevated nitrate levels in private wells may exist. The MDA has identified approximately 250-300 townships around the state where groundwater contamination is likely to occur due to geologic conditions in tandem with substantial row crop acres.

The MDA worked with the Morrison Soil and Water Conservation District to identify sensitive townships and then implement a successful nitrate testing strategy. In Morrison County, the following townships met the criteria: **Agram, Belle Prairie, Bellevue, Buh, Culdrum, Swan River, Elmdale, Little Falls, Ripley, Two Rivers, and Swanville.**

This overview provides the nitrate results termed "Round One". "Round One" basically describes the nitrate results from virtually all of the participating wells including those impacted by point sources such as nearby septic tanks, feedlots and other nitrogen sources.

Morrison County Highlights

- # Vulnerable Townships Tested: 11
- Households Receiving Kits: 3,680
- Number of Wells Tested: 1,222
- % Wells Over the Health Standard: 15

In 2013 and 2015, homeowners with a private well in the selected townships received a test kit in the mail. Homeowners played a key role since they were responsible for collecting the water sample and sending it to the certified lab. Homeowners also provided some important information about their well. The following map and table provides results from Round One.

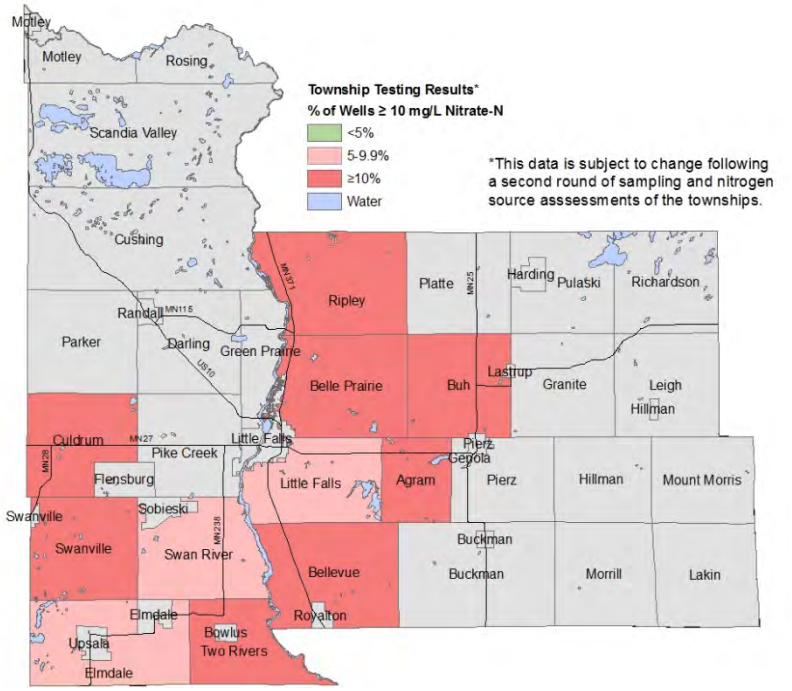

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Table: Morrison County Round One Nitrate Results in 2013 and 2015

Township	Total Wells**	Year Tested	Nitrate as Nitrogen mg/L or parts per million (ppm)				Percent of Wells ≥10
			Min	Max	Mean	Median	
Agram	109	2013	<0.03	40.8	9.8	10.2	52%
Belle Prairie	101	2013	<0.03	39	4.8	0.2	18%
Bellevue	135	2013	<0.03	43.7	3.7	0.0	11%
Buh	52	2013	<0.03	31.2	2.8	0.0	12%
Culdrum	58	2013	<0.03	28.2	2.9	0.0	14%
Swan River	70	2013	<0.03	40.9	3.7	0.0	11%
Elmdale	148	2015	<0.03	70.3	2.9	0.0	9%
Little Falls	281	2015	<0.03	48.5	3.6	0.6	7%
Ripley	106	2015	<0.03	18.1	3.6	0.5	16%
Two Rivers	113	2015	<0.03	37.8	3.7	0.2	12%
Swanville	49	2015	<0.03	25.8	2.7	0.0	12%
Total	**1,222**	**13 - 15**	**<0.03**	**70.3***	**4.0***	**11.7***	**15%***

*Represents an average. **All well types included.

Why is there a "Round Two"?

Frequently nitrate is detected because of either well construction issues or a localized area is impacted from a point source such as a septic tank or nearby feedlot. Round Two was offered to homeowners when measureable nitrate was detected during the first sampling. Trained MDA staff visited willing homeowners to resample the well and then conducted a site assessment. The assessment helps identify well results impacted by obvious construction issues and/or non-fertilizer sources of nitrogen such as septic systems.

Round Two sampling is scheduled for completion by the end of 2016. It is common for 5 to 10% of the wells to eventually be removed from the original data set. Once Round Two is completed, the MDA conducts an analysis of the results and prepares a final report for each county (visit www.mda.state.mn.us/townshiptesting). The Morrison County Final Report will be available in 2017.

The final results will indicate the severity and magnitude of nitrate in groundwater in the township. These results will help guide the decision making process in the event that corrective actions are needed. These actions are described in Minnesota's Nitrogen Fertilizer Management Plan (NFMP). Find more information about the NFMP on the MDA website at www.mda.state.mn.us/nfmp.

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CLEAN WATER LAND & LEGACY AMENDMENT

Published August 2016



INITIAL TOWNSHIP TESTING OF NITRATE IN PRIVATE WELLS

WADENA COUNTY 2013 SUMMARY

April 2015

Minnesota Department of Agriculture

Pesticide and Fertilizer Management Division

In accordance with the Americans with Disabilities Act, this information is available in alternative forms of communication upon request by calling 651-201-6000. TTY users can call the Minnesota Relay Service a 711 or 1-800-627-3529. The MDA is an equal opportunity employer and provider.

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EXECUTIVE SUMMARY

In 2013, four townships in Wadena County were selected for private well nitrate sampling as a pilot project. Results showed that 19 percent of private wells sampled in Wadena Township were above the health standard of 10 mg/L. Eighteen percent of the private wells in Aldrich Township and 13 percent of the wells in Wing River Township were above the health standard of 10 mg/L. In Thomastown Township, only four percent of wells were above 10 mg/L.

Future work that will be considered by the Minnesota Department of Agriculture (MDA) includes the following: 1) resampling wells that had high nitrate results (greater than or equal to 5 mg/L) to verify high nitrate levels; 2) performing well site visits, when possible, to rule out well construction issues and obvious point sources of nitrate, such as septic systems, livestock, etc.; and 3) increasing efforts to obtain well log information for participating wells so that nitrate results and the aquifer designation can be compared in a more comprehensive fashion.

This pilot project conducted in Wadena County will be used to guide future work as the MDA plans to offer nitrate tests to approximately 70,000 private well owners within approximately 250 to 280 townships, between 2013 and 2019. The actual number of townships may vary based on detailed county specific information. As of April 2014, 22 townships in four counties are completed.

INTRODUCTION

The MDA is currently updating the 1990 Nitrogen Fertilizer Management Plan (NFMP). The NFMP is the state's blueprint for prevention or minimization of the impacts of nitrogen fertilizer on groundwater. One of the goals of the NFMP is to minimize or mitigate the source of pollution from nitrogen fertilizer. Updating the NFMP provides an opportunity to restructure the County's and the State's strategies for reducing nitrate contamination of water resources, with more specific, localized accountability for nitrate contamination associated with row crop agricultural production.

To effectively manage nitrate contamination of water resources it is appropriate to focus on areas of greatest risk. Testing of water from private wells for nitrate is one method for identifying areas and wells at greatest risk. For this, the MDA has developed the "Township Testing Program". In the Township Testing Program the MDA works with local partners (counties and Soil and Water Conservation Districts) to collect and analyze water samples from private drinking water wells within townships that either had high nitrate results previously or exist in an area with high aquifer vulnerability and a high percentage of row crop production.

http://www.mda.state.mn.us/protecting/cleanwaterfund/gwdwprotection/townshiptesting.aspx

BACKGROUND

In many rural areas of the state, nitrate is one of the most common contaminants in Minnesota's groundwater, and in some areas of the state (e.g., the Central Sands which is a 14 county area in central Minnesota), a significant number of wells have high nitrate levels.

Nitrate is a naturally occurring, water soluble molecule that is made up of nitrogen and oxygen. Although nitrate occurs naturally, it can also originate from man-made sources such as fertilizer, animal manure and human waste. Nitrate is a concern because it can have a negative effect on human health at elevated levels. The U.S. Environmental Protection Agency (USEPA) has established a drinking water Maximum Contaminant Level (MCL) of 10 mg/L for nitrate as nitrogen (U.S. EPA, 2009) in municipal water systems. The Minnesota Department of Health (MDH) has also established a Health Risk Limit (HRL) of 10 mg/L for private drinking water wells in Minnesota.

Nitrogen present in groundwater can be found in the forms of nitrite and nitrate. Nitrite concentration is commonly less than the reporting level of 0.01 mg/L, resulting in negligible contribution to the nitrate plus nitrite concentration (Nolan and Stoner, 2000). In the environment, nitrite generally converts to nitrate, which means nitrite occurs very rarely in groundwater. Measurements of nitrate plus nitrite as nitrogen and measurements of nitrate as nitrogen will hereafter be referred to as “nitrate.”

NITRATE FATE AND TRANSPORT

Nitrate is considered a conservative anion and is highly mobile in many shallow coarse-textured groundwater systems. Once in groundwater, nitrate is often considered very stable and can move large distances from its source. Nitrate in groundwater may be converted to nitrogen gas in the absence of oxygen and the presence of organic carbon, through a natural process called denitrification. Denitrification occurs when oxygen levels are depleted and nitrate becomes the primary oxygen source for microorganisms. Shallow groundwater in coarse-textured soils (glacial outwash) generally has low concentrations of organic carbon and is well oxygenated, so denitrification is often limited in these conditions. As a result, areas like Wadena County with extensive glacial outwash aquifers and intensive row crop agriculture are particularly vulnerable to elevated nitrate concentrations. However, geochemical conditions can be highly variable within an aquifer or region and can also change over-time (MPCA, 1998).

GEOLOGY AND HYDROGEOLOGY

The geology in Wadena County is heavily influenced by outwash plains and to a lesser extent, glacial till (Figure 1). Glacial outwash is relatively coarse-textured compared to other glacial deposits such as till and drift deposits. Outwash is material consisting primarily of sand and gravel that was deposited by running water that flowed from melting ice during the last glacial period. The outwash sand and gravel is typically deposited in a stratified (layered) fashion as the glacial melt conditions changed. The coarse-textured deposits associated with glacial outwash often allow contaminants from the surface to travel rapidly to the water table aquifers.

Wadena County overlies two large surficial aquifer systems. The Pineland Sands surficial aquifer is located in the northeast portion of the county and the Wadena surficial aquifer system is located in the southwest. The Pineland surficial aquifer consists of very fine-grained sand to fine gravel and is generally underlain by till (Helgeson, 1977). The Wadena aquifer in the southern portion of the county consists of medium to coarse grained sand with minor amounts of gravel and clay.

The Wadena surficial aquifer overlies a sandy till that contains lenses of buried sand and gravel that serve as artesian aquifers (Lindholm, 1970). Regional groundwater flow direction for the surficial aquifers and uppermost confined aquifers is toward the Leaf River in the southwest and toward Crow Wing River in the northeast. In both surficial aquifers, local ground-water flow generally follows the topographic relief towards small streams and lakes (Lindholm, 1970).

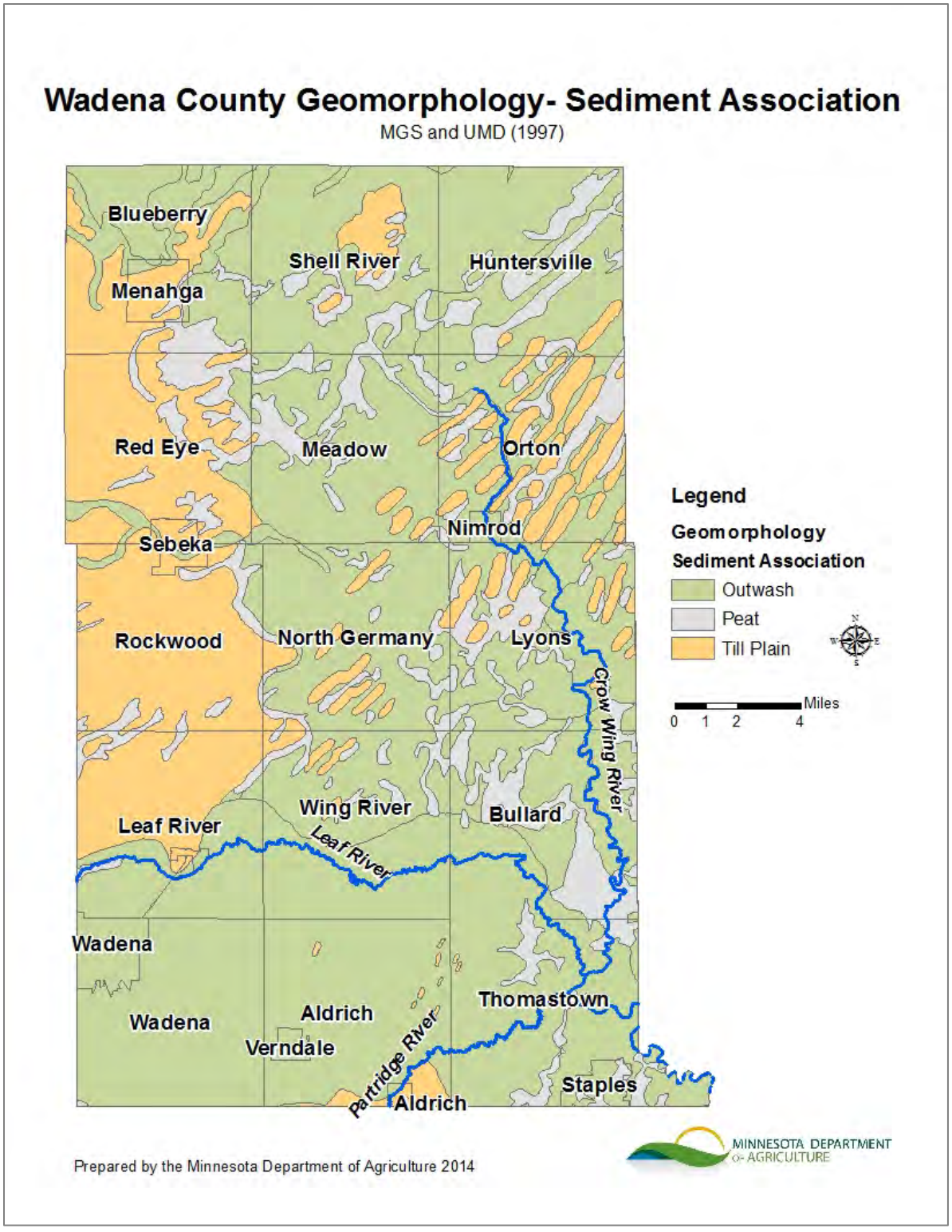

Figure 1. Statewide Geomorphology Layer, Sediment Association, Wadena County

The same geologic mapping project presented in Figure 1 was used to classify the state into aquifer sensitivity ratings. There are three ratings for aquifer sensitivity: low, medium and high. Sensitivity ratings are described in Table 1. The ratings are based upon guidance from the Geologic Sensitivity Project Workgroup's report "Criteria and Guidelines for Assessing Geologic Sensitivity in Ground Water Resources in Minnesota" (DNR, 1991) (Figure 2).

Table 1. Vulnerability Ratings Based on the Geomorphology of Minnesota, Sediment Association Layer

Sediment Association	Sensitivity/Vulnerability Rating
Alluvium, Outwash, Ice Contact, Peat, Terrace, Bedrock: Igneous, Metamorphic, and Sedimentary	High
Supraglacial Drift Complex, Lacustrine	Medium
Till Plain	Low

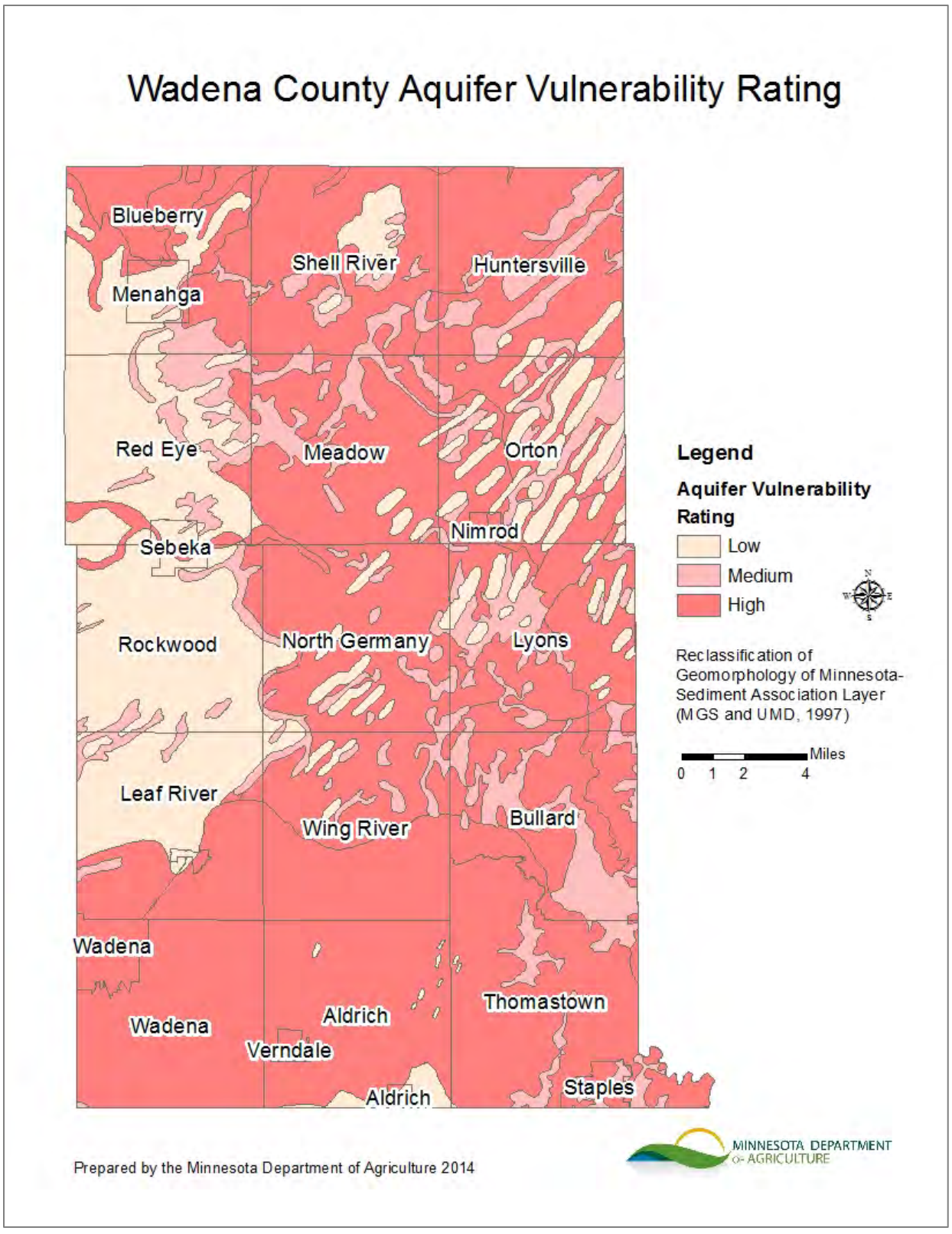

Figure 2. Water Table Aquifer Vulnerability for Wadena County

GEOLOGIC ATLAS

A County Geologic Atlas is a systematic study of a county's geologic and groundwater resources. The atlas defines aquifer properties and boundaries, as well as the connection of aquifers, to the land surface and to surface water resources (MGS, 2014). This information is essential to sustainable management of groundwater resources and can help with activities such as monitoring, appropriation, permitting, remediation, and well construction.

A complete geologic atlas consists of two parts:

- Part A (prepared by Minnesota Geological Survey (MGS)), which includes the water well database and 1:100,000 scale geologic maps showing properties and distribution of sediments and rocks in the subsurface, and
- Part B (developed by the Department of Natural Resources (DNR) Division of Waters) which includes maps of water levels in aquifers, direction of groundwater flow, water chemistry, and sensitivity to pollution.

The Wadena County Geologic Atlas Part A is currently being prepared by the MGS (as of May 2014).

COUNTY WELL INDEX

The County Well Index (CWI) is a database system developed by the Minnesota Geological Survey and the Minnesota Department of Health (MDH) for the storage, retrieval, and editing of water-well information. The database contains basic information on well records (e.g. location, depth, static water level) for wells drilled in Minnesota. The database also contains information on the well log and the well construction for many private drinking water wells. The CWI is instrumental in the development of the Geologic Atlas described in the previous section. The CWI is the most comprehensive Minnesota well database available, but contains only information for wells in which a well log is available. Most of the records in CWI are for wells drilled after 1974, when water-well construction code required well drillers to submit records to the MDH. The CWI does contain data for some records obtained by the MGS through the cooperation of drillers and local government agencies for wells drilled before 1974 (MGS, 2014).

The CWI was used to gather information about the four townships included in this pilot study. Table 2 summarizes the general aquifer types, while the following section is a brief summary of the major aquifer types with the average well depth.

According to the information from the CWI (MDH, 2014):

In Aldrich Township, there are 170 “located” wells (those with location field-verified by MDH, MGS or other local partner):

- Fifty-four percent are completed in the shallow Quaternary Water Table Aquifer (QWTA) and are 33 feet deep on average.
    - QWTA wells are defined as having less than 10 feet of confining material (clay) between the land surface and the well screen (MPCA, 1998). When there is less than 10 feet of clay, it can allow surface contaminants to travel more quickly to the water table aquifers. In general, shallower wells completed in the QWTA may be more susceptible to nitrate-nitrogen contamination.
- Thirty-five percent are completed in a Quaternary buried aquifer and are 99 feet deep on average.
    - Buried aquifer wells have more than 10 feet of confining material between the land surface and the well screen.

In Thomastown Township, there are 289 located wells:

- Twenty-seven percent are completed in the shallow QWTA and are 37 feet deep on average.
- Fifty-seven percent are completed in a Quaternary buried aquifer and are 100 feet deep on average.

In Wadena Township, there are 224 located wells:

- Sixty-three percent are completed in the shallow QWTA and are 52 feet deep on average.
- Twenty-seven percent are completed in a Quaternary buried aquifer and are 105 feet deep on average.

In Wing River Township, there are 132 located wells:

- Fourteen percent are completed in the shallow QWTA and are 47 feet deep on average.
- Thirty-five percent are completed in a Quaternary buried aquifer and are 93 feet deep on average.

Table 2. Aquifer Type Distribution of Wells in the County Well Index

Township	Total Wells	Aquifer Type				
		Water Table	Quaternary Buried	Quaternary Undifferentiated	Undesignated	Others
Aldrich	170	54%	35%	<1%	11%	<1%
Thomastown	289	27%	57%	1%	15%	0%
Wadena	224	63%	27%	3%	6%	1%
Wing River	132	14%	35%	0%	51%	0%

NITRATE PROBABILITY MAPPING

The Minnesota Department of Health (MDH) has developed nitrate probability maps to assist in local water quality planning efforts. These maps identify areas of a county with relatively high, moderate, and low probability of having elevated nitrate concentrations in groundwater. The goal of nitrate probability mapping is to help protect public and private drinking water supplies, help prevent further contamination by raising awareness and assist in local planning and prevention. The nitrate probability map is similar in appearance compared to the updated aquifer vulnerability map; however it shows less area categorized in the high rating. Wadena County's report was published in 2002 and can be accessed here:

http://www.health.state.mn.us/divs/eh/water/swp/nitrate/reports/2002method/wadena.pdf

MDA PRIVATE WELL MONITORING

The Minnesota Department Agriculture has two primary approaches to monitoring for nitrate in private drinking water wells. The first approach is to use a statistically designed private well regional network that incorporates more than one county into a region. The Central Sands Private Well network is considered a regional network; it includes a 14 county area in the central area of Minnesota. Results are considered to reflect levels of nitrate contamination across the region. The second approach is monitoring on a township level, the Township Testing program. The two approaches are discussed separately below.

CENTRAL SANDS PRIVATE WELL NETWORK RESULTS

In the spring of 2011, a total of 1555 private drinking water wells were sampled for nitrate concentrations (Figure 3 and Table 3). Homeowners from 14 counties were systematically chosen to participate in this project and had their private well water tested for free. Overall, results from the 14 counties combined showed that 89 percent of the 1555 wells had nitrate concentrations less than 3 mg/L, seven percent ranged from 3-9.9 mg/L and less than five percent of wells had concentrations greater than 10 mg/L (Kaiser, 2012). However, Wadena County results had the third highest percentage of wells greater than 10 mg/L compared to most other counties in the Central Sands Private Well Network. Because of this, Wadena County was given a high priority in the Township Testing Program.

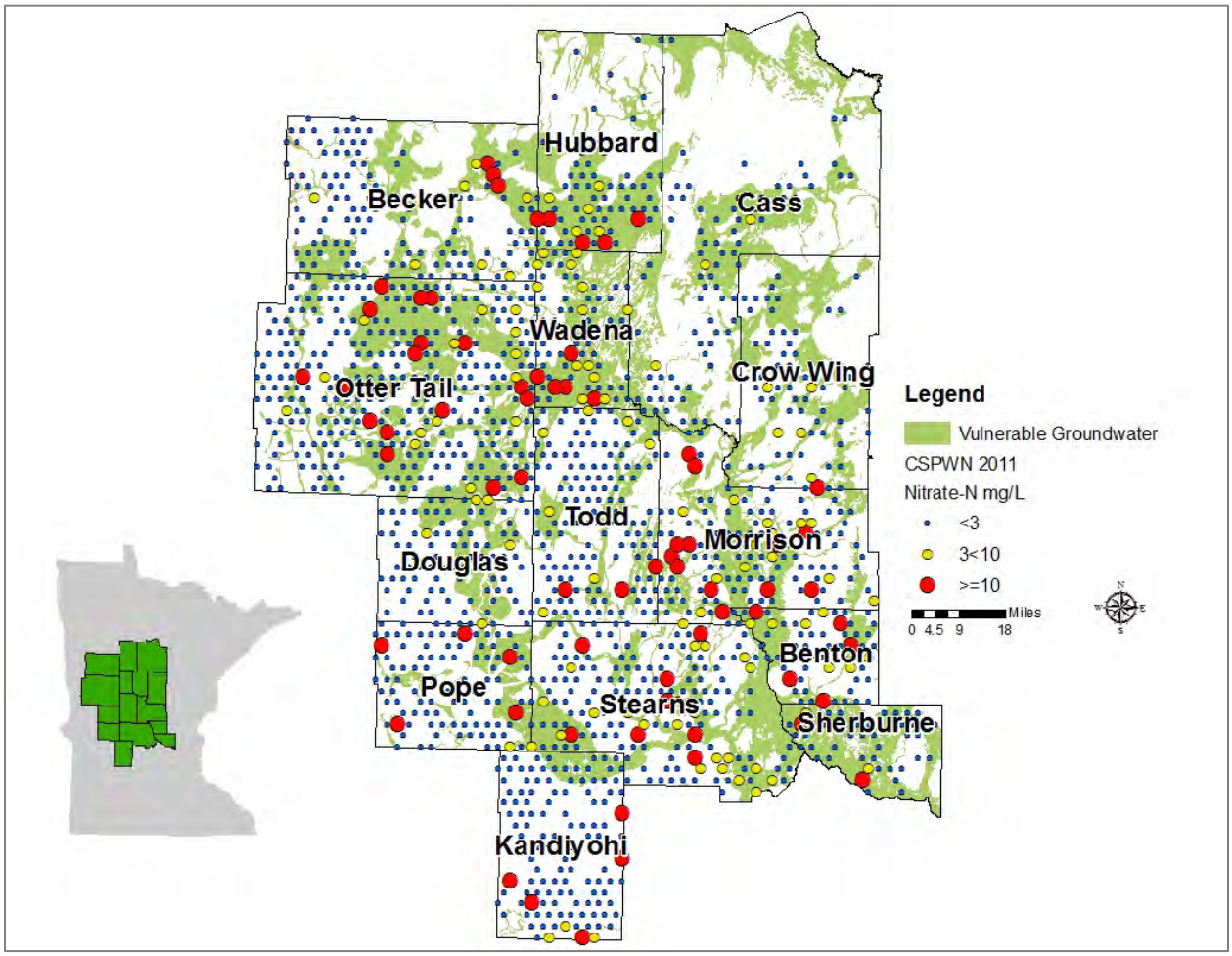

Figure 3. Central Sands Private Well Network 2011 Sampling Event

Table 3. Central Sands Private Well Network 2011 Results Summary

County	Number of Samples	2011 Results					
		Nitrate-N mg/L			Percent		
		Min	Median	Max	<3 (mg/L)	3<10 (mg/L)	=>10 (mg/L)
Becker	123	<.03	<.03	15.4	93%	5%	2%
Benton	57	<.03	<.03	15.6	79%	12%	9%
Cass	82	<.03	<.03	9.5	96%	4%	0%
Crow Wing	66	<.03	<.03	8.3	92%	8%	0%
Douglas	90	<.03	<.03	8.8	94%	6%	0%
Hubbard	65	<.03	<.03	29.3	85%	8%	8%
Kandiyohi	117	<.03	<.03	38.7	93%	3%	4%
Morrison	124	<.03	<.03	33.9	78%	11%	11%
Ottertail	320	<.03	<.03	32.7	90%	4%	5%
Pope	93	<.03	<.03	35.0	94%	1%	5%
Sherburne	42	<.03	<.03	40.0	91%	5%	5%
Stearns	167	<.03	<.03	49.8	82%	13%	4%
Todd	137	<.03	<.03	81.0	93%	5%	2%
Wadena	72	<.03	0.09	49.2	75%	17%	8%
Average	1,555 *total samples*	<.03	0.01	31.9	88.6%	6.8%	4.6%

For more information about the Central Sands Private Well Network, please visit: http://www.mda.state.mn.us/protecting/cleanwaterfund/gwdwprotection/characterizingnitrates.aspx.

TOWNSHIP TESTING

The MDA is currently updating the 1990 Nitrogen Fertilizer Management Plan (NFMP). The NFMP is the state's blueprint for prevention or minimization of the impacts of nitrogen fertilizer on groundwater. Updating the NFMP provides an opportunity to

restructure county and the state strategies for reducing nitrate contamination of groundwater, with more specific, localized accountability for nitrate contamination from agriculture. In order to effectively reduce nitrate contamination of groundwater resources, it is necessary to identify areas of concern. Areas of concern tend to be fairly localized and therefore township boundaries were selected for nitrate testing. Factors such as aquifer vulnerability, row crop production and previous nitrate results will be used to prioritize townships for sampling. Townships with at least 30 percent of the area characterized with vulnerable groundwater and at least 20 percent of the area in row crop production are shown in Figure 4 . Areas in orange are considered most vulnerable to nitrate contamination of groundwater. This map serves as a starting point for planning sample locations and is modified based on local expertise.

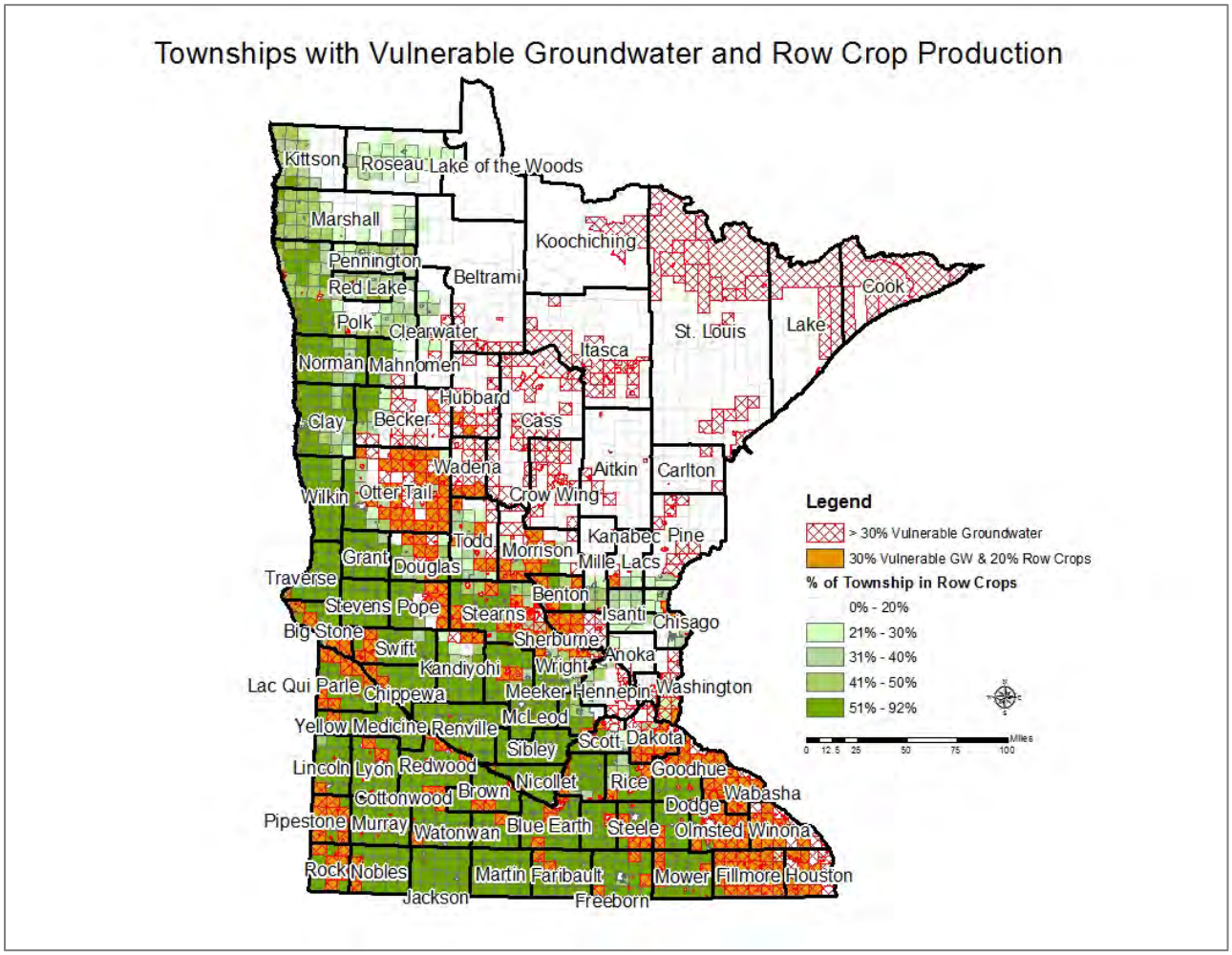

Figure 4. Townships with Vulnerable Groundwater and Row Crop Production

METHODS

Aldrich and Wing River Townships were chosen for sampling based on high results from the 2011 Central Sands Private Well Network sampling event. Thomastown and Wadena Townships were chosen based on other criteria including local Soil and Water Conservation District (SWCD) expertise, vulnerable groundwater, and row crop production.

The goal of this program is to sample a majority of available wells in the selected townships. Most households with private wells received an invitation letter to participate in the free nitrate testing. Homeowners with private wells that agreed to participate were sent a free water sample kit (by a certified lab) which included a survey about their well, sample bottle, sample instructions and a pre-paid mailer. Homeowners were asked to complete the well survey, fill the sample bottle and mail the sample to the certified lab in the prepaid mailer. Once the sample was analyzed, the lab sent homeowners their results in the mail. The selected townships included: Aldrich, Thomastown, Wadena, and Wing River.

RESULTS

Approximately 270 well owners returned water samples for analysis across the four townships (Figure 5). On average, 29 percent of households in these townships responded to the free nitrate test offered by MDA (Table 4). The results of the township nitrate sampling are displayed in Figure 5. The summary statistics are presented in Table 5, which shows all of the well types except those of hand dug construction. Only one sample came from a well that was of hand dug construction.

The minimum values for each township were less than the detection limit which is 0.03 mg/L. The maximum values range from 21.2 to 32.4 mg/L, with Aldrich Township having the highest result. Median values ranged from < 0.03 to 0.8 mg/L, with Wadena Township having the highest median value. The 90th percentiles ranged from 7.7 to 21.6 mg/L, with Aldrich Township having the highest value.

Results from the sampling showed that in Wadena Township, 19 percent of wells were greater than the 10 mg/L. In Aldrich Township, 18 percent of the wells were over 10 mg/L, Wing River Township at 13 percent and in Thomastown Township, only four percent were over 10 mg/L. Previous sampling of 72 wells in Wadena County showed that 8 percent of wells were at or over 10 mg/L (Kaiser, 2012). This data suggests Aldrich and Wadena Townships are more impacted than the other two townships sampled. Wadena Township had both the highest percent of vulnerable groundwater and highest percent of row crop production compared to the other two townships (Table 6).

With the exception of Thomastown Township, these results contrast findings from a 2010 USGS report on nitrate concentrations in private wells in the glacial aquifer systems across the upper United States in which less than five percent of sampled private wells had nitrate concentrations greater than 10 mg/L (Warner and Arnold, 2010). The differences in the study findings may be due to the higher row crop areas in the selected townships. Both studies indicate that nitrate concentrations can vary considerably over short distances.

Table 4. Township Population, Households, Sample Kit Distribution and Return Rate

Township	2012 Population	2012 Households	Kits Sent	Kits Returned	Return Rate
Aldrich	430	174	135	33	24%
Thomastown	818	300	276	110	40%
Wadena	857	342	353	95	27%
Wing River	466	183	126	32	25%
Total	2571	999	890	270	*29%

* Represents the average return rate

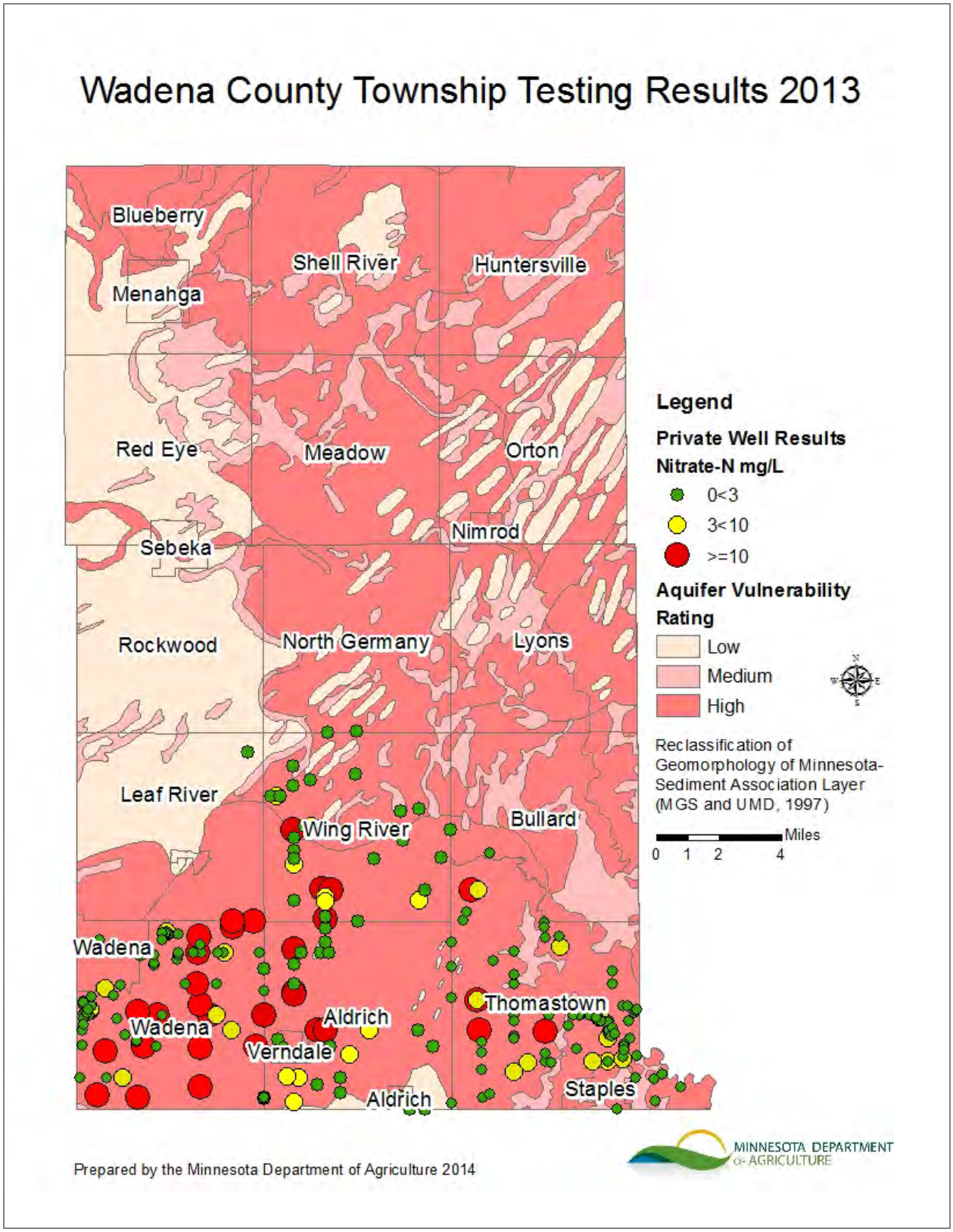

Figure 5. Wadena County Private Well Township Sampling Results 2013

Table 5. Wadena County Township Sampling Summary Statistics without Hand Dug Wells

Township	Total Wells	Values			Percentiles					Number of Wells					
		Min	Max	Mean	50th (Median)	75th	90th	95th	99th	<3 mg/L	3<10 mg/L	≥5 mg/L	≥7 mg/L	≥10 mg/L	<3 mg
		Nitrate-N mg/L or parts per million (ppm)													
Aldrich	33	<DL	32.4	4.9	<DL	5.8	21.6	23.8	32.4	22	5	9	7	6	67
Thomastown	109	<DL	21.2	1.4	<DL	0.1	7.7	9.8	16.8	94	11	15	13	4	86
Wadena	95	<DL	31.3	4.4	0.8	6.5	14.5	20.8	29.6	67	10	26	22	18	71
Wing River	32	<DL	23.4	3.5	<DL	4.1	12.7	21.8	23.4	22	6	6	5	4	69

< DL stands for less than a detectable limit. This means results are less than 0.03 mg/L. The 50th percentile (75th, 90th, 95^{t} below which 50 percent (75%, 90%, 95%, and 99%) of the observed values fall.

Table 6. Township Nitrate Results Summary Related to Vulnerable Groundwater and Row Crop Production

Township	Total Wells*	Percent Vulnerable Aquifer	Percent Row Crop Production	Percent of Wells* Nitrate-N >= 10 mg
Aldrich	33	93%	39%	18%
Thomastown	109	88%	29%	4%
Wadena	95	99%	49%	19%
Wing River	32	98%	18%	13%

*Does not include known hand dug wells

WELL SETTING AND CONSTRUCTION

WELL OWNER SURVEY

The well owner survey, sent out with the sampling kit, provided additional information about private wells that were sampled. The survey included questions about the well construction, depth and age, and nearby land use. Survey questions can be found in Appendix A. It is important to note that well information was provided by the well owners and may be approximate or erroneous. The following section is a summary of information gathered from the well owner survey (complete well survey results are located in Appendix B at the end of this document, Tables 8-22).

The majority of wells in each township are located on “rural” property. Approximately 60 percent of wells in these townships are of drilled construction and 33 percent are sand-point wells. Throughout the four townships, there was only one hand dug well, found in Thomastown Township. Sand point (drive-point) wells are typically completed at shallower depths than drilled wells. Whether a steel or plastic casing is installed, the well code requires that it be watertight and extend at least 15 feet below the ground surface. Sand point wells are also usually installed in areas where sand is the dominant geologic material and where there are no thick confining units such as clay. A confining layer can create a physical barrier to vertical nitrate movement from the water table to deeper portions of the aquifer. These factors make sand point wells more vulnerable to contamination from the surface. Most wells in these townships are less than 100 feet deep. The majority of wells are completed between 11 and 40 feet below ground surface. Well age does not seem to be as much of a factor in affecting nitrate concentrations as the well depth.

WELL LOGS

In some cases, well owners were able to provide Unique Well Identification Numbers for their wells. When the correct Unique IDs are provided, a well log can sometimes be linked to the nitrate result. In this case, 25 wells (nine percent) were identified in the CWI and well logs were obtained (Table 7).

Only Thomastown Township had more than 10 wells with Unique IDs and well logs. Two of the wells were identified as water table wells and none of those were greater than or equal to 10 mg/L. Thirteen were completed in buried sand and gravel aquifers and none of these were greater than or equal to 10 mg/L.

Table 7. Aquifer Designation and Nitrate Results

Township	Aquifer Designation	Total Wells	Ave Depth	Number			Percent		
				<3	3<10	≥10	<3	3<10	≥10
			(Feet)	Nitrate-N mg/L					
Aldrich	Water Table	1	32.0	1	0	0	100%	0%	0%
	Quaternary Buried	1	138.0	1	0	0	100%	0%	0%
Thomastown	Water Table	2	42.0	1	1	0	50%	0%	0%
	Quaternary Buried	13	98.6	12	1	0	92%	8%	0%
Wadena	Water Table	2	68.0	2	0	0	100%	0%	0%
	Quaternary Buried	4	131.0	4	0	0	100%	0%	0%
Wing River	Quaternary Buried	2	73.5	1	0	1	50%	0%	50%
Total	All	25	83.3	22	2	1	88%	8%	4%

* The aquifer designations were obtained from well logs in the CWI database.
QWTA = Quaternary Water table Aquifer
QBAA = Quaternary Buried Artesian Aquifer

POTENTIAL NITRATE SOURCE DISTANCES

The following response summary relates to isolation distances of potential point sources of nitrate that may contaminate wells. This information was obtained from the well surveys completed by homeowners (complete well survey results are located in Appendix B at the end of this document, Tables 8-22).

- On average only 15 percent of the well owners responded that they have livestock (greater than 10 head of cattle or other equivalent) on their property.
- Few well owners (one percent) across all townships store more than 500 pounds of fertilizer on their property.
- Sixty-four percent of wells are greater than 300 feet from an active or inactive feedlot.
- The majority of wells are more than 50 feet away from septic systems.
- Farming takes place on 38 percent of the properties within these four townships.

- Agricultural fields are greater than 300 feet from wells at 50 percent of the properties.

SUMMARY

Using aquifer (groundwater) vulnerability and row crop production as indicators for nitrate contamination in private wells seems to be a useful tool in targeting nitrate sampling. Results from this study indicated Aldrich Township (18 percent) and Wadena Township (19 percent) had a greater nitrate detection frequency for concentrations above 10 mg/L (which is the state Health Risk Limit (HRL)) as compared to more regional sampling studies. Evaluation of this data suggests Aldrich and Wadena Townships are more impacted than Thomastown or Wing River Townships. Aldrich and Wadena Townships also have the highest percent of vulnerable groundwater and highest percent of row crop production compared to the other two townships.

The lower concentrations in Thomastown and Wing River Townships may be due to the fact that they partially overly the Pineland Sands surficial aquifer. The Pineland Sands aquifer consists of finer-grained material than the Wadena surficial aquifer. The finer grained material appears to slow the transport of nitrate to the water table or provides conditions for denitrification as compared to coarser grained material.

Future work that will be considered by the MDA includes the following: 1) resampling wells that had high nitrate results (greater than or equal to 5 mg/L) to verify high nitrate levels; 2) performing well site visits, when possible, to rule out well construction issues and obvious point sources of nitrate, such as septic systems, livestock, etc.; and 3) increasing efforts to obtain well log information for participating wells so that nitrate results and the aquifer designation can be compared in a more comprehensive fashion.

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REFERENCES

Kaiser, K., 2012. Central Sands Private Well Network 2011, Current Nitrate Conditions Summary. Minnesota Department of Agriculture, St. Paul, MN.

Minnesota Department of Health, 2002. Benton County Nitrate-Nitrogen Probability, on-line PDF accessed on 3/11/14 at: http://www.health.state.mn.us/divs/eh/water/swp/nitrate/reports/2002method/Benton.pdf

Minnesota Department of Health, County Well Index website accessed on 4/2/2014 at: http://www.health.state.mn.us/divs/eh/cwi/

Minnesota Department of Natural Resources, 1991. Geologic Sensitivity Project Workgroup. Criteria and guidelines for assessing geologic sensitivity of ground water resources in Minnesota, Minnesota Department of Natural Resources, Division of Waters, St. Paul, Minn., 122 p.

Minnesota Department of Natural Resources, 2012. Geologic Atlas of Benton County, Minnesota, County Atlas Series C-23, Part B.

Minnesota Pollution Control Agency, 1998. Baseline Water Quality of Minnesota's Principal Aquifers, Region 2, North Central Minnesota.

Minnesota Geological Survey, DNR, University of Minnesota –Duluth (1997). Geomorphology of Minnesota, geomorphology data describing a wide variety of conditions related to surficial geology within a hierarchical classification scheme that was devised for use within Minnesota, Scale 1:100,000.

Minnesota Geologic Survey, County Atlas Website accessed on 4/2/2014 at: http://www.mngs.umn.edu/county_atlas/countyatlas.htm

Nolan, BT., and Stoner, J.D., 2000. Nutrients in Groundwaters of the Conterminous United States, 1992-95: Environmental Science and Technology, v. 34, no. 7, p. 1156-1165.

U.S. Environmental Protection Agency, 2009. National Primary Drinking Water Regulations list, on-line PDF file accessed on 12/13/2011 at http://water.epa.gov/drink/contaminants/upload/mcl-2.pdf

Warner, K.L., and Arnold, T.L., 2010. Relations that Affect the Probability and Prediction of Nitrate Concentration in Private Wells in the Glacial Aquifer System in the United States, A USGS National Water-Quality Assessment Program Scientific Investigations Report 2010.

APPENDIX A

Private Well Survey Questions

1. What setting did the water sample come from? Please choose only one.
   Answers choices: Sub-division, Lake Home, River Home, Country, Municipal/city, or Other.

2. Are there livestock on this property? Yes or No

3. Do you mix or store fertilizer (500lbs or more) on this property? Yes or No

4. Does farming take place on this property? Yes or No

Well Information Section

5. Does your well have a Unique Well ID number? Yes or No
6. If yes, what is the Unique ID?
   (6 digit number found on a metal tag attached to your well casing)

7. Type of well construction?
   Answer choices: Drilled, Sandpoint, Hand dug, Other, Other, and don't know.

8. Approximate age (years) of your well?
   Answer choices: 0-9.9 years, 10-19.9 years, 20-39.9 years, and 40 or more years old.

9. Approximate depth of your well
   Answer choices: 0-50 feet, 51-100 feet, 101-300 feet, and 300 or more feet.

10. Distance to an active or inactive feedlot
    Answer choices: 0-50 feet, 51-100 feet, 101-300 feet, and 300 or more feet.

11. Distance to a septic system
    Answer choices: 0-50 feet, 51-100 feet, 101-300 feet, and 300 or more feet.

12. Distance to an agricultural field
    Answer choices: 0-50 feet, 51-100 feet, 101-300 feet, and 300 or more feet.

13. Is this well currently used for human consumption? Yes or no

14. Please check any water treatment you have other than a water softener.
    Answer choices: None, Reverse osmosis, distillation, filtering system and other.

15. When did you last have your well tested for nitrates?
    Answer choices: Never, with the last year, within the last 3 years, the last 10, or 10 or more.

16. What was the result of your last nitrate test?
    Answer choices: 0<3, 3<10, 10 and greater, or don't know.

APPENDIX B

Table 8. Property Setting for Well Location

Property Setting					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Setting	Percent				
Country	97%	80%	82%	97%	89%
Lake	0%	2%	0%	0%	0%
Sub-division	0%	4%	8%	0%	3%
Not available	3%	14%	10%	3%	7%

Table 9. Well Construction Type

Well Construction Type					
Well Type	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Well Type	Percent				
Drilled	58%	71%	42%	69%	60%
Sand point	36%	18%	51%	28%	33%
Hand dug well	0%	1%	0%	0%	0%
Not available	6%	10%	7%	3%	7%

Table 10. Age of Well

Well Age					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Age	Percent				
0-10 years	6%	21%	13%	22%	15%
11-20 years	30%	25%	23%	31%	27%
21-40 years	48%	36%	39%	31%	39%
over 40 years	9%	10%	15%	13%	12%
Not available	6%	8%	11%	3%	7%

Table 11. Depth of Well

Well Depth					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Depth	Percent				
0-50 feet	48%	29%	54%	34%	41%
51-100 feet	27%	34%	26%	34%	30%
101-300 feet	12%	25%	12%	25%	19%
over 300 feet	0%	0%	0%	0%	0%
Not available	12%	12%	8%	6%	10%

Table 12. Unique Well ID Known

Does the Well have a Unique ID					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Unique ID	Percent				
No	52%	27%	39%	28%	36%
Yes	6%	17%	8%	6%	10%
Not available	42%	55%	53%	66%	54%

Table 13. Livestock Located on Property

Livestock on Property					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Livestock	Percent				
No	70%	79%	84%	69%	75%
Yes	27%	8%	7%	19%	15%
Not available	3%	13%	8%	13%	9%

Table 14. Fertilizer Stored on Property

Fertilizer Stored on Property					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Fertilizer	Percent				
No	97%	88%	93%	94%	93%
Yes	0%	0%	1%	3%	1%
Not available	3%	12%	6%	3%	6%

Table 15. Farming on Property

Does Farming take place on Property					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Farming	Percent				
No	48%	60%	66%	50%	56%
Yes	48%	28%	27%	47%	38%
Not available	3%	12%	6%	3%	6%

Table 16. Distance to an Active Feedlot

Feedlot located on Property					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Distance to Feedlot	Percent				
0-50 feet	6%	8%	5%	0%	5%
51-100 feet	6%	4%	0%	3%	3%
101-300 feet	24%	4%	7%	19%	13%
over 300 feet	48%	65%	66%	75%	64%
Not available	15%	20%	21%	3%	15%

Table 17. Distance to Septic System

Distance to Septic System					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Distance to Septic	Percent				
0-50 feet	6%	2%	5%	0%	3%
51-100 feet	24%	34%	36%	41%	34%
101-300 feet	55%	44%	41%	47%	47%
over 300 feet	9%	12%	7%	9%	9%
Not available	6%	9%	11%	3%	7%

Table 18. Distance to an Agricultural Field

Distance to an Agricultural Field					
Agricultural Field	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Distance to Field	Percent				
0-50 feet	15%	5%	3%	9%	8%
51-100 feet	9%	8%	11%	3%	8%
101-300 feet	27%	19%	29%	28%	26%
over 300 feet	39%	58%	46%	56%	50%
Not available	9%	10%	11%	3%	8%

Table 19. Drinking Water Well

Is the Well used for Drinking Water					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Drinking Water	Percent				
No	0%	0%	2%	3%	1%
Yes	94%	92%	93%	94%	93%
Not available	6%	8%	5%	3%	6%

Table 20. Treatment System Present

Treatment System used for Drinking Water					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Treatment System	Percent				
None	58%	61%	55%	50%	56%
Filtering System	3%	10%	10%	28%	13%
Reverse Osmosis	18%	9%	13%	9%	12%
Distillation	0%	0%	0%	0%	0%
Other	3%	0%	5%	0%	2%
Not available	18%	20%	17%	13%	17%

Table 21. Last Tested for Nitrate

When was the Well Last Tested for Nitrate					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Last Tested	Percent				
Within the last year	6%	3%	8%	3%	5%
Within the last 3 years	9%	15%	11%	34%	17%
Within the last 10 years	18%	17%	24%	13%	18%
Never Tested	15%	20%	12%	16%	16%
Greater than 10 years	33%	15%	20%	25%	23%
Not sure	12%	23%	20%	6%	15%
Not available	6%	7%	5%	3%	5%

Table 22. Last Nitrate Test Result

What was the Last Nitrate Result					
Township	Aldrich	Thomastown	Wadena	Wing River	Average
Total Wells	33	110	95	32	68
Last Nitrate-N Result	Percent				
<3 mg/L	15%	23%	14%	31%	21%
3-10 mg/L	12%	5%	10%	13%	10%
> 10 mg/L	9%	<1%	12%	9%	8%
Not available	64%	72%	64%	47%	62%

Minnesota Department of Agriculture

Hubbard County: Overview of Nitrate Levels in Private Wells (2016)

The Minnesota Department of Agriculture (MDA) determines current nitrate-nitrogen concentrations in private wells, on a township scale, through the Township Testing Program. The MDA has identified townships throughout the state that are vulnerable to groundwater contamination and have significant row crop production. The MDA plans to offer nitrate testing to 70,000 private well owners in over 300 townships by 2019.

Each selected township is offered testing in two steps, the "initial" sampling and the "follow-up" sampling. In the initial sampling, all township homeowners using private wells are sent a nitrate test kit. If nitrate is detected in their initial sample, the homeowner is offered a follow-up nitrate test, pesticide test and well site visit. Trained MDA staff visit willing homeowners to resample the well and then conduct a site assessment. The assessment helps to identify possible non-fertilizer sources of nitrate and to see the condition of the well. A well with construction problems may be more susceptible to contamination.

Hubbard County Highlights

- # of Vulnerable Townships Tested: 6
- Households Receiving Kits: 2,899
- # of Wells Tested: 1,106
- % of Wells Over the Health Standard: 10.5%

The MDA and the Hubbard Soil and Water Conservation District worked together to select townships and implement the nitrate testing project. The following townships were selected: **Badoura, Crow Wing Lake, Henrietta, Hubbard, Straight River and Todd.** The initial sampling in Hubbard County started in 2016 and follow-up sampling is scheduled for 2017.

Results

The initial well dataset contains all wells tested (1,106) regardless of well construction issues and sources of nitrate. The Health Standard for nitrate-N in drinking water is 10 mg/L. The results from the initial well dataset are summarized in the table and map below.

Table: Hubbard County Initial Well Dataset Results, 2016.

Township	Number of Wells Tested	Min Nitrate-N mg/L or PPM	Max Nitrate-N mg/L or PPM	Mean Nitrate-N mg/L or PPM	Median Nitrate-N mg/L or PPM	Percent of Wells ≥10 mg/L
Badoura	41	<0.03	32.8	3.8	<0.03	17.1%
Crow Wing Lake	208	<0.03	32.6	2.0	<0.03	8.7%
Henrietta	259	<0.03	20.2	1.5	0.1	3.5%
Hubbard	241	<0.03	46.3	5.2	0.3	19.5%
Straight River	137	<0.03	26.1	2.6	<0.03	10.2%
Todd	220	<0.03	26.9	2.7	<0.03	9.5%
Total	**1,106***	**<0.03**	**46.3**	**2.9**	**<0.03**	**10.5%**

**All well types included.*

Published January 2017

Minnesota Department of Agriculture

Figure: Hubbard County Initial Well Dataset Map, 2016.

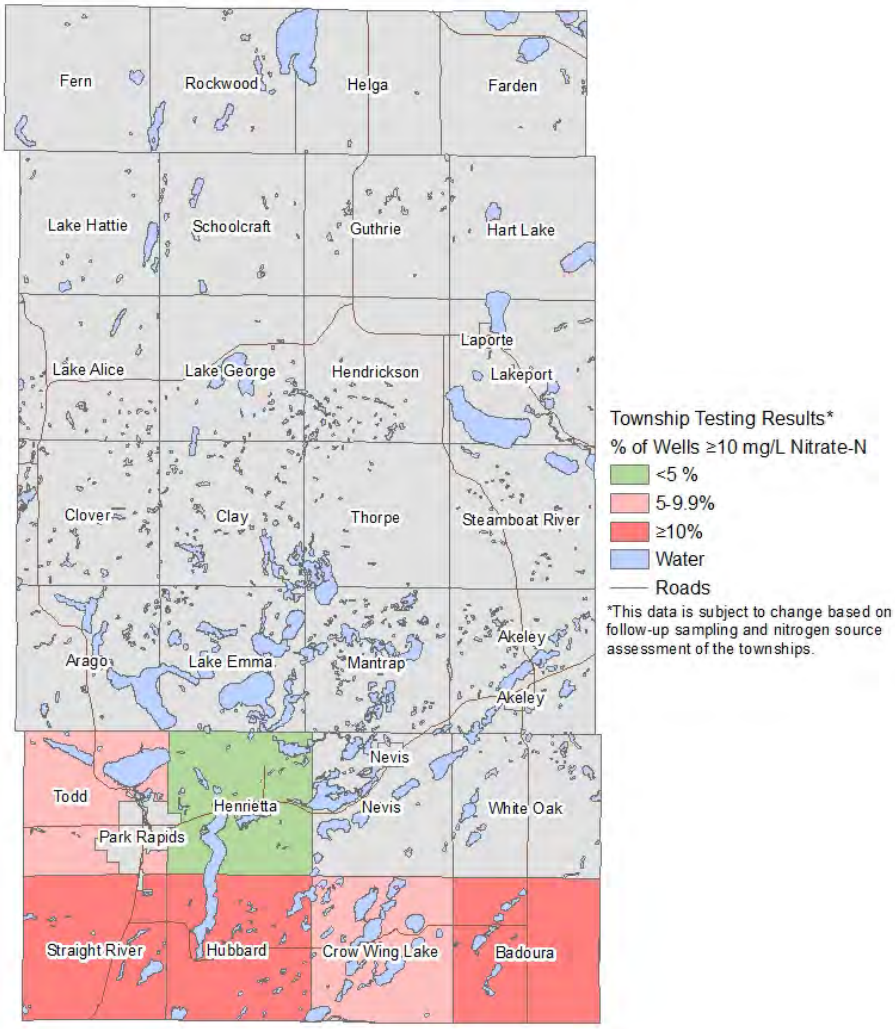

Next Steps

Once the follow-up sampling is completed, the MDA conducts an analysis of the results and prepares a final report for each county (visit www.mda.state.mn.us/townshiptesting). The Hubbard County Final Report will be available in 2018.

The MDA uses the final results to determine if additional action is needed, as described in the Minnesota Nitrogen Fertilizer Management Plan (NFMP). Find more information about the NFMP on the MDA website at www.mda.state.mn.us/nfmp.

Funding Acknowledgement

Funding for this project is provided by the Clean Water, Land and Legacy Amendment

CLEAN WATER LAND & LEGACY AMENDMENT

In accordance with the Americans with Disabilities Act, this information is available in alternative forms of communication upon request by calling 651-201-6000. TTY users can call the Minnesota Relay Service at 711. The MDA is an equal opportunity employer and provider.

MINNESOTA POLLUTION CONTROL AGENCY

WATER POLLUTANT

Nitrogen

Nitrogen, like phosphorus, is a nutrient that pollutes in state waters, and its concentration in many rivers has been increasing from historic natural levels over time due to human influences.

Statewide, data on nitrate concentrations in rivers over the past 20 years show a mixed bag:

- Many monitoring sites with variable levels and no trend
- Many sites where levels have increased
- Some sites where levels have decreased

Sources

More than 70% of the nitrate in Minnesota waters is coming from cropland, the rest from regulated sources such as wastewater treatment plants, septic and urban runoff, forests, and the atmosphere. Nitrate leaching into groundwater below cropped fields and moving underground until it reaches streams contributes an estimated 30% of nitrate to surface waters. Groundwater nitrate can take from hours to decades to reach surface waters.

Cropland sources account for an estimated 89% to 95% of the nitrate load in the Minnesota, Missouri, and Cedar Rivers, and Lower Mississippi River basins.

Tile drainage pathway

In tiled cropland, most of the rainwater that ends up in surface water (ditches, streams) flows through tile drainage. This water can be high in nitrate, but it is also potentially easier to control.

Groundwater pathway

In cropland without tile drainage, most rainwater flows through the ground to get to surface waters. As it travels through the earth, some of the nitrate is removed, resulting in less nitrate reaching our streams and rivers. However, there are fewer options of controlling this kind of nitrate pollution once it moves below the crop roots.

Crop drainage with tiling

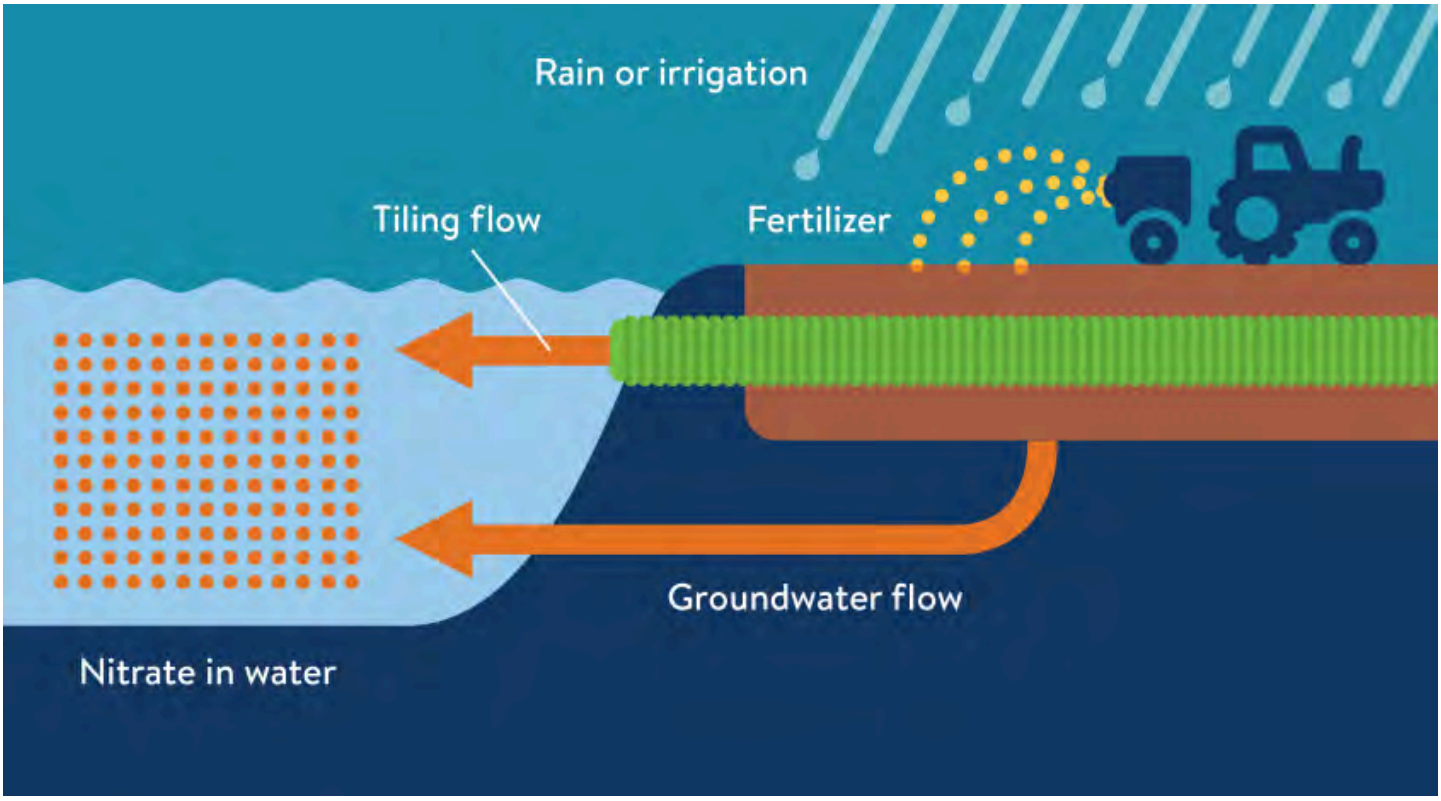

Crop drainage without tiling

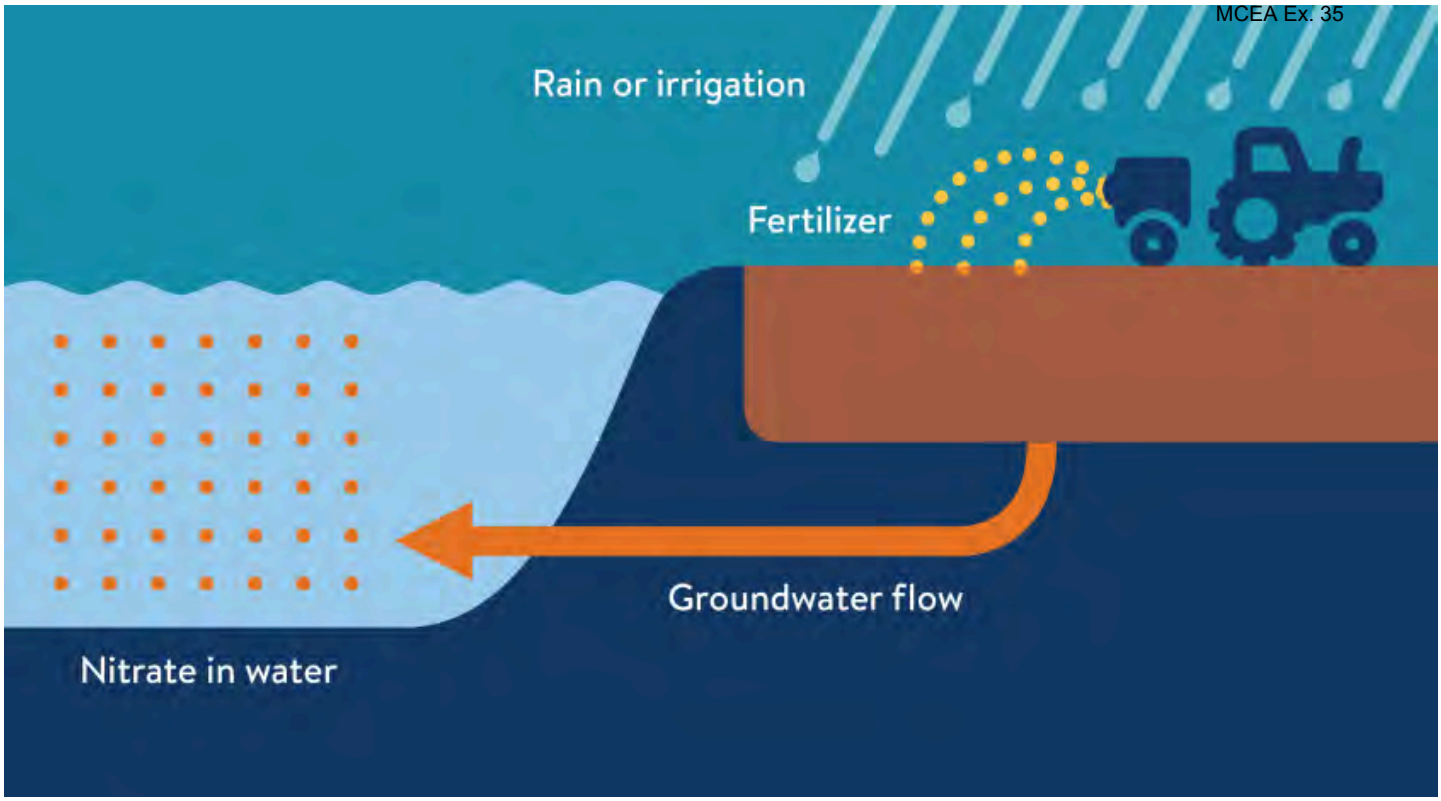

Human health and environmental concerns

Nitrate (a form of nitrogen) in lakes, rivers, and streams is toxic to fish and other aquatic life; in drinking water, it's potentially harmful to humans. Proposed reductions in nitrogen will benefit both Minnesota waters and water downstream from us.

Ammonia is a form of nitrogen that is directly toxic to aquatic life. It comes from wastewater treatment plants and animal waste or air pollution and runoff from agricultural land. Water with high concentrations of ammonia allow the chemical to build up in the tissues and blood of fish, and can kill them.

Nitrate in the Mississippi River

On average, 158 million pounds of nitrate leave Minnesota per year in the Mississippi River — 75% comes from Minnesota watersheds.

Nitrate leaving Minnesota via the Mississippi River contributes to the oxygen-depleted dead zone in the Gulf of Mexico. This dead zone cannot support aquatic

life, affecting commercial and recreational fishing and the overall health of the Gulf. Nitrate concentrations have steadily increased in the Mississippi River since the mid-1970s.

Monitoring, reporting, and regulations

The MPCA's research shows elevated nitrate levels in water, particularly in the southern third of Minnesota.

Reducing nitrate

Tactics for reducing cropland nitrate that reaches surface waters fall into three categories:

- **Manage in-field nutrients** – Optimize fertilizer rates, apply fertilizer closer to timing of crop use
- **Manage and treat tile drainage water** – Plan tile spacing and depth, control drainage, construct and restore wetlands for treatment purposes, use bioreactors
- **Diversify vegetation/landscape** – Plant cover crops, plant more perennials on marginal cropland

Nitrate fertilizer efficiency is improving and further refinements in fertilizer rates and application timing could reduce nitrate loads by roughly 13% statewide. But additional and more costly practices will also be needed to make further reductions and meet downstream needs. Statewide reductions of more than 30% are not realistic with current practices.

Bigger reductions would require limiting nitrate leaching across large parts of southern Minnesota, particularly on tile-drained fields and row crops over thin or sandy soils. Only collective incremental changes by many over broad acreages will result in significant nitrogen reductions to downstream waters.

The Department of Agriculture's Nitrogen Fertilizer Management Plan is the state's blueprint for prevention or minimization of the impacts of nitrogen fertilizer on

groundwater.

More information

- Nitrogen in Minnesota surface waters (wq-s6-26a)
- Nitrate in surface waters summary (wq-s6-26c)
- Reducing nutrients in waters
- Nitrogen in wastewater

Contact

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Drinking Water Requirements for States and Public Water Systems

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Revised Total Coliform Rule And Total Coliform Rule

- Rule Summary
- Rule History
- Compliance

Rule Summary

The Environmental Protection Agency (EPA) published the Revised Total Coliform Rule (RTCR) in the Federal Register (FR) on February 13, 2013 (78 FR 10269) and minor corrections on February 26, 2014 (79 FR 10665). The RTCR is the revision to the 1989 Total Coliform Rule (TCR) and is intended to improve public health protection.

All public water systems (PWSs), except aircraft PWSs subject to the Aircraft Drinking Water Rule (ADWR) (40 CFR 141 Subpart X), must comply with the RTCR starting April 1, 2016, or an earlier state effective date. Until then, PWSs must continue complying with the 1989 TCR.

Total coliforms are a group of related bacteria that are (with few exceptions) not harmful to humans. A variety of bacteria, parasites, and viruses, known as pathogens, can potentially cause health problems if humans ingest them. EPA considers total coliforms a useful indicator of other pathogens for drinking water. Total coliforms are used to determine the adequacy of water treatment and the integrity of the distribution system.

For more information about total coliforms, please go to the webpage Basic Information about Pathogens and Indicators in Drinking Water

Key provisions of the RTCR include:

- Setting a maximum contaminant level goal (MCLG) and maximum contaminant level (MCL) for E. coli for protection against potential fecal contamination.

- Setting a total coliform treatment technique (TT) requirement.
- Requirements for monitoring total coliforms and E. coli according to a sample siting plan and schedule specific to the PWS.
- Provisions allowing PWSs to transition to the RTCR using their existing Total Coliform Rule (TCR) monitoring frequency, including PWSs on reduced monitoring under the existing TCR.
- Requirements for seasonal systems (such as, Non-Community Water Systems not operated on a year-round basis) to monitor and certify the completion of a state-approved start-up procedures.
- Requirements for assessments and corrective action when monitoring results show that PWSs may be vulnerable to contamination.
- Public notification (PN) requirements for violations.
- Specific language for CWSs to include in their Consumer Confidence Reports (CCRs) when they must conduct an assessment or if they incur an E. coli MCL violation.

Quick Reference Guides

- Revised Total Coliform Rule: A Quick Reference Guide (PDF)
  (3 pp, 450 K, About PDF) EPA 815-B-13-001, September 2013
- Total Coliform Rule: A Quick Reference Guide (PDF)
  (2 pp, 114 K, About PDF) EPA 816-F-01-035, September 2001

Guidance for People with Severely Weakened Immune Systems

- A joint EPA and CDC guidance document for people who are immunocompromised (PDF)
  (2 pp, 21 K, About PDF) EPA 816-F-99-005, June 1999
- Spanish version – "Guía Para Individuos Con El Sistema Inmunológico Severamente Debilitado" (PDF)
  (2 pp, 36 K, About PDF) EPA 815-F-00-005, April 2000

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Rule History

Revised Total Coliform Rule (RTCR)

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- The Federal Register Final RTCR

Minor corrections to the final RTCR became effective on April 28, 2014. No comments were received on the Direct Final Rule published on February 26, 2014. The corrections therefore became effective without further notice.

- The *Federal Register* notice of the minor corrections

All public water systems (PWSs), except aircraft PWSs subject to the Aircraft Drinking Water Rule (ADWR) (40 CFR 141 Subpart X), must comply with the RTCR starting April 1, 2016, or an earlier state effective date. Until then, PWSs must continue complying with the 1989 TCR.

- Revised Total Coliform Webinar- April 10, 2013

RTCR Federal Register Notice and Supporting Documents

- National Primary Drinking Water Regulations: Revisions to the Total Coliform Rule; Final Rule.
- National Primary Drinking Water Regulations: Revisions to the Total Coliform Rule; Proposed Rule
- Fact Sheet: Announcement of Revisions to the Total Coliform Rule (PDF)
  (3 pp, 44 K, About PDF) EPA 815-F-12-007, December 2012
- Economic Analysis for the Final Revised Total Coliform Rule, including Appendices (PDF)
  (609 pp, 4.1 MB, About PDF) EPA 815-R-12-004, February 2013

EPA established the Total Coliform Rule Distribution System Advisory Committee (TCRDSAC) under the Federal Advisory Committee Act. The purpose was to make recommendations to the Agency on revisions to the 1989 TCR. For more information about the Federal Advisory Committee that recommended changes to the 1989 TCR, please review Total Coliform Rule Distribution System Advisory Committee (TCRDSAC).

Total Coliform Rule (TCR)

The Total Coliform Rule (TCR), a National Primary Drinking Water Regulation (NPDWR), was published in 1989 and became effective in 1990. The rule set both a health goal (Maximum Contaminant Level Goal (MCLG)) and legal limits (Maximum Contaminant Levels (MCLs)) for the presence of total coliforms in drinking water.

EPA set the MCLG for total coliforms at zero because there have been waterborne disease outbreaks in which researchers found very low levels of coliforms. The MCL levels are based on the positive sample tests for total coliforms (monthly MCL), or for total coliforms and Escherichia coli (E. coli) or fecal coliforms (acute MCL).

The purpose of the 1989 TCR is to protect public health by ensuring the integrity of the drinking water distribution system and monitoring for the presence of microbial contamination.

The rule requires all public water systems (PWSs) to monitor for the presence of total coliforms in the distribution system at a frequency proportional to the number of people served.
TCR Federal Register Notice

Compliance

TCR Key Provisions

To comply with the monthly MCL for total coliforms (TC), PWSs must not find coliforms in more than five percent of the samples they take each month to meet EPA's standards. If more than five percent of the samples contain coliforms, PWS operators must report this violation to the state and the public.

If a sample tests positive for TC, the system must collect a set of repeat samples located within 5 or fewer sampling sites adjacent to the location of the routine positive sample within 24 hours.

When a routine or repeat sample tests positive for total coliforms, it must also be analyzed for fecal coliforms or E. coli, which are types of coliform bacteria that are directly associated with fresh feces. A positive result for fecal coliforms or E. coli can signify an acute MCL violation, which necessitates rapid state and public notification because it represents a direct health risk.

At times, an acute violation due to the presence of fecal coliform or E. coli may result in a "boil water" notice. The system must also take at least 5 routine samples the next month of operation if any sample tests positive for total coliforms.

RTCR Key Provisions	
Provision Category	**Key Provisions**
Contaminant Level	• Addresses the presence of total coliforms and E. coli in drinking water. • For E. coli (EC), the Maximum Contaminant Level Goal (MCLG) is set at zero. The Maximum Contaminant Level (MCL) is based on the occurrence of a condition that includes routine and repeat samples. • For total coliforms (TC), PWSs must conduct a Level 1 or Level 2 assessment of their system when they exceed a specified frequency of total coliform occurrences. • An MCL violation or failure to take repeat samples following a routine total coliform-positive sample will trigger a Level 1 or Level 2 assessment. • Any sanitary defect identified during a Level 1 or Level 2 assessment must be corrected by the PWS. These are the treatment technique requirements of the RTCR.
Monitoring	• Develop and follow a sample siting plan that designates the PWS's collection schedule. This includes location of routine and repeat water samples. • Collect routine water samples on a regular basis (monthly, quarterly, annually). Have samples tested for the presence of total coliforms by a state certified laboratory. • Analyze all routine or repeat samples that are total coliform positive (TC+) for E. coli. • Collect repeat samples (at least 3) for each TC+ positive routine sample. • For PWSs on quarterly or annual routine sampling, collect additional routine samples (at least 3) in the month after a TC+ routine or repeat sample. • Seasonal systems must monitor and certify the completion of a state-approved start-up procedures.
Level 1 and Level 2 Assessments and Corrective Actions	• PWSs are required to conduct a Level 1 or Level 2 assessment if conditions indicate they might be vulnerable to contamination. PWSs must fix any sanitary defects within a required timeframe.

RTCR Key Provisions	
Reporting and Recordkeeping	• PWSs are required to report certain items to their states. These reporting and recordkeeping requirements are essentially the same as under TCR. The addition to the Requirements is the Level 1 and Level 2 requirements.
Violations, Public Notification (PN) and Consumer Confidence Report (CCR)	• PWSs incur violations if they do not comply with the requirements of the RTCR. The violation types are essentially the same as under the TCR with few changes. The biggest change is no acute or monthly MCL violation for total coliform positive samples only. • PN is required for violations incurred. Within required timeframes, the PWS must use the required health effects language and notify the public if they did not comply with certain requirements of the RTCR. The type of PN depends on the severity of the violation. • Community water systems (CWSs) must use specific language in their CCRs when they must conduct an assessment or if they incur an E. coli MCL violation.

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LAST UPDATED ON FEBRUARY 23, 2016

MINNESOTA POLLUTION CONTROL AGENCY

WATER POLLUTANT

Bacteria

Countless bacteria can be found in land, water, humans, and animals. Most bacteria are beneficial, serving as food for larger organisms and playing critical roles in natural processes such as organic matter decomposition and food digestion. But about 10% of bacteria, such as *E. coli,* are harmful and, if ingested by humans, can cause sickness or even death.

Sources

Bacteria in Minnesota lakes and streams mainly come from sources such as failing septic systems, wastewater treatment plant releases, livestock, and urban stormwater. Waste from pets and wildlife is another, lesser source of bacteria.

Human health and environmental concerns

In addition to bacteria, human and animal waste may contain pathogens such as viruses and protozoa that could be harmful to humans and other animals. The behavior of bacteria and pathogens in the environment is complex. Levels of bacteria and pathogens in a body of water depend not only on their source, but also on weather, current, and water temperature. As these factors fluctuate, the level of bacteria and pathogens in the water may increase or decrease. Some bacteria can survive and grow in the environment while many pathogens tend to die off with time.

Monitoring, reporting, and regulations

Testing for specific disease-producing bacteria or other pathogens is difficult, expensive, and time-consuming. The MPCA tests for fecal coliform and *E. coli* bacteria, which are commonly found in fecal waste and are easy to measure. They are often used as "indicator organisms" to denote the potential presence of fecal waste. Although using indicator bacteria to assess the presence of pathogens in not a perfect process, it is the best available option at this time. Lakes and streams in Minnesota meet water quality standards if they have a monthly geometric mean less than 126 colony-forming units of *E. coli* per 100 milliliters of water, between April and October.

Most lakes and streams in Minnesota meet water quality standards for bacteria. MPCA uses the *E. coli* water quality standard to identify water bodies that may be contaminated with fecal waste. Higher levels of *E. coli* in the water may or may not be accompanied by higher levels of pathogens and an increased risk of harm; varying survival rates of bacteria make is impossible to definitively state when pathogens are present. See the Minnesota Department of Health Waterborne Illness web page for more information on how to reduce your risk for waterborne illnesses when swimming, boating, or wading.

Is my lake or stream safe for swimming?

Minnesota does not have a list of "safe" bodies of water for recreation. Sometimes a city or county health department will close a swimming beach due to bacterial contamination. Conditions can change over time, and state water-testing efforts are not frequent enough to be time current, particularly in streams and rivers. If you have questions about a specific beach, check with the proper beach authority for their current information and recommendations.

Check with your city or county environmental services to see if your local lake is tested on a regular basis. Two examples of local testing programs:

- Minnesota Lake Superior Beach Monitoring Program
- Hennepin County public swimming beaches

Addressing bacterial contamination

Some bacteria and pathogens will always be present in surface waters. While most of the bacteria and pathogens from fecal waste in the water will die off over time, some may survive. Pathogens from fecal waste generally die off in the environment much faster than bacteria. While there is not a way to rid water bodies of all pathogens, we can reduce bacteria in surface waters by combining the efforts of many individuals and groups. The best methods include:

- Controlling runoff on feedlot properties and where manure is spread on farmland
- Repairing or replacing failing septic systems
- Improving wastewater treatment processes at some facilities
- Controlling erosion with practices such as conservation tillage and riparian buffers
- Rotational livestock grazing, which reduces both sedimentation and fecal coliform concentrations
- Urban stormwater management – runoff detention, infiltration, and street sweeping

Many government entities and groups across Minnesota are working to better understand sources of bacteria in water and mitigate them. Some examples include:

- Pollutant reduction studies that lead to limits on bacteria discharged by wastewater treatment facilities to lakes and streams
- Feedlot runoff controls and other conservation practices installed by farmers because of permit requirements or a statewide water quality certification program
- County and state programs to bring failing sewer systems into compliance

More information

- Water quality and bacteria frequently asked questions (wq-s1-93)
- Gray water management for houseboats and cabin cruisers (wq-s1-100)

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Nitrate contamination of Minnesota waters shows little sign of going away, despite years of effort

www2.startribune.com/nitrate-pollution-minnesota-groundwater-farm-fertilizer-mpca-wells-epa/600310942

Jeff Hargarten, Jennifer Bjorhus, Star Tribune November 29, 2023

Farm pollution persists despite hundreds of millions spent to clean it up.

By Jeff Hargarten and Jennifer Bjorhus Star Tribune
November 28, 2023 — 6:20pm



Brian Peterson, Star Tribune file

Utica, Minn., a farm town of about 200 people surrounded by fields in Winona County, is preparing to dig a new, deeper well to find clean water because the city's water is contaminated with nitrate. It's one example of the state's stubborn problem with reducing nitrate contamination from farm pollution.

Minnesota has spent hundreds of millions of dollars and decades of effort to reduce nitrate that's contaminating drinking water and rivers. The progress so far: negligible.

The main source of the nitrate is nitrogen fertilizer, a pillar of production agriculture that includes animal manure and synthetic chemicals. Farmers apply tens of thousands of tons of fertilizers to their fields every year, and what isn't absorbed by crops can seep into aquifers and any runoff can end up in rivers.

Despite numerous programs designed to encourage farmers to change their ways, purchases of fertilizer keep growing. In many parts of Minnesota farm country, drinking water wells and streams carry that legacy: A decades-old state law limits how much nitrate is allowed in drinking water, although some researchers now say that level needs to be much stricter to protect people.

The three agencies tasked with keeping Minnesota waters clear of harmful levels of nitrate acknowledge that the situation isn't improving, particularly for private wells in the vulnerable topography of the state's hilly southeastern corner. In that region, frustrated residents have called for the federal government to intervene on what environmental groups call a public health emergency — and the EPA recently responded with a directive that Minnesota clean up its act.

A lack of progress

Nitrate levels of 10 milligrams per liter of water or higher have violated federal health standards since the 1960s, since those concentrations are known to cause the potentially life-threatening condition methemoglobinemia, or blue baby syndrome, that starves infants of oxygen.

But there's a push to reduce the state and federal nitrate standard from the 10 mg/l limit, given growing research around links to cancer and other damaging health impacts from drinking water with nitrate at half the legal maximum concentration, or even lower.

Community drinking water supplies, which serve cities, towns and mobile home parks, are regularly tested to assure nitrate levels are below the state and federal health limit.

While those with the highest nitrate concentrations have taken action to reduce it, about 177,000 Minnesotans still lived in communities with average readings above 3 milligrams of nitrate per liter of water as of 2022, levels considered by health authorities to be caused by human activity, not nature.

At least 400,000 Minnesotans in more than 100 communities live in areas where water has tested at least once for elevated nitrate levels since 2013. They're mostly spread across central and southern parts of the state.

Separately, there are some 980,000 private wells in Minnesota, according to the Minnesota Well Owners Organization. And people who rely on them for drinking water are on their own to have them tested and, if necessary, find remedies.

Far more Minnesotans could be affected by elevated nitrate levels in their water, but a lack of one central testing agency means it is difficult to gather and compare data.

The volunteer private well tests the Department of Agriculture has helped run show the problem is widespread. In southeast Minnesota from 2008 through 2018, about 8% to 15% of the hundreds of private wells tested each year showed nitrate pollution above the 10 mg/L health limit. In 2021, about 30% of those private wells showed results above 3 milligrams.

In the 14-county Central Sands Region from 2011-2018, about 3% to 5% of the hundreds of private wells tested each year were polluted with nitrate above the 10 mg/L limit.

Public drinking water systems — not private wells — that violate federal nitrate contamination standards must report them to the EPA. Those violations in Minnesota totaled 34 last year in the EPA's Safe Drinking Water Information System and included gas stations, bars and churches.

Impaired rivers and streams

Nitrate also endangers fish and other aquatic life when it leaches into lakes, streams and rivers.

The nitrate entering the Mississippi River contributes to the huge oxygen-starved dead zone in the Gulf of Mexico. As part of the Hypoxia Task Force of states up and down the river, Minnesota has pledged to cut the nitrate in the Mississippi by 20% by 2025. But nitrate has actually risen in spots, as it has in most of the state's major rivers.

Lawmakers directed the Minnesota Pollution Control Agency in 2010 to set limits on nitrate to protect fish and aquatic life. It hasn't happened. It would be too expensive for small wastewater treatment plants, and wouldn't effectively reduce the nitrate from the farms it has no power to regulate, the agency told the Star Tribune.

About 5% — or 165 miles — of Minnesota's rivers and streams used for drinking water are impaired by nitrogen and/or phosphorus as of 2022, meaning they don't meet federal quality standards. In all, the EPA lists more than 300 bodies of water across the state including parts of the Minnesota, Mississippi and St. Croix rivers, as well as other streams and rivers, as threatened or impaired by nitrogen and phosphorus and in need of a restoration plan.

Spending with little impact

Hundreds of millions in federal and state funding has paid for nitrate research, efforts to change farming and other practices and nitrate filtration systems for water supplies in Hastings, Cold Spring, Adrian and four other cities.

That's paid for Nitrogen Smart farmer training in the past, water research, conservation programs, source water protection work and guidance for farmers on adopting best management practices — and that's just a few examples. The state covers this list in its five year progress reports on the state's 2014 Nutrient Reduction Strategy to cut nitrogen and phosphorus in waters.

The state's Clean Water Fund, part of the sales-tax funded Legacy Amendment, has directed at least $148 million to the nitrate problem since 2010, according to a Star Tribune analysis, and is just one of several spending sources.

None of it appears to have made a dent in the overall demand for nitrogen fertilizer. As cropland has expanded, farmers bought a record high 824,000 tons of nitrogen fertilizer in 2020, the most recent year for which data is available, according to sales tracked by the state Department of Agriculture.

Agency response

The responsibility for reducing nitrate lies mostly with three state agencies: Minnesota Department of Health, the Minnesota Department of Agriculture and the Minnesota Pollution Control Agency (MPCA). All said their efforts will pay off eventually.

The MPCA blamed climate change's effect on precipitation for the failure to show progress on nitrate reduction.

"It will take time to see the benefit of this work, especially as more frequent and extreme weather events caused by climate change are both masking our progress and worsening the nitrate problem by forcing nitrate pollution off lands, into groundwater, rivers, and downstream," said MPCA spokeswoman Andrea Cournoyer.

The Health Department said 30 years of data doesn't show increasing nitrate violations in the public water supplies it watches, but that it's a "different story" for private well owners in certain highly vulnerable parts of the state.

The Agriculture Department agrees that in parts of southeast Minnesota, the nitrate in private water wells "has been going up slowly for decades."

"Nowhere in the U.S. is a state tackling nitrate issues like Minnesota," the agriculture department said.

Some in southeast Minnesota, a land of heavy agriculture and a porous karst geography, say they can't wait any longer for help. A group from Dodge, Goodhue, Fillmore, Houston, Mower, Olmstead, Wabasha and Winona counties asked the EPA to declare a public health emergency because state and local authorities haven't controlled nitrate pollution of groundwater.

About 80,000 residents in those counties rely on private wells for their drinking water and about 300,000 use public water systems, according to the request for help, filed in April by the Minnesota Center for Environmental Advocacy, the Minnesota Well Owners Association and others.

The EPA responded with a letter this month, warning Minnesota's three responsible agencies of possible enforcement actions if they don't enact measures to better warn residents of nitrate dangers, provide bottled water and develop plans to reduce nitrate pollution in the region.

Further reading

Sources: Environmental Protection Agency, EPA Safe Drinking Water Information System, Minnesota Pollution Control Agency, Minnesota Department of Health, Minnesota Department of Agriculture, Environmental Working Group, Star Tribune reporting and analysis

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MCEA Ex. 39

Groundwater quality

pca.state.mn.us/air-water-land-climate/groundwater-quality

Image



Groundwater is the source of drinking water for about 75% of all Minnesotans and provides almost all of the water used to irrigate crops. Groundwater in parts of the central and southwestern regions of the state is contaminated with high nitrate concentrations from agriculture and, to a lesser extent, failing septic systems. Nitrate levels are higher in groundwater under agricultural land than water below urban areas. Groundwater availability in Minnesota varies by region. It is more difficult to access in the northeast, when it's available at all, and is scarce in some areas of the southwest.

Overall conditions

- The quality of groundwater varies around the state. Even within an aquifer, the quality can change at different depths. Near-surface groundwater in areas of high urban density or intensive agriculture is more likely to be contaminated by chloride or nitrate.
- The overuse of groundwater threatens surface water quality, and draws contaminated near-surface water into our drinking water aquifers.

Current regulations and voluntary best management practices will not be sufficient to maintain healthy groundwater and shield contaminated wells and aquifers from additional pollution. Even if all existing laws were followed to the letter, groundwater would still be subject to unacceptable levels of nutrients and other contaminants. Targeted action will be required to cut off unregulated sources of pollution.

Northeast Minnesota

Availability issues. Higher volume supplies of groundwater can be difficult to obtain in the northeast, compared to the central part of the state.

Central region

- **Availability good.** Groundwater is available throughout this region in volumes sufficient to satisfy residential use.
- **Nitrate pollution.** About 40 percent of the shallow wells (less than 30 feet deep) in the central region have higher nitrate concentrations than the EPA allows for drinking water.

Metro area and the southeast

- **Availability issues.** Though this region has multiple aquifers, groundwater availability is threatened by high consumption in the Twin Cities metro area.
- **Chloride pollution.** Groundwater in the Twin Cities metro area shows high concentrations of chloride.
- **Nitrate pollution.** Most of the sand and gravel aquifers in southern Minnesota have nitrate concentrations that exceed EPA guidelines for human health.

Western and southwestern Minnesota

Nitrate pollution. About 20 percent of the monitored shallow wells in the southwestern region have nitrate concentrations higher than the EPA allows for drinking water.

How groundwater affects surface water

Groundwater contamination and diminishing water levels in the ground can affect bodies of water on the surface. Groundwater feeds surface waters and helps maintain water levels during droughts. If groundwater is being used up and the water level in a stream goes down as a result, the pollutants in the stream will be concentrated, doing greater environmental damage.

The low water levels in Little Rock Creek north of St. Cloud illustrate how groundwater interacts with surface water. Heavy groundwater pumping in the area contributes to low stream flows in the summer, killing off fish. Downstream at Little Rock Lake, low water and excess nutrients cause massive summer algae blooms. The local soil and water conservation district is working with farmers on irrigation management strategies that will use less groundwater.

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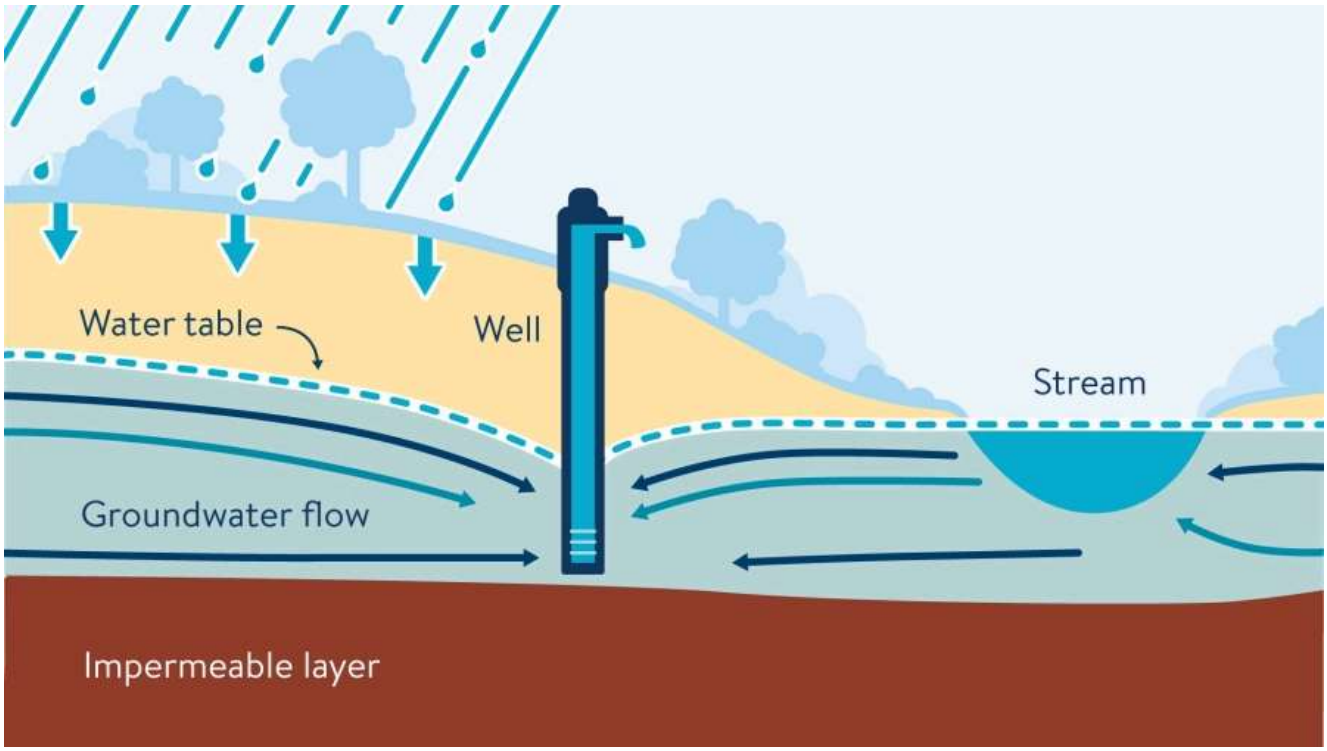
Water table
Well
Stream
Groundwater flow
Impermeable layer

MINNESOTA POLLUTION CONTROL AGENCY

www.pca.state.mn.us

Livestock and the environment

MPCA Feedlot Program overview



In Minnesota there are an estimated 18,000 livestock feedlots registered under the state's feedlot rule. They range in size from small farms to large-scale commercial livestock operations. Agriculture including livestock comprises a major portion of the state's economy. Many organizations and programs work with livestock producers to ensure that Minnesota continues to have a healthy livestock industy and a healthy natural environment.

The Minnesota Pollution Control Agency (MPCA) regulates the collection, transportation, storage, processing and disposal of animal manure and other livestock operation wastes. The MPCA Feedlot Program implements rules governing these activities, and provides assistance to counties and the livestock industry. The feedlot rules apply to most aspects of livestock management including the location, design, construction, operation and management of feedlots and manure handling facilities.

The MPCA feedlot staff are located in six offices: Brainerd, Detroit Lakes, Mankato, Marshall, Rochester, and St. Paul. They work in the areas of land application of manure, permitting, data management, technical assistance, and compliance with feedlot rules. On the web: www.pca.state.mn.us/water/feedlots.

Protect water

There are two primary concerns about feedlots in protecting water in our agricultural areas:

- Ensuring that manure on a feedlot or manure storage area does not run into water;
- Ensuring that nutrient-rich manure is applied to cropland at a rate, time and method that prevents nutrients and other possible contaminants from entering streams, lakes and ground water.

The MPCA works with farmers to make sure their feedlots are environmentally safe. Staff provides technical assistance to farmers, and conducts inspections at feedlots to be certain they comply with environmental requirements. Some of those requirements for feedlots include:

- Construction specifications for manure storage areas;
- Manure management plans for medium and large-sized feedlots; and
- Land application of manure on fields.

Feedlot rule

Feedlot rules have been in effect in Minnesota since the early 1970s. In October 2000 a major revision of the feedlot rule (Minn. R. ch. 7020) went into effect, followed by an update in 2014. The main goals are:

- Register all feedlots capable of holding 50 or more animal units (AU-see page 4), or 10 or more animal units within shoreland areas;
- Focus on animal feedlots and manure storage areas that have the greatest potential for environmental impact;
- Support the role of delegated counties in the feedlot program; and
- Maintain agency and delegated-county staff field presence.

The feedlot rule does not specifically regulate pasture operations; however, they still must abide by Minnesota Rules chapter 7050 prohibiting pollution of state waters.

Delegated county program



In 50 counties (current as of January 2021) the feedlot program is conducted through a cooperative arrangement between the MPCA and county government. County feedlot programs have responsibility for implementing state feedlot regulations for facilities with fewer than 1,000 animal units (AU) that are not subject to state or federal operating permit requirements. These responsibilities include: registration, permitting, inspections, education and assistance, and complaint follow-up. Current map of delegated counties: www.pca.state.mn.us/sites/default/files/wq-f1-12.pdf

Delegated counties receive state grants to help fund their programs. Funds are awarded based on the number of feedlots in the county with more than 50 AU (10 or more AU in shoreland) and the level of inspections completed. In recent years annual grants statewide have totaled nearly $2 million. Delegated counties work together through the Minnesota Association of County Feedlot Officers: www.pca.state.mn.us/water/minnesota-association-county-feedlot-officers

Feedlot permits

Most smaller-sized feedlots are not required to have permits. Most large feedlots operate with state and federal permits. The National Pollutant Discharge Elimination System (NPDES) permit and the State Disposal System (SDS) permit require specific conditions to comply with state law and the federal Clean Water Act. Of the approximately 1,200 feedlots operating with an NPDES or SDS permit, most have a general permit; about 50 have individual permits. A general permit is a single document that can apply to all livestock facilities whose operations are similar. The MPCA or delegated counties also issue permits for feedlot construction, and interim permits allowing feedlots with pollution problems to operate in a two-year period during which the problems are corrected.

Nutrient and manure management



Livestock manure is a valuable resource if managed properly. It has been estimated that the amount of manure generated by livestock in Minnesota would be equivalent to that of a human population of about 50 million. Land application removes livestock manure from feedlots and provides fertilizer for crops. There are many ways to ensure that land-applied manure does not run off into waters, and is not over-applied beyond crop nutrient needs. Manure management plans are required when producers need to apply for a feedlot permit, or when a facility has 300 or more AU and does not use a licensed commercial applicator. Manure management plans help ensure that application rates do not exceed crop nutrient needs, and that setbacks from waters and drain tile intakes are observed.

Environmental assessment at large feedlots

An environmental assessment looks at how a proposed feedlot project will affect the air, water and land, and at ways to mitigate any problems so that the project can go forward and be environmentally safe. Environmental Assessment Worksheets (EAWs) are mandatory for proposed feedlots over 1,000 AU, or over 500 AU in a sensitive area. More information is available on the Environmental Quality Board Web site: www.eqb.state.mn.us/.

Pasture



Pastures are a common type of livestock operation. Typical examples include beef grazing and cow/calf operations. A pasture operation is not required to have a feedlot permit. Distinguishing pastures from feedlots is not always easy. Some operations include both pasture and feedlot components. An area of an operation with accumulated manure and a lack of vegetative cover beyond the immediate vicinity of supplemental feeding or watering devices, working areas, or access lanes, will not be considered to be pasture.

Winter feeding areas are exempt from feedlot rules, but they must be part of a larger grazing area where grass or other growing plants are used for grazing. Even if an operation is not required to get a permit because it is considered to be pasture, that operation is not allowed to discharge to waters of the state. For example, a pasture with a flow of manure-contaminated runoff from a supplemental feeding or watering area to a stream will be required to terminate the discharge. Seasonal or crop residue grazing may also be considered pasture. However, if the concentration of animals is such that unvegetated "feedlot" conditions develop and adequate forage is not available for livestock, requiring regular feed to be provided, the MPCA will require a feedlot permit for animals confined on cropland.

Air quality

As some livestock operations have grown larger and more people are living near livestock farms, odor (particularly hydrogen sulfide) has become an issue. There are regulations for hydrogen sulfide, which can be toxic at high levels. The MPCA does not regulate odor in general; however some local units of government may have restrictions related to odor.

The MPCA does regulate hydrogen sulfide emissions and requires the following:

- Requiring odor management plans to be included in the permits of large feedlots; and
- Monitoring hydrogen sulfide emissions at feedlots where there have been odor complaints.



Training and technical assistance

The MPCA provides training opportunities and assistance to counties and livestock producers. County feedlot officers receive inspection and permitting training, covering all aspects of the program. MPCA technical staff conduct workshops and presentations for county staff and producer groups.

Contacts

Contact information for feedlot program staff is available at www.pca.state.mn.us/water/mpca-feedlot-staff-contacts, or by calling the MPCA at 651-296-6300, or 800-657-3864.

For more information

Producer organizations also provide environmental management information to their members. The following Web sites are good information sources for feedlots and manure management:

- Manure and Odor Education Research – University of Minnesota Extension: extension.umn.edu/livestock-operations/manure-management.
- Minnesota Department of Agriculture: www.mda.state.mn.us/siting-livestock-farms-minnesota.
- National Agriculture Compliance Assistance Center: www.epa.gov/oecaagct/anafocom.html.

Animal units

Minnesota uses animal units to quantify the size of livestock feedlots. One animal unit is equivalent to the amount of manure produced by a 1,000-lb. steer. Following is a list of animal unit factors for several livestock types. The number livestock times the animal unit factor gives the number of animal units.

Mature dairy cow over 1,000 lbs.	1.4	AU
Cow/calf pair	1.2	”
Stock cow/steer	1.0	”
Horse	1.0	”
Dairy heifer	0.7	”
Swine 55-300 lbs.	0.3	”
Sheep	0.1	”
Broiler (over 5 lbs., dry manure)	0.005	”
Turkey over 5 lbs.	0.018	”

(Example: 3,334 market hogs = 1,000 AU)







Nutrient & Manure Management Tables

MINNESOTA DEPARTMENT OF AGRICULTURE

UNIVERSITY OF MINNESOTA EXTENSION

Table 1. Annual Manure Production and Nutrient Excretion from Livestock

Animal Type	Manure Production per 1,000 lb. of Animal Weight		Excreted Nutrients in Manure per 1,000 lb. of Animal Weight		
	Solid tons/year	Liquid gal./year	N lb./year	P2O5 lb./year	K2O lb./year
BEEF CATTLE					
Calf	19.5	4,591	162	73	130
Finishing	9.0	2,141	131	39	83
Cow	16.8	3,982	128	66	106
DAIRY CATTLE					
Calf	14.6	3,358	146	24	122
Heifer	11.0	2,536	112	39	112
Lactating	20.3	4,876	263	135	146
Dry Cow	9.3	2,241	110	40	88
Veal	4.8	1,153	44	29	73
SWINE					
Nursery	13.9	3,358	292	146	146
Finishing	9.0	2,166	219	73	97
Gestating Sow	4.1	998	61	37	49
Lactating Sow	8.5	2,025	165	107	127
Boar	3.8	900	49	37	37
POULTRY					
Layer	9.1	2,068	316	97	146
Broiler	17.3	4,198	383	256	183
Turkey (F)	8.6	2,044	285	186	124
Turkey (M)	6.8	1,606	203	135	88
Duck	20.1	4,836	392	310	237
HORSE					
Pleasure	9.9	2,394	66	22	22
"Racer"	10.1	2,446	110	55	84
SHEEP					
Feeder	7.5	1,825	146	73	146

Adapted From: Manure Characteristics, MWPS-18 Section 1, Midwest Plan Service, 2004 Second Edition

Table 2. Nitrogen Losses From Animal Manure as Affected by Method of Handling and Storage

Manure Storage and Handling method	Manure Type	% Storage Nitrogen Loss
Daily scrape and haul	Solid (tons)	25
Manure pack	Solid (tons)	30
Open lot	Solid (tons)	50
Litter	Solid (tons)	35
Above ground tank	Liquid (gallons)	20
Below ground covered pit	Liquid (gallons)	20
Below ground open pit	Liquid (gallons)	25
Under-floor dry storage	Solid (tons)	25
Under-floor liquid storage	Liquid (gallons)	20
Earthen storage	Liquid (gallons)	30
Lagoon	Liquid (gallons)	75

Adapted From: Animal Manure as a Plant Nutrient Source, ID-101, Cooperative Extension Service, Purdue University, 2001

Table 3. Nutrient Content of Stored Manure

Animal Type	Liquid Manure (lb./1000 gallons)			Solid Manure (lb./Tons)		
	N	P2O5	K20	N	P2O5	K20
BEEF						
Cows	20	16	24	7	4	7
Finishing Cattle	29	18	26	11	7	11
DAIRY						
Cows	31	15	19	10	3	6
Heifers	32	14	28	10	3	7
SWINE						
Farrowing	15	12	11	14	6	4
Nursery	25	19	22	13	8	4
Gestation	25	25	24	9	7	5
Finishing	58	44	40	16	9	5
POULTRY						
Broilers	63	40	29	46	53	36
Layers	57	52	33	34	51	26
Tom Turkeys	53	40	29	40	50	30
Hen Turkeys	60	38	32	40	50	30
HORSE				14	4	14
SHEEP				18	11	26

Manure Management in Minnesota, FO-3553-C, University of Minnesota Extension, 2012 Manure Characteristics, MWPS-18 Section 1, Midwest Plan Service, 2004







Table 4. Nitrogen Availability and Loss as Affected by Method of Manure Application and Animal Species

Year Available (1)	% of Total Nitrogen Available Per Year				
	Broadcast Incorporation Time (2)			Injection	
	> 96 hrs	12-96 hrs.	<12 hrs.	Sweep	Knife
BEEF					
Year 1	25	45	60	60	50
Year 2	25	25	25	25	25
Lost	*40*	*20*	*5*	*5*	*10*
DAIRY					
Year 1	20	40	55	55	50
Year 2	25	25	25	25	25
Lost	*40*	*20*	*10*	*5*	*10*
SWINE					
Year 1	35	55	75	80	70
Year 2	15	15	15	15	15
Lost	*50*	*30*	*10*	*5*	*15*
POULTRY					
Year 1	45	55	70	NA	NA
Year 2	25	25	25	NA	NA
Lost	*30*	*20*	*5*		

From: Manure Management in Minnesota, FO-3553-C, University of Minnesota Extension Service, 2007

(1) Third year available N is not listed but can be computed by adding 1st and 2nd year and lost percentages and subtracting this sum from 100.

(2) Timing categories refer to the length of time between manure application and incorporation.

Calibrating Your Manure Spreader

1. Determine manure weight (solid manure) or manure volume (liquid manure) per spreader load (*Use measured manure weight or 90% of the manufacturer's listed volume for liquid).*
2. Calculate rate based on loads applied per field of known size **OR** calculate rate based on acres covered per load (*Length x Width of Spread (ft.²)/43,560*).

Table 5. Average Nutrient Removal Rates for Crops in the Northcentral Region

Crop	Crop Nutrient Removal (lb. per unit)			
	Yield Units	N	P2O5	K2O
Alfalfa	ton (air dry)	51	12	49
Alsike clover	ton (air dry)	41	11	54
Barley (grain)	bushel	0.99	0.4	0.32
Barley (grain & straw)	bushel	1.39	0.56	1.52
Birdsfoot trefoil	ton (air dry)	45	11	42
Canola	bushel	1.9	1.2	2
Corn (grain)	bushel	0.9	0.38	0.27
Corn silage	ton (as fed)	9.7	3.1	7.3
Beans, dry	bushel	3	0.79	0.92
Bromegrass	ton	32	10	46
Orchardgrass	ton	36	13	54
Oats (grain)	bushel	0.77	0.28	0.19
Oats (straw)	ton	12	6.3	37
Potatoes (tuber)	cwt	0.32	0.12	0.55
Red clover	ton	45	12	42
Rye (grain)	bushel	1.4	0.46	0.31
Rye (straw)	ton	12	3	22
Soybeans	bushel	3.8	0.84	1.3
Sugar beets	ton	3.7	2.2	7.3
Sunflowers	cwt	2.7	0.97	0.9
Wheat (grain)	bushel	1.5	0.6	0.34
Wheat (straw)	ton	14	3.3	24

Source: International Plant Nutrition Institute (IPNI) Sept. 2005 http://nanc.ipni.net/articles/NANC0005-EN

Table 6. Common Fertilizer Analyses

Example to calculate fertilizer price per pound:
Urea (46-0-0) = $600/ton
(2000 lb. X .46% N) = 920 lb. N/ton
$600 / 920 lb.= $0.65/lb.

Fertilizer	Analysis
N	
Anhydrous Ammonia	82-0-0
Ammonium Nitrate	34-0-0
Urea	46-0-0
UAN Solution (*Urea Ammonium Nitrate*)	28 to 32-0-0
Ammonium Sulfate	21-0-0-24(S)
P	
Triple Superphosphate (TSP)	0-44 to 0-46
Diammonium Phosphate (DAP)	18-46-0
Monoammonium Phosphate (MAP)	11-52-0
Ammonium Polyphosphate Liquid (APP)	10-34-0
Ammonium Polyphosphate Dry (APP)	15-62-0
K	
Potassium Chloride (*Muriate of Potash*)	0-0-60
Potassium Sulfate	0-0-50-18(S)
Potassium-Magnesium Sulfate (*Sul-fo-mag*)	0-0-22-22(S)-11(Mg)
Potassium Nitrate	13-0-44

Table 7. Nitrogen Rate Guidelines for Corn (When Using a Manure Source)

Previous Crop[1]	Soil / Field Productivity Potential	
	Highly Productive Soils	Medium Productive Soils[2]
	---------- lb. N/A ----------	
CORN	130 - 180	130
SOYBEAN	100 - 140	100

[1]For previous crops other than corn or soybeans use the corn following corn rate guideline and subtract any previous crop N credits in Table 8.

[2]Soil and environmental conditions that limit crop production such as erosion, poor soil drainage, restriction to root growth, short growing season, and marginal growing season rainfall, among others, would qualify a site as having medium productivity potential.

Table 8. Legume Nitrogen Credits

For Corn, Wheat, and Barley grown the 1st and 2nd year after a legume crop

Legume (*Previous Crop*)	Corn		Wheat & Barley	
	1st year	2nd year	1st year	2nd year
Soybeans	40	0	20	0
Edible beans	20	0	10	0
Field peas	20	0	10	0
Red Clover	75	35	35	20
Harvested sweet clover	20	0	10	0
Harvested alfalfa or nonharvested sweet clover (plants/ft 2)				
4 or more	150	75	75	35
2-3	100	50	50	25
1 or less	40	0	0	0

Table 9. Nitrogen Sources Per Pound Conversions

Anhydrous Ammonia (82-0-0)		Urea (46-0-0)		UAN (28-0-0)	
Price per ton	N Price per. lb	Price per ton	N Price per. lb	Price per ton	N Price per. lb
400	$0.25	350	$0.38	200	$0.36
450	$0.28	385	$0.42	225	$0.40
500	$0.30	420	$0.46	250	$0.45
550	$0.34	455	$0.49	275	$0.49
600	$0.37	490	$0.53	300	$0.54
650	$0.40	525	$0.57	325	$0.58
700	$0.43	560	$0.61	350	$0.63
750	$0.46	595	$0.65	375	$0.67
800	$0.49	630	$0.68	400	$0.71
850	$0.52	665	$0.72	425	$0.76
900	$0.55	700	$0.76	450	$0.80
950	$0.58	735	$0.80	475	$0.85
1,000	$0.61	770	$0.84	500	$0.89
1,050	$0.64	805	$0.88	525	$0.94
1,100	$0.67	840	$0.91	550	$0.98
1,150	$0.70	875	$0.95	600	$1.07
1,200	$0.73	910	$0.99	650	$1.16

Table 10. Conversion Factors

1 acre = 43,560 sq. ft
1 cubic ft. = 7.48 gallons
1 gallon of water = 8.33 lb.
1 ton = 2000 lb.
SOIL TESTING CONVERSIONS
Plow Layer (6-7 in) = ppm X 2 = lb./acre
Top 12 inches = ppm X 4 = lb./acre
Top 24 inches = ppm X 8 = lb./acre
P2O5 X 0.44 = P
P X 2.29 = P2O5
K2O X 0.83 = K
K X 1.20 = K20
FERTILIZER CONVERSIONS
1 gal. of UAN (28%) = 10.66 lb.
1 gal. (10-34-0) = 11.65 lb.
1 gal. (7-21-7) = 11.0 lb.
1 gal. (9-18-9) = 11.11 lb.

Manure Management Related Websites

Certified Manure Testing Laboratories: http://www2.mda.state.mn.us/webapp/lis/manurelabs.jsp
University of Minnesota Manure Management: http://www.manure.umn.edu/
Minnesota Department of Ag Manure Management: http://www.mda.state.mn.us/protecting/conservation/practices/manuremgmt.aspx
Minnesota NRCS Manure Management: http://www.mn.nrcs.usda.gov/technical/ecs/nutrient/manure/manure.htm
Nitrogen Best Management Practices (BMPs): http://www.mda.state.mn.us/nitrogenbmps
Nitrogen Rate Calculator: http://extension.agron.iastate.edu/soilfertility/nrate.aspx
Minnesota Pollution Control Agency: http://www.pca.state.mn.us/index.php/topics/feedlots/feedlot-nutrient-and-manure-management.html?menuid=&redirect=1

In accordance with the Americans with Disabilities Act, this information is available in alternative forms of communication upon request by calling 651/201-6000. TTY users can call the Minnesota Relay Service at 711 or 1-800-627-3529. The MDA is an equal opportunity employer and provider.

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MCEA Ex. 42

NPDES and SDS feedlot permits

pca.state.mn.us/business-with-us/npdes-and-sds-feedlot-permits



Federal National Pollutant Discharge Elimination System (NPDES) and State Disposal System (SDS) permits are issued to the larger feedlots in Minnesota for construction and operation.

NPDES and SDS permits for feedlots (wq-f3-48)

Applying for a permit

The MPCA recently finalized new State Disposal System (SDS) and National Pollutant Discharge Elimination System (NPDES) feedlot general permits. The new state SDS general permit will become effective on June 1, 2025, and the new federal NPDES general permit on Feb. 1, 2026.

Applications for the new SDS general permit are now being accepted. Those with current SDS permit coverage should reapply by May 31, 2025, to avoid a lapse in permit coverage.

2025-2035 SDS general permit MNG450000 (wq-f3-63)
effective June 1, 2025

Applications for the new NPDES general permit will begin in fall 2025.

2026-2031 NPDES general permit MNG440000 (wq-f3-62)
effective Feb. 1, 2026

Until the fall 2025, applications can continue to be submitted for the current NPDES general permit.

2021-2026 General NPDES Permit MNG440000 (wq-f3-58)
ends Jan. 31, 2026

The MPCA no longer accepts paper or email applications for NPDES or SDS permits. This includes applications for issuance, reissuance, and all types of modifications. All NPDES and SDS permit applicants must use the online feedlot permit application service. You can also make changes to your facility name, ownership information, and contact person through MPCA Online Services.

Even if you plan to have a consultant prepare your permit application you will need to use the online service to set up an account in order to sign the application.

Apply for a permit

Guidance materials

- Online feedlot permitting overview (wq-f1-25)
- Applying for a feedlot permit (wq-f3-06)

Online training

- Getting started with online feedlot permitting

  Owners and consultants need to interact with the online service to submit a feedlot permit application. Lean about setting up an account and gaining access to the facility that you own or are working with.
- Applying for a NPDES or SDS permit online

  Are you having trouble understanding how to complete the permit application online? This interactive course covers the entire process, screen by screen, and step by step. Text, images, and videos are used to help guide you through the process. You can navigate the to the specific screen you are having trouble with or complete the entire course from start to finish.
- Completing an application prepared by a consultant

  Consultants cannot sign permit applications on behalf of feedlot owners. This guidance will highlight the steps you, as the feedlot owner, need to take to sign and submit a consultant-prepared permit application.

Other required forms

As part of the application process, you will be asked to upload an emergency response plan using the provided template (required).

Emergency response plan (wq-f3-12)

All NPDES and SDS permit applications will be required to submit a manure management plan (MMP) developed using the new online Nutrient Management Tool. You will access this tool from the same online services homepage used to begin a feedlot permit application. Refer to the Land Application of Manure page for more Nutrient Management Tool information and guidance.

Other information

- Modification of NPDES and SDS feedlot permits (wq-f3-49)
- Multiple site determination for NPDES and SDS feedlot permits (wq-f6-63)
- NPDES and SDS permits for multi-site feedlot operations (wq-f6-83)
- Animal feedlot or manure storage annual report (wq-f3-22b)
- e-Service: Permit termination
- Water line inspection log sheet (wq-f3-41)
- Weekly storage and containment structure inspections log sheet (wq-f3-42)
- Weekly stormwater management structure inspections log sheet (wq-f3-43)
- 2025 feedlot inspection records calendar (wq-f5-21)

Find forms for manure application recordkeeping on the Land application page

Find construction guidance and location and notification requirements on the Construction, operation, and technical requirements page.

Permit public notices

Prior to issuing coverage under a NPDES or SDS permit, a 30-day public comment period is provided. NPDES and SDS permitting actions open for public comment are available at the link provided below.

Public notices explain:

- How to submit written comment
- The MPCA office where the application is being processed
- How to request a public information meeting or a contested case hearing
- How to submit a petition to the MPCA Commissioner

MPCA public notices and draft permits are listed during the public comment period. (Note: There may or may not be feedlot-related public notices available in the current listing of public notices. Feedlot listings will include the term “Feedlot”.)

What other permits may be required?

This may not be a complete list of all required permits. Contact the MPCA, your county feedlot officer and local zoning officials for information about other possible requirements, such as setbacks from residential areas, other local zoning regulations, and stormwater pollution prevention controls.

- **Construction stormwater:** All feedlot construction activities that disturb one or more acres must comply with construction stormwater regulations, including the preparation of a stormwater pollution prevention plan. When feedlot construction activity will disturb 5 or more acres, the owner must apply for a construction stormwater permit, unless the feedlot has obtained coverage under a feedlot NPDES permit.
- A water use (appropriation) permit from the DNR is required for all users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year.
- Local ordinances regulating livestock in Minnesota (Minn. Dept. of Agriculture) has links to individual county feedlot ordinances.

Regulatory Definitions of Large CAFOs, Medium CAFO, and Small CAFOs

A **Large CAFO** confines at least the number of animals described in the table below.

A **Medium CAFO** falls within the size range in the table below and either:

- has a manmade ditch or pipe that carries manure or wastewater to surface water; **or**
- the animals come into contact with surface water that passes through the area where they're confined.

If an operation is found to be a significant contributor of pollutants, the permitting authority may designate a medium-sized facility as a CAFO.

A **Small CAFO** confines fewer than the number of animals listed in the table **and** has been designated as a CAFO by the permitting authority as a significant contributor of pollutants.

Animal Sector	Size Thresholds (number of animals)		
	Large CAFOs	Medium CAFOs[1]	Small CAFOs[2]
cattle or cow/calf pairs	1,000 or more	300 - 999	less than 300
mature dairy cattle	700 or more	200 - 699	less than 200
veal calves	1,000 or more	300 - 999	less than 300
swine (weighing over 55 pounds)	2,500 or more	750 - 2,499	less than 750
swine (weighing less than 55 pounds)	10,000 or more	3,000 - 9,999	less than 3,000
horses	500 or more	150 - 499	less than 150
sheep or lambs	10,000 or more	3,000 - 9,999	less than 3,000
turkeys	55,000 or more	16,500 - 54,999	less than 16,500
laying hens or broilers (liquid manure handling systems)	30,000 or more	9,000 - 29,999	less than 9,000
chickens other than laying hens (other than a liquid manure handling systems)	125,000 or more	37,500 - 124,999	less than 37,500
laying hens (other than a liquid manure handling systems)	82,000 or more	25,000 - 81,999	less than 25,000
ducks (other than a liquid manure handling systems)	30,000 or more	10,000 - 29,999	less than 10,000
ducks (liquid manure handling systems)	5,000 or more	1,500 - 4,999	less than 1,500

[1]Must also meet one of two "method of discharge" criteria to be defined as a CAFO or may be designated.
[2] Never a CAFO by regulatory definition, but may be designated as a CAFO on a case-by-case basis.

Grand Forks Herald
GrandForksHerald.com

NEWS NORTH DAKOTA

As dairy declines in ND, could new facilities prompt a renewal? Boosters, and opponents, are watching

New dairy facilities are proposed at Hillsboro and Abercrombie.



Dairy cows are milked twice daily at Waukon Dairy, Gary, Minnesota. The rotary milking parlor features 128 stalls for the 9,500 milking cows. Eric Hylden/Grand Forks Herald

By Delaney Otto
June 14, 2025 at 7:00 AM

Comments Share News Reporting

GARY, Minn. — At this rural northwest Minnesota dairy, cows casually make their way onto a large rotating platform, where an employee ensures they're properly situated for their regular milking. As the platform spins in a slow circle while the cows are milked, it's a bit like watching a giant merry-go-round.

With milking complete, suction pieces remove themselves automatically, allowing the animals to disembark and make their way to bedding, water and food. Another group then takes their place.

The Waukon Dairy, located near Gary, Minnesota, and operated by Riverview LLP, is home to 10,500 cows. About 9,000 are milked twice a day, while the remaining 1,500 are "dry cows" waiting to give birth.

Proposed Riverview dairies near the North Dakota communities of Hillsboro and Abercrombie would be similarly operated.

"This carousel, this rotary, would be the style that you'd see in our other farms," said Erica Boyum, a Riverview spokeswoman. "We do have some different robots or automated technology. … We're always looking at different innovations to help with our labor needs, repetitive processes."

Waukon Dairy has about 50 employees at the Norman County, Minnesota, facility. Eric Hylden/Grand Forks Herald

In 2024, Riverview, based in Morris, Minnesota, announced its plans to build two North Dakota dairies, an ongoing process being followed by supporters – among them North Dakota livestock officials and nearby producers – as well as opponents.

The company has received permitting and is working on a timeline for the Abercrombie dairy, while it awaits permitting for the Hillsboro project.

If both farms are built, the combined 25,000 cows planned for the dairy near Hillsboro and 12,500 cows at the Abercrombie dairy would more than quadruple North Dakota's dairy cattle population.

The state's dairy cow numbers have declined by the tens of thousands over the past 40-some years, according to data from the United States Department of Agriculture. Statistics compiled by North Dakota State University Extension show North Dakota had 93,000 dairy cows as recently as 1980. The number dropped about 46% by the year 2000, down to 50,000. By 2023, it had fallen to 14,000.

Today, the number is somewhere around 9,000 to 9,500, said North Dakota Livestock Alliance Executive Director Amber Wood. Dairy facility numbers have fallen in corresponding fashion as well, including the 2023 closing of Prairie Farms in Bismarck.

That closure forced some remaining dairy operations to ship milk elsewhere. Wood said many transported their milk to a Pollock, South Dakota, processor, which then closed in August 2024. North Dakota only has one major dairy processor, Wood said, in Fargo – Cass Clay Creamery.

The growing distance to get dairy products to a processor has been a key factor in some North Dakota dairies shutting down, Wood said. Dairies in the west and central parts of the state have felt the strain worse, as Cass Clay sits on the eastern side of the state, and

with others farther away in states like Minnesota and South Dakota.

And as farmers retire, succeeding generations have less desire to take over the business, Wood said.

For Wood, the fading numbers of cows and dairies make Riverview's entrance into North Dakota a welcomed one.

"I think anything that can be done to try to correct the losses we have had in the milk processing industry is a good thing," she said.

Erica Boyum, Riverview Dairy, checks out the newest calves in the herd at the Waukon Dairy near Gary, Minnesota, Friday, April 18, 2025. Eric Hylden/Grand Forks Herald

Though Riverview is entering from Minnesota, interest from in-state students and legislators signal potential growth in the industry.

At NDSU, the Dairy Research and Teaching Center has seen rising interest in dairy, said Manager Todd Molden. The center, which milks about 100 cows, does research trials and tours, teaching students about milk and other products.

The university's dairy club is also as big as it's ever been, Molden said. The group goes on trips to tour dairies, assists with ag in classrooms and does outreach for the dairy industry.

The center has received several renovations in the last couple of months.

"There's a lot more interest in dairy than people might think at NDSU," he said. "As I look at these students I can see that they're going to be terrific leaders in the dairy industry when they get into it."

At the state level, there's an effort to entice more processors to come to North Dakota. Senate Bill 2342 – passed by the 2025 Legislature and signed by Gov. Kelly Armstrong – will create a value-added milk processing facility incentive program and authorize a Bank of North Dakota line of credit. In testimony favoring the bill, Greg Lardy, vice president for agriculture at NDSU, said North Dakota has been lagging behind neighboring states for decades when it comes to its livestock sector's economic contribution.

"Livestock development is crucial to enhancing the long-term economic impact of agriculture on the state's economy," he said. "As North Dakota continues to look to the future, enhancing livestock development through incentivizing food processing will be critical to our overall success."

Wood said Riverview presents an opportunity for North Dakota, as more cows could incentivize increased milk production.

"You have to have enough cows to justify milk processing infrastructure, but then you have to have milk processing in order to justify more cows," she said. "It all needs to happen at the same time."

Riverview is searching for a processor and won't start building without having a destination for the milk, Boyum said. The agribusiness has other factors it considers when going through a permitting process, she said, such as access to water, if there are nearby growers who can provide silage for the cows and if the community will be supportive. In terms of water and growers, North Dakota is a good spot, Boyum believes.

Community support has come from some residents near the planned dairies. During an open house in Hillsboro, some voiced their interest in the dairy and what it could do for their community or farming business.

Sarah Hall Lovas, an agronomist, believes the dairy will be a boon, as more people will be in town for local businesses and farmers will have the opportunity to work with Riverview.

"The way I think Riverview is going to be working, they contract a lot with the local farmers for different things," she said. "I think it's going to really provide a lot of great opportunities for our farmers, as far as opportunities to plant some of the crops. Fertilizer is really expensive right now, and the opportunity to take manure is just huge."

Also during the open house, Tom McNamee, a farmer, said he's been excited about the proposed dairy since word of it started. He agreed it will give farmers more opportunities for growing silage for the cows and getting nutrients for their crops. He's been on a tour to Waukon Dairy and he said concerned residents will be at ease when they see it.

"These guys really want to be good neighbors, from what I've seen," he said.

Opponents are watching, too. A group called the Dakota Resource Council has expressed concerns about what they believe are potential environmental impacts of the dairies, such as the

Abercrombie dairy's proximity to the Red River and other local water infrastructure. The group has been focused on trying to overturn the North Dakota Department of Environmental Quality's approval of a permit for the Abercrombie dairy. On April 3, the council hosted a public meeting(https://www.inforum.com/news/north-dakota/group-opposed-to-abercrombie-dairy-farm-holds-fargo-meeting) in Fargo to discuss concerns.

"These mega-large facilities will come with problems that you would not necessarily see in an 800- to 1,000-cow operation," said Sam Wagner, lead organizer from the Dakota Resource Council, at the meeting.

In a letter to the editor published in the Grand Forks Herald and The Forum of Fargo-Moorhead, Candace Kraft, of Fargo, outlined her issues with the incoming facilities.

"Many deficiencies exist for both factory farms' current nutrient management plans, including high potential for manure overapplication and poor timing of dung application to fields," she wrote. "With both mega-dairies at full capacity, 321 million gallons of manure sludge containing nitrogen, phosphorus, E. Coli, parasites and other pathogens will be spread on farm fields. Private wells are especially vulnerable to groundwater contamination around mega-dairies."

At Waukon Dairy, Boyum and Ron Visser, one of the site managers, addressed Riverview's handling of manure and water. Boyum said all the manure at the dairy is vacuumed and separated between solid and liquid. The solid fertilizer is used for bedding for the cows — Visser said people are surprised to find it essentially has no odor. Liquid manure is sent to lagoons on the property. The lagoons are covered with synthetic tarps, said Riverview's Martha Koehl during an open house in Hillsboro. The tarps, as well as twice-daily cleanings of the farms, help mitigate smell, she said. All of the liquid manure is sold as a fertilizer source.

Also, Riverview buys 100% of its feed for the cows.

Ron and Kari Visser returned home to Norman County near Gary, Minnesota, to work at Waukon Dairy. Kari Visser leads tours and support and Ron Visser is a manager at the dairy. Eric Hylden/Grand Forks Herald

Visser said the team does everything within its control to manage water. Waukon Dairy uses rainwater and snow melt on the site for 30% to 40% of its water source. The site has holding ponds and a retention pond, and that water is used for drinking water for the cows. However, the dairy can't use that water for everything – for example, cooling the milk and washing requires well water. The dairy is working to raise the percentage of rainwater and runoff water it's using, Visser said.

"We're innovative," he said.

Boyum said that anyone with concerns or interest in the dairies are free to reach out to Riverview for a tour of the dairy closest to them.

"I think it is very normal for people to be curious about what we're doing or ask questions," she said. "We want to be good neighbors."

Visser's wife, Kari, runs tours at the dairy and said both she and her husband grew up in the county.

"At first I was like, 'they're going to build a dairy up here, I'm not quite sure how that's going to go,'" she said. "But it's been so fun to see the community just spread their arms around it."

Two stainless steel 70,000-gallon silos store milk at the Waukon Dairy for seven tanker trucks that transport the milk daily to Bongards' Creameries in Perham, Minnesota. Eric Hylden/Grand Forks Herald

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By Delaney Otto(https://www.grandforksherald.com/delaney-otto)

Otto is the region reporter for the Grand Forks Herald.

(https://www.grandforksherald.com/delaney-otto)

CONVERSATION

Herberg Dairy Manure Application Fields

updated 3/3/2025

Field No.	Field Name	T	R	S	Quarter	Landowner Reported Acres	Total Acres	Excluded Acres	Spreadable Acres	Setback map	Drain tile*	Flood risk	Owner	Easement Signed	PI - year done	PI Rating	N Soil lb/acre	Soil test	Soil map	P Soil Olson ppm	Lat.	Long.	Water Shed	Receiving Stream
001	Clyde's	144	50	12 & 13	Irregular	507.2	484.4	72.3	412.1	yes	yes	partial	Jason Lovas	6/28/2024	2024	low	18	yes	yes	15	47.30113	-96.95430	90201070303	Borke Drain No 16-North Branch Elm River
002	Mabel's	145	50	25	NW 1/4	154.1	154.1	1.6	152.5	yes	no	no	Jason Lovas	6/28/2024	2024	low	6	yes	yes	24	47.34901	-96.97951	90201070602	90201070602
003	South 1/4	145	50	33	W 1/2	214.2	211.0	46.4	164.6	yes	no	partial	Jason Lovas	6/28/2024	2024	low	8	yes	yes	16	47.33208	-97.04346	90201070303	Borke Drain No 16-North Branch Elm River
004	Behind Shop	145	50	28	S 1/2	279.4	279.4	0.1	279.3	yes	yes	no	Jason Lovas	6/28/2024	2024	low	5	yes	yes	31	47.34209	-97.03830	90201070603	Grandin Lake-Red River
005	Kyle's 1/4	145	50	27	SW 1/4	156.2	156.2	0.0	156.2	yes	yes	no	Jason Lovas	6/28/2024	2024	low	22	yes	yes	27	47.34220	-97.02219	90201070602	90201070602
006	Danny's	145	50	31	ALL	516.8	508.9	48.5	460.4	yes	no	partial	Jason Lovas	6/28/2024	2024	low	6	yes	yes	7	47.33112	-97.08060	90201070603	Grandin Lake-Red River
007	Andys	144	50	7	W 1/2	272.1	272.1	0.0	272.1	yes	yes	no	Jason Lovas	6/28/2024	2025	low	9	yes	yes	8	47.30399	-97.06566	90201070303	Borke Drain No 16-North Branch Elm River
008	Shornecks	144	50	8	NW 1/4	154.8	154.8	0.0	154.8	yes	yes	no	Jason Lovas	6/28/2024	2025	low	8	yes	yes	28	47.30759	-97.04508	90201070303	Borke Drain No 16-North Branch Elm River
009																								
010	Evenson Home	146	49	30		removed	227.2	25.3		yes	no	yes	Missing (EVENSON, MILES & KATHLEEN)		2024	low	8	yes	yes	11	47.43226	-96.95074	90201090605	Goose River
011	Gene Section 3	144	49	3	E 1/2	removed	282.5	1.5		yes	no	yes	Gene Christianson	7/1/2024	2024	low	45	yes	yes	28	47.31722	-96.86373	90201070603	Grandin Lake-Red River
012	Gene Section 11	144	49	11	W 1/2	removed	309.4	2.7		yes	yes	yes	Gene Christianson	7/1/2024	2024	low	12	yes	yes	11	47.30310	-96.85303	90201070601	Love Lake-Red River
013	Anderson Home	145	49	20	E 1/2	302.5	302.5	2.3	300.2	yes	no	no	Michael & Joanne Warner		2024	low	12	yes	yes	4	47.36026	-96.92671	90201070603	Grandin Lake-Red River
014	McNamee South of Home	144	50	1	All	534.2	534.2	7.4	526.8	yes	yes	no	Thomas & Elena McNamee	7/8/2024	2025	low	8	yes	yes	10	47.31780	-96.95433	90201070303	Borke Drain No 16-North Branch Elm River
015	McNamee Home	145	49	31	S 1/2	288.6	288.6	3.6	285.0	yes	yes	no	Thomas & Elena McNamee	7/8/2024	2024	low	9	yes	yes	15	47.32759	-96.95293	90201070602	90201070602
016	McNamee Section 6	144	49	6	SW 1/4	156.1	156.1	0.0	156.1	yes	yes	no	Thomas & Elena McNamee	7/8/2024	2024	low	2	yes	yes	12	47.31513	-96.93830	90201070303	Borke Drain No 16-North Branch Elm River
017	McNamee Section 7	144	49	7	NW 1/4	156.5	156.5	6.9	149.6	yes	yes	partial	Thomas & Elena McNamee	7/8/2024	2024	low	4	yes	yes	7	47.30769	-96.93824	90201070303	Borke Drain No 16-North Branch Elm River
018	15F2	144	50	15	S 1/2	309.5	309.5	0.6	308.9	yes	yes	no	Donald McInnes	7/9/2024	2024	low	39	yes	yes	42	47.28598	-96.99691	90201070303	Borke Drain No 16-North Branch Elm River
019	McInnes Section 10	144	50	10	SW 1/4	152.9	152.9	4.8	148.1	yes	no	no	Donald McInnes	7/9/2024	2024	medium	29	yes	yes	52	47.30035	-97.00235	90201070303	Borke Drain No 16-North Branch Elm River
020	Kelso 16	144	50	16	E 1/2, NW 1/4	54.3	54.3	2.3	52.0	yes	yes	no	Donald McInnes	7/9/2024	2025	low	38	yes	yes	7	47.29315	-97.02050	90201070303	Borke Drain No 16-North Branch Elm River
021	Noble 6	143	49	6	NE 1/2	154.7	154.7	10.3	144.4	yes	yes	no	Donald McInnes	7/9/2024	2025	low	15	yes	yes	9	47.23492	-96.92711	90201070106	County Ditch No 13-Red River
022	22 W	144	50	22	W 1/2, W 1/2	151.9	151.9	1.9	150.0	yes	yes	no	Tyler McInnes	7/10/2024	2025	low	7	yes	yes	18	47.27504	-97.00478	90201070406	Grandin Cemetery-Elm River
023	Harvey 11	144	49	11	E 1/2	removed	199.0	5.2		yes	no	yes	Harvey Christianson	7/8/2024	2024	low	16	yes	yes	14	47.30297	-96.84248	90201070601	Love Lake-Red River
024	Harvey 10	144	49	10	E 1/2	309.4	309.4	44.9	264.5	yes	no	partial	Harvey Christianson	7/8/2024	2024	low	8	yes	yes	24	47.30318	-96.86384	90201070601	Love Lake-Red River
025	Henka Section 32	145	49	32	NW 1/4	150.9	150.9	4.9	146.0	yes	no	no	Keith & Kevin Henka	7/8/2024	2024	low	23	yes	yes	19	47.33469	-96.93683	90201070602	90201070602
026	Henka Section 30 1/4	145	49	30	SW 1/4	157.7	157.7	2.2	155.5	yes	no	no	Keith & Kevin Henka	7/8/2024	2024	low	8	yes	yes	9	47.34163	-96.95813	90201070602	90201070602
027	Henka Section 30 80	145	49	30	S 1/2, SE 1/4	79.7	79.7	2.4	77.3	yes	no	no	Keith & Kevin Henka	7/8/2024	2024	low	7	yes	yes	35	47.33967	-96.94747	90201070602	90201070602
028	Henka Section 14	145	50	14	SE 1/4	153.9	153.9	6.5	147.4	yes	no	no	Keith & Kevin Henka	7/8/2024	2024	low	4	yes	yes	6	47.37092	-96.99047	90201070603	Grandin Lake-Red River
029	Henka Home	145	50	12	0.75	447.9	447.9	4.7	443.2	yes	yes	no	Keith & Kevin Henka	7/8/2024	2024	low	8	yes	yes	9	47.38904	-96.97460	90201070604	Steenerson Drain
030	Henka Section 7	145	49	7	ALL	610.8	610.8	9.0	601.8	yes	yes	no	Keith & Kevin Henka	7/8/2024	2024	low	16	yes	yes	14	47.38905	-96.95309	90201070604	Steenerson Drain
031	Henka North of Home	145	50	1	SW 1/4	158.4	158.4	0.0	158.4	yes	no	no	Keith & Kevin Henka	7/8/2024	2024	low	4	yes	yes	8	47.39998	-96.98000	90201070604	Steenerson Drain
032	Herberg 27	145	49	27	ALL	632.2	632.2	73.0	559.2	yes	no	partial	Bruce & Jeanne Viker	7/8/2024	2024	low	8	yes	yes	6	47.34597	-96.88879	90201070602	90201070602
033	Herberg 26 North	145	49	26	N 1/2	removed	301.9	12.0		yes	yes	yes	Bruce & Jeanne Viker	7/8/2024	2024	low	4	yes	yes	8	47.34972	-96.86742	90201070603	Grandin Lake-Red River
034	Herberg 26 South	145	49	26	S 1/2	removed	319.3	2.8		yes	no	partial	Bruce & Jeanne Viker	7/8/2024	2024	low	5	yes	yes	10	47.34254	-96.86742	90201070602	90201070602
035	Herberg 25	145	49	25	ALL	removed	257.9	9.5		yes	no	yes	Bruce & Jeanne Viker	7/8/2024	2024	low	4	yes	yes	20	47.34605	-96.84733	90201070602	90201070602
036	Jeremy's Farm	144	49	2	N 1/2	removed	266.5	3.0		yes	no	yes	Jeremy Paulsrud	7/9/2024	2024	low	4	yes	yes	8	47.32044	-96.84693	90201070603	Grandin Lake-Red River
037	Kim's Section 10	144	49	10	NW 1/4	155.2	155.2	3.1	152.1	yes	no	no	Kim & Tod Harrington	7/16/2024	2024	low	15	yes	yes	19	47.30694	-96.87422	90201070601	Love Lake-Red River
038	Tod Section 10	144	49	10	SW 1/4	154.3	154.3	0.0	154.3	yes	no	no	Tod & Rebecca Harrington	7/9/2024	2024	low	9	yes	yes	12	47.29972	-96.87424	90201070601	Love Lake-Red River
039	Section 23 North	144	49	23	N 1/2	230.6	230.6	123.5	107.1	yes	yes	partial	Tod & Rebecca Harrington	7/9/2024	2024	low	10	yes	yes	17	47.27771	-96.84975	90201070601	Love Lake-Red River
040	Section 23 South	144	49	23	SW 1/4	removed	149.4	1.5		yes	yes	partial	Tod & Rebecca Harrington	7/9/2024	2024	low	3	yes	yes	9	47.27053	-96.85088	90201070601	Love Lake-Red River
041	Tod's House	144	49	28	N 1/2, N 1/2	96.6	96.6	11.0	85.6	yes	no	partial	Tod & Rebecca Harrington	7/9/2024	2024	low	2	yes	yes	14	47.26577	-96.89004	90201070406	Grandin Cemetery-Elm River
042	Tod Section 28	144	49	28	S 1/2	316.6	316.6	59.7	256.9	yes	yes	partial	Tod & Rebecca Harrington	7/9/2024	2024	low	4	yes	yes	3	47.25640	-96.88993	90201070406	Grandin Cemetery-Elm River
043	West of Jeremy's	145	49	36	SW 1/4	removed	148.9	1.0		yes	no	yes	Randy Paulsrud	7/9/2024	2024	low	10	yes	yes	6	47.32790	-96.84985	90201070603	Grandin Lake-Red River
044	Jeff McInnes Section 10	144	50	10	NW 1/4	148.5	148.5	0.0	148.5	yes	no	no	Jeff McInnes	7/9/2024	2024	low	15	yes	yes	50	47.30744	-97.00243	90201070303	Borke Drain No 16-North Branch Elm River
045	McInnes Home	144	50	15	N 1/2	295.1	295.1	9.8	285.3	yes	yes	no	Jeff McInnes	7/9/2024	2024	low	14	yes	yes	30	47.29315	-96.99706	90201070303	Borke Drain No 16-North Branch Elm River
046	McInnes Section 23	144	50	23	SE 1/4	154.5	154.5	0.9	153.6	yes	no	no	Jeff McInnes	7/9/2024	2024	medium	26	yes	yes	63	47.27152	-96.97004	90201070406	Grandin Cemetery-Elm River
047	Substation	144	50	22	E 1/2, W 1/2	159.2	159.2	2.1	157.1	yes	yes	no	Jeff McInnes	7/9/2024	2024	low	6	yes	yes	24	47.27499	-96.99962	90201070406	Grandin Cemetery-Elm River
048	Section 21 E of Tracks	144	50	21	E 1/2	227	227.0	4.4	222.6	yes	no	no	Jeff McInnes	7/9/2024	2024	low	10	yes	yes	14	47.27505	-97.01270	90201070406	Grandin Cemetery-Elm River
049	Viker Home	145	49	21	ALL	590.7	590.7	5.4	585.3	yes	no	no	DEWEL III VIKER	7/10/2024	2024	low	7	yes	yes	17	47.36035	-96.91019	90201070603	Grandin Lake-Red River
050	South Home	145	49	28	ALL	573.4	573.4	36.3	537.1	yes	yes	no	DEWEL III VIKER	7/10/2024	2024	low	11	yes	yes	6	47.34574	-96.91021	90201070602	90201070602
051	South of Dairy	145	49	34	S 1/2	311.2	311.2	74.2	237.0	yes	no	partial	DEWEL III VIKER	7/10/2024	2024	low	9	yes	yes	27	47.32785	-96.88894	90201070602	90201070602
052	East of Dairy	145	49	35	N 1/2	removed	309.2	34.2		yes	no	yes	HARRIS, VICTORIA ANN, Elliot Vike	7/10/2024	2024	low	35	yes	yes	32	47.33515	-96.86751	90201070602	90201070602
053	Herberg 24	145	49	24	SW 1/4	removed	63.0	1.4		yes	no	yes	DEWEL III VIKER	7/10/2024	2024	low	2	yes	yes	4	47.35717	-96.85137	90201070603	Grandin Lake-Red River
054	August's	145	49	32	0.75	423.9	423.9	8.6	415.3	yes	no	no	DEWEL III VIKER	7/10/2024	2024	low	5	yes	yes	19	47.33121	-96.93164	90201070303	Borke Drain No 16-North Branch Elm River
055	Poland	145	49	30	NW 1/4	155.4	155.4	5.8	149.6	yes	no	no	DEWEL III VIKER	7/10/2024	2024	low	4	yes	yes	5	47.34879	-96.95822	90201070602	90201070602
056	East Section 5	145	49	5	E 1/2	302	302.0	0.0	302.0	yes	no	no	Arlen & Darin Oanes	7/10/2024	2024	low	16	yes	yes	25	47.40365	-96.92649	90201070604	Steenerson Drain
057	NW Section 11	145	49	11	NW 1/4	removed	155.9	0.0		yes	no	yes	Arlen & Darin Oanes	7/10/2024	2024	low	13	yes	yes	17	47.39341	-96.87294	90201070604	Steenerson Drain
058																								
059	Caledonia 30	146	49	30	E 1/2, SE 1/4	56.2	56.2	20.1	36.1	yes	no	partial	Darin Oanes	7/10/2024	2024	low	12	yes	yes	19	47.42879	-96.94534	90201070605	Augustana Church-Red River
060	Herberg 17	145	49	17	N 1/2	317.3	317.3	18.2	299.1	yes	no	no	Darin Oanes	7/10/2024	2024	low	12	yes	yes	20	47.37835	-96.93172	90201070604	Steenerson Drain
061	Herberg 14	145	49	14	NW 1/4	removed	160.4	2.7		yes	no	yes	Arlen Oanes	7/10/2024	2024	low	15	yes	yes	34	47.37880	-96.87285	90201070604	Steenerson Drain
062	Oanes Home	145	49	17	S 1/2	295.4	295.4	0.7	294.7	yes	no	no	Arlen Oanes	7/10/2024	2024	low	4	yes	yes	6	47.37104	-96.93155	90201070604	Steenerson Drain
063	South Herberg 15	145	49	15	S 1/2, S 1/2	removed	131.9	3.9		yes	no	yes	Arlen Oanes	7/10/2024	2024	low	7	yes	yes	29	47.36933	-96.88886	90201070604	Steenerson Drain
064	South Herberg 14	145	49	14	S 1/2	removed	299.9	1.0		yes	no	yes	Arlen Oanes	7/10/2024	2024	low	19	yes	yes	23	47.37159	-96.86752	90201070604	Steenerson Drain
065	Riverbend	145	49	24	NW 1/4	removed	48.3	2.7		yes	no	yes	Arlen Oanes	7/10/2024	2024	low	22	yes	yes	19	47.36273	-96.85307	90201070603	Grandin Lake-Red River
066																								
067	Home Section	145	50	24	ALL	600	600.0	13.3	586.7	yes	yes	no	Paul Kozojed	7/11/2024	2024	low	10	yes	yes	9	47.35987	-96.97431	90201070602	90201070602
068	Herberg 6	145	49	6	W 1/2, SW 1/4	76.9	76.9	0.0	76.9	yes	yes	no	Paul Kozojed	7/11/2024	2024	low	4	yes	yes	12	47.39986	-96.96130	90201070604	Steenerson Drain
069	Warner 80	145	49	16	N 1/2, NE 1/4	77.9	77.9	2.3	75.6	yes	no	no	Brian & Kevin Kuehl	7/10/2024	2024	low	6	yes	yes	10	47.38044	-96.90508	90201070604	Steenerson Drain
070	Red River North	146	49	23	S 1/2, S 1/2	removed	80.2	0.1		yes	no	yes	Gerald & Ann Boeddeker	7/11/2024	2024	low	6	yes	yes	9	47.44087	-96.86822	90201070605	Augustana Church-Red River
071	Red River South	146	49	26	N 1/2, N 1/2	removed	120.9	1.2		yes	no	yes	Gerald & Ann Boeddeker	7/11/2024	2024	low	5	yes	yes	4	47.43807	-96.86797	90201070605	Augustana Church-Red River
072	Home 1/4	146	49	29	SE 1/4	148.3	148.3	23.4	124.9	yes	yes	partial	Gerald & Ann Boeddeker	7/11/2024	2024	low	6	yes	yes	3	47.42890	-96.92651	90201070605	Augustana Church-Red River
073	N 80	146	49	8	N 1/2, SW 1/4	79.8	79.8	0.0	79.8	yes	no	no	Gerald & Ann Boeddeker	7/11/2024	2024	low	31	yes	yes	3	47.47411	-96.93640	90203010401	Judicial Ditch No 54-Red River
074	Dales 1/2 Section	146	49	31	S 1/2	309.6	309.6	1.4	308.2	yes	no	no	Dale & Joyce Boeddeker	7/11/2024	2024	low	39	yes	yes	11	47.41432	-96.95333	90201070605	Augustana Church-Red River
075	Jay's Section 28	146	49	28	SE 1/4	155.1	155.1	0.0	155.1	yes	no	no	Jay Boeddeker	7/9/2024	2024	low	9	yes	yes	19	47.42894	-96.90540	90201070605	Augustana Church-Red River

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	AK	AL	AM	AN	AP	AQ	AR	AS
2		Field No.	Field Name	T	R	S	Quarter	Landowner Reported Acres	Total Acres	Excluded Acres	Spreadable Acres	Setback map	Drain tile*	Flood risk	Owner	Easement Signed	PI - year done	PI Rating	N Soil lb/acre	Soil test	Soil map	P Soil Olson ppm	Lat.	Long.	Water Shed	Receiving Stream
78		076	Dallas 1/2 Section	146	49	34	N 1/2	removed	317.2	0.0		yes	no	partial	Jay Boeddeker	7/9/2024	2024	low	6	yes	yes	11	47.42156	-96.88918	90201070605	Augustana Church-Red River
79		077	Halstad 1/2	145	49	23	N 1/2	removed	286.4	3.5		yes	yes	yes	Jay Boeddeker	7/9/2024	2024	low	6	yes	yes	8	47.36416	-96.86744	90201070603	Grandin Lake-Red River
80		078	Jay's W of Co Rd 2	145	49	11	SE 1/4	removed	149.6	9.9		yes	no	yes	Jay Boeddeker	7/9/2024	2024	low	9	yes	yes	11	47.38617	-96.86235	90201070604	Steenerson Drain
81		079	Jay's E of Co Rd 2	145	49	12	SW 1/4	removed	143.0	4.0		yes	no	yes	Jay Boeddeker	7/9/2024	2024	low	9	yes	yes	6	47.38559	-96.84813	90201070605	Augustana Church-Red River
82		080	Caledonia 1/4	146	49	10	NE 1/4	156.2	156.2	0.0	156.2	yes	no	no	Jay Boeddeker	7/9/2024	2024	low	19	yes	yes	11	47.47965	-96.88294	90203010401	Judicial Ditch No 54-Red River
83		081	Foss Farm	146	49	2	NW 1/4	removed	156.9	3.1		yes	no	yes	Jay Boeddeker	7/11/2024	2024	low	11	yes	yes	2	47.49392	-96.87127	90203010401	Judicial Ditch No 54-Red River
84		082	Solee Red River	146	49	26	S 1/2, N 1/2	removed	103.3	1.1		yes	no	yes	Phyllis Solee	7/11/2024	2024	low	5	yes	yes	4	47.43453	-96.87035	90201070605	Augustana Church-Red River
85		083	Solee 28	146	49	28	S 1/2, SW 1/4	76.4	76.4	0.0	76.4	yes	yes	no	Phyllis Solee	7/11/2024	2024	low	12	yes	yes	5	47.42690	-96.91587	90201070605	Augustana Church-Red River
86		084	Solee 1/2 Section	145	49	15	S 1/2, N 1/2	removed	159.6	0.0		yes	yes	yes	Phyllis Solee	7/11/2024	2024	low	8	yes	yes	5	47.37739	-96.88877	90201070604	Steenerson Drain
87		085	Brady	144	49	19	W 1/2	304.4	304.4	124.7	179.7	yes	no	partial	Brady Bernadine (William J BRADY	4/15/2024	2024	low	16	yes	yes	8	47.27491	-96.93533	90201070406	Grandin Cemetery-Elm River
88		086	Tungseth 1/4	144	49	20	NE 1/4	155.2	155.2	0.0	155.2	yes	no	no	Loren & Sharon Tungseth	7/16/2024	2024	low	38	yes	yes	15	47.27836	-96.90623	90201070406	Grandin Cemetery-Elm River
89		087	Tungseth 51	144	49	20	E 1/2, SE 1/4	46.7	46.7	0.0	46.7	yes	yes	no	Loren & Sharon Tungseth	7/16/2024	2024	low	38	yes	yes	15	47.27120	-96.90239	90201070406	Grandin Cemetery-Elm River
90		088	Gadberry Section 4	143	49	4	N 1/2 & SW 1/4	467.7	467.7	14.5	453.2	yes	yes	no	Wayne Gadberry	7/15/2024	2025	low	79	yes	yes	9	47.23098	-96.88961	90201070106	County Ditch No 13-Red River
91		089	Gadberry 200	143	49	3	S 1/2	194.8	194.8	9.8	185.0	yes	yes	no	Wayne Gadberry	7/15/2024	2025	low	44	yes	yes	9	47.22713	-96.87011	90201070106	County Ditch No 13-Red River
92		090	Gadberry Home	144	49	30	N 1/2	278.2	278.2	0.0	278.2	yes	yes	no	Wayne Gadberry	7/15/2024	2024	low	19	yes	yes	7	47.26407	-96.93267	90201070406	Grandin Cemetery-Elm River
93		091	Highline	144	50	24	NW 1/4	152	152.0	4.5	147.5	yes	yes	no	Kevin Weller		2024	low	20	yes	yes	10	47.27863	-96.95951	90201070406	Grandin Cemetery-Elm River
94		092	Herberg 3	145	49	3	NW 1/4	removed	140.1	0.0		yes	no	yes	Paul Fossum	7/15/2024	2024	low	10	yes	yes	9	47.40729	-96.89447	90201070604	Steenerson Drain
95		093	Caledonia 32	146	49	32	NE 1/4	154.5	154.5	0.0	154.5	yes	no	no	Paul Fossum	7/15/2024	2024	low	9	yes	yes	7	47.42146	-96.92663	90201070605	Augustana Church-Red River
96		094	Fossum 28	146	49	28	W 1/2, NW 1/4	75.3	75.3	22.1	53.2	yes	no	partial	Paul Fossum	7/15/2024	2024	low	6	yes	yes	30	47.43601	-96.91850	90201090605	Goose River
97		095	McAndrew 100	144	49	35	NE 1/4	removed	98.0	1.2		yes	no	yes	James McAndrew	7/17/2024	2024	low	30	yes	yes	7	47.24862	-96.84145	90201070106	County Ditch No 13-Red River
98		096	McAndrew 80	143	49	3	S 1/2, NW 1/4	79.8	79.8		79.8	yes	yes	no	Margaret McAndrew Beasley	7/17/2024	2025	low	53	yes	yes	9	47.23254	-96.87364	90201070106	County Ditch No 13-Red River
99		097	Section 10	143	49	10	NE 1/4	158.1	158.1	5.1	153.0	yes	yes	no	Margaret McAndrew Beasley	7/17/2024	2025	low	13	yes	yes	10	47.21973	-96.86286	90201070106	County Ditch No 13-Red River
100		098	River 1/4	143	49	11	NW 1/4	153.3	153.3	0.1	153.2	yes	yes	no	Margaret McAndrew Beasley	7/17/2024	2025	low	30	yes	yes	6	47.21966	-96.85211	90201070106	County Ditch No 13-Red River
101		099	Derek's Section 2	144	49	2	SW 1/4	removed	159.8	7.7		yes	yes	yes	Derek Paulsrud	7/15/2024	2024	low	7	yes	yes	35	47.31364	-96.85132	90201070601	Love Lake-Red River
102		100	Hillboro 15	145	50	15	E 1/2	225.9	225.9	0.0	225.9	yes	no	no	Derek Paulsrud	7/15/2024	2024	low	34	yes	yes	23	47.37299	-97.01181	90201070604	Steenerson Drain
103		101	Elm River 8	144	49	8	0.75	removed	391.4	23.8		yes	yes	partial	Kevin Paulsrud	7/19/2024	2024	low	12	yes	yes	18	47.30369	-96.90866	90201070303	Borke Drain No 16-North Branch Elm River
104		102	Paulsrud Section 6	144	49	6	N 1/2	241.2	241.2	10.1	231.1	yes	yes	no	Kevin Paulsrud	7/19/2024	2024	low	6	yes	yes	13	47.32116	-96.93281	90201070303	Borke Drain No 16-North Branch Elm River
105		103	Elm River 18	144	49	18	ALL	554.7	554.7	132.8	421.9	yes	yes	partial	Kevin Paulsrud	7/19/2024	2024	low	10	yes	yes	14	47.28950	-96.93295	90201070303	Borke Drain No 16-North Branch Elm River
106		104	Elm River 17	144	49	17	SE 1/4	122.2	122.2	19.5	102.7	yes	yes	partial	Kevin Paulsrud	7/19/2024	2024	low	9	yes	yes	9	47.28530	-96.90640	90201070406	Grandin Cemetery-Elm River
107		105	Kevin's on The River	144	49	14	Part of	removed	182.0	4.0		yes	yes	yes	Kevin Paulsrud	7/19/2024	2024	low	8	yes	yes	4	47.28836	-96.85003	90201070601	Love Lake-Red River
108		106	Derek's Place	144	49	11	NE 1/4	removed	62.6	0.8		yes	no	yes	Kevin Paulsrud	7/19/2024	2024	low	8	yes	yes	21	47.30523	-96.83914	90201070601	Love Lake-Red River
109		107	Paulsrud Section 7	144	49	7	SW 1/4	156.3	156.3	24.4	131.9	yes	yes	partial	Kevin Paulsrud	7/19/2024	2024	low	5	yes	yes	5	47.30061	-96.93816	90201070303	Borke Drain No 16-North Branch Elm River
110		108	Elm River 21	144	49	21	N 1/2, NE 1/4	80.2	80.2	0.0	80.2	yes	no	no	Kevin Paulsrud	7/15/2024	2024	low	2	yes	yes	5	47.28059	-96.88531	90201070406	Grandin Cemetery-Elm River
111		109	Section 2 Kinyon	143	50	2	All	624.3	624.3	10.9	613.4	yes	yes	no	Kevin Paulsrud	7/15/2024	2025	low	12	yes	yes	7	47.23157	-96.97499	90201070106	County Ditch No 13-Red River
112		110	Kinyon Highway	143	50	10	NE 1/4	143	143.0	5.8	137.2	yes	yes	no	Kevin Paulsrud	7/15/2024	2025	low	8	yes	yes	4	47.22057	-96.99098	90201070106	County Ditch No 13-Red River
113		111	Kelso 27	144	50	27	E 1/2	312.1	312.1	6.4	305.7	yes	yes	no	Kevin Paulsrud	7/15/2024	2024	medium	130	yes	yes	51	47.26045	-96.99133	90201070406	Grandin Cemetery-Elm River
114		112	Elm River 5	144	49	5	ALL	569.5	569.5	80.9	488.6	yes	no	partial	ILLENE MASTERS	7/16/2024	2024	low	8	yes	yes	8	47.31753	-96.91132	90201070303	Borke Drain No 16-North Branch Elm River
115		113	Dallas/Mary Ann's 80	146	49	8	S 1/2, SW 1/4	76.4	76.4	0.0	76.4	yes	no	no	Dallas & MaryAnn Boeddeker	7/15/2024	2024	low	10	yes	yes	3	47.47065	-96.93657	90203010401	Judicial Ditch No 54-Red River
116		114	Kim's Section 15	144	49	15	N 1/2, NW 1/4	76.9	76.9	0.0	76.9	yes	no	no	Kim & Tod Harrington	7/16/2024	2024	low	8	yes	yes	15	47.29448	-96.87417	90201070406	Grandin Cemetery-Elm River
117		115																								
118		116																								
119		117																								
120		118																								
121		119	Caledonia 26	146	49	26	N 1/2, S 1/2	removed	110.9	0.0		yes	no	yes	Lucas Steinberger	7/29/2024	2024	low	10	yes	yes	13	47.43070	-96.87030	90201070605	Augustana Church-Red River
122		120	Caledonia 27	146	49	27	N 1/2, SW 1/4	79.5	79.5	16.5	63.0	yes	no	partial	Lucas Steinberger	7/29/2024	2024	low	5	yes	yes	4	47.43064	-96.89438	90201070605	Augustana Church-Red River
123		121	Hansen Section 11	145	49	11	E 1/2, NE 1/4	removed	74.6	3.8		no	no	yes	Bob & Priscilla Hanson	7/29/2024	2024	low	23	yes	yes	38	47.39347	-96.85938	90201070604	Steenerson Drain
124		122																								
125		123	Hansen Section 16	144	49	16	E 1/2, SW 1/4	79	79.0	8.2	70.8	yes	yes	partial	Bob & Priscilla Hanson	7/29/2024	2024	low	43	yes	yes	8	47.28563	-96.89333	90201070406	Grandin Cemetery-Elm River
126		124	Marshall Hansen Sec 16	144	49	16	W 1/2, SW 1/4	78.6	78.6	0.0	78.6	yes	yes	no	Marshall & Holly Hansen	7/29/2024	2024	low	5	yes	yes	10	47.28567	-96.89861	90201070406	Grandin Cemetery-Elm River
127		125	Helgoe	145	50	15	SW 1/4	154.5	154.5	0.0	154.5	yes	no	no	Jon Diehl	7/30/2024	2024	low	61	yes	yes	16	47.37107	-97.02251	90201070604	Steenerson Drain
128		126	Bovard 1/2	145	50	9	E 1/2	312	312.0	11.5	300.5	yes	no	no	Jon Diehl	7/30/2024	2024	low	7	yes	yes	9	47.38928	-97.03317	90201090605	Goose River
129		127	Clara's	145	50	8	SW 1/4	117.2	117.2	3.1	114.1	yes	no	no	Jon Diehl	7/30/2024	2024	low	6	yes	yes	3	47.38564	-97.06515	90201090605	Goose River
130		128	Diehl Home	145	50	8	E 1/2	152.1	152.1	3.4	148.7	yes	no	no	Jon Diehl	7/30/2024	2024	low	10	yes	yes	7	47.38751	-97.05365	90201090605	Goose River
131		129	McInness Farm	143	49	4	SE 1/4	154.8	154.8	3.9	150.9	yes	yes	no	Wayne Diekrager	7/24/2024	2025	low	5	yes	yes	3	47.22727	-96.88433	90201070106	County Ditch No 13-Red River
132		130	Johnson Farm	144	49	33	SW 1/4	removed	151.8	1.1		yes	no	partial	Wayne Diekrager	7/24/2024	2024	low	6	yes	yes	7	47.24190	-96.89516	90201070406	Grandin Cemetery-Elm River
133		131	Annastasia North	145	49	2	NW 1/4	removed	138.1	0.0		yes	yes	yes	Anastasia Boedekker Bassil	7/31/2024	2024	low	6	yes	yes	10	47.40726	-96.87293	90201070604	Steenerson Drain
134		132	Annastasia South	145	49	2	SW 1/4	removed	146.6	0.0		yes	yes	yes	Anastasia Boedekker Bassil	7/31/2024	2024	low	8	yes	yes	30	47.40060	-96.87280	90201070604	Steenerson Drain
135		133	Karla NE	145	50	22	NE 1/4	158.8	158.8	2.6	156.2	yes	no	no	Karla Diehl	7/31/2024	2024	low	11	yes	yes	12	47.36281	-97.01171	90201070603	Grandin Lake-Red River
136		134	Karla SW	145	50	22	SW 1/4	155.6	155.6	0.0	155.6	yes	yes	no	Karla Diehl	7/31/2024	2024	low	29	yes	yes	19	47.35662	-97.02223	90201070602	90201070602
137		135	Karla SE	145	50	22	SE 1/4	129.7	129.7	0.0	129.7	yes	yes	no	Karla Diehl	7/31/2024	2024	low	13	yes	yes	15	47.35660	-97.01177	90201070602	90201070602
138		136	Hustad's	145	49	15	S 1/2	removed	189.2	0.0		yes	yes	yes	Robert Stenerson	7/26/2024	2024	low	50	yes	yes	21	47.37305	-96.88882	90201070604	Steenerson Drain
139		137	Home Buildings	145	49	13	NW 1/4	removed	97.9	2.6		yes	no	yes	Todd Stenerson	7/17/2024	2024	low	35	yes	yes	14	47.37896	-96.85068	90201070605	Augustana Church-Red River
140		138	Home Drive	145	49	13	W 1/2	removed	27.6	0.1		yes	no	yes	Todd Stenerson	7/17/2024	2024	low	7	yes	yes	7	47.37335	-96.85395	90201070605	Augustana Church-Red River
141		139	Stenerson Home 1/4	145	49	14	NE 1/4	removed	155.4	1.2		yes	yes	yes	Todd Stenerson	7/17/2024	2024	low	32	yes	yes	5	47.37880	-96.86226	90201070604	Steenerson Drain
142		140	L&R	145	49	1	W 1/2, SW 1/4	removed	78.0	0.4		yes	yes	yes	Devin Stenerson	7/17/2024	2024	low	28	yes	yes	7	47.40076	-96.85377	90201070605	Augustana Church-Red River
143		141	Cactus Section	146	49	33	ALL	620.9	620.9	65.5	555.4	yes	yes	no	Brianna Watson	7/29/2024	2024	low	13	yes	yes	6	47.41803	-96.91058	90201070605	Augustana Church-Red River
144		142	Cactus Woods	145	49	12	Irregular	removed	177.5	3.9		yes	no	yes	Brianna Watson	7/29/2024	2024	low	18	yes	yes	31	47.39159	-96.84836	90201070605	Augustana Church-Red River
145		143	South Herberg 35	145	49	35	N 1/2, S 1/2	removed	159.4	0.0		yes	no	yes	Heidi Christianson	7/28/2024	2024	low	5	yes	yes	5	47.32958	-96.86768	90201070602	90201070602
146		144	North Herberg 36	145	49	36	N 1/2	removed	286.5	6.3		yes	no	yes	Heidi Christianson	7/28/2024	2024	low	3	yes	yes	3	47.33539	-96.84417	90201070603	Grandin Lake-Red River
147		145	Larry 80	145	49	11	W 1/2, NE 1/4	removed	81.3	3.7		yes	no	yes	Larry Chandler	7/28/2024	2024	low	7	yes	yes	10	47.39344	-96.86463	90201070604	Steenerson Drain
148		146	Larry 40	145	49	12	SW 1/4, NW 1/4	removed	38.3	0.0		yes	no	yes	Larry Chandler	7/28/2024	2024	low	9	yes	yes	6	47.39152	-96.85380	90201070605	Augustana Church-Red River
149		147																								
150		148																								
151		149	Half Section	146	49	27	E 1/2	removed	315.6	0.0		yes	no	yes	Michael, Douglas, Gregory, Betty A	8/1/2024	2024	low	4	yes	yes	4	47.43249	-96.88391	90201070605	Augustana Church-Red River
152		150	South 80+	146	49	26 & 35	S 1/2, SW 1/4	removed	140.9	1.0		yes	no	yes	Michael, Douglas, Gregory Anders	8/1/2024	2024	low	6	yes	yes	7	47.42536	-96.86663	90201070605	Augustana Church-Red River
153		151	McDonald 1/4	146	49	10	SE 1/4	159.8	159.8	0.0	159.8	yes	no	no	Michael, Douglas, Gregory Anders	8/1/2024	2024	low	8	yes	yes	3	47.47247	-96.88301	90203010401	Judicial Ditch No 54-Red River

MCEA Ex. 45

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	AK	AL	AM	AN	AP	AQ	AR	AS
2		Field No.	Field Name	T	R	S	Quarter	Landowner Reported Acres	Total Acres	Excluded Acres	Spreadable Acres	Setback map	Drain tile*	Flood risk	Owner	Easement Signed	PI - year done	PI Rating	N Soil lb/acre	Soil test	Soil map	P Soil Olson ppm	Lat.	Long.	Water Shed	Receiving Stream
154		152	The 120	146	49	3	SW 1/4	114.6	114.6	0.0	114.6	yes	no	no	Michael, Douglas, Gregory Anders	8/1/2024	2024	low	4	yes	yes	6	47.48599	-96.89339	90203010401	Judicial Ditch No 54-Red River
155		153	North 80	146	49	3	N 1.2, NW 1/4	74.6	74.6	5.0	69.6	yes	no	no	Michael, Douglas, Gregory Anders	8/1/2024	2024	low	13	yes	yes	7	47.49570	-96.89348	90203010401	Judicial Ditch No 54-Red River
156		154	L&R	145	49	1	Pt of S 1/2	removed	90.4	0.0		yes	yes	yes	Tim O'Gorman	8/1/2024	2024	low	28	yes	yes	7	47.40055	-96.84605	90201070605	Augustana Church-Red River
157		155	Holland 1/4	145	49	2	W 1/2, E 1/2	removed	147.3	5.3		yes	no	yes	Mark Dudgeon	8/5/2024	2024	low	4	yes	yes	6	47.40400	-96.86482	90201070604	Steenerson Drain
158		156	Gary 180	144	49	28	S 1/2, N 1/2	182.4	182.4	22.6	159.8	yes	no	partial	Gary Cossette	7/31/2024	2024	low	6	yes	yes	5	47.26230	-96.89007	90201070406	Grandin Cemetery-Elm River
159		157	Gary 120	144	49	29	SE 1/4	114.6	114.6	0.0	114.6	yes	no	no	Gary Cossette	7/31/2024	2024	low	10	yes	yes	14	47.25658	-96.90467	90201070406	Grandin Cemetery-Elm River
160		158	Gary 60	144	49	33	W 1/2, NW 1/4	69.6	69.6	0.0	69.6	yes	no	no	Gary Cossette	7/31/2024	2024	low	11	yes	yes	8	47.24913	-96.89861	90201070406	Grandin Cemetery-Elm River
161		159	Roberta 80	145	49	2	E 1/2, SE 1/4	removed	76.5	4.0		yes	no	yes	Dale Schuader	8/7/2024	2024	low	5	yes	yes	5	47.40083	-96.85961	90201070604	Steenerson Drain
162		160	Herberg 18	145	49	18	0.75	463.3	463.3	21.7	441.6	yes	no	no	Mavis Hettervig	7/31/2024	2024	low	16	yes	yes	14	47.37438	-96.95295	90201070604	Steenerson Drain
163		161	Herberg 8	145	49	8	W 1/2	317.7	317.7	7.1	310.6	yes	no	no	Mavis Hettervig	7/31/2024	2024	low	10	yes	yes	7	47.38916	-96.93706	90201070604	Steenerson Drain
164		162	Herberg 19	145	49	19	S 1/2, SE 1/4	74.3	74.3	0.0	74.3	yes	no	no	Mavis Hettervig	7/31/2024	2024	low	8	yes	yes	24	47.35464	-96.94753	90201070602	90201070602
165		163	Dairymple Section 7	144	49	7	E 1/2	removed	309.0	16.5		yes	no	yes	J Dalrymple	8/14/2024	2024	low	18	yes	yes	35	47.30406	-96.92751	90201070303	Borke Drain No 16-North Branch Elm River
166		164	Zimmerman	144	49	19	E 1/2	285.9	285.9	65.5	220.4	yes	yes	partial	J Dalrymple	8/14/2024	2024	low	28	yes	yes	37	47.27493	-96.92742	90201070406	Grandin Cemetery-Elm River
167		165	Herberg 31	145	49	31	N 1/2	289.8	289.8	5.0	284.8	yes	yes	no	J Dalrymple	8/14/2024	2024	low	12	yes	yes	18	47.33438	-96.95292	90201070602	90201070602
168		166	Herberg 33	145	49	33	ALL	619.5	619.5	12.9	606.6	yes	no	no	J Dalrymple	8/14/2024	2024	low	25	yes	yes	16	47.33135	-96.91026	90201070602	90201070602
169		167	Hillsboro Airport	145	50	20	0.75	348.8	348.8	4.1	344.7	yes	no	no	J Dalrymple	8/14/2024	2024	low	13	yes	yes	27	47.36013	-97.06057	90201070603	Grandin Lake-Red River
170		168	Hillsboro 28	145	50	28	N 1/2	198.8	198.8	0.0	198.8	yes	no	no	J Dalrymple	8/14/2024	2024	low	22	yes	yes	8	47.34927	-97.03499	90201070603	Grandin Lake-Red River
171		169	Hillsboro 34	145	50	34	E 1/2	306.5	306.5	0.0	306.5	yes	yes	no	J Dalrymple	8/14/2024	2024	low	5	yes	yes	12	47.33133	-97.01176	90201070602	90201070602
172		170	Hillsboro 35	145	50	35	ALL	606.9	606.9	12.3	594.6	yes	no	no	J Dalrymple	8/14/2024	2024	low	14	yes	yes	32	47.33111	-96.99563	90201070602	90201070602
173		171	Hillsboro 36	145	50	36	ALL	594.1	594.1	10.6	583.5	yes	no	no	J Dalrymple	8/14/2024	2024	low	24	yes	yes	28	47.33120	-96.97428	90201070602	90201070602
174		172	Herberg 29	145	49	29	S 1/2	310.8	310.8	30.9	279.9	yes	no	no	Neal & Bonnie Messer	8/5/2024	2024	low	16	yes	yes	7	47.34200	-96.93161	90201070602	90201070602
175		173	Herberg 29 NW	145	49	29	NW 1/4	149.2	149.2	3.6	145.6	yes	no	no	Neal & Bonnie Messer	8/6/2024	2024	low	3	yes	yes	8	47.34906	-96.93688	90201070602	90201070602
176		174	Hillsboro 29	145	50	29	ALL	550.8	550.8	4.0	546.8	yes	no	no	J Dalrymple	8/14/2024	2024	low	4	yes	yes	21	47.34564	-97.06048	90201070603	Grandin Lake-Red River
177		175	North Quarter	146	50	2	NW 1/4	157.4	157.4	1.6	155.8	yes	no	no	Michael Anderson	7/1/2024	2025	low	9	yes	yes	9	47.49417	-97.00046	90203010401	Judicial Ditch No 54-Red River
178		176	Orlin	146	50	2	SE 1/4	143.8	143.8	0.5	143.3	yes	no	no	Michael Anderson	7/1/2024	2025	low	7	yes	yes	2	47.48703	-96.98979	90203010401	Judicial Ditch No 54-Red River
179		177	Mike & Mark Red Barn	146	50	11	NW 1/4	156.6	156.6	0.0	156.6	yes	no	no	Michael Anderson	7/1/2024	2025	low	10	yes	yes	5	47.47953	-97.00065	90201090605	Goose River
180		178	Henka Sec 14 Bloomfield	145	51	14	S 1/2	295.6	295.6	32.7	262.9	yes	yes	no	Keith & Keneth Henka	7/8/2024	2025	low	22	yes	yes	12	47.37101	-97.12373	90201070303	Borke Drain No 16-North Branch Elm River
181		179	Taft Road East	146	50	13	SE 1/4	187	187.0	3.4	183.6	yes	no	no	Gerald & Ann Boeddeker	7/11/2024	2025	low	44	yes	yes	11	47.45789	-96.97051	90201090605	Goose River
182		180	Taft Road West	146	50	13	E 1/2, SW 1/4	38.8	38.8	0.0	38.8	yes	no	no	Dale & Joyce Boeddeker	7/11/2024	2025	low	44	yes	yes	11	47.45791	-96.97841	90201090605	Goose River
183		181	Bohn 22	144	51	22	S 1/2	291.2	291.2	43.9	247.3	yes	no	no	Dennis Peterson	7/29/2024	2025	low	43	yes	yes	16	47.27141	-97.12315	90201070405	Town of Greenfield-Elm River
184		182	Bohn 19	144	51	19	S 1/2	298.6	298.6	0.0	298.6	yes	no	no	Dennis Peterson	7/29/2024	2025	low	65	yes	yes	34	47.27149	-97.18687	90201070405	Town of Greenfield-Elm River
185		183	Green 24	144	52	24	SE 1/4	156.6	156.6	0.0	156.6	yes	no	no	Dennis Peterson	7/29/2024	2025	low	34	yes	yes	39	47.27154	-97.20269	90201070405	Town of Greenfield-Elm River
186		184	Green 36	144	52	36	SW 1/4 & S 1/2, NW 1/4	217.9	217.9	0.2	217.7	yes	no	no	Dennis Peterson	7/29/2024	2025	low	18	yes	yes	38	47.24425	-97.21254	90201070203	Lower South Branch Elm River
187		185	Beitz Home	145	49	6	NE 1/4	140.8	140.8	0.0	140.8	yes	no	no	Eugene & Margaret Beitz	8/16/2024	2025	low	10	yes	yes	3	47.40694	-96.948	90201070604	Steenerson Drain
188		186	NW Herberg 5	145	49	5	NW 1/4	149	149.0	0.0	149.0	yes	no	no	Eugene & Margaret Beitz	8/16/2024	2025	low	8	yes	yes	2	47.40709	-96.93727	90201070604	Steenerson Drain
189		187	SW Herberg 5	145	49	5	East 11 ac	11.3	11.3	0.0	11.3	yes	no	no	Eugene & Margaret Beitz	8/16/2024	2025	low	12	yes	yes	11	47.40012	-96.93219	90201070604	Steenerson Drain
190		188	SW Herberg 5	145	49	5	SW 1/4	145.7	145.7	0.0	145.7	yes	no	no	Lorraine Reinpold	8/16/2024	2025	low	14	yes	yes	9	47.40013	-96.9375	90201070604	Steenerson Drain
191		189	Steve Reinpold Home	145	49	18	NE 1/4	150.3	150.3	4.8	145.5	yes	no	no	Lorraine Reinpold	8/16/2024	2025	low	8	yes	yes	4	47.37807	-96.9479	90201070604	Steenerson Drain
192		190	Madsons	145	48	31	NE 1/4 & E 1/2, NW 1/4	229.8	229.8	0.4	229.4	yes	yes	no	Randy Aarestad	7/24/2024	2025	low	45	yes	yes	3	47.33551	-96.69553	90201070507	Lower Marsh River
193		191	Church	145	48	9	NW 1/4 & N 1/2, SW 1/4	213.5	213.5	0.6	212.9	yes	no	no	Randy Aarestad	7/24/2024	2025	low	14	yes	yes	2	47.39161	-96.78801	90201070507	Lower Marsh River
194		192	Gilbertsons	145	48	23	NE 1/4	157.2	157.2	0.0	157.2	yes	no	no	Randy Aarestad	7/24/2024	2025	low	18	yes	yes	5	47.36475	-96.73458	90201070507	Lower Marsh River
195		193	Charlies	145	48	22	N 1/2	288.9	288.9	5.2	283.7	yes	no	no	Randy Aarestad	7/24/2024	2025	low	11	yes	yes	4	47.36483	-96.761	90201070603	Grandin Lake-Red River
196		194	REA	145	48	20	SW 1/4	143.2	143.2	0.0	143.2	yes	no	no	Randy Aarestad	7/24/2024	2025	low	41	yes	yes	3	47.35728	-96.80907	90201070603	Grandin Lake-Red River
197		195	Hellerud Home 1/4	145	48	23	SE 1/4	140.7	140.7	0.4	140.3	yes	yes	no	Philip Hellerud	unknown	2025	low	22	yes	yes	5	47.35732	-96.73468	90201070603	Grandin Lake-Red River
198		196	Warner 1/2	145	49	16	W 1/2	320	320.0	4.0	316.0	yes	yes	no	The Warner Group	8/13/2024	2025	low	27	yes	yes	17	47.37496	-96.91562	90201070604	Steenerson Drain
199		197	Elm River Sec 15	144	49	15	SW 1/4 & S 1/2, NE 1/4	221	221.0	49.7	171.3	yes	no	partial	Wendy & Guy Solemsaas	11/14/2024	2025	low	20	yes	yes	3	47.28785	-96.87397	90201070406	Grandin Cemetery-Elm River
200		198	Bohn 31	144	51	31	SW 1/4	147.2	147.2	0.6	146.6	yes	no	no	Donald McInnes	7/9/2024	2025	low	16	yes	yes	14	47.24255	-97.19185	90201070203	Lower South Branch Elm River
201		199	Reimer NW	145	50	23	NW 1/4	140.8	140.8	2.8	138.0	yes	no	no	Donald Riemer Residuary Trust	9/11/2024	2025	low	16	yes	yes	9	47.36379	-97.00092	90201070603	Grandin Lake-Red River
202		200	Reimer NE	145	50	23	NE 1/4	150.2	150.2	2.6	147.6	yes	no	no	Marjorie Riemer	9/10/2024	2025	low	14	yes	yes	9	47.3636	-96.99043	90201070603	Grandin Lake-Red River
203										Total Spreadable Acres	30,221				* Drain tile determination was based on best profesional judgement of aerial maps.											

MCEA Ex. 45

2025

Feedlot Inspection Records

NPDES and SDS permitted sites



MINNESOTA POLLUTION CONTROL AGENCY

MPCA Feedlot Program Contacts

https://www.pca.state.mn.us/feedlots

Rochester
- Paul Brietzke 507-206-2616
  Nutrient management lead staff
- Peter Kuisle 507-424-9132
- Chelsea Habberstad 507-226-3898
- Isaac Johnson 507-206-2606

Mankato
- Mark Gernes 507-344-5260
  Permitting lead staff
- Dave Malakowsky 507-461-3168
  County programs lead staff
- Rebecca Novey 507-995-2623
- Max Miller 507-344-5264

Marshall
- Josh Kircher 507-476-3375
- Jason Kaare 507-735-8584
- Nick Timmerman 507-476-4286
- Dana Leibfried 507-421-7648

Detroit Lakes
- Taylor Waskow 218-849-7359
- Ellen Teiken 218-940-1922

Brainerd
- Rhonda Adkins 218-821-9727
- Kourtney Frank 218-232-9709

Engineers
- George Schwint 320-894-5866
  Principal engineer
- Toby Sunderland 320-212-1910
- Brian Hetchler 612-283-6303

Manager
- Randy Hukriede 320-295-2227

Supervisors
- Steve Schmidt (East) 507-206-2618
- Lisa Scheirer (West) 218-846-8122

Compliance Coordinator
- Brent Riess 507-476-4268

Summary of Required Inspections

MCEA Ex. 46

The following visual inspections are required:

1. **Daily** visual inspection of water lines (NPDES only)
2. **Weekly** visual inspection of ALL permitted components
   - Animal holding areas
   - Manure storage areas and associated handling/transfer systems (liquid and solid)
   - Feed storage areas
   - Mortality handling areas
   - Vegetative treatment/infiltration areas
3. **Weekly** visual inspection of the LMSA freeboard marker
4. **Monthly** visual inspection of the LMSA perimeter drain tile

Inspections of land application fields are also required (SDS only – NPDES begins in 2026)
- At least once each day manure is applied to the field
- At the end of application to the field
- Within 24 hours of ½ inch or more rainfall that occurs within 14 days of application, unless the manure is injected or incorporated

Keep records of inspections for at least 6 years.

Important info about NPDES and SDS permits

When a permit modification is required
- Construction/Expansion of animal holding capacity
- Construction/Expansion of manure storage capacity
- Construction/Expansion of outdoor feed storage capacity (even if covered by plastic)
- Addition of a new land application field to the MMP
- Change of ownership or name

For more info about permit modifications see the fact sheet: *Feedlot Permit Modifications*

How to apply for a permit or permit modification
Applications are only accepted via the online permit application service available at: https://webapp.pca.state.mn.us/services/login/.

Applications received via email or the postal service will be automatically returned.

Annual permit fees
NPDES and SDS general permits have an annual fee of $345. ($1,230 for individual permits)

You are billed in February or March for the previous year's permit coverage.

Annual reports
Both NPDES and SDS permits require submittal of an annual report by March 1 each year.

The required form is found at: https://www.pca.state.mn.us/sites/default/files/wq-f3-22b.docx

Records of land application activities must be included with the annual report.

2025 January 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Reminder **2024 annual report due March 1**	✓ **Liquid manure application prohibited** ✓ **Solid manure application restricted** (see permit for details) ✓ **Obtain manure application records.** ✓ **Obtain soils test analysis.** ✓ **Obtain manure test analysis.**		**1** ❑ **Inspect water line** ❑ **Inspect LMSA perimeter tile**	**2** ❑ **Inspect water line**	**3** ❑ **Inspect water line**	**4** ❑ **Inspect water line**
5 ❑ **Inspect water line**	**6** ❑ **Inspect water line**	**7** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**8** ❑ **Inspect water line**	**9** ❑ **Inspect water line**	**10** ❑ **Inspect water line**	**11** ❑ **Inspect water line**
12 ❑ **Inspect water line**	**13** ❑ **Inspect water line**	**14** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**15** ❑ **Inspect water line**	**16** ❑ **Inspect water line**	**17** ❑ **Inspect water line**	**18** ❑ **Inspect water line**
19 ❑ **Inspect water line**	**20** ❑ **Inspect water line**	**21** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**22** ❑ **Inspect water line**	**23** ❑ **Inspect water line**	**24** ❑ **Inspect water line**	**25** ☑ **Inspect water line**
26 ❑ **Inspect water line**	**27** ❑ **Inspect water line**	**28** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**29** ❑ **Inspect water line**	**30** ❑ **Inspect water line**	**31** ❑ **Inspect water line**	

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 February 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
✓ **Liquid manure application prohibited** ✓ **Solid manure application restricted** (see permit for details) ***Reminder*** ***2023 annual report due March 1!***						**1** ❑ **Inspect water line** ❑ **Inspect LMSA perimeter tile**
2 ❑ **Inspect water line**	**3** ❑ **Inspect water line**	**4** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**5** ❑ **Inspect water line**	**6** ❑ **Inspect water line**	**7** ❑ **Inspect water line**	**8** ❑ **Inspect water line**
9 ❑ **Inspect water line**	**10** ❑ **Inspect water line**	**11** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**12** ❑ **Inspect water line**	**13** ❑ **Inspect water line**	**14** ❑ **Inspect water line**	**15** ❑ **Inspect water line**
16 ❑ **Inspect water line**	**17** ❑ **Inspect water line**	**18** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**19** ❑ **Inspect water line**	**20** ❑ **Inspect water line**	**21** ❑ **Inspect water line**	**22** ❑ **Inspect water line**
23 ❑ **Inspect water line**	**24** ❑ **Inspect water line**	**25** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**26** ❑ **Inspect water line**	**27** ❑ **Inspect water line**	**28** ❑ **Inspect water line**	

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 March 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
✓ **Liquid manure application prohibited*** ✓ **Solid manure application** • **Prohibited* at NPDES sites** • **Restricted* at SDS sites** (see permit for details) * When fields are frozen or snow-covered						**1** ❑ **Inspect water line** ❑ **Inspect LMSA perimeter tile** **Annual Report Due!**
2 ❑ **Inspect water line**	**3** ❑ **Inspect water line**	**4** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**5** ❑ **Inspect water line**	**6** ❑ **Inspect water line**	**7** ❑ **Inspect water line**	**8** ❑ **Inspect water line**
9 ❑ **Inspect water line**	**10** ❑ **Inspect water line**	**11** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**12** ❑ **Inspect water line**	**13** ❑ **Inspect water line**	**14** ❑ **Inspect water line**	**15** ❑ **Inspect water line**
16 ❑ **Inspect water line**	**17** ❑ **Inspect water line**	**18** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**19** ❑ **Inspect water line**	**20** ❑ **Inspect water line**	**21** ❑ **Inspect water line**	**22** ❑ **Inspect water line**
23 ❑ **Inspect water line**	**24** ❑ **Inspect water line**	**25** ❑ **Inspect water line** ❑ **Inspect all permitted components** ❑ **LMSA freeboard inspection**	**26** ❑ **Inspect water line**	**27** ❑ **Inspect water line**	**28** ❑ **Inspect water line**	**29** ❑ **Inspect water line**
30 ❑ **Inspect water line**	**31** ❑ **Inspect water line**					

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 April 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
		1 ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**2** ❑ Inspect water line ❑ Inspect LMSA perimeter tile	**3** ❑ Inspect water line	**4** ❑ Inspect water line	**5** ❑ Inspect water line
6 ❑ Inspect water line	**7** ❑ Inspect water line	**8** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**9** ❑ Inspect water line	**10** ❑ Inspect water line	**11** ❑ Inspect water line	**12** ❑ Inspect water line
13 ❑ Inspect water line	**14** ❑ Inspect water line	**15** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**16** ❑ Inspect water line	**17** ❑ Inspect water line	**18** ❑ Inspect water line	**19** ❑ Inspect water line
20 ❑ Inspect water line	**21** ❑ Inspect water line	**22** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**23** ❑ Inspect water line	**24** ❑ Inspect water line	**25** ❑ Inspect water line	**26** ❑ Inspect water line
27 ❑ Inspect water line	**28** ❑ Inspect water line	**29** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**30** ❑ Inspect water line	**Review Manure Management Plan for spring applications** ✓ **Determine rates of manure to apply** ✓ **Calibrate manure spreader, check equipment** ✓ **Land apply according to MMP and setbacks from waters.** Note: Water line inspections optional for SDS permitted sites. Equivalent water meter or pressure gauge check is allowed alternative.		

2025 May 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1 ❑ Inspect water line ❑ Inspect LMSA perimeter tile	**2** ❑ Inspect water line	**3** ❑ Inspect water line
4 ❑ Inspect water line	**5** ❑ Inspect water line	**6** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**7** ❑ Inspect water line	**8** ❑ Inspect water line	**9** ❑ Inspect water line	**10** ❑ Inspect water line
11 ❑ Inspect water line	**12** ❑ Inspect water line	**13** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**14** ❑ Inspect water line	**15** ❑ Inspect water line	**16** ❑ Inspect water line	**17** ❑ Inspect water line
18 ❑ Inspect water line	**19** ❑ Inspect water line	**20** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**21** ❑ Inspect water line	**22** ❑ Inspect water line	**23** ❑ Inspect water line	**24** ❑ Inspect water line
25 ❑ Inspect water line	**26** ❑ Inspect water line	**27** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**28** ❑ Inspect water line	**29** ❑ Inspect water line	**30** ❑ Inspect water line	**31** ❑ Inspect water line

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 June 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1 ❑ Inspect water line ❑ Inspect LMSA perimeter tile **New general SDS permit effective**	**2** ❑ Inspect water line	**3** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**4** ❑ Inspect water line	**5** ❑ Inspect water line	**6** ❑ Inspect water line	**7** ❑ Inspect water line
8 ❑ Inspect water line	**9** ❑ Inspect water line	**10** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**11** ❑ Inspect water line	**12** ❑ Inspect water line	**13** ❑ Inspect water line	**14** ❑ Inspect water line
15 ❑ Inspect water line	**16** ❑ Inspect water line	**17** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**18** ❑ Inspect water line	**19** ❑ Inspect water line	**20** ❑ Inspect water line	**21** ❑ Inspect water line
22 ❑ Inspect water line	**23** ❑ Inspect water line	**24** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**25** ❑ Inspect water line	**26** ❑ Inspect water line	**27** ❑ Inspect water line	**28** ❑ Inspect water line
29 ❑ Inspect water line	**30** ❑ Inspect water line	✓ **Cover crop required for manure application to harvested fields**				

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 July 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
		1 ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**2** ❑ Inspect water line ❑ Inspect LMSA perimeter tile	**3** ❑ Inspect water line	**4** ❑ Inspect water line	**5** ❑ Inspect water line
6 ❑ Inspect water line	**7** ❑ Inspect water line	**8** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**9** ❑ Inspect water line	**10** ❑ Inspect water line	**11** ❑ Inspect water line	**12** ❑ Inspect water line
13 ❑ Inspect water line	**14** ❑ Inspect water line	**15** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**16** ❑ Inspect water line	**17** ❑ Inspect water line	**18** ❑ Inspect water line	**19** ❑ Inspect water line
20 ❑ Inspect water line	**21** ❑ Inspect water line	**22** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**23** ❑ Inspect water line	**24** ❑ Inspect water line	**25** ❑ Inspect water line	**26** ❑ Inspect water line
27 ❑ Inspect water line	**28** ❑ Inspect water line	**29** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**30** ❑ Inspect water line	**31** ❑ Inspect water line	✓ **Cover crop required for manure application to harvested fields**	

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 August 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
✓ Cover crop required for manure application to harvested fields. ✓ Update MMP for fall and spring applications. ✓ Determine rates of manure to apply per field/acre and from each manure source. ✓ Submit MMP modifications for new acreage.					**1** ❑ Inspect water line	**2** ❑ Inspect water line ❑ Inspect LMSA perimeter tile
3 ❑ Inspect water line	**4** ❑ Inspect water line	**5** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**6** ❑ Inspect water line	**7** ❑ Inspect water line	**8** ❑ Inspect water line	**9** ❑ Inspect water line
10 ❑ Inspect water line	**11** ❑ Inspect water line	**12** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**13** ❑ Inspect water line	**14** ❑ Inspect water line	**15** ❑ Inspect water line	**16** ❑ Inspect water line
17 ❑ Inspect water line	**18** ❑ Inspect water line	**19** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**20** ❑ Inspect water line	**21** ❑ Inspect water line	**22** ❑ Inspect water line	**23** ❑ Inspect water line
24 ❑ Inspect water line **31** ❑ Inspect water line	**25** ❑ Inspect water line	**26** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**27** ❑ Inspect water line	**28** ❑ Inspect water line	**29** ❑ Inspect water line	**30** ❑ Inspect water line

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 September 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	1 ❑ Inspect water line ❑ Inspect LMSA perimeter tile	**2** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**3** ❑ Inspect water line	**4** ❑ Inspect water line	**5** ❑ Inspect water line	**6** ❑ Inspect water line
7 ❑ Inspect water line	**8** ❑ Inspect water line	**9** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**10** ❑ Inspect water line	**11** ❑ Inspect water line	**12** ❑ Inspect water line	**13** ❑ Inspect water line
14 ❑ Inspect water line	**15** ❑ Inspect water line	**16** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**17** ❑ Inspect water line	**18** ❑ Inspect water line	**19** ❑ Inspect water line	**20** ❑ Inspect water line
21 ❑ Inspect water line	**22** ❑ Inspect water line	**23** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**24** ❑ Inspect water line	**25** ❑ Inspect water line	**26** ❑ Inspect water line	**27** ❑ Inspect water line
28 ❑ Inspect water line	**29** ❑ Inspect water line	**30** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	✓ **Cover crop required for manure application to harvested fields** Note: Water line inspections optional for SDS permitted sites. Equivalent water meter or pressure gauge check is allowed alternative.			

2025 October 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Vulnerable groundwater areas Oct 1 - 14: • Application to living crop or use of cover crops required *(NPDES permits allow use BMPs below as alternative)* **Other areas Oct 1 - 14, choose one of the following:** • Soil temp 50°F or less • Cover crop • Nitrification inhibitor • Split application			**1** ❑ Inspect water line ❑ Inspect LMSA perimeter tile	**2** ❑ Inspect water line	**3** ❑ Inspect water line	**4** ❑ Inspect water line
5 ❑ Inspect water line	**6** ❑ Inspect water line	**7** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**8** ❑ Inspect water line	**9** ❑ Inspect water line	**10** ❑ Inspect water line	**11** ❑ Inspect water line
12 ❑ Inspect water line	**13** ❑ Inspect water line	**14** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**15** ❑ Inspect water line	**16** ❑ Inspect water line	**17** ❑ Inspect water line	**18** ❑ Inspect water line
19 ❑ Inspect water line	**20** ❑ Inspect water line	**21** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**22** ❑ Inspect water line	**23** ❑ Inspect water line	**24** ❑ Inspect water line	**25** ❑ Inspect water line
26 ❑ Inspect water line	**27** ❑ Inspect water line	**28** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**29** ❑ Inspect water line	**30** ❑ Inspect water line	**31** ❑ Inspect water line	**Report spills to MN Duty Officer 1-800-422-0798**

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 November 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
✓ **Observe Manure Application Setbacks** *(Applying Manure in Sensitive Areas)* ✓ **Report manure application spills to State Duty Officer: 1-800-422-0798**						**1** ❑ Inspect water line ❑ Inspect LMSA perimeter tile
2 ❑ Inspect water line	**3** ❑ Inspect water line	**4** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**5** ❑ Inspect water line	**6** ❑ Inspect water line	**7** ❑ Inspect water line	**8** ❑ Inspect water line
9 ❑ Inspect water line	**10** ❑ Inspect water line	**11** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**12** ❑ Inspect water line	**13** ❑ Inspect water line	**14** ❑ Inspect water line	**15** ❑ Inspect water line
16 ❑ Inspect water line	**17** ❑ Inspect water line	**18** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**19** ❑ Inspect water line	**20** ❑ Inspect water line	**21** ❑ Inspect water line	**22** ❑ Inspect water line
23 ❑ Inspect water line	**24** ❑ Inspect water line	**25** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**26** ❑ Inspect water line	**27** ❑ Inspect water line	**28** ❑ Inspect water line	**29** ❑ Inspect water line
30 ❑ Inspect water line						

Note: Water line inspections optional for SDS permitted sites.
Equivalent water meter or pressure gauge check is allowed alternative.

2025 December 2025

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	1 ❑ Inspect water line ❑ Inspect LMSA perimeter tile	**2** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**3** ❑ Inspect water line	**4** ❑ Inspect water line	**5** ❑ Inspect water line	**6** ❑ Inspect water line
7 ❑ Inspect water line	**8** ❑ Inspect water line	**9** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**10** ❑ Inspect water line	**11** ❑ Inspect water line	**12** ❑ Inspect water line	**13** ❑ Inspect water line
14 ❑ Inspect water line	**15** ❑ Inspect water line	**16** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**17** ❑ Inspect water line	**18** ❑ Inspect water line	**19** ❑ Inspect water line	**20** ❑ Inspect water line
21 ❑ Inspect water line	**22** ❑ Inspect water line	**23** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**24** ❑ Inspect water line	**25** ❑ Inspect water line	**26** ❑ Inspect water line	**27** ❑ Inspect water line
28 ❑ Inspect water line	**29** ❑ Inspect water line	**30** ❑ Inspect water line ❑ Inspect all permitted components ❑ LMSA freeboard inspection	**31** ❑ Inspect water line	✓ **Liquid manure application prohibited*** ✓ **Solid manure application restricted*** (see permit for details) * When fields are frozen or snow-covered Note: Water line inspections optional for SDS permitted sites. Equivalent water meter or pressure gauge check is allowed alternative.		

DEPARTMENT OF HEALTH

Protecting Vulnerable Drinking Water Sources

SOURCE WATER PROTECTION

Background

Of the approximately 50 million acres in Minnesota, 1.2 million acres are located in Drinking Water Supply Management Areas (DWSMAs). DWSMAs are the areas surrounding public water supply wells that contribute water to the well or surface water intake.

Land within DWSMAs can be highly vulnerable to contamination from the land surface because of their geologic conditions. Currently, there are approximately 400,000 acres in vulnerable groundwater DWSMAs, although this may change over time as DWSMA delineations are updated. Vulnerable groundwater DWSMAs represent less than 1 percent of the overall land area of the state (see right). These vulnerable areas cover a wide range of land uses, ranging from urban to agricultural to forested areas.

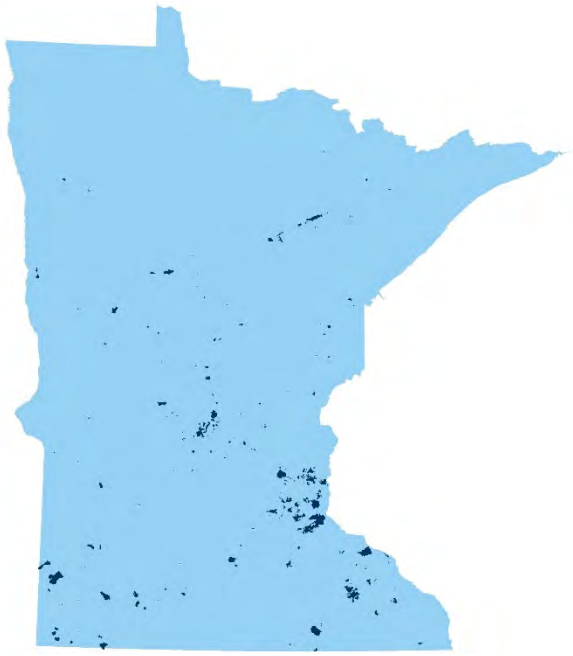

Map of DWSMAs in Minnesota with high and very high vulnerability

Surface water DWSMAs can also be vulnerable to contaminants in runoff from the land surface. MDH is working towards delineating DWSMAs for all systems using surface water, but there are over 7 million acres in Source Water Assessment areas for these systems.

In vulnerable DWSMAs, land use is an important factor that can influence water quality. Certain land uses are more protective of water quality than others, such as forested land, wetlands, perennial cover, prairies, or public parks. There are increasing efforts to target vulnerable areas in DWSMAs and protect them with conservation practices, easements, zoning overlays or other measures.

Goal and objectives

The Source Water Protection Program at Minnesota Department of Health (MDH) has a goal to protect vulnerable land in DWSMAs statewide by 2034. MDH plans to achieve this goal by working with state and local partners to protect vulnerable areas with land uses and activities that benefit water quality. State partners can help manage point sources of contamination, such as tanks and landfills, and local partners can assist with management of nonpoint sources of contamination, such as fertilizer or pesticide application. In doing so, state and local partners can assure continued safety of drinking water sources.

In cases where threats extend beyond the scope and jurisdiction of local partners, this initiative will also inform priorities for state planning through comprehensive watershed framework.

What it means to protect vulnerable sources

MDH aims to secure long-term sustainability of source water quality and quantity for all Minnesotans. While "protection" sounds like a simple concept, in practice, it can be difficult and complex to achieve because settings and threats vary considerably across Minnesota.

Given the diversity in settings and threats, activities to achieve protection need to vary as well. In some places, protection may involve land use controls, conservation measures, or easements, while in others, protection may be achieved by managing potential sources of contamination. MDH is developing a conceptual framework and resources to characterize DWSMAs' physical settings, assess risks to the source, and address risks in a systematic fashion.

Our approach

MDH is planning activities to measure and evaluate protection of the vulnerable areas within DWSMAs. MDH will also work with state and local partners to create the tools and plan needed to advance this initiative. These resources will allow MDH, public water systems, and other stakeholders to identify appropriate protection measures for the diverse DWSMAs in the state, and measure progress accordingly.

Our approach includes the following steps:

- **Characterizing DWSMAs** – MDH will assess and categorize vulnerable DWSMAs based on their characteristics, such as physical setting, land use, and risks to drinking water.
- **Comparative risk assessment** – MDH will compare, evaluate, and rank potential contaminant sources in vulnerable DWSMAs by their public health risk.
- **Creating a framework** – MDH will develop a conceptual framework that outlines appropriate protection measures based on DWSMA characteristics and potential contaminant sources.
- **Developing a measurement and evaluation plan** – MDH will develop indicators, tools, and benchmarks to measure and evaluate progress towards the goal.

After developing the framework and associated resources, MDH, public water systems, and partners will work together to identify, implement, and evaluate protection measures in DWSMAs.

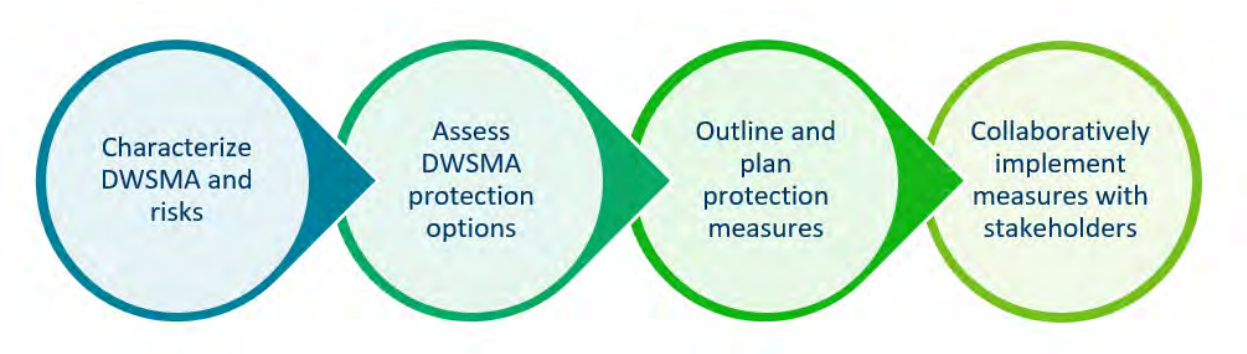

Considerations for planning and implementation

1. DWSMAs have diverse characteristics

Across Minnesota, landscapes can look dramatically different. Below the land surface, the geology of Minnesota is also varied. DWSMAs across the state can have diverse characteristics that affect the types of contaminant threats they face, their vulnerability to contamination, and the feasibility of protection.

Factors that can affect contaminant risks within a DWSMA include:

- ***Land use*** - Activities or features on the land can affect the quality of drinking water sources. Land use varies across urban, rural, and suburban settings. Examples of different land uses include row crop agriculture, forested land, and sewered subdivisions.
- ***Potential contaminant sources*** **-** Certain activities and features in the DWSMA can introduce contamination to the drinking water source. These can include abandoned wells, septic systems, feedlots, or aging wastewater or stormwater infrastructure. Practices on the land surface can also introduce contamination into source waters, such as fertilizer and pesticide application.

Factors that can affect the vulnerability of the DWSMA include:

- ***Hydrogeology*** **-** The geology in the DWSMA affects how easily and quickly contaminants can move through soils and subsoils into the aquifers that supply drinking water. The hydrogeology across the state is diverse and there are several unique regions, such as the karst region in southeastern Minnesota and the Central Sands region.

- ***Water use –*** The type and amount of water use can affect the vulnerability of drinking water sources. High pumping at wells can influence vulnerability by creating flow conditions that draw water from shallow, vulnerable environments into deeper settings.
- ***Groundwater-surface water interactions*** – In many settings across Minnesota, water is exchanged between surface water bodies and groundwater aquifers. This can be a concern where vulnerable surface water recharges or infiltrates into groundwater near public water system wells. These conditions can create pathways for contaminants in surface water to enter groundwater.

Factors that can affect the feasibility of protecting land in the DWSMA include:

- ***Ownership –*** Land within a DWSMA may be publicly owned, privately owned, or a combination of both. Privately owned land may also be rented, and the owner may not reside in the area.
- ***Jurisdictional area of the public water system -*** MDH and public water systems have limited ability to influence land use in DWSMAs, since much of the land is privately owned and outside of municipal jurisdiction.
- ***Type of contaminant source -*** Addressing nonpoint source contamination on a regional scale is a major challenge. Activities to address regional nonpoint source contamination can also be affected by changes to programs such as Clean Water Fund programs, Clean Water Act programs, or the Farm Bill.
- ***Groundwater or surface water source*** - In Minnesota, most community public water systems use groundwater for their source of drinking water, but 23 systems use surface water. Source water protection is required for systems using groundwater, but voluntary for systems that use surface water.
- ***Geographic DWSMA characteristics*** – The geographic characteristics of a DWSMA can also affect the feasibility of protection, such as DWSMA size. Surface water DWSMAs often receive water from large watersheds.
- ***Area*** - DWSMAs in urban, suburban, and rural areas may face different regional water-related issues and pressures based on their characteristics, such as land use, potential for urbanization, and industries. Additionally, the types of appropriate implementation activities and tools can vary across urban, suburban, and rural settings.
- ***Updated DWSMA delineation from amendment process –*** The boundaries of some communities' DWSMAs may change over time as they update and amend their Source Water Protection Plans. Changing boundaries may affect the size of the DWSMA and properties within it.

2. There is no one-size-fits-all approach to protection

Since DWSMAs have diverse characteristics and potential contaminants, there are many ways to protect them from contamination. This means there is no one-size-fits-all approach to protecting our drinking water sources.

For example, conservation easements on former agricultural lands place significant land use restrictions on enrolled lands for long periods of time. In urban areas, "protected" lands may feature BMPs that reduce contamination from stormwater, underground storage tanks, turf management practices, or aging wastewater infrastructure. An array of protection measures is needed to address different potential sources of contamination, land uses, and settings.

Protection measures will also need to be tailored for individual DWSMAs based on what is economically, socially, or politically feasible for the community. Indicators to track and measure progress will need to be flexible to the situation within each DWSMA. Certain protection measures will be more beneficial than others based on their:

- ***Duration*** - For example, one-year easement contracts do not provide the same benefits to water quality as permanent easements.
- ***Renewal*** - For example, annual payments for cover crop adoption do not guarantee that cover crops will be planted the following year.
- ***Impact*** - Managing a potential source of contamination does not provide the same protection as eliminating or removing it.
- ***Location and coverage*** - Protection measures are generally more impactful if they cover a larger area and are closer to the intake or well.
- ***Multiple benefits*** - Some protection measures may provide benefits to the community or ecosystem in addition to drinking water protection.
- ***Local support and feasibility*** **-** Certain measures will be more successful in areas where there is existing technical expertise, support, and capacity at the local level.

3. There are practical barriers to land use changes

Achieving the highest level of protection may require substantial land use changes, which has several practical barriers. Most lands within DWSMAs are outside the jurisdictional boundaries of public water systems, and systems have limited influence on how those lands are used. Agricultural land uses and practices are driven by complex existing agricultural and economic systems, which are difficult to change. Lastly, where land use changes are recommended for protection, implementation of Source Water Protection Plans is largely voluntary.

However, truly sustainable protection for the most vulnerable drinking water sources may require transformational change, and that is the ultimate goal for vulnerable DWSMAs.

4. Land use data is limited, and multiple data sources will be needed

There are several data challenges to tracking and evaluating progress towards this goal. One challenge in tracking changes in land use over time is the availability of data. While some lands within DWSMAs are permanently protected through easements or conservation, this data is not currently available. Having publicly available data on land in conservation would provide a more accurate representation of long-term protection of drinking water sources. Making these data available would help local implementers plan activities to protect Minnesota drinking water now and in the future. However, some of this data is protected by statute or rule and will not be readily available for this initiative.

Statewide data on land use is available through the National Land Cover Database (NLCD). These data show land uses such as forestry, wetlands, agriculture, and development. However, these land use categories are an insufficient indicator for drinking water protection. Land use categories do not account for BMPs that protect water quality. For example, conservation practices can mitigate contamination in agricultural areas, and stormwater BMPs can reduce contamination from runoff in urban areas. Additionally, updated NLCD data is only released every five years.

We also lack predictive tools to predict and evaluate the impacts of protection measures on water quality. Without these tools, it is difficult to assess the number of acres and practices needed to maintain or reduce contaminant levels.

Multiple data sources will be needed to track the various protection measures used in DWSMAs. A number of indicators will be needed to reflect protection activities and BMPs that are appropriate across various settings. Some of these activities and BMPs may be tracked by other state agencies or partners, although data may be reported at the county, watershed, or state scale, requiring MDH to estimate or request data at the DWSMA scale.

In summary, this initiative will require multiple sources and types of data, and additional challenges remain for data availability and obtaining DWSMA-scale data. MDH will need to work with its state and local partners to identify and modify existing tools and create new tools to collect data needed for this initiative.

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3/23/2021

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10-27-2020

Examination of Soil Water Nitrate-N Concentrations from Common Land Covers and Cropping Systems in Southeast Minnesota Karst

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Missouri State University

Jeppe Kjaersgaard

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DEPARTMENT OF AGRICULTURE

Examination of Soil Water Nitrate-N Concentrations from Common Land Covers and Cropping Systems in Southeast Minnesota Karst

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Abstract

The purpose of this study was to identify the range of soil water nitrate-nitrogen (nitrate) concentrations measured at a four-foot depth from nine different land covers and cropping systems in southeast Minnesota. Results from the five-year study (2011-2015) found low concentrations of soil water nitrate, generally less than 2 mg/L, from prairie, forest and low maintenance homeowner lawn sites. Cattle pasture sites and a golf course averaged 5.1 and 3.7 mg/L, respectively. A grass field border and grassed waterway had similar concentrations and averaged between 5.9 mg/L (non-fertilized) and 8.9 mg/L (fertilized). Concentrations from the grass strips were higher than expected and likely explained by subsurface mixing of soil water between adjacent land covers. Nitrate concentrations collected from lysimeters in cultivated row crop settings were comparable to tile drained sites in Minnesota, but were highly variable and averaged 22.3 mg/L with a typical range of 8.0 to 28.0 mg/L. Corn fields with alfalfa in the rotation had nitrate concentrations averaging 6.6 mg/L which were 70% lower when compared to sites without perennials. When considered within the context of this study's limitations, data collected from the Southeast Lysimeter Network could serve as a useful educational tool for farmers, crop advisors, rural homeowners and groundwater advisory groups.

Background and Purpose

The geology of southeastern Minnesota's Driftless Area is comprised of carbonate bedrock (limestone and dolostone), sandstone and shale. Over millennia, naturally acidic rain and soil water has interacted with carbonate bedrock to form karst features including dissolutionally-enlarged fractures, subterranean conduits, sinkholes, and springs. Most of the bedrock formations in this area are covered by less than 50 feet of surficial deposits (Mossler, 1995) and in many areas, moderate to well-drained soils are less than ten feet thick (Dogwiler, 2013). This can result in direct hydrologic connections between the land surface and underlying bedrock and can facilitate the rapid movement of water and potential contaminants from the land surface into bedrock aquifers used for drinking water (Green et al, 2014; Runkel et al, 2014), and ultimately groundwater return flow to springs, streams and rivers. One of the most common nutrients found in southeast Minnesota groundwater is nitrate-nitrogen (NO_3^--N, from this point forward referred simply as nitrate). Nitrate is a common form of plant-available nitrogen that is water soluble and can primarily come from nitrogen fertilizer, manure, sewage, or the breakdown of soil organic matter. If not utilized by plants or retained in soil organic material, nitrate can move rapidly by water and leach through the soil and into groundwater.

The loss of nitrogen from agricultural lands has both local and regional impacts. Regionally, excess nitrogen lost from agricultural applications, primarily from the upper Midwest, are one of the main contributors to the hypoxic zone in the Gulf of Mexico (Alexander et al, 2008, Robertson et al, 2019). A 2013 report estimated that about 89% of the nitrogen measured in surface water in southeast Minnesota watersheds was derived from cropland, primarily through groundwater pathways (MPCA, 2013). More locally, results from private drinking water testing in Houston, Fillmore and Winona Counties have shown 15.3% to 19.1% of the sampled wells were at or above the drinking water health standard of 10 mg/L for nitrate (MDA, 2017).

Understanding the source of nitrate and how it moves into groundwater is a key step in helping manage the region's water resources. A common question raised during nitrate reduction planning discussions is how do nitrates compare between different crops or landcovers? The objective of this five-year study was to identify the range of nitrate concentrations present in soil water infiltrating from the unsaturated

root zone across common land covers and cropping systems in southeast Minnesota. Land use in this region mainly consists of cultivated row crops so much of this investigation focused on agricultural land covers, but other non-agricultural land covers including prairies, forests, pastures and turf were also studied. Although this investigation does not attempt to fully quantify the magnitude of the nitrate flux or loading to aquifers, our results provide insight to the potential risk of loss to groundwater associated with various land covers. These data will help inform farmers, their advisors and other stakeholders as they work toward reducing nitrate in drinking water and surface water.

Information presented in this report were collected as part of an initiative known as the Southeast Minnesota Lysimeter Network (SLN). This undertaking represented a collaboration among several partners, including the Fillmore Soil and Water Conservation District (SWCD), Winona SWCD, Winona State University-Southeastern Minnesota Water Resources Center (SMWRC), Minnesota Pollution Control Agency (MPCA) and Minnesota Department of Agriculture (MDA). Funding for this work was provided in-part by Minnesota's Clean Water Fund from MPCA and through MDA's Root River Field to Stream Partnership (RRFSP).

Methods

The study took place across four counties and 23 sites in southeast Minnesota from 2011-2015 (Figure 1). Table 1 summarizes the 2015 land use across the four-county study area. On average, land managed for corn-soybean production, forest, and grass/pasture was over 80% while landcovers in alfalfa, turf and golf courses were less than 10%. Sampling sites were located on private property and cooperators were identified by staff from the Fillmore SWCD, Winona SWCD and MDA. The most common agricultural practices in southeast Minnesota were sampled, as well as several other common non-agricultural land cover types (Table 2). Land covers were grouped into three categories: non-agriculture, ag pasture/grass strips and ag row-crop. Crop and nitrogen management information were collected for each agricultural site and consisted of nitrogen application rates, timing, source and placement (Table 3). Nitrogen application rates included the actual amount of nitrogen from commercially applied fertilizers, first and second year manure credits and credits from alfalfa. Total nitrogen rates also included incidental nitrogen sources from starter, ammonium thiosulfate (AMS), diammonium phosphate (DAP) and monoammonium phosphate (MAP) fertilizers containing nitrogen. Tables 1 and 2 provide additional management details about each site. Soils at the monitoring locations consisted of well drained to moderately well drained silt-loam soil types. The typical range of organic matter in these soils is 2.7% to 3.9% with an average of 3.3%.

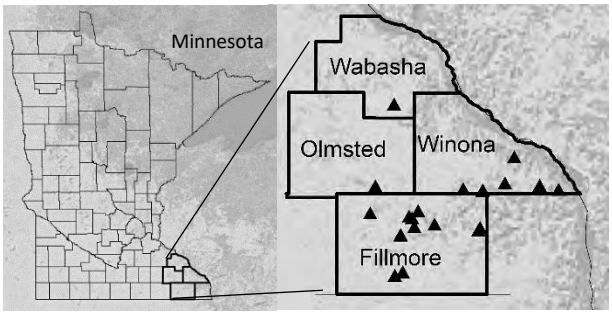

Figure 1. Lysimeter network locations across a four County area in southeast Minnesota.

Table 1. Land use as a percentage of county area. (Source: 2015 Cropscape Cropland Data Layer-Center for Spatial Information and Science Systems)

County	Corn and Soybeans	Alfalfa	Forest	Grass/Pasture	Turf/Homeowner Lawns[1]	Golf Course[2]
	----------% of county area----------					
Fillmore	45%	6%	22%	21%	3%	<0.1%
Olmsted	43%	4%	15%	23%	6%	0.1%
Winona	22%	6%	39%	21%	4%	0.1%
Wabasha	33%	5%	24%	23%	3%	<0.1%
Overall Avg.	36%	5%	25%	22%	4%	<0.1%

[1]Uses the developed open space classification in CropScape and likely overestimates the area managed for turf.
[2] Digitized from the MNGEO 2015 aerial photography.

Equipment

Soil water samples were collected using 50 porous cup tensiometers (Figure 2), more commonly called suction cup lysimeters. Lysimeters consisted of a 24-inch long piece of PVC pipe, sampling and suction lines and porous ceramic tip. The basic construction involved attaching and sealing a ceramic tip to one end of a 1.5 inch diameter PVC pipe with epoxy and attaching a rubber stopper to the other end. The rubber stoppers were secured with electrical tape and special adhesive to ensure complete sealing. Two, 0.25 inch diameter plastic tubes were passed through the rubber stopper to ensure an air tight seal. One tube was used as the sample line. It extended to the bottom of the porous ceramic tip and was used for sampling water from the lysimeter. The other line, the suction line, was used to create a vacuum within the lysimeter.

At cultivated row crop sites, lysimeters were installed to a depth of four feet within the vadose zone and placed a minimum of 40 feet into the field. This distance was used to minimize edge of field variability caused by compaction, non-uniform fertilizer applications, and help avoid other factors that can be common in the headland areas of row-crop fields. At most locations, at least two lysimeters were paired together at each site to better understand variability. Having two lysimeters also provided redundancy in the event one lysimeter failed. Typically, paired lysimeters were installed 20 feet apart. To prevent damage from tillage equipment, a trenching machine was used to create a 2.5 foot deep trench to route the sample and suction lines from lysimeters to the field edge. The sample and suction line tubing was routed through PVC conduit to protect it from being crushed by the soil during reburial and terminated in a single sampling port. At the desired lysimeter location within the field, an additional 1.5 foot deep hole was excavated within the bottom of the trench using a four-inch diameter soil auger. To minimize soil disturbance directly above the lysimeters, the hole was hand augered at an approximate 20-degree angle from the bottom and long axis of the machined trench. This ensured that the sampling tip was beneath undisturbed soil and not directly under the

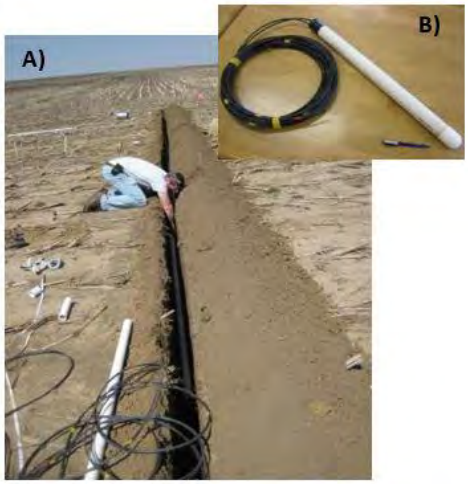

Figure 2. A) Installation of lysimeter sample and vacuum lines in a field managed for continuous corn silage and dairy manure. Sample lines were trenched 2.5 feet below the surface while lysimeters were placed four feet below the soil surface. **B)** Porous tension ceramic cup lysimeter with vacuum and sampling lines. Pen in lower right corner of photograph used for scale and is pointing at the ceramic tip.

excavated trench. A distilled water and silica slurry mixture was placed in the augered hole around the ceramic tip to ensure adequate hydraulic contact and movement of water to the lysimeter. Bentonite clay was packed above the ceramic tip during backfill to prevent drainage along the side of the lysimeter. At the golf course and homeowner lawn sites, lysimeters were installed using a hand auger to a depth of about two feet. At two row-crop sites, the full four-foot depth was not achieved because of refusal due to shallow bedrock. In all cases the lysimeters were installed a minimum of 4 to 6 inches above the bedrock at least two feet below the surface. At all sites the depth of the lysimeter sampling tip was below the rooting depth of the associated land cover vegetation. Lysimeters were permanently installed at each location and not removed during the study period. Lysimeter construction, installation and training was provided by MDA and SMWRC with assistance from Fillmore SWCD and MPCA.

Sampling and Analysis

A 30-40 centibar vacuum was applied to the lysimeters between sampling periods. Sampling intervals were consistent throughout the study period and were collected every two weeks during the frost-free period, typically from April through October (Figure 3). In some years it was possible to start sampling in March and extend sampling through November due to above normal temperatures. Samples were collected using a hand operated vacuum pump and one-liter Erlenmeyer flask. In most cases 300-600 mL of water was available for sampling of which 100 mL was used for nitrate analysis. Samples were placed on ice in a cooler and kept refrigerated until analysis. Water samples were analyzed using a Hach® DR6000 UV spectrophotometer (pour-through method 357-10049, DOC 316.53.01072) located in the MDA Preston field office within a week of sample collection. The detection limit using this method is 0.1 mg/L. Samples were analyzed using standardized quality assurance and control (QA/QC) procedures. As part of the QA/QC, a duplicate of no less than 10% of the water samples were selected randomly and analyzed by the Minnesota Department of Agriculture (MDA Lab) certified laboratory located in St. Paul. It should be noted that the MDA lab method includes both nitrite and nitrate (NO_2-N + NO_3-N) while the DR6000 method does not report nitrite(NO_2-N). Nitrite is seldom present in groundwater and if detected is typically less than 0.3 mg/L, transforms quickly to the more stable nitrate form (USEPA, 1987), and therefore is not considered to be a significant factor when comparing the two methods. Additional details regarding the duplicate sample results are included in Appendix C of this report. Statistical group tests were used to identify significant differences between the various land covers. If *p* values were less than or equal to 0.05 when using non-parametric tests on the nitrate median, the groups were considered statistically different. The Mann-Whitney test was used when comparing individual pairs while the Kruskal-Wallis multiple comparison test was used across all land covers. Statistical analysis was conducted using R and Minitab® statistical software.



Figure 3. *Soil water nitrate collection from a continuous corn grain site (OM70/90). The sampling port was located in a grassed waterway.*

Table 2. Land cover and farming practices evaluated during the five-year soil water nitrate study.

Land Cover	Land Cover Grouping	Lysimeter ID	Location (# of lysimeters)	Description
Prairie	Non-Agriculture	CW/CY QW/QY	Fillmore (2) Winona (2)	CW/CY field had previously been in row crops and was enrolled in the conservation reserve program (CRP) for five years prior to sampling. QW/QY field was managed since the 1980's as a long-term bluff-top prairie with no contributing area from other land covers or uses. Vegetation at both sites consisted of well-established warm season grasses and forbs.
Forest	Non-Agriculture	JW/JY	Winona (2)	Mature deciduous hardwood hillslope with a moderate level of understory vegetation. Site JW was uphill while JY was downhill, about 20 feet apart.
Lawn	Non-Agriculture	LW/LY KW/KY	Winona (4)	LW/LY did not receive fertilizer while KW/KY received a one-time application during the first year. Both residential lawn sites consisted of Kentucky bluegrass.
Golf Course	Non-Agriculture	MW/MY	Wabasha (2)	Samples collected from the fairway (MW-rough) and an adjacent tee box (MY). The fairway site received low maintenance fertilizers while the tee box received an annual rate of 120 lb N/ac divided between three different applications.
Pasture	Pasture and Grass	GW/GY RW/RY PW/PY	Winona (2) Fillmore (4)	Pastures with cow/calf beef herds that consisted of both rotationally grazed and non-rotational management with low to moderate stocking density. Site GW/GY received 50-60 lb N/ac of urea and AMS broadcast applied every spring. RW/RY was a rotationally grazed dairy pasture site. About 15 cows were pastured in a 30'x30' pen and rotated out once a month with 1-2 weeks of recovery between rotations. Heavy grazing resulted in excessive manure coverage. PW/PY received spring broadcast liquid dairy manure which contained about 30 lb N/ac. Due to lysimeter failure, this site was not sampled in 2013 and 2014.
Grass Strip (non-fertilized)	Pasture and Grass	CFE20	Fillmore (1)	This site was managed as a grassed field border. Kentucky blue and brome grasses were mowed periodically. The field border was 60 feet wide and no nitrogen fertilizers were applied. Surrounding fields consisted of corn and soybeans and had slopes between 4-6%. The lysimeter was placed in the middle of the strip near the toe slope.
Grass Strip (Fertilized)	Pasture and Grass	OMAgw OMCgw	Fillmore (2)	This site was a fertilized grassed waterway in a field managed for continuous corn grain. The grassed waterway was about 15 feet wide and was mowed occasionally and consisted of brome and timothy. The grassed waterway received the same amount of commercial nitrogen fertilizer as the corn field. The continuous corn field received 150 to 240 lb N/ac.
Alfalfa with Corn	Row Crops	A70/90, CFE60/80, F70/90, NW/NY	Fillmore (8)	All fields had a minimum of three out of the five years with alfalfa and at least one year of corn. A70/90 was an organic field that received nitrogen from organic fertilizer (fish), manure and alfalfa credits. CFE 60/80 was managed for soybeans in 2011 and corn in 2012 and then rotated to alfalfa from 2013-2015. Field F70/90 was managed for alfalfa from 2011-2014 and then rotated to corn in 2015. About 40 lb N/ac was applied annually to this alfalfa field. During the corn year it received a total of 185 lb N/ac (125 lb N/ac from commercial fertilizer at preplant, sidedress and 60 lb N/ac alfalfa credit). NW/NY was managed for alfalfa the first four years and the last year was corn. The alfalfa received periodic liquid dairy manure applications.
Corn and Soybean Rotations & Continuous Corn	Row Crops	B70/90, E70/90, H70/90,CFW40/60/80, D70/90, I70/90 (OMA7090,OMB7090, OMC7090,OMD7090B)	Fillmore (19) Olmsted (2)	All sites contained a mix of row crop fields managed for corn-soybean rotations or continuous corn. Three sites received manure while other sites received only commercial fertilizer. All sites also applied a wide range of application rates (140 lb/ac to 240 lb/ac). At one continuous corn site (OMABCD), four different rates of manure and commercial fertilizer were applied (140, 160, 190, 220 lb N/ac) during a two-year period to evaluate the relationship between nitrogen credits from dairy beef bedding pack manure and soil water nitrate. Site B70/90 was a no-till site and transitioned from CRP to row cropping in 2009. Typical N rates were 150 lb/ac for C/S and 180 lb/ac for C/C. D70/90 was continuous corn from 2011-2013 with an average 200 lb N/ac from liquid dairy manure. E70/90 was mainly managed for corn silage and soybeans. Fall seeded cover crops were established in the fall to extend cattle grazing in the spring. About 160 lb N/ac was applied for C/S and 190 lb N/ac for C/C. Lysimeters were placed below a terrace and could have been affected by upgradient lateral flow. H70/90 was managed for continuous corn and total nitrogen rates ranged from 180 to 200 lb N/ac with split nitrogen applications.

Table 3. Land cover and nitrogen management details by site and year. Total nitrogen rates in pounds per acre (lb/ac) from manure or commercial fertilizers is displayed in parenthesis. Total nitrogen includes first and second year manure nitrogen credits and credits associated with alfalfa and other incidental nitrogen sources from starter, AMS, DAP and MAP fertilizers.

Site ID	Land Cover	Land Cover Grouping	2011	2012	2013	2014	2015
CW/CY	Prairie	Non ag	CRP/Prairie (0)	CRP/Prairie (0)	CRP/Prairie (0)	CRP/Prairie (0)	CRP/Prairie (0)
QW/QY	Prairie	Non ag	Prairie (0)	Prairie (0)	Prairie (0)	Prairie (0)	Prairie (0)
JW/JY	Forest	Non ag	Forest (0)	Forest (0)	Forest (0)	Forest (0)	Forest (0)
LW/LY	Lawn	Non ag	Lawn (0)	Lawn (0)	Lawn (0)	Lawn (0)	Lawn (0)
KW/KY	Lawn	Non ag	Lawn-fertilized (160)	Lawn (0)	Lawn (0)	Lawn (0)	Lawn (0)
MW/MY	Golf Course	Non ag	Golf Course (140)	Golf Course (140)	Golf Course (140)	Golf Course (140)	Golf Course (140)
GW/GY	Pasture	Pasture and grass	Pasture, spring bdcst. No-inc. (50)	Pasture, spring bdcst. No-inc. Urea/AMS (56)	Pasture, spring bdcst. No-inc. Urea/AMS (56)	Pasture, spring bdcst. No-inc. Urea/AMS (56)	Pasture, spring bdcst. No-inc. Urea/AMS (56)
RW/RY[1]	Pasture	Pasture	Pasture (manure N, qty unknown)	Pasture (manure N, qty unknown)	Pasture (manure N, qty unknown)	Pasture (manure N, qty unknown)	Pasture (manure N, qty unknown)
PW/PY	Pasture	Pasture and grass	Pasture[1] (manure N, qty unknown)	Pasture, summer bdcst. No-inc. liquid dairy manure (13)	Pasture, summer bdcst. No-inc. liquid dairy manure (33)	Pasture, summer bdcst. No-inc. liquid dairy manure (33)	Pasture, summer bdcst. No-inc. liquid dairy manure (33)
CFE20	Grass strip NF	Pasture and grass	Grass field border (0)	Grass field border (0)	Grass field border (0)	Grass field border (0)	Grass field border (0)
OMACgw	Grass strip F	Pasture and grass	Grassed waterway (186)	Grassed waterway (180)	Grassed waterway (200)	Grassed waterway (200)	Grassed waterway (240)
A70/90	Alfalfa with corn	Row crop (organic)	Corn, spring knife inj. Swine, bank liq. Fish, legume crdt. (285)	Oats/alfalfa, foliar liq. Fish, 2nd yr manure and legume crdts (101)	Alfalfa, foliar liq fish (20)	Corn, spring bdcst, noinc. Bedding pack beef manure, band liq. Fish, 1st yr legume crdt. (140)	Oats/alfalfa, foliar liq. Fish, 2nd yr manure credit (21)
CFE60/80	Alfalfa with corn	Row crop	Soybean	Corn, fall liquid hog inject (180)	Oats/alfalfa	Alfalfa	Alfalfa
F70/90	Alfalfa with corn	Row crop	alfalfa, summer bdcst, no inc. DAP (9)	alfalfa, summer bdcst, no inc. DAP (36)	Alfalfa, summer bdcst, no inc. DAP (36)	Alfalfa, summer bdcst, no inc. DAP (36)	Corn, fall P&K strip till, side dres incorp. UAN, legume credits (185)
NW/NY[1]	Alfalfa with corn	Row crop	Alfalfa	Alfalfa	Alfalfa	Alfalfa	Corn
B70/90	C-S	Row crop	Corn, spring 4x4 band UAN Rawson cart, no till (179, split)	Soybeans, spring bdcst AMS and 9-23-30, no till (11)	Corn, spring 4x4 band UAN Rawson cart, no-till (150,split)	Soybeans, spring bdcst AMS, 9-23-30 (11), no till	Soybeans, spring bdcst AMS, no-till (2)
BCE40 /60/80	C-C	Row crop	Corn, spring commercial bdcst/incorp. urea (178)	Corn, spring commercial bdcst/incorp. urea (180)	Corn silage, spring urea, bdcst/incorp. (189)	Corn silage, fall, liquid dairy inject (151)	Corn silage, fall liquid inject (168)

Site ID	Land Cover	Land Cover Grouping	2011	2012	2013	2014	2015
CFW40/ 60/80	C-C	Row crop	Corn silage, fall liquid dairy inject (182)	Corn silage, Fall liquid dairy inject (180)	Corn silage with rye cover. Spring Urea, bdcst/incorp (207)	Corn silage, fall liquid dairy inject (199)	Corn silage, Fall liquid dairy inject (190)
D70/90	C-C	Row crop	Corn (prev. CRP), spring liq. dairy bdcst-inc., pp bdcst Urea/AMS, starter (198)	Corn, spring pp, bdcst-inc., Urea/AMS, starter, 2nd yr manure credits (204)	Corn, spring pp, bdcst-inc., Urea/ams, starter (191)	Oats/alfalfa, spring pp bdcst-inc. AMS (21)	Alfalfa (21)
E70/90	C-S w/ Rye	Row crop	Corn silage w/ rye grazed, spring pp bdcst inc. UAN/DAP, starter (188)	Corn silage w/rye grazed, spring pp bdcst, inc. UAN/DAP/start er (188)	Soybeans, spring cattle grazed off cover crop (0)	Corn w/rye grazed off in spring, spring starter, post UAN bdcst, no incorp. (156)	Soybeans, spring cattle grazed off cover crop (0)
H70/90	C-C	Row crop	Corn, fall strip till, DAP/AMS, spring Urea/ESN bdcst, inc., starter, sidedress (UAN) (183)	Corn, fall strip till, DAP/AMS, spring Urea/ESN bdcst, inc., starter, sidedress (UAN) (183)	Corn, fall strip till, DAP/AMS, spring Urea/ESN bdcst, inc., starter, sidedress (UAN) (183)	Corn, fall strip till, DAP/AMS, spring Urea/ESN bdcst, inc., starter, sidedress (UAN) (204)	Corn, fall strip till, DAP/AMS, spring Urea/ESN bdcst, inc., starter, sidedress (UAN) (204)
I70/90[1]	C-C	Row crop	Corn	Corn	Corn	Soybeans	CRP
OM70/90	C-C	Row crop	Corn, bdcst-inc. within 12 hours, fall applied beef bedding pack and UREA. Replicated test strips (175)	Corn, bdcst-inc. within 12 hours, 2nd year beef bedding pack credits and UREA. Replicated test strips (175)	Corn bdcst-inc. Urea/AMS, sidedress UAN w/coulter (240)	Corn bdcst-inc. Urea/AMS, sidedress UAN w/coulter (240)	Corn bdcst-inc. Urea/AMS, sidedress UAN w/coulter (240)

[1] Some or all nitrogen fertilizer records were not available

Abbreviation key: C-C = corn following corn rotation, C-S = Corn following soybean rotation, bdcst-inc. = broadcast-incorporate, DAP = diammonium phosphate, MAP = monoammonium phosphate, AMS = ammonium sulfate, UAN = urea ammonium nitrate, ESN = environmentally stable nitrogen, pp = preplant

Study Considerations and Limitations

Lysimeters are one of the most basic and economical ways to collect soil water samples for nitrate monitoring. See Appendix A for additional discussion: *Considerations when Interpreting Soil Water Nitrate Concentrations from Lysimeters.* This study's interpretations were constrained by several factors. The main objective was to assess the relative range of nitrate concentrations across a wide range of land covers. As such, there was limited ability to replicate some of the land cover categories at multiple sites. About two-thirds of the land cover categories had less than three replications. In the case of the golf course or homeowner lawns, only one or two sites were monitored and there were no turf sites with high nitrogen fertilizer inputs. As a percentage of the county land use, however, turf represents less than 5% of the county area and golf courses less than 0.1% (Table 2). Due to time and labor constraints and the practicality of retrieving samples, usually fewer than three lysimeters were installed within the row crop field sites. Other studies have preferred to use sub-surface pattern tile research plots to better control for other variables. (Randall and Goss, 2008 and Brouder et al, 2005). Monitoring nitrate

concentrations and loss from tile drainage systems are preferred since drainage water measured at the tile outlet represents an integrated average across the entire field rather than a few point locations. However, this study was motivated to specifically assess nitrate concentration ranges associated with non-tile drained karst landscapes. The relatively steep topography and moderate to well-drained silt loam soils that are characteristic of the Driftless Area of southeastern Minnesota are generally not suitable for intensive, patterned subsurface tile drainage systems and, as such, the practice is not common within the region.

This experimental design attempted to address the cautions (described in Appendix A) that must be taken when interpreting results collected from lysimeters. Primarily, the inclusion of at least a pair of lysimeters located a minimum of 20 feet apart at each field site provides an opportunity to compare the results for each sampling event and assess if the nitrate concentrations of the paired samples were consistent, and therefore likely representative of the larger site.

Precipitation During the Study Period

Precipitation can influence the range of nitrate concentrations measured in soil water. Small soil water sample volumes collected during dry conditions tend to have higher concentrations while during very wet conditions nitrates can be reduced due to dilution. Additionally, nitrate can be 'stored' in the soil profile during unusually dry periods and then be flushed out during subsequent wet periods (Kaushal et al, 2010). This has been well documented in several studies in southeast Minnesota, northeast Iowa and Midwest streams (Schilling et al, 2019, Van Metre et al, 2016, Barry et al, 2020).

Annual precipitation totals were summarized from the National Weather Service station at Preston during the study period (Table 4). The weather station at the City of Preston was selected because it is centrally located within the study area and has a long-term precipitation record. The 30-year (1981-2010) normal or average for Preston was 35.6 inches per year. Annual precipitation totals ranged from a low 28.1 inches in 2012 to a high of 47.6 inches in 2013 with a five-year average of 34.9 inches. When compared to the percent departure from normal, values ranged from 21% below normal to 34% above normal in 2012 and 2013, respectively. When the departure from normal was within 10%, precipitation was considered near normal. If precipitation was below normal by more than 10% it was considered dry and when 10% above normal it was considered wet. Years 2011 and 2012 were both dry while years 2014 and 2015 were near normal. Figure 4 shows that 2013 was very wet with most precipitation occurring from April through June and October.

Table 4. Annual precipitation totals, departure from normal and classification during the study period. The 30-year (1981-2010) normal or average for Preston is 35.6 inches.

Year	2011	2012	2013	2014	2015
Total Annual Precip. (in.)	28.6	28.1	47.6	36.3	34.0
Departure from normal (%)	-20%	-21%	+34%	+2%	-4%
Classification	Dry	Dry	Wet	Near Normal	Near Normal

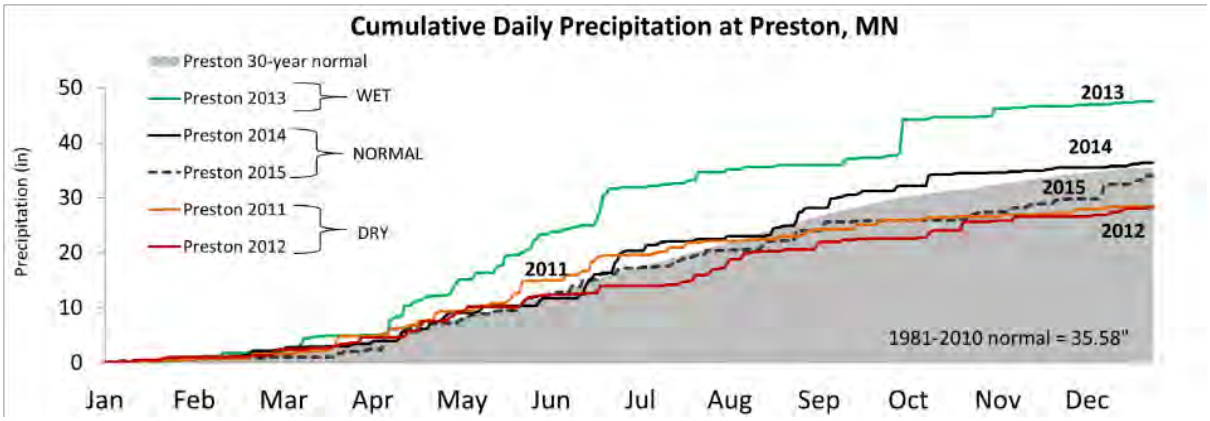

Figure 4. Cumulative daily precipitation at Preston during the study period (2011-2015). The study period contained a mixture of wet, dry and normal conditions.

Interpreting Nitrate Concentrations from Row-Crop Fields

General guidelines for interpreting nitrate concentrations measured in sub-surface tile drainage water were summarized in a 2005 report from Purdue University Extension (Brouder et al, 2005). A modified table from this report is provided as Table 5 and includes data from the Midwest corn-belt. Although soil water samples collected during this study may not be a direct comparison to tile drainage water, Table 5 is a useful reference for helping interpret soil water nitrate concentrations. Brouder et al. (2005) indicates that concentrations between 10 to 20 mg/L would be typical for Midwestern corn belt row crop systems with nitrogen applied at economically optimum nitrogen rates. It should be noted these concentrations can vary considerably by site and weather conditions.

Table 5. General guidelines for interpreting nitrate-N concentrations in tile drainage water. The interpretation is derived from numerous studies conducted throughout the Midwest corn belt and highlights land management strategies commonly found in association with a concentration measured in tile water leaving the field (modified from Brouder et al, 2005).

Tile Drainage Nitrate Concentration (mg/L)	Interpretation
≤ 5	Native grassland, Conservation Reserve Program (CRP) land, alfalfa, managed pastures.
5-10	Row crop production on a mineral soil without N fertilizer. Row crop production with N applied at 45 lb/acre below the economically optimum N rate row crop production with successful winter crop to "trap" N.
10-20	Row crop production with N applied at optimum N rate
≥ 20	Row crop production where: **a)** N applied exceeds crop need **b)** N applied is not synchronized with crop needs **c)** environmental conditions limit crop production and N fertilizer use efficiency **d)** environmental conditions favor greater than normal mineralization of soil organic matter.

Lysimeter Comparison Values

Northcentral Lysimeters

For the past several decades the MDA's Fertilizer Field unit has initiated groundwater protection demonstration projects using lysimeters. These sites have been used to help foster partnerships among farmers, their crop advisors, citizens and local, state and university staff. Some of the longest running demonstration sites are located on coarse textured irrigated soils in northcentral Minnesota (Figure 5).

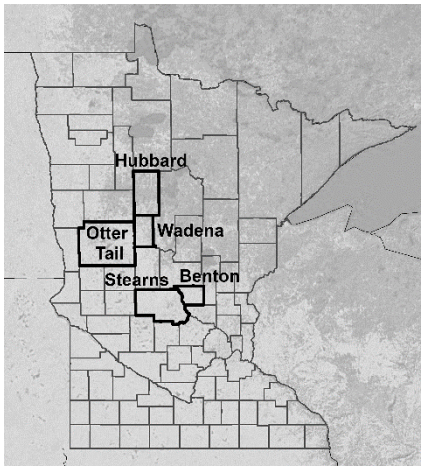

Figure 5. MDA northcentral water quality demonstrations sites. Project counties outlined in black.

Soil water nitrate collected from a wide range of cropping systems and weather conditions provide a useful comparison with the SLN. It should be noted that all the northcentral sites contain coarse textured sandy loam or loamy sand soil textures and many sites were irrigated. Table 6 provides the summary statistics and reflect sampling conducted between years 2000-2019.

Table 6. Soil water nitrate-N summary statistics across various cropping systems in northcentral Minnesota. Data reflect years from 2000-2019.

Crops grown	Number of Samples	Mean	St Dev	Min.	Q1	Median	Q3	Max.
		----------Soil water nitrate-N (mg/L)----------						
corn-soybeans	4,755	30.4	17.9	<0.1	16.3	28.0	41.1	120.0
corn, soybeans, edible beans, potato, alfalfa	5,787	35.1	29.2	<0.1	15.0	29.0	46.0	240.0

Table 7 displays the summary statistics of soil water nitrate measured from turf sites located in Otter Tail and Stearns county. Data collected from the Otter Tail county site reflect years 2000-2004 and the Stearns site reflect years 2014-2019. Lysimeter depth was about 16 to 20 inches at these sites. The Stearns site is a long-term study to evaluate the relationship between soil water nitrate and lawn nitrogen fertilizer application rates. Replicated and randomized treatments included a zero-rate check, a low rate of 3 lb N/1,000 ft^2, a medium rate of 6 lb N/1,000 ft^2 and a high rate of 9 lb N/1,000 ft^2. These data provide a very useful reference for nitrate concentrations measured from fertilized and non-fertilized turf sites in Minnesota.

Table 7. Soil water nitrate-N summary statistics from the two turf sites in northcentral Minnesota. Data reflects years from 2000-2019.

Cover Type	Number of Samples	Mean	St Dev	Min.	Q1	Median	Q3	Max.
		----------Soil water nitrate-N (mg/L)----------						
Turf/Lawn	1,946	2.3	4.1	<0.1	0.7	1.1	2.1	50.0

Lysimeter Comparison Values

MDA and Discovery Farms Minnesota On-Farm Drainage Tile Monitoring

Another source of information that can be used for comparison with the SLN is from a network of on-farm sub-surface tile drainage monitoring sites associated with the MDA and Discovery Farms Minnesota. Table 8 summarizes the annual flow weighted mean concentrations (FWMC) and yield (lb/ac) from 2011-2015. Samples were collected across nine counties (Figure 6) using automated equal flow increment composite sampling methods. Crops grown included corn, soybean and corn with alfalfa rotations. It also included sites that received dairy and hog manure and sites with only commercial fertilizer. The FWMC across all sites was 21.4 mg/L with a typical range (i.e. interquartile range) of 15.6 mg/L to 25.6 mg/L. The average nitrate loss was 17.0 lb/ac with an interquartile range of 5.5 lb/ac to 31.1 lb/ac.

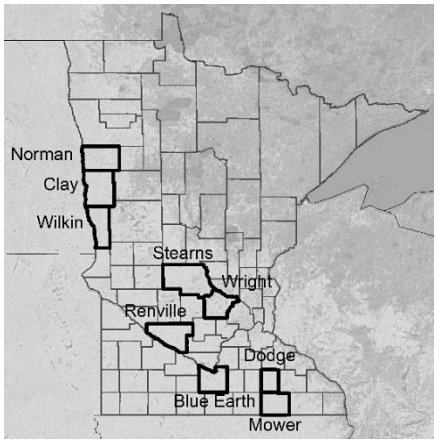

Figure 6. On-farm drainage tile monitoring locations associated with the MDA and Discovery Farms Minnesota. Project counties are outlined in black.

Table 8. Annual FWMC's and loss from sub-surface tile drainage across in nine counties from 2011-2015. Data from Discovery Farms Minnesota and Minnesota Department of Agriculture.

Number of Site Years	Mean	St Dev	Minimum	Q1	Median	Q3	Maximum
	----------FMWC (mg/L)----------						
34	21.4	8.9	3.7	15.6	19.8	25.6	50.3
	----------Loss (lb/ac)----------						
35	17.0	15.2	0.0	5.5	10.5	31.1	55.1

Results and Discussion

Soil water nitrate concentrations measured across nine different types of land covers in the SLN are summarized in Figure 7 and Table 9. Nearly 3,000 individual nitrate tests were analyzed from 50 different lysimeters across 23 different sites during the five-year study. In Figure 7, land cover types were grouped into three different categories and the averages were sorted from lowest to highest N concentration within each category. The box plot represents the middle 50% of the data or the interquartile range. Although soil water sampled from lysimeters is not used directly for drinking water, the Environmental Protection Agency (EPA) maximum contaminant level of 10 mg/L for drinking water is provided for reference and shown as a dashed horizontal line. The length of each box indicates variability. Figure 7 clearly shows that the non-agriculture sites have much less variability and lower soil water nitrate while the agricultural sites have both higher nitrate and higher variably. Results from the group statistical tests are also provided in Figure 7 and last row of Table 9. Time-series charts showing

the average monthly nitrate concentrations by individual site can be found in Appendix B. Table 10 provides the statistical analysis results between the various paired land cover types. When significant, the value in parenthesis below the *p* value represents the median point difference in mg/L between the respective pairs. For instance, when comparing the prairie versus forest land covers there were no significant differences (*p* value = 0.718). However, when comparing the prairie to the golf course, the golf course had significantly higher concentrations (*p* <0.01) and this difference was estimated to be 2.4 mg/L.

Non-Agriculture

The lowest nitrate concentrations were found in the 'non-agriculture' group which included grassland prairie (CRP), deciduous forest, low maintenance homeowner lawns and a golf course. Soil water nitrate concentrations within this category averaged between 0.1 mg/L to 3.7 mg/L with a typical range (i.e. interquartile range) of <0.1 to 5.3 mg/L. Standard deviations for the prairie and forest were very small and ranged from 0.3 mg/L to 0.9 mg/L. For comparison, Randall et al, (1997) found flow weighted average nitrate concentrations of 2 mg/L from a drainage tile research plot managed for CRP in southcentral Minnesota. The highest concentration observed at one of the lysimeter network prairie sites was 3.1 mg/L. This high reading is likely related to a millipede infestation within one of the lysimeter sampling ports. This particular species, a yellow-spotted millipede (Apheloria tigana), produces cyanide to fend off potential predators. Under aerobic conditions, the biodegradation of cyanide compounds produces ammonia which is then converted to nitrite and nitrate in the presence of nitrifying bacteria (Richards and Shieh, 1989).

For the lawn and golf course sites the average concentrations ranged from 1.1 to 3.3 mg/L. For comparison, average soil water nitrate concentrations from the northcentral Minnesota turf sites were similar and averaged 2.3 mg/L (Table 7) . A maximum concentration of 26 mg/L was observed at the homeowner lawn site in 2011. This was the result of a one-time over-application of nitrogen to the lawn by the homeowner. The golf course represented samples collected from the fairway and tee box. The fairway received minimal nitrogen fertilizer applications while the tee box received scheduled applications throughout the growing season. Fertilizer application records were not available, but conversations with the course manager indicated that low rates (less than 1.0 lb/1000ft^2 or ~40 lb/ac) were applied typically three times a year on the tee and only one time on the fairway. A 2015 and 2016 study sampled nitrate from shallow monitoring wells across six golf courses in Iowa (Schilling et al, 2018). The average nitrogen rate applied to the tee box, fairway and rough was estimated at less than 40 lb N/ac. Results from that study found that nitrate was not detected above 1.0 mg/L at half of the six courses and the overall mean concentration was 2.2 mg/l. Schilling et al. (2018) also approximated the mass of nitrate recharge to groundwater. This was estimated to be less than 10% of the commercial fertilizer nitrogen that was applied.

Statistically, the prairie and forest sites had the same concentrations. The homeowner lawn sites had higher concentrations when compared to the prairie and forest while the golf course had the highest average concentrations of 3.7 mg/L. When comparing the golf course site to the row crop sites, the row crop sites had significantly higher concentrations (*p* = <0.01) and this median point difference was estimated to be 14.0 mg/L.

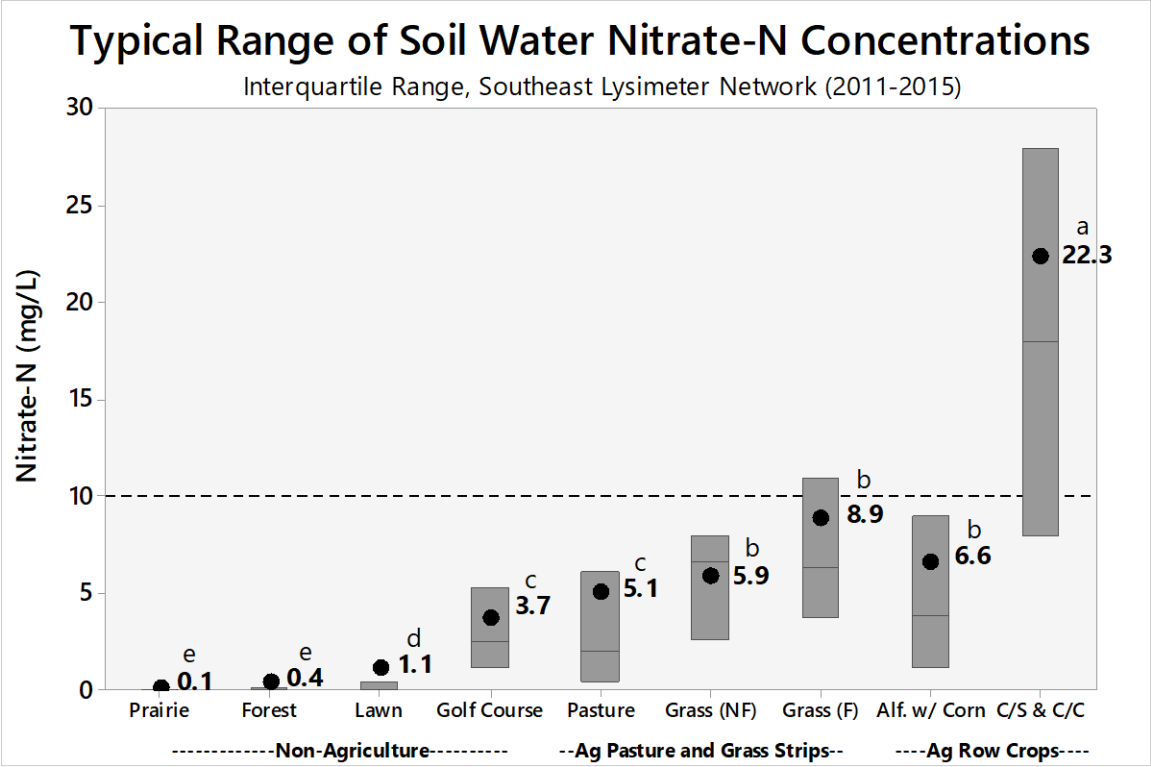

Figure 7. Typical range of soil water nitrate concentrations measured across nine different types of land covers in southeast Minnesota from 2011-2015. This chart represents nearly 3,000 individual samples collected from suction-cup lysimeters, typically from a depth of four feet. The boxes represent the interquartile range or middle 50% of the data. Average values as black dots are displayed next to each box while the median is represented by the horizontal line. Sites that do not share the same letter (displayed above the average value) are significantly different at the 0.05 level when using a Kruskal-Wallis multiple comparison test on the median. Although soil water is not used directly for drinking water, the dashed horizontal line is included as a reference and represents the 10 mg/L drinking water standard. For the grass strip sites, NF is non-fertilized, and F is fertilized. For the Ag row crops, alfalfa with corn had at least three years of alfalfa in the rotation and one year of corn during the sampling period. C/S were fields managed for corn-soybean rotations while C/C were sites managed for corn following corn or continuous corn. These two rotations were grouped together.

Table 9. Soil water nitrate-N summary statistics by land cover type from 2011-2015.

	--------Non-Agriculture-------				-Ag Pasture and Grass Strips -			--Ag Row Crops--	
Variable	Prairie	Forest	Lawn	Golf Course	Pasture	Grass Strip (NF)	Grass Strip (F)	Alf. w/ Corn	C-S and C-C
	----------Nitrate-N mg/L----------								
Mean	0.1	0.4	1.1	3.7	5.1	5.9	8.9	6.6	22.3
Std. dev.	0.3	0.9	3.6	3.2	8.2	3.3	9.6	8.2	21.8
Minimum	<0.1	<0.1	<0.1	0.1	<0.1	1.0	0.1	<0.1	0.1
Q1	0.1	<0.1	0.1	1.2	0.5	2.6	3.8	1.2	8.0
Median	0.1	0.1	0.1	2.6	2.0	6.7	6.3	3.9	18.0
Q3	0.1	0.2	0.5	5.3	6.2	8.0	11.0	9.0	28.0
Maximum	3.1	4.5	26.0	16.0	46.0	13.0	64.0	64.0	170.0
# of sites	2	1	2	1	3	1	1	4	8
# of lys.	4	2	4	2	6	1	2	8	21
# samples	150	96	235	104	198	60	106	546	1,478
Significance*	e	e	e	c	c	b	b	b	a

*(NF) = non-fertilized, (F) = fertilized, C-S = corn following soybeans and C-C = corn following corn *Sites that do not share the same letter were considered significantly different at the 0.05 level when using a Kruskal-Wallis multiple comparison test between medians.*

Table 10. Statistical analysis results between paired land cover types. The top value represents the *p* value. Cells shaded gray were considered statistically different at the 0.05 level when using the Mann-Whitney paired test between medians. Shaded cells with an asterisk are significant at the <0.01 level. When significant, the median point nitrate-nitrogen concentration (mg/L) difference between respective pairs is displayed in parentheses. For instance, when comparing the prairie versus the forest there were no significant differences (*p* value = 0.718). However, when comparing the prairie (column) to the golf course (row), the golf course had significantly higher concentrations ($p < 0.01$) and this difference was estimated to be 2.4 mg/L.

**p value < 0.01*	Prairie	Forest	Lawn	Golf Course	Pasture	Grass Strip non-fertilized	Grass Strip fertilized	Alfalfa w/Corn
Forest	0.718							
Lawn	* (<0.1)	0.033 (<0.1)						
Golf Course	* (2.4)	* (2.2)	* (2.0)					
Pasture	* (1.9)	* (1.7)	* (1.6)	0.123				
Grass Strip- non-fertilized	* (6.5)	* (6.3)	* (6.1)	* (2.4)	* (2.5)			
Grass Strip- fertilized	* (6.2)	* (6.0)	* (5.7)	* (3.3)	* (3.5)	0.187		
Alfalfa w/Corn	* (3.8)	* (3.8)	* (3.4)	* (1.0)	* (1.2)	0.092	* (-2.0)	
C-S and C-C	* (17.9)	* (17.9)	* (17.0)	* (14.0)	* (14.5)	* (12.1)	* (10.1)	* (12.3)

Ag Pasture and Grass Strips

The average soil water nitrate concentrations in the 'ag pasture and grass strip' category averaged between 5.1 to 8.9 mg/L with an interquartile range 0.5 mg/L to 11.0 mg/L. Nitrate concentrations from pasture sites averaged 5.1 mg/L and were significantly lower than the ag grass strips ($p < 0.01$), but were not significantly different from the golf course ($p = 0.123$). Pasture sites were seeded to perennial cool season forage grasses and grazed by cow/calf beef operations. Nitrogen inputs were limited to that supplied by manure and low amounts of commercial fertilizer. Some sites were rotationally grazed with no additional commercial fertilizer applied during the study while other sites received up to 60 lb N/ac/year of nitrogen fertilizer. At some sites, nitrogen inputs from manure were underestimated due to limited grazing records. At pasture site GW/GY it was observed in 2015 that cattle were loafing near the lysimeter sampling port. This presumably resulted in concentrated manure and urine input directly above the lysimeter, resulting in atypical nitrate transport to the lysimeter. Six months of samples ranging in nitrate-N concentrations of 66 to 360 mg/L were considered outliers and not used in the analysis.

In addition to the three pasture sites, two grass strips were monitored. One was managed as a grass field border while the other was a grassed waterway. The field border did not receive nitrogen while the grassed waterway received the same amount of fertilizer as the adjacent corn field. At the field border site, the 50-foot wide strip of grass ran parallel with the field slope and was located between two row-crop fields. This site was managed for cool-season grasses and was mowed occasionally for forage. At a second site, a grass strip was managed as a grassed waterway within a concentrated flow area within a field managed for continuous corn. Typical of most commercial fertilizer applications, the grassed waterway received the same rate of fertilizer as the adjacent corn field. Even though the field border didn't receive fertilizer while the grassed waterway did, statistically both grass strip sites had similar concentrations (p=0.187). It's possible that in some years, some of the nitrogen fertilizer applied to the field could have been broadcast beyond the target application area and incidentally fertilized the field border as well. Another contributing factor could be related to shallow sub-surface soil water flow from an adjacent crop field. Lateral flow and mixing of shallow soil water from adjacent corn fields likely occurred at both the fertilized and non-fertilized grass strip sites. Adjacent fields near the non-fertilized field border site have slopes of 4-6%, therefore, soil water sampled from the lysimeter could have been a mix of water that infiltrated through both the grass strip and an adjacent crop field that received nitrogen fertilizer. Piezometers were not installed to measure groundwater flow direction, but visual evidence during lysimeter installation suggested that subsurface groundwater flow direction was consistent with surface slope of the field. With that said, nitrate concentrations were significantly lower in both the fertilized and non-fertilized grass strips when compared to continuous corn or corn-soybean rotations (p<0.01). When comparing the ag grass strips to average nitrate concentrations found in corn-soybean land covers, the non-fertilized and fertilized grass strips had 60-74% less nitrate in soil water. Grass strips placed at the field edge were likely helping reduce concentrations contained in shallow, lateral flow from adjacent cropland. This reduction could be caused by a variety of factors including lower nutrient inputs within the grass strip, dilution from rainwater infiltrating within the grass strip, nitrogen uptake by the cool-season grass over a longer growing season when compared to the adjacent row crops, landscape position, immobilization and denitrification.

Ag Row Crop

The third category, 'Ag Row Crop', represented row crop fields managed for corn and soybean rotations (C-S) and continuous corn (C-C) and corn rotations with alfalfa. The 'Alfalfa with corn' classification had at least three years of alfalfa in the rotation and one year of corn during the sampling period. Row crop sites without alfalfa received a mix of both manure and commercial fertilizers and one site was organic. Soil water nitrate averaged 6.6 mg/L under row crop sites with alfalfa which equated to 70% less nitrate when compared to row crop fields without alfalfa in the rotation. Randal et al (1997) found that nitrate loss in subsurface drainage water from continuous corn and corn-soybean systems were about 37 and 35 times higher, respectively, than from alfalfa and CRP systems primarily due to greater evapotranspiration. This results in less drainage and greater uptake and/or immobilization of nitrogen by perennial crops.

Sites managed for continuous corn and corn-soybean rotations without perennials had the highest concentrations in the lysimeter network and averaged 22.3 mg/L with an interquartile range between 8 mg/L to 28 mg/L. This range indicates a high degree of variability and likely reflects the wide range of nitrogen management on the selected farms, diverse weather conditions and inherent variability associated with lysimeters. The standard deviation for the corn and soybean row-crop sites was 21.8 mg/L. For comparison, the standard deviations from the non-agriculture sites ranged from just 0.3 to 3.2 mg/L.

Results from a row-crop field in Fillmore County, site B70/90, were interesting. It was expected that this site would have concentrations between a typical range of 10-20 mg/L. However, in four of the five study years, concentrations remained at or below 10 mg/L and during the first two years nitrate concentrations were typically below 2.0 mg/L. This field was previously in CRP for ten years and did not receive nitrogen fertilizer. This resulted in less residual soil nitrate stored within the soil profile and less nitrate available for leaching in subsequent years. A legacy effect caused by the CRP grassland combined with dry conditions in 2011 and 2012 likely explain why concentrations remained very low during the first two years of row crop production. This farmer also applied lower rates of nitrogen because less nitrogen was expected to be lost through volatilization and leaching with a split nitrogen application program. Although the effectiveness of split applications can be mixed and weather dependent, this practice generally results in higher nitrogen use efficiencies and about 7% less nitrate loss when compared to a pre-plant nitrogen fertilizer application program (Iowa State University, 2013).

Nitrate loss calculation estimates

Nitrate loading was approximated from the SLN row crop sites. Nitrate loss expressed in traditional farm scale units (pounds per acre) was estimated by multiplying the volume of recharge passing through the soil by the nitrate concentration when using the following equation:

Nitrate loss (lb/ac) = 27,154 gal/ac. in. *8.34 lb/gal / 1,000,000 * nitrate concentration (mg/L) * drainage (in.) This equation results in a conversion factor of 0.226 and the following simplified equation:

0.226 * nitrate (mg/l) * drainage (in.) = lb/ac nitrate

For example, assuming a nitrate concentration of 10.0 mg/L and 5-acre inches of drainage water, the amount of nitrate loss equates to 0.226 * 10.0 * 5.0 = 11.3 lb/ac. In this study, drainage volumes were not measured directly from the lysimeters, but were estimated from a nearby long-term tile monitoring site and applied to the row crop sites in the lysimeter network. This comparison assumes that drainage and evapotranspiration rates were similar across the lysimeter network. Where accurate weather data

exist, nitrate loading estimates from the lysimeter network could be improved by using a water balance method and applying an evapotranspiration model that is specific to each site. At a tile drainage monitoring site located about 30 miles west of the Lysimeter Network study area (station SRT, MDA-Root River Field to Stream Partnership) in Mower county, Minnesota an average 24% of the annual precipitation or 8.0 inches of drainage per acre was measured from 2011-2015 (Table 8). This equated to a FWMC of 15.7 mg/L or when 25.3 lb/ac nitrate loss. This field was managed for a corn-soybean rotation and the corn crop typically received a total of 170 lb/ac of pre-plant nitrogen.

Table 11. Annual sub-surface drainage, and nitrate FWMC's and loss from a 59-acre field managed for corn and soybeans in Mower County. This long-term monitoring site is located about 30 miles west of the Lysimeter Network and is one of several edge of field demonstration sites associated with the Root River Field to Stream Partnership.

	2011*	2012	2013	2014	2015	Average
Annual precip. (in.)	22.6	23.4	40.0	32.0	34.1	30.4
Drainage (in./ac)	3.0	0.9	11.9	9.8	14.5	8.0
Drainage: Precip (%)	13%	4%	30%	31%	43%	24%
Nitrate-N (FWMC, mg/L)	13.0	23.7	13.5	15.8	12.5	15.7
Nitrate-N (lb/ac)	8.8	5.1	36.6	35.0	40.9	25.3

*Values are underestimated and represent a partial season. Data were not available from January 1, 2011 through May 17, 2011.

With the assumption that 8-acre inches of drainage water also occurred on the lysimeter network fields, the average nitrate loss was estimated to be 40.3 lb/ac with an interquartile range of 14.5 lb/ac to 50.6 lb/ac. For comparison, the average nitrate loss from the Mower site was 25.3 lb/ac. This was about 60% lower than the SLN. These differences can be partly explained by the following factors: (1) Lower permeability of the glacial till soils at the Mower county site could result in higher rates of denitrification under certain years and conditions and therefore less nitrate measured in drainage leachate (Rodvang and Simpkins, 2001) (2) Nitrate losses from 2011 reflect a partial year at the Mower county site and are underestimated due to a partial year of sampling (3) lysimeter loss estimates may not represent the entire field when compared to tile drainage samples, and (4) the SLN contains a greater diversity of nitrogen management practices including rotations with continuous corn and manure that had higher nitrogen fertilizer inputs.

Row-crop Nitrate Comparisons

To aid interpretation, results from the SLN were compared to other lysimeter and tile drainage sites in Minnesota and Midwest corn belt.

Generally, nitrates measured from the corn-soybean and continuous corn sites in the SLN were within the range of concentrations found in sub-surface drainage tile across Minnesota (Table 8). Nitrate concentrations were not significantly different ($p=0.212$) and both data sets averaged between 21.4 to 22.3 mg/L. Although the averages were very similar, the standard deviation from the lysimeter network was 12.9 mg/L higher. The likely reason for this difference is because lysimeters represent small point measurements within the field and therefore subject to more variation. In contrast, pattern tiled drainage sites have less variation since the concentration measured at the tile outlet represents a composite mixture of drainage water that is representative of the entire area of the drained field. When concentrations were compared to tile drainage sites across the Midwest corn belt (Table 5), the SLN concentrations were about 12% higher than the 20 mg/L row crop reference value contained in that report.

When the SLN corn-soybean and continuous corn sites were compared to a irrigated northcentral corn-soybean site (Table 6) during the same monitoring period of 2011-2015, the northcentral site had significantly higher concentrations ($P<0.05$) and the median point difference was estimated to be 6.6 mg/L. Higher nitrate concentrations are to be expected in this region of the state because the sandy soils that are common in this area can result in greater nitrate loss below the crop root zone. Furthermore, row crops grown on coarse textured soils require higher rates of nitrogen fertilizer, therefore, soil pore water can contain higher nitrate in solution.

Suggestions for Further Study

Where appropriate weather data are available, nitrate loss estimates could be refined using a water balance method and evapotranspiration model for each site. In future studies, performance monitoring of septic system drain fields in areas with low and high density housing, cover crops and alternative crops such as hemp should be explored. For site B70/B90, concentrations were much lower than expected and additional investigation could be warranted regarding the effect of no-till and split nitrogen applications in a corn-soybean rotation. Additional monitoring of grassed waterways and edge of field grass strips would also be beneficial. Grassed waterways are one of the most widely used conservation practices by farmers in southeast Minnesota and quantifying the effect of these practices would be beneficial as an input for groundwater modeling. For best management practice (BMP) comparison sites, additional statistical analysis should be conducted to estimate how many samples would be needed to detect a given percent change in nitrate concentration at the 0.10 and 0.05 confidence levels. This could help lower labor and analytical costs in future monitoring efforts.

Summary and Conclusions

Low levels of soil water nitrate, generally less than 0.5 mg/L, were consistent across the prairie and forest sites. In these land covers, nitrate concentrations are very low because nitrogen is mineralized from soil organic sources and the nitrogen supplied is in equilibrium with plant nitrogen needs. A fertilized golf course site averaged less than 4 mg/L and had similar concentrations when compared to cattle pasture sites. Fertilized and non-fertilized grass strips (grassed waterway and field border) were higher than expected but averaged less than 9.0 mg/L. Elevated concentrations, especially in the non-fertilized grass field border, are likely explained by subsurface mixing of soil water between adjacent land covers. Nitrate concentrations in row crop settings averaged 22.3 mg/L and were spread across a large range of values as depicted by a standard deviation of 21.8 mg/L. This high degree of variability can be explained by the wide range of cropping systems and management systems sampled, diverse weather conditions and variability that is inherent with lysimeter sampling. Although highly variable, average row crop nitrate levels from the lysimeter network were similar to flow weighted concentrations collected from sub-surface drainage tile sites across Minnesota during the same monitoring period.

Any nitrate not used by row crops is susceptible to leaching from the rooting zone and can increase the risk for transport to groundwater, especially in karst landscapes. The use of BMPs, especially proper rate and timing of nitrogen, are key practices to help reduce nitrate concentrations in groundwater. Though, it's important to recognize that these practices alone may not consistently obtain levels below the drinking water standard of 10 mg/L. Integrating perennials into row crop systems can be a key practice for reducing nitrate in groundwater. The use of perennials is used by many livestock farmers in southeast Minnesota and the performance of this practice was measured. In corn rotations with alfalfa, soil water nitrate averaged 6.6 mg/L which was 70% lower when compared to row crop sites without perennials. This reduction can be explained by lower nitrogen inputs, increased nitrogen uptake and/or immobilization and higher rates of evapotranspiration by perennial covers over a longer growing season when compared to row crops (Randal et al, 2008).

The use of lysimeters proved to be a cost-effective tool to estimate the relative range of concentrations and nitrate risk to groundwater between various types of land covers. When shared within the context of this study's limitations, data collected from the Southeast Lysimeter Network serves as a useful educational tool for farmers, crop advisors, rural homeowners and groundwater advisory groups.

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Literature Cited

Alexander, Richard B., Smith, Richard A., Schwarz, Gregory E., Boyer, Elizabeth W., Nolan, Jacquelin V. and Brakebill, John W. (2008). Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environmental Science and Technology. 42, 822-830, pg. 828.

Barry, John D., Miller, Tom, P.,Steenberg, Julia R., Runkel, Anthony C, Kuehner, Kevin J, Alexander, Calvin E. Jr. (2020). Combining high resolution spring monitoring, dye tracing, watershed analysis, and outcrop and borehole observations to characterize the Galena Karst, Southeast Minnesota, USA. 16th Sinkhole Conference, NCKRI symposium 8.

Brouder, S., Hofmann, B., Kladivko, E., Turco, R., Bongen, A. and Frankenberger, J., (2005). Interpreting nitrate concentration in tile drainage water. Purdue University Extension.

Cropscape. Year 2015 Cropland Data Layer. Center for Spatial Information and Science Systems, George Mason University. https://nassgeodata.gmu.edu/CropScape/.

Dogwiler, Toby. (2013). Southeastern Minnesota Soil Water Lysimeter Network Project Final Report. Winona State University Department of Geosciences.

Faaga, J. and Selker, J. (2004). Field Measurements of Nitrate Leaching Below Willamette Valley Row and Mint Crops. Oregon State University Extension Service.

Green, Jeffrey A., John D. Barry and E. Calvin Alexander, Jr., (2014). Springshed Assessment Methods for Paleozoic Bedrock Springs of Southeastern Minnesota. Report to the LCCMR. Sept. 2014, 48 pp.

Haarder, E.B, M.C, Looms, Johnson, K.H and L. Nielsen. (2011). Vadose Zone J. 10:84-97.

Iowa State University, (2013). Nutrient Reduction Strategy. Reducing Nutrient Loss: Science shows what works. Retrieved from https://store.extension.iastate.edu/product/Reducing-Nutrient-Loss-Science-Shows-What-Works.

Kaushal, S.S., Pace, M.L., Groffman, P.M., Band, L.E., Belt, K.T., Meyer, P.M., and Welty, C., (2010), Land Use and Climate Variability Amplify Contaminant Pulses: Eos, Transactions, American Geophysical Union, v. 91, p. 221–222, doi:10.1029/2010EO250001.

Minnesota Department of Agriculture Township Testing Program. Various reports retrieved from https://www.mda.state.mn.us/township-testing-program.

Mossler, J.H., (1995). C-08 Geologic atlas of Fillmore County, Minnesota [Parts A and C]. Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/58513.

Nitrogen in Minnesota Surface Waters, (2013). Minnesota Pollution Control Agency. Report, wq-s6-26a, Minnesota Pollution Control Agency, 2013. Retrieved from https://www.pca.state.mn.us/sites/default/files/wq-s6-26a.pdf.

Randall, G. W. and M.J. Goss. (2008). Nitrate Losses to Surface Water through Subsurface, Tile Drainage. In Nitrogen in the Environment: Sources, Problems, and Management, ed. J.L. Hatfield, and R.F. Follett. P. 145- 175. Elsevier Sciences B.V.

Randall, G.W., Huggins, D.R., Russelle, M.P., Fuchs, D.J., Nelson, W.W. and Anderson, J.L., (1997). Nitrate Losses through Subsurface Tile Drainage in Conservation Reserve Program, Alfalfa, and Row Crop Systems. Journal of Environmental Quality, 26: 1240-1247. doi:10.2134/jeq1997.00472425002600050007x.

Richards DJ, Shieh WK. (1989). Anoxic activated-sludge treatment of cyanides and phenols. Biotechnology Bioengineering. 33:32-38. Referenced in chapter 6 of Agency for Toxic Substances and Disease Registry (ATSDR). 2006. Toxicological profile for Cyanide. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

Robertson, D.M., and Saad, D.A. (2019), Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the Midwestern United States: U.S. Geological Survey Scientific Investigations Report 2019–5114, 74 p. including 5 appendixes, https://doi.org/10.3133/sir20195114.

Rodvang, S.J. & Simpkins, William.(2001). Agricultural Contaminants in Quaternary Aquitards: A Review of Occurrence and Fate in North America. Hydrogeology Journal. 9. 44-59. 10.1007/s100400000114.

Runkel, Anthony C.; Steenberg, Julia R.; Tipping, Robert G.; Retzler, Andrew J. (2014). OFR14-02, Geologic controls on groundwater and surface water flow in southeastern Minnesota and its impact on nitrate concentrations in streams. Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/162612.

Schilling, K. E. and Streeter, M.T. (2018). Groundwater Nutrient Concentrations and Mass Loading Rates at Iowa Golf Courses. Journal of the American Water Resources Association (JAWRA) 54(1): 211-224. https://doi.org/10.1111/1752-1688.12604.

Schilling, K.E., Jones, C.S., Clark, R.J. et al (2019). Contrasting NO3-N concentration patterns at two karst springs in Iowa (USA): insights on aquifer nitrogen storage and delivery. Hydrogeology Journal 27, 1389-1400. https://doi.org/10.1007/s10040-019-01935-y.

USEPA, (1987). Estimated national occurrence and exposure to nitrate and nitrite in public drinking water supplies. Washington, DC, United States Environmental Protection Agency, Office of Drinking Water.

Van Metre, P.C., Frey, J.W., Musgrove, M., Nakagaki, N., Qi, S., Mahler, B.J., Wieczorek, M.E. and Button, D.T. (2016). High Nitrate Concentrations in Some Midwest United States Streams in 2013 after the 2012 Drought. J. Environ. Qual., 45: 1696-1704. doi:10.2134/jeq2015.12.0591.

APPENDIX A

Considerations when interpreting soil water nitrate-nitrogen concentrations collected from lysimeters

Lysimeters are one of the most basic, versatile and economical ways to collect samples for measuring nitrate-nitrogen (nitrate) concentrations in soil water. Measuring nitrate concentrations in the unsaturated vadose zone and lowermost depth of the crop rooting zone of cultivated crops can provide important insights and feedback regarding nitrogen management practices. However, results can be highly variable. For instance, nitrate results collected two lysimeters separated only a few feet apart can vary considerably. The following is a brief list of factors to consider when interpreting results collected from lysimeters.

Soils are complex systems with various chemical, physical and biological interactions, and measuring the movement of nitrate through soil is controlled by the complex interaction of these properties combined with variations in precipitation. Consider the complex movement of water through the soil. Water moves in an irregular manner through the soil profile along a path of least resistance. During dry conditions, water moves between the small pore spaces between the soil particles very slowly. This slow form of water movement is called matrix flow. During wet conditions, such as during a large rain event when the soil is approaching saturation, flow through larger pores such as worm holes or old root channels occurs. This is a fast form of water movement called preferential flow. Nitrate concentrations vary between matrix flow and preferential flow which helps explain why soil water nitrate concentrations from lysimeters located only a few feet apart can be substantially different. These concepts are best illustrated in Figure 1 (adapted from Haarder et al., 2011) showing the cross section of a soil profile after infiltrating four inches of water-soluble blue dye on a sandy textured soil. The wetting front and irregular preferential flow pattern are clearly shown as the blue dye percolates through the soil. In this case, if a lysimeter had been placed on the left side of the soil profile, nitrate concentrations could have been much different when compared to the right side.



Figure 1. This photograph shows the cross section of a soil profile with blue dye poured at the soil surface. The wetting front and irregular preferential flow pattern are clearly shown as the blue dye percolates through the soil. This can help explain why soil water nitrate concentrations from one lysimeter can have markedly different concentrations when compared to another lysimeter only a few feet away. Figure adapted from Haarder et al, 2011.

Another factor to consider is that nitrate measured by lysimeters within the crop root zone represents the amount of nitrate present at that specific point in the soil profile and may not always correspond to what is observed in deeper groundwater. At common lysimeter install depths, usually about four feet, the fate and movement of nitrate can take several pathways. Some of those include: (i) percolate to deeper bedrock layers where it can mix with older groundwater that has been diluted from non-crop land covers (ii) migrate back to the root zone through capillary rise or (iii) be converted into nitrogen gas

(N_2) by denitrification or other reduction processes deeper in the soil profile or aquifer. Despite these factors, nitrate concentrations measured in coarse-textured/sandy aquifers or shallow, unconfined karst aquifers in southeast Minnesota can have nitrates that are consistent with the range of concentrations measured in soil water beneath row-crop fields.

Due to sample and labor constraints involved with lysimeter sampling, typically only a few lysimeters are installed within a small area of a crop field. Lysimeters in effect become point measurements that may not capture the high level of spatial variability represented within the field. This makes it difficult to discern if nitrate concentrations are an accurate representation of the entire field and management system or just that particular point within the field. That is why sub-surface pattern tile drainage sites or groundwater springs are preferred monitoring locations for nitrate, since concentrations represent a composite mixture that is averaged across the drained field area or springshed contributing area. To reduce uncertainty, pairs or groups of lysimeters are typically installed and a mean concentration is applied to the lysimeter group.

Additional factors to consider:

- Typically, a vacuum is paced on the lysimeter to allow collection of a soil water sample. This vacuum could bias preferential flow to the lysimeter within the soil column, causing the sample to not fully represent the water moving through the soil profile.
- Ideally, drainage volume from lysimeters should also be measured to help normalize for differences in sample size between sites and lysimeters by calculating a flow weighted mean concentration (FWMC). A FWMC is defined as the total mass load divided by the total water volume. This normalization process allows comparison among different sites based on the total volume of water rather than the concentration itself. Flow weighted averaging is an appropriate method to represent the average nitrate concentration over multiple sampling events and are much better than simply averaging the individual concentrations since sampling events with low volumes can bias results with sample events that collect small volumes with very high concentrations. Accurately measuring drainage volume from lysimeters is challenging so FWMCs are typically not calculated.
- The soil immediately surrounding lysimeters is disturbed during installation. It may take at least a year for the soil to fully settle around the lysimeters resulting in higher uncertainty in the measurements during that period.
- Samples can be influenced by adjacent, upgradient land use due to lateral movement of shallow groundwater flow paths. This can be a factor for some locations with steeper field slopes.

With these considerations in mind, the use of lysimeters can be a cost-effective tool for evaluating nitrate concentrations and can serve as an important educational tool for farmers, crop advisors, rural homeowners and groundwater advisory groups.

APPENDIX B- Average monthly nitrate by lysimeter site

Non-Ag Prairie/CRP

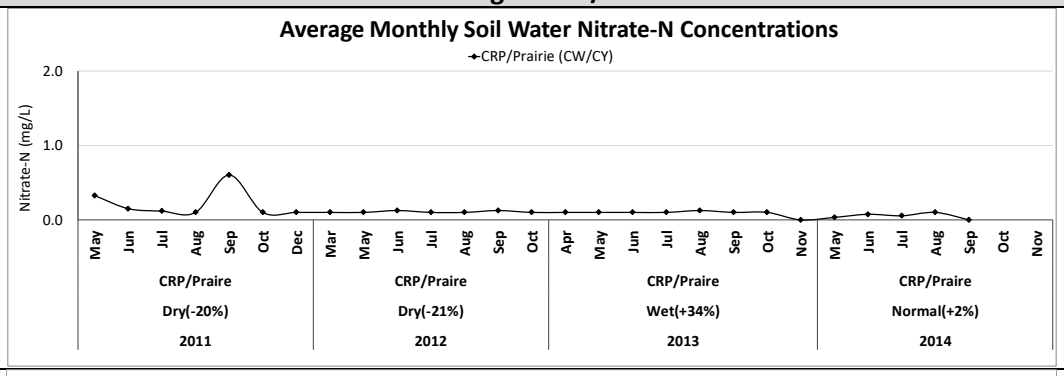

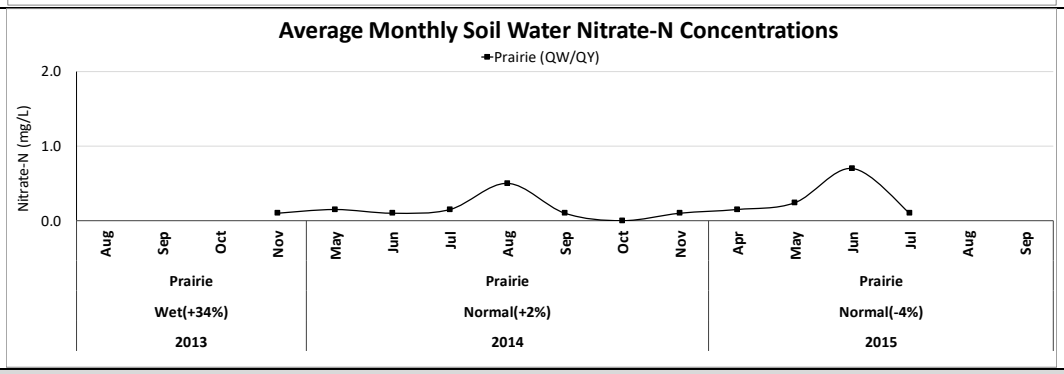

Non-Ag-Forest

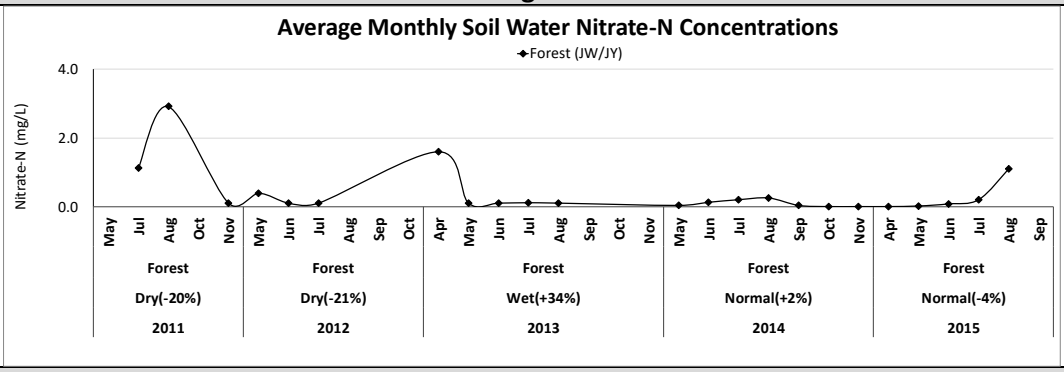

Non-Ag-Homeowner Lawn

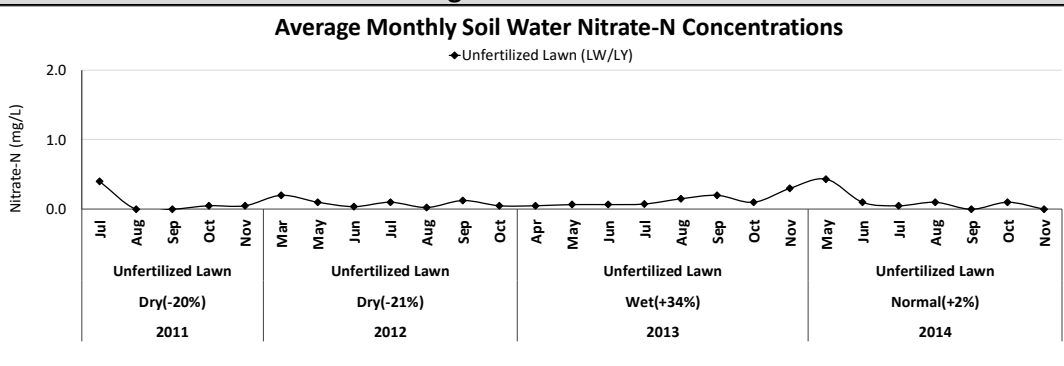

Homeowner Lawn

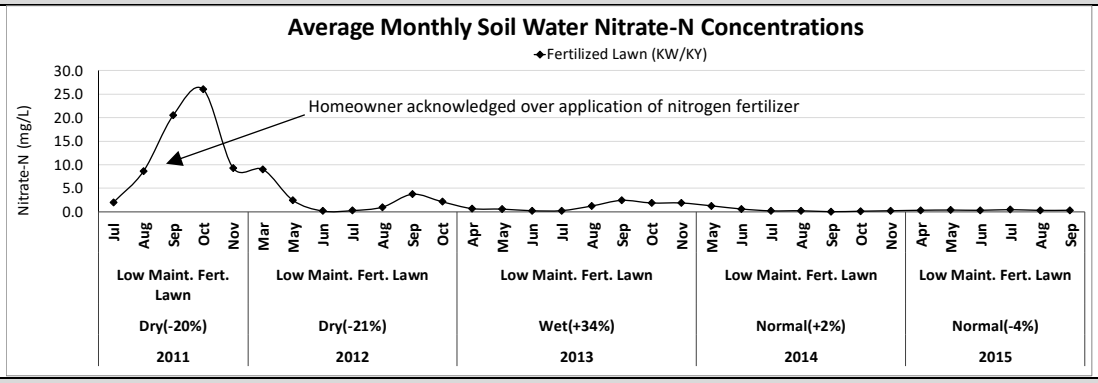

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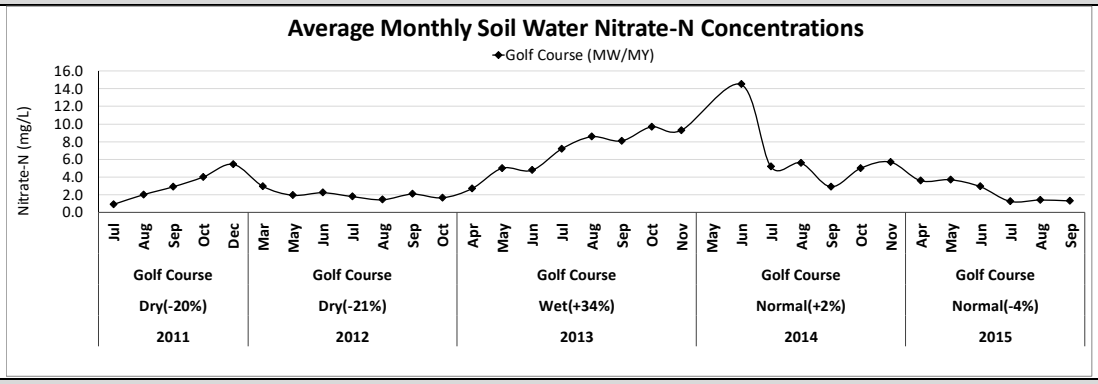

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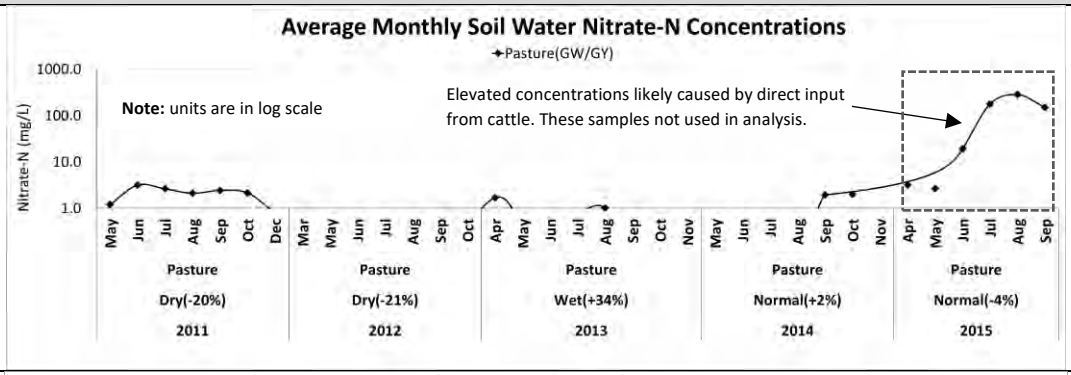

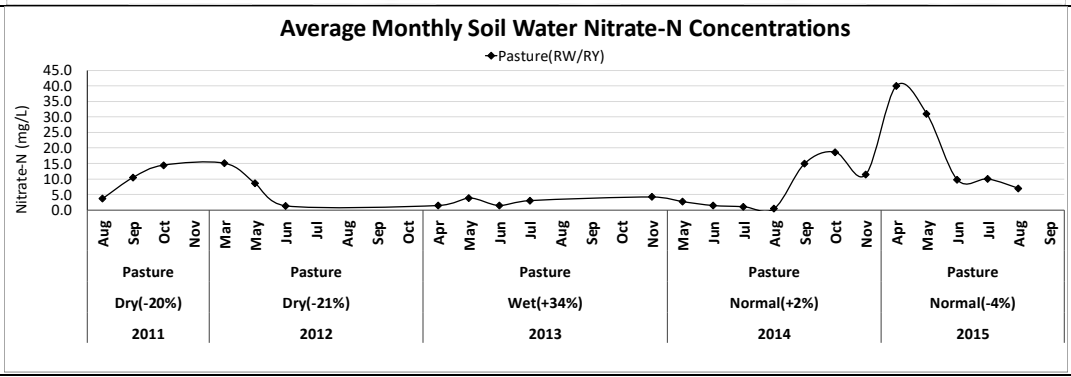

Pasture

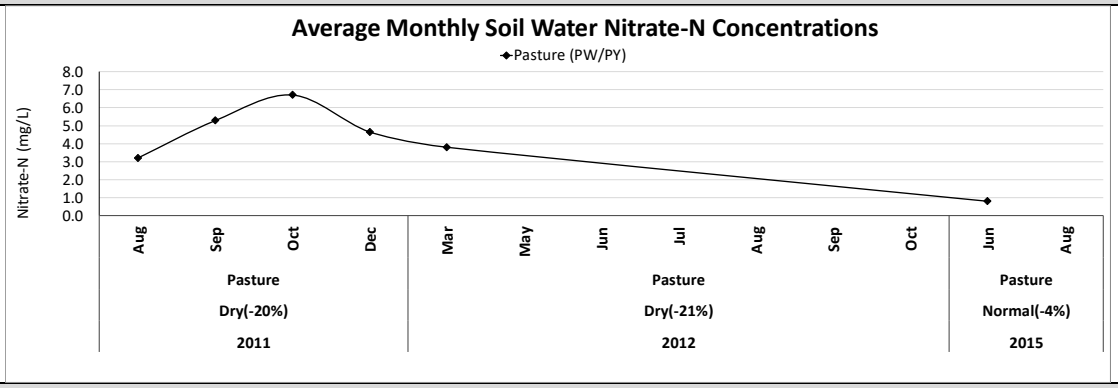

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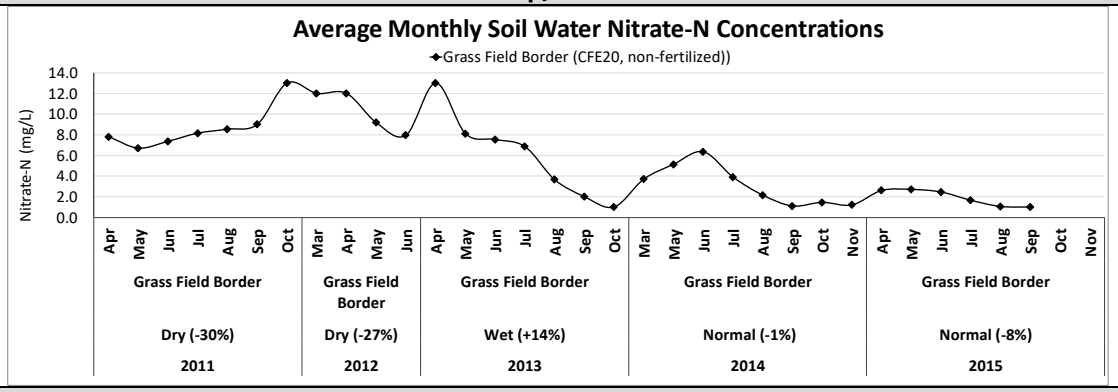

Grass Strip/ Grassed Waterway

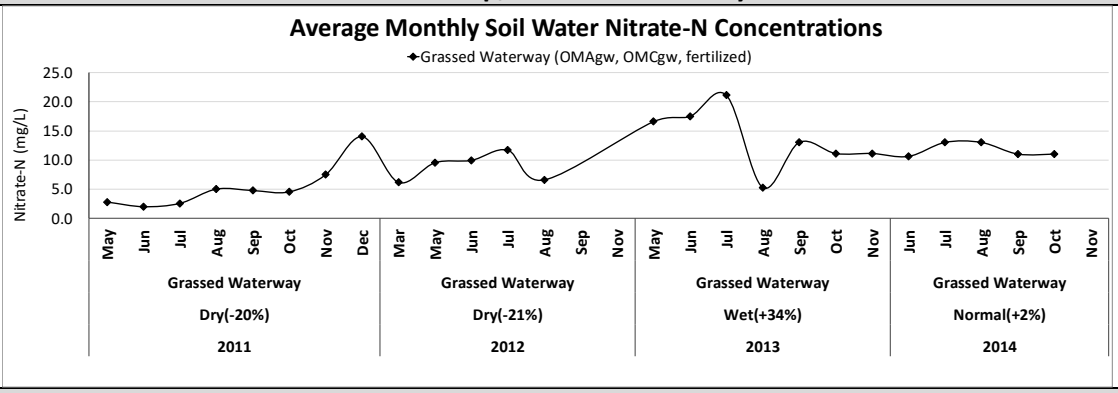

Alfalfa with Corn

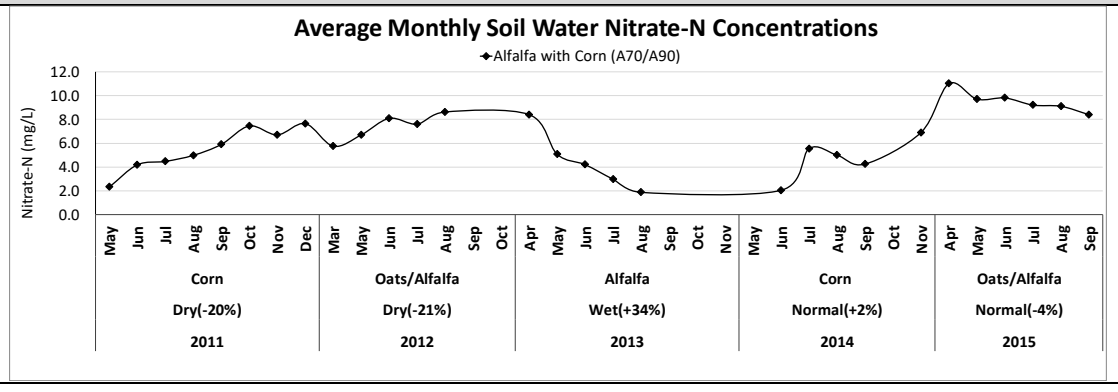

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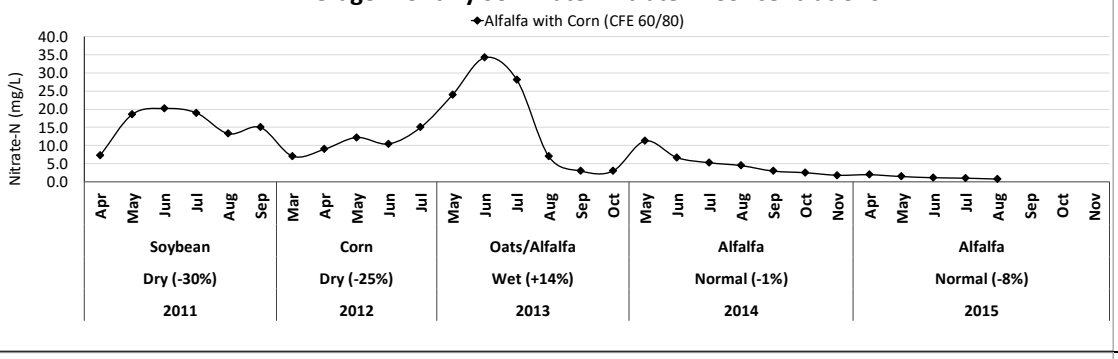

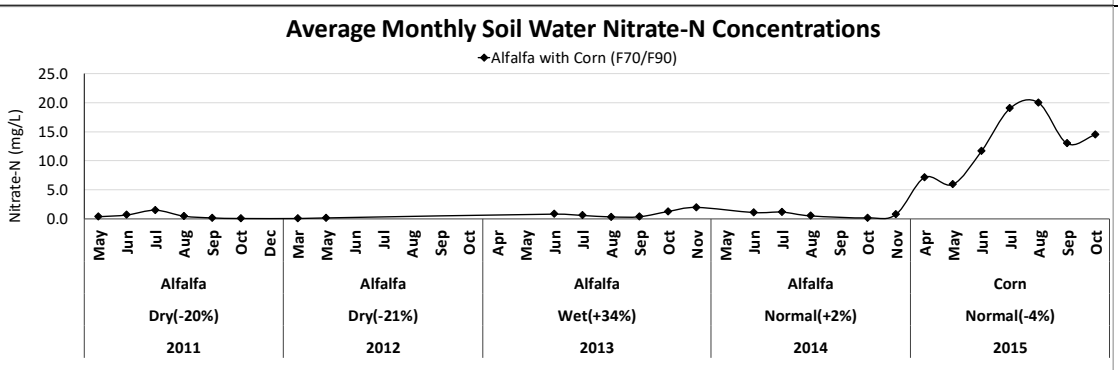

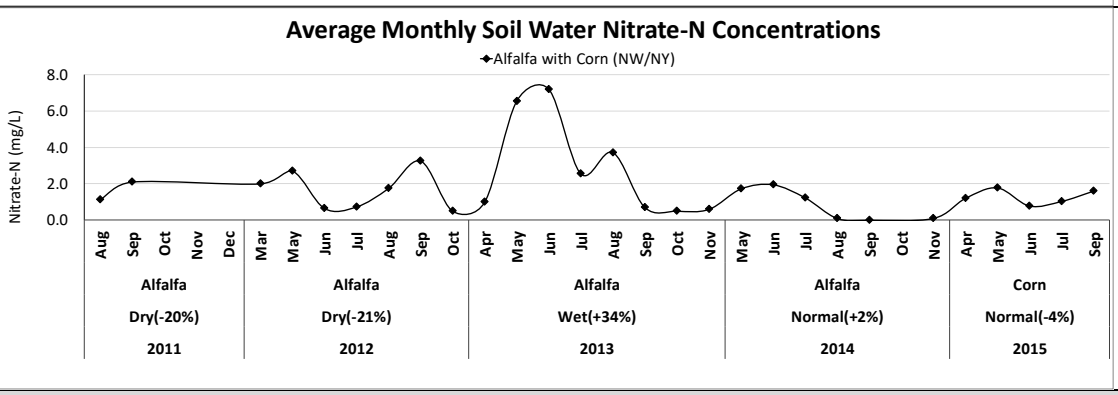

Corn-Soybeans

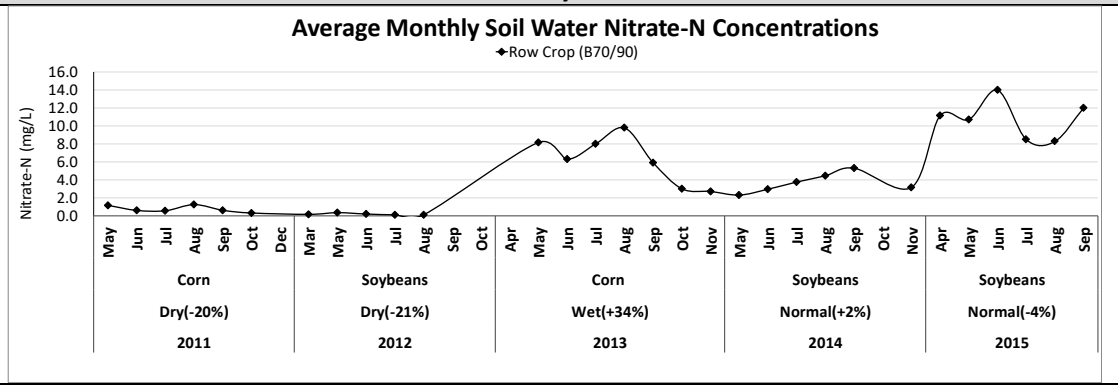

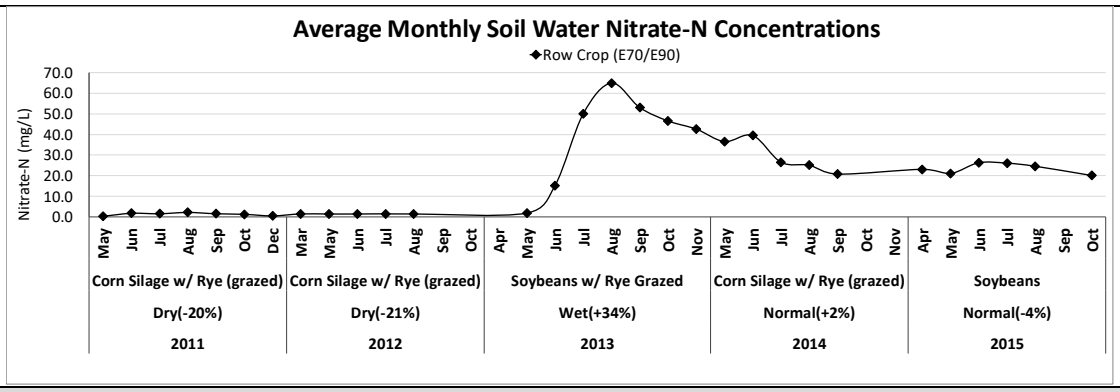

Continuous Corn

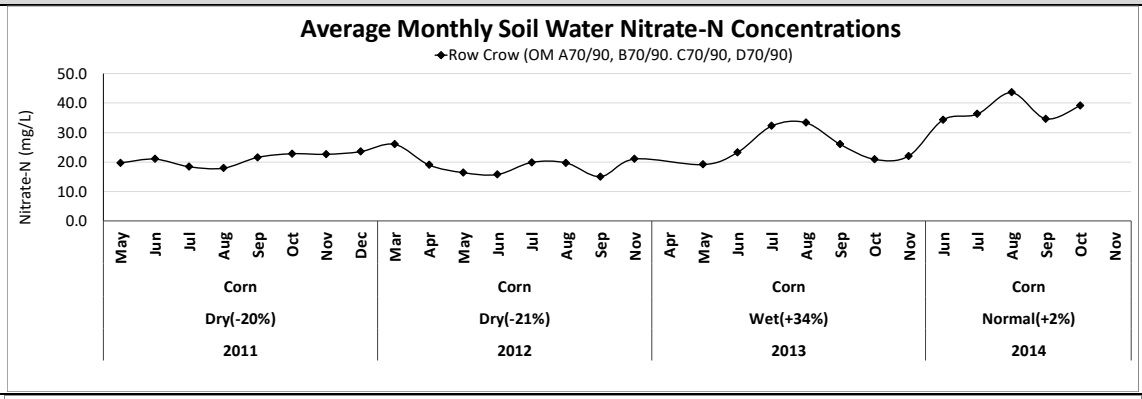

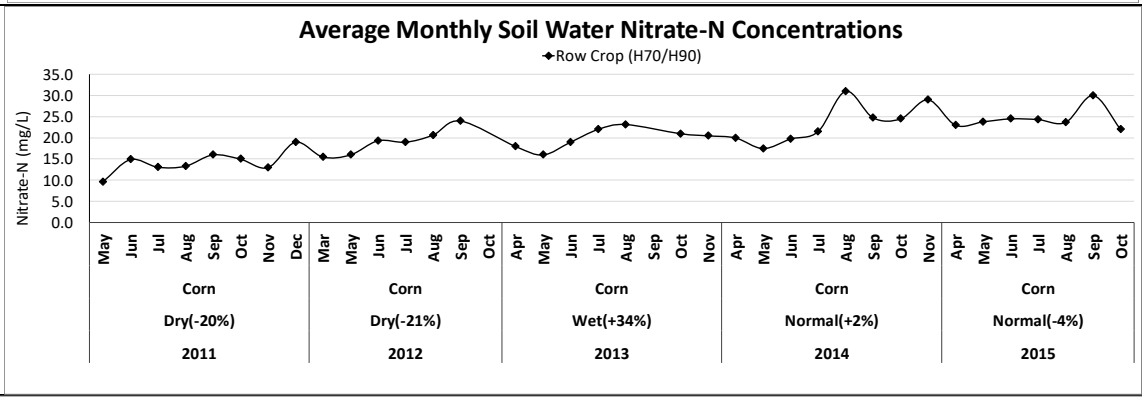

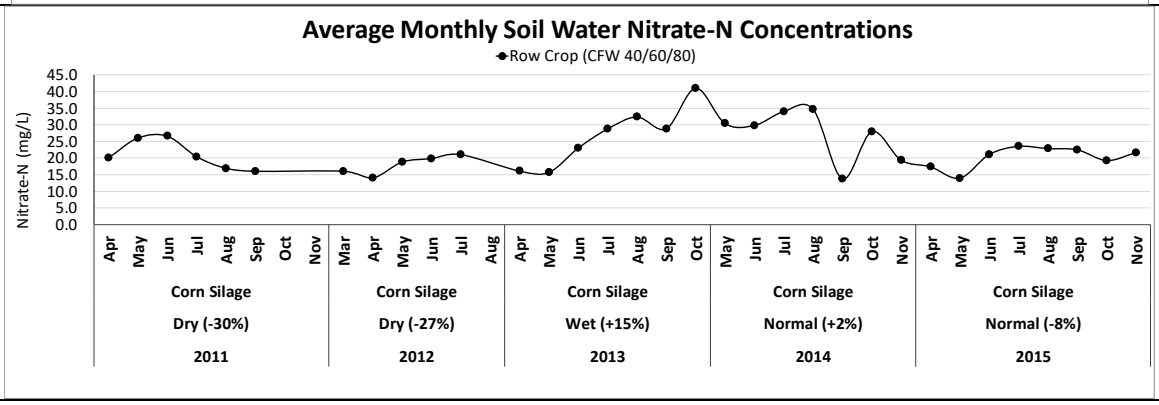

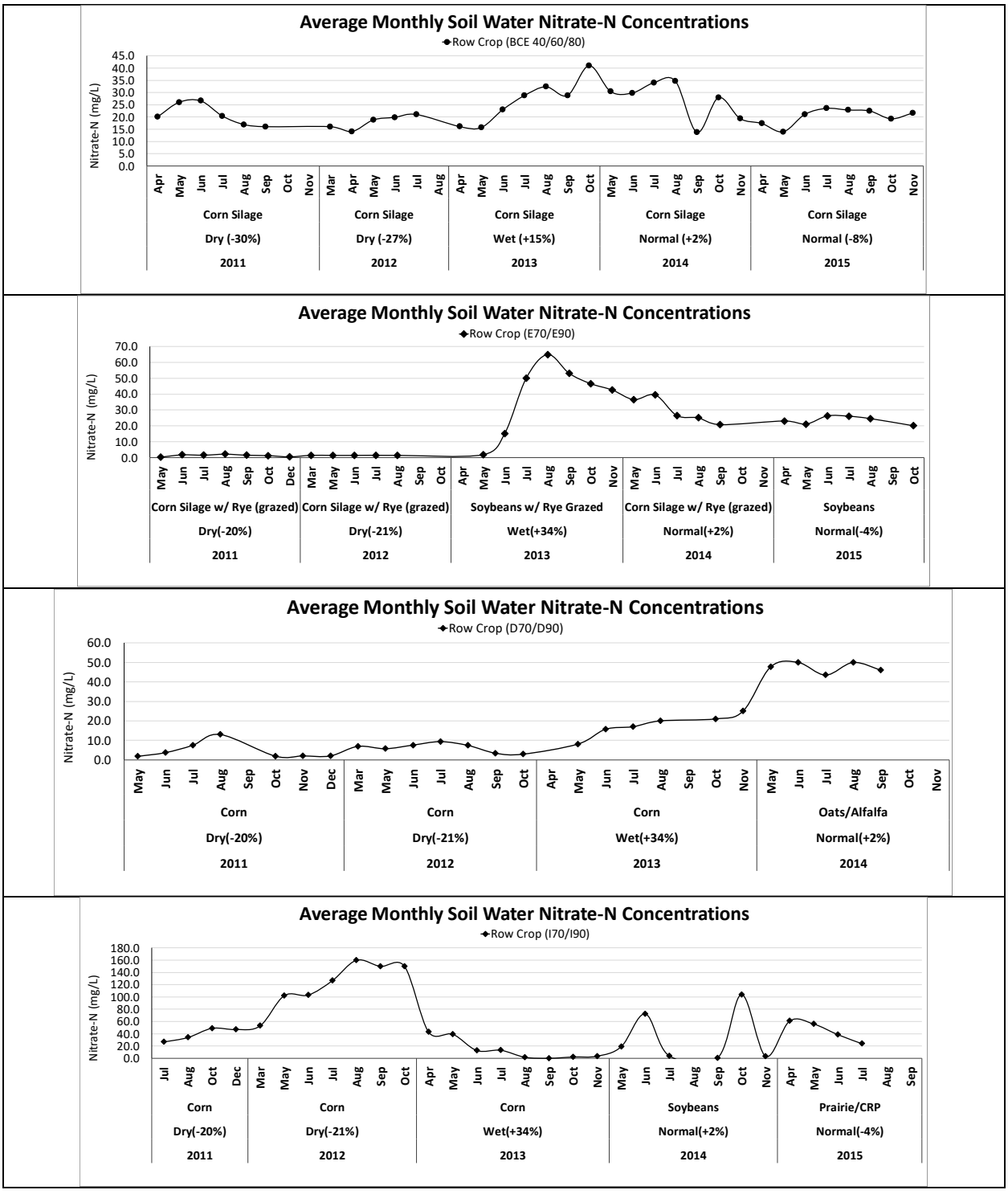
Average Monthly Soil Water Nitrate-N Concentrations
Row Crop (BCE 40/60/80)
Nitrate-N (mg/L)
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Apr May Jun Jul Aug Sep Oct Nov
Mar Apr May Jun Jul Aug
Apr May Jun Jul Aug Sep Oct
May Jun Jul Aug Sep Oct Nov
Apr May Jun Jul Aug Sep Oct Nov
Corn Silage
Dry (-30%)
2011
Corn Silage
Dry (-27%)
2012
Corn Silage
Wet (+15%)
2013
Corn Silage
Normal (+2%)
2014
Corn Silage
Normal (-8%)
2015
Average Monthly Soil Water Nitrate-N Concentrations
Row Crop (E70/E90)
Nitrate-N (mg/L)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
May Jun Jul Aug Sep Oct Dec
Mar May Jun Jul Aug Sep Oct
Apr May Jun Jul Aug Sep Oct Nov
May Jun Jul Aug Sep Oct Nov
Apr May Jun Jul Aug Sep Oct
Corn Silage w/ Rye (grazed)
Dry(-20%)
2011
Corn Silage w/ Rye (grazed)
Dry(-21%)
2012
Soybeans w/ Rye Grazed
Wet(+34%)
2013
Corn Silage w/ Rye (grazed)
Normal(+2%)
2014
Soybeans
Normal(-4%)
2015
Average Monthly Soil Water Nitrate-N Concentrations
Row Crop (D70/D90)
Nitrate-N (mg/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
May Jun Jul Aug Sep Oct Nov Dec
Mar May Jun Jul Aug Sep Oct
Apr May Jun Jul Aug Sep Oct Nov
May Jun Jul Aug Sep Oct Nov
Corn
Dry(-20%)
2011
Corn
Dry(-21%)
2012
Corn
Wet(+34%)
2013
Oats/Alfalfa
Normal(+2%)
2014
Average Monthly Soil Water Nitrate-N Concentrations
Row Crop (I70/I90)
Nitrate-N (mg/L)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Jul Aug Oct Dec
Mar May Jun Jul Aug Sep Oct
Apr May Jun Jul Aug Sep Oct Nov
May Jun Jul Aug Sep Oct Nov
Apr May Jun Jul Aug Sep
Corn
Dry(-20%)
2011
Corn
Dry(-21%)
2012
Corn
Wet(+34%)
2013
Soybeans
Normal(+2%)
2014
Prairie/CRP
Normal(-4%)
2015

APPENDIX C
Quality assurance report: duplicate RPD results

Water samples were analyzed using a Hach® DR6000 UV spectrophotometer (pour-through method 357-10049, DOC 316.53.01072) located in the MDA Preston field office within a week of sample collection. Samples were analyzed using standardized quality assurance and control (QA/QC) procedures. To evaluate the performance of the machine during this study, a minimum of 10% of the nitrate samples were split in the field and sent to the Minnesota Department of Agriculture certified laboratory (MDA Lab) located in St. Paul. Field duplicate samples were used as a part of the quality assurance plan to evaluate the performance and precision of the DR6000 and determine the extent of any analytical problems. Due to budget constraints, duplicate samples were sent in two out of the five years during the study. The MDA lab method (SM 4500-No3 F) using flow injection includes both nitrite and nitrate (NO_2 + NO_3-N) while the DR6000 method does not report nitrite. Nitrite (NO_2-N) is seldom elevated in groundwater because it is typically transformed quickly to nitrate, therefore, it is not considered to be a significant factor when comparing the two methods.

The Relative Percent Difference (RPD) calculation method was used to evaluate the precision of duplicate samples when comparing the DR6000 to the MDH certified lab for years 2014 and 2015. The RPD is the difference between the MDH certified lab and samples analyzed by the DR6000 machine divided by their average and expressed as a percent. The RPD calculation is:

$$RPD = \frac{|X1 - X2|}{(X1 + X2)/2} * 100$$

X1 = sample concentration determined by Hach DR6000 X2= sample concentration determined by MDA certified lab

A goal of this testing program was to have 90% of the duplicate samples within 10% of the RPD. Table 1 and Figure 1 summarize the RPD results. For 2014, 61 field duplicate pairs were analyzed representing 17% of the total samples analyzed on the DR6000. Of the 61 pairs, 87% of the DR6000 duplicate samples were within the 10% RPD goal and 95% were within 20% RPD. In 2015, 114 sample pairs were analyzed representing 31% of the total samples. Of the 114 sample pairs, 89% of the DR6000 samples were within 10% of the RPD and 95% of the duplicate samples were within the 20% RPD. Across both years, 88% of the samples were within 10% of the RPD. Across both years, 90% of the samples were within a RPD of 11%. The overall difference between the DR6000 samples and those analyzed by the MDH lab ranged from -0.3 mg/L to 0.6 mg/L (IQR). The median difference between the DR6000 method and the MDH certified lab was 0.3 mg/L. The method report limit is 0.1 mg/L for the DR6000.

Table 1. Relative Percent Difference (RPD) results between Hach DR6000 and MDA certified lab.

Year	Duplicates	<10% RPD	<15% RPD	<20% RPD
		-----% of duplicate samples-----		
2014	61	87%	93%	95%
2015	114	89%	96%	96%
All Years	175	88%	95%	96%

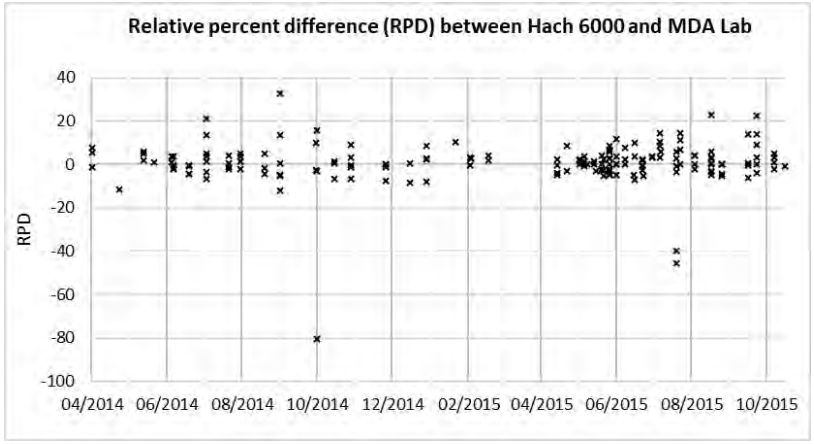

Figure 1. Time series chart of RPD results

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OUTDOORS

Seventeen manure pits reportedly overflow at large feedlots in southern Minnesota

Heavy rain has spilled an unknown amount of livestock waste into the environment.

By Greg Stanley
The Minnesota Star Tribune

JUNE 26, 2024 AT 3:45PM



The flooded Minnesota River has come up to the bottom of the Hwy. 99 bridge in St. Peter on Tuesday. (Glen Stubbe/The Minnesota Star Tribune)

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Relentless rains this month have caused 17 manure pits at 15 large farms in southwestern Minnesota to overflow, releasing livestock waste into the environment.

The overflows, all at open pit lagoons, happened in Rock, Nobles and Jackson counties, said Andrea Cournoyer, a spokeswoman for the Minnesota Pollution Control Agency (MPCA). The agency is working to monitor and mitigate any potential damage from the spills, she

said.

High concentrations of manure can be dangerous to human health and can cause fish kills and threaten water quality even after floodwaters recede. But the manure in the basins overflowing from the extreme rainfall is heavily diluted, said Randy Hukriede, feedlot program manger for the MPCA. None of the basins that overflowed contained pure manure.

“When these do overflow the solids and things collected tend to settle out,” he said. “Generally speaking, when we’re dealing with very, very dilute material like this, we haven’t received reports of any fish kills or things like that.”

The overflows have so far been contained to nearby farm fields, and none of the 17 overflowing pits have directly discharged into a river or stream, Hukriede said.

The state’s largest feedlots, which include dairies and pig and turkey operations that have roughly 1 million pounds of total livestock or more, are required to report any manure overflows to the state. There are about 1,000 feedlots of that size in the state. State regulators ask smaller farms to report overflows as well, but they are not required to.

Hukriede said the agency is working with the flooded feedlots to mitigate spillage. That can be done by diverting manure onto a dry enough field, or finding a storage basin that has room, or building up berms and sealing culverts.

“This is a big challenge right now, you might imagine, because there has just been so much precipitation that a lot of these options are off the table,” he said.

Thom Petersen, the Minnesota Department of Agriculture Commissioner, viewed the flooding in southern Minnesota by helicopter on Tuesday afternoon.

“Those feedlots [with overflows] are working closely with the Minnesota Pollution Control Agency and did not discharge into bodies of water but rather out into fields,” he said.

Peter Bakken, a rancher who operates a feedlot in Rock County, said the heavy rains have put his manure storage facility at the brink of overflowing.

He said it’s the second time since securing his permit that he’s had to phone into the state to report a potential overflow because of flooding. He and his family get their drinking water from the property, he said, and potential manure pollution is one of a host of complications the historic rain has caused farmers in the area.

“We build for a 100-year flood,” Bakken said. “And we get 100-year floods every other year it seems.”

Minnesota Department of Health officials warned that contamination from both animal and human waste is one of many reasons people need to avoid floodwater.

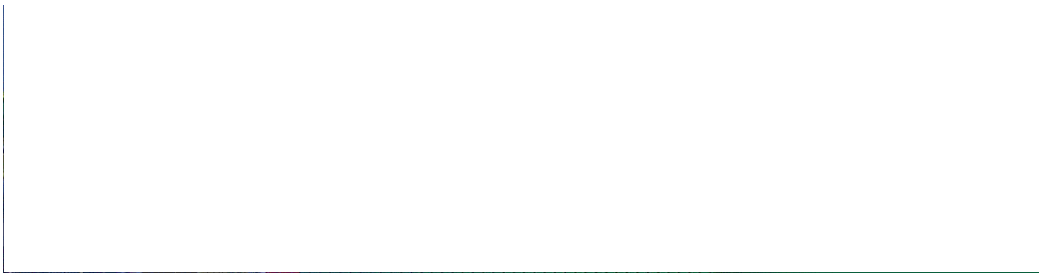

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ABOUT THE WRITER

Greg Stanley

REPORTER

Greg Stanley is an environmental reporter for the Minnesota Star Tribune. He has previously covered water issues, development and politics in Florida's Everglades and in northern Illinois.

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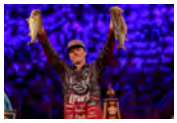

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United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 651
Agricultural Waste Management
Field Handbook

Chapter 10 Agricultural Waste Management System Component Design

Appendix 10D Design and Construction Guidelines for Waste Impoundments Lined with Clay or Amendment-treated Soil

Appendix 10D Design and Construction Guidelines for Impoundments Lined with Clay or Amendment-treated Soil

Introduction

Waste storage ponds and treatment lagoons are used in agricultural waste management systems to protect surface and ground water and as a component in a system for properly utilizing wastes. Seepage from these structures has the potential to pollute surface water and underground aquifers. The principal factors determining the potential for downward and/or lateral seepage of the stored wastes are the:

- permeability of the soil and bedrock horizons near the excavated limits of a constructed waste treatment lagoon or waste storage pond
- depth of liquid in the pond that furnishes a driving hydraulic force to cause seepage
- thickness and permeability of horizons between the boundary of the lagoon bottom and sides to the aquifer or water table

In some circumstances, where permitted by local and/or State regulations, designers may consider whether seepage may be reduced from the introduction of manure solids into the reservoir. Physical, chemical, and biological processes can occur that reduce the permeability of the soil-liquid interface. Suspended solids settle out and physically clog the pores of the soil mass. Anaerobic bacteria produce by-products that accumulate at the soil-liquid interface and reinforce the seal. The soil structure can also be altered in the process of metabolizing organic material.

Chemicals in waste, such as salts, can disperse soil, which may also be beneficial in reducing seepage. Researchers have reported that, under some conditions, the seepage rates from ponds can be decreased by up to an order of magnitude (reduced 1/10th) within a year following filling of the waste storage pond or treatment lagoon with manure. Manure with higher solids content is more effective in reducing seepage than manure with fewer solids content. Research has shown that manure sealing only occurs when soils have a minimal clay content or greater. A rule of thumb supported by research is that manure sealing is not effective unless soils have at least 15 percent clay content for monogastric animal generated waste and 5 percent clay content for ruminant animal generated waste (Barrington, Jutras, and Broughton 1987a, 1987b). Manure sealing is not considered effective on relatively clean sands and gravels, and these soils always require a liner as described in the following sections.

Animal waste storage ponds designed prior to about 1990 assumed that seepage from the pond would be minimized by the accumulation of manure solids and a biological seal at the foundation surface. Figure 10D–1 shows one of these early sites, where the soils at grade were somewhat permeable sands. Monitoring wells installed at some sites with very sandy soils showed that seepage containing constituents from the pond was still occurring even after enough time had passed that manure sealing should have occurred.

This evidence caused U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) engineers to reconsider guidance on suitable soils for siting an animal waste storage pond. In the late 1980s guidance was developed that designs should not rely solely on the seepage reduction that might occur from the accumulation of manure solids in the bottom and on the sides of the finished structure. That initial design document was entitled "South National Technical Center (SNTC) Technical Guide 716." It suggested that if any of four site conditions were present at a proposed structure location, a clay liner or other method of reducing seepage would be used in NRCS designs. A few revisions were made, and the document was re-issued in September 1993.

Figure 10D–1 Animal waste storage pond constructed before the implementation of modern design guidelines



NRCS was reorganized in 1994, and guidance in old SNTC documents was not part of the revised document system of the Agency. Consequently, the 716 document was revised considerably, and the revised material was incorporated into appendix 10D of the Agricultural Waste Field Management Handbook (AWMFH) in October 1998. This 2008 version of appendix 10D continues to update and clarify the process of designing an animal waste storage pond that will meet NRCS-specified engineering design criteria and stated specified permeability requirements.

General design considerations

Limiting seepage from an agricultural waste storage pond has two primary goals. The first is to prevent any virus or bacteria from migrating out of the storage facility to an aquifer or water source. The second is to prevent the conversion of ammonia to nitrate in the vadose zone. Nitrates are very mobile once they are formed by the nitrification process. They can then accumulate significantly in ground water. The National drinking water standard for nitrate is 10 parts per million, and excessive seepage from animal waste storage ponds could increase the level of nitrates in ground water above this threshold. Other constituents in the liquid manure stored in ponds may also be potential contaminants if the seepage from the pond is unacceptably high.

Defining an acceptable seepage rate is not a simple task. Appendix 10D recommends an allowable seepage quantity that is based on a historically accepted tenet of clay liner design, which is that a coefficient of permeability of 1×10^{-7} centimeters per second is reasonable and prudent for clay liners. This value, rightly or wrongly, has a long history of acceptability in design of impoundments of various types, including sanitary landfills.

Assuming that a typical NRCS waste impoundment has a maximum liquid depth of 9 feet, a compacted clay liner thickness of 1 foot, and a one order of magnitude reduction in seepage due to manure sealing effects, the resulting seepage associated with this historically accepted permeability rate is about 1×10^{-6} centimeters per second, or about 9,240 gallons per acre per day. However, the NRCS no longer recommends basing design decisions on the assumption that a full one order of magnitude reduction will be achieved. The following criteria should be used in assessing the adequacy of a compacted clay liner system:

- When credit for a reduction of seepage from manure sealing (described later in the document) is allowed, NRCS guidance considers an acceptable initial seepage rate to be 5,000 gallons per acre per day. This higher value used for design assumes that manure sealing will result in at least a half order of magnitude reduction in the initial seepage. If State or local regulations are more restrictive, those requirements should be followed.
- If State or local regulations prohibit designs from taking credit for future reductions in seepage from manure sealing, then NRCS recommends the initial design for the site be based on a seepage rate of 1,000 gallons per acre per day. Applying an additional safety factor to this value is not recommended because it conservatively ignores the potential benefits of manure sealing.

One problem with basing designs on a unit seepage value is that the approach considers only unit area seepage. The same criterion applies for small and large facilities. More involved three-dimensional type analyses would be required to evaluate the potential impact of seepage on ground water regimes on a whole-site basis. In addition to unit seepage, studies for large storage facilities should consider regional ground water flow, depth to the aquifer likely to be affected, and other factors.

The procedures in appendix 10D to the AWMFH provide a rational approach to selecting an optimal combination of liner thickness and permeability to achieve a relatively economical, but effective, liner design. It recognizes that manipulating the permeability of the soil liner is usually the most cost-effective approach to reduce seepage quantity. While clay liners obviously allow some seepage, the limited seepage from a properly designed site should have minimal impact on ground water quality. Numerous studies, such as those done by Kansas State University (2000), have shown that waste storage ponds located in low permeability soils of sufficient thickness have a limited impact on the quality of ground water.

If regulations or other considerations require that unit seepage be less than 500 gallons per acre per day (1/56 inch per day), synthetic liners such as high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), ethylene propylene diene monomer (EPDM), or geosynthetic clay liners (GCL), concrete liners, or aboveground storage tanks may be more feasible and economical and should be considered. Figure 10D–2 shows a pond lined with a synthetic liner, figure 10D–3 shows a concrete-lined excavated pond, and figure 10D–4 shows an aboveground concrete tank. Aboveground tanks may be also constructed of fiberglass-lined steel. NRCS has significant expertise in the selection, specification, and construction of sites using these products in addition to clay liners. Guidance on these other technologies is contained in other chapters of the AWMFH.

Figure 10D–2 Pond with synthetic liner *(Photo credit NRCS)*



Figure 10D–3 Excavated animal waste storage pond with concrete liner *(Photo credit NRCS)*



Figure 10D–4 Aboveground storage tank for animal waste *(Photo credit Mitch Cummings, Oregon NRCS)*



Progressive design

Waste storage ponds and waste treatment lagoons are usually designed with specific objectives that include cost, allowable seepage, aesthetics, and other considerations. Designs are usually evaluated in a progressive manner, with less costly and simple methods considered first, and more costly and complex methods considered next. These design concepts should generally be considered in the order listed to provide the most economical, yet effective, design of these structures. The following descriptions cover details on design and installation of these individual design measures.

- The least expensive and least complex design is to locate a waste impoundment in soils that have a naturally low permeability and where horizons are thick enough to reduce seepage to acceptable levels. The site should also be located where the distance to the water table conforms to requirements of any applicable regulations.
- Soils underlying the excavated boundaries of the pond may not be thick enough or slowly permeable enough to limit seepage to acceptably low values. In this case, the next type of design often considered is a liner constructed of compacted clay or other soils with appropriate amendments. This type of liner may be constructed with soils from the excavation itself or soil may be imported from nearby borrow sources. If the soils require amendments such as bentonite or soil dispersants, the unit cost of the compacted liner will be significantly higher than for a liner that only requires compaction to achieve a satisfactorily low permeability.
- A synthetic liner may be used to line the impoundment to reduce seepage to acceptable levels. Various types of synthetic materials are available.
- A liner may be constructed of concrete, or a concrete or fiberglass-lined steel tank can be constructed above ground to store the wastes.

A useful tool in comparing design alternatives is to evaluate unit costs. Benefits of alternatives may then be compared against unit costs to aid in selecting a design alternative. Benefits may include reduced seepage, aesthetics, or other considerations. Many geomembrane suppliers may be able to provide rough cost estimates based on the size and locale of the site. In estimating the cost of a compacted clay liner, one should evaluate the volume of compacted fill involved in a liner of given thickness. Table 10D–1 illustrates a cost comparison for different thicknesses of compacted clay liners. If methods other than compacted clay liners are used, higher unit costs may apply (table 10D–2).

Table 10D–1 Cost comparisons of design options for compacted clay liner

Thickness of compacted liner (ft)	Number of cubic yards of fill per square foot (yd^3)	Assumed cost of compacted fill, per cubic yard ($)	Unit cost of stated thickness liner ($/ft²)
1.0	0.037037	3.00–5.00	0.11–0.19
1.5	0.055555	3.00–5.00	0.17–0.28
2.0	0.074074	3.00–5.00	0.22–0.37
3.0	0.111111	3.00–5.00	0.33–0.56

Table 10D–2 Cost comparison for other design options

Liner type	Unit costs ($/ft²)
Geosynthethic	0.50–1.25
Concrete, reinforced 5 inches thick	7.50–8.00

Soil properties

The permeability of soils at the boundary of a waste storage pond depends on several factors. The most important factors are those used in soil classification systems such as the Unified Soil Classification System (USCS). The USCS groups soils into similar engineering behavioral groups. The two most important factors that determine a soil's permeability are:

- The percentage of the sample which is finer than the No. 200 sieve size, 0.075 millimeters. The USCS has the following important categories of percentage fines:
  - Soils with less than 5 percent fines are the most permeable soils.
  - Soils with between 5 and 12 percent fines are next in permeability.
  - Soils with more than 12 percent fines but less than 50 percent fines are next in order of permeability.
  - Soils with 50 percent or more fines are the least permeable.
- The plasticity index (PI) of soils is another parameter that strongly correlates with permeability.

When considered together with percent fines, a grouping of soils into four categories of permeability is possible. The following grouping of soils is based on the experience of NRCS engineers. It may be used to classify soils at grade as an initial screening tool. Estimating permeability is difficult because so many factors determine the value for a soil. For *in situ* soils, the following factors, in addition to percent fines and PI, affect the permeability of the natural soils:

- The dry density of the natural soil affects the permeability. Soils with lower dry densities have higher percentage of voids (porosity) than more dense soils.
- Structure strongly affects permeability. Many clay soils, particularly those with PI values above 20, develop a blocky structure from desiccation. The blocky structure creates preferential flow paths that can cause soils to have an unexpectedly high permeability. Albrecht and Benson (2001) and Daniel and Wu (1993) describe the effect of desiccation on the permeability of compacted clay liners.
- While not considered in the USCS, the chemical composition of soils with clay content strongly affects permeability. Soils with a preponderance of calcium or magnesium ions on the clay particles often have a flocculated structure that causes the soils to be more permeable than expected based simply on percent fines and PI. Soils with a preponderance of sodium or potassium ions on the clay particles often have a dispersive structure that causes the soils to be less permeable than soils with similar values of percent fines and PI. The NRCS publication TR–28, Clay Minerals, describes this as follows:

  > *In clay materials, permeability is also influenced to a large extent by the exchangeable ions present. If, for example, the Ca (calcium) ions in a montmorillonite are replaced by Na (sodium) ions, the permeability becomes many times less than its original value. The replacement with sodium ions reduces the permeability in several ways. For one thing, the sodium causes dispersion (disaggregation) reducing the effective particle size of the clay minerals. Another condition reducing permeability is the greater thickness of water adsorbed on the sodium-saturated montmorillonite surfaces which diminishes the effective pore diameter and retards the movement of fluid water.*
- Alluvial soils may have thin laminations of silt or sand that cause them to have a much higher horizontal permeability than vertical permeability. This property is termed anisotropy and should be considered in flow net analyses of seepage.
- Other types of deposits may have structure resulting from their mode of deposition. Loess soils often have a high vertical permeability resulting from their structure. Glacial tills may contain fissures and cracks that cause them to have a permeability higher than might be expected based only on their density, percent fines and PI of the fines.

The grouping of soils in table 10D–3 is based on the percent passing the No. 200 sieve and PI of the soils. Table 10D–4 is useful to correlate the USCS groups to one of the four permeability groups.

Table 10D–3 Grouping of soils according to their estimated permeability. Group I soils are the most permeable, and soils in groups III and IV are the least permeable soils

Group	Description
I	Soils that have less than 20 percent passing a No. 200 sieve and have a PI less than 5
II	Soils that have 20 percent or more passing a No. 200 sieve and have PI less than or equal to 15. Also included in this group are soils with less than 20 percent passing the No. 200 sieve with fines having a PI of 5 or greater
III	Soils that have 20 percent or more passing a No. 200 sieve and have a PI of 16 to 30
IV	Soils that have 20 percent or more passing a No. 200 sieve and have a PI of more than 30

Table 10D–4 Unified classification versus soil permeability groups 1/

Unified Soil Classification System Group Name	Soil permeability group number and occurrence of USCS group in that soil			
	I	II	III	IV
CH	N	N	S	U
MH	N	S	U	S
CL	N	S	U	S
ML	N	U	S	N
CL–ML	N	A	N	N
GC	N	S	U	S
GM	S	U	S	S
GW	A	N	N	N
SM	S	U	S	S
SC	N	S	U	S
SW	A	N	N	N
SP	A	N	N	N
GP	A	N	N	N

1/ ASTM Method D–2488 has criteria for use of index test data to classify soils by the USCS.

A = Always in this permeability group

N = Never in this permeability group

S = Sometimes in this permeability group (less than 10 percent of samples fall in this group)

U = Usually in this permeability group (more than 90 percent of samples fall in this group)

Permeability of soils

Table 10D–5 shows an approximate range of estimated permeability values for each group of soils in table 10D–3. The ranges are wide because the classification system does not consider other factors that affect the permeability of soils, such as the electrochemical nature of the clay in the soils. Two soils may have similar percent finer than the No. 200 sieves and PI values but have very different permeability because of their different electrochemical makeup. The difference can easily be two orders of magnitude (a factor of 100). The most dramatic differences are between clays that have a predominance of sodium compared to those with a preponderance of calcium or magnesium. High calcium soils are more permeable than high sodium soils.

Table 10D–5 summarizes the experienced judgment of NRCS engineers and generally used empirical correlations of other engineers. The correlations are for *in situ* soils at medium density and without significant structure or chemical content. Information shown in figure 10D–5 is also valuable in gaining insight into the probable permeability characteristics of various soil and rock types.

Some soils in groups III and IV may have a higher permeability than indicated in table 10D–5 because they contain a high amount of calcium. High amounts of calcium result in a flocculated or aggregated structure in soils. These soils often result from the weathering

Table 10D–5 Grouping of soils according to their estimated permeability. Group I soils are the most permeable and soils in groups III and IV are the least permeable soils.

Group	Percent fines	PI	Estimated range of permeability, cm/s	
			Low	High
I	< 20	< 5	3×10^{-3}	2
II	≥ 20	≤ 15	5×10^{-6}	5×10^{-4}
	< 20	≥ 5		
III	≥ 20	16 ≤ PI ≤ 30	5×10^{-8}	1×10^{-6}
IV	≥ 20	> 30	1×10^{-9}	1×10^{-7}

of high calcium parent rock, such as limestone. Soil scientists and published soil surveys are helpful in identifying these soil types.

High calcium clays should usually be modified with soil dispersants to achieve the target permeability goals. Dispersants, such as tetrasodium polyphosphate, can alter the flocculated structure of these soils by replacement of the calcium with sodium. Because manure contains salts, it can aid in dispersing the structure of these soils, but design should not rely on manure as the only additive for these soil types.

Soils in group IV usually have a very low permeability. However, because of their sometimes blocky structure, caused by desiccation, high seepage losses can occur through cracks that can develop when the soil is allowed to dry. These soils possess good attenuation properties if the seepage does not move through cracks in the soil mass. Soils with extensive desiccation cracks should be disked, watered, and recompacted to destroy the structure in the soils to provide an acceptable permeability. The depth of the treatment required should be based on design guidance given in the section **Construction considerations for compacted clay liners.**

High plasticity soils like those in group IV should be protected from desiccation in the interim period between construction and filling the pond. Ponds with intermittent storage should also consider protection for high PI liners in their design.

Figure 10D–5 Permeability of various geologic material (from Freeze and Cherry 1979)

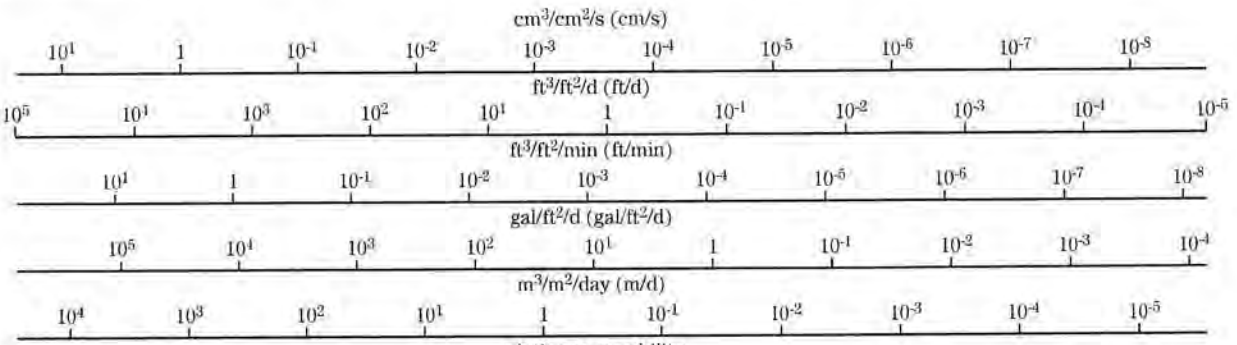

	Very high	High	Moderate	Low	Very low
			Representative materials		
Soil types	Clean gravel (GP)	Clean sand, clean sand and gravel mixes (GW, GP, SW, SP, SM)	Fine sand, silty sand and gravel mixes (SP, SM, GM, GW–GM, GP–GM, SW–SM, SP–SM)	Silt, clay, and sand-silt-clay mixes, organic silts, organic clays (GM, GC, SM, SC, MH, ML, ML–CL, OL, OH, GW–GC, GC–GM, SW-SC, SP–SC, SC–SM)	Massive clay, no soil joints or other macropores (CL, CH)
			Any soil mass with joints, cracks or other macroporosity		
Rock types		Cavernous and karst limestones and dolomites, permeable basalts	Limestones, dolomites, clean sandstones	Interbedded sandstones, siltstones, and shales	Most massive rocks, unfractured and unweathered
			Fractured igneous and metamorphic rocks		

In situ soils with acceptable permeability

For screening purposes, NRCS engineers have determined that if the boundaries of a planned pond are underlain on the sides and bottom both by a minimum thickness of natural soil in permeability groups III or IV, the seepage from those ponds is generally low enough to cause no degradation of ground water. This assumes that soils do not have a flocculated structure. Unless State regulations or other requirements dictate a more conservative method of limiting seepage, it is the position of NRCS that special design measures generally are not necessary where agricultural waste storage ponds or treatment lagoons are constructed in these soils, provided that:

- at least 2 feet of natural soil in groups III or IV occur below the bottom and sides of the lagoon
- the soils are not flocculated (high calcium)
- no highly unfavorable geologic conditions, such as karst formations, occur at the site
- the planned depth of storage is less than 15 feet

Ponds with more than 15 feet of liquid should be evaluated by more precise methods. If the permeability and thickness of horizons beneath a structure are known, the predicted seepage quantities may be estimated more precisely. In some cases, even though a site is underlain by 2 feet of naturally low permeability soil, an acceptably low seepage rate satisfactory for some State requirements cannot be documented. In those cases, more precise testing and analyses are suggested. The accumulation of manure can provide a further decrease in the seepage rate of ponds by up to 1 order of magnitude as noted previously. If regulations permit considering this reduction, a lower predicted seepage can be assumed by designers.

Definition of pond liner

Compacted clay liner—Compacted clay liners are relatively impervious layers of compacted soil used to reduce seepage losses to an acceptable level. A liner for a waste impoundment can be constructed in several ways. When soil alone is used as a liner, it is often called a clay blanket or impervious blanket. A simple method of providing a liner for a waste storage structure is to improve a layer of the soils at the excavated grade by disking, watering, and compacting the soil to a thickness indicated by guidelines in following sections. Compaction is often the most economical method for constructing liners if suitable soils are available nearby or if soils excavated during construction of the pond can be reused to make a compacted liner. Soils with suitable properties can make excellent liners, but the liners must be designed and installed correctly. Soil has an added benefit in that it provides an attenuation medium for many types of pollutants. NRCS Conservation Practice Standard (CPS) 521D, Pond Sealing or Lining Compacted Clay Treatment, addresses general design guidance for compacted clay liners for ponds.

If the available soils cannot be compacted to a density and water content that will produce an acceptably low permeability, several options are available, and described in the following section. The options involve soil additives to improve the permeability of the soils and adding liners constructed of materials other than natural soils.

Treat the soil at grade with bentonite or a soil dispersant—Designers must be aware of which amendment is appropriate for adding to specific soils at a site. In the past, bentonite has been inappropriately used to treat clay soils and soil dispersants have inappropriately been used to treat sands with a small clay content.

The following guidelines are helpful and should be closely followed.

- ***When to use bentonite***—Soils in groups I and II have unacceptably high permeability because they contain an insufficient quantity of clay or the clay in the soils is less active than required. A useful rule of thumb is that soils amenable for treatment with bentonite will have PI values less than 7, or they will have less than 30 percent finer than the No. 200 sieve, or both.

  Bentonite is essentially a highly concentrated clay product that can be added in small quantities to a sand or slightly plastic silt to make it relatively low in permeability. CPS 521C, Pond Sealing or Lining Bentonite Treatment, covers this practice. NRCS soil mechanics laboratories have found it important to use the same type

and quality of bentonite planned for construction in the laboratory permeability tests used to design the soil-bentonite mixture. Both the quality of the bentonite and how finely ground the product is before mixing with the soil will strongly affect the final permeability rate of the mixture. It is important to work closely with both the bentonite supplier and the soil testing facility when designing treated soil liners.

- **When to use soil dispersants**—Soils in groups III and IV may have unacceptably high permeability because they contain a preponderance of calcium or magnesium on the clay particles. Unfortunately, field or lab tests to determine when soils are likely to have this problem are not available. High calcium soils often occur when parent materials have excessive calcium. Many soils developed from weathering of limestone and gypsum may have this problem. See the section Design and construction of clay liners treated with soil dispersants, for more detail. Some States require the routine use of soil dispersants in areas that are known to have high calcium clay soils.

Use of concrete or synthetic materials such as geomembranes and geosynthetic clay liners (GCLs)—Concrete has advantages and disadvantages for use as a liner. A disadvantage is that it will not flex to conform to settlement or shifting of the earth. In addition, some concrete aggregates may be susceptible to attack by continued exposure to chemicals contained in or generated by the waste. An advantage is that concrete serves as an excellent floor from which to scrape solids. It also provides a solid support for equipment such as tractors or loaders.

Geomembranes and GCLs are the most impervious types of liners if designed and installed correctly. Care must be exercised both during construction and operation of the waste impoundment to prevent punctures and tears. The most common defects in these liners arise from problems during construction. Forming seams in the field for geomembranes can require special expertise. GCLs have the advantage of not requiring field seaming, but overlap is required to provide a seal at the seams. Geomembranes must contain ultraviolet inhibitors if exposed to sunlight. Designs should include provision for protection from damage during cleaning operations. Concrete pads, double liners, and soil covering are examples of protective measures. Figure 10D–6 shows an agricultural waste storage facility with a geomembrane liner with ultraviolet inhibitors.

Figure 10D–6 Agricultural waste storage impoundment lined with a geomembrane *(Photo credit NRCS)*



When a liner should be considered

A constructed liner may be required if any of the conditions listed are present at a planned impoundment.

Proposed impoundment is located where any underlying aquifer is at a shallow depth and not confined and/or the underlying aquifer is a domestic or ecologically vital water supply—State or local regulations may prevent locating a waste storage impoundment within a specified distance from such features. Even if the pond bottom and sides are underlain by 2 feet of naturally low permeability soil, if the depth of liquid in the pond is high enough, computed seepage losses may be greater than acceptable. The highest level of investigation and design is required on sites like those described. This will ensure that seepage will not degrade aquifers at shallow depth or aquifers that are of vital importance as domestic water sources.

Excavation boundary of an impoundment is underlain by less than 2 feet of suitably low permeability soil, or an equivalent thickness of soil with commensurate permeability, over bedrock—Bedrock that is near the soil surface is often fractured or jointed because of weathering and stress relief.

Many rural domestic and stock water wells are developed in fractured rock at a depth of less than 300 feet. Some rock types, such as limestone and gypsum, may have wide, open solution channels caused by chemical action of the ground water. Soil liners may not be adequate to protect against excessive leakage in these bedrock types. Concrete or geomembrane liners may be appropriate for these sites. However, even hairline openings in rock can provide avenues for seepage to move downward and contaminate subsurface water supplies. Thus, a site that is shallow to bedrock can pose a potential problem and merits the consideration of a liner. Bedrock at a shallow depth may not pose a hazard if it has a very low permeability and has no unfavorable structural features. An example is massive siltstone.

Excavation boundary of an impoundment is underlain by soils in group I—Coarse grained soils with less than 20 percent low plasticity fines generally have higher permeability and have the potential to allow rapid movement of polluted water. The soils are also deficient in adsorptive properties because of their lack of clay. Relying solely on the sealing resulting from manure solids when group I soils are encountered is not advisable. While the reduction in permeability from manure sealing may be one order of magnitude, the final resultant seepage losses are still likely to be excessive, and a liner should be used if the boundaries of the excavated pond are in this soil group.

Excavation boundary of an impoundment is underlain by some soils in group II or problem soils in group III (flocculated clays) and group IV (highly plastic clays that have a blocky structure)—Soils in group II may or may not require a liner. Documentation through laboratory or field permeability testing and computations of specific discharge (unit seepage quantities) is advised. Higher than normal permeability can occur when soils in group III or IV are flocculated or have a blocky structure. These are special cases, and most soils in groups III and IV will not need a liner provided the natural formation is thick enough to result in acceptable predicted seepage quantities.

These conditions do not always dictate a need for a liner. Specific site conditions can reduce the potential risks otherwise indicated by the presence of one of these conditions. For example, a thin layer of soil over high quality rock, such as an intact shale, is less risky than if the thin layer occurs over fractured or fissured rock. If the site is underlain by many feet of intermediate permeability soil, that site could have equivalent seepage losses as one underlain by only 2 feet of low permeability soil.

Some bedrock may contain large openings caused by solutioning and dissolving of the bedrock by ground water. Common types of solutionized bedrock are limestone and gypsum. When sinks or openings are known or identified during the site investigation, these areas should be avoided and the proposed facility located elsewhere. However, when these conditions are discovered during construction or alternate sites are not available, concrete or geosynthetic liners may be required, but only after the openings have been properly cleaned out and backfilled with concrete.

Specific discharge

Introduction

One way to require a minimal design at a site is to require a minimum thickness of a given permeability soil for a natural or constructed liner. An example of this would be to require that a clay liner constructed at a waste storage pond should be at least 1 foot thick, and the soil should have a coefficient of permeability of 1×10^{-7} centimeters per second or less.

However, using only permeability and thickness of a boundary horizon as a criterion ignores the effect of the depth of liquid on the predicted quantity of seepage from an impoundment. Using this approach would mean that the same design would be used for a site with 30 feet of water as one with 8 feet of water, for instance. A more rational method for stating a limiting design requirement is to compute seepage using Darcy's law for a unit area of the pond bottom.

A rational method of comparing design alternatives at a given site is needed. Such a method allows designers to evaluate the effect of changing one or more of the design elements in a site on the predicted seepage quantities. This document presents methods for computing the term "specific discharge" to use in comparing alternatives and to document a given design goal for a site. Specific discharge is defined as unit seepage.

It does not reflect the total seepage from a site, but rather provides a value of seepage per square unit area of pond bottom.

This document uses calculations of specific discharge to compare design alternatives and to determine if a given design meets regulatory requirements and guidelines. In some cases, the total seepage from a pond may be of interest, particularly for larger ponds in highly environmentally sensitive environments.

In those cases, more elaborate three-dimensional seepage computations using sophisticated finite-element computer programs may be warranted. It is outside the scope of this document to describe these types of analyses. Specialists who are experienced in using the complex software used for these computations should be consulted.

The parameters that affect the seepage from a pond with a natural or constructed clay liner are:

- The size of the pond—The total bottom area and area of the exposed sides of the pond holding the stored waste solids and liquids.
- The thickness of low permeability soil at the excavation limits of the pond—For design, the thickness of the soil at the bottom of the pond is often used because that is where seepage is likely to be highest. In some cases, however, seepage from the sides of the pond may also be an important factor. Seepage from the sides of ponds is best analyzed using finite element flow net programs. In some cases, rather than a single horizon, multiple horizons may be present.
- The depth of liquid in the pond—The depth of liquid at the top of the reservoir when pumping should commence is normally used.
- The coefficient of permeability of the soil forming the bottom and sides of the pond—In layered systems, an average or weighted permeability may be determined as shown in figure 10D–7.

Figure 10D–7 Conversion of permeability in layered profile to single value

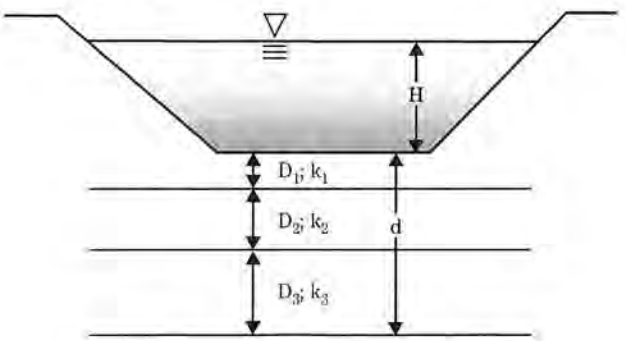

$$k_{average} = \frac{d}{\frac{D_1}{k_1} + \frac{D_2}{k_2} + \frac{D_3}{k_3}}$$

Example 10D–1 shows how to convert a multiple layer system into a single equivalent permeability. Using this method allows a designer to compute specific discharge when several horizons of constructed or natural soils occur below a site.

Example 10D–1

The excavated pond is underlain by 15 feet of soil consisting of three different horizons (fig. 10D–8). The thickness and permeability of each horizon is shown in the sketch. Compute the average vertical permeability of the 15 feet of soil.

Figure 10D–8 Idealized soil profile for example 10D–1

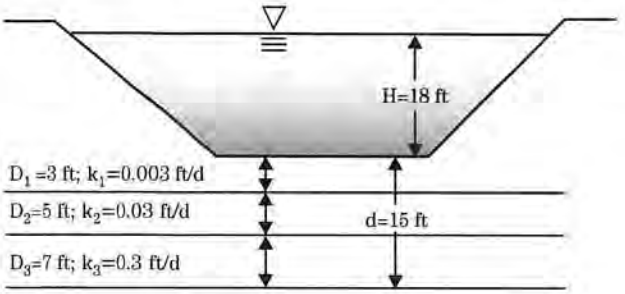

Solution

$$k_{average} = \frac{d}{\frac{D_1}{k_1} + \frac{D_2}{k_2} + \frac{D_3}{k_3}}$$

$$k_{average} = \frac{15}{\frac{3}{0.003} + \frac{5}{0.03} + \frac{7}{0.3}} = 0.0126 \text{ ft/d}$$

Definition of specific discharge

The term "specific discharge" has been coined to denote the unit seepage that will occur through the bottom of a pond with a finite layer of impervious soil. Specific discharge is the seepage rate for a unit cross-sectional area of a pond. It is derived from Darcy's law as follows. First, consider Darcy's law.

$$Q = k \times i \times A$$

For a pond with either a natural or constructed liner, the hydraulic gradient is the term i in the equation, and it is defined in figure 10D–9 as equal to (H+d)/d.

Given:

The Darcy's law for this situation becomes:

$$Q = k \times \frac{H+d}{d} \times A$$

where:

Q	= total seepage through area A	(L^3/T)
k	= coefficient of permeability (hydraulic conductivity)	($L^3/L^2/T$)
i	= hydraulic gradient	(L/L)
H	= vertical distance measured between the top of the liner and top of the liquid storage of the waste impoundment (fig. 10D–9)	(L)
d	= thickness of the soil liner (fig. 10D–9)	(L)
A	= cross-sectional area perpendicular to flow	(L^2)
L	= length	
T	= time	

Figure 10D–9 Definition of terms for clay liner and seepage calculations

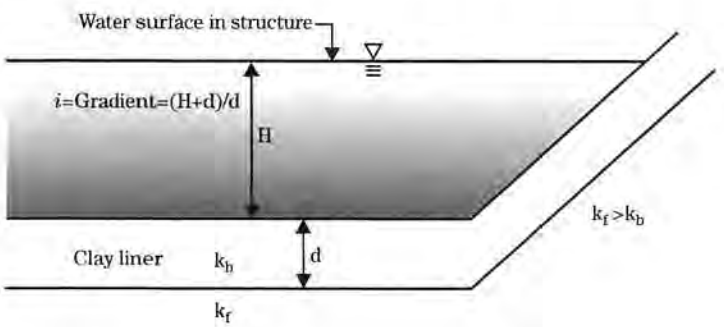

Rearrange terms:

$$\frac{Q}{A} = \frac{k(H+d)}{d} \qquad (L/T)$$

By definition, unit seepage or specific discharge, is Q÷A. The symbol v is used for specific discharge:

$$v = \frac{k(H+d)}{d} \qquad (L^3/L^2/T)$$

Specific discharge may be confused with permeability because the units are the same. In the metric system, specific discharge and permeability are often expressed in units of centimeters per second. The actual units are cubic centimeters of flow per square centimeter of cross section per second, but this reduces to centimeters per second. Specific discharge is different than permeability because specific discharge is an actual flow rate of liquid through a cross section of a soil mass, whereas permeability is a property of the soil mass itself. Permeability is independent of the hydraulic gradient in a particular site, whereas specific discharge accounts for both permeability of the soil and the gradient causing the flow, as illustrated in figure 10D–9. Because hydraulic gradient is dimensionless, the units of specific discharge and permeability are then the same.

Because specific discharge expressed as L/T has the same units as velocity, specific discharge is often misunderstood as representing the average rate or velocity of water moving through a soil body rather than a quantity rate flowing through the soil. Because the water flows only through the soil pores, the actual cross-sectional area of flow is computed by multiplying the soil cross section (A) by the porosity (n). The seepage velocity is then equal to the unit seepage or specific discharge, v, divided by the porosity of the soil, n. Seepage velocity = (v/n). In compacted liners, the porosity usually ranges from 0.3 to 0.5. The result is that the average linear velocity of seepage flow is two to three times the specific discharge value. The units of seepage velocity are L/T.

To avoid confusion between specific discharge and permeability, one possibility is to use different units for specific discharge than for the coefficient of permeability. Common units for permeability are recommended to be in feet per day or centimeters per second. Units for specific discharge should be in gallons per acre per day, acre-feet per acre per day, or acre-inches per acre per day.

To illustrate a typical computation for specific discharge, assume the following:

- A site has a liquid depth of 12 feet.
- The site is underlain by 2 feet of soil that has a coefficient of permeability of 1×10^{-6} centimeters per second (assume that a sample was obtained at the grade of the pond and sent to a laboratory where a flexible wall permeability test was performed on it).
- Compute the specific discharge, v. First, the coefficient of permeability may be converted to units of feet per day by multiplying the given units of centimeters per second by 2,835.

$$k = \left(1\times10^{-6}\ \text{cm/s}\right)\times 2{,}835 = 0.002835\ \text{ft/d}$$

Then, the specific discharge v is computed as follows:

$$\begin{aligned} v &= k\times\frac{H+d}{d} \\ &= 0.002835\times\frac{12+2}{2} \\ &\cong 0.02\ \text{ft}^3/\text{ft}^2/\text{d} \\ &\cong 0.02\ \text{ft/d} \end{aligned}$$

Conversion factors for specific discharge are given in table 10D–6.

Table 10D–6 Conversion factors for specific discharge

To convert from	To units of	Multiply by
$ft^3/ft^2/d$	$in^3/in^2/d$	12
$ft^3/ft^2/d$	gal/acre/d	325,829
$in^3/in^2/d$	gal/acre/d	27,152.4
$in^3/in^2/d$	$cm^3/cm^2/s$	2.94×10^{-5}
$cm^3/cm^2/s$	gal/acre/d	9.24×10^{8}
$cm^3/cm^2/s$	$in^3/in^2/d$	34,015
$cm^3/cm^2/s$	$ft^3/ft^2/d$	2,835

To convert the computed specific discharge in the example into units of gallons per acre per day and cubic inches per square inch per day (in/d), use conversion factors given in table 10D–6.

- 0.02 foot per day×325,829 ≅ 6,500 gallons per acre per day
- 0.02 foot per day×12 = 0.24 cubic inch per square inch per day

A variety of guidelines have been used and regulatory requirements stated for specific discharge. Usually, guidelines require the specific discharge for a given waste storage structure to be no higher than a stated value. The following example demonstrates the unit seepage that will result from a typical size animal waste storage lagoon or storage pond with 2 feet of either very good natural soil or a very well constructed, 2-foot-thick clay liner in the bottom of the lagoon. A practical lower limit for the assumed permeability of a compacted clay or a very good natural liner is a coefficient of permeability equal to 5×10^{-8} centimeters per second. This is based on considerable literature on field and laboratory tests for compacted clay liners used in sanitary landfills.

The specific discharge for this ideal condition follows, assuming:

- The pond has a liquid depth of 15 feet.
- The site is underlain by 2 feet of soil (either a natural layer or a constructed clay liner) that has a coefficient of permeability of 5×10^{-8} centimeters per second
- Compute the specific discharge, v. First, the coefficient of permeability is converted to units of feet per day by multiplying the given units of centimeters per second by 2,835. Then,

$$k = \left(1\times10^{-6}\ \text{cm/s}\right)\times 2,835 = 0.002835\ \text{ft/d}$$

Then, the specific discharge v is computed as follows:

$$v = k\times\frac{H+d}{d}$$
$$= 1.42\times10^{-4}\ \text{ft/d}\times\frac{15\ \text{ft}+2\ \text{ft}}{2\ \text{ft}}$$
$$\cong 0.0012\ \text{ft}^3/\text{ft}^2/\text{d}$$
$$\cong 0.0012\ \text{ft/d}$$

Converting this into units of gallons per acre per day:

$$0.0012\ \text{ft/d}\times 325,829 \cong 393\ \text{gal/acre/d}$$

Table 10D–7 lists typical specific discharge values used by State regulatory agencies. Requirements vary from State to State. Individual designers may regard minimum requirements as too permissive. Some States permit a designer to assume that the initial computed seepage rate will be reduced in the future by an order of magnitude by taking credit for a reduction in permeability resulting from manure sealing. Although the State or local regulations should be used in design for a specific site, the NRCS no longer recommends assuming that manure sealing will result in one order of magnitude reduction. A more conservative assumption described previously allows an initial seepage rate of 5,000 gallons per acre per day, which for the assumed typical site dimensions of 9 feet of liquid and 1 foot thickness of liner, assumes a one half order of magnitude reduction.

Table 10D–7 Typical requirement for specific discharge used by State regulatory agencies

Example specific discharge value	Equivalent value in gallons per acre per day
1/56 $in^3/in^2/d$	485
1/8 $in^3/in^2/d$	3,394
1/4 $in^3/in^2/d$	6,788
1×10^{-6} $cm^3/cm^2/s$	924

Design of compacted clay liners

If a site does not have a sufficient thickness of *in situ* low permeability soil horizons to limit seepage to an acceptably low value, a clay liner may be required. Some State regulations may also require a constructed clay liner regardless of the nature of the *in situ* soils at a site. Regulations sometimes require a specific thickness of a compacted soil with a documented permeability of a given value. An example of this is a State requirement that a waste storage pond must have in the bottom and sides of the pond at least 2 feet of compacted clay with a documented coefficient of permeability of 1×10^{-7} centimeters per second.

Clay liners may also be designed based on a stated allowable specific discharge value. Computations may be performed as detailed in following sections to determine a design that will meet a design specific discharge goal.

Detailed design steps for clay liners

The suggested steps for design of a compacted clay or amendment-treated liner are:

Step 1—Size the impoundment to achieve the desired storage requirements within the available construction limits and determine this depth or the height, H, of storage needed.

Step 2—Determine (from a geologic investigation) the thickness and permeability of horizons of natural clay underlying the bottom of the planned excavated pond. Investigate to a minimum of 2 feet below the planned grade of the pond or to depths required by State regulations, if greater. If natural low permeability horizons at least 2 feet thick or an equivalent thickness of soil with different permeability do not underlie the site, assume that a compacted clay liner (with or without amendments) will be constructed. The liner may be constructed of soils from the excavation if they are suitable for use, or soil may be imported from a nearby borrow source.

Step 3—Measure or estimate the permeability of the natural horizons or the compacted liner planned at the site. Use procedures shown in example 10D–1 to obtain a weighted permeability for the natural horizons.

Step 4—Compute the specific discharge using the values of head in the pond and thickness of natural horizons and their equivalent permeability in the specific discharge equation. If State or local regulations provide a required value for allowable specific discharge, design on the basis of those regulations. Currently, State regulations for specific discharge range from a low of about 500 gallons per acre per day (1/56 inch per day) to a high of about 6,800 gallons per acre per day (1/4 inch per day). If no regulations exist, a value of 5,000 gallons per acre per day may be used. If a designer feels that more conservative limiting seepage is advisable, that rate should be used in computations. It is seldom technically or economically feasible to meet a design specific discharge value of less than 500 gallons per acre per day using compacted clay liners or amendment-treated soil liners. To achieve lower values of unit seepage usually requires synthetic liners, concrete liners, or aboveground storage tanks.

Step 5—If the computed specific discharge meets design objectives, the site is satisfactory without additional design and may be designed and constructed.

Step 6—If the computed specific discharge at the site does not meet design objectives, use either method A or method B shown in following sections to design a compacted clay liner or a liner with soil amendment.

Notes to design steps:

- The calculated thickness of the soil liner required is sensitive to the relative values of soil permeability and the assumed allowable specific discharge value.
- The best and most economical way to reduce the required liner thickness is by reducing the soil's permeability. Liner permeability may be reduced by compacting soils to a higher degree, compacting them at a higher water content, and by using an appropriate additive such as bentonite or soil dispersants.
- By using higher compaction water contents and compacting soils to a high degree of saturation, permeability often can be reduced by a factor of 1/100.
- The liner soil must be filter compatible with the natural foundation upon which it is compacted. Filter compatibility is determined by criteria in NEH 633, chapter 26. As long as the liner soil will not pipe into the foundation, the magnitude of hydraulic gradient across the liner need not be limited.
- Filter compatibility is most likely to be a significant problem when a liner is constructed directly on top of very coarse soil, such as poorly graded gravels and gravelly sands.
- The minimum recommended thickness of a compacted clay liner is given in CPS 521D. The

minimum thickness varies with the depth of liquid in the pond.

- Clay liners constructed by mixing bentonite with the natural soils at a site should have a minimum thickness shown in CPS 521C. These minimum thicknesses are based on construction considerations rather than calculated values for liner thickness requirement from the specific discharge equations. In other words, if the specific discharge equations indicate a 7-inch thickness of compacted bentonite-treated liner is needed to meet suggested seepage criteria, the CPS 521C could dictate a thicker liner. That guidance should be considered in addition to the specific discharge computations.
- Natural and constructed liners must be protected against damage by mechanical agitators or other equipment used for cleaning accumulated solids from the bottom of the structure. Liners should also be protected from the erosive forces of waste liquid flowing from pipes during filling operations. CPSs provide guidance for protection.
- Soil liners may not provide adequate confidence against ground water contamination if foundation bedrock beneath the pond contains large, connected openings. Collapse of overlying soils into the openings could occur. Structural liners of reinforced concrete or geomembranes should be considered because the potential hazard of direct contamination of ground water is significant.
- Liners should be protected against puncture from animal traffic and roots from trees and large shrubs. The subgrade must be cleared of stumps and large angular rocks before construction of the liner.
- If a clay liner (or a bentonite-treated liner) is allowed to dry, it may develop drying cracks or a blocky structure. Desiccation can occur during the initial filling of the waste impoundment and later when the impoundment is emptied for cleaning or routine pumping. Disking, adding water, and compaction are required to destroy this structure created by desiccation. A protective insulating blanket of less plastic soil may be effective in protecting underlying more plastic soil from desiccation during these times the liner is exposed. CPSs address this important consideration.
- Federal and State regulations may be more stringent than the design guidelines given, and they must be considered in the design. Examples later in this section address consideration of alternative guidelines.

Two methods for designing constructed clay liner

Two methods for designing a clay liner are available. In method A, designers begin with an assumed or required value for allowable specific discharge. Using the depth of liquid storage in the pond and known or estimated values of the liner's coefficient of permeability, a required thickness of liner is computed. If the value obtained is unrealistic, different values for the liner permeability are evaluated to determine what values produce a desirable thickness of liner. CPSs also determine minimum liner thicknesses.

In method B, designers begin with a desired thickness of liner and an assumed or required value for specific discharge. Using the depth of liquid storage in the pond and the desired thickness of liner, a required coefficient of permeability for the liner is computed. If the value obtained is unrealistic, different values for the liner thickness are evaluated to determine what values produce an achievable permeability. Coordinating with soil testing laboratories is helpful in evaluating alternatives that can provide the required permeability for the liner.

Each of these methods is illustrated with detailed design examples as follows:

Method A—Using assumed values for the coefficient of permeability of a compacted clay based on laboratory tests of the proposed liner soil, compute the required thickness of a liner to meet the given specific discharge design goal. In the absence of more restrictive State regulations, assume an acceptable specific discharge of 5,000 gallons per acre per day.

The required thickness of a compacted liner can be determined by algebraically rearranging the specific discharge equation, as follows. Terms have been previously defined.

$$d = \frac{k \times H}{v - k}$$

Note: If the k value assumed for the liner is equal to or greater than the assumed allowable specific discharge, meaningless results are attained for d, the calculated thickness of the liner in the last equation. The reason is that the denominator would be zero, or a negative number. Another way of stating this is that the allowable specific discharge goal cannot be met if the liner soils have k values equal to or larger than the assumed allowable specific discharge, in consistent units. Note also that CPS 521D has requirements for minimum thickness of compacted clay liners. If the computed value for the required thickness is less than that given in CPS 521D, then the values in the CPS must be used.

Example 10D–2—Design a clay liner using method A

Given:

Site design has a required depth of waste liquid, H, in the constructed waste impoundment of 12 feet. A soil sample was obtained and submitted to a soil mechanics laboratory for testing. A permeability test on a sample of proposed clay liner soil resulted in a permeability value of 6.5×10^{-7} centimeters per second (0.00184 ft/d) for soils compacted to 95 percent of maximum Standard Proctor dry density at a water content 2 percent wet of optimum. The State requirement for the site requires a specific discharge no greater than an eighth of an inch per day. Compute the required thickness of liner to be constructed of soil having the stated permeability that will achieve this specific discharge.

Solution:

First, convert the required specific discharge into the same units as will be used for the coefficient of permeability. Using values for permeability of feet per day, convert the stated eighth of an inch per day specific discharge requirement into feet per day. To convert, divide an eighth by 12 to obtain a specific discharge requirement of 0.010417 foot per day. It is given that the k value at the design density and water content is 0.00184 foot per day. Calculate the required minimum thickness of compacted liner as follows:

The equation for required d is:

$$d = \frac{k \times H}{v - k}$$

Using English system units, substituting the given values for H and k, assuming an allowable specific discharge, v, of 0.010417 foot per day, then

$$d = \frac{0.00184 \text{ ft/d} \times 12 \text{ ft}}{0.010417 \text{ ft/d} - .00184 \text{ ft/d}} = 2.6 \text{ ft}$$

CPS 521D requires a pond with a depth of water of 12 feet to have a minimum thickness liner of 1 foot, so the 2.6 foot requirement governs.

Method B—Using a given value for depth of liquid in the pond, assumed values for the thickness of a compacted clay based on construction considerations, CPS 521D requirements, State regulations, or the preference of the designer, compute the required permeability of a liner to meet the given specific discharge design goal. In the absence of more restrictive State regulations, assume an acceptable specific discharge of 5,000 gallons per acre per day. The required permeability of a compacted liner can be determined by algebraically rearranging the specific discharge equation as follows. Terms have been previously defined.

$$k = \frac{v \times d}{H + d}$$

If the computed value for the required permeability is less than 5×10^{-8} centimeters per second (1.4×10^{-4} ft/d), NRCS engineers' experience is that lower values are not practically obtainable and a thicker liner or synthetic liners should be used to achieve design goals.

Example 10D–3—Design a clay liner using method B

Given:

Site design has a required depth of waste liquid, H, in the constructed waste impoundment of 19 feet. CPS 521D requires a liner that is at least 18 inches (1.5 feet) thick. The site is in a State that allows NRCS design guidance of 5,000 gallons per acre per day to be used in the design. The NRCS guidance assumes that manure sealing will reduce this seepage value further and no additional credit should be taken.

Solution:

Step 1 First, convert the required specific discharge into the same units as will be used for the coefficient of permeability. Using values for permeability of feet per day, convert the stated 5,000

gallons per acre per day specific discharge requirement into feet per day. To convert using conversions shown in table 10D–6, divide 5,000 by 325,829 to obtain a specific discharge requirement of 0.0154 foot per day. The thickness of liner is given to be 1.5 feet. Calculate the required coefficient of permeability of the compacted liner as follows:

$$k = \frac{v \times d}{H + d}$$

Using English system units, substituting the given values for H of 19 feet and for d of 1.5 feet, assuming an allowable specific discharge, v, of 0.0154 foot per day, then:

$$k = \frac{.0154 \text{ ft/d} \times 1.5 \text{ ft}}{19 \text{ ft} + 1.5 \text{ ft}}$$
$$= 1.1 \times 10^{-3} \text{ ft/d}$$

Convert to centimeters per second by dividing by 2,835.

$$k = \frac{1.1 \times 10^{-3} \text{ ft/d}}{2{,}835}$$
$$k = 4.0 \times 10^{-7} \text{ cm/s}$$

Step 2—The designer should coordinate testing with a laboratory to determine what combinations of degree of compaction and placement water content will result in this value of permeability or less. Design of the 1.5-foot-thick liner may proceed with those recommendations.

Construction considerations for compacted clay liners

Thickness of loose lifts

The permissible loose lift thickness of clay liners depends on the type of compaction roller used. If a tamping or sheepsfoot roller is used, the roller teeth should fully penetrate through the loose lift being compacted into the previously compacted lift to achieve bonding of the lifts. A loose lift thickness of 9 inches is commonly used by NRCS specifications. If the feet on rollers cannot penetrate the entire lift during compaction, longer feet or a thinner lift should be specified. A loose layer thickness of 6 inches may be needed for some tamping rollers that have larger pad type feet that do not penetrate as well.

Method of construction

Several methods are available for constructing a clay liner in an animal waste impoundment. Each has its advantages and disadvantages as described in following sections. A designer should consider the experience of local contractors and the relative costs of the methods in selecting the most appropriate design for a given site. The thickness of the planned soil liner, haul distance, planned side slopes for the pond, and other factors also guide a designer's decision on the best method to use.

Bathtub construction

This method of construction consists of a continuous thickness of soil compacted up and down or across the slopes. Figure 10D–10 shows the orientation of the lifts of a compacted liner constructed using this method, as contrasted to the stair step method, which is covered next. Figure 10D–11 shows two sites where the bathtub method of construction is being used.

This construction method has the following advantages over the stair-step method:

- The layers of compacted clay are oriented perpendicular to flow through the liner in this method. If the lifts making up the liner are not bonded well, the effect on seepage is minor, compared to the stair-step method.
- This method lends itself to constructing thinner lifts, which is more economical.

The bathtub construction method has the following disadvantages compared to the stair-step method:

- Side slopes must be considerably flatter than for the stair-step method, creating a pond with a larger surface area. A pond with a larger surface area has to store more precipitation falling on it, which could be considered an extra cost of the method.
- To permit equipment traversing up and down the slopes, slopes must be an absolute minimum of 3H:1V. Shearing of the soil by the equipment on steeper slopes is a concern. To prevent shearing of the compacted soil, the slopes of

Figure 10D–10 Methods of liner construction (after Boutwell 1990)

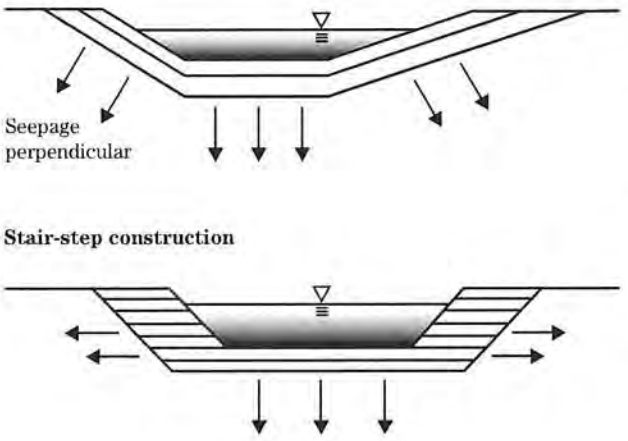

Figure 10D–11 Bathtub construction of clay liner *(photo courtesy of NRCS Virginia (top) and NRCS Nebraska (bottom))*



many compacted liners in ponds constructed using this method use 4H:1V slopes so that equipment will exert more normal pressure on the slope than downslope pressure.

Stair-step construction

The stair-step method of construction is illustrated in figure 10D–10. Construction of the liner consists of compacting lifts of soil around the perimeter of the liner in a stair-step fashion, finishing the job by shaving off some of the side liner and placing it in the bottom of the pond. This method of construction is required if the side slopes of the pond are any steeper than about 3H:1V. Advantages of this method of construction are:

- A thicker blanket, measured normal to the slope, will result compared to the bathtub method of construction (fig. 10D–10). This is a positive factor in seepage reduction.
- It allows steeper side slopes, and thus the surface area of the pond exposed to rainwater accumulation is smaller than a bathtub construction would permit.
- The thicker blanket reduces the impact of shrinkage cracks, erosive forces, and potential mechanical damage to the liner.
- Ponds constructed with this method are deeper for a given volume of waste than ponds constructed with the bathtub method, which favors anaerobic processes in the pond.

Disadvantages of the method are:

- This method may be more expensive than the bathtub method because the liner on the sides of the pond are thicker.
- Flow is parallel to the orientation of the layers forming the compacted liner on the pond sides. If care is not taken to obtain good bonding between lifts, seepage through the interface between lifts could be higher than expected.
- Contractors may be less familiar with this method of operation of equipment.

In the stair-step method of construction, the pond is first excavated. Borrow soil is then imported with a truck or scraper and spread in thin lifts (8 to 9 in thick) prior to compaction. Figure 10D–12a shows the first layer being constructed on the sides of the pond. This pond used a bentonite application. Each lift of

soil is compacted with a sheepsfoot roller to obtain the desired dry density at the specified water content (fig. 10D–12b). The interior liner is constructed by bringing up lifts the full depth of the pond. Photo 10D–12c provides an overview of the stair-step process of constructing a clay liner in an animal waste storage pond. After the sides are constructed, some of the liner is shaved off and used to construct a liner in the bottom of the pond (fig. 10D–12c).

Soil type

Soils in groups III and IV are the most desirable for constructing a clay liner (table 10D–3). Some soils in group II may also be good materials for a clay liner, but definitely require laboratory testing to document their permeability characteristics. Soils in group I always require bentonite to form a liner with acceptably low permeability. Some soils in group II may also require bentonite to be an acceptable material for a liner. Some soils in groups III and IV require a soil dispersant to create an acceptably low permeability.

Classification

The most ideal soils for compacted liners are those in group III. The soils have adequate plasticity to provide a low permeability, but the permeability is not excessively high to cause poor workability. Group IV soils can be useful for a clay liner, but their higher plasticity index (PI greater than 30) means they are more susceptible to desiccation. If clay liners are exposed to hot dry periods before the pond can be filled, desiccation and cracking of the liner can result in an increase in permeability of the liner. A protective layer of lower PI soils is often specified for protection of higher PI clay liners to prevent this problem from developing.

Highly plastic clays like those in group IV are also difficult to compact properly. Special effort should be directed to processing the fill and degrading any clods in high plasticity clays to prevent this problem.

Size of clods

The size and dry strength of clay clods in soil prior to compaction have a significant effect on the final quality of a clay liner. Soil containing hard clayey clods is difficult to break down and moisten thoroughly. Adding water to the soil is difficult because water penetrates the clods slowly. High speed rotary pulverizers are sometimes needed if conditions are especially unfavorable. If soils containing large clay clods are

Figure 10D–12 Stair-step method *(Photo credit John Zaginaylo, PA, NRCS)*

(a)



(b)



(c)



not treated properly, the resultant permeability will be much higher than might otherwise be true. Figure 10D–13 shows the structure that results from compacting soils containing clods that are not adequately broken down.

Figure 10D–13 Macrostructure in highly plastic clays with poor construction techniques (from Hermann and Elsbury 1987)

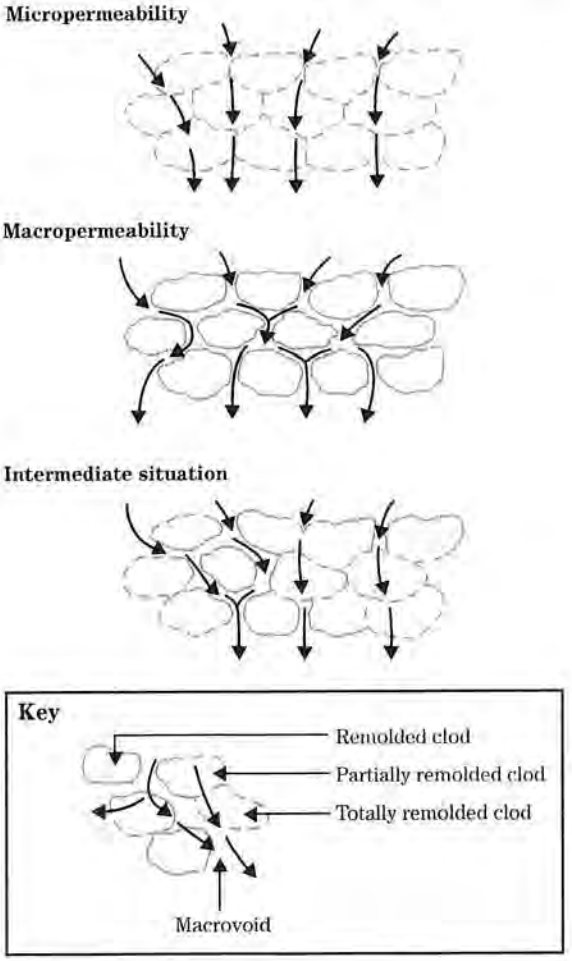

Natural water content of borrow

The water content of soils used to construct a clay liner is the most important factor in obtaining a low permeability liner for a given soil. If soils are too dry, they cannot effectively be compacted to a condition where their structure is acceptable and their permeability may be higher than desirable. Compacting a soil at the proper water content creates a structure that is most favorable to a low permeability. Adding water to compacted clay liners is an additional expense that must be considered. A good rule of thumb is that it requires about 3.2 gallons of water to increase the water content of a cubic yard of compacted soil by 1 percent.

Dry conditions in the borrow

If soils in the borrow area are dry, several problems may need to be addressed. If the soils are clays with relatively high plasticity (PI values greater than about 20), they are likely to be very cloddy when excavated. Water is slow to penetrate the clods and compaction is less likely to degrade clods if enough time has not elapsed between adding the water and compaction. More descriptions follow in subsequent sections, and figure 10D–13 illustrates how clods left in the compacted fill will likely cause the soil to have a higher than expected permeability.

If the water content of borrow soils is more than 3 or 4 percent drier than required for specified compaction conditions, consideration should be given to wetting the soils in the borrow prior to construction. Adding large amounts of water during processing on the fill is difficult and inefficient. Sprinklers can be set up in the borrow some time before construction is planned and then time will allow water to soak into the soils more thoroughly.

Wet conditions in the borrow

If the natural water content of the borrow soil is significantly higher than optimum water content, achieving the required degree of compaction may be difficult. A good rule of thumb is that a soil will be difficult to compact if its natural water content exceeds about 90 percent of the theoretical saturated water content at the dry density to be attained. The following procedure can help to determine if the soils in the borrow are too wet for effectively compacting them.

Step 1 Measure the natural water content of the soil to be used as a borrow source for the clay liner being compacted.

Step 2 Compute the highest dry density to which the soil can be compacted at this water content using the following equation, which assumes that the highest degree of saturation achievable is 90 percent:

$$\text{Achievable } \gamma_{dry} \text{ lb/ft}^3 = \frac{62.4}{\frac{w_n\%}{90} + \frac{1}{G_s}}$$

where:
$w_n(\%)$ = natural water content of borrow soils, %
G_s = specific gravity of the soil solids (dimensionless)

Specific gravity values are obtained by ASTM Standard Test Method D854. An average value for specific gravity is often assumed to be 2.68. However, soils with unusual mineralogy may have values significantly different. Soils with volcanic ash may have specific gravity values as low as 2.3, and soils with hematite in them may have values as high as 3.3, based on NRCS laboratory results.

Step 3 Perform a Standard Proctor (ASTM D698) compaction test on the same soil and determine the maximum dry density value. Compute the achievable degree of compaction by dividing the computed value of achievable dry density by the maximum Standard Proctor dry density.

Step 4 If the computed achievable degree of compaction is less than 95 percent, then drying of the sample will probably be required. In rare cases, compaction to a lower degree, such as 90 percent of Standard Proctor, at higher water contents will achieve an acceptably low permeability. Laboratory tests should be performed to evaluate whether a lower degree of compaction will result in an acceptable permeability value.

Note: The experience of NRCS engineers is that when the natural water content of a soil is more than 4 percent above optimum water content, it is not possible to achieve 95 percent compaction. Computations should always be performed, as this rule of thumb sometimes has exceptions. In most cases, drying clay soils by only disking is somewhat ineffective, and it is difficult to reduce their water content by more than 2 or 3 percent with normal effort. It may be more practical to delay construction to a drier part of the year when the borrow source is at a lower water content. In some cases, the borrow area can be drained several months before construction. This would allow gravity drainage to decrease the water content to an acceptable level.

Step 5 Another way of examining this problem is to assume that soils must be compacted to 95 percent of their Standard Proctor (ASTM D698) dry density and then compute the highest water content at which this density is achievable. Commonly, soils are difficult to compact to a point where they are more than 90 percent saturated. The following equation is used to determine the highest feasible placement water content at which the dry density goal is achievable:

$$\text{Highest placement } w(\%) = \frac{90(\%)}{100} \times \left[\frac{62.4}{\gamma_{dry} \text{ lb/ft}^3} - \frac{1}{G_s} \right]$$

Example 10D–4—Compute the achievable dry density of a potential borrow source

Given:

A borrow source is located and found to be in a desirable group III type soil. The soil has 65 percent finer than the No. 200 sieve and a PI of 18. The soil was sampled and placed in a water tight container and shipped to a soils laboratory. The natural water content of the soil was measured to be 21.8 percent. The lab also performed a specific gravity (G_s) test on the soil, and measured a value of 2.72. A Standard Proctor Test was performed on the sample and values for maximum dry density of 108.5 pounds per cubic foot and an optimum water content of 17.0 percent were measured.

Solution:

The maximum degree of compaction of this soil at the measured water content. If the soil is too wet to be compacted to 95 percent of maximum standard Proctor dry density, how much will it have to be dried to achieve compaction to 95 percent of maximum density?

$$\text{Achievable } \gamma_{dry} \text{ lb/ft}^3 = \frac{62.4}{\frac{w_n\%}{90} + \frac{1}{G_s}}$$

$$\text{Achievable } \gamma_{dry} \text{ lb/ft}^3 = \frac{62.4}{\frac{21.8\%}{90} + \frac{1}{2.72}} = 102.3 \text{ lb/ft}^3$$

Next, compute the achievable degree of compaction by dividing the achievable dry density by the maximum Standard Proctor dry density, expressed as a percentage. The achievable degree of compaction is then equal to 102.3 divided by 108.5×100=94.3 percent.

Now, determine how wet the sample could be and still achieve 95 percent compaction. Ninety-five percent of the maximum Standard Proctor dry density is 0.95×108.5=103.1 pounds per cubic foot. Substitute this value into the equation given:

$$\text{Highest placement w\%} = \frac{90}{100} \times \left[\frac{62.4}{\gamma_{dry} \text{ lb/ft}^3} - \frac{1}{G_S} \right]$$

$$\text{Highest placement w\%} = \frac{90}{100} \times \left[\frac{62.4}{103.1 \text{ lb/ft}^3} - \frac{1}{2.72} \right] = 21.4\%$$

This computation confirms the rule of thumb given that it is difficult to achieve 95 percent degree of compaction if the natural water content is greater than 4 percent above optimum. The stated value for optimum water content is 17.0 percent, so the rule of thumb says that if the natural water content exceeds 21.0 percent, achieving 95 percent degree of compaction will be difficult.

Methods of excavating and processing clay for liners

Clods in borrow soil

If borrow soils are plastic clays at a low water content, the soil will probably have large, durable clods. Disking may be effective for some soils at the proper water content, but pulverizer machines may also be required. To attain the highest quality liner, the transported fill should be processed by adding water and then turned with either a disk or a high-speed rotary mixer before using a tamping roller. Equipment requirements depend on the strength and size of clods and the water content of the soil.

Placement of lifts

Individual lifts of soil usually consist of an equipment width (often about 8 to 10 feet wide) layer of soil about 6 inches thick, after compaction. These lifts should be staggered to prevent preferential flow along the inter-lift boundaries. Figure 10D–14(a) shows the preferred way of offsetting the lifts. Figure 10D–14(b) shows a method that should be avoided. Bonding between the 6-inch lifts is also important so that if water does find its way down the boundary between two lanes of compacted soil that it cannot flow laterally and find the offset boundary.

Macrostructure in plastic clay soils

Clods can create a macrostructure in a soil that results in higher than expected permeability because of preferential flow along the interfaces between clods. Figure 10D–13 illustrates the structure that can result from inadequate wetting and processing of plastic clay. The permeability of intact clay particles may be quite low, but the overall permeability of the mass is high because of flow between the intact particles.

Dry density and optimum water content

Compaction specifications for most earthfill projects normally require a minimum dry density (usually referenced to a specified compaction test procedure) and an accompanying range of acceptable water contents (referenced to the same compaction test procedure). This method of fill specification is usually based on en-

Figure 10D–14 Construction methods to limit interlift preferential flow paths

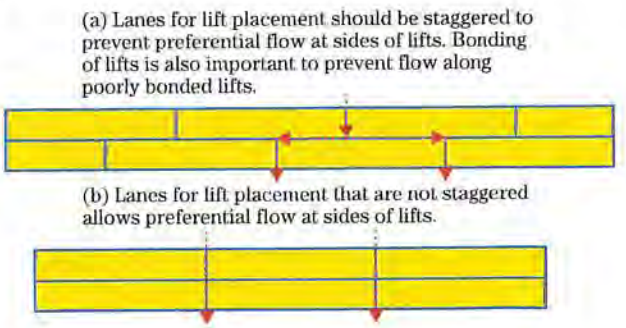

gineering property tests such as shear strength, bearing capacity, and permeability. When permeability is the primary engineering property of interest, as would be the case for a compacted clay liner, an alternative type of compaction specification should be considered. The reason for this is a given permeability value can be attained for many combinations of compacted density and water contents (Daniels and Benson 1990). Figure 10D–15 illustrates a window of compacted dry density and water content in which a given permeability could be obtained for an example soil. The principles involved can be illustrated as follows.

Assume that a given soil is being used to construct a clay liner for an animal waste impoundment. A moderately plastic silty clay classifying as CL in the USCS is used. In case 1, the soil being obtained from a nearby borrow area has a relatively high natural water content. The contractor elects to use lighter construction equipment that applies a relatively low energy in compacting the soil. The result is the soil is compacted to a condition where the compacted density is relatively low and the placement water content is relatively high. This is labeled as point 1 in the figure 10D–15. In case 2, the same soil is being used, but the site is being constructed in a drier time of year. The contractor elects to use a larger sheepsfoot roller and apply more passes of the equipment to achieve the desired product.

This time the same soil is compacted to a significantly higher density at a significantly lower water content. This is labeled point 2 in the figure 10D–15.

Laboratory tests can be used to establish the boundary conditions and arrive at a window of acceptable densities and water contents for a clay liner. Figure 10D–16 shows how a different structure results between soils compacted wet of optimum and those compacted dry of optimum water content. It also illustrates that soils compacted with a higher compactive effort or energy have a different structure than those compacted with low energy.

Mitchell (1965) was instrumental in explaining how the permeability of clay soils is affected by the conditions under which they were compacted. Figure 10D–17 illustrates results of one series of experiments summarized in the study. Two samples of a soil were compacted using different energy at different water contents and their permeability was measured. Soil C was compacted using higher energy, like that used when a heavy sheepsfoot roller passed over each compacted lift multiple times. Soil B was compacted using a lower energy, equating to a smaller roller with a smaller number of passes used in the compaction process.

Figure 10D–15 Range at acceptable moisture/density for a typical clay liner

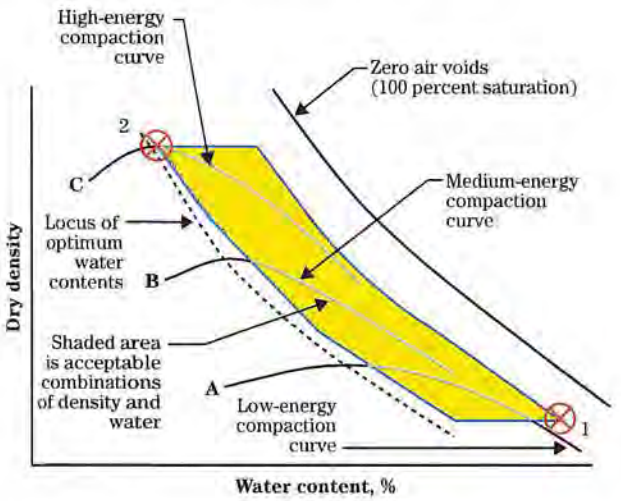

Figure 10D–16 Effect of water content and compactive effort on remolding of soil structure in clays (from Lambe 1958)

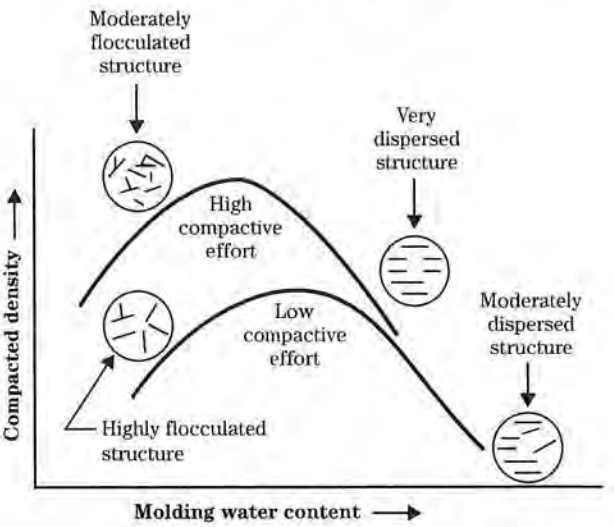

The curves show the relationship between the permeability of the compacted soil and the compaction water content, for the two energies used. The following general principles are seen:

- The permeability of the low energy soil (curve B) is high unless the compaction water content is significantly wet of optimum. Very high permeability results for compaction dry of optimum.
- The permeability of the higher energy soil (curve C) is relatively high for water contents less than optimum.

Lambe (1958) explains how the energy used and the water content of the soil at the time of compaction affect the permeability of the soil by creating structure in the soil. Figure 10D–16 summarizes his explanation of how different soil structures results from these two factors. Soils compacted with higher energy (heavier equipment and numerous passes of the equipment) at a higher water content have a dispersed structure. This structure creates very small plate-shaped voids that are resistant to water flow. Soils that are compacted with lower energy and/or lower water contents have a flocculated structure. This structure involves larger voids that are more conducive to water flow.

Figure 10D–17 Plot showing effect of molding water content on permeability (Mitchell 1965)

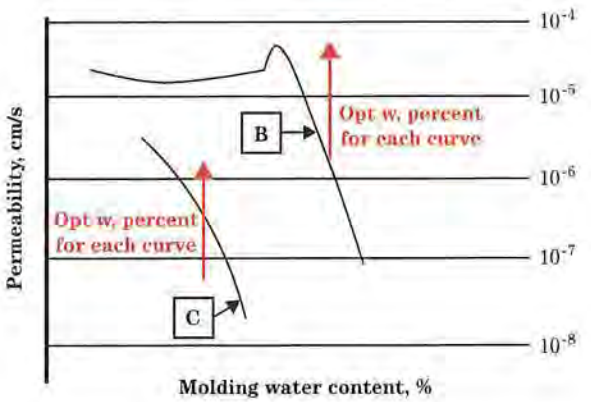

Percent saturation importance

Benson and Boutwell (2000) studied the correlation between field measured permeability values on compacted liners with laboratory measured values. The study found that when soils were compacted at drier water contents, even if a high density were obtained, that correlation between field and lab permeability test values was poor. The study found good correlation when soils were compacted at relatively higher water contents. Clods in clay soils are probably not broken down as well at lower compaction water contents which explains the higher permeability in the field. In lab tests, breaking down clods and obtaining test specimens without a structure is easier than done with field compaction procedures.

The conclusions of Benson and Boutwell's research were that if a designer is going to rely on laboratory permeability tests to predict the permeability of a compacted clay liner, the following rules of thumb apply.

- Soils should generally be compacted wet of the line of optimums. The line of optimums is illustrated in figure 10D–15. It is the locus of optimum water content values for a given soil for a range of compactive energy. A soil compacted with a low energy (like that resulting from a small sheepsfoot roller), curve A in figure 10D–15, will have a relatively low maximum density and high optimum water content. A soil compacted with a high energy (like that resulting from using a large heavy tamping roller), curve C in figure 10D–15, will have a high value for maximum density and a low value of optimum water content. The line of optimums is the locus of points connecting the values of optimum water content. Remember that optimum water content depends on the energy used and that Standard Proctor (ASTM D698) is only one standard type of compaction test. ASTM D1557, the modified energy test is also used for design of some clay liners.
- Eighty percent of field tests of dry density and water content should plot to the right of the line of optimums if the field permeability is expected to reflect the same values obtained in laboratory testing.
- The average water content of all quality control tests should be from 2 to 4 percent wetter than the line of optimums as defined.

Energy level of compaction

The relationship of maximum dry density and optimum water content varies with the compactive energy used to compact a soil. Higher compactive energy results in higher values of maximum dry unit weight and lower values of optimum water content. Lower compactive energy results in lower values of maximum dry unit weight and higher values of optimum water content. Because optimum water content varies with the energy used in compaction, its nomenclature can be misleading. The optimum water content of a soil varies with the particular energy used in the test to measure it.

Compactive energy is a function of the weight of the roller used, thickness of the lift, and number of passes of the roller over each lift. Rollers should be heavy enough to cause the projections (teeth or pads) on the roller to penetrate or almost penetrate the compacted lift. Enough passes must be used to attain coverage and break up any clods. Additional passes do not compensate for rollers that are too light.

Roller size is often specified in terms of contact pressure exerted by the feet on sheepsfoot or tamping rollers. Light rollers have contact pressures less than 200 pounds per square inch, while heavy rollers have contact pressures greater than 400 pounds per square inch.

Limited data are available for various sizes of equipment to correlate the number of passes required to attain different degrees of compaction. Typically, from 4 to 8 passes of a tamping roller with feet contact pressures of 200 to 400 pounds per square inch are required to attain degrees of compaction of from 90 to 100 percent of maximum Standard Proctor dry density. However, this may vary widely with the soil type and weight of roller used. Specific site testing should be used when possible.

Equipment considerations

Size and shape of teeth on roller

Older style sheepsfoot-type projections on rollers are best suited for compacting clay soils to achieve the lowest possible permeability. They are better suited than the modern style rollers called tamping rollers that have more square, larger area projections. The longer teeth on the older style sheepsfoot rollers are better at remolding plastic clay soils that are wet of optimum water content, and they are better at degrading clods in the soils (fig. 10D–18). The modern tamping-type rollers are effective in compacting soils at a drier water content when high bearing capacity is needed, like soils being compacted for highway subgrades (fig. 10D–19). The older style of sheepsfoot roller compactors are better suited for compaction to achieve low permeability.

Total weight of roller

To attain penetration of the specified loose lift, the roller weight must be appropriate to the specified thickness and the shape of the roller projections. Many modern rollers are too heavy to compact soils that are more than 1 or 2 percent wet of optimum water content. When the specified compaction water content is 2 percent or more wet of optimum water content, lighter rollers are essential. Permeability of clays is minimized by compaction at water contents wet of optimum.

Speed of operation

Heavy rollers operated at excessive speed can shear the soil lifts being compacted, which may result in higher permeability. Close inspection of construction operations should indicate if this problem is occurring, and adjustments to equipment or the mode of operation should then be made.

Vibratory versus nonvibratory sheepsfoot and tamping rollers

Some sheepsfoot and tamping rollers have an added feature, a vibratory action. This feature can usually be activated or deactivated while soils are being compacted. Vibratory energy adds little to the effectiveness of these rollers when the soils being compacted are clays. At the same time, the vibration of the equipment is not usually detrimental. One condition in which the vibratory energy of this type of equipment might be detrimental is when a clay liner is being constructed on a subgrade of low plasticity silts or sands that are saturated. The vibration of the equipment often causes these types of foundation soils to become dilatant as they densify, and the water expelled in this process can create a trafficability problem. For this reason, when subgrade soils are saturated low plasticity silts

and sands, the vibratory action of the compaction equipment should be disabled.

Vibratory smooth-wheeled rollers

Vibratory smooth-wheeled rollers are well suited to compacting bentonite-treated liners. They should not be used for compacting clay liners, however. The smooth surface of the roller results in poor bonding between lifts and can cause problems like those shown in figure 10D–14. The load distribution of the rollers also causes the top of a lift to be compacted well but the bottom of the lift not as well, when fine-grained soils are being compacted. A vibratory smooth wheeled roller is shown in figure 10D–20.

Figure 10D–18 Longer style of teeth preferable for compacting soils for clay liner



Figure 10D–19 Modern type of tamping roller less well suited for compacting soils for clay liner



Freeze-thaw and desiccation

Freeze-thaw

Compacted clay liners may become damaged when the liner is exposed during freezing weather. Articles by Kim and Daniel (1992) and Benson and Othman (1993) describe the effects of freezing on clay liners and how the damage resulting from freezing may be permanent. Laboratory tests show that permeability rates may increase by 2 to 3 orders of magnitude (100–1,000 times). Freeze-thaw damage is more likely to affect the side slopes of a clay-lined pond than it will the bottom of the pond after it is filled. If freeze-thaw damage is regarded as likely to increase the permeability of the

Figure 10D–20 Smooth-wheeled steel roller compactor



soils on the side slopes of the pond, a thicker liner or protective cap of cover soil should be considered. The extra cost of freeze-thaw protection may cause a designer to consider a synthetic liner alternative for reasons of economy and confidence in the low permeability of the synthetic liner. For instance, Minnesota designs often include the use of GCL liners for this reason.

Desiccation

Compacted clay liners may also be damaged when the liner is exposed during hot, dry weather after construction and before the pond is filled. Desiccation may also occur during periods the pond is emptied. Articles by Daniel and Wu (1993) and Kleppe and Olson (1985) describe factors that affect desiccation. Using the sandiest soil available that will be adequately impermeable is helpful. Compacting the soil as dense and dry as practical while still achieving the design permeability goal is also helpful. Protective layers must be at least 12 inches thick to be effective, and even thicker layers may be needed for more plastic clay liners, those with PI values of 30 or higher.

Design and construction of bentonite amended liners

When soils at grade of an excavated pond are low plasticity sands and silts in groups I or II of table 10D–3, an unlined pond will result in unacceptably high seepage losses. Several design options are normally considered for this situation. The options are listed as follows in order of increasing cost:

- Clay soils suitable for a clay liner are located in a nearby borrow area and imported to the site to construct a compacted clay liner. CPS 521D applies to this practice.
- Soils from the excavation and at the excavated subgrade are treated with bentonite to create a compacted liner with the required permeability and thickness. CPS 521C applies to this practice.
- The pond may be lined with geosynthetic, a GCL, or lined with concrete. An aboveground storage tank is also an option.

Bentonite type and quality

Several types of bentonite are mined and marketed for use in treating soils to produce a low permeability liner. The most effective type of bentonite (less volume required per cubic foot of treated soil) is finely ground sodium bentonite that is mined in the area of northeast Wyoming, southeast Montana, and western South Dakota. This sodium bentonite is derived from weathered volcanic ash. Sodium bentonite is a smectite clay composed primarily of the mineral montmorillonite (Bentofix 2007). It has the ability to swell up to 10 to 15 times its dry natural volume when exposed to water. Other types of bentonite, usually calcium bentonite are also mined and marketed for treating soils. These types of bentonites are less active (less free swell potential) and more volume of bentonite per treated cubic yard of soil will be required to produce a target permeability than would be required if sodium bentonite were used.

Two methods of evaluating a bentonite source being considered for use as an additive for a liner has high swell properties exist. They are:

- Determine the level of activity based on its Atterberg limit values as determined in a soil testing laboratory. High-quality sodium bentonite has LL values greater than 600 and PI values greater than 550.
- High-quality sodium bentonite has a free swell value of 22 milliliter or higher, based on experience of NRCS engineers and generally accepted guidance. An ASTM Standard test method to evaluate the free swell potential of bentonite is used to verify the quality of bentonite used in GCL liners and is also suitable for evaluating bentonite proposed for a liner being constructed using CPS 521C. The ASTM method is D5890. A summary of the method follows.
  - Prepare a sample for testing that consists of material from the total sample that is smaller than a No. 100 sieve.
  - Partially fill a 100-milliliter graduated cylinder with 90 milliliters of distilled water.
  - Add 2 grams of bentonite in small increments to the cylinder. The bentonite will sink to the bottom of the cylinder and

swell as it hydrates. Wash the sides of the cylinder and fill to the 100-milliliter level.

— After 2 hours, inspect the hydrating bentonite column for trapped air or water separation in the column. If present, gently tip the cylinder at a 45-degree angle and roll slowly to homogenize the settled bentonite mass.

— After 16 hours from the time the last of sample was added to the cylinder, record the volume level in milliliters at the top of the settled bentonite. Record the volume of free swell, for example, 22 milliliters free swell in 24 hours.

Figure 10D–21 shows an excellent quality bentonite reaction to the test. It has a free swell of about 27 milliliters.

Bentonite is furnished in a range of particle sizes for different uses. Fineness provided by the bentonite industry ranges from very finely ground, with most particles finer than a No. 200 sieve, to a granular form, with particles about the size of a No. 40 sieve. Laboratory permeability tests have shown that even though the same bentonite is applied at the same volumetric rate to a sample, a dramatic difference in the resulting permeability can occur between a fine and a coarse bentonite. It is important to use in construction the same quality and fineness as was used by the soils laboratory for the permeability tests to arrive at recommendations. Fineness for use in treating liners for waste impoundment can also be specified by an acceptable bentonite by supplier and designation, or equivalent. An example specification is Wyo Ben type Envirogel 200, CETCO type BS–1, or equivalent.

Figure 10D–21 Free swell test for bentonite ASTM D5890



Design details for bentonite liner

The criteria given in CPS 521C, Pond Sealing or Lining, Bentonite Treatment, provide minimum required liner thicknesses for various depth of liquids.

CPS 521C provides guidance on rates of application of bentonite for preliminary planning purposes or where the size and scope of the project does not warrant obtaining samples and having laboratory tests performed. These preliminary recommended rates of application are based on using high-quality sodium bentonite that is finely ground. The CPS 521C includes a table that shows a range of recommended application rates which vary with the type of soil being treated. Higher rates of application are needed for coarse, clean sands and lower rates for silts. The table shows a recommended application rate expressed in pounds of bentonite per square foot per inch of liner to be built. For example, a typical rate of application for a relatively clean sand would be about 0.625 pounds per square foot per inch of compacted bentonite-treated liner. The most up-to-date CPS 521C should always be consulted for recommended rates, in case they have changed since this document was written.

For planning purposes, using these recommended rates, the amount of bentonite needed for a job can be estimated. For example, assume that a pond is to be constructed with an area of the sides and bottom totaling one acre. Assume that considering the planned depth of water in the pond, a design has been formulated that calls for a 1-foot-thick bentonite-treated liner and that an application rate of 0.625 pounds per square foot per inch is needed. The total amount of bentonite required per square foot will be

$$0.625 \text{ lb/ft}^2 \times 12 \text{ in/ft} = 7.5 \text{ lb}$$

of bentonite per square foot. For an acre of pond area, the total amount needed will be

$$7.5 \text{ lb/ft}^2 \times 43{,}560 \text{ ft}^2\text{/acre} = 326{,}700 \text{ lb}$$
$$= 163 \text{ tons}$$

The cost of bentonite is affected strongly by freight, and the further a site is from the area of the United States where bentonite is produced, the more costly it will be. Better unit prices are available for larger quantities.

Remember that the preliminary rates of application provided in CPS 521C assume that finely ground high-swell sodium bentonite is used. If plans anticipate that a lower quality bentonite with a free swell less than about 22 milliliters or a coarsely ground bentonite may be used, laboratory testing is required to establish a rate of application that will create a suitably low permeability. Design using the specific discharge approach will establish what the target permeability value should be.

The recommended procedure to arrive at a design for a bentonite-treated liner then is as follows:

Step 1 Obtain a sample of the soil to which the bentonite is to be added. Have the sample tested in a soils laboratory to determine its basic index properties, including percent fines and plasticity.

Step 2 Have a standard Proctor (ASTM D698) test performed to determine the maximum dry density and optimum water content.

Step 3 From the preliminary design of the site, determine the depth of water in the structure. Use CPS 521C to determine the minimum thickness of liner required.

Step 4 Using given or assumed values for allowable specific discharge, compute the required permeability of the bentonite-treated liner.

Step 5 Coordinate with a soils laboratory on testing to determine what degree of compaction, water content, and rate of application of the proposed additive is required to obtain this permeability. Consider whether high quality (free swell > 22 mL) is being used and whether finely ground or coarsely ground bentonite is proposed.

Step 6 Design the final liner based on the results of step 5.

Example 10D–5—Design of a bentonite-treated liner

Given:

A waste storage pond is planned with a depth of liquid of 21 feet. The State requirement for the location is a specific discharge no greater than one-fifty-sixth of an inch per day of seepage. Assume the soils at grade have been tested and found to be suitable for bentonite treatment. Find the minimum thickness liner required according to CPS 521C, and determine the required permeability to meet this specific discharge requirement.

First, consult CPS 521C to determine the minimum required thickness. Assume the current CPS requires a liner that is 18 inches thick (1.5 ft).

Convert the specified unit seepage rate (specific discharge) of one-fifty-sixth of an inch per day into the same units as will be used for permeability (centimeters per second). To convert, use conversion values shown in table 10D–6, multiply:

$$v = \frac{1}{56}\ \text{in/d} \times 2.94 \times 10^{-5} = 5.25 \times 10^{-7}\ \text{cm/s}$$

The thickness of the liner and depth of liquid in the pond must also be converted to metric units. To convert the liner thickness of 18 inches to centimeters, multiply by 2.54, which equals a liner thickness, d, of 45.72 centimeters. The liquid depth, H, of 21 feet is equal to

$$H = 21\ \text{ft} \times 12\ \text{in/ft} \times 2.54\ \text{cm/in} = 640.1\ \text{cm}$$

Using the equation described previously, solve for the required permeability:

$$k = \frac{v \times d}{H + d}$$

$$k = \frac{5.25 \times 10^{-7}\ \text{cm/s} \times 45.72\ \text{cm}}{640.1\ \text{cm} + 45.72\ \text{cm}} = 3.5 \times 10^{-8}\ \text{cm/s}$$

The designer should coordinate with a soils laboratory to determine how much bentonite of given quality is required to obtain this low a permeability. In the experience of NRCS engineers, relying on this low a permeability means that construction quality control must be excellent and all the procedures and materials used are of highest quality. Seldom should designs for clay liners rely on a design permeability much lower than 5×10^{-8} centimeters per second. A designer might want to proceed with this design but require a slightly thicker liner (24 in) to provide additional assurance of obtaining the design specific discharge.

Considerations for protective cover

CPS 521C recommends considering the addition of a protective soil cover over the bentonite-treated compacted liner in waste impoundments. There are several reasons why a soil cover should be provided:

- Desiccation cracking of the liner after construction and prior to filling is a significant problem because the bentonite used in treatment is highly plastic.
- Desiccation cracking of the liner on the side slopes may occur during periods when the impoundment is drawn down for waste utilization or sludge removal. Desiccation cracking would significantly change the permeability of the liner. Rewetting generally does not completely heal the cracks.
- Bentonite-treated liners are generally thinner than compacted clay liners. Because the liner is thin, it can be more easily damaged by erosion from rainfall and runoff while the pond is empty. Rills in a thin liner provide a direct pathway for seepage.
- Over excavation by mechanical equipment during sludge removal can damage the liner. A minimum thickness of 12 inches measured normal to the slope and bottom is recommended for a protective cover. The protective cover should be compacted to reduce its erodibility.

Construction specifications for bentonite liner

The best equipment for compacting bentonite-treated liners is smooth-wheeled steel rollers, as shown in figure 10D–20. Crawler tractor treads are also effective. Sheepsfoot rollers that are often used in constructing clay liners are not as effective. CPS 521C specifies that for mixed layers, the material shall be thoroughly mixed to the specified depth with disk, rototiller, or similar equipment. In addition, intimate mixing of the bentonite is essential to constructing an effective liner. If a standard disk is used, several passes should be specified. A high-speed rotary mixer is the best method of obtaining the desired mix (fig. 10D–22). A minimum of two passes of the equipment is recommended to assure good mixing. When multiple passes of equipment are used for applying and mixing the bentonite, the passes should be in directions perpendicular to each other. This encourages a more homogeneous mixture.

Another construction consideration is the moisture condition of the soil into which the bentonite is to be mixed. Unless the soil is somewhat dry, the bentonite will most likely ball up and be difficult to thoroughly mix. Ideally, bentonite should be spread on a relatively dry soil, mixed thoroughly, then watered and compacted.

Depending on the type of equipment used, tearing of the liner during compaction can occur on slopes of 3H:1V or steeper. Compacting along, rather than up and down slopes, could be unsafe on 3H:1V or steeper side slopes. For most sites, slopes of 3.5H:1V or 4H:1V should be considered.

Bentonite-treated liners are often constructed in lifts that are 4-inch compacted thickness. Liners should be designed in multiples of 4 inches for this reason. Often, the first layer of bentonite-treated soil is the soil exposed in the bottom of the excavation. By applying bentonite to the exposed grade, disking it in to a depth of about 6 inches, and compacting it, the first layer is formed. Subsequent lifts are formed by importing loose fill adequate to form additional 4-inch-thick lifts.

Figure 10D–22 Pulvermixer (high-speed rotary mixer) *(Photo credit Stacy Modelski, NRCS)*



Design and construction of clay liners treated with soil dispersants

Previous sections of this appendix caution that soils in groups III and IV containing high amounts of calcium may be more permeable than indicated by the percent fines and PI values. Groups III and IV soils predominated by calcium usually require some type of treatment to serve as an acceptable liner. The most common method of treatment to reduce the permeability of these soils is use of a soil dispersant additive containing sodium.

Types of dispersants

The dispersants most commonly used to treat high calcium clays are soda ash (Na_2CO_3) and polyphosphates. The two most common polyphosphates are tetrasodium pyrophosphate (TSPP), and sodium tripolyphosphate (STPP). Common salt (NaCl) has been used in the past, but it is considered less permanent than other chemicals and is not permitted in the current CPS 521B. NRCS experience has shown that usually about twice as much soda ash is required to effectively treat a given clay when compared to the other two dispersants. However, because soda ash is often less expensive, it may be the most economical choice in many applications.

Design details for dispersant-treated clay liner

CPS 521B, Pond Sealing or Lining, Soil Dispersant, provides minimum thicknesses of liners using the dispersant-treated layer method, based on the depth of liquid in the pond. CPS 521B provides guidance on approximate rates of application of soil dispersants based on testing performed by the NRCS laboratories. Rates provided in the CPS are in terms of pounds of dispersant required per 100 square feet for each 6-inch layer of liner. The total amount of dispersant per 100 square feet is then equal to the number of 6-inch lifts in the completed liner multiplied by the rate per lift.

Example 10D–6—Steps in design of a dispersant-treated liner

Assume for the purposes of this example that a soil has been tested at a site and found to be a flocculated clay with an unacceptably high permeability. The designer chooses to evaluate a soda ash-treated liner. Consult the current CPS 521B for guidance on application rates for soda ash. Assume that the current CPS suggests an application rate of 15 pounds of soda ash per 100 square feet of liner for each 6-inch-thick lift of finished liner. Next, assume that based on the depth of water in the pond that the CPS 521B requires a total liner thickness of 12 inches. Then, because each 6-inch-thick lift requires 15 pounds of soda ash per 100 square feet, the total amount of soda ash required for this example would be 30 pounds of soda ash per 100 square feet. The most up-to-date CPS 521B should always be consulted for recommended rates, in case they have changed since this document was written.

The recommended rates of application of dispersants in CPS 521B are based on the most up-to-date information from the NRCS soils testing laboratories. The rates are in general conservative, and if a designer wanted to evaluate lower rates of application, samples should be obtained and sent to a laboratory for documenting the efficacy of lower rates. If this procedure is followed, the following steps are usually implemented.

Step 1 Obtain a sample of the soil to which the dispersant is to be added. Have the sample tested in a soils laboratory to determine its basic index properties, including percent fines and plasticity.

Step 2 A standard Proctor (ASTM D698) test is performed to determine the maximum dry density and optimum water content.

Step 3 From the preliminary design of the site, determine the depth of water in the structure and use CPS 521B to determine the minimum thickness of liner required.

Step 4 Using given or assumed values for allowable specific discharge, compute the required permeability of the dispersant-treated liner.

Step 5 Coordinate with a soils laboratory on testing to determine what degree of compaction, water content, and rate of application of the proposed additive is required to obtain this permeability. Consider local practice and consult sup-

pliers to determine the relative costs of soda ash versus polyphosphates.

Step 6 Design the final liner based on the results from previous steps.

Example 10D–7—Comprehensive example for a dispersant-treated liner

Given:

A waste storage pond is planned with a depth of liquid of 18 feet. The State requirement for the location is a specific discharge no greater than 2,000 gallons per acre per day of seepage. Assume the soils at grade have been tested and found to require dispersant treatment. Assume that the current CPS 521B requires a minimum liner thickness of 1.5 feet. The example problem is to determine what permeability is required to meet the stated specific discharge requirement.

Solution:

First, the required specific discharge value, which is given in units of gallons per acre per day has to be converted the same units that will be used for required permeability. Assume that permeability will be expressed in centimeters per second, so use table 10D–6 to convert the value of 2,000 gallons per acre per day to centimeters per second as follows:

$$v = \frac{2{,}000 \text{ gal/acre/d}}{9.24 \times 10^{8}} = 2.2 \times 10^{-6} \text{ cm/s}$$

Next, convert the liner thickness and depth of liquid from units of feet to centimeters:

$$d = 18 \text{ in} \times 2.54 \text{ cm/in} = 45.72 \text{ cm}$$

$$H = 18 \text{ ft} \times 12 \times 2.54 \text{ cm/ft} = 548.64 \text{ cm}$$

Using the equation described previously, solve for the required permeability:

$$k = \frac{v \times d}{H + d}$$

$$= \frac{2.2 \times 10^{-6} \text{ cm/s} \times 45.72 \text{ cm}}{548.64 \text{ cm} + 45.72 \text{ cm}}$$

$$= 1.7 \times 10^{-7} \text{ cm/s}$$

The designer should coordinate with a soils laboratory to determine how much soil dispersant of the desired type is required to obtain this low a permeability. In the experience of NRCS engineers, obtaining this value of permeability using a soil dispersant should not require special effort or unusual amounts of additive. At the same time, seldom should designs for dispersant-treated clay liners rely on a design permeability much lower than 5×10^{-8} centimeters per second. A designer should proceed with this design specifying the application rate recommended by the soils lab and a 1.5-foot-thick liner to obtain the design specific discharge.

Construction specifications for a dispersant-treated clay liner

The best equipment for compacting clays treated with dispersants is a sheepsfoot or tamping type of roller. CPS 521B specifies that the material shall be thoroughly mixed to the specified depth with a disk, high speed rotary mixer, or similar equipment. Because small quantities of soil dispersants are commonly used, uniform mixing of the dispersants is essential to constructing an effective liner. If a standard disk plow is used, several passes should be specified. A high-speed rotary mixer is also essential to obtain a thorough mixture of the dispersant with the clay being amended. Figure 10D–23 shows this type of equipment. At least two passes of the equipment is recommended to assure good mixing.

Other construction considerations are also important. Using the bathtub method of construction on slopes of 3H:1V or steeper can cause tearing of the liner during compaction and reduce the effectiveness of compac-

Figure 10D–23 High-speed rotary mixer used to mix dispersants into clays (*Photo credit Jody Kraenzel, NRCS*)



tion equipment. Slopes as flat as 3.5H:1V or 4H:1V should be considered for this factor alone, for bathtub type construction.

Current CPSs usually require a liner thicker than 6 inches. A liner generally can be satisfactorily constructed in a series of lifts by mixing in the required amount of soil dispersant to a 9-inch-thick loose depth and then compacting it to the 6 inches. Thicker liners should be constructed in multiple lifts, with the final compacted thickness of each lift being no greater than 6 inches.

Uplift pressures beneath clay blankets

A clay blanket may be subject to uplift pressure from a seasonal high water table in the foundation soil underneath the clay liner. The uplift pressure in these cases can exceed the weight of the clay liner, and failure in the clay blanket can occur (fig. 10D–24). This problem is most likely to occur during the period before the waste impoundment is filled and during periods when the impoundment may be emptied for maintenance and cleaning. Figure 10D–25 illustrates the parameters involved in calculating uplift pressures for a clay blanket. The most critical condition for analysis typically occurs when the pond is emptied. Thicker blankets to attain a satisfactory safety factor should be used if they are required.

Figure 10D–24 Failure of compacted liner from uplift forces below clay blanket *(Photo credits NRCS, TX)*





Figure 10D–25 Uplift calculations for high water table and clay blanket (from Oakley 1987)

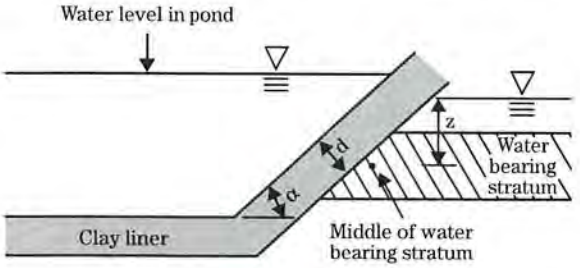

The factor of safety against uplift is the ratio of the pressure exerted by a column of soil to the pressure of the ground water under the liner. It is given by the equation:

$$FS = \frac{\gamma_{sat} \times d \times \cos(\alpha)}{z \times \gamma_{water}}$$

where:

- d = thickness of liner, measured normal to the slope
- α = slope angle
- γ_{water} = unit weight or density of water
- γ_{sat} = saturated unit weight of clay liner
- z = vertical distance from middle of clay liner to the seasonal high water table

A factor of safety of at least 1.1 should be attained. The safety factor can be increased by using a thicker blanket or providing some means of intercepting the ground water gradient and lowering the potential head behind the blanket. Often, sites where seasonal high water tables are anticipated designs include a perimeter drain to collect the water and prevent this type of damage. Another option is a concrete structure above ground.

Another situation where a clay liner may be damaged from hydrostatic pressure is one where a site is located in a flood plain of a stream or river. The site may have to be built above ground level in this location to avoid a seasonal high water table. Figure 10D–26 illustrates the problem that may occur that must be considered by designers. A temporary flood condition in the flood plain can subject the agricultural waste impoundment to a differential head when the pond is empty. The pond could be empty shortly following construction or it could be empty to apply waste to crops. Uplift pressure may cause piping of sandy horizons underlying the site and boils, and sloughing of side slopes can occur as shown in figure 10D–26. The photo shows a clay-lined animal waste impoundment where the clay liner was damaged from excessive hydrostatic uplift forces caused by temporary storage of flood waters outside the embankment. The liner must be thick enough to resist predicted buoyant forces if it is possible for the pond to be empty or near empty during a flood. Drains will be ineffective because in a flood, outlets will be submerged.

Figure 10D–26 Uplift conditions caused by temporary flood stage outside lagoon (*Photo credit NRCS, WA*)

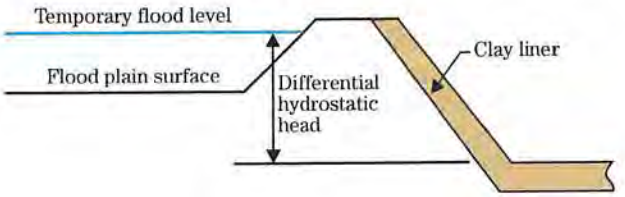





Perimeter drains for animal waste storage ponds

When a high water table is anticipated and uplift pressures are anticipated, one approach to solving the problem is to install a drain around the pond. The drain may completely encircle the pond if a designer anticipates a general elevated water table in the site vicinity. At other sites with a more sloping ground surface, the perimeter drain may only be installed on the side(s) of the impoundment where the elevated water table is anticipated. Drains may be used both for clay liners and geosynthetic liners.

Drains usually are constructed by

- digging a trench to the depth needed to draw down the water table
- placing a perforated or slotted drainage pipe
- surrounding the drain with granular material that is compatible with both the slot size in the pipe and the gradation of the surrounding foundation soils

Pipes with small slots that are compatible with a filter sand like ASTM C–33 are preferred to avoid having to use two filter gradations. If pipes with larger perforations are used, they should be surrounded with gravel to prevent particles from moving into the pipe. Figure 10D–27 (a, b, and c) show typical installations where a single filter and perforated pipe is used. Another approach to installing a drain is to dig a trench, line it with geotextile, and after putting a slotted collector pipe in the trench, filling it with gravel. Figure 10D–28 shows this type of installation.

Several types of drain pipe may be used. One type is a low strength corrugated pipe with slots or perforations surrounded by a filter envelope of granular material. Figure 10D–29 is an example of this type of collector pipe. If a higher strength pipe is required, figure 10D–30 shows another type of pipe that is sometimes used for these types of installations.

Figure 10D–27 Typical drain installations using single filter with well-screened collector pipe

(a)

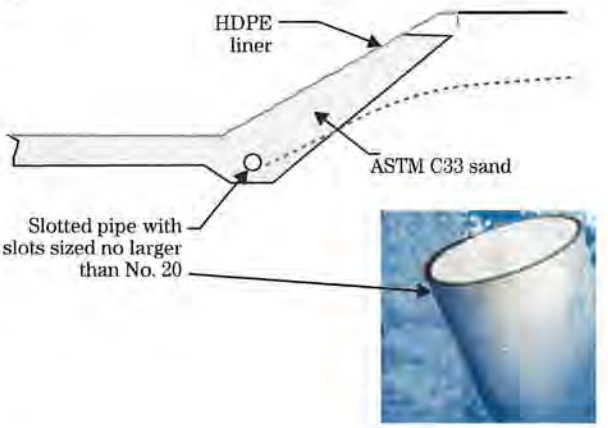

(b)

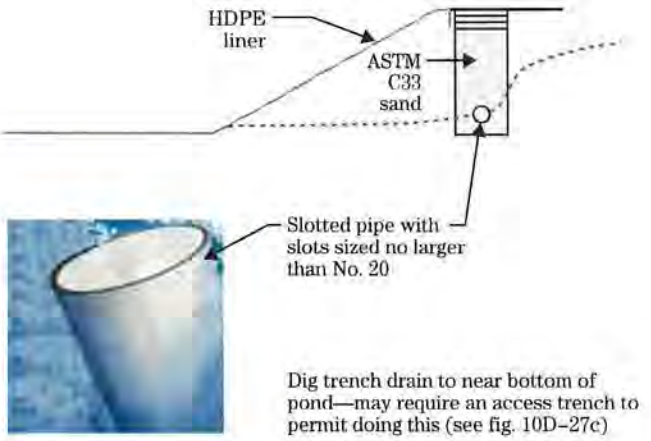

(c)

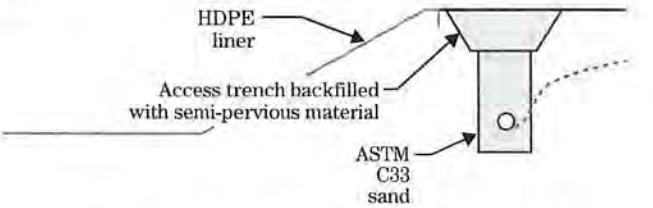

Illustrated access trench construction to permit installing deeper trench drain. Access trench filled with semi-pervious soil to limit infiltration of surface runoff.

Figure 10D–28 Perforated collector pipe installed the gravel envelope with trench lined with geotextile



Figure 10D–29 Low-strength perforated drainage tubes



Figure 10D–30 Corrugated drainage pipe with slots, doubled walled pipes may be specified if higher strengths are needed



Soil mechanics testing for documentation

Laboratory soil testing may be required by regulations for design, or a designer may not choose to rely on correlated permeability test values. The NRCS National Soil Mechanics Center Laboratories have the capability to perform the necessary tests. Similar testing is also available at many commercial labs. The accepted method of permeability testing is by ASTM Standard Test Method D5084, Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. Figure 10D–31 shows the equipment used for performing the test.

Contact the labs for more detailed information on documentation needed and for procedures for submitting samples.

Figure 10D–31 Equipment used for performing ASTM D5084



Molding a sample for a flexible wall permeability test



Disassembled mold with compacted specimen



Preparing sample in cell for flexible wall permeability test

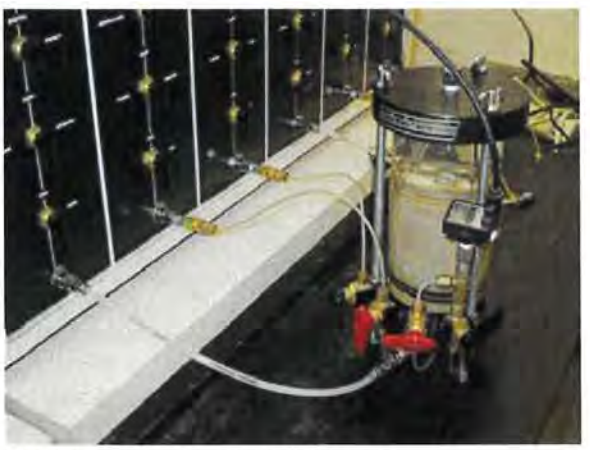

Molded sample after dissembling mold

If the only tests requested are gradation and Atterberg limit tests, smaller samples are needed. The size of sample that should be submitted depends on the gravel content. The following recommendations should be adhered to:

Estimated gravel content of the sample 1/ (%)	Sample moist weight (lb)
0–10	5
10–50	20
>50	40

1/ The sample includes the gravel plus the soil material that passes the No. 4 sieve (approx. 1/4-inch mesh).

If gradation analysis, Atterberg limits, compaction, and permeability testing are requested, considerably larger samples are required. When all these tests are needed, the sample size should be as follows:

Estimated gravel content of the sample 1/ (%)	Sample moist weight (lb)
0–10	50
10–50	75
>50	100

1/ The sample includes the gravel plus the soil material that passes the No. 4 sieve (approx. 1/4-inch mesh).

Submitting samples at their natural water content is important so designers can compare the natural water content to reference compaction test values. Samples should always be shipped in moisture proof containers for this reason. The best container for this purpose is a 5-gallon plastic pail commonly obtained in hardware stores. These pails have tight fitting lids with a rubber gasket that ensures maintenance of the water content in the samples during shipping. These 5-gallon pail containers are much more robust and less likely to be damaged during shipment than cardboard containers.

If designs rely on a minimum degree of compaction and water content to achieve stated permeability goals in a clay liner, testing of the clay liner during construction may be advisable to verify that design goals have been achieved. Field density and water content measurements are routinely made using procedures shown in NEH, Section 19, Construction Inspection.

Other methods for documenting liner seepage

Performing density/water content tests during construction is a generally accepted method of documenting that a clay liner has been constructed according to specifications. If the liner is found to meet the requirements of the compaction specifications, the assumption is that the permeability values documented from laboratory testing on samples that were compacted at the specified density and water content will be achieved. In some cases, no additional documentation is required. In other cases, regulations require obtaining samples of the completed liner and performing permeability tests on them. Figure 10D–32 shows one way that a Shelby tube type of sample may be obtained without mobilizing a drilling rig. The Shelby tube used is typically a standard tube with a 3-inch outside diameter and 2 7/8-inch inside diameter. This size sample can be placed directly in a flexible wall permeameter for testing, after extrusion in the laboratory.

Another method for obtaining a sample of a compacted clay liner is with a drive sampler like that shown in figure 10D–33.

Figure 10D–32 Shelby tube sample being obtained with backhoe bucket used to force tube into clay liner *(Photo credit Jody Kraenzel, NRCS, NE)*



Figure 10D–33 Obtaining undisturbed sample of compacted clay liner using thin-walled drive cylinder







In the situation where a storage pond was constructed several years before documentation on quality of construction and permeability was required, studies are sometimes made in an attempt to measure seepage losses directly. One approach that has been used was developed by researchers at Kansas State University. This approach involves installing precise water level monitoring devices and evaporation stations. Seepage losses can be estimated by carefully monitoring the levels in the pond during periods when no waste is introduced into the pond and no rainfall occurs. After estimating the amount of evaporation, and subtracting that from the total decline in the level of the pond during that period, seepage loss can be estimated. Figure 10D–34 shows equipment for measuring evaporation in a pond.

Figure 10D–34 Equipment used to monitor evaporation at an agriculture waste storage lagoon. Measurements are used in total lagoon seepage evaluations.



Summary

- The reduction in the quantity of seepage that occurs as manure solids accumulate in the bottom and on the sides of storage ponds and treatment lagoons is well documented. However, manure sealing is not effective for soils with a low clay content. Its effectiveness is not accepted by all designers and cannot be used in the designs of storage ponds by some State and local regulations.
- Soils can be divided into four permeability groups based on their percent fines (percent finer than the No. 200 sieve) and plasticity index (PI). Soils in groups III and IV may be assumed to have a coefficient of permeability of 1×10^{-6} centimeters per second or lower unless they have an unusual clay chemistry (high calcium), or they have a very blocky structure.
- Group I soils will generally require a liner. Soils in group II will need permeability tests or other documentation to determine whether a desirable permeability rate can be achieved for a particular soil.
- If natural clay blankets are present at a site below planned grade of an excavated pond, the seepage rate should be estimated based on measured or estimated permeability values of the low permeability horizons beneath the liner and above an aquifer. If the estimated seepage rate is less than that given in NRCS guidance or State regulations, no special compacted liner may be required. If the soils at grade are not of sufficient thickness and permeability to produce a desirably low seepage rate, a liner should be designed to achieve the seepage rate that is the design goal.
- Guidance is given on factors to consider whether a constructed liner may be required. Four conditions are listed in which a liner should definitely be considered.
- Allowable specific discharge values are discussed and guidance is provided on reasonable values to use for design when other regulatory requirements are not specified.
- Flexibility is built into the design process. The depth of the liquid, the permeability, and thickness of the soil liner can be varied to provide an acceptable specific discharge.
- The guidelines provided for design of clay liners in this appendix provide designers with the tools to evaluate the probable unit seepage or specific discharge through a clay liner. The methods presented allow a designer to determine what treatment is required to achieve specific discharge or permeability goals.
- Methods provide designers with the ability to evaluate the effect of changes in a proposed design on the estimated unit seepage rate.
- As additional research becomes available, practice standards and guidance in this document may warrant revision.

References

Albrecht, B.A., and C.H. Benson. 2001. Effect of desiccation on compacted natural clays. *In* J. of Geotechnical and Geoenvironmental Engineering. pp. 67–75.

Barrington, S.F., P.J. Jutras, and R.S. Broughton. 1987a. The sealing of soils by manure: I. Preliminary investigations. Canadian Agric. Eng. 29(2):99–103.

Barrington, S.F., P.J. Jutras, and R.S. Broughton. 1987b. The sealing of soils by manure: II. Sealing mechanisms. Canadian Agric. Eng. 29(2):105–108.

Benson, C.H., and G.P. Boutwell. 2000. Compaction conditions and scale-dependent hydraulic conductivity of compacted clay liners. *In* Constructing and Controlling Compaction of Earth Fills. ASTM STP 1384, D.W. Shanklin, K.R. Rademacher and J.R. Talbot, eds. American Society for Testing and Materials, West Conshohocken, PA.

Benson, C.H., and M. Othman. 1993. Hydraulic conductivity of compacted clay frozen and thawed *in situ*. *In* J. of Geotechnical Engineering, Amer. Soc. of Civil Eng. Vol 119, No. 2. pp. 276–294.

Boutwell, G., and C.L. Rauser. 1990. Clay liner construction. Amer. Soc. of Civil Eng./Penn DOT Geotechechnical Seminar. Hershey, PA.

Daniel, D.E. 1993. Compacted clay liners and covers for arid sites. *In* J. of Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol. 119, No. 2. pp. 223–237.

Daniel, D.E., and C.H. Benson. 1990. Water content-density criteria for compacted soil liners. *In* Journal of Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol. 116, No. 12. pp. 1811–1830.

Daniel, D.E., and Yung-Kwang Wu. 1993. Compacted clay liners and covers for arid sites. *In* J. of Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol. 119, No. 2, pp. 223–237.

Ham, J.M., and T.M. Desutter. 1998. Seepage losses from swine-waste lagoons: a water balance of study. Evaluation of Lagoons Containment of animal waste. Kansas State University. Manhattan, KS. 3.2–3.19

Hermann, J.G., and B.R. Elsbury. 1987. Influential factors in soil liner construction for waste disposal facilities. Proc. Geotechnical Practice for Waste Disposal. Amer. Soc. of Civil Eng., Ann Arbor, MI. pp. 522–536.

Kansas State University. 2000. Animal waste lagoon water quality study. Ham, J.M., L.N. Redd, and C.W. Rice. Manhattan, KS.

Kim, W., and D. Daniel. 1992. Effects of freezing on hydraulic conductivity of compacted clay. *In* J. Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol. 118, No. 7.

Kleppe, J.H., and R.E. Olson. 1985. Desiccation cracking of soil barriers. ASTM Special Technical Publication 874, Hydraulic Barriers in Soil. Philadelphia, PA. pp. 263–275.

Lambe, T.W. 1958. The structure of compacted clay. *In* J. of the Soil Mechanics and Foundation Division, Amer. Soc. of Civil Eng., Vol. 84, No. Soil Mechanics 5, pp. 1654–1 to 1654–34.

Mitchell, J.K., D.R. Hooper, and R.G. Campanella. 1965. Permeability of compacted clay. J. Soil Mechanics and Foundation Div., Amer. Soc. of Civil Eng.. Vol. 91, No. 4. pp. 41–65.

Oakley, R. 1987. Design and performance of earth-lined containment systems. Amer. Soc. of Civil Eng. Conf. Geotech. Prac. Waste Disposal, p. 117–136.

U.S. Department of Agriculture, Natural Resources Conservation Service. 1994. Guide for determining the gradation of sand and gravel filters. National Engineering Handbook, Part 633, Chapter 26.

U.S. Department of Agriculture, Soil Conservation Service. 1970. TR–28 Clay Minerals.

Survey of Nitrogen Fertilizer Use on Corn in Minnesota

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In accordance with the Americans with Disibilities Act, an alternative form of communication is available upon request. TDD: 1-800-627-3529. Minnesota Department of Agriculture is an equal opportunity employer and provider.

Executive Summary

A survey was conducted in the spring of 2010 to characterize the use of nitrogen (N) fertilizer on field corn by Minnesota farmers in the 2009 growing season. Detailed information on N fertilizer management practices was collected from interviews with 1496 farmers distributed across all of the corn growing regions in the state. Their total corn acreage represented about 7% of the corn acres harvested in Minnesota in 2009. This report summarizes data on: 1) N fertilizer rates, 2) Major N sources, 3) Application timing of the major N source, 4) Use of nitrification inhibitors, additives, and specialty N fertilizer formulations, 5) Fertilizer placement and incorporation practices, 6) Use of starter fertilizer, split and sidedress applications, and other N sources such as ammonium phosphates, 7) N fertilization of irrigated corn, and 8) Use of soil testing as a fertility management tool. Many of the survey results are reported as statewide averages, but where regional differences occurred the data are broken down and presented separately for different parts of the state. This survey provides the most comprehensive set of data on N fertilizer use on corn that has been collected in Minnesota. The information can be used to target research and education programs to improve N management for both production and environmental goals. Overall results indicate that N fertilizer use by Minnesota corn farmers is generally consistent with University of Minnesota Extension N management guidelines.

Introduction

A farmer survey of nitrogen (N) fertilizer use on field corn in Minnesota was conducted as part of a research project investigating emissions of the greenhouse gas nitrous oxide (N_2O) from agricultural soils and the contribution of N fertilizers as a source of N for these emissions. The project was carried out by scientists from the USDA-Agricultural Research Service Soil & Water Research Management Unit, the Department of Soil, Water, & Climate at the University of Minnesota, and University of Minnesota Extension. Funding was provided by the USDA National Research Initiative Competitive Grants Program (NRI). Objectives of the project were to:

1. Develop improved methods and protocols for monitoring direct and indirect N_2O emissions from fertilized soils,
2. Quantify the effectiveness of alternative agricultural management practices for mitigating N_2O emissions and related N losses, and
3. Disseminate information obtained from the above activities to agricultural producers, industry, conservation officials, and other stakeholders that encourages improved management practices to reduce impacts on air quality.

The N-use survey was designed to support Objective #3 and collect current information on N management practices with respect to: 1) application rates (lb N/acre), 2) timing (fall or spring, single or multiple applications), 3) method (surface or subsurface), and 4) chemical form. Knowledge of current N management practices was necessary to form a basis for developing effective educational tools, decision-support tools, and Extension programs to improve N management. The survey was restricted to N management on corn because corn is the most widely grown crop in Minnesota that requires N application and the majority of the N fertilizer applied in the state is used in corn production. Project personnel collaborated with the

Minnesota Department of Agriculture (MDA) to develop survey questions and MDA worked with the USDA National Agricultural Statistics Service (NASS), Minnesota Field Office to conduct the survey. This survey was supported by the MDA using dollars provided by the Clean Water Fund (from the Clean Water, Land and Legacy Amendment).

Survey Methods

Farmers in the survey were from a database of the Minnesota Field Office of NASS. An initial pool of 7,000 farmers was randomly selected by NASS from their database of about 31,000 Minnesota farmers who have recently grown corn. The survey was carried out through phone interviews conducted at the North Dakota Field Office of NASS in Fargo. Interview staff were the same experienced interviewers that are routinely used to perform the regular surveys conducted by NASS. The survey consisted of 42 questions and it took about one-half hour to complete the interview with farmers who were able to finish the entire survey. Interviews and follow-up calls necessary to clarify some of the responses were conducted between February and June of 2010.

Interviewers were able to contact 4,461 of the initial pool of 7,000 farmers. Those not contacted were called more than once, but failed to answer the phone. Of the farmers contacted, 3,358 grew corn in 2009. The 2,769 farmers who continued the interview grew corn on 656,312 acres in 2009. Manure had been applied to 32% of these acres in the previous five years. The focus of the survey was use of manufactured N fertilizers, so to avoid the complicating effects of previous manure application on N fertilizer rates the farmers were asked to report on an average field with no manure applied in the last five years. The 866 farmers who did not have a field where no manure had been applied in the last five years were eliminated. Also eliminated were 407 of the remaining farmers who did not have a field where they knew the total amount of N applied per acre. This left 1,496 farmers, who grew corn on 482,812 acres in 2009. The survey results reported below are from this subsample of Minnesota corn farmers.

There were survey participants from 74 of Minnesota's 87 counties and they were distributed across all of the major corn growing regions in the state (Fig. 1). Their total corn acreage represents about 6.8% of the 7.15 million corn acres harvested in Minnesota in 2009 (NASS Minnesota Field Office, 2010). The number of corn acres on surveyed farms was different than the distribution of corn acres reported for all Minnesota farms growing corn in 2007 (Table 1). About 44% of surveyed farms grew more than 250 acres of corn, compared with 31% of all Minnesota corn farms in the 2007 Census of Agriculture (NASS, 2009). This suggests that surveyed farms were slightly larger than the state-wide average, although some of the difference could have been due to increases in farm size between 2007 and 2009.

Before interviewers began asking the series of questions on specific aspects of N fertilizer use, they instructed farmers to "think about an average corn field you planted in 2009 with no manure or compost applied in the last five years" and to answer questions in relation to that specific field. If fertilizer was applied at more than one rate or at a variable rate in this field, they were asked to report a field average rate. Therefore, responses of individual farmers in this survey represent their "average" or "typical" N management practices. In some cases farmers may have

strayed from the "average field" restriction, especially as the interview progressed, and some of their answers may have reflected the entire range of the N management options they employed.

All data in this report are expressed as averages among the participating farmers for the individual fields they are reporting on. They are averages among these fields and data are not adjusted to account for differences in field size. Data analysis also does not reflect differences among the farmers in their total acreage of corn.

Many of the survey results are reported as statewide averages, but where regional differences occurred the data are broken down and presented separately for different parts of the state. For this purpose, the state was divided into the regions defined in the publication *Best Management Practices for Nitrogen Use In Minnesota* (Lamb et al., 2008) These divisions are based on geographic differences in soil parent material and climate. There are five regions: 1) Northwestern, 2) Coarse-textured Soils, 3) Southwestern and West Central, 4) South Central, and 5) Southeastern. The regions are mapped in Fig. 1. The original publication used the term "Irrigated and Non-irrigated Sandy Soils" for one of the regions, which is changed to "Coarse-textured Soils" in this report.

Survey Results

The average size of the corn fields reported on by farmers in this survey was 81 acres. The average yield of these fields over the previous three corn crops was 159 bushels/acre (Table 2).

Average N rates

The overall average N fertilizer rate for all surveyed fields was 140 lb N/A (Table 2). Average rates varied across the different BMP regions of the state, ranging from 129 to 146 lb N/A. The lowest rates were in the Northwestern and Coarse-textured Soils regions and the highest average N rate was in the South Central region. Differences in N rates for the different regions may have been caused by differences in productivity potential. Average yields for the previous three corn crops in the surveyed fields ranged from 127 to 174 bu/A across the different BMP regions (Table 2) and there was a strong correlation between previous corn yield and average N rate ($r = 0.98$). The productivity potential of the soil is an important factor in the determination of University of Minnesota Extension N rate guidelines (Rehm et al., 2006). For a crop of corn following corn in a year with an N price to crop value ratio of 0.10, the maximum return to N fertilizer on a highly productive soil would occur at a rate of 140 lb N/A. Under the same conditions, the maximum return to N fertilizer on a soil with medium productivity would occur at a rate of 120 lb N/A.

The effect of productivity potential on N fertilizer rate is evident in the differences between irrigated and non-irrigated corn fields in the Coarse-textured Soils region (Table 2). Average yield for the previous three corn crops was 36 bu/A greater in irrigated fields than in non-irrigated fields and the average N rate was 24 lb N/A greater. About 8.1% of the surveyed corn fields in the Coarse-textured Soils region were irrigated.

The amount of N fertilizer applied varied with the preceding crop (Table 3), although differences were not as great as might have been expected. For corn following soybeans, which accounted for about 75% of all fields in the survey, the state-wide average N rate was 140 lb N/A. When corn followed corn, the average N rate was 145 lb N/A. These results suggest that many farmers did not take full advantage of the N supplying capacity of soybeans. Soybeans are a leguminous crop capable of fixing atmospheric N, and N requirements for corn are commonly about 30 lb N/A lower following a healthy soybean crop (Rehm et al., 2006). Another possibility is that farmers were not as aggressive in choosing N rates for corn following corn as they were for corn following soybeans, and that they did not apply enough N to corn following a previous corn crop.

Alfalfa is a legume with an even greater capacity to fix N than soybeans and N requirements for corn following alfalfa are frequently less than the average N rates of 97 lb N/A for the first year of corn, and 129 lb N/A for the second year of corn, found in this survey. Following alfalfa crops with good to excellent stands, University of Minnesota guidelines suggest an N credit of 100 to 150 lb N/A for 1st year corn and 50 to 75 lb N/A for 2nd year corn (Rehm et al., 2006). This survey included only 30 fields of 1st year corn following alfalfa, and 30 fields of 2nd year corn following alfalfa, so survey results may have been skewed by factors such as a higher than normal number of fields where the alfalfa stand was poor. The methods used to conduct the survey may also have caused N rates for corn following alfalfa to be underestimated. Fields that did not receive any N fertilizer were not included in the survey, so corn following an excellent stand of alfalfa that could supply all of the N needed by the crop would have been excluded. Therefore, no zero N fertilizer fields were used to calculate the average N rate for corn following alfalfa, but it is not known how many fields like this were included in the survey sample.

The average N rate for corn following a crop other than soybeans, corn, or alfalfa was 131 lb N/A. The survey did not provide information on what was included in the category “Other”, so it is not clear why the average N rate was lower than for corn following corn or soybeans. It may have resulted from the fact that 63% of the fields where corn followed “Other” crops were in the Northwestern and Coarse-textured Soils regions, which had the lowest average N rates (Table 2).

For 23% of farmers the field they reported on was fertilized using variable rate application methods, so the N rate they reported for the survey was an average for the field. When asked whether they applied the same amount of N on all fields with similar crop rotations and no manure applied in the last five years, 29% of the farmers reported that they used different N rates on some fields.

The overall average N fertilizer rate of 140 lb N/A found in this survey was similar to the statewide average of 139 lb N/A reported by NASS for the 2005 crop year in their most recent survey of N fertilizer use in Minnesota (NASS, 2006). Both of these rates were greater than the average N rates of 108 to 122 lb N/A reported by NASS for Minnesota in the five-year period from 1999 to 2003 (NASS, 2000-2004). The surveys by NASS did not exclude fields where both manure and commercial N fertilizer were applied, which would probably result in lower average N rates than a survey like the one reported on here where manured fields were excluded.

Major N sources

Anhydrous ammonia and urea were the most commonly used chemical forms of N (Fig. 2). About 91% of survey participants used one of these fertilizers to apply the majority of the N used on their average field. Anhydrous ammonia was used by 46.3% of the farmers, while 44.9% used urea. Liquid N products, defined by the survey as UAN (urea-ammonium nitrate) solutions, were the major N source for about 6.5% of the farmers. The remaining 2.4% of the farmers either used another fertilizer as their major N source or did not know the major source of N applied to their typical field. The survey did not ask for additional information on what may have been included in the category "Other" for the major N source.

The major N source varied across the different BMP regions (Figs. 3 to 7). Urea was the dominant N source in the Northwestern (79%) and the Coarse-textured Soils (67%) regions, where only about 20% of farmers used anhydrous ammonia as their major N source. The greatest use of anhydrous ammonia was in the South Central region (64%), where urea was used as the major N source by about 29% of the farmers. The second highest rate of anhydrous ammonia use was in the Southwestern and West Central region (48%), where nearly as many farmers (43%) used urea as their major N source. In the Southeastern region, 55% used urea as their major N source and 35% used anhydrous ammonia. The Southeastern region had the greatest use of liquid N fertilizers with 9% of the farmers using them as their major N source. None of the surveyed farmers in the Northwestern region used liquid N as the major N source on the average field they reported on.

The three major N sources tended to be applied at different rates, with differences in both the amount of N applied from the major N source and the total N rate after including all N applications (Table 4). Average N rates (state-wide) from the three major sources were 132 lb N/A from anhydrous ammonia, 123 lb N/A from urea, and 113 lb N/A from liquid N. Total N rates were 146 lb N/A when anhydrous ammonia was the major N source, 136 lb N/A when urea was the major N source, and 131 lb N/A when liquid N was the major N source. Differences in N rate were probably affected by differences in the price of N among the three major N sources. The cost per unit of N is highest for liquid N, lowest for anhydrous ammonia, and intermediate for urea. As the price of N goes up, the N rate providing the maximum economic return goes down (Rehm et al., 2006).

Another factor in the greater N rates for anhydrous ammonia compared with urea may have been differences in productivity potential of the fields involved. Average yields for the previous three corn crops were 168 bu/A for the fields fertilized in 2009 with anhydrous ammonia and 152 bu/A for the fields fertilized with urea. Differences in productivity potential were not a factor in the fields fertilized with liquid N having the lowest N rates, since their average yield for the previous three corn crops was 162 bu/A.

Application timing of the major N source

About 59% of the surveyed farmers applied the majority of their N fertilizer in the spring, 32.5% did their main N application in the fall, and about 9% used sidedress (beside the row after plant emergence) applications for the majority of their N (Fig. 8). For sidedress applications, the

survey did not ask whether the major N source was applied in a single application or in a series of split sidedress applications.

Application timing varied considerably, depending on the major N source. Anhydrous ammonia was applied 63% of the time in the fall and 28% of the time in the spring (Fig. 9), whereas urea was applied 90% of the time in the spring and only 4% of the time in the fall (Fig. 10). For farmers using liquid N as their major N source, 7% made fall applications, 71% made spring applications, and 23% made sidedress applications (Fig. 11).

Application timing of the major N source also varied across the different BMP regions of the state (Fig. 12). Spring N applications dominated in the Northwestern (89%), Coarse-textured Soils (70%), and Southeastern (88%) regions, fall and spring applications were equally common in the Southwestern & West Central region (about 47%), and in the South Central region 43% of surveyed farmers made their major N application in the fall and 53% in the spring. Sidedressing the major N source was most common in the Coarse-textured Soils region (25%), was not used at all in the Northwestern region, and was used by 4 to 7% of surveyed farmers in the other three regions.

Application timing is an important criteria differentiating BMPs for N use in various parts of Minnesota. In the Coarse-textured Soils and Southeastern regions, which have the highest leaching potential, fall application is not a recommended practice for any of the N sources (Rehm et al., 2008a; Randall et al., 2008a). About 5% of surveyed farmers in both of these regions made their major N application in the fall (Fig. 12), primarily as anhydrous ammonia, so there is some potential for increasing NUE in these regions by eliminating this practice. This potential may be limited in the Coarse-textured Soils region, where some of the fall N was probably applied to finer-textured soils present in the region.

In the South Central region, less than 5% of urea and liquid N applications were in the fall, but 63% of anhydrous ammonia was fall-applied. Fall N application is not a recommended BMP in this region (Randall et al., 2008b), although fall application of anhydrous ammonia is an acceptable practice if it includes a nitrification inhibitor. Use of nitrification inhibitors is discussed in the next section.

Use of N-Serve® with anhydrous ammonia

N-Serve® is a nitrification inhibitor that can be applied with anhydrous ammonia to delay the conversion of ammonium-N to nitrate-N. This can reduce N losses from nitrate leaching or denitrification. Overall, about 20.8% of the farmers applying anhydrous ammonia used N-Serve® (Table 5). The additional cost of applying N-Serve® may be a barrier to more widespread use, but there were important regional differences and differences related to the timing of anhydrous ammonia application.

Use of N-Serve® was most common in the South Central BMP region, where it was included with 35.1% of all anhydrous ammonia applications. It was used with about 15.6% of the anhydrous ammonia applications in the Southeastern region, 15.6% in the Coarse-textured Soils region, 6.7% in the Southwestern and West Central region, and 0% in the Northwestern region.

The risk of N loss is greatest with fall application, because of the long time period between N application and crop uptake, and use of N-Serve® was most common in the fall. N-Serve® was included with 28.6% of anhydrous ammonia applications made in the fall, 7.4% of spring applications, and 8.3% of sidedress applications (Table 5). Over 95% of the fall anhydrous ammonia applications were in the South Central or the Southwestern and West Central regions, but there were large differences in the use of N-Serve® between these two regions. N-Serve® was included with 51.1% of fall anhydrous ammonia applications in the South Central region and only 6.6% of fall applications in the Southwestern and West Central region. This is consistent with greater rainfall and greater potential for leaching and gaseous N losses in the South Central region and University of Minnesota Extension best management practices for N use (Randall et al., 2008b; Rehm et al., 2008b).

Use of additives and specialty formulations of urea or liquid N fertilizers

There are a number of additives and specialty formulations of urea and urea-containing liquid N fertilizers that are designed to reduce N loss. Volatilization losses of ammonia-N can occur after breakdown of urea by the enzyme urease. As with anhydrous ammonia, N losses from nitrate leaching or denitrification can occur after nitrification of ammonia/ammonium-N to nitrate-N. Gaseous N losses can also occur during nitrification itself. Products to delay these reactions and reduce the potential for N losses were used by only 8.3% of the farmers who applied urea or liquid N fertilizers as their major N source (Fig. 13). Agrotain®, a urease inhibitor that can be combined with dry urea or liquid N fertilizers, was the most commonly used additive; but it was used by only 4.2% of the farmers who applied these fertilizers. Nutrisphere® contains a water soluble polymer that is intended to protect against N losses from both volatilization and leaching. It can also be combined with both dry urea and liquid N fertilizers, but it was used by only 1.1% of the farmers who applied urea or liquid N fertilizers as their major N source. ESN® is a slow release form of N where the release of urea is physically delayed by a polymer coating on urea granules that slowly degrades. ESN® was used by 1.0% of these farmers. Super U® is a form of urea that contains inhibitors of both urease and nitrification. It was used by 0.3% of the farmers applying this group of N fertilizers as their major N source. "Other" unspecified additives were used by 1.7% of these farmers. Herbicides were probably included in this category. Use of additives and specialty formulations of urea and urea-containing liquid N fertilizers may be limited by the added costs, as well the uncertain effectiveness of some of these products.

Although their overall use across the state was low, 46% of the farmers who used additives and specialty formulations of urea and urea-containing liquid N fertilizers were in the Coarse-textured Soils BMP region of the state. This is logical, since the potential for nitrate leaching is greatest on these soils. In this region, 15% of the farmers who applied urea or liquid N fertilizers as their major N source used an additive or specialty formulation. They used Agrotain 74% of the time, presumably for non-incorporated sidedressed urea to prevent ammonia volatilization as described in the next section.

Incorporation of urea and liquid N fertilizers

Soil incorporation of urea and urea-containing liquid N fertilizers is an effective method of reducing loss of N through volatilization, although the amount of time urea remains on the surface of the soil is an important factor. The University of Minnesota Extension best management practice is to incorporate urea-containing fertilizers within three days or less following application (Randall et al., 2008b). About 75% of fall urea applications, 94% of spring applications, and 58% of sidedress applications were incorporated in less than 24 hours (Table 6). About 17% of fall applications and 40% of sidedress applications were never incorporated. Some of these may have been on irrigated fields and were watered in.

Because spring was the most common time to apply urea (Fig. 10), about 89% of all urea applications were incorporated within 24 hours (Table 6). This varied slightly throughout the state. The 24-hour incorporation rate was 100% in the Northwestern BMP region, 94% in the South Central and Southeastern regions, 88% in the Southwestern and West Central region, and 82% in the Coarse-textured Soils region. The lower rate in the Coarse-textured Soils region may have been affected by the inclusion of irrigated fields where urea was watered in after application.

All fall-applied liquid N and about 95% of spring and sidedress liquid N applications were incorporated in less than 24 hours (Table 7). The remaining spring and sidedress applications were incorporated, but incorporation occurred more than 24 hours after application.

Starter fertilizer

Nitrogen was applied in starter fertilizer by 58% of the surveyed farmers (Fig. 14). The average starter N rate was 15 lb N/A, although this varied with the physical form of the fertilizer applied. Liquid fertilizer was used by 53% of the farmers applying starter at an average N rate of 11 lb N/A. The other 47% of the farmers applying starter used a granular fertilizer at an average rate of 20 lb N/A.

Different regions of the state tended to use different forms of starter (Table 8). Liquid starter dominated in the South Central, Southwestern and West Central, and Northwestern regions. Granular starter was more common in the Southeastern and the Coarse-textured Soils regions. These results are consistent with use of granular starter fertilizers in areas where potassium application is more likely to be needed.

Rates of N applied with liquid starter were lowest in the Northwestern region, but were similar across the rest of the state. Rates of N applied with granular starter tended to be greater in the Coarse-textured Soils and the Southwestern and West Central regions than in the South Central and the Southeastern regions.

Ammonium phosphate

Nitrogen was applied as part of the phosphorus fertilizers monoammonium phosphate (MAP) and diammonium phosphate (DAP) by 57% of the surveyed farmers (Fig. 15). The average rate

of N applied through MAP or DAP was 22 lb N/A. About 65% of these farmers used DAP and 35% used MAP, 55% of the applications were made in the spring and 45% in the fall, and 91% of the applications were incorporated. There was probably some overlap (double-counting) in the reporting on use of starter fertilizers and use of ammonium phosphates applied in the spring.

Split and sidedress N applications, other N sources

Farmers were also asked if they made other N applications not included in previous questions, such as "split applications, sidedress, or other forms of fertilizer containing N". About 4% of the farmers made such applications (Fig. 16), at an average N rate of 30 lb N/A. Seventeen percent of these applications were ammonium nitrate, 33% were ammonium sulfate, 23% were urea or liquid N fertilizers, 17% were unknown N sources, and the remaining 10% were from a variety of other products. These data exclude the 9% of farmers who reported using sidedress applications for their major N source (Fig. 8), some of which may have included a series of split sidedress applications.

Irrigated corn

The survey included 37 farmers who reported on an average corn field that was irrigated. This was 2.5% of the total number of farmers surveyed (Fig. 17). The 2007 Census of Agriculture reported that 4.1% of the Minnesota farms growing corn used irrigation (NASS, 2009). About 54% of the farmers in this survey who grew irrigated corn were in the Coarse-textured Soils region. The irrigated corn in other parts of the state was presumably also grown on coarse-textured soils in those regions. The number of farmers reporting on irrigated corn in this survey may not have been a large enough sample to draw reliable conclusions about average N management practices on irrigated corn in Minnesota.

The average N rate for irrigated corn was 151 lb N/A, which was greater than the overall average rate applied by all surveyed farmers of 140 lb N/A. This may have been caused by greater than average productivity potential of the irrigated corn fields included in the survey. Their average yield for the last three corn crops was 169 bu/A, compared with the overall survey average of 159 bu/A. As previously discussed in the "Average N rates" section, the differences in yield (36 bu/A) and N rate (24 lb N/A) between irrigated and non-irrigated corn in the Coarse-textured Soils region were even larger than these overall averages (Table 2).

Anhydrous ammonia and urea were the most commonly used chemical forms of N on irrigated corn (Fig. 18). Anhydrous ammonia was used as the major N source by 46% of the farmers reporting on irrigated corn and urea was the major N source for 43% of them. These percentages are very similar to the state-wide averages for use of these N sources (Fig. 2). Liquid N fertilizers supplied the majority of the N used on about 11% of the irrigated corn fields, which was more than twice their overall rate of use state-wide.

Application timing of the major N source was different for irrigated corn (Fig. 19) than the state-wide distribution of N timing reported by all surveyed farmers (Fig. 8). The largest difference was for sidedress applications, which supplied the majority of the N fertilizer used by 54% of the farmers reporting on irrigated corn compared with only 8% of all surveyed farmers. There was

also a large difference in fall N applications. Less than 3% of the farmers reporting on irrigated corn applied the majority of their N in the fall, compared with nearly 35% of all surveyed farmers. Spring applications of the major N source were used by 43% of the farmers reporting on irrigated corn and 53% of all surveyed farmers. On a state-wide basis, the timing of N fertilizer application varied considerably depending on the major N source (Figs. 9 to 11), but similar variability among N sources in application timing did not occur on irrigated corn. In addition to the 54% of irrigated corn fields where the major N source was sidedressed in single or multiple applications, about 5% of the irrigated fields received a supplemental application of sidedressed N.

Fertigation was used by 19% of the farmers growing irrigated corn, meaning that some of the N was applied through the irrigation water. Irrigated corn that was fertigated received greater overall N rates (163 lb N/A) than irrigated corn that was not fertigated (148 lb N/A), although it is not clear how much of the extra N was applied through fertigation since none of these farmers reported their fertigation rates. Information was also not obtained on the number of times each of these farmers used fertigation.

The timing of N fertilizer application on irrigated corn was consistent with University of Minnesota Extension best management practices for N use on coarse-textured soils (Rehm et al., 2008b). Coarse-textured soils have a high potential for N leaching losses, so minimizing the amount of time between N application and crop uptake is a key factor in N management guidelines. Irrigated corn growers reduced the risk of N losses by avoiding fall N applications and applying N when the crop was actively growing through sidedressing and fertigation.

Soil testing

Soil testing was used as a fertility management tool by most of the farmers in the survey. About 84% of the surveyed fields had been tested in the last five years (Table 9). Farmers employed a variety of methods to collect soil samples for testing and many of them had used more than one method on their surveyed field in the last five years. More than one-half of the farmers had used traditional, random sampling methods. Almost 31% had used grid or zone sampling methods, which provide a basis for applying variable fertilizer rates within a field.

The two survey questions on soil sampling provided contradictory results on use of the nitrate-N soil test. When farmers were asked “Which methods did you use to soil sample this field within the last five years?” and given the five options listed in Table 9, less than 1% selected “Nitrate”. However, when asked “Did you take a soil nitrate sample from this field within the last five years?”, almost 47% of farmers said “Yes” (Fig. 20). The large discrepancy between these two answers may be due to ambiguity in the first question asking about the nitrate soil test. For this question there may have been some confusion about the “Nitrate” option summarized in Table 9, since “Nitrate” refers to a type of soil test and the other options are methods of selecting where in a field soil samples are collected for testing.

Use of the nitrate-N soil test was most common in the western part of the state (Table 10). About 60% of the farmers in the Northwestern and the Southwestern and West Central regions used the nitrate test, compared with about 40% of the farmers testing for nitrate-N in the

Southeastern, Coarse-textured Soils, and South Central regions. These differences are not surprising. The test measures residual nitrate-N in the field after the previous crop and is used to adjust N fertilizer recommendations for the next crop. In the drier western part of the state, leaching of nitrate is less likely to occur and the nitrate test has long been recommended to account for residual N (Rehm et al., 2006). It is also routinely used for sugar beets grown in that part of the state (Lamb et al., 2001). A spring nitrate test was developed more recently for other parts of the state, but it is recommended for a more limited range of conditions (Rehm et al., 2006) and its use by 40% of farmers outside of western Minnesota was probably greater than expected. It could be that many farmers in those parts of the state are not familiar with the nitrate-N soil test and answered the second question under the assumption that an N test would have been included with the standard set of soil fertility tests.

Conclusions

This survey provides the most comprehensive set of data on N fertilizer use on field corn that has been collected in Minnesota. It includes detailed information on application rates, timing, placement, and the chemical form of the fertilizer used. The number of farmers successfully interviewed and their distribution across the state indicates that the results can be used to accurately characterize current N fertilizer management practices in the state. This information can be used to target research and education programs to improve N management for both production and environmental goals. An important conclusion from the survey data is that N fertilizer use by Minnesota corn farmers is generally consistent with University of Minnesota Extension N management guidelines.

References

Lamb, John, Gyles Randall, George Rehm, Carl Rosen. 2008. *Best Management Practices for Nitrogen Use In Minnesota*. Publication #08560, University of Minnesota Extension.

Lamb, John A., Albert L. Sims, Larry J. Smith, and George W. Rehm. 2001. Fertilizing Sugar Beet in Minnesota and North Dakota. Publication #WW-07715, University of Minnesota Extension.

National Agricultural Statistics Service (NASS), 2000-2004, 2006. Agricultural Chemical Usage: 1999-2003, 2005 Field Crops Summaries. United States Department of Agriculture. http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1560

National Agricultural Statistics Service (NASS). 2009. 2007 Census of Agriculture. United States Department of Agriculture. http://www.agcensus.usda.gov/Publications/2007/Full_Report/Census_by_State/Minnesota/index.asp

National Agricultural Statistics Service (NASS), Minnesota Field Office. 2010. 2010 Minnesota Agricultural Statistics. United States Department of Agriculture and Minnesota Department of Agriculture.

http://www.nass.usda.gov/Statistics_by_State/Minnesota/Publications/Annual_Statistical_Bulletin/index.asp

Randall, Gyles, George Rehm, John Lamb. 2008a. *Best Management Practices for Nitrogen Use in Southeastern Minnesota*. Publication #08557, University of Minnesota Extension.

Randall, Gyles, George Rehm, John Lamb, Carl Rosen. 2008b. *Best Management Practices for Nitrogen Use in South-Central Minnesota*. Publication #08554, University of Minnesota Extension.

Rehm, George, John Lamb, Carl Rosen, Gyles Randall. 2008a. *Best Management Practices for Nitrogen on Coarse Textured Soils*. Publication #08556, University of Minnesota Extension.

Rehm, George, John Lamb, Jodi DeJong Hughes, Gyles Randall. 2008b. *Best Management Practices for Nitrogen Use in Southwestern and West-Central Minnesota*. Publication #08558, University of Minnesota Extension.

Rehm, George, Gyles Randall, John Lamb, Roger Eliason. 2006. *Fertilizing Corn in Minnesota*. Publication #FO-0379O, University of Minnesota Extension.

Table 1. Number of corn acres grown on surveyed farms in 2009 compared with the distribution of corn acres on all Minnesota farms growing corn in 2007.

Acres of corn grown	**Surveyed farms**	**All MN farms***
	---------- % of total ----------	
1-24	5.0	12.5
25-99	20.1	30.1
100-249	30.5	27.1
250-499	24.1	17.0
500-999	14.2	9.5
1000 or more	6.1	4.1

*2007 Census of Agriculture (NASS, 2009). Percentages sum to 100.3% because of rounding.

Table 2. Average N fertilizer rates applied to corn in 2009 by surveyed farmers reporting on an average field, and average yields of previous corn crops grown in that same field, in different BMP regions of Minnesota.

BMP region	**N rate**	**Previous yield***
	lb/acre	bu/acre
Northwestern	131	137
Coarse-textured Soils	129**	127**
Irrigated***	151	160
Non-irrigated	127	124
Southwestern and West Central	139	161
South Central	146	174
Southeastern	140	166
Overall	140	159

*Average yields of the previous 3 corn crops in the surveyed fields.

**Average for all fields in the region.

***8.1% of the fields in the Coarse-textured soils region were irrigated.

Table 3. Nitrogen fertilizer rates on corn following different crops in 2009 by surveyed farmers reporting on an average field.

Previous crop	**N rate** (lb/acre)	**% of fields**
Soybeans	140	74.8
Corn	145	16.8
Corn/alfalfa*	129	2.0
Alfalfa	97	2.0
Other	131	4.4
Overall	140	100

*2009 was the 2nd year of corn following a previous alfalfa crop.

Table 4. Differences in N rate among the three major N sources applied to corn in 2009 by surveyed farmers reporting on an average field.

Major N source	N rate from major source	Total N rate
	---------- lb/acre ----------	
Anhydrous ammonia	132	146
Urea	123	136
Liquid N	113	131

Table 5. Anhydrous ammonia application to corn and use of the nitrification inhibitor N-Serve in 2009 by surveyed farmers reporting on an average field.

AA application time	N-Serve used (%)
Fall	28.6
Spring	7.4
Sidedress	8.3
Overall	20.8

Table 6. Incorporation practices following application of urea as the major N source for corn in 2009 by surveyed farmers reporting on an average field.

Urea application time	Incorporation timing (%)		
	< 24 hours	> 24 hours	Not incorporated
Fall	74.3	8.6	17.1
Spring	93.8	1.7	4.5
Sidedress	57.5	2.5	40.0
Overall	89.3	2.6	8.2

Table 7. Incorporation practices following application of liquid N fertilizer as the major N source for corn in 2009 by surveyed farmers reporting on an average field.

Liquid N application time	Incorporation timing (%)		
	< 24 hours	> 24 hours	Not incorporated
Fall	100.0	0.0	0.0
Spring	95.7	4.3	0.0
Sidedress	94.7	5.3	0.0
Overall	95.9	4.1	0.0

Table 8. Differences in the physical form and N rate of starter fertilizer used on corn in different BMP regions of the state in 2009 by surveyed farmers reporting on an average field.

BMP region	**Form**	**% of farmers**	**N rate** (lb/acre)
Northwestern	liquid	84.2	7
	granular	15.8	---
Coarse-textured Soils	liquid	20.5	13
	granular	79.5	25
Southwestern and West Central	liquid	79.5	11
	granular	20.5	20
South Central	liquid	73.1	11
	granular	26.9	15
Southeastern	liquid	35.4	13
	granular	64.6	16

Table 9. Soil sampling methods used in the last five years by surveyed farmers reporting on an average field.

Sampling method	**% of farmers***
Traditional	56.8
Grid	20.1
Zone	10.5
Nitrate	0.9
None	15.9

*Total is greater than 100%, because some farmers used more than one method.

Table 10. Use of the soil nitrate test in the last five years in different BMP regions of the state by surveyed farmers reporting on an average field.

BMP region	**% of farmers**
Northwestern	65.9
Coarse-textured Soils	38.2
Southwestern and West Central	57.7
South Central	41.9
Southeastern	36.6

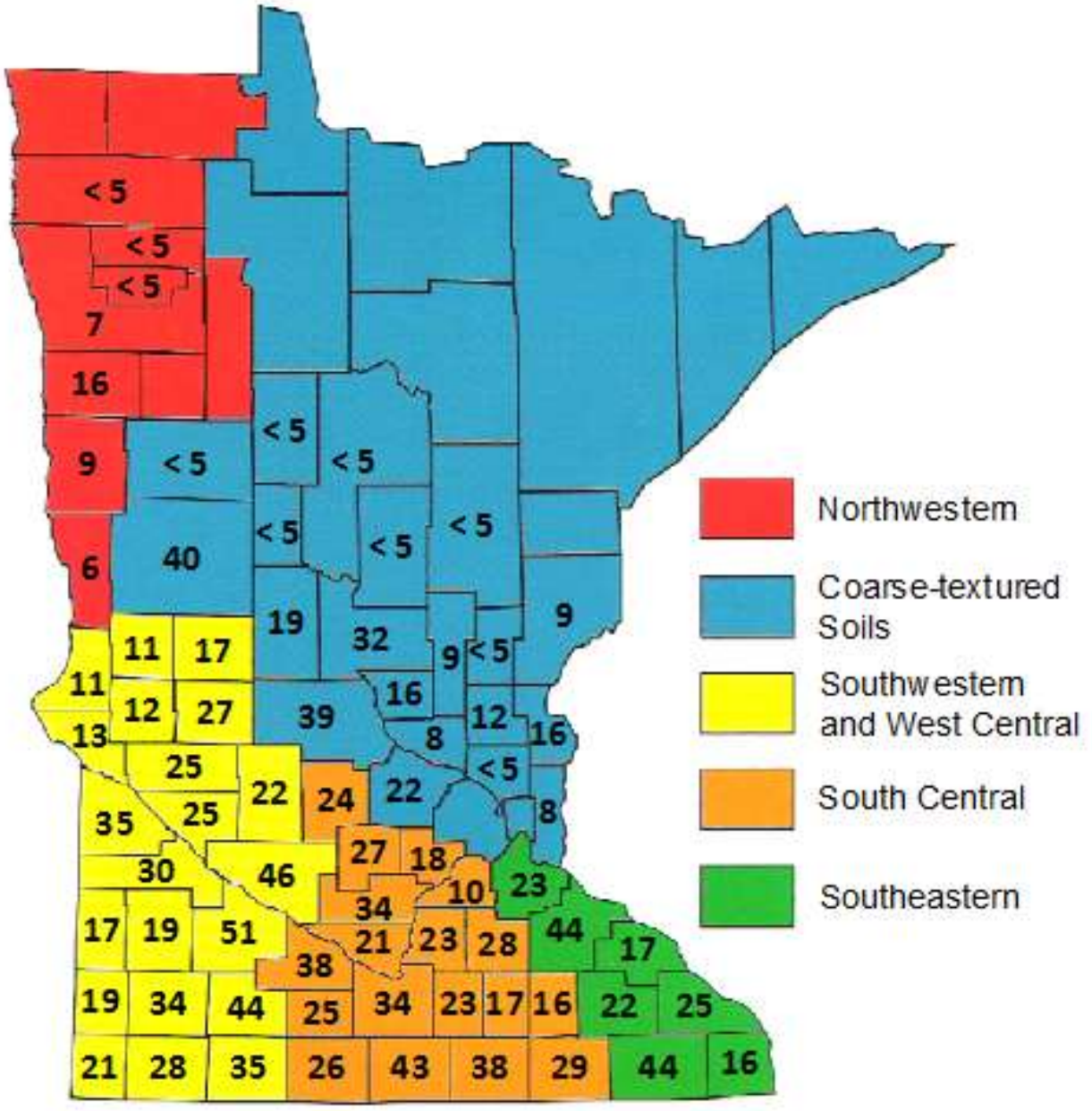

Figure 1. State-wide distribution by county of farmers participating in the survey of nitrogen fertilizer use on corn in the 2009 growing season and division of the state into regions for nitrogen Best Management Practices.

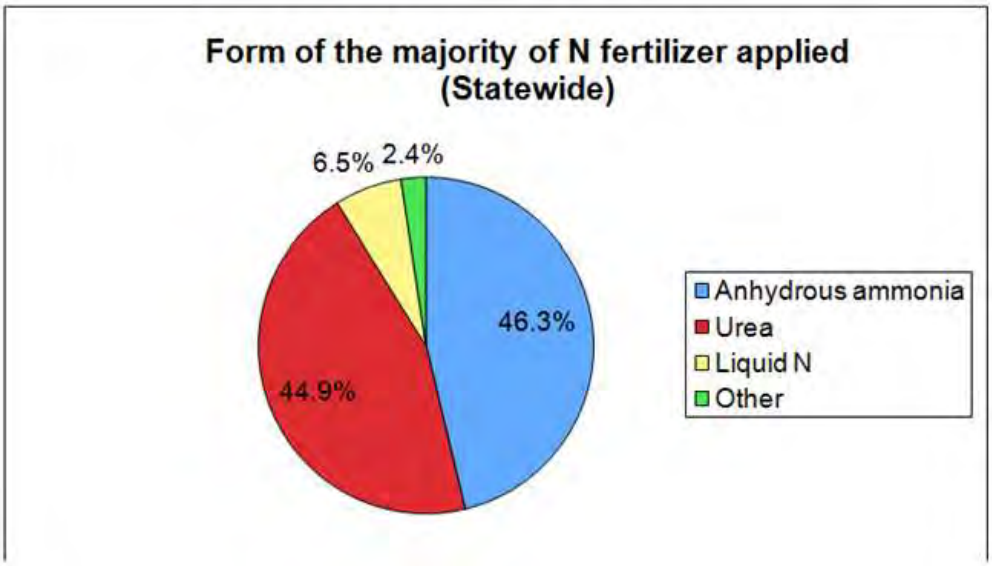

Figure 2. Chemical form of the majority of the N applied to corn in 2009 by surveyed farmers reporting on an average field. Percentages sum to 100.1% because of rounding.

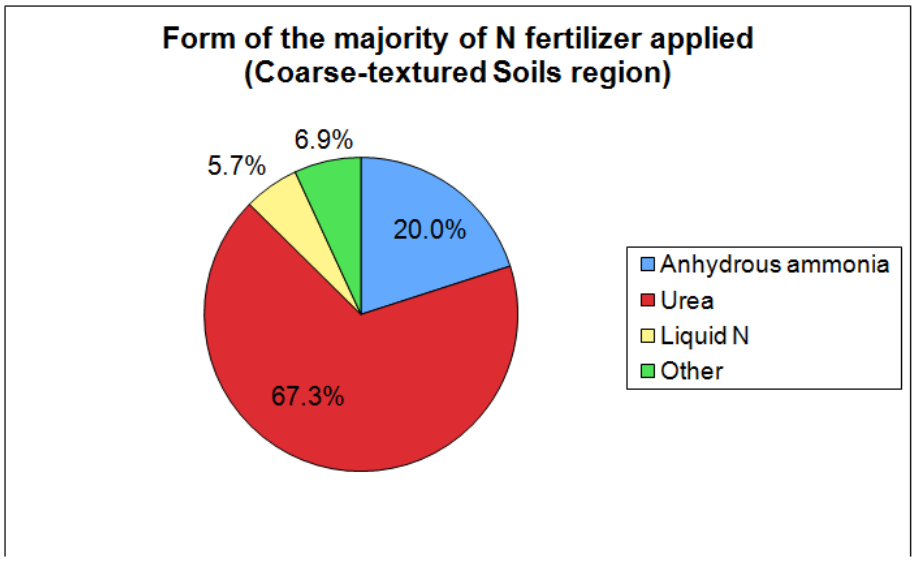

Figure 3. Chemical form of the majority of the N applied to corn in the Coarse-textured Soils region in 2009 by surveyed farmers reporting on an average field. Percentages sum to 99.9% because of rounding.

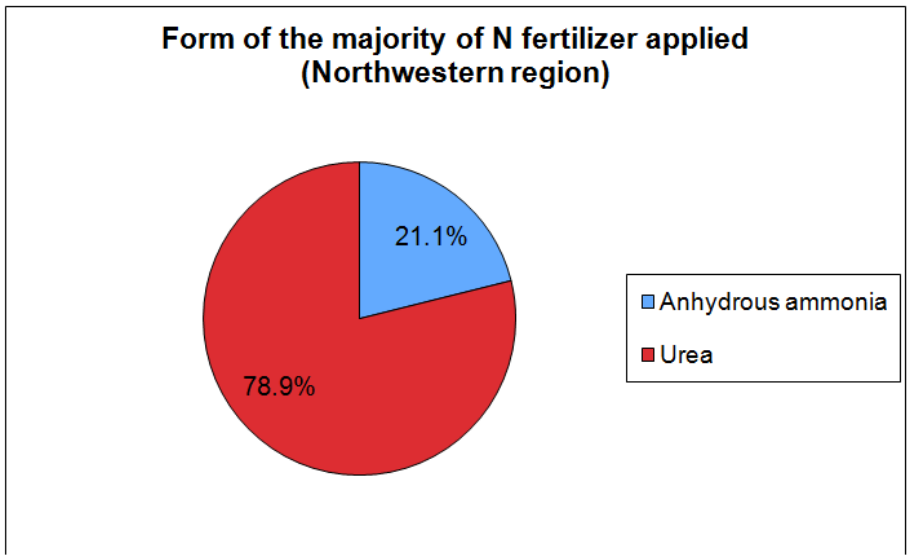

Figure 4. Chemical form of the majority of the N applied to corn in the Northwestern region in 2009 by surveyed farmers reporting on an average field.

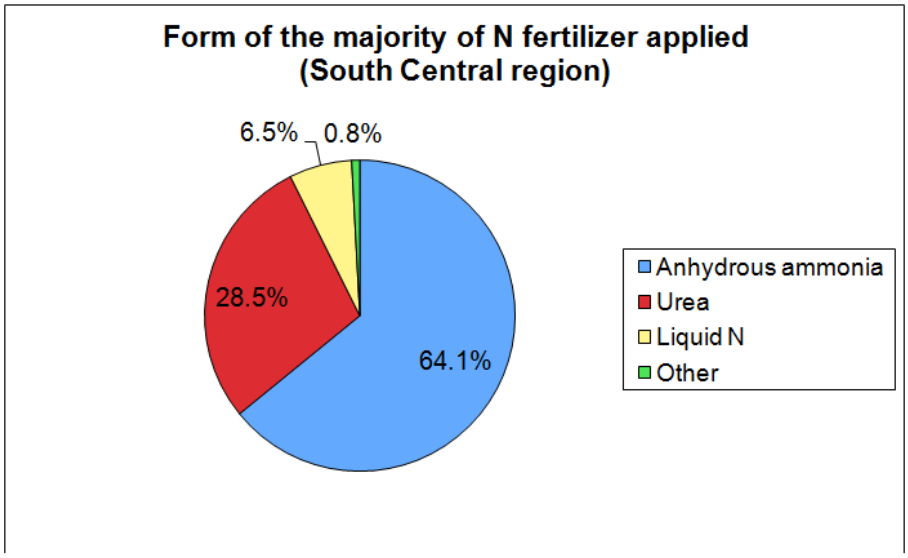

Figure 5. Chemical form of the majority of the N applied to corn in the South Central region in 2009 by surveyed farmers reporting on an average field. Percentages sum to 99.9% because of rounding.

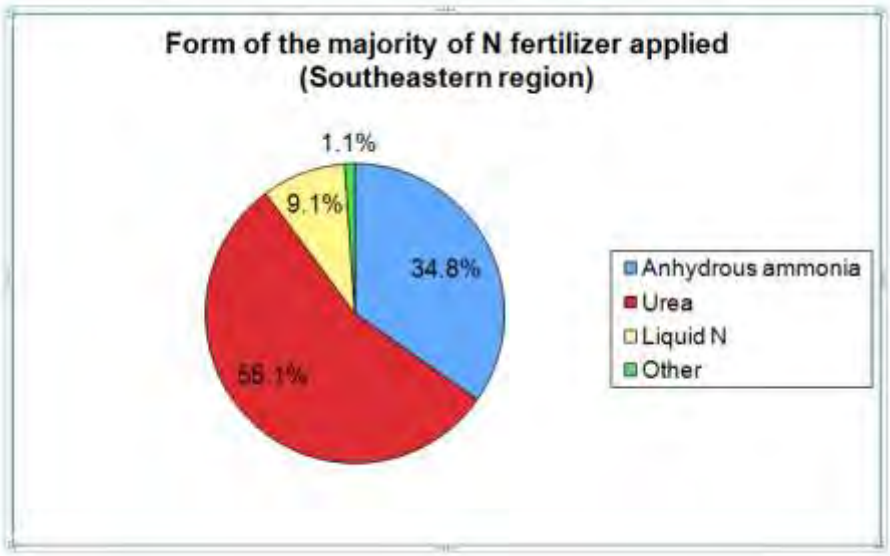

Figure 6. Chemical form of the majority of the N applied to corn in the Southeastern region in 2009 by surveyed farmers reporting on an average field. Percentages sum to 100.1% because of rounding.

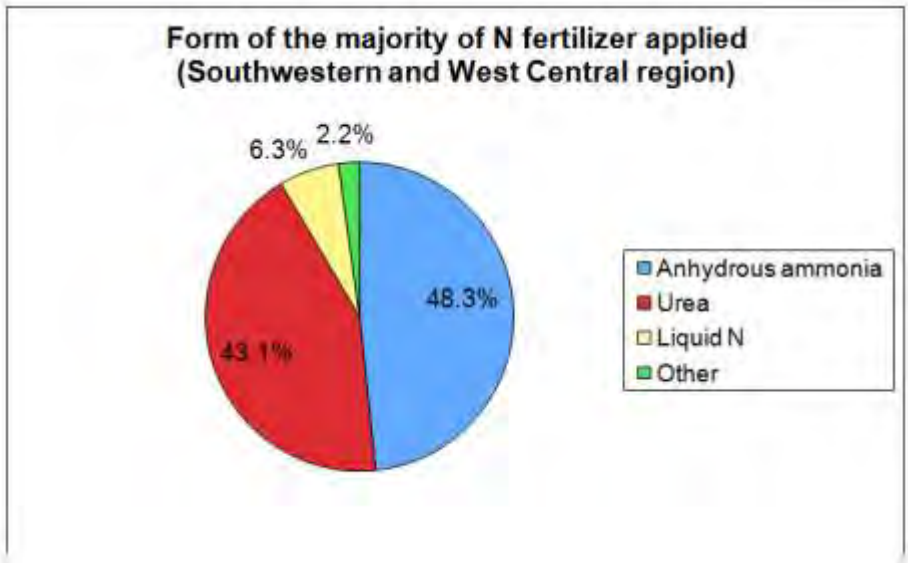

Figure 7. Chemical form of the majority of the N applied to corn in the Southwestern and West Central region in 2009 by surveyed farmers reporting on an average field. Percentages sum to 99.9% because of rounding.

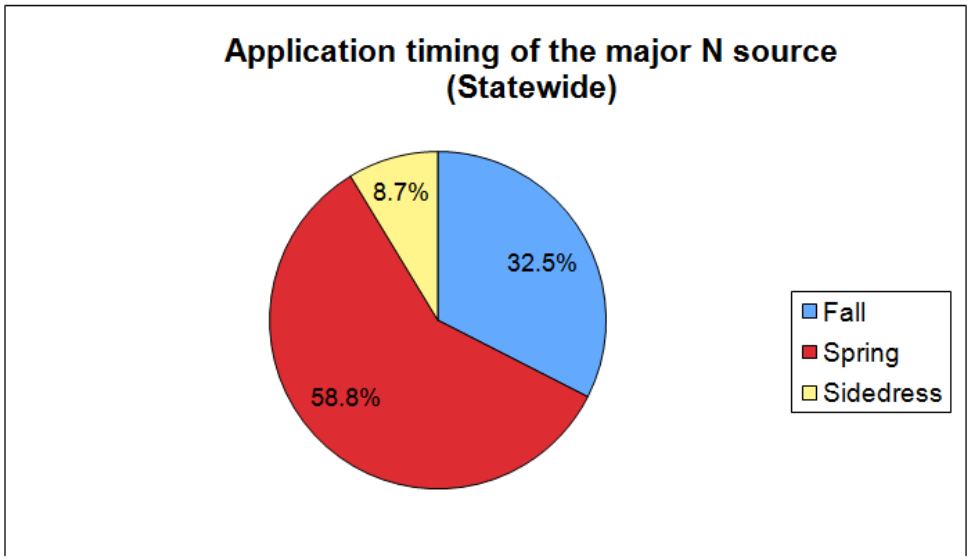

Figure 8. Application timing for the major source of N applied to corn in 2009 by surveyed farmers reporting on an average field.

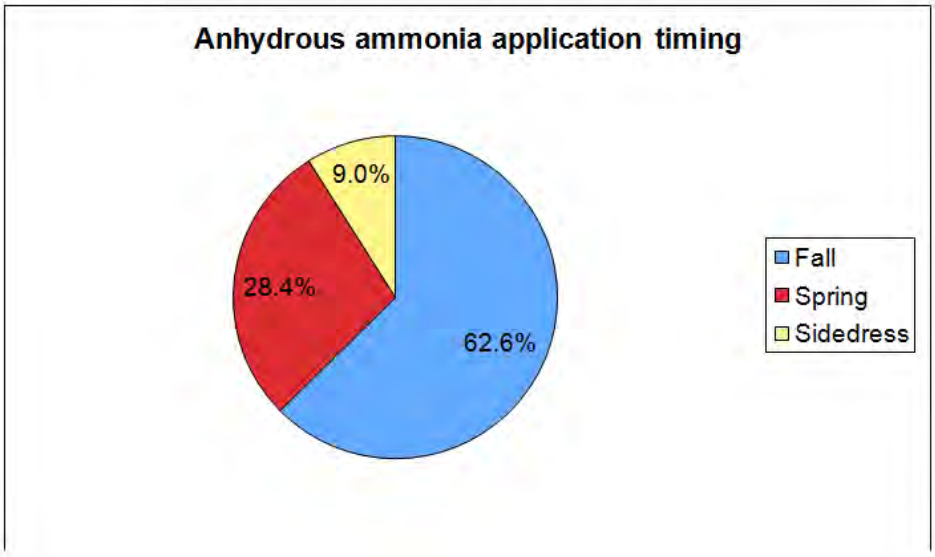

Figure 9. Application timing for anhydrous ammonia used as the major source of N applied to corn in 2009 by surveyed farmers reporting on an average field.

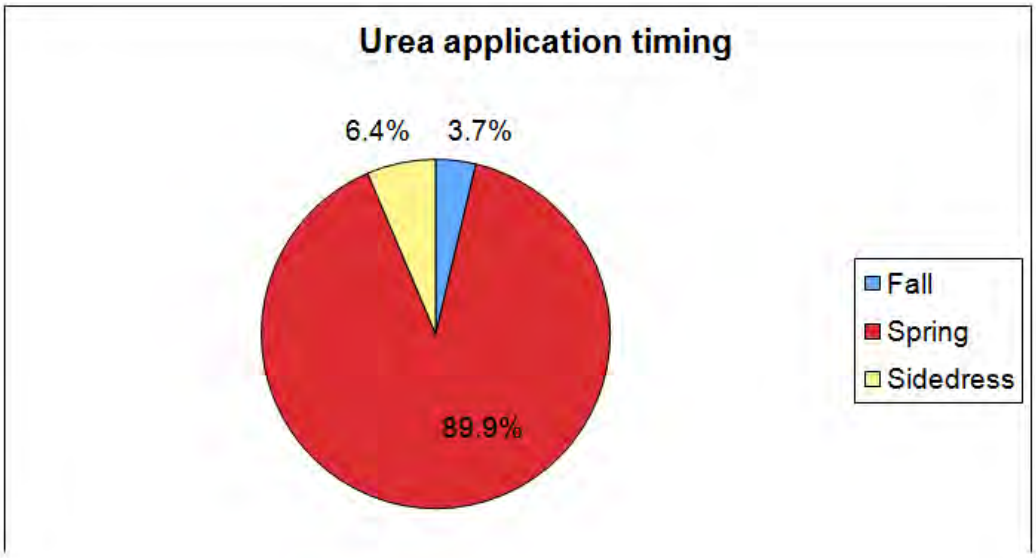

Figure 10. Application timing for urea used as the major source of N applied to corn in 2009 by surveyed farmers reporting on an average field.

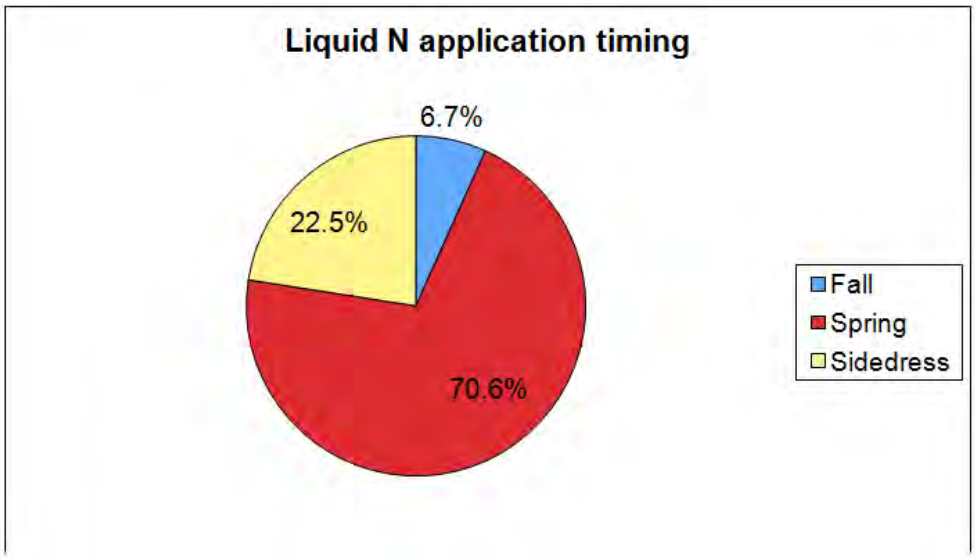

Figure 11. Application timing for liquid N fertilizers used as the major source of N applied to corn in 2009 by surveyed farmers reporting on an average field. Percentages sum to 99.8% because of rounding.

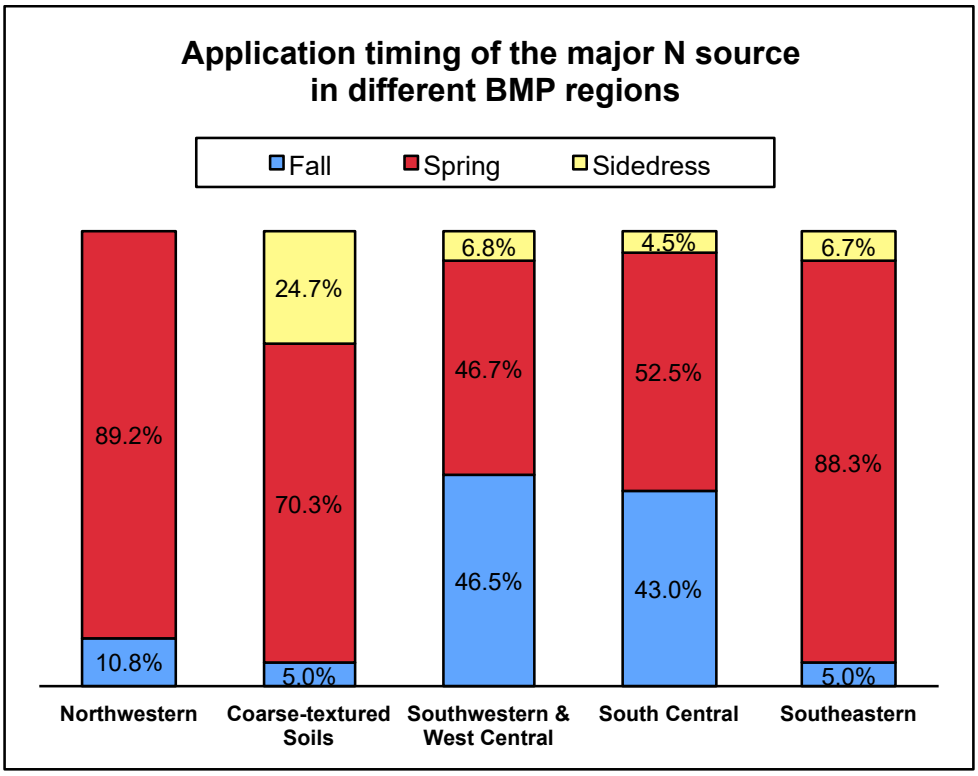

Figure 12. Application timing for the major source of N applied to corn in different BMP regions of the state in 2009 by surveyed farmers reporting on an average field.

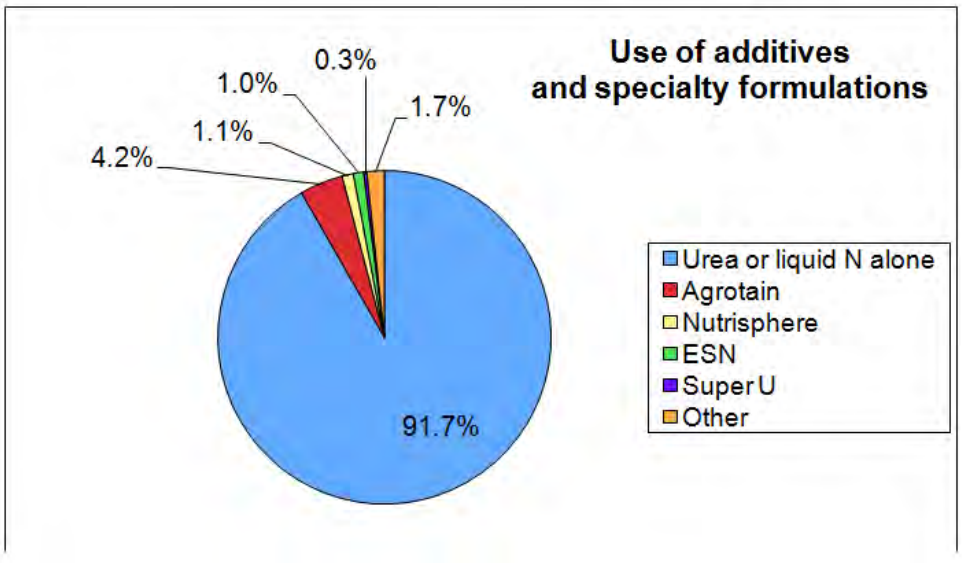

Figure 13. Use of additives and specialty formulations of urea and liquid N fertilizers applied to corn in 2009 by surveyed farmers reporting on an average field.

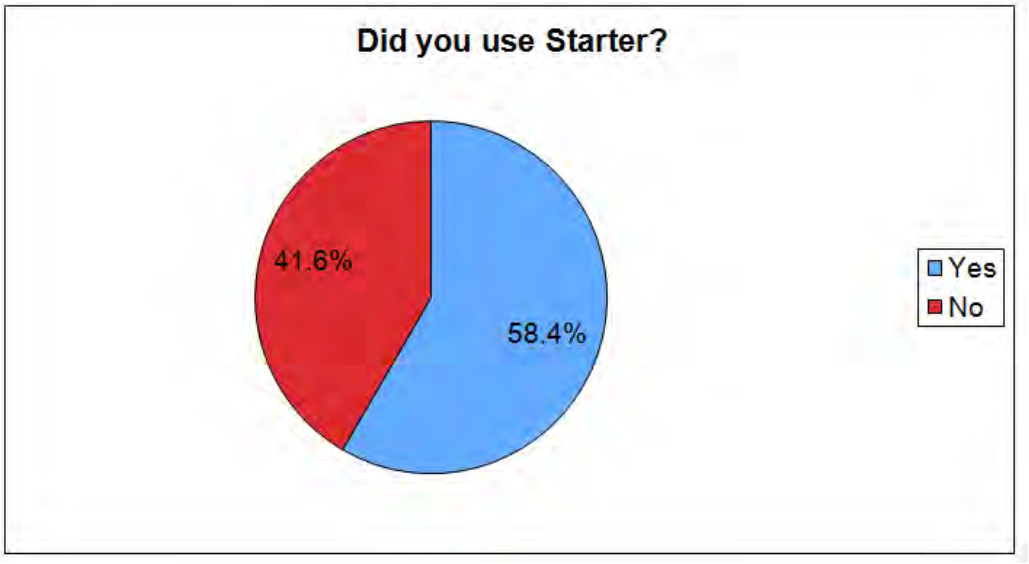

Figure 14. Application of N in starter fertilizer applied to corn in 2009 by surveyed farmers reporting on an average field.

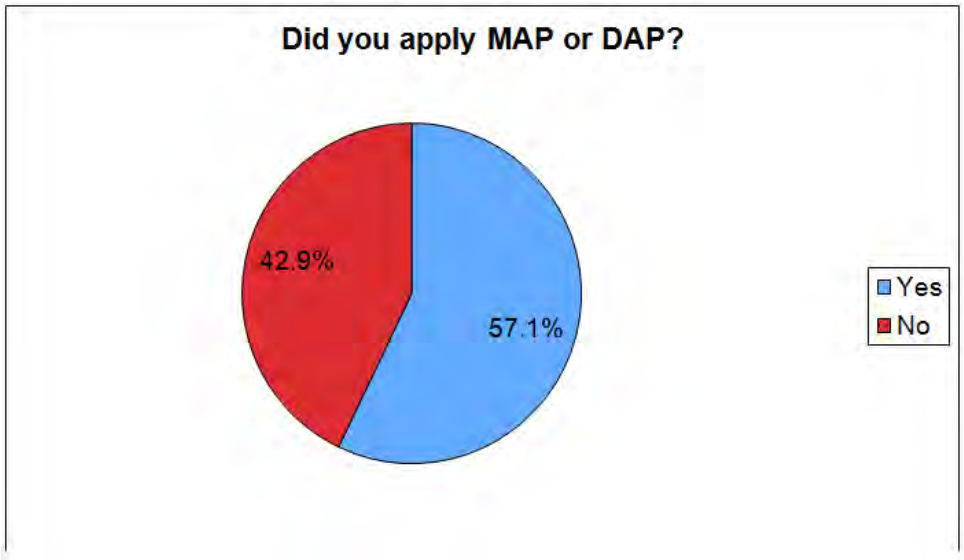

Figure 15. Application of N in MAP (monoammonium phosphate) or DAP (diammonium phosphate) applied to corn in 2009 by surveyed farmers reporting on an average field.

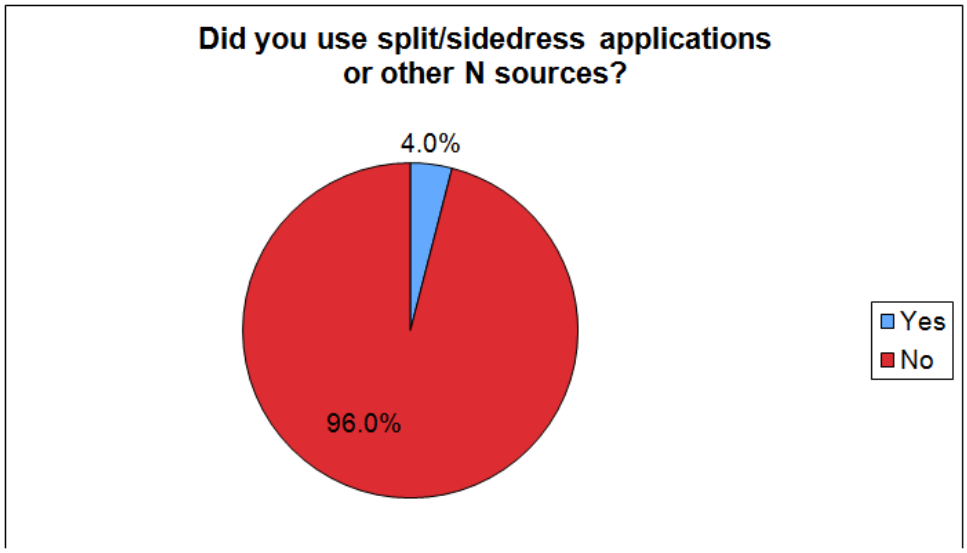

Figure 16. Use of split applications, sidedress applications, or other forms of fertilizer containing N applied to corn in 2009 by surveyed farmers reporting on an average field.

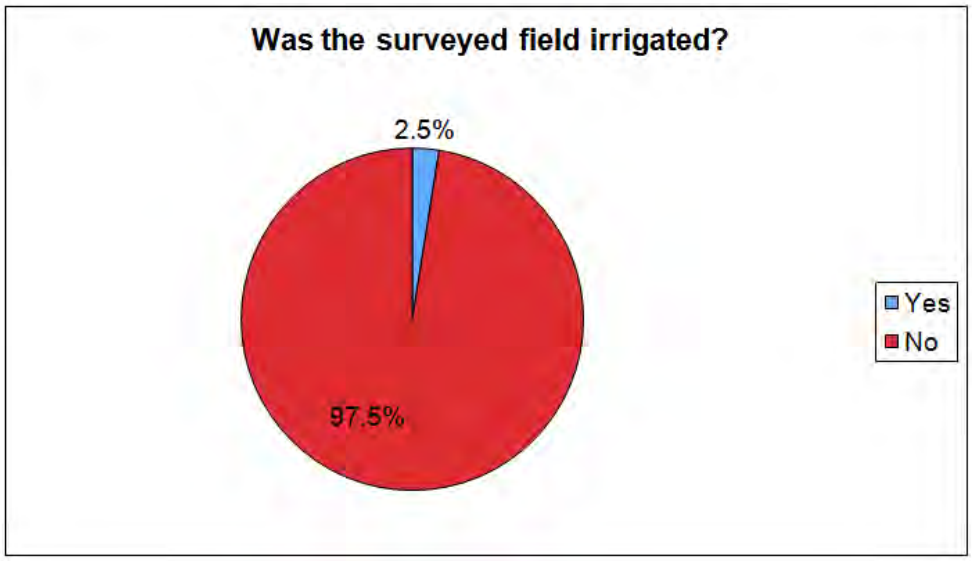

Figure 17. Use of irrigation on corn in 2009 by surveyed farmers reporting on an average field.

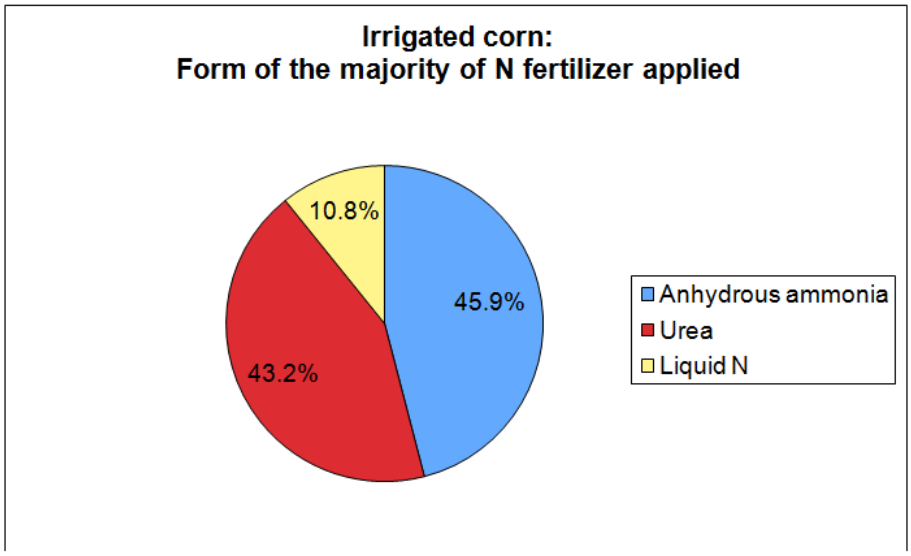

Figure 18. Chemical form of the majority of the N applied to irrigated corn in 2009 by surveyed farmers reporting on an average field. Percentages sum to 99.9% because of rounding.

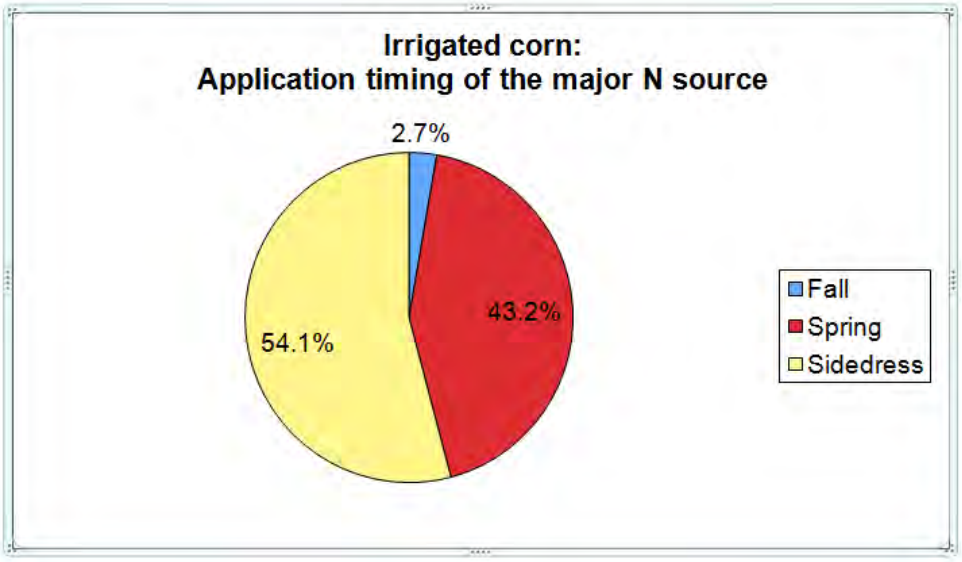

Figure 19. Application timing for the major source of N applied to irrigated corn in 2009 by surveyed farmers reporting on an average field.

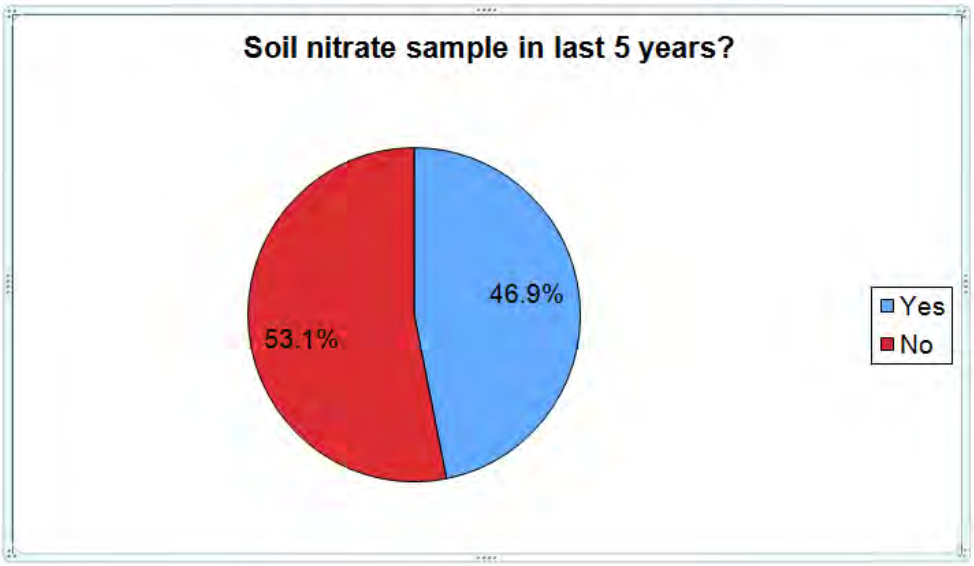

Figure 20. Use of the nitrate-N soil test in the last five years by surveyed farmers reporting on an average field.

MCEA Ex. 52

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Cover crops

Cover crops are grown outside of the cash crop growing season, usually seeded in the fall and killed before spring planting.



Keeping living roots in the ground year-round can improve water management, soil protection and nutrient scavenging, but they need to be given the same attention as a cash crop to ensure success.

Try cover crops on a small scale first, and look into cost-share from state and local governments.

Some of the best opportunities are with early-harvested cash crops like corn silage, small grains, and canning crops like beans and peas, as you'll get more vigorous fall growth if you plant in late summer and early fall.

In fields where wheat was just harvested, simply allowing it to reseed itself without tilling the land would work as a cover crop. But cover crops can work with standard corn-soybean rotations as well.

Benefits of cover crops

Erosion control

Cover crops reduce erosion in a few different ways.

- Aboveground, living cover crops protect the soil from rainfall impact and reduce the effect of wind. Runoff is reduced along the way.
- Belowground, roots hold soil in place during active erosion events and build structure. Better soil structure means the soil is less likely to erode even if left bare later in the season, such as between harvest and cover crop planting.
- Runoff sediment also contains soil phosphorus, so reducing runoff is an important strategy for reducing P loading in surface water.

Infiltration and water management

Cover crop root systems create large channels through the soil to allow increased infiltration. This effect is especially significant for species with large taproots, but other cover crops also increase infiltration.

- Increased infiltration means fields are less likely to stay saturated during Minnesota's rainy springs.
- Many farmers report dry field conditions more quickly after a rain event when they use cover crops.

Cover crops can also help soil store water by building soil structure and creating a network of large and small pores.

- Once water enters the soil through infiltration, this pore network retains water for plants to take up as necessary.
- This increase in soil water holding capacity can be especially beneficial in dry years.

Nitrate reduction

Soil nitrate reduction is well-established in Minnesota for a variety of cover crops.

- Nitrate is often left in the soil after fall harvest of corn.
- A winter cover crop takes up soil nitrogen, so less nitrogen is leached. This is an important benefit for reducing groundwater nitrate contamination.
- Farmers should expect some nitrate drawdown by cover crops and plan the subsequent season's fertility accordingly.
- Soil testing before applying N to cash crops can help with field-specific recommendations.

Minnesota cover crop recipes

For a quick way to get started, Minnesota cover crop recipes provide step-by-step guidance to some of the lowest-risk starting points for cover crops. These recipes don't cover all possibilities, but they can help beginners incorporate cover crops into a farm operation.

- Post corn, going into soybean: Use cereal rye
- Post soybean, going to corn: Use oats
- Post corn silage, going to corn: Use cereal rye
- Post corn silage, going to soybean: Use cereal rye

Learn more about reducing tillage and incorporating cover crops:

Getting started and cover crop selection

Getting started with cover crops ›

- Benefits of cover crops.
- Choosing a cover crop (consider crop rotation, harvest timing, overwintering, etc.).
- Recommended planting dates and seeding rates for cover crops.
- Comparison of cover crop benefits by crop.

Planting green in Minnesota ›

- Benefits of biomass production
- How termination date affects biomass production

Planting date matters for cover crops, too ›

- Timing of fall seeding
- Termination timing on biomass production

Reduce risk of fallow or flooded soil syndrome with cover crops ›

- How and when fallow syndrome occurs.
- How it affects crops.
- How cover crops can help.
- How to manage fallow syndrome.

Establishment

New cover cropping opportunities in Minnesota ›

- Research summary: Interseeding cover crops into V7 corn using several species and planting techniques.

Early season cover crop interseeding in corn ›

- Potential for interseeding cover crops into corn.
- Managing cover crops to reduce competition with corn.
    - Optimum seeding time.
- Interseeding strategies.

Using herbicides and cover crops in corn and soybean ›

- Residual herbicides can impact cover crop establishment and growth.
- Considerations for grazing or harvesting cover crops for forage.
- Cover crop sensitivity to herbicide carryover.

Herbicide persistence and carryover to cover crops ›

- How to manage carryover risk to cover crops
- Cover crop rotations, commonly used herbicides and potential injury
- Sensitivity of different cover crops

Termination

Spring management of cover crops ›

- Guidance on mechanical and chemical termination, including carbon-to-nitrogen ratios of common crops.

- Factors affecting residue.
- Pest management tips.
- How to time spring termination for cash crop planting.

Research webinar: Fertility and crop rotation with cover crops

In this Strategic Farming webinar, researchers Monica Schauer, UW-Madison, and Anna Cates, UMN Extension educator, discuss fertility and crop rotation with cover crops.

Minnesota Crop News

2025 CAWT Recertification: In-person at FarmFest on August 7th, online until October 31st

3 hours ago

Northern corn rootworm extended diapause problems in Minnesota in 2025

4 days ago

Variable rate nitrogen: What are we trying to accomplish?

4 days ago

Field Notes offered an update on Palmer amaranth in Minnesota

4 days ago

Soybean gall midge larvae found in Dakota County, MN

5 days ago

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Please scan the above QR code to visit the live webpage for links.

https://extension.umn.edu/soil-and-water/cover-crops

MINNESOTA POLLUTION CONTROL AGENCY

Climate change impacts

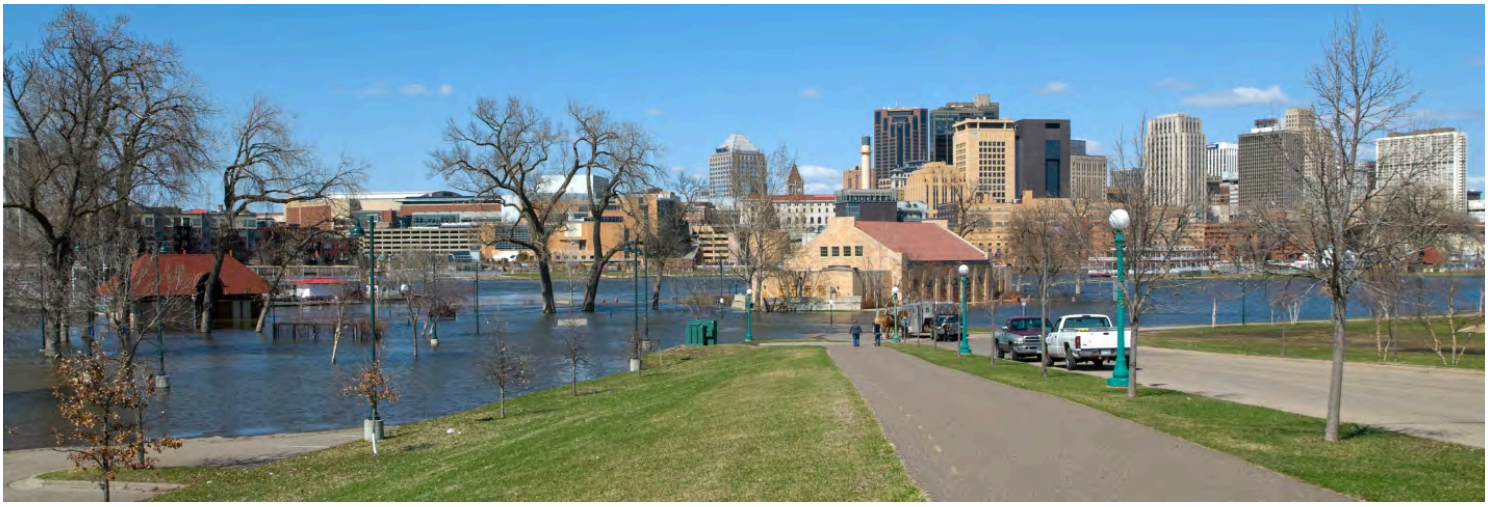

SECTION MENU

Our climate has already changed and will continue to change. Minnesotans are feeling impacts of climate change, from higher temperatures, more extreme storms with intense flooding, and changes in our unique and cherished ecosystems. These impacts will continue to have serious effects on the economy, natural environment, and quality of life in Minnesota.

Storms and flooding

Frequent and intense storms are now occurring more than any time on record, and the trend is projected to continue. Record-breaking floods damage streets, wastewater facilities, businesses, homes, farms, and natural resources, costing local governments, business owners, and residents millions of dollars in cleanup and

repairs. Annual precipitation has increased as well, especially in the southern parts of the state.

Rising temperatures statewide

Minnesota is getting warmer, especially winter nights in the northern parts of the state. Daily average minimum temperatures during winter (Dec-Feb) have increased 7.3 degrees from 1895-2021 in northern Minnesota, 6 degrees in central Minnesota and 4.9 degrees in southern Minnesota. Minnesota lakes have lost an average of 10 to 14 days of ice cover in the past 50 years, affecting lake and fish health, outdoor recreation opportunities, local governments, and business owners.

A costly cumulative impact

The years ahead will bring even warmer winters and nights, and even larger rainfalls, along with increased summer heat and longer dry spells. Even if we drastically reduce or halt greenhouse gas emissions immediately, the climate has already changed and will continue to change. Costly repairs to infrastructure, increasing home and crop insurance rates, destructive shifts in our native ecosystems, and more hospitalizations for heat-related illness are some of the impacts climate change is having on Minnesotans and the economy. These impacts are experienced even more acutely by communities in areas of concern for environmental justice.

Climate trends and projected (future) data

The Minnesota Climate Explorer is a simple, user-friendly climate information portal that allows users to graph and analyze past and projected future climate information at a variety of scales across Minnesota. For more information, refer to the Climate Explorer FAQ.

More information

- Climate trends (Minnesota Department of Natural Resources)

- Minnesota State Climatology Office (Minnesota Department of Natural Resources)

Contact Us

Main contact: 800-657-3864
Environmental emergencies (24 hours): 800-422-0798

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Applying Manure in Sensitive Areas









State requirements and recommended practices to protect water quality

Revised May 2005

Minnesota Pollution Control Agency

NRCS Natural Resources Conservation Service

Applying Manure in Sensitive Areas



Purpose

This publication describes Minnesota state rule requirements and recommended practices to protect water quality when applying manure in the most common environmentally sensitive areas. All people applying manure, including those who do not need a permit or written manure management plan, are required to follow setbacks and other rules regarding sensitive areas.

Overview

Manure can be a valuable resource or a pollutant. When properly managed and applied, manure supplies nutrients and improves soil properties. But when poorly managed and applied, manure can degrade water quality. Some sites are more vulnerable to contamination of surface or ground water quality, including land near waters or near pathways to water.

Surface water protection. The risk of polluting surface waters increases when manure is applied to high phosphorus soils, steep slopes, or land near lakes, streams, ditches, wetlands, or open tile intakes. Surface runoff can carry phosphorus, microbial pathogens, ammonia, and oxygen-depleting substances. Water quality in sensitive areas can be protected by practices like using immediate incorporation or injection, maintaining setback distances, applying manure less frequently, planting vegetative buffers, and reducing excess nutrient additions.

Ground water protection. Groundwater can be contaminated by microbial pathogens or nutrients from manure. Pathogens can move directly to ground water through cracks in the soil, especially near old wells, mines, quarries, sinkholes, and shallow soils over fractured bedrock. Diverting or filtering runoff before it enters these paths to ground water prevents pollution. Incorporating manure into the soil before runoff occurs also decreases the chances of pollution. Because nitrate leaching through the soil from manure and fertilizer can contaminate ground water, nitrogen must be applied at the proper rate. To further reduce nitrate leaching, manure application should be properly timed, especially in coarse-textured soils and vulnerable lands near public water supply wells.

Rules for applying manure to all land



Several rules apply to all land where manure is applied, regardless of the distance to sensitive areas. For example, state rules limit nitrogen rates on all fields where manure is applied. Estimated plant-available nitrogen from all sources may not exceed expected crop nitrogen needs for non-legumes and expected nitrogen removal for legumes. Manure from all storage areas holding manure from more than 100 animal units must be tested for nutrient content. In addition, for all feedlots where manure management plans are required, manure cannot be applied to bare, harvested fields in June, July, or August unless a cover crop is planted for the remainder of the growing season.

For more information about nitrogen rate limits, manure and soil testing requirements, or manure management plan and record-keeping requirements, see the Minnesota Pollution Control Agency (MPCA) publication *Land Application of Manure—Minimum State Requirements* on-line at www.pca.state.mn.us/hot/feedlot-management.

Storing and stockpiling manure in sensitive areas

State requirements for manure stockpiling or liquid manure storage in sensitive areas are described in Minnesota Rules pts. 7020.2125 and 7020.2100. Information about stockpiling restrictions is at www.pca.state.mn.us/hot/feedlots.html.

Local ordinances

When local ordinances are more restrictive than state rules, the local ordinances must be followed. To find more information about local ordinances that may be more restrictive than state rules, contact your county planning and zoning office.

Recommended practices

Some practices are not required in state and local rules, but are recommended regardless of livestock numbers. For example, sheet, rill and gully erosion should be controlled on all land receiving nutrient applications. Recommended management practices for sensitive areas are noted throughout this publication. The USDA Natural Resources Conservation Service (NRCS) requires many of these management practices as a condition of receiving cost share money for nutrient management. More information about recommended nitrogen practices throughout the state is on-line at www.manure.umn.edu/applied/application.html.

To find out more about identifying and protecting sensitive areas, contact your county University of Minnesota Extension Service, USDA NRCS, soil and water conservation district, planning and zoning office, county environmental services office, or the nearest subdistrict office of the Minnesota Pollution Control Agency.

Finding the Information *You* Need

You will probably not need to read this publication from cover to cover. Turn to the pages describing sensitive areas on your farm and find out:

1. How to identify the sensitive area
2. Minimum state requirements for applying manure in the area
3. Recommended management practices that may also be necessary to receive state/federal cost share payments

Perennial and intermittent streams 3
Lakes and protected wetlands 4
Drainage ditches 5
Open tile intakes 6
Steeply sloping land 6
Road ditches 7
Frequently flooded soils 7
High water table soils 7
High phosphorus soils 8
Wells and wellhead protection areas 9
Sinkholes 9
Coarse-textured soils 10
Shallow soils over bedrock 10
Mines and quarries 10
Summary of winter/non-winter setbacks ..... Back cover



Perennial and intermittent streams

Identifying perennial and intermittent streams

Perennial streams flow continuously. Intermittent streams typically flow after storms or when snow melts, and can flow continuosly for extended periods of time. Both are on United States Geological Survey quadrangle maps found at county soil and water conservation district offices or on-line at www.terraserver-usa.com.

Minimum state requirements

- 0 to 25 feet
  - ✔ No manure application is permitted within 25 feet from the ordinary high water level.
- 25 to 300 feet
  - ✔ Inject or incorporate within 24 hours and before rainfall.
  - ✔ Manage phosphorus to prevent long-term build-up of soil P (see page 8: High phosphorus soils).
  - ✔ Do not apply manure to frozen or snow-covered soils in this zone, even if a buffer exists.
  - ✔ Do not apply with irrigation equipment such as a center pivot or traveling gun.
- An interim permit is needed if applying manure from feedlots with more than 300 animal units along streams and intermittent streams where average soil phosphorus levels exceed 75 ppm Bray P1 (or 60 ppm Olsen) or where slopes exceed six percent.

Rule options for non-winter months

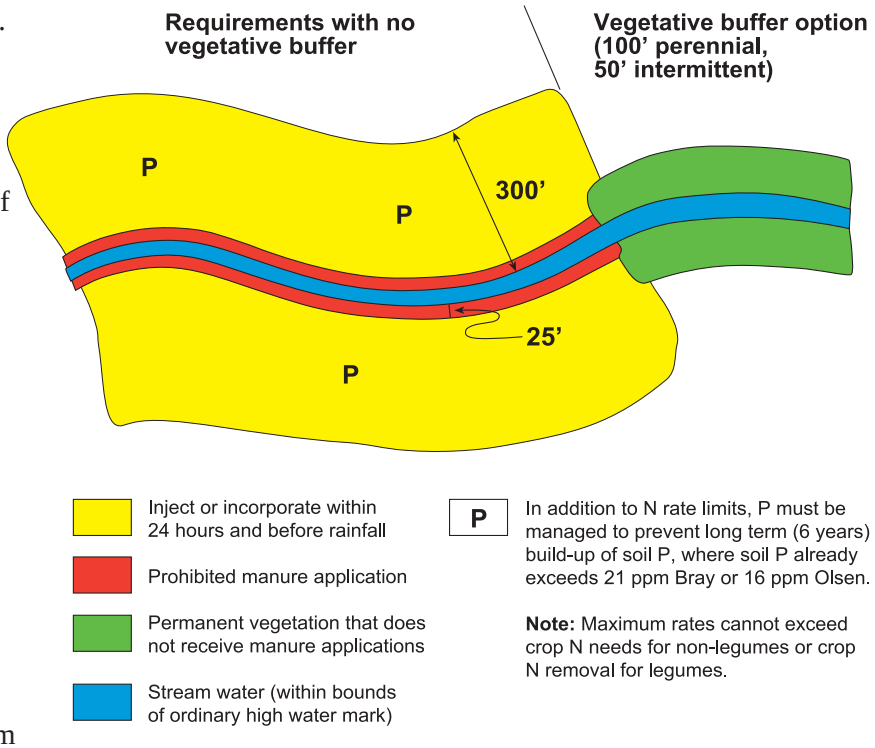

Exceptions to state requirements

- Immediate incorporation and phosphorus management are recommended, but not required, if a 100-foot-wide permanent vegetative buffer (non-manured) is planted along perennial streams, or a 50-foot-wide buffer is planted along intermittent streams.
- Requirements for manure application exclude areas of intermittent streams that are maintained as in-field grassed waterways for erosion control.

Recommended voluntary practices

- Phosphorus management and immediate incorporation are recommended on all land that slopes toward streams, even if the land is more than 300 feet from the stream and has vegetative buffers.
- See page 7: Frequently flooded soils.



Lakes and protected wetlands

Identifying lakes and protected wetlands

State-required setbacks apply to all protected lakes and wetlands identified on Minnesota Department of Natural Resources protected waters and wetlands maps. Protected wetlands are typically more than ten acres in rural areas. Maps showing protected lakes and protected wetlands are available at local Soil and Water Conservation District offices or on-line at www.dnr.state.mn.us/waters/watermgmt_section/pwi.

Minimum state requirements

- 0 to 25 feet
  - ✔ No manure application is permitted within 25 feet of the ordinary high water level.
- 25 to 300 feet
  - ✔ Inject or incorporate within 24 hours and before rainfall.
  - ✔ Manage phosphorus to prevent long-term build-up of soil P (see page 8: High phosphorus soils).
  - ✔ Do not apply manure to frozen or snow-covered soils in this zone, even if a buffer exists.
  - ✔ Do not apply manure with irrigation equipment such as a center pivot or traveling gun.
- An interim permit is needed if applying manure from feedlots with more than 300 animal units along lakes and protected wetlands where average soil phosphorus levels exceed 75 ppm Bray P1 (or 60 ppm Olsen) or where slopes exceed six percent.

Rule options for non-winter months

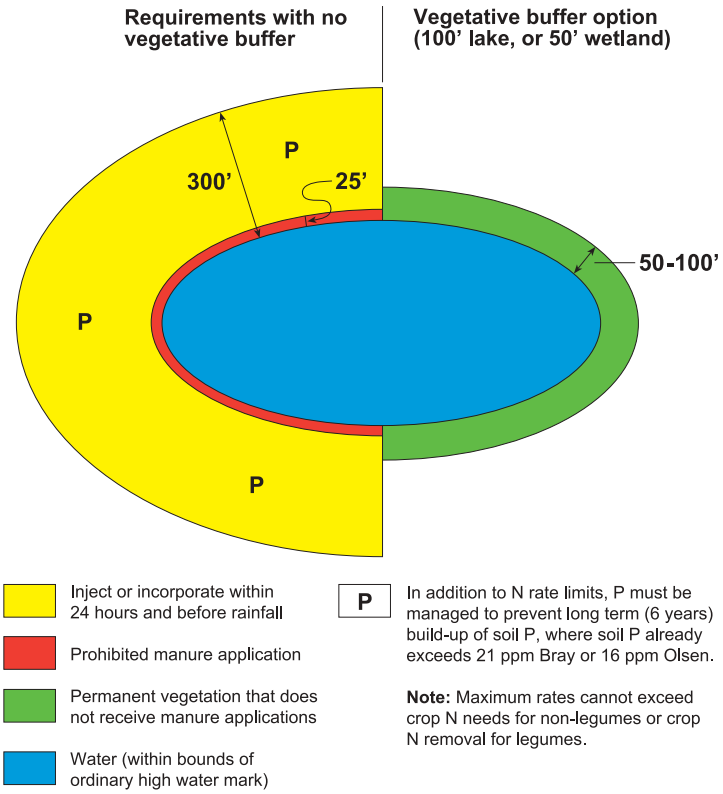

Exceptions to state requirements

- Immediate incorporation and phosphorus management are recommended, but not required, if a 50-foot-wide permanent vegetative buffer (non-manured) is planted along the wetland or a 100-foot-wide vegetative buffer is planted along the lake.
- Manure applications are allowed on seasonally saturated soils that are seeded to annual farm crops or crop rotations of perennial grasses or legumes.

Recommended voluntary practices

- Phosphorus management and immediate incorporation are recommended on all land that slopes toward lakes or wetlands, even if the land is more than 300 feet from the lake or wetland and even if the wetland is not considered a DNR-protected wetland.
- See page 8: High phosphorus soils.



Drainage ditches

Identifying drainage ditches

These requirements apply to edge-of-the-field drainage ditches shown on United States Geological Survey quadrangle maps and other ditches constructed after the maps were developed. The maps can be found at county Soil and Water Conservation District offices or on-line at www.terraserver-usa.com.

Minimum state requirements

- 0 to 25 feet
  - ✔ No manure application is permitted.
- 25 to 300 feet
  - ✔ Inject or incorporate within 24 hours and before rainfall.
  - ✔ Manage phosphorus to prevent long-term build-up of soil P (see page 8: High phosphorus soils).
  - ✔ Do not apply manure to frozen or snow-covered soils in this zone, even if a buffer exists.
  - ✔ Do not apply manure through irrigation equipment such as a center pivot or traveling gun.
- An interim permit is needed if applying manure from feedlots with more than 300 animal units along drainage ditches where average soil phosphorus levels exceed 75 ppm Bray P1 (or 60 ppm Olsen) or where slopes exceed six percent.

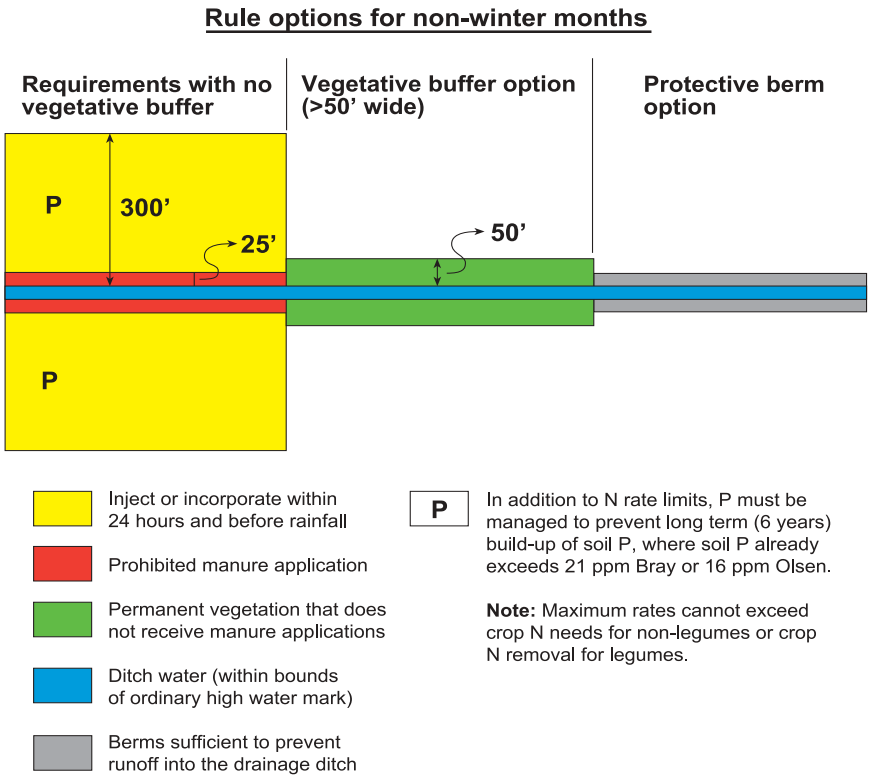

Exceptions to state requirements

- These practices are not required if an earthen berm along the drainage ditch prevents runoff into the drainage ditch. If drainage water enters side inlets through the berm, the practices are required.
- Immediate incorporation and phosphorus management are recommended, but not required, if a permanent vegetative buffer (at least 50 feet wide and non-manured) is planted along the ditch.

Recommended voluntary practices

- Phosphorus management and immediate incorporation are recommended on all land that slopes toward drainage ditches, even if the land is more than 300 feet from the ditch and a vegetative buffer is planted.
- See page 8: High phosphorus soils.



Open tile intakes

Identifying open tile intakes

Open tile intakes include man-made openings in the ground that move unfiltered and untreated runoff waters into underground pipes, which discharge the runoff into ditches or other surface waters.

Minimum state requirements

- Inject or incorporate manure within 24 hours.
- An interim permit is needed if applying manure from feedlots with more than 300 animal units within 300 feet of open tile intakes where average soil phosphorus levels exceed 75 ppm Bray P1 (or 60 ppm Olsen) or where slopes exceed six percent.

Exceptions to state requirements

- NPDES permit conditions must be followed when they are more restrictive than minimum state requirements.

Recommended practices

- Phosphorus management and immediate incorporation are recommended on all land that slopes toward open tile intakes, even if the land is more than 300 feet from the intake.

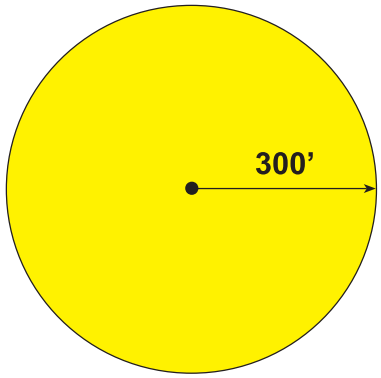

Open tile intake

Inject or incorporate within 24 hours and before rainfall

Note: Maximum rates cannot exceed crop N needs for non-legumes or crop N removal for legumes.



Steeply sloping land

Identifying steeply sloping land

Slopes of more than six percent are identified on soil survey maps with the letter C or D after the soil name. Slopes between two and six percent are identified with the letter B after the soil name. Soils with slopes of more than six percent are listed in the table “Sensitive Soil Features for Nutrient Management” available at NRCS offices and on-line at www.mn.nrcs.usda.gov/technical/ecs/nutrient/assessment/assessment.htm.

Minimum state requirements

- An interim feedlot permit is needed if manure from facilities with more than 300 animal units is to be applied regularly to soils within 300 feet of lakes, streams, intermittent streams, DNR-protected wetlands, and open tile intakes *with slopes of more than six percent.*
- NPDES permitted feedlots must follow winter-time slope restrictions of 2% (liquid) and 6% (solid), or as required in the permit.

Recommended voluntary practices

- Avoid applying manure on land where gully erosion is not controlled.
- Control sheet and rill soil losses (< 2-5 tons/acre/year) when manure is applied to steep slopes.
- Avoid winter application to steep slopes if possible. Use contour tillage if winter application is planned. (Required for NPDES permitted feedlots.)



Road ditches

Identifying road ditches

Road ditches are low-lying areas next to roads that could become channels for storm water or melted snow. If a road ditch is identified on United States Geological Survey quadrangle maps as an intermittant stream, follow requirements for intermittant streams on page 3.

Minimum state requirements

- No manure application directly into road ditches, including all land from the lowest point in the channel to the crests of ditch banks.

Recommended voluntary practices

- After storms or when snow melts, a road ditch can become a flowing channel that carries pollutants to waters. Consider using the same protective management practices as for "Perennial and intermittent streams" (page 3) when applying manure near road ditches.

Frequently flooded soils

Identifying frequently flooded soils

Frequently flooded soils (flooded 50-100 times in 100 years) are identified on soil surveys, listed in the table "Sensitive Soil Features for Nutrient Management" available at NRCS offices and on-line at www.mn.nrcs.usda.gov/technical/ecs/nutrient/assessment/assessment.htm.

Minimum state requirements

- No specific state requirements are set for applying manure on frequently flooded soils. Nitrogen rate limits (based on expected yields) pertain to all soils where manure is applied. Nutrient rate requirements are described in the publication *Land Application of Manure: Minimum State Requirements*, which can be found on-line at www.pca.state.mn.us/hot/feedlot-management.

Recommended voluntary practices

- Avoid manure application during peak flooding periods.
- Avoid manure application when the ground is frozen, snow-covered, or actively thawing.
- Immediately incorporate manure when there is risk of flooding.

High water table soils

Identifying high water table soils

Soils with water tables of two feet or less in depth are identified on the table "Sensitive Soil Features for Nutrient Management" available at NRCS county offices (along with soil survey information showing water table depths) and on-line at www.mn.nrcs.usda.gov/technical/ecs/nutrient/assessment/assessment.htm.

Minimum state requirements

- No specific state requirements are set for manure application onto high water table soils.

Recommended voluntary practices

- To reduce the chance of bacteria moving into ground water, select fields and manure application techniques that maximize the separation between applied manure and the water table. Try to keep at least a 24-inch separation above seasonal high water tables.

High phosphorus soils

Identifying high phosphorus soils

High phosphorus soils can be identified through a soil sampling and testing program. Soil sampling techniques are described on the nutrient management page at www.manure.coafes.umn.edu/applied/soil_testing. Laboratories that analyze for soil phosphorus can be found at www.mda.state.mn.us (go to "MDA A to Z" and click on "S" and "Soil Testing Laboratories").

Minimum state requirements

- Required phosphorus management practices for manure from all feedlots are summarized in the table below. The phosphorus levels refer to field average.
- Soil phosphorus testing is required by cropland managers when manure is applied from feedlots with 300 or more animal units (including when manure ownership is transferred).

Bray P1 (ppm)*	< 22	22 – 75	76 – 150	> 150
Olsen (ppm)*	< 17	17 – 60	61 – 120	> 120
More than 300 ft from lakes, streams, intermittent streams, protected wetlands, or unbermed drainage ditches	No phosphorus management requirements	No phosphorus management requirements	No phosphorus management requirements unless within 300 ft of tile intakes.	***Permit needed if manure is from feedlot with more than 300 au
Less than 300 ft from lakes, streams, intermittent streams, protected wetlands, or unbermed drainage ditches	No phosphorus management requirements	**Prevent long-term build-up of soil P	**Prevent long-term build-up of soil P ***Permit needed if manure is from feedlot with more than 300 au	**Prevent long-term build-up of soil P ***Permit needed if manure is from feedlot with more than 300 au

*If soil P test results are reported in lb/acre, divide by 2 for approximate levels in ppm (e.g., 200 lb/acre = 100 ppm). If a Mehlich III test is used (instead of Bray P1 or Olsen), then the values in the table columns are roughly <30, 31-90, 91 to 180, and over 180.

** The rate and frequency of manure applications must not allow soil phosphorus build-up over any six-year period. Single-year applications can be based on crop nitrogen needs if excess phosphorus is removed by subsequent crops. Depending on the crop, soil type, and manure nutrient levels, soil P build-up can usually be prevented when applying manure one to three times over a six-year period. Phosphorus build-up is not prohibited if a vegetative buffer is planted along the water (see exceptions).

*** Interim permit applications must include a manure management plan that describes how phosphorus will be managed to prevent pollution from phosphorus transport. Options include reducing frequency/amount of application, changing feed or feed additives to reduce phosphorus in manure, soil conservation practices, and planting crops to remove excess phosphorus. The Minnesota Phosphorus Index or NRCS 590 Standard can be used to demonstrate adequate protection of waters.

Exceptions to state requirements

Phosphorus is allowed to build up to 75 ppm Bray P1 or 60 ppm Olsen on soils within 300 feet of waters if a permanent, non-manured, vegetative buffer is established along the water. The vegetative buffer must be a minimum of 100 feet wide along lakes and streams and 50 feet wide along intermittent streams, wetlands and unbermed drainage ditches.

Recommended voluntary practices

- Begin manure applications on soils with lower phosphorus levels and use all available acres.
- Avoid build-up of soil phosphorus once levels reach the point where additional phosphorus seldom increases crop yield (21 ppm Bray P1 and 16 ppm Olsen).
- Avoid continuous annual manure applications onto soils with phosphorus levels of more than 75 ppm Bray P1 (60 ppm Olsen) regardless of the distance to waters.
- Avoid manure applications to soils with phosphorus levels of more than 150 ppm.
- Increase soil erosion control measures as phosphorus levels increase. For example, control erosion to less than 4 tons per acre per year on fields with phosphorus levels exceeding 21 ppm Bray P1 (16 ppm Olsen).
- Use grain types and feed additives that reduce phosphorus in manure.
- Inject or incorporate manure within 24 hours and prior to rainfall.
- Plant field edge vegetative filter strips.

Wells and wellhead protection areas

Identifying wells and wellhead protection areas

Wells include all active wells and inactive wells that have not been sealed in accordance with Minnesota Department of Health (MDH) requirements. Wellhead protection areas include all land supplying water to a public water system, through which potential contaminants are likely to move and reach the well. Drinking Water Supply Management Areas (DWSMAs) encompass the technically defined wellhead protection area and have identifiable landmarks as boundaries. To identify DWSMAs, contact the local public water supplier or the MDH at (800) 818-9318 or on-line at www.health.state.mn.us/divs/eh/water/swp/swa.

Minimum state requirements

- Maintain a 50-foot setback when applying manure.
- Nitrogen rate limits (based on expected yields) pertain to all soils where manure is applied. Nutrient rate requirements are described in the publication *Land Application of Manure: Minimum State Requirements* found on-line at www.pca.state.mn.us/hot/feedlot-management.
- Detailed manure application records must be kept when feedlots with 100 or more animal units apply manure in a DWSMA where the aquifer has been determined to be vulnerable in the local wellhead protection plan.

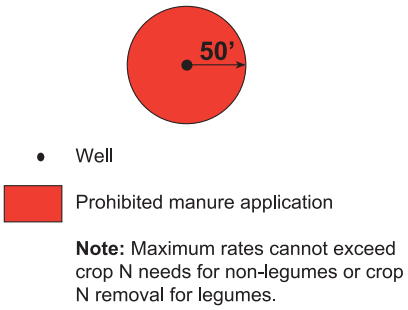

- An interim permit is needed if manure from facilities with more than 300 animal units is to be applied regularly in a DWSMA where the well and area are designated vulnerable. The permit application must include a manure management plan.

Exceptions to state requirements

- The required set back increases to 100 ft. for agricultural wellheads in fields managed by NPDES permit holders.

Recommended voluntary practices

- Inject or immediately incorporate all manure applied to land where runoff waters may flow toward active wells that are not properly grouted or inactive wells that are not properly sealed.
- Delay manure applications in the fall until average daily soil temperatures at a six-inch depth are below 50 degrees F (to maintain nitrogen in forms that generally do not leach).
- Divert field runoff away from wells, especially old or poorly constructed wells.

Sinkholes

Identifying sinkholes

Sinkholes are surface depressions caused by a collapse of soil or overlying formation above fractured or cavernous bedrock. For the purposes of manure application restrictions only, sinkholes include easily recognizable depressions in the landscape.

Minimum state requirements

- Maintain a 50-foot setback from the edge (100 ft. for NPDES permitted feedlots).
- Inject or immediately incorporate when applying manure within 50 to 300 feet on the upslope side of a sinkhole.

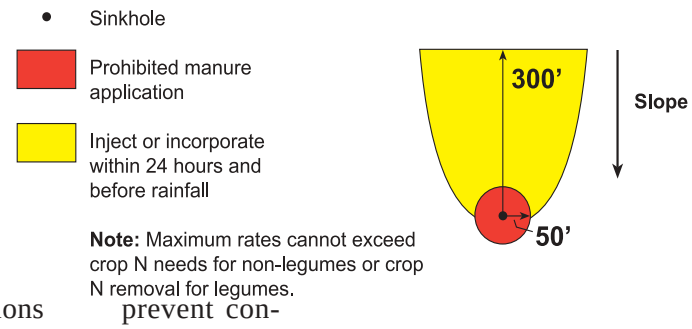

Exceptions to state requirements

- Incorporation is not required if berms or diversions prevent contaminated runoff from entering the sinkhole.

Recommended voluntary practices

- Divert field runoff from sinkholes (where needed to protect water quality), or plant vegetative filter strips on the upslope side of sinkholes.

Coarse-textured soils

Identifying coarse-textured soils

Coarse-textured soils include all soils identified in soil surveys as a sand, loamy sand, loamy coarse sand, fine sand, loamy fine sand, loamy very fine sand, very fine sand, or any soil modified by the word "gravelly." If a soil is questionable, refer to soil survey manuals found at the county Soil and Water Conservation District office. Additionally, coarse-textured soil mapping units are identified on the table "Sensitive Soil Features for Nutrient Management" available at NRCS county offices and on-line at www.mn.nrcs.usda.gov/technical/ecs/nutrient/assessment/assessment.htm.

Minimum state requirements

- At NPDES permitted feedlots, fall application onto fields with more than 1/3 coarse-textured soils must be delayed until soil temperatures in the upper six inches are less than 50° F.
- Nitrogen rate limits (based on expected yields) pertain to all soils where manure is applied.

Recommended voluntary practices

- Avoid fall applications to coarse-textured soils whenever possible. If fall application is necessary, wait until average daily soil temperatures at a six-inch depth are below 50 degrees F.

Shallow soils over bedrock

Identifying shallow soils over bedrock

Areas with bedrock less than or equal to 40 inches deep are identified in the table "Sensitive Soil Features for Nutrient Management" available at NRCS county offices and on-line at www.mn.nrcs.usda.gov/technical/ecs/assessment/assessment.htm. Metal rods or soil probes can also verify whether fractured bedrock is within two feet of the ground surface.

Minimum state requirements

- No specific state requirements are set for manure application onto shallow soils over fractured bedrock.

Recommended voluntary practices

- To reduce the chance of bacteria moving into ground water, select fields and manure application techniques that maximize the separation between applied manure and fractured bedrock. Try to keep at least a 24-inch soil separation above bedrock.
- Avoid fall applications to areas with shallow soils over bedrock if possible. If fall application is necessary, wait until average daily soil temperatures at a six-inch depth are below 50 degrees F.

Mines and quarries

Identifying mines and quarries

Mines and quarries include human excavations to remove stone, gravel, sand, iron, or other minerals.

Minimum state requirements

- Maintain a 50-foot setback for manure application from the edge of the mine or quarry.

Recommended voluntary practices

- Within 300 feet upslope of the mine or quarry, inject or incorporate manure within 24 hours of rainfall or runoff.
- Divert runoff waters from entering the mine or quarry.
- Plant vegetative buffers around mines or quarries.

MINIMUM STATE REQUIREMENTS FOR MANURE APPLICATION IN SENSITIVE AREAS

Sensitive Areas	Winter Setbacks	Non-Winter Setbacks			Other Requirements
		A: Surface Application	**B:** Incorp. + P mgmt	**C:** Incorp. NO P mgmt	
Streams/inter. streams	300’	*300’	25’	*300’	
Lakes and wetlands	300’	*300’	25’	*300’	
Drainage ditches	300’	*300’	25’	*300’	
Open tile intakes	**300’	**300’	0’	0’	
Steeply sloping land	—	—	—	—	Permit may be needed
Road ditches	—	—	—	—	No application into ditch
Frequently flooded soils	—	—	—	—	Consider in mgmt. plan
High phosphorus soils	—	—	—	—	Permit may be needed No P build-up at some sites
High water table soils	—	—	—	—	Consider in mgmt. plan
Wells/wellhead protection	50’	50’	50’	50’	Permit may be needed
Sinkholes (without berms or diversions)	50’ down 300’ up	50’ down 300’ up	50’	50’	
Coarse-textured soils	—	—	—	—	Consider in mgmt. plan
Shallow soils over bedrock	—	—	—	—	Consider in mgmt. plan
Mines and quarries	50’	50’	50’	50’	

A = Surface application with NO incorportation within 24 hours

B = Injection or incorporation within 24 hours AND phosphorus management***

C = Injection or incorporation within 24 hours with NO phosphorus management***

— = No specific requirements.

*Setbacks can be reduced from 300’ to either 100’ (lakes and perennial streams) or 50’ (wetlands, drainage ditches, and intermittent streams) if permanent vegetative buffers that are at least 100 and 50 feet wide are planted along the waters.

The 300' open tile intake setback for non-incorporated surface application of **solid manure is exempted until 2005.

***Phosphorus management means that the application rate and frequency over six-year periods will not result in soil P build-up where soil P already exceeds 21 ppm Bray P1 or 16 ppm Olsen.

This publication was developed by the Minnesota Pollution Control Agency and the USDA Natural Resources Conservation Service with the assistance of the University of Minnesota Extension Service.

Photographs provided by the Minnesota Pollution Control Agency, the USDA Natural Resources Conservation Service, and the University of Minnesota Extension Service

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FIELD RUNOFF

Root River Field to Stream Partnership



PRIMARY PROJECT GOAL

Determine the range of sediment and nutrient losses associated with runoff from representative farming systems and small watersheds in southeastern Minnesota.

Status:

Data collected from four fields, collected over seven years (2010-2016).

Contact:

Kevin Kuehner
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507-765-4530
kevin.kuehner@state.mn.us
www.mda.state.mn.us/rrfsp

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WHERE DOES THE WATER GO?

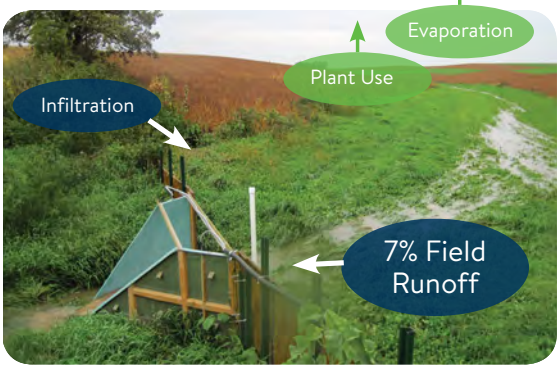

On average, 36 inches of precipitation was received annually. During the study, 7% of this total was measured as field surface runoff with a range of 1% in a dry year and up to 24% during a very wet year. How we manage this runoff can make a big difference for clean water.

- **On average, 42% of the total runoff volume occurred when the soil was frozen.**
- Over 50% of the annual nutrient and sediment losses typically occurred during 1-2 rain events each year.

High Risk Periods

Sediment and nutrient losses peak at varying times of the year. Understanding these risk periods is key to reducing loss.

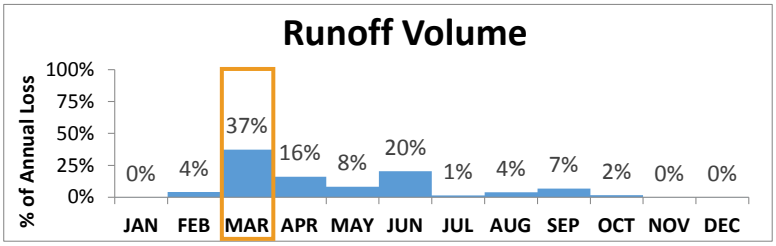

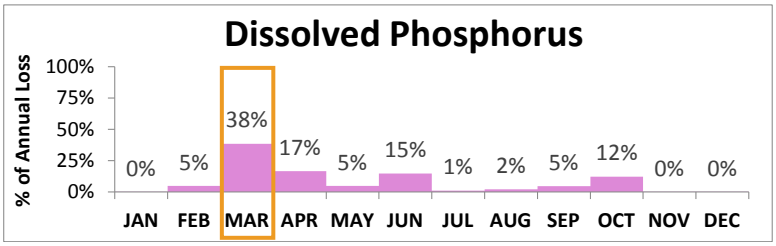

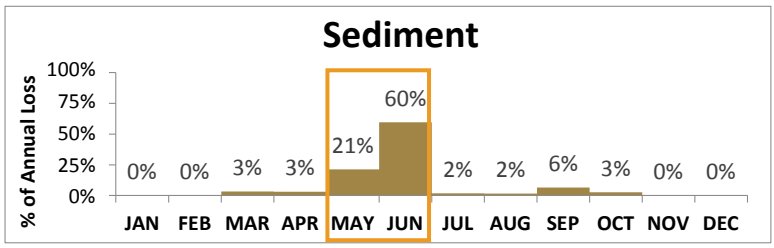

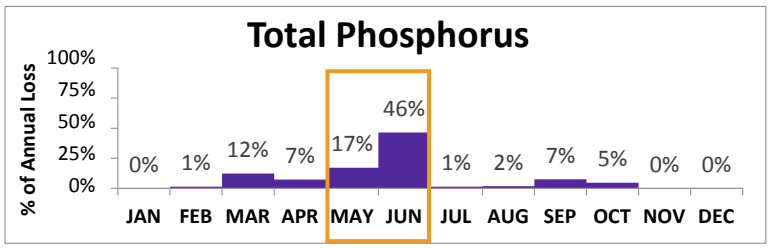

- Dissolved phosphorus losses were highest in March and often occur when the ground is frozen. **Incorporation of fertilizer and proper management of soil test phosphorus levels will help reduce these losses.**
- Over 80% of the sediment loss occurred during May and June. Total phosphorus loss is closely linked to soil loss. **Good soil conservation practices will help reduce these losses.**

Precipitation & Runoff

- Precipitation averaged 1% above normal during the study period with a mix of dry, normal and wet conditions.
- Field runoff averaged 2.7 inches (7% of annual precip.) with 42% occurring during frozen soil conditions.
- Field surface runoff has been observed in every month averaging 24 runoff events each year (runoff does not occur every time it rains).

Field Sediment Loss

- **Average sediment loss:** 1,428 lb/ac. (0.7 tons/ac.)
  Range: 2 to 8,970 lb/ac.
- **Sustainable soil loss:** < 1,000 lb/ac./year
  If erosion is visible, losses likely exceed this.
- 81% of annual loss occurred during select storms in May & June. During this critical time, fields were prepared for planting, but not at full canopy.

Field Phosphorus Loss

- **Average total phosphorus (P) loss:** 1.6 lb/ac.
  Range: <0.1 to 8.8 lb/ac.
- **Dissolve P (not attached to sediment):**
  Accounts for 17% of total P loss
  Almost 50% of this loss occurs when the ground is frozen.
- **Particulate P (attached to sediment):**
  72% of loss occurred in May & June.
- For every 1,000 lb/ac. of sediment loss about 1.0 lb/ac. of P is lost.

Field Nitrogen Loss

- **Average total nitrogen loss:**
  9.5 lb/ac. (includes organic form of N) If substantial soil loss occurs, TN in surface runoff can exceed 37 lb/ac.
  - **Nitrate-N form:**
    16% of TN
    Range: 0.2 to 4.9 lb/ac.
    Surface average runoff loss: 1.1 lb/ac.
    Sub-surface average tile loss: 36 lb/ac., max 63 lb/ac.
- **Surface Runoff:** Total nitrogen transported in surface runoff can be controlled through soil conservation.
- **Sub-Surface Leaching:** Most nitrogen is lost this way and is detected as nitrate-nitrogen in tile drainage, springs, streams, rivers, and groundwater.

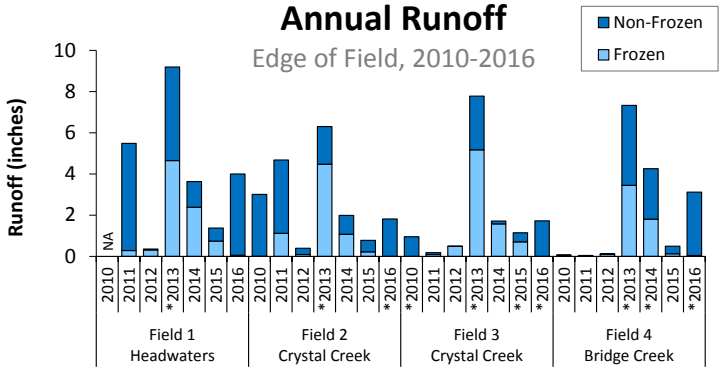

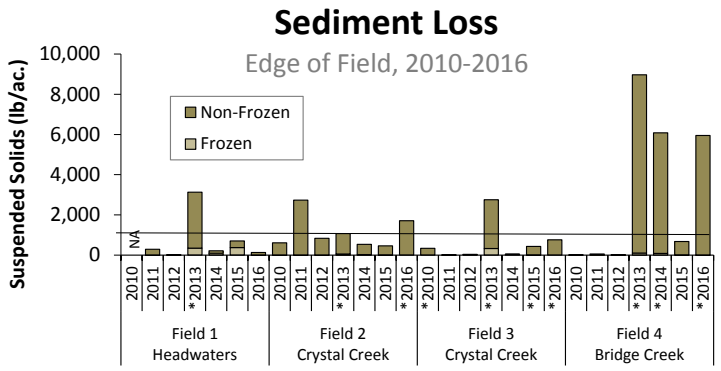

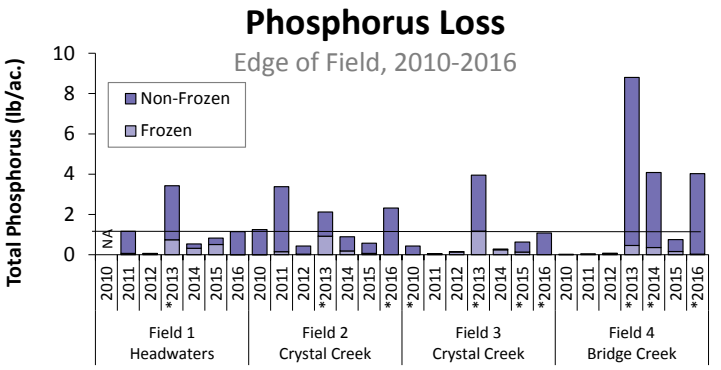

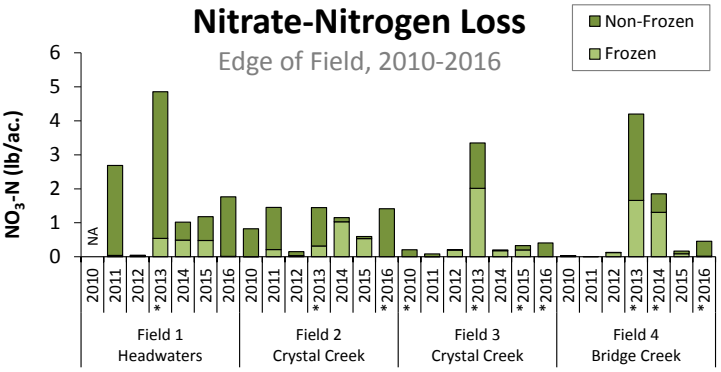

*Loss was underestimated during overtop events

Reducing nitrate leaching losses will be challenging, but it is a very important task. Fine-tuning nitrogen rates, growing perennials, crediting legumes and manure, split applying nitrogen and using cover crops are important practices.

Annex I
Sources for Footnote 259

1. *Big Fork River WRAP* 16-17 (Oct. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-37a.pdf ("Common nonpoint and natural pollutant sources in the Big Fork River Watershed are: . . . Livestock overgrazing in stream. Livestock grazing/water in the riparian zone can cause localized damage and erosion of the stream bank, and is a source of phosphorus and bacteria pollutants.").
2. *Blue Earth River Wrap* 22 (July 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-95a.pdf ("Livestock are potential sources of bacteria, phosphorus, and nitrogen to streams in the Blue Earth River Watershed, particularly when direct access is not restricted and/or where feedings structures are located adjacent to riparian areas.")
3. *Buffalo River WRAP* 18-19 (Aug. 2016), https://www.pca.state.mn.us/sites/default/files/wq-ws4-11a.pdf.
4. *Chippewa River WRAP* 11, 42 (Apr. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-24a.pdf.
5. *Clearwater River WRAP* 55-58, 60, 90-91 (Jan. 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-80a.pdf.
6. *Cottonwood River WRAP* 21 (Dec. 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-93a.pdf ("Livestock animals are potential sources of bacteria, phosphorus, and nitrogen to streams in the Cottonwood River Watershed, particularly when direct access is not restricted and/or where feeding structures are located adjacent to riparian areas.").
7. *Crow Wing River WRAP* 15 (Jan. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-09a.pdf.
8. *Lac qui Parle WRAP* 37 (Aug. 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-74a.pdf (identifying "[l]ivestock in stream channel" as a source of pollution in some areas).
9. *Lake of the Woods WRAP* 18, 38 (Feb. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-66a.pdf.
10. *La Sueur River WRAP Update* 36 (May 2025), https://www.pca.state.mn.us/sites/default/files/wq-ws4-102a.pdf.
11. *Missouri River Basin Watersheds WRAP* 23 (Jan. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-40a.pdf.
12. *Long Prairie River WRAP* 136 (Apr. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-19a.pdf.
13. *Lower Minnesota River WRAP*, iii, 51 (Feb. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-58a.pdf.
14. *Lower Rainy River WRAP* 7, 20-21, 49, 52 (Sept. 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-91a.pdf.

15. *Lower Red River of the North WRAP* 39 (Mar. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-48a.pdf.
16. *Minnesota River – Headwaters WRAP* 40-41 (Mar. 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-75a.pdf.
17. *Mississippi River – Brainerd WRAP*, 15, 18, 40 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-65a.pdf.
18. *Mississippi River – Grand Rapids WRAP* 19 (Sept. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-61a.pdf.
19. *Mississippi River – Headwaters WRAP* 34 (Aug. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-50a.pdf.
20. *Mississippi River – La Crescent WRAP* 22-23, 29, 31 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-71a.pdf.
21. *Mississippi River – Lake Pepin WRAP* 27 (Mar. 2015), https://www.pca.state.mn.us/sites/default/files/wq-iw9-15n.pdf.
22. *Vermillion River WRAPs* [Mississippi River - Lake Pepin] 23 (June 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-14a.pdf/.
23. *Upper Iowa River and Mississippi River – Reno WRAP* 12 (Mar. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-68a.pdf.
24. *Mississippi River – Sartell WRAP* ix, x, 38 (Nov. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-78a.pdf.
25. *Mississippi River – St. Cloud WRAP* 28-30 (Jan. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-07a.pdf.
26. *Mississippi River – St. Cloud WRAP Update* 61 (June 2024), https://www.pca.state.mn.us/sites/default/files/wq-ws4-99a.pdf (internal citation omitted).
27. *Nemadji River WRAP* 16 (June 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-30a.pdf.
28. *North Fork Crow River WRAP* 24-25 (Dec. 2014), https://www.pca.state.mn.us/sites/default/files/wq-ws4-06a.pdf.
29. *North Fork Crow River WRAP Update* 63 (Mar. 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-92a.pdf.
30. *Otter Tail River WRAP* 34, 36-38 (Sept. 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-82a.pdf.
31. *Pine River WRAP* 22 (Oct. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-33a.pdf.
32. *Pomme de Terre WRAP* 10 (Mar. 2013), https://www.pca.state.mn.us/sites/default/files/wq-ws4-01.pdf.
33. *Pomme de Terre WRAP Update* 55, 70 (Aug. 2024), https://www.pca.state.mn.us/sites/default/files/wq-ws4-100a.pdf.
34. *Rainy River – Headwaters WRAP* 8 (June 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-87a.pdf.

35. *Red Lake River WRAP* 57, 73, 76 (Nov. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-60a.pdf.
36. *Grand Marais Creek WRAP* [Red River of the North – Grand Marais Creek] 22 (Apr. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-56a.pdf (internal citation omitted).
37. *Marsh River WRAP* [Red River of the North – Marsh River] 10 (July 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-83a.pdf.
38. *Sand Hill River WRAP* [Red River of the North – Sand Hill River] 17-18 (Oct. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-26a.pdf.
39. *Redeye River WRAP* 17-18 (Oct. 2016), https://www.pca.state.mn.us/sites/default/files/wq-ws4-17a.pdf.
40. *Redwood River WRAP* 27 (Apr. 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-94a.pdf.
41. *Roseau River WRAP* vii, 14 (Dec. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-76a.pdf.
42. *Sauk River WRAP* 11, 26 (Mar. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-08a.pdf.
43. *Sauk River WRAP Update* 24, 29 (July 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-96a.pdf.
44. *Snake River – St. Croix Basin WRAP* 8 (Aug. 2014), https://www.pca.state.mn.us/sites/default/files/wq-ws4-04.pdf.
45. *South Fork Crow River WRAP* 34-36 (Oct. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-47a.pdf.
46. *St. Louis River WRAP* 23, 38 (Sept. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-46a.pdf.
47. *Thief River WRAP* 47-48, 72, 109-110 (Mar. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-49a.pdf.
48. *Two Rivers WRAP* 16, 36 (June 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-57a.pdf.
49. *Upper Red River of the North WRAP* 18, 24 (Dec. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-36a.pdf.
50. *Upper/Lower Red Lake WRAP* 10 (May 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-81a.pdf.
51. *Watonwan River WRAP*, 26 (Jan. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-62a.pdf.
52. *Wild Rice River WRAP*, 30-31 (May 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-89a.pdf.

Annex II
Sources for Footnote 274

1. *Blue Earth River Wrap* 99, 102, (July 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-95a.pdf.
2. *Chippewa River WRAP* 12, 94 (Apr. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-24a.pdf.
3. *Clearwater River WRAP* 169 (Jan. 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-80a.pdf.
4. *Cloquet River WRAP* 54 (Nov. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-72a.pdf (listing "[e]xclusion fencing for cattle" as a strategy in Bear Trap Creek).
5. *Cottonwood River WRAP* 75, 80, 85, 90, 94, 100, 105, 110 (Dec. 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-93a.pdf.
6. *Crow Wing River WRAP* 45, 50, 65-68, 71-73, 75, 76, 78,79 (Jan. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-09a.pdf (discussing cattle exclusion policies as a strategy).
7. *Crow Wing River WRAP Update* 32, 35-36 (Dec. 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-97a.pdf.
8. *Des Moines River Basin WRAP* 82, (Mar. 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-52a.pdf.
9. *Kettle River and Upper St. Croix River WRAP* 67, 68, 76, 95, 96, 98- 101, 107, 109-111, 120 (Mar. 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-73a.pdf.
10. *Lac qui Parle WRAP* 128 (Aug. 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-74a.pdf ("Reducing bacteria concentrations within the waterbodies of the Lac qui Parle River Watershed will require livestock are kept away from waterbodies . . ."). *See also* 132.
11. *Lake of the Woods WRAP* 57, 63, 68, 71, 73, 74 (Feb. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-66a.pdf.
12. *Lake Superior – South WRAP* 55, 58, 59, 61, 63, 65 (Dec. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-41a.pdf.
13. *La Sueur River WRAP* 28 (Aug. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-10a.pdf.
14. *Leech Lake River WRAP* 59, 63, 66, 67, 69 (June 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-31a.pdf.
15. *Little Fork River WRAP* 20 (Nov. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-21a.pdf.
16. *Missouri River Basin Watersheds WRAP* 23, 65-68 (Jan. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-40a.pdf.

17. *Long Prairie River WRAP* 83 (Apr. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-19a.pdf.
18. *Lower Red River of the North WRAP* [Lower Red River/Red River of the North – Tamarc River] 58, 61, 62 (Mar. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-48a.pdf.
19. *Minnesota River – Headwaters WRAP* 134, 136, 142 (Mar. 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-75a.pdf.
20. *Minnesota River – Mankato WRAP* 86 (Jan. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-63a.pdf.
21. *Minnesota River – Yellow Medicine River WRAP* 42 (Nov. 2016), https://www.pca.state.mn.us/sites/default/files/wq-ws4-13a.pdf.
22. *Hawk Creek WRAP*, 9, 10, 47 (Sept. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-29a.pdf.
23. *Mississippi River – Brainerd WRAP*, 40 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-65a.pdf ("Therefore, limiting livestock access to streams and properly managing manure application rates and runoff is vital to addressing bacteria impairments.").
24. *Mississippi River – Grand Rapids WRAP* 90, 96, 102, 117 (Sept. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-61a.pdf.
25. *Mississippi River – Headwaters WRAP* 97-98 (Aug. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-50a.pdf.
26. *Mississippi River – La Crescent WRAP* 57 (Aug. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-71a.pdf.
27. *Vermillion River WRAPs* [Mississippi River - Lake Pepin] 53, 59, 62, 64, 66 (June 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-14a.pdf
28. *Upper Iowa River and Mississippi River – Reno WRAP* 70-75, 77, 78 (Mar. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-68a.pdf.
29. *Mississippi River – Sartell WRAP* 75, 84, 89, 91, 93, 95, 99, 104, 106, 110, 112, 115, 117, 124, 129, 133 (Nov. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-78a.pdf.
30. *Mississippi River – St. Cloud WRAP* 62, 65 (Jan. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-07a.pdf.
31. *Mississippi River – Winona WRAP* 75-81, 84, 90, 91, 97 (Oct. 2016), https://www.pca.state.mn.us/sites/default/files/wq-ws4-28a.pdf.
32. *Nemadji River WRAP* 52, 54 (June 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-30a.pdf.
33. *North Fork Crow River WRAP* 94 (Dec. 2014), https://www.pca.state.mn.us/sites/default/files/wq-ws4-06a.pdf.
34. *North Fork Crow River WRAP Update* 62 (Mar. 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-92a.pdf.

35. *Otter Tail River WRAP* 81, 99, 100 (Sept. 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-82a.pdf.
36. *Pine River WRAP* 23, 80, 88, 89 (Oct. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-33a.pdf.
37. *Pomme de Terre WRAP Update* 70 (Aug. 2024), https://www.pca.state.mn.us/sites/default/files/wq-ws4-100a.pdf.
38. *Rainy River – Headwaters WRAP* 78 (June 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-87a.pdf.
39. *Red Lake River WRAP* 126, 141, 147 (Nov. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-60a.pdf.
40. *Marsh River WRAP* [Red River of the North – Marsh River] 27, 30 (July 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-83a.pdf.
41. *Sand Hill River WRAP* [Red River of the North – Sand Hill River] 58-63, 65, 66 (Oct. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-26a.pdf.
42. *Redeye River WRAP* 31, 34, 37-39, 41, 42, 45-47, 49, 54, 55 (Oct. 2016), https://www.pca.state.mn.us/sites/default/files/wq-ws4-17a.pdf (discussing cattle exclusion).
43. *Redwood River WRAP* 85, 91, 96, 101 (Apr. 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-94a.pdf.
44. *Roseau River WRAP* 47 (Dec. 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-76a.pdf.
45. *Rum River WRAP* 32, 35, 37, 40, 47, 53 (July 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-34a.pdf.
46. *Sauk River WRAP* 41, 45 (Mar. 2015), https://www.pca.state.mn.us/sites/default/files/wq-ws4-08a.pdf.
47. *Sauk River WRAP Update* 31-33, 54 (July 2023), https://www.pca.state.mn.us/sites/default/files/wq-ws4-96a.pdf.
48. *Snake River – St. Croix Basin WRAP* 28, 30-35 (Aug. 2014), https://www.pca.state.mn.us/sites/default/files/wq-ws4-04.pdf.
49. *South Fork Crow River WRAP* 68, 73, 78, 83, 85, 87, 90 (Oct. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-47a.pdf.
50. *St. Louis River WRAP* 57, 72, 73, 81, 92, 94, 96, 97, 99 100, 107, 111, 112 (Sept. 2018), https://www.pca.state.mn.us/sites/default/files/wq-ws4-46a.pdf.
51. *Thief River WRAP* 126 (Mar. 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-49a.pdf.
52. *Two Rivers WRAP* 50, 52, 55, 56, 61, 63, 66, 67, 75, 82, 84, 87 (June 2019), https://www.pca.state.mn.us/sites/default/files/wq-ws4-57a.pdf.
53. *Upper Red River of the North WRAP* 37, 38 (Dec. 2017), https://www.pca.state.mn.us/sites/default/files/wq-ws4-36a.pdf.

54. *Upper/Lower Red Lake WRAP* 69, 71, 72 (May 2021), https://www.pca.state.mn.us/sites/default/files/wq-ws4-81a.pdf.
55. *Wild Rice River WRAP*, 57 (May 2022), https://www.pca.state.mn.us/sites/default/files/wq-ws4-89a.pdf.
56. *Winnebago River WRAP* 75, 76 (June 2020), https://www.pca.state.mn.us/sites/default/files/wq-ws4-69

United States Department of Agriculture

472-CPS-1

Natural Resources Conservation Service

CONSERVATION PRACTICE STANDARD

ACCESS CONTROL

Code 472

(ac)

DEFINITION

The temporary or permanent exclusion of animals, people, vehicles, and equipment from an area.

PURPOSE

Achieve and maintain desired resource conditions by monitoring and managing the intensity of use by animals, people, vehicles, and equipment in coordination with the application schedule of practices, measures, and activities specified in the conservation plan.

CONDITIONS WHERE PRACTICE APPLIES

This practice applies on all land uses.

CRITERIA

General Criteria Applicable to All Purposes

Use-regulating activities (e.g., posting of signs, patrolling, gates, fences and other barriers, permits) must achieve the intended purpose and include mitigating associated resource concerns to acceptable levels during their installation, operation, and maintenance. Activities will complement the application schedule and life-span of other practices specified in the conservation plan.

Each activity or measure will identify the entity to be monitored and regulated (animals, people, vehicles, and equipment) and specify the intent, intensity, amounts, and timing of exclusion by that entity. Activities may involve temporary to permanent exclusion of one to all entities.

Placement, location, dimensions, and materials (e.g., signs, gates), and frequency of use (e.g., continuous, specific season, or specific dates) must be described for each activity including monitoring frequency**.**

CONSIDERATIONS

Even though usage of the area is monitored and controlled, the land manager and/or tenant should be advised about emergency preparedness agencies and related information (e.g., the local fire/wildfire control agency and pumper truck water sources) on or near the area. Information should be designated initially and redesignated annually.

NRCS reviews and periodically updates conservation practice standards. To obtain the current version of this standard, contact your Natural Resources Conservation Service State office or visit the Field Office Technical Guide.
USDA is an equal opportunity provider, employer, and lender.

PLANS AND SPECIFICATIONS

Specifications for applying this practice must be prepared for each area and recorded using approved specification sheets, job sheets, and narrative statements in the conservation plan, or other acceptable documentation.

OPERATION AND MAINTENANCE

Monitoring of the effectiveness of use-regulating activities will be performed routinely and at least annually with changes made to specifications and operation and maintenance requirements as necessary.

Modifications to activities and use of measures are allowed temporarily to accommodate emergency-level contingencies such as wildfire, hurricane, drought, or flood if resource conditions are maintained

REFERENCES

Gucinski, H., M.J. Furniss, R.R. Ziemer, M.H. Brookes. 2001. Forest roads: A Synthesis of Scientific Information. Gen. Tech. Rep. PNWGTR-509. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, OR.

U.S. Department of Transportation, Federal Highway Administration. 2009. Manual on Uniform Traffic Control Devices for Streets and Highways - Part 5, Traffic Control Devices for Low-Volume Roads. Washington, DC. https://mutcd.fhwa.dot.gov/pdfs/2009r1r2/pdf_index.htm.

MINNESOTA POLLUTION CONTROL AGENCY

www.pca.state.mn.us

NPDES and SDS permits for multi-site feedlot operations

When two or more feedlots under common ownership are located near one another they may be required to obtain either a National Pollutant Discharge Elimination System (NPDES) permit or a State Disposal System (SDS) permit even if they are registered with the Minnesota Pollution Control Agency (MPCA) as separate facilities.



Applicability

Federal regulations state that two or more feedlots under common ownership are considered to be a single feedlot for the purposes of determining the number of animals at an operation, if they adjoin each other or if they use a common area or system for disposal of wastes (40 CFR 122.23 (b)(2)). The MPCA commonly refers to this situation as a multi-site operation.

While this is a federal regulation applicable to the NPDES permit program, MPCA policy is to use this same criteria to determine the need for SDS permit coverage as well. It is important to note that this is only used to determine the need for a NPDES or SDS permit and does not affect other aspects of Minnesota Rule 7020 implementation.

The MPCA considers two or more animal feedlots to be one multi-site operation when:

- The sites have common ownership and
- One of the following conditions apply:
  - Any portion of the animal feedlots are located within ¼ mile of each other.
  - The animal feedlots share a liquid or solid manure storage area.

Common ownership

Common ownership exists when at least one person or entity is the full or partial owner of two or more animal feedlots. This includes instances where a single person owns one site but is a partner in a group that owns a second site. This also includes instances where a husband owns one site and his wife owns the other.

Distance between feedlots

Distance between animal feedlots is measured from the closest feedlot component (barn, manure storage area, etc.) of one site to the closest component of the other site (see examples on page 3 for illustration).

Shared manure storage

Feedlots that transport solid or liquid manure from one feedlot site to storage structures at another feedlot site are considered to share a manure storage area.

Sharing a liquid or solid manure storage area does **NOT** include:

- Two or more animal feedlots including the same fields in a manure management plan.
- Manure transfer to a third party who collects from numerous feedlots then manages the manure as a separate entity.
- Manure/litter transfer to another site to be used as bedding material.
  (i.e. litter from a turkey brood barn transported with the birds to a finishing barn)

Permit coverage

The MPCA multi-site policy is only used to determine if NPDES or SDS permit coverage is needed. When multiple feedlot sites are determined to be part of a multi-site operation, the combined animal holding capacity of all sites is used to determine if a NPDES or SDS permit is required (examples are included on page 3).

- A NPDES permit may be required if the combined animal holding capacity meets or exceeds any one of the federal large confined animal feeding operation (CAFO) thresholds.
- A SDS permit is required if the combined animal holding capacity is 1,000 or more animal units (AU). A facility may choose to obtain an NPDES permit in lieu of the SDS permit.

Table: Common large CAFO and 1,000 animal unit thresholds

Animal Type	Large CAFO Threshold (Head count)	1,000 Animal Units[a] (Head count)
Mature Dairy Cows	700	715
Beef Cattle (steers)[b]	1,000	1,000
Heifer or Background Feeder[b]	1,000	1,429
Swine – Finishing	2,500	3,334
Broiler Chickens >5 lb.	125,000	200,000
Turkeys >5 lb.	55,000	55,556

[a]The AU numbers from multiple animal types are counted in aggregate to determine the multi-site total AU.

[b]All cattle, other than mature dairy cows, are counted in aggregate for the large CAFO threshold.

More information about NPDES and SDS permits is found in the fact sheet *NPDES and SDS permits for feedlots*.

Obtaining NPDES or SDS permit coverage

For **each** feedlot considered to be part of a multi-site operation, the owner must complete the following:

- Obtain permit coverage, including payment of applicable application fees, for each feedlot. See the MPCA fact sheet *Applying for a feedlot permit* for more information on the application process.
- By March 1 of each year submit an annual report for each feedlot.
- Pay the annual permit fee for each feedlot.
- Maintain registration for each feedlot.

The MPCA uses registration data to determine how many permits a multi-site operation must obtain. If a multi-site operation consists of three registered feedlots, it must obtain three permits, one for each registered feedlot.

Permit modification

When a modification is proposed for one, or more, of the feedlots determined to be a part of a multi-site operation, the permittee is only required to submit the appropriate permit application and application fee for the feedlot that is being modified.

Getting help or more information

The formal multi-site policy can be viewed on the MPCA website at: https://www.pca.state.mn.us/sites/default/files/wq-f6-63.pdf.

Further questions about the multi-site policy can be directed to MPCA feedlot staff. Contact information can be found on the MPCA website at: https://www.pca.state.mn.us/water/mpca-feedlot-staff-contacts

For more information about the feedlot program, visit the feedlot program homepage at: www.pca.state.mn.us/feedlots

Examples

Use the diagram to the right as reference for all examples.

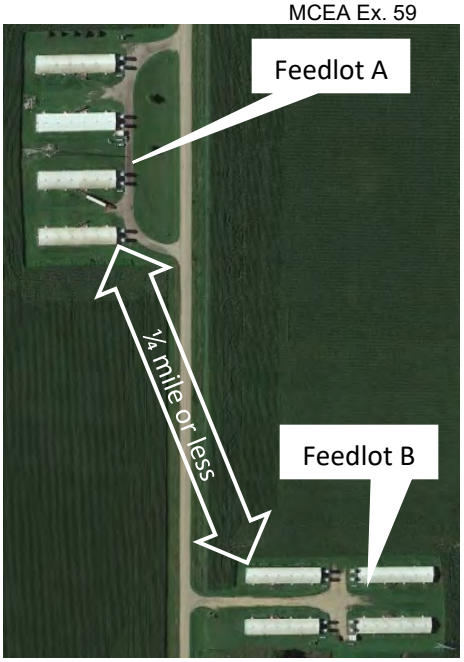

Example 1.

	Feedlot A	Feedlot B
Owner:	John Doe	John Doe
Capacity:	2,400 finishing swine (720 AU)	2,400 finishing swine (720 AU)

- This is a multi-site operation. There is common ownership and the sites are within ¼ mile.
- A SDS (or NPDES) permit is required because the combined capacity exceeds 1,000 AU. A NPDES permit may be required as the combined number of animals exceeds a large CAFO threshold.
- The owner is required to obtain two permits, one for each feedlot.

Example 2.

	Feedlot A	Feedlot B
Owner:	John Doe	Doe Bros LLP (John Doe is a partner)
Capacity:	2,400 finishing swine (720 AU)	2,400 finishing swine (720 AU)

- This is a multi-site operation. There is common ownership, since John is a partner in Doe Bros LLP, and the sites are within ¼ mile.
- A SDS (or NPDES) permit is required because the combined capacity exceeds 1,000 AU. A NPDES permit may be required as the combined number of animals exceeds a large CAFO threshold.
- Each owner is required to obtain a permit, one for each feedlot.

Example 3.

	Feedlot A	Feedlot B
Owner:	John Doe	Jane Doe (Jane is John's wife)
Capacity:	2,400 finishing swine (720 AU)	4,800 nursery swine (240 AU)

- This is a multi-site operation. There is common ownership, since John and Jane are married, and the sites are within ¼ mile.
- No permit is required because the combined capacity does not exceed 1,000 AU or a large CAFO threshold.

Example 4. Assume the feedlots are ½ mile apart

	Feedlot A*	Feedlot B
Owner:	John Doe	John Doe
Capacity:	2,400 finishing swine (720 AU)	2,400 finishing swine (720 AU)

**Manure is pumped from shallow pits at Feedlot A to deep pits at Feedlot B for storage*

- This is a multi-site operation. There is common ownership and, although the feedlots are more than ¼ mile apart, the feedlots share manure storage at Feedlot B.
- A SDS (or NPDES) permit is required because the combined capacity exceeds 1,000 AU. A NPDES permit may be required as the combined number of animals exceeds a large CAFO threshold.
- The owner is required to obtain two permits, one for each feedlot.

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Jay Eidsness Attachment

July 22, 2025

Minnesota Pollution Control Agency
520 Lafayette Rd.
St Paul, MN 55155

Via Office of Administrative Hearings Rulemaking eComments Website at https://minnesotaoah.granicusideas.com/discussions

Re: Planned Amendments to Rules Governing Animal Feedlots, Minnesota Rules, Chapter 7020, Revisor's ID Number R-4928 (OAH Docket No. 25-9003-40661)

The undersigned organizations submit this comment in response to the Minnesota Pollution Control Agency's (MPCA's) request for comments on proposed amendments to Minn. R. Ch. 7020—the rules governing animal feedlots (the "Rule" or "Feedlots Rule"). While the agency's stated focus is primarily on water quality, the Feedlots Rule also addresses air pollution, another important area within the scope of MPCA's authority. The same facilities that pose serious risks to Minnesota's lakes, rivers, and groundwater are among the largest unregulated sources of potent greenhouse gas (GHG) emissions in the state.[1] Methane and nitrous oxide emissions from feedlots and manure management systems are accelerating climate change and all of its attendant harms.[2] Yet, even as the state's GHG inventory shows no progress in reducing agricultural GHG emissions,[3] MPCA's Feedlots Rule continues to overlook this growing threat. We urge MPCA to use this rulemaking to address these critical and long-ignored air emissions.

MPCA has both the authority and the obligation to act. Requiring feedlot operators to engage in GHG mitigation, including monitoring and reporting, addresses air and water co-pollutants (e.g., ammonia, volatile organic compounds, and nitrates) and aligns with MPCA's mandate as well as Minnesota's climate and public health goals.[4] The need to address air emissions from feedlots is especially critical now, as Minnesota's Climate Action Framework is also undergoing revision.[5] This rulemaking presents a timely opportunity to ensure consistency between the state's regulatory tools and its broader climate commitments.

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[1] *Minnesota Issue Guide: Feedlots*, MINN. LEGIS. REFERENCE LIB. (Feb. 2025), https://www.lrl.mn.gov/guides/guides?issue=feedlots (discussing longstanding air pollution concerns about feedlots); MINN. POLLUTION CONTROL AGENCY (MPCA), GREENHOUSE GAS EMISSIONS IN MINNESOTA 2005-2022 9 (2025), https://www.pca.state.mn.us/sites/default/files/lraq-3sy25.pdf [hereinafter MPCA GHG EMISSIONS IN MINNESOTA].

[2] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 3.

[3] *Id.* at 9.

[4] *Climate Change Impacts*, MPCA, https://www.pca.state.mn.us/air-water-land-climate/climate-change-impacts (last visited July 17, 2025) [hereinafter *MPCA Climate Change Impacts*]; MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 3, 5, 9-12); *infra* Part I.B (discussing co-pollutants).

[5] MINNESOTA, MINNESOTA'S CLIMATE ACTION FRAMEWORK (2022), https://climate.state.mn.us/sites/climate-action/files/Climate%20Action%20Framework.pdf [hereinafter MINNESOTA'S CLIMATE ACTION FRAMEWORK]; *Climate Action Framework*, MINNESOTA, https://climate.state.mn.us/minnesotas-climate-action-framework (last visited July 17, 2025).

At a minimum, MPCA must adopt a Rule that strengthens the permit application's required air emission plans.[6] But MPCA should go further: the Rule must be updated to explicitly address GHG emissions from animal feedlots, which represent one of the largest sources of climate pollution in Minnesota's agricultural sector.[7] Regulatory inaction is no longer an option.

This comment covers four major topics concerning the regulation and mitigation of GHGs from feedlots. The first section explains why the Rule must require feedlots to track and mitigate GHGs, and why MPCA should monitor and regulate these emissions. The second section analyzes MPCA's legal authority to regulate GHGs through the Feedlots Rule. The third section highlights the shortcomings of air emission plans under Minn. R. 7020.0505, subp. 4(B)(1). Finally, this comment concludes by offering pathways to GHG mitigation.

I. MPCA Must Start Regulating GHG Emissions From Feedlots To Comply With Its Obligations And For Minnesota To Meet Its Statutory Climate Goals

A. Minnesota's Animal Agriculture GHG Emissions Problem

MPCA should take this opportunity to update the Feedlots Rule to confront the reality that Minnesota will not meet its GHG emission reduction goals without addressing emissions from feedlots.[8] Beginning with the Next Generation Energy Act in 2007 and embodied in the more recent statutory commitment to achieving net-zero emissions by 2050, Minnesota has set important and appropriate climate goals.[9] The Climate Action Framework, which is currently being revised, lays out a roadmap for achieving these emissions reductions.[10] These policies are grounded in the need to protect the "public health and welfare" from the worsening effects of climate change.[11] Yet the agriculture sector remains a glaring gap in Minnesota's emission reduction efforts.

MPCA's reporting shows that the agriculture sector is the second largest source of GHG emissions in the state, responsible for approximately 25% of net emissions.[12] Animal agriculture is responsible for most methane emissions in Minnesota, and a significant portion of the sector's nitrous oxide emissions stem from manure management and growing feed for livestock.[13] Unlike

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[6] MINN. R. 7020.0505, subp. 4(B)(1); *see also* ENV'L PROT. AGENCY (EPA), *Minnesota: Air Emissions Planning*, *in* COMPENDIUM OF STATE APPROACHES FOR MANURE MANAGEMENT (2017), https://www.epa.gov/sites/default/files/2017-01/documents/c_minnesota_air_emissions_planning.pdf.

[7] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 9.

[8] *See id*; *see also Climate Change Trends and Data*, MPCA, https://www.pca.state.mn.us/air-water-land-climate/climate-change-trends-and-data (last visited June 15, 2025).

[9] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 5; MINN. STAT. § 216H.02, subd. 1(a).

[10] MINNESOTA'S CLIMATE ACTION FRAMEWORK, *supra* note 5; *Climate Action Framework*, *supra* note 5.

[11] Press Release, EPA, Greenhouse Gases Threaten Public Health and the Environment (Dec. 7, 2009), https://www.epa.gov/archive/epapages/newsroom_archive/newsreleases/08d11a451131bca585257685005bf252.html; *see also MPCA Climate Change Impacts*, *supra* note 4 ("Minnesotans are feeling impacts of climate change, from higher temperatures, more extreme storms with intense flooding, and changes in our unique and cherished ecosystems. These impacts will continue to have serious effects on the economy, natural environment, and quality of life in Minnesota.").

[12] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 9.

[13] *Id.* at 3, 10; *Minnesota Greenhouse Gas Inventory: Sector-Level Details, Agriculture Sector*, MPCA, https://data.pca.state.mn.us/views/Greenhousegasemissionsdata/Sectordetails (last visited July 18, 2025) [hereinafter

other sectors such as electrical generation and transportation that have seen reduced emissions since 2005, emissions from agriculture increased 1% between 2005 and 2022.[14] Without regulatory action targeting these emissions, Minnesota will be unable to meet its statutory climate targets or fulfill its duty to protect public health.

Minnesota's need to address GHG emissions from feedlots is consistent with and supported by our knowledge of the global climate system. Even if fossil fuel emissions ended immediately, global emissions related to food production alone could preclude reaching the goals of the Paris Climate Agreement.[15] Animal agriculture is responsible for the lion's share of food system emissions.[16] Addressing food system emissions requires addressing the "cow in the room."[17]

Moreover, the scale of methane emissions from animal agriculture means that animal agriculture presents one of the most promising near-term mitigation opportunities. Animal agriculture is the United States' top anthropogenic source of methane, responsible for 36.6% of methane emissions.[18] In Minnesota, methane emissions from manure management and enteric fermentation were more than 8.2 million metric tons of CO_2 equivalent in 2022,[19] far more than the less than 1.6 million metric tons of CO_2 equivalent emitted from landfills.[20] And methane emissions from animal agriculture are trending upward in Minnesota: "since 2005, methane emissions from animal agriculture have increased 10% in the state . . . ."[21]

Methane is about 80 times more warming than carbon dioxide over a 20-year period.[22] But because of its relatively short persistence in the atmosphere—with an average methane molecule

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MPCA GHG Inventory: Agriculture Sector Details]. Minnesota is comparable to the rest of the nation in this respect. Animal agriculture is the largest agricultural emitter in the United States: nearly 80% of U.S. agriculture emissions are from the production of animals for food and their feed. Peter H. Lehner & Nathan A. Rosenberg, *Farming for Our Future: The Science, Law, and Policy of Climate-Neutral Agriculture*, WEST ACADEMIC 43 (2021).

[14] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 9; *GHG Emissions and Sequestration from 2005 to 2022, by Sector*, MPCA, https://data.pca.state.mn.us/views/Greenhousegasemissionsdata/Emissionsbysector2005-2022 (last visited July 20, 2025).

[15] Michael A. Clark et al., *Global Food System Emissions Could Preclude Achieving the 1.5º and 2ºC Climate Targets*, 370 SCIENCE 705-08 (2020).

[16] Xiaoming Xu et al., *Global Greenhouse Gas Emissions from Animal-Based Foods Are Twice Those of Plant-Based Foods*, 2 NATURE FOOD 724, 726 (2021) (estimating that global GHG emissions from animal-based foods are 57% of all food system emissions).

[17] *E.g.*, Phoebe Weston and Jonathan Watts, *The Cow in the Room: Why Is No One Talking About Farming at COP26?*, GUARDIAN (Nov. 9, 2021), https://www.theguardian.com/environment/2021/nov/09/the-cow-in-the-room-why-is-no-one-talking-about-farming-at-cop26-aoe.

[18] EPA, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990–2022 ES-18 (2024) (EPA 430-R-24-004), https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf [hereinafter EPA GHG INVENTORY]. Animal agriculture is responsible for about a third of all anthropogenic emissions globally. *Methane Emissions Are Driving Climate Change: Here's How to Reduce Them*, U.N. ENV'T PROGRAMME (Aug. 20, 2021), https://www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them.

[19] *MPCA GHG Inventory: Agriculture Sector Details*, *supra* note 13.

[20] *Minnesota Greenhouse Gas Inventory: Sector-Level Details, Waste Sector*, MPCA, https://data.pca.state.mn.us/views/Greenhousegasemissionsdata/Sectordetails (last visited July 18, 2025).

[21] Ben Lilliston, *Minnesota Agriculture Emissions: The CAFO Challenge*, INST. FOR AGRIC. & TRADE POL'Y 2 (Mar. 2023), https://www.iatp.org/sites/default/files/2023-03/MN%20GHG%20analysis%202023.3.pdf.

[22] Piers Forster et al., *The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS. CONTRIBUTION OF WORKING GROUP I TO THE SIXTH ASSESSMENT REPORT OF

remaining for about ten years[23] (as compared to carbon dioxide, which can cause warming for hundreds or even thousands of years[24])—reducing methane emissions in the coming years can play an important role in curbing warming.[25] Moreover, reducing carbon dioxide emissions without serious action on super-pollutants, including methane, will preclude achievement of the Paris Climate Agreement and Minnesota's GHG reduction goals.[26]

Nitrous oxide, like methane, is a climate super-pollutant closely associated with animal farming.[27] Nitrous oxide is one of the most powerful GHGs—estimated to contribute 273 times more than carbon dioxide to global warming over a 100-year timescale[28]—and is also harmful to the ozone layer.[29] Human-caused emissions of nitrous oxide have increased more than 40% over the past forty years, driven in large part by the use of nitrogen fertilizer and manure from farmed animals.[30] According to a U.N. estimate, animal agriculture is responsible for at least half of global anthropogenic nitrous oxide emissions.[31] The agricultural sector is responsible for nearly all of Minnesota's nitrous oxide emissions, and a significant portion of those emissions are attributed to the land application of manure.[32] Since 2005, "nitrous oxide emissions related to both manure and synthetic fertilizer use have increased 9%" in Minnesota.[33]

Thus, failing to address GHG emissions from feedlots will aggravate climate change-related consequences in Minnesota. Rising temperatures and the increase in size and frequency of storms and disasters has resulted in unprecedented damage.[34] Per MPCA, "[d]aily average minimum temperatures during winter (Dec-Feb) have increased 7.3 degrees from 1895-2021 in northern

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THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 923, 1017 tbl.7.15 (Valérie Masson-Delmotte et al. eds., 2021).

[23] *Understanding Global Warming Potentials*, EPA (Jan. 16, 2025), https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

[24] *Carbon Dioxide Emissions*, EPA (Feb. 13, 2025), https://www.epa.gov/ghgemissions/carbon-dioxide-emissions.

[25] U.N. ENV'T PROGRAMME, GLOBAL METHANE ASSESSMENT 11 (2021), https://www.ccacoalition.org/sites/default/files/resources//2021_Global-Methane_Assessment_full_0.pdf [hereinafter GLOBAL METHANE ASSESSMENT]. As observed by one of the lead reviewers of a 2021 U.N. Intergovernmental Panel on Climate Change (IPCC) report: "Cutting methane is the biggest opportunity to slow warming between now and 2040. We need to face this emergency." Fiona Harvey, *Reduce Methane or Face Climate Catastrophe, Scientists Warn*, GUARDIAN (Aug. 6, 2021), https://www.theguardian.com/environment/2021/aug/06/reduce-methane-or-face-climate-catastrophe-scientists-warn; *see also* GLOBAL METHANE ASSESSMENT, *supra*, at 8 ("Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5ºC.").

[26] Gabrielle B. Dreyfus et al., *Mitigating Climate Disruption in Time: A Self-Consistent Approach for Avoiding Both Near-Term and Long-Term Global Warming*, PROCS. NAT'L ACAD. SCIS., May 23, 2022, at 1-8.

[27] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 3.

[28] *Understanding Global Warming Potentials*, *supra* note 23.

[29] Robert Portmann et al., *Stratospheric Ozone Depletion Due to Nitrous Oxide: Influences of Other Gases*, 367 PHIL. TRANSACTIONS ROYAL SOC'Y B 1256, 1263 (2012).

[30] Hanqin Tian, *Global Nitrous Oxide Budget (1980-2020)*, 16 EARTH SYS. SCI. DATA 2543, 2545, 2549 (2024).

[31] Pierre J. Gerber et al., *Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities*, FOOD & AGRIC. ORG. OF THE U.N. (FAO) 15 (2013), https://www.fao.org/3/i3437e/i3437e.pdf (relying on 2004 and 2005 data).

[32] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 9; *MPCA GHG Inventory: Agriculture Sector Details*, *supra* note 13.

[33] Lilliston, *supra* note 21.

[34] *Climate Change Impacts*, *supra* note 4.

Minnesota, 6 degrees in central Minnesota and 4.9 degrees in southern Minnesota."[35] Lakes are now experiencing an average of up to two fewer weeks of ice cover each year.[36] These changes put an increasing strain on Minnesota's budget.[37] According to MPCA: "Over the past decade . . . our state has been experiencing a much higher rate of natural disasters, with a higher number of individual storms that cause more than $1 billion in damage."[38]

Agricultural producers are themselves intensely vulnerable to the impacts of climate change. In the summer of 2023, the administrator of the U.S. Department of Agriculture's (USDA's) Farm Service Agency observed:

> The recent heat domes plaguing many parts of the country have proven to be unsurvivable for some animals and temperatures are not expected to let up any time soon. This is one of the latest, many examples of how a changing climate is creating immediate challenges for farmers and ranchers . . . .[39]

According to MPCA, farmers are already experiencing (and can expect to continue experiencing) a range of negative impacts from climate change.[40] Rising temperatures, unpredictable precipitation, and more frequent extreme weather events are disrupting planting schedules, reducing crop yields, and increasing crop losses from pests, diseases, and disasters.[41] While some areas experience heavy rainfall and flooding, others suffer from prolonged dry spells and drought, often within the same growing season. This variability not only lowers crop yields but also degrades soil and water quality.[42] Here in Minnesota, climate change is driving more intense and erratic droughts in this water-rich state, and extreme droughts are stressing water supplies and state budgets. Just a few years ago in 2021, a historic drought across the state prompted $10 million in emergency funding to help producers weather the dry conditions.[43] The lack of rain has also prompted producers to increase irrigation. That summer farmers collectively withdrew 6.1 billion gallons of water more than their permits allowed.[44]

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[35] *Id*.
[36] *Id*.
[37] *Id*. ("Costly repairs to infrastructure, increasing home and crop insurance rates, destructive shifts in our native ecosystems, and more hospitalizations for heat-related illness are some of the impacts climate change is having on Minnesotans and the economy.").
[38] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 2.
[39] News Release, U.S. Department of Agriculture (USDA), USDA Updates Livestock Disaster Payment Rate to Assist Producers Hard-Hit by Heat and Humidity (Aug. 25, 2023), https://www.fsa.usda.gov/news-events/news/08-25-2023/usda-updates-livestock-disaster-payment-rate-assist-producers-hard-15.
[40] *Climate Impacts on Agriculture*, MPCA, https://www.pca.state.mn.us/air-water-land-climate/climate-impacts-on-agriculture (last visited July 18, 2025).
[41] *Id*.; *Farmers Face New Challenges for Crops, Livestock*, OUR MINNESOTA CLIMATE, https://climate.state.mn.us/farmers-face-new-challenges-crops-livestock (last visited July 18, 2025).
[42] *Climate Impacts on Agriculture*, *supra* note 40; *Climate Change in Minnesota*, UNIV. OF MINN. CLIMATE ADAPTATION P'SHIP, https://climate.umn.edu/climate-change-minnesota-0 (last visited July 18, 2025).
[43] Press Release, Office of Governor Tim Walz & Lt. Governor Peggy Flanagan, Governor Walz Announces $10 Million Drought Relief Package for Farmers, Producers, Minn. (Sept. 24, 2021), https://mn.gov/governor/newsroom/press-releases/?id=1055-500585.
[44] Dionne Searcey, *Big Farms and Flawless Fries Are Gulping Water in the Land of 10,000 Lakes*, N.Y. TIMES (Sept. 3, 2023), https://www.nytimes.com/interactive/2023/09/03/climate/minnesota-drought-potatoes.html.

Recent reports from Smithfield Grain, a major feed purchaser and subsidiary of Smithfield Foods, one of the world's largest pig producers, highlight how these climate stressors are already affecting Minnesota producers. As of June 2025, spring crop planting and development in some parts of the Upper Midwest was delayed by extreme weather events including strong winds, dust storms, and erratic rainfall that disrupted planting and damaged crops.[45] The University of Minnesota Research and Outreach Center at Lamberton reported below-average rainfall and the lowest soil moisture levels in five years.[46] Abnormally dry to moderate drought conditions were documented across western and northern Minnesota.[47] These impacts not only threaten crop yields and farm incomes but can also increase feed costs and risk food system instability.

Climate change is also producing more severe storms that dump large amounts of water on the land in a short amount of time. These "mega-rain" events are not as helpful for growing crops as slow, soaking rains, and climate change is bringing more of the intense, unhelpful storms to Minnesota.[48] Minnesota farmers increasingly face the added burden of managing wet pastures and feed soaked by these storms, and animals suffer and have even drowned in flash flood conditions.[49] Just last month, the Minnesota State Cattlemen's Association president observed: "With this drastic change in cool to hot and the water stresses, we did have a feedlot call that had fairly higher death loss due to some of this water and stress that they're dealing with in cattle . . . ."[50]

Rising temperatures will further harm livestock health and productivity. For example, "[h]eat-stressed hogs eat less, and heat may interfere with breeding, gestation, and lactation."[51] A USDA animal scientist estimated that extreme summer heat may cost the U.S. pork industry nearly $500 million annually.[52] During a heat wave in 2011, an estimated 1,000 cattle died in south central and southwestern Minnesota due to extreme temperatures, causing estimated losses of roughly $1 million.[53] These challenges underscore the urgent need for MPCA to address GHG emissions from feedlots. Mitigating emissions will not only protect against future climate damage but also help stabilize Minnesota's agricultural economy and food supply in the face of increasing environmental volatility.

Global warming also has widespread impacts on ecosystems and the environment in Minnesota. Tree species more vulnerable to high temperatures, such as black spruce, may be

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[45] Kent Thiesse, *Crops Have Been Slow to Develop in the Upper Midwest*, SMITHFIELD GRAIN (June 5, 2025), https://smithfieldgrain.com/story-crops-been-slow-develop-upper-midwest-0-255565.
[46] *Id.*
[47] *Id.*
[48] *Mega-Rains Overwhelm Rivers, Roads, and Budgets*, OUR MINNESOTA CLIMATE, https://climate.state.mn.us/mega-rains-overwhelm-rivers-roads-and-budgets (last visited July 18, 2025); Alexandra Witze, *Why Extreme Rains Are Getting Worse*, 563 NATURE 458, 458 (2018).
[49] *Managing Grazing Livestock During Wet Weather*, UNIV. OF MINN. EXTENSION (2024), https://extension.umn.edu/beef-cow-calf/managing-grazing-livestock-during-wet-weather; *Cows Swept Away by Flash Flooding in Southeastern Minnesota*, FOX5 N.Y. (Jun. 30, 2019), https://www.fox5ny.com/news/cows-swept-away-by-flash-flooding-in-southeastern-minnesota.
[50] Mark Dorenkamp, *Flooding Results in Livestock Losses*, BROWNFIELD (Jun. 25, 2024), https://www.brownfieldagnews.com/news/flooding-results-in-livestock-losses.
[51] *Farmers Face New Challenges for Crops, Livestock*, *supra* note 41.
[52] *Hot Situation for Hogs*, USDA AGRIC. RSCH. SERV. (Nov. 21, 2023), https://www.ars.usda.gov/oc/dof/hot-situation-for-hogs/.
[53] Elizabeth Baier, *Cattle Dying Due to Heat Wave*, MPR NEWS (July 20, 2011), https://www.mprnews.org/story/2011/07/20/cattle-die-from-heat-wave.

replaced with more heat resilient species like oaks. Such "changes in tree cover are accompanied by changes in wildlife and soil habitat."[54] Higher temperatures and increased runoff from storms can cause toxic algae blooms.[55] Rising temperatures and volatile changes in precipitation have altered the travel patterns of migratory species, making it more difficult for them to locate reliable food sources.[56]

Despite these high stakes, Minnesota currently lacks meaningful monitoring or reporting requirements for feedlot GHG emissions. GHG calculations used to track Minnesota's progress on its emission reduction goals are not based on reported emissions or monitoring from the feedlots themselves. Instead, reported emissions are estimated from sources including the U.S. Environmental Protection Agency's (EPA's) emissions inventory.[57] EPA's estimates are calculated using USDA's census, which relies on self-reporting from the animal agriculture sector.[58] But research using machine learning suggests that the size and polluting activities of industrial animal agriculture facilities are underreported.[59] As observed by the U.S. Government Accountability Office: "No federal agency collects accurate and consistent data on the number, size, and location of" large industrial animal agriculture facilities.[60] For these reasons and others, real-world measurements of methane emissions from animal agriculture are often much higher than emissions calculated using current models—indicating the potential that emissions are much higher than we realize.[61]

In sum, obtaining better data on and reducing GHG emissions from animal agricultural is vital for Minnesota to reach its GHG goals. This rulemaking presents an opportunity for MPCA to incorporate common sense regulations into the Feedlots Rule to start addressing GHG

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[54] *Climate Impacts on the Environment*, MPCA, https://www.pca.state.mn.us/air-water-land-climate/climate-impacts-on-the-environment (last visited June 18, 2025).
[55] *Id*.
[56] *Id*.
[57] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 27 (citing EPA GHG INVENTORY, *supra* note 18).
[58] EPA GHG INVENTORY, *supra* note 18, at 1-13, 5-6, 5-8, 5-15; USDA NAT'L AGRIC. STAT. SERV. (NASS), 2022 CENSUS OF AGRICULTURE METHODOLOGY app. A, https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/usappxa.pdf; USDA NASS, CENSUS OF AGRICULTURE MINNESOTA STATE AND COUNTRY DATA (AC-22-A-23), https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_State_Level/Minnesota/mnv1.pdf.
[59] Ben Chugg et al., *Detecting Environmental Violations with Satellite Imagery in Near Real Time: Land Application under the Clean Water Act*, 31 ASS'N FOR COMPUTING MACH. INT'L CONF. ON INFO. & KNOWLEDGE MGMT. 3052, 3059 (2022), https://dl.acm.org/doi/10.1145/3511808.3557104; Cassandra Handan-Nader & Daniel E. Ho, *Deep Learning to Map Concentrated Animal Feeding Operations*, 2 NATURE SUSTAINABILITY 298, 298-99 (2019), https://dho.stanford.edu/wp-content/uploads/CAFO_Final.pdf.
[60] U.S. GOV'T ACCOUNTABILITY OFF., TECH. REP. NO. GAO-08-944, CONCENTRATED ANIMAL FEEDING OPERATIONS: EPA NEEDS MORE INFORMATION AND A CLEARLY DEFINED STRATEGY TO PROTECT AIR AND WATER QUALITY FROM POLLUTANTS OF CONCERN TECHNICAL REPORT 4 (2008), https://www.gao.gov/assets/gao-08-944.pdf.
[61] Matthew N. Hayek & Scot M. Miller, *Underestimates of Methane from Intensively Raised Animals Could Undermine Goals of Sustainable Development*, ENV'T RSCH. LETTERS, June 4, 2021, at 1, 5 (reviewing studies finding that atmospheric measurements taken above or downwind of animal production regions in the United States showed 39–90% higher methane emissions than model estimates); Justine J. Owen & Whendee L. Silver, *Greenhouse Gas Emissions from Dairy Manure Management: A Review of Field-Based Studies*, 21 GLOB. CHANGE BIOLOGY 550, 559, 563 (2014) (reviewing research suggesting that current emissions models underestimate emissions from dairy facilities, including in the United States).

emissions in this sector. The Feedlots Rule has not been substantially updated since 2000.[62] In the past 25 years, advances in knowledge, technology, and societal values all highlight the urgency of adding GHG emissions into the updated Feedlots Rule. The lack of regulatory pressure has provided zero incentive for feedlots to take control of their GHG emissions. MPCA cannot continue to take a hands-off approach with feedlot emissions; now is the time to start collecting better data and regulating GHGs from feedlots. Failing to do so will torpedo Minnesota's chance at meeting its climate targets.

B. Other Negative Outcomes of Failing to Regulate Emissions

MPCA's failure to regulate GHG emissions from feedlots is part of a broader regulatory gap that permits feedlots to contribute significantly to a range of environmental and public health harms. Regulating GHG emissions offers a powerful opportunity to address these overlapping issues. Many of the same interventions that reduce GHGs—such as improved manure management and reduced herd size—can simultaneously mitigate other harmful pollutants, delivering wide-ranging co-benefits for Minnesota communities.

For example, in addition to their GHG emissions, large animal feedlots impair air quality at the local level. Working at a feedlot can results in negative "[r]espiratory health effects, including symptoms of pulmonary disease and lung function test result abnormalities . . . ."[63] Industrial dairy operations emit ammonia, hydrogen sulfide, and other pollutants, and have been linked to exacerbation of asthma in nearby residents.[64] Dairy manure can also harm the health of nearby people by contaminating water.[65] Fine particulate matter pollution, which is associated with feedlots,[66] can have serious health effects including "death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, [and] increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing."[67] Reducing GHG emissions through strategies like improved manure handling and less concentrated herd sizes can concurrently reduce these harmful co-pollutants, directly improving local air quality and respiratory health.

Feedlots also introduce numerous toxic chemicals into the environment. For example, high concentration of animal waste results in ammonia pollution, which contributes to acid deposition and eutrophication—diminishing soil and water quality, impairing aquatic life and damaging

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[62] *Animal Feedlots*, MPCA, https://www.pca.state.mn.us/get-engaged/animal-feedlots (last visited July 20, 2025).
[63] Susanna G. Von Essen & Brent W. Auvermann, *Health Effects from Breathing Air Near CAFOs for Feeder Cattle or Hogs*, 10 J. OF AGROMEDICINE 55, 55 (2005).
[64] Sara G. Rasmussen et al., *Proximity to Industrial Food Animal Production and Asthma Exacerbations in Pennsylvania, 2005–2012*, INT'L J. ENV'T RSCH. & PUB. HEALTH, 2017 at 1, 7-8; Christine Loftus et al., *Estimated Time-Varying Exposures to Air Emissions from Animal Feeding Operations and Childhood Asthma*, INT'L J. HYGIENE ENV'T & HEALTH, Jan. 2020, at 9-10.
[65] *See, e.g.*, Cmty. Ass'n for Restoration of the Env't, Inc. v. Cow Palace, LLC, 80 F. Supp. 3d 1180, 1228 (E.D. Wash. 2015) (finding dairy operation's manure management "may present an imminent and substantial endangerment to the public who is consuming the contaminated water").
[66] *E.g.*, Amanda D. Emert et al., *Atmospheric Transport of Particulate Matter and Particulate-Bound Agrochemicals from Beef Cattle Feedlots: Human Health Implications for Downwind Agricultural Communities*, SCI. TOTAL ENV'T, 2023, at 2.
[67] *Health and Environmental Effects of Particulate Matter (PM)*, EPA (May 23, 2025), https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm.

crops.[68] Feedlots emit volatile organic compounds (VOCs), including malodorous sulfur compounds.[69] Mitigating methane and nitrous oxide emissions often requires the adoption of better manure management techniques, which can reduce ammonia volatilization and VOC emissions.[70] Animal manure also releases nitrates, which are harmful to humans and the environment.[71] Nitrate pollution often occurs when crops are over saturated with manure from feedlot operations.[72] Nitrates may enter groundwater instead of staying in the soil,[73] and can have significant human health impacts, including "blue baby syndrome."[74] When nitrates reach the ocean, they nourish toxic algae blooms and have caused large ocean dead zones.[75] GHG mitigation practices such as precise nutrient management in field application of manure and lower animal concentrations can reduce nitrate leaching, protecting water quality and public health.[76]

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[68] *Ammonia*, EPA (Feb. 7, 2025), https://www.epa.gov/caddis/ammonia; *Ammonia (NH3) Emissions*, EUR. ENV'T AGENCY, https://www.eea.europa.eu/data-and-maps/indicators/eea-32-ammonia-nh3-emissions-1 (last visited July 21, 2025).

[69] *Characterizing Emissions from Animal Feedlots*, NAT'L OCEANIC & ATMOSPHERIC ADMIN. CHEM. SCIS. LAB'Y (Apr. 20, 2017), https://csl.noaa.gov/news/2017/208_0420.html ("VOCs can react to form ozone and fine particles, affecting air quality and human health.").

[70] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 12; EPA, DEVELOPMENT DOCUMENT FOR THE FINAL REVISIONS TO THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM REGULATION AND THE EFFLUENT GUIDELINES FOR CONCENTRATED ANIMAL FEEDING OPERATIONS 6-30 (Dec. 2002), (estimating that a quarter of total nitrogen deposition onto beef feedlot surfaces is lost to volatilization); CALIFORNIA DAIRY RESEARCH FOUND., SMALL DAIRY CLIMATE CHANGE RESEARCH: AN ECONOMIC EVALUATION OF STRATEGIES FOR METHANE EMISSION REDUCTION EFFECTIVENESS AND APPROPRIATENESS IN SMALL AND LARGE CALIFORNIA DAIRIES 35 (Mar. 31, 2020), https://www.cdfa.ca.gov/oefi/research/docs/CDFA_SmallDairyResearch_FINAL_Report.pdf (finding that dry handling practices result in emissions reductions); B. Yuan et al., *Emissions of Volatile Organic Compounds (VOCs) from Concentrated Animal Feeding Operations (CAFOs): Chemical Compositions and Separation of Sources*, 17 ATMOS. CHEM. PHYS. 4945,4946 (2017), https://doi.org/10.5194/acp-17-4945-2017 (describing that animal waste management practices have impacts on VOC concentrations).

[71] *Nitrogen in the Environment: Nitrate Poisoning*, UNIV. MO. EXTENSION (Mar. 2022), https://extension.missouri.edu/publications/wq258.

[72] Chugg et al., *supra* note 59, at 3053.

[73] *Id*.

[74] Lynda Knobeloch et al., *Blue Babies and Nitrate-Contaminated Well Water*, 108 GRAND ROUNDS ENV'L MED. 675, 675-76 (2000); *Why is Nitrate Contamination a Concern?*, EPA (June 11, 2025), https://www.epa.gov/mn/why-nitrate-contamination-concern.

[75] *The Effects: Dead Zones and Harmful Algal Blooms*, EPA (Feb. 5, 2025), https://www.epa.gov/nutrientpollution/effects-dead-zones-and-harmful-algal-blooms.

[76] *Sources and Solutions: Agriculture*, EPA (Mar. 20, 2020), https://www.epa.gov/nutrientpollution/sources-and-solutions-agriculture (listing nutrient management techniques as a method to reduce nutrient losses); THOMAS HARTER ET AL., NICHOLAS INSTITUTE FOR ENVIRONMENTAL POLICY SOLUTIONS, ASSESSING POTENTIAL IMPACTS OF LIVESTOCK MANAGEMENT ON GROUNDWATER 4-7 (2014) (charting studies documenting leaching from CAFO corrals and feedlot surfaces, manure lagoons, and land application areas); MELANIE REDDING, WASH. STATE DEP'T OF ECOLOGY, MANURE AND GROUNDWATER QUALITY: LITERATURE REVIEW 18-23, 63 (June 2016) (describing communities impacted by nitrogen pollution, in large part caused by seepage from liquid manure lagoons at dairies); Tullo et al., *Review: Environmental Impact of Livestock Farming and Precision Livestock Farming as a Mitigation Strategy*, 650 SCI. OF THE TOTAL ENV'T 2751, 2752 (2019) (noting that "the high density of animals reared in relatively small areas, results in the deposition of large amounts of excretory nitrogen, phosphorus, organic matter, and fecal microbes in the watershed where the CAFO is located").

Importantly, all of these negative externalities disproportionately affect disadvantaged and rural communities, further exacerbating environmental injustice in the state.[77] Regulating GHG emissions can serve as a lever to reduce cumulative environmental harms to overburdened communities, advancing environmental justice by curbing co-pollutants and improving overall environmental conditions. In this context, regulating GHG emissions from feedlots should be seen not as an isolated climate action but as a gateway to addressing a suite of environmental and public health crises. It is an integral step toward more sustainable, just, and healthy agricultural systems.

II. MPCA Has Legal Authority To Regulate GHG Emissions From Animal Feedlots

MPCA has both the statutory duty and authority to establish standards and regulate air pollution, including GHGs. Minn. Stat. § 116.07, subd. 2 directs the agency to improve air quality by promoting energy sources and waste disposal methods that emit the fewest air contaminants, consistent with its overarching goal of reducing all forms of pollution.[78] MPCA is also directed to adopt air quality standards based on scientific knowledge, technical criteria, and commonly accepted practices.[79] MPCA's statutory authority includes rulemaking for any purpose related to the prevention, abatement, or control of air pollution, and may apply statewide or under specific conditions.[80] This includes regulating emission sources, the composition of emissions, and the quality of ambient air.[81]

GHGs fall squarely within the statutory definitions of "air contaminants" and "air pollution." An "[a]ir contaminant" includes any gas or vapor different in composition from or exceeding the concentration in the natural atmosphere,[82] and "air pollution" refers to any air contaminant present in quantities or conditions that harm human health or welfare, animal or plant life, or

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[77] *Climate-Vulnerable Populations and Strategies to Reduce Risk*, MPCA, https://www.pca.state.mn.us/air-water-land-climate/climate-vulnerable-populations-and-strategies-to-reduce-risk (last visited July 20, 2025). Communities of color and economically disadvantaged communities are more likely to be exposed to large-scale feedlots. *E.g.*, Arbor J.L. Quist et al., *Disparities of Industrial Animal Operations in California, Iowa, and North Carolina*, Exh. 5 to AL. STATE ASSOC. OF COOPS. ET AL., PETITION TO EPA TO ADOPT A REBUTTABLE PRESUMPTION THAT LARGE CAFOS USING WET MANURE MANAGEMENT SYSTEMS ACTUALLY DISCHARGE POLLUTANTS UNDER THE CLEAN WATER ACT (Oct. 2022), https://earthjustice.org/wp-content/uploads/cafo_presumptionpetition_withexhibits_oct2022.pdf ("[D]airy CAFOs in California are disproportionately located in low-income communities and near [people of color]."); Phoebe Gittelson et al., *The False Promises of Biogas: Why Biogas Is an Environmental Justice Issue*, 15 ENV'T JUST. 352, 355-56 (2022) ("[I]t has been established that CAFOs are disproportionally located in communities of color and, or [sic] low income communities—a form of environmental injustice that has negative impacts on community health."); Laura Fox, *The Intersectionality of Environmental Injustice, Societal Harms, and Farmed Animal Welfare*, 17 ENV'T JUST. 101, 106 (2024), https://www.liebertpub.com/doi/epub/10.1089/env.2021.0125 ("[C]ommunity members [living near CAFOs] suffer many discrete and pervasive harms from health problems and reduced life spans to air and water pollution to noise, odor, and aesthetic harms to decreased property values and diminished ability to use outdoor space or recreate safely. In Judge Wilkinson's view [in the *McKiver* case], these 'harms are well established, almost to the point of judicial notice, to be visited disproportionately upon the dispossessed—on minority populations and poor communities.'") (citing *McKiver v. Murphy-Brown, LLC*, 980 F.3d 937, 982 (4th Cir. 2020) (Wilkinson, J., concurring)).

[78] MINN. STAT. § 116.07, subd. 2(a).

[79] *Id*.

[80] *Id*. subd. 2(b).

[81] *Id*. subd. 4(a).

[82] *Id*. § 116.06, subd. 2.

property, or that interfere with the enjoyment of life or property.[83] Anthropogenic GHGs, including methane and nitrous oxide from animal feedlots, plainly meet these definitions and pose well-documented threats to public and environmental health.[84]

MPCA's permitting authority further reinforces its power to regulate GHGs. Under Minn. Stat. § 116.07, subd. 4(a), MPCA may issue, deny, modify, or revoke permits "under such conditions as it may prescribe for the prevention of pollution," including the emission of air contaminants.[85] This authority would allow MPCA to require that permittees monitor, report, and manage GHG emissions, including not exceeding designated allowances and adopting mitigation technologies, as part of their operating conditions.

MPCA has previously exercised its authority to regulate GHGs. In 2011, MPCA implemented the EPA's Greenhouse Gas Tailoring Rule, which required facilities seeking certain major air permits to adopt the best available technology to limit their GHG emissions.[86] MPCA promulgated GHG requirements through both temporary and permanent rulemaking procedures, citing Minn. Stat. § 116.07, subd. 4(a) as the legal basis.[87] An administrative law judge reviewed the rule and affirmed that MPCA had the statutory authority to regulate GHGs.[88] EPA has also implicitly recognized MPCA's regulatory authority under Minnesota state law to regulate GHGs. In 2010, the federal agency issued a formal notice to thirteen states, finding they lacked adequate state legal authority to regulate GHGs through technology-based permitting requirements.[89] Minnesota was not one of those states, further reinforcing MPCA's authority to regulate GHGs.[90]

Additionally, in 2022, MPCA adopted a Clean Cars rule to reduce GHG emissions from passenger vehicles.[91] In a document aimed at informing the public about the upcoming rulemaking, MPCA explained that its statutory authority to pursue these regulations came from section 116.07's mandate to adopt standards to improve air quality: "GHGs are harmful air pollutants that contribute to global climate change. MPCA therefore has the authority under Minnesota statute to regulate emissions of GHGs from motor vehicles."[92] Citing the state's

[83] *Id.* subd. 4.
[84] *Supra* Part I.
[85] MINN. STAT. § 116.07, subd. 4(a)(a).
[86] Prevention of Significant Deterioration and Title V Greenhouse Gas Tailoring Rule, 75 Fed. Reg. 31,514, 31,516 (June 3, 2010).
[87] In re the Proposed Rules of the Minnesota Pollution Control Agency Governing Permits for Greenhouse Gas Emissions, Minnesota Rules Chapters 7005, 7007 and 7011 (OAH 8-2200-22910-1), 2012 WL 6645129, at *4 (Minn. Off. Admin. Hearings Nov. 9, 2012); *see also Federal Greenhouse Gas "Tailoring" Rule: Impacts on Minnesota's Air Permit Program*, MPCA AIR QUALITY (June 2010), https://www.pca.state.mn.us/sites/default/files/aq2-31.pdf.
[88] In re the Proposed Rules of the Minnesota Pollution Control Agency Governing Permits for Greenhouse Gas Emissions, 2012 WL 6645129, at *4.
[89] Action to Ensure Authority to Issue Permits Under the Prevention of Significant Deterioration Program to Sources of Greenhouse Gas Emissions: Finding of Substantial Inadequacy and SIP Call, 75 Fed. Reg. 77698, 77,700 (Dec. 13, 2010).
[90] *Id.* at 77,702 tbl.III-1.
[91] MINN. STAT. § 7023.
[92] *Clean Cars Minnesota*, MPCA (aq-rule4-10b), at 1.

emissions reductions targets, MPCA further explained that "[s]tate-level regulation is needed in order to achieve the necessary emission reductions in this sector."[93]

MPCA thus has clear and ample legal authority to promulgate rules to address GHG emissions from feedlots. Enacting these rules would fulfill the agency's statutory mandate to improve air quality[94] and to prevent, abate, and control air pollution,[95] as well as support Minnesota's broader goal of achieving net-zero emissions by 2050.[96] Given the magnitude of the climate crisis and animal agriculture's major contribution to the problem, MPCA is on firm legal and factual footing to begin regulating GHG emissions from animal feedlots.

III. MPCA Must Also Enforce Existing Rules Aimed At Air Emissions

While MPCA has the statutory authority to regulate GHG emissions from animal feedlots, the most straightforward path to doing so already exists in current law. The Feedlots Rule—specifically the requirement for an air emission plan under Minn. R. 7020.0505—already provides an existing regulatory framework that could and should be used to require feedlot operators to track and mitigate GHG emissions. In addition to promulgating more robust rules, MPCA must start enforcing the Rule as currently in effect, which is designed (albeit inadequately) to address air pollution.

The following section outlines how the plain language of the existing Feedlots Rule already encompasses GHGs and why MPCA must begin enforcing these requirements. It then examines MPCA's failure to enforce even the explicitly required elements of the air emission plan, such as those related to hydrogen sulfide and odor. Together, these enforcement gaps highlight the need for immediate action to ensure full and faithful implementation of the Rule currently on the books.

A. Air Emission Plans Must Include GHG Emissions Mitigation Measures

The existing Feedlots Rule requires applicants for certain feedlot permits to submit an air emission plan.[97] Under the plain meaning of the current Rule, GHG emissions should already be addressed in the air emission plan. In particular, the Rule states that air emission plans should list "methods and practices that will be used to *minimize air emissions resulting from animal feedlot or manure storage area operations . . . .*"[98] MPCA's operating statute defines "emission" as a "release or discharge into the outdoor atmosphere of any air contaminant or combination thereof."[99] As explained above, GHGs are a type of air contaminant under the statute and therefore should be regulated by the Feedlots Rule and included in the air emission plan.[100]

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[93] *Id.*
[94] MINN. STAT. § 116.07, subd. 2(a).
[95] *Id.* subds. 2(b), 4.
[96] *Id.* § 216H.02, subd. 1(a).
[97] MINN. R. 7020.0505, subp. 4(B)(1). An air emission plan is required for "an animal feedlot capable of holding 1,000 animal units or more or a manure storage area capable of holding the manure produced by 1,000 animal units or more." *Id.* subp. 4(B).
[98] *Id*. subp. 4(B)(1)(a) (emphasis added).
[99] MINN. STAT. § 116.06, subd. 9.
[100] *Id*. subd. 2 (defining "[a]ir contaminant"); *supra* note 82 and accompanying text.

The Rule requires that an applicant's air emission plan include:

- Mitigation measures, including: a description of the methods and practices the facility will use to minimize air emissions during key operations such as manure storage start-up, loading, and removal; and strategies to mitigate emissions if ambient hydrogen sulfide levels exceed state standards.[101]
- A complaint response protocol, including: a list of all potential odor sources at the facility; an assessment identifying which sources are most likely to generate significant odors; and a plan for controlling those odors, including anticipated odor mitigation strategies.[102]
- An emergency response plan, including: a description of the procedures that will manage and mitigate adverse effects of unauthorized discharges.[103]

Although hydrogen sulfide and odor are the only types of emissions singled out for additional mitigation and complaint-response procedures, the plan's core requirement (of making plans to minimize emissions) applies to *all* air emissions, necessarily including GHGs such as methane and nitrous oxide—major byproducts of livestock digestion and manure management.[104] The specific mentions of hydrogen sulfide and odors in Minn. R. 7020.0505, subps. 4(B)(1)(b) and 4(B)(1)(c) respectively do not negate MPCA's requirement to minimize other air emissions under subp. 4(B)(1)(a). Nonetheless, MPCA's standard air emission plan (discussed *infra* in Part III.B) lacks any discussion of strategies to reduce GHG emissions. This omission reflects a failure to fully enforce the Rule's plain requirements and undermines Minnesota's broader air quality and climate objectives.

B. MPCA's Failure to Enforce Air Emission Plan Requirements

Despite clear legal requirements, MPCA accepts and approves feedlot permit applications that do not comply with the air emission plan requirements set out in the current Feedlots Rule. While these plan requirements are located in regulation, they are critical to fulfilling MPCA's statutory obligations. MPCA is statutorily mandated to "improve air quality by promoting, in the most practicable way possible, the use of energy sources and waste disposal methods which produce or emit the least air contaminants consistent with the agency's overall goal of reducing all forms of pollution."[105] To meet this duty, the Feedlots Rule must contain provisions—such as those found in the section requiring an air emission plan—to reduce air emissions, including GHGs. Without the information required by the Rule's air emission plan, MPCA cannot meet this statutory mandate.

[101] MINN. R. 7020.0505, subp. 4(B)(1)(a)-(b).
[102] *Id*. subp. 4(B)(1)(c).
[103] *Id*. subp. 4(B)(2).
[104] *Id*. subp. 4(B)(1)(b), (c)(i)-(iii); *see also Sources of Greenhouse Gas Emissions*, EPA (Mar. 31, 2025), https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
[105] MINN. STAT. § 116.07, subd. 2(a).

Based on correspondence with MPCA and commenters' review of four recent general permit applications,[106] we understand that—rather than creating a tailored air emission plan as required by Minn. R. 7020.0505, subp. 4(B)—MPCA merely requires applicants to "check a box" to indicate their agreement to a standard air emission plan created by MPCA,[107] via the feedlot permitting form:

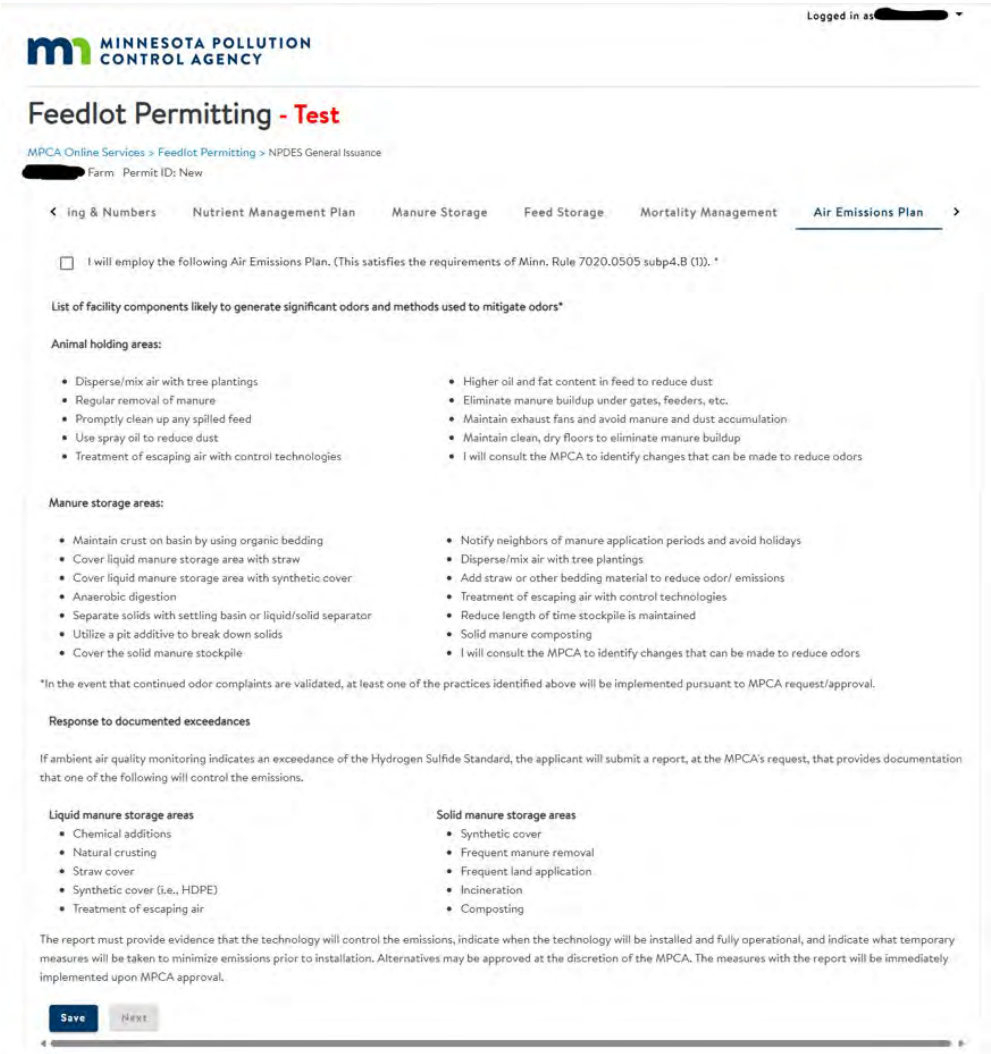

[108]

[106] Lass Farms, Inc., *Feedlot Permitting - SDS General Permit Issuance*, Transaction ID 89158, MPCA 3-4 (July 23, 2024); Deerview Dairy LLLP, *Feedlot Permitting - NPDES General Permit Issuance*, Transaction ID 131565, MPCA 6-7 (Apr. 15, 2025); Dunn Family Farms, *Feedlot Permitting - SDS General Permit Issuance*, Transaction ID 132904, MPCA 4 (Apr. 9, 2025); Flagship Pork Properties, *Feedlot Permitting - SDS General Permit Issuance*, Transaction ID 136147, MPCA 4 (May 8, 2025).

[107] E-mail from Leonard Richards, MPCA, to Jay Eidsness, Minn. Ctr. for Env't Advocacy (June 30, 2025, 18:47 CDT) ("The applicant is basically checking a box when filling out their application to indicate that they agree with the standard plan and after they check the box it shows up in the Copy of Record that they 'Affirmed' that they will employ the plan.").

[108] *Id*. (July 1, 2025, 15:07 CDT) (including a screenshot of MPCA's Feedlot Permitting form with checkbox followed by the language, "I will employ the following Air Emissions Plan. (This satisfies the requirements of Minn. R. 7020.0505, subp4.B (1)).").

This approach is contrary to the Rule. The Rule requires an applicant to submit an air emission plan that, *inter alia*, includes: (1) a list of each potential odor source at the facility; (2) a determination of the sources most likely to generate significant odors; and (3) a list of potential actions that will be taken if there are odor complaints.[109] MPCA's standard air emission plan does not require applicants to identify specific odor sources that may be present at their specific facilities or to prioritize those most likely to emit odors.[110] This omission violates the Rule's plain language and renders the plan (and the permit it supports) incomplete under Minnesota law.

Moreover, the Rule requires air emission plans to describe mitigation strategies in the event that hydrogen sulfide emissions exceed state ambient air standards.[111] This provision is forward-looking and requires facilities to identify and commit to specific mitigation strategies prior to permit issuance.[112] The Rule thus is meant to ensure that mitigation plans are part of the permit record, allowing for regulatory review, public scrutiny, and enforceable terms from the outset.[113] But, rather than including proactive defined mitigation measures that will be used in the event of an exceedance, MPCA's standard air emission plan merely requires:

> If ambient air quality monitoring indicates an exceedance of the Hydrogen Sulfide Standard, the applicant will submit a report, at the MPCA's request, that provides documentation that one of the following [boilerplate suggested mitigation strategies] will control the emissions.[114]

This approach is inconsistent with the regulatory requirements. It defers identification of mitigation strategies to a later date, contingent upon an exceedance and, if requested, a subsequent agency report. Such post hoc reporting does not satisfy the Rule's requirement that mitigation measures be part of the air emission plan included in the original application.[115]

This failure to follow the law is especially problematic because there are no requirements in the Rule for how often air quality must be tested for hydrogen sulfide, and no reporting requirements for incidents of exceedance of the hydrogen sulfide standard.[116] When feedlots are randomly tested, they tend to exceed the standard.[117] And MPCA itself primarily only tests hydrogen sulfide levels if there is a complaint.[118] This system creates a reality in which feedlots are likely often exceeding their hydrogen sulfide emissions requirements. Taken together with the deficiencies outlined above, these oversights underscore the urgent need for stricter enforcement and more robust review of air emission plans.

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[109] MINN. R. 7020.0505, subp. 4(B)(1)(c).
[110] MPCA Feedlot Permitting Form, *supra* note 108.
[111] MINN. R. 7020.0505, subd. 4(B)(1)(b).
[112] *Id*.
[113] *Id*.
[114] MPCA Feedlot Permitting Form, *supra* note 108.
[115] MINN. R. 7020.0505, subd. 4(B)(1)(b).
[116] *Id*.
[117] *Minnesota Air Emissions Planning*, EPA 1-2 (2017), https://www.epa.gov/sites/default/files/2017-01/documents/c_minnesota_air_emissions_planning.pdf.
[118] *Minnesota Air Emissions Planning*, *supra* note 117, at 2; *see also* MPCA, LEGIS. REP. OF THE FEEDLOT HYDROGEN SULFIDE PROGRAM 9-10 (1998), https://www.lrl.mn.gov/docs/pre2003/mandated/980083.pdf.

IV. Recommended Actions

Since MPCA does not interpret the current Feedlot Rule as covering all air pollutants from these facilities, there is a regulatory gap that allows feedlots to emit limitless GHGs without oversight or consequence. MPCA should use this rulemaking to close this gap, allowing Minnesota to make significant progress toward meeting its statutory climate goals. The following section outlines requirements MPCA should incorporate into the Feedlot Rule to start regulating GHG emissions from animal feedlots, including:

a. Monitoring and reporting provisions specific to GHG emissions;

b. Mitigation strategies to reduce emissions from manure management and livestock operations; and

c. Enforcement measures to ensure compliance with existing air emission plan requirements.

Incorporating these changes would help to bring the Feedlots Rule in line with Minnesota's statutory obligations and climate goals while safeguarding air quality and public health.

A. Require Monitoring and Reporting of GHG Emissions from Feedlots

As a common sense first step, MPCA should require feedlots to monitor and report their actual GHG emissions. MPCA has long acknowledged that "[e]nvironmental protection begins and ends with monitoring."[119] Indeed, "[t]o determine what kind of pollution control is necessary and how effective it is, the MPCA regularly monitors the status of the environment."[120] As the agency further explains, "the primary tool in controlling pollution is the environmental permit," which "include[s] monitoring and reporting requirements [that] often compel remedies for pre-existing pollution problems."[121] With accurate monitoring data in hand, MPCA can "set standards to protect the environment and to establish Agency rules" and, when the data shows that existing rules are insufficient, "MPCA rules are altered in response to the information."[122]

This critical principle should be applied to GHG emissions from animal feedlots, especially given the lack of information about these emissions.[123] To meaningfully reduce GHG emissions from animal agriculture—one of Minnesota's largest and most persistent sources of climate pollution[124]—the state must significantly improve its monitoring and reporting of emissions from feedlots. This is especially true given that, as previously discussed, current GHG accounting is based on animal numbers that are most likely under reported and inaccurate, and that current

[119] MPCA, MINN. POLLUTION CONTROL AGENCY 1967-1987: TWENTY YEARS PROTECTING THE ENV'T 1 (1987).
[120] *Id*.
[121] *Id*. at 2.
[122] *Id*.
[123] *See* Peter H. Lehner & Nathan A. Rosenberg, *Advancing Climate-Neutral Agriculture in New York*, 33 ENV'T L. N.Y. 79, 81–82 (2022) (discussing the "current[] woeful lack of accurate information about agricultural practices . . .," including as to GHG emissions from large animal agriculture facilities).
[124] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 9; *see also supra* Part I.A.

models have been shown to underestimate emissions when compared to real-world measurements.[125]

Currently, the Rule does not explicitly require feedlot operators to estimate, track, or report their GHG emissions.[126] This omission represents a significant regulatory gap, particularly for medium and large operations—which are responsible for the bulk of methane and nitrous oxide emissions from the agricultural sector.[127] Recent data shows that 12 active beef or dairy cattle feedlots in Minnesota have over 10,000 animal units.[128] These massive operations produce enormous amounts of methane and nitrous oxide emissions. It makes regulatory sense for these large emitters to adhere to stricter environmental controls than the thousands of feedlots with fewer than 100 animal units. For many feedlots, permits granted under the current Rule already require operators to assess environmental impacts related to other pollutants;[129] integrating GHG emissions into this process is a logical and necessary extension that can be designed in a way to not burden producers while allowing MPCA to gather vital data to inform policy changes to reduce GHG emissions from animal agriculture.

MPCA should revise Minn. R. 7020.0405 (Permit Requirements) and Minn R. 7020.0505 (Permit Applications) to require feedlot operators to provide emissions reporting, including:

- A comprehensive GHG emissions inventory quantifying emissions from all major sources, including enteric fermentation, manure storage, land application of manure, transportation, energy use, and other on-farm activities;
- A description of scientific methods used for quantification to ensure consistency and transparency;[130]
- Additional relevant supporting information including an animal inventory (with animal type and average mass) and estimated feed sources and quantities; and
- Regular reporting frequency depending on feedlot size and third-party verification to ensure ongoing accountability and accuracy.

This recommendation is aligned with existing practices in Minnesota's environmental review process. The Minnesota Environmental Quality Board (EQB) recently amended the Alterative

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[125] *See supra* notes 57-61 and accompanying text. Notably, while the EPA's Greenhouse Gas Reporting Program requires animal agriculture facilities that have manure management systems and that have a certain number of animals to report on methane emissions (40 C.F.R. § 98.360), a series of Congressional riders has prevented implementation of that requirement. *E.g.*, Consolidated Appropriations Act, Public Law No. 116–260, 116th Congr. § 437 (2021) ("Notwithstanding any other provision of law, none of the funds made available in this or any other Act may be used to implement any provision in a rule, if that provision requires mandatory reporting of greenhouse gas emissions from manure management systems."). Given the lack of federal regulation in this area, Minnesota's leadership is needed.

[126] MINN. R. Ch. 7020.

[127] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 3.

[128] *Feedlots in Minnesota*, MPCA, https://gisdata.mn.gov/dataset/env-feedlots (last visited July 17, 2025) (click "Download" next to "Comma-Separated Values File" to access the data file: feedlots.csv).

[129] MINN. R. 7020.0505, subp. 4(B).

[130] There are various options for measuring CAFO emissions, with new methods coming online as technology develops. *See* Letter from Earthjustice et al. to the N.Y. State Dep't of Env't Conservation, *Comments on Proposed Part 253 Related to Agriculture* 3-5 (July 1, 2025). MPCA must take care to ensure use of credible methodologies.

Environmental Assessment Worksheet (EAW) Form for Animal Feedlots.[131] This form requires proponents to quantify and disclose GHG emissions, including identifying sources and estimation methods.[132] EQB also published guidance last year that provides tools and resources for project proposers to meaningfully engage with the emissions information required by the EAW form.[133] Incorporating similar requirements into the operational phase of feedlot permitting would ensure consistency and allow MPCA to apply the same standards to ongoing sources of pollution—not just to proposed developments. Moreover, MPCA can rely on and point to EQB's guidance for information and instruction for how feedlot operators can approach calculating their actual GHG emissions.

Requiring estimations of GHG emissions during environmental review is a start, but MPCA must do more. The climate information collected on an EAW form is static, representing anticipated emissions premised on a proposed facility. This one-time data collection point is helpful, but recurring reporting will ensure that MPCA has up-to-date information that more accurately represents emissions.

To ensure the greatest climate impact, these expanded requirements should apply to all registered feedlots on a schedule that varies depending on the size or operational practices of the feedlot. MPCA should require annual monitoring and reporting for all feedlots that require either a State Disposal System (SDS) or a National Pollutant Discharge Elimination System (NPDES) permit, both of which MPCA administers.[134] These permits already serve as key regulatory triggers for significant water and air quality impacts and provide a logical and administratively feasible threshold for GHG oversight. For facilities that do not meet the threshold number of animal units to require NPDES/SDS permits, MPCA should consider incentives that would encourage voluntary monitoring and reporting. Annual reporting should also be required of all facilities of any size that use anaerobic digesters or cover and flare systems.[135]

Emissions information about the latter group of facilities (those that operate anaerobic digesters or use cover and flare systems) is important because, although these systems have been promoted as measures to reduce GHG emissions, the current understanding of their emissions impacts—including their touted climate benefits—is inadequate.[136] Moreover, because these facilities already use advanced infrastructure, including gas collection, compression, and flaring or combustion systems, they are particularly well suited to monitor emissions. Many of the technologies used to operate anaerobic digestion and gas capture systems can also be equipped with monitoring instruments, making it technically feasible and cost-effective to track actual

[131] *Environmental Assessment Worksheet*, MINN. ENV'T QUALITY BOARD (EQB) (Dec. 2024), https://www.eqb.state.mn.us/sites/eqb/files/Approved%20Alternative%20Feedlot%20EAW%20Dec.%202024.pdf.
[132] *Id*. at 16-17.
[133] *Environmental Assessment Worksheet (EAW) Guidance*, EQB 5-16 (June 2024), https://www.eqb.state.mn.us/sites/eqb/files/2024_eaw_climate_guidance_2.pdf.
[134] MINN. R. 7020.0405.
[135] Anaerobic digesters are discussed *infra* at notes 168-174 and accompanying text. In cover and flare systems, manure storage facilities are covered by a gas-tight cover and collected methane is then burned, converting it to carbon dioxide. Earthjustice et al., *supra* note 130, at 5.
[136] *See infra* notes 168-174; Earthjustice et al., *supra* note 130, at 5.

GHG outputs.[137] Requiring emissions reporting from these operations is therefore both scientifically necessary and practically achievable.

For the large facilities, which account for a small subset of total feedlots in Minnesota, requiring them to annually collect and report emissions data from their operations is not overly burdensome or financially harmful. Current available MPCA data shows that around 1,000 of the nearly 24,500 feedlots in Minnesota are over the 1,000-animal unit threshold for SDS permitting.[138] In fact, the top 2% of the largest feedlots in Minnesota house roughly 20% of all the animal units in the state.[139] These large facilities are sophisticated operations with larger amounts of resources that are knowledgeable about environmental controls. MPCA should establish a workable monitoring and reporting schedule for smaller-sized facilities. In establishing reporting frequencies based on facility size, MPCA should balance the regulatory burden of gathering this information from the feedlot operator with the improved data collection that more frequent monitoring will produce.

Importantly, MPCA must also strengthen enforcement to ensure that operations meeting the thresholds for SDS or NPDES permits are actually obtaining them. Nationally, many Concentrated Animal Feeding Operations (CAFOs) operate without NPDES permits despite meeting eligibility criteria, resulting in significant amounts of manure, litter, and process wastewater being discharged without regulatory oversight.[140] MPCA should not replicate this gap in its approach to GHG emissions. Instead, tying GHG reporting to existing permit frameworks (assuming permitting is enforced) can help ensure accountability and align environmental regulation with Minnesota's climate goals. Without consistent monitoring and reporting, Minnesota cannot credibly track progress toward its goals or hold the agricultural sector accountable. As MPCA has acknowledged, data drives both accountability and action: only when we know the scope and source of pollution can we begin to implement meaningful controls. Incorporating GHG reporting into the feedlot permitting system is not only feasible, legally authorized, and consistent with EQB guidance—it is essential to meet Minnesota's GHG emissions reduction goals.

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[137] Shunchang Yang et al., *Development of Inexpensive, Automatic, Real-Time Measurement System for On-Line Methane Content and Biogas Flowrate*, WASTE & BIOMASS VALORIZATION (2022), https://link.springer.com/article/10.1007/s12649-022-01835-5.

[138] *Feedlots in Minnesota*, *supra* note 128.

[139] *Id.*

[140] NATURAL RES. DEF. COUNCIL, CAFOS: WHAT WE DON'T KNOW IS HURTING US 10 (2019), https://www.nrdc.org/sites/default/files/cafos-dont-know-hurting-us-report.pdf (citing William M. McLaren, *The Death of the Duty to Apply: Limitations to CAFO Oversight Following Waterkeeper & National Pork Producers*, 11 J. OF ANIMAL & NATURAL RES. L 87, 106 (2015)); Terence J. Centner, *Clarifying NPDES Requirements for Concentrated Animal Feeding Operations*, 14 PENN ST. ENV'T. L. REV. 361, 362 (2006); FOOD & WATER WATCH, THE EPA'S FAILURE TO TRACK FACTORY FARMS 1 (2013), https://foodandwaterwatch.org/wp-content/uploads/2021/03/EPA-Factory-Farms-IB-Aug-2013_0.pdf (stating that "as of 2011, the EPA estimated that only 41 percent of NPDES-defined CAFOs actually had NPDES permits"); *see also*, Letter from Food & Water Watch to EPA, *Detailed Study of Concentrated Animal Feeding Operations Point Source Category* 15 (June 13, 2025) (discussing "widespread failure to permit discharging CAFOs in the first place.").

B. Require and Support Best Available Approaches to Mitigate GHG Emissions

In addition to adding monitoring and reporting requirements to the permit provisions, MPCA should build on the already existing requirement to submit an air emission plan and require feedlot operators and applicants to submit a GHG emissions plan detailing expected emissions and reduction strategies—not just a description of the methods and practices the facility will use to minimize air emissions during key operations, as already required in an air emission plan.[141] Such plans should include a reduction strategy with measurable, time-bound targets and mitigation measures, using best available approaches and technologies. In supporting mitigation efforts, MPCA should require or encourage proven, low-risk and low-cost interventions that directly target GHG sources and align with broader environmental and public health goals. MPCA should also consider establishing emissions reduction targets for high-emitting feedlots. Setting specific, time-bound reduction targets for the highest emitters would be a critical step toward aligning the feedlot sector with Minnesota's broader climate commitments. Of course, the most stringent requirements should be levied against the biggest operations—which could have significant mitigation impacts without burdening smaller farmers.[142]

Many of the ideas and suggestions presented herein are not new. The Intergovernmental Panel on Climate Change's earliest assessments explained that "[o]pportunities exist to reduce methane from enteric fermentation and animal waste storage, for example, by modifying feeding practices, using productivity enhancing practices and agents, and modifying waste, management practices."[143] In the ensuing years, the science showing that management practices can reduce GHG emissions from animal agriculture has crystallized, and technological advances have made emissions reductions more achievable for farms of all sizes.

Various approaches have been shown to reduce GHG emissions from animal agriculture, including changing animal feed, the use of more climate-friendly practices to grow animal feed, and better manure management.[144] Certain feed formulations (such as those with lower crude protein and higher digestibility) can reduce enteric methane emissions from ruminants,[145] as can some feed additives.[146] Conventional animal feed production such as planting, fertilizing, and harvesting feed emits carbon dioxide, nitrous oxide, and methane; feed sources developed through lower carbon intensity practices can reduce total feedlot-associated GHGs.[147]

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[141] MINN. R. 7020.0405, 7020.0505.
[142] Lehner & Rosenberg, *supra* note 123 at 84 ("The State could focus its financial support on the smaller farmers and use its regulatory authority to speed change in these few largest facilities.").
[143] IPCC, CLIMATE CHANGE: THE IPCC 1990 AND 1992 ASSESSMENTS 34 (1992), https://www.ipcc.ch/site/assets/uploads/2018/05/ipcc_90_92_assessments_far_full_report.pdf.
[144] Lehner & Rosenberg, *supra* note 123, at 81.
[145] Yue Wang et al., *Mitigating Greenhouse Gas and Ammonia Emissions from Beef Cattle Feedlot Production: A System Meta-Analysis*, 52 ENV'T SCI TECH. 11232, 11236-37 (Oct. 2018).
[146] While some feed additives have shown promise, many of them have not been tested or adopted by industry at scale, and their mitigation potential is limited. Daina Bray, *Reining in Animal Agriculture's Emissions by Shrinking the Herd: Early Signs of a Necessary Global Policy Shift*, 54 ENV'T LAW 489, 523–31 (2024); *see also* François Xavier Philippe & Baudouin Nicks, *Review on Greenhouse Gas Emissions from Pig Houses: Production of Carbon Dioxide, Methane, and Nitrous Oxide by Animals and Manure*, 199 AGRIC., ECOSYSTEMS & ENV'T 10, 21 (2015).
[147] Muxi Cheng et al., *Climate Change and Livestock Production: A Literature Review*, 8 ATMOSPHERE 1, 8 (2022).

Manure management releases methane, nitrous oxide, and carbon dioxide and makes up a significant portion of dairy cow emissions.[148] Dairy and beef feedlots often use wet management systems that collect manure in lagoons or ponds.[149] The anaerobic, water-rich, and warm conditions characteristic of wet systems create an ideal environment for methanogenic bacteria, leading to significant methane emissions.[150] Transitioning from long-term liquid storage systems to dry or composting systems paired with non-digester covered storage can significantly reduce methane emissions.[151]

Improved livestock management can also significantly reduce the volume and intensity of GHG emissions from feedlots. Reducing use of nontherapeutic antibiotics can prevent increased methane emissions from animals' disrupted microbiomes.[152] Healthier animals are more productive and emit fewer GHGs per unit of output.[153] By contrast, animals in overcrowded conditions experience more stress, contributing to disease spread and inefficient feed conversion, all of which can increase methane and nitrous oxide emissions per animal.[154] Indeed, the most impactful strategy to reduce GHG emissions from feedlots is to directly address the scale and intensity of animal production.[155] Such approaches would align with Minnesota's longstanding commitment to maintaining small, family-owned farms:

> The legislature finds that it is in the interests of the state to encourage and protect the family farm as a basic economic unit, to insure it as the most socially desirable mode of agricultural production, and to

[148] *Id*. at 11-13; Søren O. Petersen, *Greenhouse Gas Emissions from Liquid Dairy Manure: Prediction and Mitigation*, 101 J. DAIRY SCI. 6642, 6651 (2018).
[149] FAO, GREENHOUSE GAS EMISSIONS FROM RUMINANT SUPPLY CHAINS: A GLOBAL LIFE CYCLE ASSESSMENT 68-70 (2013), https://www.fao.org/3/i3461e/i3461e.pdf; EMMETT INST. ON CLIMATE CHANGE & ENV'T, UCLA L. SCH., MITIGATING EMISSIONS FROM CALIFORNIA'S DAIRIES: CONSIDERING THE ROLE OF ANAEROBIC DIGESTERS 16 (2024), https://law.ucla.edu/sites/default/files/PDFs/Publications/Emmett%20Institute/UCLA_Emmett_CA_Dairies_1%2018%2024.pdf.
[150] FAO, GREENHOUSE GAS EMISSIONS FROM RUMINANT SUPPLY CHAINS, *supra* note 149149. According to EPA, "manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems." EPA GHG INVENTORY, *supra* note 18, at 5-12; *see also* IPCC, GOOD PRACTICE GUIDANCE AND UNCERTAINTY MANAGEMENT IN NATIONAL GREENHOUSE GAS INVENTORIES 1, 322-23 (2000), *available at* https://www.ipcc-nggip.iges.or.jp/public/gp/gpg-bgp.html.
[151] FAO, GREENHOUSE GAS EMISSIONS FROM RUMINANT SUPPLY CHAINS, *supra* note 149; Jan Broucek, *Nitrous Oxide Production from Cattle and Swine Manure*, 5 J. ANIMAL BEHAVIOR & BIOMETEOROLOGY 13, 13-16 (2017); Philippe & Nicks, *supra* note 146, at 12.
[152] Tobin J. Hammer et al., *Treating Cattle with Antibiotics Affects Greenhouse Gas Emissions, and Microbiota in Dung and Dung Beetles*, 283 PROCEEDINGS ROYAL SOC'Y BIOLOGICAL SCI. 1, 5 (2016).
[153] FAO, PATHWAYS TOWARDS LOWER EMISSIONS: A GLOBAL ASSESSMENT OF GHG EMISSIONS & MITIGATION OPTIONS FROM LIVESTOCK AGRIFOOD SYSTEMS 1, 32 (2023) (reporting that increased productivity and improved animal health can reduce global livestock emissions by 30%); Tara L. Felix, *Beef Cattle Spacing Requirements*, PENNSTATE EXTENSION (Mar. 7, 2023), https://extension.psu.edu/beef-cattle-spacing-requirements.
[154] FAO, PATHWAYS TOWARDS LOWER EMISSIONS, *supra* note 153, at 24; Felix, *supra* note 153; *see also* WORLD ORG. FOR ANIMAL HEALTH, TERRESTRIAL ANIMAL HEALTH CODE Ch.7.1. (2018), https://www.woah.org/fileadmin/Home/eng/Health_standards/tahc/2018/en_chapitre_aw_introduction.htm (suggesting giving animals more space to improve their health).
[155] Bray, *supra* note 146, at 523-31.

> enhance and promote the stability and well-being of rural society in Minnesota and the nuclear family.[156]

Yet, despite this statutory commitment, the number of permits for new farms is going down while the number of animals per farm goes up.[157] Beef feedlots in the United States have become increasingly consolidated, with a small number of large operations handling most cattle.[158] The trend in Minnesota mirrors this national shift.[159]

This concentration significantly magnifies the GHG emissions and cumulative environmental impacts per site. Large-scale feedlots that store manure in anaerobic lagoons produce significantly more GHG emissions.[160] From a climate perspective, concentration creates GHG "hotspots" with emissions comparable to industrial sources.[161] Moreover, the volume of manure generated at these facilities often exceeds the nutrient absorption capacity of surrounding land, leading to runoff and leaching that pollutes water sources and contributes further to nitrous oxide emissions.[162] And the sheer density of animals intensifies emissions of ammonia, hydrogen sulfide, and particulate matter, exacerbating local air quality problems and posing risks to nearby communities.[163]

High-density operations are also more vulnerable to climate-related events, such as heavy rainfall and lagoon overflows, increasing the likelihood of catastrophic pollution events.[164] As MPCA's feedlot program manager recently commented: "Minnesota has also been getting more extreme and unpredictable rain storms than it did when its rules were last updated, which have caused manure lagoons to overflow and increased runoff on farms."[165] Without rules limiting the scale and density of feedlots, Minnesota risks entrenching a model of production that not only

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[156] MINN. STAT. § 500.24, subd. 1.
[157] Office of the Legis. Auditor, *Animal Feedlot Regulation*, MINN. LEG., https://www.auditor.leg.state.mn.us/ped/1999/fedlt99.htm (last visited July 20, 2025); *see also Request for Comments, infra* note 159.
[158] USDA, OVERVIEW OF THE U.S. CATTLE INDUSTRY 14 (2016), *available at* https://usda.library.cornell.edu/concern/publications/8s45q879d (noting the combined capacity of large feedlots with over 1,000 head of cattle increased by 100,000 head between 2006 and 2016). Across the county, roughly 5% of feedlots house more than 1,000 cattle, yet those facilities are responsible for over 85% of all beef cattle production. *Id*.; *Sector at a Glance: Cattle & Beef*, ECON. RSCH. SERV. (May 22, 2025), https://www.ers.usda.gov/topics/animal-products/cattle-beef/sector-at-a-glance.
[159] *Request for Comments*, MPCA 2 (2025), https://www.pca.state.mn.us/sites/default/files/wq-rule4-29a.pdf (There are "[f]ewer total number of feedlots in the state [since the last major update to the Feedlots Rule in 2000], with feedlots now having more animal units per facility.").
[160] April Leytem et al., *Methane Emissions from Dairy Lagoons in the Western United States*, 100 J. OF DAIRY SCI. 6785, https://www.sciencedirect.com/science/article/pii/S0022030217305799.
[161] A meta-analysis of 104 studies showed that a single feedlot emits approximately 2,786 kg CO_2-equivalent per animal unit annually, primarily through enteric fermentation and manure management. Wang et al, *supra* note 145.
[162] ECON. RSCH. SERV., MANAGING MANURE TO IMPROVE AIR AND WATER QUALITY 2 (2005); Chugg et al., *supra* note 59, at 3053.
[163] Wendee Nicole, *CAFOs and Environmental Justice: The Case of North Carolina*, 121 ENV'T HEALTH PERSPECTIVES 182, 186 (2013), https://pmc.ncbi.nlm.nih.gov/articles/PMC3672924/; *supra* Part I.B.
[164] *Id*.; JoAnn Burkholder et al., *Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality*, 115 ENV'T HEALTH PERSPECTIVES 308 (Feb. 2007), https://ehp.niehs.nih.gov/doi/10.1289/ehp.8839.
[165] Greg Stanley, *Minnesota Looks to Tighten Regulations on Feedlots to Deal with Persistent Pollution from Manure*, MINN. STAR TRIBUNE (June 13, 2025), https://www.startribune.com/minnestoa-will-rewrite-feedlot-rules-to-curb-nitrate-pollution-in-drinking-water/601369770.

worsens its climate footprint but also undermines its broader environmental, public health, and equity goals. Another pivotal regulatory change MPCA could add to the Feedlots Rule is to restrict new large feedlots from being constructed or expanded.

MPCA has the authority to restrict the number of permits it authorizes and to put limitations on those permits. As explained above, pursuant to Minn. Stat. § 116.07, subds. 2, 4, and 4a, MPCA is empowered to adopt and enforce rules and permit conditions necessary to prevent and control pollution, including emissions of air contaminants and discharges to water.[166] This broad authority allows MPCA to manage cumulative environmental impacts and protect public health and the environment through prospective, statewide rulemaking. In developing or revising the baseline technical criteria in the Feedlots Rule, MPCA should consider broader environmental and public health consequences, including the climate and ecological effects of regional concentration and expansion of large animal operations. Existing permit regulations under Minn. R. 7020.0405 and 7020.0505 provide a foundation for incorporating such criteria, and environmental review rules under Minn. R. Ch. 4410 further reinforce the relevance of scale and impact in regulatory decisions.

If the Feedlots Rule is updated to address GHG emissions, it is important to distinguish between genuinely effective mitigation strategies and those that offer limited or even counterproductive results. Many touted technologies are not fully tested or scalable; others cannot deliver emissions reductions at the necessary scale and fail to address other harmful externalities.[167] Anaerobic digesters, which capture methane from decomposing manure to produce biogas, are the most prominent example of a purported mitigation approach that emerging evidence and real-world experience suggest is deeply problematic.[168] Digesters do not eliminate methane emissions, leak significant amounts of methane, and can worsen other pollutants.[169] They have been associated with dangerous gas buildup, methane explosions, and storage tank ruptures, posing serious risks to human safety, groundwater, and local ecosystems.[170] Biogas is expensive and usually heavily-subsidized: gas from manure costs about four times more to produce than extracted natural gas—even excluding the large up-front capital

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[166] *Supra* Part II.

[167] Bray, *supra* note 146, at 523–31.

[168] *We're Challenging the NC Permit for Hog Waste Operations Causing Pollution and Harm to Communities*, S. ENV'T L. CTR. (Aug. 4, 2022), https://www.southernenvironment.org/news/were-challenging-the-n-c-permit-for-hog-waste-operations-causing-pollution-and-harm-to-communities; *see also* RUTHIE LAZENBY, CTR. AGRIC. & FOOD SYS., VT. L. SCH., RETHINKING MANURE BIOGAS: POLICY CONSIDERATIONS TO PROMOTE EQUITY AND PROTECT THE CLIMATE AND ENVIRONMENT 18 (2022), https://www.vermontlaw.edu/sites/default/files/2022-08/Rethinking_Manure_Biogas.pdf.

[169] Thomas Flesch et al., *Fugitive Methane Emissions from an Agricultural Biodigester*, 35 BIOMASS & BIOENERGY 3927, 3927 (2011); Semra Bakkaloglu et al., *Methane Emissions Along Biomethane and Biogas Supply Chains Are Underestimated*, 5 ONE EARTH 724, 730–731 (2022); Norah Efosa et al., *Emissions of Nitrous Oxide and Methane After Field Application of Liquid Organic Fertilizers and Biochar*, 356 AGRIC., ECOSYSTEMS & ENV'T 1, 1 (2023); Thomas Kupper et al., *Ammonia and Greenhouse Gas Emissions from Slurry Storage – A Review*, 300 AGRIC., ECOSYSTEMS & ENV'T 1, 1 (2020).

[170] Ji-Qin Ni, *Cases, Causes, and Impacts of Safety Incidents at AD Systems*, (unpublished workshop presentation, PURDUE UNIV.) 7-23 (Mar. 10, 2023), https://engineering.purdue.edu/adt/workshop/230310/ni.pdf; Frank H. Hedlund, *Biomass Accident Investigations—Missed Opportunities for Learning & Accident Prevention*, 25TH EUR. BIOMASS CONF. & EXHIBITION (June 2017) (describing "an increase of serious biomass related accidents involving fires, gas explosions, combustible dust explosions and the release of biomass related accidents involving fires, gas explosions, combustible dust explosions and the release of toxic gasses").

costs of building digesters.[171] Biogas investment entrenches large, intensified production (typically requiring manure from at least 500 cows) and could even encourage industrial cattle operations to expand to realize the associated, government-subsidized profits.[172] This dynamic is at odds with Minnesota's commitment to protecting smaller farmers, as well as its broader climate and water quality goals.[173] States that have promoted digesters as low-carbon fuel sources, such as California, are facing lawsuits for facilitating pollution and environmental injustice through biogas programs.[174] Minnesota should not follow this path.

Other jurisdictions have adopted or considered imposing limitations on feedlots for environmental reasons. For example, North Carolina put a moratorium on new hog farming operations in 1997 through the federal Clean Water Responsibility Act.[175] The New York Senate recently proposed a law "prohibiting the department of environmental conservation from issuing or authorizing any permits to new or expanding large concentrated animal feeding operations,"[176] and the New York State Department of Conservation has published a draft rule that would require reporting of GHG emissions from animal agriculture.[177] At the federal level, several bills have been proposed to begin to address the climate problem of animal agriculture.[178]

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[171] Aaron Smith, *What's Worth More: A Cow's Milk or Its Poop?*, AG DATA NEWS BLOG (Feb. 3, 2021), https://asmith.ucdavis.edu/news/cow-power-rising.

[172] LAZENBY, RETHINKING MANURE BIOGAS, *supra* note 168168, at 18; EUR. SCI. ADVISORY BD. ON CLIMATE CHANGE, TOWARDS EU CLIMATE NEUTRALITY: PROGRESS, POLICY GAPS, AND OPPORTUNITIES, ASSESSMENT REPORT 2024, at 169 (2024), https://climate-advisory-board.europa.eu/reports-and-publications/towards-eu-climate-neutrality-progress-policy-gaps-and-opportunities (noting that biogas digesters have the potential to "increase[] incentives to maintain livestock herd numbers"); Aaron Smith, *Cow Poop Is Now a Big Part of California Fuel Policy*, AG DATA NEWS BLOG (Jan. 22, 2024), https://asmith.ucdavis.edu/news/cow-poop-now-big-part-california-fuel-policy; Phred Devorak, *California's Green-Energy Subsidies Spur a Gold Rush in Cow Manure*, WALL ST. J. (Feb. 19, 2022).

[173] *See* MINN. STAT. § 500.24, supd. 1 ("[I]t is in the interests of the state to encourage and protect the family farm"); *see also* MINNESOTA'S CLIMATE ACTION FRAMEWORK, *supra* note 5.

[174] Compl., *Cmtys. For a Better Env't v. Cal. Air Res. Bd.* et al., No. 24-ECG-05430 (Cal. Super. Ct., filed Dec. 18, 2024); Zoe Woodcraft & Gissela Chavez, *Environmental Justice Group Sues California Agency Over Flawed Low Carbon Fuel Standard Changes*, EARTHJUSTICE (Dec. 18, 2024), https://earthjustice.org/press/2024/environmental-justice-group-sues-california-agency-over-flawed-low-carbon-fuel-standard-changes.

[175] 15A N.C. Admin. Code 02T .1307-.1308; 15A N.C. Admin. Code 02D .1808; *Program Summary*, N.C. DEPT. OF ENV'T QUALITY, https://www.deq.nc.gov/about/divisions/water-resources/permitting/animal-feeding-operations/program-summary (last visited July 20, 2025).

[176] N.Y. S.B. 6530 (2025), https://www.nysenate.gov/legislation/bills/2025/S6530 (An act to amend the environmental conservation law, in relation to prohibiting the department of environmental conservation from issuing or authorizing any permits to new or expanding large concentrated animal feeding operations.)

[177] *Express Terms Part 253 Mandatory Greenhouse Gas Reporting Program*, 6 N.Y. Code, Rules & Regs. Part 253 (2025), https://dec.ny.gov/sites/default/files/2025-03/part253expressterms.pdf; *see also Recently Proposed and Adopted Regulations and Policies*, N.Y. DEP'T OF ENV'T CONSERVATION, https://dec.ny.gov/regulatory/regulations/proposed-emergency-recently-adopted-regulations/air-pollution-regulatory-revisions (last visited July 20, 2025).

[178] Agriculture Resilience Act, H.R. 5861, 116th Cong. (2020) (reintroduced: H.R. 2803, 117th Cong. (2021)); Industrial Agriculture Conversion Act of 2024, H.R. 9794, 118th Cong. (2024); Industrial Agriculture Accountability Act of 2023, S. 272, 118th Cong. (2023).

In Minnesota, the White Earth Nation Tribal Council passed a temporary moratorium on CAFOs within the boundaries of the White Earth Reservation, located in northwestern Minnesota.[179]

Large animal agriculture corporations are exploiting statutory and regulatory loopholes that allow them to consolidate operations and sidestep the State's interest in promoting family farms. Compared to alternative food production approaches, large-scale feedlots emit more GHGs and cause greater water pollution, odor, and community-level environmental burdens. Accordingly, MPCA should amend its Feedlots Rule to include animal unit caps per permit or watershed to prevent over-concentration; deny permits for new large-scale feedlots, especially in vulnerable or already overburdened watersheds; and require improved livestock management practices, including space and density standards, to reduce emissions and support animal health. MPCA can also require and encourage established practices to reduce GHG emissions from animal agriculture, including changes to animal feed, the use of more climate-friendly practices to grow animal feed, and better manure management. For over three decades, it has been well-understood that on-the-ground management changes at the farm will drive down GHG emissions. Despite that knowledge, animal agriculture has succeeded in evading any real responsibility to manage and mitigate GHG emissions. It is time for MPCA to act.

C. Enforce Air Emission Plans Under the Current Rule

While commenters encourage MPCA to implement the above suggestions to adequately prevent and mitigate emissions from animal feedlots. At a minimum, MPCA must enforce existing requirements under the Rule. As discussed above, Minn. R. 7020.0505, subp. 4(B), requires that certain feedlot permit applications include an air emission plan describing how the facility will minimize emissions and respond to air quality exceedances.[180] This plan must contain forward-looking, substantive detail—specifying the methods and practices the facility will use to reduce air emissions from feedlot and manure storage operations, the measures to mitigate emissions in the event of a violation of the state's hydrogen sulfide standard, and a clear complaint response protocol.[181]

While the Rule specifically references hydrogen sulfide and odor emissions, it begins with a broader mandate: the plan must outline how the facility will minimize air emissions generally, without limiting the requirements to any particular pollutant.[182] This general obligation necessarily includes GHG emissions—such as methane, nitrous oxide, and carbon dioxide—which are known, as harmful byproducts of animal digestion, manure management, and feedlot operations.[183]

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[179] White Earth Reservation Business Committee White Earth Band of Chippewa Indians, *Resolution No. 057-23-006-A*, DIV. OF NATURAL RES. (2022), https://www.whiteearth.com/media/pages/divisions/judicial-services/codes-ordinances/85620627e1-1727298852/ord-skm_c554e22120713480.pdf.
[180] MINN. R. 7020.0505, subp. 4(B); *see supra* Part III.A.
[181] *Supra* notes 101-103 and accompanying text.
[182] MINN. R. 7020.0505, subp. 4(B)(1)(a).
[183] *See supra* Part II; MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 1, at 9.

To fulfill the purpose and legal requirements of the rule, MPCA should:

1. Clarify that the air emission plan must address all significant air pollutants associated with the facility, including GHGs;
2. Require that feedlot operators provide specific, forward-looking statements detailing how they will monitor and reduce GHG emissions;
3. Ensure and enforce that each plan includes contingency measures to mitigate emissions in the event of any air quality exceedance—not only for hydrogen sulfide, but for any pollutant that poses a threat to air quality or public health; and
4. Reject permit applications in which the air emission plan fails to meet these standards, as required by the Rule.

Without a clear, complete air emission plan at the time of permitting, enforcement becomes reactive and ineffective. MPCA must consistently apply and enforce the plain language of the current Rule to ensure that facilities proactively plan for, and minimize, all harmful air emissions, including GHGs. Doing so is not only legally justified, but essential for aligning permitting practices with the state's broader environmental and climate protection goals.[184]

V. Conclusion

MPCA has the duty, authority, and urgency to regulate GHG emissions from feedlots. MPCA should enforce existing air emission plan requirements and adopt a Feedlots Rule that specifically regulates GHG emissions. The Rule should include monitoring, reporting, and mitigation of GHG emissions from animal feedlots. MPCA has the obligation to regulate GHG emissions to be in compliance with its mandate, statutory climate goals, and the state's Climate Action Framework. MPCA's leadership in this area could have widespread positive impacts, as municipalities, other states, and countries are realizing that regulation and emissions mitigation is needed to support the development of more resilient, secure, and climate-friendly food systems.

We look forward to engaging throughout the rulemaking process and submitting further input on proposed language.

Respectfully Submitted,

The Climate Change & Animal Agriculture Litigation Initiative,
Law, Environment & Animals Program at Yale Law School*

Minnesota Center for Environmental Advocacy

[Signatures continue on next page]

[184] *See generally,* MINNESOTA'S CLIMATE ACTION FRAMEWORK, *supra* note 5.

Center for Biological Diversity

Center for Food Safety

Clean Up the River Environment

FarmSTAND

Food & Water Watch

Institute for Agriculture Trade Policy

Minnesota Interfaith Power & Light

MN350 Action

Socially Responsible Agriculture Project

Third Act Minnesota

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position not endorsed by Yale University or Yale Law School

Cattle dying due to heat wave

mprnews.org/story/2011/07/20/cattle-die-from-heat-wave

Elizabeth Baier July 20, 2011

An estimated 1,000 cattle have died this week across Minnesota because of the unusually hot weather. Most have been in south central and southwestern Minnesota.

The University of Minnesota's Extension office estimates the losses could total about $1 million.

Most of the losses have been large, black-hided cattle, according to Grant Crawford, an extension livestock instructor.

"A lot of times they've been in open lots that don't have a lot of shade or covering," he said.

Crawford says the typical steps that farmers take to keep cattle cool haven't worked as well because of the extended heat wave.

"It's not that producers weren't prepared. It's that this is the worst that we've had in a while," said Crawford. "The practices they took this time around probably worked in the past. It's just that because this heat was so extreme and so dangerous, the normal practices didn't work as well as they worked in the past."

Across the border in South Dakota, officials estimate as many as 1,500 cattle have died in that state because of this week's heat wave.

One Earth

Article

Methane emissions along biomethane and biogas supply chains are underestimated

Graphical abstract

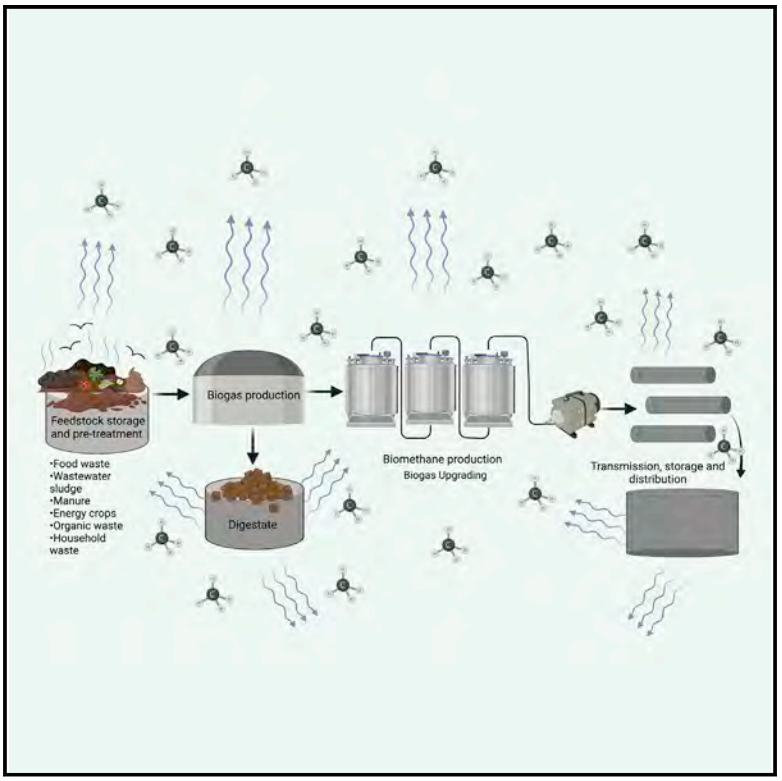

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In brief

Biomethane and biogas have emerged as cleaner alternatives for natural gas, as they generate fewer greenhouse-gas emissions. However, their production and distribution can still result in methane emissions, the magnitude of which remains unclear. Here, we evaluate methane emissions throughout the biomethane and biogas supply chains and show that emissions are greater than previously estimated. The digestate stage generated the most CH_4, and 62% of total emissions were released by just 5% of emitters.

Highlights

- The biomethane and biogas supply chain may emit up to 18.5 Tg CH_4 per year
- Biomethane and biogas emit much less CH_4 than oil and natural gas
- CH_4 loss rates in biomethane and biogas supply chain exceed those in oil and natural gas
- The top 5% of emitters account for 62% of CH_4 emissions

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Article

Methane emissions along biomethane and biogas supply chains are underestimated

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SCIENCE FOR SOCIETY An immediate shift away from coal and oil for energy is necessary to limit rising temperatures but is challenging due to energy needs, particularly in areas like heating and cooling that require substantial energy supply all year round. Natural gas is presently being used as a bridging fuel. It delivers the same performance as coal and oil but has lower CO_2 emissions. However, natural gas releases methane (CH_4), which is a more powerful warming agent than CO_2. Biomethane and biogas have emerged as strong candidates to replace gas and lower CO_2 and CH_4 emissions. However, these replacement fuels are not CH_4 emission free. Indeed, CH_4 is released at various points during production and distribution, but a thorough understanding of where, when, and how much CH_4 is released remains absent. A synthesis and analysis of existing biomethane and biogas CH_4 emission data reveal that CH_4 emissions throughout the supply chains have been underestimated. The majority of CH_4 comes from just a few super-emitters and mainly at the digestate stage. Mitigating CH_4 throughout biomethane and biogas supply chains is urgently needed if we are to limit global warming to 1.5°C.

SUMMARY

Although natural gas generates lower CO_2 emissions, gas extraction, processing, and distribution all release methane, which has a greater global warming potential than CO_2. Biomethane and biogas that use organic wastes as a feedstock have emerged as alternatives to natural gas, with lower carbon and methane emissions. However, the extent to which methane is still emitted at various stages along biogas and biomethane supply chains remains unclear. Here, we adopt a Monte Carlo approach to systematically synthesize the distribution of methane emissions at each key biomethane and biogas supply chain stage using data collected from the existing literature. We show that the top 5% of emitters are responsible for 62% of emissions. Methane emissions could be more than two times of greater than previously estimated, with the digestate handling stage responsible for the majority of methane released. To ensure the climate benefits of biomethane and biogas production, effective methane-mitigation strategies must be designed and deployed at each supply chain stage.

INTRODUCTION

As we move further into the 21st century, energy systems must move away from fossil fuels and grow in renewable energy capacity if Paris Agreement temperature targets are to be met. However, due to challenges in adopting low-carbon technologies, certain areas of global energy systems are difficult to decarbonize. These include heavy industry, transport, and heating and cooling systems, which together account for a significant portion of carbon dioxide (CO_2) emissions.[1] Natural gas has therefore been used as an important alternative fuel, which can offer large-scale energy supply, especially for domestic space heating and hot water needs, electricity generation, and industrial applications, with much lower CO_2 emissions compared with oil and coal. Although replacing oil and coal with natural gas reduces CO_2 emissions, fugitive emissions from the supply chain of natural gas—gas extraction, processing, and distribution—can all release CH_4. Around 39.6 million tonnes of CH_4 were emitted in 2021,[2] representing 61% of oil and gas emissions and 30% of total-energy-sector CH_4 emissions. Since CH_4 has a much stronger global warming potential than CO_2 and is currently responsible for at least one-quarter of global warming, there are strong calls for natural gas use to be reduced by at least 35% by 2050 and 70% by 2100 relative to 2019;[3]

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therefore, alternative clean-energy methods are vital to replace natural gas to limit global warming to 1.5°C.

An alternative method of decarbonizing natural gas is via replacing it with biomethane or biogas, which is a mixture of gases (mostly CH_4 and CO_2) produced from biodegradable materials. Biomethane and biogas production and use have been put forward as part of mitigation efforts,[4] with up to 37 exajoule (EJ)/year of biomass-based gases in Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C (IPCC SR1.5C) scenarios,[5] which limits temperature rises to below 2°C. The International Energy Agency (IEA)[6] reported that global biomethane and biogas production could satisfy nearly 20% of global gas demand if its sustainable potential was fully utilized.[6] Because biomethane is similar to natural gas, it can be easily stored and injected into the existing natural gas infrastructure, potentially providing reliable and affordable energy.[7] At the time of writing, Europe is the world leader in biomethane production by upgrading biogas, followed by the United States, China, and Canada.[8] According to the World Biogas Association (2019), 700 biogas-upgrading plants are operating worldwide, with 195 in Germany (the largest producer), with biogas currently dominating biomethane production. Biomethane and biogas production are expected to grow further, with demand predicted to grow 9-fold by 2040 compared with 2018 levels,[6,9] driven by increases in the volume of organic waste generated by modern societies, changes in waste practices, and the phasing out of fossil fuels aimed at reducing greenhouse gas (GHG) emissions and meeting government targets. Given this host of commitments, investments, and developments, biomethane and biogas could be crucial in helping to establish a clean, reliable, and affordable global energy system.

However, large quantities of CH_4 can still be emitted from the biomethane and biogas supply chains, including digestate handling, anaerobic digesters, upgrading units, feedstock storages and transmission, and storage and distribution stages.[4] CH_4 is a relatively short-lived GHG but has a global warming potential (GWP) 27.2 ± 11 times larger than CO_2 over a 100-year horizon and 80.8 ± 25.8 times larger over a 20-year time horizon for biogenic sources.[10] The importance of reducing CH_4 emissions to meet Paris Agreement[11] targets has been demonstrated by Rogelj et al.,[12] as it is an important GHG in terms of potential overshooting of Paris Agreement targets, where warming exceeds "well below 2°C" and then returns to the target level by 2100,[10] leading to potential tipping points in physical and socio-economic systems. The IPCC (Intergovernmental Panel on Climate Change) Sixth Assessment Report (AR6) (Working Group III)[13] highlighted CH_4 as playing a significant role in determining whether or when 1.5°C is achieved, as reducing CH_4 emissions will offset global temperature increase much more quickly than CO_2, due to its relatively short lifetime and higher GHG potency. The AR6 report also noted that reductions to CH_4 emissions will need to occur more rapidly than CO_2 and that reducing CH_4 (and other non-CO_2 GHG) emissions is essential for lowering warming.[13] As the AR6 scenarios predict biomethane capacity to increase by up to 200-fold between 2020 and 2050,[14] understanding where CH_4 emissions occur and how much is emitted is crucial.

There are some emissions-measurement studies to date focusing on specific biomethane facilities,[4,15–22] which have measured on site (measurement of emissions at each individual point source) and off site (measurement of emissions based on observations made away from the site). These can also be referred to as bottom-up (on-site) and top-down (off-site) studies. These have found that emissions from biomethane facilities can be up to 97 kg h^{-1} CH_4.[4,16–24] However, a comprehensive evaluation by characterizing the distribution of CH_4 emissions at each biomethane and biogas supply chain stage remains unclear.

Here, we bring together the published emissions data from CH_4-measurement studies to assess and synthesize the distribution of emissions from each supply chain stage in order to characterize the emissions profile of the biomethane and biogas supply chain (see experimental procedures and Figure S1 for the selected supply chain route). A Monte Carlo aggregation examines the distribution of supply chain emissions. This allows for the emission profile of biomethane and biogas supply chains to be characterized. We find that, while the biomethane and biogas supply chain emits less CH_4 than the oil and natural gas supply chain, the emission rate is higher. Furthermore, we find that 62% of cumulative emissions are released by just the top 5% of emitters. We also find that methane emissions could be more than two times higher than previously estimated, and the digestate-handling stage contributed to the largest CH_4 emissions along the supply chain. Our results will allow for a greater understanding of how to improve the sustainability of biomethane and biogas production by providing plant operators, investors in the supply chain, and policymakers with information on where improvements can be made in biomethane and biogas supply chains to reduce CH_4 emissions, as well as whether existing or proposed CH_4 regulations are sufficient or need to be revised.

RESULTS

Method summary

To assess overall supply chain emissions, the biomethane supply chain is divided into five major stages: (1) feedstock; (2) biogas production; (3) biogas upgrading; (4) transmission, distribution, and gas storage; and (5) digestate storage. This study was compiled from several published studies and the data from on-site (taken at each individual emission source) and off-site measurements (reported for the entire site). The kernel density estimation (KDE) function was used to assess the characteristics of the data distribution gathered from individual sources for each stage of the supply chain. Following that, a Monte Carlo simulation was performed to estimate total supply chain emissions, which were then compared with the off-site emissions reported from whole-site measurements in previously published studies (see the experimental procedures for further details).

Total supply chain emissions

The cumulative distribution of the supply chain CH_4 emissions is shown in Figure 1A. Median and mean emissions are 40.0–42.3 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (41.1–41.3 at the 95% confidence interval [CI]) and 51.4–52.7 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (52.2–52.4 at the 95% CI), respectively, with a 5th percentile of 11.0–16.3 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (15.6–15.7 at the 95% CI) and a 95th percentile between 118.2 and 144.0 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (131–133 at the 95% CI) using

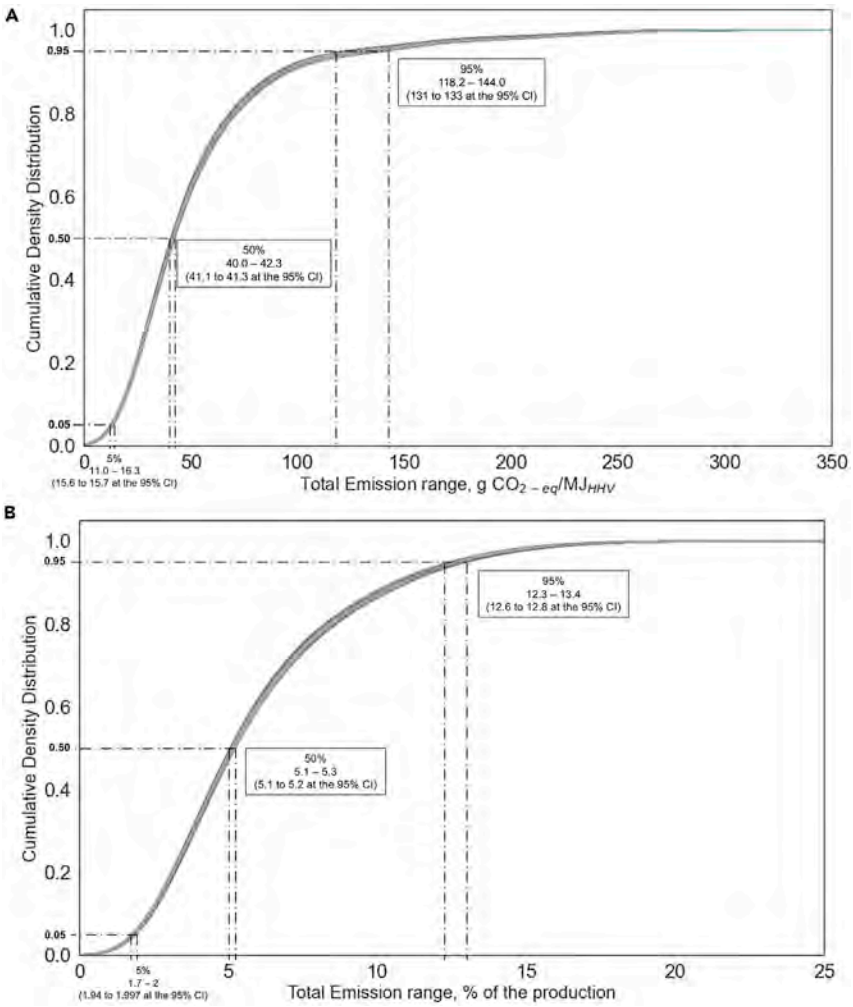

Figure 1. Cumulative distribution of CH_4 emissions from the total supply chain

(A) Cumulative distribution of total supply chain CH_4 emissions for the 10,000 Monte Carlo runs and 100 curves described in the experimental procedures, expressed as g $CO_{2\text{-eq.}}/MJ_{HHV}$.

(B) Cumulative distribution of total supply chain CH_4 emissions for the 10,000 Monte Carlo runs and 100 curves, expressed as percentage of total CH_4 production.

The range of 5th, 50th, and 95th percentile estimates are shown as dotted black lines. CI: confidence interval.

GWP_{100} values. Each curve defines the cumulative distribution for a single Monte Carlo simulation and shows that total supply chain emissions range from 2.5 to 343 g $CO_{2\text{-eq.}}/MJ_{HHV}$. The emissions distribution is highly upward skewed (Figure 1A), which is indicative of disproportionately high emitting sites referred to as "super-emitters" (see the identification of super-emitters section for details). Our findings are consistent with those observed for oil and natural-gas supply chains.[25–30] Using global biogas and biomethane production of 35 megatonnes of oil equivalent (Mtoe) (1.47×10^{12} MJ) in 2018,[6] our model-based estimate of 2018 biomethane supply chain emissions may account for up to 18.5 teragram (Tg) CH_4 per year (6.4–7.8 Tg CH_4 year^{-1} at the 95th percentile and an average of 2.8–2.9 Tg CH_4 year^{-1}), which is more than two times greater than the International Energy Agency's (IEA's) estimate of CH_4 emissions from bioenergy (9.1 Tg in 2021).[2] Our estimate of global biogas and biomethane CH_4 emissions is significantly lower than in the global oil and natural-gas supply chain (82.5 Tg in 2021);[2] on the other hand, it is comparable to the production segment of the US oil and natural-gas supply chain (6.1–7.1 Tg year^{-1})[31] based on site measurements.

The cumulative distribution of emissions as a percentage of total CH_4 produced is shown in Figure 1B. The 5th percentile is 1.7%–2.0% (1.94%–2.0% at the 95% CI) of CH_4 production, and the 95th percentile is 12.3%–13.4% (12.6%–12.8% at the 95% CI) of total gas production. The ranges in minimum, median, mean, and maximum values were fairly consistent across all estimates (Figure 1). While the low and median estimates are nearly identical, the disparity between biomethane and natural gas varies widely in the highest estimates. The median ranged from 5.1% to 5.3% (5.1%–5.2% at the 95% CI), with mean emission rates of 5.90%–6.04% (5.9%–6.0% at the 95% CI) of total CH_4 production, which is higher than natural gas (0.8%–2.2% of CH_4 production).[25,26] Rutherford et al.[31] found CH_4 emissions in the oil and natural-gas-production segment to be 1.3% (1.2%–1.4% at the 95% CI), which is significantly lower than our findings. On the other hand, despite declining gas production, one of the highest reported CH_4 emissions from oil and gas production (Uinta Basin from a multi-year record of in-site observations) reveals a higher emission rate than our results (6%–8%).[32] Although emissions from the biomethane supply chain are comparable to oil and natural-gas production in terms of Tg CH_4 year^{-1}, the production-normalized emission rate is considerably higher. This could be due to a variety of factors, including poorly managed production facilities; a lack of attention to the biomethane industry resulting in lower investments for modernization, operation, and monitoring; and employment of highly skilled plant operators[16,21] when compared with oil and natural gas. In addition, poor design and management of feedstock and digestate storage units[33] as well as a limited interest in infrastructure emissions may result in higher emission rates compared with the amount of gas produced. Because oil and natural-gas supply chains have been primarily operated by large companies for decades, they have invested more in leak detection and repair.[34,35] On the other hand, given the growth in biomethane generation due to national decarbonization strategies, more urgent efforts are also needed for the biomethane supply chain to address not only CH_4 emissions but also the sustainability of biomethane.

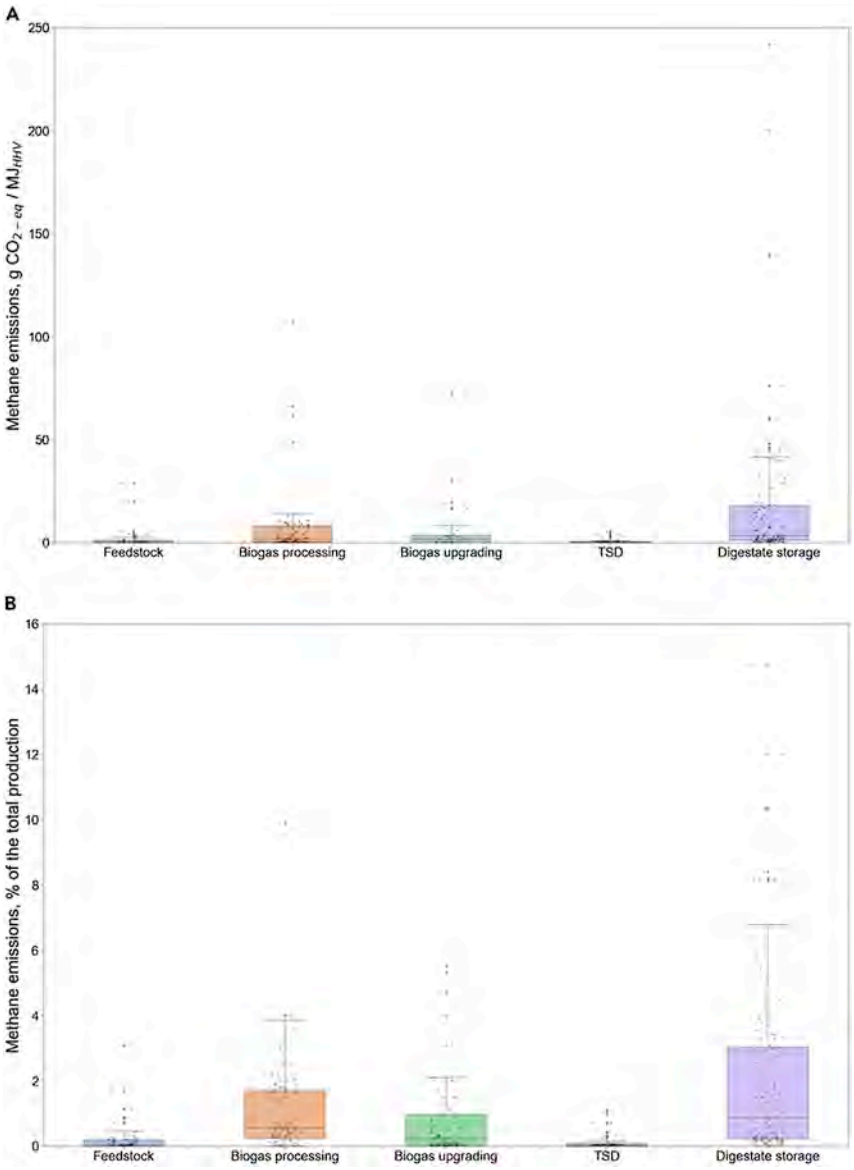

Figure 2. Literature CH_4 emissions from different stages of biomethane supply chain

(A) Emissions range of feedstock (n = 49), biogas processing (n = 100), biogas upgrading (n = 35), TSD (n = 44), and digestate storage (n = 119) stages in g $CO_{2\text{-eq.}}/MJ_{HHV}$.

(B) Emissions range of feedstock (n = 52), biogas processing (n = 95), biogas upgrading (n = 84), TSD (n = 48), and digestate storage (n = 120) stages in terms of total CH_4 emissions as a percentage of the total gas production rate.

Individual estimates are shown as circles in the same color at each stage of the supply chain, with median and 25th and 75th percentile boxes. Sample sizes for each stage are demonstrated in the Figure 3.

Identification of super-emitters

A small proportion of facilities or equipment with disproportionately large emission rates are labeled super-emitters,[36,37] causing the heavy-tailed distribution (see Figure S4). A small number of high emitters may cause under- or overestimations of emissions rates[38] if they have intermittent emissions patterns, insufficient process equipment usage, or inadequate operations and maintenance strategies. In this study, super-emitters have been investigated at various stages across the supply chain, including feeding systems; substrate storage; runoff ponds; pressure relief valves on the anaerobic digesters and gas holders; exhausts and aeration lines of upgrading units; ventilation of units, such as compressors or closed digestate tanks; open digestate storage; and flaring. Within the heavy-tail distribution (Figures 1A and 1B) and the boxplot of each stage's emissions (Figure 2), the mean emission rate is higher than the median because of super-emitters (see Table S1 for details). Since we lack information on on-site CH_4 sources, we identify them as the top 5% of highest emissions based on the cumulative density function of CH_4 emissions, parallel to natural-gas production sites.[29,36,39] The highest 5% of total emissions (199–224.8 g $CO_{2\text{-eq.}}/MJ_{HHV}$) account for 62% (CI: 58%–66%) of cumulative emissions, with a threshold of 211.9 g $CO_{2\text{-eq.}}/MJ_{HHV}$. The characteristics of super-emitters in the biomethane supply chain are similar to those of super-emitters in the oil and natural-gas supply chain (the largest 5% of leaks contribute to 50%–60% of total emissions).[29,36] Since super-emitters are unlikely to remain constant over time, continual monitoring will be required to detect intermittent emission patterns or unpredictable leaks from the biomethane supply chain. Future work is necessary to understand the characteristics of individual super-emitter sites in the biomethane supply chain. The efficiency of mitigation efforts could be improved by investing in the underlying cause of preventable operational conditions at a component level.[30]

Contribution of each supply chain stage

The contribution of each stage of the biomethane supply chain is illustrated in Figure 2A in g $CO_{2\text{-eq.}}/MJ_{HHV}$ and as a percentage of total production in Figure 2B. The distributions are almost identical. Emissions are mainly from digestate storage, followed by production and upgrading stages. Similar results were observed by Reinelt et al.,[17] where the highest emissions are from open digestate storage and pressure-release valves. Similarly, Alvarez et al.[39] found production and gathering units to be the main emission source in the US oil and natural-gas supply chain. Overall, the lowest emissions are exhibited in the transmission, storage, and distribution (TSD) stage, similar to the US oil and natural-gas supply chain.[39]

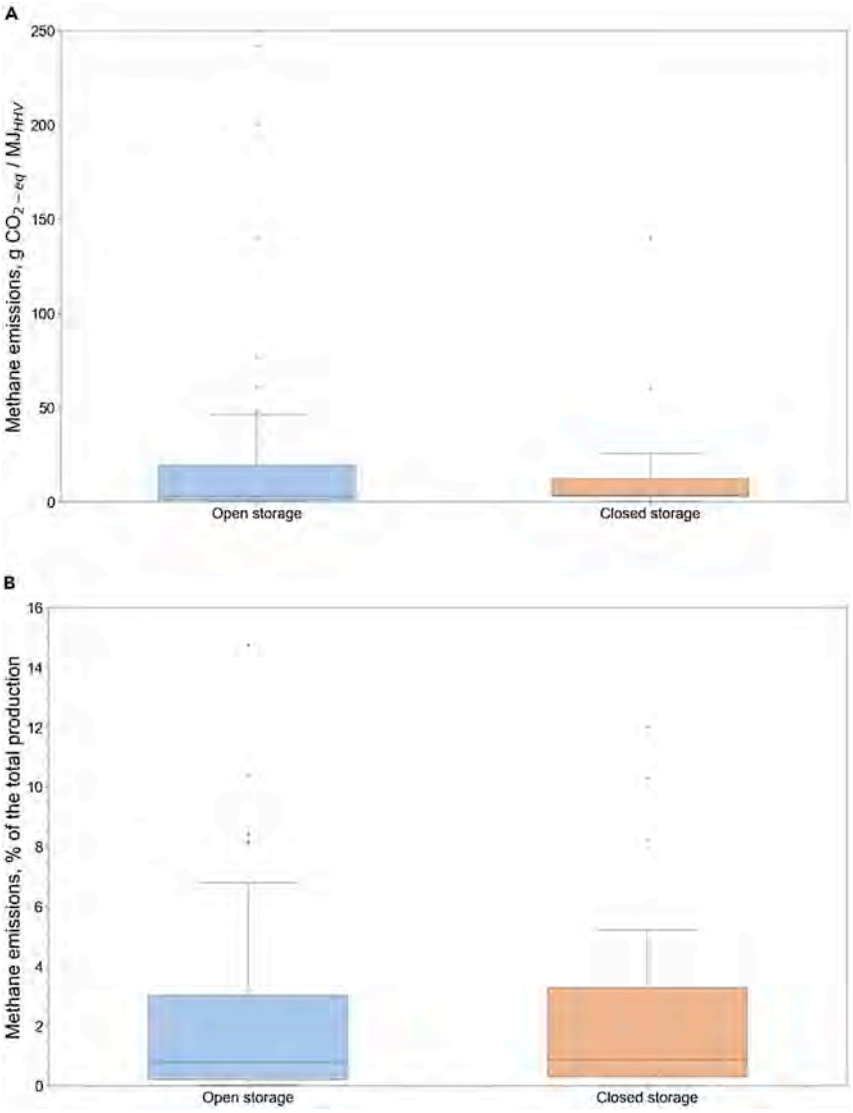

Figure 3. Literature CH_4 emissions of open and closed digestate storage

(A) Emissions from digestate handling from open (n = 98) and closed (n = 21) storage tanks in g $CO_{2\text{-eq.}}/MJ_{HHV}$.

(B) In terms of the percentage of total biomethane produced, illustrating emissions from the open (n = 95) and closed (n = 25) storage tanks.

Closed tank emissions originate mainly from leaks of covered material and ventilation of stockpile building.

Of particular note here is that the digestate storage stage is a significant source of CH_4, ranging between 0.05 and 242.1 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (Figure 2A) or 0.005% and 14.8% of the total biomethane produced (Figure 2B). Sources of emissions are open or covered digestate (liquid and solid) storage tanks and lagoons. The emissions from digestate handling, such as post-composting processes, application of digestate, thickening exhaust, dewatering units, and leaks from centrifuges, were excluded from the biomethane supply chain in this study. Our analysis revealed that CH_4 emissions from this stage are 23% higher than previously reported,[40] while they still form a substantial portion of previous studies.[19,40]

The biogas production stage is the second biggest emission source, ranging from 0.002 to 106.5 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (Figure 2A) or 0.001% to 9.9% of CH_4 production (Figure 2B). Biogas-production emissions are mainly from the anaerobic digester and hygienization tank. Hygienization tanks represent a relatively small fraction of the emissions from this stage. Emissions from the anaerobic digester are highly variable, depending on fugitive emissions from different cover types and control of venting from pressure-release valves. In addition, Zeng et al.[41] found that the fermentation temperature and quality of the feeding material have an effect on the CH_4 emissions from anaerobic digesters. Following biogas production, estimates of emissions from biogas upgrading are 0.002–72.4 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (Figure 2A) or 0.001% to 5.5% of CH_4 production (Figure 2B), which are slightly higher than what was reported by Dumont et al.[40] The emissions from the biomethane production stage arise from the exhaust or aeration of units, ventilation ducts, booster pumps, safely valves on upgrading facilities, water or chemical scrubbers, and membranes.

In addition, feedstock emissions, resulting from fugitives and vents from substrate storage, are the fourth highest contributor to the supply chain, accounting for 0.0003 to 28.8 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (Figure 2A) or 0.0003% to 3.1% of the total CH_4 production (Figure 2B), and represent the smallest proportion of total supply chain emissions. Higher emissions are associated with substrate storage. Dumont et al.[40] reported a larger range in CH_4 emission (0.2%–0.5% of CH_4 production) for feedstock storage.[40] However, their results were based on a smaller dataset than ours, and emissions may have reduced through technology improvements since their study was published.

Digestate-handling approaches

As discussed above, digestate storage is the largest emission source in the biomethane supply chain. This is because of the accumulation of organic material, which leads to CH_4 production from fermentation. According to Döhler et al.,[42] digestate storage may account for nearly 27% of global $CO_{2eq.}$ emissions from anaerobic digestion processes. How digestate is handled has a major impact on emissions, with open digestate storage tanks and lagoons emitting more than closed tanks similar to the results from Paolini et al.[33] (Figure 3). The residual gas potential, digestate temperature, substrate amount, level of filling, and meteorological conditions all have a significant influence on the emission rate from open digestate storage tanks

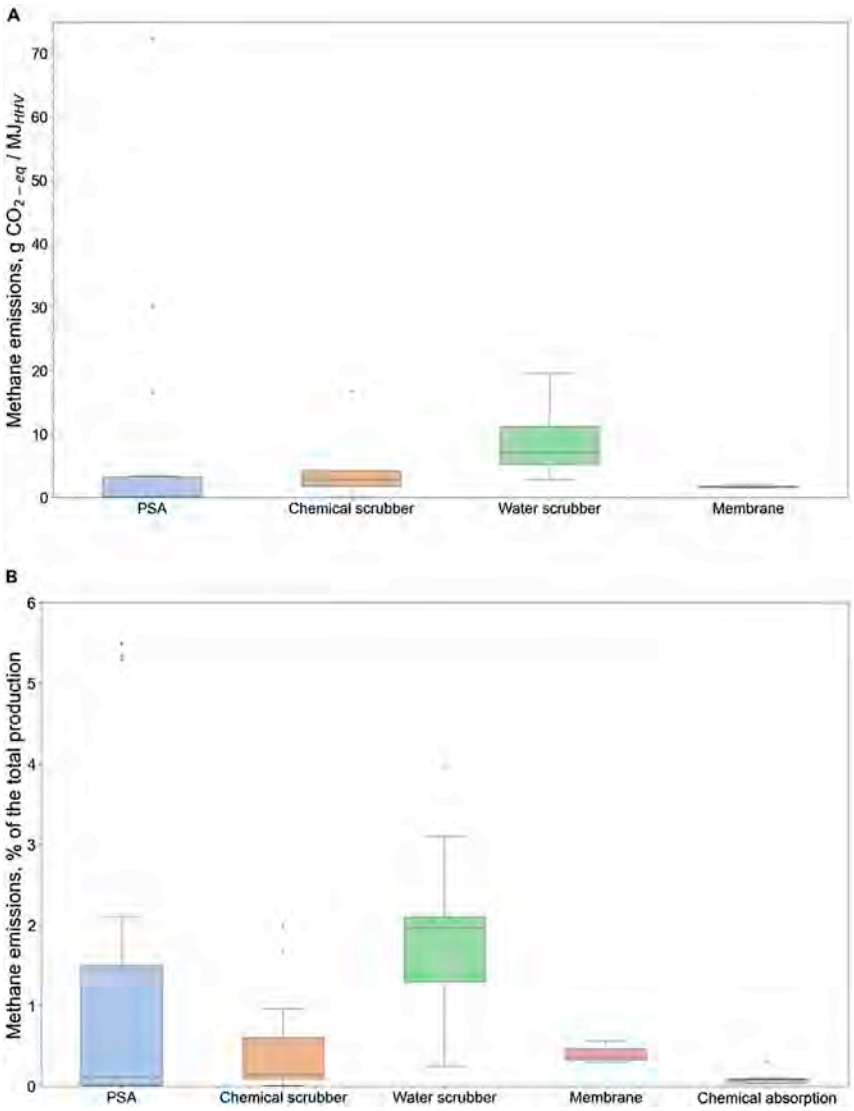

Figure 4. Literature CH_4 emissions from different biogas-upgrading technologies

(A) Emissions from biogas-upgrading technologies in g $CO_{2\text{-eq.}}/MJ_{HHV}$, pressure swing adsorption (PSA) with activated carbon filters (n = 22), water scrubber (n = 4), chemical scrubber (n = 5), and membrane (n = 4).

(B) Emissions from upgrading biogas technologies in terms of the percentage of total biomethane produced, with PSA with activated carbon filters (n = 30), water scrubber (n = 9), chemical scrubber (n = 25), chemical absorption (n = 14), and membrane technologies (n = 6).

Scrubber emissions include chemical (e.g., amine) and water scrubber emissions.

and lagoons.[15,19,43,44] Figure 3 clearly demonstrates that the closed tanks can still emit CH_4, although emissions from closed tanks can be avoided with improved covering materials, effective design, and regular maintenance. The facilities should consider becoming accredited under the Publicly Available Specification (PAS) 110 standards,[45] which recommend coverage of digestate to diminish emissions. Therefore, we recommend using closed digestate storage with vapor-recovery systems directed to the upgrading unit where economically viable to address emissions from this stage. Targeting reductions in digestate-handling emissions provides the greatest environmental improvements, though it is noted that detection and mitigation strategies would require additional expense and regulation.

Impact of biogas-upgrading technologies

Upgrading biogas to biomethane can cause significant emissions. The literature provides scant data on specific upgrading technologies, though available evidence shows that membrane filters and chemical absorption leads to lower emissions than pressure swing adsorption (PSA) and water and chemical scrubbers (see Figures 4A and 4B). Therefore, initial indications are that chemical absorption technology is the best available technology for upgrading to reduce CH_4 emissions, which is the line with previously reported values.[46,47] PSA and water scrubber utilization should be avoided, though more measurements should be conducted.

Total supply chain emission estimates versus whole-site mobile measurements

Alongside the on-site (aggregation of component-based emission) Monte Carlo approach described above, whole-site (off-site) measurements are a useful benchmark. In the literature, CH_4 emissions from 792 whole-site measurements varied between 0.1 and 483 g $CO_{2\text{-eq.}}/MJ_{HHV}$, with an average of 51.7 and a median of 24.6 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (see Figure 5A). This is a larger range with lower median and higher estimate of upper limit than our Monte Carlo simulation of on-site measurements. While the mean of the Monte Carlo runs (51.4–52.7 g $CO_{2\text{-eq.}}/MJ_{HHV}$) and whole-site measurements (51.7 g $CO_{2\text{-eq.}}/MJ_{HHV}$) are comparable, the median of the Monte Carlo runs (40.0–42.3 g $CO_{2\text{-eq.}}/MJ_{HHV}$) are greater than the whole-site measurements (24.6 g $CO_{2\text{-eq.}}/MJ_{HHV}$) due to the heavy-tailed distribution of the Monte Carlo runs. Before running the Monte Carlo simulation, the emissions probability density function of each stage is identified to establish a good fit. The heavy-tailed distribution is due to the presence of super-emitters in each supply chain stage in the Monte Carlo runs, while whole-site emissions data did not exhibit this heavy tail.[48] However, super-emitters are certainly observed in the whole-site measurements and the maximum emission is greater than in the Monte Carlo runs, but these are insufficient in quantity and magnitude to raise the median above the mean. This discrepancy between the distribution of whole-site measurements and that observed in the Monte Carlo approach (i.e., from aggregation of measurements from each stage) is

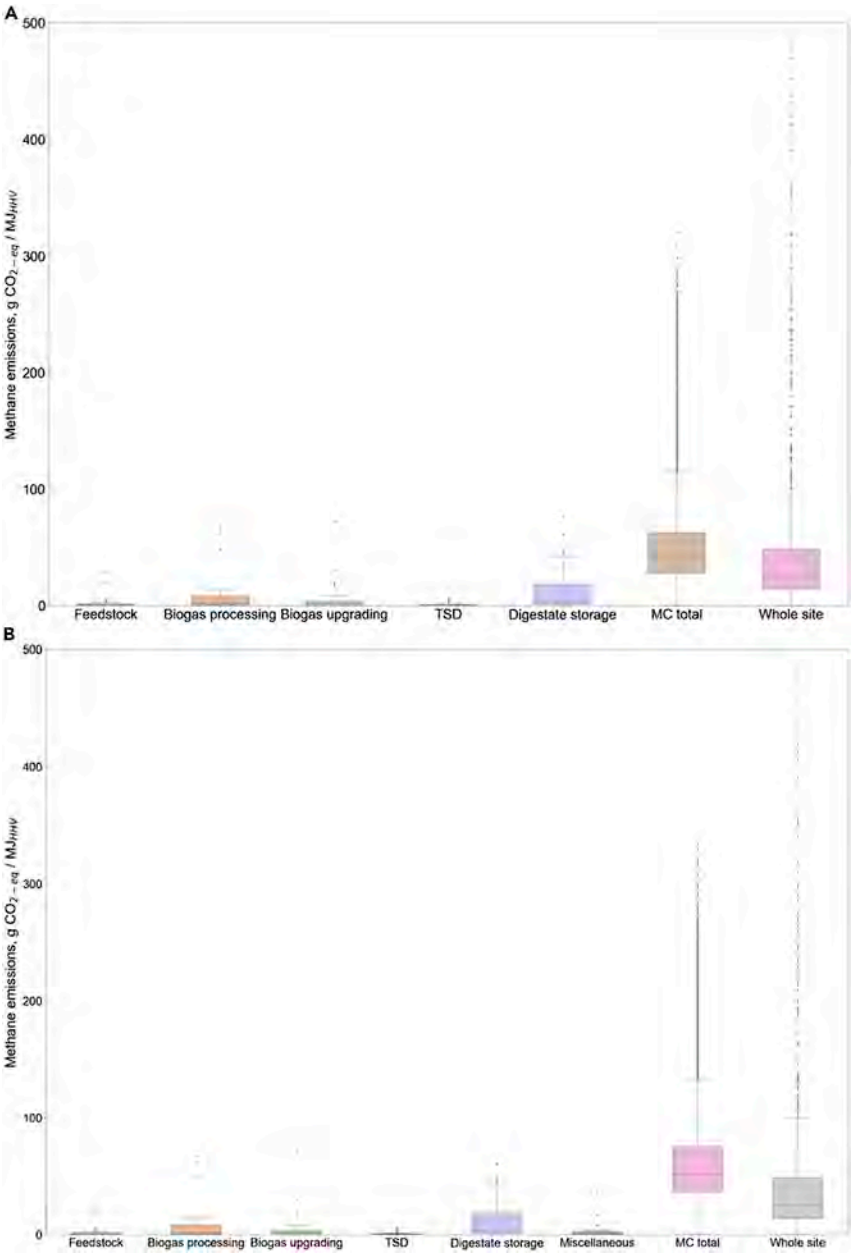

Figure 5. Each stage of emissions with the whole-site measurements and MC runs

(A) Literature emissions range for feedstock (n = 49), biogas processing (n = 100), biogas upgrading (n = 35), TSD (n = 44), and digestate storage (n = 119) stages with whole-site measurements (n = 792) and 10,000 Monte Carlo runs (MC total) with respect to g $CO_{2\text{-eq.}}/MJ_{HHV}$.

(B) Miscellaneous sources (n = 19) were added as an additional stage emission and MC total was reassessed to compare with whole-site emissions (off-site measurements).

Individual estimates are shown as circles in the same color at each stage of the supply chain, with median and 25th and 75th percentile boxes. Sample size for each stage and whole-site emissions are depicted. The median of the MC run is substantially higher than the medians of the five stages added together because (1) the medians of the derived KDE functions for each supply chain stage are substantially higher than those of the raw data and, (2) in any case, it is not expected that the sum of medians from each supply chain stage necessarily approximates the median of the sum of stages (see the experimental procedures for details).

worthy of further research in the future. A number of factors are known to affect measurements, including meteorological conditions during the survey, duration of measurements, uncertainties in emissions rate calculation models, the presence of super-emitters, and process conditions of facilities.[18] It is also likely to be influenced by miscellaneous sources (see Figure 5B),[19] such as biofilters used for odor reduction, stored solids causing fermentation, emissions from service opening,[19] or leakages located on top of units,[49] which are not quantified by the on-site measurement studies. We combined the miscellaneous sources reported in a few studies[19,23,50,51] and estimated their impacts on total emissions using a Monte Carlo simulation (see Figure S2) after identifying the associated KDE (see the experimental procedures), which impacts the data distribution.

Figure 5B demonstrated that miscellaneous sources could increase total supply chain emissions by 22%. However, it is noted that, because only four studies reported emissions from biofilters and solid separators, more detailed monitoring surveys are required to better understand the impact of miscellaneous emission sources on supply chain emissions. The high leakage rate reported in off-site measurements could also be due to process disturbances or extensive venting and flaring caused by insufficient infrastructure, which results in an intermittent and highly unpredictable emissions pattern that can overestimate or underestimate significant CH_4 sources.[38] The divergence between on-site and off-site measurements is most likely due to abnormal operating conditions resulting in high CH_4 emissions primarily from the production segment,[31] which is consistent with that of oil and natural-gas supply chains.[39] We agree with Zavala-Araiza et al.[52] and Rutherford et al.[31] that increasing on-site, component-level emission data through continuous emission monitoring and effective characterization of emission sources can reduce the uncertainty and divergence between on-site and off-site measurements.

DISCUSSION

Overall, this study showed that the broad features of the biomethane supply chain led to emission profiles similar to those of oil and natural gas, although digestate handling, biogas production, and upgrading are key differentiators. The synthesis of

available data here showed that this leads to lower direct CH_4 emissions than the oil and natural-gas supply chain but much higher CH_4 loss rates than the oil and natural-gas supply chain. This conclusion is pertinent in the context of global efforts to mitigate CH_4 emissions, which to date largely focuses on natural-gas supply chains. It is also pertinent to broaden efforts to mitigate climate change, where CH_4 emissions are increasingly recognized as a key climate forcer. Given the strong potential role of biomethane in Paris Agreement compliant energy futures, best available technology must be applied to detect and reduce supply chain emissions, policy and regulation[53] must consider these emissions more systematically, and a better understanding of the counterfactual life cycle emissions for waste and by-product biomethane feedstocks must be developed. It should be noted that, even if feedstocks are not used to generate biomethane, they may still emit CH_4; in fact, some studies have suggested that treating manure for biomethane production could be a mitigation strategy.[54] We believe that this large amount of CH_4 emissions from the biomethane supply chain, on the other hand, can be avoided by taking appropriate emission identification, detection, measurement, and quantification measurements. It is critical to emphasize that, if biomethane is widely used in the future to achieve decarbonization goals, biomethane supply chain emissions should be avoided in order to achieve net zero goals.

Reflecting on these results with respect to the EU Renewable Directive (RED) 2009/28/EC,[55] it is clear that cutting emissions from digestate handling and gas engines could underpin more sustainable biomethane production. According to an EU report[56] on the sustainability of solid and gaseous biomass used for electricity, heating, and cooling, the GHG threshold for biomethane production is 34.8 g $CO_{2\text{-eq.}}/MJ_{HHV}$,[56] excluding digestate emissions. In contrast, CH_4 emissions from the biomethane supply chain are estimated in this study to range from 2.5 to 343 g $CO_{2\text{-eq.}}/MJ_{HHV}$ and 0.8 to 182 g $CO_{2\text{-eq.}}/MJ_{HHV}$ (18.3–19.5 g $CO_{2\text{-eq.}}/MJ_{HHV}$ for the median and 64–74 g $CO_{2\text{-eq.}}/MJ_{HHV}$ for the 95th percentile) when digestate emissions are excluded (see Figure S3). In view of CO_2 and N_2O (GWP_{100} = 273 ± 130)[10] emissions from biomethane production, total GHG emissions from the biomethane supply chain are likely to exceed this threshold limit unless urgent actions are taken. Given the different lifetimes and GWPs of CO_2, CH_4, and N_2O, future research can focus on integrating emissions across different timescales in order to further expand the impact of the biomethane supply chains on global warming and climate change. Clearly, under these operating conditions and in light of the wide diversity of biogas production pathways, biomethane production may lose its advantages as a clean-energy technology and may jeopardize Paris Agreement targets if used extensively. This study would serve as a guideline for the emission ranges associated with each stage while also recommending appropriate measures for each stage to cut emissions and make progress toward Paris Agreement goals. Therefore, emission-minimizing technologies and techniques and more specific regulations on emissions and leak detection and repair are essential to significantly reduce supply chain emissions. We are also aware of the counterfactual case for what level of CH_4 emissions would occur if the feedstock had not been converted into biomethane. Future studies should focus on counterfactual analyses to assess the GHG credits under various counterfactual scenarios.

Our biomethane supply chain emissions model presented in this study represents the most common technologies used in the industry, but it has some limitations regarding data availability and resolution. Firstly, input data were taken only from measurement surveys, and the sample size is not large enough to determine a probability distribution model for each supply chain. As such, the KDE function was used rather than goodness of fit since the data could not be fitted to certain distribution functions, due to the lack of data and heavy-tailed distribution. Furthermore, much of the literature data were excluded, owing to the use of default emission factors, especially in modeling studies. Secondly, some studies could not be included because they did not report biogas or biomethane production rates despite reporting CH_4 emissions.

The most detailed measurement surveys have been conducted in various regions of Europe and mainly at agricultural plants, so this study substantially reflects European agriculture. Further possible research directions associated with this work include adapting the emissions profiles of theoretical supply chain routes, for example, using life-cycle-assessment tools. Future research should target data collection from various biomethane supply chain routes in other countries to reduce uncertainty in the data and improve size and representativeness of the samples, which can help to identify the most sustainable biomethane production routes. This accumulated database can be used to improve equipment, processes design, and operations that would mitigate CH_4 emissions.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Semra Bakkaloglu (s.bakkaloglu@imperial.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

All original datasets used in this work were made available as part of the publications referenced and described in the text. The Python code used for the Kernel density estimation (KDE) function and Monte Carlo simulation with the data have been deposited at Zenodo Data: https://doi.org/10.5281/zenodo.6550794.

Methodological approach

This study aims to estimate CH_4 emissions from the biomethane supply chain and characterize the emissions sources in the various stages of the supply chain (described in Figure S1). The screening criteria for mobile CH_4 emissions measurements required on-site or off-site direct measurements be reported by the study authors, rather than drawing on experimental, lab-scale, and theoretical studies.

The existing literature reports emission rates in different units, and some studies provide insufficient information to allow for unit conversion. In this study, CH_4 emission estimates were converted into percentage of total production (volume of CH_4 emitted/volume of produced gas) and grams of CO_2 equivalent per megajoule of energy based on higher heating value (HHV). These were chosen to allow for comparisons with the oil and natural-gas supply chain without inferring downstream services. The source emissions were divided by the total expected volume of biomethane that would be generated for energy utilization.

Assumptions were applied to convert published emission rates into metric units. It was assumed that the GWP_{100} of CH_4 is 27.2,[10] with an HHV of

38.1 MJ/m^3 or 55.5 MJ/kg. The average volume percentages of CH_4 in biogas and biomethane were taken as 65% and 95%, respectively, unless otherwise stated in a study. We assumed the CH_4 content is 55% in biogas for manure feedstock. We neglect uncertainty of measurements and GWP_{100} (±11), although measurement uncertainty exists whenever an emissions rate is quantified. Similar to Brandt et al.,[28] we evaluate all emissions at their reported levels and investigate the impact of emissions distribution. GHG emissions other than CH_4, such as CO_2, N_2O, and NH_3, were not included because they are out of the scope of this study. Moreover, CH_4 emissions based on GWP_{20} (80.8) were provided in the Figure S4. The three stages of this study are:

1. Building the emissions inventory
2. Assessing the supply chain emissions model
3. Applying Monte Carlo simulations to produce total emissions ranges.

Emissions inventory

Following systematic reviews of the existing evidence base, 51 papers reporting mobile CH_4 emissions measurements were examined, including academic papers as well as governmental and industry reports (see the supplemental experimental procedures). We utilized the data from mobile CH_4 measurements using on-site leak detection and ground-based remote sensing methods (off site). CH_4 emissions from landfill were excluded because there is a lack of data on the amount of biogas and biomethane generated from landfill-gas-collection system, which is mainly calculated using landfill-modeling tools, and CH_4 emissions depend on CH_4 oxidation rate as well as top soil cover material rather than infrastructure emissions.[57] In addition, we only considered the emissions from wastewater treatment plants with anaerobic digesters. The details of the chosen biomethane supply chain route employed in this study are described in detail in the Figure S1.

Emission inventory data availability is highly variable, owing to variations in the applied methodologies, differing plant design and operation, and insufficient data for each supply chain. Most emissions data were for Europe. Datasets for each emissions source were divided into subcategories, where there was discernible variation between feedstock materials (see Table S1). The stages in the biomethane supply chain are (1) collecting and storing organic materials (feedstock); (2) converting them to biogas under anaerobic conditions (AD); (3) upgrading biogas to biomethane (upgrading); (4) transportation, gas storage, and distribution of generated gas (TSD); and (5) digestate storage.

Feedstock storage

Any biodegradable material, such as agricultural residues, maize, crops, sewage sludges, or food and drink waste, utilized in anaerobic digestion is called feedstock. The yield of biogas from a specific feedstock can vary based on the dry-matter content, residence time in the digester, and feedstock purity.[58] Feedstock transported from a third party to the production facility is stored in the facility and pre-treated before being sent to the biogas-production stage. This stage covers four major components: runoff ponds, screw conveyor, mixing tank (homogenization tank), and substrate storage. Substrate storage tanks and biomass-receiving units, such as feedstock piles, runoff ponds, screw conveyors, and mixing (homogenization) tanks, are the main sources of emissions, although few studies have investigated emissions from this stage.[15,17,19,22,46,49,59–61] Feeding system emissions are included in substrate storage emissions (see Table S1). These emissions are mainly fugitives, predominantly from open storage tanks and feeding units.

Biogas production

The physically treated material is pasteurized and delivered to an anaerobic digester to generate biogas. The CH_4 concentration in the biogas depends on the type of digestate feedstock, type of anaerobic digester, and conditions in the digester, such as mesophilic and thermophilic. The biogas production stage consists of a buffer (hygienization) tank and a reactor (anaerobic digester). Previously reported CH_4 emissions from hygienization tanks, anaerobic digesters, and post-digesters are included in this stage (see Table S1).[15–17,19,41,49,50,59,62–76] These emissions are fugitives and venting.

Biomethane production: Biogas upgrading process

The biogas can be upgraded into biomethane by removing impurities. Depending on the biogas quality and the end use, different upgrading technologies can be used. Currently, water scrubbing is the most common commercial technology, followed by chemical scrubbers, membrane, PSA, organic physical scrubber, and cryogenic separation.[77] CH_4 emissions from various upgrading processes, such as carbon filters, chemical and water scrubbers, and membrane technologies, were reported in previous studies[17,19,46,47,49,50,71,78–81] and have been included in the upgrading processes stage (see Table S1). These are fugitives and vent from PSA exhausts and aeration and ventilation ducts.

Transmission, storage, and distribution

Biogas can be utilized to generate heat, electricity, or both. Biomethane can be injected into a gas grid or used as a renewable transport fuel in vehicles. Previous studies reported exhaust CH_4 from cogeneration, electricity production, heat utilization, combined heat and power units, gas engine slip, flare, and gas holder.[17,19,23,41,59,62,67,71,82–85] Emissions from pipeline, flare, compressors, and pressure-relief valves (PRVs) are considered in the transmission, storage, and distribution stage (see Table S1) in order to compare with natural-gas supply chain. End-use emissions mainly coming from incomplete combustion from combined heat and power (CHP), as well as fugitive leaks and vents from energy production units, were not included into emissions from this stage.

Digestate storage

Digestate can be used as is or can be further processed through different methods to be used as fertilizer. The PAS 110 for digestate quality specification is designed to ensure that digestate is no longer classified as waste and is safe and reliable to use as a fertilizer, soil improver, or conditioner, and it recommends that all types of digestate be covered.[45] Although some facilities follow the PAS 110 scheme, none of the published papers address whether the digestate complies with the standard. The solids-liquids separators, such as centrifuge and screw-press separators, membrane filters, biofilters, aerobic treatment, and composting, are widely used to process digestate.[86] The processing and storage of liquid and solid digestate can also cause emissions, depending on the temperature, wind, atmospheric pressure, plant process parameters, and storage tank filling level.[19] Emissions data by digestate types (e.g., solid or liquid) and storage properties (closed or open tanks) were collected from previous studies (see Table S1).[15–17,19,23,24,43,44,49,50,59,62,67,71–73,85,87–92] The emissions are mostly fugitives and venting from open PRVs. The emissions associated with digestate use, such as fertilizer application and post-composting, were excluded from the supply chain because digestate is not always used in the operation area and their emissions are only reported in a few studies.

Miscellaneous emissions

An additional emission stage has been added to account for a variety of sources that are not necessarily present in every biomethane supply chain. The CH_4 emissions from biofilters for odor reduction, compost filters, and separators have been reported in a few studies[19,23,50,51] and are included as miscellaneous emissions.

Whole-site mobile measurements

Whole-site mobile measurements were included for comparisons to the modeled of total emissions from each supply chain.[17,19–23,46,49–51,61–65,71,73,75,88,93] Various emission-measurement techniques were used to quantify emissions and their sources in the whole supply chain, which caused a large variation in emissions.

Supply chain emission models

It is important to determine the probability density function (PDF) of emissions in each stage before running the Monte Carlo simulation.[48] The PDF establishes a good fit of the emissions for each stage, including an uncertainty assessment. Because the emissions in each stage exhibit unique characteristics, particularly with respect to various super-emitters, their data and probability distributions differ (see Table S2 for the characteristics of PDFs). Due to the heavy-tailed distribution (Figure S3) and lack in the sample size, the nonparametric PDF ,which is the KDE, were generated to investigate the PDFs of the emissions from each stage using Python. KDE typically provides more accurate estimates of data distributions than parametric approaches.[94–96] The bandwidth of KDE for each stage was determined automatically in Python's SciPy library using Scott's Rule,[97] which is dependent on the number of data points.[97] The total sample size is 347 and 399 for g $CO_{2\text{-eq.}}/MJ_{HHV}$ and production normalized data, respectively.

Monte Carlo simulation

The total supply chain emissions were estimated using Monte Carlo simulations,[98] which has been widely applied to estimate CH_4 emissions[25,30] with

uncertainty assessment. Each supply chain's PDF, obtained from the KDE, was defined in the simulation to sample from each stage, followed by summing up each stage. Rather than separating the data by feedstock type, we divided it by stage of the supply chain, as shown in Figure S1. The total CH_4 emissions were assessed 10,000 times with random draws from the distributions for each stage. The 10,000 estimates were then used to assess the cumulative CH_4 distribution across the supply chain models by the Python code.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.05.012.

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AUTHOR CONTRIBUTIONS

Conceptualization, S.B. and A.H.; methodology, S.B., J.C., and A.H.; software, S.B.; validation, S.B. and J.C.; formal analysis, S.B. and J.C.; investigation, S.B., J.C., and A.H.; writing – original draft, S.B.; writing – review & editing, J.C. and A.H.; funding acquisition, A.H.; resources, S.B. and A.H.; supervision, A.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. The Royal Society (2021). Low-carbon Heating and Cooling: Overcoming One of World's Most Important Net Zero Challenges. https://royalsociety.org/-/media/policy/projects/climate-change-science-solutions/climate-science-solutions-heating-cooling.pdf.
2. IEA (2022). Global Methane Tracker 2022 (Paris: IEA). https://www.iea.org/reports/global-methane-tracker-2022.
3. Speirs, J., Dubey, L., Balcombe, P., Tariq, N., Brandon, N., and Hawkes, A. (2021). The Best Uses of Natural Gas within Paris Climate Targets (Sustainable Gas Institute, Imperial College London).
4. Nisbet, E.G., Fisher, R.E., Lowry, D., France, J.L., Allen, G., Bakkaloglu, S., Broderick, T.J., Cain, M., Coleman, M., Fernandez, J., et al. (2020). Methane mitigation: methods to reduce emissions, on the path to the Paris Agreement. Rev. Geophys. *58*. e2019RG000675. https://doi.org/10.1029/2019rg000675.
5. Huppmann, D. (2018). IAMC 1.5° C Scenario Explorer and Data Hosted by IIASA (Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis). https://doi.org/10.22022/SR15/08-2018.15429.
6. IEA (2020). Outlook for Biogas and Biomethane: Prospects for Organic Growth (Paris: IEA).
7. Marc-Antoine, E.M., and Mathieu, C. (2019). Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy (Études de l'Ifri). https://www.ifri.org/en/publications/etudes-de-lifri/biogas-and-biomethane-europe-lessons-denmark-germany-and-italy.
8. The World Biogas Association. (2019). Global Potential of Biogas (World Biogas Association). https://www.worldbiogasassociation.org/wp-content/uploads/2019/07/WBA-globalreport-56ppa4_digital.pdf.
9. ADBA (2019). Anaerobic Digestion Policy Report (Anaerobic Digestion & Bioresources Association).
10. IPCC (2021). AR6 Climate Change 2021: The Physical Science Basis (Cambridge University Press).
11. Paris Agreement (2015). United Nations Framework Convention on Climate Change (Paris Agreement).
12. Rogelj, J., Meinshausen, M., Schaeffer, M., Knutti, R., and Riahi, K. (2015). Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. Environ. Res. Lett. *10*, 075001. https://doi.org/10.1088/1748-9326/10/7/075001.
13. IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press). https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf.
14. Edward, B., Volker, K., Elmar, K., Keywan, R., Roberto, S., Jarmo, K., Robin, L., Zebedee, N., Marit, S., Chris, S., et al. (2022). AR6 Scenarios Database Hosted by IIASA (International Institute for Applied Systems Analysis).
15. Reinelt, T., McCabe, B.K., Hill, A., Harris, P., Baillie, C., and Liebetrau, J. (2022). Field measurements of fugitive methane emissions from three Australian waste management and biogas facilities. Waste Manag. *137*, 294–303. https://doi.org/10.1016/j.wasman.2021.11.012.
16. Reinelt, T., and Liebetrau, J. (2020). Monitoring and mitigation of methane emissions from pressure relief valves of a biogas plant. Chem. Eng. Technol. *43*, 7–18. https://doi.org/10.1002/ceat.201900180.
17. Reinelt, T., Delre, A., Westerkamp, T., Holmgren, M.A., Liebetrau, J., and Scheutz, C. (2017). Comparative use of different emission measurement approaches to determine methane emissions from a biogas plant. Waste management *68*, 173–185. https://doi.org/10.1016/j.wasman.2017.05.053.
18. Liebetrau, J., Reinelt, T., Agostini, A., and Linke, B. (2017). Methane Emissions from Biogas Plants (IEA bioenergy).
19. Liebetrau, J., Reinelt, T., Clemens, J., Hafermann, C., Friehe, J., and Weiland, P. (2013). Analysis of greenhouse gas emissions from 10 biogas plants within the agricultural sector. Water Sci. Technol. *67*, 1370–1379. https://doi.org/10.2166/wst.2013.005.
20. Bakkaloglu, S., Lowry, D., Fisher, R.E., France, J.L., Brunner, D., Chen, H., and Nisbet, E.G. (2021). Quantification of methane emissions from UK biogas plants. Waste Manag. *124*, 82–93. https://doi.org/10.1016/j.wasman.2021.01.011.
21. Scheutz, C., and Fredenslund, A.M. (2019). Total methane emission rates and losses from 23 biogas plants. Waste Manag. *97*, 38–46. https://doi.org/10.1016/j.wasman.2019.07.029.
22. Flesch, T.K., Desjardins, R.L., and Worth, D. (2011). Fugitive methane emissions from an agricultural biodigester. Biomass Bioenergy *35*, 3927–3935. https://doi.org/10.1016/j.biombioe.2011.06.009.
23. Daniel-Gromke, J., Liebetrau, J., Denysenko, V., W S, K., and J, H. (2015). The humelock hemiarthoplasty device for both primary and failed management of proximal humerus fractures: a case series. Open Orthop. J. *9*, 1–6. https://doi.org/10.2174/1874325001509010001.
24. Balde, H., VanderZaag, A.C., Burtt, S.D., Wagner-Riddle, C., Crolla, A., Desjardins, R.L., and MacDonald, D.J. (2016). Methane emissions from digestate at an agricultural biogas plant. Bioresour. Technol. *216*, 914–922. https://doi.org/10.1016/j.biortech.2016.06.031.
25. Balcombe, P., Brandon, N., and Hawkes, A. (2018). Characterising the distribution of methane and carbon dioxide emissions from the natural gas supply chain. J. Clean. Prod. *172*, 2019–2032. https://doi.org/10.1016/j.jclepro.2017.11.223.
26. Balcombe, P., Anderson, K., Speirs, J., Brandon, N., and Hawkes, A. (2017). The natural gas supply chain: the importance of methane and carbon dioxide emissions. ACS Sustain. Chem. Eng. *5*, 3–20. https://doi.org/10.1021/acssuschemeng.6b00144.

27. Balcombe, P., Anderson, K., Speirs, J., Brandon, N., and Hawkes, A. (2015). Methane and CO 2 Emissions from the Natural Gas Supply Chain (Sustainable Gas Institute).

28. Brandt, A.R., Heath, G.A., and Cooley, D. (2016). Methane leaks from natural gas systems follow extreme distributions. Environmental science & technology *50*, 12512–12520. https://doi.org/10.1021/acs.est.6b04303.

29. Omara, M., Zimmerman, N., Sullivan, M.R., Li, X., Ellis, A., Cesa, R., Subramanian, R., Presto, A.A., and Robinson, A.L. (2018). Methane emissions from natural gas production sites in the United States: data synthesis and national estimate. Environmental science & technology *52*, 12915–12925. https://doi.org/10.1021/acs.est.8b03535.

30. Zavala-Araiza, D., Alvarez, R.A., Lyon, D.R., Allen, D.T., Marchese, A.J., Zimmerle, D.J., and Hamburg, S.P. (2017). Super-emitters in natural gas infrastructure are caused by abnormal process conditions. Nat. Commun. *8*, 14012. https://doi.org/10.1038/ncomms14012.

31. Rutherford, J.S., Sherwin, E.D., Ravikumar, A.P., Heath, G.A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q., and Brandt, A.R. (2021). Closing the methane gap in US oil and natural gas production emissions inventories. Nat. Commun. *12*, 4715. https://doi.org/10.1038/s41467-021-25017-4.

32. Lin, J.C., Bares, R., Fasoli, B., Garcia, M., Crosman, E., and Lyman, S. (2021). Declining methane emissions and steady, high leakage rates observed over multiple years in a western US oil/gas production basin. Sci. Rep. *11*, 22291. https://doi.org/10.1038/s41598-021-01721-5.

33. Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., and Cecinato, A. (2018). Environmental impact of biogas: a short review of current knowledge. J. Environ. Sci. Health A Tox Hazard Subst. Environ. Eng. *53*, 899–906. https://doi.org/10.1080/10934529.2018.1459076.

34. EDF (2019). Methane Mitigation in the Oil & Gas Industry. https://business.edf.org/insights/methane-mitigation-in-the-oil-gas-industry/.

35. IEA (2021). Driving Down Methane Leaks from the Oil and Gas Industry (Paris: IEA).

36. Zavala-Araiza, D., Lyon, D., Alvarez, R.A., Palacios, V., Harriss, R., Lan, X., Talbot, R., and Hamburg, S.P. (2015). Toward a functional definition of methane super-emitters: application to natural gas production sites. Environ. Sci. Technol. *49*, 8167–8174. https://doi.org/10.1021/acs.est.5b00133.

37. Brandt, A.R., Heath, G.A., Kort, E.A., O'Sullivan, F., Pétron, G., Jordaan, S.M., Tans, P., Wilcox, J., Gopstein, A.M., Arent, D., et al. (2014). Methane leaks from North American natural gas systems. Science *343*, 733–735. https://doi.org/10.1126/science.1247045.

38. Duren, R.M., Thorpe, A.K., Foster, K.T., Rafiq, T., Hopkins, F.M., Yadav, V., Bue, B.D., Thompson, D.R., Conley, S., Colombi, N.K., et al. (2019). California's methane super-emitters. Nature *575*, 180–184. https://doi.org/10.1038/s41586-019-1720-3.

39. Alvarez, R.A., Zavala-Araiza, D., Lyon, D.R., Allen, D.T., Barkley, Z.R., Brandt, A.R., Davis, K.J., Herndon, S.C., Jacob, D.J., Karion, A., et al. (2018). Assessment of methane emissions from the US oil and gas supply chain. Science *361*, 186–188. https://doi.org/10.1126/science.aar7204.

40. Mathieu Dumont, N., Luning, L., Yildiz, I., and Koop, K. (2013). Methane emissions in biogas production. In The biogas handbook (Elsevier), pp. 248–266. https://doi.org/10.1533/9780857097415.2.248.

41. Zeng, J., Xu, R., Sun, R., Niu, L., Liu, Y., Zhou, Y., Zeng, W., and Yue, Z. (2020). Evaluation of methane emission flux from a typical biogas fermentation ecosystem in China. J. Clean. Prod. *257*, 120441. https://doi.org/10.1016/j.jclepro.2020.120441.

42. Döhler, H., Niebaum, A., Roth, U., Amon, T., Balsari, P., and Friedl, G. (2009). Greenhouse Gas Emissions and Mitigati-On Costs in Two European Biogas Plants (Gülzower Fachgespräche).

43. Gioelli, F., Dinuccio, E., and Balsari, P. (2011). Residual biogas potential from the storage tanks of non-separated digestate and digested liquid fraction. Bioresour. Technol. *102*, 10248–10251. https://doi.org/10.1016/j.biortech.2011.08.076.

44. Vergote, T.L., Bodé, S., De Dobbelaere, A.E., Buysse, J., Meers, E., and Volcke, E.I. (2020). Monitoring methane and nitrous oxide emissions from digestate storage following manure mono-digestion. Biosyst. Eng. *196*, 159–171. https://doi.org/10.1016/j.biosystemseng.2020.05.011.

45. WRAP. (2014). PAS 110:2014. Specification for Whole Digestate, Separated Liquor and Separated Fibre Derived from the Anaerobic Digestion of Source-Segregated Biodegradable Materials (The BSI). https://wrap.org.uk/sites/default/files/2021-03/PAS110_2014.pdf.

46. Ricardo Energy and Environment. (2017). Methodology to Assess Methane Leakage from AD Plants. Part I: Report on Proposed Categorisation of AD Plants and Literature Review of Methane Monitoring Technologies (Ricardo Energy and Environment). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/786756/Methodology_to_Assess_Methane_Leakage_from_AD_Plants_final_report_part1.pdf.

47. Paolini, V., Torre, M., Giacopini, W., Pastori, M., Segreto, M., Tomassetti, L., Carnevale, M., Gallucci, F., Petracchini, F., and Guerriero, E. (2019). CO2/CH4 separation by hot potassium carbonate absorption for biogas upgrading. Int. J. Greenh. Gas Control *83*, 186–194. https://doi.org/10.1016/j.ijggc.2019.02.011.

48. McMurray, A., Pearson, T., and Casarim, F. (2017). Guidance on Applying the Monte Carlo Approach to Uncertainty Analyses in Forestry and Greenhouse Gas Accounting (Winrock International).

49. Fredenslund, A.M., Hinge, J., Holmgren, M.A., Rasmussen, S.G., and Scheutz, C. (2018). On-site and ground-based remote sensing measurements of methane emissions from four biogas plants: a comparison study. Bioresour. Technol. *270*, 88–95. https://doi.org/10.1016/j.biortech.2018.08.080.

50. Holmgren, M.A., Hansen, M.N., Reinelt, T., Westerkamp, T., Jørgensen, L., Scheutz, C., and Delre, A. (2015). Measurements of Methane Emissions from Biogas Production–Data Collection and Comparison of Measurement Methods: Energiforsk report 2015: 158 (Energiforsk AB).

51. Jensen, M.B., Møller, J., Mønster, J., and Scheutz, C. (2017). Quantification of greenhouse gas emissions from a biological waste treatment facility. Waste Manag. *67*, 375–384. https://doi.org/10.1016/j.wasman.2017.05.033.

52. Zavala-Araiza, D., Lyon, D.R., Alvarez, R.A., Davis, K.J., Harriss, R., Herndon, S.C., Karion, A., Kort, E.A., Lamb, B.K., Lan, X., et al. (2015). Reconciling divergent estimates of oil and gas methane emissions. Proc. Natl. Acad. Sci. U S A *112*, 15597–15602. https://doi.org/10.1073/pnas.1522126112.

53. European Commission (2020). EU Strategy to Reduce Methane Emissions (European Commission).

54. Kupper, T., Häni, C., Neftel, A., Kincaid, C., Bühler, M., Amon, B., and VanderZaag, A. (2020). Ammonia and greenhouse gas emissions from slurry storage-A review. Agric. Ecosyst. Environ. *300*, 106963. https://doi.org/10.1016/j.agee.2020.106963.

55. European Union (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC (Official Journal of the European Union).

56. European Commission (2014). SWD(2014) 259 Final, State of Play on the Sustainability of Solid and Gaseous Biomass Used for Electricity, Heating and Cooling in the EU (European Commission).

57. Bakkaloglu, S., Lowry, D., Fisher, R.E., France, J.L., and Nisbet, E.G. (2021). Carbon isotopic characterisation and oxidation of UK landfill methane emissions by atmospheric measurements. Waste Manag. *132*, 162–175. https://doi.org/10.1016/j.wasman.2021.07.012.

58. Bioenergy, I. (2013). The Biogas Handbook (United Kingdom: Woodhead Publishing Limited).

59. Liebetrau, J., Clemens, J., Cuhls, C., Hafermann, C., Friehe, J., Weiland, P., and Daniel-Gromke, J. (2010). Methane Emissions from Biogas-producing Facilities within the Agricultural Sector*10* (Wiley Online Library), pp. 595–599. https://doi.org/10.1002/elsc.201000070.

60. Hrad, M., Piringer, M., Kamarad, L., Baumann-Stanzer, K., and Huber-Humer, M. (2014). Multisource emission retrieval within a biogas plant based on inverse dispersion calculations—a real-life example. Environ. Monit. Assess. *186*, 6251–6262. https://doi.org/10.1007/s10661-014-3852-0.

61. Hrad, M., Vesenmaier, A., Flandorfer, C., Piringer, M., Stenzel, S., and Huber-Humer, M. (2021). Comparison of forward and backward Lagrangian transport modelling to determine methane emissions from anaerobic digestion facilities. Atmos. Environ. X *12*, 100131. https://doi.org/10.1016/j.aeaoa.2021.100131.

62. Daelman, M.R., van Voorthuizen, E.M., van Dongen, U.G., Volcke, E.I., and van Loosdrecht, M.C. (2012). Methane emission during municipal wastewater treatment. Water Res. *46*, 3657–3670. https://doi.org/10.1016/j.watres.2012.04.024.

63. Delre, A., Mønster, J., and Scheutz, C. (2017). Greenhouse gas emission quantification from wastewater treatment plants, using a tracer gas dispersion method. Sci. Total Environ. *605-606*, 258–268. https://doi.org/10.1016/j.scitotenv.2017.06.177.

64. Delre, A., Mønster, J., and Scheutz, C. (2014). Quantification of Fugitive Methane Emissions from the Biogas Plant in Linköping (SE) (Technical University of Denmark, DTU Environment), p. 15.

65. Groth, A., Maurer, C., Reiser, M., and Kranert, M. (2015). Determination of methane emission rates on a biogas plant using data from laser absorption spectrometry. Bioresour. Technol. *178*, 359–361. https://doi.org/10.1016/j.biortech.2014.09.112.

66. Harper, L.A., Flesch, T.K., Weaver, K.H., and Wilson, J.D. (2010). The effect of biofuel production on swine farm methane and ammonia emissions. J. Environ. Qual. *39*, 1984–1992. https://doi.org/10.2134/jeq2010.0172.

67. Jonerholm, K., L.H. (2012). Sweco Environment AB Methane Losses in the Biogas System (Baltic Biogas Bus). https://docplayer.net/29996723-Methane-losses-in-the-biogas-system.html.

68. Paredes, M., Güereca, L.P., Molina, L., and Noyola, A. (2019). Methane emissions from anaerobic sludge digesters in Mexico: on-site determination vs. IPCC Tier 1 method. Sci. Total Environ. *656*, 468–474. https://doi.org/10.1016/j.scitotenv.2018.11.373.

69. Noyola, A., Paredes, M., Güereca, L., Molina, L., and Zavala, M. (2018). Methane correction factors for estimating emissions from aerobic wastewater treatment facilities based on field data in Mexico and on literature review. Sci. Total Environ. *639*, 84–91. https://doi.org/10.1016/j.scitotenv.2018.05.111.

70. Reinelt, T., Liebetrau, J., and Nelles, M. (2016). Analysis of operational methane emissions from pressure relief valves from biogas storages of biogas plants. Bioresour. Technol. *217*, 257–264. https://doi.org/10.1016/j.biortech.2016.02.073.

71. Ricardo Energy and Environment. (2017). Methodology to Assess Methane Leakage from AD Plants Part:2 Monitoring Methodology (Ricardo Energy and Environment). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/786757/Methodology_to_Assess_Methane_Leakage_from_AD_Plants_final_report_part2.pdf.

72. Sax, M., Schick, M., Bolli, S., Soltermann-Pasca, A., and Van Caenegem, L. (2013). Methanverluste bei landwirtschaftlichen Biogasanlagen (Methane losses from agricultural biogas plants), (Bern: Bundesamt für Energie BFE).

73. Samuelsson, J., Delre, A., Tumlin, S., Hadi, S., Offerle, B., and Scheutz, C. (2018). Optical technologies applied alongside on-site and remote approaches for climate gas emission quantification at a wastewater treatment plant. Water Res. *131*, 299–309. https://doi.org/10.1016/j.watres.2017.12.018.

74. Tauber, J., Parravicini, V., Svardal, K., and Krampe, J. (2019). Quantifying methane emissions from anaerobic digesters. Water Sci. Technol. *80*, 1654–1661. https://doi.org/10.2166/wst.2019.415.

75. Yoshida, H., Mønster, J., and Scheutz, C. (2014). Plant-integrated measurement of greenhouse gas emissions from a municipal wastewater treatment plant. Water Res. *61*, 108–118. https://doi.org/10.1016/j.watres.2014.05.014.

76. Dhingra, R., Christensen, E.R., Liu, Y., Zhong, B., Wu, C.-F., Yost, M.G., and Remais, J.V. (2011). Greenhouse gas emission reductions from domestic anaerobic digesters linked with sustainable sanitation in rural China. Environmental science & technology *45*, 2345–2352. https://doi.org/10.1021/es103142y.

77. Angelidaki, I., Boe, K., and Ellegaard, L. (2005). Effect of operating conditions and reactor configuration on efficiency of full-scale biogas plants. Water Sci. Technol. *52*, 189–194. https://doi.org/10.2166/wst.2005.0516.

78. Wolf, D., and Scherello, A. (2013). Messung der Methanemission an der Biogasanlage Einbeck mittels CHARM®(Methane Emission Measurement at Biogas Plant Einbeck using CHARM®) (Gwf GasErdgas, Deutscher Industrieverlag GmbH), pp. 1–7.

79. Kvist, T., and Aryal, N. (2019). Methane loss from commercially operating biogas upgrading plants. Waste Manag. *87*, 295–300. https://doi.org/10.1016/j.wasman.2019.02.023.

80. Westerkamp, T., Reinelt, T., and Liebetrau, J. (2014). Scientific Measurements of Methane Emissions with Remote and On-Site Methods in Comparison (Presentation at the 2nd IBBA workshop in Kiel, Germany).

81. Holmgren, M.A., Hellström, H., Petersson, A., and Blom, A. (2012). The Swedish Voluntary Agreement for Control of Methane Emissions from Biogas Plants (SP Technical Research Institute of Sweden).

82. Aschmann, V., Kissel, R., and Gronauer, A. (2006). Exhaust emissions and performances of biogas-driven combined heat and power plants. Agrartechnische Forschung *12*, 46–52.

83. de Zwart, M., van Dijk, G., and Klimstra, J. (2012). Methane emissions from gas engines driving combined heat and power installations. J. Integr. Environ. Sci. *9*, 113–125. https://doi.org/10.1080/1943815x.2012.691885.

84. Woess-Gallasch, S., Bird, N., Enzinger, P., Jungmeier, G., Padinger, R., Pena, N., et al. (2011). Greenhouse Gas Benefits of a Biogas Plant in Austria (Joanneum Research Forschungsgesellschaft mbH. Resources – Institute of Water, Energy and Sustainability).

85. Woess-Gallasch, S., Enzinger, P., Jungmeier, G., and Padinger, R. (2007). Treibhausgasemissionen aus Biogasanlagen (Graz).

86. Al Seadi, T., Drosg, B., Fuchs, W., Rutz, D., and Janssen, R. (2013). Biogas digestate quality and utilization. In The biogas handbook (Elsevier), pp. 267–301. https://doi.org/10.1533/9780857097415.2.267.

87. Czubaszek, R., and Wysocka-Czubaszek, A. (2018). Emissions of carbon dioxide and methane from fields fertilized with digestate from an agricultural biogas plant. Int. Agrophys. *32*, 29–37. https://doi.org/10.1515/intag-2016-0087.

88. Hrad, M., Piringer, M., and Huber-Humer, M. (2015). Determining methane emissions from biogas plants–Operational and meteorological aspects. Bioresour. Technol. *191*, 234–243. https://doi.org/10.1016/j.biortech.2015.05.016.

89. Jensen, M.B., Møller, J., and Scheutz, C. (2017). Assessment of a combined dry anaerobic digestion and post-composting treatment facility for source-separated organic household waste, using material and substance flow analysis and life cycle inventory. Waste Manag. *66*, 23–35. https://doi.org/10.1016/j.wasman.2017.03.029.

90. Maldaner, L., Wagner-Riddle, C., VanderZaag, A.C., Gordon, R., and Duke, C. (2018). Methane emissions from storage of digestate at a dairy manure biogas facility. Agric. For. Meteorol. *258*, 96–107. https://doi.org/10.1016/j.agrformet.2017.12.184.

91. Oshita, K., Okumura, T., Takaoka, M., Fujimori, T., Appels, L., and Dewil, R. (2014). Methane and nitrous oxide emissions following anaerobic digestion of sludge in Japanese sewage treatment facilities. Bioresour. Technol. *171*, 175–181. https://doi.org/10.1016/j.biortech.2014.08.081.

92. Awiszus, S., Meissner, K., Reyer, S., and Müller, J. (2018). Ammonia and methane emissions during drying of dewatered biogas digestate in a two-belt conveyor dryer. Bioresour. Technol. *247*, 419–425. https://doi.org/10.1016/j.biortech.2017.09.099.

93. Bühler, M., Häni, C., Ammann, C., Brönnimann, S., and Kupper, T. (2022). Using the inverse dispersion method to determine methane emissions

from biogas plants and wastewater treatment plants with complex source configurations. Atmos. Environ. *13*, 100161. https://doi.org/10.1016/j.aeaoa.2022.100161.

94. Senga Kiessé, T., Corson, M.S., and Eugène, M. (2022). The potential of kernel density estimation for modelling relations among dairy farm characteristics. Agric. Syst. *199*, 103406. https://doi.org/10.1016/j.agsy.2022.103406.
95. Čížek, P., and Sadıkoğlu, S. (2020). Robust nonparametric regression: a review. Wiley Interdiscip. Rev. Comput. Stat. *12*, e1492. https://doi.org/10.1002/wics.1492.
96. Selingerova, I., Katina, S., and Horova, I. (2021). Comparison of parametric and semiparametric survival regression models with kernel estimation. J. Stat. Comput. Simulat. *91*, 2717–2739. https://doi.org/10.1080/00949655.2021.1906875.
97. Scott, D.W. (2015). Multivariate Density Estimation: Theory, Practice, and Visualization (John Wiley & Sons). https://doi.org/10.1002/9781118575574.
98. Rubinstein, R.Y., and Kroese, D.P. (2011). Simulation and the Monte Carlo Method (John Wiley & Sons).

ARTICLES

REINING IN ANIMAL AGRICULTURE'S EMISSIONS BY SHRINKING THE HERD: EARLY SIGNS OF A NECESSARY GLOBAL POLICY SHIFT

BY
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We will be unable to achieve the temperature goals of the Paris Agreement without radically reforming our food systems. Despite animal agriculture's significant responsibility for climate change—emitting the majority of agricultural greenhouse gases (GHGs), likely 15% or more of all human-caused GHGs, around a third of anthropogenic methane and more than half of nitrous oxide (two climate super-pollutants)—policymakers have so far largely failed to rein in its emissions. In recent years, international bodies including the Intergovernmental Panel on Climate Change, U.N. Environment Programme, World Health Organization, and World Bank have begun to explicitly make the connection between animal agriculture's outsized emissions and the need to reduce consumption of animal products, especially in high-income, high-consuming countries. While national-level policy in the United States has not yet embraced these recommendations, policymakers in other countries—led by Europe—are experimenting with policies that would change diets and ultimately "shrink the herd," i.e., reduce the number of animals raised for food. Recent farmer protests and

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weakening of policy proposals in Europe illustrate the political realities of seeking reform in this area. But sooner government action would enable better outcomes, before the climate crisis forces changes to food systems. Developing effective and lasting policy on climate and animal agriculture will require consensus building, incremental approaches, attention to international equity, and a commitment to a just transition.

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I. INTRODUCTION

> Say the order of your time feels unjust and unsustainable and yet massively entrenched, but also falling apart before your eyes.
>
> ~Kim Stanley Robinson,
> *The Ministry for the Future*[1]

> [A]s the world keeps warming, it will become clear that political leaders' climate pledges require that we phase down all sorts of polluting machines: not just the metal ones that burn fossil fuels but also the ones that have brains, and hearts, and use up three-quarters of the world's agricultural land, and overheat the planet.

[1] KIM STANLEY ROBINSON, THE MINISTRY FOR THE FUTURE 124 (2020) (including a cover inscription by writer Jonathan Lethem describing it as "[t]he best science fiction nonfiction novel I've ever read").

~Noah Gordon,
Carnegie Endowment for
International Peace[2]

Despite the immense scale of greenhouse gas (GHG) emissions from the U.S. animal agriculture sector,[3] the federal government remains largely unwilling to espouse reductions to meat and dairy consumption as part of its climate mitigation strategy. Indeed, after a British tabloid article falsely implied that President Biden was planning to limit meat consumption in order to meet emissions targets and Republican politicians began spreading the story (some even calling him "The Hamburglar"), a Biden spokesperson was quick to post a reassuring photo of Biden smiling while grilling steaks.[4]

U.S. Agriculture Secretary Tom Vilsack, a former dairy lobbyist,[5] has downplayed the growing momentum—led by some other national governments and in the international arena[6]—around elevating plant-based foods to help the climate. Despite the unprecedented focus on food systems and dietary change at the Conference of the Parties to the U.N. Framework Convention on Climate Change in Dubai (COP28),[7] when asked about reducing meat consumption as part of climate mitigation, Secretary Vilsack replied: "I don't hear much about that."[8]

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[2] Noah Gordon, *No, the Government Isn't Coming for Your Burger—But Maybe It Should Be*, NEW REPUBLIC (Oct. 3, 2023), https://newrepublic.com/article/175875/no-government-isnt-coming-burgerbut-maybe.

[3] *E.g.*, *Sector at a Glance*, U.S. DEP'T AGRIC., ECON. RSCH. SERV., https://www.ers.usda.gov/topics/animal-products/cattle-beef/sector-at-a-glance (Aug. 30, 2023) (noting that the United States has "the world's largest fed-cattle industry" and "is also the world's largest consumer of beef"); GRAIN & INST. FOR AGRIC. & TRADE POL'Y, EMISSIONS IMPOSSIBLE: HOW BIG MEAT AND DAIRY ARE HEATING UP THE PLANET 6 (2018) [hereinafter EMISSIONS IMPOSSIBLE], https://grain.org/article/entries/5976-emissions-impossible-how-big-meat-and-dairy-are-heating-up-the-planet (identifying the United States as one of the "main culprits" for animal agriculture GHG emissions, which "have surplus production *and* high per capita consumption of meat and dairy").

[4] Katie Shepherd, *Biden's Climate Plan Doesn't Ban Meat. But Baseless Claims Left Republicans Fuming: 'Stay Out of My Kitchen*,' WASH. POST (Apr. 26, 2021, 4:58 AM), https://www.washingtonpost.com/nation/2021/04/26/republicans-meat-biden-climate-plan; David Bauder & Ali Swenson, *The Hamburglar? How a Story About Meat Limits Fell Apart*, ASSOCIATED PRESS (Apr. 28, 2021, 8:55 AM), https://apnews.com/article/joe-biden-new-york-climate-climate-change-media-529b0cb6d7393c225c8b9baf040c1904.

[5] Tom Philpott, *It's Official: A Former Dairy Exec Now Runs Biden's Agriculture Department*, MOTHER JONES (Feb. 23, 2021), https://www.motherjones.com/food/2021/02/its-official-a-former-dairy-exec-now-runs-bidens-agriculture-department.

[6] *See* discussion *infra* Parts III–IV.

[7] *See infra* notes 101–122 and accompanying text.

[8] Marcia Brown & Meredith Lee Hill, *Tom Vilsack at COP28*, POLITICO (Dec. 11, 2023, 10:00 AM), https://www.politico.com/newsletters/weekly-agriculture/2023/12/11/tom-vilsack-at-cop28-00131018. More than 250 advocacy groups and experts sent Secretary Vilsack a letter in response, noting the prominent discussions of meat and dairy reduction at COP28 and arguing that the United States must incorporate meat and dairy reduction into its climate strategies. Letter from Ctr. for Biological Diversity et al. to Thomas J. Vilsack, U.S. Sec'y of Agric. 2 (Jan. 11, 2024), https://www.biologicaldiversity.org/programs/population_and_sustainability/pdfs/usda_sec_vilsack_letter.pdf.

Other U.S. lawmakers did not share his insouciance. Commenting on ongoing food system discussions at COP28, U.S. Senator Chuck Grassley of Iowa asserted that the talks were "targeting farmers" and that "[t]hey're really after the livestock business."[9] Representative Mike Flood of Nebraska went so far as to propose that the U.S. House of Representatives adopt a resolution to express disapproval of the recommendations shared by the U.N. Food & Agriculture Organization (FAO) at COP28[10] and "oppose[] the use of any Federal resources to support attempts to reduce meat consumption."[11]

The reactionary posture of many U.S. lawmakers when it comes to the animal agriculture industry has been a frustration for decades for those who seek to address its numerous and significant externalized harms to people, animals, and the environment.[12] But changemakers may take inspiration from a nascent wave of policies around the world that would have the concomitant impact of reducing both GHG emissions and animal numbers. Such policies may address supply (e.g., by buying out farmers) or demand (e.g., by shifting dietary guidelines and procurement policies), and they may combine various approaches. This Article focuses on policies that would ultimately result in a reduction of the total number of animals (rather than technological approaches[13]) because policies that "shrink the herd" are the only ones that guarantee a reduction in emissions while at the same time reducing the other harmful externalities of industrial animal agriculture.

These are not new ideas.[14] What is new is the acceleration of policy proposals and activity over the last half decade. This Article aims to collect progress and challenges for policymakers and advocates who would look to learn from leading examples—and who may also be inspired by the degree of activity in a policy area that can sometimes seem intractable. Part II provides background on animal agriculture's role in the climate crisis, followed by an overview of global momentum and international signaling in Part III. Part IV describes examples of climate animal agriculture policies around the world. Recent farmer

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9 Marc Heller, *Grassley Laments Climate Talks 'Targeting' Farmers*, E&E DAILY (Dec. 6, 2023, 6:19 AM), https://subscriber.politicopro.com/article/eenews/2023/12/06/grassley-laments-climate-talks-targeting-farmers-00130164.

10 *See* discussion of the FAO Roadmap *infra* notes 111–115 and accompanying text.

11 H.R. Res. 920, 118th Cong. §§ 3–4 (2023); *see also* Press Release, Rep. Mike Flood, Rep. Flood Introduces Resolution Condemning UN's Anti-Beef Food Strategy (Dec. 11, 2023), https://flood.house.gov/media/press-releases/rep-flood-introduces-resolution-condemning-uns-anti-beef-food-strategy ("The resolution I'm introducing today makes it clear that the United States opposes any attempt to reduce or eliminate meat production.").

12 *See infra* notes 244–256 and accompanying text.

13 *See* discussion *infra* Section IV.E.

14 *E.g.*, Herve Guyomard et al., *Review: Why and How to Regulate Animal Production and Consumption: The Case of the European Union*, ANIMAL: INT'L J. ANIMAL BIOSCIS., Dec. 2021, No. 100383, at 9 (citing articles published in 2011 and 2017) ("In order to significantly diminish GHG emissions of food systems, it will be necessary to reduce livestock activity levels.").

protests in the Netherlands are described in Part V as an example of political headwinds, followed by a gathering of lessons in Part VI.

II. BACKGROUND: ANIMAL AGRICULTURE AND CLIMATE

Last year was the hottest year on record,[15] shattering prior temperatures and causing scientists to use words like "mind-boggling," "staggering," and "absolutely gobsmackingly bananas."[16] The summer of 2024 was the warmest on record,[17] and this year is "virtually certain" to be the warmest year on record, exceeding even the unprecedented temperatures of 2023.[18] While some of the recent warming was likely associated with the El Niño weather pattern, many scientists are concerned at what may be the beginning of an accelerating trend.[19]

Higher temperatures not only have major impacts around the world—including extreme heat and drought and associated wildfires, tropical cyclones, and major floods[20]—but are also concerning because of their ability to induce irreversible changes. Tipping points are changes to climatic systems that become self-perpetuating at certain levels of warming.[21] A 2023 report found that at least five major systems were at risk of reaching tipping points, namely: the Greenland and West Antarctic ice sheets, warm-water coral reefs, North Atlantic Subpolar Gyre circulation, and permafrost regions.[22] The report described the risk of triggering tipping points as amongst "the gravest threats faced by humanity," which would "severely damage our planet's life-support systems and threaten the stability of our societies."[23]

To confront this challenge collectively, nearly all countries in the world have signed onto the Paris Agreement, a climate change treaty.[24] The primary goals of the Agreement are to maintain global average

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[15] Press Release No. 24-008, Roxana Bardan, Nat'l Aeronautics & Space Admin., NASA Analysis Confirms 2023 as Warmest Year on Record (Jan. 12, 2024), https://www.nasa.gov/news-release/nasa-analysis-confirms-2023-as-warmest-year-on-record.

[16] Zeke Hausfather, Opinion, *I Study Climate Change. The Data Is Telling Us Something New.*, N.Y. TIMES (Oct. 13, 2023), https://www.nytimes.com/2023/10/13/opinion/climate-change-excessive-heat-2023.html.

[17] Sally Younger, *NASA Finds Summer 2024 the Hottest to Date*, NASA (Sept. 11, 2024), https://www.nasa.gov/earth/nasa-finds-summer-2024-hottest-to-date.

[18] Press Release, Eur. Comm'n et al., Copernicus: 2024 Virtually Certain to Be the Warmest Year and First Year Above 1.5ºC (Nov. 7, 2024), https://climate.copernicus.eu/copernicus-2024-virtually-certain-be-warmest-year-and-first-year-above-15degc.

[19] Hausfather, *supra* note 16.

[20] Press Release, World Meteorological Org., 2023 Shatters Climate Records, with Major Impacts (Nov. 30, 2023), https://wmo.int/news/media-centre/2023-shatters-climate-records-major-impacts.

[21] David I. Armstrong McKay et al., *Exceeding 1.5ºC Global Warming Could Trigger Multiple Climate Tipping Points*, 377 SCIENCE 1171 (2022).

[22] UNIV. OF EXETER GLOB. SYS. INST., GLOBAL TIPPING POINTS: SUMMARY REPORT 2023, at 5 (2023).

[23] *Id.* at 3.

[24] *The Paris Agreement*, U.N. FRAMEWORK CONVENTION ON CLIMATE CHANGE, https://unfccc.int/process-and-meetings/the-paris-agreement (last visited Sept. 16, 2024).

temperatures well below 2ºC above pre-industrial levels, and to use best efforts to limit the increase to 1.5ºC.[25] According to the Intergovernmental Panel on Climate Change (IPCC), the UN body responsible for assessing the science related to climate change,[26] limiting the temperature increase to as close as possible to 1.5ºC is necessary to avoid the worst effects of climate change.[27] But, on our current path, we will reach 3.2ºC by 2100.[28] 2024 is on track to be the first year averaging more than 1.5ºC above preindustrial temperatures.[29] While one year spent above an average of 1.5ºC does not breach the Paris Agreement targets—which require a sustained increase over a longer period[30]—there is a growing understanding amongst scientists that breaching 1.5ºC is, at this point, likely inevitable.[31] To increase the chances of a safer future, time is of the essence. In 2023, the United Nations advised that GHG emissions would need to be halved by the end of this decade, describing a looming "climate cataclysm."[32]

But policy makers the world over have so far largely failed to address a key contributor to climate change: animal agriculture.[33] It will not be possible to adhere to climate targets without addressing food systems.[34] Animal agriculture is the biggest factor,[35] accounting for

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[25] *Id.*

[26] INTERGOV'TAL PANEL ON CLIMATE CHANGE, https://www.ipcc.ch (last visited Sept. 16, 2024).

[27] U.N. INTERGOV'TAL PANEL ON CLIMATE CHANGE [IPCC], GLOBAL WARMING OF 1.5°C, at v–vi (Valérie Masson-Delmotte et al. eds., 2018) [hereinafter 2018 IPCC REPORT], https://www.ipcc.ch/sr15/download.

[28] WILLIAM R. SUTTON ET AL., RECIPE FOR A LIVABLE PLANET: ACHIEVING NET ZERO EMISSIONS IN THE AGRIFOOD SYSTEM (OVERVIEW), WORLD BANK 6 (2024), https://openknowledge.worldbank.org/server/api/core/bitstreams/a0431f46-c65e-441a-9eed-8783d8b00272/content.

[29] Eur. Comm'n et al., *supra* note 18.

[30] Paris Agreement art. 2, ¶ 1, *adopted* Dec. 12, 2015, T.I.A.S. No. 16-1104, 3156 U.N.T.S. 79.

[31] *E.g.*, Jeff Tollefson, *Is It Too Late to Keep Global Warming Below 1.5°C? The Challenge in 7 Charts*, NATURE (Nov. 21, 2023), https://www.nature.com/immersive/d41586-023-03601-6/index.html.

[32] U.N. DEP'T OF ECON. & SOC. AFFAIRS, THE SUSTAINABLE DEVELOPMENT GOALS REPORT 2023, at 38 (Jennifer Ross ed., 2023), https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf.

[33] *E.g.*, Simona Vallone & Eric Lambin, *Public Policy and Vested Interests Preserve the Animal Farming Status Quo at the Expense of Animal Product Analogs*, 6 ONE EARTH 1213, 1221 (2023) ("Despite the climate and biodiversity crises and the urgency to implement effective mitigation measures, both the EU and U.S. governments are slow to act decisively to mitigate the environmentally damaging role played by the dominant animal production systems.").

[34] Michael A. Clark et al., *Global Food System Emissions Could Preclude Achieving the 1.5° and 2°C Climate Change Targets*, 370 SCIENCE 705, 705 (2020) ("[E]ven if fossil fuel emissions were immediately halted, current trends in global food systems would prevent the achievement of the 1.5°C target and, by the end of the century, threaten the achievement of the 2°C target. Meeting the 1.5°C target requires rapid and ambitious changes to food systems as well as to all nonfood sectors."); *see also* U.N. ENV'T PROGRAMME, EMISSIONS GAP REPORT 2022: THE CLOSING WINDOW—CLIMATE CRISIS CALLS FOR RAPID

nearly sixty percent of global food system emissions[36] and almost eighty percent of U.S. agricultural emissions.[37] Overall, animal agriculture is likely responsible for somewhere between 14.5% and 20% of global GHG emissions.[38]

Animal agriculture also bears outsized responsibility for emissions of the climate super-pollutants methane and nitrous oxide. Nitrous oxide is an exceptionally powerful GHG, around 280 times more potent than carbon dioxide over its first twenty years in the atmosphere.[39] According to a U.N. estimate, more than half of all nitrous oxide comes from animal agriculture.[40]

Animal agriculture is also responsible for almost one third of all anthropogenic methane emissions globally and 36% in the United States.[41] During its first twenty years after release, methane is about 80

TRANSFORMATION OF SOCIETIES, at xxv (2022), https://www.unep.org/emissions-gap-report-2022 ("To get on an emissions pathway aligned with the Paris Agreement temperature goal, . . . [r]equired transformations include shifting diets, protecting natural ecosystems, improving food production and decarbonizing the food value chain.").

35 2018 IPCC REPORT, *supra* note 27, at 327.

36 U.N. ENV'T PROGRAMME, WHAT'S COOKING? AN ASSESSMENT OF THE POTENTIAL IMPACTS OF SELECTED NOVEL ALTERNATIVES TO CONVENTIONAL ANIMAL PRODUCTS, at viii (2023) [hereinafter UNEP WHAT'S COOKING?], https://wedocs.unep.org/20.500.11822/44236.

37 PETER H. LEHNER & NATHAN A. ROSENBERG, FARMING FOR OUR FUTURE; THE SCIENCE, LAW, AND POLICY OF CLIMATE-NEUTRAL AGRICULTURE 43 (2021).

38 UNEP WHAT'S COOKING?, *supra* note 36, at viii; *see also* Dan Blaustein-Rejto & Chris Gambino, *Livestock Don't Contribute 14.5% of Global Greenhouse Gas Emissions*, BREAKTHROUGH INST. (Mar. 20, 2023), https://thebreakthrough.org/issues/food-agriculture-environment/livestock-dont-contribute-14-5-of-global-greenhouse-gas-emissions (describing prominent estimates of livestock's global emissions responsibility between 11.1% and 19.6%). The U.N. Food & Agriculture Organization's (FAO's) most recent estimate is the low end of that range, and the only one below 14.5%. U.N. FOOD & AGRIC. ORG., PATHWAYS TOWARDS LOWER EMISSIONS: A GLOBAL ASSESSMENT OF THE GREENHOUSE GAS EMISSIONS AND MITIGATION OPTIONS FROM LIVESTOCK AGRIFOOD SYSTEMS 4 (2023), https://www.fao.org/3/cc9029en/cc9029en.pdf. Given that FAO's prior estimates were higher (14.5% and 17.8%) and that a number of commentators have questioned the recent lower estimate, this Article provides the UNEP's recent description above: 14.5%–20%. *E.g.*, Blaustein-Rejto & Gambino, *supra* (noting that "FAO's [recent] analysis has several limitations and uncertainties," and that it may not accurately estimate GHG emissions of grazing and the impacts of deforestation and land-use change); Arthur Neslen, *Ex-Officials at UN Farming Body Say Work on Methane Emissions Was Censored*, GUARDIAN (Oct. 20, 2023).

39 Piers Forster et al., *The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS 923, 1017 (Valérie Masson-Delmotte et al. eds., 6th ed. 2021).

40 P.J. GERBER ET AL., U.N. FOOD & AGRIC. ORG., TACKLING CLIMATE CHANGE THROUGH LIVESTOCK 15 (2013), https://www.fao.org/3/i3437e/i3437e.pdf (relying on 2004 and 2005 data).

41 U.S. ENV'T PROT. AGENCY, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2022, at ES-18 (2023), https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf; PETER H. LEHNER & NATHAN A. ROSENBERG, FARMING FOR OUR FUTURE: THE SCIENCE, LAW, AND POLICY OF CLIMATE-NEUTRAL AGRICULTURE 41 (2021); Jo-Anne McArthur, *Methane Emissions Are Driving Climate Change. Here's How to Reduce Them*, U.N. ENV'T PROGRAMME, (Aug. 20, 2021)

times more powerful than carbon dioxide.[42] But an average methane molecule only lasts in the atmosphere for about a decade, while carbon dioxide can persist for hundreds of years.[43] The potency of methane, combined with its shorter life in the atmosphere, creates a mitigation opportunity. As explained by the U.N. Environment Programme (UNEP): "[R]educing methane emissions now would have an impact in the near term and is critical for helping keep the world on a path to 1.5°C."[44] In light of both its emissions of climate super-pollutants and association with land use change, a "global phaseout" of animal agriculture over the next fifteen years "would have the same effect, through the end of the century, as a 68% reduction of CO_2 emissions."[45]

Nonetheless, animal agriculture has frequently benefitted from light or no environmental regulation around the world.[46] The United States is a particularly cogent example. In the climate realm, the United States has consistently and almost entirely exempted the animal agriculture industry from air pollution GHG regulation regimes.[47] Even in Europe—while ahead of the United States in addressing animal agriculture's climate impacts[48]—significant continent-wide policy has so far failed to address the climate harms of animal agriculture. Efforts to use the EU Industrial Emissions Directive (IED), which regulates pollutants from industrial facilities, to regulate GHG emissions from large-scale animal agriculture floundered in 2023 when industry lobbying resulted in the European Parliament removing all cattle farms and some targeted pig and poultry farms from the reach of the

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[hereinafter *UNEP Methane Emissions*], https://www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them.

[42] Forster et al., *supra* note 39, at 1017.

[43] *Overview of Greenhouse Gases*, U.S. ENV'T PROT. AGENCY, https://www.epa.gov/ghgemissions/overview-greenhouse-gases (Feb. 16, 2024); *Understanding Global Warming Potentials,* U.S. ENV'T PROT. AGENCY, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials (Apr. 18, 2023); *UNEP Methane Emissions*, *supra* note 41.

[44] *UNEP Methane Emissions*, *supra* note 41; *see also* U.N. INTERGOV'TAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2023: SYNTHESIS REPORT 26 (Hoesung Lee & José Romero eds., 2023) [hereinafter IPCC SIXTH ASSESSMENT REPORT SYNTHESIS] ("Strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*).").

[45] Michael B. Eisen & Patrick O. Brown, *Rapid Global Phaseout of Animal Agriculture Has the Potential to Stabilize Greenhouse Gas Levels for 30 Years and Offset 68 Percent of CO_2 Emissions This Century*, PLOS CLIMATE, Feb. 1, 2022, No. e0000010, at 2–3, 7, https://doi.org/10.1371/journal.pclm.0000010 (accounting for both the "emission reduction and biomass recovery" that would result from phaseout of animal agriculture).

[46] *See* Claire Regenstreif, *Animal Agricultural Exceptionalism in the 21st Century*, 37 J. ENV'T L. & LITIG. 249, 250 (2022); Charlotte E. Blattner & Odile Ammann, *Agricultural Exceptionalism and Industrial Animal Food Production: Exploring the Human Rights Nexus*, J. FOOD L. & POL'Y, Spring 2019, at 92, 117–18, 121–22; Alexander Zahar, *Agricultural Exceptionalism in the Climate Change Treaties*, 12 TRANSNAT'L ENV'T L. 42, 55–56 (2023).

[47] Ryan Levandowski, *Polluting 'til the Cows Come Home: How Agricultural Exceptionalism Allows CAFOs Free Range for Climate Harm*, 33 GEO. ENV'T L. REV. 151, 152–53 (2020).

[48] *See* discussion *infra* Part III.

regulation.[49] The decision to postpone the implementation of stronger animal agriculture emissions controls in the IED was recently identified as an "ambition gap" by the European Scientific Advisory Board on Climate Change,[50] an independent body established in 2021 by the European Climate Law to advise the EU on climate change.[51] Moreover, the removal of a reference from the EU 2040 Climate Roadmap to efforts to reduce non-carbon dioxide GHGs (primarily methane and nitrous oxide) in agriculture by at least 30% by 2040 was viewed by many as a capitulation to the industry.[52]

In addition to benefitting from regulatory exclusion and gaps, animal agriculture enjoys high levels of government support.[53] For example, a recent report from the European Scientific Advisory Board on Climate Change described how the EU Common Agricultural Policy's subsidization of "the livestock sector . . . is a direct subsidy for GHG-intensive food products and undermines the goal of having food products reflect their true costs."[54] Across the EU and United States, animal

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[49] *Questions and Answers on Revised EU Rules on Industrial Emissions*, EUR. COMM'N (Apr. 5, 2022), https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_2239; Antonia Zimmerman, *EU Conservatives Score Big Win on Industrial Emissions Rules*, POLITICO (July 11, 2023), https://www.politico.eu/article/eu-conservative-big-win-industrial-emissions-directive.

[50] EUR. SCI. ADVISORY BD. ON CLIMATE CHANGE, TOWARDS EU CLIMATE NEUTRALITY: PROGRESS, POLICY GAPS, AND OPPORTUNITIES (ASSESSMENT REPORT 2024) 155 (2024) [hereinafter EU ASSESSMENT REPORT 2024], https://climate-advisory-board.europa.eu/reports-and-publications/towards-eu-climate-neutrality-progress-policy-gaps-and-opportunities.

[51] *About the Advisory Board*, EUR. SCI. ADVISORY BD. ON CLIMATE CHANGE, https://climate-advisory-board.europa.eu/about (last visited Mar. 8, 2024).

[52] *E.g.*, Maria Simon Arboleas, *EU Commission Backtracks on Agricultural Emissions Cuts*, EURACTIV (Feb. 6, 2024), https://www.euractiv.com/section/agriculture-food/news/eu-commission-backtracks-on-agricultural-emissions-cuts.

[53] Gordon, *supra* note 2 ("About a third of global public agricultural subsidies, which totaled $233 million in 2017, are for the production of meat, milk, or dairy—even though the livestock that feeds us is also responsible for around 15 percent of global greenhouse gas emissions. . . . In other words, governments are decidedly not trying to take away your burgers. . . ."); *see also* U.N. FOOD & AGRIC. ORG. ET AL., A MULTI-BILLION DOLLAR OPPORTUNITY: REPURPOSING AGRICULTURAL SUPPORT TO TRANSFORM FOOD SYSTEMS xvii (2021) ("[E]mission-intensive commodities (e.g. beef, milk, and rice) receive the most support worldwide, despite the potentially negative impacts on health as well as on climate change adaptation and mitigation, and the (relative) disincentives this support creates towards producing healthier and more nutritious foods, such as fruits and vegetables.").

[54] EU ASSESSMENT REPORT 2024, *supra* note 50, at 161–62; *see also id.* at 182 ("[T]he current CAP continues to financially support livestock production (policy inconsistency), which drives demand for land for feed production. . . . EU policies on agriculture should better reflect the need to maintain and expand the area of forests and wetlands for carbon sequestration purposes."); Elena Sánchez Nicolás & Carolin Sprick, *Dismay Over EU Plans to Keep Paying for Meat*, EUOBSERVER (May 29, 2022, 7:07 PM), https://euobserver.com/green-economy/ar0b815ce4 (analyzing EU Commission data and finding that the EU had spent €143 million to promote European meat products in last five years); *see also* Mose Apelblat, *Climate Change: Is the EU Doing Enough to Reduce Methane Emissions in Agriculture?*, BRUSSELS TIMES (May 7, 2023), https://www.brusselstimes.com/493849/climate-change-is-the-eu-doing-enough-to-reduce-

agriculture receives about one thousand times more government funding—including for research and development—than alternative products, even though it is dramatically more established.[55]

Meanwhile, global consumption of animal products continues to increase. Per the FAO, by 2030, global meat consumption will increase fourteen percent as compared to 2018–2020 levels.[56] Increasing consumption of animal products will increase their related GHG emissions (including the potential to undo any efficiency gains in production[57]) and exacerbate the many harms of the industry, including other environmental damage and harms to health, communities, and animals.[58]

III. GLOBAL MOMENTUM AND INTERNATIONAL SIGNALING

This Part describes emergent recognition from international and multinational bodies and in international agreements about the need to reduce GHG emissions from animal agriculture through dietary change. The first section provides a chronology of international and EU developments—with the EU highlighted because it is a leader in this area—and the second describes COP28 as an example both of progress and obstacles to change.

A. International and EU Activity

Widespread awareness of the significant contributions of animal agriculture to climate change goes back at least as far as the publication of the FAO report, *Livestock's Long Shadow*, in 2006.[59] The report did not shy away from animal agriculture's environmental impacts, noting in its opening lines that "[l]ivestock activities have significant impact on virtually all aspects of the environment, including air and climate change, land and soil, water and biodiversity" and that "[l]ivestock's impact on the environment is already huge, and it is growing and rapidly changing."[60] In the report, the FAO determined that animal agriculture "has such deep and wide-ranging environmental impacts that it should rank as one of the leading focuses for environmental policy" and estimated that the sector was responsible for 18% of all

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methane-emissions-in-agriculture (discussing the EU's commitment to the Global Methane Initiative, which does not reach agricultural emissions).

55 Vallone & Lambin, *supra* note 33, at 1213.

56 U.N. FOOD & AGRIC. ORG., OECD-FAO AGRICULTURAL OUTLOOK 2021–2030, at 164 (2021), https://doi.org/10.1787/19428846-en.

57 *See* discussion *infra* Section IV.E. Tech Fixes and Climate Efficiency Approaches

58 *See infra* notes 244–256 and accompanying text.

59 U.N. FOOD & AGRIC. ORG., LIVESTOCK'S LONG SHADOW: ENVIRONMENTAL ISSUES AND OPTIONS (2006) [hereinafter LIVESTOCK'S LONG SHADOW], https://www.fao.org/3/a0701e/a0701e.pdf.

60 *Id.* at 3.

global GHG emissions.[61] This was the first global emissions reckoning for the industry, which had not been evaluated as its own sector in any of the IPCC synthesis reports issued beginning in 1990.[62] These findings reportedly resulted in significant industry pushback on the FAO.[63] Several years later, the UNEP also commented on the environmental and climate profile of animal agriculture in a report aimed at identifying the highest impact goods: "Animal products, both meat and dairy, in general require more resources and cause higher emissions than plant-based alternatives."[64] In their reports, neither the FAO nor the UNEP explicitly called for a reduction in consumption of animal products as a part of the response to climate change.

Recent years have seen international bodies more willing to make that connection. In a 2018 report, the IPCC considered the differing impacts of global warming of 1.5ºC and 2.0ºC above preindustrial levels—concluding that the former was near certain to occur and the latter would be dramatically worse—along with GHG emission pathways to both scenarios.[65] The IPCC explicitly recognized the importance of reducing consumption of animal products—"particularly where consumption is higher than suggested human health guidelines"—as well as the uncertainty of the best policy pathways to achieve that end in the face of increasing consumption.[66] The report highlighted that "plant-based proteins" and "cultured meat" could "radically reduce agricultural and land-use emissions," "less resource-intensive diets" would reduce demand for land, and "[l]ower consumption of livestock products by 2050 could also substantially reduce deforestation and cumulative carbon losses."[67]

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[61] *Id.* at xxiv, 112.

[62] Viveca Morris & Jennifer Jacquet, *The Animal Agriculture Industry, US Universities, and the Obstruction of Climate Understanding and Policy*, CLIMATIC CHANGE, Mar. 2024, No. 41, at 2.

[63] Arthur Neslen, *Ex-Officials at UN Farming Body Say Work on Methane Emissions Was Censored*, GUARDIAN (Oct. 20, 2023), https://www.theguardian.com/environment/2023/oct/20/ex-officials-at-un-farming-fao-say-work-on-methane-emissions-was-censored; Arthur Neslen, *'The Anti-Livestock People Are a Pest': How UN Food Body Played Down the Role of Farming in Climate Change*, GUARDIAN (Oct. 20, 2023), https://www.theguardian.com/environment/2023/oct/20/the-anti-livestock-people-are-a-pest-how-un-fao-played-down-role-of-farming-in-climate-change; EMISSIONS IMPOSSIBLE, *supra* note 3, at 15; *see also* Susannah Savage et al., *The Global Power of Big Agriculture's Lobbying*, FIN. TIMES (Aug. 22, 2024), https://www.ft.com/content/5f4e0538-10a4-4c8f-bc3c-28f255f20f0b ("Henning Steinfeld, former head of the [FAO's] livestock analysis unit, says officials within the UN itself 'diminished' and 'defamed' his team for more than a decade after it published [*Livestock's Long Shadow*].").

[64] EDGAR G. HERTWICH ET AL., U.N. ENV'T PROGRAMME, ASSESSING THE ENVIRONMENTAL IMPACTS OF CONSUMPTION AND PRODUCTION: PRIORITY PRODUCTS AND MATERIALS 79 (2010).

[65] 2018 IPCC REPORT, *supra* note 27, at 4, 7–10, 12.

[66] *Id.* at 327 (internal citations omitted); *see also id.* at 382 (noting that the extent and feasibility of dietary shifts will "[d]epend[] on individual behavior, education, cultural factors and institutional support").

[67] *Id.* at 16, 112, 146; *see also id.* at 316 ("Shifts in dietary choices towards foods with lower emissions and requirements for land . . . could reduce emissions and increase adap-

Also in 2018, announcing the awarding of the Champions of the Earth Award in the Science and Innovation Category to the founders of two prominent plant-based meat companies, the UNEP issued a statement strikingly entitled "*Tackling the World's Most Urgent Problem: Meat*," and shared the awardees' views in these terms: "[O]ur use of animals as a food-production technology has brought us to the verge of catastrophe. . . . There is no pathway to achieve the Paris climate objectives without a massive decrease in the scale of animal agriculture . . . ."[68]

In 2019, the "EAT-*Lancet* Commission," a group of experts in human health, agriculture, political sciences, and sustainability, released an influential report.[69] The Commission described the effort as "the first attempt to set universal scientific targets for the food system that apply to all people and the planet."[70] The report concluded:

> Transformation to healthy diets by 2050 will require substantial dietary shifts. Global consumption of fruits, vegetables, nuts and legumes will have to double, and consumption of foods such as red meat and sugar will have to be reduced by more than 50%. A diet rich in plant-based foods and with fewer animal source foods confers both improved health and environmental benefits.[71]

Also in 2019, a joint report from the FAO and the World Health Organization (WHO) described "the combined health and environmental benefits of shifting towards a more plant-based diet."[72]

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tation options . . . ."); *see also* Cheikh Mbow et al., *Food Security*, *in* CLIMATE CHANGE AND LAND: AN IPCC SPECIAL REPORT ON CLIMATE CHANGE, DESERTIFICATION, LAND DEGRADATION, SUSTAINABLE LAND MANAGEMENT, FOOD SECURITY, AND GREENHOUSE GAS FLUXES IN TERRESTRIAL ECOSYSTEMS 437, 481 (Valérie Masson-Delmotte et al. eds., 2022) [hereinafter IPCC, CLIMATE CHANGE AND LAND] ("[A] dietary pattern that is higher in plant-based foods . . . and lower in animal-based foods is more health-promoting and is associated with lesser environmental impact (GHG emissions and energy, land, and water use) than is the current average 'meat-based' diet.").

[68] *Tackling the World's Most Urgent Problem: Meat*, U.N. ENV'T PROGRAMME: CHAMPIONS OF THE EARTH (Sept. 26, 2018), https://www.unep.org/championsofearth/news-and-stories/tackling-worlds-most-urgent-problem-meat (describing awarding of prize to Ethan Brown and Patrick O'Reilly Brown, founders of Beyond Meat and Impossible Foods, respectively).

[69] Walter Willett et al., *Food in the Anthropocene: The EAT*-Lancet *Commission on Healthy Diets from Sustainable Food Systems*, 393 LANCET 447 (2019); *see also* Ayesha I.T. Tulloch et al., *How the EAT*-Lancet *Commission on Food in the Anthropocene Influenced Discourse and Research on Food Systems: A Systematic Review Covering the First 2 Years Post-publication*, 11 LANCET GLOB. HEALTH e1125, e1133 (2023) (discussing popularity and impact of the report).

[70] EAT, SUMMARY REPORT OF THE EAT-*LANCET* COMMISSION 5 (2019), https://eatforum.org/eat-lancet-commission/eat-lancet-commission-summary-report.

[71] *Id.* at 3.

[72] U.N. FOOD & AGRIC. ORG. & WORLD HEALTH ORG., SUSTAINABLE HEALTHY DIETS: GUIDING PRINCIPLES 34 (2019), https://iris.who.int/bitstream/handle/10665/329409/9789241516648-eng.pdf.

In Europe, in September 2020, the European Commission recognized in a communication about its 2030 climate ambition that a "strong decrease of consumption of animal products for nutrition could potentially reduce emissions by more than 30 million tonnes by 2030."[73] The next month, in its strategy to reduce methane emissions, the Commission recognized that, "[g]iven the high share of methane emissions in agriculture that result from livestock, lifestyle and diet changes can also contribute significantly to reducing EU methane emissions."[74]

Then, in 2021, the European Parliament adopted its "Farm to Fork Strategy," which the European Commission described as "at the heart of the European Green Deal."[75] The Strategy aims to make food systems "fair, healthy and environmentally-friendly,"[76] recognizes both the health and environmental benefits of reducing meat consumption,[77] and commits to dedicating EU funds to research alternative proteins.[78] But advocates said that it was "deeply disappointing" that a call to end government spending on promoting meat production and consumption that had appeared in an earlier draft did not make it into the final strategy.[79] Moreover, as one European agriculture expert put it: "Remarkably, the EU Farm-to-Fork Strategy, while emphasizing the need to reduce methane and nutrient emissions from livestock, does not mention a reduction in total livestock numbers as either a goal or a policy option."[80]

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[73] *Stepping Up Europe's 2030 Climate Ambition: Investing in a Climate-Neutral Future for the Benefit of Our People*, at 5 n.2, COM (2020) 562 final (Sept. 17, 2020).

[74] *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions*, at 3–4, COM (2020) 663 final (Oct. 14, 2020) [hereinafter *EU Strategy to Reduce Methane Emissions*]; *see also id.* at 11 (noting that, in addition to efficiency and technological improvements, further reductions in methane emissions could be achieved "by more sustainable diets").

[75] EUR. COMM'N, FARM TO FORK STRATEGY FOR A FAIR, HEALTHY AND ENVIRONMENTALLY-FRIENDLY FOOD SYSTEM 4 (2020) [hereinafter FARM TO FORK STRATEGY]. The European Green Deal is a set of policies that aims to make Europe the first climate-neutral continent by 2050. *The European Green Deal*, EUR. COMM'N, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (last visited Oct. 12, 2024).

[76] FARM TO FORK STRATEGY, *supra* note 75, at cover.

[77] *Id.* at 14 ("Moving to a more plant-based diet with less red and processed meat and with more fruits and vegetables will reduce not only risks of life threatening diseases, but also the environmental impact of the food system.").

[78] *Id.* at 16.

[79] *European Commission Will Start Supporting Plant-Based Diets in New Farm to Fork Strategy, but 'Chickened Out' of Removing EU Funding for Meat Promotion*, HUMANE SOC'Y INT'L (May 20, 2020), https://www.hsi.org/news-resources/european-commission-supports-plant-based-diets-farm-to-fork-strategy.

[80] Daan Boezeman et al., *Less Livestock in North-Western Europe? Discourses and Drivers Behind Livestock Buyout Policies*, EUROCHOICES, Aug. 2023, at 4, 4 (internal citation omitted). As discussed below, four years on, the promise of the Farm to Form Strategy has largely not been realized. *See infra* note 286.

According to the UNEP's 2021 Global Methane Assessment, "the adoption of healthy diets (vegetarian or with a lower meat and dairy content)" is one of three key measures to reduce emissions from animal agriculture.[81] Also in 2021, at COP26 in Glasgow more than a hundred countries signed the "Global Methane Pledge," undertaking to reduce methane emissions by 30 percent by 2030.[82] But the Pledge took quite different approaches to the other two main sectoral sources of methane than it did to agriculture, calling for "all feasible reductions in the energy and waste sectors" but only "abatement of agricultural emissions through technology innovation as well as incentives and partnerships with farmers."[83] The signatories apparently were not willing to commit to "all feasible reductions" in emissions from agriculture.

A 2022 IPCC report on "Climate Change and Land" identified "a shift toward plant-based diets" as one of the top three options (along with reducing deforestation and food waste) to reduce emissions from agriculture, forestry, and other land use.[84] Less clearly, the IPCC's Sixth Assessment Report released in March 2023 stated that "unbalanced diets" contribute to "agricultural expansion," "increase[] ecosystem and human vulnerability and lead[] to competition for land and/or water resources."[85] The report also recognized that, along with other measures, shifting to "sustainable healthy diets" could "reduce ecosystem conversion, and methane and nitrous oxide emissions, and free up land for reforestation and ecosystem restoration."[86]

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[81] U.N. ENV'T PROGRAMME, GLOBAL METHANE ASSESSMENT 13 (2021) [hereinafter GLOBAL METHANE ASSESSMENT], https://www.ccacoalition.org/sites/default/files/resources//2021_Global-Methane_Assessment_full_0.pdf.

[82] *COP26: Together for Our Planet*, UNITED NATIONS: CLIMATE ACTION, https://www.un.org/en/climatechange/cop26 (last visited Oct. 14, 2024).

[83] GLOBAL METHANE PLEDGE (Nov. 22, 2023), https://www.globalmethanepledge.org/sites/default/files/documents/2023-11/Global%20Methane%20Pledge.pdf; *see also* CHANGING MARKETS FOUND., BLINDSPOT: HOW LACK OF ACTION ON LIVESTOCK METHANE UNDERMINES CLIMATE TARGETS 8 (2021) [hereinafter BLINDSPOT], https://changingmarkets.org/report/blindspot-how-lack-of-action-on-livestock-methane-undermines-climate-targets ("[T]he Global Methane Pledge . . . ignore[s] the potential to reduce methane emissions by addressing people's overconsumption of meat and dairy—where some of the biggest cuts in emissions can be achieved.").

[84] IPCC, CLIMATE CHANGE AND LAND, *supra* note 67, at 49; *see also* Mustafa Babiker et al., *Cross-sectoral Perspectives, in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE 1279 (Priyadarshi R. Shukla et al. eds., 2022) ("[M]itigation actions need to go beyond food producers and suppliers to incorporate dietary changes and consumers' behavioural patterns . . . .").

[85] IPCC SIXTH ASSESSMENT REPORT SYNTHESIS, *supra* note 44, at 50. A prior 2022 IPCC report had defined "balanced diets" as "featur[ing] plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable, and low-greenhouse gas emissions systems." INTERGOV'TAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2022: IMPACTS, ADAPTATION AND VULNERABILITY 12 n.32 (Hans-Otto Pörtner et al. eds., 2022).

[86] IPCC SIXTH ASSESSMENT REPORT SYNTHESIS, *supra* note 44, at 29; *see also id.* at 106. The IPCC defines "[s]ustainable healthy diets" as "promot[ing] all dimensions of individuals' health and well-being; hav[ing] low environmental pressure and impact; [being] accessible, affordable, safe and equitable; [and] culturally acceptable . . . ." *Id.* at 29 n.53.

According to reporting after the release of the 2023 report, more direct references to the climate impacts of animal agriculture were removed from drafts after pressure from delegates from Brazil and Argentina (both major meat-producing and exporting countries).[87] In particular, a leaked draft had reportedly included much more precise and definitive language:

> A shift to diets with a higher share of plant-based protein in regions with excess consumption of calories and animal-source food can lead to substantial reductions in GHG emissions . . . . Plant-based diets can reduce GHG emissions by up to 50% compared to the average emission intensive Western diet.[88]

The European Commission's Agricultural Outlook for 2022–2032 evaluated the impacts of reducing farm animal density in Europe to comply with nitrogen pollution and habitat protection laws. The Commission concluded that reductions would reduce GHG emissions in the EU, and that such measures should be paired with complementary policies (including dietary changes, improved emissions efficiency, and trade measures) to prevent "leakage," i.e., European consumers importing more animal products to meet demand.[89] Interestingly, the analysis showed that farmer incomes would grow even as production declined, as a result of higher prices for animal products and reduced feed costs.[90]

In late 2023, the European Union announced that, through the European Innovation Council, it would spend €50 million in 2024 to help scale up alternative proteins including precision fermentation.[91] And lest it seem that the United States is lagging entirely behind international bodies and the European Union in acknowledging the role of dietary shifts in climate mitigation, in late 2023, the Fifth National Climate Assessment addressed food systems for the first time, notably

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[87] Michael Thomas, *How Meat and Fossil Fuel Producers Watered Down the Latest IPCC Report*, DISTILLED (Mar. 23, 2023), https://www.distilled.earth/p/how-meat-and-fossil-fuel-producers; *see also* Mustafa Zia et al., *Brazil Once Again Becomes the World's Largest Beef Exporter*, U.S. DEP'T OF AGRIC. (July 1, 2019), https://www.ers.usda.gov/amber-waves/2019/july/brazil-once-again-becomes-the-world-s-largest-beef-exporter; Maximilian Heath, *Argentina to Loosen Restrictions on Beef Exports*, REUTERS (Dec. 9, 2021, 3:58 PM), https://www.reuters.com/markets/commodities/argentine-meat-industry-says-fatter-cows-may-help-end-export-impasse-with-2021-12-09 ("Argentina is a key global supplier of beef . . . .").

[88] Thomas, *supra* note 87.

[89] DIRECTORATE-GEN. FOR AGRIC. & RURAL DEV., EUR. COMM'N, EU AGRICULTURAL OUTLOOK: FOR MARKETS, INCOME AND ENVIRONMENT 2022–2032, at 48, 53 (2022), https://agriculture.ec.europa.eu/system/files/2023-04/agricultural-outlook-2022-report_en_0.pdf.

[90] *Id.* at 48, 52.

[91] Cate Lawrence, *The EU Invests €50M to Help Startups Scale Up Alternative Proteins*, TECH EU (Dec. 15, 2023), https://tech.eu/2023/12/15/eics-eur50m-challenge-scaling-up-alternative-protein-production-in-europe.

acknowledging that shifts to plant-based and cultivated meats "offer the potential to reduce GHG emissions."[92]

In a January 2024 report on EU progress toward climate neutrality, the European Scientific Advisory Board on Climate Change included the following in its key recommendations:

> The [EU common agricultural policy] CAP should be better aligned with EU climate goals . . . [including by] shifting CAP support away from emission-intensive agricultural practices, including livestock production, and towards lower-emitting products . . . .
>
> [T]he EU should strengthen measures to encourage healthier, more plant-based diets, and develop a strategy for a just transition to a food system consistent with climate neutrality.[93]

The Board also noted that the EU's 2018 Long-Term Strategy was not ambitious enough in the timelines it considered for dietary change, and that "further (and faster) reductions in animal product consumption would be recommended," both for climate and health reasons.[94]

Most recently, a groundbreaking 2024 report from the World Bank on emissions from the agrifood system encouraged high-income countries to "decrease consumer demand for emissions-intensive, animal-source foods by fully pricing environmental and health externalities, repurposing subsidies, and promoting sustainable food options."[95] A lead author of the report commented that the recommendation is decidedly *not* to shift support away from agriculture, but rather to "use it in more effective ways that actually contribute to healthier diets and a healthier planet."[96]

In addition to the climate context, calls for dietary change away from animal products have emerged in relation to other critical and related global issues, most prominently public health and biodiversity. Such guidance is based not only on the specific risks that dietary change could help address (for example, zoonotic disease for public health and

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92 Carl H. Bolster et al., *Chapter 11: Agriculture, Food Systems, and Rural Communities*, *in* FIFTH NATIONAL CLIMATE ASSESSMENT 11-1, 11-12 (Allison Crimmins et al. eds., 2023) (internal citations omitted); Marianne Lavelle et al., *Report Charts Climate Change's Growing Impact in the US, While Stressing Benefits of Action*, INSIDE CLIMATE NEWS (Nov. 14, 2023), https://insideclimatenews.org/news/14112023/biden-national-cliimate-assessment.

93 EU ASSESSMENT REPORT 2024, *supra* note 50, at 11–12; *see also id.* at 153–54, 173, 179.

94 *Id.* at 173.

95 SUTTON ET AL., *supra* note 28, at 12. The World Bank estimated that prices that "reflect the true health, climate, and environmental costs of meat" would be 20%–60% higher than current prices. *Id.* at 13.

96 Agnieszka de Sousa, *Cut Aid for Livestock Farms to Help Climate Fight, World Bank Says*, BLOOMBERG (May 6, 2024), https://www.bloomberg.com/news/articles/2024-05-07/cut-aid-for-livestock-farms-to-help-climate-fight-world-bank-says.

deforestation for biodiversity[97]), but also because climate change will itself exacerbate public health and biodiversity risks.[98] In one prominent example, the Kunming-Montreal Global Biodiversity Framework (GBF), adopted by the parties to the Convention on Biological Diversity in 2022, requires establishment of national targets to encourage sustainable consumption choices and, "by 2030, [to] reduce the global footprint of consumption in an equitable manner."[99] Focusing on the food system in its plan for implementation of the GBF, the International Union for Conservation of Nature, a membership group of government and civil society organizations that advises and works at the intersection of development, economics, and conservation, called for "[m]inimizing impacts of food production on species by reducing consumption of animal protein . . . especially in developed countries [to limit] negative impacts on wild species."[100]

B. COP28

The meeting of the Conference of the Parties to the U.N. Framework Convention on Climate Change in Dubai in November 2023 (COP28), which included a flurry of activity around food systems, is a prominent, recent example of the growing energy around this issue on the global stage.[101] While this new focus was laudable, the fact that food systems had never before received this level of attention—despite their

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97 Matthew N. Hayek, *The Infectious Disease Trap of Animal Agriculture*, SCI. ADVANCES, Nov. 2022, No. eadd6681, at 3–4; Marta Kozicka et al., *Feeding Climate and Biodiversity Goals with Novel Plant-Based Meat and Milk Alternatives*, NATURE COMMC'NS., Sept. 12, 2023, No. 5316, at 6–7.

98 *E.g.*, Howard Frumkin et al., *Climate Change: The Public Health Response*, 98 AM. J. PUB. HEALTH 435, 435 (2008) (discussing potential and already experienced negative impacts of climate change on human health); K.R. Shivanna, *Climate Change and Its Impact on Biodiversity and Human Welfare*, 88 PROC. INDIAN NAT'L SCI. ACAD. 160, 164–66 (discussing climate change's detrimental effects on biodiversity).

99 Conference of the Parties to the Convention on Biological Diversity, *Kunming-Montreal Global Biodiversity Framework*, ¶ 13, U.N. Doc. CBD/COP/DEC/15/4, annex (Dec. 19, 2022).

100 INT'L UNION FOR CONSERVATION OF NATURE, GLOBAL SPECIES ACTION PLAN: SUPPORTING IMPLEMENTATION OF THE KUNMING-MONTREAL GLOBAL BIODIVERSITY FRAMEWORK 37 (2023), https://portals.iucn.org/library/node/51362; *Int'l Union for Conservation of Nature (IUCN)*, U.N. ENV'T PROGRAMME, https://www.unep.org/explore-topics/oceans-seas/what-we-do/working-regional-seas/partners/international-union (last visited Oct. 17, 2024).

101 One might wonder whether the prominence of food at COP28 was driven, at least in part, by the interest of its host country and president, Sultan Al Jaber, who is the CEO of the United Arab Emirates national fuel company, in diverting attention away from fossil fuels. Fiona Harvey, *Cop28 President Denies on Eve of Summit He Abused His Position to Sign Oil Deals*, GUARDIAN (Nov. 29, 2023, 12:17 PM), https://www.theguardian.com/environment/2023/nov/29/cop28-president-denies-on-eve-of-summit-he-abused-his-position-to-sign-oil-deals. Nonetheless, as described herein, COP28 was the most significant COP to date for food.

significant emissions—is illustrative of the lack of attention to the climate impacts of agriculture.[102]

1. COP28: Progress

During the second day of the meeting, the COP president announced the Emirates Declaration on Sustainable Agriculture, Resilient Food Systems and Climate Action, which more than 160 countries have signed.[103] The nonbinding declaration acknowledges that food systems "must urgently adapt and transform" to respond to the climate crisis.[104] Signatory countries committed to "[m]aximize the climate and environmental benefits—while containing and reducing harmful impacts—associated with agriculture and food systems [including] by . . . shifting from higher greenhouse gas-emitting practices to more sustainable production and consumption approaches . . . ."[105] The Declaration tasks governments, for the first time, with including agriculture in their Nationally Determined Contributions[106] by COP30 in 2025,[107] and commits countries to improve their approaches to bolstering animal and ecosystem health within agriculture and food systems.[108]

In a short video message prepared for COP28, WHO Director-General Tedros Adhanom Ghebreyesus recognized that food systems are harming people and the planet, and noted their significant climate

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[102] *See supra* text accompanying notes 34–36; *see also, e.g.*, Jan Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, NEW REPUBLIC (Dec. 14, 2023) [hereinafter Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*], https://newrepublic.com/article/177575/never-trust-green-meat ("Given the urgency of the climate crisis, one would think that tackling the single biggest source of food-sector emissions would have been central to serious climate discussions for the past decade and a half.").

[103] *Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action*, COP28 UAE [hereinafter COP28 UAE DECLARATION], https://www.cop28.com/en/food-and-agriculture (last visited Oct. 20, 2024); Daphne Ewing-Chow, *COP28 Leaders Transforming Food Systems in Face of Climate Change*, FORBES (Dec. 2, 2023, 3:25 AM), https://www.forbes.com/sites/daphneewingchow/2023/12/02/cop28-leaders-transforming-food-systems-in-face-of-climate-change.

[104] COP28 UAE DECLARATION, *supra* note 103.

[105] *Id.*

[106] *All About the NDCs*, U.N.: CLIMATE ACTION, https://www.un.org/en/climatechange/all-about-ndcs (last visited Oct. 11, 2024) (explaining that Nationally Determined Contributions, or NDCs, are a requirement of the Paris Agreement under which each party must create a climate action plan to reduce emissions and adapt to the effects of climate change, and update the plan every five years).

[107] SUTTON ET AL., *supra* note 28, at 18 ("147 of 167 second-round NDCs include [agriculture, food systems and/or land use] in their mitigation commitments."); Kenny Torrella, *There's Less Meat at the UN's COP28 Climate Talks. But There's Plenty of Bull.*, VOX (Nov. 30, 2023, 6:30 AM), https://www.vox.com/future-perfect/2023/11/30/23981529/cop28-meat-livestock-dairy-farming-plant-based-united-nations-dubai-uae (noting that all countries that already have agriculture mitigation NDCs are low- and middle-income countries—with relatively less animal product consumption).

[108] COP28 UAE DECLARATION, *supra* note 103.

impacts. Returning to the message of the WHO's 2019 report,[109] he called for transforming food systems by "shifting toward healthier, diversified, and more plant-based diets."[110]

During Food, Agriculture and Water Day—the first COP day ever dedicated to food systems[111]—the FAO announced its first "Roadmap" to achieve food security[112] without breaching the Paris Agreement goals.[113] The Roadmap addressed the differing climate impacts of food and the need for dietary change as follows: "High consumption of food products with high GHG footprints in some locations contribute unnecessarily to the emissions of agrifood systems. . . . The issue is to know not 'if' diets should change—for they absolutely must for human and planetary health—but how to obtain these results."[114] The Roadmap also recognized the need to consider environmental factors in national dietary guidelines and to utilize public food procurement programs to achieve climate goals.[115]

Also during COP28, references to food systems were included in the first-ever Global Stocktake of progress since the 2015 Paris Agreement,[116] although only after pressure from civil society and only in the adaptation (rather than mitigation[117]) section and in general terms.[118] In addition, UNEP released a report on the potential impacts

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109 FAO & WORLD HEALTH ORG., *supra* note 72.

110 World Health Org., *Our Food Systems Are Harming the Health of People and Planet*, YOUTUBE, at 0:40 (Dec. 21, 2023), https://www.youtube.com/watch?v=kHXJ5O5EDIc.

111 Brown & Hill, *supra* note 8.

112 Sustainable Development Goal 2 (SDG2), "Zero Hunger," aims for an end to hunger by 2030. *Goal 2: Zero Hunger*, U.N. SUSTAINABLE DEVELOPMENT GOALS, https://www.un.org/sustainabledevelopment/hunger (last visited Oct. 14, 2024).

113 U.N. FOOD & AGRIC. ORG., ACHIEVING SDG2 WITHOUT BREACHING THE 1.5C THRESHOLD: A GLOBAL ROADMAP 1–2 (2023) [hereinafter FAO ROADMAP], https://www.fao.org/interactive/sdg2-roadmap/assets/3d-models/inbrief-roadmap.pdf.

114 *Id.* at 19; *see also id.* at 1 ("Providing healthy food for all, today and tomorrow, is crucial; as is aligning agrifood systems transformation with climate actions.").

115 *Id.* at 19–21.

116 *Why the Global Stocktake Is Important for Climate Action This Decade*, UNFCCC, https://unfccc.int/topics/global-stocktake/about-the-global-stocktake/why-the-global-stocktake-is-important-for-climate-action-this-decade (last visited Oct. 13, 2024).

117 *Cf.* SUTTON ET AL., *supra* note 28, at 2 ("[A]ccording to scientists, we cannot adapt our way out of the climate crisis, and now is the time to put agriculture and food at the top of the mitigation agenda. If not, the world will be unable to ensure a livable future for future generations." (internal quotation and citation omitted)).

118 Silvia Mantilla, *Hope amid Challenges: Key Outcomes & Missed Opportunities at COP28*, WORLD FED'N FOR ANIMALS (Dec. 17, 2023), https://wfa.org/hope-amid-challenges-key-outcomes-missed-opportunities-at-cop28; *Good COP, Bad COP: Brighter Green's Take on COP28*, BRIGHTER GREEN (Dec. 20, 2023) [hereinafter *Good COP, Bad COP*], https://mailchi.mp/brightergreen/end-of-year-2023 (both noting that, before advocacy by environmental and animal NGOs, food systems seemed likely to be left out of the Global Stocktake altogether). The Global Stocktake calls for "the implementation of integrated, multisectoral solutions, such as . . . sustainable agriculture [and] resilient food systems," and for "[a]ttaining climate-resilient food and agricultural production and supply and distribution of food, as well as increasing sustainable and regenerative production and equitable access to adequate food and nutrition for all." Conference of the Parties Serving as the Meeting of

of meat and dairy alternatives.[119] A "key finding" of the report was that "[n]ovel plant-based meat, cultivated meat, and fermentation-derived foods show potential for reduced environmental impacts compared to many conventional [animal-sourced foods]. They also show promise for reduced risk of zoonoses and antimicrobial resistance . . . ."[120]

Last but not least in terms of pragmatic impact, following advocacy by youth groups and NGOs, the COP president adopted a "Climate Conscious Catering" plan with the stated goal of having two-thirds of the food served be vegan or vegetarian.[121] COP28 also featured a "Food for Climate Pavilion" and more than 650 food-related events.[122]

2. COP28: Critiques

While all of these COP firsts are undoubtedly steps forward, many are skeptical of their impact and seriousness. Environmental writer and activist George Monbiot pointedly observed that COP28 "was meant to be the first climate summit at which the impacts of the food system were properly considered. But by the time 120 meat and dairy lobbyists had done their worst, nothing meaningful came out of it."[123] Indeed, the meat and dairy industries reportedly had at least 120 delegates present in Dubai, about three times as many as had attended the COP the year before in Egypt.[124]

Another damning assessment of the transformative value of COP28 for animal agriculture emissions was published in the U.S. industry publication *Meatingplace*, which noted the lack of concrete outcomes: "Discussing the transition to plant-based meat and dairy was on the agenda during COP28, but as the annual event wraps up, the

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the Parties to the Paris Agreement, *Decision 1/CMA.5: Outcome of the First Global Stocktake*, ¶¶ 55, 63(b), U.N. Doc. FCCC/PA/CMA/2023/16/Add.1 (Mar. 15, 2024).

119 Press Release, U.N. Env't Programme, Novel Meat and Dairy Alternatives Could Help Curb Climate-Harming Emissions (Dec. 8, 2023), https://www.unep.org/news-and-stories/press-release/novel-meat-and-dairy-alternatives-could-help-curb-climate-harming.

120 UNEP WHAT'S COOKING?, *supra* note 36, at viii.

121 *Good COP, Bad COP, supra* note 118. Compare this to COP24 in 2018, where plant-based options were less common than meat and dairy dishes, which included beef with smoked bacon, gnocchi with ham, and cheeseburgers. FARM FORWARD ET AL., THE CLIMATE COST OF FOOD AT COP24 1 (2018), https://www.biologicaldiversity.org/programs/population_and_sustainability/sustainability/pdfs/COP24-menu-analysis-fact-sheet.pdf; *see also* Torrella, *supra* note 107 (discussing how COP28's catering decision marked a notable change from past, meat-heavy menus).

122 Philip Lymbery, *COP28 Climate Change Summit Saw Landmark Declaration that Should Dramatically Affect What We Eat*, SCOTSMAN (Dec. 15, 2023), https://www.scotsman.com/news/opinion/columnists/cop28-climate-change-summit-saw-landmark-declaration-that-should-dramatically-affect-what-we-eat-philip-lymbery-4445538; *Good COP, Bad COP, supra* note 118.

123 George Monbiot, *Call Me All the Names You Want—I Won't Stop Telling the Truth About Livestock Farming*, GUARDIAN (Dec. 14, 2023, 7:33 AM EST), https://www.theguardian.com/commentisfree/2023/dec/14/livestock-farming-soy-soyboy.

124 Rachel Sherrington et al., *Big Meat and Dairy Delegates Triple at COP28*, DESMOG (Dec. 8, 2023), https://www.desmog.com/2023/12/08/big-meat-dairy-delegates-triple-cop28.

conversation doesn't seem to have inspired any actual change."[125] The publication also observed that the FAO Roadmap "focused more on incremental improvements to the current food system without moves to change the animal agriculture sector or promote a move toward alt-meat and -dairy products."[126] Specifically as to the Declaration issued during the second day of COP28,[127] critics pointed out that its language "sidestepped" the "contentious issue" of meat consumption.[128]

Many observers were particularly critical of the shortcomings of the Roadmap issued by the FAO on Food Day,[129] noting that it did not adequately address the need for meat reduction, focused instead on technological fixes[130] and "intensified productivity,"[131] and "fail[ed] to express the urgency of reducing meat and dairy consumption and production to meet the targets set by the Paris climate agreement."[132] As observed by one expert in response to the Roadmap:

> This current draft puts a huge emphasis on incremental changes to the current industrial food system. But this is a flawed system that is wrecking nature, polluting the environment, and starving millions of

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125 Melissa Sue Sorrells, *Push for Meat Reduction MIA in COP28 Resolutions*, MEATINGPLACE (Dec. 12, 2023), https://www.meatingplace.com/Industry/News/Details/112595?allowguest=true.

126 *Id.*; *see also* Rachel Sherrington, *US Meat Lobby Delighted at 'Positive' Prospects for Industry After Cop28*, GUARDIAN (Apr. 8, 2024), https://www.theguardian.com/environment/2024/apr/08/us-meat-lobby-delighted-at-positive-prospects-for-industry-after-cop28.

127 *See supra* notes 103–108 and accompanying text.

128 Carissa Wong & Nature Magazine, *World Leaders Agree to a Climate Deal on Food for the First Time*, SCI. AM. (Dec. 11, 2023), https://www.scientificamerican.com/article/world-leaders-agree-to-a-climate-deal-on-food-for-the-first-time.

129 *See supra* notes 113–115 and accompanying text.

130 Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, *supra* note 102; Statement, Animal Prot. Denmark et al., *A Collective Call for a Holistic Food Systems Approach in FAO's Roadmap*, WORLD FED'N FOR ANIMALS (Dec. 11, 2023), https://wfa.org/a-collective-call-for-a-holistic-food-systems-approach-in-faos-roadmap; Monbiot, *supra* note 123.

131 FAO ROADMAP, *supra* note 113, at 6.

132 Brown & Hill, *supra* note 8 (quoting Stephanie Feldstein, Center for Biological Diversity); *see also* Cleo Verkuijl et al., *FAO's 1.5°C Roadmap for Food Systems Falls Short*, 5 NATURE FOOD 264, 264–65 (2024). Comments by the FAO's Chief Economist Maximo Torero also garnered critical responses. Referring to the recommendation in the Roadmap that animal production be intensified "in relevant locations," Torero "said the way forward was for countries that are 'very efficient in producing livestock,' such as the Netherlands and New Zealand, to produce more meat and dairy and then ship those products across the world." Susannah Savage, *Ramp Up Meat Production to Address Health Challenge in Poorer Countries*, FIN. TIMES (Dec. 10, 2023), https://www.ft.com/content/2eb93884-0aa3-4590-98ec-5b15cc1d9f44. George Monbiot queried in response:

> Could he really be unaware that both these countries have been thrown into severe ecological and political crisis by the scale of their livestock industries? Yet now he wants them to produce even more—and for poorer nations to become dependent on these imports? Greetings to our visitor from Planet Meat.

Monbiot, *supra* note 123.

> people. . . . The next rounds of this process will need to go much further in proposing a real transformation of the status quo . . . .[133]

Immediately following the COP, the FAO released *Pathways Towards Lower Emissions*, a report analyzing options to mitigate the GHG impact of animal agriculture.[134] Experts and advocates criticized the report on a number of bases, including its focus on productivity and efficiency improvements, as well as for minimizing and questioning the positive climate impacts of dietary changes.[135] Two scientists whose studies were referenced in the report sent a letter to the FAO, requesting a retraction and stating that the report "seriously distort[ed]" their findings and underestimated the climate mitigation potential of dietary change.[136]

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While progress has thus been limited and imperfect, after a long lag following the FAO's first analysis of the climate harms of animal agriculture in 2006, since 2018 a picture begins to emerge of growing calls on the international stage and in the EU for reduced consumption of animal products in response to the climate crisis.

IV. POLICY OPTIONS AND EXAMPLES

What options are available to leaders who would follow this international guidance and signaling? In fact, there are many policies that could reduce the climate harms of animal agriculture. Not only are these policies known and quite well understood,[137] as discussed in this Part, they are each currently being tried or considered somewhere in the world.

Notably, this Part does not include examples of mandatory limitations on animal agriculture's emissions via regulation. At present,

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133 Fiona Harvey, *UN Sets Out Roadmap to Combat Global Hunger amid Climate Crisis*, GUARDIAN (Dec. 10, 2023), https://www.theguardian.com/environment/2023/dec/10/un-sets-out-roadmap-to-combat-global-hunger-amid-climate-crisis (quoting Emile Frison, member of the thinktank International Panel of Experts on Sustainable Food Systems). Despite the Roadmap's limitations, the same expert also acknowledged: "The FAO should be applauded for this first step in laying out a plan" to eliminate hunger and address the GHG emissions from the food system. *Id.*

134 FOOD & AGRIC. ORG. OF THE U.N., PATHWAYS TOWARDS LOWER EMISSIONS: A GLOBAL ASSESSMENT OF THE GREENHOUSE GAS EMISSIONS AND MITIGATION OPTIONS FROM LIVESTOCK AGRIFOOD SYSTEMS (2023), https://www.fao.org/3/cc9029en/cc9029en.pdf.

135 *E.g.*, Jessica Bridgers, *New FAO Report Provides Entry Points for Animal Advocates but also Poses Risks*, WORLD FED'N FOR ANIMALS (Dec. 20, 2023), https://wfa.org/new-fao-report-provides-entry-points-for-animal-advocates-but-also-poses-risks.

136 Letter from Paul Behrens, Leiden Univ. & Matthew Hayek, New York Univ., to Thanawat Tiensin, Dir. of Animal Prod. & Health Div., FAO (Apr. 9, 2024), https://www.universiteitleiden.nl/binaries/content/assets/science/cml/essays/retraction-request-pathways-to-lower-emissions.pdf.

137 *E.g.*, Gordon, *supra* note 2 ("One day, if governments really do come for your burgers, they will do it by expanding the policies for phasing out polluting [animals] that we are already familiar with today.").

no country is limiting GHG emissions from animal agriculture through caps or other such mechanisms.[138] This is not surprising, as it is only relatively recently that such limits are being imposed by some countries on emissions from the largest source of GHG emissions: fossil fuels.[139] While there is an increasing focus around the world on limiting methane emissions—exemplified by the contrasting approaches in the Global Methane Pledge discussed above[140]—the early mandatory methane regulations apply to the energy sector and not to animal agriculture.[141] This is despite the fact that, as discussed above, animal agriculture is one of the most significant sources of anthropogenic methane.[142] Even *disclosure* of supply chain GHG emissions from animal agriculture is, for the most part, not required or provided at present.[143]

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138 *See supra* notes 46–52 and accompanying text.

139 *E.g.*, Rosie Frost, *The End of Fossil Fuels: Which Countries Have Banned Exploration and Extraction?*, EURONEWS (Aug. 12, 2021), https://www.euronews.com/green/2021/08/12/the-end-of-fossil-fuels-which-countries-have-banned-exploration-and-extraction; Editorial, *The EPA Sends a Powerful Signal on Ending Fossil Fuels*, 618 NATURE 433 (2023), https://www.nature.com/articles/d41586-023-01825-0 (discussing proposed U.S. Environmental Protection Agency rule that would force fossil-fuel power plants to reduce their emissions).

140 *See supra* notes 82–83 and accompanying text.

141 Regulation 2024/1787 of the European Parliament and of the Council of 13 June 2024 on the Reduction of Methane Emissions in the Energy Sector and Amending Regulation 2019/942, 2024 O.J. (L) at 13–14; Press Release, U.S. Env't Prot. Agency, Biden-Harris Administration Finalizes Standards to Slash Methane Pollution, Combat Climate Change, Protect Health, and Bolster American Innovation (Dec. 2, 2023), https://www.epa.gov/newsreleases/biden-harris-administration-finalizes-standards-slash-methane-pollution-combat-climate (announcing new rule that will limit methane emissions from oil and gas).

142 *See supra* notes 41–45 and accompanying text.

143 Georgina Gustin & Phil McKenna, *Reducing Methane from Livestock Is Critical for Stabilizing the Climate, but Congress Continues to Block Farms from Reporting Emissions Anyway*, INSIDE CLIMATE NEWS (Dec. 22, 2023) ("We do have emissions estimating methodologies, which you can use if you know the number of animals and which manure management strategy is being used. But we don't even know how many animals are on these farms." (quoting a senior manager at environmental group Friends of the Earth)). At COP28, promises by six major dairy multinationals to disclose their methane emissions and develop methane action plans by 2024 were notable as far ahead of the industry norm. Leah Douglas, *COP28 Summit: Global Dairy Companies Join Alliance to Cut Methane*, REUTERS (Dec. 5, 2023), https://www.reuters.com/sustainability/climate-energy/global-dairy-companies-announce-alliance-cut-methane-cop28-2023-12-05. This will change, however, as new reporting requirements passed in the EU, California, and elsewhere begin to take effect and impose disclosure requirements (including Scope 3 supply chain emissions) on large animal agriculture companies and their business partners. Amanda Carter, *Corporate Climate Disclosure Has Passed a Tipping Point. Companies Need to Catch Up*, WORLD RES. INST. (May 6, 2024), https://www.wri.org/insights/tipping-point-for-corporate-climate-disclosure.

A. Public Relations and Information: Advertising Bans, Climate Labeling, and Confronting Industry Deception

One province and three cities in the Netherlands—first Haarlem in 2022, followed by the cities of Bloemendaal and Utrect and the province of Noord-Holland in 2023—are the first jurisdictions in the world to have banned meat and dairy advertising for climate reasons. The bans will apply to advertising spaces owned by the municiplaties, such as bus stops and billboards, and will take time to come into force (either because they have phase-in dates or will honor current contracts).[144] None of the bans are limited to meat and dairy; they also include other damaging industries and products such as fossil fuels, combustion engines, airline travel, alcohol, and gambling.[145]

A statement from the city of Bloemendaal explained that meat and dairy are included in the ban as part of necessary actions to reduce GHG emissions and deforestation.[146] When asked for the reasoning behind the ban, the leader of the Party for the Animals who had proposed it explained: "The main reason is that meat production leads to climate change. . . . Another reason is animal welfare."[147] A professor of sustainability from the University of Amsterdam observed that, while the bans may not be expected to directly change behavior, they have norm-setting power and can "stimulate the social debate."[148] As a case in point, he noted that the bans have been discussed well outside of the municipalities, indeed all over the world.[149]

In addition to such advertising limits, governments can set affirmative requirements for climate labeling on foods and also help police misleading claims. For example, in its Farm to Fork Strategy, the European Commission called for review of voluntary green claims and to creating a sustainability labelling framework to include climate impacts.[150] Similarly, in its Roadmap, the FAO recommends

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144 *Dutch Municipalities to Ban Meat and Dairy Ads in Public Spaces*, VEGCONOMIST (Nov. 6, 2023) [hereinafter *Dutch Municipalities to Ban Meat Ads*], https://vegconomist.com/politics-law/dutch-municipalities-ban-meat-dairy-ads-public-spaces; *Noord-Holland to Ban Ads for Meat and Fossil Fuels from Bus Shelters*, DUTCH NEWS (Jan. 5, 2023), https://www.dutchnews.nl/2023/01/noord-holland-to-ban-ads-for-meat-and-fossil-fuels-from-bus-shelters; *More Municipalities Banning Meat, Air Travel Ads in Bus Shelters*, NL TIMES (Nov. 16, 2023) [hereinafter *More Municipalities Banning Meat*], https://nltimes.nl/2023/11/16/municipalities-banning-meat-air-travel-ads-bus-shelters (explaining that most municipalities' bans will "take effect when existing contracts expire").

145 *Dutch Municipalities to Ban Meat Ads*, *supra* note 144; *More Municipalities Banning Meat, supra* note 144.

146 *Dutch Municipalities to Ban Meat Ads*, *supra* note 144.

147 *More Municipalities Banning Meat, supra* note 144 (quoting Maarten van Heuven).

148 *Id.*

149 *Id.*; *see also* Samantha Dixon, *No More Burger Ads: These Dutch Cities Are Going Vegetarian*, DUTCHREVIEW (Nov. 17, 2023), (explaining that whether or not the bans will reduce meat consumption is beside the point: "This is a way to convey a message. As a municipality, you make a statement with this." (quoting Sjoukje Goldman, a researcher in sustainable marketing at the Amsterdam University of Applied Sciences)).

150 FARM TO FORK STRATEGY, *supra* note 75, at 14.

improvements to food labeling to inform consumers of the environmental and social impacts of products.[151]

Governments are also starting to bring litigation to enforce consumer protection laws against animal agriculture companies that mislead the public about their climate impacts. In Sweden, the consumer protection agency successfully sued Arla Foods, a major dairy producer, obtaining an injunction preventing the company from continuing to pronounce that its dairy products have a "net-zero climate footprint."[152] Similarly, in a landmark U.S. lawsuit against the meat giant JBS, the New York State Attorney General alleges that JBS's "net zero by 2040" commitment is not only misleading to the public, but perhaps even impossible at JBS's current levels of production.[153]

B. Positive Supports: Shifting Subsidies, Food System Transition Plans, Dietary Guidelines, and Procurement

Most fundamentally, governments can shift subsidies and supports from animal agriculture to non-animal foods.[154] The industry is heavily subsidized around the world, with nearly a third of global agricultural support measures going to meat, milk, and other dairy production.[155] As discussed above, the World Bank has recently called for a shift of subsidies from high-emitting animal foods to alternatives,[156] and reformers decried the failure of the EU's Farm to Fork Strategy to end government subsidization of meat production and consumption.[157] At an EU meeting in late 2023, the Netherlands Minister of Agriculture, Nature, and Food Quality argued that, in line with its sustainability commitments, the European Union should stop providing subsidies for meat production.[158]

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151 FAO ROADMAP, *supra* note 113, at 20.

152 Andy Coyne, *Swedish Court Bans Arla's Net-Zero Advertising Claim*, JUST FOOD (Feb. 6, 2023), https://www.just-food.com/news/swedish-court-bans-arlas-net-zero-advertising.

153 Press Release, Letitia James, N.Y. State Att'y Gen., Attorney General James Sues World's Largest Beef Producer for Misrepresenting Environmental Impacts of Their Products (Feb. 28, 2024), https://ag.ny.gov/press-release/2024/attorney-general-james-sues-worlds-largest-beef-producer-misrepresenting.

154 *E.g.*, Vallone & Lambin, *supra* note 33, at 1221 ("[T]he lack of support to alternative technologies at a level sufficient to allow them to compete on the food market against a well-supported incumbent system [is] symptomatic of a sociotechnical system still resisting fundamental systemic changes.").

155 *See* Marco Springmann & Fabian Freund, *Options for Reforming Agricultural Subsidies from Health, Climate, and Economic Perspectives*, NATURE COMMC'NS, Jan. 10, 2022, No. 82, at 2 (2022) (analyzed by final use, 22% of agricultural support measures in 2017 were used for meat products and 10% for milk and dairy products).

156 SUTTON ET AL., *supra* note 28, at 13.

157 *See supra* notes 79–80 and accompanying text.

158 Jan Braakman, *Adema: Geen EU-Geld Naar Promotie Vlees*, BOERDIREJ (Nov. 2, 2023), https://www.boerderij.nl/adema-geen-eu-geld-naar-promotie-vlees; Hugo Struna, *Eleven EU Countries Call for More 'Flexibility' on CAP's Fallow Land Rules*, EURACTIV (Nov. 21, 2023), https://www.euractiv.com/section/agriculture-food/news/eleven-eu-

Breaking new ground, several countries have announced food system transition plans of varying ambition levels that seek to promote plant-based eating through a collection of policy approaches. For example, Taiwan has taken important steps in a 2023 climate law calling for government promotion of low-carbon diets, including plant-based and local foods and reduction of food waste.[159] Subsequent legislative resolutions in Taiwan also recognized the climate impact of dietary choices and that environmental impacts should be considered when developing dietary guidelines.[160] A private-public partnership in the Netherlands is developing a policy aimed at doubling consumption of legumes by 2030.[161] In late 2023, South Korea announced a national plant-based food promotion plan, describing development in this area as a "new growth engine," including for export.[162]

For the first time, Germany has budgeted significant funds (€38 million in 2024) for the promotion of alternative protein sources.[163] A Green Party elected representative described this investment as a "paradigm shift" and "a clear commitment to the protein transition."[164] Activities to be funded include: amendment of the national food and agriculture agency's protein crop strategy to focus primarily on proteins for human nutrition rather than for animal feed; a new center and stakeholder forum around the protein transition; €20 million for an

countries-call-for-more-flexibility-on-caps-fallow-land-rules (providing more information on the agriculture ministers' meeting). A U.S. industry publication referred to the Minister's comment as "an opening shot in a potential war on meat." Joanne Cleaver, *Netherlands Ag Minister Suggests No Subsidies for Meat Production*, MEATINGPLACE (Nov. 10, 2023), http://www.meatingplace.com/Industry/News/Details/112257?allowguest=true.

159 Climate Change Response Act art. 8, FAWUBU FAGUI ZILIAOKU, *translated in Climate Change Response Act*, L. & REGULS. DATABASE OF THE REPUBLIC OF CHINA (TAIWAN) (Feb. 15, 2023), https://law.moj.gov.tw/ENG/LawClass/LawAll.aspx?pcode=O0020098; *see also* Marissa Sheldon, *Taiwan's Climate Bill Requires Promotion of Low-Carbon Diets*, HUNTER COLL. N.Y.C. FOOD POL'Y CTR. (Jan. 31, 2023), https://www.nycfoodpolicy.org/food-policy-snapshot-taiwan-climate-bill-promotes-low-carbon-diets.

160 *Taiwan Nutrition Law Gives Nod to Animals and Climate, Though Falls Short of Full Embrace*, ENV'T & ANIMAL SOC'Y OF TAIWAN (Dec. 20, 2023), https://www.east.org.tw/en/8704.

161 Flora Southey, *The 'Master Plan' to Double Legume Consumption in the Netherlands by 2030*, FOOD NAVIGATOR EUR. (Feb. 20, 2023), https://www.foodnavigator.com/Article/2023/02/20/The-master-plan-to-double-legume-consumption-in-the-Netherlands-by-2030; *Five Major Players Launch Masterplan for Protein Transition as Economic Engine in The Netherlands*, WAGENINGEN UNIV. & RSCH. (Feb. 20, 2023), https://www.wur.nl/en/newsarticle/five-major-players-launch-masterplan-for-protein-transition-as-economic-engine-in-the-netherlands.htm.

162 India Bourke, *Denmark: The Major Pork Producer Trying to Wean Itself Off Eating Meat*, BBC (Dec. 1, 2023) https://www.bbc.com/future/article/20231201-denmark-the-major-meat-producer-switching-to-a-plant-based-diet; Torrella, *supra* note 107; *Korea Introduces More Rules to Enhance Oversight of Alternative Protein Foods,* KELLER & HECKMAN (Dec. 12, 2023), https://www.khlaw.com/insights/korea-introduces-more-rules-enhance-oversight-alternative-protein-foods.

163 *Paradigm Shift in German Federal Budget 2024: €38M for 'Conversion of Animal Husbandry' and Protein Transition*, VEGCONOMIST (Nov. 17, 2023), https://vegconomist.com/politics-law/german-federal-budget-38m-protein-transition.

164 *Id.*

"opportunity program" to encourage exits from animal husbandry and into alternatives; and €10 million for projects to support promotion and production of alternatives.[165]

The most groundbreaking plan to date was enacted by Denmark in October 2023.[166] This is especially notable because Denmark has a powerful animal agriculture industry: it is the only European country with more pigs than people.[167] Denmark's Action Plan for Plant-Based Foods includes nearly $10 million for promotion of plant-based foods and $195 million to support the plant-based food transition,[168] and the Danish government investments will be supplemented by additional EU funding.[169] The Plan calls for significant reductions in consumption and production of meat and dairy. The Danish approach includes a broad variety of complimentary measures, including grants to support innovation and research, behavior change efforts, voluntary state-reviewed climate labels, training for chefs, changes to public procurement, promotion of export markets for alternatives, efforts to attract expertise and learn from other countries, improvement of the regulatory approval process for new products, and more.[170] In developing the Plan, advocacy groups like the Vegetarian Society worked with farmers' unions and the food lobby, focusing on consensus building and positive opportunities around new products and job creation.[171] A Danish MP and former environment minister described the collaboration this way: "Get the farmers on board, get the unions on board, but also be clear in your vision: say this is where we're going and do it incrementally."[172] Notably, an explicit goal of the Plan is to "serve as an example for the rest of the world."[173]

Early in 2023 in a separate effort, the Danish Parliament created a "Fund for Plant-Based Foods" with an investment of more than €90 million to support the production of more plant-based foods.[174] A

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165 *Id.*

166 *See generally* MINISTRY OF FOOD, AGRICULTURE AND FISHERIES OF DENMARK, DANISH ACTION PLAN FOR PLANT-BASED FOODS (2023) [hereinafter DANISH PLANT-BASED ACTION PLAN], https://en.fvm.dk/Media/638484294982868221/Danish-Action-Plan-for-Plant-based-Foods.pdf; Daniela De Lorenzo, *How Denmark Made the Plant-Based Action Plan Possible*, FORBES (Nov. 23, 2023, 8:26 AM), https://www.forbes.com/sites/danieladelorenzo/2023/11/23/how-denmark-made-the-plant-based-action-plan-possible.

167 Bourke, *supra* note 162.

168 De Lorenzo, *supra* note 166; Henry Mance, *Denmark Leads the Way in Incentivising Low-Meat Diets*, FIN. TIMES (Jan. 24, 2024), https://www.ft.com/content/3f4d58f4-2a3b-4aef-88a8-83784b36c835.

169 De Lorenzo, *supra* note 166.

170 DANISH PLANT-BASED ACTION PLAN, *supra* note 166, *passim*.

171 Mance, *supra* note 168; De Lorenzo, *supra* note 166; Bourke, *supra* note 162.

172 Bourke, *supra* note 162.

173 DANISH PLANT-BASED ACTION PLAN, *supra* note 166, at 5.

174 *Denmark Invests Over €90 Million in Fund for Development of Plant-Based Foods*, FOOD NATION, https://foodnationdenmark.com/news/denmark-invests-over-eur-90-million-in-fund-for-development-of-plant-based-foods (last visited Oct. 13, 2024).

number of other countries have also announced funding for alternative proteins, including China, India, Japan, and the United Kingdom.[175]

In a sign of potential future developments in France, in mid-2023 the French Court of Accounts—which counsels the government on spending—advised the French government to develop "a strategy to reduce cattle herds" in order to achieve methane reduction targets, which the Court found "necessarily call for a significant reduction in livestock."[176] The Court recommended new policies to transition from existing subsidies to supports for sustainable farming and retraining for farmers.[177]

Dietary guidelines are another lever that policymakers can pull to reduce GHG emissions. To date, while most dietary guidelines do not incorporate environmental sustainability, a growing number do.[178] In its recent Roadmap, the FAO recommended that dietary guidelines should include environmental considerations.[179] Many of the supportive policies described above were preceded or accompanied by changes to dietary guidelines. For example, two years before Denmark adopted its comprehensive Action Plan for Plant-Based Foods, updates to its dietary guidelines called for reduction of the recommended adult meat consumption in line with EAT-*Lancet* guidelines.[180]

In other examples, Canada revised its dietary guidelines in 2019 to recommend that Canadians "consume plant-based more often,"[181] and in 2021 the U.K. National Food Strategy, an independent review commissioned by the government, called for a 30% decrease in meat production by 2032.[182] The Nordic Nutrition Recommendations, released in 2023 by the Nordic Council of Ministers,[183] integrates environmental

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175 Björn Ólafsson, *8 Alternative Protein Market Predictions for 2024*, SENTIENT FOOD (Jan. 18, 2024), https://sentientmedia.org/alternative-protein-market-predictions-2024; Mance *supra* note 168.

176 *French Farmers Up in Arms over Call to Cut Cow Numbers for Sake of Climate*, RFI (May 25, 2023), https://www.rfi.fr/en/france/20230525-french-farmers-up-in-arms-over-call-to-cut-cow-numbers-for-sake-of-climate.

177 *Id.*

178 *See* Genevieve James-Martin et al., *Environmental Sustainability in National Food-Based Dietary Guidelines: A Global Review*, 6 LANCET PLANETARY HEALTH e977, e977, e979 (2022) (noting that 37 of 83 national guidelines surveyed mentioned sustainability); *see also Analysis: U.S. Lags Behind Other G20 Nations at Adding Sustainability into Dietary Guidelines*, CTR. FOR BIOLOGICAL DIVERSITY (Sept. 12, 2023), https://biologicaldiversity.org/w/news/press-releases/analysis-us-lags-behind-other-g20-nations-at-adding-sustainability-into-dietary-guidelines-2023-09-12.

179 *See supra* text accompanying note 115.

180 Mance, s*upra* note 168; *see* discussion of the Eat-*Lancet* Commission *supra* notes 69–71 and accompanying text.

181 HEALTH CANADA, CANADA'S DIETARY GUIDELINES FOR HEALTH PROFESSIONALS AND POLICY MAKERS 9 (2019), https://food-guide.canada.ca/sites/default/files/artifact-pdf/CDG-EN-2018.pdf.

182 HENRY DIMBLEBY ET AL., NATIONAL FOOD STRATEGY: THE PLAN 142 (2021), https://assets.publishing.service.gov.uk/media/61684fe3e90e071979dfec4a/national-food-strategy-the-plan.pdf.

183 The Nordic Council of Ministers includes representatives from Denmark, Finland, Iceland, Norway, Sweden, Greenland, the Faroe Islands (an autonomous region of Den-

considerations for the first time. The Nordic Council described the Recommendations as "our bravest step yet" and "well aligned with our global commitments."[184] The Recommendations call for "a predominantly plant-based diet . . . , moderate intake of low fat dairy products, limited intake of red meat and poultry, and minimal intake of processed meat . . . ."[185] While the Recommendations are not binding and implementation is up to each individual country, they are usually widely followed and used for schools, hospitals, and elderly care.[186]

Another area of supportive policy is procurement, i.e., harnessing the government's purchasing power for dietary changes that are beneficial to the environment and to people's health. In a first step in its Farm to Fork Strategy, the European Commission committed to "determin[ing] the best way of setting minimum mandatory criteria for sustainable food procurement."[187] As a national-level example, a French climate law passed in 2021 requires school cafeterias to provide vegetarian meals once a week and public catering to offer vegetarian options.[188]

Many local governments around the world are using their authority and procurement power to move away from high-emitting animal-based foods.[189] For example, sixteen cities have signed onto the Good Food Cities Accelerator, committing to increase healthy plant-based food consumption and align food procurement with the EAT-*Lancet* "Planetary Health Diet" (about half the plate occupied by vegetables and fruit) by 2030.[190] The Good Food Purchasing Program in the United States, in which large municipalities like New York City participate, provides a set of tools and support to empower public institutions to

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mark), and Åland (an autonomous region of Finland). *About the Nordic Council of Ministers*, NORDIC CO-OPERATION, https://www.norden.org/en/information/about-nordic-council-ministers (last visited Oct. 14, 2024).

184 NORDIC COUNCIL OF MINISTERS, NORDIC NUTRITION RECOMMENDATIONS 2023: INTEGRATING ENVIRONMENTAL ASPECTS 7 (2023), https://norden.diva-portal.org/smash/get/diva2:1769986/FULLTEXT06.pdf.

185 *Id.* at 9.

186 Lisbeth Kirk, *Nordic Nutrition Guidelines Advise to Eat Less Meat—But Sweden Revolts*, EUOBSERVER (June 20, 2023), https://euobserver.com/nordics/157165. *But see id.* (noting that, even before the plant-forward Nordic Nutrition Recommendations were published, Sweden's Minister of Rural Affairs came out publicly against reduction of meat consumption).

187 FARM TO FORK STRATEGY, *supra* note 75, at 14.

188 Fiona Harvey, *Outrage and Delight as France Ditches Reliance on Meat in Climate Bill*, GUARDIAN (May 29, 2021), https://www.theguardian.com/world/2021/may/29/france-outrage-delight-meat-ditch-reliance-climate.

189 INT'L PANEL OF EXPERTS ON SUSTAINABLE FOOD SYS., FROM PLATE TO PLANET: HOW LOCAL GOVERNMENTS ARE DRIVING ACTION ON CLIMATE CHANGE THROUGH FOOD 18–19, 22 (2023), https://www.ipes-food.org/_img/upload/files/PlatetoPlanetEN.pdf (noting that national food policies are missing the opportunity to move away from GHG-intensive animal-sourced foods toward plant-based foods, and describing successful local efforts).

190 *Good Food Cities Accelerator*, C40 CITIES, https://www.c40.org/accelerators/good-food-cities (last visited Oct. 20, 2024); *The Planetary Health Diet*, EAT, https://eatforum.org/eat-lancet-commission/the-planetary-health-diet-and-you (last visited Mar. 9, 2024).

purchase food aligned with "five core values: local economies, health, valued workforce, animal welfare, and environmental sustainability."[191] New York City has also taken significant measures to decrease meat consumption, serving plant-based meals as the default option in public hospitals and twice weekly in public schools.[192] The City of Amsterdam adopted a motion put forward by the Party for the Animals aiming to make Amsterdam a "Plant-Based Capital," including plans to offer plant-based options and Vegan Fridays in public facilities and to move toward a set animal-plant protein ratio for public catering by 2030.[193] In a proposed comprehensive approach to food system change, thirty municipalities around the world, including Amsterdam, Edinburgh, and Los Angeles,[194] have called for the negotiation of a "Plant-Based Treaty" by which signatories would commit to: ending land use change for animal agriculture; promoting plant-based foods and transitioning away from animal-based foods; and restoring key ecosystems and reforesting.[195]

A final important type of supportive policy is regulatory approval for animal product alternatives in the context of cultivated meat. Cultivated or cultured meat is animal meat produced by cultivating cells.[196] Cultivated meat has already received regulatory approval for commercial sale in Singapore and the United States, and other countries may soon follow.[197]

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191 *Our Work*, CTR. FOR GOOD FOOD PURCHASING, https://goodfoodpurchasing.org (last visited Oct. 22, 2024); Errol Schweizer, *How New York City Is Revolutionizing Good Food Policy*, FORBES (Mar. 23, 2021, 9:45 AM), https://www.forbes.com/sites/errolschweizer/2021/03/23/how-new-york-city-is-revolutionizing-good-food-policy.

192 Mance, *supra* note 168.

193 *Amsterdam Becomes the First EU Capital City to Endorse the Call for a Plant Based Treaty in Response to the Climate Emergency*, PLANT BASED TREATY (Feb. 1, 2024), https://plantbasedtreaty.org/amsterdam-endorses-pbt.

194 *Plant Based Treaty Endorsers: Cities, Towns, and Regions*, PLANT BASED TREATY, https://plantbasedtreaty.org/cities (last visited Oct. 20, 2024).

195 *The Treaty*, PLANT BASED TREATY, https://plantbasedtreaty.org/the-pbt (last visited Oct. 14, 2024).

196 Elliot Swartz & Claire Bomkamp, *The Science of Cultivated Meat*, GOOD FOOD INST., https://gfi.org/science/the-science-of-cultivated-meat (last visited Oct. 14, 2024).

197 Ólafsson, *supra* note 175.

C. Taxes[198]

Taxes on meat production or consumption have long been contemplated as a possible approach to reducing associated GHG emissions.[199] While a tax of this type could generally be expected to impact low-income households disproportionately because they spend a greater proportion of their income on food, pairing taxes with subsidies can reduce regressivity and encourage shifts to more sustainable diets.[200]

The most prominent current example is the Danish Parliament's approval in late 2024 of the world's first emissions tax on animal agriculture, to take effect in 2030.[201] The tax will apply to emissions from cattle, sheep, and pigs.[202] As with the consensus-building approach that led to the Danish Action Plan for Plant-Based Foods,[203] the proposal was discussed and agreed upon amongst a group including policymakers, labor unions, industry, and environmental groups.[204]

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198 Another possible approach to limiting emissions from GHG-intensive products is rationing, or limiting each person's consumption below a specified cap. A recent survey of respondents from five countries on five continents found that, while rationing was about as accepted as taxation when applied to fossil fuels, taxation was consistently more acceptable than rationing when applied to meat. Oskar Lindgren et al., *Public Acceptability of Climate-Motivated Rationing*, HUMANS. & SOC. SCIS. COMMC'NS., Sept. 26, 2024, No. 1252, at 3. Of the countries surveyed, the United States had the lowest percentage (22%) who responded that meat rationing for climate protection purposes would be acceptable to them. *Id.* at 4. This research has not identified serious consideration of meat rationing anywhere in the world. *Id.* at 1.

199 *E.g.*, Marya Torrez, *Accounting for Taste: Trade Law Implications of Taxing Meat to Fight Climate Change*, 27 GEO. ENV'T L. REV. 61, 62 (2014); *see also* Zia Mehrabi et al., *Livestock Policy for Sustainable Development*, 1 NATURE FOOD 160, 164 (2020) (recommending "[r]aising taxes on food items for populations at risk of overconsumption" and suggesting that "[t]axes may focus on worst products or incorporate carbon and biodiversity costs, although care must be taken to not to [sic] reduce food access for the poor" (internal quotations and citations omitted)).

200 Dariush Mozaffarian et al., *The Real Cost of Food: Can Taxes and Subsidies Improve Public Health?*, 312 JAMA 889, 889 (2014). Increasing prices or imposing taxes may not be effective without supportive interventions. 2018 IPCC REPORT, *supra* note 27, at 383 ("[F]or dietary change, combining supply-side measures with value-driven communication and economic instruments may help make a lasting transition, while an economic instrument, such as enhanced prices or taxation, on its own may not be as robust.").

201 Isabelle Yr Carlsson, *Denmark Will Be First to Impose CO2 Tax on Farms, Government Says*, REUTERS (June 25, 2024, 3:30 AM), https://www.reuters.com/sustainability/denmark-will-be-first-impose-co2-tax-farms-government-says-2024-06-25; Somini Sengupta, *Taxing Farm Animals' Farts and Burps? Denmark Gives It a Try*, N.Y. TIMES (Nov. 26, 2024), https://www.nytimes.com/2024/11/26/climate/denmark-methane-farm-animal-tax.html.

202 Jan M. Olsen, *Gassy Cows and Pigs Will Face a Carbon Tax in Denmark, a World First*, ASSOCIATED PRESS, https://apnews.com/article/denmark-cow-tax-greenhouse-gases-9a570518639e0a1990806fd1a05ac11a (June 26, 2024, 8:19 AM).

203 The Danish Action Plan included a commitment to eventually institute an agricultural emissions tax. *See infra* note 327 and accompanying text.

204 Carlsson, *supra* note 201.

A tax on cow emissions proposed in New Zealand in 2022 by the center-left Labour Party was scrapped after the center-right National Party gained control in the October 2023 election.[205] The proposal had resulted in farmer protests and an outcry from the meat and dairy industries,[206] which have embraced the new government's plan.[207]

In 2022, the German government announced plans to spend €1 billion on investing in improving farmed animal housing and husbandry systems, for "animal welfare and climate protection."[208] One option being discussed to fund the proposal and other reforms to the animal agriculture sector is a tax on meat modeled on the existing coffee tax.[209]

D. Buyouts

Animal buyout programs, i.e., "schemes that compensate for the loss or decline in the value of production assets on livestock farms on the condition that production will be ceased permanently,"[210] are the most direct policy mechanism available to shrink the herd. While not common, animal buyouts have been used historically by governments for various reasons.[211] Past examples include the voluntary 1986 "Whole-Herd Buyout" program in the United States aimed at reducing the milk supply,[212] voluntary buyouts in the Netherlands and Flanders (the autonomous northern region of Belgium where Brussels in located)

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[205] Rachel Pannett, *How New Zealand Plans to Tackle Climate Change: Taxing Cow Burps*, WASH. POST (Feb. 1, 2023), https://www.washingtonpost.com/climate-solutions/interactive/2023/new-zealand-cows-burps-methane-tax; Renju Jose & Lucy Craymer, *New Zealand's National Party Clinches Deal to Form Government*, REUTERS (Nov. 23, 2023), https://www.reuters.com/world/asia-pacific/new-zealands-national-party-reaches-deal-form-government-2023-11-23; *New Zealand Scraps 'Burp Tax' on Livestock After Backlash from Farmers*, AL JAZEERA (June 11, 2024), https://www.aljazeera.com/economy/2024/6/11/new-zealand-scraps-burp-tax-on-livestock-after-backlash-from-farmers. A previous proposed tax in New Zealand on methane emissions, put forward in 2003, was dropped after industry opposition. BLINDSPOT, *supra* note 83, at 27.

[206] Pannett, *supra* note 205; *New Zealand Scraps 'Burp Tax' on Livestock*, *supra* note 205.

[207] Tracy Withers, *New Zealand Farmers Welcome Opposition's Agriculture Emissions Policy*, BLOOMBERG (June 11, 2023), https://www.bloomberg.com/news/articles/2023-06-12/new-zealand-farmers-welcome-opposition-s-agriculture-emissions-policy.

[208] Boezeman et al., *supra* note 80, at 8.

[209] Olivia Logan, *German Minister Announces Plan for Excise Tax on Meat*, I AM EXPAT (Feb. 7, 2024), https://www.iamexpat.de/lifestyle/lifestyle-news/german-minister-announces-plan-excise-tax-meat; Bundesministerium für Ernährung und Landwirtschaft [BMEL], Konzept zur Einführung einer Verbrauchsteuer auf bestimmte tierische Produkte [Concept for an Excise Duty on Certain Animal Products] (translation on file with author).

[210] Boezeman et al., *supra* note 80, at 4.

[211] *Id.* at 5–6.

[212] *Id.* at 6; Robert A. Hamilton, *U.S. Offers Dairymen a Buyout*, N.Y. TIMES (Mar. 23, 1986), https://www.nytimes.com/1986/03/23/nyregion/us-offers-dairymen-a-buyout.html; Mich. Farm Bureau, *Results of Past U.S. Dairy Supply Management—Will History Repeat Itself?*, MICH. FARM NEWS (May 13, 2019), https://www.michiganfarmnews.com/results-of-past-us-dairy-supply-management-will-history-repeat-itself.

starting around 2000 to reduce manure in order to comply with EU rules on nitrogen pollution,[213] and mandatory buyouts of mink in the Netherlands that were initially implemented in 2013 based on animal welfare concerns and then accelerated for public health reasons after coronavirus infections spread through mink farms.[214]

In order to achieve the intended population reductions and benefits, buyout programs must be carefully structured. For example, one expert advises that voluntary dairy cow buyout policies must ensure: additionality—in other words, that the animals who are removed are actually productive dairy cows (and not already at the end of milk production when they would be slaughtered anyway); that removed cows are not replaced, via some assurance of long-term stock diminishment; and that the program is attractive to farmers (a challenge when dairy production is profitable).[215]

In a leading example, the Dutch government appears to have been the first in the world to utilize an animal buyout program with an explicit purpose of reducing GHG emissions.[216] A 2019 pig buyout program that was initially requested by farmers to address odor problems was later granted additional government funding as a way of reaching climate and nitrogen pollution goals.[217] In addition, the 2019 Dutch Climate Agreement—the national policy to achieve emissions reductions in-line with the Paris Agreement—included plans for a voluntary buyout of dairy farmers in peat meadow areas, which are notable for their emissions reduction potential and biodiversity.[218] Provinces submitted initial buyout plans in late 2023.[219]

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213 Boezeman et al., *supra* note 80, at 6.

214 *Id.* at 4, 6; *Dutch to Permanently Ban Mink Farming from April 2021*, NL TIMES (Aug. 27, 2020), https://nltimes.nl/2020/08/27/dutch-permanently-ban-mink-farming-april-2021.

215 Jan Dutkiewicz, *Ireland Isn't Culling Cows for Climate. But Maybe It Should Be?*, BULL. OF THE ATOMIC SCIENTISTS (Oct. 25, 2023) [hereinafter Dutkiewicz, *Ireland Isn't Culling Cows*], https://thebulletin.org/2023/10/ireland-isnt-culling-cows-for-climate-but-maybe-they-should-be; *see also* Bruce L. Dixon et al., *Supply Impact of the Milk Diversion and Dairy Termination Programs*, AM. J. AGRIC. ECON. 633, 639 (1991) (evaluating buy-out programs and noting effectiveness limitations, including that some producers reentered the market immediately after the required cessation period and that strong product demand may have encouraged nonparticipating producers to increase production).

216 Boezeman et al., *supra* note 80, at 6, 9.

217 *Id.* at 7, 10; *European Commission: 'Dutch Plans to Buy Out Pig Farmers Are in Accordance with the EU Rules on State Aid*,' LOYENS & LOEFF (Oct. 23, 2019), https://www.loyensloeff.com/insights/news—events/news/european-commission-dutch-plans-to-buy-out-pig-farmers-are-in-accordance-with-the-eu-rules-on-state-aid.

218 Boezeman et al., *supra* note 80, at 7, 10; GOV'T OF THE NETHERLANDS, CLIMATE AGREEMENT 143–44 (2019), https://www.government.nl/documents/reports/2019/06/28/climate-agreement.

219 *Kamerbrief voortgang provinciale gebiedsprogramma's en eerste maatregelpakketten*, RIJKSOVERHEID (Oct. 24, 2023), https://www.rijksoverheid.nl/ministeries/ministerie-van-landbouw-natuur-en-voedselkwaliteit/documenten/kamerstukken/2023/10/24/voortgang-provinciale-gebiedsprogramma-s-en-eerste-maatregelpakketten; Letter from Christianne van der Wal-Zeggelink, Minister for Nature & Nitrogen, to the President of the House of

The Netherlands is perhaps a predictable place for the first buyouts related to climate goals, given that it has high farm animal densities, a serious nitrogen pollution problem with more than half of all nitrogen pollution coming from manure,[220] and a history of utilizing animal buyout programs for other purposes (e.g., odor control and reducing nitrogen pollution).[221] Nitrogen pollution can harm biodiversity and also contributes to climate change.[222] Measures that reduce nitrogen pollution also reduce emissions of the GHG nitrous oxide, the majority of which is formed when microbes process excess nitrogen from farmed animal manure and urine and from synthetic nitrogen fertilizer.[223]

Acute pressure on the Dutch government to reduce nitrogen pollution arose from a lawsuit filed in 2018 by a Dutch NGO against the national government.[224] The lawsuit alleged that high levels of nitrogen pollution in certain protected areas violated the EU Habitats Directive.[225] Eventually, the Court of Justice of the European Union agreed.[226] In response, the government announced plans to reduce the herd by as much as a third,[227] eventually identifying significant funds (€24.3 billion) for the transition, including to buy out 3,000 "peak emitter" farms at up to 120% of their value.[228] As of late 2024, 1,474 farmers had submitted applications for one or both of the buyout programs, with nearly a third committing to a buyout.[229] As described below in Part V.B, this Dutch "stikstofcrisis" (nitrogen crisis) resulted in widespread farmer protest and a significant political shakeup in the Netherlands. Indeed, buyout plans—while amongst the most direct

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Representatives of the States-General, at 1–2 (Jan. 23, 2024), https://open.overheid.nl/documenten/c9e74d60-5396-45bf-83f2-9132df5ae151/file.

220 Erik Stokstad, *Nitrogen Crisis from Jam-Packed Livestock Operations Has 'Paralyzed' Dutch Economy*, SCIENCE (Dec. 4, 2019), https://www.science.org/content/article/nitrogen-crisis-jam-packed-livestock-operations-has-paralyzed-dutch-economy.

221 Boezeman et al., *supra* note 80, at 6–7.

222 *Facts about Nitrogen Pollution*, U.N. ENV'T PROGRAMME, https://www.unep.org/facts-about-nitrogen-pollution (last visited Mar. 7, 2024).

223 *See* Klaus Butterbach-Bahl et al., *Nitrous Oxide Emissions from Soils: How Well Do We Understand the Processes and Their Controls?*, PHIL. TRANSACTIONS ROYAL SOC'Y LONDON, SERIES B, BIOLOGICAL SCIS., July 2013, No. 20130126, at 1–2 (explaining that dominant sources of both anthropogenic and natural nitrous oxide are "closely related to microbial production processes in soils, sediments and water bodies"); Alfi Syakila & Carolien Kroeze, *The Global Nitrous Oxide Budget Revisited*, 1 GREENHOUSE GAS MEASUREMENT & MGMT. 17–18 (2011) (quantifying global nitrous oxide sources).

224 Case C-293/17, Coöperatie Mobilisation for the Environment UA v. College van Gedeputeerde Staten van Limburg, ECLI:EU:C:2018:882 (Nov. 7, 2018).

225 *Id.* ¶¶ 50, 52; Kasja Pira, *The Dutch Nitrogen Crisis*, ACID NEWS, Dec. 2019, at 3.

226 *Coöperatie Mobilisation for the Environment UA*, ECLI:EU:C:2018:882, ¶¶ 69, 120.

227 Andy Bounds, *Dutch Farmers in Uproar over Plans to Curb Animal Numbers to Cut Nitrogen Emissions*, FIN. TIMES (Aug. 2, 2022), https://www.ft.com/content/90e38fb5-e942-4afd-994d-048dc40579a2.

228 Ashoka Mukpo, *In the Clash over Dutch Farming, Europe's Future Arrives*, MONGABAY (Sept. 8, 2023) [hereinafter *Clash over Dutch Farming*], https://news.mongabay.com/2023/09/in-the-clash-over-dutch-farming-europes-future-arrives.

229 *Lbv en Lbv-plus actueel*, RIJKSDIENST VOOR ONDERNEMEND NEDERLAND, https://www.rvo.nl/onderwerpen/lbv-plus-actueel (Nov. 26, 2024).

approaches to reducing GHG emissions from animal agriculture—can face significant opposition and political blowback if not structured and rolled out carefully.

Somewhat similar events played out in Flanders. In 2021, a climate policy committee advised the government that it should reduce animal numbers and encourage dietary shifts as part of meeting climate targets.[230] While the proposal was not taken up, after a ruling by the highest Flemish administrative court in 2021 ordering the government to reduce nitrogen pollution,[231] animal agriculture was again at the center of policy discussions. The responsive plan eventually approved by the government included both voluntary and mandatory animal buyouts, depending on their proximity to and impact on certain protected areas.[232] Uptake on the voluntary offers was low as of early 2024, reportedly with only seven pig farmers having accepted the buyout offer out of the 982 contacted by the government.[233] An industry publication explains: "The low interest in the scheme can be attributed to the economic trend of high pig prices, as well as criticism of the buyout conditions, such as limited benefits for older stables and restrictions on expanding other livestock activities on the farm."[234]

E. Tech Fixes and Climate Efficiency Approaches

> At this point it is naïve to expect that technological improvements alone will slow the impacts of growth and reduce the burden on the biosphere. And yet many still exhibit this naiveté.
>
> ~Kim Stanley Robinson,
> *The Ministry for the Future*[235]

The policy approaches discussed above have the potential to reduce the number of farmed animals or "shrink the herd," with animal food products replaced by more sustainable alternatives. There is another category of interventions that could be described as "climate efficiency" approaches—including feed additives, genetic engineering, and biogas digesters[236]—which aim to reduce emissions from animal agriculture by making each animal (or group of animals) more efficient in climate terms. An example of a climate efficiency policy is Canada's proposal

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230 Boezeman et al., *supra* note 80, at 7.

231 Karel Veuchelen & Els Empereur, *Nitrogen in Flanders: Will the Dust Finally Settle?*, PWC LEGAL (Mar. 27, 2023), https://www.pwclegal.be/en/news/nitrogen-in-flanders---will-the-dust-finally-settle-.html.

232 Boezeman et al., *supra* note 80, at 7–8.

233 *Belgium: Enthusiasm for the Buyout Scheme for Pig Farms Is Not Yet Great*, TRIDGE (Jan. 18, 2024), https://www.tridge.com/news/enthusiasm-for-buyout-scheme-for-flemish-pig-farms.

234 *Id.*

235 ROBINSON, *supra* note 1, at 165.

236 *See* discussion of biogas digesters *infra* notes 272–278 and accompanying text.

that would allow farmers to generate offset credits if they reduce enteric emissions from their cattle through strategies such as changing feed.[237]

Because such approaches do not challenge the fundamental structure or scale of the industry, they have been referred to as "industry-led" and "industry-friendly" and typically receive greater buy-in from industry actors.[238] For example, the authors of a recent survey of animal agriculture and climate policy in four countries in Western Europe note: "In general terms, in all countries, we observe the reproduction of a 'technology versus volume' discourse. Farmers' organisations and their supporting parties stress the importance of eco-efficiency and technical innovation to resolve environmental concerns. Environmental NGOs and green parties advocate reducing livestock production and changing human diets."[239]

This Article does not take the position that climate efficiency approaches are harmful or without merit.[240] The urgency of the climate crisis—which will affect all life on this planet, to varying degrees—demands that we act with urgency on all potentially helpful fronts.[241] But, for the reasons that follow, efficiency approaches by themselves will

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[237] ENV'T & CLIMATE CHANGE CANADA, DRAFT FEDERAL OFFSET PROTOCOL: REDUCING ENTERIC METHANE EMISSIONS FROM BEEF CATTLE 1 (2023), https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/ghg-offset/REME%20protocol%20-%20EN.pdf.

[238] *E.g.*, Morris & Jacquet, *supra* note 62, at 1 (referring to "industry-led climate 'solutions' that maintain production"); Torrella, *supra* note 107 (describing "industry-friendly changes like tinkering with how livestock are fed and farmed"); Dutkiewicz, *Ireland Isn't Culling Cows*, *supra* note 215 ("Emissions restrictions policies quite simply interfere with a profitable and entrenched business model, which explains why farming groups, where they have participated in discussion about policy proposals, have favored soft interventions like developing methane-inhibiting feed additives over harder interventions like voluntary culls."). One expert draws this analogy: "Much as the coal industry starting hawking 'clean coal' in 2008 to avoid policies promoting a phaseout, the meat industry and its defenders are now arguing for clean cows." Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, *supra* note 102.

[239] Boezeman et al., *supra* note 80, at 9; *see also Clash over Dutch Farming*, *supra* note 228 ("[T]echnologies [that reduce emissions] could potentially allow [Dutch] farmers to dodge the tougher approach that some policymakers have in mind: big cuts to the number of livestock in the Netherlands.").

[240] *E.g.*, 2018 IPCC REPORT, *supra* note 27, at 146 ("[E]ven within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability." (internal citations omitted)); EU ASSESSMENT REPORT 2024, *supra* note 50, at 157 ("[Methane] emissions can be reduced by measures to reduce emissions from enteric fermentation (the digestion process of ruminant livestock such as cattle) and by improved manure management.").

[241] *See* Torrella, *supra* note 107 ("Numerous environmental scientists . . . have called on wealthy countries to cut back on meat and eat more plant-based meals . . . . Down another path lies the more politically palatable, yet far less effective, approach of continuing to eat record amounts of meat in the West while deploying a host of technologies and farming practices, each of which can only marginally shave off livestock emissions. The world needs a mix of both approaches, but policy makers, out of political expediency and corporate capture, are barreling down the second path, a choice they'll likely come to regret as climate change intensifies.").

not be sufficient and should not be pursued at the exclusion of or to the detriment of other approaches.[242]

Indeed, some advocates refer to efficiency approaches to the climate problem of animal agriculture as "false solutions" for several reasons.[243] First, and perhaps most essentially, reducing the GHG emissions of animals in industrial systems does nothing to address the many other externalities of those systems,[244] which include harms to environmental justice communities,[245] zoonotic disease risks[246] and antimicrobial resistance,[247] other public health harms,[248] dangerous and exploitative

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[242] Fredrik Hedenus et al., *The Importance of Reduced Meat and Dairy Consumption for Meeting Stringent Climate Change Targets*, 124 CLIMATIC CHANGE 79, 89 (2014) ("[D]ietary changes are crucial for meeting the 2°C target with high probability."); Willett et al., *supra* note 69, at 472 ("Although food production practices have an important role, many studies highlight that a dietary change towards increased adoption of plant-based diets has high mitigation potential, which is probably needed to limit global warming to a less than 2°C increase.").

[243] *E.g.*, Letter from Ctr. for Biological Diversity et al. to Thomas J. Vilsack, *supra* note 8 ("[F]alse solutions such as feed additives . . . have minimal impact in reducing emissions and aren't scalable, and biogas . . . worsens the problem of pollution and greenhouse gas emissions. Improving agricultural production is only one piece of the puzzle, and ignoring dietary shifts in consumption creates an ineffective and weak climate response.").

[244] *E.g.*, GLOBAL METHANE ASSESSMENT, *supra* note 81, at 116 ("Achieving very low emissions per kilogram of protein may involve large-scale industrialized agriculture, which can have other social and environmental impacts beyond greenhouse gas emissions and hence such policies need to be considered with care."); Cleo Verkuijl et al., *Climate Change, Public Health, and Animal Welfare: Towards a One Health Approach to Reducing Animal Agriculture's Climate Footprint*, FRONTIERS ANIMAL SCI., May 15, 2024, No. 1281450, at 9–10 ("[C]ommon climate mitigation interventions targeting animal agriculture have implications for public health and animal welfare. . . . When seeking to reduce the climate impacts of animal farming, it is thus crucial to look beyond GHG emissions alone: a wider set of social goods merits serious attention."); LIVESTOCK'S LONG SHADOW, *supra* note 59, at 267 ("[T]he livestock sector is a major stressor on many ecosystems and on the planet as whole. Globally it is one of the largest sources of greenhouse gases and one of the leading causal factors in the loss of biodiversity, while in developed and emerging countries it is perhaps the leading source of water pollution.").

[245] *E.g.*, Melba Newsome, *Unchecked Growth of Industrial Animal Farms Spurs Long Fight for Environmental Justice in Eastern NC*, N.C. HEALTH NEWS (Oct. 20, 2021), https://www.northcarolinahealthnews.org/2021/10/20/environmental-justice-and-industrial-farming-in-eastern-nc.

[246] ANN LINDER ET AL., ANIMAL MARKETS & ZOONOTIC DISEASE IN THE UNITED STATES 82 (2023), https://animal.law.harvard.edu/wp-content/uploads/Animal-Markets-and-Zoonotic-Disease-in-the-United-States.pdf ("In [concentrated animal feeding operations (CAFOs)], hundreds of thousands or millions of animals can be held together in intense confinement with limited air flow, making these facilities ripe for pathogen transmission among animals as well as between animals and workers."); *see also* Hayek, *supra* note 97, at 3–4.

[247] Christy Manyi-Loh et al., *Antibiotic Use in Agriculture and Its Consequential Resistance in Environmental Sources: Potential Public Health Implications*, MOLECULES, April 2018, No. 795, at 3–4, 17.

[248] *E.g.*, Nina G.G. Domingo et al., *Air Quality–Related Health Damages of Food*, PNAS, May 10, 2021, No. e2013637118, at 1 ("80% of the 15,900 annual deaths that result from food-related fine particulate matter . . . pollution are attributable to animal-based foods."); Amanda D. Emert et al., *Atmospheric Transport of Particulate Matter and Particulate-*

labor conditions,[249] systemic animal cruelty,[250] biodiversity loss[251] and habitat destruction,[252] soil and water pollution,[253] intensive water use,[254] market consolidation and antitrust abuses,[255] and harms to rural communities.[256] On a related note, while some recommend a species

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Bound Agrochemicals from Beef Cattle Feedlots: Human Health Implications for Downwind Agricultural Communities, SCI. TOTAL ENV'T, October 2023, No. 164678, at 12.

[249] *E.g.*, Fred Gerr, *Meatpacking Plant Workers: A Case Study of a Precarious Workforce*, 18 J. OCCUPATIONAL & ENV'T HYGIENE 154, 157 (2021); Leah Douglas, *Big U.S. Chicken Company, Mountaire, Asks Contractors to Oppose Transparency Rule*, REUTERS (Aug. 5, 2022, 10:04 AM), https://www.reuters.com/world/us/big-us-chicken-company-mountaire-asks-contractors-oppose-transparency-rule-2022-08-05 ("Poultry farmers have said for years that they fear publicly airing grievances with the tournament [payment] system because of potential retaliation from companies . . . .").

[250] *E.g.*, Nicholas Kristof, *The Ugly Secrets Behind the Costco Chicken*, N.Y. TIMES (Feb. 6, 2021), https://www.nytimes.com/2021/02/06/opinion/sunday/costco-chicken-animal-welfare.html ("[F]uture generations will look back at our mistreatment of livestock and poultry with pain and bafflement."); Letter from Rep. Veronica Escobar et al., Members of Congress, to Thomas J. Vilsack, Sec'y of Agric. & Dr. José Emilio Esteban, Undersec'y for Food Safety, U.S. Food Safety & Inspection Servs. (Dec. 6, 2023), https://escobar.house.gov/uploadedfiles/final_letter_to_secretary_vilsack_and_under_secretary_esteban_.pdf ("[U]ndercover footage has revealed widespread and entirely unnecessary abuse and neglect of pigs—particularly nonambulatory pigs—at certain facilities. In slaughterhouses, workers have been known to try to force [downed pigs] to move by kicking, dragging, shoving, or even electroshocking them" (internal citations and quotations omitted)).

[251] *E.g.*, U.N. FOOD & AGRIC. ORG., THE IMPACT OF LIVESTOCK ON BIODIVERSITY (2019) https://www.fao.org/3/ca4960en/ca4960en.pdf, ("Livestock is among the sectors with highest impacts on biodiversity."); Bradley J. Bergstrom, *Carnivore Conservation: Shifting the Paradigm from Control to Coexistence*, 98 J. MAMMALOGY 1, 2 (2017) (describing the killing of thousands of predator animals and noting that USDA's Wildlife Services' "field operations in the western United States have been criticized for their over-reliance on lethal means of resolving wildlife conflicts with livestock"); Jeremy Burke, *How Eating Meat Creates a 'Dead Zone' the Size of New Jersey in the Gulf of Mexico Every Year*," BUS. INSIDER (Apr. 7, 2018, 8:55 AM), https://www.businessinsider.com/eating-meat-affects-environment-dead-zone-2018-4.

[252] *E.g.*, TIM G. BENTON ET AL., CHATHAM HOUSE, FOOD SYSTEM IMPACTS ON BIODIVERSITY LOSS 6–7 (2021) ("Over the past 50 years, the biggest driver of habitat loss has been the conversion of natural ecosystems for crop production or pasture. . . . The rapid expansion of animal farming has been behind much of this land expansion.").

[253] *E.g.*, Laima Cesoniene et al., *The Impact of Livestock Farming Activity on the Quality of Surface Water*, 26 ENV'T SCI. & POLLUTION RSCH. 32678, 32684 (2019) ("One of the most dangerous pollution sources is intensive livestock facilities, whose production waste has a negative impact on soil and water quality.").

[254] *E.g.*, Brian D. Richter et al., *Water Scarcity and Fish Imperilment Driven by Beef Production*, 3 NATURE SUSTAINABILITY 319, 320 (2020) ("[I]rrigation of cattle-feed crops . . . is the single largest consumptive [water] user at both regional and national scales [in the United States], accounting for 23% of all water consumption nationally, 32% in the western US and 55% in the Colorado River basin.").

[255] *E.g.*, Shefali Sharma, *Mighty Giants: Leaders of the Global Meat Complex*, INST. FOR AGRIC. & TRADE POL'Y (Apr. 10, 2018), https://www.iatp.org/blog/leaders-global-meat-complex; Brianna L. Alderman et al., *Ruffled Feathers: The Chicken Cartel in the United States*, 68 ANTITRUST BULL. 47, 48 (2023); Tom Polansek, *Explainer: How Four Big Companies Control the U.S. Beef Industry*, REUTERS (June 17, 2021, 10:12 AM), https://www.reuters.com/business/how-four-big-companies-control-us-beef-industry-2021-06-17.

[256] *E.g.*, BROTHER DAVID ANDREWS & TIMOTHY J. KAUTZA, PEW COMM'N ON INDUS. FARM ANIMAL PROD., IMPACT OF INDUSTRIAL FARM ANIMAL PRODUCTION ON RURAL

shift to reduce GHG emissions, such shifts (for example, from cows to pigs, or pigs to chickens[257]) do nothing to address these other externalities of industrialized animal agriculture systems.[258] The vast majority of animal products in the United States are raised in industrial settings.[259]

Second, reducing per animal emissions will not necessarily lead to reductions in total emissions if production and consumption of animal products continues to rise as predicted.[260] Also, increasing the productivity of individual animals often requires additional inputs with attendant GHG emissions.[261] Moreover, efficiency improvements can sometimes paradoxically result in increased demand and production (for

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COMMUNITIES 35 (2008) ("[I]ndustrialization [of animal agriculture] draws wealth and life away from the very rural communities it purports to benefit and which once thrived as a result of diverse, and more sustainable, forms of livestock production.").

257 FAO ROADMAP, *supra* note 113, at 12 ("[S]hifting from large ruminant to small ruminant animals for meat products, and from ruminant to monogastric animals, in particular chicken, will reduce the GHG impacts of animal-food based [sic] products."); SUTTON ET AL., *supra* note 28, at 13 (proposing shifting subsidies from "red meat and dairy" to "low-emission foods, like *poultry* or fruits and vegetables" (emphasis added)).

258 Verkuijl et al., *supra* note 244, at 6–8. Looking specifically at animal welfare and the suffering of individual animals, it takes about 100 chickens to get the same amount of meat as one cow. Marina Bolotnikova & Kenny Torrella, *How Big Are Factory Farms? How Mega-Sized Factory Farms Took Over America's Food System, Explained in 9 Charts*, VOX (Feb. 26, 2024, 4:30 AM), https://www.vox.com/future-perfect/24079424/factory-farming-facts-meat-usda-agriculture-census.

259 Hannah Ritchie, *How Many Animals Are Factory Farmed?* OUR WORLD IN DATA (Sept. 25, 2023), https://ourworldindata.org/how-many-animals-are-factory-farmed (citing estimates based on USDA data that 99% of U.S. farm animals are raised on industrial-scale concentrated animal feeding operations, or "CAFOs," as defined by EPA, including 70% of cows, 98% of pigs and egg-laying hens, 99.9% of turkeys, and 99.97% of broiler (meat) chickens).

260 *See* IPCC, CLIMATE CHANGE AND LAND, *supra* note 67, at 440 ("Reductions in GHG emissions intensity (emissions per unit product) from livestock can support reductions in absolute emissions, *provided appropriate governance to limit total production is implemented at the same time* . . . ." (emphasis added)). Indeed, some animal agriculture companies have preferred to report on decreases in their per animal emissions while failing to be clear that overall emissions have increased because of growth in the size of the herd. *See* EMISSIONS IMPOSSIBLE, *supra* note 3, at 14–15. Similarly, campaigns like the "continuous improvement" campaign of the Meat Institute, a U.S.-based trade association, offer industry a comfortable baseline and will not necessarily result in emissions reductions. *See generally* N. AM. MEAT INST., IMPLEMENTING TOOLS: 2024 CONTINUOUS IMPROVEMENT REPORT (2024), https://meatinstitute.org/sites/default/files/documents /20241021%20Protein%20PACT%20continuous%20improvement%20report.pdf.

261 Gert-Jan Nabuurs et al., *Agriculture, Forestry and Other Land Uses*, *in* INTERGOV'TAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE 750, 771 (Priyadarshi R. Shukla et al. eds., 2022) [hereinafter *IPCC Agriculture, Forestry and Other Land Uses*] ("[I]ncreased individual animal productivity generally requires increased inputs (e.g., feed) and this generates increased emissions . . . . In addition, the production of inputs to facilitate increased animal productivity, may indirectly drive further absolute GHG emissions along the feed supply chain.").

example as happened with more efficient cars and air conditioners),[262] or to shifts in production that undo emissions reductions.[263]

Third, many efficiency approaches are as yet unproven and potentially unscalable.[264] For example, an Irish government study found that, even if methane-inhibiting technologies and other mitigation measures were successfully implemented, agriculture would not be able to achieve Paris Agreement targets without also "limiting animal number increases and develop[ing] . . . new science."[265] Moreover, efficiency approaches usually come at a cost, and for that reason producers may be slow to implement them without regulatory pressure.[266] For example, the feed additive Bovaer has been shown to

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[262] This phenomenon is known as the "Jevons Paradox" (named after 19th century economist William Stanley Jevons) or the "Rebound Effect." Jaume Freire González, *The Jevons Paradox and Rebound Effect: Are We Implementing the Right Energy and Climate Change Policies?*, OECD F. NETWORK (Sept. 22, 2022), https://www.oecd-forum.org/posts/the-jevons-paradox-and-rebound-effect-are-we-implementing-the-right-energy-and-climate-change-policies.

[263] *E.g.*, David Styles et al., *Climate Mitigation by Dairy Intensification Depends on Intensive Use of Spared Grassland*, 24 GLOB. CHANGE BIOLOGY 681, 681 (2018) (undertaking life cycle assessment of potential indirect GHG effects of dairy intensification in the United Kingdom and describing replacement beef production in Brazil (because dairy cattle also become beef) resulting in a "small GHG savings for the UK GHG inventory, but . . . a net increase in international GHG emissions"). As observed in the recent EU Assessment Report, "reductions in the production and consumption of GHG-intensive agricultural products (especially livestock products) need to go hand in hand, otherwise emission reduction efforts risk being offset by increased imports (displacing emissions to other countries) or exports (maintaining EU emissions in spite of consumption changes)." EU ASSESSMENT REPORT 2024, *supra* note 50, at 155.

[264] *E.g.*, Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, *supra* note 102 ("[T]he technologies proposed to reduce [methane from cows] might look good in small trials. But they haven't been implemented or shown to be effective or affordable at any meaningful scale."); *Novel Meat and Dairy Alternatives Could Help Curb Climate-Harming Emissions*, U.N. ENV'T PROGRAMME (Dec. 8, 2023), https://www.unep.org/news-and-stories/press-release/novel-meat-and-dairy-alternatives-could-help-curb-climate-harming ("[F]eed additives to reduce emissions from animal agriculture . . . have struggled so far to win government support and achieve impacts at the desired scale or speed."); *IPCC Agriculture, Forestry and Other Land Uses*, *supra* note 261, at 830 (identifying the need for more research into technological mitigation measures as a knowledge gap, including research regarding their practical use, feasibility, and impact on absolute GHG emissions).

[265] TEAGASC CLIMATE CTR., MARGINAL ABATEMENT COST CURVE 2023: EXECUTIVE SUMMARY 11 (2023), https://www.teagasc.ie/publications/2023/marginal-abatement-cost-curve-2023---executive-summary.php; *see also id.* at 9 (finding that further research is needed to determine whether feed additives are effective and whether they have constraints or pose risks).

[266] Ben Elgin, *This Quick Fix Reduces Methane Emissions from Cow Burps*, BLOOMBERG L. (June 28, 2023), https://www.bloomberglaw.com/product/blaw/bloombergterminalnews/bloomberg-terminal-news/RWY8O5T0AFB4 ("[C]orporate giants that have promised huge and rapid cuts to their greenhouse gas emissions, like Danone, Nestle, Starbucks and JBS . . . have publicly declared an interest in using methane-curbing feed additives with the farmers or feedlots who supply their ingredients, but have yet to follow through at any sort of magnitude.").

reduce enteric methane from cows by thirty percent.[267] But it costs about $100 per cow per year and uptake has been slow, even by large companies.[268] In the words of one campaigner: "If you're going to talk about [feed additives], buy them and do this. Invest the money and make it a part of your emission-reduction plan. Some companies are presenting this as a silver bullet, but they're not at all serious about scaling it up, probably because of the cost."[269]

Fourth, even if efficiency approaches were affordable, feasible, and implemented at scale, farmed animals—and cattle in particular—would still be significant sources of GHG emissions. For example, even if the Bezos Earth Fund is correct that its methane-inhibiting research could reduce emissions by as much as thirty percent, "that would still make cows the highest-emission part of the food system."[270] Shifting diets would be more effective.[271]

Fifth, where efficiency approaches make industrial animal agriculture more profitable or even encourage its expansion and entrenchment, such efforts can act contrary to climate mitigation goals. Anaerobic digesters, which are systems that cap manure lagoons to seek to capture emitted methane, are perhaps the best example. As discussed elsewhere in this volume,[272] digesters have been the target of sustained criticism on a number of fronts,[273] including that they can make large-scale animal agriculture more profitable and even encourage expansion of facilities.[274] In California, where digesters have benefitted from

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267 *Id.*

268 *Id.* (noting that JBS had previously vowed to use Bovaer but had then "gone silent" on the topic).

269 *Id.* (quoting Nusa Urbancic, campaigns director at Changing Markets Foundation).

270 Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, *supra* note 102.

271 SUTTON ET AL., *supra* note 28, at 13 ("[T]he cost-effective mitigation potential from shifting diets away from meat is about twice as high as that from reducing enteric fermentation and other livestock production mitigation methods."); GLOBAL METHANE ASSESSMENT, *supra* note 81, at 13 ("Behavioural change measures and innovative policies are particularly important to prevent emissions from agriculture, given the limited potential to address the sector's methane emissions through technological measures.").

272 Randall S. Abate, *Putting Lipstick on a Pig: Biogas, Methane Digesters, and the Greenwashing Playbook*, 54 ENV'T L. 545 (2024).

273 *See, e.g.*, RUTHIE LAZENBY, VT. L. & GRADUATE SCH., RETHINKING MANURE BIOGAS: POLICY CONSIDERATIONS TO PROMOTE EQUITY AND PROTECT THE CLIMATE AND ENVIRONMENT 16 (2022), https://www.vermontlaw.edu/sites/default/files/2022-08/Rethinking_Manure_Biogas.pdf (discussing environmental harms resulting from digesters).

274 EU ASSESSMENT REPORT 2024, *supra* note 50, at 169 (noting that biogas digesters have the potential to "increase[] incentives to maintain livestock herd numbers"); MARTIN BOWMAN & KRYSIA WORONIECKA, FEEDBACK, GREEN GAS WITHOUT THE HOT AIR: DEFINING THE TRUE ROLE OF BIOGAS IN A NET ZERO FUTURE 57–60 (2020), https://feedbackglobal.org/wp-content/uploads/2020/09/Feedback-2020-Green-Gas-Without-the-Hot-Air-report.pdf (describing how intensive factory farming of pigs and chickens expanded in Northern Ireland following the institution of biogas subsidies); CHLOË WATERMAN & MOLLY ARMUS, FRIENDS OF THE EARTH, BIOGAS OR BULL****? THE DECEPTIVE PROMISE OF MANURE BIOGAS AS A METHANE SOLUTION 5 (2024), https://foe.org/wp-content/uploads/2024/03/Factory-Farm-Gas-Brief_final-0312.pdf ("CAFOs with digesters are more likely to

substantial government investment and support via the Low Carbon Fuel Standard and other programs,[275] some observers refer to a dangerous "manure gold rush."[276] In a recent piece on biogas digesters, a professor at UC Davis wrote:

> In colonial India, the British government wanted to reduce the number of cobras in Delhi, so it offered a bounty for dead cobras. Profit-seek[ers] responded by breeding cobras to receive the bounty. This phenomenon is known as the "cobra effect." There is a risk of the same thing happening when we pay people to capture methane from dairy cow manure.[277]

Moreover, digesters have benefitted from substantial government investment, an opportunity cost for other more beneficial mitigation approaches.[278]

Sixth, efficiency approaches can distract attention from other policy paths that prioritize the urgent need to reduce overall emissions from animal agriculture. In the parallel context of geoengineering (removing carbon from the atmosphere by technical means),[279] the U.N. Human Rights Council's Advisory Committee has warned that such approaches

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increase their herd sizes relative to statewide populations."); Aaron David Smith, *Cow Poop Is Now a Big Part of California Fuel Policy*, U.C. DAVIS: AG DATA NEWS (Jan. 22, 2024), https://asmith.ucdavis.edu/news/cow-poop-now-big-part-california-fuel-policy ("High profits from operating digesters create the incentive for farmers to expand dairy herds for the purpose of generating manure rather than for producing milk."). *But see* Aaron David Smith, *Where Are California's Dairy Cows?*, U.C. DAVIS: AG DATA NEWS (Feb. 16, 2024), https://asmith.ucdavis.edu/news/how-many-dairy-cows (reviewing recently released USDA agricultural census data and concluding that "[p]erhaps the digester programs accelerated consolidation or inspired some farmers to add cows, but it is difficult make definitive conclusions from these data").

275 Emma Foehringer Merchant, *A Battle Is Underway Over California's Lucrative Dairy Biogas Market*, INSIDE CLIMATE NEWS, https://insideclimatenews.org/news/28122023/milking-it-battle-underway-california-dairy-biogas-market (Dec. 28, 2023) ("[S]ome California dairies have seen a windfall unrelated to agricultural products; 131 of them have received state grants to install anaerobic digesters . . . ."); *see also* Pegga Mosavi, *Manure, Methane, and Money: The Anaerobic Digester Disaster in California*, 29 ANIMAL L. 41, 52–53 (2023).

276 Jessica Fu, *Brown Gold: The Great American Manure Rush Begins*, GUARDIAN (Feb. 2, 2023, 6:00 AM), https://www.theguardian.com/environment/2023/feb/02/manure-renewable-natural-gas-california; Phred Dvorak, *California's Green-Energy Subsidies Spur a Gold Rush in Cow Manure*, WALL ST. J. (Feb. 19, 2022, 9:00 AM), https://www.wsj.com/articles/californias-green-energy-subsidies-spur-a-gold-rush-in-cow-manure-11645279200; Aaron David Smith, *The Dairy Cow Manure Goldrush*, AG DATA NEWS BLOG (Feb. 2, 2022), https://asmith.ucdavis.edu/news/revisiting-value-dairy-cow-manure; *see also IPCC Agriculture, Forestry and Other Land Uses*, *supra* note 261, at 823 ("It is critical that [agricultural] intensification does not drive expansion of unsustainable practices. Increased productivity with associated economic reward could incentivise and reward agricultural land expansion, or environmentally and socially damaging practices . . . .").

277 Aaron David Smith, *Are Manure Subsidies Causing Farmers to Milk More Cows?*, U.C. DAVIS: AG DATA NEWS (Apr. 7, 2023), https://asmith.ucdavis.edu/news/are-digesters.

278 LAZENBY, *supra* note 273, at 9–14.

279 *Geoengineering*, SALATA INST. FOR CLIMATE & SUSTAINABILITY AT HARV. UNIV., https://salatainstitute.harvard.edu/sgrp (last visited Oct. 17, 2024).

may discourage immediate efforts to reduce emissions, "which makes disastrous future scenarios more probable."[280] Denmark's Minister for Global Climate Policy remarked about geoengineering: "It very easily becomes an excuse for not doing all the things that we already can do and that we know will work."[281]

Finally, efficiency approaches may delay large animal agriculture companies from seriously considering transformative change and investing in alternative production models. Looking past posturing about farmers and meat culture, these are profit-focused companies that (at least in theory and setting aside transition costs) should not have a vested interest in continuing to raise and slaughter animals.[282] Large meat and dairy companies have invested in non-animal alternatives[283] (although often not at the scale that they suggest),[284] and may to some extent identify as "protein" producers.[285]

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[280] Impact of New Technologies Intended for Climate Protection on the Enjoyment of Human Rights, Rep. of the Human Rights Council Advisory Comm., ¶ 12, U.N. Doc. A /HRC/54/47 (2023).

[281] Eric Niiler, *Scientists Resort to Once-Unthinkable Solutions to Cool the Planet*, WALL ST. J. (Feb. 14, 2024), https://www.wsj.com/science/environment/geoengineering-projects-cool-planet-weather-f0619bf7 (quoting Dan Jørgensen); *see also Clash over Dutch Farming*, *supra* note 228 ("There is a kind of technological optimism that leads us into delay, and . . . consolidation of existing power. And the [technologies] that do emerge and get funded are the ones that integrate nicely with the current model." (quoting environmental professor Adam Calo)). Responsible use of geoengineering approaches could mean using them in the short term to create time to make the policy and behavior choices that are necessary in the long-term. *See* Niiler, *supra*.

[282] *But see* Mack Graves, *Population Changes and Their Effect on Beef Production*, MEATINGPLACE (Feb. 15. 2024) https://www.meatingplace.com/Industry/Blogs/Details /113370?allowguest=true (arguing that, to "see our industry survive" we must address threats including climate change, dampened population growth, and changing diet recommendations, all of which "are existential threats to our collective livelihoods" that nonetheless "*can be won by beef*" (emphasis added)); *cf.* DANIEL JONES ET AL., FEEDBACK, IT'S BIG LIVESTOCK VERSUS THE PLANET: A CASE TO CUT OFF MEAT AND DAIRY CORPORATIONS' FINANCIAL FODDER 23 (2020), https://feedbackglobal.org/wp-content/uploads/2020/04 /Feedback-Big-Livestock-versus-the-Planet-Final-April-2020.pdf (noting that some meat and dairy company executives view plant-based products "as an addition to, not a subtraction from, their overall existing production models").

[283] Andy Coyne, *Eyeing Alternatives—Meat Companies with Stakes in Meat-Free and Cell-Based Meat*, JUST FOOD (July 13, 2023), https://www.just-food.com/features/eyeing-alternatives-meat-companies-with-stakes-in-meat-free-and-cell-based-meat.

[284] BLINDSPOT, *supra* note 83, at 38–39, 42.

[285] *E.g.*, *Tyson Food Facts*, TYSON FOODS: INV. RELS., https://ir.tyson.com/about-tyson /facts/default.aspx (last visited Oct. 18, 2024) ("Tyson Foods is a modern, multi-national protein-focused food company," but then detailing meat production and meat brands); Melissa Sue Sorrells, *Cargill, ENOUGH Expand Mycoprotein Partnership*, MEATINGPLACE (Feb. 21, 2024), https://www.meatingplace.com/Industry/News/Details /113456?allowguest=true (quoting the managing director of Cargill's meat and dairy alternatives discussing partnership with alternative protein company: "We remain committed to bringing alternative and traditional protein source options to the table").

V. POLITICAL REALITIES: THE EXAMPLE OF FARMER PROTESTS AND RETRENCHMENT IN EUROPE

As with all policy change, each of the approaches described above would benefit some stakeholders and not be aligned with the current interests of others. It is not surprising then that significant political pushback has arisen in response to the acceleration of policy around climate and animal agriculture.

As background, the last several years have seen widespread farmer protests in Europe, and abandonment of core agricultural reforms that would be necessary to achieve the promise of the Green New Deal and the Farm to Fork Strategy.[286] The protests share certain themes and motivations in common, but also differ significantly in their causes and contexts. For example, an interactive map of European farmer protests during 2023 prepared by Politico shows they were motivated by a variety of concerns including: cheap imports, electricity and fuel costs (including the removal of diesel fuel subsidies), low prices for farm products, delays in promised subsidy payments, and the EU requirement to leave four percent of land fallow.[287]

While not all of the farmers' grievances are closely connected to efforts to reduce animal agriculture's GHG emissions,[288] some of them are. Relevant themes include anger about the EU's Green Deal as well as frustration about responses to nitrogen pollution from manure.[289]

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[286] Piet Ruig, *Farm-to-Fork, to Protestors with Pitchforks: The Death of EU's Sustainable Food Policy*, EUOBSERVER (Apr. 28, 2024), https://euobserver.com/green-economy/arf1589b03 ("[F]armers' protests and industry pressures have forced the commission to drop most of the proposals."); PIERRE-MARIE AUBERT, IDDRI, THE FARM TO FORK STRATEGY: REASONS FOR FAILURE AND HOW TO MOVE FORWARD 2–3 (2024), https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Autre%20Publication/NOTE%20Veblen%20paper%20agri%20EN.pdf. In late 2023, a pesticide reduction measure at the heart of the Farm to Fork Strategy was voted down by the European Parliament, and then abandoned altogether in early 2024. Ruig, *supra*; Somini Sengupta & Monika Pronczuk, *Making Farming More Climate-Friendly Is Hard. Just Ask Europe's Politicians*, N.Y. TIMES (Feb. 6, 2024), https://www.nytimes.com/2024/02/06/climate/europe-farming-protests-policy.html. Similarly, in April 2024, the European Parliament loosened environmental standards in the Common Agricultural Policy. Thin Lei Win, *Farmers' Protests Are About More Than Green Policies*, LAND CLIMATE (May 2, 2024), https://www.landclimate.org/farmers-protests-are-about-more-than-green-policies.

[287] Hanne Cokelaere & Bartosz Brzeziński, *Europe's Farmer Protests Are Spreading. Here's Where and Why*, POLITICO (Jan. 31, 2024, 9:08 PM), https://www.politico.eu/article/farmer-protest-europe-map-france-siege-paris-germany-poland; *see also* Orla Dwyer, *Analysis: How Do the EU Farmer Protests Relate to Climate Change?*, CARBONBRIEF (Feb. 5, 2024, 4:36 PM), https://www.carbonbrief.org/analysis-how-do-the-eu-farmer-protests-relate-to-climate-change (including a chart of protest motivations by country and dividing protests, roughly evenly, into three categories: climate/emissions, biodiversity/conservation, and neither).

[288] Win, *supra* note 286 (noting that the "protests have consistently been driven by local contexts" but have been framed "as a rebellion against environmental regulations" and policy responses have focused on "dismantling green policies but not much else").

[289] *See, e.g.*, Manuela Andreoni, *Europe Struggles to Balance Climate and Farming*, N.Y. TIMES: CLIMATE FORWARD (Feb. 6, 2024) (discussing farmer frustration with EU's

Following protests, in early 2024 references to cutting non-carbon dioxide agricultural emissions—including methane and nitrous oxide from animal agriculture—were removed in the final version of the European Commission's communication launching the process for setting 2040 climate goals.[290] Advocacy groups described this "last-minute watering down" as a capitulation.[291]

The Netherlands, Ireland, and Flanders have had active farmer protests relating to climate and animal agriculture. Notably, in each of those countries, while many sectors are facing emissions limitations in order to meet binding climate targets, the outcry has been especially loud from farmers. In the Netherlands, a court order prevented the government from issuing permits for all sorts of projects (not just animal agriculture facilities) that emitted nitrogen.[292] Even though "[o]vernight, 18,000 construction projects, including critical infrastructure and housing development, were mothballed," the loudest response came from the farmers.[293] Downtown Brussels was inundated with hundreds of tractors in 2023, as farmers there protested plans to reduce nitrogen pollution in the Flanders region.[294] And in Ireland, where government plans seek a 50% reduction of emissions from the transport sector, 40% from commercial and public buildings, and only

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Green Deal); Stokstad, *supra* note 220 (discussing farmer protests against nitrogen emissions regulations).

290 According to sources who saw a draft version, the European Commission's climate target plan originally called for the agricultural sector to reduce non-CO2 greenhouse gas emissions by at least 30 percent. Angelo Di Mambro, *Agriculture 'Core Area' for EU's 2040 Climate Targets – Commission Report*, EURACTIV (Jan. 29, 2024), https://www.euractiv.com/section/agriculture-food/news/agriculture-core-area-for-eus-2040-climate-targets-commission-report. However, this language is absent from the final document. *Securing Our Future: Europe's 2040 Climate Target and Path to Climate Neutrality by 2050 Building a Sustainable, Just, and Prosperous Society*, COM (2024) 63 final (Feb. 6, 2024); *see also* Alice Hancock, *EU Backs Down on Agricultural Emissions After Farmers' Protests*, FIN. TIMES (Feb. 5, 2024) https://www.ft.com/content/00b344d9-8ff9-4a71-ae31-a76daecb96ab.

291 Press Release, Eurogroup for Animals, 2040 Climate Target—EU Commission Half-Heartedly Recognises the Role of Shifting Diets (Feb. 6, 2024), https://www.eurogroupforanimals.org/news/2040-climate-target-eu-commission-half-heartedly-recognises-role-shifting-diets; *see also* Andreoni, *supra* note 289 ("Bending to farmers' demands, the European Commission . . . softened its recommendations on cutting agricultural pollution.").

292 Ashoko Mukpo, *How Manure Blew Up the Netherlands*, MONGABAY (Sept. 6, 2023) [hereinafter *How Manure Blew Up the Netherlands*], https://news.mongabay.com/2023/09/how-manure-blew-up-the-netherlands.

293 *Id.*; Monika Pronczuk & Claire Moses, *Labeled Climate Culprits, European Farmers Rebel Over New Standards*, N.Y. TIMES (Aug. 26, 2023), https://www.nytimes.com/2023/08/26/world/europe/europe-farmers-climate-change.html ("The government has also imposed measures in the sectors of construction, mobility, and industry. But the biggest challenge lies with the farmers." (quoting spokesman for Dutch Agriculture Ministry)).

294 Angela Symons, *Hundreds of Dutch Farmers Sign Up to Close Their Livestock Farms Under New Scheme*, EURONEWS (Nov. 30, 2023), https://www.euronews.com/green/2023/11/30/dutch-farmers-could-be-paid-to-close-their-livestock-farms-under-new-scheme.

25% from agriculture—agricultural cuts have generated the most vocal opposition.[295]

The Dutch farmer protests are a particularly instructive example of political peril around environmental animal agriculture policy. As described above,[296] after court judgments found that the Dutch government was not compliant with EU directives requiring the protection of natural areas from nitrogen pollution, the government announced its intention to shrink the national herd by as much as a third.[297] The Dutch Minister for Nitrogen and Nature Policy recognized at the time that the plan did not allow for a "future for all [Dutch] farmers," and the plan itself noted that "this approach will be so radical that it will take a great deal from many to shape it."[298]

In response, tens of thousands of farmers blocked roads with tractors, staged mass protests, and set hay and manure on fire.[299] The farmer protests have, in some instances, become linked to or instrumentalized by far-right parties.[300] Right-wing Dutch leader Geert Wilders and Marine le Pen in France expressed support for the farmers, and former U.S. President Donald Trump warned that "climate fanatics" would come next for U.S. farmers.[301] A Dutch academic expert in social movements observed: "Political scientists call it issue expansion. It's a small issue, but it expands because of vicious circles and before you

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295 Rory Carroll, *Irish Farmers Say They Will Be Forced to Cull Cows to Meet Climate Targets*, GUARDIAN (Aug. 29, 2022), https://www.theguardian.com/world/2022/aug/29/irish-farmers-cull-cows-meet-climate-targets.

296 *See supra* notes 224–229 and accompanying text.

297 Mongabay's series on these events in the Netherlands is a thorough and thought-provoking read. Ashoka Mukpo, *The Dutch Farmers' Protests of 2022: A Mongabay Series*, MONGABAY (Sept. 14, 2023), https://news.mongabay.com/2023/09/the-dutch-nitrogen-crisis-a-mongabay-series.

298 MARIT VAN DER HOEK, U.S. DEP'T OF AGRIC. FOREIGN AGRIC. SERV., GOVERNMENT PRESENTS NATIONAL PROGRAM TO REDUCE NITROGEN GREENHOUSE GAS EMISSIONS IN RURAL AREAS 1, 5 (2022), https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Government%20Presents%20National%20Program%20to%20Reduce%20Nitrogen%20Greenhouse%20Gas%20Emissions%20in%20Rural%20Areas%20_The%20Hague_Netherlands_NL2022-0035.pdf.

299 *How Manure Blew Up the Netherlands*, *supra* note 292.

300 *E.g.*, Patrick Smith, *How Dutch Farmers Became the Center of a Global Right-Wing Culture War*, NBC NEWS (Dec. 12, 2022), https://www.nbcnews.com/news/world/dutch-farmers-emissions-global-right-wing-culture-war-rcna60269; *see also* Lili Bayer, *German Vice-Chancellor Warns of Extremism as Far-Right Groups Join Farmers' Protest—As It Happened*, GUARDIAN (Jan. 8, 2024), https://www.theguardian.com/world/live/2024/jan/08/germany-farmers-tractors-block-roads-protests-cuts-agricultural-subsidies-pay-europe-latest-updates (discussing far-right groups' infiltration of protests by German farmers over subsidy reductions); Andreoni, *supra* note 289 ("If policymakers push[] too far on initiatives to protect biodiversity and combat climate change, especially without involving farmers in the decision-making process, it could empower far-right populists who want to reverse such policies."); Dwyer, *supra* note 287 (discussing right-wing political groups using farmer frustration as a political tool).

301 Ashoko Mukpo, *In the Netherlands, Pitchforks Fly for an Empire of Cows*, MONGABAY (Sept. 7, 2023) [hereinafter *In the Netherlands, Pitchforks Fly*], https://news.mongabay.com/2023/09/in-the-netherlands-pitchforks-fly-for-an-empire-of-cows.

know it, it's all about the great reset,"[302] referring to a white nationalist conspiracy theory.[303]

In March 2023, the new Farmer-Citizen Movement (BBB), which had run explicitly against the nitrogen reduction policies, stunningly won a larger share of the vote than any other Dutch party.[304] Far-right leader Geert Wilders and his Freedom Party now have the largest bloc of seats in parliament and ministers from his party were appointed to the cabinet for the first time in summer 2024.[305] Wilders ran an anti-EU campaign including a focus on immigration and climate policy, calling for a withdrawal from international climate obligations.[306]

All of this political turmoil has delayed and endangered the prospects for addressing the pressing environmental issue of nitrogen pollution from animal agriculture.[307] If the country cannot reduce nitrogen pollution in high-value conservation areas in line with EU rules and as directed by the Court of Justice of the European Union, it will face substantial fines.[308] Dutch naturalists fear that the fate of fragile habitats hangs in the balance.[309]

As another example, Ireland may eventually face similar challenges. The European Commission successfully sued Ireland for its failures to limit nitrogen pollution, and later issued a ruling condemning Ireland's continuing noncompliance, noting among other things the challenges of "overgrazing" and "agricultural activities causing nitrogen deposition."[310] Like the Netherlands, Ireland has a large animal agriculture industry, with seven million commercially farmed cows for its five million people.[311] Cows are responsible for about one-fifth of all of Ireland's anthropogenic GHG emissions.[312] As part of meeting its Paris Agreement commitment to reach carbon neutrality by 2050, the Irish government has undertaken to reduce GHG emissions from agriculture by 25% by 2030.[313]

An online kerfuffle originating from Ireland illustrates the potential for dramatic reactions to factual policy discussions of the environmental

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302 Smith, *supra* note 300.

303 Aoife Gallagher & Ciarán O'Connor, *The 'Great Reset'*, INST. FOR STRATEGIC DIALOGUE (Mar. 14, 2023), https://www.isdglobal.org/explainers/the-great-reset.

304 *In the Netherlands, Pitchforks Fly*, *supra* note 301.

305 *Dutch Right-Wing Government Installed as Wilders' Shadow Looms Large*, REUTERS (July 2, 2024), https://www.reuters.com/world/europe/dutch-right-wing-government-installed-wilders-shadow-looms-large-2024-07-02.

306 Cagan Koc & Diederik Baazil, *Dutch Far-Right Leader Wilders Scores Shock Election Victory*, BLOOMBERG (Nov. 23, 2023), https://www.bloomberg.com/news/articles/2023-11-22/far-right-leader-wilders-scores-shock-victory-in-dutch-election.

307 *In the Netherlands, Pitchforks Fly*, *supra* note 301.

308 *Clash over Dutch Farming*, *supra* note 228.

309 *How Manure Blew Up the Netherlands*, *supra* note 292; *In the Netherlands, Pitchforks Fly*, *supra* note 301 ("For those who'd hoped the 2019 court ruling meant that Dutch ecosystems might have a fighting chance to recover, the election was a disaster.").

310 Case C-444/21, Eur. Comm'n v. Ireland, ECLI:EU:C:2023:524, ¶ 117 (June 29, 2023).

311 Dutkiewicz, *Ireland Isn't Culling Cows*, *supra* note 215.

312 *Id.*

313 TEAGASC CLIMATE CTR., *supra* note 265, at 6.

impacts of animal agriculture. A 2022 report from a working group of the Irish Department of Agriculture suggested the possibility of a "voluntary exit/reduction scheme" under which farmers would be paid for removing cows and agree not to replace them for at least five years.[314] A similar idea was described in a government document obtained by a journalist, which stated that removing about ten percent of Ireland's dairy cows would be needed to keep binding emissions targets within reach.[315] Even though no such plan was enacted or even formally proposed or debated, an international media firestorm ensued, surrealistically leading to Elon Musk tweeting: "This really needs to stop. Killing some cows doesn't matter for climate change."[316]

Thus, even the suggestion of an Irish government policy to shrink the herd caused international controversy. But Ireland may not be able to achieve its agricultural emission goals without reducing the number of cattle. A 2023 report by Ireland's Agriculture and Food Development Authority found that "limiting animal number increases" will be necessary to reach emissions targets.[317] In the words of one Irish climate scientist: "Various tried and untried methods have been advanced to suggest compliance with the 25% emissions ceiling," but without success; "[o]nly a reduction in numbers can achieve the targets in the short term."[318]

VI. PATHS FORWARD

> [T]he last four years in the Netherlands have been a warning sign for the global environmental movement. When plans to address biodiversity and climate change—whether through decarbonization, expansion of conservation areas, or agriculture reform—collide with people's livelihoods and sense of place in the world, chaos can and will follow. . . . Already, the Netherlands' political miasma has begun to seep across its borders, a cloud descending onto other parts of Europe like ammonia from a megafarm.
>
> ~In the Clash over Dutch Farming,
> Europe's Future Arrives,
> Ashoka Mukpo[319]

> If there is some kind of main message of the Netherlands towards the world, it would be to act now. The environmental and societal costs will be much higher and more painful if we wait too long, for farmers and citizens alike.

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314 Dutkiewicz, *Ireland Isn't Culling Cows*, *supra* note 215.
315 *Id.*
316 *Id.*
317 TEAGASC CLIMATE CTR., *supra* note 265, at 11.
318 Carroll, *supra* note 295.
319 *Clash over Dutch Farming*, *supra* note 228.

~Kirsten Haanraads,
World Wildlife Fund
Netherlands[320]

Building from the preceding discussion and examples, this Part discusses considerations that could be important in advancing policy to mitigate animal agriculture's climate harms. One clear lesson from the political difficulties in the Netherlands is that earlier action, before the threat of a court judgment and potential fines, may have offered policymakers better options and more opportunity to ease into change. With the benefit of hindsight, the Dutch government seems to have missed an earlier opportunity to "draw[] up long-term plans to reform agricultural production before the situation worsened."[321]

The time-sensitivity and lack of maneuverability in the Dutch situation arose in part from the fact that the policy change was driven by a court decision.[322] Should the conclusion be that litigation is an overly rigid tool for such complicated matters as climate and animal agriculture policy? On the other hand, if environmental advocates had not resorted to litigation, pollution could have continued unchecked, ultimately resulting in an even more difficult situation and more harms to nature and society. Indeed, the Dutch advocates reportedly "begged" for attention from policymakers before resorting to litigation.[323] Even without the catalyst of litigation, the current lack of adequate climate mitigation, if continued, will force urgent changes to food systems.[324] Rather than imperiling our food systems, early mitigation action to curtail emissions from agriculture can be expected to lower long-term food prices, reduce hunger risk, and use less water.[325]

Starting policy change sooner also creates time to build consensus and sequence interventions. The Danish Plant-Based Action Plan provides examples of both. The Plan reportedly grew out of a yearslong process of stakeholder discussions including farmers, industry,

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320 *Id.*

321 *In the Netherlands, Pitchforks Fly*, *supra* note 301.

322 *Supra* notes 224–229 and accompanying text.

323 *How Manure Blew Up the Netherlands*, *supra* note 292; *see also* Daina Bray & Thomas Poston, *The Methane Majors: Climate Change and Animal Agriculture Litigation in U.S. Courts*, 49 COLUM. J. ENV'T L. 145, 247 (2024) ("Well-founded litigation might be uniquely positioned to facilitate action—which likely must include reduced production and consumption of animal products—where gridlocked political processes have failed.").

324 BLINDSPOT, *supra* note 83, at 43 ("If we fail to act now, runaway climate change will force us to adapt our eating habits because of collapsing food-production systems, increasing poverty and inequality. If we act quickly, we can manage the transition to healthier and more nature- and climate-friendly diets that are more just and equitable. This is where our choices and opportunities lie."); *see also* SUTTON ET AL., *supra* note 28, at 1 ("[C]onditions are set to deteriorate even further as the world attempts to feed a global population that will grow by 2 billion by 2050. More food means accelerating food production, land use changes, and related emissions, which exacerbate global heating. In turn, global heating will affect future agricultural yields and food security.").

325 SUTTON ET AL., *supra* note 28, at 8–10, 13.

government, and environmental and animal groups.[326] Another key characteristic of the Danish approach is that the initial measures focus on building demand and opportunity (the carrot); it is not until those efforts are well underway that measures like an agriculture carbon tax (the stick) would be implemented.[327] While carrots will not be sufficient by themselves,[328] the sequencing being tried in Denmark seems promising.

Indeed, the role of building in time for sustained discussion amongst stakeholders, allowing them an opportunity to appreciate each other's positions and challenges, emerges as an important strategy for avoiding the most adversarial of outcomes. In 2020, after farmer protests prompted by environmental regulation, Germany created a "Commission on the Future of Agriculture" bringing together consumers, farmers, environmentalists, and researchers.[329] The German coalition was modeled on a similar coalition that had been created around moving away from coal.[330] The Commission succeeded in arriving at a consensus position, with all participants recognizing that the current food system requires reform to achieve both economic and environmental sustainability.[331] Policy makers can look to prior transitions for lessons on both the adversarial battles that can result without creating space for consensus-building, and the new opportunities that can be created by such discussions.

If we might expect the grim realities of our changing climate and the patent harms of industrial animal agriculture to push stakeholders to a consensus around the need for some level of change, what principles should guide our consideration of policy options? Ensuring international equity and a just transition will be critical. As to the first, not all policy approaches and goals are appropriate in all places.[332] As recognized by the EAT-*Lancet* Commission, some populations depend on animal agriculture, and others face nutrition challenges in contexts where available plant-sourced foods may not be sufficient.[333] Moreover,

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326 Bourke, *supra* note 162.

327 *Id.* ("The world-first Danish strategy to encourage plant-based foods may contain a lesson for other nations looking to cut back on meat: build new demand first.").

328 EU ASSESSMENT REPORT 2024, *supra* note 50, at 173 ("EU policies to encourage sustainable diets focus primarily on information provision and voluntary codes of conduct, but these measures are not sufficient by themselves.").

329 BLINDSPOT, *supra* note 83, at 31; AUBERT, *supra* note 286, at 4 (noting that the German Commission "offer[s] grounds for believing that such a dialogue [amongst stakeholders] is possible").

330 *Id.*

331 *Id.*; ZUKUNFTSKOMMISSION LANDWIRTSCHAFT, THE FUTURE OF AGRICULTURE: A COMMON AGENDA 8 (2021), https://www.bmel.de/SharedDocs/Downloads/EN/Publications/abstract-zukunftskommission-landwirtschaft.pdf?__blob=publicationFile&v=4.

332 *See* SUTTON ET AL., *supra* note 28, at 3 ("[C]ountries have different opportunities to combat climate change through the agrifood system.").

333 EAT, *supra* note 70, at 12 ("[T]he role of animal source foods in people's diets must be carefully considered in each context and within local and regional realities."); FAO ROADMAP, *supra* note 113, at 9 ("Sacrificing food security and nutrition for vulnerable

responsibility for historical emissions, scale of consumption of animal products, and stage of development are highly relevant to discussions of which countries should lead the way on dietary change.[334]

In looking at the various approaches around the world—as well as the political repercussions experienced in the Netherlands and elsewhere—a key grounding principle for a discussion of climate policy for animal agriculture is the need for a just transition for farmers, ranchers, and workers.[335] The International Labour Organization defines a just transition as "greening the economy in a way that is as fair and inclusive as possible to everyone concerned, creating decent work opportunities and leaving no one behind."[336] Most discussions of just transitions in climate policy to date have focused on the shift from fossil fuels to renewable energy, but the applicability and utility of this concept to agricultural climate transitions is now also being discussed.[337] Both the European Green Deal and the Farm-to-Fork strategy recognize the importance of a just transition.[338] In the context of climate reform of the food system, a just transition "means reducing emissions while ensuring jobs, good health, livelihoods, and food security to vulnerable groups and smallholder farmers."[339] A Green Party Member of EU Parliament observed earlier this year that one of the flaws in the Farm to Fork Strategy that may have diminished its chances of success was a lack of economic support, particularly for farmers.[340]

It is an understatement to say that achieving a just transition in animal agriculture will be complex.[341] Dietary choices implicate familial

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populations is not an option; meaning increasing pressure on high-consumption consumers and transitioning toward resource-efficient food choices.").

334 *E.g.*, Mehrabi et al., *supra* note 199, at 162 ("Addressing poverty-limited access versus the demand choices of rich citizens involves balancing very different goals.").

335 Danielle Nierenberg et al., *Devising a Just Transition for Sustainable Livestock Agriculture*, AGRIC. DIVE (Nov. 20, 2023), https://www.agriculturedive.com/news/livestock-emissions-agriculture-cop28-just-transition-oped/700100.

336 *Climate Change and Financing a Just Transition*, INT'L LABOUR ORG. (July 9, 2024), https://www.ilo.org/resource/other/climate-change-and-financing-just-transition.

337 Cleo Verkuijl et al., *A Just Transition in Animal Agriculture Is Necessary for More Effective and Equitable One Health Outcomes*, CABI ONE HEALTH, Oct. 12, 2023, No. ohcs202300021, at 2.

338 FARM TO FORK STRATEGY, *supra* note 75, at 4 ("Ensuring a sustainable livelihood for primary producers, who still lag behind in terms of income, is essential for the success of the [COVID-19 pandemic] recovery and the transition."). In its recent document launching the process to identify steps toward 2040 climate targets, the European Commission observed: "[D]iverse and family-owned farms and those who combine crop and animal production are the backbone of EU farming and should be accompanied in the transition to a climate-neutral land sector, taking into account its social, environmental and economic dimension." *Securing Our Future*, *supra* note 290, at 21–22.

339 SUTTON ET AL., *supra* note 28, at 20.

340 Ruig, *supra* note 286.

341 *See* David De Pue et al., *A Farmer's Perspective on Farm Relocation: Lessons Learnt from Relocated Farmers in Belgium and the Netherlands*, 64 J. ENV'T PLAN. & MGMT. 1474, 1479–92 (2021) (describing, in the parallel context of relocating farmers, the complexity of

and cultural traditions, nutrition, livelihoods, significant industry profits and power, and more.[342] Electoral timeframes are in many ways poorly suited for this challenge. While food system reform may benefit farmers in the medium and long run—by improving resilience in the face of climate change, reducing environmental damage, and creating new income streams—substantial investment will be required to assist those most affected.[343] Delaying the necessary changes can result in a "Pyrrhic victory" for farmers, who may then face more drastic changes and a loss of social support down the road.[344] And given that farmers directly experience the realities of a changing climate, many of them are in favor of adaptation. One Italian farmer criticized the EU Commission's decision to lessen environmental regulation in the Common Agriculture Policy, explaining: "Climate change is there. This is not a political opinion. We are not environmentalists. We are peasants. But we see that it's costly to work against nature."[345]

Engaging with farmers and others who work within the industrial animal agriculture system to ensure a just transition will be essential. One Dutch farmer put it this way: "The farmers are the victims of this whole system. And the agri-industry is earning the money."[346] Tim Benton, director of research on food production and the environment at the Chatham House think tank in London, also encourages a focus on the farmers' perspective:

> The EU's reversal on agriculture-specific climate goals highlights the need for a meticulously-planned 'just transition'—a shift toward climate-friendly farming that doesn't ignore farmers' economic needs. Farmers are increasingly fed up with being seen as the whipping boy of food-systems emissions, in terms of them being told they are bad people and bad

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factors required to promote smooth transitions, both in terms of the farmers' situation and characteristics and the procedural and financial supports provided).

342 *Project: Just Transitions in Animal Agriculture*, STOCKHOLM ENV'T INST., https://www.sei.org/projects/just-transitions-animal-agriculture (last visited Nov. 14, 2024).

343 Kerstine Appunn, *Farming Commission's Proposals Require Next Govt to Undertake Food System Transformation – Merkel*, CLEAN ENERGY WIRE (July 6, 2021, 1:25 PM), https://www.cleanenergywire.org/news/farming-commmissions-proposals-require-next-govt-undertake-food-system-transformation-merkel ("[T]he current food system is neither economically nor ecologically sustainable but that the transformation would be cheaper for society and farmers in the medium term than the current system." (quoting German Environment Minister Svenja Schulze)).

344 Guyomard et al., *supra* note 14, at 10.

345 Win, *supra* note 288.

346 *In the Netherlands, Pitchforks Fly*, *supra* note 301; *see also* Pronczuk & Moses, *supra* note 293 ("Many farmers say they are not resistant to addressing the problem of climate change, and they note that their livelihoods are more directly affected by it than those of many others. But they say the burden should be more evenly spread."); Andreoni, *supra* note 289 ("What the farmers I have spoken to have told me is that the burden and the cost of fighting climate change should be shared more evenly.").

> managers of the land. If we are going to do transitions, then we have to bring people along with us.[347]

Another fundamental question in terms of supporting those most affected by the transition is who should bear the cost. While there is of course a role for government support—which could be achieved in part by reducing or eliminating subsidies for meat[348]—others assert that the agribusinesses that have long benefited from externalizing the costs of their environmental harms should be held accountable,[349] either by policy-driven resource shifts or, where necessary, by litigation.

Whether and how these approaches could be effectively translated to the U.S. context is an urgent question, particularly in light of the scale of the U.S. industry and its emissions. To date, U.S. climate policies have focused on voluntary and incentive-based approaches to animal agriculture.[350] In her insightful article, *Is Meat the New Tobacco?*, Professor Lingxi Chenyang posits that reducing meat demand may actually be easier in some respects than it was to reduce tobacco demand.[351] She recommends two categories of U.S. federal policy reforms as a starting point: (i) removing barriers to information about how industrial meat is produced[352] (such as by repealing ag-gag laws),[353] reforming the federal checkoff programs that collect funds from producers for generic promotion of animal products,[354] reforming federal certification programs to incorporate climate sustainability goals, and (ii) implementing place-based substitutions starting with schools and the National School Lunch Program.[355] While acknowledging that these

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347 Max Graham, *What Europe's Egg-Hurling Farmers Can Teach Us About Climate Progress*, GRIST (Feb. 20, 2024), https://grist.org/agriculture/europe-farmer-protests-eu-climate-progress.

348 *See supra* notes 79, 158 and accompanying text.

349 *Clash over Dutch Farming*, *supra* note 228 ("I think if the government makes clear that behind the nitrogen crisis, there are big corporations that have contributed to it and are still profiting from it, and also show their willingness to hold them accountable for their role and ask them to pay their fair share to finance a just transition, that could be a way out." (quoting Wouter Kolk, campaign leader at environmental group Milieudefensie)).

350 *See, e.g.*, Brown & Hill, *supra* note 8 ("[T]he U.S.' efforts to transform American agriculture are based on 'incentive-driven and market-based' mechanisms.").

351 Lingxi Chenyang, *Is Meat the New Tobacco? Regulating Food in the Age of Climate Change*, 49 ENV'T L. REP. 10344, 10352–57 (2019).

352 *E.g.*, *People Don't See Industrial Meat as a Key Cause of Global Warming—Poll*, MADRE BRAVA (Mar. 17, 2023), https://madrebrava.org/insight/people-don-t-see-industrial-meat-as-a-key-cause-of-global-warming-poll ("[W]hen a simple definition of industrial meat was provided . . . citizens . . . showed concern about the impacts of the industrial meat system.").

353 State "ag-gag" laws seek to criminalize whistleblowing and undercover investigations of food production. Justin Marceau, *Ag Gag Past, Present, and Future*, 38 SEATTLE U. L.R. 1317, 1332 (2015).

354 *See* Chenyang, *supra* note 351, at 10358 ("Mandatory contribution to generic promotional efforts removes incentives for individual producers to differentiate and market their commodity on production attributes like climate sustainability.").

355 *Id.* at 10357–61.

reforms will not by themselves significantly reduce meat consumption, she presents them as "steps in the right direction" to "create a friendlier environment for more drastic regulatory measures."[356] Her approach is thus sensitive to the sequencing of interventions, and similar to the Danish effort in that respect. While the United States doubtless has further to go than even high-producing countries in Europe, starting with more modest legal reforms to help change the atmosphere could be a way in.

VII. CONCLUSION

> We cannot continue doing animal agriculture as we now practice it and is accepted. Let me change that just a bit: if we want to have a healthier population, reduce the incidence of respiratory illnesses and cancer-causing agents, and if we wish to have a healthier environment, with cleaner water, renewable resources, replenishable soil, wildlife habitat, and overall cleaner air to breathe, then we cannot continue doing animal agriculture as we now practice it and is widely accepted.
>
> ~Former U.S. Senator from Iowa Tom Harkin, remarks at *Industrial Farm Animal Production, the Environment, and Public Health* conference at Drake University (2024)[357]

Politicians and policy makers are beginning to acknowledge that the industrial animal agriculture system is not sustainable on its current trajectory.[358] Having surveyed this developing policy landscape, one is left with the impression that progress is not inevitable—far from it, in light of significant political pushback—but that there is an emerging scaffold of both international signaling and national and provincial policy onto which future efforts can be built. Such efforts must be informed by prior clashes between environmental protection and livelihoods, seeking to redirect government support away from large-scale agribusiness and toward ensuring a just transition for communities.

If politicians fall short, private actors will increasingly look for other avenues, through litigation or otherwise.[359] In the first prominent move of its kind, in March 2024 the Dutch supermarket chain Jumbo stopped offering price promotions (i.e., discounts) on fresh beef, pork,

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[356] *Id.* at 10346; *see also id.* at 10351 ("[N]on-price regulatory intervention[s] . . . are generally less expensive to implement than subsidies, and require less political willpower to adopt than taxes.").

[357] Harkin Inst., *Tom Harkin Remarks 2024 09 25*, YOUTUBE (Sept. 25, 2024), https://www.youtube.com/watch?v=HOSsmeBMsg0&t=192s. Senator Harkin's remarks are especially notable because Iowa is ground zero for industrial pork production in the United States. *Iowa Leads States in Hog Production*, U.S. DEP'T OF AGRIC. (Mar. 13, 2024), https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=108733.

[358] MARIT VAN DER HOEK, *supra* note 298, at 7 ("[T]he herd will have to be smaller, there is no escaping that." (quoting position of Dutch political party D66)).

[359] Bray & Poston, *supra* note 323, at 247.

and chicken.[360] The company has also lowered prices of its own-brand meat substitutes to reach price parity, explaining these changes as part of the company's work toward "the protein transition."[361] Perhaps it is not surprising that this innovation would come in the Netherlands, amidst the striking mix of innovation and obstacles that have arisen there. Perhaps the supermarket was inspired by the municipal meat advertising bans in Dutch cities. Or perhaps, in response to the furor of the farmer protests and political turmoil, the company thought it could help support the transition using its own toolbox.

Reining in industrial animal agriculture's emissions, and remedying its many other harms, will require a multitude of actors and solutions. If we are unable to muster the political will to address the harms of animal agriculture before the changing climate further imperils our food systems, we will have missed a critical opportunity to protect our collective future.

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[360] Dayeeta Das, *Jumbo to Cease Price Promotions on Fresh Meat in the Netherlands*, EUR. SUPERMKT. MAG. (Mar. 15, 2024), https://www.esmmagazine.com/retail/jumbo-to-cease-price-promotions-on-fresh-meat-in-the-netherlands-261595; *see also* Toby L.S. Watt et al., *Reducing Consumption of Unhealthy Foods and Beverages Through Banning Price Promotions: What Is the Evidence and Will It Work?*, 23 PUB. HEALTH NUTRITION 2228, 2228 (2020) (concluding that "price promotions increase purchasing of unhealthy food").

[361] Das, *supra* note 360.

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REVIEW

Nitrous oxide production from cattle and swine manure

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Abstract The aim of this review is to summarize the current knowledge of nitrous oxide (N_2O) production from manure. The article investigates the scientific literature regarding N_2O emissions according to different factors, such as microclimate, season, manure composition, microbial population, management, storage conditions, and type of digestion. Nitrous oxide is formed through the microbiological processes of nitrification and denitrification. The amount of N_2O produced from manure storage depends on type of manure management. The anaerobically stored farm yard manure (FYM) emitted more N_2O emissions than the composted FYM. The anaerobic storage of liquid manure reduces N_2O production. Covering the slurry store (SLR) with a chopped straw increased N_2O emissions. Finally, emission factors from manure treatment and management are listed in table.

Keywords: nitrous oxide, manure, slurry, housing

Introduction

Contemporary agriculture is characterized by the intensive production of livestock in confined facilities and land application of stored waste as an organic fertilizer. Animal agriculture potentially contributes up to 50 % of total agricultural nitrous oxide (N_2O) emissions (Klein de and Eckard 2008). The anthropogenic greenhouse gas emission from animal manure is estimates on 20 % of N_2O (Sommer and Moller 2000).

N_2O emissions from nitrogen (N) excreted as animal waste alone could be as much as 30–50 % of the global agricultural N_2O emissions, suggesting that the contribution of animal agriculture to total agricultural N_2O emissions could be in excess of 50 % when including emissions from N fertilizer use (Oenema et al 2005; Klein and Eckard 2008). N_2O emissions occur high when N fertilizers are used for production of concentrates to feed the animals, as well as from excretal returns (Davidson 2009; Petersen and Sommer 2011).

N_2O is produced during several microbial processes in the nitrogen (N) cycle of terrestrial and aquatic systems. Typically, 70 % to 90 % of the N ingested by herbivores is excreted, either during grazing or via application of manure collected outside grazing periods (Schils et al 2013). Housed animals excrete as dung and urine according to Paustian et al (2004) 80 to 95 % of the N in their diet, and some proportion of this N is emitted as N_2O during collection, storage, and application. Ruminants excrete between 75 and 95 % of the N they ingest, with excess dietary N increasingly excreted in the urine, while dung N excretion remains relatively constant (Castillo et al 2000; Eckard et al 2007).

In animal husbandry, N_2O emissions are associated with manure management and the application and deposition of manure in crop or pasture land. Manure treatment can be an important source of N_2O emissions, accounting for an estimated 5 % of global N_2O emissions (Owen and Silver 2015). Major agricultural manure emission sources are reported to be N_2O from poultry sheds and from beef feedlots (Pratt et al 2014).

Collected manure may be handled in solid (farmyard manure, deep litter) or liquid form (slurry with typically 1 % to 10 % of dry matter) (Schils et al 2013). Dung and urine are often separated to solid stacked manure and slurry (SLR), with or without subsequent composting of the stacked manure and (anaerobic or aerobic) treatment of the SLR. In other production systems, effluent from barns is transferred into open anaerobic ponds (lagoons) where the effluent is typically stored for many months, with the potential of generating large quantities of emissions (McGahan et al 2016).

N_2O is released from excrement and urine excreta, from SLR applied for crop or pasture production, and aerobic and anaerobic degradation of livestock waste in the lagoons and dry manure pile (Saggar et al 2004; Fabbri et al 2007; Borhan et al 2011; Redding et al 2015).

Formation N_2O

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The various pathways of N_2O formation could describe for apply to the manure environment, but the potential for N_2O emissions will depend on manure management practice. Manure contains most elements necessary for stimulating soil nitrification and denitrification processes that form N_2O. These processes are transient, depending on the amount and form of available N (NH_4^+ or NO_3^-), soil oxidation–reduction potential, degradable carbon (C) sources, soil temperature, water content, and microbial population (Montes et al., 2013). Poor correlations between N_2O efflux and soil physicochemical variables and fertilizer loading rate point to the complexity of interacting factors affecting N_2O production and emission (Whalen 2000).

The main sources of N_2O from agriculture are nitrification and denitrification processes in soil. Farms primarily emit N_2O arising mainly from nitrogen fertilizer (organic manures or inorganic fertilizers) application to soil, direct N deposition by grazing animals, or manure storages (Whalen et al 2000; Crosson et al 2011; Adler et al 2015). Nitrous oxide can also be produced indirectly when manure N is lost through volatilization as NH_3, NO, and N_2O and is nitrified and denitrified in soil following redeposition (Montes et al 2013). The smaller contributions from barn floors, where both aerobic and anaerobic conditions can exist (Chianese et al 2009; Van Middelaar et al 2013; Eckard et al 2003).

The major N_2O contributor is normally the denitrification process under anaerobic conditions, but nitrification under aerobic conditions may also contribute. Nitrification and denitrification rates are affected by numerous soil and climatic or seasonal factors (Monaghan and Barraclough 1993; Chadwick et al 2000; de Klein and Eckard 2008). The rate of formation and emission of N_2O varies through time with changes in the porosity, moisture content, temperature, amount of solids in the manure, and N or dietary protein content of the soil or manure substrate (Külling et al 2001; Kebreab et al 2006; Chianese et al 2009; Li et al 2014). Anaerobically stored solid manure emitted much more N_2O than the compost (Amon et al 1998a). Chadwick et al (2000) also reported that immediate emissions of N_2O from the beef manure was likely due to rapid nitrification of ammonium or denitrification of nitrate already in the manure.

Most of the N_2O resulting from manure is produced in manure-amended soils through microbial nitrification under aerobic conditions and partial denitrification under anaerobic conditions, with denitrification generally producing the larger quantity of N_2O (Montes et al 2013). Nitrogen in liquid manure is mostly in the form of ammonium (NH_4^+) and organic N, and though anaerobic lagoons are generally anaerobic, aerobic conditions which could promote denitrification exist at inlets. Other N_2O formation reactions are also possible, such as denitrification of nitrate (NO_3^-) (Owen and Silver 2015).

Mahimairaja et al (1995) examined the denitrification loss of N from fresh poultry and animal (dairy, sheep, pig and horse) manures, and from poultry manure during composting with different amendments. The results indicated that during denitrification, the amount of N_2 produced is generally greater than that of N_2O. The ratio of N_2O:N_2 varied from 0.09 to 0.21.

Factors affecting N_2O releasing

When fecal matter is excreted by animals, it undergoes a series of reactions such as decomposition, hydrolysis, nitrification, denitrification, fermentation etc., from which N_2O can be produced. Based on the principles of thermodynamics and reaction kinetics, these reactions are commonly controlled by a group of environmental factors such as temperature, moisture, stacking, density, litter addition, mixing, composition, and aerobic decomposition during storage of the manure, also redox potential, pH, substrate concentration gradient, etc. (Oenema et al 2005; Yamulki 2006; Kebreab et al 2006; Li et al 2012; Rzeźnik and Mielcarek 2016). The influencing factors appeared to be also the manure removal frequency, dry matter content, and time deposit of the manure (Fournel et al 2012). After 6 weeks of storage N_2O emission from farmyard manure (FYM) and deep litter manure reached a maximum (Külling et al 2002).

N_2O emissions are strongly correlated with all these parameters (Mihina et al 2012; Owen and Silver 2015). This suggests that in FYM, at least a portion of the N_2O fluxes were derived from denitrification, which requires the same general environmental conditions as methanogenesis (warm temperatures, abundant labile C, anaerobic conditions) (Owen and Silver 2015).

One main factor influencing the amount of N_2O emissions seems to be the manure temperature. This would explain why under summer conditions the emission rates of N_2O are different than under winter conditions (Jungbluth et al 2001). Sommer and Moller (2000) studied composting of pig deep litter during a 4-month period. Emissions of N_2O were only significant in the low temperature phases. N_2O was also produced in the center both initially and after the temperature of the compost had dropped to below 45 °C (Sommer and Moller 2000).

The initial C: N ratio and dry matter content of the stored FYM are also the most important factors affecting N_2O emissions. The greater C content in the organic FYM compared with the conventional FYM corresponded to a reduction in total N_2O emission (Yamulki 2006). N_2O emissions increase with the N content of waste, the extent to which waste is allowed to become aerobic (allowing the

initiation of nitrification-denitrification reactions) and the length of storage (Mosier et al 1998). Further, owing to interactions between available C and N sources in the correct oxidation form, semi-permeable manure storage covers can enhance N_2O formation (Hansen et al 2009; Nielsen et al 2010; Gerber et al 2013).

Table 1 N2O production and emission factors from manure storage facilities (per animal)

Cattle manure, without covering; 0.78 mg.m^{-2} h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
Manure, summer, 3.5 t, winter, 7 t; anerobically stored vs. composted, 3 times per week, ODC, 74.7 g.t^{-1} vs. 49.8 g.t^{-1} (Amon et al 1998a).
Cattle manure (housing, storage, spreading); ODC, FTIR; yearly average 0.62 g.LU^{-1}.d^{-1} (Amon et al 1998b, cited by Amon et al 2006a).
Dairy solid manure system; 25.8 mg.LU^{-1}.h^{-1} (Amon et al 1999; cited by Amon et al 2006a).
Dairy liquid manure system; 25.4 mg.LU^{-1}.h^{-1} (Amon et al 1999; cited by Amon et al 2006a).
Dairy SLR, storage, 1200 m^3; winter, TDL; 14 mg.m^{-3}.d^{-1} (Hensen et al 2006).
12 Brown Swiss, 52 DIM, 637 kg LBW, 30,9 kg MY, individual stalls, slatted floor, TMR, 4 MS (DL, SLR, urine-rich SLR, FYM); 7 wks, TDL; according MS: 9.3 ng.m^{-2}.s^{-1}, 5.6 ng.m^{-2}.s^{-1}, 12.1 ng.m^{-2}.s^{-1}, 556.4 ng.m^{-2}.s^{-1}; (DL, SLR, FYM) 42 mg.d^{-1}, 12 mg.d^{-1}, 886 mg.d^{-1} (Külling et al 2001).
Pig manure, without covering; from containers (0,5 m^3) closed for 1 h gas measurement, summer, GC; 0.67 mg.m^{-2}.h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
Pig manure, with straw covering; from containers (0,5 m^3) closed for 1 h gas measurement, summer, GC; 0.95 mg.m^{-2}.h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
Pig manure, without covering; winter, FMC, GC; 0.35 mg.m^{-2}.h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
Pig manure, with straw covering, winter, FMC, GC; 0.30 mg.m^{-2}.h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
160 fattening pigs, uncovered SLR vs. covered SLR; warm, FC; after 50 days, 23 g.m^{-3} vs. 30 g.m^{-3}; after 200 days, 119 g.m^{-3} vs. 114 g.m^{-3} (Amon et al 2007).
160 fattening pigs, uncovered SLR, covered SLR; cold, FMC; after 50 days, 36 g.m^{-3} vs. 18 g.m^{-3} (Amon et al 2007).
Fattening pigs; FS housing, anaerobic effluent pond, short hydraulic retention tank; 2x30 ds; N_2O from housing and pond, or below the detection limits, total emissions from the short hydraulic retention tank: winter 0.001 mg N_2O-N.LU^{-1}.d^{-1}, summer 5.9 mg N_2O-N.AU^{-1}.d^{-1} (McGahan et al., 2016).
3 fattening pigs farms; SLR lagoons; every M, MBIGA; lagoon concentration 636.8 mg NH_4-N kg^{-1}, 201.0 mg NH_4-N kg^{-1}, 236.6 mg NH_4-N kg^{-1}, 0.3 kg N_2O-N ha^{-1} d^{-1}, 0.4 kg N_2O-N ha^{-1} d^{-1}, 0.0 kg N_2O-N ha^{-1} d^{-1} (Harper et al 2004).
Manure, fattening pigs, DL, stored 113 ds; every wk, RC (tent), GC; d 11: 28 mg N_2O-N.kg DM^{-1} d^{-1}, after d 40: 6 mg N_2O-N.kg DM^{-1} d^{-1} (Wolter et al 2004).

The increase in manure organic matter accelerates soil metabolism, depleting oxygen, triggering denitrification and N_2O emissions (Hristov et al 2013; Gerber et al 2013). On the contrary, anaerobic digestion, or separation of manure solids, lowers the organic content of manure, which generally results in lower emissions of N_2O (Clemens et al 2006; Velthof and Mosquera 2011; Gerber et al 2013). Manure affects the balance between NH_3 and N_2O emissions. This interaction may be positive (e.g., both emissions are reduced by an airtight cover during storage and stimulated by composting), or negative (e.g., direct N_2O emissions from soil will potentially increase if losses of NH_3 are prevented during storage or field application) (Petersen and Sommer 2011). N_2O release from stored manure was low when NH_3 was high (Külling et al 2002).

The amount of N_2O produced from manure storage depends on the amount of N excreted and duration of storage (Merino et al 2011). Solid manure rich in high fiber bedding material has a high porosity that promotes aerobic fermentation, and heat, which can stimulate N_2O emissions (Petersen et al 1998). Also, the higher the density the lower the emission of N_2O (Oenema et al 2005). However, covering delayed aeration of the stored manure; this reduced internal heat production, degradation of organic matter, and emission of greenhouse gases and ammonia (Hansen et al 2006). At the study of Sommer and Moller (2000) was production of N_2O restricted to the surface layers during the thermophilic phase of composting (Sommer and Moller 2000). Brown et al (2000) found that the mean N_2O-N fluxes were between 0 and 0.33 g N m^{-2} d^{-1}, and N_2O was only generated in samples from the top two layers of the dairy FYM pile. Manure samples from the 30 to 45 cm depth were adjusted by amendment with chopped straw to 70, 75, and 80 % water content. These samples produced twice as much N_2O-N as the unamended samples.

Slurry separation reduces emissions if losses during storage of the solid fraction can be kept on a low level (Amon et al 2006b). At the study of Hansen et al (2006), emissions of N_2O from an uncovered and covered heap of solid manure separated from pig SLR were compared, and related to the oxygenation level inside the manure heap. Approximately 15 % of the initial nitrogen content of the solids separated was found to be lost when the separated solids were stored uncovered. Almost 5 % of the initial N content was found to be lost as N_2O. Emissions of N_2O were reduced by 12 %, when the manure heap was covered with

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an airtight material. The oxygenation level inside heaps of solids separated from pig SLR was found to influence the production and emission of greenhouse gases during the storage period (Hansen et al 2006).

In contrast, in liquid manure lagoons particulate organic matter is a physical barrier against gas exchange when a surface crust forms (Petersen and Sommer 2011). Anaerobic digestion is in fact an effective means to reduce greenhouse gas emission (Amon et al 2006a). However, the anaerobically stored FYM emitted more N_2O emissions than the composted farm yard manure (Amon et al 1998a; Amon et al 2001).

Covering the SLR store with a layer of chopped straw increased greenhouse gas emissions mainly by increasing N_2O emissions. When liquid manure stored as anaerobic SLR, N_2O emission is low, but NH_3 and CH_4 emissions are high, depending on the cover of the slurry and mixing rate (Oenema et al 2005). N_2O emissions can occur from SLR when a dry crust is formed on the surface with combination of anaerobic and aerobic micro-sites (Philippe and Nicks 2013). Therefore, straw cover and SLR aeration showed negative environmental effects (Amon et al 2006b).

Natural surface crusts may develop into a porous matrix with high O_2 availability that harbors an active population of aerobic microorganisms. The occurrence of NO_2^- and NO_3^- in the crusts also indicate the presence of actively metabolizing NH_3^- oxidizing bacteria (Nielsen et al 2010). The floating crust is important because it provides a substrate that spans anaerobic and aerobic environments, where N_2O production can occurs (Petersen and Sommer 2011).

Floating crusts on manure storages are environments with intense microbial activity, and microbial processes are governed by the extent of oxic conditions that are governed by the moisture of the crust. Hansen et al (2009) study investigated whether physical properties of the crust or crust microbiology had an effect on the emission of the N_2O when crust moisture was manipulated (dry, moderate, and wet). However, an increase in N_2O emission was observed in all crusted treatments exposed to anoxia, and this was probably a result of denitrification based on NO_x that had accumulated in the crust during oxic conditions.

Comparison of manure types

The type of manure can be crucial factors in reducing the extent of nitrogen lost (Bell et al 2016). The amount of N_2O produced from manure storage depends on type of manure management (Yamulki 2006; Merino et al 2011; Rzeźnik and Mielcarek 2014). Total manure emissions are the product of the amount of N excreted during storage multiplied by the associated emission factor for that manure management system and animal population (Crosson et al 2011).

A lower dietary protein content furthermore reduced N_2O emission rates in most manure types but increased CH_4 emission from urine-rich SLR. In deep litter manure, characterized by the highest C: N ratio, emission rates of total N, N_2O values were intermediate. Substantial emission of N_2O occurred with FYM. C: N ratio of manure was shown to be suitable to predict total N loss during storage in all manure types whereas urine N proportion and manure pH were only of use with liquid manures (Külling et al 2002).

Amon et al. (1998b) compared N_2O emission in solid and liquid manure management systems. In the tie-stall housing of dairy cows no differences were found between a SLR based and a straw based system. Only deep litter systems with straw showed higher N_2O emissions. This reflected the higher microbial biomass content and approximately neutral pH at FYM field (Mogge et al 1999).

N_2O synthesis needs close combination of aerobic and anaerobic areas. These heterogeneous conditions are not met within SLR but deep litter (Philippe and Nicks 2013). Therefore, for waste of a given N content, anaerobic lagoons will result in the least N_2O emissions whereas solid storage and dry-lot handling will promote emissions (Paustian et al 2004). The anaerobic nature of liquid manure systems reduces N_2O production (Kebreab et al 2006).

Majority of swine production systems use anaerobic or liquid-slurry systems for waste holding or disposal (Harper et al 2000). A model has been developed to predict pig manure evolution (mass, dry and organic matter, and N contents) and related gaseous emissions nitrous oxide (N_2O) from pig excreta up to manure stored before spreading. This model simulates contrasted management systems, including different options for housing (slatted floor or deep litter), outside storage of manure and treatment (anaerobic digestion, biological N removal processes, SLR with straw and solid manure composting (Rigolot et al 2010).

The results of Fournel et al (2012) showed that liquid manure from deep-pit housing systems produces greater emissions of nitrous oxide (N_2O) than natural and forced dried manure from belt housing systems. The study of Cabrera et al (1994) on N_2O emissions from poultry litter compared pellets or fine particles. Cumulative emission of N_2O was slightly higher for pelletized (6.8 % of applied N) than for fine-particle litter (5.5 %). Authors indicate that the effect of poultry litter physical characteristics on N_2O emissions can be expected to vary depending on the soil water regime (Cabrera et al 1994).

Application method

N_2O emissions are strongly dependent on the method and timing of fertilizer application. Manure incorporation

increased N_2O emissions and yield for the perennial system, but both effects were dependent on the interannual weather variability and crop growth (Webb et al 2014). High temperatures, high wind speed and low rainfall immediately following manure application promote emissions from manures containing a high amount of readily available N. Emissions of N_2O were significantly affected by the timing of manure application, with greatest N_2O emissions measured from manures applied and incorporated into bare soil in warmer and wetter autumn conditions. Mean annual N_2O emissions across all manure treatments were greater from autumn (2 kg N_2O–N ha^{-1}) than spring (0.35 kg N_2O – N ha^{-1}) applications (Bell et al 2016).

The more frequent soil application may increase N_2O emissions, if application occurs during prolonged periods with warm temperature, wet soil and low plant-N uptake. Therefore, a combination of decreased storage time in warm weather and extended winter storage is a viable option in many regions (Hristov et al 2013; Gerber et al 2013). Following field application, infiltration of liquid is influenced by manure organic matter, and retention of ammoniacal N at the soil surface will enhance NH_3 volatilization (Petersen and Sommer 2011).

Final considerations

Farms emit N_2O arising mainly from manure application to soil, faces deposition by grazing animals, or manure storages. The various pathways of N_2O formation described above also apply to the manure environment, but the potential for N_2O emissions will depend on manure management practice. Nitrification and denitrification rates of manure are affected by numerous soil and climatic or seasonal factors.

Emissions of N_2O are significantly affected by the timing of manure application, with greatest N_2O emissions measured from manures applied and incorporated into bare soil in warmer and wetter autumn conditions. Straw cover, floating crust and aeration of slurry showed negative environmental effects. An extended review revealed that more data are needed to better quantify emissions from manure management.

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References

Adler AA, Doole GJ, Romera AJ, Beukes PC (2015) Managing greenhouse gas emissions in two major dairy regions of New Zealand: A system-level evaluation. Agricultural Systems, 135:1–9.

Amon B, Amon T, Boxberger J, Pöllinger A (1998a) Emissions of NH3, N2O and CH4 from composted and anaerobically stored farmyard manure. In: Martinez J, Maudet MN (eds) Management Strategies for Organic Wastes in Agriculture. FAO European Cooperative Research Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture; Ramiran, pp 209–216.

Amon B, Boxberger J, Amon T, Zaussinger A, Pöllinger A (1998b) Emissions of NH3, N2O and CH4 from a tying stall for milking cows during storage of farmyard manure and after spreading. In Martinez J, Maudet MN (eds) Management Strategies for Organic Wastes in Agriculture. FAO European Cooperative Research Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture; Ramiran, pp 269–278.

Amon B, Amon T, Boxberger J, Alt Ch (2001) Emissions of NH3, N2O, and CH4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutrient Cycling Agroecosystems, 60:103–113.

Amon B, Kryvoruchko V, Amon T, Zechmeister-Boltenstern S (2006a) Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agriculture Ecosystems & Environment, 112:153–162.

Amon B, Kryvoruchko V, Moitzi G, Amon T (2006b) Greenhouse gas and ammonia emission abatement by slurry treatment. International Congress Series, 1293:295–298.

Amon B, Kryvoruchko V, Frohlich M, Amon T, Pollinger A, Mosenbacher I, Hausleitner A (2007) Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: housing and manure storage. Livestock Science, 112:199–207.

Bell MJ, Hinton NJ, Cloy JM, Topp CFE, Rees RM, Williams JR, Misselbrook TH, Chadwick DR (2016) How do emission rates and emission factors for nitrous oxide and ammonia vary with manure type and time of application in a Scottish farmland? Geoderma, 264:81–93.

Borhan MS, Capareda S, Mukhtar S, Faulkner WB, McGee R, Parnell Jr. CB (2011) Determining Seasonal Greenhouse Gas Emissions from Ground Level Area Sources in a Dairy Operation in Central Texas. Journal of Air and Waste Management, 61:786–795.

Brown HA, Wagner-Riddle C, Thurtell GW (2000) Nitrous oxide flux from solid dairy manure in storage as affected by water content and redox potential. Journal of Environmental Quality, 29:630–638.

Cabrera ML, Chiang SC, Merka WC, Pancorbo OC, Thompson SA (1994) Nitrous-oxide and carbon-dioxide emissions from pelletized and nonpelletized poultry litter incorporated into soil. Plant and Soil, 163:189–195.

Castillo AR, Kebreab E, Beever DE, France J (2000) A review of efficiency of nitrogen utilisation in lactating dairy cows and its relationship with environmental pollution. Journal of Animal and Feed Sciences, 9:1–32.

Chadwick DR, Pain BF, Brookmann SKE (2000) Nitrous oxide and methane emissions following application of animal manures to grassland. Journal of Environmental Quality, 29:277–287.

Chianese DS, Rotz CA, Richard TL (2009) Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. Transactions the ASABE, 52:1325–1335.

Clemens J, Trimborn M, Weiland P, Amon B (2006) Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. Agriculture, Ecosystems & Environment, 112:171–177.

Crosson P, Shalloo L, O'Brien D, Lanigan GJ, Foley PA, Boland TM, Kenny DA (2011) A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Animal Feed Science and Technology, 166–167:29–45.

Davidson EA (2009) The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. Nature Geoscience, 2:659–662.

Eckard RJ, Chen D, White RE, Chapman DF (2003) Gaseous nitrogen loss from temperate grass and clover dairy pastures in south eastern Australia. Australian Journal of Agriculture Research, 54:561–570.

Eckard RJ, Chapman DF, White RE (2007) Nitrogen balances in temperate perennial grass and clover dairy pastures in south-eastern Australia. Australian Journal of Agriculture Research, 58:1167–1173.

Fabbri C, Costa A, Guarino M, Valli L, Mazzotta V (2007) Ammonia, Methane, Nitrous Oxide and Particulate Matter Emissions from Two Different Buildings for Laying Hens. Biosystems Engineering, 97:441–455.

Fournel S, Pelletier F, Godbout S, Lagacé R, Feddes J (2012) Greenhouse Gas Emissions from Three Cage Layer Housing Systems. Animals, 2:1–15.

Gerber PJ, Hristov AN, Henderson B, Makkar H, Oh J, Lee C, Meinen R, Montes F, Ott T, Firkins J, Rotz A, Dell C, Adesogan AT, Yang WZ, Tricarico JM, Kebreab E, Waghorn G, Dijkstra J. Oosting S (2013) Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. Animal 7, 2:220–234.

Hansen MN, Henriksen K, Sommer SG (2006) Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: Effects of covering. Atmospheric Environment, 40:4172–4181.

Hansen R, Nielsen D, Schramm A, Nielsen L, Revsbech N, Hansen M (2009) Greenhouse gas microbiology in wet and dry straw crust covering pig slurry. Journal of Environmental Quality, 38:1311–1319.

Harper LA, Sharpe RR, Parkin TB (2000) Gaseous nitrogen emissions from anaerobic swine lagoons: ammonia, nitrous oxide, and dinitrogen gas. Journal of Environmental Quality, 29:1356–1365.

Harper LA, Sharpe RR, Parkin TB, Visscher de A, Cleemput van O, Byers FM (2004) Nitrogen Cycling through Swine Production Systems: Ammonia, Dinitrogen, and Nitrous Oxide Emissions. Journal of Environmental Quality, 33:1189–1201.

Hristov AN, Oh J, Firkins J, Dijkstra J, Kebreab E, Waghorn G, Makkar HPS, Adesogan AT, Yang W, Lee C, Gerber PJ, Henderson B, Tricarico JM (2013) Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. Journal of Animal Science, 91:5045–5069.

Jungbluth T, Hartung E, Brose G (2001) Greenhouse emissions from animal houses and manure stores. Nutrients Cycling Agroecosystem, 60:133–145.

Kebreab E, Clark K, Wagner-Riddle C, France J (2006) Methane and nitrous oxide emissions from Canadian animal agriculture: A review. Canadian Journal of Animal Science, 86:135–158.

Klein de CAM, Eckard RJ (2008) Targeted technologies for nitrous oxide abatement from animal agriculture. Australian Journal of Experimental Agriculture, 48:14–20.

Külling DR, Henzi HK, Krober TF, Neftel A, Sutter F, Lischer P, Kreuzer M (2001) Emissions of ammonia, nitrous oxide and methane from different types of dairy manure during storage as affected by dietary protein content. Journal of Agricultural Science, 137:S235–250.

Li C, Salas W, Zhang R, Krauter C, Rotz AC, Mitloehner F (2012) Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutrient Cycling in Agroecosystems, 93:163–200.

Li J, Shi Y, Luo J, Zaman M, Houlbrooke D, Ding W, Ledgard S, Ghani A (2014). Use of nitrogen process inhibitors for reducing gaseous nitrogen losses from land-applied farm effluents. Biology and Fertility of Soils, 50:133–145.

Mahimairaja S, Bolan NS, Hedley MJ (1995) Denitrification losses of N from fresh and composted manures. Soil Biology and Biochemistry, 27:1223–1225.

McGahan EJ, Phillips FA, Wiedemann SG, Naylor TA, Warren B, Murphy CM, Griffith DWT, Desservettaz M (2016). Methane, nitrous oxide and ammonia emissions from an Australian piggery with short and long hydraulic retention-time effluent storage. Animal Production Science, 56:1376–1389.

Merino P, Ramirez-Fanlo E, Arriaga H, del Hierro O, Artetxe A, Viguria M (2011) Regional inventory of methane and nitrous oxide emission from ruminant livestock in the Basque Country. Animal Feed Science and Technology, 166-167:628–640.

Middelaar Van CE, Berentsen PBM, Dijkstra J, De Boer IJM (2013) Evaluation of a feeding strategy to reduce greenhouse gas emissions from dairy farming: The level of analysis matters. Agricultural Systems, 121:9–22.

Mihina S, Kazimirova V, Copland TA (2012) Technology for farm animal husbandry. 1st Edition. Nitra: Slovak Agricultural University. 99 p.

Mogge B, Kaiser EA, Munch JC (1999) Nitrous oxide emissions and denitrification N-losses from agricultural soils in the Bornhoved Lake region: influence of organic fertilizers and land-use. Soil Biology and Biochemistry, 31:1245–1252.

Monaghan RM, Barraclough D (1993) Nitrous oxide and dinitrogen emissions from urine-affected soil under controlled conditions. Plant and Soil, 151:127–138.

Montes F, Meinen R, Dell C, Rotz A, Hristov AN, Oh J, Waghorn G, Gerber PJ, Henderson B, Makkar HPS, Dijkstra J (2013) Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. Journal of Animal Science, 91:5070–5094.

Mosier AR, Duxbury JM, Freney JR, Heinemeyer O, Minami K (1998) Assessing and mitigating N_2O emissions from agricultural soils. Climatic Change, 40:7–38.

Nielsen D, Schramm A, Revsbech N (2010) Oxygen distribution and potential ammonia oxidation in floating liquid manure crusts. Journal of Environmental Quality, 39:1813–1820.

Oenema O, Wrage N, Velthof G, Groenigen JW, Dolfing J, Kuikman P (2005) Trends in Global Nitrous Oxide Emissions from Animal Production Systems. Nutrient Cycling in Agroecosystems, 72:51–65.

Owen JJ, Silver WL (2015) Greenhouse gas emissions from dairy manure management: a review of field-based studies. Global Change Biology, 21:550–565.

Paustian K, Babcock B, Kling C, Hatfield J, Lal R, McCarl B, McLaughlin S, Post WM, Mosier A, Rice C, Robertson GP, Rosenberg NJ, Rosenzweig C, Schlesinger WH, Zilberman D (2004) In Agricultural Mitigation of Greenhouse Gases: Science and Policy Options; Council on Agricultural Science and Technology (CAST); Report #R141, ISBN 1- 887383-26-3.

Petersen SO, Lind AM, Sommer SG (1998) Nitrogen and organic matter losses during storage of cattle and pig manure. Journal of Agricultural Science, 130:69–79.

Petersen SO, Sommer SG (2011) Ammonia and nitrous oxide interactions: roles of manure organic matter management. Animal Feed Science and Technology, 166:503–513.

Philippe FX, Nicks B (2013) Emissions of ammonia, nitrous oxide and methane from pig houses: Influencing factors and mitigation techniques. In Reconciling livestock management to the environment - Applying Best Available Technique (BAT): From the lab to the farm. European Workshop: Reconciling the environment with livestock management, du 19 au 20 mars 2013, IRSTEA, Rennes, France. 10 p.

Pratt C, Redding M, Hill J, Shilton A, Chung M, Guieysse B (2014) Good science for improving policy: greenhouse gas emissions from agricultural manures. Animal Production Science, 55:691–701.

Redding M, Devereux J, Phillips F, Lewis R, Naylor T, Kearton T, Hill CJ, Weidemann S (2015) Field measurement of beef pen manure methane and nitrous oxide reveals a surprise for inventory calculations. Journal of Environmental Quality, 44:720–728.

Rigolot C, Espagnol S, Robin P, Hassouna M, Beline F, Paillat JM, Dourmad JY (2010) Modelling of manure production by pigs and NH3, N2O and CH4 emissions. Part II: effect of animal housing, manure storage and treatment practices. Animal, 4:1413–1424.

Rzeźnik W, Mielcarek P (2014) Comparison of greenhouse gas emissions during summer from deep litter and fully-slatted piggery. Agricultural Engineering, 151:169-177.

Rzeźnik W, Mielcarek P (2016) Greenhouse Gases and Ammonia Emission Factors from Livestock Buildings for Pigs and Dairy Cows. Polish Journal of Environmental Studies, 25:1-9.

Saggar S, Bolan NS, Bhandral R, Hedley CB, Luo J (2004) A review of emissions of methane, ammonia and nitrous oxide from animal excreta deposition and farm effluent application in grazed pastures. New Zealand Journal of Agricultural Research, 47:513–544.

Schils RLM, Eriksen J, Ledgard SF, Vellinga TV, Kuikman PJ, Luo J, Petersen SO, Velthof GL (2013) Strategies to mitigate nitrous oxide emissions from herbivore production systems. Animal, 7:29–40.

Sommer SG, Moller HB (2000) Emission of greenhouse gases during composting of deep litter from pig production - effect of straw content. Journal of Agricultural Science, 134:327–335.

Velthof GL, Mosquera J (2011) The impact of slurry application technique on nitrous oxide emission from agricultural soils. Agriculture, Ecosystems & Environment, 140:298–308.

Whalen SC, Phillips RL, Fischer EN (2000) Nitrous oxide emission from an agricultural field fertilized with liquid lagoonal swine effluent. Global Biogeochemical Cycles, 14:545-558.

Whalen SC (2000) Nitrous Oxide Emission from an Agricultural Soil Fertilized with Liquid Swine Waste or Constituents. Soil Science Society of America Journal, 64:781–789.

Webb J, Thorman R, Fernanda-Aller M, Jackson D (2014) Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types. Atmospheric Environment, 82:280–287.

Wolter M, Prayitno S, Schuchardt F (2004) Greenhouse gas emission during storage of pig manure on a pilot scale. Bioresource Technology, 95:235–244.

Yamulki S (2006) Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. Agriculture, Ecosystems & Environment, 112:140–145.

Abbreviations

C = carbon
CCH = closed chamber
CO_2 = carbon dioxide
CV = coefficient of variation
d = day
ds = days
DIM = days in milk
DL = deep litter
DM = dry mater
ds = days
FC = flux chamber
FMC = floating measuring chamber
FS = fully slatted
FTIR = Fourier transform infrared spectroscopy
FYM = farmyard manure
GC = gas chromatography
h = hour
LBW = live body weight
LU = live unit (500 kg of LBW)
M = month
MBIGA = mass balance method from 24 h gas sampling
MC = measuring chamber
MY = milk yield
MS = manure system
N = nitrogen
NH_3 = ammonium
ODC = open dynamic chamber
RC = respiration chamber
SLR = slurry
TDL = Tuneable Diode Laser absorption spectrometer
TMR = total mixed ration
yr = year
yrs = years
wk = week
wks = weeks

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Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality

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Waste from agricultural livestock operations has been a long-standing concern with respect to contamination of water resources, particularly in terms of nutrient pollution. However, the recent growth of concentrated animal feeding operations (CAFOs) presents a greater risk to water quality because of both the increased volume of waste and to contaminants that may be present (e.g., antibiotics and other veterinary drugs) that may have both environmental and public health importance. Based on available data, generally accepted livestock waste management practices do not adequately or effectively protect water resources from contamination with excessive nutrients, microbial pathogens, and pharmaceuticals present in the waste. Impacts on surface water sources and wildlife have been documented in many agricultural areas in the United States. Potential impacts on human and environmental health from long-term inadvertent exposure to water contaminated with pharmaceuticals and other compounds are a growing public concern. This workgroup, which is part of the Conference on Environmental Health Impacts of Concentrated Animal Feeding Operations: Anticipating Hazards—Searching for Solutions, identified needs for rigorous ecosystem monitoring in the vicinity of CAFOs and for improved characterization of major toxicants affecting the environment and human health. Last, there is a need to promote and enforce best practices to minimize inputs of nutrients and toxicants from CAFOs into freshwater and marine ecosystems. *Key words:* **ecology, human health, poultry, swine, water contaminants, wildlife.** *Environ Health Perspect* **115:308–312 (2007). doi:10.1289/ehp.8839 available via** *http://dx.doi.org/* **[Online 14 November 2006]**

Background and Recent Developments

Concentrated animal feed operations and water quality. Animal cultivation in the United States produces 133 million tons of manure per year (on a dry weight basis) representing 13-fold more solid waste than human sanitary waste production [U.S. Environmental Protection Agency (U.S. EPA) 1998]. Since the 1950s (poultry) and the 1970s–1980s (cattle, swine), most animals are now produced for human consumption in concentrated animal feeding operations (CAFOs). In these industrialized operations, the animals are held throughout their lives at high densities in indoor stalls until they are transported to processing plants for slaughter. There is substantial documentation of major, ongoing impacts on aquatic resources from CAFOs, but many gaps in understanding remain.

Contaminants detected in waste and risk of water contamination. Contaminants from animal wastes can enter the environment through pathways such as through leakage from poorly constructed manure lagoons, or during major precipitation events resulting in either overflow of lagoons and runoff from recent applications of waste to farm fields, or atmospheric deposition followed by dry or wet fallout (Aneja 2003). The magnitude and direction of transport depend on factors such as soil properties, contaminant properties, hydraulic loading characteristics, and crop management practices (Huddleston 1996). Many contaminants are present in livestock wastes, including nutrients (Jongbloed and Lenis 1998), pathogens (Gerba and Smith 2005; Schets et al. 2005), veterinary pharmaceuticals (Boxall et al. 2003; Campagnolo et al. 2002; Meyer 2004), heavy metals [especially zinc and copper; e.g., Barker and Zublena (1995); University of Iowa and Iowa State Study Group (2002)], and naturally excreted hormones (Hanselman et al. 2003; Raman et al. 2004). Antibiotics are used extensively not only to treat or prevent microbial infection in animals (Kummerer 2004), but are also commonly used to promote more rapid growth in livestock (Cromwell 2002; Gaskins et al. 2002; Liu et al. 2005). In addition, pesticides such as dithiocarbamates are applied to sprayfields (Extension Toxicology Network 2003). Although anaerobic digestion of wastes in surface storage lagoons can effectively reduce or destroy many pathogens, substantial remaining densities of microbial pathogens in waste spills and seepage can contaminate receiving surface- and groundwaters (e.g., Burkholder et al. 1997; Mallin 2000). Pharmaceuticals can remain present as parent compounds or degradates in manure and leachates even during prolonged storage. Improper disposal of animal carcasses and abandoned livestock facilities can also contribute to water quality problems. Siting of livestock operations in areas prone to flooding or where there is a shallow water table increases the potential for environmental contamination.

The nutrient content of the wastes can be a desirable factor for land application as fertilizer for row crops, but overapplication of livestock wastes can overload soils with both macronutrients such as nitrogen (N) and phosphorous (P), and heavy metals added to feed as micronutrients (e.g., Barker and Zublena 1995). Overapplication of animal wastes or application of animal wastes to saturated soils can also cause contaminants to move into receiving waters through runoff and to leach through permeable soils to vulnerable aquifers. Importantly, this may happen even at recommended application rates. As examples, Westerman et al. (1995) found 3–6 mg nitrate (NO_3)/L in surface runoff from sprayfields that received swine effluent at recommended rates; Stone et al. (1995) measured 6–8 mg total inorganic N/L and 0.7–1.3 mg P/L in a stream adjacent to swine effluent sprayfields. Evans et al. (1984) reported 7–30 mg NO_3/L in subsurface flow draining a sprayfield for swine wastes, applied at recommended rates. Ham and DeSutter (2000) described export rates of up to 0.52 kg ammonium m^{-2} $year^{-1}$ from lagoon seepage; Huffman and Westerman (1995) reported that groundwater near swine waste lagoons averaged 143 mg inorganic N/L, and estimated export rates at 4.5 kg inorganic N/day. Thus, nutrient losses into receiving waters can be excessive relative to levels (~ 100–200 μg inorganic N or P/L)

This article is part of the mini-monograph "Environmental Health Impacts of Concentrated Animal Feeding Operations: Anticipating Hazards—Searching for Solutions."

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known to support noxious algal blooms (Mallin 2000). In addition to contaminant chemical properties, soil properties and climatic conditions can affect transport of contaminants. For example, sandy, well-drained soils are most vulnerable to transport of nutrients to underlying groundwater (Mueller et al. 1995). Nutrients can also readily move through soils under wet conditions (McGechan et al. 2005).

Presence of contaminants in water sources. The presence of many contaminants from livestock waste has been documented in both surface water and groundwater supplies in agricultural areas within the United States (e.g., Campagnolo et al. 2002; Kolpin et al. 2002; Meyer 2004). Urban wastewater streams also contain these contaminants, and efforts to accurately determine sources of contamination are under way (Barnes et al. 2004; Cordy et al. 2004; Kolpin DW, unpublished data). The U.S. Geological Survey (USGS) began pilot surveillance programs for organic wastewater contaminants in 1999 and expanded that effort to a national scale over the past 5 years (Kolpin et al. 2002). Recent USGS efforts have focused specifically on water quality in agricultural locations (Kolpin DW, unpublished data). Nutrient levels have been detected in high parts per million (milligrams per liter) levels; pharmaceuticals and other compounds are generally measured in low levels (ppb [micrograms per liter]). In Europe, surveillance efforts conducted in Germany documented the presence of veterinary pharmaceuticals in water resources (Hirsch et al. 1999).

Animal wastes are also rich in organics and high in biochemical oxygen-demanding materials (BOD); for example, treated human sewage contains 20–60 mg BOD/L, raw sewage contains 300–400 mg BOD/L, and swine waste slurry contains 20,000–30,000 mg BOD/L (Webb and Archer 1994). Animal wastes also carry parasites, viruses, and bacteria as high as 1 billion/g (U.S. EPA 1998). Swine wastes contain > 100 microbial pathogens that can cause human illness and disease [see review in Burkholder et al. (1997)]. About one-third of the antibiotics used in the United States each year is routinely added to animal feed to increase growth (Mellon et al. 2001). This practice is promoting increased antibiotic resistance among the microbial populations present and, potentially, increased resistance of naturally occurring pathogens in surface waters that receive a portion of the wastes.

Contaminant impacts. Some contaminants pose risks for adverse health impacts in wildlife or humans. The effects of numerous waterborne pathogens on humans are well known, although little is known about potential impacts of such microorganisms on aquatic life. With respect to nutrients, excessive phosphorus levels can contribute to algal blooms and cyanobacterial growth in surface waters used for recreation and as sources of drinking water. Research is beginning to investigate the environmental effects, including endocrine disruption and antibiotic resistance issues (Burnison et al. 2003; Delepee et al. 2004; Fernandez et al. 2004; Halling-Sorensen et al. 2003; Sengelov et al. 2003; Soto et al. 2004; Wollenberger et al. 2000). However, knowledge is limited in several crucial areas. These areas include information on metabolites or environmental degradates of some parent compounds; the environmental persistence, fate, and transport and toxicity of metabolites or degradates (Boxall et al. 2004); the potential synergistic effects of various mixtures of contaminants on target organisms (Sumpter and Johnson 2005); and the potential transport and effects from natural and synthetic hormones (Hanselman et al. 2003; Soto et al. 2004). Further, limited monitoring has been conducted of ecosystem health in proximity to CAFOs, including monitoring the effects on habitats from lagoon spills during catastrophic flooding (Burkholder et al. 1997; Mallin et al. 1997; Mallin et al. 2000).

Ecologic and wildlife impacts. Anoxic conditions and extremely high concentrations of ammonium, total phosphorus, suspended solids, and fecal coliform bacteria throughout the water column for approximately 30 km downstream from the point of entry have been documented as impacts of waste effluent spills from CAFOs (Burkholder et al. 1997; Mallin et al. 2000). Pathogenic microorganisms such as *Clostridium perfringens* have been documented at high densities in receiving surface waters following CAFO waste spills (Burkholder et al. 1997). These degraded conditions, especially the associated hypoxia/anoxia and high ammonia, have caused major kills of freshwater fish of all species in the affected areas, from minnows and gar to largemouth bass, and estuarine fish, including striped bass and flounder (Burkholder et al. 1997). Waste effluent spills also stimulated blooms of toxic and noxious algae. In freshwaters, these blooms include toxic and noxious cyanobacteria while in estuaries, harmful haptophytes and toxic dinoflagellates arise. Most states monitor only water-column fecal coliform densities to assess whether waterways are safe for human contact. World Health Organization (WHO) guidelines for cyanobacteria in recreational water are 20,000 cyanobacterial cells/mL, which indicates low probability of adverse health effects, and 100,000 cyanobacterial cells/mL, which indicates moderate probability of adverse health effects (WHO 2003). Yet fecal bacteria and other pathogenic microorganisms typically settle out to the sediments where they can thrive at high densities for weeks to months following CAFO waste effluent spills (Burkholder et al. 1997).

The impacts from CAFO pollutant loadings to direct runoff are more substantial after such major effluent spills or when CAFOs are flooded and in direct contact with surface waters (Wing et al. 2002). Although the acute impacts are often clearly visible—dead fish floating on the water surface, or algal overgrowth and rotting biomass—the chronic, insidious, long-term impacts of commonly accepted practices of CAFO waste management on receiving aquatic ecosystems are also significant (U.S. EPA 1998). One purpose of manure storage basins is to reduce the N content of the manure through volatilization of ammonia and other N-containing molecules. Many studies have shown, for example, that high nutrient concentrations (e.g., ammonia from swine CAFOs, or ammonia oxidized to NO_3, or phosphorus from poultry CAFOs) commonly move off-site to contaminate the overlying air and/or adjacent surface and subsurface waters (Aneja et al. 2003; Evans et al. 1984; Sharpe and Harper 1997; Sharpley and Moyer 2000; Stone et al. 1995; U.S. EPA 1998; Webb and Archer 1994; Westerman et al. 1995; Zahn et al. 1997). Inorganic N forms are added to the atmosphere during spray practices, and both ammonia and phosphate can also adsorb to fine particles (dust) that can be airborne. The atmospheric depositions are noteworthy, considering that a significant proportion of the total ammonium from uncovered swine effluent lagoons and effluent spraying (an accepted practice in some states) reenters surface waters as local precipitation or through dry fallout (Aneja et al. 2003; U.S. EPA 1998, 2000). The contributed nutrient concentrations from the effluent greatly exceed the minimal levels that have been shown to promote noxious algal blooms (Mallin 2000) and depress the growth of desirable aquatic habitat species (Burkholder et al. 1992). The resulting chronically degraded conditions of nutrient overenrichment, while not as extreme as during a major waste spill, stimulate algal blooms and long-term shifts in phytoplankton community structure from desirable species (e.g., diatoms) to noxious species.

A summary of the findings from a national workshop on environmental impacts of CAFOs a decade ago stated that there was "a surprising lack of information about environmental impacts of CAFOs to adjacent lands and receiving waters" (Thu K, Donham K, unpublished data). Although the knowledge base has expanded since that time, especially regarding adverse effects of inorganic N and P overenrichment and anoxia, impacts of many CAFO pollutants on receiving aquatic ecosystems remain poorly understood. As examples, there is poor understanding of the impacts of fecal bacteria and other microbial pathogens from CAFO waste effluent contamination on

aquatic communities; impacts of antibiotic-resistant bacteria created from CAFO wastes on aquatic life; impacts of organic nutrient forms preferred by certain noxious plankton; impacts from the contributed pesticides and heavy metals; and impacts from these pollutants acting in concert, additively or synergistically. This lack of information represents a critical gap in our present ability to assess the full extent of CAFO impacts on aquatic natural resources.

Despite their widespread use, antibiotics have only recently received attention as environmental contaminants. Most antibiotics are designed to be quickly excreted from the treated organism. Thus, it is not surprising that antibiotics are commonly found in human and animal waste (Christian et al. 2003; Dietze et al. 2005; Glassmeyer et al. 2005; Meyer 2004) and in water resources affected by sources of waste (Glassmeyer et al. 2005; Kolpin et al. 2002). Although some research has been conducted on the environmental effects from antibiotics (e.g., Brain et al. 2005; Jensen et al. 2003), much is yet to be understood pertaining to long-term exposures to low levels of antibiotics (both individually and as part of complex mixtures of organic contaminants in the environment). The greatest risks appear to be related to antibiotic resistance (Khachatourians 1998; Kummerer 2004) and natural ecosystem functions such as soil microbial activity and bacterial denitrification (Costanzo et al. 2005; Thiele-Bruhn and Beck 2005).

Human health impacts. Exposure to waterborne contaminants can result from both recreational use of affected surface water and from ingestion of drinking water derived from either contaminated surface water or groundwater. High-risk populations are generally the very young, the elderly, pregnant women, and immunocompromised individuals. Recreational exposures and illnesses include accidental ingestion of contaminated water that may result in diarrhea or other gastrointestinal tract distress from waterborne pathogens, and dermal contact during swimming that may cause skin, eye, or ear infections. Drinking water exposures to pathogens could occur in vulnerable private wells; under normal circumstances community water utilities disinfect water sufficiently before distribution to customers. Cyanobacteria (blue–green algae) in surface water can produce toxins (e.g., microcystins) that are known neurotoxins and hepatotoxins. Acute and chronic health impacts from these toxins can occur from exposures to both raw water and treated water (Carmichael et al. 2001; Rao et al. 2002). Removal of cyanotoxins during drinking water treatment is a high priority for the drinking water industry (Hitzfield et al. 2000; Rapala et al. 2002). The WHO has set a provisional drinking water guideline of 1 μg microcystin-LR/L (Chorus and Bartram 1999). While there are no drinking water standards in the United States for cyanobacteria, they are on the U.S. EPA Unregulated Contaminant Monitoring Rule List 3 (U.S. EPA 2006).

Exposure to chemical contaminants can occur in both private wells and community water supplies, and may present health risks. High nitrate levels in water used in mixing infant formula have been associated with risk for methemoglobinemia (blue-baby syndrome) in infants under 6 months of age, although other health factors such as diarrhea and respiratory disease have also been implicated (Ward et al. 2005). The U.S. EPA drinking water standard of 10 mg/L NO_3–N and the WHO guideline of 11 mg/L NO_3–N were set because of concerns about methemoglobinemia. (Note: "nitrate" refers to nitrate–nitrogen). Epidemiologic studies of noncancer health outcomes and high nitrate levels in drinking water have reported an increased risk of hyperthyroidism (Seffner 1995) from long-term exposure to levels between 11–61 mg/L (Tajtakova et al. 2006). Drinking water nitrate at levels < 10 mg/L has been associated with insulin-dependent diabetes (IDDM; Kostraba et al. 1992), whereas other studies have shown an association with IDDM at nitrate levels > 15 mg/L (Parslow et al. 1997) and > 25 mg/L (van Maanen et al. 2000). Increased risks for adverse reproductive outcomes, including central nervous system malformations (Arbuckle et al. 1988) and neural tube defects (Brender et al. 2004; Croen et al. 2001), have been reported for drinking water nitrate levels < 10 mg/L.

Anecdotal reports of reproductive effects of nitrate in drinking water include a case study of spontaneous abortions in women consuming high nitrate water (19–26 mg/L) from private wells (Morbidity and Mortality Weekly Report 1996).

While amassing experimental data suggest a role for nitrate in the formation of carcinogenic *N*-nitroso compounds, clear epidemiologic findings are lacking on the possible association of nitrate in drinking water with cancer risk. Ecologic studies have reported mixed results for cancers of the stomach, bladder, and esophagus (Barrett et al. 1998; Cantor 1997; Eicholzer and Gutzwiller 1990; Morales-Suarez-Varela et al. 1993, 1995) and non-Hodgkin lymphoma (Jensen 1982; Weisenburger 1993), positive findings for cancers of the nasopharynx (Cantor 1997), prostate (Cantor 1997), uterus (Jensen 1982; Thouez et al. 1981), and brain (Barrett et al. 1998), and negative findings for ovarian cancer (Jensen 1982; Thouez et al. 1981). Positive findings have generally been for long-term exposures at > 10 mg/L nitrate. Case–control studies have reported mixed results for stomach cancer (Cuello et al. 1976; Rademacher et al. 1992; Yang et al. 1998); positive results for non-Hodgkin lymphoma at > 4 mg/L nitrate (Ward et al. 1996) and colon cancer at > 5 mg/L (De Roos et al. 2003); and negative results for cancers of the brain (Mueller et al. 2001; Steindorf et al. 1994), bladder (Ward et al. 2003), and rectum (De Roos et al. 2003), all at < 10 mg/L. Cohort studies have reported no association between nitrate in drinking water and stomach cancer (Van Loon et al. 1998); positive associations with cancers of the bladder and ovary at long-term exposures > 2.5 mg/L (Weyer et al. 2001); and inverse associations with cancers of the rectum and uterus, again at > 2.5 mg/L (Weyer et al. 2001).

Exposure to low levels of antibiotics and other pharmaceuticals in drinking water (generally at micrograms per liter or nanograms per liter) represent unintentional doses of substances generally used for medical purposes to treat active disease or prevent disease. The concern is more related to possible cumulative effects of long-term low-dose exposures than on acute health effects (Daughton and Ternes 1999). A recent study conducted in Germany found that the margin between indirect daily exposure via drinking water and daily therapeutic dose was at least three orders of magnitude, concluding that exposure to pharmaceuticals via drinking water is not a major health concern (Webb et al. 2003). It should be noted that when prescribing medications, providers ensure patients are not taking incompatible drugs, but exposure via drinking water is beyond their control.

Endocrine-disrupting compounds are chemicals that exhibit biological hormonal activity, either by mimicking natural estrogens, by canceling or blocking hormonal actions, or by altering how natural hormones and their protein receptors are made (McLachlan and Korach 1995). Although very low levels of estrogenic compounds can stimulate cell activity, the potential for human health effects, such as breast and prostate cancers, and reproductive effects from exposure to endocrine disruptors, is in debate (Weyer and Riley 2001).

Workshop Recommendations

Priority research needs.

- Ecosystems monitoring: Systematic sustained studies of ecosystem health in proximity to large CAFOs are needed, including effects of input spikes during spills or flooding events.
- Toxicologic assessment of contaminants: Identification and prioritization of contaminants are needed to identify those that are most significant to environmental and public health. Toxicity studies need to be conducted to identify and quantify contaminants

(including metabolites), and to investigate interactions (synergistic, additive, and antagonistic effects).

- Fate and transport: Studies of parent compounds and metabolites in soil and water must be conducted, and the role of sediment as a carrier and reservoir of contaminants must be evaluated.
- Surveillance programs: Programs should be instituted to assess private well water quality in high-risk areas. Biomonitoring programs should be designed and implemented to assess actual dose from environmental exposures.

Translation of science to policy.

- Wastewater and drinking water treatment: Processes for water treatment must be monitored to ensure adequate removal or inactivation of emerging contaminants.
- Pollution prevention: Best management practices should be implemented to prevent or minimize release of contaminants into the environment.
- Education: Educational materials should be continued to be developed and distributed to agricultural producers.

References

Aneja VP, Nelson DR, Roelle PA, Walker JT. 2003. Agricultural ammonia emissions and ammonium concentrations associated with aerosols and precipitation in the southeast United States. J Geophys Res 108(D4):ACH12-1–12-11.

Arbuckle TE, Sherman GJ, Corey PN, Walters D, Lo B. 1988. Water nitrates and CNS birth defects: a population-based case-control study. Arch Environ Health 43:162–167.

Barker JC, Zublena JP. 1995. Livestock Manure Nutrient Assessment in North Carolina. Final Report. Raleigh, NC: North Carolina Agricultural Extension Service, North Carolina State University.

Barnes KK, Christenson SC, Kolpin DW, Focazio MJ, Furlong ET, Zaugg SD, et al. 2004. Pharmaceuticals and other organic wastewater contaminants within a leachate plume downgradient of a municipal landfill. Ground Water Monitoring Rev 24:119–126.

Barrett JH, Parslow RC, McKinney PA, Law GR, Forman D. 1998. Nitrate in drinking water and the incidence of gastric, esophageal, and brain cancer in Yorkshire, England. Cancer Causes Control 9:153–159.

Boxall ABA, Kolpin DW, Halling-Sorenson B, Tolls J. 2003. Are veterinary medicines causing environmental risks? Environ Sci Technol 37:286A–294A.

Boxall ABA, Sinclair CJ, Fenner K, Kolpin DW, Maund SJ. 2004. When synthetic chemicals degrade in the environment. Environ Sci Technol 38:369A–375A.

Brain RA, Wilson CJ, Johnson DJ, Sanderson H, Bestari K, Hanson ML, et al. 2005. Effects of a mixture of tetracyclines to *Lemna gibba* and *Miriophyllum sibiricum* evaluated in aquatic microcosms. Environ Pollution 138:425–442.

Brender JD, Olive JM, Felkner M, Suarez L, Marckwardt W, Hendricks KA. 2004. Dietary nitrites and nitrates, nitrosable drugs, and neural tube defects. Epidemiology 15:330–336.

Burkholder JM, Mallin MA, Glasgow HB, Larsen LM, McIver MR, Shank GC, et al. 1997. Impacts to a coastal river and estuary from rupture of a large swine waste holding lagoon. J Environ Qual 26:1451–1466.

Burkholder JM, Mason KM, Glasgow HB. 1992. Water-column nitrate enrichment promotes decline of eelgrass (*Zostera marina* L.): evidence from seasonal mesocosm experiments. Mar Ecol Prog Ser 81:163–178.

Burnison BK, Hartmann A, Lister A, Servos MR, Ternes T, Van der Kraak G. 2003. A toxicity identification evaluation approach to studying estrogenic substances in hog manure and agricultural runoff. Environ Toxicol Chem 22:2243–2250.

Campagnolo ER, Johnson KR, Karpati A, Rubin CS, Kolpin DW, Meyer MT, et al. 2002. Antimicrobial residues in animal waste and water resources proximal to large-scale swine and poultry feeding operations. Sci Total Environ 299:89–95.

Cantor KP. 1997. Drinking water and cancer. Cancer Causes Control 8:292–308.

Carmichael WW, Azevedo SMFO, An JS, Molica RJR, Jochimsen EM, Lau S, et al. 2001. Human fatalities from cyanobacteria: chemical and biological evidence for cyanotoxins. Environ Health Perspect 109:663–668.

Chorus I, Bartram J, eds. 1999. Toxic Cyanobacteria in Water—A Guide to their Public Health Consequences, Monitoring and Management. Geneva:World Health Organization. Available: http://www.who.int/water_sanitation_health/resourcesquality/toxicyanbact/en/ [accessed 5 January 2007].

Christian T, Schneider RJ, Barber HA, Skutlarek D, Meyer GT, Goldrach HE. 2003. Determination of antibiotic residues in manure, soil, and surface waters. Acta Hydrochim Hydrobiol 31:36–44.

Cordy G, Duran N, Bower H, Rice R, Kolpin DW, Furlong ET, et al. 2004. Do pharmaceuticals, pathogens, and other organic wastewater compounds persist when wastewater is used for recharge? Ground Water Monitoring Rev 24:58–69.

Costanzo SD, Murby J, Bates J. 2005. Ecosystem response to antibiotics entering the aquatic environment. Marine Pollut Bull 51:218–223.

Croen LA, Todoroff K, Shaw GM. 2001. Maternal exposure to nitrate from drinking water and diet and risk for neural tube defects. Am J Epidemiol 153:325–331.

Cromwell GL. 2002. Why and how antibiotics are used in swine production. Anim Biotechnol 13:7–27.

Cuello C, Correa P, Haenszel W, Gordillo G, Brown C, Archer M, et al. 1976. Gastric cancer in Columbia. 1. Cancer risk and suspect environmental agents. J Natl Cancer Inst 57:1015–1020.

Daughton CG, Ternes TA. 1999. Pharmaceuticals and personal care products in the environment: agents of subtle change? Environ Health Perspect 107:907–938.

Delepee R, Pouliquen H, Le Bris H. 2004. The bryophyte *Fontinalis antipyretica* Hedw. bioaccumulates oxytetracycline, flumequine and oxolinic acid in the freshwater environment. Sci Total Environ 322:243–253.

De Roos AJ, Ward MH, Lynch CF, Cantor KP. 2003. Nitrate in public water supplies and the risk of colon and rectum cancers. Epidemiology 14:640–649.

Dietze JE, Scribner EA, Meyer MT, Kolpin DW. 2005. Occurrence of antibiotics in water from 13 fish hatcheries, 2001–03. Intern J Environ Anal Chem 85:1141–1152.

Eicholzer M and Gutzwiller F. 1990. Dietary nitrates, nitrites and *N*-nitroso compounds and cancer risk: a review of the epidemiologic evidence. Nutr Rev 56:95–105.

Evans, RO, Westerman PW, Overcash MR. 1984. Subsurface drainage water quality from land application of swine lagoon effluent. Trans Am Soc Agric Eng 27:473–480.

Extension Toxicology Network. 2003. Exotoxnet—A Pesticide Information Project of the Cooperative Extension Offices of Cornell University, Michigan State University, Oregon State University, and the University of California at Davis. U.S. Department of Agriculture, Extension Service, and the National Agricultural Pesticide Impact Assessment Program. Available: http://ace.orst.edu/info/extoxnet/ [accessed 26 September 2005].

Fernandez C, Alonso C, Babin MM, Pro J, Carbonell G, Tarazona JV. 2004. Ecotoxicological assessment of doxycycline in aged pig manure using multispecies soil systems. Sci Total Environ 323:63–69.

Gaskins HR, Collier CT, Anderson DB. 2002. Antibiotics as growth promoters: mode of action. Anim Biotechnol 13:29–42.

Gerba CP, Smith JE Jr. 2005. Sources of pathogenic microorganisms and their fate during land application of wastes. J Environ Qual 34:42–48.

Glassmeyer ST, Furlong ET, Kolpin DW, Cahill JD, Werner SL, Meyer MT, et al. 2005. Transport of chemical and microbial contaminants from known wastewater discharges: Potential for use as indicators of human fecal contamination. Environ Sci Technol 39:5157–5169.

Halling-Sorensen B, Sengelov G, Ingerslev F, Jensen LB. 2003. Reduced antimicrobial potencies of oxytetracycline, tylosin, sulfadiazine, streptomycin, ciprofloxacin, and olaquindox due to environmental processes. Arch Environ Contam Toxicol 44:7–16.

Ham JM, DeSutter TM. 2000. Toward site-specific design standards for animal-waste lagoons: protecting ground water quality. J Environ Qual 29:1721–1732.

Hanselman TA, Graetz DA, WIlkie AC. 2003. Manure-borne estrogens as potential environmental contaminants: a review. Environ Sci Technol 37:5471–5478.

Hirsch R, Ternes T, Haberer K, Kratz KL. 1999. Occurrence of antibiotics in the aquatic environment. Sci Total Environ 225:109–118.

Hitzfield BC, Hoger SJ, Dietrich DR. 2000. Cyanobacterial toxins: Removal during drinking water treatment, and human risk assessment. Environ Health Perspect 108:113–122.

Huddleston JH. 1996. How Soil Properties Affect Groundwater Vulnerability to Pesticides Contamination. Oregon State Extension Service. Available: http://wwwagcomm.ads.orst.edu/AgComWebFile/EdMat/EM8559.pdf [accessed 26 September 2005].

Huffman RL, Westerman PW. 1995. Estimated seepage losses from established swine waste lagoons in the lower coastal plain of North Carolina. Transact Am Soc Agric Eng 38:449–453.

Jensen K, Krogh PH, Sverdup LE. 2003. Effects of the antibacterial agents tiamulin, olanquindox and metronidazole and the antihelminthic ivermectin on the soil invertebrate species *Folsomia fimeteria* (Collembola) and *Enchytraeus crypticus* (Enchytraeidae). Chemosphere 50:437–443.

Jensen OM. 1982. Nitrate in drinking water and cancer in northern Jutland, Denmark, with special reference to stomach cancer. Ecotoxicol Environ Saf 9:258–267.

Jongbloed AW, Lenis NP. 1998. Environmental concerns about animal manure. J Anim Sci 76:2641–2648.

Khachatourians GG. 1998. Agricultural use of antibiotics and the evolution and transfer of antibiotic-resistant bacteria. Can Med Assoc J 159:1129–1136.

Kolpin DW, Furlong ET, Meyer MT, Thurman EM, Zaugg SD, Barber LB, et al. 2002. Pharmaceuticals, hormones and other organic wastewater contaminants in U.S. streams, 1999–2000: a national reconnaissance. Environ Sci Technol 36:1202–1211.

Kostraba JN, Gay EC, Rewers M, Hamman RF. 1992. Nitrate levels in community drinking waters and risk of IDDM: an ecological analysis. Diabetes Care 15:1505–1508.

Kummerer K. 2004. Resistance in the environment. J Antimicrob Chemother 54:311–320.

Liu X, Miller GY, McNamara PE. 2005. Do antibiotics reduce production risk for U.S. pork producers? J Agric Appl Econ 37:565–575.

Mallin MA. 2000. Impacts of industrial-scale swine and poultry production on rivers and estuaries. Am Sci 88:26–37.

Mallin, MA, Burkholder JM, Shank GC, McIver MR, Glasgow HB, Springer J, et al. 1997. Comparative impacts of effluent from poultry and swine waste holding lagoon spills on receiving rivers and tidal creeks. J Environ Qual 26:1622–1631.

McGechan MB, Lewis DR, Hooda PS. 2005. Modelling through-soil transport of phosphorous to surface waters from livestock agriculture at the field and catchment scale. Sci Total Environ 344:185–199.

McLachlan JA, Korach KS. 1995. Symposium on Estrogens in the Environment, III. Environ Health Perspect 103:3–4.

Mellon MC, Benbrook C, Benbrook KL. 2001. Estimates of antimicrobial abuse in livestock. Cambridge, MA:Union of Concerned Scientists.

Meyer MT. 2004. Use and Environmental Occurrence of Veterinary Pharmaceuticals in the United States. In: Pharmaceuticals in the Environment: Sources, Fate, Effects, and Risks (Kummerer K, ed). New York:Springer-Verlag,155–163.

Morales-Suarez-Varela M, Llopis-Gonzales A, Tejerizo-Perez ML, Ferrandiz Ferragud J. 1993. Concentration of nitrates in drinking water and its relationship with bladder cancer. J Environ Pathol Toxicol Oncol 12:229–236.

Morales-Suarez-Varela MM, Llopis-Gonzalez A, Tejerizo-Perez ML. 1995. Impact of nitrates in drinking water on cancer mortality in Valencia, Spain. Eur J Epidemiol 11:15–21.

Morbidity and Mortality Weekly Report (MMWR). 1996. Spontaneous abortions possibly related to ingestion of nitrate-contaminated well water—LaGrange County, Indiana, 1991–1994. MMWR 45:569–572.

Mueller BA, Newton, K, Holly EA, Preston-Martin S. 2001. Residential water source and the risk of childhood brain tumors. Environ Health Perspect 109:551–556.

Mueller DK, Hamilton PA, Helsel DR, Hitt KJ, Ruddy BC. 1995.

Nutrients in groundwater and surface water of the United States—an analysis of data through 1992. US Geological Survey Water Resour Invest Rep 95–4031.

Parslow RC, McKinney PA, Law GR, Staines A, Williams B, Bodansky HJ. 1997. Incidence of childhood diabetes mellitus in Yorkshire, northern England, is associated with nitrate in drinking water: an ecological analysis. Diabetologia 40(5):550–556.

Rademacher JJ, Young TB, Kanarek MS. 1992. Gastric cancer mortality and nitrate levels in Wisconsin drinking water. Arch Environ Health 47:292–294.

Raman DR, Williams EL, Layton AC, Burns RT, Easter JP, Daugherty AS, et al. 2004. Estrogen content of dairy and swine wastes. Environ Sci Technol 38:3567–3573.

Rao PV, Gupta N, Bhaskar AS, Jayaraj R. 2002. Toxins and bioactive compounds from cyanobacteria and their implications on human health. J Environ Biol 23:215–224.

Rapala J, Lahti K, Rasanen LA, Esala AL, Niemela SI, Sivonen K. 2002. Endotoxins associated with cyanobacteria and their removal during drinking water treatment. Water Res 36:2627–2635.

Schets FM, During M, Italiaander R, Heijnen L, Rutjes SA, van der Zwaluw WK, et al. 2005. *Escherichia coli* O157:H7 in drinking water from private water supplies in the Netherlands. Water Res 39:4485–4493.

Seffner W. 1995. Natural water contents and endemic goiter. Zantralblatt Hyg Umwelt 196:381–398.

Sengelov G, Agerso Y, Halling-Sorensen B, Baloda SB, Andersen JS, Jensen LB. 2003. Bacterial antibiotic resistance levels in Danish farmland as a result of treatment with pig manure slurry. Environ Int 28:587–595.

Sharpe RR and Harper LA. 1997. Ammonia and nitrous oxide emissions from sprinkler irrigation applications of swine effluent. J Environ Qual 26:1703–1706.

Sharpley A, Moyer B. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J Environ Qual 29:1462–1469.

Soto AM, Calabro JM, Prechtl NV, Yau AY, Orlando EF, Daxenberger A, et al. 2004. Androgenic and estrogenic activity in water bodies receiving cattle feedlot effluent in eastern Nebraska, USA. Environ Health Perspect 112:346–352.

Steindorf K, Schlehofer B, Becher H, Hornig G, Wahrendorf J. 1994. Nitrate in drinking water: a case-control study on primary brain tumours with an embedded drinking water survey in Germany. Int J Epidemiol 23:451–457.

Stone KC, Hunt PG, Coffey SW, Matheny TA. 1995. Water quality status of A USDA water quality demonstration project in the Eastern Coastal Plain. J Soil Wat Conserv 50:567–571.

Sumpter JP, Johnston AC. 2005. Lessons from endocrine disruption and their application to other issues concerning trace organics in the aquatic environment. Environ Sci Technol 39:4321–4332.

Tajtakova M, Semanova Z, Tomkova Z, Szokeova E, Majoroa J, Radikova Z, et al. 2006. Increased thyroid volume and frequency of thyroid disorders signs in schoolchildren from nitrate polluted area. Chemosphere 62:559–564.

Thiele-Bruhn S, Beck IC. 2005. Effects of sulfonamide and tetracycline antibiotics on soil microbial activity and microbial biomass. Chemosphere 59:457–465.

Thouez J-P, Beauchamp Y, Simard A. 1981. Cancer and the physicochemical quality of drinking water in Quebec. Soc Sci Med 15D:213–223.

University of Iowa and Iowa State Study Group. 2002. Iowa Concentrated Animal Feeding Operations Air Quality Study. Iowa City, IA:The University of Iowa College of Public Health.

U.S. EPA. 1998. Environmental Impacts of Animal Feeding Operations. Washington, DC:U.S. Environmental Protection Agency, Office of Water, Standards and Applied Sciences Division. Available: http://www.epa.gov/ostwater/guide/feedlots/envimpct.pdf [accessed 26 September 2005].

U.S. EPA. 2000. Deposition of Air Pollutants to the Great Waters. 3rd Report to the U.S. Congress. (1) Section A. Washington, DC:U.S. Environmental Protection Agency.

U.S. EPA. 2006. Approved Methods for Unregulated Contaminants. U.S. Environmental Protection Agency. Available: http://www.epa.gov/ogwdw/methods/unregtbl.html [accessed 5 January 2007].

Van Loon AJM, Botterweck AAM, Goldbohm RA, Brants HAM, van Klaveren JD, van den Brandt PA. 1998. Intake of nitrate and nitrite and the risk of gastric cancer: a prospective cohort study. Br J Cancer 7:129–135.

Van Maanen JM, Albering HJ, de Kok TM, van Breda SG, Curfs DM, Vermeer IT, et al. 2000. Does the risk of childhood diabetes mellitus require revision of the guideline values for nitrate in drinking water? Environ Health Perspect 108(5):457–461.

Ward MH, Cantor KP, Riley D, Merkle S, Lynch CF. 2003. Nitrate in public water supplies and risk of bladder cancer. Epidemiology 14:183–190.

Ward MH, deKok TM, Levallois P, Brender J, Gulis G, Nolan BT, et al. 2005. Workgroup report: drinking-water nitrate and health—recent findings and research needs. Environ Health Perspect 113:1607–1614.

Ward MH, Mark SD, Cantor KP, Weisenburger DD, Correa-Villasenore A, Zahm SH. 1996. Drinking water and the risk of non-Hodgkin's lymphoma. Epidemiology 7:465–471.

Webb J, Archer JR. 1994. Pollution of soils and watercourses by wastes from livestock production systems. In: Pollution in Livestock Production Systems (Dewi IA, Axford RFE, Marai IFM, Omed HM, eds). Oxfordshire, UK:CABI Publishing, 189–204.

Webb S, Ternes T, Gibert M, Olejniczak K. 2003. Indirect human exposure to pharmaceuticals via drinking water. Toxicol Lett 142:157–167.

Weisenburger D. 1993. Potential health consequences of ground-water contamination of nitrates in Nebraska. Nebr Med J 78:7–10.

Westerman PW, Huffman RL, Feng JS. 1995. Swine-lagoon seepage in sandy soil. Transact ASAE 38(6):1749–1760.

Weyer P, Riley D. 2001. Endocrine Disruptors and Pharmaceuticals in Drinking Water. Denver, CO:AWWA Research Foundation and the American Water Works Association.

Weyer PJ, Cerhan JR, Kross BC, Hallberg GR, Kantamneni J, Breuer G, et al. 2001. Municipal drinking water nitrate level and cancer risk in older women: the Iowa Women's Health Study. Epidemiology 11:327–338.

WHO. 2003. Algae and cyanobacteria in fresh water. In: Guidelines for Safe Recreational Water Environments. Vol 1: Coastal and Fresh Waters. Geneva:World Health Organization, 136–138.

Wing S, Freedman S, Band, L. 2002. The potential impact of flooding on confined animal feeding operations in eastern North Carolina. Environ Health Perspect 110:387–391.

Wollenberger L, Halling-Sorensen B, Kusk KO. 2000. Acute and chronic toxicity of veterinary antibiotics to *Daphnia magna*. Chemosphere 40:723–730.

Yang C-Y, Cheng M-F, Tsai S-S, Hsieh Y-L. 1998. Calcium, magnesium, and nitrate in drinking water and gastric cancer mortality. Jpn J Cancer Res 89:124–130.

Zahn JA, Hatfield JL, Do YS. 1997. Characterization of volatile organic emissions and wastes from a swine production facility. J Environ Qual 26:1687–1696.

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Disclaimer

The statements and conclusions in this Report are those of the contractor and not necessarily those of the California Department of Food and Agriculture. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

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EXECUTIVE SUMMARY

The California dairy industry is complex, diverse and dynamic. It grew rapidly for decades before reaching its current size about a dozen years ago, producing about 40 billion pounds of milk and more than $6 billion per year in farm revenue. It has long faced and continues to face complex economic and environmental issues that demand informed, research-based and data-driven public and private responses. The trend for increased herd size and decreased number of herds translates to increased fixed costs per cow in smaller herds when capital improvements are developed.

California's efforts to reduce greenhouse gas emissions have identified methane emissions reductions targets of 40 percent from dairy manure handling from 2013 levels, by 2030. The state initiated two major programs, the Dairy Digester Development and Research Program and the Alternative Manure Management Program, that seek to facilitate voluntary reductions in methane emissions from dairy manure handling in California.

Study Objectives

This research study was sponsored by the California Department of Food and Agriculture to examine relationships between manure handling practices, dairy farm size and methane emissions reductions options. The study begins by describing detailed technical relationships in California dairies. It goes on to quantify manure methane emissions by manure handling practices and dairy farm size and reviews technical applicability of strategies for methane emissions reductions used on farms of different sizes and housing design.

The study turns next to the economic relationships and implications of the highlighted practices. The approach developed a detailed mathematical simulation model calibrated to data on costs associated with manure handling practices, dairy farm size and housing categories. Impacts were projected for different potential configurations of manure handling practices on milk production and methane emissions for each herd size category. Specifically, analyses evaluated how manure handling patterns link to dairy farm size and methane emissions patterns when alternative time horizons were considered.

Manure Management Practices

Detailed description of housing and herd sizes show that 91 percent of mature dairy cows (lactating and dry) in California were in the Central Valley. About 20 percent of mature cows in this region were in herds of 1,035 mature cows or fewer and about 20 percent were in herds with 4,120 mature cows or more. These represent the lower and upper two deciles of Central Valley mature dairy cattle. Since herd housing affects manure handling and emissions, it is important to recognize that about three-fourths of mature cows were in dairies with freestall housing systems (where cows are fed and may lie down in stalls within open sided, roofed permanent structures) about one-fourth were in non-freestall housing (where cows are mainly in corrals, often with shaded areas and an adjacent feeding apron). A large majority of herds (about 74 percent) had some form of gravity or mechanical separation of solids from liquid manure components, which contributed to reduced methane emissions.

About 6 percent of California's mature cows were in Southern California, mostly in San Bernardino and Riverside Counties. These were non-freestall facilities and manure was handled predominantly in a dry form (scraped from corrals and removed regularly). Northern California coastal dairies represent 3 percent of mature cows. These are smaller dairies when compared with dairies from other parts of California. When cattle were pastured, no manure was collected. When cattle were not pastured, solid, liquid or slurry manure was collected. The amount of manure collected varied by location, weather and grazing opportunities.

Analyses of Alternative Manure Management Program practices for freestall and non-freestall facilities by different herd sizes were conducted. At any given herd size, freestall dairies were assumed to collect 2.4 times more manure and had greater emissions when compared with non-freestall dairies. This provided the greatest opportunity for emissions reductions. Across manure treatment technologies, weeping walls had the greatest emissions reductions (about 43 percent) followed by screw press separators (about 24 percent) and stationary inclined screens (about 16 percent). Partial flush to scrape conversion at 30 percent of manure scraped was similar to emissions reductions from screw press separators.

The Alternative Manure Management Program has been used by many producers to install methane emissions reduction technologies. As a percent of herds within a herd size category, less than 10 percent of herds sought funding in herds less than 751 cows and about 15 percent or more of freestall herds sought funding for herd sizes 751 to 2,000. Non-freestall dairies had about 15 percent application rate for herds between 1,751 and 2,500 cows. In the Central Valley far more projects were funded on freestall dairies than non-freestall dairies. More freestall and non-freestall dairies received funding with fewer than 1,250 cows. In the Central Valley 70 percent of funded projects included solid separation. Dairies in the North Coast were funded for compost bedded pack barns (34 percent of projects funded) and solid separation (39 percent). The difference in preferences was a function of how animals were housed and manure was managed.

To achieve useful and interpretable economic simulations, California dairy farms were characterized in one of seven groups of producers, based on herd-size and housing. Different herd distributions of mature cattle were used for economic analysis to incorporate the greatest amount of existing data. Herd sizes of fewer than 500 cows per herd, between 500 and 2,000 cows per herd and greater than 2,000 cows per herd were used to allow greatest inclusion of existing economic data. One group, with fewer than 500 cows per herd, represented organic milk production. The organic farms used more pasture, had much higher costs and sold into a separate high-priced local market. The six groups of conventional dairies included two housing types—freestall and non-freestall, for each of three herd size categories. For these analyses, the seven groups with estimated share of statewide total cows were:

- Organic (less than 2% of cows)
- Freestall, less than 500 cows (about 3.6% of cows)
- Non-freestall, less than 500 cows (about 1.3% of cows)
- Freestall, between 500 cows and 2,000 cows (about 32.9% of cows)
- Non-freestall, between 500 cows and 2,000 cows (about 8.2% of cows)

- Freestall, more than 2,000 cows (43.9% of cows), and
- Non-freestall, more than 2,000 cows (8.8% of cows)

These shares are approximate and were used only as base for the economic simulations that are reported as percentage changes from the baseline. For the smaller herds especially, the precise share has negligible impact on any results. We used data on size distributions in the U.S. Census of Agriculture as discussed in Chapter 7, and information summarized in Section 4.2 related to housing.

In this report herd size and housing groups are used to categorize herds based on manure handling, emissions and projected economic outcomes. The terms upper or lower two deciles or larger and smaller herd sizes (more than 2,000 cows or less than 500 cows) are used in separate sections of the report. These three herd size categories are used to organize the data, analyses and simulation outcomes. However, these are not definitions of large or small dairy farms because the physical and economic relationships in dairy farming are not so simple. Whether a dairy farm is considered larger or smaller depends on many complex considerations. Farms with the same number of cows may be considered larger or smaller depending on the economic and physical context and the purposes of the categorization or analyses. For example, milk production, an alternative measure of farm size, accommodates difference in animal productivity. Other considerations include vertical integration—the degree to which the farm produces its own feed and replacement heifers, and the degree to which it further processes milk into consumer products. For some purposes milk revenue is a useful measure of the size of dairy farms, but that measure can vary from period to period by 50 percent or more depending on the price of milk. Financial value added, the economic returns to own-supplied inputs, can also be a useful measure of dairy farm size that subsumes cow productivity, vertical integration and revenue. Therefore, it is often misleading to refer to a farm with more or fewer cows as simply large or small.

For each group methane emissions reductions and cost change were evaluated compared to a 2013 baseline when some share of dairies in that group shift to an alternative manure handling practice.

The baseline manure collection was a flush system for the conventional dairies and a scrape system for the organic dairies. The five alternative practices evaluated included:

- Compost bedded pack barn (dairies with less than 500 cows)
- Solid separation, with open solar drying
- Solid separation, with composting
- Scrape conversion, and
- Lagoon digesters (not for dairies with less than 500 cows or non-freestall dairies with less than 2000 cows).

Main Results for Economic Impacts of Methane Emissions Reductions

Adopting the manure handling practices listed above would reduce manure methane emissions per cow. These practices were also more costly than the baseline practice. The economic logic underlying the detailed model derived in Chapter 4 is straightforward. Manure handling practices that are costly relative to the baseline reduce potential

profitability and economic viability of adopting dairy farms. Groups with larger cost increases per unit of milk production lose out in competition with groups that experience smaller cost increases. In our simulations, as these economic pressures play out over time, they have impacts on aggregate emissions, costs and herd size distributions.

Both manure emissions reductions per cow and cost per cow differed by group. For example, for freestall dairies with less than 500 cows that adopted a compost bedded pack barn, the estimated methane emissions reductions was almost 87 percent compared to the baseline technology. The reduction in emissions was about 65 percent for the non-freestall herds, which had lower emissions in the baseline. The compost bedded pack barn practice raised the cost of milk production by 9 percent per cow—a very large increase in costs, equivalent to half of labor costs.

Adopting a digester reduced methane emissions by almost 83 percent on freestall dairies and by almost 58 percent for the non-freestall dairies. In the scenarios examined, adoption of digesters added very little cost per cow to the dairy farm due to current public (California Climate Investment funds) and private (digester developer company) investments. To date, different business models have been used for digester development with State funds contributing up to 50 percent of the development cost. The remainder of the financing has ranged from 100 to zero percent dairy producer equity owned. Under current practices and policies, non-farm companies have partially financed the construction and operation of some digesters in exchange for use of biogas generated. The biogas produced qualifies for credits under the federal Renewable Fuel Standard and the California Low Carbon Fuel Standard programs.

Alternative manure handling practices affected emissions differently and provided opportunities for dairies with smaller herds to contribute to methane emissions reductions. Installation of digesters on smaller facilities in particular is location specific and requires connection to a cluster biogas line with an end use identified. Not all dairies are located well for digester installation and these dairies are likely to rely on alternative manure management practices to accomplish emissions reductions. Additionally, business longevity risks must also be considered prior to anaerobic digester development. The fixed costs per cow is increasingly greater for smaller dairies to install methane mitigation practices. This is due to both the smaller number of cows over which fixed costs are distributed as well as the increase in project costs due to rising costs of resources needed (concrete, steel, labor).

A series of adoption scenarios were examined across six groups and the manure handling practices were compared to the baseline. Each scenario evaluated the effect of a specific rate of adoption of one of the alternative practices by each herd size group.

Adoption rates for the 2021 base line or zero scenario were identified for what was anticipated in summer of 2019. Scenarios evaluated 30 percent (Scenarios 1 and 3), 40 percent (Scenario 2), variable between 5 and 60 percent (Scenarios 4 and 5) rate of adoption within groups. Implications were calculated within each group for farm costs, price of milk, quantity of milk production and methane emissions reductions. Aggregating across the groups identified impacts—in percentage terms—of a scenario of practice adoption rate on statewide milk production and methane emissions reductions.

For example, Scenario zero considered a set of practices that approximated what will likely to be in place by 2021 after the adoption of new manure handling practices by California dairies since 2013. These assumptions were made pre-COVID-19. As a result of this adoption pattern, and with a 5-year adoption horizon, milk production decreased by about one percent for the smaller dairies and rises slightly for the larger dairies, while the California milk price remains unaffected. Overall methane emissions decline by about 23 percent for all the groups. In this scenario, about 82 percent of the overall decline in methane is contributed by the digester adoption among the freestall dairies with more than 2,000 cows.

Scenario 5 used different adoption rates of the same practices as Scenario zero. With the adoption pattern of Scenario 5, use of only the less costly manure handling practices by the dairies with less than 2,000 cows just about eliminates the reduction in milk production on these dairies observed in scenarios that assume adoption of higher cost practices. In Scenario 5, milk production is essentially unchanged from the baseline for any group and neither total milk production nor the farm price of milk change for California. Because of the low-cost manure handling practices used in Scenario 5, dairies with less than 500 cows contribute very little to aggregate reduction in methane emissions. Under Scenario 5, digester adoption among herds with more than 500 cows contributes 99 percent of the total emission reduction. Aggregate methane reduction reached almost 35 percent over a five-year horizon.

It is useful to put the impacts of adoption of manure management practices that reduce methane emissions in the context of the changes underway in the California dairy industry, especially in the evolution in patterns of dairy farm size. For many years, in California and throughout the United States, consolidation within the industry resulted in fewer and larger dairy herds while aggregate milk production has risen.

In California, for several decades until 2007, the number of dairy herds was decreasing while aggregate milk production and mature cow numbers were increasing. Since 2007, California's total milk production has been relatively stable. This report has considered the economic situation of the California dairy industry in the context of national and global milk markets. The California dairy industry also competes for land and water, especially in the San Joaquin Valley, with industries that produce tree nuts, other tree and vine crops as well as vegetables. The median projection (recognizing inherent uncertainty) used similar aggregate number of milk cows (pre-COVID-19) to be roughly constant looking into the future.

Against this backdrop of a stable number of cows overall, detailed Census of Agriculture data were used for the past three decades to estimate underlying trends in number of cows in each of the three size categories among our groups. Over this period, the number of cows in herds of fewer than 500 cows has declined by an average of about 5 percent per year. This estimated rate was used as part of the baseline to consider the impact of the Scenarios of manure handing practices listed above.

The impacts of the underlying trend toward dairy herd consolidation is more strongly noticeable the longer the time horizon. The empirical logic is clear. As time passes, some of the dairies with fewer than 500 cows exit, while other dairies within this category move into larger herd size categories. The net result is fewer cows in herds with less than

500 mature cows, and more cows in herds with more than 500 cows. A potential exception to the gradual reduction in the number of smaller herds is related to the organic segment found mostly in north coast counties of California. This is a small share of the industry and follows a somewhat different set of supply and demand patterns. In our long-term Scenarios, the number of cows in the organic segment remained unchanged. This specific assumption about organic farms has no measurable impact on the aggregate results.

The next analysis evaluated impacts of changes in manure management practices coinciding with the herd size trends operating over time. For example, Scenario zero, represented the approximate pattern of manure handling practices already adopted and implemented. Data from the 10-year forward projection identified milk production declines among dairies with fewer than 500 cows by about 42 percent. In that scenario, emissions decline only slightly faster, by about 44 percent. Milk production on dairies with between 500 and 2,000 cows decreased by about 14 percent and methane emissions from those herds decreased by about 20 percent. But for the dairies with more than 2,000 cows, underlying trends cause milk production to rise by about 14 percent, while methane emissions decreased by 25 percent. Thus, under Scenario zero the larger herds produce much more milk, but because emissions per cow declines, they produce much less methane in aggregate.

In Scenario zero, overall milk production remains roughly unchanged while California methane emissions are reduced by 25 percent. The reduction in emissions is caused by a combination of two factors. The first is the reduction in manure methane emissions per cow due to adoption of manure handling practices. The second is the shift in the number of cows from practices with higher manure emissions per cow to practices with lower manure emissions per cow. This pattern is stronger over the 20-year horizon with 66 percent decrease in milk production on dairies with fewer than 500 cows and 26 percent increase in milk production on dairies with more than 2,000 cows. Over 20 years, aggregate methane emissions decline by about 27 percent for Scenario zero.

It is useful to consider effects of the underlying herd size trends on results of Scenario 5. Scenario 5 assumed adoption of relatively low-cost manure handling practices on about 10 percent of the dairies with fewer than 500 cows and adoption of digesters on a significant share of the dairies with more than 500 cows, especially the largest freestall herds. When the Scenario 5 pattern of manure handling practices is applied to the baseline with underlying trends toward larger herd sizes, the two forces that each reduce methane emissions reinforce each other.

Over the 10-year horizon milk production on the dairies with less than 500 cows decreased by about 40 percent and methane emissions decreased similarly. However, the freestall dairies with between 500 and 2,000 cows now also reduce manure methane emissions per cow as they adopt digesters. Emissions decreased by 29 percent as milk production decreased by 14 percent on these dairies. On the freestall dairies with more than 2,000 cows, which operate with most of the cows in the state, milk production increased by 15 percent and methane emissions was reduced by 48 percent. Overall methane emissions decreased by about 37 percent.

These impacts are even larger for the 20-year horizon. After 20 years, because of underlying trends in the economics of dairy farm size, milk production and methane emissions among farms with fewer than 500 cows decreased by about 65 percent. Meanwhile production decreased by

about 26 percent on the farms with between 500 and 2,000 cows. Milk production increased by 26 percent on the farms with more than 2,000 cows. Despite producing more milk, methane emissions decreased by 43 percent on the freestall dairies with more than 2,000 cows. These farms have a 66 percent digester adoption rate under Scenario 5. The result is that overall, methane emissions from manure management for the state decreased by about 40 percent.

Conclusion

Economic impact of methane emissions reductions varies by herd size and manure management practices employed. Methane emissions from California dairy manure management are declining with adoption of alternative manure management practices and installation of dairy digester projects with biogas capture and use. Continued funding of Alternative Manure Management Program practices provides assistance to dairy producers regardless of herd size to participate in and contribute to manure methane emissions reductions. It is likely that without public funds smaller dairies will be disproportionately impacted by higher fixed costs per cow associated with mitigation measure practice installation resulting in faster migration to either larger herds or cessation of business.

PROJECT INTRODUCTION

Assembly Bill 32 (AB 32, 2006) began California's greenhouse gas (GHG) reductions path. The first step was to determine a statewide GHG emissions limit equivalent to 1990 and return to 1990 emissions 2020. It further established a goal to reduce emissions 80 percent below the 1990 amounts by 2050. Senate Bill 32 (SB 32, 2016) provided an interim target of a reduction of GHG to 40 percent below the 1990 inventory by 2030. As a result of Senate Bill 1383 (SB 1383, 2016) the California Air Resources Board was directed to approve and implement a comprehensive strategy to reduce emissions of short-lived climate pollutants to achieve a reduction in methane and hydrofluorocarbon gasses by 40% and anthropogenic black carbon by 50 percent below 2013 levels by 2030. The California Air Resources Board (CARB) (CARB, 2014) identified that methane was nine percent of California's total GHG emissions. Methane is an important component of the GHG family and is far more potent in global warming potential than carbon dioxide, especially in a shorter term, 20-year horizon. Fifty-eight percent of the state's methane emissions have been attributed to agricultural sources, primarily dairy manure (25 percent), dairy enteric (20 percent), non-dairy enteric (10 percent) and rice (3 percent) (CARB, 2017).

California is home to about 1.7 million dairy cows and nearly as many replacement heifers (USDA, 2020). Cattle consume, digest and convert feed to human edible food (milk and meat). Cattle consume forages (non-human edible food) that, along with other feed (predominantly co-products and by-products of other commodities), are digested by microorganisms in the rumen, which acts as a large fermentation vat. Feces and urine are excreted and comprise manure. Manure managed under anaerobic conditions produces methane.

Dairy operations provide critical economic contributions to local rural communities in the form of steady, year-round on-farm employment, allied industry careers beyond the farm gate, and local community civic support. Understanding the whole-farm environmental and economic impacts of implementing methane emission reduction strategies for both small and large operations is needed to foster wise investment of time, management and capital resources.

Similar sized dairy operations have similar housing and manure handling practices. Yet large variations exist in how individual facilities are operated. Local climate (precipitation, fog and solar radiation) play a role in manure handling. Dairies of similar size also differ in current equipment, manure system handling capacity, and resource management. Labor available for manure handling and management is variable and increasingly becoming less available.

Dairy managers, industry leaders and policy makers need credible and relevant information regarding multiple methane emissions reduction options and strategies, including associated analyses of costs and revenues. Although several research projects have recently begun to better understand the methane emission reduction potential of various manure management strategies, none include a thorough assessment for the applicability of those strategies to operations based on size, scale and existing production facility configuration. Both short- and long-term economic impact assessment of methane reduction potential for small and large dairies is needed to allow for optimal investment and greatest environmental benefit.

Investment of public and private funds is necessary to reduce manure methane emissions. Baseline information regarding manure management and treatment are unknown statewide. Previous work (Meyer et al., 1997; Meyer et al., 2011) surveyed manure management in Glenn and Tulare Counties and Tulare, Fresno and Madera Counties. These studies focused on management practices irrespective of herd size.

It is unknown if the best methane reduction strategies are similar regardless of dairy size. Understanding baseline manure management conditions and cost-effective and appropriate methane emission reductions strategies for both smaller and larger dairy facilities is paramount to achieving the 40% reduction goal and ensuring efficient and effective investment of resources. Each of seven tasks were completed to provide the required analyses.

This project specifically addressed the question of how smaller dairies may differ from larger dairies in manure management practices and potential methane emissions reduction strategies. Each of seven tasks was analyzed and is presented in subsequent chapters. For the purpose of these analyses two teams of researchers were used. Tasks 1 through 3 were conducted by investigators familiar with dairy housing and manure management. Tasks 4 through 7 were conducted by investigators familiar with dairy economic analyses.

Project tasks:

1. Categorize California dairies by herd size, animal housing, manure treatment and storage practices in order to evaluate best metrics for small and large dairies.
2. Quantify estimated methane emissions as low, high and average based on herd size (small and large), housing design and manure handling categories.
3. Review strategies and technologies currently or potentially used to reduce manure methane emissions for applicability to small and large dairies.
4. Compare economic impact of methane emission reduction strategies identified on small dairies versus large dairies.
5. Compare whole-farm economic and environmental impacts of methane emission reduction strategies identified on small and large dairies.
6. Compare methane reduction potential at small and large dairies, presented as a cost-benefit analysis of environmental and economic impacts on an estimated 1, 5 and 10-year scale.
7. Model and project sustainability (especially economic feasibility) of small dairies in California over an estimated 5, 10 and 20-year time scale in consideration of new environmental regulations including reductions for methane emissions, inflation, interest rates, feed prices, dairy product prices, labor costs and location of the dairies.

CHAPTER 1 CATEGORIZE CALIFORNIA DAIRIES BY HERD SIZE, ANIMAL HOUSING, MANURE TREATMENT AND STORAGE PRACTICES IN ORDER TO EVALUATE BEST METRICS FOR SMALL AND LARGE DAIRIES.

Introduction

Dairy farmers are dedicated and innovative individuals. Herd size (number of mature and replacement animals) and productivity changed as new advances occurred. Mechanization during the industrialization of agriculture first reduced the labor needed to grow crops. Later, electrification of rural areas led to mechanical milking machines and then refrigeration of milk (bulk tanks). Research breakthroughs in sperm collection and preservation led to artificial insemination. Nutritional research led to greater understanding of animal needs and the ability to formulate rations for specific energy, protein, and fiber requirements of cattle. As herd sizes increased, utilization of allied industry services also increased. What was once done by farm labor became a fee for service contract.

The face of today's dairy industry began during the time of farm specialization in the 1950s and 1960s (Blayney, 2002). Defining smaller or larger herd sizes is relative to herd size distribution at a specific point in time. Information about changing herd size by geographic area is available since the United States Department of Agriculture (USDA) conducts a census every five years. The USDA National Agricultural Statistics Service (NASS) identifies facilities by size. In 1978, the USDA NASS data for milk cow herd size included a category for 100 or more dairy cattle. Additional categories were added as herd sizes grew and the number of herds declined. In 1992 and 1997, the 500 to 999 and 1,000 or more categories were added. The 2007 census included a 2,500 and greater category, and in 2017 the analysis included a category for herds with 5,000 or greater head. In each of these census years discussed, the smallest category was 1 to 9 milk cows.

In addition to the USDA NASS, there are regulatory Acts with herd size definition. The Reauthorization of the Coastal Zone Management Act (1990) identified specific categories of nonpoint source pollution for each coastal state to incorporate into their programs. Small dairies were defined as 20 to 69 head (28 to 97 animal units). Small dairies were to design and implement manure management systems that included collection and control of waters contacting feed and manure nutrients up to and including a 25-year, 24-hour storm event. Large dairies (70 or greater head; greater than 98 animal units) were required to incorporate specific storage structure design criteria for facility wastewater and the runoff from the 25-year, 24-hour storm event. Both sized facilities needed appropriate existence and management of waste utilization facilities. Separate Federal Regulations, the Clean Water Act, as amended (1972), defined the term animal feeding operation as a lot or facility where animals have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period and crops, vegetation, forage growth, or post-harvest residues are not sustained in the normal growing season over any portion of the lot or facility. Herd size categories were defined as: small (less than 200), medium (between 200 and 699) and large (700 and more) mature dairy cow herds, whether milked or dry. Although many modifications to the Clean Water Act have

occurred since 1972, these categories and their numeric definitions have remained in place (US EPA, 2012).

All California dairies generate liquid manure from the milking parlor. This includes water used for udder hygiene, to clean milk contact surfaces and to wash down the milking barn area. Federal and State regulations prescribe mandatory equipment and barn cleaning required to maintain Grade A status. Manure and milk residue collected is transferred to liquid manure storage. Milk barn water generation was evaluated and highly variable in the Central Valley (Meyer et al., 2006). Once milk is harvested it goes through plate coolers for heat exchange to transfer heat from milk (chill) to water or propylene glycol before milk enters the bulk tank. Inclusion of ice chillers on dairies during the last 15 years has reduced the fresh water needed to cool milk and ultimately reduced the total volume of the liquid waste stream.

Animal housing and facility infrastructure are designed and built with specific manure collection and handling practices. Two predominant housing types exist in California (Meyer et al., 2011). Freestall housing consists of an open barn structure typically joined with a corral. The barn roof covers a drive through feeding lane as well as animal housing. Freestalls are open cubicles that provide sufficient space for animals to rest comfortably on a clean, dry environment and minimize injuries to animals. These are aligned in a row perpendicular to the feeding lane. Cubicles are aligned so animals on one side of a pen are parallel to one another and are nose to nose with animals on the opposite side of their cubicle. The number of rows of freestalls within a pen may vary (two rows head to head is most common). A center drive lane is present with animal pens on either side. This lane is utilized to deliver feed to cattle. Feedline misters or soakers are used to modify ambient temperature and cool cattle when temperatures are elevated. Freestalls are bedded with dried manure usually. Almond shells or rice hulls may be used to extend dried manure use. Sand is an alternative which is not available or cost effective in most locations. Sand requires additional management to minimize damage to pumps in the manure system. Manure deposited on concrete surfaces associated with freestalls is collected and transported to liquid manure storage structures.

Non-freestall housing consists of earthen lots or corrals. Drive lanes are present for feed delivery. Similar to freestall facilities, cattle stand on concrete feed aprons to access feed. Manure deposited on earthen lots dries and is managed in its solid form. Manure deposited on the concrete feed apron may be scraped into earthen lots and distributed to maximize solar drying or may be flushed or scraped for liquid/slurry storage.

Manure collected in the liquid form will gravity flow to the liquid storage structure. Liquid structures may be designed for storage or treatment depending on initial retention time and volatile solids loading rate design criteria. In some instances, pumping is required to get manure to its final destination. Solid liquid separation is accomplished by mechanical (stationary inclined, vibrating or inclined screen with drag conveyor paddles) or gravity systems (concrete basins with small dewatering area, small or large earthen basins, or large concrete lined basin with large side dewatering surfaces made of tri-bar flooring or other durable material). When solid liquid separation is used it prevents entry of solids into the storage/treatment structure.

Modifications to manure collection, transfer, treatment and storage must be done with a complete analysis of the ramifications to the entire manure stream management and potential impacts to animal husbandry.

Key to understanding potential use of methane emission reduction strategies is understanding how manure is managed and if differences in manure management exist based on herd size. The approach for this Task was to obtain and harmonize existing public data to describe animal housing and manure management systems present on California dairies.

Materials and Methods

Task 1.1: Obtain records of dairies from Regional Water Quality Control Boards and San Joaquin Valley Air Pollution Control District to identify herd sizes, animal housing and manure management system design.

Data of mature cows (milking and dry) from Regional Water Quality Control Boards (Region) 1 (North Coast), 2 (San Francisco Bay), 5 (Central Valley), 6 (Lahontan) and 8 (Santa Ana), San Joaquin Air Pollution Control District (SJVAPCD), and the State Water Resources Control Board (SWRCB) Fee Unit were obtained and harmonized (Figure 1.1). Direct dairy information was not obtained from other regions as they have less than 5 commercial dairies each. These herds were identified from the SWRCB Fee Unit or personal communication. The term mature cows is used to represent lactating and dry (not lactating) cows at dairies. This term is used by Water Regulatory Agencies in California. Lists for Grade A and Grade B dairies were obtained from the California Department of Food and Agriculture (2018). List contents were current as of November, 2018. Lists have no animal information inserted and were revised based on November, 2019 SWRCB Fee Unit information when dairies not on the list could be identified and cross referenced to the previous list from the California Department of Food and Agriculture. No one list contained all information needed to fully describe herd size, animal housing and manure management systems. San Joaquin Valley Air Pollution Control District permit information (2016) provided information on housing and some information on manure management. The animal numbers represented facility capacity numbers and not necessarily actual animals at the facility. The SWRCB Fee Unit list was used to identify mature cow herd size, the basis for fee calculations. All lists were used to verify location and when possible herd housing and manure management characteristics. An aerial analysis of each dairy was conducted to verify select information in SJVAPCD permits, animal housing and manure collection/handling systems. Inconsistencies were resolved by roadside verification of facilities or by contacting an individual familiar with the facility. Figure 1.1 depicts data harmonization processes.

Facilities were binned by 250 mature cattle intervals. Intervals were identified to capture roughly the lower and upper two deciles, and the remainder of mature cow numbers for dairies in Region 5. Figure bin values differ in Region 5 for herd sizes over 3,000 mature cows due to fewer herd numbers.

Task 1.2: Determine the use of mechanical or gravity separation systems, liquid manure storage impoundments or anaerobic digesters on farm related to facility size and type.
Analysis evaluated aerial images of dairies in the Central Valley to identify presence of gravity separation systems (small or large) and manure storage/treatment ponds. Presence or absence and actual number of separation and storage or treatment ponds were documented. Analysis of each dairy and its manure treatment process was completed for each dairy in the Central Valley to determine the use of mechanical or gravity separation systems, liquid manure storage impoundments or on-farm anaerobic digesters. The analysis of Google Earth images was coded to identify if liquid manure storage structures were likely to be handled as gravity separation (solids removed on some regular interval) or as liquid storage. Gravity separation systems (GSS) were further refined by looking at facilities chronologically to see if solids were removed on any regular interval or if structural surface area size was narrow enough and sized appropriately to be managed as a separation system. Small gravity separation systems were identified based on professional judgment and assumed to have solids cleaned out less than every six months. Large gravity separation systems were assumed to have solids cleaned out more than every six months. Presence of mechanical separators was identified by data in SJVAPCD permits and verified with aerial analysis. However, functionality of separators was not determined. Presence of anaerobic digesters or use of vacuum manure collection systems was identified by SJVAPCD permit information.

Detailed information regarding manure management is not part of the Annual Reports dairy operators submit to their Regional Water Quality Control Board (dairies in Regions 1, 2, 6, and 8). Professional experience from farm visits made prior to this project was used to describe manure management practices in these Regions.

Task 1.3: Evaluate and analyze herd size by manure collection, treatment and storage categories.
Integrate information from Task 1.1 and 1.2 to represent manure collection, treatment and storage categories by herd size.

Task 1.4: Evaluate a subset of Waste Management Plan volatile solids loading rate and liquid storage retention time, volume and surface area by herd size and/or pounds milk produced.
A random subset of Waste Management Plans was obtained from Region 5. These Plans were developed by Professional Engineers as a requirement of the Dairy General Order to identify storage needs and submitted in 2012 per the General Order requirements. Plans were reviewed and preliminary analyses were conducted to determine relationships between volatile solids loading rate and liquid retention time, or volume and surface area of storage area by herd size.

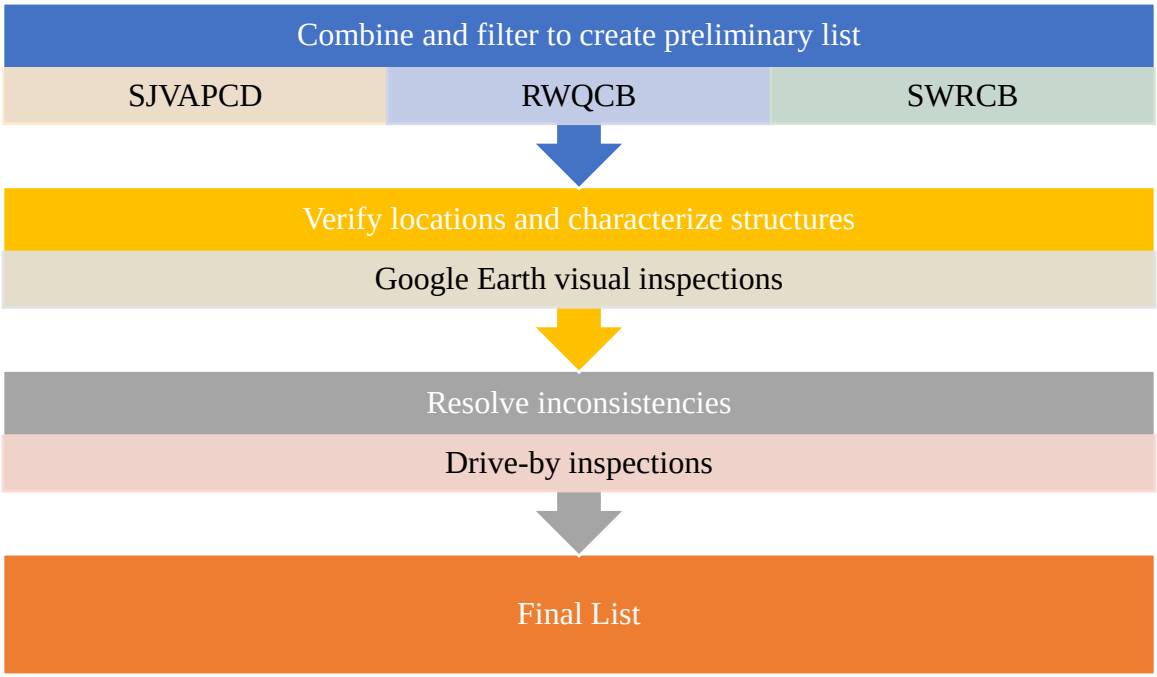

Figure 1.1 California dairies list construction process. Records were obtained from San Joaquin Valley Air Pollution Control District (SJVAPCD), Regional Water Quality Control Board records (RWQCB), and State Water Resources Control Board (SWRCB) fees division.

Results

Task 1.1 Herd size, animal housing and manure management system design. Tremendous regional differences exist in California dairy herd numbers and animals (Table 1.1). Herd size distributions are not normally distributed. Distribution curves have positive skew and are leptokurtic. Herd size distribution is shown in Figures 1.2 (Region 1), 1.3 (Region 2), 1.4 (Region 8) and 1.5 (Region 5).

Region 5 has 90.99 percent of milking and dry cows in California. Region 8 has 4.33 percent of milking and dry cows in California. Together, mature cows (milking and dry) in Regions 1, 2, 6, 7 and 9 make up the remainder (4.68 percent). Average herd size ranged from 333 (Region 1) to 2,802 (Region 6).

Table 1.1 Dairy herd number, size and cumulative animal count by geographic region.

Regional Water Quality Control Board [1]	Herd number	Animals[2]	Animals as percent of CA dairy herd	Herd size range	Average (Standard Deviation)
1	114	38,016	2.14	30-1,700	333 (270)
2	38	14,342	0.81	40-950	377 (204)
5[3]	1,116	1,615,013	90.99	36-10,776	1,447 (1,384)
6	8	22,126	1.25	1,540-4,600	2,802 (1,599)
7	2	3,600	0.20	800-3,998	2,599 (1,326)
8	66	76,922	4.33	215-5,000	1,165 (787)
9	4	4,987	0.28	319-1,955	1,247 (686)
Total	1,348	1,775,006			

[1]Regional Water Quality Control Board jurisdiction: 1, North Coast; 2, San Francisco Bay; 5, Central Valley; 6, Lahontan; 7, Imperial; 8, Santa Ana; 9, San Diego (available online)

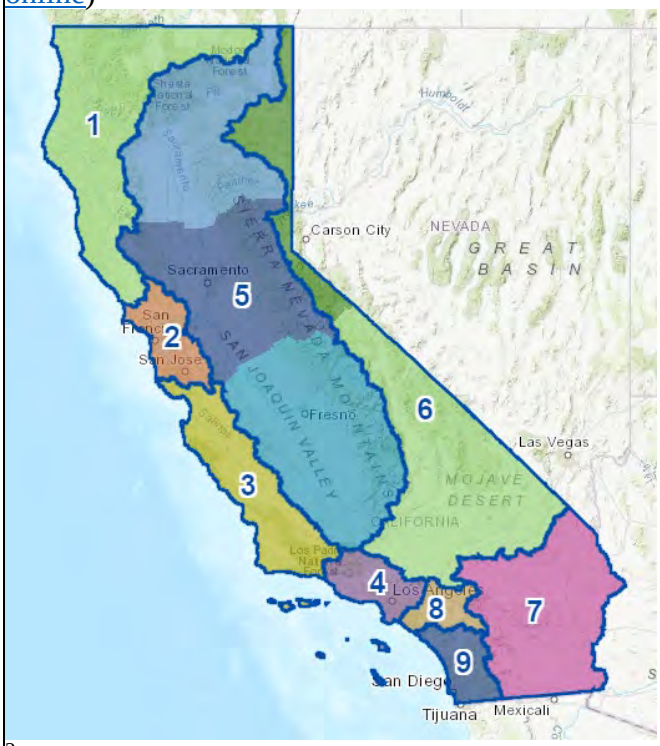

[2]Mature (lactating and dry) cows.
[3]Includes 8 pasture dairies containing 3,874 cows.

Coastal dairies (Regions 1 and 2) have smaller herd sizes when compared to dairies in other regions of California. Coastal dairy herd size is based on land available for pasture or cropping, access to water, labor availability, and ability to sell milk. As a group, dairies in these regions are older with some barns more than 100 years old. Many dairies produce organic milk, thereby restricting their feed purchase and milk market options. Some herds have processor-imposed limits on milk production.

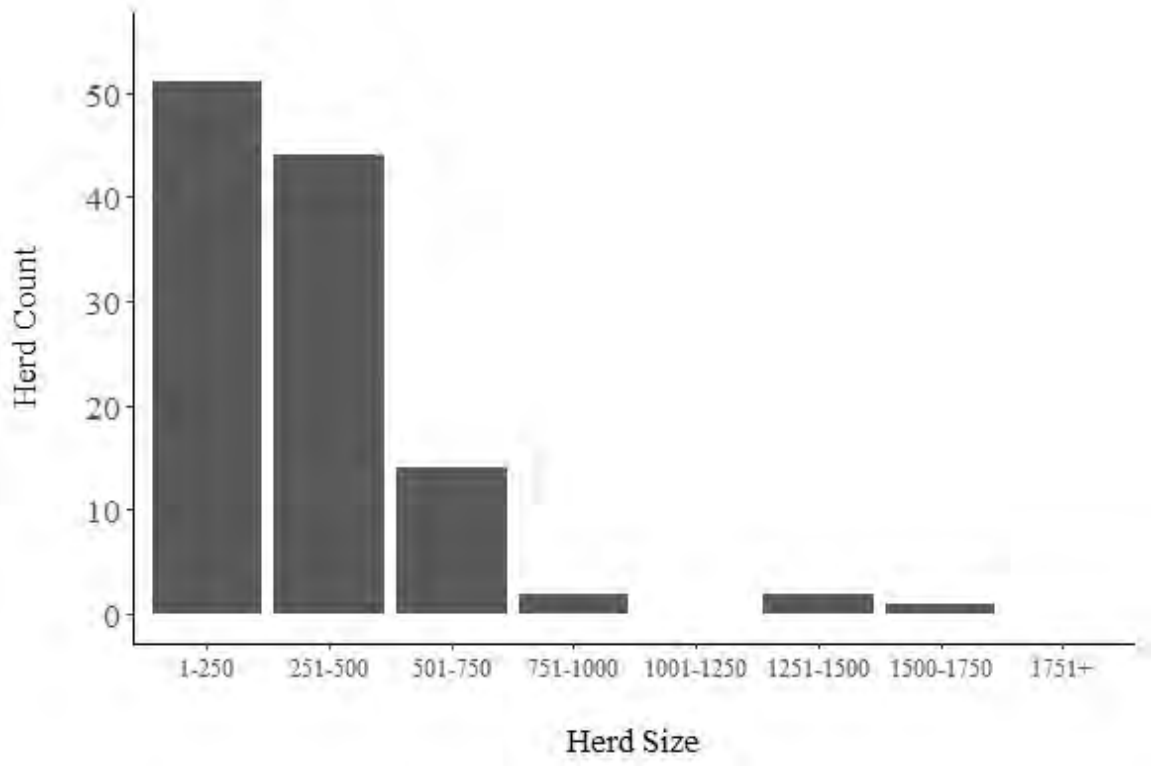

Figure 1.2 Distribution of dairy herd count by size in Region 1, North Coast.

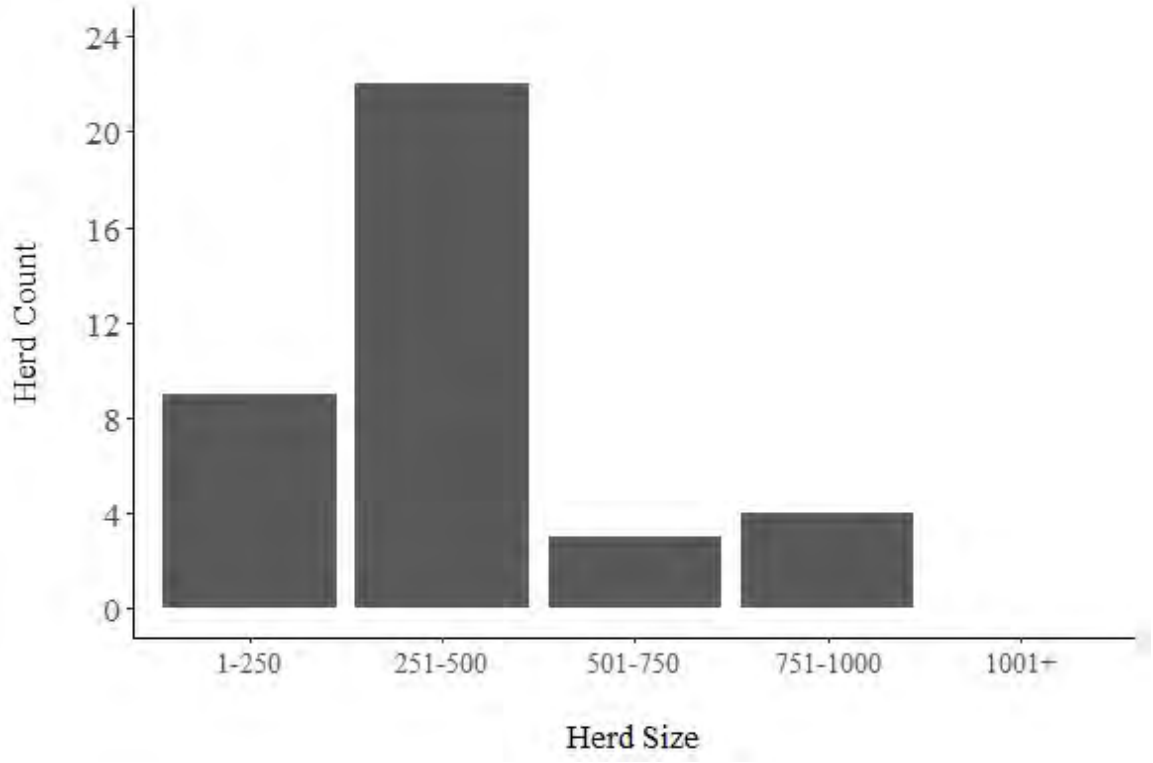

Figure 1.3 Distribution of dairy herd count by size in Region 2, San Francisco Bay.

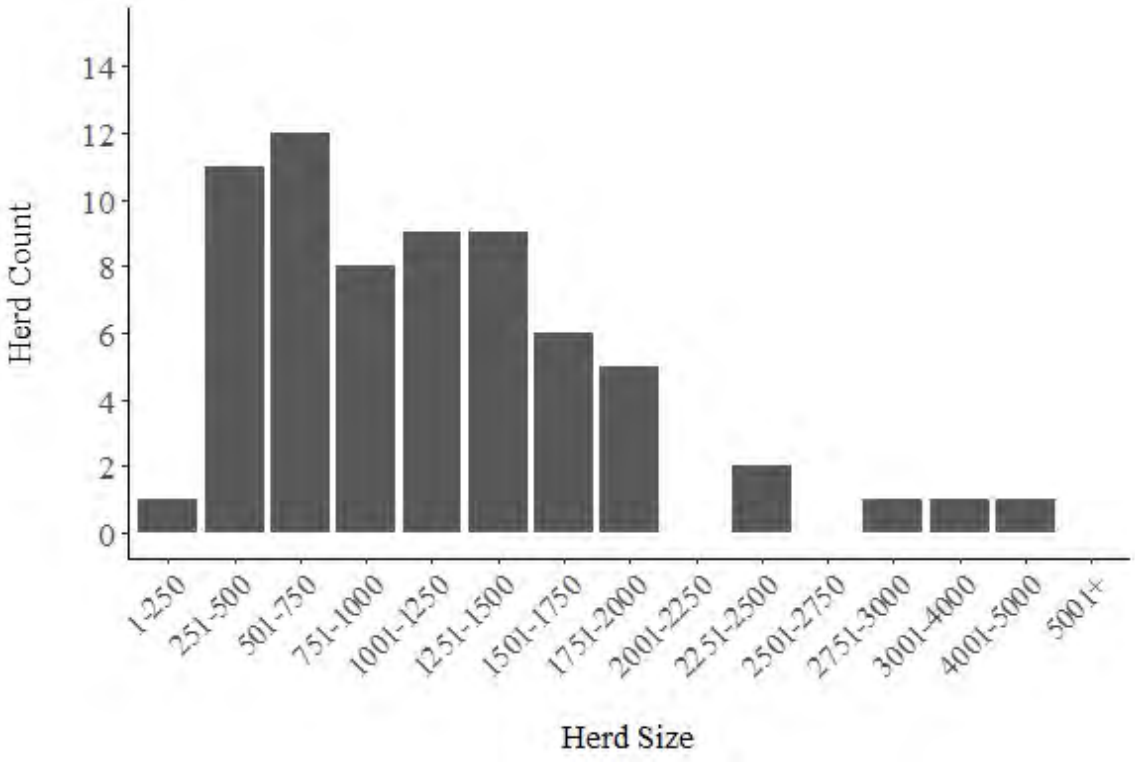

Figure 1.4 Distribution of dairy herd count by size in Region 8, Santa Ana.

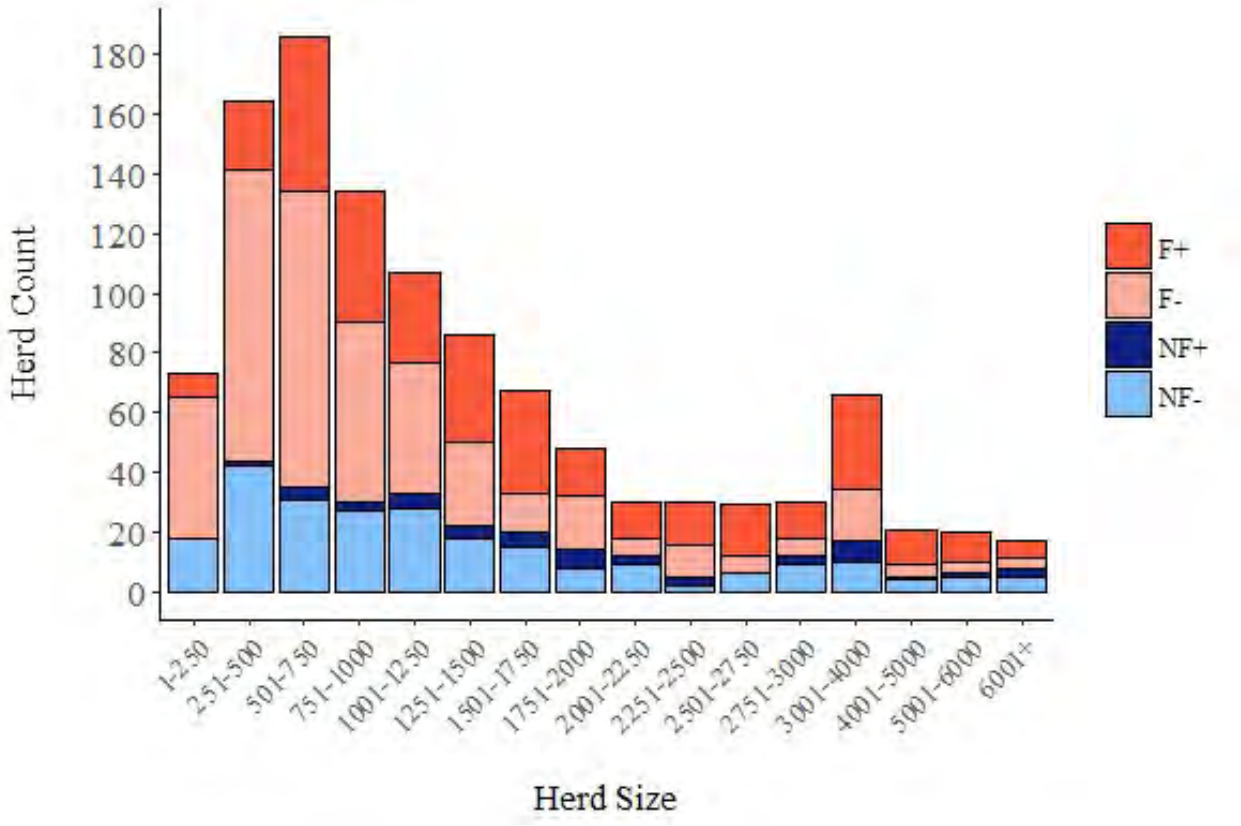

Figure 1.5 Herd size distribution in Region 5 dairies by presence (+) or absence (-) of mechanical separator for dairies with freestall housing (F) and non-freestall housing (NF). Pasture-based dairies not included.

Dairies in Region 5 mostly use freestalls for lactating cow housing (74.10 percent) compared with those dairies that have no freestalls (25.90 percent, Table 1.2). Animals housed at facilities that have freestalls make up 71.29 percent of the Region's dairy herd. Note, not all of these animals (particularly dry cows) are typically housed in freestalls when freestalls are present. Herd population and animal counts are summarized in Table 1.3 by separating out the lower and upper two decile groups of mature cows. Statewide, the lower two deciles of herds resides on dairies with 385 mature cows.

Table 1.2 Percent of herd and mature cow (animals) and distribution by housing type for Region 5 (Central Valley) dairies.

Lactating cow housing type	Herds	Animals
Freestall	74.10	71.29
Non-freestall	25.90	28.71

Table 1.3 Distribution of mature cows by herd size in Region 5 (Central Valley; includes eight pasture herds).

Mature cows per herd	Number of herds	Percent of herds in category	Mature cows	Average herd size (standard deviation)
36 to 1,035	573	51.34	322,153	562 (255)
1,040 to 4,100	487	43.64	966,726	1,985 (799)
4,120 plus	56	5.02	326,134	5,824 (1,518)

Task 1.2 Determine the use of mechanical or gravity separation systems, liquid manure storage impoundments or anaerobic digesters on farm related to facility size and type; and Task 1.3 Evaluate and analyze herd size by manure collection, treatment and storage categories.

Dairies in Regions 1 and 2 utilize a variety of animal housing and manure collection techniques. Professional experience based on farm visits to one-third to one-half of these dairies is the basis for the information herein. Liquid manure is generated from harvesting milk and washing down milk contact surfaces. Flushing to collect manure from animal housing areas is uncommon in these Regions. Typically, manure in animal housing areas (loafing or freestall barns) is scraped and stored as a solid, semi-solid or slurry. Manure is land applied by spreader, honey wagon or irrigation.

Dairies in the northern part of Region 1 utilize pasture for most of the year (Humboldt and Del Norte Counties). The cooler climate, longer rainy season and shallow depth to groundwater allow for greater pasture season and use. Presence of groundwater provides water for pasture irrigation when needed. Dairies in the southern part of Region 1 or in Region 2 use pasture for less than 6 months per year (Sonoma and Marin Counties) unless irrigated. Water is scarce for most dairies in this area. Summer pasture is virtually non-existent. The exception is dairies that use municipal treated water for irrigation. Typically, rainfall is greater for dairies in Region 1 and 2 than in other parts of California. Predominantly, manure is scraped and stored as a slurry, semi-solid or solid, or it is not collected (land applied by animals on pasture).

Few dairies in Regions 1 and 2 continue to use mechanical separators. Two dairies in these Regions have operational anaerobic digesters.

Dairies in Region 6 (Lahontan) and Region 8 (Santa Ana) minimize parlor water use. Liquid manure is generated from harvesting milk and washing down milk contact surfaces. Cattle are housed in corrals and no freestall facilities are present. Animal housing areas utilize scraping and solar drying as the primary manure management practice. South Coast Air Management District

Rule 1127 (SCAQMD, 2004) is applicable to dairies in Region 8. Rule 1127 requires solid manure be cleaned out four times per year. At one point there was an anaerobic digester on a Region 6 dairy.

Dairies in Regions 7 (Imperial) and 9 (San Diego) are non-freestall facilities with dry manure scraped and hauled two to four times per year. Feed apron manure is scraped in these areas and does not enter liquid anaerobic storage system. Manure from the harvesting milk and washing down milk contact surfaces enters liquid manure storage. One dairy in Region 7 has an anaerobic digester.

The majority of California's dairy cattle (90.99 percent) reside in Region 5 (Central Valley). Animals in this region are housed in freestalls with access to corrals, or in corrals with or without shade structures. Specific practices are required to mitigate particulate matter (dust) and volatile organic compound emissions for dairies in the SJVAPCD jurisdiction (SJVAPCD, 2004; SJVAPCD, 2010). Dry manure from corrals is removed four times per year. For many dairies with freestalls where manure is collected via flush, flushing occurs more frequently than the milking schedule. Based on SJVAPCD information, 24.23 percent of non-freestall dairies utilize flush with scrape systems for manure collection. The remaining non-freestall dairies utilize scrape systems for manure collection. No differentiation was made in these permits regarding the percent of manure collected via flush versus scrape activities.

Baseline data from 2016 identified 1.16 percent of dairies used vacuum collection (partial or complete) of manure from mature cows. Flushing may also occur at these dairies. Five dairies outside of the SJVAPCD had digesters installed in recent years. Some are still functional. Twelve dairies within the SJVAPCD identified digesters present, although some were not functional (personal knowledge) at the time data were collected. These anaerobic digesters were installed prior to 2015, the beginning of the Dairy Digester Development and Research Program. Definitions of weeping walls and aerators were not included in the SJVAPCD permitting process. Yet, 1.01 percent and 1.52 percent of herds identified at least one weeping wall or the presence of aerators.

Solid liquid separation occurs with different manure handling techniques. Liquid manure will gravity flow through a gravity separation system. Systems are designed based on frequency of clean-out. Settling basins are typically concrete lined structures with three sides and a bottom. Water enters, is slowed, and then exits. This allows dense particles to settle along with some fibrous material. Clean out frequency is typically less than 45 days. Larger gravity settling systems are cleaned out less frequently (3 months to 2 years). Greater retention times allow for greater accumulation of solids when compared to smaller gravity separation systems. The 2019 benefit calculator used for AMMP applications does not incorporate the use of these systems. Microbial decomposition does occur in these cells; yet, volatile solids are physically removed at the time of clean out from gravity separation cells. The regularity of solids removal is design and management dependent.

For Region 5 dairies, 58.16 percent use some type of gravity separation system; 36.49 percent have a mechanical separator; 25.69 percent use no solid separation system; 20.34 percent use both gravity separation systems and a mechanical separator (Table 1.4). Previous research (Arndt et al., 2018) indicated methane emissions did occur from gravity separation systems.

The focus of detailed analyses of herd distribution by separation type focused on mechanical separators. Use of mechanical separators by herd size and by housing type (Figure 1.5) are presented. Presence of mechanical separators increased as herd size expanded beyond 1,250 milking and dry cows. Roughly 10 to 15 percent of herds (range 1 to 250, 251 to 500 milking and dry cows) had mechanical separators present. Mechanical separators were present on 32.32 percent of herds in 501 to 1,250 milking and dry cow range. Mechanical separators were present on 53.74 percent of herds greater than 1,251 milking and dry cows. The combinations of gravity separation system type (small or large) and mechanical separator by housing type are presented (Figures 1.6 and 1.7). Facilities with no separation system (gravity or mechanical) are presented (Figures 1.8 and 1.9).

Table 1.4 Percent of herds with solid liquid manure separation by manure treatment system for dairies in Region 5.

Use of mechanical separator	Use of gravity separation system	
	NO	YES
NO	25.69	37.82
YES	16.15	20.34

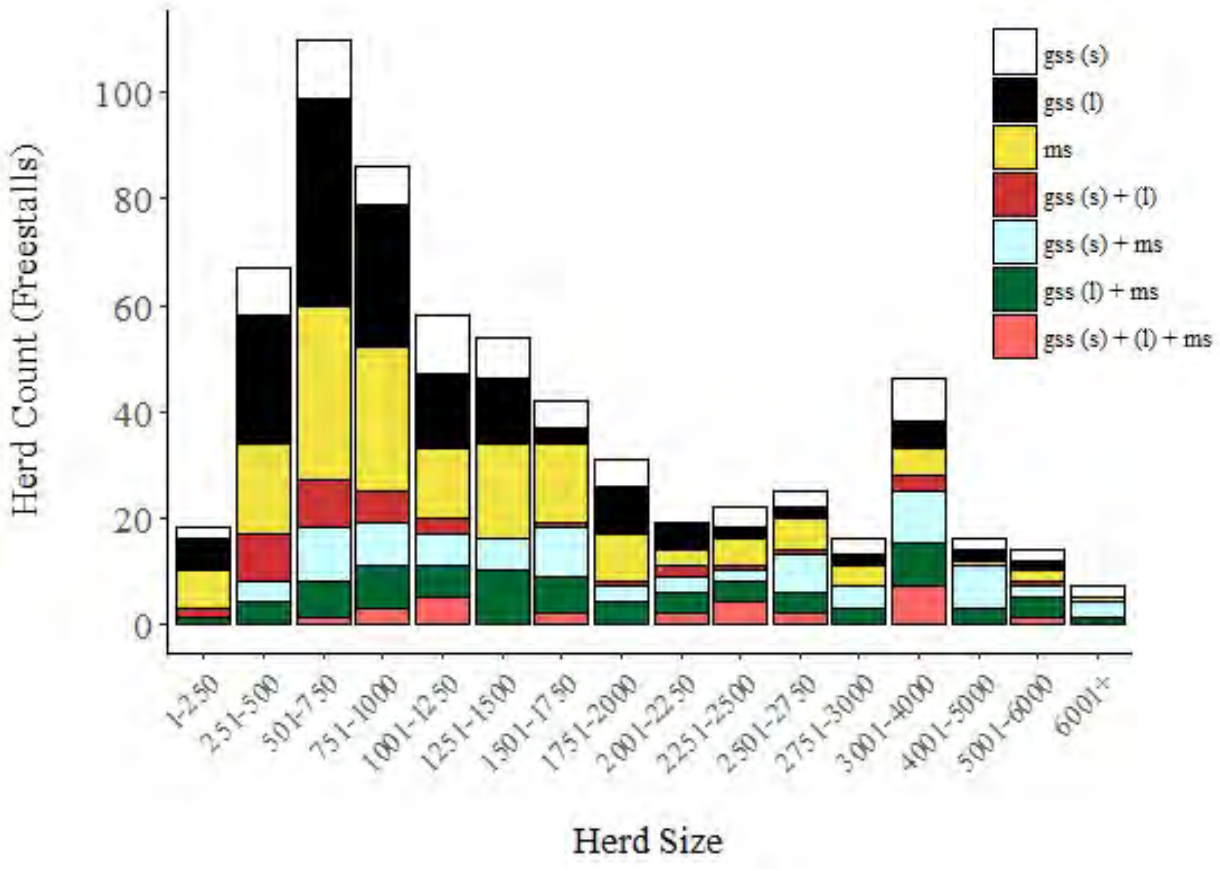

Figure 1.6 Herd size distribution in Region 5 dairies by presence of small (gss (s)) or large (gss (l)) gravity separation system and or mechanical separator (ms) for dairies with freestalls.

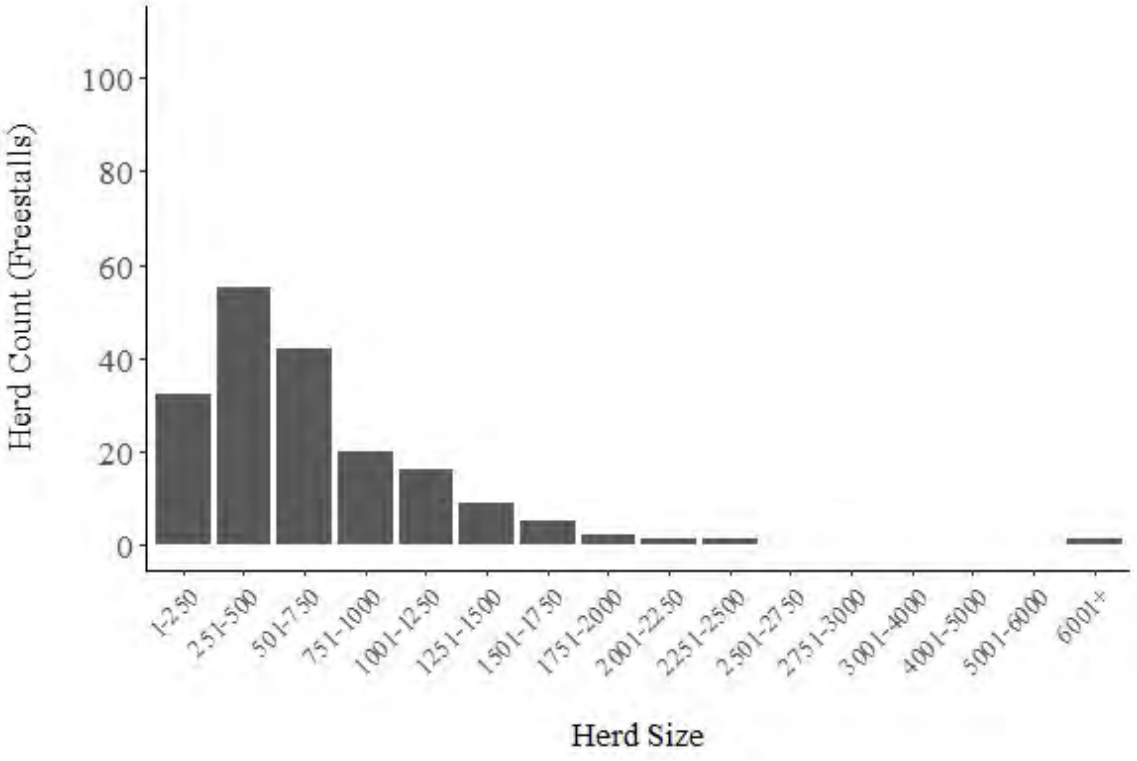

Figure 1.7 Herd size distribution in Region 5 dairies by absence of gravity separation system and mechanical separator for dairies with freestalls.

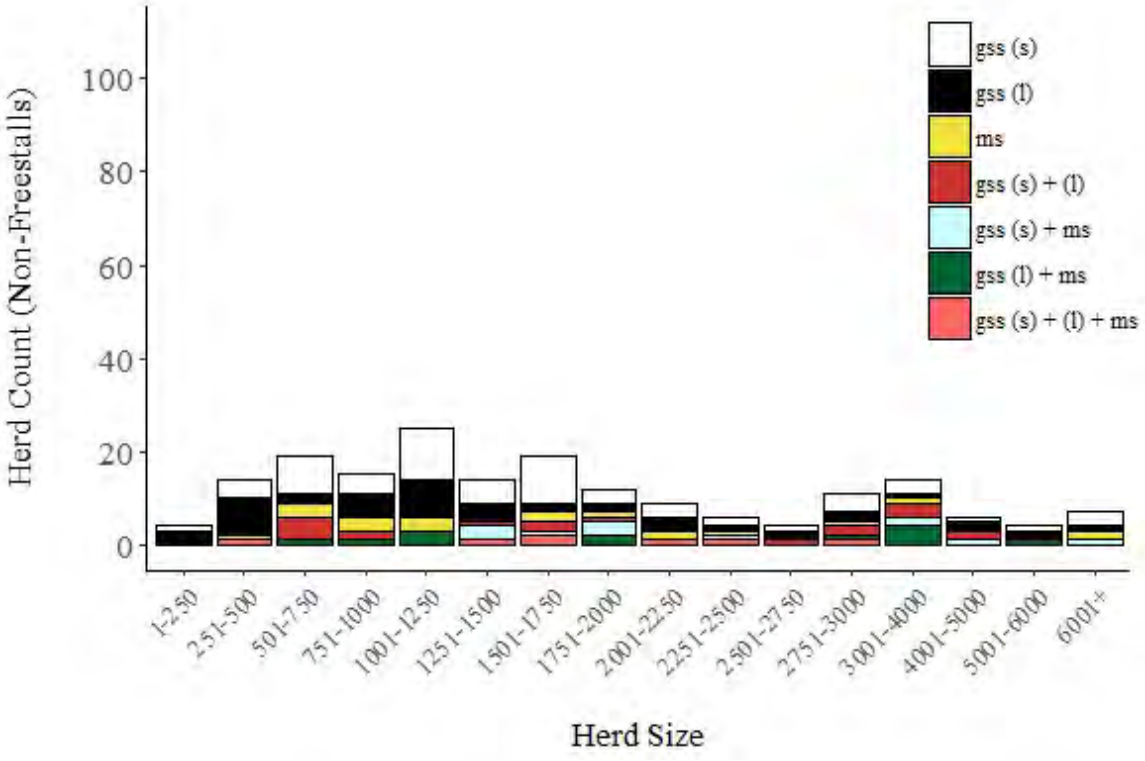

Figure 1.8 Herd size distribution in Region 5 dairies by presence of small (gss (s)) and or large (gss (l)) gravity separation system and or mechanical separator (ms) for non-freestall dairies.

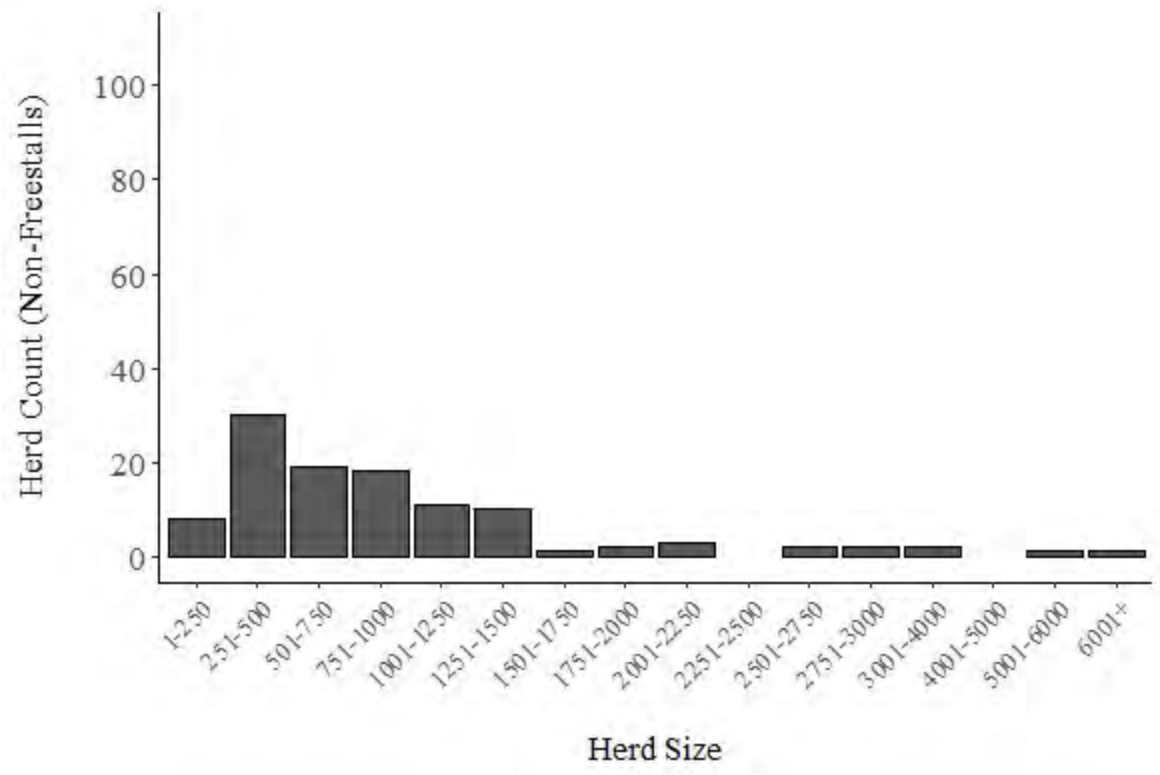

Figure 1.9 Herd size distribution in Region 5 dairies by absence of gravity separation system and mechanical separator for non-freestall dairies.

Task 1.4 Waste Management Plan evaluation.

A random subset of Waste Management Plans was evaluated to determine if greater understanding of the manure handling system could be obtained. Difficulties arose as each engineering firm utilized its own process. Plans were not consistent in determining loading rates. Some identified base assumptions for manure collection. Most did not include calculations for volatile solids collected. All had detailed information or assumptions used for water generated at facilities being collected through the liquid system. Most firms included volume of gravity separation cells in total storage calculations. Inconsistencies existed (due to lack of uniform definition) in description of gravity separation cells. Tremendous variability existed in storage pond design depending on soil type and depth to water table. In some areas, ponds were partially above ground. In other areas, ponds were completely in ground. Storage volume and surface area were variable. Some larger surfaced ponds (shallow) were similar in surface area to deeper ponds regardless of herd size. Historic information for each facility including design criteria at original build with animal numbers and productivity and additional cattle and manure collection/treatment/storage capabilities added over time may have improved interpreting information in Waste Management Plans.

Discussion

Data harmonization activities were challenging as each agency maintained their list of individual operations with permits, and these lists do not always have a common variable for cross reference purposes. The list of dairies maintained by a specific agency serves the agency's need.

No universal variables were included in these lists. Dairies were identified by the owner and or operator. The address was a physical address or a mailing address. Addresses were associated with where to send fee bills, where to send compliance information or where to go to make a site inspection. Some lists used names of owners and not names of operator or herd name. Names were not consistently spelled the same on all lists. Tremendous effort was used to harmonize the information. Since lists were predominantly obtained from Regional Water Quality Control Board sources, the geographic references used in the results refer back to Regional Water Quality Control Board jurisdictions. Within the Central Valley (Region 5), the eight counties comprising the SJVAPCD represented the San Joaquin Valley and the remainder of dairies were located in the Sacramento Valley. Dairies and animals were predominantly located in the Central Valley (90.99 percent) with most of these in the San Joaquin Valley. Primary focus of data analysis was Region 5 and Region 8 as these two Regions contained 94.33 of the California dairy herd.

Herd size distribution for California dairies is not normally distributed. In all major dairy areas (Region 5, 8, 1 and 2) dairies' herd size distribution curves had positive skew and were leptokurtic (Figures 1.2 through 1.4). There was no straightforward way to define smaller and larger sized dairies based on distribution curves. Furthermore, the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) provides no definitions. From an environmental perspective, when animal facilities were first permitted through the Clean Water Act (1972), large dairies were defined as over 700 mature cows. Although herd sizes have changed since 1972 no modifications to these size definitions have occurred.

The Reauthorization of the Coastal Zone Management Act (1990) identified specific categories of nonpoint source pollution for each coastal state to incorporate into their programs. Small dairies were defined if there were 20 to 69 head (28 to 97 animal units). Large dairies were categorized with 70 or greater head (greater than 98 animal units). Separate Federal Regulations, the Clean Water Act as amended (1972), defined small (less than 200), medium (between 200 and 699) and large (700 and more) herds with mature dairy cows whether milked or dry. Although many modifications to the Clean Water Act have occurred since 1972, these categories and their numeric definitions have remained (US EPA, 2012).

Clearly, the definition of small, medium or large is relative to a population at a given time and for a specific reason. The 1974 USDA NASS agricultural census identified dairies with more than 500 milking cows as their largest category and included both medium and large dairies as defined by the Clean Water Act. This category was less than .2 percent of dairies and 5.7 percent of dairy cows in the United States (USDA NASS, 1974). The average herd size (total cows/number of herds in category) was 914 cows. The 2017 census category of 5,000 cows and greater contained 15 percent of the United States dairy herd on 0.4 percent of herds (USDA NASS, 2017). The 2017 USDA NASS statistics for California were used as a comparison for our dataset. The USDA NASS data and the data we obtained from individual agencies were similar enough, understanding differences in comparing these datasets. This is due in part to our analysis for the lower two and upper two deciles calculated for Region 5 dairies alone. Whereas USDA data include all dairies in CA. The USDA NASS dairy population statewide was 17.25 percent in

herds of 1,000 milking (a slightly smaller herd size than 1,035 mature cows; the upper boundary for the lower two deciles) and 14.97 percent in herds with more than 5,000 mature dry cows. The latter category did not include herds between 4,100 and 5,000 mature cows, included in the upper two deciles of the current dataset. Analyses of USDA NASS data emphasized that a categorization of herd size is time dependent and therefore reflects the industry at any specific point in time.

Data on herd size distribution are provided herein for staff at the California Department of Food and Agriculture. For our analytical purposes, the upper and lower two deciles of mature cow population were identified.

Manure management for non-freestall dairies varies by geographic area. Dairies in Regions 6, 7, 8 and 9 scraped manure. The majority of non-freestall dairies in Region 5 scraped manure. For these cattle, manure was dry scraped or managed to enhance solar drying and then handled dry. A small amount of non-freestall dairies in Region 5 flushed lanes. Also uncertain based on this analysis was the end fate and disposition of heifer and dry cow manure as no set of available data sufficiently delineated management of manures from these categories of animals.

Previous work conducted for the California Air Resources Board analyzed time on concrete on two freestall and two non-freestall dairies in the San Joaquin Valley. These analyses were conducted during three seasons representing winter, spring/fall and summer conditions. Results indicated lactating cows housed in freestall dairies spent 78.2 and 69.8 percent of their time on concrete (Cohen-Davidyan et al., 2020). Lactating cattle on non-freestall dairies spent 31.0 and 37.0 percent of their time on concrete. Assuming time on concrete was a surrogate for percent of manure collected through the liquid system (freestall dairies) and potentially collected through the liquid system (non-freestall dairies) this provided an upper boundary for the amount of manure collected. Dry cows and replacement animals spent 21.0, 25.1, and 23.8 percent of their time on concrete for three of these dairies (one freestall and two non-freestall). The fourth dairy reared replacement animals at a separate location. Manure from replacement animals was flushed on the freestall facility, inconsistently flushed on one non-freestall facility and not flushed on the other non-freestall facility.

Manure management at any given snapshot in time is a function of the initial design of the facility and subsequent growth in animal population, infrastructure and management. Manure management in the 1970s was often a function of scraping concrete lanes with tractors. As facility infrastructure improved and freestalls were built, flush lanes were introduced to the California dairy landscape. Water used to clean milk contact surfaces was re-used to clean concrete lanes. Water drained to manure lagoons for biological treatment. This reduced challenges associated with tractor scraping of lanes and potential injuries to animals and people. Further advances in manure management, the concern to separate out solids to manage manure better within the production facility as well as during fertigation, have gained momentum over the last two decades.

Mechanical separators were present on 43.61 percent of freestall and 17.07 percent of non-freestall dairies. Presence of mechanical separators differed by lactating cow housing type and

herd size (Figures 1.6 and 1.7). As herd size increased, dairies had an increased percent of facilities with mechanical separators present. A higher percent of freestall facilities had mechanical separators across all categories when herds were binned by 1,000 mature cow intervals. Mechanical separators were present on 29.53, 52.97, 64.48, 65.31 and 66.67 percent of dairies with <1,001, 1,001 to 2,000, 2,001 to 3,000, 3,001 to 4,000, and >4,001 mature cows. The corresponding values for presence of mechanical separators on non-freestall dairies was 7.09, 22.47, 25.71, 35.29, and 27.27 percent of dairies with <1,001, 1,001 to 2,000, 2,001 to 3,000, 3,001 to 4,000, and >4,001 mature cows. Dairies likely collecting more manure through a liquid system (freestall dairies) had a larger percent of herds with mechanical separators and dairies likely collecting less manure through the liquid system (non-freestall dairies) had a lower percent of herds with mechanical separators present.

Integration of these results (Figures 1.6 and 1.7; Table 1.3) with results from previous work (time on concrete) allowed calculation of approximate amount of lactating cow manure collected in liquid form and potentially subjected to mechanical separation. Approximately 36.93 percent of manure from lactating cows was estimated to be collected in a liquid form where a mechanical separator was present. This value was approximate as it assumed all animals produce the same amount of manure regardless of herd size and housing design.

It is important to note that the analysis is the presence or absence of a mechanical separator and does not imply it is always operational. Once a separator is installed, operation and maintenance of the equipment is important to keep it functional. Also, resources (labor and equipment) must be allocated to solids management to be successful.

Solids removed from mechanical separators were stackable (due to particle size) and moisture content. Standard stationary inclined screens had an additional pressure roller on the end of the conveyor belt to reduce moisture. Moisture content of solids just separated was near 83 to 85 percent (professional experience). The solids were handled (labor and equipment) to distribute for open solar drying, creation and turning for compost windrows, or relocated for temporary storage and subsequent handling (common in winter). Solids may be stockpiled wet or dry for subsequent application to fields between crops.

Gravity separation systems (58.16 percent) were more common than mechanical separation (36.49 percent). Standard gravity separation systems (settling basins, settling ponds) were not included as part of the Alternative Manure Management Program practice list although weeping wall systems were included. The 2019 GHG benefit calculator did not allow input for project baseline or project use of standard gravity separation systems. These vary on farm from concrete lined settling basins that were cleaned out on a 4 to 8 week cycle to earthen impoundments that were cleaned annually or every other year. Separated solids were handled in both mechanically and gravity separated systems. Often, farm labor and equipment (tractor, manure slinger wagon) were used to manage separated solids. Solids from gravity separated system were handled similarly to mechanically separated solids in some cases. More often, these solids were handled through contracted services. The services used a dredger to remove solids and supplied manure trucks to haul manure to fields or drying areas.

Use of vacuum or scraped collection of manure was low. A devoted and specialized management system was used to collect and subsequently manage vacuumed or scraped manure. This material does not stack when collected from lactating cattle areas. Different management techniques were used to handle vacuumed manure and included addition to an already existing solid manure pile or incorporating it into other dry material prior to composting, storing it in its wet form, or doing some open solar drying before it was managed further.

Conclusions

California dairies were analyzed by herd size, animal housing, manure treatment and storage practices. Herd distributions by geographic regions were identified. Ninety-one percent of mature cows (milking and dry) were on dairies in Region 5. Herd distribution between those with freestalls and those without were 74.10 and 25.90 percent. This represented 71.29 and 28.71 percent of animals. The lower and upper two deciles of dairy cattle in the Central Valley were on dairies of less than 1,035 or over 4,120 mature cows. The lower two deciles of herds were on dairies with 385 mature cows. Manure treatment technology and storage practices were described for dairies in Region 5. No definitive practices were used based on herd size or housing type. Some 25.69 percent of herds in Region 5 used neither mechanical separation nor gravity separation systems. The remaining 74.31 percent used gravity separation system only (37.82 percent), mechanical separation system only (16.15 percent) or both (20.34 percent). Mechanical separators were present on 43.61 percent of freestall and 17.07 percent of non-freestall dairies. Approximately 36.93 percent of lactating cow manure was estimated to be collected in a liquid form where a mechanical separator was present. Dairies in Regions 1, 2, 8 and 6 comprised 2.14, 0.81, 1.25, and 4.33 percent of mature cows in California. Liquid manure from dairies in these regions was associated with milking parlor activities and any associated rain runoff. Manure management on dairies with housing in Regions 1 and 2 was wet scraped (slurry) or dry scraped (semi-solid or solid). Manure was managed as a dry solid on dairies in Regions 6 and 8. These results provide useful information should targeted implementation of manure management practices be desired to reduce GHG emissions.

Recommendations

Any designation of small or large herd size selection is Region and time specific and requires re-evaluation over time as herd size distributions change. It would be useful to evaluate the 2013 greenhouse gas emissions inventory to determine if values used for dairy cattle manure emissions reasonably represented herd design and manure collection processes.

CHAPTER 2 QUANTIFY ESTIMATED METHANE EMISSIONS AS LOW, HIGH AND AVERAGE BASED ON HERD SIZE (SMALL AND LARGE), HOUSING DESIGN AND MANURE HANDLING CATEGORIES.

Introduction

The purpose of the AMMP program is to divert volatile solids from anaerobic conditions conducive to methane formation. The percent of emissions reduced with each project type is a function of herd size, animal housing, and manure management.

Methane emissions from manure is a function of the amount of volatile solids excreted, subsequently collected and handled under anaerobic conditions (IPCC, 2006). Bedding and wasted (animals drop feed into manured areas) or spoiled feed may be added to the manure stream (ASAE, 2004). Volatile solids that enters anaerobic conditions may contribute to emissions (IPCC, 2006). Animal housing (freestall versus non-freestalls) is a key factor in the percent of excreted manure likely to be deposited on a concrete surface and be handled in anaerobic conditions. Time animals spend on concrete serves as a surrogate to estimate amount of manure potentially collected in a liquid or slurry form. Design and environmental management of freestalls, including barn directional orientation, feedline soakers/misters and fans over freestalls impact animal use of freestalls. Animal management, specifically animal access to corrals, impacts how much time animals spend on concrete. As previously indicated, another project evaluated time on concrete for sentinel pens of cattle at four commercial dairies (two freestall; two non-freestall) (Cohen-Davidyan et al., 2020). These analyses were conducted during three seasons representing winter, spring/fall and summer conditions. Results indicated that lactating cows housed in freestall dairies spent 78.2 and 69.8 percent of their time on concrete (Meyer et al., 2019). Lactating cattle on non-freestall facilities spent 31.0 and 37.0 percent of their time on concrete. Assuming time on concrete was a surrogate for percent of manure collected through the liquid system (freestall dairies) and potentially collected through the liquid system (non-freestall dairies) this provided an upper boundary for the amount of manure potentially collected in the liquid system. Some dairies scraped concrete lanes to a transfer lane where wash water from the milking parlor or other flushing water would ultimately mix with slurry and convey the material to the liquid storage structure. Other dairies scraped concrete lanes into corrals where manure was distributed for solar drying. Dry cows and replacement animals spent 21.0, 25.1, and 23.8 percent of their time on concrete for three of these dairies (one freestall and two non-freestall facilities). The fourth reared replacement animals at a separate location. Manure from replacement animals was flushed on the freestall facility, inconsistently flushed on one non-freestall facility and not flushed on one non-freestall facility. Collection of manure on concrete varies by facility infrastructure and manager preferences for resource (labor and tractors available for manure management) use. This is why it is important to consider site specific practices when estimating baseline and project emissions.

Manure handling differs by region within California. Manure is handled (in order of amount of manure) by manure consistency as: slurry, solid or liquid, Regions 1 and 2; liquid, solid or slurry, Region 5; solid or liquid, Regions 6, 7, 8 and 9.

The objective was to quantify estimated methane emissions as low, high and average based on herd size (small and large), housing design and manure handling categories. Suggested modifications to the 2019 GHG benefit calculator are provided based on use during these analyses.

Materials and Methods

Task 2.1 Quantify estimated methane emissions as low, high and average based on herd size (small and large), housing design and manure handling categories

Results of Task 1.3 inform regional dairy populations (categorized by Water Quality Control Board) and manure treatment technology presence (specific in detail to Region 5). Essential for this analysis was information submitted in AMMP applications to define the percent of manure volatile solids (VS) collected through a liquid or non-liquid stream as well as the estimated percent of VS removed by practices. Quantification of GHG emissions was calculated with the 2019 GHG benefit calculator for AMMP practices (CARB, 2019).

Data from individual AMMP applications were sought to normalize applications and compare results of baseline and post project emissions across projects within and between farms. A public records request was made to obtain copies of AMMP applications submitted to CDFA. Additionally, some individual dairy producers and technical assistance providers were contacted to obtain copies of submitted applications. Some technical assistance providers were contacted to gain greater insight into the AMMP application process and obtain additional information and impressions about their understanding of the effectiveness of select practices.

Hypothetical analyses. Baseline emissions and post AMMP installation emissions were determined by analysis and interpretation of project narratives from 2017 and 2018 AMMP applications. Tulare County was used for this hypothetical analysis. Inputs included: project location, baseline livestock population by category, baseline data (manure collection, solid separation, storage/treatment practice for separated or scraped solids) and project manure collection and solid separation specific information was not available for changes in energy use (electricity and diesel fuel consumption) pre and post AMMP. Statewide data for average values for milk production and composition were used to estimate project emission reductions (CDFA, 2018). These data populated the Project Date Input tab in the 2019 GHG benefit calculator. Emissions were estimated for herd sizes 250, 750, 1250, 1750, 2250, 3250, and 3750 (freestall and non-freestall) for baseline and select AMMP projects. This normalization was necessary for comparison purposes. The resultant analysis provided comparison of individual AMMP practices within and between dairy herd sizes and housing types. Single project analyses were conducted. No allowance was made for dairies with gravity separation systems in their baseline management. Scrape to flush narrative indicated an unknown number of days of collection (data redaction). A value of 30 percent collection (70 percent remaining in flush) was used. This overestimates reductions if manure is collected 104 days a year. Results from low and high emissions were selected. Averages were calculated by AMMP practice categories for solid separation and flush to scrape systems as the sum of the emissions by herd type and size divided by the number of rows used to contribute to the sum.

Results

Application specific information was necessary to normalize individual applications and compare results between farms. Initially, the intent was to obtain application specific information from AMMP applications submitted to CDFA and received through a public records request. This process required CDFA staff to redact out confidential business information. Unfortunately, herd size, milk production and composition information were deemed confidential and not provided, per Government Code Section 6254(k) and Evidence Code Section 1060. Additionally, percent of manure collected and efficiency of AMMP practice values were redacted from these applications. This was crucial information to normalize data. The 2017 and 2018 GHG benefit calculators allowed applicants to modify the percent of manure collected and the effectiveness of a particular practice. Facility energy use for baseline and post AMMP implementation was also redacted from applications. These important pieces of information were essential to do a more precise analysis of baseline GHG emissions and GHG emissions reduction for each facility. In the absence of important project-specific information (animal numbers, milk production and composition, manure collection and effectiveness of AMMP practices), project summary information had limited value for comparison purposes. Summaries did not consistently reflect actual project practices as GHG benefit calculator spreadsheets used in 2017 and 2018 allowed user justified modifications along with the explanation of the modifications. Without full application information or justification of user modifications, it was difficult to evaluate the final GHG emissions reduction results in context of each dairy or determine whether the reduction values represented each facility appropriately. Selection of baseline and project solid liquid separation (sections 4c and 7c respectively in the 2019 GHG benefit calculator) were consistent in these analyses for analytical purposes. It was not possible to determine if these were selected consistently in applications as this information was redacted.

The project team reached out to individual producers and industry contacts to obtain AMMP applications directly from dairy producers who submitted applications in 2017 and 2018. Less than 12 application packages were received. Although these provided more precise information for those applications received, too few applications were received and there was an insufficient number of applications received for any specific AMMP practice category to conduct the analyses on directly acquired producer information.

Hypothetical analyses. After detailed discussions with CDFA staff, it was determined a streamlined analysis was appropriate. Emissions were estimated using the 2019 GHG benefit calculator for herd sizes 250, 750, 1250, 1750, 2250, 3250, and 3750 (freestall and non-freestall) for baseline and select AMMP projects. Herd sizes were identified as the upper threshold for bins of cattle described in Chapter 1. Assumptions for the amount of volatile solids collected and removed by different AMMP practices is not readily accessible in the application process. The 2019 GHG benefit calculator served to standardize calculations based on percent of manure collected and effectiveness of different AMMP practices.

Analysis of baseline conditions indicated the 2019 GHG benefit calculator assumed freestall manure collection was 2.4 times greater than manure collection at non-freestall facilities. Differences in solid separation with open solar drying or composting were impacted more by the type of separator used and not the type of drying identified. Weeping walls had the greatest emissions reductions (about 43 percent) based on the 2019 GHG benefit calculator. Stationary inclined screens (about 16 percent) and screw press separators (about 24 percent) were more

comparable to one another than weeping wall separation. Partial flush to scrape conversion (at 30 percent of manure scraped; 70 percent of manure flushed) achieved more GHG emissions reductions (about 24 percent, freestall; 18 percent non-freestall) when compared with emissions reductions from stationary inclined screens and similar emissions reductions when compared with emissions reductions from screw press separators. Emissions reductions were similar within a practice category and herd size regardless of housing type (freestall or non-freestall) for solid liquid separation. Emissions reductions were about 33 percent greater for flush to scrape systems and compost bedded pack barns on freestall facilities when compared with emissions reductions from non-freestall facilities. Region 5 AMMP funded dairy projects (project years 2017-2019) were in herds with mature cows in the lower two deciles of (n=35; less than 1,035), middle six deciles (n=49, between 1,035 and 4,200) and upper two deciles (n=2, above 4,200)

Low and high emissions analyses were identified and average emissions reductions were calculated by AMMP practice categories for mechanical solid liquid separation and flush to scrape systems. The results reflected the imbedded assumptions used in calculations for each specific AMMP category. Results of these analyses are summarized in Table 2.1. Conversations with individuals assisting producers with AMMP applications identified the primary GHG savings for compost bedded pack barn and pasture improvements was due to differences in diesel use for facilities where baseline manure collection was solid manure.

Table 2.1 Estimated greenhouse gas emissions for flush manure collection and no solid separation (baseline) and project estimated emissions after implementation of Alternative Manure Management Program practice (units are MTCO2e per year).

Herd description (number of animals)																
Dry cows	37.5		112.5		187.5		262.5		337.5		487.5		562.5		637.5	
Lactating cows[1]	212.5		637.5		1062.5		1487.5		1912.5		2762.5		3187.5		3612.5	
Total cows	250		750		1250		1750		2250		3250		3750		4250	
Housing[2]	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF
Baseline	1334	551	3999	1650	6663	2750	9327	3850	11991	4950	17319	7149	19983	8249	22647	9349
Conversion to solid separation with open solar drying from:																
F/WW[3]	752	321	2253	962	3755	1603	5256	2244	6757	2885	9760	4166	11261	4807	12762	5448
F/SS[4]	1114	464	3339	1390	5564	2317	7789	3243	10014	4170	14463	6023	16688	6949	18913	7875
F/SP[5]	1011	423	3029	1268	5047	2113	7065	2958	9083	3802	13119	5492	15137	6337	17156	7182
Conversion to solid separation with composting (passive or intensive windrow) from:																
F/WW	747	319	2240	956	3732	1594	5224	2231	6716	2868	9700	4143	11192	4780	12685	5418
F/SS	1113	463	3334	1388	5555	2313	7777	3238	9998	4163	14441	6014	16662	6939	18884	7864
F/SP	1008	422	3021	1265	5034	2108	7047	2951	9060	3793	13086	5479	15099	6322	17112	7165
Low	747	319	2240	956	3732	1594	5224	2231	6716	2868	9700	4143	11261	4780	12685	5418
Average	958	402	2869	1205	4781	2008	6693	2811	8605	3614	12428	5220	14340	6022	16252	6825
High	1114	464	3339	1390	5564	2317	7789	3243	10014	4170	14463	5492	15137	6337	17156	7182
Partial conversion to scrape with open solar drying[6]																
	1012	450	3032	1350	5052	2249	7073	3149	9093	4048	13133	5847	15153	6746	17174	7646
Partial conversion to scrape with composting (passive or intensive windrow)[6]																
	1003	447	3005	1341	5008	2235	7010	3129	9012	4023	13017	5811	15020	6705	17022	7598
Low (composting)	1003	447	3005	1341	5008	2235	7010	3129	9012	4023	13017	5811	15020	6705	17022	7598
Average	1008	449	3019	1346	5030	2242	7042	3139	9053	4036	13075	5829	15087	6726	17098	7622
High (open solar)	1012	450	3032	1350	5052	2249	7073	3149	9093	4048	13133	5847	15153	6746	17174	7646
Compost bedded pack barn																
	179	191	536	573	894	955	1251	1337	1608	1719	2323	2482	2680	2864	3037	3246

[1]Assumed milk production 75 lbs, fat 3.85, true protein 3.43, and lactose 4.97; [2]F – freestall, NF – non-freestall; [3]Flush collection, weeping wall separation; [4]Flush collection, slant screen separation; [5]Flush collection, screw press separation; [6]30 percent flush/70 percent scrape (annualized) after AMMP project implementation.

Discussion

Baseline emissions were always greater than project emissions for all scenarios evaluated. If energy consumption was increased for the project (not included in our analyses) it is possible for project emissions to exceed baseline emissions if sufficient emissions decreases do not occur from manure management. The assumption that the manure entering lagoons at 2.4 times the rate for freestall versus non-freestall facilities for lactating cattle was greater than 2.2, the ratio of average time on concrete from freestall (74.0 percent) and non-freestall (34.0 percent) facilities. Comparing high and low time on concrete the ratio of manure collection from freestall versus non-freestall facilities ranged from 2.5 to 1.9 (Cohen-Davidyan et al., 2020). Animal management practices at freestall dairies impacts time on concrete. Animals with restricted time in corrals spend more time where manure is deposited on concrete and therefore a greater amount of manure would encounter manure treatment technologies. Data provided in Table 2.1 are useful to those estimating GHG emissions reductions or interested in comparing project emissions from different sized herds within or across AMMP practices. Actual herd calculations will vary when herd specific milk production and composition data, animal and manure management and energy use data are available. As anticipated, baseline emissions on dairies with freestalls are greater at a specific herd size than at dairies with no freestalls. This reflects the fact that dairies with freestalls collect more manure on a concrete surface that is handled in liquid form under anaerobic conditions when compared with dairies with no freestalls.

Neither baseline calculations nor project calculations allowed for inclusion of gravity separation systems. These separation systems do exist on farm (as presented in Chapter 1) and should be included in both baseline and project emissions calculations.

Anomalies could occur when using the 2019 GHG benefit calculator. This is not an exhaustive list. If baseline manure collection is flush and baseline solid separation is none, there is no need to have a storage/treatment practice for separated or scraped solids. A different example is that once a Category 4 practice is selected (2 Project data inputs) then 4a should be flush and 7 should only include scrape/vacuum options. Since many applications were for partial vacuum (i.e. 104 days a year) it is unclear why an option for 7a is flush when the new practice identified in 2 already selected a scrape/vacuum option. Additionally, 7c allows selection of separation type. It is not clear if this project separation is for the 70 percent of manure that is not vacuumed or if it is for the 30 percent of manure that is vacuumed (assuming a partial collection via vacuum at 30 percent).

Conclusions

A hypothetical analysis of baseline conditions was compared to post AMMP emissions with an assumption that collection of manure from freestall dairies was 2.4 times greater than from non-freestall dairies. As calculated, estimated emissions differences in solid separation with open solar drying or composting were a function of the type of separator used and not the type of drying identified. Weeping walls had nearly twice the emissions reductions than mechanical separators. The 2019 GHG benefit calculator emissions reduction estimates were greater for screw press separators than for stationary inclined screens. Emissions reductions from partial flush to scrape conversion (at 30 percent of manure scraped) was similar to emissions reductions for screw press separators and greater than stationary inclined screens. Actual project emissions

reductions will vary when herd specific milk production and composition data, animal and manure management and energy use data are available.

Recommendations

Baseline assumptions used in the GHG benefit calculator for percent of manure collected should be clearly defined within the benefit calculator so users may better understand how well a specific practice will work given their herd animal and manure handling practices.

Gravity separation systems that are cleaned frequently should be incorporated into baseline and project descriptions (sections 4c and 7c of the 2019 GHG benefit calculator) to more closely reflect practices on farm and reductions in volatile solids entering liquid storage systems.

Consideration should be given to lock some cells based on practice selected to minimize potential errors in data entry.

Refine the emissions estimate GHG benefit calculator to improve data entry for unusual combinations of manure management.

Review the GHG benefit calculator inputs for stacked practices and provide examples of how to include multiple practices within an application so applications are calculated similarly.

Modify the GHG benefit calculator to allow input of compost bedded pack barn manure collection and clearly define fate and management of manure dropped on transfer lanes and while at the milking parlor as well as feed apron manure.

Retain flexibility in the application process to allow use of different practices for different groups of cattle.

CHAPTER 3 REVIEW STRATEGIES AND TECHNOLOGIES CURRENTLY OR POTENTIALLY USED TO REDUCE MANURE METHANE EMISSIONS FOR APPLICABILITY TO SMALL AND LARGE DAIRIES.

Introduction

Improving manure management on dairies in California has been an important topic for over two decades. An analysis of manure treatment technologies was conducted (SJVDMTFAP, 2005). Representatives from regulatory agencies, academia, industry and environmental/conservation organizations came together to evaluate and identify technologies potentially able to improve manure management in the San Joaquin Valley. This review was conducted through an open solicitation to vendors with known products as well as to potential vendors not yet involved in dairy manure management. Technologies were organized in broad categories that included: thermal conversion (combustion, gasification and pyrolysis); solid-liquid separation and filtration; composting; anaerobic digestion; aerators/mixers; covers for lagoons and compost piles; microbial cultures, enzymes, and other additives; feed management; nitrification/denitrification; and miscellaneous. Of great importance during the review process was the need to identify potential benefits and detriments of individual technologies to air and water emissions. A useful outcome of the group's effort was a uniform scorecard developed to assess individual technologies. Insufficient data from unbiased research resulted in most scorecard analyses relying on best professional judgment on behalf of panel members based on known practices, chemistry and physical conditions present on dairy farms. Few companies had data beyond anecdotal. Of particular interest to panel members at that time, and all concerned with manure management at this time, is the ultimate fate and form of manure constituents as they enter, move through and exit potential processing technologies.

More recently, many dairy processors in the United States came together to form Newtrient. Newtrient seeks to evaluate and identify technologies that advance manure management and technology adoption related to energy production and nutrient recovery. Newtrient creates a space where technology providers can provide proprietary information (including efficacy, maintenance costs and location on dairies) to a panel for review. Similar to the previous effort in California, Newtrient has found that many vendors have insufficient data from actual field trials to allow detailed scientific review.

The AMMP application process established practice categories to reduce methane emissions. These practices were reviewed recently through California Air Resourced Board's Dairy and Livestock Greenhouse Gas Emissions Working Group Subgroups 1 (Fostering Markets for Non-digester Projects) and 3 (Research Needs, Including Enteric Fermentation). The purposes of the Subgroup analyses were to assemble a comprehensive overview and discussion on available non-digester methane emissions reduction alternatives (CARB, 2018a) and to identify research needs, better understand mitigation strategies to achieve emissions reductions and better understand options for reduced enteric emissions (CARB, 2018b).

These recent endeavors to evaluate effectiveness of non-digester manure treatment technologies have identified similar technology categories as the work from 2005. Subgroup 1 had a presentation by Newtrient to share information on new technology assessment. Familiar technologies were discussed (mechanical separation) with addition of polymers and diffused air filtration to improve separation capability. Newtrient also discussed use of membranes to remove salts, centrifuges, vermiculture, evaporative systems, torrefaction and hydrothermal carbonization. The end products from more intensive treatment technologies were identified as humus, custom fertilizers, biochar, algae, worm castings and fuel. Few of these newer technologies were or are being tested or demonstrated in California. In state demonstrations are critical to understand how effective technologies may be under California animal and manure management conditions. Additionally, these technologies repartition nutrients into other products. Markets for end products must be identified to determine technology economic feasibility. The information obtained through the two Subgroups and continued information from Newtrient's data collection methodologies are useful for directionality of potential nutrient and emission changes.

Our objective was to review strategies and technologies currently or potentially used to reduce manure methane emissions for applicability to small and large dairies.

Materials and Methods

California AMMP proposal data were used when possible to inform current and future manure management conditions.

Task 3.1: Obtain information included in AMMP proposals regarding strategies and technologies currently used to reduce manure methane emissions

Data from individual AMMP applications were obtained through a Public Records request. Additionally, some individual dairy producers and technical assistance providers were contacted to obtain copies of submitted applications. Some technical assistance providers were contacted to gain greater insight into the AMMP application process and obtain additional information and impressions about their understanding of the effectiveness of select practices.

Task 3.2: Evaluate reduction strategies applicability to small and large dairies for San Joaquin Valley and North Coast dairies based on associated manure collection, treatment and storage categories.

AMMP application analyses of practices. Redacted project narratives, budget sheets and GHG benefit calculator results were used to obtain information on pre-AMMP manure management and proposed post-AMMP manure management. For those herds with multiple practices (solid liquid separation and composting as well as a compost bedded pack barn) the solid liquid separation was used as there was no way to differentiate percent of manure destined for each of the AMMP categories. Often solid liquid separation and composting of manure were to be implemented on one animal class and compost bedded pack barn was for a different class of animals. Project type information was extracted from 2017 and 2018 applications. Herd size (milking and dry cow numbers; harmonized information Chapter 1) and average milk production and composition data were used consistent with Chapter 2 (CDFA, 2018). Data from each AMMP funded project from 2017 and 2018 were input into the 2019 GHG benefit calculator to

estimate baseline emissions and emissions reductions for gross practice level. No data were available for energy use to include in the analysis. Each dairy appeared only once even though some applied in both 2017 and 2018. Additionally, some dairies identified multiple practices would be implemented. Each of these was assigned to what was understood as the primary manure treatment practice given the available information. When possible data from 2019 applications were included. The AMMP information for 2019 was from the summary of applications and not necessarily from actual applications as all 2019 files were not obtained prior to the analysis.

Percent of dairies seeking AMMP funding was determined by dividing the number of dairies in each herd range and housing category seeking funding by the total number of dairies in each herd range and housing category and multiplying the results by 100.

Average emissions estimates were estimated by funded project and averaged within AMMP category. Percent reduction was calculated as the value of baseline emissions minus project emissions divided by baseline emissions, multiplied by 100.

AMMP emissions reductions. Information from herd narratives was extracted to identify manure management pre and post AMMP project implementation. Statewide data for average values for milk production and composition were used to estimate project emission reductions, normalized with the 2019 GHG benefit calculator (CDFA, 2018). Results of emissions reduction by project type were summarized by AMMP practice for those herds in the lower two deciles of cows for herds in Region 5. Note, the definition of the lower two deciles was a mere snapshot in time and will change as herd sizes change.

Results

AMMP application analyses of practices. Distribution of herds by housing type is in Figure 3.1. In 2017, Region 5 funded AMMP dairies were predominantly freestall (n=12; 2 non-freestall facilities). In 2018, 33 freestall facilities were funded in Region 5. In 2019, 38 dairies were funded in Region 5; 7 were non-freestall. Applications from herds with animal population in the lower two deciles represented 52.42 percent of total applications from Region 5.

More applications were received from dairies with freestalls than dairies without freestall. Distribution of herds applying for AMMP funds was somewhat different than the population distribution of herds in Region 5 (Figure 3.1 and Chapter 1 Figure 1.5). More dairies with less than 1,035 milking and dry cows applied for AMMP funds. This was consistent with herd distribution in that 51.34 percent of herds had less than 1,035 milking and dry cows. Percent of dairies seeking AMMP funding by herd size range and housing category is presented in Figure 3.2.

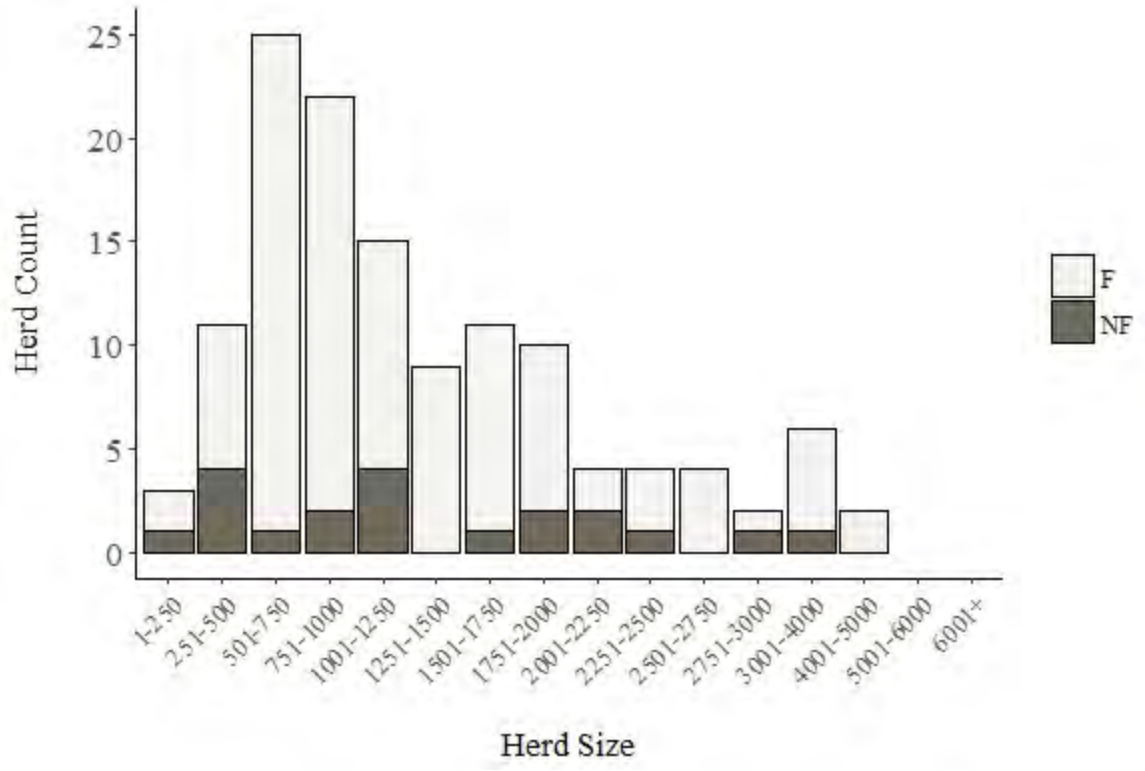

Figure 3.1 Region 5 AMMP dairy project applications in 2017, 2018 and 2019 by herd size and housing type (F=freestall; NF=non-freestall). Individual dairies are represented once even though they may have applied multiple times. Pasture based dairies not included.

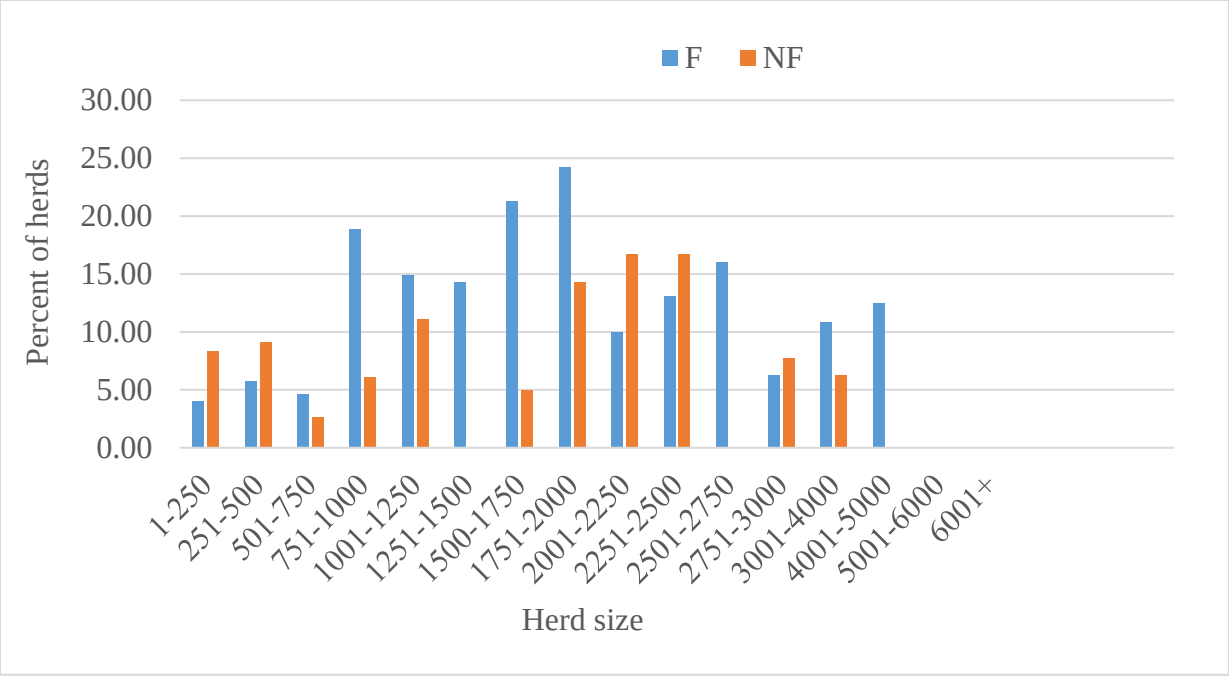

Figure 3.2 Percent of Region 5 herds by housing type (F=freestall; NF=non-freestall) and herd size seeking AMMP funding in 2017, 2018 or 2019. Individual dairies are represented once even though they may have applied for AMMP projects multiple times. Pasture based dairy not included.

Three rounds of funding have occurred for the AMMP process. Descriptions of each project category for the 2019 application cycle are provided (Table 3.1).

Table 3.1 Project category descriptions

2019 Project Category	Project Description
1a	Pasture based management
2a	Compost bedded pack barn
3	Solid separation without project narrative to determine category (2019 applications)
3a	Solid separation with open solar drying
3e	Solid separation with solid storage
3g	Solid separation with composting (passive or intensive windrow)
4a	Scrape conversion with open solar drying
4g	Scrape conversion with composting (passive or intensive windrow)

AMMP applications submitted by dairies from 2017, 2018, and 2019 were analyzed to determine which project category applied to each proposed project in the Central Valley (Region 5) and North Coast (Region 1 and 2 combined). Baseline manure management practices for AMMP applicant dairies is identified (Table 3.2). Nearly all of the applicants collected manure in flush

systems (n=36, 2017; n=50, 2018), and mechanical separation technology was absent as a baseline practice (58.3 percent 2017; 82.3 percent 2018).

Table 3.2 Baseline conditions for Region 5 dairies at time of AMMP application (funded (Fd) and unfunded (UF) projects) for 2017 and 2018 applications.

	Application Year			
	2017 Fd	2017 UF	2018 Fd	2018 UF
Manure collection				
Flush	14	22	32	18
Scrape	0	0	0	0
Scape/Vacuum	0	0	1	0
Treatment				
None	10	11	27	15
Solid separation				
Stationary screen	3	7	6	3
Vibrating screen	1	1		
Roller drum		1		
Screw press		1		
Weeping wall		1		

Dairy herd demographics are provided for 2017 (Table 3.3), 2018 (Table 3.4) and 2019 (Table 3.5) projects in Region 5. Most applications submitted (85.7 percent) and funded projects (89.8 percent) were on dairies with freestalls. Solid liquid separation was identified as the primary or only practice on 63.8 percent of applications submitted. Compost bedded pack barn requests were involved with 19.8 percent of applications followed by conversion from flush to scrape on 16.3 percent of applications. All funded projects for solid separation with open solar drying, solid separation with compost, and flush to scrape with open solar drying were on dairies with freestalls. Most funded compost bedded pack barns (76.5 percent), solid separation with solid storage (76.0 percent) and flush to scrape conversion with composting (60.0 percent) were on dairies with freestalls. Summary of funded AMMP projects for Region 5 dairies is in Figure 3.3. Management strategies that reduce methane emissions used on dairies that applied for AMMP funding included some form of solid separation from the liquid waste stream. A general Category 3 solid separation (unable to decipher management practice used post separation) was used for 2019 funded projects as most files were not available for analysis.

Table 3.3 Summary of 2017 funded dairy AMMP project herd demographics by housing design for Region 5[1].

		Housing[2]		Herd Size	
2019 Project category[3]	Number	F	NF	Range	Average
1a	1	1	0	795	
2a[4]	3	2	1	950-1992	1521
3a	1	1	0	1898	
3e	1	1	0	940	
3g	4	4	0	1225-3330	2164
4a	2	2	0	890-900	895
4g	3	2	1	2237-3090	2642
Summary of 2017 non-funded dairy AMMP project herd demographics					
2a	1	0	1	510	
3a	10	7	3	182-3385	1175
3e	2	2	0	441-1600	1021
3g	9	9	0	345-3215	1758

[1] Applications received across species and across California: 53. Region 5 dairy applications awarded: 15. Dairies initially awarded that did not utilize funds: 2 (not counted in funded applications). Region 5 dairy applications not awarded: 24. Region 5 non-dairy applications not awarded: 4. Applications outside of Region 5: 8.

[2] Freestall, F; non-freestall, NF.

[3]Project categories: 2, compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage, g. solid composting (passive or intensive windrow); 4, partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).

[4]Two of these are in conjunction with other projects (i.e. 2a/4g, 2a/4a).

Table 3.4 Summary of 2018 funded dairy AMMP project herd demographics by housing design (freestall, F; non-freestall, NF) for Region 5.[1]

		Housing[2]		Herd Size	
2019 Project category[3]	Number	F	NF	Range	Average
2a[4]	4	4	0	610-2730	1948
3a	13	13	0	330-1800	1053
3e	2	2	0	515-1356	936
3g[5]	11	11	0	322-2095	1005
4a	2	2	0	1207-1520	1364
4g	1	1	0	2400	
Summary of 2018 non-funded dairy AMMP project herd demographics.					
2a[6]	2	2	0	858-941	900
3a	11	9	2	785-2000	1175
3e	2	2	0	193-505	349
3f	1	1	0	980	
3g	2	2	0	792-1272	1032
4a	1	1	0	1040	

[1]Applications received across species and across California: 63. Region 5 dairy applications awarded: 33. Dairies initially awarded that did not utilize funds: 2 (not counted in awarded applications). Region 5 non-dairy project awarded: 1. Region 5 dairy applications not awarded: 19. Region 5 non-dairy applications not awarded: 0. Applications outside of Region 5: 8.

[2]Freestall, F; non-freestall, NF.

[3]Project categories: 2, compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage, g. solid composting (passive or intensive windrow); 4, partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).

[4]Three of these are in conjunction with other projects (i.e. 2a/4g, 2a/1a, 2a/3g).

[5]Two of these are in conjunction with other projects (i.e. 3g/3a, 3g/3a).

[6]Both are in conjunction with other projects (i.e. 2a/3g, 2a/4g).

Table 3.5 Summary of 2019 funded dairy AMMP project herd demographics by housing design for Region 5.[1]

2019 Project category[3]	Number	Housing[2]		Herd Size	
		F	NF	Range	Average
2a	10	7	3	575-4200	1558
3	12	12	0	345-1840	1054
3a	10	7	3	430-4750	1539
3e[4]	2	2	0	941-3185	2063
3g	5	5	0	644-1600	1099
4a	1	0	1	920	920
Summary of 2019 non-funded dairy AMMP project herd demographics					
2a	7	5	2	149-1020	565
3	7	6	1	182-3515	1211
3a	4	3	1	530-1160	815
3e	1	0	1	345	
3g	4	3	1	580-2400	1114
4	3	2	1	450-1469	803

[1]Applications received across species and across California: 91; Region 5 dairy applications awarded: 40. Dairies initially awarded that did not utilize funds: 0 based on information available at time of report. Region 5 non-dairy project awarded: 2. Region 5 dairy applications not awarded: 26. Region 5 non-dairy applications not awarded: 3. Applications outside of Region 5: 20.

[2]Freestall, F; non-freestall, NF.

[3]Project categories: 2, compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage, g. solid composting (passive or intensive windrow); 4, partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).

[4]Two of these are in conjunction with other projects (i.e. 2a/4g, 2a/4a).

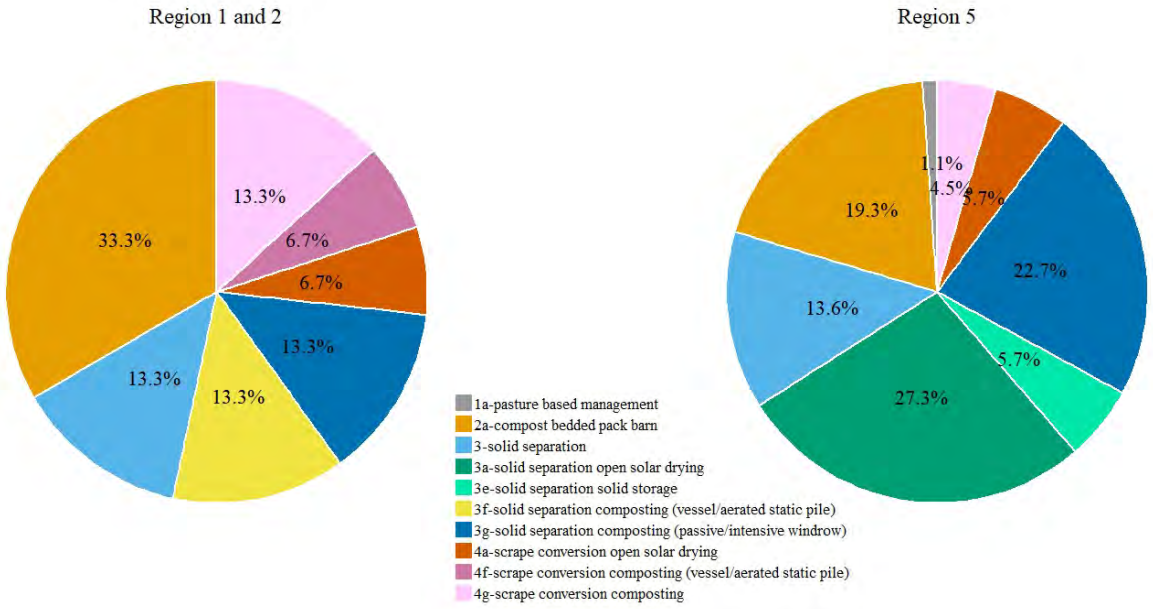

Figure 3.3 Percent of AMMP projects in each project category funded 2017 through 2019 on dairies in Regions 1 and 2 (left) and in Region 5 (right).

Fewer dairies reside in Regions 1 and 2. A summary of herd size (HS) demographics by application year, project type and project status (funded or unfunded) for milking and dry cows is provided (Table 3.6). The most requested AMMP practice was compost bedded pack barn and solid liquid separation (34.48 percent of applicants each) for applications from Regions 1 and 2. Conversion of flush to scrape was requested by five applicants (17.24 percent). Funded projects are compared with Region 5 in Figure 3.3.

Table 3.6 Summary of funded (Fd) and unfunded (UF) dairy AMMP project herd demographics in Regions 1 and 2.

	2017		2018		2019	
2019 Project category[1]	Fd	UF	Fd	UF	Fd	UF
1a	--	--	--	1	--	3
HS range						330-575
HS average				260		463
2a	2	--	--	--	3	5
HS range	290-690				299-500	
HS average	490				433	
3	--	--	--	--	2	--
HS range					375-900	
HS average					638	
3f	--	1	1	--	1	3
HS range						275-600
HS average		1120	1120		1700	387
3g	--	--	1	--	1	--
HS range						
HS average			290		290	
4f	--	--	--	1	1	--
HS range						
HS average				189	405	
4g	1	1	1	1	--	--
HS range						
HS average	550	189	400	280		

[1]Project categories: 2 compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage; g. solid composting (passive or intensive windrow); 4 partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).

AMMP emissions reductions. Estimated project emissions and percent of emissions reduction from baseline emissions are shown in Table 3.7 for dairies in the lower two deciles of animal populations in Region 5. One project in these herds was to manage manure in compost bedded pack barns. This project assumed great reductions in manure handled in anaerobic conditions. Those projects on facilities seeking to implement mechanical separation with some form of subsequent solids drying (open solar, n=6; solid storage, n=1; passive or intensive composting, n=4) were most prevalent. Emission reductions from these projects ranged from 8.78 to 86.78 percent. Two facilities had flush to scrape conversions. One had lower emissions reduction of 8.78 percent and one had higher emissions reduction 81.90 percent.

Table 3.7 Estimated AMMP project emissions[1] and percent reduction of emissions from baseline for Region 5 funded projects with herd population less than 1035 mature cows.

Project category[2]	Project description	Count	Project emission ($MTCO^2e/yr$)	Average percent reduction
2[3]	2a	1	429	86.78
3	3a	6	2288	21.43
	3e[4]	1	DNC	DNC
	3g	4	2360	23.45
4	4a[5]	1	3628	8.78
	4e	1	429	81.90

[1]Calculation for reduction based on baseline project emissions using the 2019 GHG benefit calculator.
[2]Project categories: 2, compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage, g. solid composting (passive or intensive windrow); 4, partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).
[3]Compost bedded pack barn projects were for dry cows, heifers and or special needs cattle.
[4]Data do not compute (DNC). Herd project transitioned manure management from scrape with deposition into liquid storage area, to vacuum and process through a screw press separator. Assumptions could not be made for percent of manure collected and percent of collected manure diverted from anaerobic conditions.
[5]Project converts from flush with mechanical separator to vacuum and open solar drying. Assumed 104 days a year of vacuum collection with flush the remaining time (30 percent collection).

Discussion

AMMP application analyses of practices. By default, the primary AMMP applications submitted and funded were for practices already functioning on California dairies. A few self-motorized vacuum systems (dedicated machine not tractor driven) were funded. This was a new practice for California dairies. A few applications requested funding for unique technologies, including vermicompost or solid liquid separation with additional effluent stream treatment post separation. Although new technologies for enhanced nutrient removal exist (available for viewing at the World Ag Expo in 2018, 2019 and 2020) they have not fully entered the California market place, yet. It is anticipated that once some of these technologies have been demonstrated in California their use will increase, assuming financial opportunities are present. These more advanced separation technologies remove additional nutrients (beyond standard mechanical separators) and yield pelleted or other solids. This additional carbon removal comes with additional capital as well as operation and maintenance costs.

Using redacted files had some limitations as essential project information was unavailable making it difficult to fully understand how emissions reductions were influenced. A few examples are provided here regarding potential GHG benefit calculator assumptions. Many applications indicated they were installing a mechanical separator (stationary inclined screen or double screen system). Some indicated a screw press with auger or conveyor was included.

Based on project narratives and information provided within applications, the purpose of the screw press was to remove moisture not to remove solids. This was interpreted as the screw press received the solids from the stationary inclined screen and produced an effluent that went to anaerobic storage. One application proposed to vacuum manure and then send it through a screw press separator to remove solids. The fate of effluent was not described. In this circumstance, the GHG benefit calculator would assume all vacuumed manure was diverted from anaerobic storage although effluent from the screw press likely would end up in anaerobic storage.

Within a Region, no specific trends or tendencies existed between use of different practices and herd size. Different practices were preferred by Region. Compost bedded pack barns were funded on a higher percent of dairies in Regions 1 and 2. Compost bedded pack barns (34 percent) and solid liquid separation (39 percent) were nearly equal in funded projects for Region 1 and 2 dairies. Over two-thirds of Region 5 projects were solid liquid separation. Differences in manure collection, treatment and storage can explain why such a large percent of Region 5 dairies applied for solid liquid separation compared with dairies in Regions 1 and 2. Liquid manure is more dilute on Region 5 dairies than dairies in Regions 1 and 2. Knowledge of specific facility information may elaborate why tendencies did not exist. Information about facility age, previous herd (animal) or facility (infrastructure) expansion, acres available for infrastructure development, herd economics, age of operator and succession planning may have contributed to interest in AMMP. Additional barriers for participation may exist. Considerable time was needed to complete AMMP applications and get all documentation necessary uploaded for review. Construction costs changed between the time proposals were submitted and awarded. This may explain why some awarded projects were not utilized. In application years 2017 and 2018 two Central Valley dairies each were awarded projects and did not construct them. Clearly, interest did exist from those who applied for the AMMP program. As funded projects move forward and come on-line more individuals may be interested in seeking AMMP funding to contribute to GHG emissions reductions. Future participation will depend in part on fund availability for the program and dairy economics.

One of the many goals on dairies is to produce high quality milk. To achieve this goal, attention is given to animal housing and resting areas. Manure management on concrete surfaces is an essential tool to provide cattle with a clean environment to produce a high quality product. As such, attention to freestall beds and concrete lanes and alleys is important. Since cattle spend more time in freestalls their manure is deposited on a concrete surface that is either flushed or scraped and typically destined to anaerobic storage. The nature of freestall dairies requires that more manure be managed daily at a given herd size as this manure is dropped on concrete surfaces animals frequent. The 2019 GHG benefit calculator assumed 2.4 times more manure was collected from freestall facilities than from non-freestall facilities and was subject to treatment and or storage under anaerobic conditions thereby contributing to methane production. In any given herd size range below 3,500 mature cows more dairies with freestalls applied for funding than non-freestall. It does not appear that this was a function of amount of manure collected and managed. It may be a function of facility size, age, profitability and probability of continuing in the dairy business. It may also be a function of awareness of herd owners to access AMMP funds.

As identified in Chapter 1 mechanical separators were present on 53.74 percent of herds greater than 1,251 milking and dry cows and present in 32.32 percent of herds with 501 to 1,251 milking and dry cows. However, presence does not mean functionality.

Prior to AMMP compost bedded pack barns were uncommon in California. These barns require daily management and incorporation of fresh manure into the bedded pack. Sufficient labor and equipment must be available daily on dairies to incorporate fresh manure into bedded packs. As of November 2019, there were five completed compost bedded pack barns, six partially completed, and two not yet started. No energy inputs were available for pre and post AMMP implementation. The manure emissions reductions for animals in compost bedded pack barns should account for time away from barns during milking. It is unclear how the manure on feed aprons would be managed without analyzing barn design. If feed apron manure is scraped daily and incorporated into the bedded pack then the reduction seems reasonable. If feed apron manure is not incorporated daily into the bedded pack then the emissions reduction may be an overestimate.

Vacuum systems were used in select facilities in California (Region 5) prior to AMMP. Prior to AMMP, vacuum systems were predominantly tractor driven tanks with a vacuum component attached to the tractor through a power take off device. Introduction of fully operated equipment (no need for tractor as tank and engine are on the same piece of dedicated equipment) was attractive to a few dairy producers interested in modifying their manure management practices. Management of vacuum equipment requires dedicated labor to operate equipment. Additionally, this activity is subject to potential challenges as the equipment operator needs to dismount to open and close gates and the activity requires synchronization with milking schedule to ensure to minimize animal stress. Many of the flush to scrape projects proposed to vacuum 104 days a year (personal communication) in some or all lactating pens, then subsequently air dry or compost manure. A value of 30 percent of manure vacuumed was assumed. In herds where manure is vacuumed twice weekly and no flushing occurs, then near total collection of the manure from concrete feed aprons will be collected. In herds where manure is vacuumed twice weekly and flushed the other days of the week, markedly less manure will be diverted from liquid storage compared with the previous example. Some residual manure remains in concrete grooves after vacuuming. Manure defecated while cows travel to and from the milking parlor or at the milking parlor is not likely collected via vacuum.

Dairies located in Regions 1 and 2 pasture cattle for part or much of the year (southern or northern locations, respectively). Pasture based dairies manage manure and wash water collected from the milking parlor daily. Additional manure is managed from animal housing areas. Climatic conditions (high rainfall and extended rainy season) result in minimal flushing associated with manure collection so less wash water is generated for subsequent storage. Mostly, manure is scraped from animal housing areas and stored as a slurry or solid. Requests for compost bedded pack barns and solid liquid separation were consistent with the climate and current management conditions. Daily attention is necessary for proper maintenance of the compost bedded pack barn. The advantage for organic producers in Regions 1 and 2 was the end product should have markedly fewer weed seeds and required fewer additional management considerations when land applied on pasture.

AMMP emissions reductions. Emissions reductions for any given project implemented were evaluated on the subset of manure it treats. As used, the 2019 GHG benefit calculator asks for specific practices and may focus only on the part of the herd receiving the practice. Complex combinations of multiple classes of animals and multiple practices for manure management were submitted by some application. For some facilities, modifications to different classes of animals and their associated manure management may yield greater emissions reductions than merely

focusing on one class of animals. Flexibility in the application process is important to allow subscription of different practices for different groups of cattle. As an example, one AMMP project will have a compost bedded pack barn for one group of animals and manure from other animals at the facility will be flushed and be subject to mechanical separation. It is critical to take into consideration the percent of emissions reduction from a specific practice with a specific class of animals compared with the total emissions from the farm. It is the actual reduction in emissions across all dairies that is necessary to achieve the 2030 target of 40 percent reduction from 2013 inventory emissions values.

Conclusions

The primary applications for AMMP were for known and existing practices already on farms in California. More dairies in the lower two deciles of lactating and dry cow population applied for AMMP funds. This represented a smaller percent of dairies in each herd size category for freestall (4.76 percent) and non-freestall (6.38 percent) dairies with less than 750 milking and dry cows. Funded AMMP projects were predominantly solid separation (Category 3) in Region 5 and solid separation or compost bedded pack barns in Regions 1 and 2. Continued funding of AMMP provides opportunity for producers to participate actively in GHG emissions reductions. This is critical given the current economic outlook for dairies.

Recommendations

Continued funding of AMMP provides opportunity for producers to participate actively in GHG emissions reductions. This is critical given the current economic outlook for dairies.

CHAPTER 4 THE ECONOMIC MODEL, SIMULATION APPROACH, AND DATA USED TO ASSESS THE ECONOMIC IMPACTS OF METHANE EMISSION REDUCING PRACTICES FOR SMALLER AND LARGER CALIFORNIA DAIRIES

Introduction

Chapter 4 describes a conceptual model, a simulation framework and the data used to implement the model.

This chapter provides background to the simulation model results contained in Chapters 5, 6 and 7. Therefore, this chapter itself does not offer specific results or practical conclusions, but rather is an input to such results and conclusions.

The first part of Chapter 4 documents the modeling framework developed to assess impacts and describes the simulation methodology. The detailed computation model, written in R is available from the authors.

The second part of Chapter 4 provides data and parameter values used for the simulations. This provides a detailed list of manure management practices, and their effects on costs and therefore are used in specifying cost equations and shifts in cost equations that are part of the model developed in the first part of the chapter.

Materials and Methods

4.1 Economic Modeling Framework

Economic modeling was applied in the context of technical change or policy changes to better understand economic and related implications of such variables as prices, quantities and environmental outcomes. A novel approach was developed in the context of manure management practices and impacts on size distributions of farms. Similar simulations have been used to address issues in environmental, resource and agricultural economics. See for example, Lee, Sumner and Champetier (2019); Perrin (1980); and Rickard and Sumner (2008) and the articles they cite.

4.1.1 Overview of the modeling framework

An economic model was developed representative of dairies for operations of different sizes and manure handling types where manure and methane management costs may be adjusted to reflect the implementation of methane emissions reduction practices. Each dairy size/type was characterized by a herd size and associated costs and emission factors for current and alternative practices.

In order to simulate the response of the whole dairy industry, each representative dairy model was scaled up by multiplying each specific outcome by the number of operations in each group type. Milk production was matched to the demand for milk products for all of California. This scaling up allowed the model to assess the methane emissions abatement in California's inventory and to track market adjustments in milk supply and demand.

In the model, a shift upwards in production costs from increased methane abatement efforts results in a shift upwards of supply on the milk market. Given a stable demand for milk, these cost shifts result in an increase in milk price, decrease in quantity produced and consumed.

Thus, the complete model reflects the full production and market effects of policy on the dairy sector while allowing differences in costs and emission reductions among different sized dairies and as well as among freestall and non-freestall operations.

Four time horizons were considered: 1 year, 5 years, 10 years and 20 years. These horizons differ in terms of the values of parameters that reflect the extent and pace of adjustments in producer and consumer behaviors (i.e. supply and demand elasticities) including the extent of entry and exit for dairy operators.

4.1.2 Groups of dairy operations according to size and other characteristics

Dairy operations of California were assigned to one of seven groups. For non-organic dairies each group was characterized by a combination of three herd size ranges and two current housing systems that affect manure handling. The seventh group represented organic dairies which represented substantial differences in costs, revenues and production practices.

In the equations below, the notation "*z*" indicates the group index. All operations within one size category were assumed to have the same production costs including the same cost changes related to methane abatement practices. Treating operations as homogenous within group allowed considering a representative operation for each size-group and building a detailed economic model of farm choice, profitability and methane emission.

4.1.3 The treatment of marginal cost, abatement practice adoption and representative operations in size-practice groups

The model has one representative set of parameters per group. The model does not include an explicit mechanism for progressive adoption of practices among dairies of one group. The model produces a step-wise methane abatement cost curve. The model and parameterization faced the standard trade-off between model complexity, available parameter estimates and robustness. Adding heterogeneity in costs within groups can be readily added when data and parameter estimates are available to calibrate such patterns of heterogeneity.

Importantly, this simplified model specification is unlikely to generate systematic bias related to size distribution implications. Adoption of manure management practices is implicitly random within each group, which is expected if factors other than abatement marginal cost, such as location, access to information, or other farm-specific management drive dairy farms to adopt abatement practices.

4.1.4 Bio-economic model of a representative dairy

A representative dairy operation was characterized with the help of a set of biophysical variables. The number of milking cows in the herd, *c*, indicated size. If data were available, the model would be robust to other size measures. The quantity of milk produced was denoted *Q* and the quantity of methane emitted through manure management was denoted *GE*.

In addition to biophysical variables and parameters, operations were characterized by a set of economic metrics. On the income side, these included the price of milk, which was denoted by P;

the milk revenue R = P*Q; and non-milk revenue OtherR. The costs included feed, FeedC; hired labor, LabC and costs specific to manure management that are discussed in detail below. Table 4.2 lists notation starting with those representing the income size, then variable costs, then capital investment costs, management and finally the economic summary concepts marginal cost and total costs.

Many of the biophysical and economic variables can be usefully considered on a per unit basis with several units in the denominator. Costs and revenues are defined per unit such as: per cow, per hundredweight of milk or per dairy operation. Subscripts and superscripts used to facilitate the tracking of units for each variable are in table 4.2

Table 4.1 List of symbols used in the equations and the description of economic characteristics of dairy operations in the model

Symbol	Interpretation
P	Price
R	Revenue
OtherR	Other revenues (not milk)
FeedC	Feed costs
LabC	Labor costs (hired)
MaOpC	Manure management operations costs
OtherOpC	Other operations costs
OpC	Total operations costs
MaInvC	Manure management capital investment costs
OtherInvC	Other (non-manure related) investment costs
InvC	Total investment costs
MgC	Management costs
MC	Marginal cost
TC	Total costs

Table 4.2 Subscripts and superscripts for model variables and parameters

Symbol	Interpretation
c	Per cow
m	Per cwt of milk
o	Per dairy operation
g	Total for a group of operations
T	Total for California
z	Indicator for size/type group
Conv, Org	Indicates conventional and organic markets

The subscript c, represents a measure per cow, m represents a measure per hundredweight of milk, and o represents a measure per dairy farm operation. The index g, refers to a group as specified above and T represents the total for the California dairy industry. Index z will be used as a subscript when considering groups of operations and the entire industry.

Using this notation, for example, Q_c would be the quantity of milk produced per cow in a representative operation and GE_m the amount of methane emitted per cwt of milk. Note that not all combination of variables and indexes are useful to consider. All equations and variables are yearly measures unless otherwise specified.

Equipped with this notation, the rest of this subsection describes the main economic tradeoffs involved in a representative dairy operation. The next few equations were used to characterize the important economic and methane-related mechanisms and tradeoffs in our representative operation.

The dairy operation produces Q_o cwt of milk per year from its C_0lactating cows. The sales of the milk production generate the revenue given by

$$R_o = P_m * Q_o + OtherR_o. \quad (1)$$

Note that P_m the price is per cwt of milk and was assumed to be the same for all operation sizes, with organic milk in a separate group. The farm revenues not accruing from milk sales were accounted for in the term $OtherR_o$.

The quantity of milk produced is a function of the number of lactating cows:

$$Q_o = C_o * Q_c \quad (2)$$

where Q_c is the amount produced per cow in this representative dairy size and manure management group.

The amount of methane emissions for the operation reflects the manure management practice and the characteristics of the operation size/type:

$$GE_o = GE_c^i * C_o \quad (3)$$

where superscript "i" indicates the methane mitigation practice.

A more intensive effort of methane emission reduction means that the amount of methane per lactating cow GE_c^i is smaller (emission factor). It is this index i which allowed linking the methane abatements to the corresponding manure management costs on the operation. As with other parameters of the simulation, the emissions factors for a given manure management practice were allowed to differ across dairy sizes. Note that equation (3) tracks the emissions from lactating cows in the calculation of amount of methane per lactating cow GE_c^i. As discussed in sections 4.2 and 4.3, the emission factor includes the dry cow as well as the cows that are currently lactating. The heifers are not included.

The economic costs of milk and manure management for the operation were represented in the equation for costs of production. The total costs of an operation (calculated per year) were split in three main categories: operations costs, capital investment costs, and management costs. This is represented by the following relationship per operation:

$$TC_o = OpC_o + InvC_o + MgC_o. \quad (4)$$

These costs were converted to costs per cow or cwt of milk produced by dividing by the number of cows or milk production and would then have subscripts "c" or "m". We track the different cost types separately to allow them to differ across time horizon, which is important in the relevant simulations, as well as for the composition of costs to differ across dairy types.

Operating costs can be thought of as costs applying on a per unit of milk basis or per cow basis. Investment costs will vary depending on the lifetime of the investment considered and the opportunity cost of capital (equivalent to the interest rate). Management costs will vary across dairy sizes reflecting differences in the number, behavior, and capacity of owner/managers.

We incorporated the details of the cost implications of methane abatement practices, which required a further break down of each cost category.

Costs of operations were split into four items:

$$OpC_o = FeedC_o + LabC_o + MaOpC_o(i) + OtherOpC_o \quad (5)$$

which tracks feed costs, labor costs (excluding manure management operations), manure management operations, and other miscellaneous costs. Feed and labor costs are functions of the number of cows in the herd and the amount of milk produced and are tracked separately in order to assess the effect of long-term trends in dairy profitability related to potential changes in labor and feed prices over time (see Task 7).

The manure operations costs include the fuel, labor and materials for scraping and other manure management operations but do not include the initial capital investment or the time and effort spent by the operation management. Operating costs for manure are a function of the amount of manure to be processed and the methane abatement practice indicated by the index i. Both parameters were allowed to vary across dairy size/types.

For investment costs, we only differentiated between investments related to manure management (machinery, storage infrastructure, etc.) and all other investments:

$$InvC_o = MaInvC_o(i) + OtherInvC_o \quad (6)$$

where Ma stands for manure. These investment cost for manure infrastructure *MaInv* do not include the opportunity cost of the manager's time.

The annualized cost of investment in manure management capital such as infrastructure or specialized machinery were represented by $MaInvC$ and other annualized capital investment costs were represented by $OtherInvC$. The cost of manure-related infrastructure and equipment depends on the methane practice adopted as well as the amount of manure to be processed, which is captured in the choice of parameters for each dairy size group. Annualization means that the one-time expenditure for purchase of material and building is spread over the useful lifetime of the infrastructure or equipment. The investment cost also includes the payment of interest on the capital required for the initial investment. Thus, annualization requires two assumptions: the lifetime of the infrastructure or equipment and the underlying interest rate.

This itemization of costs and distinction between operation, investment, and managerial costs related to manure management practices is important to the extent that these cost components are expected to differ across farm sizes. This level of detail also allows a careful representation of differences across the practices discussed in Task 3. Each methane management practice identified by index "i" was characterized in our simulations by methane emissions per cow GE_c^i from equation (3) and its corresponding costs $MaOpC_o$ and $MaInvC_o$.

The third term in equation (4) is the cost of management MgC_o and represents the time and effort of the managers of the dairy. For hired managers, this term could be calculated like other hired labor costs and an increase in management effort resulting from the adoption of methane abatement practices could be represented by simply increasing the amount of manager time needed. However, the management and ownership organization of dairies varies greatly across dairy sizes as well as idiosyncratic characteristics and therefore a systematic accounting of management costs is practically impossible. In fact, in many dairy operations, the managers are also owners and the compensation for their labor as managers cannot be separated from the returns to their investment as owners of the operation. For that reason, most datasets on dairy operation costs only report total costs excluding management costs.

In equation (4) we included management costs explicitly to emphasize that these costs affect dairy profitability directly. However, given the difficulty in quantifying management costs and their change in relation to new methane abatement practices, we did not include them in the rest of the modeling. We do nevertheless account for their potential effect when modeling exit decisions as discussed below. We argue that increases in management effort could greatly affect small operations where there is only one operator/manager who is unable to increase management effort through hire or dedicating more of his or her time.

The profit margin for the operation is the difference between revenue and total costs:

$$\Pi_o = \mathrm{R}_o - \mathrm{TC}_o \quad (7)$$

In addition, if the equipment maintains some salvage value at the end of the useful lifetime, this value, adequately discounted, should be subtracted from the initial total costs of the investment. Here, salvage values are likely to be very small and are ignored.

This profit margin is a central indicator of economic profitability in our simulation framework and in the literature on the economics of dairy operations (see for instance MacDonald, Cessna and Mosheim (2016), Bouchard (2016), Bragg and Dalton (2004) and others).

All equations presented so far were characterizing one representative operation and all variables were measured in units per operation or per cow (e.g. tons of CO2-equivalent of methane per operation, dollars of revenue per operation, and etc.). Below, we now expand the model to include all groups of operations adding up to the entire industry. In each group, all operations were assumed to be identical to the representative operation. Each group was characterized by a different set of values for its representative operation.

4.1.5 From representative dairy operations to groups and industry

The notation introduced in tables 4.1, and 4.2 allowed the model to scale up from representative dairy operations to the size groups and to the industry as a whole where the market mechanisms are at play in the determination of milk prices and quantities produced and consumed.

Given the assumption of representative operations for each size group, the equations (1) to (7) above given for each operation can be scaled up for their respective group by multiplying each variable with subscript "*o*" by the number of operations in each group N_z. The revenue, quantity of milk produced and all other variables for each group were indicated by subscript g. The variables introduced for representative operations above are now superscripted with z to reflect differences across groups. For instance, Q_o^A is the amount of milk produced by an operation in group A, while Q_c^D is the amount of milk per cow in group D.

As a result, equations (1) and (3) above become:

$$R_g^z = P_m * Q_g^z + OtherR_g^z = N_z * [P_m * Q_o^z + OtherR_o^z] \quad (8)$$

$$GE_g^z = N_z * [GE_c^i * C_0] \quad (9)$$

Cost and profit equations (4) to (7) can be aggregated for the groups of operations in the same fashion.

The next step is to add variables across groups to obtain milk production and methane emissions for the two milk markets as well as the corresponding economic returns, costs and profit margins.

The total quantity of milk produced is the sum of the quantities from each group:

$$Q_T^{conv} = \sum_z Q_g^z = Q_g^A + Q_g^B + \cdots + Q_g^F \quad (10)$$

$$Q_T^{org} = \sum_z Q_g^z = Q_g^G + Q_g^H \quad (11)$$

where "T" indicates the industry's total production and equation (11) allows for more than one organic group if needed.

Methane emissions can be calculated in a similar manner:

$$GE_T = \sum_z GE_g^z, \tag{12}$$

which combines emissions from producers in the organic and conventional milk markets.

4.1.6 Characterizing the response of dairies to changes in prices and costs.
Equations (1) to (12) above provide an organized description of costs of production and revenues for the production of milk with a breakdown of how methane-related practices might affect the operations of dairies. However, these equations do not provide a model of how producers will adjust their operations to changes in milk prices or costs of production through the adoption of new manure management practices.

The profit margin equation in (7) provides a useful benchmark as it allows modeling the behavior of operators as maximizing profit. We first present this profit optimization model before showing how it can be enriched with additional and more complex behaviors relating for instance to uncertainty about prices or investment diversification.

The profit of an individual operation from a group of size *z* is given by equation (7) above. To highlight the economic trade-off underlying profit maximization, we included the quantity of milk produced:

$$\Pi_o^z(Q_o^z) = \mathrm{R}_o^z(Q_o^z) - \mathrm{TC}_o^z(Q_o^z) \tag{13}$$

The profit is maximized by the quantity of milk that brings the marginal profit to zero, which means setting the marginal revenue to the marginal cost:

$$\frac{d\mathrm{R}_o^z}{dQ_o^z}|_{Q_o^{z*}} = \frac{d\mathrm{TC}_o^z}{dQ_o^z}|_{Q_o^{z*}} \text{ or } P_m = \mathrm{MC}_o^z(Q_o^{z*}, i) \tag{14}$$

using expression (1) for the revenue of the operation and where the star in Q_o^{z*} indicates the profit maximizing quantity. Index i indicates that the marginal cost of production will depend on the manure and methane management practice. A higher operation cost per hundredweight of manure will result in a higher marginal cost per hundredweight of milk.

The important intuition in equation (14) is that the quantity of milk will respond to price changes according to the shape of the marginal cost function. If the marginal cost changes substantially for a small change in the quantity of milk produced, the managers will not adjust production significantly for even large changes in prices. In contrast, if marginal costs differ only a little over a range of milk production volumes, a small price change will require the manager to adjust output quantity by a greater amount.

In a similar fashion, the equations in (14) captured adjustments that would follow from changes in the prices of feed, labor and other factors affecting costs. Equation (14) is the inverse of the supply equation where quantity of milk produced is given as a function of price as shown in (15):

$$Q_o^z = S_o^z(P_m, i). \tag{15}$$

We indicate that the supply function depends on the set of methane management practices implemented with the index i.

The supply function for the representative operation in each group (15) can be aggregated to the group in equation (16):

$$Q_g^z = S_g^z(P_m) = N_z * S_o^z(P_m, i) \quad (16)$$

The supply function for the industry is in (17):

$$Q_T = \sum_z Q_g^z = \sum_z N_z * S_o^z(P_m, i). \quad (17)$$

The slope (or derivative) of this supply function with respect to the price determines how much the industry will adjust milk output to price changes. A common way to represent different time horizons in this setting is to assume that this derivative is larger when more time is given to producers to adjust to price changes.

This profit maximization model has been expanded in the economics literature on dairy production, to better account for the dynamic nature of production decisions as well as the behavior of dairy manager/owners who may pursue profit as well as other objectives.

First, production decisions in the dairy industry carry significant inertia. Given that infrastructure determines to a large extent the size of the herd and the amount of milk produced, investment decisions lock in producers for long periods of time, in the range of years. Over the course of weeks or months, only limited adjustment for output and costs can be made to herd size or by changing feed and other practices. As a result, the response of dairy producers to changes in input costs or milk price is lagged and based on profit margins averaged over months or years.

MacDonald et al. (2007) Tauer (2006), Foltz (2004) and others show that dairy operations have remained in production when revenues fall below total costs but above the salvage value of the invested capital. This range of prices where profits margins are negative but dairy operators do not exit is called a zone of hysteresis or asset fixity. This zone depends on farm characteristics as well as regional factors such as opportunity cost of land.

A second important aspect of the economic behavior of dairy operators relates to asset investment and opportunity cost of management effort. When dairy owners are also the operators, investment decisions in the dairy and labor decisions by the owners are tied. For instance, Bragg and Dalton (2004) find that higher off-farm income opportunities and greater diversification of farm income were more likely associated with dairy exit decisions.

There was no available economic model of dairy exit that was specific to the California industry and context. The development of such model, which would require extensive data collection through surveys, was beyond the scope of this study. Accordingly, we used a heuristic model that combines a standard supply function for individual operations with a pattern of exit calibrated on observed trends in California.

The supply functions were specified by an elasticity (representing the slope of the supply) and shifts. The value of the elasticity parameter reflects the amount of adjustment that operators can implement for the 5, 10 and 20-year horizon. The shifts represent the change in costs due to the adoption of methane emission abatement practices as well as feed price and labor and are calculated using the cost equations (4), (5) and (6).

In parallel to this standard supply specification, the number of dairy operations in each group was adjusted for each simulation period considered. As discussed in the parameterization section 4.2 below, trends of exit observed over the last two decades for each size group were used to

build projections of exit over the next two decades. This was implemented by changing N_z in equation (16), which aggregates individual operations to groups. With this composite model of standard supply and exit, the supply side with heterogeneous dairy operations is complete.

We now turn to the demand for milk.

4.1.7 Characterizing milk demand facing California dairies.

We used two demand equations to represent the behavior of consumers on the conventional and organic milk markets. For the conventional market, an aggregate demand for raw milk facing the industry that combines the ranges of processed products and the demands and policies affecting those products. This simplified representation of the demand for dairy products is suitable for the purpose of our analysis. Individual producers face prices that vary by month and over which producers have little influence except in the characteristic of their milk (components and quality). Prices received by producers are determined to a large extent by the quantity of milk produced in California and elsewhere. Thus, our specification captures the main mechanism of equilibrium adjustments to a methane emission change. Since prices for organic milk are much higher and determined by a different demand segment, we represented the organic market separately despite its relatively small size.

Accordingly, we captured the response in the aggregate demand functions for conventional and organic milk:

$$Q_D^{Conv} = D(P_m^{Conv}) \text{ and } Q_D^{Org} = D(P_m^{Org}) \quad (18)$$

where D( ) is the demand function giving the quantity demanded annually Q_D in hundredweight per year for a given price P_m.

The shape, and in particular the slope of this function, characterizes how quickly the quantity demanded and consumed will change when price changes.

The supply and demand equations are connected by "market clearing conditions", which recognize that buyers and producers respond to the same price P_m and that, adjusting for a limited amount of storage over time, the quantity produced Q_t must be equal to the quantity demanded Q_D.

$$Q_D = Q_T \quad (19)$$

The demand function in (18), and the supply functions in (17), provide a complete model that tracks how implementation of methane abatement measures will impact production costs of dairies of different sizes and through market adjustment, the price and quantity of milk.

Figure 4.1 is a schematic representation of how the supplies of the different groups of dairies and the conventional and organic demands are connected in the model. The diagrams labeled "organic" represent two groups of dairies supplying the organic milk market. The three diagrams along the right side of Figure 4.1 represent the other 6 groups, housing systems are combined for each of three size groups.

Figure 4.1 helps illustrate how farm groups categorized by herd size relate to industry supply and demand conditions that determine market prices. When changes in manure handling practices affect costs of farms they affect the overall supply function in that market and therefore affect

price and the demand facing the categories, which, in turn, affects milk production of farms in that size category.

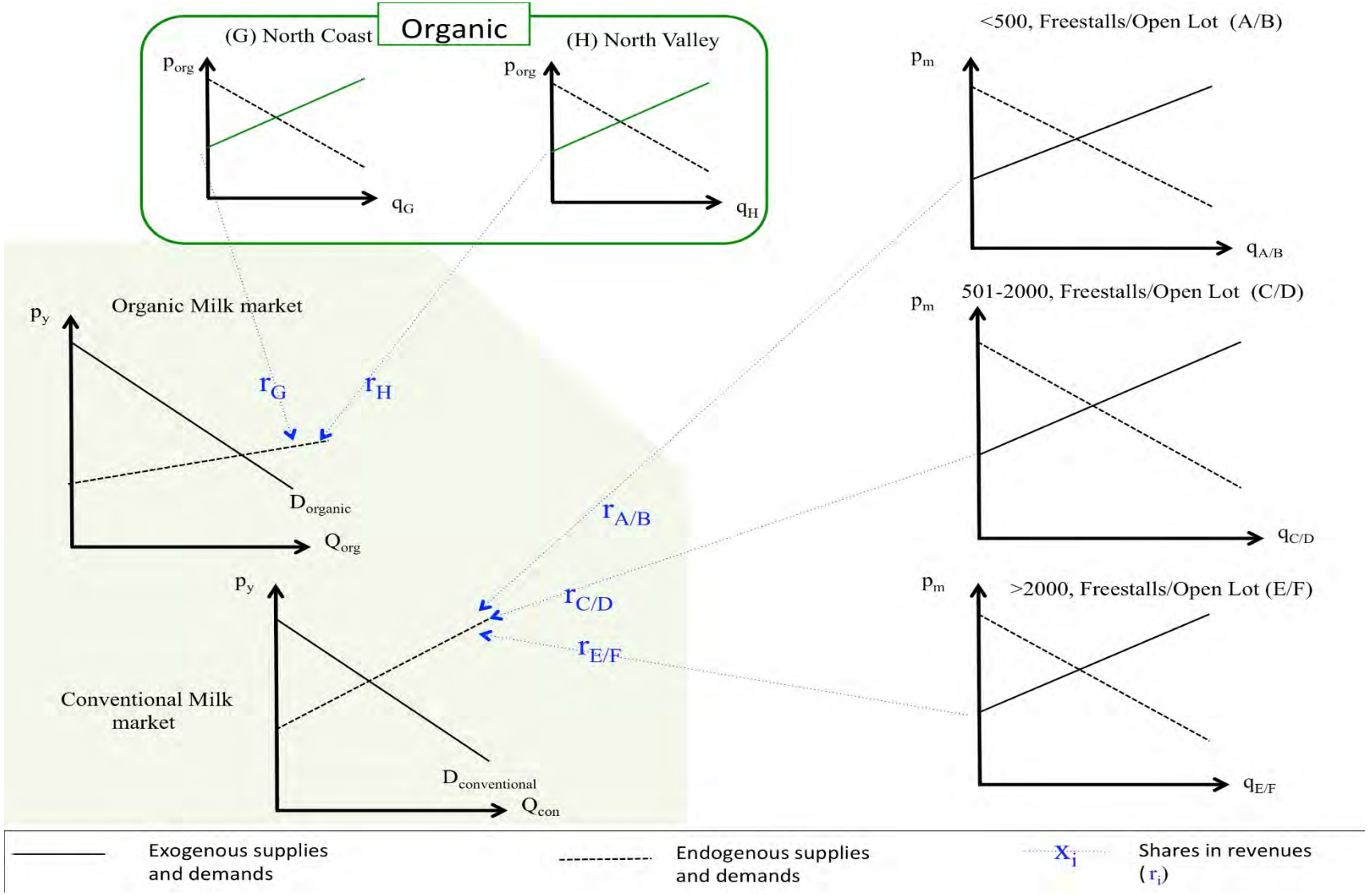

Figure 4.1 Break down of milk markets by dairy groups

4.1.8 Definition of scenarios in the economic model

Equipped with this sectorial model of the dairy industry in California, the impact assessment of the methane abatement policies can be implemented through scenarios, which show how economics and emissions outcomes would change under the adoption of different practices. The scenarios as defined by pattern of adoption of certain methane abatement practices which results in both an increase in production costs and a reduction in methane emissions.

We illustrate the effect cost increases in the economic modeling in Figure 4.2 and focus on dairy operations in group A. The diagram shows the demand for milk D_T (conventional here) as well the supplies for group A alone, S_A and for the whole industry, S_T. These supplies, which correspond to equations (16) and (17) above reflect the costs of operating before any new practice adoption. The starting price and quantity for the market is found where the total industry supply S_T meets the demand D_T and is labeled P_m, Q_T the figure. At that price, the quantity produced by group A is where the supply of the group S_A meets the dotted line indicating price P_m. By construction, the vertical distance between Q_A and Q_T is the sum of milk quantities produced by all other groups in the market (B through F).

When group A adopts a new methane abatement practice, the supply curve of the group "shifts up", reflecting a cost increase. In cases where some operations also exit the industry, the supply function also shifts left, since the total production of the group is reduced. The net effect of the shifts is a new supply for the group S'_A. Similarly, other groups may or may not see their supply move and by different amounts according to the specific patterns of adoption costs for different dairy sizes and types. The aggregated effect of these supply shifts is visible in Figure 4.2 in the new supply for the market S'_T.

The new market price and quantity is where the new total supply meets the demand and is the point (P'_m, Q'_T). Where S'_A, the new supply for group A meets the new price line P'_m determines the amount of milk produced by group A, after the adoption of new practices and market readjustment. It is labeled Q'_A and the horizontal different between Q_A and Q'_A is the change in quantity produced by group A. The vertical different between P'_m and P_m is the increase in price resulting from cost increases throughout the industry. Note however that producers are for the most part not benefiting from this price increase since they see their cost increase at the same time. The net effect will vary from group to group depending on how cost shifts affect different groups.

Implementation of this model includes several operation groups, three different time horizons (5 years, 10 years and 20 years) and the alternative methane abatement practices. The values of the supply and demand elasticities differ across time horizons and recognize that longer time horizons tend to allow for more score adjustment in practices, production and consumptions in response to changes in prices and costs. We also incorporate observed and projected trends in dairy farm exit, hired labor costs, and dairy feed costs.

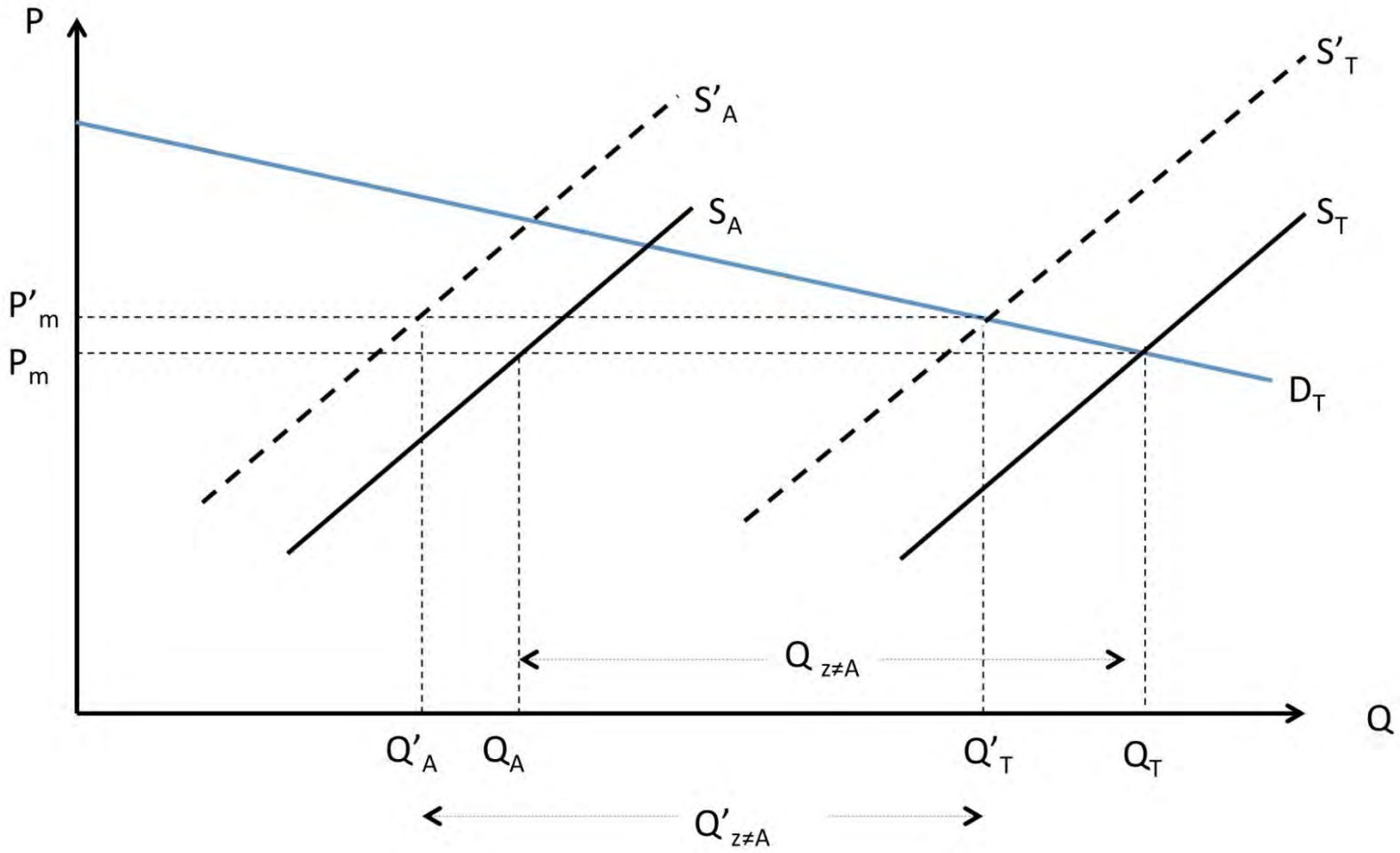

Figure 4.2 Equilibrium displacement in the milk market due to a production cost increase

Our simulations focused on modeling implications of costs of manure management patterns among groups and how these have changed and may change. These differ by dairy size and types. The patterns of adoption of practices used in our simulations are specified the second half of this chapter.

We considered four time-horizons and included dairy farm exit patterns across sizes based on historical experience. Furthermore, we allowed adoption to be partial within a group meaning that in the same group, some dairies adopt and others not. This means we did not impose an assumption that all operations in a group behave identically. There are several ways to model and explain differences in adoption or exit among operations and we discuss them when necessary when presenting simulation results.

4.1.9 Framework of equilibrium displacement model expressed in logarithmic differentials

We adopted a standard method to significantly reduce the requirements of parameterization in which we focused on changes or displacements induced by a policy or other scenario. Rather than calculating the operating costs (or another variable of interest) before and after implementation of a methane regulation policy, we tracked *by how much*, in percentage terms, the operating costs have changed. Similarly, instead of calculating quantity of milk, price of milk and profit margin before and after practice adoption, we estimated the percentage change in each of these variables. This methodology is commonly used in economics and is sometimes called an equilibrium displacement model.[1]

We used the notation *dln* to represent the percentage change of the variables. For instance, the percentage change in quantity of milk produced by the industry is noted $dlnQ_T$ and is calculated as the change in quantity dQ_T divided by the quantity before the equilibrium change (or the initial quantity) Q_T. Here we lay out the model using notation for the non-organic milk market. The organic market follows the exact same derivations.

The relationships above can be rewritten in percentage terms. For instance, equation (17) becomes by differentiation:

$$dQ_T^{Conv} = \sum_z dQ_g^z \tag{20}$$

which can be divided by dQ_T^{Conv} can be rewritten as:

$$dlnQ_T^{Conv} = \frac{dQ_T}{Q_T^{Conv}} = \sum_z \frac{Q_g^z}{Q_T^{Conv}} * \frac{dQ_g^z}{Q_g^z} = \sum_z s_g^z * dlnQ_g^z \tag{21}$$

where s_g^z are the shares of milk production from each group of dairy sizes in the total output of the conventional milk market.

Equation (21) reflects that the percentage change in total output is the average of the changes in each group weighted by the share of each group in the total production.

[2] To directly implement the full model as characterized by the set of equations in levels as written above would requires that each equation be fully parameterized against data. Furthermore, functional forms, which would typically be non-linear, must be chosen to represent all relationships.

The demand equation for conventional milk in (18) can similarly be transformed in a dln form by making a first order approximation of the demand function:

$$dlnQ_D^{Conv} = \eta^{Conv} * dlnP_m^{Conv} \quad (22)$$

where η is the elasticity of demand (the percentage change in quantity for a percentage change in price), and $dlnP_m$ is the percentage change in milk price.

The demand elasticity is a negative number, reflecting that quantity demanded moves in opposite direction to price facing consumers.

The implementation of the equilibrium displacement method for the supply equations requires additional steps because the supply side is where the assumptions about cost changes and exits come into play.

The basic supply functions for individual dairies from equation (15) is first transformed similarly to the log differential demand equation:

$$dlnQ_o^z = \varepsilon_z \, dlnP_m, \quad (23)$$

where ε_z is the supply elasticity, which represents the slope of the marginal cost function in log differential terms.

Next, we introduce the change in costs resulting from the adoption of practice i. We combine equations (4), (5) and (6) so that we write a detailed expression of the total costs for a given practice i:

$$TC_o = FeedC_o + LabC_o + MaOpC_o(i) + OtherOpC_o + MaInvC_o(i) + OtherInvC_o + MgC_o \quad (24)$$

Notice that when comparing this cost expression before and after the adoption of a new practice j, only the terms with index (i) change. Therefore, the change in total costs are:

$$dTC_o = MaOpC_o(j) - MaOpC_o(i) + MaInvC_o(j) - MaInvC_o(i) \quad (25)$$

This expression can be converted in proportional change as well by dividing by the initial total cost and introducing the cost shares of the manure operations costs and the manure investment costs.

$$dlnTC_o = cs_{MaOp} dln\, MaOpC_o + cs_{MaOp} dlnMaInvC_o \quad (26)$$

where *cs* stands for cost share and the change considered, the *dln*, refers to the change from practice i to j.

For clarity of expression, in these expressions, we have not tracked the group index z. Each of the equations in log differential form for each group has different parameters for cost shares and changes in manure related costs. These are laid out in detail in the model parameterization section below. Furthermore, each supply-side equation has been written for the operation as indicated by index "o". In the context of a displacement model, these equations apply to costs per hundredweight of milk, or per cow, since the changes in production of milk per operation are in the first order approximation.

Another use of equation (24) is in the simulation of the effect of trends in labor and feed costs for each horizon. When these costs are expected to change over time, the terms $FeedC_o$ and $LabC_o$ do not cancel each other and two additional terms appear in the dln expression of the cost change (26) which becomes:

$$dlnTC_o = \delta_Z = cs_{MaOp} dln\ MaOpC_o + + cs_{MaOp} dlnMaInvC_o + cs_{Feed} dlnFeed_o + cs_{Lab} dln\ Lab_o \quad (27)$$

For clarity in notation, we call δ_Z this expected proportional change costs, understanding that it will take different expressions depending on the scenario and the time horizon considered.[2]

The last step to implementing the displacement framework is to aggregate the individual supply responses into group supply responses. This is done following equation (16), which multiplies the individual responses by the number of operations in each group. However, the number of operations in each group (N_z) may change both following exit trends and additionally in response to management costs, especially for some small operations. As a result, the N_z is not just a parameter but a variable and is therefore present in the *dln* form:

$$dlnQ_g^z = \varepsilon_z\, dlnP_m - \varepsilon_z \delta_Z + dlnN_z \quad (28)$$

The implementation of methane abatement practices was therefore represented by a change (upward shift) in the marginal cost curves of dairy operations as well as a change in the number of operations in the group in the relevant cases. The cost shift δ_Z are percentage increases in costs (percentage calculated at the baseline costs and prices). Note that the shifts in costs were converted in quantity shifts by multiplying by the elasticities. The sign was also inverted since an increase in marginal cost is a vertical shift up for the cost curve (positive in price dimension) but horizontal left (negative in quantity dimension).

This supply equation for individual groups (28), combined with equation (21) which aggregates group outputs into the industry milk output constitutes the supply side of the market equilibrium displacement model.

The market clearing condition in equation (19), which states that the total quantity produced is equal to the quantity consumed, translates directly in proportional changes:

$$dlnQ_D = dlnQ_T \quad (29)$$

This market clearing conditions connects the demand side (22) with the supply side (28) and (21) and completes the model in its proportional change form. The derivations detailed here for the conventional milk market are identical for the organic market.

Once the displacement market equilibrium has been solved for and the changes in milk price and quantities determined, the other variables of interest, including methane emissions, can be calculated.

[3] We considered all financial variables and parameters in inflation adjusted terms, so only trends in relative prices would be of interest.

4.1.10 Solving of the system of equations and computational methods.
In its *dln* form, the model is linear and solving for the changes in prices and quantities involves solving a system of linear equations. Separation between the supply and demand of organic milk from that of conventional milk means that we have used two independent sets of equations. The market for organic milk is small (a few percent of production) and concentrated in select products (liquid and soft milk products) that tend to stay within California. Therefore, we simulate the displacement of the two markets separately.

For the conventional market, there are several group supply equations (28) in which quantity supplied related to the market price and one equation that aggregates the group supplies into the industry's total (21). There is one aggregated demand equation (22). The market clearing condition (29) is not useful for the resolution of the model as the quantity demanded and the total quantity produced are the same by construction of the group functions and do not need to be tracked separately in aggregated form.

Given the large number of scenarios of practice adoption as well as time horizons simulated, it was practical to write the system of equations in a matrix forms that can be easily inverted numerically. We use the programming language R to implement the numerical simulations. (An appendix with the operative computational program is available upon request.)

4.2 Information and Data About Manure Handling Used to Implement Economic Simulations

To allow manageable modeling, dairy farms in California have been categorized in to seven groups: three herd size groups each with freestall and non-freestall housing, plus an organic category. Farms in each of these groups have a set of engineering, management, and capital situations that determine, in part, the manure management practice chosen.

In the following summary, we report the manure methane emission baseline in 2013 from which all adjustments are referenced. We also report how much manure methane emissions have declined since 2013 as a result of the AMMP and DDRDP funded projects.

Next, we document and explain the engineering, management, and capital considerations that affect responses to manure management incentive and policy implementation. This explanation is based on available data and related documents. These considerations include the technologies that are most common, the inputs used by those practices, and other characteristics that vary by farm and farm operator.

These considerations are relevant to and affect responses of farms across size and therefore relate to dairy farm size distribution for several reasons.

First, scalability of capital. Some dairy equipment and facilities have discrete capacities. These capabilities are sometimes related to economic considerations, but have physical limits as well.

Second, suitability of technology and practices to scale. Manure management practices are chosen for how well they integrate into existing farm infrastructure, including available management. Practices with higher methane reductions may not be adopted on farms that are constrained in their adoption by capital, land, and management time.

Third, avoided costs of the baseline practice. The baseline manure practices were costly when adopted on the farms. The process of changing practices implies new investments and farms would not shift if such a shift would make obsolete or require replacement of significant recent investments that have a long useful life. The cost-benefit calculation of manure handing investments must be done in the context of existing investments and their useful life.

Fourth and finally, the section documents and explains some areas where we lack verifiable widespread data about practices and uses of technologies, but for which there is anecdotal evidence about costs and benefits of specific practices. For example, there seems to be information that compost bedded pack barns increase cow comfort and hence increase milk yield per cow. However, we lack a statistical study that verifies this observation. Each of these four points: scalability, suitability, baseline costs, and anecdotal information about costs and benefits, are discussed, where relevant, in the sections below.

4.2.1 Baseline Practices

Conventional Milk Production – Freestall Facility

We base the cost of the freestall facility on flushed manure collection. In addition to the electricity and maintenance cost of the flush operation, the facility also has labor costs associated with occasional scraping of the alleyways. This is necessary where bedding material and manure cake on edge of the alleyway freestall and is not washed away with the flush. There is the labor and equipment cost of maintaining the freestall bedding. In the baseline practice, flushed manure will be processed through gravity separation cells for solid liquid separation. The liquid fraction is then recycled through the flush system.

Findings in Chapter 1 show that 58 percent of region 5 facilities use some form of gravity separation technique and 36 percent use some form of mechanical separation. Separation practices are therefore an established practice on many dairies. Furthermore, the practice of using well dried manure solids as bedding in freestall facilities is common practice. Meyer et al. (2011) reported that 80 percent of freestall facilities use dried manure bedding. Alternatively, freestall facilities using sand will recycle sand separated and dried from the manure as bedding. From this perspective, utilization of manure solids as bedding is a familiar practice on most facilities. We use the gravity separation cells in the baseline cost for flushed freestalls and flushed non-freestall facilities.

Based on data from a 2,200-cow herd in the Central Valley, farm operations pay a contractor to come to the farm to excavate and transport the separated solids from the separation cells. Based on invoice data, excavation costs $27 per load with each cow producing the equivalent of 0.6 loads of solids per year. The excavation cost varies between $26 to $28 per load throughout the year (Meyer, D. personal conversation, March 2020a). Depending on the season the solids will be land applied, a cost we do not consider, or taken for solar drying to be used for bedding. The solar drying component involves labor and equipment costs in the frequent turning of the windrows and stacking of the material for winter storage.

The cost of excavating these separation cells is removed in the alternative management practice.

Conventional Milk Production – Non-freestall Facility

Data for the labor cost of non-freestall manure management were collected from an 1,800-cow Central Valley dairy (Meyer, D., personal conversation, March 2020b). Manure management

costs on a non-freestall facility of 1,800 equates to the equivalent cost of one full time member of staff plus the equipment and fuel costs. The labor costs break down as two workers spending eight hours per day, three days a week for seven months of the year on manure management. Then for the other five months of the year the labor equivalent is one worker spending eight hours for three days a week on maintaining the pens. In addition, there is the equivalent of 20 hours per week spent on maintaining the dry cow and heifer pens. The tasks that occur every second day are using a tractor mounted tine cultivator to incorporate the manure into the surface of the pen and scraping the feed aprons even where flush systems are used. The less frequent tasks involve the use of a tractor mounted box scraper to gather the decomposed manure from the surface of the pen, loading, and transporting the material. If flush is the primary method of manure collection for the feed apron, there is also the cost of operating that flush system, and the labor and equipment cost of loading, transporting, and stacking the separated solids from the gravity separation cell.

Organic

In the baseline cost of manure management, we based our cost estimate on housing cows for six months. This represents months of November through March for which the majority of farms house cows 100 percent of the time plus the equivalent of one extra month to represent times when cows are housed at night. We understand that some farms choose to house cows during the night during some of the grazing season. Farms may also provide supplementary feeding post milking. These practices further increase the amount of manure collected. The decision to house or supplement the ration is driven by forage availability and how close the farm is to achieving 120 days on pasture with 30 percent dry matter intake required for the organic status.

From an extension farm advisor working in the North Coast region, we understand most organic facilities are deep-bedded freestall barns (~75 percent) or mattress freestalls (~20 percent), with a small number providing no housing or bedded pack barns. Within the freestall organic facility, scrape collection is most common. It is estimated that 25 percent of facilities will use flush in some capacity and go over with a tractor mounted scrape when necessary (UCANR Dairy Adviser, personal conversation, March 2020).

4.2.2 Alternative Practices

From DDRDP funded projects from 2015 through 2019 and AMMP funded projects from 2017 through 2019, the majority of the emission reductions have been from DDRDP funded projects. Further to the data reported in Table 4.3, the industry has seen a reduction of 65,326 milking cows in the state herd between 2012 and 2017 (National Agricultural Statistics Service, USDA Agricultural Census, 2017). Ceteris paribus, herd reductions further contribute to manure emissions reductions.

Table 4.3 DDRDP and AMMP Contribution to Reductions

	CDFA Contribution ($Million)	Private Contribution ($Million)	Annual Emissions Reduction (Million $MTCO_2e$/yr)	Contribution to Reduction (percent)
DDRDP Estimated Reduction (107 Projects, 2015 - 2019)*	183.3	369.4	1.98	89.92
AMMP Estimated Reduction (107 Projects, 2017-2019)**	62.3	9.0	0.22	10.08
Estimated Total Reduction From Projects			2.20	100
2013 Dairy Manure Methane Emissions***			9.84	
percent Reduction			22.35	

*DDRDP data from CDFA, (2020b), excludes two projects funded and canceled.
** AMMP data from CDFA, (2020a)
***(CARB, 2020)

Table 4.4 Projects awarded and respective subsidy value and matching funds by year.

	Count of Projects Awarded		Awarded ($ M.)	Matching Funds ($ M.)	Awarded ($ M.)	Matching Funds ($ M.)
	DDRDP	AMMP	DDRDP	DDRDP	AMMP	AMMP
2015	6		11.1	23.4		
2017	16	18	30.7	74	9.6	2.1
2018	42	39	72.4	102	21.3	2.7
2019	43	50	69.1	170	31.4	4.2
2020*			22.1		10.2	

*2020 Values are based on a 65 percent, 30 percent, 5 percent split between DDRDP, AMMP, and admin costs for the $34 million Budget act appropriation.
AMMP Data from CDFA, (2020a), DDRDP data from CDFA, (2020b).

Table 4.5 Annual GHG reductions by herd size/funding group

Herd Size Grouping		Annual GHG Emissions Reduction (Million $MTCO_2e/yr$)	Percentage contribution of each group to total funded reductions
<500	AMMP	10,021.00	0.5
500-2000	AMMP	154,622.80	7.0
>2000	AMMP	57,019.40	2.6
500-2000	DDRDP	169,447.70	7.7
>2000	DDRDP	1,807,446.80	82.2
Total	AMMP+DDRDP	2,198,557.70	100.0

AMMP Data from CDFA, (2020a), DDRDP data from CDFA, (2020b).
Facilities were grouped by matching the awardee in the CDFA data to the best available data of facility herd size.
Authors calculations based on table 2.1 in chapter 2. Columns for herd sizes 250, 1250 and 3250 were used to represent herds within the <500, 500-2000 and >2000 herd size groupings respectively. In the case of organic the column for herd size 250 was used and prorated to reflect 180 days housed.

4.2.3 Manure collection and technologies after adoption of alternative practices

Flushing

Flushing remains the most common method of manure collection because of cost and convenience. For these reasons, facilities continue to flush in many cases and separate solids after collection. Costing post adoption of 3a, 3g and lagoon digesters continues to incur the cost of flush manure collection. This follows the practice detailed in chapter 2.

Vacuum Scrape

Vacuum scraping has previously been found to be the most expensive method of manure collection on farms of less than 750 lactating cows (Kaffka et al, 2016). Farmers of all herd sizes need to consider whether the concrete alleyways are strong enough to support the weight of the equipment. Farmers may encounter future expense where this equipment breaks through alley way concrete that subsequently has to be replaced.

Costs include the capital expense, operational cost, and maintenance cost of one self-propelled vacuum scraper per farm. However, large facilities will consider two vacuum scrapers, to fit with the farm logistics and as backup. A 4,300-gallon tanker can be filled in approximately five minutes depending on the length of the alleys (Vacuum scraper manufacturer engineer, personal conversation, March 2020). Emptying the tank takes less time. While labor time is small and scraping can be achieved in the time that a group is out for milking, the vacuum scrape adds labor costs above the baseline flush method. It remains unclear whether the task of bedding the freestalls and vacuum scraping can be achieved with the existing labor allocation. We expect that on large farms additional labor will have to be allocated to operating the vacuum scrape, while existing labor maintains the freestall bedding. Once the scraping task is complete, the operator is available for other tasks, like bedding, before the next group goes to milking.

Automatic Scrape

There are some examples of AMMP applicants who propose automatic scrape manure collection. The installation of automatic scrape is a scalable cost because 70-80 percent of the costs are construction costs with equipment costs as the remainder (Kaffka et al 2016). The equipment costs comprise of an electric drive motor that can drive scrapers on two lanes up to 500 feet long, plus the scraper and cable components. Freestall barns that are too long, or have an insufficient gradient, are likely to be unsuitable for this practice.

Tractor Mounted Scrape

Like a vacuum scraper, a tractor mounted scraper is used in the time that cows are at milking. A scraper has a fixed volume of manure that it can push at a time. Because of this, a tractor mounted scrape is only suitable for small dairies. Where scrape replaces flushing on small dairies, it remains unclear if the scraping and bedding activities can be achieved with the existing labor allocation in the time that the group is at milking. We expect that on smaller dairies the farmer will make necessary adjustments to achieve the scraping and bedding with the existing labor. These adjustments may be the order in which the alleyways are scraped and beds are maintained, or holding cows at a feed barrier for a longer time before the freestalls are ready and cows can get access again.

Compost Bedded Pack Barns

Compost bedded pack barns (CBPs) are a feasible option for small dairies, both organic and conventional. A CBP facility collects manure in two forms. The majority of manure is collected on the pack where cows spend most of their time. The remainder of manure is collected on the concrete feed apron and walkways to the parlor and from the parlor area. The daily cost of operating a CBP includes the cost of kiln dried wood shavings that is incorporated into the pack. Our cost estimates are for a $2,000 load of dried wood shavings every two weeks for a 280-cow herd in the conventional dairy. This cost is highly variable through the season, with humid months requiring more wood shavings. The cost can also be reduced with the addition of cheaper materials like almond shells. Included in the cost estimate are labor and fuel costs for 30-minute aeration of the pack, twice per day while the cows are at milking, plus fuel and labor for the scraping of the feed apron (UCANR Dairy Advisor, personal conversation, March 2020).

CBP provides increased cow comfort and there is some evidence to suggest that it provides economic benefits from lower lameness rates and improved milk yield (AMMP application narrative).

Mechanical Separation

There are several options for type and capacity of mechanical separation equipment. Despite this, we find that equipment costs increase for small facilities. This is especially true for small non-freestall facilities that have collected ~70 percent less manure than the freestall facility of equal size and therefore require equipment of proportionately less capacity.

Open Solar Drying

The practical operation of open solar drying of scraped manure remains ambiguous. We understand that farms will deposit scraped manure, either from the vacuum scrape or pumped from the collection cell, into shallow concrete curbed channels. This requires zero participation so is practical for eight months of the year. Once dry enough to stack, the solids can be put in to piles or windrows.

For solid separation with open solar drying, the separated solids are transported from the separator to drying pad daily. These separated solids can be stacked and dried faster than the scraped manure without separation.

The area for concrete drying pads was informed by Kaffka et al. (2016) and the cost per square foot of constructing the drying pad was informed by the AMMP applications.

Composting

The cost of composting is highly dependent upon the management decision of how composting should be carried out. The options open to the manager are to intensively manage the composting process, with aeration or frequent turning to speed up the process. Intensive management reduces the area required because once composting has occurred the material can be stacked on a smaller area. Alternatively, the windrows can be turned less frequently, requiring a larger area. In-vessel composting remains an option at higher energy and capital cost but requiring less area.

The area for concrete drying pads was informed by Kaffka et al. (2016) and the cost per square foot of constructing the drying pad was informed by the AMMP applications.

Lagoon Digesters

Herd size is not the sole determinant of the suitability of a digester on a dairy facility. To pipe methane from the digester, by low pressure pipes, to the centralized gas cleaning and injection site, the dairy facility location plays an important role.

Third party project developers are responsible for the matching funds, construction, and operation of the lagoon digester. Each lagoon digester has a solid liquid separation system installed to process manure before the liquid fraction enters the digester. Installation of this separation system is part of the capital cost of the lagoon digester system. The farm owner is thereafter responsible for the operation and maintenance of the separation system while the project developer operates the lagoon digester (DDRDP application narrative).

Manure management cost of the lagoon digester therefor includes the continued operation of the flush system, all freestall or non-freestall bedding labor and equipment costs, plus the labor and equipment costs for handing the separated solids during the solar drying process.

Alternative Practices – Non-freestall Facility

The scalability question is particularly pertinent to the case of non-freestall dairies. Non-freestall facilities collect 30 percent of the daily manure compared to the volume of manure collected on a freestall facility of equal size (see chapter 2 for detailed discussion). Manure is collected on the feed apron and walkways to and from the parlor. The remainder of the manure is deposited on the corral and is handled separately in an aerobic process. The non-freestall facility therefore has a need for equipment with 30 percent of the capacity of a comparable freestall facility. Small non-freestall facilities are therefore in the position where they need equipment that does not scale down linearly to their required size. This imposes a higher capital cost per unit of manure handled than the comparable freestall facility.

Table 4.6 Baseline emissions per cow and reductions in emissions

			Percentage reduction after implementation of alternative practice				
Herd Size Grouping	Housing System and manure collection *	Baseline Emissions Per Cow ($MTCO_2e/yr$)	2a. Compost Bedded Pack Barn	3a. Solid separation with open solar drying, Screw Press	3g. Solid separation with composting, screw press	4a. Scrape conversion with open solar drying	Lagoon Digester
<500	Freestalls - Flushed	5.34	86.6	24.2	24.4	59.1	82.5
<500	Non-freestall – Flushed	2.20	65.3	23.2	23.4	44.6	-
500-2000	Freestalls – Flushed	5.33	86.6	24.3	24.4	59.1	82.5
500-2000	Non-freestall – Flushed	2.20	65.3	23.2	23.3	44.5	-
>2000	Freestalls – Flushed	5.33	-	24.3	24.4	59.1	82.6
>2000	Non-freestall - Flushed	2.20	-	23.2	23.4	44.5	86
<500	Organic (Freestall) - Scrape	2.59	86.0	21.9	22.2	-	-

*On non-freestall facilities 30 percent of manure is collected by flush in the baseline.

Source: Authors calculations based on table 2.1 in chapter 2. Columns for herd sizes 250, 1250 and 3250 were used to represent herds within the <500, 500-2000 and >2000 herd size groupings respectively. In the case of organic the column for herd size 250 was used and prorated to reflect 180 days housed.

Table 4.7 Adoption of alternative manure management practices and digesters and the average emissions per cow in each group once the new practices are operational in 2021.

	Herd Size Grouping	Housing and Collection	Count of Digesters*	Count of Other Alternative Practices**	Percentage adoption rate of digesters	Percentage adoption rate of other alternative practices	Average Percentage reduction emissions among adopting farms of Digesters	Average Percent. reduction emissions among adopting farms of Other Alternative Practices (excludes Digesters)	2021 Interim baseline emissions per cow (average among group)	Percent. reduction emissions per cow (between 2013 baseline and 2021 interim baseline)
A	<500	Freestall	0	8	0	4		60	5.21	2
B	<500	Non-freestall	0	6	0	9		60	2.09	5
C	500-2000	Flushed	14	53	3	11	82	30	5.03	6
D	500-2000	Non-freestall	1	18	1	15	60	30	2.09	5
E	>2000	Flushed	82	14	41	7	82	30	3.43	36
F	>2000	Non-freestall	10	1	25	3	60	30	1.85	16
G	<500	Organic	0	7	0	7		50	2.50	4

*(CDFA, 2020a) **(CDFA, 2020b). Facilities were grouped by matching the awardee in the CDFA data to the best available data of facility herd size. Average percentage reductions, interim baseline and emission reduction per cow are authors calculations based on the practices funded. The 2013 baseline emissions per cow can be found in table 6.

Taking the baseline emissions per herd size/housing type group presented in Table 2.1 of chapter 2 the baseline emissions per cow in each group were calculated. We use this baseline emission per cow to represent the 2013 emissions per cow by assuming that no methane reducing manure management practices were adopted on farm without AMMP or DDRDP subsidy support. Then, as shown in Table 7, the 107 AMMP and 107 DDRDP projects funded from 2015 through 2019 were matched to a group using the best available data on farm herd sizes and housing type.

Among the awardees of AMMP funding in each group, farms were funded to install one of eight distinct project types (2a or 3a etc.). From this we produced the best estimate of a percentage reduction in emissions among adopting farms of alternative practices. For digesters, the best estimate of average percentage reduction in emissions among adopting farms of digesters was calculated.

Knowing the number of farms in each group and the adoption rate in each group, we calculated for each group the 2013 baseline emissions per cow and the average percentage reduction in emissions from adoption the 2021 interim emissions per cow. By 2021 we expect the 2015 through 2019 funded projects will be operational and providing reductions in manure emissions. The reduction in emissions that results from our approximations is commensurate with the 22 percent reduction in emissions described in Table 4.5.

4.2.4 Cost Parameters

Practices chosen for the economic analysis are versions of practices discussed in chapter three. The choice of practices was informed by chapter three and constrained by the data availability.

Capital costs of AMMP installations were determined by analysis of 2017 and 2018 project applications. No information was available for the volume of manure the project will process or the number of cattle from which the manure will be processed. Instead we inferred the capacity of the project from dimensions of buildings or by inferring information from the application narrative (e.g. whether the project was for lactating, heifer or dry cow groups). When a farm included multiple project practices, we included only the costs relevant to our analysis. We used publicly available information on the capacity of equipment and contacted equipment manufacturers where required for further details. We also used publicly available data to match a herd size to the application. From here we estimated the number of cows from which manure will be processed by the AMMP project and estimated a capital cost per cow.

Given the subsidy limit, farms in the small herd group were at the subsidy limit. Further analysis was conducted to achieve a similar cost structure in the small herd group as in the medium and large herds.

We recognize that 36 percent of Central Valley facilities have mechanical separators in operation. Therefor the change in operation and maintenance costs will be less on these facilities.

Table 4.8 Capital Cost Calculations

Name of practice	Calculation and Assumptions
2a - Installation of compost bedded pack barn	By analysis of the AMMP applications budgets we found the same capital cost per cow for small herd size both converted from freestall and non-freestall and organic. Costs include construction of roofed barn to required dimensions for herd size including all metal gates and feed barriers plus all electrical and water installation.
3a - Solid separation with open solar drying	Costs for all herd sizes both freestall and non-freestall were based on mechanical separation plus concrete collection pits, concrete pad for manure solids collection, construction and installation costs. The concrete solar drying pads were costed as an area sufficient for drying manure for relevant herd size. In the case of non-freestall this is the equivalent to a drying pad large enough for manure solids for the 30 percent of manure collected from the relevant herd size.
3g - Solid separation with composting (passive or intensive windrow)	Costs include construction and installation of concrete collection pits, all required mechanical separation equipment, and concrete pad for separated manure solids collection. Larger concrete composting pads are required compared to the equivalent herd size using open solar drying because of the longer time composting takes compared to solar drying. The small herd use existing farm tractor to operate the compost turner.
4a - Scrape conversion with open solar drying: vacuum truck	Includes the purchase of a vacuum scraper and the construction of solar drying pads of suitable dimensions for handling all manure collected. Includes the cost of compost turning equipment and the purchase of a tractor for dedicated compost management activities.
Lagoon Digesters	Assessment of the DDRDP applications indicate that the third-party digester developers contribute all of the matching funds capital cost towards the lagoon digester installation.

Table 4.9 Operational and Maintenance Cost Calculations

Name of practice	Note
2a - Installation of compost bedded pack barn	All manure management costs associated with freestall housing and non-freestall housing are replaced with labor costs for managing the pack barn and scraping concrete areas. Costs are dominated by payment for kiln dried wood shavings which cost $0.71/cow/day as an annual average. For organic, we take 180 days housed.
3a - Solid separation with open solar drying	Freestalls: Continue to incur the cost of flushing and bedding freestalls. Non-freestall: Continue to incur the cost of flushing all concrete areas where manure collects, and the maintenance of the non-freestall pens. The size of the separator installed is one with capacity to handle the equivalent of 30 percent of manure from the herd. Organic: 180 days housed. Continue to incur the cost of scraping, bedding freestalls. All groups: The cost of excavating and solar drying the manure solids from separation cells is replaced with the cost of solar drying the mechanically separated manure solids for use as freestall bedding. Includes the operational and maintenance costs associated with the mechanical separator.
3g - Solid separation with composting (passive or intensive windrow)	Non-freestall: Continue to incur the cost of flushing all concrete areas where manure collects, and maintenance of the non-freestall pens. In addition, operation and maintenance of the mechanical separator continues. The separator must have capacity to handle the equivalent of 30 percent of manure. We include the cost of composting the separated solids.
4a - Scrape conversion with open solar drying: vacuum truck	All flushing costs are replaced with labor and maintenance costs of vacuum scraping. Labor and equipment costs for bedding freestalls remain. Costs of excavating and solar drying manure solids from separation cells are replaced with cost of solar drying. Fuel use and labor time data were provided by vacuum scraper manufacturer and other industry sources.
Lagoon Digesters	Continue to incur the cost of flushing and bedding freestalls. The cost of excavating and drying manure from separation cells has been replaced with the operation and maintenance cost of mechanical separator plus the cost of solar drying separated solids.

Results

The results of this chapter is a set of equations that are implemented in a simulation model that can characterize responses in the California dairy industry to changes in manure management practices. Using the descriptions and data provided in the second part of the chapter, and other baseline data and supply and demand parameters, the simulation model generates impacts on dairy industry aggregates, including implications by herd size categories. These impacts are developed fully in Chapters 5, 6 and 7.

Discussion

We have explained the economic rationales and implications of model equation as they were developed in the first part of the chapter. We have explained the information and data about manure handling practices and underlying assumptions in the second part of the chapter.

Our simulation approach is one that is often employed by economists to investigate impacts of changes in farm practices that affect demand or cost conditions. The approach is grounded in economic principles that recognize incentives that changes in cost conditions created for producers, processors, and buyers. The approach traces the implications through the affected markets. Thus, the model is well grounded in economic theory and practice. Our implementation relies on changes in logarithmic form, essentially percentage changes. This allows the model to rely on cost share and percentage changes as inputs.

Broad industry level baseline information is used to characterize shares. The key unique input to this study related to the alternative manure handling practices. Our detailed information presented in this chapter was drawn from the sources to which we refer that are specific the California situation.

Conclusion

The outcome of this chapter is the model ready to be applied in subsequent chapters.

Recommendations

We have not recommendations from this chapter alone. Any recommendations come from applying the model and data to the situations discussed in the following three chapters.

CHAPTER 5 WHOLE-FARM ECONOMIC AND ENVIRONMENTAL IMPACTS OF METHANE EMISSION REDUCTION STRATEGIES ON SMALLER AND LARGER DAIRIES

Introduction

This chapter uses our economic model and simulation framework to consider how methane strategies affect dairy farm choices, profitability and economic feasibility. It uses the data base developed in the second part of Chapter 4 and additional parameters that are discussed in this chapter. We present a set of simulation results for six scenarios of adoptions and for a 5-year horizon. Other time horizons are covered in Chapters 6 and 7. The simulation results show the effect of practice adoption on emissions and costs and tracks these cost effects through the milk markets, including adjustment in quantity demanded for dairy products.

The economic modeling framework presented in Chapter 4 includes a complete economic model of farm economics and accounts for revenues from milk and other sources. We include the economic tradeoff related to sustainability of the whole farm. Because practices designed to reduce methane emissions from collected manure are not likely to have major effects on non-milk revenues, such revenues do not appear in the equilibrium displacement model, since they remain mostly unchanged by practice adoption.

Many dairy farms in California have some degree of vertical integration. For example, some are integrated with forage production (silage or hay), upstream of the milk production operation. They are also commonly (about 80 percent) members of marketing and processing cooperatives and therefore are vertically integrated downstream. These forms of whole farm output are tied directly to milk production and revenues and in that way do not alter the results of our simulations, which are presented in terms of percentage changes in milk production and revenue.

Some farms have additional crop enterprises such as tree nuts. The methane emission reduction practices that we simulated and present in this chapter have relatively small impacts on these enterprises. The investments in other farm or non-farm businesses have relatively small effects on the direct economics of the dairy enterprise. If other investments are attractive relative to dairy farming, capital and management will move toward those investments whether or not current dairy farms currently have such investments. When considering exit and consolidation decisions (Chapter 7), we explain how other revenues may affect exit decisions.

Materials and Methods

In the second part of Chapter 4, we identified a shortlist of practices for each of the dairy farm groups and estimated the cost increases and methane emissions abatements resulting from their adoption on each of the seven dairy farm groups that we have used to categorize farms by size and other characteristics. As presented in the economic framework in Chapter 4, these costs combine operation and management costs, as well as fixed capital investment costs related to the constructions of infrastructure for instance.

Scalability considerations were captured in two ways, in that both components of the costs were allowed to vary across farm groups that are defined by herd size. Operation and maintenance costs were adjusted to reflect differences in labor requirements for the same practice across farm sizes and other characteristics. The capital cost of initial investment also captured non-divisibility, as it was calculated on a per farm basis rather than a per cow basis and therefore is often larger per cow for smaller herds.

In addition, the economic impact on the whole-farm was tracked through the size of manure management costs relative to total costs on the farm. This share of manure handling costs in total costs varies across farm sizes and characteristics in our model. As a result, the adoption of a practice having the same cost across farms, would still have different impacts on each farm size. Typically, larger operations tend to have costs of manure handling representing a smaller share of total costs, relative to smaller operations. Accordingly, our calibrated model reflects differences of practice adoption on whole farm economic sustainability consistently by adjusting operation and management costs, capital investment costs, and share of manure to the herd size.

The methane emission reduction resulting from a given practice adoption also varies according to farm size and other characteristics. Table 5.1 summarizes information discussed in detail in Chapter 4 about the costs and emissions per farm size and other group-defining characteristics for practices that define the emission-reduction strategies considered. Table 5.1 lists the methane reduction practices that represent typical options used by herd size and initial manure collection groups. Table 5.1 then lists the emission per cow for each practice if adopted by dairies in that group. The annual manure management cost per cow and capital cost per cow for that practice group combination is then provided. These data are key inputs into the simulation models that determine economic outcomes and imply emission reductions. As shown in Table 5.1, costs are high on a per cow basis for the farms with fewer than 500 cows. Table 5.1 lists high per cow capital cost for pack barns. Notice that we listed zero for capital cost for digesters because, we understand that under current arrangements between farms and digester operation companies, these costs are covered by the companies that use the methane collected to produce and sell natural gas and profit from renewable and low-carbon fuel credits.

In Chapter 4 we described six scenarios of patterns of adoption of methane-reducing practices across the seven groups. These scenarios were based on already observed adoption and AMMP and digester program data. For clarity, these scenarios are organized in Table 5.2. For each scenario we show the list of practices for each dairy farm group and an assumed percentage rate adoption of that practice among farms in the group.

Table 5.1 Costs and emissions for manure reduction practices by farm groups

Herd Size	Animal housing	Methane reduction practice	Emissions per Cow	Yearly Manure Management Cost per Cow	Capital Cost per Cow
<500	Freestall	2a - Installation of compost bedded pack barn	0.72	315.45	1728.00
<500	Freestall	3a - Solid separation with open solar drying	4.04	110.45	586.00
<500	Non-freestall	2a - Installation of compost bedded pack barn	0.76	315.45	1728.00
<500	Non-freestall	3g - Solid separation with composting (passive or intensive windrow)	1.69	111.52	574.00
500-2000	Freestall	3a - Solid separation with open solar drying	4.04	89.39	525.00
500-2000	Freestall	Lagoon Digester	0.74	89.39	0
500-2000	Freestall	4a - Scrape with open solar drying, Vacuum scrape	2.18	78.07	625.00
500-2000	Non-freestall	3a - Solid separation with open solar drying	1.69	65.04	517.00
>2000	Freestall	4a - Scrape with open solar drying, Vacuum scrape	2.18	54.15	500.00
>2000	Freestall	Lagoon Digester	0.93	56.55	0
>2000	Non-freestall	3a - Solid separation with open solar drying	1.69	56.22	496.00
>2000	Non-freestall	Lagoon Digester	0.93	56.55	0
Organic*	Scrape	2a - Installation of compost bedded pack barn	0.36	133.87	1728.00
Organic*	Scrape	3a - Solid separation with open solar drying	2.02	87.06	586.00

*Organic operations are assumed to have fewer than 500 head in this analysis.

Table 5.2 Group share of cows and supply and demand elasticities in the 5-year time horizon.

Group	Share of Cows (%)	Supply elasticity, 5-year horizon
A <500 Freestall	3.6	2.0
B <500 Non-freestall	1.3	2.0
C 500 -2,000 Freestall	32.9	2.0
D 500-2,000 Non-freestall	8.2	2.0
E >2,000 Freestall	43.9	2.0
F >2,000 Non-freestall	8.8	2.0
G Organic	1.3	2.0
		Demand elasticity, 5-year horizon
Conventional		1.0
Organic		0.5

Table 5.3 Practice adoption and rate of adoption per group in 6 scenarios

Group	Practice	Rate adoption per group (%)	
		Scenario 0	
<500 Freestall	2a - Compost bedded pack barn	4.0	
<500 Non-freestall	2a - Compost bedded pack barn	9.0	
500-2000 Freestall	4a - Vacuum Scrape, solar drying	14.0	
500-2000 Non-freestall	3a - Solid separation, solar drying	16.0	
>2000 Freestall	Lagoon Digester	46.0	
>2000 Non-freestall	Lagoon Digester	25.0	
Organic	2a - Compost bedded pack barn	7.0	
		Scenario 1	Scenario 2
<500 Freestall	2a - Compost bedded pack barn	30.0	40.0
<500 Non-freestall	2a - Compost bedded pack barn	30.0	40.0
500-2000 Freestall	3a - Solid separation, solar drying	30.0	40.0
500-2000 Non-freestall	3a - Solid separation, solar drying	30.0	40.0
>2000 Freestall	4a – Vacuum Scrape, solar drying,	30.0	40.0
>2000 Non-freestall	3a - Solid separation, solar drying	30.0	40.0
Organic	2a - Compost bedded pack barn	30.0	40.0
		Scenario 3	Scenario 4
<500 Freestall	2a - Compost bedded pack barn	30.0	5.0
<500 Non-freestall	2a - Compost bedded pack barn	30.0	10.0
500-2000 Freestall	Lagoon Digester	30.0	20.0
500-2000 Non-freestall	3a - Solid separation, solar drying	30.0	15.0
>2000 Freestall	Lagoon Digester	30.0	60.0
>2000 Non-freestall	Lagoon Digester	30.0	30.0
Organic	2a - Compost bedded pack barn	30.0	10.0
		Scenario 5	
<500 Freestall	3a - Solid separation, solar drying	5.0	
<500 Non-freestall	3g - Solid separation, composting	10.0	
500-2000 Freestall	Lagoon Digester	20.0	
500-2000 Non-freestall	3a - Solid separation, solar drying	15.0	
>2000 Freestall	Lagoon Digester	66.0	
>2000 Non-freestall	Lagoon Digester	35.0	
Organic	3a - Solid separation, solar drying	10.0	

Additional Environmental concerns

California faces pressures related to a range of environmental issues. With most California milk production located in the San Joaquin Valley, most dairy farms face similar environmental concerns. (Remaining dairies in Southern California and the organic farms located mostly in the North Coast region are the main exceptions.) Major concerns are related to local air and water quality.

As a first order approximation, given any set of abatement practices already adopted, the environmental impacts are roughly proportional to milk production. The practices we considered as ways to reduce methane emissions do not seem to have major negative implications for local environmental concerns. That means simulations that capture changes in cows and milk quantity are likely to capture the most important other environmental implications.

For the analysis presented here, we have not separately simulated local environmental impacts for the scenarios or for specific dairy groups or methane emissions management practices. These practices directly affect methane rather than other environmental outcomes. Non-climate-related environmental impacts may result from these practices. However, as documented below, the economic scenarios do not imply major impacts on total number of cows in California or the quantity of milk they produce.

Results

The scenarios are summarized in Table 5.3. We now turned to the results from the simulations of estimated effects, which are reported in Tables 5.4 to 5.9.

Scenario 0.

The results of this scenario are discussed in detail. The other scenarios will only be clarified in comparison with relatively little repetition.

The set of methane reduction strategies and adoption rates in Scenario 0 are representative of adoption patterns observed between 2013 and 2021. The projects set to be completed between today and 2021 are included in the estimates. The effects of this pattern of adoption are summarized in Table 5.3. The first two numerical columns report the effect of practice adoption on farms that adopt. The installation of pack barns for smaller herd size dairy operations brings a reduction of 86.6 percent of methane emissions. Emission reductions in non-freestall are smaller than in freestall operations because manure recovery rates are smaller.

Pack barns are expensive both in terms of capital investment and management and operation costs and result in increases in total production costs for the dairies. Conventional smaller herd size dairies who adopt packed barn see their total cost per unit of milk increase by around 9 percent, whereas organic dairies see a smaller increase in total costs due to the fact that they operate at higher total costs to start with. Note that the cost shift is almost identical per cow or per unit of milk in our model since the differences are in costs per cow or milk across size groups, but not within one group or one representative operation.

For medium size dairies, vacuum scrape with open solar drying brings some reductions at moderate costs for freestall operations, while solid separation brings limited methane abatement at a low cost for the non-freestall operations.

For larger operations, digesters bring large abatements when manure recovery rates are elevated. Here the costs of adoption are shown to be small because subsidies are accounted for and only a moderate increase in operation and management costs is accrued to the change in total costs of production.

Table 5.4 Effect of practices of Scenario 0 in 5-year time horizon

		Practice adoption pattern				Percentage changes for group in:			
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	4.0	0.36		-0.57	-4.0	0.7
<500 Non-freestall	2a	-65.3	9.3	9.0	0.84		-1.53	-7.3	0.2
500-2000 Freestall	4a	-59.1	1.1	14.0	0.15	0.07	-0.16	-8.4	13.6
500-2000 Non-freestall	3a	-23.2	1.0	16.0	0.16		-0.17	-3.9	0.6
>2000 Freestall	Digester	-82.6	0.1	46.0	0.04		0.06	-37.9	82.1
>2000 Non-freestall	Digester	-57.8	0.1	25.0	0.03		0.08	-14.4	2.6
Organic	2a	-86.2	3.2	7.0	0.22	0.18	-0.09	-6.1	0.2
Total California								-22.9	100

The third numerical column in Table 5.4 reports the adoption patterns for each group as presented before in Table 5.3. These are useful as they help understand the next column where the average increase in total costs per group is reported. This change in cost is the percentage increase in total production costs per unit of milk averaged across adopted and non-adoptees in each group. For instance, in the smaller herd size freestall dairies, only 4 percent of operations adopt the methane mitigation practice and incur the 9 percent increase in total cost. Thus, the average increase in total costs for the whole group is only 0.36 percent (the product of adoption rate and cost increase). For smaller herd size non-freestall operations, the average cost increase is of 0.84 percent because both adoption rate and cost shift per operation are near 9 percent.

Note that because manure management costs rarely exceed two or three percent of total production costs, even expensive practices like pack barn do not result in very large increases in total costs. In turn, this means that adjustments in price and quantities in the market will be relatively small throughout all scenarios.

The last two columns of Table 5.4 report the effect of the scenario on methane emission in two related measures. First, the group methane emission percentage abatement column reports by how much in each group have methane emissions been reduced, relative to the initial emissions in that group. The largest reduction there is for the group of larger freestall operations where 46 percent of operations have adopted digesters, which reduce emissions by 82.6 percent on adopting operations. The bottom line is a 22.9 percent abatement in methane emissions relative to the baseline for the California dairy industry as a whole. In other words, Scenario 0 achieves a reduction of 22.9 percent in the emissions of manure methane. Second, the last column in Table 5.4 reports the contribution of each group to this total abatement. There, larger freestall operations dominate since they are both the largest source of emissions initially and experience the largest reduction of emission as a group. Large non-freestall operations only contribute 2.6 percent in the aggregate abatement because their contribution to initial emissions is relatively small and despite an average abatement for the group itself of 14.4 percent of its emissions.

Scenarios 1, 2 and 3.

Recall that the scenarios each apply a different pattern of adoption rates to alternative practices as described in Table 5.3. Scenario 1, applies a uniform 30 percent adoption rate to the same practices as in Scenario 0, except that it does not include digesters for the two groups with more than 2,000 cows. The detailed results of Scenario 1 are in Table 5.5. Increasing adoption rates to 30 percent for the smaller dairies raises their costs, and thereby lowers their quantities by about 5 percent. Together they reduce emissions by about 25 percent.

The group of dairies with freestalls and 500 to 2,000 cows now uses the practice 3a, which includes open solar drying and vacuum scrape. This practice yields less emission reduction for this group than Scenario 0, even with adoption increasing to 30 percent from 14 percent. However, the big difference is that this scenario does not include digesters for the larger dairies. This scenario includes 30 percent of the larger freestall dairies using practice 4a, which reduces methane by 59 percent. Therefore, this group has a reduction in methane of almost 18 percent and contributes the majority of emission reduction (64.3 percent). Overall this scenario yields a methane reduction of 13.6 percent statewide (Table 5.5).

Scenario 2 simply increases the adoption rate to 40 percent. The results, shown in detail in Table 5.6, are proportional and the impact on quantity, costs per cwt of milk, and milk output per group change in proportion to the assumed adoption rate. As shown in the last row of Table 5.6, for scenario 2 methane declines by 18.1 percent, which is one-third more than the reduction for scenario 1 reported in Table 5.5.

Scenarios 3 uses 30 percent adoption, but includes digesters for the mid-sized freestall dairies and both the larger herd size groups. The results for Scenario 3, detailed in Table 5.7, are that methane reduction decreased by about 24 percent statewide. As shown in Table 5.7, about 90 percent of the emission reduction is contributed by the midsized and larger freestall dairies, where most of the state's cows are located. Large emission reduction per dairy also occurs on the smaller dairies, in part because their higher costs reduce production on these farms by more than 5 percent. The results in Table 5.7 show that organic dairies maintain production because their cost increase is almost wholly matched by the consequent higher price in the organic market, which tends to be within California, and therefore has a more inelastic demand.

Scenarios 4 and 5.
Scenario 4 has an adoption rates that differ across farm categories for the same set of practices as scenario 3. In scenario 4 the adoption of pack barns for the smaller herd size dairies is lower. As shown in the details of Table 5.8, smaller herd size dairies have lower cost increases compared to scenario 3 in Table 5.7 and therefore reduced the rate of decline in their milk production. The assumed rate of digester adoption for the midsize freestall dairies was also lower than 30 percent to reflect the fact that there are fewer digesters among that group currently compared to the larger freestall dairies. To compensate for these differences, we assume a higher rate of digester adoption on the larger freestall dairies of 60 percent, about one third higher than are currently implemented or under development on dairies in this category. As a result, as shown in Table 5.8, the overall methane emissions decreased by 32.1 percent statewide.

Finally, in scenario 5 we assume that smaller dairies use the practice of solid separation with solar drying (practice 3a) rather than the expensive pack barns. As Table 5.9 shows, assuming that this technology is adopted causes reduced costs of manure handling and just about eliminates the implied decline in milk production for smaller dairies. Table 5.9 shows that under this adoption assumption, smaller dairies now contribute very little to statewide emission reductions. In addition, scenario 5 assumes higher digester adoption on the larger farms compared to scenario 4. In scenario 5, a 66 percent adoption rate is assumed for larger farms with freestalls and a 35 percent adoption rate is assumed for larger non-freestall farms. Table 5.9 shows that under scenario 5 the total methane emissions decreased by 34.5 percent from the base, with 78 percent of the reduction contributed by the larger freestall dairies and another almost 19 percent contributed by the mid-sized freestall dairies.

Table 5.5 Effect of practices of Scenario 1 in 5-year time horizon

	Practice adoption pattern					Percentage changes for group in:			
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	30.0	2.69		-4.84	-29.6	8.9
<500 Non-freestall	2a	-65.3	9.3	30.0	2.80		-5.05	-23.7	1.0
500-2000 Freestall	3a	-24.3	1.3	30.0	0.38	0.27	-0.21	-7.5	20.4
500-2000 Non-freestall	3a	-23.2	1.0	30.0	0.29		-0.04	-7.0	2.0
>2000 Freestall	4a	-59.1	0.7	30.0	0.22		0.10	-17.6	64.3
>2000 Non-freestall	3a	-23.2	0.8	30.0	0.25		0.04	-6.9	2.1
Organic	2a	-86.2	3.2	30.0	0.95	0.76	-0.38	-26.1	1.4
Total California								-13.6	100.0

Table 5.6 Effect of practices of Scenario 2 in 5-year time horizon

Practice adoption pattern						Percentage changes for group in:			
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	40.0	3.59		-6.45	-38.9	8.8
<500 Non-freestall	2a	-65.3	9.3	40.0	3.73		-6.74	-31.1	1.0
500-2000 Freestall	3a	-24.3	1.3	40.0	0.50	0.36	-0.28	-10.0	20.4
500-2000 Non-freestall	3a	-23.2	1.0	40.0	0.39		-0.06	-9.3	2.0
>2000 Freestall	4a	-59.1	0.7	40.0	0.30		0.13	-23.5	64.4
>2000 Non-freestall	3a	-23.2	0.8	40.0	0.34		0.05	-9.2	2.1
Organic	2a	-86.2	3.2	40.0	1.27	1.01	-0.51	-34.8	1.4
Total California								-18.1	100.0

Table 5.7 Effect of practices of Scenario 3 in 5-year time horizon

	Practice adoption pattern					Percentage changes for group in:			
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	30.0	2.69		-5.08	-29.7	5.0
<500 Non-freestall	2a	-65.3	9.3	30.0	2.80		-5.29	-23.9	0.6
500-2000 Freestall	Digester	-86.1	0.5	30.0	0.15	0.15	-0.01	-25.8	39.4
500-2000 Non-freestall	3a	-23.2	1.0	30.0	0.29		-0.28	-7.2	1.1
>2000 Freestall	Digester	-82.6	0.1	30.0	0.03		0.25	-24.6	50.2
>2000 Non-freestall	Digester	-57.8	0.1	30.0	0.04		0.22	-17.2	2.9
Organic	2a	-86.2	3.2	30.0	0.95	0.76	-0.38	-26.1	0.8
Total California								-24.3	100.0

Table 5.8 Effect of practices of Scenario 4 in 5-year time horizon

		Practice adoption pattern					Percentage changes for group in:		
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	5.0	0.45		-0.76	-5.1	0.6
<500 Non-freestall	2a	-65.3	9.3	10.0	0.93		-1.73	-8.1	0.2
500-2000 Freestall	Digester	-86.1	0.5	20.0	0.10	0.07	-0.07	-17.3	19.9
500-2000 Non-freestall	3a	-23.2	1.0	15.0	0.15		-0.16	-3.6	0.4
>2000 Freestall	Digester	-82.6	0.1	60.0	0.05		0.03	-49.5	76.4
>2000 Non-freestall	Digester	-57.8	0.1	30.0	0.04		0.05	-17.3	2.2
Organic	2a	-86.2	3.2	10.0	0.32	0.25	-0.13	-8.7	0.2
Total California								-32.1	100.0

Table 5.9 Effect of practices of Scenario 5 in 5-year time horizon

		Practice adoption pattern				Percentage changes for group in:			
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	3a	-24.2	1.6	5.0	0.08		-0.05	-1.3	0.1
<500 Non-freestall	3g	-23.4	1.9	10.0	0.19		-0.28	-2.6	0.0
500-2000 Freestall	Digester	-86.1	0.5	20.0	0.10	0.05	-0.10	-17.3	18.6
500-2000 Non-freestall	3a	-23.2	1.0	15.0	0.15		-0.18	-3.7	0.4
>2000 Freestall	Digester	-82.6	0.1	66.0	0.06		-0.01	-54.5	78.3
>2000 Non-freestall	Digester	-57.8	0.1	35.0	0.05		0.01	-20.2	2.4
Organic	3a	-22.0	0.7	10.0	0.07	0.06	-0.03	-2.2	0.0
Total California								-34.5	100.0

Discussion

One central observation of the detailed results presented in this chapter is that under all scenarios we find small changes on price of milk and quantity of milk production. Manure management costs change substantially in percentage terms in some scenarios for some categories of dairy farms. However, manure management continues to contribute a relatively small share of total dairy farm costs, which are still dominated by feed costs, herd replacement costs and labor costs, especially labor costs for milking.

The calibrated simulation model shows that with a more costly methane reduction practice for a category of farm, the implied reduction in milk production is larger indicate more potential impact on economic sustainability. This common-sense result indicates that the model has successfully captured some of the realistic economic forces facing dairy farms.

The practices that we included to reduce methane emissions in the simulations of Chapter 5, represent practices now being used on some California dairies. When applied more widely they contribute subst

antial reductions in overall methane from dairy manure management in California. Most of the reduction occurs on the midsize and larger freestall dairies where most of the milk in California is produced. The bulk of the most cost-effective methane reduction occurs in scenarios that impose higher digester adoption on the larger dairies.

Conclusion

This chapter focuses on applying our simulation model to adoption of manure management practices and develops the implications with a five-year horizon. The calibrated simulation model shows that with a more costly methane reduction practice for a category of farm, the implied reduction in milk production is larger indicate more potential impact on economic sustainability.

The model preformed as expected and the calibrations and parameter choices yield a pattern of results and implications that are consistent with broader observations about the California dairy economy. More scenarios with other time horizons a studied in detail in the next two chapters.

Recommendations

By themselves the results of this chapter do not yield recommendations. The results do indicate that the simulation approach can be an effective tool and the next two chapters also contain additional results of interest to the industry participants, policymakers and other researchers.

CHAPTER 6 COSTS, BENEFITS AND IMPLICATIONS OF ADOPTION OF METHANE REDUCTION PRACTICES ACROSS SMALLER AND LARGER DAIRIES FOR 1-YEAR, 5-YEAR, AND 10-YEAR TIME HORIZONS

Introduction

This chapter uses the economic model and simulation framework developed in Chapter 4 to examine three distinct time horizons. The scenarios are the same as those examined in Chapter 5 and in that sense this chapter builds directly on those results. For that reason, we avoid duplication of all the background already explained in Chapter 5.

The alternative time horizons considered here in Chapter 6 affect the supply and demand elasticities and the implications of fixed costs of adopting manure management practices. Generally large investments are not economic if the time horizon facing a farm or other business is short. Therefore, when horizons are longer, more larger investments in fixed costs become economically feasible.

The model includes components of scale of capital investment, management and location in the context of cost-benefit analysis. Our economic model incorporates both costs and benefits to dairy operations. Results generate implications for the price and quantity of milk produced and marketed in California.

Materials and Methods

The time horizons that we considered in this chapter have the following interpretation. Table 6.1 describes the demand and supply elasticities that apply to each horizon. We assumed that the manure management practice has been fully implemented and consider the time period after implementation. We did not consider effects while projects are being built. The practices affect costs and these costs affect the quantity of milk produced more when more time has passed. That is the major implication shown in the results.

Importantly, we note that, as shown in Table 6.1, the demand and supply elasticities both are larger for longer time horizons as producers and buyers have more time to adjust to the new cost situations. These are standard implication of economic modeling. Recall that supply and demand elasticities are defined as the proportional change in quantity for a one percent change in price. That is the elasticities are unitless ratios of percentage changes. Generally, when producers or consumers have a longer time horizon over which to consider adjustments, the costs of a change of a given magnitude is smaller and therefore the economically effective adjustment is larger. Another way to describing this result is simply to say some factors that are constraints in a very short time horizon are less binding when there is more time over which to consider adjustment.

We did not include any evaluation of the effects of California dairy methane emissions on the global or California economies. That broad and complex topic is beyond the scope of this study, which focused on economic implication for dairy farms of different herd size category and for the price and quantity of milk in California.

Moreover, as noted in Chapter 5, there are a range of environmental issues that affect the California dairy industry and dairy production regions. We have noted that those local environmental issues are only tangentially affected by the economics of methane emission strategies that we considered in this chapter.

Table 6.1 Values of supply and demand elasticities in 1, 5 and 10-year time horizon.

Group		Supply Elasticities	
	1 year	5 year	10 year
A	0.5	2.0	3.0
B	0.5	2.0	3.0
C	0.5	2.0	3.0
D	0.5	2.0	3.0
E	0.5	2.0	3.0
F	0.5	2.0	3.0
G	0.5	2.0	3.0
Market		Demand Elasticities	
	1 year	5 year	10 year
Conventional	1.0	1.0	2.0
Organic	0.5	0.5	1.0

Results

Effects of adoption of patterns of adoption across size groups over different horizons

This section is organized by scenarios just as was chapter 5. Results are similar to those presented there. We document that time horizons are not crucial in this context when trends in herd size patterns and consolidations are not yet incorporated. Those trends are discussed extensively in Chapter 7. Here we describe briefly the implication of scenarios 0 through scenario 5 for each of the three specified time horizons. Results are similar across scenarios and we provide more detail about results of scenario 0. We set out some key results of each scenario, but attempt to avoid undue repetition.

Scenario 0. Implemented projects scenario

Recall that this scenario includes representative practices for each group and adoption rates that are roughly consistent with CDFA-funded projects under the AMMP and digester programs. In the top panel of Table 6.2 a manure management practice was listed for each group along with the associated percentage emission reductions, cost increases per cow, and adoption rates. These are identical to what is shown in Chapter 5 for this scenario and each of the other scenarios.

The second part of Table 6.2 shows the impacts of the scenario, for each farm size and housing group, on costs per cwt of milk, price of milk, quantity of milk, methane emission reduction, and the contribution of that group to the overall impact on methane emissions. In each case, the definition of the horizon 1-year, 5-year, and 10-year is the period of time over which market adjustments take place. That is for the 1-year horizon after the practices are implemented only adjustments that are complete in a single year are included in the scenario results.

The impacts of time horizons are minor for methane emissions, but significant for milk quantity produced, particularly for the smaller dairies. Consider for example, the decline in quantities of milk for groups A and B, which are the conventional dairies with less than 500 cows. Table 6.2 shows that after a 1-year adjustment quantity of milk decreases by 0.17 percent for group A and by 0.41 percent for group B. But after 10 years, with more elastic supply and thus more implied quantity response, the decline in quantity of is 0.88 percent for group A and a significant 2.3 percent for group B, which is assumed to have a higher adoption rate for the practice.

Milk price does not rise much in any of the horizons and emissions are similar across the time horizons. Note that the total change in emissions for California is an average of changes for each group, weighted by the share of total emissions of each group.

Scenarios 1, 2 and 3.
Scenario 1 (Table 6.3) applies a 30 percent adoption rate for a set of non-digester practices for every group. As in Chapter 5, these scenarios have less emission reduction than Scenario 0, but also lower milk quantity produced, particularly for the smaller dairies. After one year the quantity of milk production is down by more than 1.3 percent for the two groups of conventional dairies that have less than 500 cows and down about 0.32 percent for organic dairies (which are all assumed to be small). Table 6.3 shows that for the smaller conventional dairies, after a 10-year adjustment period, loss of production rises to 7.34 percent for group A and 7.66 percent for group B. These are major losses over this longer-term horizon.

Scenario 2 is identical to scenario 1, except that it uses a 40 percent adoption rate for the practices. Table 6.4 shows, as found in Chapter 5, the impacts on costs, prices, production and emissions are about one-third larger than scenario 1 (Table 6.3). The losses in quantities produced for the smaller size groups of conventional dairies for the 10-year horizon is even more pronounced. That is, Table 6.4 shows that a 40 percent rate of adoption of these practices would result in a reduction in milk output of the smaller dairies of about 10 percent and almost no change in the milk output of the larger dairies.

Scenarios 3 (Table 6.5) adds digesters, with a standard 30 percent adoption rate, to the pattern of assumed methane reducing practices. Assuming digester adoption increases total emission reductions for all time horizons. Losses of production quantity for the smaller conventional dairies remains large—almost 8 percent for the 10-year time horizon. The impact production on the larger dairies remains very small. Generally, the cost of digesters for larger dairy farms is assumed to be small, given that non-farm companies have generally accepted the costs of building and operating digesters in return for access to the methane and the strong market price for the biogas, which is assumed to continue to qualify as a renewable fuel under federal regulations and a low carbon fuel under California regulation (Lee and Sumner, 2018).

Scenarios 4 and 5.
Recall scenario 4 assumed moderate adoption of practices for smaller dairies and larger adoption of digesters for larger dairies. These practices and adoption rates are spelled out in Table 6.6. The quantity losses in Scenario 4for the smaller dairies are moderate for all time horizons shown in Table 6.6. After a 10-year adjustment period the loss is -1.2 percent for group A and -2.6

percent for group B. Other impacts change little over time (Table 6.6). The emission reduction over each horizon about 32 percent.

As discussed in Chapter 5 and shown in Table 6.7, Scenario 5 implied lower costs of methane reducing practices for the smaller dairies by assuming the adoption of lower cost alternative practices for these farms. Scenario 5 also assumes higher rate of adoption of digesters on the larger dairies than does scenario 4. Time horizons matter little for this scenario. Table 6.7 shows that even in the 10-year horizon, because the assumed practices have relatively low-cost impacts, the effects on quantities produced are small over all horizons. As shown in Table 6.7 the loss of output from smaller dairies is less than one-half of one percent. The impact on the larger dairies is even less.

Table 6.2 Effect of practices of Scenario 0 in 1, 5 and 10-year time horizons.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	4.0
B	<500 Non-freestall	2a	-65.3	9.3	9.0
C	500-2000 Freestall	4a	-59.1	1.1	14.0
D	500-2000 Non-freestall	3a	-23.2	1.0	16.0
E	>2000 Freestall	Digester	-82.6	0.1	46.0
F	>2000 Non-freestall	Digester	-57.8	0.1	25.0
G	Organic	2a	-86.2	3.2	7.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.36	0.02	-0.17	-3.6	0.6
B	0.84		-0.41	-6.3	0.2
C	0.15		-0.07	-8.3	13.5
D	0.16		-0.07	-3.8	0.6
E	0.04		-0.01	-38.0	82.3
F	0.03		-0.01	-14.4	2.6
G	0.22	0.07	-0.07	-6.1	0.2
		Total California		-22.9	100.0
5 -Year					
A	0.36	0.07	-0.57	-4.0	0.7
B	0.84		-1.53	-7.3	0.2
C	0.15		-0.16	-8.4	13.6
D	0.16		-0.17	-3.9	0.6
E	0.04		0.06	-37.9	82.1
F	0.03		0.08	-14.4	2.6
G	0.22	0.18	-0.09	-6.1	0.2
		Total California		-22.9	100.0
10-Year					
A	0.36	0.07	-0.88	-4.3	0.8
B	0.84		-2.32	-8.1	0.2
C	0.15		-0.26	-8.5	13.7
D	0.16		-0.27	-4.0	0.7
E	0.04		0.07	-37.9	81.9
F	0.03		0.09	-14.4	2.6
G	0.22	0.17	-0.17	-6.2	0.2
		Total California		-23.0	100.0

Table 6.3 Effect of practices of Scenario 1 in 1, 5 and 10-year time horizons.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	30.0
B	<500 Non-freestall	2a	-65.3	9.3	30.0
C	500-2000 Freestall	3a	-24.3	1.3	30.0
D	500-2000 Non-freestall	3a	-23.2	1.0	30.0
E	>2000 Freestall	4a	-59.1	0.7	30.0
F	>2000 Non-freestall	3a	-23.2	0.8	30.0
G	Organic	2a	-86.2	3.2	30.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	2.69	0.08	-1.30	-26.9	8.2
B	2.80		-1.36	-20.7	0.9
C	0.38		-0.15	-7.4	20.3
D	0.29		-0.11	-7.0	2.0
E	0.22		-0.07	-17.8	65.1
F	0.25		-0.09	-7.0	2.1
G	0.95	0.32	-0.32	-26.1	1.4
		Total California		-13.5	100.0
5 -Year					
A	2.69	0.27	-4.84	-29.6	8.9
B	2.80		-5.05	-23.7	1.0
C	0.38		-0.21	-7.5	20.4
D	0.29		-0.04	-7.0	2.0
E	0.22		0.10	-17.6	64.3
F	0.25		0.04	-6.9	2.1
G	0.95	0.76	-0.38	-26.1	1.4
		Total California		-13.6	100.0
10-Year					
A	2.69	0.24	-7.34	-31.4	9.4
B	2.80		-7.66	-25.8	1.1
C	0.38		-0.40	-7.6	20.6
D	0.29		-0.14	-7.1	2.0
E	0.22		0.06	-17.7	63.6
F	0.25		-0.03	-7.0	2.1
G	0.95	0.71	-0.71	-26.4	1.4
		Total California		-13.8	100.0

Table 6.4 Effect of practices of Scenario 2 in 1, 5 and 10-year time horizon.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	40.0
B	<500 Non-freestall	2a	-65.3	9.3	40.0
C	500-2000 Freestall	3a	-24.3	1.3	40.0
D	500-2000 Non-freestall	3a	-23.2	1.0	40.0
E	>2000 Freestall	4a	-59.1	0.7	40.0
F	>2000 Non-freestall	3a	-23.2	0.8	40.0
G	Organic	2a	-86.2	3.2	40.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	3.59	0.11	-1.74	-35.8	8.1
B	3.73		-1.81	-27.5	0.9
C	0.50		-0.20	-9.9	20.3
D	0.39		-0.14	-9.4	2.0
E	0.30		-0.09	-23.7	65.1
F	0.34		-0.11	-9.4	2.1
G	1.27	0.42	-0.42	-34.7	1.4
		Total California		-18.4	100.0
5-Year					
A	3.59	0.11	-6.45	-38.9	8.8
B	3.73		-6.74	-31.1	1.0
C	0.50		-0.28	-10.0	20.4
D	0.39		-0.06	-9.3	2.0
E	0.30		0.13	-23.5	64.4
F	0.34		0.05	-9.2	2.1
G	1.27	0.42	-0.51	-34.8	1.4
		Total California		-18.1	100.0
10-Year					
A	3.59	0.32	-9.79	-41.0	9.2
B	3.73		-10.21	-33.7	1.1
C	0.50		-0.53	-10.2	20.6
D	0.39		-0.19	-9.4	2.0
E	0.30		0.09	-23.6	63.7
F	0.34		-0.04	-9.3	2.1
G	1.27	0.95	-0.95	-35.1	1.4
		Total California		-18.3	100.0

Table 6.5 Effect of practices of Scenario 3 in 1, 5 and 10-year time horizon.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	30.0
B	<500 Non-freestall	2a	-65.3	9.3	30.0
C	500-2000 Freestall	Digest.	-86.1	0.5	30.0
D	500-2000 Non-freestall	3a	-23.2	1.0	30.0
E	>2000 Freestall	Digest.	-82.6	0.1	30.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	30.0
G	Organic	2a	-86.2	3.2	30.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	2.69	0.05	-1.32	-27.0	4.6
B	2.80		-1.38	-20.7	0.5
C	0.15		-0.05	-25.9	39.5
D	0.29		-0.12	-7.1	1.1
E	0.03		0.01	-24.8	50.6
F	0.04		0.00	-17.3	2.9
G	0.95	0.32	-0.32	-26.1	0.8
		Total California		-24.4	100.0
5-Year					
A	2.69	0.15	-5.08	-29.7	5.0
B	2.80		-5.29	-23.9	0.6
C	0.15		-0.01	-25.8	39.4
D	0.29		-0.28	-7.2	1.1
E	0.03		0.25	-24.6	50.2
F	0.04		0.22	-17.2	2.9
G	0.95	0.76	-0.38	-26.1	0.8
		Total California		-24.3	100.0
10-Year					
A	2.69	0.14	-7.66	-31.6	4.6
B	2.80		-7.98	-26.0	0.5
C	0.15		-0.05	-25.9	39.5
D	0.29		-0.47	-7.4	1.2
E	0.03		0.33	-24.5	49.9
F	0.04		0.28	-17.1	2.9
G	0.95	0.71	-0.71	-26.4	0.8
		Total California		-24.4	100.0

Table 6.6 Effect of practices of Scenario 4 in 1, 5 and 10-year time horizon.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	5.0
B	<500 Non-freestall	2a	-65.3	9.3	10.0
C	500-2000 Freestall	Digest.	-86.1	0.5	20.0
D	500-2000 Non-freestall	3a	-23.2	1.0	15.0
E	>2000 Freestall	Digest.	-82.6	0.1	60.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	30.0
G	Organic	2a	-86.2	3.2	10.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.45	0.07	-1.52	-5.8	0.7
B	0.93		-3.46	-9.8	0.2
C	0.10		-0.14	-17.3	20.0
D	0.15		-0.31	-3.8	0.4
E	0.05		0.06	-49.5	76.3
F	0.04		0.11	-17.2	2.2
G	0.32	0.25	-0.25	-8.8	0.2
		Total California		-32.2	100.0
5-Year					
A	0.45	0.07	-0.76	-5.1	0.6
B	0.93		-1.73	-8.1	0.2
C	0.10		-0.07	-17.3	19.9
D	0.15		-0.16	-3.6	0.4
E	0.05		0.03	-49.5	76.4
F	0.04		0.05	-17.3	2.2
G	0.32	0.25	-0.13	-8.7	0.2
		Total California		-32.1	100.0
10-Year					
A	0.45	0.06	-1.16	-5.4	0.7
B	0.93		-2.61	-9.0	0.2
C	0.10		-0.12	-17.3	20.0
D	0.15		-0.25	-3.7	0.4
E	0.05		0.03	-49.5	76.3
F	0.04		0.06	-17.3	2.2
G	0.32	0.24	-0.24	-8.8	0.2
		Total California		-32.2	100.0

Table 6.7 Effect of practices of Scenario 5 in 1, 5 and 10-year time horizon.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	3a	-24.2	1.6	5.0
B	<500 Non-freestall	3g	-23.4	1.9	10.0
C	500-2000 Freestall	Digest.	-86.1	0.5	20.0
D	500-2000 Non-freestall	3a	-23.2	1.0	15.0
E	>2000 Freestall	Digest.	-82.6	0.1	66.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	35.0
G	Organic	3a	-22.0	0.7	10.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.08	0.02	-0.03	-1.2	0.1
B	0.19		-0.09	-2.4	0.0
C	0.10		-0.04	-17.3	18.6
D	0.15		-0.06	-3.5	0.4
E	0.06		-0.02	-54.5	78.4
F	0.05		0.02	-20.2	2.4
G	0.07	0.03	-0.06	-2.2	0.0
		Total California		-34.5	100.0
5-Year					
A	0.08	0.05	-0.05	-1.3	0.1
B	0.19		-0.28	-2.6	0.0
C	0.10		-0.10	-17.3	18.6
D	0.15		-0.18	-3.7	0.4
E	0.06		-0.01	-54.5	78.3
F	0.05		0.01	-20.2	2.4
G	0.07	0.06	-0.03	-2.2	0.0
		Total California		-34.5	100.0
10-Year					
A	0.08	0.05	-0.09	-1.3	0.2
B	0.19		-0.43	-2.8	0.0
C	0.10		-0.16	-17.3	18.6
D	0.15		-0.29	-3.8	0.4
E	0.06		-0.03	-54.5	78.3
F	0.05		0.00	-20.2	2.4
G	0.07	0.05	-0.05	2.3	0.0
		Total California		34.5	100.0

Discussion

This chapter has investigated the effects of manure management practices that reduce methane emissions on economic and environmental outcomes over 1-year, 5-year and 10-year time horizons. The longer time horizons allow more adjustment to the cost increases caused by adopting the practices.

Our analysis does not explicitly incorporate the uncertainties about market outcomes, technologies or policies that surround all business or farm enterprises, dairy included. Such uncertainties apply in the immediate run, when sudden shocks in supply and demand can disrupt plans. Over a long-term horizon such shocks may average out. But, over a 10-year horizon or longer, uncertainty about longer term trends become more important. Chapter 7 considers some of those trend issues.

We note that our simulation model did not include an explicit mechanism to specify which individual farms within each group adopted the methane reducing practices. That is a 30 percent adoption rate for the group does not isolate which farms adopt and which do not. The model produces a step-wise (group-by-group) cost curve for methane abatement as adoption increases within a group and there are different costs for each practice within each group. An extension of the model would add explicit measurable heterogeneity in costs across individual dairies within each group. We do not now have the necessary cost data to calibrate the patterns of heterogeneity. This model limitation does not bias any aggregate results. We interpret the results as using an implicitly random adoption across farms within each group. Such a pattern of adoption is consistent with adoption patterns in which important factors other than simply measured marginal costs of a practice contribute to driving adoption.

We recognize that some of the manure management practices considered in the simulations may have complex and subtle benefits or costs beyond those incorporated in our data. However, we note that these manure management practices have not been broadly adopted by California dairy farms until there have been government programs providing cost-sharing or other incentives.

Local environmental outcomes are affected by impacts related to number of cows and milk output. Generally, more cows and more milk production in a region are associated with local environmental concerns and pressures. It may be the case that smaller or larger dairies have differential local environmental impacts per cow or per unit of milk production. If that is the case, those local environmental impacts might be affected by a shift in number of cows and production over time. More research is needed to investigate these questions.

Our modeling and simulation methodology were based on assessing costs and benefits. Therefore, the results presented here are consistent with cost-benefit analysis principles. However, measuring the broad societal benefits of reduced methane emissions is beyond the scope of this project.

Conclusion

This chapter is comprised mainly of a set of detailed tables of result of applying our simulation model to alternative time horizons for each scenario. These details are important for some very specific questions but the overall conclusions for smaller dairies may be quickly summarized.

Especially for the longer 10-year time horizon, the supply and demand elasticities are relatively large. That means that the milk quantity impacts of adoption of more costly manure management practices may become larger. Furthermore, the larger impacts on per unit costs are for the smaller dairies. Therefore, we find that for the scenarios that include adoption of the more costly practices by smaller farms adopt, the decline in the production of these smaller dairies is substantial. Output declines for smaller dairies reaches about 10 percent for the 10-year horizon. In scenarios that allow adoption of lower cost practices have output declines for smaller dairies of well less than 0.5 percent. In general, the output effects on larger dairies are small in all scenarios and in all time horizons. This result is because we found that the manure management practices adopted imposed small to moderate costs per unit of output for the larger dairies.

Recommendations

In this chapter, a pattern is beginning to emerge that adoption of the most costly manure management practices may have significant negative output implications for the smaller dairies, while contributing relatively little to aggregate methane reduction. This may suggest a strategy to focus efforts of adoption on larger dairies where more cost-effective methane reduction could be achieved.

CHAPTER 7 PROJECTED ECONOMIC SUSTAINABILITY OF SMALLER DAIRIES IN CALIFORNIA OVER 5-YEAR, 10-YEAR AND 20-YEAR TIME HORIZONS, INCLUDING CONSIDERATION OF ECONOMIC AND ENVIRONMENTAL CONCERNS SUCH AS METHANE EMISSIONS REDUCTIONS

Introduction

This chapter has two major parts. In part 7.1 we used a data intensive consideration of how the dairy industry in California is likely to evolve over the next few decades in light of changes in the past few decades. In the second part of the chapter we incorporated the findings of the first part into the economic modeling and simulation approach developed in Chapter 4 and used in Chapters 5 and 6.

The California dairy industry has faced many economic challenges related to state, national and global markets for milk, national and global markets for grain and oilseeds, local costs of forage and labor, among other challenges. At the same time period over which economic challenges have become stronger, the costs of dairy farming and dairy product manufacturing have risen in California. These California cost challenges relate to costs of land, water, electricity and labor (among others) that are due, in part, to California regulatory choices. It is impossible to quantify here all these factors that drive the sustainability of the California dairy industry. Instead we offer a few introductory assessments before turning to the consequences.

First, California has long had a strong a resilient dairy industry comprised of both farming and dairy product processing. The industry was an early adopter of large-scale milk production and processing that lowered costs and attracted top managers to the business. With rapid consolidation and strong economic incentives, only the best managers have remained in the business. These economic incentives and pressures continue and consolidation continues.

Second, only a small share of California milk is used locally consumed fluid milk products in markets that are insulated from competition. Most California milk is used to make processed products that enter national and international markets. The prices in these markets are determined globally rather than locally. As dairy production has become more efficient in other competitive regions the national and international prices are lower. This competitive pressure and growing efficiency among competitors mean that the inflation-adjusted prices of dairy products have declined. Some of the efficiency gains in other locations has been due to their adoption of scale and management for which California was long known.

Third, because California remains a large net exporter of dairy products and because the costs of dairy product manufacturing has risen in California, the price of raw milk is relatively low compared to places to which California dairy products are shipped.

None of these underlying conditions seem likely to change materially in the next few decades and thus a return to very rapid growth of California milk production is unlikely. However, the inherent strengths of the California dairy industry remain. Therefore, it seems unlikely that significant aggregate declines in California milk production are on the horizon. California milk

output has been roughly constant, with many moderate ups and downs, for about 13 years. That aggregate pattern seems likely to continue.

Of course, unforeseeable events may be on the horizon. As this is written, in March 2020, expecting the unexpected seems more appropriate than ever. Any projections therefore must be handled with caution.

Materials and Methods

Two methodologies are used in this chapter. Section 7.1 of the results section develops projections of a likely path for California dairy over the next 20 years and explains implications for different sized dairies in this context. A myriad of factors drives the economic future and subsection 7.1 cannot review them all. Moreover, no projections can be correct in all particulars with such a complex set of drivers, including both local and global supply and demand conditions well into the future. Nonetheless, it is important to consider protected paths, especially for the size of the industry and for the numbers of farms and share of farms and production by size categories.

The second methodology is a simulation model developed in Chapter 4 and was applied also in Chapters 5 and 6. In Section 7.2 the simulation model incorporates features on the projections developed in section 7.1 and shows how the manure handling practices affect farms in different size categories differentially against the baseline that includes projected changes that are likely to underway already.

Results

7.1 Economic Projections of the California Dairy Industry

The California dairy industry remains the single largest producer of milk and processed dairy products in the United States accounting for about 18 percent of all U.S. milk production. Almost all of the milk produced in California is also processed in California, and almost all of the milk processed in California is produced on dairy farms in the state. Much of California processed dairy product quantity and value is shipped out of California in the form of cheese, whey, lactose, milk powders, butter and other processed products that are used in the rest of the United States and globally.

7.1.1 California dairy overview and comparisons with the rest of the United States

Figure 7.1 shows a quick history of the evolution of the California dairy industry over the past three decades (See also Sumner, 2019 and Matthews and Sumner, 2019). All three lines, milk production, number of cows, and production per cow have been scaled to equal 100 in 1987. The data, based on USDA, NASS run through 2018. The beginning and ending values in pounds and cows are shown in the chart. We start in 1987 with 17.9 billion pounds of milk from a little over one million cows and therefore a little less than 17,000 pounds per cow.

The first 20 years, continuing from previous decades, was a period of remarkably steady growth that saw milk production rise by more than 120 percent with large increases in cow numbers and production per cow. That all came to an abrupt stop around 2008. Since then there has been

essentially no growth in output as cow numbers have declined slightly and milk per cow has risen slowly.

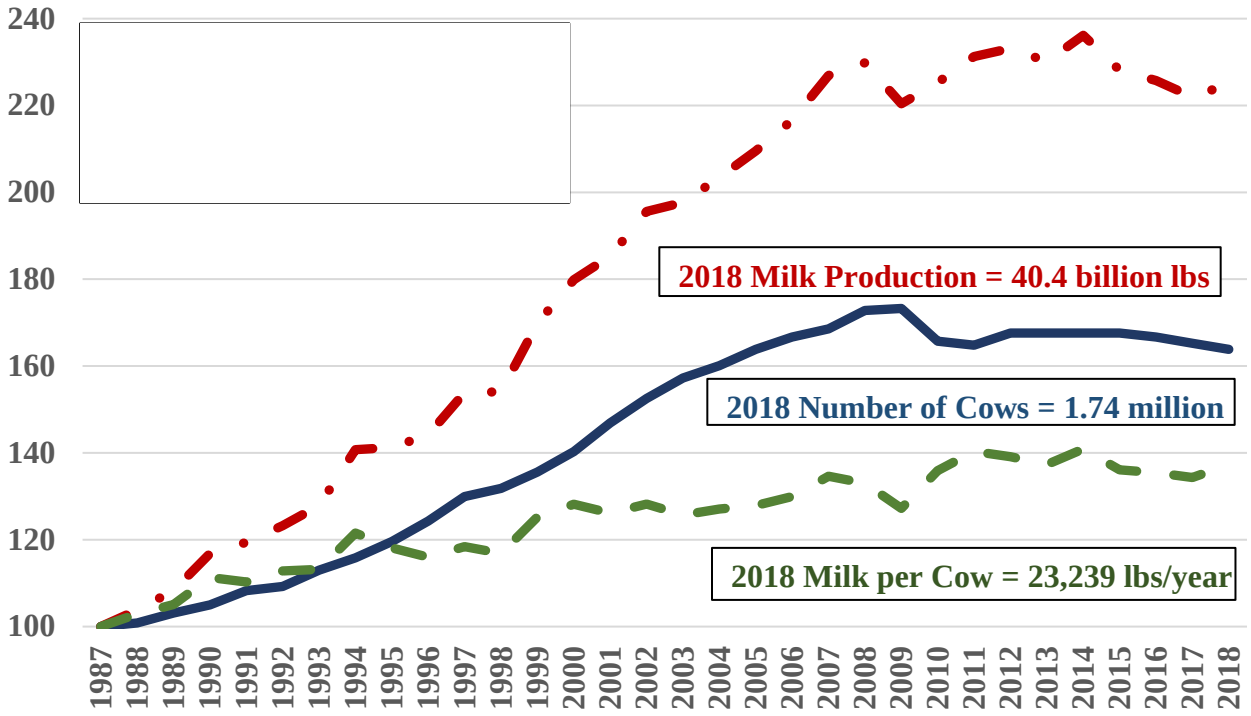

Data Source: NASS, USDA

Figure 7.1 California Milk Production and Productivity Indexed to 1987

As decades of growth ended in California, in the rest of the United States milk production per cow has grown steadily, the number of cows has grown slightly, so that total milk production has risen, offsetting the reductions in California.

The lack of growth in the California milk cow herd over more than a decade has been in contrast with growth in other Western states such as Idaho and Texas and closer to the national average (Table 7.1). The decline in number of dairies in California has actually been slower than the national average and much slower than in states such as Texas and Wisconsin (Table 7.2). The implication is that cow numbers per farm have grown rapidly in California, and, as with other Western States, remain well above the national average. While the growth rate in cows per dairy farm has risen in California, it has done so much more quickly in Wisconsin, and even in Idaho and Texas. Herd size in Idaho and Texas are not quite similar to average herd size in California (Table 7.3).

Table 7.1 Number of Cows in Top Five Milk Producing States in the U.S. for 2004 and 2018.

	Number of Cows (1,000 cows)		Percentage change
	2004	2018	
California	1,700	1,740	5
Wisconsin	1,245	1,275	2
New York	658	625	-5
Idaho	412	600	46
Texas	317	515	62
U.S. Total	8,988	9,400	2

Data Source: NASS, USDA

Table 7.2 Number of Dairies in Top Five Milk Producing States in the U.S. for 2004 and 2017.

	Number of Dairies		Percentage
	2004	2017	Change
California	2,030	1,390	-32
Wisconsin	15,570	9,090	-42
New York	6,600	4,490	-32
Idaho	755	510	-32
Texas	810	400	-51
U.S. Total	66,825	40,219	-40

Data Source: NASS, USDA

Table 7.3 Number of Cows per Dairy in Top Five Milk Producing States and U.S. Average for 2004 and 2017

	Number of Cows per Dairy		Percentage
	2004	2017	Change
California	837	1,263	51
Wisconsin	80	141	76
New York	100	138	38
Idaho	546	1,176	116
Texas	391	1,225	213
U.S. Average	134	232	73

Data Source: NASS, USDA

The comparison with other parts of the United States is useful to help us consider future trends and drivers as the competitive position of California dairy in the national and international market has changed in the most recent decade or two. The evolution of dairy processing plant

capacity is consistent with little aggregate growth in milk production in California (McCully, 2018).

Within California the dairy industry has continued to be concentrated in eight counties of the San Joaquin Valley, led by Tulare County (Figure 7.2). The number of dairies has decreased rapidly in all these counties except Kern County (Figure 7.3). Kern County, which has relatively few dairy farms, has, by far, the largest average herd size in California at about 3,200 cows (Figure 7.4). But, herd size has grown rapidly for all these counties and for the California average (Figure 7.4). Overall, these data indicate that while much has changed for the California dairy industry, milk production remains large, and has not declined despite many challenges. At the same time, the trend is toward farm consolidation, a trend which California shares with the rest of the United States.

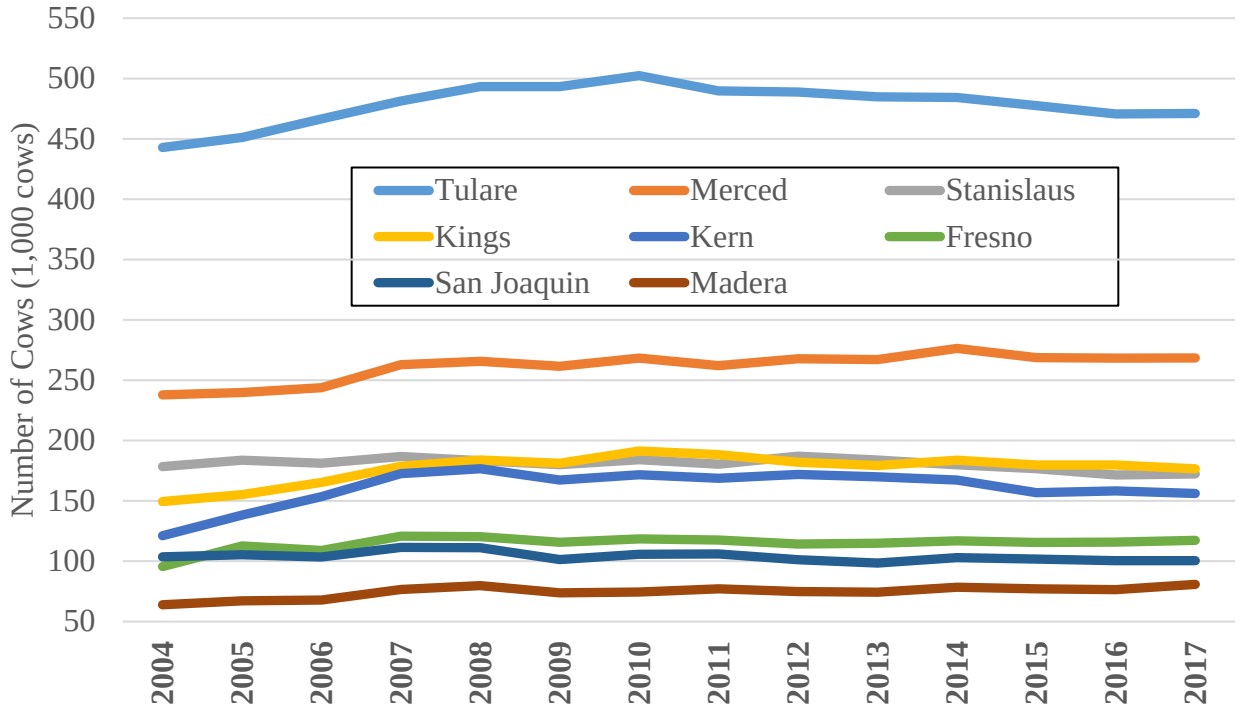

Source: CDFA California Dairy Statistics Annual, 2004 to 2017

Figure 7.2 Number of Cows in Top Milk Producing Counties in California, 2004 to 2017.

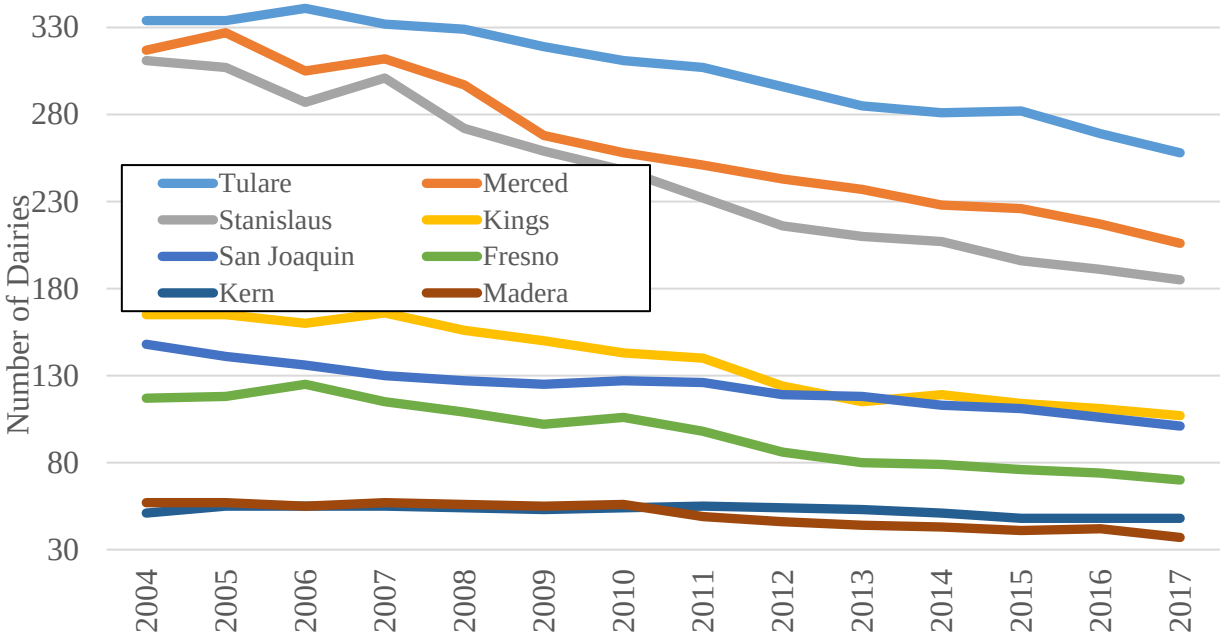

Source: CDFA California Dairy Statistics Annual, 2004 to 2017

Figure 7.3 Number of Dairies in Top Milk Producing Counties in California, 2004 to 2017.

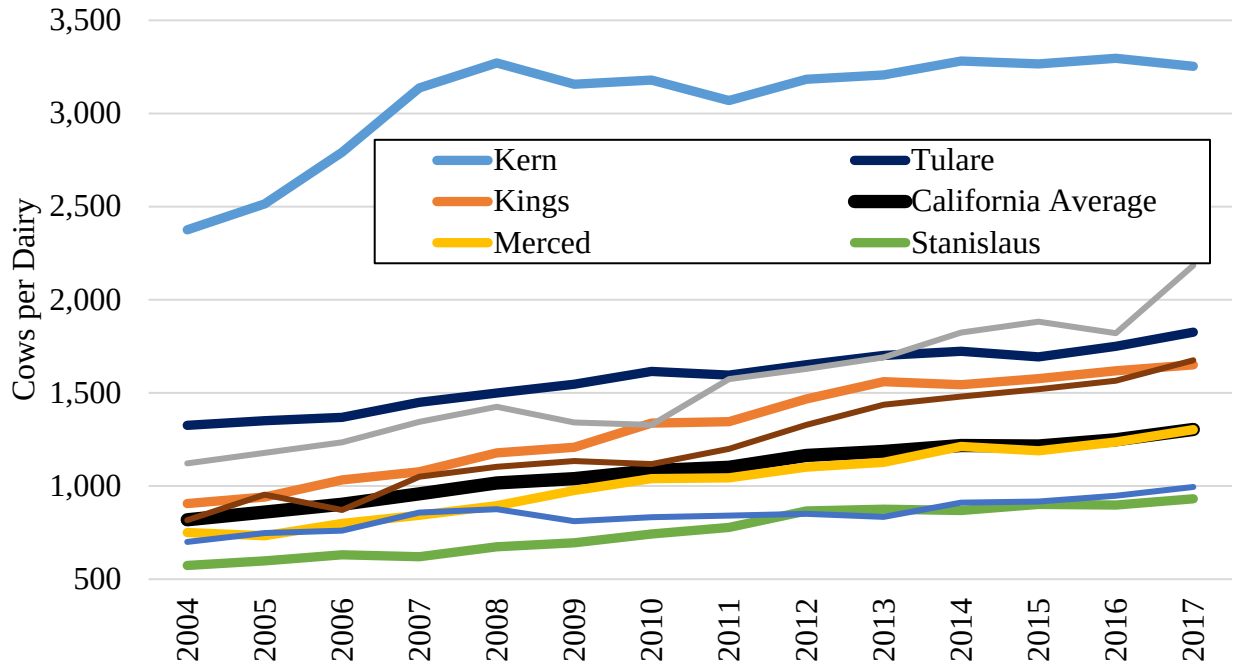

Source: CDFA California Dairy Statistics Annual, 2004 to 2017

Figure 7.4 Average Number of Cows per Dairy in Top Milk Producing Counties in California, 2004 to 2017.

7.1.2 Dairy farm consolidation in California over three decades

Every five years for more than 150 years the U.S. Census of Agriculture provides consistently defined and statistically rigorous data on many characteristics of farms and agricultural markets. Despite some deficiencies, these data are useful in tracking herd size distributions for California dairy farms.

The biggest deficiency with the Census data for tracking the distribution of dairy herds by size category for California dairies is that the great detail about the smallest dairies (less than 100 cows) is irrelevant for California and information about distributions of herds by size categories of more than 1,000 cows has appeared only in the last decade or so. The other problem is that the Census provides great detail about dairy cow numbers on farms that market no milk. These farms may have a few milk cows for household use or to nurse calves, but they are irrelevant to our interest in the commercial dairy industry. In spite of these limitation, we can learn much by examining data from seven Census rounds that span three decades from 1987 through 2017.

Figures 7.5 through 7.10 show patterns of number of dairy farms that have milk sales by herd size category. The figures include trends and trend regressions for size categories from herds with less than 500 cows through herds with 2,500 cows or more.

Consider first the number of dairies with herd size 1-499 cows. There were 1908 herds in this category in 1987 and only 395 herds in 2017, a decline of about 80 percent in 30 years (Figure 7.5). The exponential regression trend line through these data explains 95 percent of the variation in the data. The trend shows a 26.7 percent decline in the number of herds every 5 years. This is substantially faster than 5 percent per year on a cumulative basis. We extend the trend line out one decade, to 2027 and note that the trend projection is for less than 250 herds remaining in this category (Figure 7.5).

Next, consider the number of dairies with 500 cows to 999 cows (Figure 7.6). This category is only available since 1992, so we have six census data points spanning 25 years. The number of herds in this category is also declining rapidly. The trend line does not fit quite so well, explaining 81 percent of the variation. The herd numbers were about constant for the first decade and rapid from 2012 through 2017. There were 558 herds in 2002 and only 300 herds in 2017 in this size category. Over the full 25 years, the rate of decline is about 14 percent every five years.

The exponential trend line explains about 81 percent of the variation in number of herds with 1,000 cows or more, but indicates continued rapid growth at about 12 percent every five years (Figure 7.7). This exponential trend projects almost 900 herds in 2027. However, a natural log trend fits these data much better (R^2 =0.93) and shows a flattening rate of growth. The logarithmic trend projects about 700 herds in 2027 (Figure 7.8).

We can break down the data for larger herds sizes only in the 2007, 2012 and 2017 Census rounds. The number of dairies from 1,000 to 2,499 cows (Figure 7.9) declined by about 9 percent over this 10-year period, but rose in the first five years before falling by 13 percent in the most recent 5 years. The number of dairies with more than 2,500 cows grew by 17 percent from 169 to 198 herds. We expect most of that growth was herds in the smaller category adding cows to their herds over this decade (Figure 7.10).

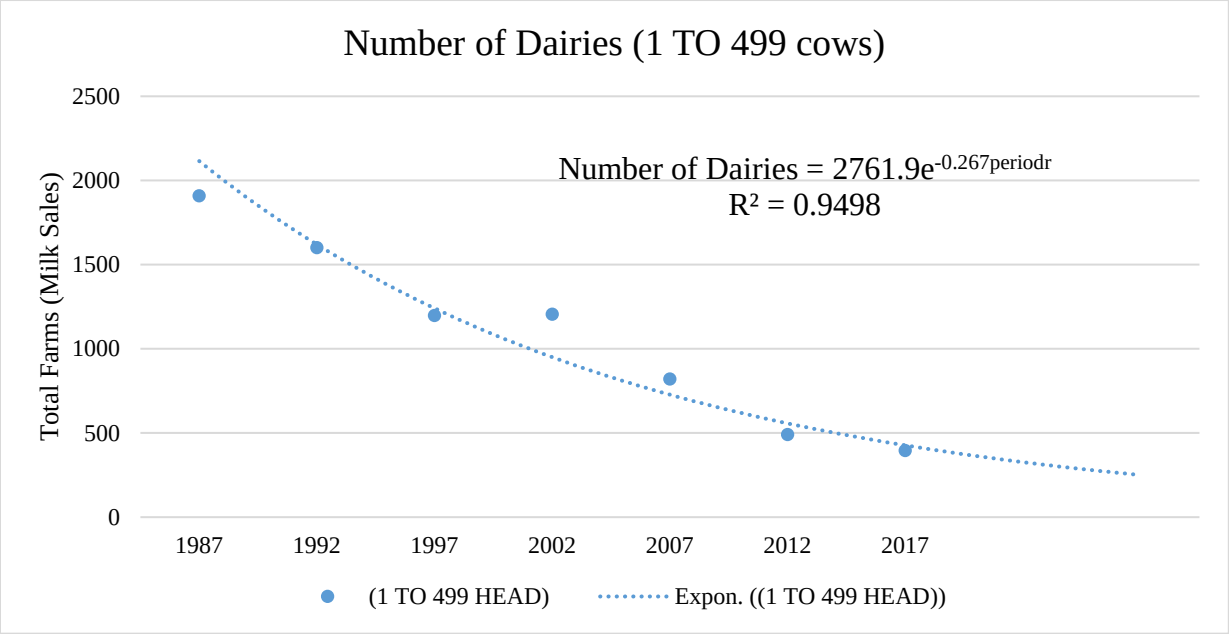

Figure 7.5 Trend in number of dairies by herd size categories in California for dairies of 1 to 499 cows.

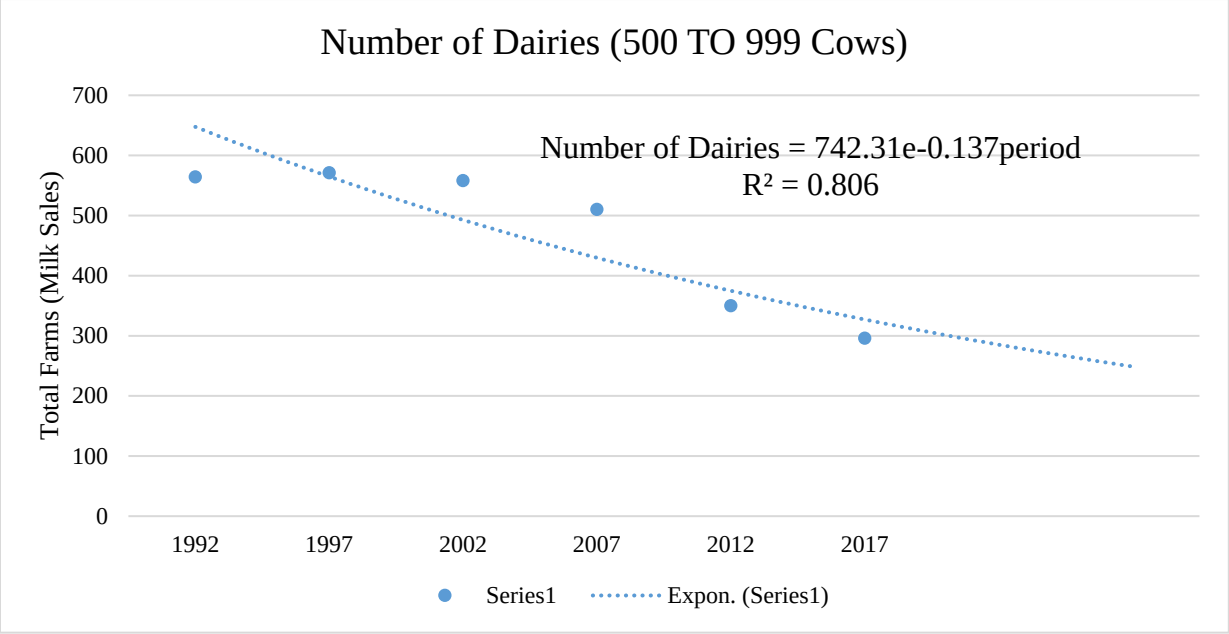

Figure 7.6 Trend in number of dairies by herd size categories in California for dairies of 500 to 999 cows.

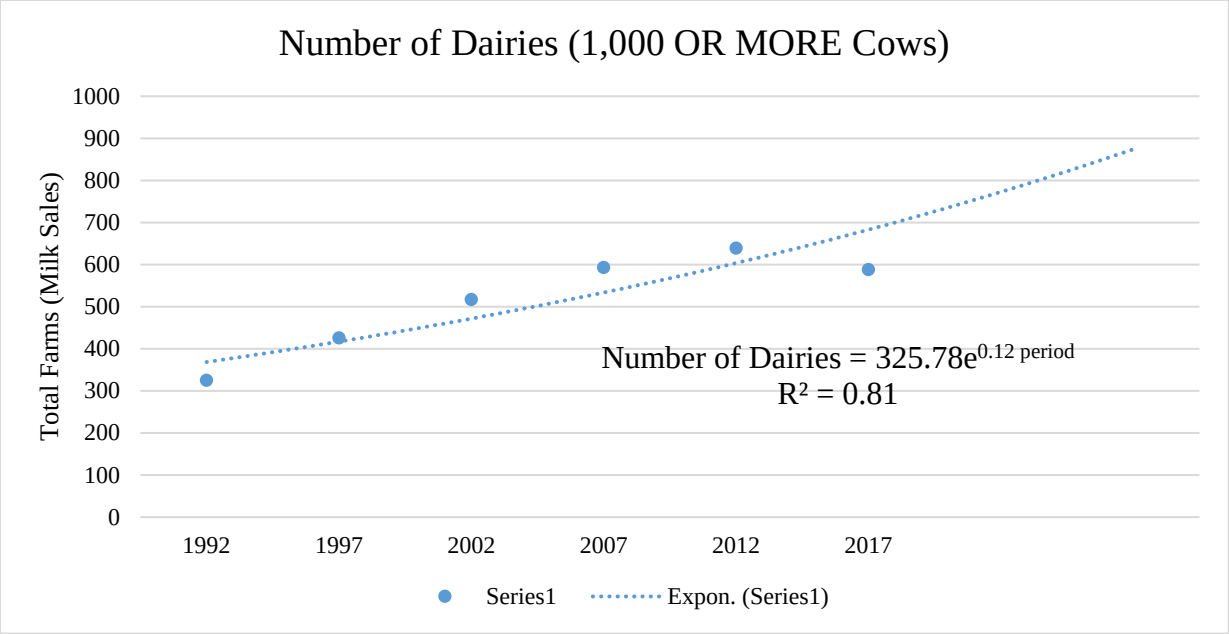

Figure 7.7 Exponential trend in number of dairies by herd size categories in California for dairies of 1,000 cows or more.

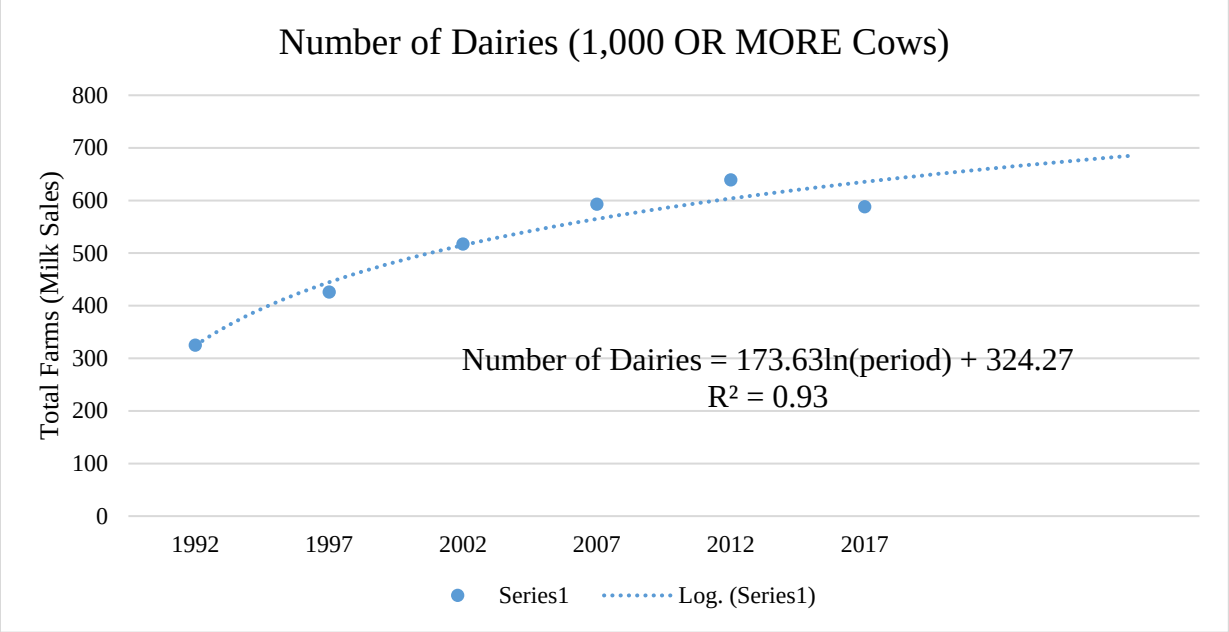

Figure 7.8 Logarithmic trend in number of dairies by herd size categories in California for dairies of 1,000 cows or more.

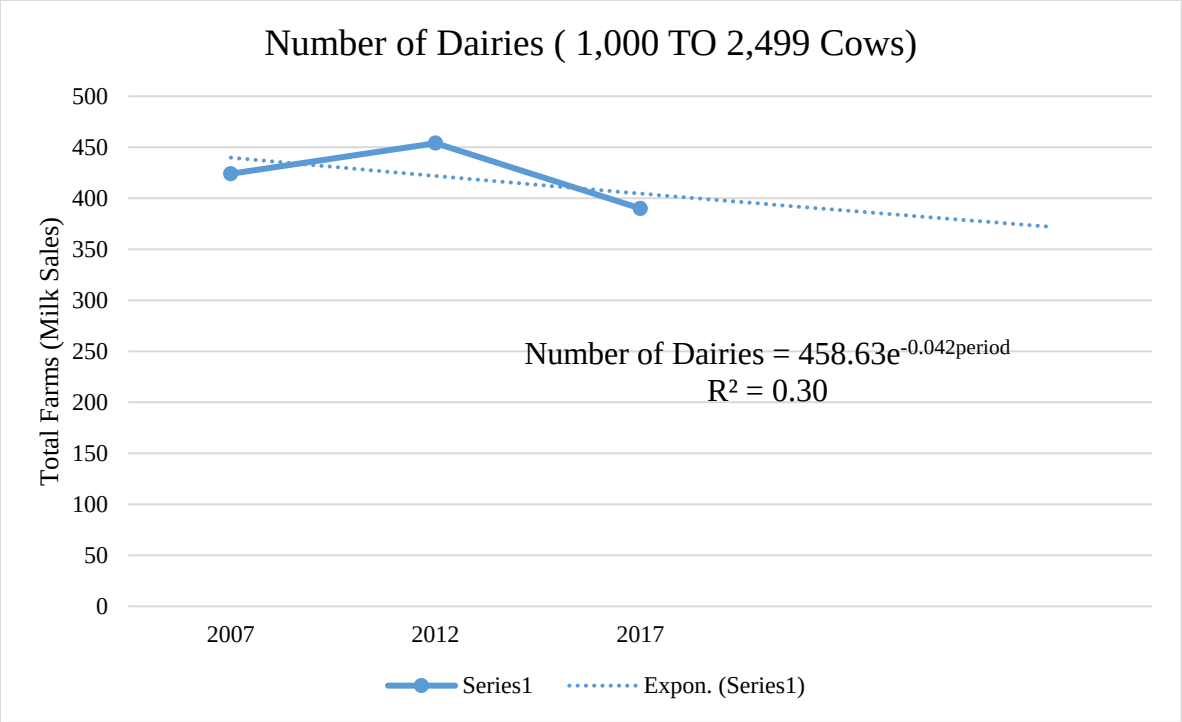

Figure 7.9 Trend in number of dairies by herd size categories in California for dairies of 1,000 to 2,499 cows.

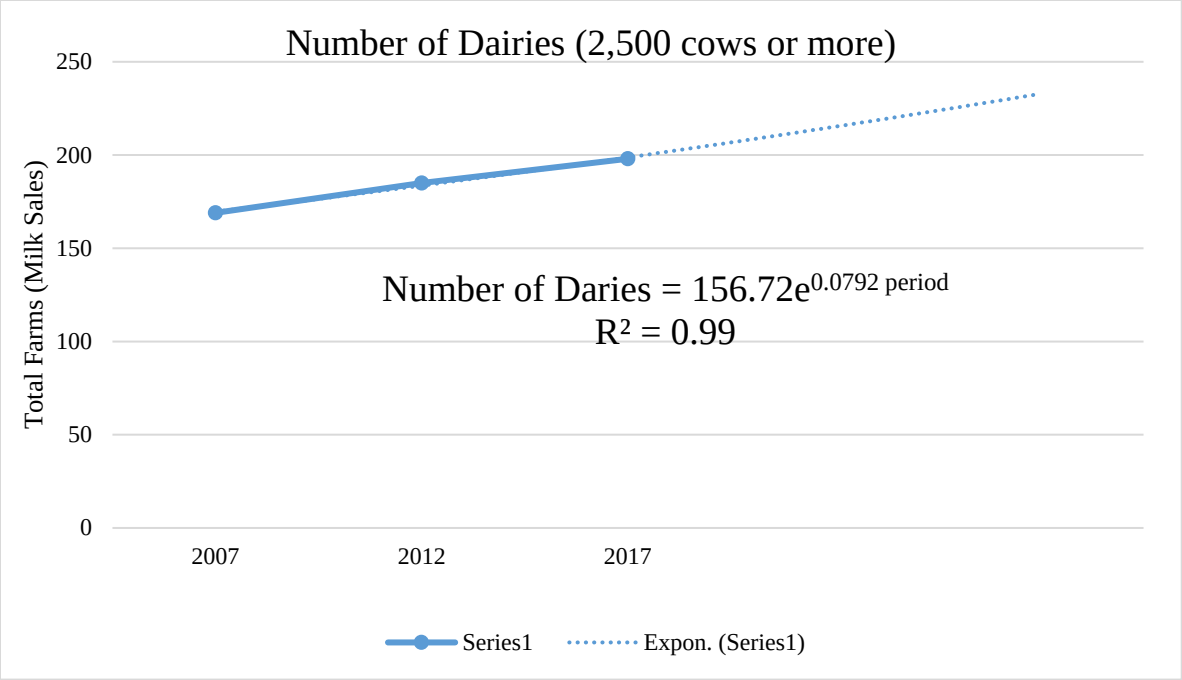

Source: NASS, USDA. *U.S. Census of Agriculture.* Various years.

Figure 7.10 Trend in number of dairies by herd size categories in California for dairies of 2,500 or more cows.

The Census data of distributions across size categories in 2017 are shown in Table 7.4. The Census found 1,279 herds that sold milk that year, milk sales of about $6.5 billion and about 1.75 million cows. Other data show different aggregates due to different statistical procedures or differing administrative coverage.

Table 7.4 Distributions of Farms, Milk Revenue and Milk Cows by Herd Size Category in California, 2017.

Herd Size	Dairy Farms		Milk Revenue		Milk Cows	
Cows/Farm	Number	Percent	$ millions	Percent	Number	Percent
1 to 499	395	30.9	$364.4	5.6	94,120	5.4
500 to 999	296	23.1	$829.3	12.8	209,626	12.0
1,000 to 2,499	390	30.5	$2,385.2	36.8	638,080	36.5
2,500 to 4,999	163	12.7	$1,968.0	30.4	546,617	31.2
5,000 or more	35	2.7	$930.5	14.4	261,886	15.0
Total	1,279	100	$6,477.3	100	1,750,329	100

Source: NASS, USDA U.S. Census of Agriculture 2017.

About 31 percent of herds have fewer than 500 cows, but these herds account for about 5.6 percent of milk revenue and about 5.4 percent of cows. About 23 percent of farms have 500-999 cows and they account for about 12 percent of cows. About 30.5 percent of farms have 1,000-2,499 cows and they account for 36.5 percent of cows. About 12.7 percent of farms have 2,500-4,999 cows and they account for 31 percent of the total cows. Finally, the category with more than 5,000 cows per farm includes 2.7 percent of farms but 15 percent of the cows. These data, especially the percentages are consistent with other information about the size distribution of farms in the California dairy industry.

Based on these data, and underlying forces driving dairy economics in California, we expect a rough continuation of the trends of the past two or three decades to continue. We see no aggregate growth in cow numbers over the next 20 years. Very gradual growth in milk production may continue as milk per cow grows at its recent trend rates. The aggregate number of herds and share of cows in the size category of less than 500 cows will both decline by about 5 percent per year. The exception among this herd size category is that organic herds may maintain their farm numbers and cow numbers because they service a steady or growing niche demand. The reason this category does not grow more is that it serves primarily beverage and other liquid or soft product markets and this has been a declining share of California milk usage.

The number of herds and number of cows in the category of herd size between 500 and 2,000 cows will also decline. We project that decline to be about 1.5 percent per year consistent with recent trends. The most economically sustainable of these farms may join the larger herd size categories over time. The rate of growth in the larger herd size categories is about 1.6 percent per year initially. The number of cows in this category must grow to capture milk demand no longer supplied by smaller herd size categories and in order to be consistent with recent trends that the total cow numbers in California have not declined.

The percentage growth rate continues to be positive, but gradually declines to about 0.8 percent per year. This is an arithmetic requirement as fewer cows in the two smaller size categories, and more cows in the larger herd size categories, means that the constant rate of percentage decline implies gradually falling percentage increase in the larger herd size categories. These data and implications for shares of cows by herd size category over time are shown in table 7.5.

Table 7.5 Projected Trend Changes in Herds and Cow Numbers by Size Category, With Total Cow Numbers Constant.

	Organic	<500 cows	500-2000 cows	>2000 cows
Annual Percent Rate of Change	0	-5	-1.50	1.63 first period 0.084 last period
Initial Share of Cows in Year 1 (%)	1.3	4.9	41.1	52.7
Ending Share of Cows after 20 Years (%)	1.3	1.8	30.4	66.6
Cumulative % Change, 5 Years	0.0	-22.6	-7.3	7.8
Cumulative % Change, 10 Years	0.0	-40.1	-14.0	14.7
Cumulative % Change, 20 Years	0.0	-64.2	-26.1	26.3

Source: Calculations based on adjustments to historical trends outlined above.

The reductions in the herds with less than 500 cows is consistent with declines in numbers of herds that is likely to represent mainly exits. The reduction in the midsize herds is likely to be a combination of exits and shifting some herds into the larger size category. For the larger herds, the growth is likely to be a few more herds, but mostly larger herds. We assume that the organic share remains roughly constant as organic share of fluid milk demand grows but fluid milk of all demand declines.

Table 7.5 shows that at the end of 5 years there are about 22.6 percent fewer cows (and herds) in the category of farms with less than 500 cows due to these underlying trends. There are about 7.3 percent fewer cows and herds in the midsize groups (500 to 2,000 cows) and a growth of about 7.8 percent in the larger category of more than 2,000 cows (although consistent with past trends this is not primarily growth in numbers of herds, but rather more herds with many thousands of cows. At the end of 20 years about 64 percent of the smaller herds have exited. This rate of decline is fully consistent with trends of the past 20 or 30 years and is independent of changes in manure management practice. We note, however, policy risks as described by Lee and Sumner, (2018) may have implications for economic sustainability for some farms.

The rest of Chapter 7 explains how our simulations of the scenarios, combined with the underlying trends, have implications for changes in emissions, milk production and production of milk in each size group.

7.2 Incorporation of projections across groups on impacts of manure management practices to reduce methane emissions

In order to incorporate the trends in exits among dairy operations with smaller herd sizes and the parallel growth of cow numbers in herds in the larger herd sizes, we introduced exogenous trends for the number of cows over the 5, 10 and 20-year time horizons. For the four groups of operations with less than 2,000 cows in the model, we extended trends of observed reductions in number of herds rates as described in section 7.1. The bulk of this section consists in a set of tables that are similar in format to those displayed in Chapter 6.

7.2.1 Exogenous projections of cow numbers by group

Table 7.6 shows explicitly the exogenous annual trends in cow numbers by group. We assumed that rates of decline in numbers of cows observed over the last two decades will remain at about -5 percent per year for the operations of less than 500 cows, and about -1.5 percent for the dairies with 500 to 2,000 cows. These annual rates of change are visible in the column labeled "1 Year" and are assumed to be constant over the whole period of the simulations. However, since these rates are cumulative (5 percent every year for the smaller dairies), we also report the resulting rates for the 5, 10 and 20 year-horizons, which are the time horizons we consider in the simulations of this chapter. These rates correspond to the trends identified in the first part of this chapter and do not include the effect of GHG-mitigation costs.

Table 7.6 Projections of changes in cow numbers by dairy group over 5, 10 and 20-year time horizons used the scenarios.

		Projections in changes in numbers of cows by group (%)			
		1 year	5 year	10 year	20 year
A	<500 Freestall	-5.00	-22.62	-40.13	-64.15
B	<500 Non-freestall	-5.00	-22.62	-40.13	-64.15
C	500-2000 Freestall	-1.50	-7.28	-14.03	-26.09
D	500-2000 Non-freestall	-1.50	-7.28	-14.03	-26.09
E	>2000 Freestall	NA	7.78	14.66	26.30
F	>2000 Non-freestall	NA	7.78	14.66	26.30
G	Organic	0.00	0.00	0.00	0.00

Source: Author projections based on trends established in Section 7.1.

The 1-year rate of change in Table 7.6 is provided as reference for a yearly growth rate but is not included in the simulations in this chapter. (See Table 7.5 for further information.) We expect the negative changes proportional for smaller herd size groups to be mainly in farm exits with some farms to the next larger size category. Increase in average herd sizes is likely to represent most of the growth in cow numbers for the larger groups.

Table 7.6 also displays the rates of increase in cow numbers for the two groups with 2,000 or more cows per operation. These rates are consistent with the limited historical evidence on the growth of larger dairies and we project continued growth, much of which occurs through consolidation. There may be some growth in the number of dairies in the larger size category, but most of the growth will be in average number of cows per farm. Consistent with the projections

of section 7.1, we held the total number of cows in the state constant over each of these horizons. That implies that the annual percentage rate of increase in the groups of larger dairies cannot be constant over time. Accordingly, we calculated the rate of increase among the two groups of larger operations that offsets the reduction in number of cows of the smaller dairies.

These exogenous rates of change are included in the simulation model as described in chapter 4 and result in significant shifts in methane emissions that occur simultaneously with the direct abatement effect of adoption of manure management practices that reduce methane emissions.

In addition, the supply and demand elasticities are different for each time horizon, as in chapter 6, in order to reflect adjustments in quantities supplied and demanded. As in Chapter 6, the share of manure management costs in total costs of production is relatively small (2.4 percent at most) across groups.

7.2.2 Economic effects of adoption of methane emission reduction practices with exogenous trends

Scenario 0.

The economic and emission effects of adoption of practices in the pattern of Scenario 0 are reported in Table 7.7. To facilitate interpretation and comparisons, the top section provides again the description of the impact of adoptions on production costs and emissions for each of the dairy groups as well as the proportion of farms adopting the practice. As before, the practices are fully implemented and we consider impacts after a 5-year adjustment horizon.

Let us consider first the 5-year time horizon. Relative to the case where no trend changes were simulated, additional changes in emissions abatement distribution occur though the reallocation of cows and milk production among groups. This reallocation is visible in the large decreases in milk production of 23 percent and 24 percent for the two groups with fewer than 500 cows. The endogenous quantity effects are small, of a few percentage points at most, since they are exclusively driven by cost changes which are 0.36 percent and 0.84 percent here and as before. The reallocation results also affects the middle groups that see a reduction in quantities of 7.44 percent, mostly due to exogenous trends. The two groups of dairies with more than 2,000 cows see their output increase by 7.84 percent and 7.85 percent, reflecting in large part the increase in herd sizes within these groups. The price effect linked to cost shifts derived from adoption of manure practices remain below 1 percent.

Table 7.7 Effect of practices of Scenario 0 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	4.0
B	<500 Non-freestall	2a	-65.3	9.3	9.0
C	500-2000 Freestall	4a	-59.1	1.1	14.0
D	500-2000 Non-freestall	3a	-23.2	1.0	16.0
E	>2000 Freestall	Digest.	-82.6	0.1	46.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	25.0
G	Organic	2a	-86.2	3.2	7.0
	Percentage changes for group in:				
5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.36		-23.19	-25.7	4.4
B	0.84		-24.15	-28.3	0.7
C	0.15	0.07	-7.44	-15.1	23.3
D	0.16		-7.44	-10.9	1.7
E	0.04		7.84	-33.1	68.4
F	0.03		7.85	-7.7	1.3
G	0.22	0.18	-0.09	-6.1	0.2
			Total California	-24.0	100.0
10 -Year					
A	0.36		-41.01	-42.7	7.0
B	0.84		-42.45	-45.0	1.1
C	0.15	0.07	-14.29	-21.3	31.7
D	0.16		-14.30	-17.4	2.7
E	0.04		14.74	-28.8	57.1
F	0.03		14.76	-1.8	0.3
G	0.22	0.17	-0.17	-6.2	0.2
			Total California	-25.0	100.0
20-Year					
A	0.36		-65.30	-65.8	10.1
B	0.84		-67.22	-67.3	1.5
C	0.15	0.07	-26.41	-32.4	45.1
D	0.16		-26.42	-29.1	4.2
E	0.04		26.43	-21.6	40.1
F	0.03		26.45	8.2	-1.3
G	0.22	0.18	-0.18	-6.2	0.2
			Total California	-26.6	100.0

The reallocation of quantity of output among groups has a large impact on emissions as well, since manure and methane emissions can be estimated as proportional to milk production. While the milk and emission quantities are not exactly proportional and many factors related to diet and other livestock management practices alter methane emissions for a given milk output, these effects are small relative to the very large exogenous effects of a reduction in cow numbers for smaller dairies and an increase in cow numbers on larger dairies. The relationship between milk production and methane emissions is reflected in the result that the changes in methane emissions for the dairies of less than 500 cows are only a few percent larger than their respective changes in quantity of milk. For instance, Table 7.7 shows that group A sees a milk output reduction of 23.2 percent and methane emission reduction of 25.7 percent. These are both close to the exogenous 22.6 percent reduction in cow numbers for the 5-year horizon. Actual methane reduction from adoption of pack barn by 4 percent of the dairies in the group contributes to the difference between milk production and methane emission changes. The situation of the dairies in the intermediate size groups is similar to the case of the groups of farms with fewer than 500 cows.

The two groups of dairies with more than 2,000 cows show the opposite trend. The quantity of milk in each group increases by 7.8 percent. This expansion in milk quantity for these groups offsets some of the emission reduction per cow due to adoption of practices that reduce emissions. The group of freestall dairies adopting digesters reduces emissions by 33 percent instead of 38 percent when no consolidations were projected (see table 6.2).

Organic dairies are again assumed to see no exogenous changes in cow numbers and are supplying a separate dairy product market from conventional dairies, therefore their results are the same as in Chapter 6 and will not be discussed further.

With trends in cow numbers across groups, the total methane emission reduction for the industry is 24 percent in the 5-year horizon. The reallocation of cows across size groups results in a slightly larger emission reduction than without trends because some of the cows that shift into the operations with digesters and high emission reduction rates come from operations with no adoption of manure practices that reduce methane or do little to reduce emissions.

These patterns are reinforced and stronger in the 10-year and 20-year time horizons. The reduced cow numbers on smaller dairies dominate any impacts from methane reducing practices. In contrast, the net reduction of methane for the groups with large herd sizes is progressively reduced because the addition of cows to the larger size groups tends to offset most of the methane emission reductions that are caused by adoption of practices that reduce methane emissions per cow.

When interpreting the results for the “contribution” of each group to total methane abatement, one must be careful to account for the changes in cow numbers across groups. For instance, the share of group E’s contribution to methane reductions decreases from 68.4 percent in the 5-year horizon to 40.1 percent in the 20-year horizon because of a growth in number of cows and milk production in the group. The reduction in methane emission per cow caused by adoption of digesters remains unchanged.

Scenarios 1, 2 and 3.
The results for Scenarios 1, 2 and 3 are dominated by changes in milk production related to changes in aggregate cow numbers in each group. As the length of the horizon increases, the dairy farms in groups with larger herd size groups increasingly have larger shares of the total milk production in California.

In Table 7.8 (Scenario 1, which has the 30 percent adoption rate), total emissions decline only about 14 percent over the 20-year horizon because, with about 26 percent more production from more total cows in the groups, the total emissions from dairies with more than 2,000 mature cows increase. The very large decline in milk production of the two conventional production groups with smaller herds sized are accompanied by growth in production in the larger herd size groups.

Table 7.9, which shows results for Scenario 2, which has a 40 percent adoption rate, simply increases the impacts of methane reducing practices by about one third. However, in Table 7.9 the impacts across groups is dominated by the exogenous trends that result in a shift of cows and milk quantity from dairies with less than 2,000 mature cows towards dairies with more than 2,000 mature cows. The dominant impacts revealed in this scenario as in others are the importance of underlying herd size trends more than the impacts of adoption of manure handling practices. Overall, methane emissions decrease by about 18.7 percent for the 20-year horizon.

Table 7.10 applies the 30 percent adoption rate to a set of practices that include digesters for the largest groups initially. The result is a reduction in emission by about 24 percent across all the time horizon. This is slightly smaller than the reduction with no trends in cows per group that were shown for a 10-year horizon in Chapter 6. The implication is that for this scenario the groups with slightly lower emissions per cow experience reduced cow numbers, so average emission per cow increases because of the different changes in total numbers of cows per group.

Scenarios 4 and 5.
Scenario 4, in Table 7.11, applies relatively low adoption rates for the smaller farms and high digester adoption rates for larger farms. Therefore, for this scenario, the trends to larger herd sizes over time tend to reinforce adoption of methane reducing practices by the larger dairies. Smaller herd size dairies that have relatively high emission per cow have progressively fewer cows mainly because of the underlying trends. Group E, which has a high rate of digester adoption continues to have a net emission reduction despite a 26 percent increase in milk quantity. Overall methane reduction increases from 33.4 percent for the 5-year horizon to 36.5 percent for the 20-year horizon.

Finally, scenario 5, which is shown in Table 7.12, has modest adoption of low cost and low methane-reduction practices for the smaller dairies. It has high adoption of digesters for the larger dairies. Aggregate cow numbers are declining on the smaller dairies that have higher emissions per cow in this scenario. This almost completely a consequence of the underlying trends not the result of adoption of manure practices. Table 7.12 shows that aggregate methane emission reductions are 39.7 percent over the 20-year horizon because the large emission reduction from digester adoption in group E offsets the 26 percent increase in milk quantity.

Table 7.8 Effect of practices of Scenario 1 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern					
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	30.0
B	<500 Non-freestall	2a	-65.3	9.3	30.0
C	500-2000 Freestall	3a	-24.3	1.3	30.0
D	500-2000 Non-freestall	3a	-23.2	1.0	30.0
E	>2000 Freestall	4a	-59.1	0.7	30.0
F	>2000 Non-freestall	3a	-23.2	0.8	30.0
G	Organic	2a	-86.2	3.2	30.0

Percentage changes for group in:					
5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	2.69		-27.46	-45.5	13.7
B	2.80		-27.67	-40.9	1.8
C	0.38	0.27	-7.49	-14.2	38.6
D	0.29		-7.32	-13.8	3.9
E	0.22		7.87	-11.2	40.8
F	0.25		7.81	0.3	-0.1
G	0.95	0.76	-0.38	-26.1	1.4
			Total California	-13.6	100.0%
10 -Year					
A	2.69		-47.47	-58.9	17.5
B	2.80		-47.79	-55.5	2.4
C	0.38	0.24	-14.43	-20.6	55.2
D	0.29		-14.17	-20.1	5.6
E	0.22		14.73	-5.6	20.0
F	0.25		14.64	6.7	-2.0
G	0.95	0.71	-0.71	-26.4	1.3
			Total California	-13.8	100.0
20-Year					
A	2.69		-73.83	-76.0	22.3
B	2.80		-74.25	-74.1	3.1
C	0.38	0.27	-26.51	-31.8	84.4
D	0.29		-26.17	-31.3	8.6
E	0.22		26.49	4.1	-14.6
F	0.25		26.37	17.6	-5.2
G	0.95	0.76	-0.76	-26.4	1.3
			Total California	-14.0	100.0

Table 7.9 Effect of practices of Scenario 2 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	40.0
B	<500 Non-freestall	2a	-65.3	9.3	40.0
C	500-2000 Freestall	3a	-24.3	1.3	40.0
D	500-2000 Non-freestall	3a	-23.2	1.0	40.0
E	>2000 Freestall	4a	-59.1	0.7	40.0
F	>2000 Non-freestall	3a	-23.2	0.8	40.0
G	Organic	2a	-86.2	3.2	40.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	3.59		-29.07	-52.7	11.9
B	3.73		-29.36	-46.7	1.5
C	0.50	0.36	-7.56	-16.5	33.6
D	0.39		-7.33	-15.9	3.3
E	0.30		7.91	-17.6	47.8
F	0.34		7.82	-2.2	0.5
G	1.27	1.01	-0.51	-34.8	1.4
			Total California	-18.2	100.0
10 -Year					
A	3.59		-49.91	-64.7	14.3
B	3.73		-50.34	-60.3	1.9
C	0.50	0.32	-14.56	-22.8	45.6
D	0.39		-14.22	-22.1	4.6
E	0.30		14.75	-12.4	33.1
F	0.34		14.63	4.0	-0.9
G	1.27	0.95	-0.95	-35.1	1.3
			Total California	-18.5	100.0
20-Year					
A	3.59		-77.06	-79.6	17.4
B	3.73		-77.62	-77.1	2.4
C	0.50	0.36	-26.65	-33.6	66.6
D	0.39		-26.20	-33.0	6.7
E	0.30		26.56	-3.3	8.7
F	0.34		26.39	14.7	-3.2
G	1.27	1.01	-1.01	-35.1	1.3
			Total California	-18.7	100.0

Table 7.10 Effect of practices of Scenario 3 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	30.0
B	<500 Non-freestall	2a	-65.3	9.3	30.0
C	500-2000 Freestall	Digest.	-86.1	0.5	30.0
D	500-2000 Non-freestall	3a	-23.2	1.0	30.0
E	>2000 Freestall	Digest.	-82.6	0.1	30.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	30.0
G	Organic	2a	-86.2	3.2	30.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	2.69		-27.70	-45.6	7.8
B	2.80		-27.91	-41.1	1.0
C	0.15	0.15	-7.28	-31.2	48.0
D	0.29		-7.56	-14.0	2.2
E	0.03		8.02	-18.7	38.4
F	0.04		7.99	-10.7	1.8
G	0.95	0.76	-0.38	-26.1	0.8
			Total California	-24.1	100.0
10 -Year					
A	2.69		-47.79	-59.1	10.1
B	2.80		-48.11	-55.7	1.4
C	0.15	0.14	-14.08	-36.3	55.9
D	0.29		-14.49	-20.4	3.2
E	0.03		14.99	-13.5	27.7
F	0.04		14.95	-4.9	0.8
G	0.95	0.71	-0.71	-26.4	0.8
			Total California	-24.0	100.0
20-Year					
A	2.69		-74.31	-76.2	13.1
B	2.80		-74.74	-74.2	1.9
C	0.15	0.15	-26.10	-45.2	70.5
D	0.29		-26.65	-31.6	5.1
E	0.03		26.79	-4.5	9.4
F	0.04		26.73	4.9	-0.8
G	0.95	0.76	-0.76	-26.4	0.8
			Total California	-23.8	100.0

Table 7.11 Effect of practices of Scenario 4 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	5.0
B	<500 Non-freestall	2a	-65.3	9.3	10.0
C	500-2000 Freestall	Digest.	-86.1	0.5	20.0
D	500-2000 Non-freestall	3a	-23.2	1.0	15.0
E	>2000 Freestall	Digest.	-82.6	0.1	60.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	30.0
G	Organic	2a	-86.2	3.2	10.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.45		-23.38	-26.5	3.3
B	0.93		-24.35	-28.9	0.5
C	0.10	0.07	-7.35	-23.3	25.9
D	0.15		-7.43	-10.6	1.2
E	0.05		7.81	-45.6	67.6
F	0.04		7.83	-10.9	1.3
G	0.32	0.25	-0.13	-8.7	0.2
			Total California	-33.4	100.0
10-Year					
A	0.45		-41.29	-43.4	5.1
B	0.93		-42.74	-45.5	0.8
C	0.10	0.06	-14.15	-28.9	31.0
D	0.15		-14.28	-17.2	1.9
E	0.05		14.69	-42.1	60.4
F	0.04		14.72	-5.2	0.6
G	0.32	0.24	-0.24	-8.8	0.2
			Total California	-34.6	100.0
20-Year					
A	0.45		-65.67	-66.2	7.4
B	0.93		-67.61	-67.7	1.1
C	0.10	0.07	-26.22	-38.9	39.5
D	0.15		-26.40	-28.9	3.0
E	0.05		26.36	-36.2	49.2
F	0.04		26.40	4.5	-0.5
G	0.32	0.25	-0.25	-8.8	0.2
			Total California	-36.5	100.0

Table 7.12 Effect of practices of Scenario 5 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	3a	-24.2	1.6	5.0
B	<500 Non-freestall	3g	-23.4	1.9	10.0
C	500-2000 Freestall	Digest.	-86.1	0.5	20.0
D	500-2000 Non-freestall	3a	-23.2	1.0	15.0
E	>2000 Freestall	Digest.	-82.6	0.1	66.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	35.0
G	Organic	3a	-22.0	0.7	10.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.08		-22.67	-23.6	2.7
B	0.19		-22.90	-24.6	0.4
C	0.10	0.05	-7.37	-23.3	24.0
D	0.15		-7.46	-10.7	1.1
E	0.06		7.77	-51.0	70.1
F	0.05		7.79	-14.0	1.6
G	0.07	0.06	-0.03	-2.2	0.0
			Total California	-36.0	100.0
10 -Year					
A	0.08		-40.22	-40.9	4.5
B	0.19		-40.56	-41.8	0.7
C	0.10	0.05	-14.19	-28.9	28.7
D	0.15		-14.32	-17.3	1.8
E	0.06		14.64	-47.8	63.4
F	0.05		14.67	-8.5	0.9
G	0.07	0.05	-0.05	-2.3	0.0
			Total California	-37.4	100.0
20-Year					
A	0.08		-64.25	-64.6	6.7
B	0.19		-64.71	-65.2	1.0
C	0.10	0.05	-26.28	-38.9	36.4
D	0.15		-26.45	-28.9	2.8
E	0.06		26.28	-42.5	53.2
F	0.05		26.32	0.8	-0.1
G	0.07	0.06	-0.06	-2.3	0.0
			Total California	-39.7	100.0

Discussion

Adoption of manure management practices that reduce methane emissions per cow can be costly and if dairy farms bear those costs, the implication is likely to be some acceleration of the trend toward consolidation of the milk cow herd on fewer and larger herds. This is true in part because current regulations and earnings from using manure-generated methane as renewable natural gas mean digesters are a low-cost methane reducing option, especially on larger dairies. Indeed, in California digesters have been adopted most by the larger dairies and that has been especially true in the past few years in which the CDFA programs have stimulated more rapid adoption of digesters as a manure management strategy. Many smaller dairies find manure management strategies to reduce methane emissions reduction not cost effective and therefore are less economically sustainable.

This chapter began with an explanation of drivers of the future of the California dairy industry. Based on these forces, and the three-decade long trends in herd size patterns, we derived a set of projections for the next two decades. We project that the aggregate number of cows remains unchanged into the future, but the number of cows in the smaller herd size categories decline rapidly. The number of cows in the larger herd size rise, but not so rapidly in percentage terms because their herd size categories already account for most of the milk cows in California.

We next examine the impacts of our different scenarios of methane-reducing manure management practices in the context of our projections, including the underlying trends in number of cows in the different herd size categories.

We have discussed above the impacts of manure management scenarios, which each has a different pattern of adoption across groups of dairy farms with different housing and herd sizes. We find the impacts of the manure management practices remain, but in the longer time horizons manure management practices have small impacts, especially for the smaller dairies where they are dominated by the declining aggregate numbers of cows on the smaller farms.

Conclusions

Chapter 7 has placed our simulation modeling of Chapter 4 and the results introduced in Chapters 5 and 6 in the context of the steady long-term trend of reduced cow numbers on farms with smaller herd sizes and more cows on farms with larger herd sizes. We document that these trends have being on-going for at least three decades and, in fact, they have continued for much longer than that.

The most salient results of this chapter are exemplified by the implications of Scenario 5. This scenario illustrated a pattern of manure management practices in which smaller dairies have a relatively low adoption rate of practices that reduce emission by relatively small percentage amounts. There may be a set of digester-related practices that are suitable and cost-effective for smaller herd sizes, but we did not explore those in this study. In scenario 5, a high share of larger dairies adopt digester practices that, while relatively low cost to the dairies, have large methane reduction impacts. With a 5-year horizon aggregate reduction of methane emission

reaches 36 percent. The groups with smaller dairies reduce emissions mainly because the number of cows in these have declined. The groups with larger dairies have more cows, but emission per cow declines enough that aggregate emissions also decline for these groups.

With longer time horizons, this pattern of results is reinforced and stronger. Especially over the 20-year horizon low-cost digester adoption among large dairies, together with little methane reduction among the smaller dairies, leads to an aggregate methane emission reduction of almost 40 percent. A part of the reduction in methane emissions is reinforced by a continuation of the trend toward consolidation that has been underway for decades.

Recommendations

The conclusions of this chapter suggest that trends to fewer dairies in the smaller herd size categories and more average cows per herd in larger herd size categories. In addition, with the adoption of digesters by a high share of dairies in the larger herd size categories their methane emissions per cow decline and are well below those of the smaller herds.

One implication is that it is unlikely to be effective to target methane reduction strategies on alternative manure handling practices of smaller dairies if the goal is to achieve low-cost reductions in methane emissions. Of course, there may be other social objectives for targeting methane reductions on smaller dairies, so this implication is not the only consideration.

REFERENCES

Arndt, C., A.B. Leytem, A.N. Hristov, D. Zavala-Araiza, J.P. Cativiela, S. Conley, C. Daube, I. Faloona, S.C. Herndon. 2018. Short-term methane emissions from 2 dairy farms in California estimated by different measurement techniques and US Environmental Protection Agency inventory methodology: A case study. *Journal of Dairy Science*, 101 (12):11461-11479. DOI: https://doi.org/10.3168/jds.2017-13881 .

ASAE (American Society of Biological and Agricultural Engineers). 2004. Uniform terminology for rural waste management. Standard 292.5, February. ASABE St. Joseph, MI.

Assembly Bill 32. 2006. California global warming solutions Act of 2006. September 27. Available http://www.leginfo.ca.gov/pub/05-06/bill/asm/ab_0001-0050/ab_32_bill_20060927_chaptered.pdf.

Bouchard, D. D. 2016. *An Analysis of Farm Profitability, Exit Decision, and Price Supports in the Maine Dairy Industry.*

Bragg, L. A., & Dalton, T. J. 2004. Factors affecting the decision to exit dairy farming: a two-stage regression analysis. *Journal of Dairy Science*, 87(9), 3092-3098.

California Air Resources Board. 2017. Short lived climate pollution reduction strategy. March. https://ww2.arb.ca.gov/sites/default/files/2018-12/final_slcp_report%20Final%202017.pdf .

California Air Resources Board. 2018a. Findings and Recommendations. Subgroup 1: Fostering markets for non-digester projects, Senate Bill 1383 Dairy and Livestock Working Group. November 26. https://ww3.arb.ca.gov/cc/dairy/dairy_subgroup_recommendations_to_wg_11-26-18.pdf. Accessed in January, 2020.

California Air Resources Board. 2018b. Dairy research prospectus to achieve California's SB 1383 climate goals. November 26. https://ww3.arb.ca.gov/cc/dairy/dsg3/dsg3_final_dairy_air_research_prospectus_11-26-18.pdf Accessed in January, 2020.

California Air Resources Board. 2019. Benefits calculator tool for the Alternative Manure Management Program. California climate Investments. Version 2. February 8. Available at https://ww2.arb.ca.gov/resources/documents/cci-quantification-benefits-and-reporting-materials .

California Air Resources Board. 2020. Sector GHG Emissions. https://www.arb.ca.gov/app/ghg/2000_2017/ghg_sector.php downloaded January 2020. Accessed in January 2020.

California Department of Food and Agriculture. 2018. California dairy statistics annual 2017 data. Division of Marketing Services, Dairy marketing Branch in collaboration with the United States Department of Agriculture. Also prior years of the same publications. No longer accessible online.

California Department of Food and Agriculture. 2020a. List of Award Recipients. https://www.cdfa.ca.gov/oefi/ddrdp/ . Accessed in January 2020

California Department of Food and Agriculture. 2020b. List of Award Recipients. https://www.cdfa.ca.gov/oefi/AMMP/. Accessed in January 2020

Cohen-Davidyan, T. D. Meyer, and P.H. Robinson. 2020. Development of an on-farm model to predict flow of fecal volatile solids to the liquid and solid handling systems of commercial California Dairy Farms. Waste Management 109: 127-135. https://doi.org/10.1016/j.wasman.2020.04.018 .

Foltz, J. D. (2004). Entry, exit, and farm size: assessing an experiment in dairy price policy. *American Journal of Agricultural Economics*, 86(3), 594-604.

Frick, F., & Sauer, J. (2018). Deregulation and Productivity: Empirical Evidence on Dairy Production. *American Journal of Agricultural Economics*, 100(1), 354-378.

IPCC (Intergovernmental Panel on Climate Change. 2006. Chapter 10: Emissions from livestock and manure management. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf. Accessed January 15, 2020.

Kaffka, S., Barzee, T., El-Mashad, H., Williams, R., Zicari, S., & Zhang, R. 2016. Evaluation of Dairy Manure Management Practices for Greenhouse Gas Emissions Mitigation in California. Contract, 14.

Kaffka, S., Barzee, T., El-Mashad, H., Williams, R., Zicari, S. & Zhang, R. 2016. Evaluation of Dairy Manure Management Practices for Greenhouse Gas Emissions Mitigation in California. *Final Technical Report to the State of California Air Resources Board.*

Lee, Hyunok and Sumner, Daniel A. 2018. Dependence on policy revenue poses risks for investments in dairy digesters. *California Agriculture* (December)72(4):226-235. https://doi.org/10.3733/ca.2018a0037.

Lee, Hyunok, Sumner, Daniel A. and Champetier. Antoine. 2019. “Pollination Markets and the Coupled Futures of Almonds and Honey Bees: Simulating Impacts of Shifts in Demands and Costs.” American Journal of Agricultural Economics. 101(1): 230-249.

MacDonald, J. M., Cessna, J., & Mosheim, R. 2016. Changing structure, financial risks, and government policy for the US dairy industry (No. 1477-2017-3966).

MacDonald, J. M., McBride, W. D., O'Donoghue, E., Nehring, R. F., Sandretto, C., & Mosheim, R. 2007. Profits, costs, and the changing structure of dairy farming. *USDA-ERS Economic Research Report, (47).*

Matthews, W.A. and Sumner, Daniel A. 2019. Contributions of the California Dairy Industry to the California Economy in 2018 A Report for the California Milk Advisory Board. University of California Agricultural Issues Center. https://aic.ucdavis.edu/wp-content/uploads/2019/07/CMAB-Economic-Impact-Report_final.pdf

McCully, M. 2018. What's next for U.S. dairy plant capacity*? Cheese Market News* (August) https://cheesemarketnews.com/guestcolumn/2018/24aug18.html

Meyer, D., B. Reed, C. Batchelder, I. Zallo, P.L. Ristow, G. Higginbotham, M. Arana, T. Shultz, D.D. Mullinax, J. Merriam. 2006. Water use and winter liquid storage needs at central valley dairy farms in California. Applied Eng. Ag. 22: 121-126.

Meyer, D., I. Garnett & J.C. Guthrie. 1997. A survey of dairy manure management practices in California. J. Dairy Science, 80, 1841-1845. https://doi.org/10.3168/jds.S0022-0302(97)76119-8

Meyer, D., Price, P. L., Rossow, H. A., Silva-del-Rio, N., Karle, B. M., Robinson, P. H., DePeters, E.J. & Fadel, J. G. 2011. Survey of dairy housing and manure management practices in California. Journal of Dairy Science, 94, 4744–4750. https://doi.org/10.3168/jds.2010-3761.

Meyer, D., J. Heguy, B. Karle and P Robinson. 2019. Characterize physical and chemical properties of manure in California dairy sytems to improve greenhouse gas (GHG) emission estimates. Final Report Contract No. 16RD002.

Meyer, D., personal conversation, March 2020a. Conversation referenced information from a dairy farmer with freestall housing. Farmer provided herd size and invoices for the contractor service, itemized by date and number of loads excavated.

Meyer, D., personal conversation, March 2020b. Conversation referenced information provided by a dairy farmer with an open lot facility. Farmer provided herd size and a times per activity commensurate with the manure management on the open lot facility.

Mosheim, R., & Lovell, C. K. 2009. Scale economies and inefficiency of US dairy farms. American Journal of Agricultural Economics, 91(3), 777-794.

Newtrient. https://newtrient.com .

Perrin, Richard K. 1980. "The Impact of Component Pricing of Soybeans and Milk." American Journal of Agricultural Economics 62 (3): 445–55.

Rickard, Bradley J. and Sumner, Daniel A. 2008. Domestic Support and Border Measures for Processed Horticultural Products: Analysis of EU Tomato Protection and Subsidies. American Journal of Agricultural Economics, 90(1): 55-68.

San Joaquin Valley Dairy Manure Technology Feasibility Assessment Panel. 2005. An assessment of technologies for management and treatment of dairy manure in California's San Joaquin Valley. December. Available https://ww3.arb.ca.gov/ag/caf/dairypnl/dmtfaprprt.pdf

San Joaquin Air Pollution Control District. 2004. Rule 4550. Conservation Management Practices. Re-adopted August 19, 2004. https://www.valleyair.org/rules/currntrules/r4550.pdf .

San Joaquin Air Pollution Control District. 2010. Rule 4570. Confined Animal Facilities. Re-adopted June 18, 2009. Amended October 21, 2010. https://www.valleyair.org/rules/currntrules/R4570_1010.pdf .

Senate Bill 32. 2016. California Global Warming Solutions Act of 2006: emissions limit. September 8.
Available:https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB32 .

Senate Bill 1383. 2016. Chapter 395. September 19. Available:
https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB1383

South Coast Air Quality Management District. 2004. Rule 1127. Emission reductions from livestock waste. Adopted August 6. http://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1127.pdf.

Stokes, J. R. 2006. Entry, exit, and structural change in Pennsylvania's dairy sector. *Agricultural and Resource Economics Review*, 35(2), 357-373.

Sumner, D.A., and N.L.W. Wilson. 2000. Creation and Distribution of Economic Rents by Regulation: Development and Evolution of Milk Marketing Orders in California. *Agricultural History* 74(2):198–210.

Sumner, D. A. (2014). American farms keep growing: Size, productivity, and policy. *Journal of Economic Perspectives*, 28(1), 147-66.

Sumner, Daniel A. 2018. New California Milk Marketing Regulations Will Not Change Economic Fundamentals *Choices.* 4th Quarter 2018. 33(4).

Susanto, D., Rosson, C. P., Anderson, D. P., & Adcock, F. J. (2010). Immigration policy, foreign agricultural labor, and exit intentions in the United States dairy industry. *Journal of Dairy Science*, 93(4), 1774-1781.

Tauer, L. W. (2006). When to get in and out of dairy farming: a real option analysis. *Agricultural and Resource Economics Review*, 35(2), 339-347.

United State Department of Agriculture. 2019 State agriculture overview, Livestock inventory January 1, 2020.
https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=CALIFORNIA

University of California Agriculture and Natural Resources Dairy Advisor, personal conversation, (March 2020). Conversation between author and dairy adviser with expertise in compost bedded pack barns.

United States Department of Agriculture, National Agricultural Statistics Service. 1974. Table 21.Cattle and Calves—Inventory and sales: 1074 and 1069.
http://usda.mannlib.cornell.edu/usda/AgCensusImages/1974/01/51/305/Table-21.pdf .

United States Department of Agriculture, National Agricultural Statistics Service. 2017. Table 17. Milk cow herd size by inventory and sales: 2017.
http://usda.mannlib.cornell.edu/usda/AgCensusImages/1974/01/51/305/Table-21.pdf

United States Department of Agriculture, National Agricultural Statistics Service, Agricultural Census, (2017). Available at https://www.nass.usda.gov/AgCensus/ accessed February 2020.

United States Department of Agriculture, National Agricultural Statistics Service, 2018. *Milk Production, Disposition and Income, 2017 Summary*. Washington, DC: U.S. Department of Agriculture, April. http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1105

United States Environmental Protection Agency. 2012. Part 122. EPA Administration Programs: the National Pollutant Discharge Elimination System. Clean Water Act, 33 U.S.C. 1251 *et seq.* Compiled CAFO Final Rule. July 30. https://www.epa.gov/sites/production/files/2015-08/documents/cafo_final_rule2008_comp.pdf . Accessed March, 2020.

Vacuum scraper manufacturer engineer, personal conversation, (March 2020). Telephone conversation between author and engineer for vacuum scraper manufacture.

Weiss, W. P., St-Pierre, N. R., & Willett, L. B. (2007). Factors affecting manure output on dairy farms. *Tri-State Dairy Nutrition Conf*erence, Ft. Wayne, (pp. 55-62).

APPENDIX 1 OUTREACH ACTIVITIES

Outreach activities for this project were conducted through a presentation at the Golden State Dairy Management Conference, the California Dairy Newsletter (information about the AMMP program as well as specific information from the grant products), and handouts prepared for the California Dairy Sustainability Summit originally to be held in March, 2020 and now postponed. An abstract for a poster for the California Dairy Sustainability Summit was accepted.

Meyer, D., Z. Joaquin-Morales, J. Heguy, B. Karle, P. L. Price, C. Miller, D. Mullinax. 2020. Manure management practices on California dairies. Presented at the Golden State Dairy Management Conference. March 4, 2020. Modesto. Available online.

Meyer, D., J. Heguy, B. Karle, Z. Joaquin Morales. 2020. What do California dairies look like? California Dairy Newsletter. Vol 11 Issue 4. November. Available online (pdf download).

Meyer, D. 2018. Buyer beware: homework is important when reducing methane emissions. California Dairy Newsletter. Volume 10 Issue 3. September. Available online (pdf download).

Meyer, D. 2018. Funding available to reduce manure methane emissions. California Dairy Newsletter. Vol 10 Issue 4. December. Available online (pdf download).

Meyer, D. 2020. Funds available for dairies to reach 40% reduction in greenhouse gases. California Dairy Newsletter. Vol 12 Issue 1. February. Available online (pdf download).

Handouts for the California Dairy Sustainability Summit.

Price, P.L., D. Meyer. 2020. Scrape/Vacuum conversion with windrow composting.
Price, P.L., D. Meyer. 2020. Scrape/Vacuum conversion with open solar drying.
Price, P.L., D. Meyer. 2020. Solids separation with windrow composting.
Price, P.L., D. Meyer. 2020. Solids separation with open solar drying.

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Clarifying NPDES Requirements for Concentrated Animal Feeding Operations

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Articles

Clarifying NPDES Requirements for Concentrated Animal Feeding Operations

Terence J. Centner*

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I. Introduction

The Clean Water Act of 1972 sought to restore and maintain the chemical, physical, and biological integrity of our nation's waters.[1] Central to achieving the act's goals was a permitting system prohibiting discharges of pollutants from point sources into navigable waters except as authorized by a National Pollutant Discharge Elimination System (NPDES) permit.[2] Permits issued by the U.S. Environmental Protection Agency (EPA)[3] or an authorized state[4] regulate the type and quantity of discharges that are permitted from point sources.[5] Point sources are defined to include discernible, confined, and discrete conveyances including concentrated animal feeding operations (CAFOs).[6]

Although CAFOs have been regulated for years,[7] many have not secured permits,[8] and there is evidence that a lack of permits has contributed to the impairment of our nation's waters.[9] As the result of

1. 33 U.S.C. § 1251(a) (2000); *see e.g..*, Arkansas v. Oklahoma, 503 U.S. 91, 106 (1992) (noting that the achievement of state water quality standards was a major objective of the Clean Water Act); S. Fla. Water Mgmt. Dist. v. Miccosukee Tribe of Indians, 541 U.S. 95, 102 (2004) (noting the objective of the Clean Water Act is "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters").

2. 33 U.S.C. §§ 1311(a), 1342 (2000) (precluding the discharge of some pollutants and requiring permits for the discharge of others); *see, e.g.*, Friends of the Earth, Inc. v. Laidlaw Envtl. Servs., 528 U.S. 167, 174 (2000) (noting that NPDES permits impose limitations on the discharge of pollutants to improve the cleanliness and safety of the nation's waters); Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 491 (2d Cir. 2005) (noting the use of permits to set restrictions on the quality and character of water pollution); *see also* N. Plains Res. Council v. Fid. Exploration & Dev. Co., 325 F.3d 1155 (9th Cir. 2003) (noting the requirement of a permit).

3. 33 U.S.C. § 1342(a) (2000) (authorizing the administrator to issue permits).

4. *Id.* § 1342(b)(1) (authorizing states with approved programs to issue permits).

5. *See S. Fla. Water Mgmt. Dist.*, 541 U.S. at 102 (noting the limitation on discharges).

6. 33 U.S.C. § 1362(14) (2000).

7. In 1974, effluent regulations had been adopted to address discharges from CAFOs. National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitations Guidelines and Standards for Concentrated Animal Feeding Operations (CAFOs), 68 Fed. Reg. 7176, 7186 (2003) (preamble) [hereinafter EPA Final Rule]. The CAFO Rule is codified at 40 C.F.R. pts. 122, 412 (effective Apr. 14, 2003) and included a preamble with a lengthy explanation of considerations taken into account with the adoption of the rule.

8. EPA Final Rule, *supra* note 7, at 7201 (preamble).

9. National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitations Guidelines and Standards for Concentrated Animal Feeding Operations, Proposed CAFO Regulations, 66 Fed. Reg. 2960, 3080 (proposed Jan. 12, 2001) (preamble) [hereinafter EPA Proposed Rule]. Data from 1997 suggested that only about 20% of the nation's CAFOs had secured permits. *Id.* (preamble). *See, e.g.*, Cmty. Ass'n for Restoration of the Env't v. Henry Bosma Dairy, 305 F.3d 943, 949 (9th Cir. 2002) (noting penalties imposed on a CAFO for discharging pollutants).

litigation,[10] the EPA entered a consent decree whereby a new CAFO Rule would be adopted.[11] The new CAFO Rule became effective on April 14, 2003[12] after extensive input from environmental and agricultural groups.[13] During consideration of the proposed rule, public input expressed strong feelings that regulators were not doing enough to abate agricultural pollution, but also that additional governmental oversight could impose significant costs on the livestock industry.[14] The final CAFO Rule contained provisions that were objectionable to both environmental and farm groups, and organizations from both groups challenged EPA's regulations in *Waterkeeper Alliance, Inc. v. Environmental Protection Agency*.[15]

The petitioners challenged several aspects of the CAFO Rule.[16] For the Environmental Petitioners,[17] flaws in provisions regarding governmental oversight included allegations of deficiencies in the NPDES permits,[18] the absence of a review of permits by a permitting authority,[19] and the lack of public participation.[20] Both the Farm[21] and Environmental Petitioners challenged the provisions on agricultural stormwater discharges.[22] The Farm Petitioners challenged the permitting scheme whereby CAFOs have a duty to either apply for NPDES permits

10. Natural Res. Def. Council v. Reilly, *modified sub. nom.*, Natural Res. Def. Council v. Whitman, No. 89-2980 (D.D.C. 1992) (requiring EPA to develop new effluent limitation guidelines for some CAFOs).

11. EPA Final Rule, *supra* note 7, at 7186 (preamble).

12. 40 C.F.R. pts. 122, 412 (2004). While the rule became effective in 2003, certain provisions were to take effect at later dates. *Id.* §§ 122.21(a)(1)(x), 122.23(g)(2), 122.23(g)(3)(iii), 122.42(e)(1), 412.31(b)(3), 412.43(b)(2). Moreover, due to the judicial ruling in Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486 (2d Cir. 2005), some provisions were vacated so they do not apply.

13. EPA Final Rule, *supra* note 7, at 7178 (preamble). The government received 11,000 comments. *Id.*

14. *Id.* at 7178-89 (preamble).

15. 399 F.3d 486 (2d Cir. 2005).

16. *Id.*

17. These include Waterkeeper Alliance, Inc., Am. Littoral Soc'y, Sierra Club, Inc., and the Natural Res. Def. Council, Inc. Brief for the Environmental Petitioners at 1, *Waterkeeper Alliance*, 399 F.3d 486 (2d Cir. 2005) [hereinafter Brief for the Environmental Petitioners].

18. *Waterkeeper Alliance,* 399 F.3d at 502-03. *See infra* notes 43-65 and accompanying text.

19. *Waterkeeper Alliance,* 399 F.3d at 498-502. *See infra* notes 66-89 and accompanying text.

20. *Waterkeeper Alliance,* 399 F.3d at 503-04. *See infra* notes 90-106 and accompanying text.

21. These included the Am. Farm Bureau Fed'n, Nat'l Chicken Council, and the Nat'l Pork Producers Council. Brief for the Farm Petitioners at 1, Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486 (2d Cir. 2005) [hereinafter Brief for the Farm Petitioners].

22. *Waterkeeper Alliance,* 399 F.3d at 506-11. *See infra* notes 107-175 and accompanying text.

or otherwise demonstrate that they have no potential to discharge.[23] The Second Circuit Court of Appeals found merit in some of the challenges from both sets of petitioners.[24] It vacated selected provisions of the CAFO Rule and remanded other aspects to EPA for further clarification and analysis.[25]

The findings by the Second Circuit constitute important guidelines regarding the Clean Water Act's regulations for CAFOs.[26] Pursuant to *Waterkeeper Alliance*, owners and operators of CAFOs that only have a potential to pollute need not apply for permits.[27] In the absence of a duty for an owner or operator of a CAFO to apply for a permit, fewer permit applications are expected to be submitted to permitting agencies,[28] which suggests that the government's cost estimates of the CAFO Rule are inaccurate.[29] The decision to allow EPA to regulate land application discharges by CAFOs, except those qualifying as agricultural stormwater discharges, means that CAFOs need to be concerned about runoff from

23. *Waterkeeper Alliance*, 399 F.3d at 504-06. *See infra* notes 176-234 and accompanying text.

24. *Waterkeeper Alliance*, 399 F.3d at 524.

25. *Id.*

26. EPA was directed to revise its regulations to conform with the findings of the court. *Id.* Some states will also find it necessary to revise their water quality regulations for CAFOs due to the need to require nutrient management plans in permit applications. *See infra* notes 57-65 and accompanying text. States may also have to delete provisions that require CAFOs with a potential to pollute to apply for permits. *See infra* notes 176-200 and accompanying text.

27. The *Waterkeeper Alliance* ruling removes the regulatory duty to apply for a permit and requires nutrient management plans be a part of a permit. *Waterkeeper Alliance*, 399 F.3d at 499, 506. This may lead to fewer CAFO owners and operators applying for permits due to the expense and the difficulties involved in defining nutrient management plans that would withstand public scrutiny. Moreover, because permits subject applicants to public oversight and present opportunities for allegations of violations of conditions set forth in the permit under a citizen suit, owners and operators often are not keen in applying. For other owners and operators, the Second Circuit's decision may encourage them to use greater care in applying manure to avoid discharges that would require them to apply for a permit.

28. Securing permits is time-consuming and costly. If owners and operators can avoid these costs, they improve their financial well-being. One of the criticisms of the CAFO Rule was that it was foisting expenses on firms based upon their potential to pollute rather than actual pollution. *See* Terence J. Centner, *Developing Institutions to Encourage the Use of Animal Wastes as Production Inputs*, 21 AGRIC. & HUMAN VALUES 367, 372 (2004) (noting that governmental expenses directed at potential pollution may be misdirected and advocating strategies to use manure as a production input); *see also* Terence J. Centner, *Regulating Concentrated Animal Feeding Operations to Enhance the Environment*, 6 ENV'T SCI. & POL'Y 433, 437 (2003) (noting the shortcoming of regulating potential pollution and advocating controls that regulate polluters and champion small-scale operations and activities). The *Waterkeeper Alliance* decision precludes EPA from regulating potential pollution from CAFOs. *Waterkeeper Alliance*, 399 F.3d at 506.

29. In the absence of a duty, fewer operations will be required to secure permits so the estimated costs delineated in the preamble of the CAFO Rule are probably too high. EPA Final Rule, *supra* note 7, at 7242-52.

the application of manure, litter, or process wastewater.[30] Simultaneously, nutrient management plans are required and permitting authorities must review them.[31]

II. NPDES Permit Requirements

Congress established an NPDES permitting system with technology-based discharge limits for water pollution from point sources to reduce discharges and improve water quality.[32] Permits issued by the federal government and authorized states[33] allow some discharges, but the NPDES system has drastically curtailed the amounts of pollutants entering the nation's waterbodies.[34] However, the permitting regulations for CAFOs developed in the 1970s were not sufficiently addressing the impairment of water quality by animal feeding operations.[35] Dissatisfaction with efforts to meet water quality goals led to the

30. Under earlier CAFO regulations, many owners and operators believed that the land application of manure was not regulated by the point-source provisions of the Clean Water Act. While the Second Circuit Court of Appeals found in *Concerned Area Residents for the Env't v. Southview Farm*, 34 F.3d 114, 118 (2d Cir. 1994), that manure application could result in a discharge for which an NPDES permit was required, the fact that most CAFOs did not secure permits underscores a belief that owners and operators felt they were excepted from the permitting regulations. Furthermore, a storm event exemption under earlier federal regulations led some owners and operators to believe they did not need permits. *See* Terence J. Centner, *Enforcing Environmental Regulations: Concentrated Animal Feeding Operations*, 69 MO. L. REV. 697, 712 (2004) (discussing the possible explanations for the lack of permits by CAFO owners and operators); *see also* Water Keeper Alliance, Inc. v. Smithfield Foods, Inc., 2001 U.S. Dist. LEXIS 21314, at *7-8 (E.D. N.C. Sept. 20, 2001) (denying defendants' assertion that the storm event exception meant defendants did not need an NPDES permit).

31. 40 C.F.R. § 122.42(e)(1) (2004) (requiring a permit to include a nutrient management plan); *see also* 40 C.F.R. § 412.4(c)(1) (requiring a nutrient management plan for effluent limitations). Some authorized states will need to start reviewing nutrient management plans submitted as part of the NPDES permit. *See infra* notes 57-61 and accompanying text.

32. 33 U.S.C. § 1342 (2000); *see also* EPA v. Nat'l Crushed Stone Ass'n, 499 U.S. 64, 71 (1980) (noting discharge requirements under the permitting system); Tex. Oil & Gas Ass'n v. EPA, 161 F.3d 923, 927 (5th Cir. 1998) (noting the use of permits and effluent limitation guidelines to reduce pollution).

33. 33 U.S.C. § 1342(a)-(b) (2000); *see also* Arkansas v. Oklahoma, 503 U.S. 91, 102 (1992) (discussing the state and federal permitting provisions).

34. *See, e.g.*, ROBERT W. ADLER ET AL., THE CLEAN WATER ACT 20 YEARS LATER 16-17 (1993) (reporting a 99 percent reduction of selected toxic pollutants since 1972 and significant progress in reducing pollutants from specific sources, although problems remain); JACKSON B. BATTLE & MAXINE I. LIPELES, WATER POLLUTION 3 (3d ed. 1998) (reporting the elimination of most of the conspicuous water pollution of the late 1960s); Daniel W. Oberle, *Contaminated Sediment Prevention and Remediation: A Need for Consistent Policy and Sound Science*, 2000 TOL. J. GREAT LAKES' L. SCI. & POL'Y 26, 46 (noting the success of reducing discharges from point sources and a redirection of attention to nonpoint sources).

35. EPA Final Rule, *supra* note 7, at 7176 (preamble).

modifications set forth in the 2003 CAFO Rule.[36]

Although the provisions of the CAFO Rule were expected to enhance water quality,[37] proponents for cleaner water did not feel that the regulations were sufficient to meet the requirements of the Clean Water Act.[38] In *Waterkeeper Alliance*, the Environmental Petitioners argued that the CAFO Rule improperly empowered NPDES authorities to issue permits to owners and operators of "Large CAFOs"[39] without proper review, oversight, and public participation.[40] Due to one or more of these shortcomings, the CAFO Rule provisions were alleged to be arbitrary and capricious.[41] The Second Circuit agreed and vacated the provisions of the CAFO Rule pertaining to the three challenges.[42]

A. Terms Lacking in the NPDES Permits

Section 301 of the Clean Water Act requires that all applicable effluent limitations be included in each NPDES permit.[43] EPA set effluent limitations for CAFOs apart from the NPDES permitting provisions.[44] For CAFO effluent limitations, EPA promulgated best management practices for Large CAFOs as qualitative effluent limitation guidelines that were technology-based restrictions on water pollution.[45] Because numeric effluent limitations were not feasible,[46] best

36. *See* EPA Proposed Rule, *supra* note 9, at 2962 (noting in the preamble that environmental concerns included ecological and human health effects).

37. *See e.g.*, Centner, *supra* note 30, at 728 (suggesting that the removal of exceptions, enumeration of further requirements, and coverage of additional operations should eliminate practices leading to water impairment).

38. *See* Brief for the Environmental Petitioners, *supra* note 17, at 33-39.

39. Large CAFOs are CAFOs with more than an enumerated number of animals as defined by the CAFO Rule. 40 C.F.R. § 122.23(b)(4) (2004) (enumerating minimum numbers of species of animals required at a location for a CAFO to constitute a Large CAFO).

40. *Id.* § 122.23(b)(4); Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 498-502 (2d Cir. 2005).

41. *Waterkeeper Alliance*, 399 F.3d at 498, 502-03. The court's inquiry was guided by the standard set forth in *Motor Vehicle Manufacturers Association v. State Farm Mutual Automobile Insurance Co.*, 463 U.S. 29 (1983).

42. *Waterkeeper Alliance*, 399 F.3d at 524.

43. 33 U.S.C. § 1311(a)-(b) (2000); *see also id.* § 1342(a) (noting that permits must meet the requirements of other provisions of the Clean Water Act).

44. 40 C.F.R. pt. 412 (2004) (delineating effluent limitations for CAFOs); *see also id.* pt. 122 (delineating NPDES requirements for CAFOs).

45. *Waterkeeper Alliance,* 399 F.3d at 496; *see also* Brief for the Respondents at 105-106, *Waterkeeper Alliance,* 399 F.3d 486 (2d Cir. 2005) (No. 03-4470(L)) [hereinafter Brief for the Respondents].

46. EPA Final Rule, *supra* note 7, at 7212 (noting in the preamble that the amount or rate at which manure can be applied to ensure appropriate agricultural utilization of nutrients varies based on site-specific factors at the CAFO so that reliance on numeric effluent limitation guidelines to control land application discharges was infeasible).

management practices were adopted and the terms of nutrient management plans were not required to be included in the permit applications.[47] The *Waterkeeper Alliance* court disagreed with EPA's argument and held that the CAFO Rule violated the Clean Water Act and the Administrative Procedure Act[48] by failing to require that the terms of the nutrient management plans be included in NPDES permits.[49]

The Second Circuit noted that best management practices are nonnumerical effluent limitations.[50] Under the CAFO Rule, certain Large CAFOs need to develop nutrient management plans that minimize phosphorus and nitrogen transport.[51] Limitations on land discharges exist due to the terms of a nutrient management plan.[52] As the definition of "effluent limitation" means any restriction on quantities, rates, and concentrations of nutrients,[53] nutrient management plans are effluent limitations.[54] Since effluent limitations need to be set forth in permits,[55] a nutrient management plan must be included in an NPDES permit application.[56]

The *Waterkeeper Alliance* holding may require owners and operators to reconsider the role of their nutrient management plan.[57] While such plans were traditionally viewed as documents detailing a farmer's plans for nutrient applications, they now must be written to meet more absolute regulatory dictates.[58] States have adopted different approaches to the inclusion of nutrient management plans in permit

47. Brief for the Respondents, *supra* note 45, at 106-07.

48. 5 U.S.C. § 706(2)(A) (2000).

49. *Waterkeeper Alliance*, 399 F.3d at 502-03.

50. *Id.* at 502. Best management practices are still technology-based because they are derived from standards prescribed by the Clean Water Act. *Id.* at 496.

51. 40 C.F.R. § 412.4(c)(1) (2004). This includes the determination of application rates for manure applied to land, manure and soil sampling, inspection of application equipment, and setback requirements. 40 C.F.R. § 412.4(c)(2)-(6). The provisions on nutrient management plans only apply to Large CAFOs with dairy and beef cattle, swine, poultry, and veal calves. 40 C.F.R. § 412.4(a).

52. 40 C.F.R. §412.4(c). In fact, both EPA and the Second Circuit noted that "the only way to ensure that non-permitted point source discharges of manure, litter, or process wastewaters from CAFOs do not occur is to require . . . [land application] in accordance with site specific nutrient management practices." *Waterkeeper Alliance*, 399 F.3d at 504 (citing the preamble to the final rule).

53. 33 U.S.C. §1362(11) (2000); *see also Waterkeeper Alliance*, 399 F.3d at 502.

54. *Waterkeeper Alliance*, 399 F.3d at 502.

55. 33 U.S.C. §§ 1311(a)-(b) (2000); *Id.* § 1342(a).

56. *Waterkeeper Alliance*, 399 F.3d at 502-03.

57. JOHN LORY, COURT RULING RAISES QUESTIONS ABOUT NUTRIENT MANAGEMENT PLANS IN CAFO PERMITS, ANIMAL MANURE MANAGEMENT (2005) (suggesting a shift in the role of nutrient management plans if they are public documents), *available at* http://www.heartlandwq.iastate.edu/NR/rdonlyres/F7FFCD60-5C34-4B75-95EC-603AC636AF06/24399/HeartlandJuneNewsletter0605.pdf.

58. *Id.* The issue involves flexibility for nutrient management to respond to weather variables.

applications.[59] For example, Georgia requires owners to prepare and implement comprehensive nutrient management plans, but does not require submission of the plans to the Georgia Environmental Protection Division unless the Division makes a request in writing.[60] Thus, Georgia regulations do not seem to meet the prescribed federal requirements that the plans be included in NPDES permits.[61]

Some states have recognized that CAFO permit applications ought to include the CAFO's manure management plan.[62] For example, owners or operators of CAFOs in Wisconsin applying for a Wisconsin Pollutant Discharge Elimination System permit must submit a preliminary manure management plan describing how manure and other types of waste are proposed to be stored and spread on lands.[63] Wisconsin also requires that manure management plans be submitted to the Wisconsin Department of Natural Resources "for review and approval detailing the amounts, timing, locations and other aspects regarding the disposal of manure and other wastes."[64] These Wisconsin requirements appear to be consistent with the finding of the Second Circuit that nutrient management plans need to be a part of a permit application.[65]

B. Absence of A Meaningful Review

Under the effluent limitation provisions of the CAFO Rule, certain Large CAFOs need NPDES permits covering the land application of manure.[66] Under the regulatory provisions, each permit needs to include best management practices that include a nutrient management plan delineating criteria that minimize the movement of nitrogen and phosphorus to surface waters.[67] While the regulations require the development and implementation of nutrient management plans, there is

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59. *See, e.g.*, VERMONT AGENCY OF AGRICULTURE, FOOD & MARKETS, LARGE FARM OPERATION subch. 5, 1(a)(5) (1999), *available at* http://www.vermontagriculture.com/1forules.htm#Subchapter%201.

60. GA. COMP. R. & REGS. 391-3-6-.21(10)(c), 391-3-6-.21(11)(c) (2005) (delineating requirements for animal (non-swine) feeding operation permits).

61. *Id.* There is no mandatory requirement that a nutrient management plan be part of the submitted to the regulatory agency, which is contrary to the holding of *Waterkeeper Alliance*, 399 F.3d at 502-03.

62. *See, e.g.*, MINN. R. 7020.0505 subpart 4(A)(10) (2003) (requiring submission of a manure management plan that meets requirements prescribed in rule 7020.2225, subpart 4).

63. WIS. ADMIN. CODE [NR] § 243.12(1)(c)(2) (2002).

64. *Id.* § 243.14(1).

65. *See id.* Minnesota's Rules also appear to comport with the *Waterkeeper Alliance* decision. MINN. R. 7020.0505 subpart 4(A)(10) (2003).

66. 40 C.F.R. §§ 122.23, 412.4 (2003). *See supra* note 51 (noting animal species).

67. 40 C.F.R. § 412.4(c) (2003).

no provision that requires a permitting authority to review the plans before issuing a permit.[68] EPA felt that nutrient management plans were a planning tool.[69] The plans involved state-developed technical standards that delineate adequate effluent limitations.[70]

The Second Circuit found that absence of a meaningful review of nutrient management plans meant the CAFO Rule did not comply with the statutory effluent limitations and standards.[71] The issue involves complying with the NPDES provisions of sections 301 and 402 of the Clean Water Act.[72] Section 402 limits the issuance of permits unless there is compliance with other applicable sections of the Clean Water Act.[73] The section goes on to require that EPA prescribe conditions for permits that assure compliance with sections of the act.[74] Under these requirements, discharge permits may be issued only if they set forth effluent limitations and standards as required by the Clean Water Act.[75]

The provisions of section 402 mean that there is no authority for issuing any permit that does not incorporate appropriate effluent limitations as prescribed by section 301.[76] While the CAFO Rule required the development and implementation of best management plans incorporating nutrient management plans, the rule failed to require that the permitting authority review these plans.[77] In the absence of a meaningful review, there was no way the permitting authority could know whether a permit application was in compliance with mandated effluent limitations.[78]

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68. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 499 (2d Cir. 2005). The court was moved to state that "most glaringly, the CAFO Rule fails to require that permitting authorities review the nutrient management plans developed by Large CAFOs before issuing a permit that authorizes land application discharges."

69. *Id.* at 500-02.

70. *Id.*

71. *Id.* at 501-02.

72. 33 U.S.C. §§ 1311, 1342 (2000).

73. 33 U.S.C. §§ 1342(a)(1), (b)(1) (2000).

74. 33 U.S.C. § 1342(a)(2). "The Administrator shall prescribe conditions for such permits to assure compliance with the requirements of paragraph (1) of this subsection, including conditions on data and information collection, reporting, and such other requirements as he deems appropriate."

75. *Id.* §§ 1311(e), 1342(a)-(b); *see also* Sierra Club v. Shell Oil Co., 817 F.2d 1169, 1173 (5th Cir. 1987) (noting that effluent limitations were required to reduce pollutants discharged into waterways).

76. 33 U.S.C. § 1311 (2000). *See, e.g.,* Am. Paper Inst. v. EPA, 996 F.2d 346, 350 (D.C. Cir. 1993) (noting that once effluent limitations were developed, all permits must incorporate them).

77. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 499 (2d Cir. 2005).

78. *Id.* The Second Circuit noted that "[t]here may well be reason to fear that Large CAFOs may misunderstand their specific situation and prepare inadequate nutrient management plans as a result. . .," and that there was weighty advice to require manure management plans be prepared by trained and certified specialists. *Id.* at 500 n.19.

In reaching this decision, the Second Circuit relied on the Ninth Circuit case of *Environmental Defense Center, Inc. v. EPA*.[79] In *Environmental Defense Center*, the court found that regulations whereby a permitting authority did not review individual permits themselves were flawed.[80] EPA had employed a general permitting model under which a discharger applied for a notice of intent whereby the discharger agreed to abide to the terms of the general permit.[81] While general permits have been recognized as a lawful means of authorizing discharges,[82] the permitting scheme for small municipal separate storm sewer systems embraced a requirement whereby discharges of pollutants needed to be reduced "to the maximum extent practicable" through "minimum control measures."[83] This condition by its very nature requires review by a permitting authority.[84] Because the regulations for small municipal separate storm sewer systems omitted oversight of permitted dischargers, there was no assurance that the statutory requirements were being met.[85] This was contrary to Congress' intent that there be a meaningful review by an appropriate regulating entity to assure the required reduction of a discharge of pollutants to the maximum extent practicable.[86]

Following the reasoning of *Environmental Defense Center*, the Second Circuit found that the provision of the CAFO Rule' omitting oversight of nutrient management plans meant that permits could be issued that do not assure compliance with other requirements of the Clean Water Act.[87] By not requiring permitting authorities to review the nutrient management plans, there was no way to ascertain whether the plans would allow the application of nutrients to achieve realistic production goals while minimizing nitrogen and phosphorus movement to surface waters.[88] Therefore, the provisions of the rule that allow

79. Envtl. Def. Ctr. v. EPA, 344 F.3d 832 (9th Cir. 2003), *cert. denied*, Texas Cities Coalition on Stormwater v. EPA, 124 S. Ct. 2811 (2004) (concerning stormwater runoff and municipal separate storm sewer systems).

80. *Envtl. Def. Ctr.*, 344 F.3d at 856. (evaluating regulations for stormwater management programs).

81. *Id.* at 853-56. General permits were recognized as a tool for regulating large numbers of similar dischargers. *Id.* at 853.

82. *See, e.g.*, Natural Res. Def. Council v. Costle, 568 F.2d 1369, 1383 (D.C. Cir. 1977) (approving EPA's employment of general and area permits under section 402 of the Clean Water Act).

83. 40 C.F.R. § 122.34(a) (2004).

84. *Envtl. Def. Ctr.*, 344 F.3d at 855 (observing that to reach a determination involving the "maximum extent practicable," a permitting authority needs to review the measures taken to decide if they indeed meet the requirement).

85. *Id.* at 855-56 (referring to 40 C.F.R. § 122.34(a) (2004)).

86. 33 U.S.C. § 1342 (2000); *Envtl. Def. Ctr.*, 344 F.3d at 856.

87. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 499-502 (2d Cir. 2005) (referring to 33 U.S.C. § 1342(a)(2) (2000)).

88. *Waterkeeper Alliance*, 399 F.3d at 499-502 (referring to 40 C.F.R. § 412.4(c)(1)

permitting authorities to issue permits without reviewing the terms of the nutrient management plans were vacated.[89]

C. *Lack of Public Participation*

Waterkeeper Alliance's environmental petitioners also argued that the CAFO Rule enumerated a permitting scheme that was contrary to the public participation provisions of section 101 of the Clean Water Act.[90] The act specifically encourages and provides for public participation in the development and revision of effluent limitations.[91] By not requiring the terms of nutrient management plans to be in NPDES permits, and by failing to provide any means of public access to such plans, the CAFO Rule was found to violate the plain dictates of section 101.[92]

The Second Circuit identified three distinct issues concerning the Clean Water Act's public participation requirements and the CAFO Rule.[93] First, because nutrient management plans constitute effluent limitations that need to be in NPDES permits, the absence of review of the plans deprives the public the right to assist in the development, revision, and enforcement of an effluent limitation.[94] Citizens may be entitled to an opportunity for a public hearing prior to the issuance of a permit.[95]

Second, the absence of a public nutrient management plan compromises the ability of persons to bring citizen lawsuits concerning

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(2004)).

89. *Waterkeeper Alliance*, 399 F.3d at 524.

90. *Id.* at 503-04; 33 U.S.C. § 1251(e) (2000); *see also* Michael Steeves, *The EPA's Proposed CAFO Regulations Fall Short of Ensuring the Integrity of Our Nation's Waters*, 22 J. LAND RESOURCES & ENVTL. L. 367, 391-92 (2002) (observing the public participation shortcomings of proposed CAFO regulations).

91. 33 U.S.C. § 1251(e) (2000). "Public participation in the development, revision, and enforcement of any regulation, standard, effluent limitation, plan, or program established by the Administrator or any State under this Act shall be provided for, encouraged, and assisted by the Administrator and the States."

92. *Waterkeeper Alliance*, 399 F.3d at 504. Furthermore, public participation regulations need to be issued prior to the ratification of a state NPDES program. *See, e.g.*, Citizens for a Better Env't v. EPA, 596 F.2d 720, 725 (7th Cir. 1979).

93. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 503-04 (2d Cir. 2005).

94. *Id.* at 503; 33 U.S.C. § 1251 (e) (2000).

95. 33 U.S.C. § 1342(a)(1) (2000). Hearings are required before the issuance of a permit. Envtl. Def. Ctr. v. EPA, 344 F.3d 832, 841 (9th Cir. 2004). However, circuit courts have disagreed whether a hearing is necessary with an application for a notice of intent to seek coverage under a general permit. The Ninth Circuit concluded a hearing was required, *id.* at 857, while the Seventh Circuit found that hearings are not required. Texas Indep. Producers & Royalty Owners Ass'n v. EPA, 2005 U.S. App. LEXIS 11064, *37-39 (7th Cir. 2005); *see also* Costle v. Pac. Legal Found., 445 U.S. 198, 220 (1980) (discussing the hearing requirement and concluding that a hearing is not mandated for every permit).

effluent standards.[96] Without a plan to evaluate, the applicable effluent limitations are not available to the public.[97] Moreover, citizens cannot determine whether there exists a deviation from a plan's requirements.[98] Furthermore, the absence of a public plan frustrates an evaluation of governmental diligence in prosecuting violators.[99] The ability of citizens to initiate civil suits against polluters if the government fails to diligently prosecute violations of the Clean Water Act is a significant aspect of public participation.[100] Thus, the CAFO Rule impermissibly compromised rights accorded by the citizen suit provisions of the Clean Water Act.[101]

Finally, nutrient management plans are an indispensable feature of a plan or program to regulate CAFO land application discharges.[102] To detect unpermitted discharges, plans need to be available to the public.[103] The Environmental Petitioners in *Waterkeeper Alliance* were dissatisfied with the failure of the CAFO Rule to require that a nutrient management plan be a part of an NPDES permit.[104] Because the CAFO Rule shielded

96. *Waterkeeper Alliance*, 399 F.3d at 503 (referring to 33 U.S.C. § 1365(a)(1)-(2) (2000)). "[A]ny citizen may commence a civil action . . . against any person . . . who is alleged to be in violation of (A) an effluent standard or limitation under this Act or (B) an order issued by the Administrator or a State with respect to such a standard or limitation. . . ." 33 U.S.C. § 1365(a)(1) (2000)). Citizens may also bring suit against the administrator where there is alleged a failure of the administrator to perform any act or duty under the Clean Water Act. *Id.* § 1365(a)(2).

97. This is contrary to the public participation requirements of sections 101 and 402. 33 U.S.C. §§ 1251(e), 1342(j) (2000).

98. Without the details of the site-specific nutrient management practices that ensure appropriate agricultural utilization of nutrients from manure, citizens would not be able to determine whether the CAFO owner or operator was meeting the effluent limitations required by the CAFO Rule. 40 C.F.R. § 122.23(e) (2004); *see also* Martin A. Miller, *Coping with CAFOs: How Much Notice Must a Citizen Give?*, 68 MO. L. REV. 959, 981 (2003) (examining a citizen suit against a CAFO that suggests increased liability for CAFOs).

99. In the absence of information on nutrient management practices, there would be no way to determine whether the government was diligent in its enforcement actions. *See* Friends of Milwaukee's Rivers v. Milwaukee Metro. Sewerage Dist., 382 F.3d 743, 765 (7th Cir. 2004) (remanding the issue to the district court to determine whether there was a realistic prospect that a stipulation would result in compliance with the Clean Water Act to defeat plaintiffs' citizen suit action).

100. *See, e.g.*, Proffitt v. Rohm & Haas, 850 F.2d 1007, 1011, 1015 (3d Cir. 1988) (noting the role of public participation through citizen suits in reversing summary judgment awarded to a holder of an NPDES permit).

101. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 503 (2d Cir. 2005).

102. *Id.* at 503; 33 U.S.C. § 1251(e) (2000).

103. *Waterkeeper Alliance,* 399 F.3d 503; 33 U.S.C. § 1251(e) (2000).

104. *Waterkeeper Alliance,* 399 F.3d at 503. By not compelling permit applicants to include their management plan in permit applications, any hearing held prior to the issuance of a permit cannot involve public access to the plan. *See* Costle v. Pac. Legal Found., 445 U.S. 198, 220 (1980) (holding that although a hearing may not be required, the rule failed to provide opportunities for public scrutiny of an integral part of the permit

nutrient management plans from public scrutiny, it forestalled rather than encouraged public participation.[105] Given this shortcoming, the Second Circuit found the rule to be arbitrary and capricious in violation of the Administrative Procedure Act.[106]

III. Agricultural Stormwater and Uncollected Discharges

A major source of disagreement between environmental and industry groups has been the meaning of the agricultural stormwater discharge exemption.[107] This argument involves discharges that occur from the land application of manure from a CAFO.[108] Due to an exemption provided by federal law,[109] agricultural stormwater discharges resulting from precipitation-related events are not discharges from a point source, and thus are not subject to the NPDES permitting requirements.[110] Yet it is unclear that the exception was intended to cover discharges that occur from the land application of manure from a CAFO.[111] As point sources, CAFOs cannot have discharges unless allowed by law or through a permit.[112] To provide meaning to the regulation of discharges originating from CAFO point sources, some type of oversight of the application of CAFO-generated manure seems warranted.[113]

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application).

105. *Waterkeeper Alliance,* 399 F.3d at 504.

106. *Id.* at 503; 5 U.S.C. § 706(2)(A) (2000).

107. *See, e.g.*, Theodore A. Feitshans & Kelly Zering, *Federal Regulation of Animal and Poultry Production Under the Clean Water Act: Opportunities for Employing Economic Analysis to Improve Societal Results*, 10 PENN ST. ENVTL. L. REV. 193, 201 (2002) (noting that the statutory language concerning agricultural stormwater discharges "has often been erroneously interpreted to exempt livestock and poultry operations from the NPDES program"); Scott Jerger, *EPA's New CAFO Land Application Requirements: An Exercise in Unsupervised Self-Monitoring*, 23 STAN. ENVTL. L.J. 91, 104 (2004) (noting uncertainty regulating applications of manure due to the agricultural stormwater exemption); Steeves, *supra* note 90, at 384-90 (arguing that the CAFO Rule allows too many pollutants to enter the nation's waters).

108. *See, e.g.*, Jerger, *supra* note 107, at 110-28 (discussing the need to regulate the application of manure and the inadequacy of EPA's regulations).

109. 33 U.S.C. § 1362(14) (2000). "The 'term point source' . . . does not include agricultural stormwater discharges and return flows from irrigated agriculture." *Id.*

110. The Clean Water Act requires NPDES permits for discharges from point sources. *See* 33 U.S.C. § 1342(a)-(b) (2000).

111. Some type of limitation is needed so that manure applied to fields does not lead to the impairment of water. EPA noted that the land application of manure leads to the impairment of waters. EPA Final Rule, *supra* note 7, at 7197-98 (preamble); *See also* Jerger, *supra* note 107, at 102-04 (discussing the uncertainties involving the agricultural stormwater exemption for CAFOs).

112. *See* 33 U.S.C. § 1342(a)-(b) (2000).

113. This might involve exempting agricultural stormwater but regulating other land application discharges.

The Clean Water Act defines a discharge as an addition of any pollutant to navigable waters from a point source.[114] Point sources may discharge pollutants if the discharge is allowed in an NPDES permit.[115] For CAFOs, a zero discharge standard was enumerated in the CAFO Rule,[116] a standard that has been employed for other sources of discharges.[117] This means that any addition of manure or other pollutants from a CAFO to navigable waters constitutes an impermissible discharge, unless an exception exists.[118] Agricultural stormwater discharges are exempted from regulation.[119] Exceptions also exist for occasional discharges from permitted CAFOs that occur due to significant storms or unusual precipitation events,[120] and discharges permitted by law.[121]

The *Waterkeeper Alliance* court addressed the confusing exemption for agricultural stormwater discharges by noting that the Clean Water Act's definition of a "point source" does not include agricultural stormwater discharges.[122] Agricultural stormwater is not defined by the act; rather, the CAFO Rule defined this term to include any "precipitation-related discharge of manure, litter, or process wastewater from land areas under the control of a CAFO" where the manure, litter or process wastewater has otherwise been applied in accordance with site-specific nutrient management practices that ensure appropriate agricultural utilization of the nutrients.[123]

The CAFO Rule adopted an interpretation of agricultural stormwater discharges that reconciles the need for agricultural stormwater discharges within the context of the Clean Water Act's goal of reducing pollution.[124] Agricultural stormwater discharges are

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114. 33 U.S.C. § 1362(12) (2000).

115. *Id.* § 1342(a).

116. 40 C.F.R. §§ 412.12(a), 412.13(a), 412.15(a), 412.25(a), 412.31(a), 412.46(a) (2004).

117. *See, e.g.*, 40 C.F.R. §§ 435.43 (2004) [oil and gas extraction], 435.45 [oil and gas extraction], 455.42 [pesticide chemicals formulating and packaging[, 455.43 [pesticide chemicals formulating and packaging], 455.44[pesticide chemicals formulating and packaging].

118. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 508-09 (2d Cir. 2005).

119. *Id.*; 33 U.S.C. §1362(14) (2000).

120. 40 C.F.R. §§ 412.13(b) (2004) [chronic or catastrophic rainfall overflows], 412.15(b) [rainfall event overflows], 412.25(b) [rainfall even overflows], 412.26(b) [rainfall event overflows].

121. *See* Fisherman Against Destruction of the Env't, Inc. v. Closter Farms, Inc. 300 F.3d 1294, 1296-97 (11th Cir. 2002) (noting that a legislature may exempt discharges).

122. *Waterkeeper Alliance*, 399 F.3d at 506-11; 33 U.S.C. § 1362(14) (2000).

123. 40 C.F.R. § 122.23(e) (2004) (Stormwater is defined as "storm water runoff, snow melt runoff and drainage"); *Id.* § 122.26(b)(13).

124. EPA Final Rule, *supra* note 7, at 7176, 7179-80 (noting in the preamble that the regulation of nonpoint source pollution was not sufficient to prevent pollutants from the

permitted, but parameters are prescribed to preclude unjustified discharges.[125] For the land application of manure, agricultural stormwater discharges need to be distinguished from unpermitted discharges to preclude the addition of pollutants to waters.[126] Agricultural stormwater discharges retain their status of not being point sources, while discharges that do not meet the conditions of agricultural stormwater discharges are subject to the NPDES permitting system.[127]

A. Petitioners' Arguments

In *Waterkeeper Alliance*, both the Farm Petitioners and the Environmental Petitioners objected to the CAFO Rule's interpretation of the agricultural stormwater exemption, as each group felt that federal law required an alternative definition.[128] The Farm Petitioners argued that all discharges from lands other than the production areas of a CAFO were agricultural stormwater discharges.[129] The Environmental Petitioners argued that all discharges from lands where CAFO manure has been applied violated the provisions of the Clean Water Act.[130]

Since agricultural stormwater discharges are exempted from point sources,[131] the Farm Petitioners argued that NPDES permits should only apply to CAFO production areas.[132] Discharges from lands other than production areas should be viewed as nonpoint source pollution,[133] and pursuant to federal law, the runoff would not be subject to point source pollution provisions.[134] The differentiation of point and nonpoint source pollution was presented as support for a conclusion that CAFOs could only have point source pollution from production areas.[135]

Accompanying this bifurcation of sources of pollution was the

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land application of manure from impairing water quality).

125. 40 C.F.R. § 122.23(e) (2004) (delineating the parameters).

126. EPA Final Rule, *supra* note 7, at 7197-98 (preamble).

127. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 508 (2d Cir. 2005) (citing Concerned Area Residents for the Env't v. Southview Farm, 34 F.3d 114, 118 (2d Cir. 1994)).

128. *Waterkeeper Alliance.* 399 F.3d at 506-511.

129. Brief for the Farm Petitioners, *supra* note 21, at 75 (citing 33 U.S.C. § 1342(14) (2000).

130. Brief for the Environmental Petitioners, *supra* note 17, at 51.

131. 33 U.S.C. § 1362(14) (2000).

132. Brief for the Farm Petitioners, *supra* note 21, at 64-90.

133. *Id.* at 8-9.

134. 33 U.S.C. § 1314(f) (2000) (citing runoff from fields as being potential nonpoint source pollution). The Clean Water Act gives states primary authority for dealing with nonpoint source pollution. *Id.* §§ 1251, 1255; 33 U.S.C.A. § 1329 (West 2001 & Supp. 2005).

135. Brief for the Farm Petitioners, *supra* note 21, at 66-70.

separation in the CAFO Rule of production and land application areas.[136] Since the rule did not define a CAFO to include land application areas, it was argued that discharges from land application areas should not be classified as discharges from point sources.[137] Therefore, the Farm Petitioners reasoned that the land application of manure from a CAFO could not be regulated under the federal point source regulations.[138]

The Farm Petitioners also advanced the argument that the definition of the agricultural stormwater exemption precluded qualifications as set forth in the CAFO Rule.[139] In exempting agricultural stormwater, Congress intended that activities leading to runoff would be exempted from the point source permitting requirements.[140] The exception for agricultural stormwater thereby meant that EPA was without authority to establish nutrient management practices for determining whether runoff was within the definition of an agricultural stormwater discharge.[141] Thus, the Farm Petitioners felt that all discharges from lands where CAFO manure had been applied could not be regulated by the permitting requirements.[142]

To control pollutants from CAFOs, as mandated by the Clean Water Act, the Environmental Petitioners rationalized that discharges resulting from the land application of CAFO manure should not be classified as agricultural stormwater discharge.[143] Because CAFO production and land application areas cannot be meaningfully separated, it was argued that all land application areas should be considered to be part of the CAFO.[144] The Clean Water Act precluded discharges from CAFOs

136. 40 C.F.R. §§ 122.23(b)(3), (8) (2004).

137. Brief for the Farm Petitioners, *supra* note 21, at 65-70.

138. *Id.* at 72-74.

139. *Id.* at 77-80.

140. *Id.* at 77-78.

141. *Id.* at 78.

142. *Id.* at 83-90.

143. Brief for the Environmental Petitioners, *supra* note 17, at 43-60. A district court from North Carolina lends support for this argument. Waterkeeper Alliance, Inc. v. Smithfield Foods, Inc., 2001 U.S. Dist. LEXIS 21314, *10-11 (E.D. N.C. Sept. 20, 2001).

> Excluding parts of the waste management system from the definition of a CAFO by limiting the CAFO area to the land underneath the feeding areas would compromise the goals of the [Clean Water Act] by allowing widespread pollution by industrial feedlots pumping waste into other areas of their farms. By definition, a CAFO is not limited to the concentrated animal feeding area because the word 'operation' encompasses the entire process involved in running a concentrated animal feeding facility.

Id.

144. Brief for the Environmental Petitioners, *supra* note 17, at 49-50. This argument is consistent with a Wisconsin court decision. Maple Leaf Farms, Inc. v. State Dep't Natural Res., 633 N.W. 2d 720, 728-29 (Wis. Ct. App. 2001).

> [A] CAFO includes not only the ground where the animals are confined, but also the equipment that distributes and/or applies the animal waste produced at

unless authorized under an NPDES permit.[145] Thus, the Environmental Petitioners felt that any discharge from a CAFO land application area required the owner or operator to secure a permit.[146]

B. Evaluation by the Court

The CAFO Rule provides that land application discharges from a CAFO are subject to NPDES requirements.[147] However, to exempt agricultural stormwater discharges as required by statute,[148] the rule differentiates between agricultural stormwater discharges and other discharges:[149]

> [W]here the manure, litter or process wastewater has been applied in accordance with site specific nutrient management practices that ensure appropriate agricultural utilization of the nutrients in the manure, litter or process wastewater, as specified in § 122.42(e)(1)(vi)-(ix), a precipitation-related discharge of manure, litter or process wastewater from land areas under the control of a CAFO is an agricultural stormwater discharge.[150]

The *Waterkeeper Alliance* court found that this differentiation neither offended the exemption for agricultural stormwater discharges[151] nor the need to abate pollution accompanying the land application of manure.[152] Thus, the CAFO Rule's exemption for agricultural stormwater discharges was a reasonable interpretation of the Clean Water Act.[153]

In evaluating the rule's provisions, the Second Circuit employed the

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> the confinement area to fields outside the confinement area. Any over application of manure by Maple Leaf through its landspreading activities would then be a discharge, either because of runoff to surface waters or percolation of pollutants to groundwater. Because the off-site croplands are used by Maple Leaf to dispose of waste produced at its on-site facility, the permit conditions imposed on Maple Leaf to enforce groundwater protection standards are as applicable to Maple Leaf's off-site landspreading operations as they are on-site. Therefore, because a CAFO's over application of manure to fields can be a discharge to groundwater under the statute, we determine that the [Department of Natural Resources] has authority to issue permits regulating Maple Leaf's off-site landspreading operations.

Id.; *see also* Jerger, *supra* note 107, at 108.

145. 33 U.S.C. § 1342 (2000).

146. Brief for the Environmental Petitioners, *supra* note 17, at 49-60.

147. 40 C.F.R. § 122.23 (2004).

148. 33 U.S.C. § 1362(14) (2000).

149. 40 C.F.R. § 122.23(e) (2004).

150. *Id.*

151. *Id.* Agricultural stormwater discharges continue to be exempted so long as they meet the qualifications for such a discharge. *Id.*

152. EPA Final Rule, *supra* note 7, at 7196 (preamble).

153. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 507-10 (2d Cir. 2005).

"reasonable construction" standard set by the Supreme Court in *Chevron U.S.A. Inc. v. Natural Resources Defense Council, Inc.*[154] Whenever a statute is ambiguous as to an issue, the court should uphold the agency's interpretation if it is permissible.[155] The regulatory provisions on agricultural stormwater discharges accounted for the need to regulate CAFO discharges while deferring to immunity from liability for weather-related discharges.[156] The CAFO Rule's construction of the agricultural stormwater exemption was also consistent with earlier court opinions that looked at the primary cause of the discharge to determine whether the discharge was subject to regulation.[157]

The CAFO Rule enunciates four parameters that must be met before a discharge qualifies as an agricultural stormwater discharge.[158] First, the discharge needs to be the result of a precipitation-related event before it qualifies.[159] Applications of manure that place pollutants in waters without a precipitation event do not qualify as an agricultural stormwater discharge.[160] Second, site-specific conservation practices need to be implemented to control runoff of pollutants before a discharge is exempted.[161] Thereby, any CAFO that fails to adopt appropriate

154. 467 U.S. 837 (1984).

155. *Id.* at 843 (upholding an agency's permissible interpretation of a statute); *see also* Yellow Transp., Inc. v. Michigan, 537 U.S. 36, 45 (2002) (finding that an agency's interpretation of a statute was permissible and should be upheld).

156. *Waterkeeper Alliance*, 399 F.3d at 507.

157. Concerned Area Residents for the Env't v. Southview Farm, 34 F.3d 114, 118 (2d Cir. 1994); Cmty. Ass'n for Restoration of the Env't v. Henry Bosma Dairy, 305 F.3d 943, 953-54 (9th Cir. 2002) (observing evidence of overapplication and misapplication of manure to a field that resulted in a discharge to navigable waters); *see also* Stacey K. Garrett, *Recent Developments, Second Circuit's Holding Limits Scope of Agricultural Exemption under the Clean Water Act*, 4 S.C. ENVTL. L.J. 67, 70 (discussing the possibility of discharges arising from the oversaturation of fields); Kristen E. Mollnow, Note, *Concerned Area Residents for the Environment v. Southview Farm: Just What is a Concentrated Animal Feeding Operation Under the Clean Water Act?*, 60 ALB. L. REV. 239 (1996) (observing that CAFOs need to follow best management practices and the conditions of the permit to avoid unpermitted discharges); Susan E. Schell, Casenote, *The Uncertain Future of Clean Water Act Agricultural Pollution Exemptions After Concerned Area Residents for the Environment v. Southview Farm*, 31 LAND & WATER L. REV. 113, 117 (1996) (analyzing violations from the application of manure).

158. 40 C.F.R. § 122.23(e) (2004).

159. A discharge due to something other than precipitation is not a stormwater discharge. In an earlier Second Circuit case, it was manure application on oversaturated fields. *Concerned Area Residents for the Env't*, 34 F.3d at 121. The Ninth Circuit found that a producer who overapplies or misapplies manure may incur liability for an unpermitted discharge. *Cmty. Ass'n for Restoration of the Env't*, 305 F.3d at 954.

160. *See* 40 C.F.R. § 122.23(e) (2004). Such applications might involve spreading manure so close to a stream or waterbody that pollutants enter waters in the absence of precipitation; *see also Concerned Area Residents for the Env't*, 34 F.3d at 121 (observing that evidence showed that some of the runoff was due to oversaturation of the fields by liquid manure and not rain).

161. 40 C.F.R. § 122.23(e) (2004).

conservation practices to control runoff of pollutants may have a discharge that would subject its owner or operator to the permitting requirements.[162]

A third parameter involves the application of manure, litter, or process wastewater in accordance with site-specific nutrient management practices ensuring appropriate agricultural utilization of the nutrients.[163] If a CAFO owner or operator overapplies manure and a discharge occurs, it is regulated under the NPDES provisions of the Clean Water Act.[164] Fourth, because the appropriate utilization of nutrients is based upon a nutrient management plan, the rule identifies a need to maintain records that document the implementation and management of such a plan.[165] In the absence of a management plan with records, there may be little support for showing that the owner or operator meets the requirement of appropriate utilization of nutrients.[166]

C. Uncollected Discharges

The Farm Petitioners argued that the Clean Water Act did not provide any authority for the regulation of uncollected discharges from land areas under the control of a CAFO.[167] By regulating runoff from the application of manure, litter and wastewater, the CAFO Rule was regulating nonpoint source pollution.[168] Because runoff was not from a point source, the CAFO Rule was not authorized by the Clean Water Act.[169] The Petitioners argued that runoff needed to be channeled or collected before it became a point source that might be regulated under the act.[170]

The *Waterkeeper Alliance* court found that the rule's provisions on runoff conformed with the act.[171] Although point sources normally are discrete and discernible, the Second Circuit found that the CAFO itself was a channel under the act.[172] Land application areas were recognized

162. *Id.* This is consistent with the cases holding that manure overapplied, misapplied or applied to saturated fields resulting in a discharge does not qualify as an agricultural stormwater discharge. *See supra* note 159.

163. 40 C.F.R. § 122.23(e) (2004). Provisions on best management practices are also enumerated in the effluent limitation guidelines for CAFOs. *Id.* § 412.4.

164. 40 C.F.R. § 122.23(e) (2004).

165. *Id.*; *see also* 40 C.F.R. § 122.42(e)(2) (2004) (prescribing the maintenance of records).

166. *See* 40 C.F.R. § 122.42(e)(2) (2004).

167. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 510-11 (2d Cir. 2005); Brief for the Farm Petitioners, *supra* note 21, at 64-75.

168. Brief for the Farm Petitioners, *supra* note 21, at 64.

169. *Id.*

170. *Id.* at 74-75.

171. *Waterkeeper Alliance*, 399 F.3d at 510-11.

172. *Id.* at 510.

as integral and indispensable parts of CAFO operations.[173] Given the fact that the rule only regulates discharges from land application areas under the control of a CAFO owner or operator,[174] it was reasonable for the agency to conclude that runoff from a land application area is runoff from a CAFO.[175]

IV. The Duty to Apply for an NPDES Permit

The 2003 CAFO Rule provided that "[a]ll concentrated animal feeding operations have a duty to seek coverage under an NPDES permit. . . ."[176] Due to the burden this duty placed on CAFO owners and operators, the Farm Petitioners in the *Waterkeeper Alliance* case challenged the permitting provisions, claiming they were not authorized by the provisions of the Clean Water Act.[177] The contention was that there was no authority to require a CAFO to secure a permit in the absence of a discharge of pollutants.[178] EPA argued that the potential to discharge pollutants was sufficient to require CAFO owners and operators to secure a permit.[179] The Second Circuit found that there was no statutory authority for such a requirement and so vacated the provisions.[180]

A. Finding No Authority for a Duty

The *Waterkeeper Alliance* court found that the Clean Water Act grants EPA jurisdiction to regulate and control actual discharges but not potential discharges.[181] This interpretation of the Clean Water Act was supported by three separate provisions.[182] First, section 301 of the act

173. *Id.* at 511; *see also* EPA Final Rule, *supra* note 7, at 7196 (preamble).

174. 40 C.F.R. § 122.23(e) (2004). EPA discussed regulating manure from CAFOs that is applied to lands owned by someone else. EPA Proposed Rule, *supra* note 9, at 2964, 2994-95 (preamble). However, the final regulations only applied to manure applications on lands under control of a CAFO owner or operator. 40 C.F.R. § 122.23(e) (2004).

175. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 511 (2d Cir. 2005).

176. 40 C.F.R. § 122.21(a)(1) (2004).

177. *Waterkeeper Alliance*, 399 F.3d at 504.

178. An exception existed for owners and operators of qualifying Large CAFOs who receive notification from the director that the CAFO has no potential to discharge manure, litter or process wastewater. 40 C.F.R. § 122.23(d)(2) (2004). However, this provision was vacated by the Second Circuit. *Waterkeeper Alliance*, 399 F.3d at 524.

179. *Waterkeeper Alliance*, 399 F.3d at 501-02; *see also* EPA Final Rule, *supra* note 7, at 7202 (preamble).

180. *Waterkeeper Alliance*, 399 F.3d at 524.

181. *Id.* at 505 (citing Natural Res. Def. Council v. EPA, 859 F.2d 156, 170 (D.C. Cir. 1988)).

182. *Waterkeeper Alliance*, 399 F.3d at 504-06 (2d Cir. 2005) (citing 33 U.S.C. §§ 1311(a), 1342(a), 1362(12) (2000)).

makes it illegal to discharge pollutants.[183] To effect the prohibition on discharges, EPA is directed to promulgate effluent limitations and issue permits for the discharge of pollutants.[184] Congress did not leave room for the regulation of potential pollutants due to the fact that the act defines the term "discharge of any pollutant" to include "any addition of any pollutant to navigable waters from any point source. . . ."[185]

Second, section 402 of the act gives NPDES authorities the power to issue permits for discharges of pollutants.[186] Because states only have authority to issue permits for discharges, section 402 cannot be interpreted to encompass the issuance of permits for potential discharges.[187] Point sources do not need to secure permits; rather, discharges from point sources need to be authorized by the provisions of a permit.[188]

Third, the discharge of any pollutant is defined by section 502 in such a manner that excludes the potential for a discharge.[189] Discharges are limited to the addition of pollutants from any point source to navigable waters or waters of the contiguous zone or the ocean.[190] Given the directives of sections 301, 402, and 502, the Second Circuit concluded that

> [I]n the absence of an actual addition of any pollutant to navigable waters from any point, there is no point source discharge, no statutory violation, no statutory obligation of point sources to comply with EPA regulations for point source discharges, and no statutory obligation of point sources to seek or obtain an NPDES permit in the first instance.[191]

Congress has only authorized EPA to require permits of persons who are discharging pollutants, thus there is no authority to regulate point sources themselves.[192]

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183. 33 U.S.C. § 1311(a) (2000). "Except as in compliance with this section and [other] sections, the discharge of any pollutant by any person shall be unlawful." *Id.*

184. *Id.* § 1311(e); *Waterkeeper Alliance*, 399 F.3d at 504.

185. 33 U.S.C. § 1362(12) (2000); *see also Waterkeeper Alliance*, 399 F.3d at 504-05.

186. 33 U.S.C. § 1342(a) (2000); *see also Waterkeeper Alliance*, 399 F.3d at 498, 504.

187. *Waterkeeper Alliance*, 399 F.3d at 504.

188. *Id.*

189. 33 U.S.C. § 1362(12) (2000). "The term 'discharge of a pollutant' and the term 'discharge of pollutants' each means (A) any addition of any pollutant to navigable waters from any point source, (B) any addition of any pollutant to the waters of the contiguous zone or the ocean from any point source other than a vessel or other floating craft." *Id.*

190. *Id.*

191. *Waterkeeper Alliance*, 399 F.3d at 505.

192. *Id.*; *see also* Natural Res. Def. Council v. EPA, 859 F.2d 156, 170 (D.C. Cir. 1988) (noting that EPA's jurisdiction under the Clean Water Act is limited to regulating

This ruling is expected to have significant ramifications for CAFO owners and operators.[193] Operations raising large numbers of animals are no longer automatically obligated to apply for a permit.[194] Rather, unless they have had a discharge, or fall within a more specialized provision of the CAFO Rule that requires securing a permit,[195] they are free of the rule's permitting burdens.[196] Due to the costs of securing permits, owners and operators may claim they do not have a discharge and thereby do not need to secure a permit.[197] If owners and operators decline to voluntarily seek permits, permitting authorities will be burdened with establishing evidence of a discharge before a CAFO owner or operator can be required to secure an NPDES permit.[198] Alternatively, some requirement other than the Clean Water Act may serve as a justification for requiring CAFO owners and operators to apply for a permit.[199] State CAFO regulations, state nonpoint source provisions, or evidence of a past violation may obligate a CAFO to apply for a permit.[200]

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the discharge of pollutants).

193. CAFO owners and operators have argued that the Clean Water Act did not create a cause of action based on failure to secure a permit. *See, e.g.*, Waterkeeper Alliance, Inc. v. Smithfield Foods, 2001 U.S. Dist. LEXIS 21314, at *3, *6 (E.D. N.C. Sept. 20, 2001) (arguing that the Clean Water Act does not create a cause of action for operating a CAFO without a permit).

194. This may be especially true in arid areas where there is little likelihood of a rain event leading to a discharge.

195. The CAFO regulations allow animal feeding operations to be designated by NPDES authorities as CAFOs. 40 C.F.R. § 122.23(b)(9) (2004). Designation can only occur after an on-site inspection and a finding that the operation is a significant contributor of pollutants to waters. *Id.* § 122.23(c).

196. The Second Circuit concluded that "the Clean Water Act, on its face, prevents EPA from imposing, upon CAFOs, the obligation to seek an NPDES permit or otherwise demonstrate that they have no potential to discharge." Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 506 (2d Cir. 2005) (citing Chevron U.S.A., Inc. v. Natural Res. Def. Council, 467 U.S. 837, 842-43 (1984)). Unpermitted CAFOs with agricultural stormwater discharges need to have nutrient management plans. *See supra* notes 158-166 and accompanying text. Moreover, state law may impose requirements on other CAFOs. *See, e.g.*, MINN. STAT. § 116.07, subdivision 7 (Supp. 2005) (authorizing requirements for CAFOs beyond those established by federal law).

197. EPA estimated that the effluent limitations would cost Large CAFOs $283 million per year. EPA Final Rule, *supra* note 7, at 7224 (preamble).

198. It would appear that EPA was attempting to avoid this burden, as the agency lacks the resources to monitor and discover which CAFOs have unpermitted discharges.

199. A state may recognize a need for requiring other animal feeding operations to secure permits. *See, e.g.*, MINN. STAT. § 116.07, subdivision 7(g) (Supp. 2005) (delineating a requirement whereby animal feedlots with fewer than the numbers set forth for NPDES permits need a permit in Minnesota).

200. *Id.* (example of a state regulation requiring a permit).

B. *An Overly Strict Interpretation of the Act*

In proposing a CAFO Rule and the discussion about the Final Rule, EPA noted difficulties in fitting the problem of pollution from animal feeding operations within the context of statutory requirements.[201] Although CAFO production facilities are clearly point sources,[202] their fields are not.[203] The *Waterkeeper Alliance* court found that manure from these facilities may be regulated so long as it remains under the control of the owner or operator.[204] While the Second Circuit presented a solid argument for finding that the act did not allow the regulation of potential discharges, it neglected to fully consider practicalities in meeting these obligations imposed by the Clean Water Act.[205]

Given the longstanding noncompliance and unjustified impairment of waters by CAFOs,[206] EPA decided it was appropriate to regulate likely sources of discharges.[207] As a practical matter, additional action was

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201. *E.g.*, EPA Proposed Rule, *supra* note 9, at 2968-69 (noting in the preamble the inconsistencies of state NPDES programs in regulating CAFOs and failures to issue permits); EPA Final Rule, *supra* note 7, at 7196-98 (discussing in the preamble provisions governing agricultural stormwater discharges).

202. 40 C.F.R. §§ 122.23(b)(8), 412.1(h) (2004) (defining the production areas of CAFOs); *see also* Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 510 (2d Cir. 2005) (observing that a CAFO is a point source).

203. 40 C.F.R. §§ 122.23(a)(3), 412.1(e) (2004) (defining land application areas separate from CAFO production areas); *see also* Brief for the Farm Petitioners, *supra* note 21, at 65-70 (arguing that fields are not point sources).

204. *Waterkeeper Alliance*, 399 F.3d at 508 (approving an earlier decision whereby discharges from areas under the control of a CAFO needed to comply with the Clean Water Act's discharge requirements). This is consistent with regulations whereby an owner remains responsible for the disposal of materials that might cause environmental degradation. *See, e.g.*, United States v. Iverson, 162 F.3d 1015, 1025 (9th Cir. 1998) (finding that liability under the Clean Water Act is not limited to the person with the greatest control but rather that corporate officers could incur liability); *see also* GenCorp, Inc. v. Olin Corp., 390 F.3d 433, 449 (6th Cir. 2004) (finding liability under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) due to the control exercised by the defendant in handling hazardous waste); Croftin Ventures Ltd. P'ship v. G&H P'ship, 258 F.3d 292, 300 (4th Cir. 2001) (finding evidence supporting liability of a former property owner under CERCLA, 42 U.S.C. § 9607(a), unless the former owner did not deposit the hazardous waste and shows it was not leaking into the soil or water).

205. *Waterkeeper Alliance*, 399 F.3d at 508. It allows unpermitted CAFOs to continue with the impairment of water until their illegal discharges are found.

206. OFFICE OF WATER, U.S. ENVTL. PROT. AGENCY, NATIONAL WATER QUALITY INVENTORY: 1998 REPORT TO CONGRESS 65 (2000), *available at* http://www.epa.gov/305b/98report. CAFOs were not separated from other animal operations. Rather, animal feedlots were estimated to contribute to 16 percent of the impaired river and stream miles in the United States. *Id.*

207. *See* EPA Final Rule, *supra* note 7, at 7179 (observing in the preamble that the largest animal feeding operations present the greatest potential for water impairment); Brief for the Respondents, *supra* note 45, at 69-76 (arguing that the provisions were needed to avoid the alternative enforcement action consisting of suits only after a

needed to eliminate discharges from unpermitted CAFOs.[208] EPA was attempting to address a water impairment problem involving owners and operators of CAFOs whom the agency believed were causing pollutants to enter our nation's waterbodies.[209] Therefore, EPA argued that the definition of "point source" supports the conclusion that regulatory provisions might prescribe a duty.[210] Point sources include CAFOs "from which pollutants are or may be discharged."[211] However, the court found this definition only allows point sources to include facilities that pollute and does not allow the government to proceed beyond the regulation of actual pollution.[212] In chastising EPA, the Second Circuit claimed that no provision had been offered that gives operational effect to the "may be discharged" language of the statute.[213]

The operational effect of the court's interpretation of the act suggests that there must be an actual, unpermitted discharge before a permitting agency has the authority to regulate a CAFO through a permit.[214] The legislative history, subsequent regulations, and other provisions of the CAFO Rule do not require the Second Circuit's interpretation.[215] The overriding objectives of the Clean Water Act were to restore and maintain the integrity of waters[216] and to employ NPDES permits to prevent, reduce, and eliminate discharges to the waters of the United States.[217] While the act does not directly regulate point sources,[218] its provisions disclose responses that are intended to prevent future discharges.[219]

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violation is discovered).

208. The 2003 Rule was necessitated by legal action asserting that the federal regulations governing CAFOs were insufficient. *See supra* note 10.

209. EPA Proposed Rule, *supra* note 9, at 3080 (reporting data in the preamble suggesting that most CAFOs had not secured permits as required by law).

210. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 505 (2d Cir. 2005).

211. 33 U.S.C. § 1362(14) (2000); *see also Waterkeeper Alliance*, 399 F.3d at 505.

212. *Waterkeeper Alliance*, 399 F.3d at 505.

213. *Id.*

214. Brief for the Environmental Petitioners' Petition for Panel Rehearing or Clarification at 2, *Waterkeeper Alliance*, 399 F.3d 486 (2d Cir. 2005) (No. 03-4470(L)).

215. With the delineation of provisions for new sources and total maximum daily loads, the act shows concern with future sources of discharges. *See* 33 U.S.C. §§ 1316, 1313(d)-(e) (2000).

216. 33 U.S.C. § 1251(a) (2000).

217. *Id.* § 1251(b); *see also* Oklahoma v. EPA, 908 F.2d 595, 599 (10th Cir. 1990) (observing the purpose of preventing, reducing, and eliminating discharges); Texas Oil & Gas Ass'n v. EPA, 161 F.3d 923, 927 (5th Cir. 1998) (observing the goal of eliminating discharges of pollutants).

218. *See* Natural Res. Def. Council v. EPA, 859 F.2d 156, 170 (D.C. Cir. 1988) (observing that EPA has no authority to regulate point sources themselves).

219. *See, e.g.*, 33 U.S.C. §§ 1313(d)-(e), 1316(a) (2000) (delineating total maximum daily load (TMDL) and new source provisions that concern future pollution).

Provisions on new sources of pollutants[220] and total maximum daily loads (TMDLs)[221] address future discharges. For new sources involving buildings, structures, and facilities that are constructed after the publication of regulations,[222] the act imposes more stringent discharge standards on persons who will have a future discharge.[223] Although the act does not preclude the construction of facilities prior to the issuance of a permit,[224] its provisions were intended to be technology forcing,[225] meaning that the act was concerned about potential pollution.[226] State TMDL requirements reflect a state's designated uses for a water body rather than being dependent solely on discharges from point sources.[227] Thus, EPA is engaged in a permitting system that looks at the potential to pollute and considers nondischarges[228] and future discharges.[229]

While the Second Circuit was correct that the duty imposed in the CAFO Rule was too broad, the court declined to assist EPA in responding to the documented problem of CAFOs failing to secure permits.[230] The new source and TMDL provisions indicate there is an

220. *Id.* § 1316. Corresponding provisions for new sources were incorporated into the CAFO Rule. 40 C.F.R. § 122.23(g)(4) (2004).

221. 33 U.S.C. § 1313(d)-(e) (2000).

222. *Id.* § 1316(a)(2)-(3).

223. *See id.* § 1316(b)(1)(B) (proposing and establishing standards for new sources). Regulatory provisions concerning new sources generally provide that they must adhere to more stringent pretreatment standards than existing sources. *See, e.g.*, S. Holland Metal Finishing Co. v. Browner, 97 F.3d 932, 934 (7th Cir. 1996) (considering whether a company moving to a new location should be subject to more rigorous environmental regulations under new source provisions).

224. Natural Res. Def. Council v. EPA, 822 F.2d 104, 127-28 (D.C. Cir. 1987) (concluding that a construction ban was not authorized by section 511(c)(1) of the Clean Water Act).

225. Oklahoma v. EPA, 908 F.2d 595, 609 (10th Cir. 1990) (delineating multiple objectives of the Clean Water Act).

226. The new source provisions address future pollution, albeit owners and operators who will have a discharge. *See* 33 U.S.C. § 1316(b)(1)(B) (2000) (addressing facilities before they commence a discharge). EPA cannot ban the construction of new source facilities. *See, e.g.*, *Natural Res. Def. Council*, 859 F.2d at 170 (noting that EPA cannot stop the construction of a new facility that may generate a discharge, but can regulate the discharges once the facility commences operation).

227. Pronsolino v. Marcus, 291 F.3d 1123, 1139 (9th Cir. 2002) (allowing consideration of nonpoint source pollution for the development of TMDLs). The TMDL provisions show the Clean Water Act being concerned about pollutant loadings from future sources of pollution. 33 U.S.C. § 1313(d)-(e) (2000); *see also* Jeffrey M. Gaba, *New Sources, New Growth and the Clean Water Act*, 55 ALA. L. REV. 651, 664 (2004) (noting ambiguities in the regulations concerning new sources, TMDL provisions, and waste load allocations).

228. *See Pronsolino*, 291 F.3d at 1139-41 (upholding Clean Water Act TMDL requirements for a river only polluted by nonpoint sources).

229. *See e.g.*, 33 U.S.C. §§ 1313(d)-(e), 1316(a) (2000) (concerning TMDLs and new sources).

230. The agency was responding to documented water impairment and a consent

ambiguity under the act on how to address point sources with expected future discharges.[231] While the Clean Water Act doesn't allow EPA to regulate potential discharges, it permits provisions aimed at preventing future pollution.[232] Was there any basis for a regulation that would enumerate a duty for certain CAFOs to apply for a permit?[233] Given the need to address water impairment from CAFOs, and the ambiguities under the act of how to treat CAFO discharges involving the application of manure, the court might have examined the provisions as mechanisms addressing future discharges.[234]

V. Precluding Water Impairment

As EPA revises the CAFO Rule in response to the provisions vacated by the *Waterkeeper Alliance* decision, one of the key issues is precluding water impairment from owners and operators who apply manure to land.[235] In view of the finding that CAFOs with a potential to discharge cannot be regulated, fewer CAFOs may apply for permits.[236] Moreover, some CAFOs engaged in the land application of manure may claim they only have agricultural stormwater discharges and forgo applying for a permit.[237] Therefore, EPA might reexamine whether additional strategies are necessary to meet the water quality goals set by the Clean Water Act.[238] Two suggestions may be offered. First, EPA

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decree. *See* Natural Res. Def. Council v. EPA, 822 F.2d 104, 127-28 (D.C. Cir. 1987).

231. The court suggested that an amendment to the Clean Water Act or a regulatory presumption were possible ways to address potential CAFO pollution. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 506 (2d Cir. 2005).

232. *See* 33 U.S.C. §§ 1313(d)-(e), 1316(b)(1)(B) (2000).

233. The *Waterkeeper Alliance* court noted that the administrative record did not document a regulatory presumption that Large CAFOs actually discharge, so declined to make further inquiry as to the reasonableness of the CAFO Rule's duty provision. *Waterkeeper Alliance*, 399 F.3d at 506.

234. The issue involves restoring the integrity of U.S. waters through the elimination of discharges from the land application of manure that are not agricultural stormwater discharges. *See* EPA Final Rule, *supra* note 7, at 7196-98 (discussing in the preamble regulation of the land application of manure).

235. Given the zero discharge limitation on CAFO production areas, impairment of waters by CAFOs occurs from other activities including the land application of manure. *See* 40 C.F.R. §§ 412.30(a), 412.43(a)(1), 412.46(a) (2004).

236. The estimated numbers of CAFOs needing permits included CAFOs with a potential to discharge. *See* EPA Final Rule, *supra* note 7, at 7181-82 (noting in the preamble that all CAFOs have a duty to secure a permit). With the *Waterkeeper Alliance* ruling, some of these CAFOs do not need to apply for permits.

237. Because the CAFO Rule's duty provision was vacated in *Waterkeeper Alliance*, 399 F.3d at 524, CAFO owners and operators may claim the exception for agricultural stormwater discharges exempts them from the permitting requirements of the CAFO Rule.

238. The CAFO Rule was justified by calculations of estimated costs. EPA Final Rule, *supra* note 7, at 7242-52 (discussing cost estimates in the preamble). These are now

needs to revise and clarify the provision setting forth an obligation to apply for an NPDES permit.[239] Second, the certification of nutrient management plans should be considered as an option to strengthen oversight of activities connected with the impairment of waters.[240]

A. Reconsidering the Duty to Apply for a Permit

In vacating regulatory provisions that required CAFOs to apply for permits, the Second Circuit excised provisions that EPA deemed necessary to respond to the widespread noncompliance with the permitting provisions.[241] Although the court left open the possibility of establishing a regulatory presumption that a selected segment of CAFOs has discharges, the issue is a response that will be effective in placing a statutory duty on CAFOs with discharges.[242] A rather simple solution exists: all the agency needs to do is insert the phase "with a discharge" to meet the limitation that only owners and operators with discharges can be required to apply for a permit.[243]

Even if EPA were to adopt a new provision setting forth a duty to apply for a permit, there remains a question whether CAFOs with agricultural stormwater discharges accompanying the land application of manure need to apply for permits.[244] The Second Circuit declined to specifically address this issue.[245] Rather, the court differentiated agricultural stormwater discharges from "other" discharges to find that

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inaccurate due to the *Waterkeeper Alliance* holding. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 524 (2d Cir. 2005). Because EPA cannot require CAFOs with potential discharges to secure permits, the number of CAFOs required to secure permits is lower so that costs may be expected to be lower as well.

239. Although the overly broad duty provision of the CAFO Rule was vacated, alternatives exist for establishing a duty for CAFO owners and operators with a discharge to secure an NPDES permit. *See infra* note 243.

240. EPA noted that nutrient management plans were complex documents requiring considerable expertise. EPA Final Rule, *supra* note 7, at 7213 (preamble).

241. *Waterkeeper Alliance*, 399 F.3d at 524.

242. *Id.* at 506 n.22.

243. The sentence in regulation 122.21(a)(1) could be amended to read "All concentrated animal feeding operations with a discharge have a duty to seek overage under an NPDES permit, as described in § 122.23(d)." *See* 40 C.F.R. § 122.21(a)(1) (2004).

244. Due to the costs of applying for a permit and potential liability under citizen suits, CAFO owners and operators that only have agricultural stormwater discharges may forgo applying for permits. An owner or operator may use the effluent limitation guidelines of 40 C.F.R. pt. 412 for guidance in developing and implementing a nutrient management plan whereby all discharges would be agricultural stormwater discharges. *See* Jerger, *supra* note 107, at 112 (voicing concern about the avoidance of regulation under the Clean Water Act by CAFOs claiming to only have agricultural stormwater discharges).

245. The court found no authority to require potential dischargers to apply for permits. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 506 n.22 (2d Cir. 2005).

owners and operators with other discharges need to apply for a permit.[246] But what about CAFOs that allegedly only have agricultural stormwater discharges: are they required to apply for a permit?[247] While the Clean Water Act says that agricultural stormwater discharges are not point sources, it does not say they are not discharges.[248] Rather, the *Waterkeeper Alliance* decision suggests that because agricultural stormwater discharges are discharges, owners and operators with such discharges need a permit.[249]

To address the question of whether CAFOs with agricultural stormwater discharges need to apply for a permit, the *Waterkeeper Alliance* court's response to the issue of the inclusion of nutrient management plans in permits is instructive.[250] In requiring plans to be included in the permits, the Second Circuit expressed concern about the absence of oversight.[251] If plans were not included, permitting authorities could not conduct a meaningful review of whether the plans established conditions required by the Clean Water Act.[252] Permitting authorities need to review nutrient management plans in order to ascertain whether an applicant qualifies for a permit.[253] Otherwise, permits might be issued without knowing whether the owner or operator has complied with applicable effluent limitations and standards.[254]

In a similar manner, the only way to determine whether a discharge qualifies for the agricultural stormwater discharge exemption is to have a nutrient management plan included in an NPDES permit application.[255] Unless the owner or operator delineates the provisions of a plan showing

246. *Id.* at 508-09; 40 C.F.R. § 122.23(e) (2004).

247. These owners and operators may claim that the agricultural stormwater exemption means they do not have to secure a permit. Thus, it may be argued that such owners and operators are "outside the jurisdiction of the [Clean Water Act]." Jerger, *supra* note 107, at 98.

248. The CAFO has a discharge so under the Clean Water Act needs a permit. *See* 33 U.S.C. §§ 1311(a), 1342 (2000).

249. Agricultural stormwater discharges are not potential discharges but rather actual discharges that are sanctioned by federal law. *Id.* § 1362(12).

250. *See supra* notes 66-89 and accompanying text.

251. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 498-500 (2d Cir. 2005).

252. *Id.* The permitting authority could not determine whether an applicant was reducing land application discharges in a way to achieve realistic production goals while minimizing nutrient transport to surface waters. *Id.* at 500 (citing 40 C.F.R. § 412.4(c)(1)).

253. *Waterkeeper Alliance*, 399 F.3d at 502.

254. *Id.* at 498. This caused the court to vacate provisions that allowed permitting authorities to issue permits without reviewing the terms of the nutrient management plans. *Id.* at 524.

255. Without a nutrient management plan, the permitting agency cannot determine whether a discharge qualifies as an agricultural stormwater discharge. In the absence of review by a permitting agency, there is nothing from preventing a CAFO from misunderstanding or misrepresenting their situation. *Id.* at 502.

that the application of nutrients will achieve production goals while minimizing nutrient movement to surface waters,[256] the permitting agency and the public cannot ascertain whether the discharges qualify for the exemption.[257] Given evidence of water impairment from the application of manure, and from the *Waterkeeper Alliance* court's finding that agricultural stormwater discharges are discharges, it may be concluded that CAFOs with agricultural stormwater discharges need to be permitted.[258] The permit applications would establish whether the CAFOs discharges are exempted by the agricultural stormwater exemption.[259]

B. Certification

In its discussion of the CAFO Rule, EPA acknowledged that nutrient management plans were complex documents.[260] Furthermore, EPA admitted that there was considerable support for requiring plans prepared by trained and certified specialists.[261] Certification is a technique that uses independent experts to ascertain that minimum standards are met.[262]

For the CAFO Rule, certification would provide greater oversight of nutrient management plans to assure that the plans are appropriately tailored to the site-specific needs and conditions at each CAFO.[263] However, EPA elected not to include a certification requirement in the CAFO Rule, noting that a short-term scarcity of qualified experts would

256. 40 C.F.R. § 412.4(c)(1) (2004).

257. The only way to determine whether a discharge is an agricultural stormwater discharge is to determine whether the manure was applied according to the site-specific nitrogen- or phosphorus-based rate mandated by the CAFO Rule. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 501 (2d Cir. 2005); 40 C.F.R. § 412.4(c)(1) (2004).

258. *Waterkeeper Alliance*, 399 F.3d at 511. "[A]ny discharge 'from' a CAFO is already a point source discharge." *Id.*

259. The permits would not preclude agricultural stormwater discharges; rather, they would ascertain that the discharges qualify for the exemption.

260. EPA Final Rule, *supra* note 7, at 7213 (preamble).

261. *Id.*; 33 U.S.C. § 1362(12) (2000).

262. *See, e.g.*, H.R. Barrett, A.W. Browne, P.J.C. Harris, & A. Cadoret, *Organic Certification and the UK Market: Organic Imports from Developing Countries*, 27 FOOD POL'Y 301 (2002) (discussing the meaning of the certification of organic produce); Clyde F. Kiker & Francis E. Putz, *Ecolocical (sic) Certification of Forest Products: Economic Challenges*, 20 ECOLOGICAL ECON. 37 (1996) (discussing the advantages for a certification program for forestry products); Ewald Rametsteiner & Markku Simula, *Forest Certification: An Instrument to Promote Sustainable Forest Management?*, 67 J. ENVTL. MGMT. 87, 88 (2003) (discussing certification with respect to preserving forests and preventing the loss of biodiversity).

263. EPA Final Rule, *supra* note 7, at 7228 (preamble). "The purpose of using certified specialists is to ensure that effective nutrient management plans are developed and/or reviewed and modified by persons who have the requisite knowledge and expertise. . . ." *Id.*

make it difficult to assist CAFOs in the timely preparation of certified nutrient management plans.[264] This was due to an estimate that 11,000 CAFOs would need a plan in order to secure a permit under the CAFO Rule.[265] However, since the adoption of the CAFO Rule, many CAFOs have adopted nutrient management plans and have secured five-year permits.[266] Other CAFOs will not need permits due to the *Waterkeeper Alliance* decision.[267] Therefore, a requirement that future nutrient management plans be prepared or approved by certified specialists may be feasible as it would not overburden the existing infrastructure capacity.[268]

As noted by the *Waterkeeper Alliance* court, the omission of a certification requirement detracts from the enforcement of the water quality control measures of the federal CAFO provisions.[269] Certification serves as an ongoing quality control component to help assure that high-quality plans are being developed.[270] Producers might be expected to develop inferior plans in the absence of certification that will result in more nutrients entering waterbodies.[271] Moreover, certification might reduce the time needed for oversight by state regulators,[272] which could free up resources for other enforcement

264. *Id.* at 7213 (preamble).

265. In announcing the CAFO Rule, EPA estimated that it would apply to 15,500 livestock operations of which 4,500 were covered by permits. EPA AND AGRICULTURE WORKING TOGETHER TO IMPROVE AMERICA'S WATERS (EPA Newsroom, Dec. 16, 2002), http://yosemite.epa.gov/opa/admpress.nsf/b0789fb70f8ff03285257029006e3880/90cd807b5f2798d985256c9100706a22!OpenDocument (last visited May 15, 2006).

266. New York feels that participation of Large CAFOs in the permitting process is 100 percent. Karl Czymmek, et al., *The New York CAFO Program: Successfully Connecting Science, Policy, Regulation, and Implementation*, 35 CLEARWATERS 27 (Spring 2005), *available at* http://www.nywea.org/clearwaters/05-spring/. Wisconsin shows a marked increase in the number of permitted CAFOs since 2000. WIS. DEP'T OF NATURAL RES., STATISTICS ON WISCONSIN CONCENTRATED ANIMAL FEEDING OPERATIONS (CAFOs), http://www.dnr.state.wi.us/org/water/wm/nps/ag/stats.htm (last visited May 15, 2006). EPA anticipated that NPDES permits for CAFOs would be for 5 years and that nutrient management plans would be updated every 5 years. EPA Final Rule, *supra* note 7, at 7253 (preamble).

267. Those owners and operators without a discharge will not need a permit. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 506, 524 (2d Cir. 2005).

268. EPA referred to "infrastructure capacity" when considering effluent limitations for Large CAFOs. EPA Final Rule, *supra* note 7, at 7213 (preamble).

269. *Waterkeeper Alliance*, 399 F.3d at 501 n.19.

270. JESSICA A. CHITTENDEN, N.Y. STATE DEP'T OF AGRIC. & MKTS., STATE HELPS FARMERS MEET WATER QUALITY OBJECTIVES (2003), *available at* http://www.agmkt.state.ny.us/AD/release.asp?ReleaseID=1270.

271. *Waterkeeper Alliance*, 399 F.3d at 501 n.19.

272. *See, e.g.*, Cary Coglianese & Jennifer Nash, *Policy Options for Improving Environmental Management in the Private Sector*, 44 ENV'T 11, 12 (2002) (noting that environmental management systems encouraging desirable environmental outcomes may assist enforcement agencies with scarce resources).

efforts.[273] The implementation of a certification program for nutrient management plans might reduce the time required by state staff to evaluate permit applications.[274]

Since the federal government has not called for the certification of nutrient management plans, states might initiate such a requirement.[275] New York requires that its comprehensive nutrient management plans be developed or reviewed by a certified agricultural environment planner.[276] Wisconsin includes provisions setting forth competency requirements for persons preparing nutrient management plans.[277] Qualified nutrient management planners have basic training, and persons without qualification can be precluded from preparing plans.[278] By requiring

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273. It is argued that states have not been overly active in enforcing water quality regulations. *See, e.g.*, U.S. GEN. ACCOUNTING OFFICE, LIVESTOCK AGRICULTURE: INCREASED EPA OVERSIGHT WILL IMPROVE ENVIRONMENTAL PROGRAM FOR CONCENTRATED ANIMAL FEEDING OPERATIONS (2003) (recommending that EPA increase its oversight of state CAFO regulations); Centner, *supra* note 30, at 710-18 (noting problems in the enforcement of CAFO regulations).

274. Permitting agencies would have assurance that nutrient management plans were prepared by trained professionals. In turn, the plans should be easier to read and would more likely meet regulatory requirements. This may be helpful to permitting authorities that have limited resources. *See, e.g.*, Terence J. Centner, *New Regulations to Minimize Water Impairment from Animals Rely on Management Practices*, 30 ENV'T INT'L 539, 544 (2004) (noting constraints on the enforcement of CAFO regulations due to limited funds in state budgets).

275. EPA noted that certification should be developed by the U.S. Department of Agriculture or the states. EPA Final Rule, *supra* note 7, at 7228 (preamble). Some states have proceeded to implement certification requirements. *See, e.g.* N.Y. DEP'T OF ENVTL. CONSERVATION, STATE POLLUTANT DISCHARGE ELIMINATION SYSTEM (SPDES) GENERAL PERMIT NO. GP-04-02 (2004), *available at* http://www.dec.state.ny.us/website/dow/gp0402permit.pdf [hereinafter N.Y. DEC]; WIS. AGRIC., TRADE & CONSUMER PROT. 50.48 (2004), *available at* http://www.legis.state.wi.us/rsb/code/atcp/atcp050.pdf [hereinafter WIS. ATCP].

276. N.Y. DEC, *supra* note 275.

277. WIS. ATCP, *supra* note 275, at 50.48.

> An individual is considered a qualified nutrient planner under sub. (1), without any action by the department, if all of the following apply: (a) The individual is at least one of the following: 1. Recognized as a certified professional crop consultant by the national alliance of independent crop consultants. 2. Recognized as a certified crop advisor by the American society of agronomy, Wisconsin certified crop advisors board. 3. Registered as a crop scientist, crop specialist, soil scientist, soil specialist or professional agronomist in the American registry of certified professionals in agronomy, crops and soils. 4. The holder of other credentials that the department deems equivalent to those specified under subds. 1. to 3. A landowner is presumptively qualified to prepare a nutrient management plan for his or her farm, but not for others, if the landowner completes a department-approved training course and the course instructor approves the landowner's first annual plan. The landowner shall complete a department-approved training course at least once every 4 years to maintain his or her presumptive qualification.

Id. 50.48(2)(a).

278. The Wisconsin regulations allow the permitting authorities to issue a written

plans to be prepared or reviewed by trained personnel, the permitting agency has an added level of assurance that the plans delineate appropriate conditions for avoiding situations that would impair water quality.[279]

VI. Concluding Comments

As a result of a legal challenge in 1989, EPA was directed to revise the federal effluent guidelines for certain CAFOs by December 15, 2002.[280] The agency needed to comply with the requirements of the Clean Water Act while minimizing regulatory burdens on CAFOs that might interfere with their competitiveness in a global economy.[281] The final regulations, which became effective in 2003, contained provisions that were objectionable to farm and environmental groups, who sought relief from the judiciary.[282] In a well-reasoned opinion, the Second Circuit provided responses to three significant issues concerning the new regulations in the *Waterkeeper Alliance* lawsuit.[283] First, the court vacated provisions that allowed permitting authorities to issue permits without reviewing nutrient management plans.[284] Second, the court upheld provisions on agricultural stormwater discharges that delineated qualifications for these discharges.[285] Third, provisions delineating a duty requirement to apply for a permit regardless of the presence of a discharge were vacated.[286]

In addressing the issue of nutrient management plans, the Second Circuit showed support for assisting permitting authorities and private citizens in upholding water quality controls.[287] Nutrient management

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notice of disqualification if a nutrient management planner lacks qualifications. *Id.* 50.48(4).

279. Rametsteiner and Simula, *supra* note 262, at 88 (noting how certification can help assure the quality of forest management); James P. Wilson, Mary Ann T. Walsh, & Kim LaScola Needy, *An Examination of the Economic Benefits of ISO 9000 and the Baldrige Award to Manufacturing Firms*, 15 ENGINEERING MGMT. J. 3, 3 (2003) (noting how certification enhances quality control).

280. EPA Final Rule, *supra* note 7, at 7186 (noting in the preamble the consent decree requiring action to address water impairment by CAFOs).

281. *E.g.*, *see id.* at 7353-54 (listing in the preamble burden and cost estimates), 7354-57 (noting consideration of burdens to small operators). EPA estimated the new provisions might impose costs of $831-925 million annually on livestock producers. EPA Proposed Rule, *supra* note 9, at 3086 (preamble).

282. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 486-524 (2d Cir. 2005).

283. The court also addressed other issues not covered in this article. *Id.*

284. *Id.* at 524. Pursuant to this directive, owners and operators will be required to submit plans in applications for permits, and permitting agencies will be required to review more detailed permit applications.

285. *Id.* at 509.

286. *Id.* at 524.

287. *See supra* notes 43-106 and accompanying text.

plans need to be submitted to the permitting agency and reviewed prior to the issuance of a permit in order to determine whether the dictates of the Clean Water Act are being followed.[288] It may be expected that CAFO owners and operators will need to take greater efforts in preparing plans due to the possible public scrutiny of these documents.[289] Permitting agencies will need to spend more time reviewing permits to ascertain that they meet the requirements set forth by the federal regulations and the Clean Water Act.[290]

For agricultural stormwater discharges, the court showed flexibility and a willingness to defer to agency discretion.[291] The court found that agricultural stormwater discharges are discharges[292] and that runoff from the land application of manure can be regulated even though fields are not point sources.[293] This holding means that CAFOs applying manure to land can have discharges that need to be permitted under the CAFO Rule.[294]

The Second Circuit was not as supportive of the regulatory provisions imposing a duty to secure NPDES permits on CAFOs without actual discharges.[295] Although the rule provided an exception whereby CAFOs with no potential to discharge are not required to secure a permit,[296] the court felt that the rule imposed obligations on CAFO owners and operators regardless of whether they had discharged any

288. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 501-02 (2d Cir. 2005).

289. *See supra* note 57 and accompanying text.

290. They need to determine whether the manure application rates are based on a field-specific assessment of the potential for nitrogen and phosphorus transport from the field. 40 C.F.R. § 412.4(c)(1) (2004); *see also Waterkeeper Alliance*, 399 F.3d at 501.

291. *Waterkeeper Alliance*, 399 F.3d at 507-10; *see also supra* notes 147-166 and accompanying text. The court concluded that Congress had not addressed the precise issue so proceeded to determine whether EPA's interpretation was grounded in a permissible construction of the Clean Water Act. *Id.* at 507 (citing Chevron U.S.A., Inc. v. Natural Res. Def. Council, 467 U.S. 837, 843 (1984)). *See, e.g.*, Baltimore Gas & Elec. Co. v. Natural Res. Def. Council, 462 U.S. 87, 104-05 (1983) (observing that if an agency's assumption is within the bounds of reasoned decision-making, it should be respected); Nat'l Wildlife Fed'n v. EPA, 286 F.3d 554, 562-65 (D.C. Cir. 2002) (observing the discretion that should be granted an agency in reviewing an action).

292. Discharges from the land application of manure are discharges from a CAFO. *Waterkeeper Alliance*, 399 F.3d at 510-11.

293. *See* 40 C.F.R. §§ 122.42(e)(1)(iv) [requiring conservation measures to control runoff of pollutants], 412.4(c) [requiring best management practices and determining application rates to minimize nutrient transport from fields] (2004). Due to the fact that land application areas are an integral and indispensable part of CAFO operations, EPA can regulate runoff from these areas as runoff from a CAFO. *Waterkeeper Alliance*, 399 F.3d at 511.

294. The court noted that approximately 90 percent of animal waste from CAFOs was being applied to land. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 494 n.11. (2d Cir. 2005).

295. *See supra* notes 181-200 and accompanying text.

296. 40 C.F.R. § 122.23(f), (g)(6) (2004).

pollutants to navigable waters.[297] This was contrary to the requirement that permits are required for discharges, not potential discharges.[298]

By vacating the duty provisions, the *Waterkeeper Alliance* decision impedes EPA's efforts to regulate CAFOs employing manure application activities that impair water quality.[299] Because discharges are not allowed from CAFO production areas,[300] EPA concluded that significant impairment of waters comes from the application of CAFO manure on fields.[301] While CAFOs that have discharges must secure permits[302] and CAFOs without any likelihood of a discharge do not need a permit,[303] a more difficult question involves CAFOs with agricultural stormwater discharges.[304] An anticipated result of the *Waterkeeper Alliance* ruling may be that owners and operators of CAFOs with agricultural stormwater discharges will claim they do not need permits.[305] Will the CAFO Rule assist our nation in meeting the legislatively adopted water quality goals if significant numbers of CAFOs decline to secure permits?[306]

CAFOs are classified as point sources of pollution and need permits if they have discharges.[307] Simultaneously, point sources do not include agricultural stormwater discharges, so these discharges are exempted from the NPDES permitting provisions.[308] The Second Circuit reasoned that while agricultural stormwater discharges themselves did not constitute a point source, runoff from CAFOs were "from" a point source.[309] Therefore, the EPA can regulate runoff from CAFO land

297. *Waterkeeper Alliance*, 399 F.3d at 505.

298. 33 U.S.C. § 1311(a) (2000).

299. *See supra* note 9 (showing data whereby few CAFOs were securing NPDES permits).

300. 40 C.F.R. §§ 412.12(a), 412.13(a), 412.15(a), 412.25(a), 412.31(a), 412.46(a) (2004).

301. *See* EPA Final Rule, *supra* note 7, at 7237 (preamble); *Waterkeeper Alliance*, 399 F.3d at 495 (2d Cir. 2005).

302. This would include all medium CAFOs with discharges. 40 C.F.R. § 122.23(b)(6)(ii) (2004); *see also* Save the Valley, Inc. v. EPA, 223 F. Supp. 2d 997, 1007 (S.D. Ind. 2002) (observing that any CAFO that discharges needs a permit).

303. The Clean Water Act requires permits for discharges, not potential discharges. *See* 33 U.S.C. § 1311(a) (2000).

304. *See infra* notes 235-259 (observing that oversight may be necessary to assure compliance).

305. By claiming they only have agricultural stormwater discharges, owners and operators argue they are not under the jurisdiction of the Clean Water Act. *See* Jerger, *supra* note 107, at 112.

306. *See id.* Two years after the implementation of the CAFO Rule, nearly 60 percent of CAFOs still have not been issued permits. OFFICE OF WATER, EPA, CAFO RULE IMPLEMENTATION STATUS – NATIONAL SUMMARY, FIRST QUARTER (2005).

307. 33 U.S.C. §§ 1342(a)-(b), 1362(14) (2000).

308. *Id.* § 1342(a)-(b).

309. Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486, 511 (2d Cir. 2005).

application areas that is not agricultural stormwater discharge.[310]

Under this interpretation of federal law, EPA should assert its jurisdiction over all CAFOs with discharges and require them to apply for NPDES permits.[311] The permits cannot interfere with agricultural stormwater discharges due to the statutory exemption for these discharges.[312] However, the only way for permitting authorities to determine whether nutrient management plans set forth required effluent limitations to preclude disallowed discharges is to require all CAFOs with any type of runoff to apply for a permit.[313]

Permitting does offer owners and operators some advantages. Owners and operators with permits cannot be penalized for failure to file for a permit.[314] For CAFO production areas, although no discharges are allowed,[315] overflows arising from a precipitation event may be discharged if enumerated conditions are met.[316] CAFOs that experience rainfall events causing an overflow can thereby avoid penalties.[317]

Greater attention should also be given to the certification of nutrient management plans.[318] Given that CAFOs and permitting agencies have had more than two years to implement the provisions of the CAFO Rule, sufficient infrastructure should exist for a certification requirement.[319]

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310. *Id.*; 33 U.S.C. § 1362(14) (2000).

311. Jurisdiction exists due to the presence of a discharge. 33 U.S.C. §§ 1311(a), 1342 (2000).

312. *Id.* § 1362(14).

313. *Id.*; 40 C.F.R. pts. 122, 412 (2004) (qualified by *Waterkeeper Alliance*, 399 F.3d at 486).

314. While the duty to apply for a permit was overturned by the *Waterkeeper Alliance* case due to its application to CAFOs without discharges, there still may exist an obligation to apply for a permit if there is a discharge. *See, e.g.*, Waterkeeper Alliance, Inc. v. Smithfield Foods, 2001 U.S. Dist. LEXIS 21314, at *7 (E.D. N.C. Sept. 20, 2001) (observing that a CAFO's failure to have a required permit can constitute an independent violation of the Clean Water Act); Carr v. Alta Verde Indus., 931 F.2d 1055, 1062 (5th Cir. 1991) (observing that a failure to obtain an NPDES permit was a violation of the Clean Water Act).

315. 40 C.F.R. §§ 412.12(a), 412.13(a), 412.15(a), 412.25(a), 412.31(a), 412.46(a) (2004).

316. 40 C.F.R. § 412.31(a) (2004).

317. *Id.*

> Whenever precipitation causes an overflow of manure, litter, or process wastewater, pollutants in the overflow may be discharged into U.S. waters provided: (i) The production area is designed, constructed, operated and maintained to contain all manure, litter, and process wastewater including the runoff and the direct precipitation from a 25-year, 24-hour rainfall event; (ii) The production area is operated in accordance with the additional measures and records required by § 412.37(a) and (b).

Id.

318. This is to help the country attain its water quality goals.

319. When the rule was adopted in December 2002, there was concern about an adequate infrastructure. EPA Final Rule, *supra* note 7, at 7213 (preamble). The same

While a federal certification provision is possible, in its absence, states should proceed with their own provisions.[320] Certification would foster the development of better nutrient management plans that might be expected to reduce the impairment of waters.[321] In turn, certification might reduce the need for the further regulation of additional CAFOs.[322]

concern may no longer exist.

320. N.Y. DEC, *supra* note 275; WIS. ATCP, *supra* note 275, at 50.48.

321. *See supra* notes 275-279 and accompanying text.

322. The proposed CAFO regulation delineated alternative provisions whereby approximately 25,540 operations rather than 12,700 would be required to apply for a permit. EPA Proposed Rule, *supra* note 9, at 2985, 2997 (preamble).

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Review

Climate Change and Livestock Production: A Literature Review

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Abstract: Globally, the climate is changing, and this has implications for livestock. Climate affects livestock growth rates, milk and egg production, reproductive performance, morbidity, and mortality, along with feed supply. Simultaneously, livestock is a climate change driver, generating 14.5% of total anthropogenic Greenhouse Gas (GHG) emissions. Herein, we review the literature addressing climate change and livestock, covering impacts, emissions, adaptation possibilities, and mitigation strategies. While the existing literature principally focuses on ruminants, we extended the scope to include non-ruminants. We found that livestock are affected by climate change and do enhance climate change through emissions but that there are adaptation and mitigation actions that can limit the effects of climate change. We also suggest some research directions and especially find the need for work in developing country settings. In the context of climate change, adaptation measures are pivotal to sustaining the growing demand for livestock products, but often their relevance depends on local conditions. Furthermore, mitigation is key to limiting the future extent of climate change and there are a number of possible strategies.

Keywords: livestock production; adaptation; mitigation

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1. Introduction

Livestock products and services play an important role for humans. Globally, livestock occupy about 26% of the ice-free land with one-third of the cropland being used for feed production [1]. Livestock production generates nearly 40% of global agricultural gross domestic product (GDP). Livestock provide 33% of the global protein and 17% of the global calories consumed. Production creates substantial employment opportunities for rural households [2,3]. Additionally, livestock are a major provider of food, nutritional security, livelihood, and income in developing countries [4].

Driven by population and income growth plus urbanization, the demand for livestock products is growing rapidly. Simultaneously, livestock production is facing increasing pressure from climate change effects, such as increasing temperatures, more variable precipitation patterns, more frequent extreme events, and increasing carbon dioxide concentrations [5]. Such changes have been found to impact livestock performance across many regions and are projected to have growing impacts. Predictive models broadly indicate the impact will be negative [6]. Meanwhile, livestock are a direct source of both methane and nitrous oxide and an indirect source of those gases and carbon through land use and feed production. Globally, the livestock emissions share is an estimated 14.5% of total anthropogenic emissions [7].

The interaction between ongoing climate change and demands for increasing livestock production makes it challenging to increase production while lowering climate impacts and Greenhouse Gas (GHG) emissions. Addressing such challenges requires an understanding of climate change effects on livestock production, as well as the effect of both adaptation and mitigation actions. This paper overviews climate change impacts on livestock production, livestock emissions, and possible adaptation and mitigation actions. In constructing this

review, we relied on material from 157 references, with the papers classified as shown in Table 1.

Table 1. Counts of papers used in the review by category.

Category	Sub-Category	Number of Papers Cited
By topic	Climate change impacts and adaptation	95
	Livestock emissions and mitigation	27
	Comprehensive treatment	31
By year	Before 2000	12
	2000 to 2010	39
	2011 to 2021	102
By region	North America	42
	Europe	14
	Asia	8
	Africa and Australia	8
	Region not specified	40
	Multi-region/global	41
By livestock species	Ruminants	41
	Hogs	15
	Poultry	18
	Not livestock	32
	Multiple livestock	47

2. Impact of Climate Change on Livestock Production

The climate is changing, exhibiting higher temperatures, increasing precipitation variation, and more frequent extremes. This is driven by increasing carbon dioxide (CO_2) concentrations. Such changes have been found to alter livestock and associated feed production. We will follow Collier [8] and broadly divide the impacts into direct and indirect effects: Direct effects refer to climate and CO_2 impacts on livestock thermoregulation, metabolism, immune system function, and production. Indirect effects derive from the influence of climate on feed production, water availability, and pest/pathogen populations. A brief summary of the impacts appears in Table 2. In addition, the impacts are elaborated below.

Table 2. Climate change impacts on livestock production.

Impact Type	Observed Impacts	Major Influential Factors
Direct Impact	Reduced feed intake	Increased temperature (heat stress)
	Decline in animal milk and meat production	
	Decreased reproductive performance	
	Negatively affected immune functions	
	Increased mortality	
Indirect Impact	Changes in feedstuff crop yields	Elevated CO_2 level
	Changes in pasture composition and forage production	
	Changes in forage quality	Increased temperature and elevated CO_2 level
	Shrinking water availability and increasing water use	Increased temperature
	Larger seasonal variation in resource availability	More frequent extreme climate events
	Increased disease, pest, and parasite stress	Increased temperature and changes in the precipitation pattern

2.1. Direct Effects

The thermal environment is the major climatic factor that affects animal production. This involves a combination of air temperature, humidity, and air movement [9]. The relationship describing the best conditions of these is often referred to as the thermal comfort zone. In this zone, animals exhibit optimum performance and minimal energy expenditure [10]. When conditions rise above this zone, extra energy is required to maintain thermoregulation and production processes become less effective [11]. Animals suffer from thermal stress when the environmental temperature deviates outside the thermal comfort zone. The phenotypic response of animals to an individual source of stress can be called acclimation [12,13]. Heat stress is more problematic and has a greater effect than cold stress [14,15]. Climate change is also almost certainly increasing temperatures and, in association, increasing heat stress and lowering cold stress. Therefore, heat stress has been the dominant topic within the discussion of thermal stress.

Heat stress has been found to have negative effects on livestock. The estimated annual U.S. livestock industry loss caused by heat stress falls between $1.7 and $2.4 billion [16]. Heat stress occurs when animals are not able to dissipate sufficient heat to keep homeothermy [17]. This has been found to lead to increased respiration, pulse, and heart rate, along with increased body temperatures [18]. In turn, this can result in reduced feed intake, milk production, and reproduction efficiency, as well as changes in mortality and immune system function. Below, we discuss these impacts in more detail, with emphasis on animal performance rather than underlying biological mechanisms.

2.1.1. Feed Intake

Reduced feed intake is one response to high environmental temperatures. Ruminants experience reduced appetite, gut motility, and rumination under increased heat stress [19,20]. Lactating dairy cows exhibit a reduction in feed intake as ambient temperatures rise above 25–26 °C and show more rapid declines above 30 °C [21]. Goats are less susceptible to heat stress than other ruminants. However, their voluntary feed intake declines when the ambient temperature is more than 10 °C above their thermal comfort zone [22].

Hogs exposed to heat stress exhibit increased body temperature, and their feed intake decreases by 10.9% when temperatures increase from 20 to 35 °C [23]. Such impacts persist beyond the period when the hogs are exposed to heat stress. Hence it is suggested that feeding in early morning hours could help avoid reduced feed intake [24].

Poultry animals also exhibit reduced feed intake when exposed to high temperatures. An increase in ambient temperature from 21.1 to 32.2 °C has been found to lead to a 9.5% drop in feed intake for birds from the post-hatch period to 6 weeks of age [25]. The reduction in feed intake causes decreased feed conversion efficiency and daily weight gain [26–29].

More generally, across all the livestock types, heat-stress-related decreased feed intake leads to decreased milk, meat, and egg production, which in turn leads to further sectoral losses.

2.1.2. Animal Production: Milk and Others

Studies indicate that the dairy industry suffers greater heat-stress-related economic loss than does the other U.S. livestock sectors [16]. Under heat stress, dairy cows reduce feed dry matter intake and this explains approximately 35% of the decrease in milk production [30]. Meanwhile, as high-producing dairy cows are larger and emit more metabolic heat than lower-producing breeds, the most productive breeds exhibit more sensitivity to heat stress [3]. As a consequence, milk production declines as heat-stress-caused metabolic heat production increases [21]. In addition to milk production, hot and humid environments also affect milk composition. Ravagnolo et al. [31] and Gorniak [32] have indicated that lactating cows start to suffer from heat stress at a temperature–humidity index of 72 and above this level, milk protein and milk fat content declines as the index increases.

Similar changes in milk composition have been found for dairy goats [33] and buffaloes [34] but have only been narrowly studied.

Meat production has been found to be affected by heat stress for all major commercial livestock types [35]. Heat-stressed ruminants exhibit reduced body size, carcass weight, and fat thickness and lower meat quality [10,36,37]. Small ruminants, such as goats and sheep, have been found to be more adapted to a hot and humid environment [38]. However, feedlot cattle have been found to be more vulnerable due to their being raised with greater exposure to rough radiant surfaces and fed high-energy diets [35,39].

Similar to ruminants, hogs exhibit reduced carcass weight and meat quality when exposed to a high temperature [40]. Under high ambient temperature, they have also been found to exhibit reduced average daily gain of 9.8% when compared to thermoneutral animals [41].

Chickens exposed to heat stress increase energy expenditure to maintain thermoneutral conditions at the expense of growth [42]. Heat-stressed broilers exhibit reduced weight gain, feed conversion rates, protein concentration, and breast muscle weight [43–45]. For laying hens, egg shell strength, daily feed intake, egg mass, and egg production are more sensitive to heat stress compared to other traits [46]. In addition, significant declines in egg shell quality and egg production are observed in breeders [47]. The reduction in egg quality and production caused by heat stress can be mediated by alterations in dietary calcium [48].

2.1.3. Reproduction

Heat stress affects reproduction for both sexes. For females, heat stress reduces estrous period and fertility while increasing the incidence of anestrous and embryonic death. For males, there are declines in semen quality, testicular volume, and quantity of fertile sperm. Significant seasonal differences in reproductive performance in both sexes have been reported [49].

Although poultry reproduction is also affected by heat stress, birds may exhibit a difference in performance compared to mammals. Male broilers are reported to be more sensitive to heat-related infertility than female broilers [50]. For layers, environmental stress could delay the process of ovulation, reduce yolk quality, and affect hatchability [51].

2.1.4. Disease and Parasite Stress

Many factors, including species, breed, geographical location, disease characteristics, and animal susceptibility, contribute to the effects of climate change on livestock health [52]. In terms of animals themselves, the immune system is their major body defense that protects them from environmental stressors and other noxious insults [53]. Heat stress can negatively affect immune functions via cell-mediated and humoral immune responses [54]. As a result, periods of hot weather can cause livestock to be more vulnerable to diseases and raise the incidence of certain diseases (such as mastitis), leading to an increased potential of morbidity and death [55–57].

In addition, heat stress could affect the health condition of livestock through other functional pathways. For example, growing hogs may suffer from intestinal injuries if exposed to acute heat for several hours [28]. Broilers and laying hens are also reported to experience intestinal microbiota alterations under heat stress [58,59].

Simultaneously, increased temperature and altered precipitation may accelerate the incidence of pathogens and parasites. Although the effect of pathogens and parasites on livestock is generally regarded as an indirect effect, it is covered in this section since it is usually discussed in conjunction with animal health. This would affect the distribution and abundance of vector-borne pests and introduce new diseases [52,60]. These may increase the potential for morbidity/mortality and associated economic loss [61]. Compared to other impacts, climate change effect on livestock disease is more difficult to estimate and predict due to the nature of disease and climate-change-driven alterations to livestock. Such impact assessment is even more challenging in developing countries [52,61].

2.1.5. Mortality

Mortality is an important heat stress impact that has significant associated economic loss. Studies on dairy cows and hogs show that added heat stress increases mortality rates [62–64]. Hot and humid weather has been found to be more life threatening to cows and hogs compared to hot but dry conditions, and a temperature higher than 37.7 °C with over 50% humidity was shown to be detrimental [65].

For poultry, the body temperature of birds is usually higher and more variable than that of mammals and they are more sensitive to rising temperature. Chickens can function normally up to ambient temperature of 27 °C or a body temperature of 41 °C, but an increase of 4 °C in body temperature would be lethal to them [66].

2.2. Indirect Effects

Livestock feed is mostly composed of forages and grain/oilseed crop product. Production of those items is affected by climate, as are water supplies, both through irrigation and soil moisture. Thus climate change indirectly imposes effects, mainly through its impacts on feed supply and water. There exists a huge body of literature focusing on climate change impacts on crop production, and herein we are not trying to cover the details of this research area (for a review, see Reilly et al. [67], Shukla et al. [68], and IPCC [69]). In terms of solely livestock production, crops and forages provide feedstocks consumed by livestock. In this regard, climate change affects the supply of livestock feed but the magnitude of this impact on livestock production while commonly discussed has not been separately evaluated. We discuss the general aspects of this discussion in the remainder of this section.

First, let us introduce some terminology. The International Forage and Grazing Terminology Committee [70] defines forage as "edible parts of plants that can provide feed for grazing animals or that can be harvested for feeding." Forage plants can be roughly divided into two large groups: grasses and legumes. Besides these two groups, forage plants include others, such as woody species. As they are usually not considered as major feed for domestic animals and the impacts of climate change on woody species feed have not been well investigated, we will not cover them in this review. Two relevant studies to refer to are Papanastasis et al. [71] and Hejcman et al. [72]. Legumes can be grouped into cool season (C3) and warm season categories (C4) based on leaf anatomy [73]. Increases in atmospheric CO_2 and temperature are alter forage quantity and quality, with the magnitude dependent on the livestock system [74], location, and species. Precipitation patterns and extreme climate events are also influential, with the main impacts being production variation. Other influential factors include water supplies, which will be discussed in more detail below.

CO_2 contributes to crop growth [75]. C3 crop (soybeans, cotton, and wheat) yields increase under increased CO_2 concentrations, while yields of C4 crops (corn and sorghum) do not directly respond to the elevated CO_2 but may indirectly benefit under drought. Other climatic factors that affect livestock feed supply quantity are precipitation; temperature; and extreme events, such as drought. Increased precipitation is beneficial to corn, sorghum, rice, and soybean [76,77]. As for temperature, C4 species enjoy greater effects from temperature rise, but such effects depend on location, plant species, and production system [52,78]. Drought causes significant crop yield reductions, especially in hot regions [79,80]. A recent study in Europe found that drought stress is the main driver of losses for corn and winter wheat, especially in low-yielding years [81]. These climatic factors are often confounded, and their effects on vegetation growth are not easy to isolate. For example, higher temperatures at lower latitudes may be associated with higher water stress, while higher temperatures at higher latitudes may increase suitability for cropping and expand the length of the growing season.

Grass forage supplies are also affected by climate change. In terms of grassland and pasture, increases in average temperature bring significant changes in pasture composition, patterns, and biome distribution. Changes in precipitation patterns and more frequent droughts may lead to shorter pasture growing periods. Some research has indicated

that changes in temperature, CO_2 levels, and nitrogen deposition decrease the primary production in pasture [82], while some argue that higher temperatures favor grasses over forbs and legumes.

2.2.1. Forage Quality

Adequate nutrition is critical to weight gain, production, and reproduction, and forage is an important nutrition component for ruminants. As forage quality varies greatly within and between forage crops and nutritional needs vary among animal species, providing suitable feed to animals requires a balance. Most forage-quality studies have focused on digestibility, nutritive value, voluntary intake, and effects of anti-quality factors [83]. Forages of higher digestibility supply more energy per unit dry matter (DM) consumed. Nutritive values reported by forage analysis usually include neutral detergent fiber (NDF); acid detergent fiber (ADF); crude protein (CP); and minerals, such as calcium (Ca), phosphorus (P), magnesium (Mg), and potassium (K) [84]. Quality can be affected by climate through increased temperatures and dry conditions, which cause variations in concentrations of water-soluble carbohydrates and nitrogen [82]. Forage quality may also increase due to an increase in nonstructural carbohydrates resulting from elevated CO_2 level [85]. However, quality may also decrease since rising temperatures can increase lignin within plant tissues and therefore reduce digestibility [86]. Lee et al. [87] suggest that increasing temperature reduces forage nutritive values and correspondingly may lead to higher methane production.

2.2.2. Water

Water is scarce worldwide, and the magnitude of water scarcity depends on the supply relative to the demand. Agriculture is the single largest global water user, accounting for 69% of fresh water withdrawals [88]. As human populations, incomes, and livestock product demand increase, water scarcity will likely grow in importance as a constraint on production agriculture. The livestock sector uses water for consumption by animals, growing feed crops, and product processing [52]. It accounts for about 22% of the total evapotranspiration (ET) from global agricultural land and 41% of total consumptive water use [89].

Climate change is projected to change water availability [69,90] and water usage in animal production [3]. Rising temperatures are likely to increase per animal and per land area animal water consumption and irrigation water use [91,92]. Water salination caused by sea-level rise is another concern [93,94]. Competition for water between livestock, crops, and nonagricultural uses will increase in the coming decades, and it requires more efficient production systems to address water scarcity issue [95].

2.2.3. Seasonal Variation and Extreme Climate Events

Climate change may alter the seasonal pattern and variability of resource availability and crop yield [96,97], imposing further impacts on livestock production. As the frequency and duration of heat waves increase, animals will suffer from additional heat stress [62]. Knee et al. [98] found significant seasonal differences in cattle muscle glycogen and also that conditions with nutritious and abundant pastures coincide with better beef quality in spring and that worse pastures coincide with worse beef quality in summer. Moreover, changes in seasonal patterns of forage availability could bring additional challenges for grazing management and livestock management [99]. Increasing risk of extreme drought threatens forage quantity, and adaptation strategies are required to cope with such extreme events [100]. In addition, changes in snow melt timing alter water availability patterns during the year, which affects feed supplies [96,101].

3. Impact of Livestock Production on GHG Emissions

Livestock is a substantial contributor to global GHGs, with emissions estimated at 8.1 gigatons of CO_2-eq per annum or 14.5% of total anthropogenic emissions [7]. The three

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The GLEAM results indicate that emissions from livestock supply chains consist of 50% methane (CH_4), 24% nitrous oxide (N_2O), and 26% carbon dioxide (CO_2), with emissions by category shown in Figure 1. In terms of species, cattle are the major contributor, with about 62% of total livestock emissions. Other species (hogs, poultry, buffaloes, and small ruminants), each represent between 7 and 11% of the sector's emissions. Within cattle, beef and dairy animals generate similar amounts of total emissions. Figure 2 shows the global estimates of livestock emissions by species.

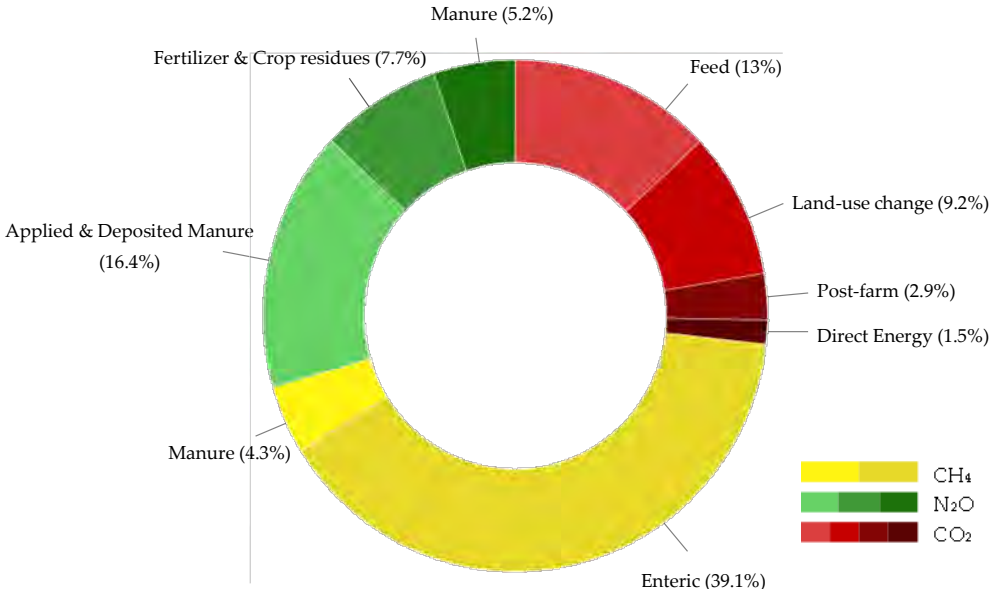

Figure 1. Emissions from livestock (by category), where methane (CH_4) emissions are portrayed in yellow, nitrous oxide (N_2O) in green, and carbon dioxide (CO_2) in red. Figure drawn by authors with data source from [7].

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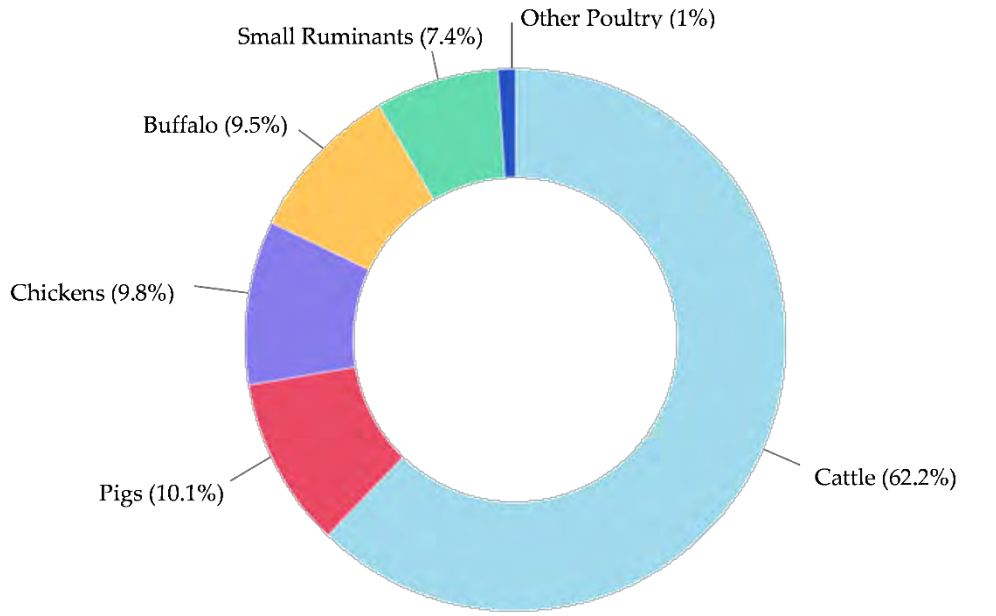

Figure 2. Emissions from livestock (by species). Figure drawn by authors with data source from [102].

Livestock GHG emissions arise directly through raising animals, including enteric fermentation, manure, and associated energy consumption. Indirect emissions mainly

Livestock GHG emissions arise directly through raising animals, including enteric fermentation, manure, and associated energy consumption. Indirect emissions mainly come from feed production and related land use change. Some studies indicate that indirect emissions exceed direct emissions, while others show the opposite [103,104].

3.1. Direct Effects: Enteric Fermentation and Manure Management

Enteric fermentation occurs mainly within ruminant animals' digestive systems, where microbes break down coarse plant materials and, in the process, produce methane, which is emitted by exhaling, belching, and other means. This is the largest ruminant emission source [105]. Non-ruminants also produce methane during digestion but in much smaller amounts. A variety of factors affect ruminant emission quantity, such as feed characteristics, use of feed additives, and animal health condition. The most influential ones are feed quality and feed intake. Higher feed digestibility leads to lower enteric methane emission and higher animal production. Increased feed intake leads to more methane being produced. The rate of conversion from feed energy intake to methane depends on species, production systems, and regional characteristics [7].

Manure also contributes to emissions in the form of methane and nitrous oxide (N_2O) emissions. The anaerobic decomposition of organic material releases methane, and nitrous oxide is released mainly from ammonia decomposition. Organic matter and nitrogen content in manure are the two chemical components that can lead to N_2O emissions during storage and processing [104]. Hogs and dairy cows are the largest source of manure-related methane emissions [106]. The largest manure-related N_2O emissions come from soil emissions associated with manure application [103]. The manure storage and handling process greatly affects resultant emissions, particularly when manure is handled in ponds or lagoons [106]. Other factors that affect manure emissions include air temperature, moisture, duration of waste management, and animal diet. If manure is handled through solid systems (e.g., deposited on pastures), N_2O emissions will be higher than methane since the generation of N_2O requires both aerobic and anaerobic conditions. Methane emissions are higher when manure is treated in liquid systems using lagoons or ponds.

3.2. Indirect Effects: Feed Production and Land Use Change

3.2.1. Feed Production

Emissions related to feed production, processing, and transport constitute about 45% of livestock-related emissions. Of all these feed-related emissions, N_2O from fertilization of feed crops and CH_4 from manure application to pasture generate about 50%, while related land use change generates about 25% [7]. Emissions from feed production consists of CO_2, N_2O, and CH_4. CO_2 emission arises from the production of fertilizers and pesticides for feed crops, feed transportation and processing, fuel used in production, and associated land use change. N_2O emissions are mainly from fertilizer use and manure application, with a small portion coming from the cultivation of leguminous feed crops (e.g., rice, soybeans, peas, alfalfa, and clover). The amount of feed-related CH_4 emissions is much smaller than that of feed-related CO_2 and N_2O emissions.

3.2.2. Land Use Change

Land use change is another indirect source of livestock-related GHG emissions. Gerber et al. [7] calculated that land use change contributes 9.2% of total livestock GHG emissions. This occurs through land use change to produce pasture (6%) and feed crops (3.2%). Agricultural land occupies 38% of the global land surface, with about two-thirds of this for livestock [107]. Driven by population growth, urbanization, and growing incomes, the demand for livestock and livestock products is expected to increase, inducing more livestock production. By 2050 compared to 2005/2007, world meat production is projected to increase by 76% and milk by 63% [108]. Associated with this, grazing intensities are projected to increase by about 70%, with feed demand almost doubled [109].

Historically, increased production of livestock and livestock feed has significantly impacted land use, which affects the natural carbon cycle [3]. Plants take CO_2 from the atmosphere and nitrogen (N) from the soil and store them in above- and below-ground biomass. Forest lands sequester more carbon in soil and vegetation than croplands and pastures, and thus when forest land is converted to cropland and pasture, much of the sequestered carbon is released into the atmosphere.

There is debate on appropriate procedures for accounting for emissions from land-use change, and there is no current shared consensus. Different scale and land-use change factors result in significantly different results. [110]. Steinfeld et al. [103] estimated that deforestation due to the expansion of pasture and feed crops is responsible for 8% of total anthropogenic CO_2 emissions. Hong et al. [111] estimated that land-use emissions accounted for 27% of global total anthropogenic GHG emissions during the 1970—2017 period.

3.2.3. Energy Consumption

Energy consumption is another source of CO_2 emissions, mainly related to fossil fuel use. For livestock, energy-related emissions occur across the supply chain spanning from production of fertilizers, use of machinery, and transport of feed and livestock. On-the farm animal-related energy includes that used for heating/cooling, ventilation, illumination, and milking. Upstream feed production uses energy in production, drying, and commodity transport. Downstream energy is used in processing livestock commodities and packing and transporting final products to retailers. The total energy consumption along the livestock supply chain contributes about 25% of total emissions in the livestock sector [7].

4. Adaptation

Climate change adaptation refers to adjustment in ecological, social, or economic systems to reduce the negative or enhance the positive impacts of climate change. In an agricultural setting, adaptation can occur through ecological change or human action. For livestock, natural adaptation results from different mechanisms through which animals adapt to climatic conditions. Human adaptation involves actions and practices that could help animals adapt to climate change and enhance the livestock performance. In a livestock context, adaptation actions can be divided into three broad classifications: animal responses, management actions, and resource [112].

4.1. Animal Responses

Animals can adapt through physiological, biochemical, immunological, anatomical, and behavioral responses [113]. Herein, we focus on behavioral responses. For details on other animal adaption mechanisms, see Gaughan et al. [112].

Commonly observed responses to heat stress include reduced feed intake, shade seeking, increased sweating and panting, increased water intake and drinking frequency, increased standing time and decreased lying time, and reduced defecation and urination frequency.

It is noteworthy that domestic animals are rarely exposed to a single stress. Besides heat stress, under feeding, lack of water, and poor nutrition may occur together. The cumulative effects of multiple stressors may be multiplicative rather than additive [112]. Animals may not be able to fully adapt to climate stressors by themselves, and thus producers may need to help in order to sustain livestock production and profitability. However, one should note that climate change can be so large that it may not be possible overcome an effect and in such cases, more extreme actions, such as changes in land use, species, or abandonment, may be in order [114].

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4.2. Human Adaptation Strategies

Human adaptation strategies involve breeding, production/management system modifications, and institutional and policy changes. Table 3 presents a brief summary of livestock management adaptation strategies, and a detailed discussion follows.

Table 3. Summary of human adaptation strategies.

Animal Genetics	
	•Choose species that are more heat-tolerant
	•Genetic selection to changed conditions
Physical modification	
	•Provide shade and sprinklers for outdoor animals
	•Improve/supply cooling systems indoors
Feed and pest management	
	•Modify diet composition and feeding time
	•Supplemental feeding
	•Adoption of integrated pest management
Livestock system	
	•Diversify livestock species
	•Adjust stocking rate
	•Integrate livestock system with forestry or crops

4.2.1. Animal Genetics

Breed selection has traditionally been used to improve livestock production efficiency and has facilitated a massive increase in livestock production. However, current species selected for higher production in some cases have higher metabolic heat production and hence can be more susceptible to heat stress [115]. As future climate is predicted to be hotter, with more frequent heat extremes, breeding techniques and breed type selection can also be an adaptation action. Genetic variation in heat stress response in livestock species has been observed and measured [116,117]. Some breeds are less affected by heat stress, such as smaller, lighter-colored animals [118], or breeds can show great physical and physiological adaptation to heat stress. If such trait is heritable, selective breeding for heat tolerance could be used to improve animal adaptation to climatic stress [119,120]. Producers can switch breeds, for example, using more Bos indicus cattle [121,122].

4.2.2. Physical Modification

Physical modification of the environment can also be undertaken and can be broadly divided into two groups: outdoor and indoor.

For animals kept outdoors on grasslands or pasture, one cost-effective adaptation method is shade provision. This lowers exposure to solar radiation and reduces heat stress [39,123]. Sprinklers and misters could also help to decrease body temperatures [124], and they are more effective in drier weather. Huynh [125] suggested the use of a combination of different methods as there exist interaction effects. For example, the combination of sprinkling and a covered pen without an outdoor yard leads to higher daily gain for hogs than the provision of sprinkling alone.

For livestock kept indoors, in buildings, physical modification options can involve use or addition of (1) ventilation systems, (2) heat reducing building materials (e.g., insulation and orientation), and (3) forced air velocity, fogging, misting, sprinkling, and pad cooling [126]. Air conditioning and pad cooling have been found to have the best performance

in terms of lowering heat stress [126], but the high initial investment and operating expense might make them impractical [127].

4.2.3. Feed and Pest Management

Feeding practices can be used to improve animal performance under heat stress. These involve modification of diet composition, changes in feeding time and/or frequency, and water management [120]. These practices help alleviate heat stress through increasing energy content, increasing nutrient and electrolytes or certain minerals intake, and maintaining water balance. Feeding modifications in cattle [128,129], hogs [130–132], and poultry [66,133,134] have all been investigated, and the general effect is positive.

Pest management has not been fully discussed as livestock adaptation, although researchers have noticed that future changes in precipitation patterns may affect the spread and quantity of some vector-borne pests [52]. There are several concerns related to livestock pest management. First, some pests will develop resistance to insecticides and drugs in a short time, which would limit the effectiveness of insecticides or drugs. Thus, in practice, it is suggested to use the rotation of insecticides with different modes of action [135]. Second, high-density or confined systems can encourage pests and disease outbreak, with poultry in particular suffering a lot from pest problems [136]. Third, drug residues in animal products due to inappropriate use of pesticides may be a potential threat to public health [137]. As a result of these considerations, integrated pest management is needed [138], as well as improved techniques in pesticides.

4.2.4. Livestock Management System

Livestock management adaptations can involve one or more of the following strategies:

(1) Diversification of livestock species: Multi-species farming enhances the producer's ability to cope with a changing climate and the associated change in rangeland conditions and can also improve the sustainability of livestock farms [139,140].
(2) Adjustment in stocking rates: Díaz-Solís et al. [141] found that adjusting stocking rate can be used to reduce the effect of drought on cow-calf in Mexican state of Coahuila. Mu et al. [142] found that in the U.S., the stocking rate of cattle decreases as THI increases and precipitation increases in summer.
(3) Integration of livestock system with forestry or crops: Because of their positive synergistic effects on soil properties and nutrient cycling, mixed crop–livestock or forestry–livestock can help with soil degradation, reduce chemical use, and generate economies of scale at the farm level [143,144].

5. Mitigation

There are mitigation measures that reduce livestock GHG emissions. Gerber et al. [7] indicated that livestock emission intensities vary greatly between production systems and regions and the mitigation potential lies in the gap between the management techniques that result in the lowest and highest emission intensities. They estimated that the emissions from the livestock sector can be reduced by 18% if producers in a given system, region, and climate adopt the practices currently applied by the top 25% of producers with the lowest emission intensity and 30% if using techniques employed by the top 10%. We summarize many potential mitigation options in Table 4 and discuss them below.

5.1. Land Resource Management

Substantial livestock mitigation lies in livestock management and land use. Thornton et al. [145] estimated that the maximum mitigation potential from livestock and pasture management is approximately 7% of the global agriculture mitigation potential to 2030. Possible strategies involve adoption of improved pastures, intensification of ruminant diets, changes in ruminant breeds, reductions in stocking rate, and lowering grazing intensity. Havlík et al. [146] indicated that significant emission reduction could be achieved through transitions to more efficient and less land-demanding livestock systems. They also found

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Table 4. Summary of mitigation strategies.

Land resource management	
	• Improve grazing management
	• Alter grazing intensity and or manure use to enhance Carbon sequestration
Enteric fermentation management	
	• Modify diet and nutrition for livestock
	• Genetic selection
Manure management	
	• Alter storage practices
	• Modify diet and nutrition for livestock
Fertilizer management	
	• Increase nitrogen efficiency
	• Offest commerial nitrogen use by using manure

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Another land-use-related mitigation category deals with carbon sequestration, which mainly relates to feed crop production. Carbon sequestering actions include using conservation tillage, selecting to produce higher yielding crops, reducing deforestation, converting cropland to grassland, and improving grass species [3,103].

5.2. Enteric Fermentation Management

As discussed above, enteric fermentation is the main source of ruminant methane emissions. This emission source can be reduced through dietary management and genetics. Knapp et al. [147] found that nutrition and feeding strategies such as improving forage digestibility can reduce enteric methane emission by 2.5–15% per unit of milk produced and that more significant reductions can be achieved if combined with genetic and management approaches. Feed additives and supplements, such as antibiotics, lipids, grain, and ionophores, have also been shown to decrease enteric methane emissions [105,148].

5.3. Manure Management

Livestock manure generates both N_2O and CH_4 emissions, and most of these are related to storage and handling methods [3]. Altered manure storage practices can reduce manure GHG emissions. These include shortened storage duration, lowered storage temperature, solid–liquid separation, and less use of water [149,150]. Anaerobic digestion processes, in which microorganisms break down manure in the absence of oxygen, produce a mixture of biogas (mainly CH_4 and CO_2) and digestate that can be captured and used as bioenergy to generate heat or electricity. This also indirectly reduces GHG emissions by replacing emission-intensive fossil energy and by changing the composition of emissions from the traditional combination of N_2O and CH_4 into a combination of CO_2 and CH_4 [151]. Anaerobic digestion can lead to an over 30% reduction in GHG emissions compared to traditional manure treatment [152]. Dietary adjustment for animals can also be used to reduce manure emission as it could change the volume and composition of the manure.

5.4. Fertilizer Management

Fertilizer application in feed crop production contributes N_2O emissions attributable to the livestock sector. Associated mitigation strategies aim at increasing nitrogen application efficiency. Possible measures include the use of time-released nitrogen, precision application, organic fertilizers, plant breeding, genetic modifications, and changes in plant species [153,154]. However, it is complex to calculate the mitigation potential of increasing fertilizer efficiency on animal feed production, and this leaves a gap for future studies to discover.

Another possible practice related to reducing emission from feed production involves shifts in types of livestock feed. Pikaar et al. [155] analyzed the potential of using microbial proteins (MP) as a feed replacement, finding that it can replace 10–19% of conventional crop-based animal feed protein demand, which leads to a reduction by 7% in agricultural greenhouse gas emission.

6. Discussion

On the one hand, climate change can affect livestock production directly through increased heat stress and indirectly through impacts on the quantity and quality of forage and crop-based feeds, as well as land and water availability. Associated adaptation strategies could target direct animal responses, by adjusting their living environment and feed, or focus on the modification of production and management systems.

On the other hand, livestock production influences climate change by contributing to 14.5% of the global anthropogenic GHG emissions. Mitigation strategies from the livestock side could help address enteric emissions and improve manure management, along with more emission efficient feed production through reduced use of N-fertilizer and land carbon sequestration. Figure 3 provides an overview of the major impacts, emission types, and actions covered in this review.

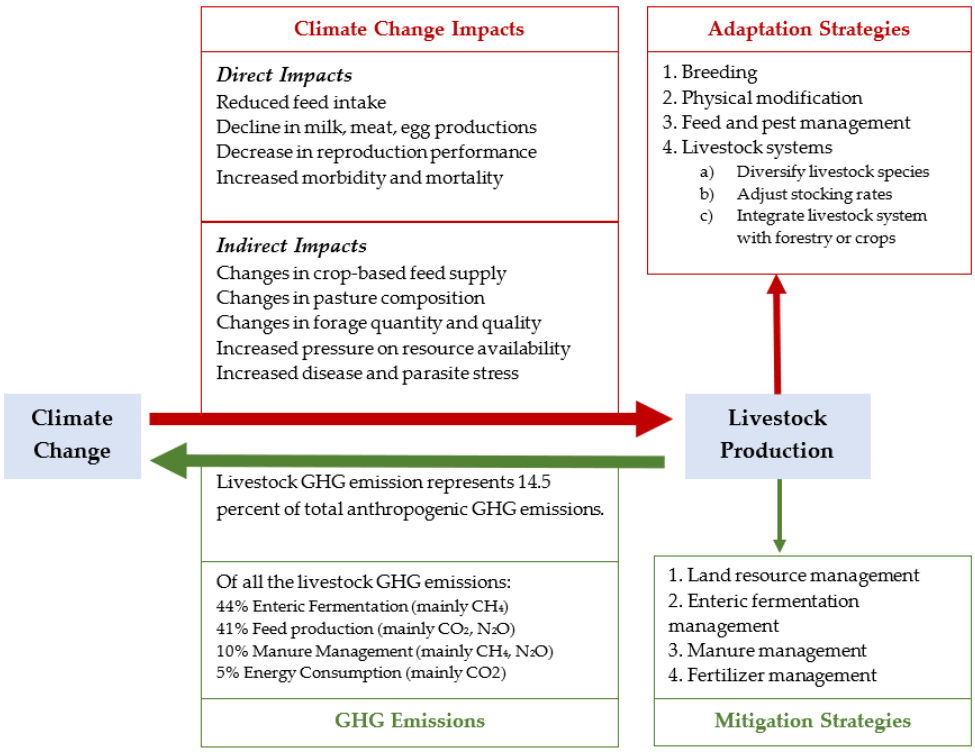

Figure 3. An overview of the relationship between climate change and livestock production.

Despite the numerous studies carried out in this field, there remain a number of research gaps. First, the literature mainly focuses on ruminants, with less coverage of other species, such as hogs and poultry. These animals are also affected, and their productivity may even be more affected than that of ruminants [13]. Considering emissions on the basis of the per-unit protein produced, chicken meat, eggs, and pork have lower emission intensities compared to beef meat, and this could be exploited as a mitigation strategy [102]. Thus, research on non-ruminants is needed. Second, current publications have a strong

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References

1. Food and Agriculture Organization of the United Nations (FAO). Livestock and Landscapes: Sustainability Pathways. *Food and Agriculture Organizations of the United Nations*. Available online: https://www.fao.org/3/ar591e/ar591e.pdf (accessed on 3 November 2021).
2. Thornton, P.K. Livestock production: Recent trends, future prospects. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 2853–2867. [CrossRef] [PubMed]
3. Rojas-Downing, M.M.; Nejadhashemi, A.P.; Harrigan, T.; Woznicki, S.A. Climate change and livestock: Impacts, adaptation, and mitigation. *Clim. Risk Manag.* **2017**, *16*, 145–163. [CrossRef]
4. Swanepoel, F.J.C.; Stroebel, A.; Moyo, S. The Role of Livestock in Developing Communities: Enhancing Multifunctionality. University of the Free State and CTA. 2010. Available online: https://cgspace.cgiar.org/handle/10568/3003 (accessed on 9 August 2021).
5. Intergovernmental Panel on Climate Change. *Climate Change 2014: Mitigation of Climate Change*; Cambridge University Press: New York, NY, USA, 2014.
6. Escarcha, J.; Lassa, J.; Zander, K. Livestock under climate change: A systematic review of impacts and adaptation. *Climate* **2018**, *6*, 54. [CrossRef]
7. Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G. Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities. 2013. Available online: https://www.cabdirect.org/cabdirect/abstract/20133417883 (accessed on 5 August 2021).
8. Collier, R.J.; Baumgard, L.H.; Zimbelman, R.B.; Xiao, Y. Heat stress: Physiology of acclimation and adaptation. *Anim. Front.* **2019**, *9*, 12–19. [CrossRef]
9. Ames, D. Thermal Environment Affects Production Efficiency of Livestock. *BioScience* **1980**, *30*, 457–460. [CrossRef]
10. Nardone, A.; Ronchi, B.; Lacetera, N.; Bernabucci, U. Climatic Effects on Productive Traits in Livestock. *Vet. Res. Commun.* **2006**, *30*, 75–81. [CrossRef]
11. Bianca, W. The signifiance of meteorology in animal production. *Int. J. Biometeorol.* **1976**, *20*, 139–156. [CrossRef]
12. Fregly, M.J. Adaptations: Some General Characteristics. In *Comprehensive Physiology*; American Cancer Society: Atlanta, GA, USA, 2011; pp. 3–15. Available online: https://onlinelibrary.wiley.com/doi/abs/10.1002/cphy.cp040101 (accessed on 1 September 2021).
13. Nardone, A.; Ronchi, B.; Lacetera, N.; Ranieri, M.S.; Bernabucci, U. Effects of climate changes on animal production and sustainability of livestock systems. *Livest. Sci.* **2010**, *130*, 57–69. [CrossRef]
14. Collier, R.J.; Beede, D.K.; Thatcher, W.W.; Israel, L.A.; Wilcox, C.J. Influences of Environment and Its Modification on Dairy Animal Health and Production. *J. Dairy Sci.* **1982**, *65*, 2213–2227. [CrossRef]

15. Maibam, U.; Hooda, O.K.; Sharma, P.S.; Upadhyay, R.C.; Mohanty, A.K. Differential level of oxidative stress markers in skin tissue of zebu and crossbreed cattle during thermal stress. *Livest. Sci.* **2018**, *207*, 45–50. [CrossRef]
16. St-Pierre, N.R.; Cobanov, B.; Schnitkey, G. Economic losses from heat stress by US livestock industries. *J. Dairy Sci.* **2003**, *86*, E52–E77. [CrossRef]
17. Daramola, J.O.; Abioja, M.O.; Onagbesan, O.M. Heat Stress Impact on Livestock Production. In *Environmental Stress and Amelioration in Livestock Production*; Sejian, V., Naqvi, S.M.K., Ezeji, T., Lakritz, J., Lal, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2012; pp. 53–73. [CrossRef]
18. Rashamol, V.P.; Sejian, V.; Bagath, M.; Krishnan, G.; Archana, P.R.; Bhatta, R. Physiological Adaptability of Livestock to Heat Stress: An Updated Review. Periodikos. 2018. Available online: http://www.jabbnet.com/journal/jabbnet/article/doi/10.31893/2318-1265jabb.v6n3p62-71 (accessed on 20 July 2021).
19. Baile, C.A.; Forbes, J.M. Control of feed intake and regulation of energy balance in ruminants. *Physiol. Rev.* **1974**, *54*, 160–214. [CrossRef]
20. Yadav, B.; Singh, G.; Verma, A.K.; Dutta, N.; Sejian, V. Impact of heat stress on rumen functions. *Vet. World* **2013**, *6*, 992–996. [CrossRef]
21. Kadzere, C.T.; Murphy, M.R.; Silanikove, N.; Maltz, E. Heat stress in lactating dairy cows: A review. *Livest. Prod. Sci.* **2002**, *77*, 59–91. [CrossRef]
22. Lu, C.D. Effects of heat stress on goat production. *Small Rumin. Res.* **1989**, *2*, 151–162. [CrossRef]
23. Lopez, J.; Jesse, G.W.; Becker, B.A.; Ellersieck, M.R. Effects of temperature on the performance of finishing swine: I. Effects of a hot, diurnal temperature on average daily gain, feed intake, and feed efficiency. *J. Anim. Sci.* **1991**, *69*, 1843–1849. [CrossRef]
24. Cervantes, M.; Antoine, D.; Valle, J.A.; Vásquez, N.; Camacho, R.L.; Bernal, H.; Morales, A. Effect of feed intake level on the body temperature of pigs exposed to heat stress conditions. *J. Therm. Biol.* **2018**, *76*, 1–7. [CrossRef]
25. Syafwan, S.; Kwakkel, R.P.; Verstegen, M.W.A. Heat stress and feeding strategies in meat-type chickens. *World's Poult. Sci. J.* **2011**, *67*, 653–674. [CrossRef]
26. Lacetera, N.; Bernabucci, U.; Ronchi, B.; Nardone, A. Physiological and productive consequences of heat stress. The case of dairy ruminants. In Proceedings of the Symposium on interaction between Climate and Animal Production: EAAP Technical Series, Viterbo, Italy, 4 September 2003; pp. 45–60.
27. Parkhurst, C.; Mountney, G.J. *Poultry Meat and Egg Production*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012; 307p.
28. Pearce, S.C.; Sanz-Fernandez, M.V.; Hollis, J.H.; Baumgard, L.H.; Gabler, N.K. Short-term exposure to heat stress attenuates appetite and intestinal integrity in growing pigs. *J. Anim. Sci.* **2014**, *92*, 5444–5454. [CrossRef]
29. Herbut, P.; Angrecka, S.; Godyń, D.; Hoffmann, G. The physiological and productivity effetcts of heat stress in cattle—A review. *Ann. Anim. Sci.* **2019**, *19*, 579–594. [CrossRef]
30. Rhoads, M.; Rhoads, R.; VanBaale, M.J.; Collier, R.; Sanders, S.R.; Weber, W.J.; Crooker, B.A.; Baumgard, L.H. Effects of heat stress and plane of nutrition on lactating Holstein cows: I. Production, metabolism, and aspects of circulating somatotropin. *J. Dairy Sci.* **2009**, *92*, 1986–1997. [CrossRef]
31. Ravagnolo, O.; Misztal, I.; Hoogenboom, G. Genetic component of heat stress in dairy cattle, development of heat index function. *J. Dairy Sci.* **2000**, *83*, 2120–2125. [CrossRef]
32. Gorniak, T.; Meyer, U.; Südekum, K.-H.; Dänicke, S. Impact of mild heat stress on dry matter intake, milk yield and milk composition in mid-lactation Holstein dairy cows in a temperate climate. *Arch. Anim. Nutr.* **2014**, *68*, 358–369. [CrossRef]
33. Salama, A.A.K.; Contreras-Jodar, A.; Love, S.; Mehaba, N.; Such, X.; Caja, G. Milk yield, milk composition, and milk metabolomics of dairy goats intramammary-challenged with lipopolysaccharide under heat stress conditions. *Sci. Rep.* **2020**, *10*, 5055. [CrossRef]
34. Seerapu, S.R.; Kancharana, A.R.; Chappidi, V.S.; Bandi, E.R. Effect of microclimate alteration on milk production and composition in Murrah buffaloes. *Vet World* **2015**, *8*, 1444–1452. [CrossRef] [PubMed]
35. Gonzalez-Rivas, P.A.; Chauhan, S.S.; Ha, M.; Fegan, N.; Dunshea, F.R.; Warner, R.D. Effects of heat stress on animal physiology, metabolism, and meat quality: A review. *Meat Sci.* **2020**, *162*, 108025. [CrossRef]
36. Elam, N.A.; Vasconcelos, J.T.; Hilton, G.; VanOverbeke, D.L.; Lawrence, T.E.; Montgomery, T.H.; Montgomery, T.H.; Nichols, W.T.; Streeter, M.N.; Hutcheson, J.P.; et al. Effect of zilpaterol hydrochloride duration of feeding on performance and carcass characteristics of feedlot cattle1. *J. Anim. Sci.* **2009**, *87*, 2133–2141. [CrossRef] [PubMed]
37. Summer, A.; Lora, I.; Formaggioni, P.; Gottardo, F. Impact of heat stress on milk and meat production. *Anim. Front.* **2019**, *9*, 39–46. [CrossRef] [PubMed]
38. Berihulay, H.; Abied, A.; He, X.; Jiang, L.; Ma, Y. Adaptation Mechanisms of Small Ruminants to Environmental Heat Stress. *Animals* **2019**, *9*, 75. [CrossRef]
39. Silanikove, N. Effects of heat stress on the welfare of extensively managed domestic ruminants. *Livest. Prod. Sci.* **2000**, *67*, 1–18. [CrossRef]
40. Pearce, S.C.; Gabler, N.K.; Ross, J.W.; Escobar, J.; Patience, J.F.; Rhoads, R.P.; Baumgard, L.H. The effects of heat stress and plane of nutrition on metabolism in growing pigs. *J. Anim. Sci.* **2013**, *91*, 2108–2118. [CrossRef]
41. da Fonseca de Oliveira, A.C.; Vanelli, K.; Sotomaior, C.S.; Weber, S.H.; Costa, L.B. Impacts on performance of growing-finishing pigs under heat stress conditions: A meta-analysis. *Vet. Res. Commun.* **2019**, *43*, 37–43. [CrossRef]

42. Zaboli, G.; Huang, X.; Feng, X.; Ahn, D.U. How can heat stress affect chicken meat quality?—A review. *Poult. Sci.* **2019**, *98*, 1551–1556. [CrossRef]
43. Song, D.J.; King, A.J. Effects of heat stress on broiler meat quality. *World's Poult. Sci. J.* **2015**, *71*, 701–709. [CrossRef]
44. Zhang, Z.Y.; Jia, G.Q.; Zuo, J.J.; Zhang, Y.; Lei, J.; Ren, L.; Feng, D.Y. Effects of constant and cyclic heat stress on muscle metabolism and meat quality of broiler breast fillet and thigh meat. *Poult. Sci.* **2012**, *91*, 2931–2937. [CrossRef]
45. Shakeri, M.; Cottrell, J.J.; Wilkinson, S.; Ringuet, M.; Furness, J.B.; Dunshea, F.R. Betaine and Antioxidants Improve Growth Performance, Breast Muscle Development and Ameliorate Thermoregulatory Responses to Cyclic Heat Exposure in Broiler Chickens. *Animals* **2018**, *8*, 162. [CrossRef]
46. Mignon-Grasteau, S.; Moreri, U.; Narcy, A.; Rousseau, X.; Rodenburg, T.B.; Tixier-Boichard, M.; Zerjal, T. Robustness to chronic heat stress in laying hens: A meta-analysis. *Poult. Sci.* **2015**, *94*, 586–600. [CrossRef]
47. Oguntunji, A.O.; Alabi, O.M. Influence of high environmental temperature on egg production and shell quality: A review. *World's Poult. Sci. J.* **2010**, *66*, 739–750. [CrossRef]
48. He, S.P.; Arowolo, M.A.; Medrano, R.F.; Li, S.; Yu, Q.F.; Chen, J.Y.; He, J. Impact of heat stress and nutritional interventions on poultry production. *World's Poult. Sci. J.* **2018**, *74*, 647–664. [CrossRef]
49. Ross, J.W.; Hale, B.J.; Seibert, J.T.; Romoser, M.R.; Adur, M.K.; Keating, A.F.; Baumgard, L.H. Physiological mechanisms through which heat stress compromises reproduction in pigs. *Mol. Reprod. Dev.* **2017**, *84*, 934–945. [CrossRef]
50. Nawab, A.; Ibtisham, F.; Li, G.; Kieser, B.; Wu, J.; Liu, W.; Zhao, Y.; Nawab, Y.; Li, K.; Xiao, M.; et al. Heat stress in poultry production: Mitigation strategies to overcome the future challenges facing the global poultry industry. *J. Therm. Biol.* **2018**, *78*, 131–139. [CrossRef]
51. Ayo, J.O.; Obidi, J.A.; Rekwot, P.I. Effects of Heat Stress on the Well-Being, Fertility, and Hatchability of Chickens in the Northern Guinea Savannah Zone of Nigeria: A Review. *ISRN Vet. Sci.* **2011**, *14*, 838606. [CrossRef]
52. Thornton, P.K.; Van de Steeg, J.; Notenbaert, A.; Herrero, M. The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agric. Syst.* **2009**, *101*, 113–127. [CrossRef]
53. Thompson-Crispi, K.A.; Mallard, B.A. Type 1 and type 2 immune response profiles of commercial dairy cows in 4 regions across Canada. *Can. J. Vet. Res.* **2012**, *76*, 120–128.
54. Bagath, M.; Krishnan, G.; Devaraj, C.; Rashamol, V.P.; Pragna, P.; Lees, A.M.; Sejian, V. The impact of heat stress on the immune system in dairy cattle: A review. *Res. Vet. Sci.* **2019**, *126*, 94–102. [CrossRef]
55. Chirico, J.; Jonsson, P.; Kjellberg, S.; Thomas, G. Summer mastitis experimentally induced by *Hydrotaea irritans* exposed to bacteria. *Med. Vet. Entomol.* **1997**, *11*, 187–192. [CrossRef]
56. Mashaly, M.M.; Hendricks, G.L.; Kalama, M.A.; Gehad, A.E.; Abbas, A.O.; Patterson, P.H. Effect of Heat Stress on Production Parameters and Immune Responses of Commercial Laying Hens. *Poult. Sci.* **2004**, *83*, 889–894. [CrossRef]
57. Dahl, G.E.; Tao, S.; Laporta, J. Heat Stress Impacts Immune Status in Cows Across the Life Cycle. *Front. Vet. Sci.* **2020**, *7*, 116. [CrossRef] [PubMed]
58. Wang, X.J.; Feng, J.H.; Zhang, M.H.; Li, X.M.; Ma, D.D.; Chang, S.S. Effects of high ambient temperature on the community structure and composition of ileal microbiome of broilers. *Poult. Sci.* **2018**, *97*, 2153–2158. [CrossRef] [PubMed]
59. Zhu, L.; Liao, R.; Wu, N.; Zhu, G.; Yang, C. Heat stress mediates changes in fecal microbiome and functional pathways of laying hens. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 461–472. [CrossRef] [PubMed]
60. Paull, S.H.; Raffel, T.R.; LaFonte, B.E.; Johnson, P.T.J. How temperature shifts affect parasite production: Testing the roles of thermal stress and acclimation. *Funct. Ecol.* **2015**, *29*, 941–950. [CrossRef]
61. Grace, D.; Bett, B.K.; Lindahl, J.F.; Robinson, T.P. Climate and Livestock Disease: Assessing the Vulnerability of Agricultural Systems to Livestock Pests under Climate Change Scenarios. 2015. Available online: https://cgspace.cgiar.org/handle/10568/66595 (accessed on 4 September 2021).
62. Vitali, A.; Felici, A.; Esposito, S.; Bernabucci, U.; Bertocchi, L.; Maresca, C.; Nardone, A.; Lacetera, N. The effect of heat waves on dairy cow mortality. *J. Dairy Sci.* **2015**, *98*, 4572–4579. [CrossRef]
63. Bishop-Williams, K.E.; Berke, O.; Pearl, D.L.; Hand, K.; Kelton, D.F. Heat stress related dairy cow mortality during heat waves and control periods in rural Southern Ontario from 2010–2012. *BMC Vet. Res.* **2015**, *11*, 291. [CrossRef]
64. Ross, J.; Hale, B.; Gabler, N.; Rhoads, R.; Keating, A.; Baumgard, L. Physiological consequences of heat stress in pigs. *Anim. Prod. Sci.* **2015**, *1*, 55. [CrossRef]
65. Jeffrey, F.; Keown, R.J.G. How to Reduce Heat Stress in Dairy Cattle. University of Missouri Extension. Available online: https://extension.missouri.edu/publications/g3620 (accessed on 3 November 2021).
66. Saeed, M.; Abbas, G.; Alagawany, M.; Kamboh, A.A.; Abd El-Hack, M.E.; Khafaga, A.F.; Chao, S. Heat stress management in poultry farms: A comprehensive overview. *J. Therm. Biol.* **2019**, *84*, 414–425. [CrossRef]
67. Reilly, J.M.; Hrubovcak, J.; Graham, J.; Abler, D.G.; Darwin, R.; Hollinger, S.E.; Izaurralde, R.C.; Jagtap, S.; Jones, J.W.; Kimble, J.; et al. Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team, US National Assessment. In *Prepared as Part of USGCRP National Assessment of Climate Variability*; Cambridge University Press: New York, NY, USA, 2002.
68. Shukla, P.R.; Skea, J.; Calvo Buendia, E.; Masson-Delmotte, V.; Pörtner, H.O.; Roberts, D.C.; Zhai, P.; Slade, R.; Connors, R.; Van Diemen, R. *IPCC, 2019: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2019.

69. Intergovernmental Panel on Climate Change. *Climate Change 2014: Impacts, Adaptation, and Vulnerability—Part B: Regional Aspects—Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; 688p. [CrossRef]
70. Allen, V.G.; Batello, C.; Berretta, E.J.; Hodgson, J.; Kothmann, M.; Li, X.; McIvor, J.; Milne, J.; Morris, C.; Peeters, A.; et al. An international terminology for grazing lands and grazing animals. *Grass Forage Sci.* **2011**, *66*, 2–28. [CrossRef]
71. Papanastasis, V.P.; Yiakoulaki, M.D.; Decandia, M.; Dini-Papanastasi, O. Integrating woody species into livestock feeding in the Mediterranean areas of Europe. *Anim. Feed Sci. Technol.* **2008**, *140*, 1–17. [CrossRef]
72. Hejcman, M.; Hejcmanová, P.; Pavlů, V.; Thorhallsdottir, A.G. Forage quality of leaf fodder from the main woody species in Iceland and its potential use for livestock in the past and present. *Grass Forage Sci.* **2016**, *71*, 649–658. [CrossRef]
73. Pearcy, R.W.; Ehleringer, J. Comparative ecophysiology of C3 and C4 plants. *Plant Cell Environ.* **1984**, *7*, 1–13. [CrossRef]
74. Rust, J.M. The impact of climate change on extensive and intensive livestock production systems. *Anim. Front.* **2019**, *9*, 20–25. [CrossRef]
75. Hatfield, J.L.; Boote, K.J.; Kimball, B.A.; Ziska, L.H.; Izaurralde, R.C.; Ort, D.; Thomson, A.M.; Wolfe, D. Climate Impacts on Agriculture: Implications for Crop Production. *Agron. J.* **2011**, *103*, 351–370. [CrossRef]
76. Cho, S.J.; McCarl, B.A. Climate change influences on crop mix shifts in the United States. *Sci. Rep.* **2017**, *7*, 40845. [CrossRef] [PubMed]
77. Kukal, M.S.; Irmak, S. Climate-Driven Crop Yield and Yield Variability and Climate Change Impacts on the, U.S. Great Plains Agricultural Production. *Sci. Rep.* **2018**, *8*, 3450. [CrossRef] [PubMed]
78. Hadi, A.; Naz, N.; Ur Rehman, F.; Kalsoom, M.; Tahir, R.; Adnan, M.; Saeed, M.S.; Khan, A.U.; Mehta, J. Impact of Climate Change Drivers on C4 Plants: A Review. *Curr. Res. Agric. Farming* **2020**, *1*, 13–18. [CrossRef]
79. Hummel, M.; Hallahan, B.F.; Brychkova, G.; Ramirez-Villegas, J.; Guwela, V.; Chataika, B.; Curley, E.; McKeown, P.C.; Morrison, L.; Talsma, E.F.; et al. Reduction in nutritional quality and growing area suitability of common bean under climate change induced drought stress in Africa. *Sci. Rep.* **2018**, *8*, 16187. [CrossRef]
80. Ray, R.L.; Fares, A.; Risch, E. Effects of Drought on Crop Production and Cropping Areas in Texas. *Agric. Environ. Lett.* **2018**, *3*, 170037. [CrossRef]
81. Webber, H.; Ewert, F.; Olesen, J.E.; Müller, C.; Fronzek, S.; Ruane, A.C.; Bourgault, M.; Martre, P.; Ababaei, B.; Bindi, M.; et al. Diverging importance of drought stress for maize and winter wheat in Europe. *Nat. Commun.* **2018**, *9*, 4249. [CrossRef]
82. Hopkins, A.; Prado, A.D. Implications of climate change for grassland in Europe: Impacts, adaptations and mitigation options: A review. *Grass Forage Sci.* **2007**, *62*, 118–126. [CrossRef]
83. Ball, D.M.; Collins, M.; Lacefield, G.; Martin, N.; Mertens, D.; Olson, K.; Putnam, D.; Undersander, D.; Wolf, M. Understanding Forage Quality. American Farm Bureau Federation Publication. 2001. Available online: http://pss.uvm.edu/pdpforage/Materials/ForageQuality/Understanding_Forage_Quality_Ball.pdf (accessed on 3 November 2021).
84. Collins, M.; Nelson, C.J.; Moore, K.J.; Barnes, R.F. *Forages, Volume 1: An Introduction to Grassland Agriculture*; John Wiley & Sons: Hoboken, NJ, USA, 2017; 432p.
85. Dumont, B.; Andueza, D.; Niderkorn, V.; Lüscher, A.; Porqueddu, C.; Picon-Cochard, C. A meta-analysis of climate change effects on forage quality in grasslands: Specificities of mountain and Mediterranean areas. *Grass Forage Sci.* **2015**, *70*, 239–254. [CrossRef]
86. Polley, H.W.; Briske, D.D.; Morgan, J.A.; Wolter, K.; Bailey, D.W.; Brown, J.R. Climate change and North American rangelands: Trends, projections, and implications. *Rangel. Ecol. Manag.* **2013**, *66*, 493–511. [CrossRef]
87. Lee, M.A.; Davis, A.P.; Chagunda, M.G.G.; Manning, P. Forage quality declines with rising temperatures, with implications for livestock production and methane emissions. *Biogeosciences* **2017**, *14*, 1403–1417. [CrossRef]
88. Food and Agriculture Organization of the United Nations. AQUASTAT Website. 2016. Available online: https://www.fao.org/aquastat/en/overview/methodology/water-use (accessed on 3 November 2021).
89. Heinke, J.; Lannerstad, M.; Gerten, D.; Havlík, P.; Herrero, M.; Notenbaert, A.M.O.; Hoff, H.; Müller, C. Water Use in Global Livestock Production—Opportunities and Constraints for Increasing Water Productivity. *Water Resour. Res.* **2020**, *56*, e2019WR026995. [CrossRef]
90. Intergovernmental Panel on Climate Change. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., et al., Eds.; Cambridge University Press: New York, NY, USA, 2021.
91. Fader, M.; Shi, S.; von Bloh, W.; Bondeau, A.; Cramer, W. Mediterranean irrigation under climate change: More efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 953–973. [CrossRef]
92. Gerten, D.; Heinke, J.; Hoff, H.; Biemans, H.; Fader, M.; Waha, K. Global Water Availability and Requirements for Future Food Production. *J. Hydrometeorol.* **2011**, *12*, 885–899. [CrossRef]
93. Watson, R.T.; Zinyowera, M.C.; Moss, R.H.; Dokken, D.J. *The Regional Impacts of Climate Change: An Assessment of Vulnerability*; Cambridge University Press: New York, NY, USA, 1998.
94. Tully, K.; Gedan, K.; Epanchin-Niell, R.; Strong, A.; Bernhardt, E.S.; BenDor, T.; Mitchell, M.; Kominoski, J.; Jordan, T.E.; Neubauer, S.C.; et al. The invisible flood: The chemistry, ecology, and social implications of coastal saltwater intrusion. *BioScience* **2019**, *69*, 368–378. [CrossRef]

95. Reynolds, C.; Crompton, L.; Mills, J. Livestock and Climate Change Impacts in the Developing World. *Outlook Agric.* **2010**, *39*, 245–248. [CrossRef]
96. Konapala, G.; Mishra, A.K.; Wada, Y.; Mann, M.E. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nat. Commun.* **2020**, *11*, 3044. [CrossRef]
97. McCarl, B.A.; Villavicencio, X.; Wu, X.M. Climate Change and Future Analysis: Is Stationarity Dying? *Am. J. Agric. Econ.* **2008**, *90*, 1241–1247. [CrossRef]
98. Knee, B.W.; Cummins, L.J.; Walker, P.; Warner, R. Seasonal variation in muscle glycogen in beef steers. *Aust. J. Exp. Agric.* **2004**, *44*, 729–734. [CrossRef]
99. Hidosa, D.; Guyo, M. Climate change effects on livestock feed resources: A review. *J. Fish. Livest. Prod.* **2017**, *5*, 259.
100. Bai, Y.; Deng, X.; Zhang, Y.; Wang, C.; Liu, Y. Does climate adaptation of vulnerable households to extreme events benefit livestock production? *J. Clean. Prod.* **2019**, *210*, 358–365. [CrossRef]
101. Hajek, I.L.; Knapp, A.K. Shifting seasonal patterns of water availability: Ecosystem responses to an unappreciated dimension of climate change. *N. Phytol.* **2021**, *233*, 119–125. [CrossRef]
102. Food and Agriculture Organization of the United Nations (FAO). Global Livestock Environmental Assessment Model (GLEAM). Available online: https://www.fao.org/gleam/results/en/ (accessed on 3 November 2021).
103. Steinfeld, H.; Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; de Haan, C. Livestock's Long Shadow. 2006. Available online: http://www.fao.org/docrep/010/a0701e/a0701e00.HTM (accessed on 24 August 2017).
104. Grossi, G.; Goglio, P.; Vitali, A.; Williams, A.G. Livestock and climate change: Impact of livestock on climate and mitigation strategies. *Anim. Front.* **2019**, *9*, 69–76. [CrossRef]
105. Beauchemin, K.A. Dietary Mitigation of Enteric Methane from Cattle. *CAB Rev.* **2009**, *4*. Available online: http://www.cabi.org/cabreviews/review/20093276253 (accessed on 9 September 2021). [CrossRef]
106. Johnson, D.E.; Ward, G.M. Estimates of animal methane emissions. *Environ. Monit. Assess.* **1996**, *42*, 133–141. [CrossRef]
107. Food and Agriculture Organization of the United Nations (FAO). Sustainable Food and Agriculture. Available online: http://www.fao.org/sustainability/news/detail/en/c/1274219/ (accessed on 3 November 2021).
108. Alexandratos, N.; Bruinsma, J. (Eds.) *World Agriculture towards 2030/2050: The 2012 Revision*; ESA Working Papers 12-03; ESA: Paris, France, 2012.
109. Yitbarek, M.B. Livestock and livestock product trends by 2050: Review. *Int. J. Anim. Res.* **2019**, *4*, 30.
110. Flysjö, A.; Cederberg, C.; Henriksson, M.; Ledgard, S. The interaction between milk and beef production and emissions from land use change—Critical considerations in life cycle assessment and carbon footprint studies of milk. *J. Clean. Prod.* **2012**, *28*, 134–142. [CrossRef]
111. Hong, C.; Burney, J.A.; Pongratz, J.; Nabel, J.E.M.S.; Mueller, N.D.; Jackson, R.B.; Davis, S.J. Global and regional drivers of land-use emissions in 1961–2017. *Nature* **2021**, *589*, 554–561. [CrossRef]
112. Gaughan, J.B.; Sejian, V.; Mader, T.L.; Dunshea, F.R. Adaptation strategies: Ruminants. *Anim. Front.* **2019**, *9*, 47–53. [CrossRef]
113. Ratnakara, P.A.; Sejian, V.; Jose, V.S.; Vaswani, S.; Bagath, M.; Krishnan, G.; Beena, V.; Devi, P.I.; Varma, G.; Bhatta, R. Behavioral Responses to Livestock Adaptation to Heat Stress Challenges. 2017. Available online: http://krishi.icar.gov.in/jspui/handle/123456789/27610 (accessed on 6 September 2021).
114. Chambwera, M.; Heal, G.; Dubeux, C.; Hallegatte, S.; Leclerc, L.; Markandya, A.; McCarl, B.A.; Mechler, R.; Neumann, J.E. Economics of adaptation. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014; Chapter 17.
115. Bernabucci, U.; Lacetera, N.; Baumgard, L.H.; Rhoads, R.P.; Ronchi, B.; Nardone, A. Metabolic and hormonal acclimation to heat stress in domesticated ruminants. *Animal* **2010**, *4*, 1167–1183. [CrossRef]
116. Daghir, N.J. (Ed.) *Poultry Production in Hot Climates*, 2nd ed.; CABI: Wallingford, UK, 2008; Available online: http://www.cabi.org/cabebooks/ebook/20083163627 (accessed on 26 October 2020).
117. Zumbach, B.; Misztal, I.; Tsuruta, S.; Sanchez, J.P.; Azain, M.; Herring, W.; Holl, J.; Long, T.; Culbertson, M. Genetic components of heat stress in finishing pigs: Parameter estimation. *J. Anim. Sci.* **2008**, *86*, 2076–2081. [CrossRef] [PubMed]
118. Hoffmann, I. Adaptation to climate change–exploring the potential of locally adapted breeds. *Animal* **2013**, *7*, 346–362. [CrossRef] [PubMed]
119. Hayes, B.J.; Lewin, H.A.; Goddard, M.E. The future of livestock breeding: Genomic selection for efficiency, reduced emissions intensity, and adaptation. *Trends Genet.* **2013**, *29*, 206–214. [CrossRef] [PubMed]
120. Renaudeau, D.; Collin, A.; Yahav, S.; De Basilio, V.; Gourdine, J.L.; Collier, R.J. Adaptation to hot climate and strategies to alleviate heat stress in livestock production. *Animal* **2012**, *6*, 707–728. [CrossRef]
121. Barendse, W. Climate adaptation of tropical cattle. *Annu. Rev. Anim. Biosci.* **2017**, *5*, 133–150. [CrossRef]
122. Zhang, Y.W.; Hagerman, A.D.; McCarl, B.A. Influence of Climate Factors on Spatial Distribution of Texas Cattle Breeds. *Clim. Change* **2013**, *118*, 183–195. [CrossRef]
123. Mitlöhner, F.M.; Morrow, J.L.; Dailey, J.W.; Wilson, S.C.; Galyean, M.L.; Miller, M.F.; McGlone, J.J. Shade and water misting effects on behavior, physiology, performance, and carcass traits of heat-stressed feedlot cattle. *J. Anim. Sci.* **2001**, *79*, 2327–2335. [CrossRef]
124. Morrison, S.R.; Givens, R.L.; Lofgreen, G.P. Sprinkling Cattle for Relief from Heat Stress. *J. Anim. Sci.* **1973**, *36*, 428–431. [CrossRef]

125. Huynh, T.T.T. Heat Stress in Growing Pigs: Wageningen University and Research. 2005. Available online: https://www.proquest.com/docview/2449468017/abstract/BAD39E82C2B7419EPQ/1 (accessed on 2 August 2021).
126. Schauberger, G.; Mikovits, C.; Zollitsch, W.; Hörtenhuber, S.J.; Baumgartner, J.; Niebuhr, K.; Piringer, M.; Knauder, W.; Anders, I.; Andre, K.; et al. Global warming impact on confined livestock in buildings: Efficacy of adaptation measures to reduce heat stress for growing-fattening pigs. *Clim. Change* **2019**, *156*, 567–587. [CrossRef]
127. West, J.W. Effects of heat-stress on production in dairy cattle. *J. Dairy Sci.* **2003**, *86*, 2131–2144. [CrossRef]
128. Mader, T.L.; Davis, M.S. Effect of management strategies on reducing heat stress of feedlot cattle: Feed and water intake1. *J. Anim. Sci.* **2004**, *82*, 3077–3087. [CrossRef]
129. Baumgard, L.; Abuajamieh, M.; Stoakes, S.; Sanz-Fernandez, M.; Johnson, J.; Rhoads, R.; Eastridge, M. Feeding and managing cows to minimize heat stress. In Proceedings of the 23rd Tri-State Dairy Nutrition Conference, Fort Wayne, IN, USA, 22–23 April 2014; pp. 14–16. Available online: http://kimiyaroshd.com/wp-content/uploads/2021/06/Feeding-and-Managing-Cows-to-Minimize-Heat-Stress.pdf (accessed on 10 January 2022).
130. Cottrell, J.J.; Liu, F.; Hung, A.T.; DiGiacomo, K.; Chauhan, S.S.; Leury, B.J.; Furness, J.B.; Celi, P.; Dunshea, F.R. Nutritional strategies to alleviate heat stress in pigs. *Anim. Prod. Sci.* **2015**, *55*, 1391–1402. [CrossRef]
131. Dos Santos, L.S.; Pomar, C.; Campos, P.H.R.F.; da Silva, W.C.; de Gobi, J.P.; Veira, A.M.; Fraga, A.Z.; Hauschild, L. Precision feeding strategy for growing pigs under heat stress conditions1. *J. Anim. Sci.* **2018**, *96*, 4789–4801. [CrossRef]
132. Mayorga, E.J.; Kvidera, S.K.; Seibert, J.T.; Horst, E.A.; Abuajamieh, M.; Al-Qaisi, M.; Lei, S.; Ross, J.W.; Johnson, C.D.; Kremer, B.; et al. Effects of dietary chromium propionate on growth performance, metabolism, and immune biomarkers in heat-stressed finishing pigs1. *J. Anim. Sci.* **2019**, *97*, 1185–1197. [CrossRef]
133. Lin, H.; Jiao, H.C.; Buyse, J.; Decuypere, E. Strategies for preventing heat stress in poultry. *World's Poult. Sci. J.* **2006**, *62*, 71–86. [CrossRef]
134. Wasti, S.; Sah, N.; Mishra, B. Impact of Heat Stress on Poultry Health and Performances, and Potential Mitigation Strategies. *Animals* **2020**, *10*, 1266. [CrossRef]
135. Levchenko, M.; Silivanova, E.; Balabanova, G.; Bikinyaeva, R. Insecticide susceptibility of house flies (*Musca domestica*) from a livestock farm in Tyumen region, Russia. *Bulg. J. Vet. Med.* **2019**, *22*, 213–219. [CrossRef]
136. Axtell, R.; Arends, J. Ecology and management of arthropod pests of poultry. *Annu. Rev. Entomol.* **1990**, *35*, 101–126. [CrossRef]
137. Battu, R.S.; Singh, B.; Kang, B.K. Contamination of liquid milk and butter with pesticide residues in the Ludhiana district of Punjab state, India. *Ecotoxicol. Environ. Saf.* **2004**, *59*, 324–331. [CrossRef]
138. Axtell, R.C. Livestock integrated pest management (IPM): Principles and prospects. *Syst. Approach Anim. Health Prod.* **1981**, 31–40.
139. Megersa, B.; Markemann, A.; Angassa, A.; Ogutu, J.O.; Piepho, H.-P.; Zárate, A.V. Livestock diversification: An adaptive strategy to climate and rangeland ecosystem changes in southern Ethiopia. *Hum. Ecol.* **2014**, *42*, 509–520. [CrossRef]
140. Martin, G.; Barth, K.; Benoit, M.; Brock, C.; Destruel, M.; Dumont, B. Potential of multi-species livestock farming to improve the sustainability of livestock farms: A review. *Agric. Syst.* **2020**, *181*, 102821. [CrossRef]
141. Díaz-Solís, H.; Grant, W.E.; Kothmann, M.M.; Teague, W.R.; Díaz-García, J.A. Adaptive management of stocking rates to reduce effects of drought on cow-calf production systems in semi-arid rangelands. *Agric. Syst.* **2009**, *100*, 43–50. [CrossRef]
142. Mu, J.E.; McCarl, B.A.; Wein, A.M. Adaptation to climate change: Changes in farmland use and stocking rate in the, U.S. *Mitig. Adapt. Strateg. Glob. Chang.* **2013**, *18*, 713–730. [CrossRef]
143. Ryschawy, J.; Choisis, N.; Choisis, J.P.; Joannon, A.; Gibon, A. Mixed crop-livestock systems: An economic and environmental-friendly way of farming? *Animal* **2012**, *6*, 1722–1730. [CrossRef]
144. Alves, B.J.R.; Madari, B.E.; Boddey, R.M. Integrated crop–livestock–forestry systems: Prospects for a sustainable agricultural intensification. *Nutr. Cycl. Agroecosyst.* **2017**, *108*, 1–4. [CrossRef]
145. Thornton, P.K.; Herrero, M. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 19667–19672. [CrossRef]
146. Havlík, P.; Valin, H.J.P.; Herrero, M.; Obersteiner, M.; Schmid, E.; Rufino, M.C.; Mosnier, A.; Thornton, P.K.; Böttcher, H.; Conant, R.T.; et al. Climate change mitigation through livestock system transitions. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3709–3714. [CrossRef]
147. Knapp, J.R.; Laur, G.L.; Vadas, P.A.; Weiss, W.P.; Tricarico, J.M. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *J. Dairy Sci.* **2014**, *97*, 3231–3261. [CrossRef]
148. Caro, D.; Kebreab, E.; Mitloehner, F.M. Mitigation of enteric methane emissions from global livestock systems through nutrition strategies. *Clim. Change* **2016**, *137*, 467–480. [CrossRef]
149. Rebellon, L.F.M. *Waste Management: An Integrated Vision*; BoD—Books on Demand: Norderstedt, Germany, 2012; 363p.
150. Montes, F.; Meinen, R.; Dell, C.; Rotz, A.; Hristov, A.N.; Oh, J.; Waghorn, G.; Gerber, P.J.; Henderson, B.; Makkar, H.P.S.; et al. SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options1. *J. Anim. Sci.* **2013**, *91*, 5070–5094. [CrossRef] [PubMed]
151. Kaparaju, P.; Rintala, J. Mitigation of greenhouse gas emissions by adopting anaerobic digestion technology on dairy, sow and pig farms in Finland. *Renew. Energy* **2011**, *36*, 31–41. [CrossRef]
152. Battini, F.; Agostini, A.; Boulamanti, A.K.; Giuntoli, J.; Amaducci, S. Mitigating the environmental impacts of milk production via anaerobic digestion of manure: Case study of a dairy farm in the Po Valley. *Sci. Total Environ.* **2014**, *481*, 196–208. [CrossRef] [PubMed]

153. Stuart, D.; Schewe, R.L.; McDermott, M. Reducing nitrogen fertilizer application as a climate change mitigation strategy: Understanding farmer decision-making and potential barriers to change in the U.S. *Land Use Policy* **2014**, *36*, 210–218. [CrossRef]
154. Balafoutis, A.; Beck, B.; Fountas, S.; Vangeyte, J.; van der Wal, T.; Soto, I.; Gómez-Barbero, M.; Barnes, A.; Eory, V. Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability* **2017**, *9*, 1339. [CrossRef]
155. Pikaar, I.; Matassa, S.; Bodirsky, B.L.; Weindl, I.; Humpenöder, F.; Rabaey, K.; Boon, N.; Bruschi, M.; Yuan, Z.; Van Zanten, H.; et al. Decoupling Livestock from Land Use through Industrial Feed Production Pathways. *Environ. Sci. Technol.* **2018**, *52*, 7351–7359. [CrossRef]
156. Thornton, P.K.; Herrero, M. Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nat. Clim. Change* **2015**, *5*, 830–836. [CrossRef]
157. Karimi, V.; Karami, E.; Keshavarz, M. Vulnerability and Adaptation of Livestock Producers to Climate Variability and Change. *Rangel. Ecol. Manag.* **2018**, *71*, 175–184. [CrossRef]



Detecting Environmental Violations with Satellite Imagery in Near Real Time: Land Application under the Clean Water Act

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ABSTRACT

This paper introduces a new, highly consequential setting for the use of computer vision for environmental sustainability. Concentrated Animal Feeding Operations (CAFOs) (aka intensive livestock farms or "factory farms") produce significant manure and pollution. Dumping manure in the winter months poses significant environmental risks and violates environmental law in many states. Yet the federal Environmental Protection Agency (EPA) and state agencies have relied primarily on self-reporting to monitor such instances of "land application." Our paper makes four contributions. First, we introduce the environmental, policy, and agricultural setting of CAFOs and land application. Second, we provide a new dataset of high-cadence (daily to weekly) 3m/pixel satellite imagery from 2018-20 for 330 CAFOs in Wisconsin with hand labeled instances of land application (n=57,697). Third, we develop an object detection model to predict land application and a system to perform inference in near real-time. We show that this system effectively appears to detect land application (PR AUC = 0.93) and we uncover several outlier facilities which appear to apply regularly and excessively. Last, we estimate the population prevalence of land application events in Winter 2021/22. We show that the prevalence of land application is much higher than what is self-reported by facilities. The system can be used by environmental regulators and interest groups, one of which piloted field visits based on this system this past winter. Overall, our application demonstrates the potential for AI-based computer vision systems to solve major problems in environmental compliance with near-daily imagery.

*Equal Contribution

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CCS CONCEPTS

• **Computing methodologies** → **Computer vision**; • **Computer systems organization** → **Real-time systems**; • **Applied computing** → **Earth and atmospheric sciences**.

KEYWORDS

computer vision, environmental protection, satellite imagery, event detection

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1 INTRODUCTION

How can advances in machine learning be used to transform environmental sustainability? We illustrate its potential in agriculture, which is the leading contributor to water pollution in the United States [57]. Of particular concern are Concentrated Animal Feeding Operations (CAFOs) (aka intensive livestock farms or "factory farms"), industrial-scale livestock operations that raise large volumes of animals in close confinement. In 2008, CAFOs were responsible for more than 50% of the total livestock production in the U.S. [20], a number that has continued to grow in recent years [27], both nationally and internationally [33].

CAFOs produce substantial amounts of manure and manure-contaminated wastewater. The U.S. Government Accountability Office (GAO) notes that a large hog farm can produce more than 1.6M tons of manure annually, more than 1.5 times the amount produced by Philadelphia (1.5M residents) [39]. A large cattle farm can produce more than 2M tons of manure [39]. In 1998, CAFOs produced more than 133M tons of solid manure overall each year, more than 13 times the annual amount of human waste across the United States [3]. Unfortunately, more up-to-date estimates are difficult to obtain because, according to the GAO, "[n]o federal agency collects accurate and consistent data on the number, size, and location of CAFOs" [39]. However, the increase in the number of CAFOs tell us that the amount of waste is likely to have increased proportionally. Given the amount of waste produced by CAFOs, ensuring it is handled appropriately is of the utmost importance.

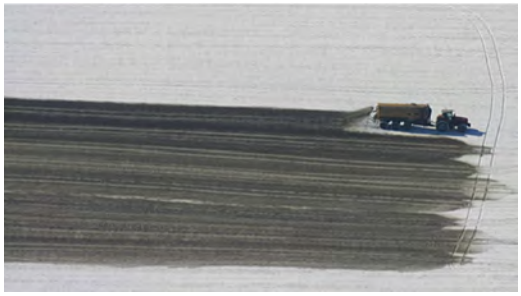

Figure 1: Ground level view of truck performing land application in the winter. Image Credit: John Klein, Environmentally Concerned Citizens of South Central Michigan (ECCSCM).

CAFO waste can be a useful natural fertilizer. When applied injudiciously, however, it can lead to severe environmental and public health problems [2]. Waste products have high concentrations of nitrogen and phosphorus, leakage of which into waterways causes eutrophication, i.e., deoxygenation and the resulting death of animal life from excessive vegetation growth [35]. Even at recommended application rates, nearby streams can be contaminated by fecal matter [36]. Other contaminants detected in both nearby groundwater and bodies of water include heavy metals (e.g., arsenic) [34, 41], antibiotics [5], microbial pathogens [16], and endocrine disrupting hormones (e.g., steroidal estrogen) [23, 45]. The effects are not limited to waterways. Application results in air emissions of ammonia, hydrogen sulfide, and methane [38]. The former are associated with health risks such as bronchitis, inflammation, and burns to the respiratory tract, while the latter increase greenhouse gas concentrations [27].

Of acute policy concern has been *land application* (i.e., the distribution of manure on land) in the winter time [33, 54]. Figure 1 illustrates the common technique for land application to a snow covered field, namely by use of a tractor-drawn tank spreader. Such winter land application poses distinct risks. Frozen and wet ground and the dearth of crops (which can take up manure nutrients) are believed to exacerbate nutrient runoff, thereby heightening the risk of ground and surface water pollution [30, 32, 54, 61]. The issue has been particularly contentious in Northern parts of the United States and Canada [54]. The International Joint Commission by the Great Lakes Water Quality Board suggested that land application in the presence of snow and heavy rain be banned in order to keep algal blooms under control [28].

1.1 Policy Setting

Due to the risks associated with winter land application, many efforts have been focused on how to regulate practices and monitor violations [33]. Transporting or storing waste is expensive and facilities are often limited in their storage capacity [2], such that some degree of winter application is likely.

Most developed countries regulate or ban winter manure application [33]. The federal Environmental Protection Agency (EPA) requires that permitted CAFOs follow a nutrient management plan (NMP) which determines where and how often they can apply. The specifics of the NMP are determined at a state level and there is significant heterogeneity in whether and how states regulate winter land application [33]. In Wisconsin, where this project is focused, application of waste is restricted in the winter time. In February and March, liquid waste may generally not be applied and solid waste may not be applied to any field that contains snow or is frozen § NR 243.14(6)(c). Outside of February and March, liquid waste remains prohibited on frozen ground absent emergencies (§ NR 243.14(7)(a)) and application of solid manure remains restricted based on the amount of snow and slope of the field (§§ NR 243.14(6)(c) & 243.14(7)(c)).

Wisconsin law also provides for "emergency application" for liquid manure in cases of "unusual weather conditions, equipment failure or other unforeseen circumstances beyond the control of the permittee." Such emergency land applications require prior verbal approval from the Wisconsin Department of Natural Resources (DNR), followed by a written description of the event to the department within five days of its occurrence (§§ NR 243.14(7)(d)(1)(c)-(d)).

All instances of land application are also required to be reported in detail. Facilities must file annual spreading reports, which include dates of application, field information, and nutrient information. Such reporting applies to "surface applications on frozen or snow-covered ground," which must also report "whether any applied manure or process wastewater ran off the application site" (§ NR 243.19(3)(c)(5)).

While such self-reporting is required in principle, many have critiqued existing requirements as lacking teeth. One article described EPA's then-rules as "an exercise in unsupervised self-monitoring" [29]. Verifying and ascertaining the extent of winter application – throughout February and March specifically – is difficult. Nor is it easy to understand the volume of approval for emergency applications. In response to a Freedom of Information Act request, the Wisconsin DNR indicated that it was not possible to release a complete list of authorized instances of land applications, as such information was not available in any database format. In the few disclosed instances of email authorizations, such land application events were not included in annual spreading reports. Moreover, while some reports include addenda that indicate winter land application, insufficient detail is provided to determine the volume, location, and dates of application. In short, very little is known about compliance with, and emergency exemptions from, prohibitions of winter land application.

As a result, local environmental interest groups and motivated residents have taken the initiative to report suspected instances of application by physical visits and documentation (see, e.g., [19]). But the information asymmetry has made enforcement of the Clean Water Act – and NMP permit terms specifically – difficult. CAFO winter land application raises acute challenges for environmental regulation, as we do not understand basic questions: how often does winter land application occur? How many facilities engage in such practices? How compliant are CAFO operators with state law and guidelines?

1.2 Our contribution

To help determine the extent of winter application, we build a real-time detection system which pulls daily 3m/pixel satellite imagery at known CAFO locations and detects land application using convolutional neural networks (CNNs). We analyze our approach on

330 CAFOs across the state of Wisconsin, where land application in violation of permit terms has long been suspected. We also use our method to gain insights into how and when application occurs, as well as variation between facilities. For instance, we find facilities which increase the number of winter application by over 150% in Winter 2020 compared to 2018 and 2019. We also discover that some facilities have some application on the ground nearly half of the winter season, and that a significant number of application events (20%), occur within one day of each other. Our model also determines that a substantial number of application events occur within a short time frame of one another.

In sum, our contributions are fivefold. First, we introduce the highly consequential environmental, policy, and agricultural setting of CAFOs and land application. Second, we provide a new dataset consisting of time series of satellite imagery at 330 verified CAFO locations across Wisconsin from 2018-2020 (n=57,697), with 1,813 instances of application identified across 96 of these facilities. Third, we develop an automated system to download satellite imagery on a daily or weekly basis and conduct inference on each image for likelihood of land application. Fourth, we prototype a method to convert image-by-image predictions into predictions of application *events* (which may span more than one image). Fifth, we conduct a retrospective estimate of the prevalence of land application events when presumptively prohibited (February - March 2022) and show that the rate of land application remains alarmingly high during these months.

Our land application detection system was used in partnership with the Environmental Law and Policy Center (ELPC) at the end of the 2021/22 winter Season to investigate several possible instances of application. The partnership is set to continue throughout the 2022/23 winter season, when the system will be used to dispatch volunteers on a weekly basis to identify possible land application.

1.3 Related Work

Our work relates to four bodies of research. First, the environmental risks posed by CAFOs have given rise to recent work on automating their detection and analysis. Computer vision techniques have been used to classify CAFOs by type in North Carolina [21], and to detect poultry CAFOs nationwide [37, 43, 51]. Approaches have also been developed to detect when a given CAFO shed was built [40, 52] and whether a facility has expanded over time [10]. This prior work is an important starting point for using computer vision in environmental sustainability. Prior work, however, has not utilized near real-time satellite imagery to detect likely violations of permit terms, as we do here.

Second, our work relates more broadly to the literature on satellite detection for the environment. Examples include forest fire detection [63], mapping crop cycles [15], and detecting droughts [58]. In general, there is an increasing awareness as to how modern computer vision techniques, and deep learning in particular, can be applied to satellite imagery to tackle environmental and regulatory challenges [22]. Our paper also bears some relationship to previous work in anomaly detection in aerial imagery, such as detecting failures in power plants [59] and building damage detection [56]. Indeed, it is straightforward to cast our problem in terms of anomaly detection. Application events themselves may

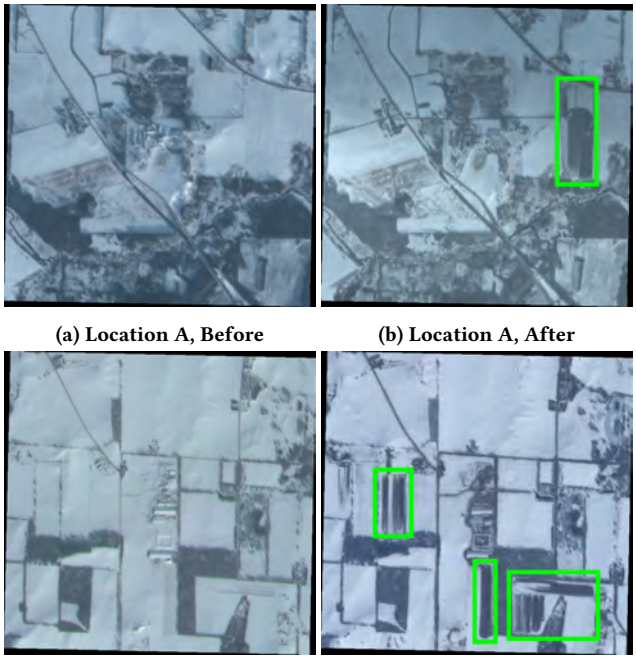

(a) Location A, Before **(b) Location A, After**

(c) Location B, Before **(d) Location B, After**

Figure 2: Examples of land application in 3m/pixel resolution satellite imagery. Images (b) and (d) show examples of application (enclosed by green rectangles) that was not present in images (a) and (c).

considered anomalies, as they appear suddenly from one image to the next. But behavior at the facility level may also be anomalous. For example, there may be a drastic increase in the number of application events from one year to the next. See Section 5.2 for results on this front.

Third, on the technical side, our work builds off the rapid evolution of and progress in deep learning for computer vision. Both objection detection and image classification have been increasingly utilized with satellite and aerial imagery, see Cheng and Han [6] and Dhingra and Kumar [12] for excellent surveys. Our method is based off of the You-Only-Look-Once (YOLO) family of object detection models [1, 47, 48].

Last, our introduction of this setting of high environmental consequence contributes to the machine learning community. Many scholars have critiqued existing machine learning work as being too fixated on a narrow set of technical benchmarks, without sufficient engagement with real-world problems [11, 31, 60]. There is growing recognition that while pursuing state-of-the-art on well-defined and rigorously curated benchmark tasks can create better models, such progress does not necessarily translate to real world impact [44]. Part of the reason lies in the significant barriers to collecting, ground truthing, and releasing meaningful real-world machine learning problems [22, 53]. We release this CAFO land application dataset and all accompanying code [1]. Our contribution here illustrates the possibility of substantial impact of machine learning in environmental sustainability and governance and we

[1] https://github.com/reglab/land-application-detection



Figure 3: Map of permitted fields for land application and permitted CAFOs in Wisconsin. Blue dots represent CAFO locations and grey areas indicate fields where land application is allowed subject to permit requirements. This map shows that land application areas are proximate to the CAFO facility.

hope to inspire the community to help solve these challenging problems [13, 25].

2 DATA

We now describe how we created a new ground truth dataset on land application. First, we obtained the location of 330 CAFOs in Wisconsin from the Environmental Working Group (EWG), which spent many months manually scanning satellite imagery to identify CAFO locations. Through a Freedom of Information Act request with WI DNR, we also obtained shape files for permitted land application areas. Figure 3 plots the CAFO locations and permitted land application areas. Because transportation of waste is expensive, most land application occurs proximate to the CAFO facility.

Second, we acquired daily satellite imagery at 3m/pixel resolution through a subscription with PlanetLabs [55]. For each CAFO location, we pulled imagery from the 2018, 2019, and 2020 winter seasons (i.e., from November 1 of the given year to March 1 of the subsequent year). The principal rationale is that land application both poses greater environmental harm in the wintertime and is restricted, particularly in February - March, under Wisconsin law (see Subsection 1.1). In addition, detecting land application from 3m/pixel resolution is a hard task, but it is much easier to train humans to determine such instances under snow cover and dates outside that range rarely contained snow. We downloaded images that were 1km by 1km squares, centered on the CAFO locations.

Figure 2 provides examples of the Planet Imagery. The left column presents CAFO locations and surroundings before land application. The right column presents those same facilities with land application events, which resemble the kind of tractor-drawn spreading events depicted in Figure 1. We filtered the images by cloud cover, clarity, existence of image artifacts, and snow cover. This process left us with approximately one image per week per location.

Third, based on a sample of images provided by subject matter experts, we trained a team of undergraduate students and staff researchers to label imagery for instances of land application. This training involved extensive consultation and learning about agricultural practices over the course of a summer, drawing on experts at the Socially Responsible Agriculture Project and the Environmental Law and Policy Center (ELPC). Land application areas within images were labeled with a bounding box, resulting in a positive label for every instance where an application event is captured within a Planet satellite image. To ensure label quality, each image was labeled by at least two members of the research team. This resulted in the identification of 1,061 images containing application and 1,813 total instances of application across 96 locations.[2] Although there are strong reasons to believe that reports are incomplete – particularly with respect to winter – we also examined a small sample of annual spreading reports and confirmed that over 40% of the reported events were visible in our data.[3]

Fourth, to construct application *events* from the image-level bounding boxes, we consider a single event to be a series of application boxes which have non-zero intersection across an unbroken series of images ordered by time. This leaves us with 151 distinct land application events.

3 PROBLEM FORMULATION

Given a series of images of the same location over time (described in Section 2), our goal is to (i) predict whether each image contains an instance of land application, and (ii) identify the unique application *events* in the series. Note that an event may (and probably does) persist across images, since application does not fade immediately.

Formally, we have a set of locations L and years Y. For each location-year pair $(\ell, y) \in L \times Y$, we have a series of 3-band images $X_1, \ldots, X_N$ and events $E_1, \ldots, E_K$. An event E_k is a tuple (k_1, k_2, B_k) where $k_1 \in \{1, \ldots, N\}$ is the index of the image in which the event starts, k_2 the index at which it ends, and B_k is a bounding box enclosing the application event in the images (it is the same for each image since each image has the same coordinates). Of course, a location-year pair might have no events.

As noted before, we consider $E_k = (k_1, k_2, B_k)$ to be an event of images $X_{k_1}, X_{k_1+1}, \ldots, X_{k_2}$ containing overlapping labeled application boxes, and X_{k_1-1}, X_{k_2+1} do not have such boxes (if they exist). Then we set B_k to be the union of all the application boxes across $X_{k_1}, \ldots, X_{k_2}$. Our three tasks are:

- **T1.** (Task 1 – Image classification) For each image X_i, determine whether it contains one or more instances of land application (image classification).
- **T2.** (Task 2 – Object Detection) For each image X_i, draw a bounding box B around any application.
- **T3.** (Task 3 – Event Detection) Detect the application events $E_1, \ldots, E_K$.

[2] 44% of positive images had multiple instances of land application.
[3] A major reason why other reported instances may not be available stems from the filtering for high quality satellite imagery.

Task 1 is useful for real-time detection of application, and prioritization of enforcement resources on a daily or weekly basis. Task 2 is useful for identifying precisely where in the image the application lies, and for aggregating image-level predictions into event detections (Task 3). Task 3 is useful for gathering descriptive statistics on past data. For instance, to estimate the total amount of application, we typically care about the number of distinct application events, not merely the number of images containing application. The latter can be influenced by exogenous factors such as a fresh snow fall or cloud cover and is thus not a good proxy for the total amount of application. Moreover, as demonstrated by Figure 2, there can be multiple instances of application in a single image. Thus, classification can undercount the true number of application events.

4 METHODS

We consider four distinct models: Two image classification methods (for Task 1), and two object detection methods (for all three tasks), all of which use CNNs. Recall the distinction: image classification methods predict a label for the image as a whole (in our case a binary label, application/no-application), while object detection predicts bounding boxes enclosing predicted classes within each image. Even though the image classification methods cannot be applied to Tasks 2 or 3, we consider them useful baselines. In principle, environmental regulators and interest groups may want to have separate models for different tasks since CNNs designed specifically for image classification may perform better on Task 1 than object detection methods.

4.1 Evaluation

The image classification methods are built for Task 1. However, we also evaluate the object detection models on Task 1. To do so, we need to extract image level classification results from bounding boxes. We do this in the natural way: For any image in which the object detection methods predicted a bounding box, we set the predicted label to True. We set the model score for that image to be the maximum confidence over all detections in the image. If the image contained no detections, we set the predicted label to False, and the model score to be 0. In this way we can evaluate the precision and recall for Task 1.

To evaluate the object detection methods on Task 3 (event detection), we aggregate image-level bounding box predictions into event predictions by considering an event to be any series of detections in an unbroken sequence of images whose bounding boxes all overlap. We compare these predictions to the true predictions as follows. For each true event E_k we ask whether there is a predicted event E'_j, any of whose bounding boxes intersect with B_k and whose dates intersect those of E_k. That is, E'_j cannot have begun after E_k ended or vice versa.

We train the four models with a 70%/10%/20% train/validation/test split. We split the data by location because the dataset contains multiple images per location per year. A random split would thus likely lead to images of the same location in both the train and test sets, potentially overfitting and/or inflating model performance based on idiosyncrasies of specific locations.

4.2 Image Classification Models

We consider two baselines for Task 1, both employing pretrained CNNs trained to predict whether there exists application in an image, i.e., as a binary classifier for each image. We use an Xception [8] CNN backbone pretrained on ImageNet and fine-tuned on our data. During training, we allow the layers of the pretrained network to be optimized. Optimization was performed with the SGD optimizer with learning rate 0.0005. We activate all nodes using the ReLU function and use a dropout rate of 0.5 for all layers. The best model was selected based on performance on a validation set of 10% of the labeled locations. Both baseline models were implemented in Keras [9].

Single CNN. The first baseline is a single Xception model with a single convolutional layer added before the pretrained layers. The outputs are run through max pooling to match the size of the input layer of Xception. The outputs from the Xception convolutional layers are flattened to one dimension using global average pooling. We remove the fully connected layers of Xception and replace them with a single fully connected hidden layer and an output layer with one node. The logistic scores from that layer are passed through a sigmoid activation.For this model, the training data was down sampled so that positives and negatives made up equal proportions of the training set. The best model was trained for 146 epochs.

Dual CNN. The second baseline compares *pairs* of images, attempting to detect whether application is present in the latter. This baseline is motivated by the observation that, for humans labelers, time-series information was often helpful. Separating application from other features (e.g., trees, dark sheds, roads) is easier if one can see whether purported application is a consistent feature across time. The dual CNN approach is inspired by several successful applications of this methodology to a wide range of tasks, such as fracture detection [7], optometry [50], and analyzing EEG [4].

The dual input model uses a single Xception backbone that is applied to both images at the same time. The model uses a similar input architecture to the single CNN (a CNN layer with max pooling). The two Xception global average pooled outputs are concatenated into one flat vector which is passed into a fully connected network with one hidden layer and a single output node. The logistic scores from that output node are passed through a sigmoid function to make the predicted confidence of the second of the input images containing application.

For the dual input model, the training samples labeled as positives were upsampled by three times and the negatives were downsampled so that the negatives and positives would compose equal proportions of the training set. The resulting best model was trained for 48 epochs.

4.3 Object Detection Models

For both object detection models we perform lightweight hyperparameter optimization via a grid search across the learning rates. We try rates of 1e-4, 2.5e-4, 5e-4, 0.001, 0.005, and 0.01. Beyond that, we engage in limited hyperparameter tuning in an attempt to demonstrate that environmental interest groups and regulators can employ off-the-shelf methods to great effect.

	Image Classification					Event and Object Detection	
Model	PR AUC	ROC AUC	F_1@0.5	F_2@0.5	$F_{0.5}$@0.5	PR AUC	mAP@0.5
Single CNN	0.84	0.87	0.65	0.56	0.78	-	-
Dual CNN	0.71	0.74	0.12	0.09	0.27	-	-
Faster R-CNN	0.92	0.92	**0.77**	**0.88**	0.67	**0.63**	**0.57**
YOLOv5	**0.94**	**0.93**	0.76	0.68	**0.87**	**0.63**	**0.57**

Table 1: Results for each method on both Tasks 1, 2 and 3 (where applicable). For each metric, we bold the results with the best performance. The"@0.5" next to the F_β scores indicates that the classification threshold is at 0.5. PR AUC is the area under the precision-recall curve, and ROC AUC is the area under the receiver operating characteristic curve. The (mean) average precision for object detection is performed at an IoU threshold of 0.5.

YOLOv5. Our object detection model is the You Only Look Once (YOLO) [47] network, trained on ImageNet and fine-tuned on our single class application dataset. We use Ultralytics implementation of YOLOv5. We use a learning rate of 0.01, momentum 0.937, and weight decay of 0.0005. We ensure the anchor boxes are well-fit to the data before training. The network was trained for 100 epochs.

Faster R-CNN. For Task 2, we use faster R-CNN as a baseline [49]. We use the Detectron2 implementation [62], pretrained on ImageNet and fine tuned on our single class application dataset. The convolutional backbone we use is ResNet-50 [24] with a fully connected faster R-CNN head for object detection. During fine-tuning, we use momentum 0.9, weight decay 0.0001, learning rate 0.000025 with a linear learning rate warm up over the first 1000 iterations. The best model was trained for 10,000 iterations.

5 RESULTS

5.1 Accuracy

Table 1 summarizes the performance statistics across models and tasks. Regarding image classification (Task 1), we find that both object detection methods (YOLOv5 and Faster R-CNN) outperform both of the networks designed specifically with classification in mind. The areas under the precision-recall (PR) and receiver operating characteristic (ROC) curves for YOLOv5 and Faster R-CNN are 0.94, 0.93 and 0.92, 0.92 respectively. This is compared to 0.84 and 0.87 for the Single CNN model, and 0.71 and 0.74 for the dual CNN. Somewhat surprisingly, the dual CNN fairs worse than the single CNN, implying the extra temporal information did not help.

We also report the F_β scores for $\beta \in \{0.5, 1, 2\}$ at a classification threshold of 0.5. We note that the parameter β determines how much weight is placed on recall relative to precision. We report all three since environmental interest groups and regulators may weigh objectives differently. For instance, some might prefer to detect as much application as possible (weighting recall higher than precision), while others may want to ensure that field visits or inspections are successful (weighting precision higher than recall). While Faster R-CNN and YOLOv5 have similar F_1 scores (0.77 and 0.76 respectively), they differ in the others. Faster R-CNN has an F_2 score of 0.88 and $F_{0.5}$ score of 0.67, while the performance of YOLOv5 is nearly reversed: 0.68 F_2 score and 0.87 $F_{0.5}$. YOLOv5 thus trades off recall for higher precision relative to Faster R-CNN.

For Task 2 (object detection), the mean average precision (mAP) (equivalent, average precision, since there is a single class) for both object detection methods at an Intersection over Union (IoU) threshold of 0.5 is the same at 0.57. For Task 3 (event detection) both YOLOv5 and Faster R-CNN achieve a AUC of 0.63 on the PR Curve, demonstrating that this task is indeed more difficult than Task 1. We do not give ROC statistics for this task because the number of true negatives is not well-defined.

Overall, we find that YOLOv5 and Faster R-CNN perform very similarly, and one can be justified in using either for both Tasks 1 and 2. We use YOLOv5 for the results in the remainder of the paper. Figure 4 gives several example of YOLO's predictions – three true positives, two false positives, and one false negative (at varying classification thresholds).

5.2 Trends and Outliers

While the previous section lends insight as to how the model performs as a real-time detection mechanism, we are also interested if it can be used to gather insights into application trends over the past few years. Consequently, we run our model over 130 CAFO locations for the 2018, 2019, and 2020 winter seasons that were not in our training or testing sets when developing the model. We restrict our analysis in this section to these unlabeled images to ensure findings are not driven by knowledge of the training data.

Number of events per facility. Figure 5 (left) plots the number of events detected per facility per season. The power law relationship suggests that some facilities are applying at much higher rates than the average. This allows us to identify outliers, which likely pose greater environmental risk: Looking at a facility in the right tail, we find a facility which applied 15 times in Winter 2018, 42 times in Winter 2019, and 16 times in Winter 2020, when the average number of events across all facilities is 5.[4] As a policy matter, the results suggest that the permit terms for such a facility may not support to intensity of livestock production, requiring larger manure storage systems, reduction in animal count, or larger land application area. Identifying such outliers using this approach can help to allocate scarce compliance resources where needed most.

Timing of application events. Figure 5 (center) demonstrates how many days after one application event the next event occurs. Interestingly, 30% of applications occur within the first day following a previous application event. In such instances, multiple instances of land application occurred in close proximity, as can be seen in Figure 2. 55% of subsequent events occur within the

[4]We note that while repeated land application is likely a high risk factor, it is also possible that such practices reflect attempts to apply in lower risk conditions (e.g., after snow has melted, in areas distant from waterways).

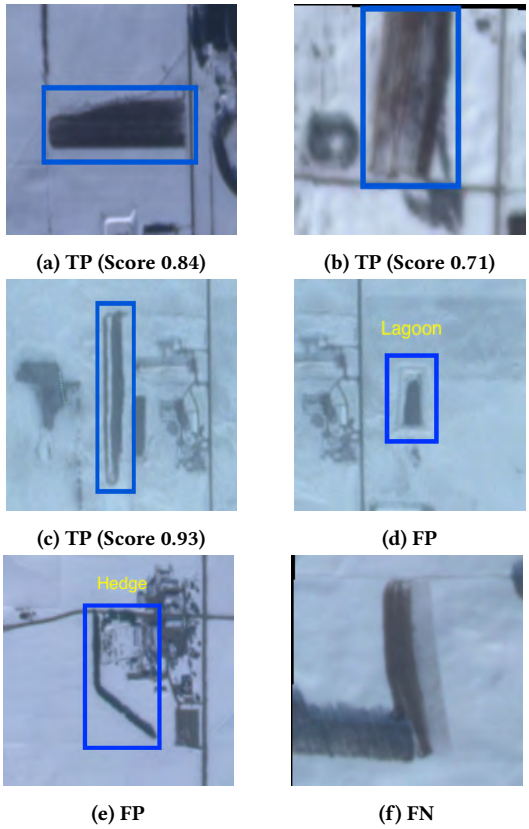

(a) TP (Score 0.84) (b) TP (Score 0.71)

(c) TP (Score 0.93) (d) FP

(e) FP (f) FN

Figure 4: Examples of true and false model predictions (blue boxes). TP = True Positive, FP = False Positive, FN = False Negative. The images have been zoomed in on the area of interest. Images (a), (b), and (c) represent true positives at the standard classification threshold of 0.5. Images (d) and (e) are false positives. (d) correctly identifies application, but it is on a lagoon and is therefore not land application. (e) identifies a hedge partly enclosing the property. (f) provides an example of a false negative, as the vertical streaks are land application but are not identified as such by the model.

first week of the first event. If we examine the percentage of the season that will have an application event visible, it is clear that the vast majority of locations spend much of the season without applying. In some locations, however, visible application exists in surrounding fields for 20-45% of the Winter months.

Number of events per month. In 2008, Wisconsin introduced the sharp prohibition on winter land application for February-March. We hence assess whether this sharper restriction in fact reduces application rates. Figure 6 (right) plots the time series of land application events, showing that the time series exhibits no reduction in application rates for those months. This suggests that the 2008 restriction, absent stronger enforcement measures, did little to reduce winter land application.

5.3 Prevalence Estimation, February-March 2022

We now use our model to estimate the total number of application events at the 330 CAFO locations in our dataset in February and March 2022. Our dataset restricts us to detecting application within a distance of 500m of each CAFO, and thus our prevalence estimates should be taken as lower bounds on the total amount of application.

To obtain the prevalence estimate we run our model over each location throughout February and March and aggregate the image-level predictions into event predictions as per Section 4. Instead of selecting an arbitrary confidence threshold and tallying the resulting event detections, we take advantage of the gradient of confidence scores to obtain a more reliable estimate. Additionally, this supplies us with more fine-grained insight into the calibration of our model.

We stratify detections according to their confidence in bins $B_1, \ldots, B_J$, with the detections in B_i having lower confidence than those in B_{i+1}. Additionally, we let B_0 contain those images with no detections. If we sample n_i items from bin B_i and find a_i true instances of application among those examples, then the estimate for the total prevalence is

$$T = \sum_{i=0}^{J} \frac{a_i}{n_i} |B_i|, \tag{1}$$

i.e., the sum of empirical probabilities multiplied by the size of each bin. The stratification of images by confidence further enables us to examine how the model's confidences compare to the obtained empirical probabilities.

We run the model with a prediction threshold of 0.25, removing all detections with confidence score below this value. We cluster the image level predictions into events and then cluster into four bins: B_0 indicating images with no predictions; and B_1, B_2, and B_3 indicating predicted events with confidence in $[0.25, 0.5)$, $[0.5, 0.75)$, and $[0.75, 1]$, respectively. We sample B_0 120 times and B_1, B_2, B_3 60 times each. For each detected event, we check whether it was a true positive (i.e., a true event). To qualify as a true positive, it must (i) overlap with a true event, and (b) be the first detected event to do so. For example, if a true event is 10 days long, the first four days of which are detected as a single event by the model, and the last four as another, the second detected event is not counted as a positive. We also check how many images of the detected event contained application (e.g., image classification accuracy). In the previous example, while the second detected event is not counted as a novel event, all four images contain application.

The results of the sampling are given in Figure 6. For event detection accuracy, buckets B_0, B_1, B_2 and B_3 has success fractions of 0.04, 0.20, 0.32, 0.61, respectively. Equation 1, gives a population estimate of 951 ([700, 1,203] 68% CI) events across all facilities during February and March.

6 DISCUSSION AND IMPLICATIONS

Our findings have substantial implications for environmental regulation.

First, we have found that despite its significant risks and presumptive ban in Wisconsin, the prevalence of winter application of manure is high. It is precisely because such activity has historically

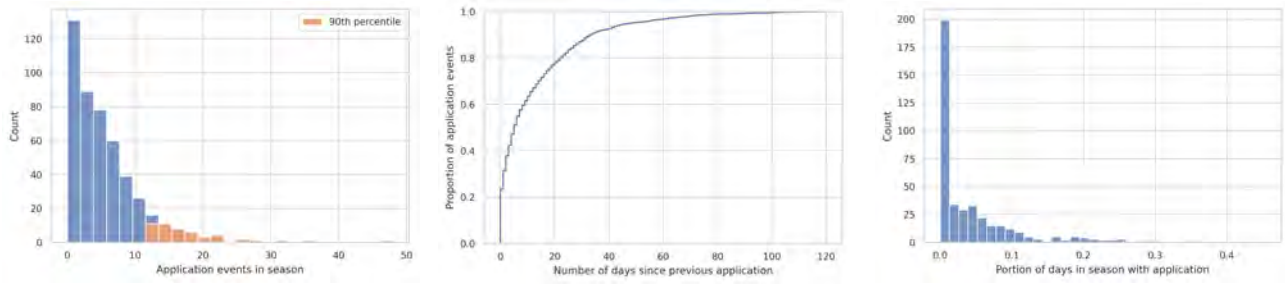

Figure 5: Left: Distribution of number of application events in a single season and location. Orange bars indicate the location-seasons in the 90th percentile. Center: Empirical cumulative distribution function of the time between subsequent application events in one location during. Right: Histogram of the percent of a location's season that was found to have visible application.

been difficult to monitor that it has engendered widespread concerns. Our work should also enable greater scientific study about runoff risks to winter land application, given some existing uncertainties in the evidence base around, for instance, nutrient loss [54]

Second, the prevalence of land application does not seem consistent with what is publicly reported about exemptions that facilities can seek from WI DNR. Given the opacity of how such exemptions are administered, there are two potential interpretations. The first is that the rate of granting exemptions is very high, which would suggest that the formal ban does not functionally restrict land application by CAFOs. If so, this suggests much needed reform, such as the expansion of manure storage requirements in permit terms. The second is that many CAFOs may be engaging in land application in violation of their permits. These would be direct violations of the Clean Water Act. Based on qualitative study of annual spreading reports, it appears that there may be significant under-reporting. From a random sample of more than 30 land application events, only 13 had publicly available spreading reports. Of those, only four had reported the event. Either way, our evidence suggests that laxness of enforcement and monitoring has resulted in widespread winter land application, in spite of the nominal presumptive ban in winter months.

Third, one of our aims is to provide information that can readily be used by environmental interest groups or regulators to prioritize scarce resources. Our outputs may be used to develop facility-level risk scores to prioritize field visits and inspections. Currently, the volume of inspections is extremely low: major facilities permitted under the Clean Water Act are required to be visited once every two years; minor facilities are required to be visited once every five years; and in fact, many facilities are never visited at all [14, 46]. Our model output can hence be exceptionally valuable in risk prioritization. Our detected land application risk can be combined with readily available information about proximity to surface water, size of the CAFO, plant cover, and permit terms to prioritize field visits.

Fourth, the challenges of WI DNR in providing machine readable information about land application self-reports illustrates a broader challenge across government that impedes innovation and accountability: severe fragmentation of data [13, 18]. Such fragmentation poses severe challenges to the use of machine learning in areas where the social benefits may be large [17]. Recent policy proposals have focused on public investments for providing improved, secure, and privacy-protecting access and integrating such administrative datasets [26, 42], which would enable far more innovation.

Fifth, methodologically, our study yields interesting implications about the complementarities of human and machine cognition. In training our team to label instances of land application, humans found it exceptionally helpful to be able to examine the time series of images. This makes sense, as it enables humans to determine whether the appearance of a potential land application area was sudden. Our early experiments, such as the dual CNN, focused on enabling a network to draw such intertemporal inferences. Yet our experiments revealed the static computer vision models outperformed models that had access to the time series of imagery. This suggests that object detection models can drastically cut down on the domain expertise humans require for detecting the subtleties of land application events (e.g., the streaks in snow that are indicative of sequential truck driving paths). At the same time, it also suggests that more work can be done to incorporate temporal methods into computer vision models.

7 LIMITATIONS

We note several limitations to our approach. First, while our study provides the first image dataset of land application events, it took significant time to train a team of five students and staff researchers to recognize such events in satellite imagery. We relied on environmental experts to provide input, but expert input time was necessarily limited. It remains hard to validate such imagery externally, precisely because there are few other sources of ground truth. As a result, our ground truth imagery may miss some instances of land application, particularly when the application technique may have been distinct from the most common methods,[5] or erroneously classify some instances of land application. We piloted potential human validation by sending environmental interest group volunteers to sites, and will be scaling that in the upcoming winter season to provide more robust external validation. While the dataset may seem small for deep learning, many public sector settings will face such constraints, as physical inspections can be costly. Our application hence demonstrates the utility of transfer learning when labels are necessarily sparse and our approach can also be conceived of as a

[5] Ground injection and spray application via hose, for instance, are common techniques that may have other imagery signatures than tractor-drawn spreading. We believe these techniques may be less prevalent in the winter, but our application will still be valuable for the most common land application method.

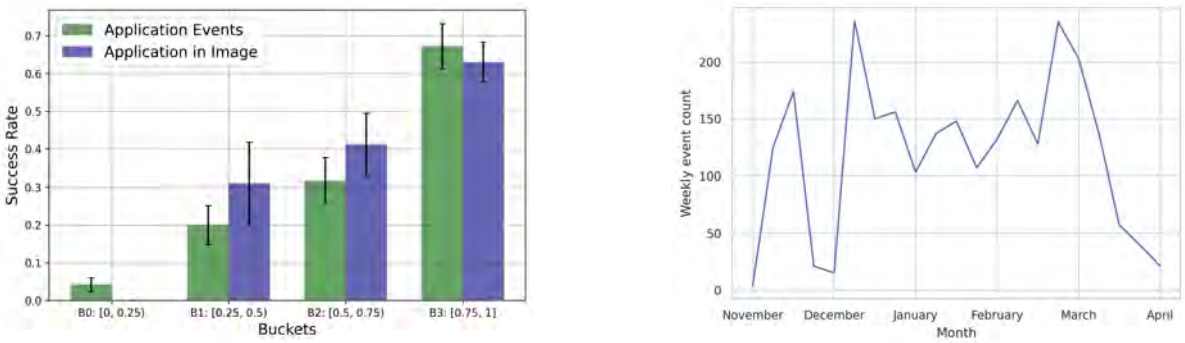

Figure 6: Left: Fraction of positively identified true events (green bars), and images containing application (blue bars). Error bars reflect 68% confidence intervals. Right: Weekly application events throughout the season. All years are combined with a sum each week.

"weak supervision" approach to generate higher fidelity data when combined with in-person validation.

Second, despite Planet Labs providing near daily imagery, after removing those images which are cropped, obscured by cloud, or have clarity issues, we are left with approximately one image a week. Thus, while our system can indeed act as a real-time monitoring system, its efficacy is dependent on the quality of images received. The need to filter out low quality imagery hence also means that we may have missed a number of land application events. Future work might try to lower the image quality standards so that a wider variety of imagery is useful. That said, the availability of satellite imagery is improving rapidly, both in terms of cadence, spatial resolution, and bands, so our demonstration here is likely to improve going forward.

Third, our application currently only searches for land application in images centered on CAFOs. This choice was made for a number of reasons. One is that there were constraints on the number of images we could label. As such, we chose to focus on the regions near CAFOs, because such regions are the most likely to contain application, thus yielding the highest ratio of positives per image examined. The other is a practical reason to reduce the absolute number of false positives, since the contemplated use case is to prioritize field and inspection visits. As emphasized in Section 5.3, this means we are not catching all application events performed by all 330 CAFOs. That said, one of the main constraints for manure disposal lies in transportation costs, so most land application events are expected to be close to the actual CAFO facility (see Figure 3). It would, however, be possible to expand the search radius based on prior knowledge about the economies of waste transportation.

Fourth, we have used an admittedly simple method to group image-level detections into events. The AUC score of 0.63 for both YOLOv5 and Faster R-CNN suggests that there is room for improvement. While we are currently grouping overlapping bounding boxes across images into an event, more sophisticated methods might take into account the amount of overlap between the boxes and the variance in their scores. In general, a potential avenue for future research would be to more formally develop time series event detection methods to model the information directly. Last, it is worth discussing the potential ethical concerns around the potential for surveillance. We emphasize that our method is a tool for resource allocation to be used in conjunction with humans on the ground. That is, all predictions made the model are validated by humans (which must respect local law, such as access rights, when checking for application). The system augments, but does not substitute for the procedural protections of environmental enforcement. Further mitigating such concerns are the fact that (a) 3m/pixel satellite imagery is only capable of detecting fairly large-scale events, and (b) CAFO operators are already mandated to report land application events. Thus, there is no legitimate claim for privacy with respect to manure application.

8 CONCLUSION

We have introduced the problem CAFO land-application detection from aerial imagery, a consequential setting at the intersection of regulatory policy and computer vision. Our main contribution is a real-time system for the detection of winter land application by CAFOs using high-cadence, medium resolution satellite imagery. This was used to allocate field inspectors to suspected application sites at the of the 2021/22 Winter season, with plans to be used throughout the 2022/23 season. We also demonstrated our system's capacity to provide useful retrospective analysis of application events, and detect outlier facilities which apply well above the average. Further, performing stratified sampling of our model predictions, we provide an estimate of 951 application events across 330 CAFO locations in Wisconsin throughout February and March, 2022. Our results suggest that winter land application is pervasive in spite of winter restrictions, but that machine learning coupled with satellite imagery could improve accountability in this environmentally important area.

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REFERENCES

[1] Alexey Bochkovskiy, Chien-Yao Wang, and Hong-Yuan Mark Liao. 2020. Yolov4: Optimal speed and accuracy of object detection. *arXiv preprint arXiv:2004.10934* (2020).

[2] Scott A Bradford, Eran Segal, Wei Zheng, Qiquan Wang, and Stephen R Hutchins. 2008. Reuse of concentrated animal feeding operation wastewater on agricultural lands. *Journal of Environmental Quality* 37, S5 (2008), S–97.

[3] JoAnn Burkholder, Bob Libra, Peter Weyer, Susan Heathcote, Dana Kolpin, Peter S Thorne, and Michael Wichman. 2007. Impacts of waste from concentrated animal feeding operations on water quality. *Environmental health perspectives* 115, 2 (2007), 308–312.

[4] Qing Cai, Zhongke Gao, Jianpeng An, Shuang Gao, and Celso Grebogi. 2020. A graph-temporal fused dual-input convolutional neural network for detecting sleep stages from EEG signals. *IEEE Transactions on Circuits and Systems II: Express Briefs* 68, 2 (2020), 777–781.

[5] Enzo R Campagnolo, Kammy R Johnson, Adam Karpati, Carol S Rubin, Dana W Kolpin, Michael T Meyer, J Emilio Esteban, Russell W Currier, Kathleen Smith, Kendall M Thu, et al. 2002. Antimicrobial residues in animal waste and water resources proximal to large-scale swine and poultry feeding operations. *Science of the Total Environment* 299, 1-3 (2002), 89–95.

[6] Gong Cheng and Junwei Han. 2016. A survey on object detection in optical remote sensing images. *ISPRS Journal of Photogrammetry and Remote Sensing* 117 (2016), 11–28.

[7] Jae Won Choi, Yeon Jin Cho, Seowoo Lee, Jihyuk Lee, Seunghyun Lee, Young Hun Choi, Jung-Eun Cheon, and Ji Young Ha. 2020. Using a dual-input convolutional neural network for automated detection of pediatric supracondylar fracture on conventional radiography. *Investigative radiology* 55, 2 (2020), 101–110.

[8] François Chollet. 2017. Xception: Deep Learning with Depthwise Separable Convolutions. In *2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. 1800–1807. https://doi.org/10.1109/CVPR.2017.195

[9] François Chollet et al. 2015. Keras. https://keras.io.

[10] Ben Chugg, Brandon Anderson, Seiji Eicher, Sandy Lee, and Daniel E Ho. 2021. Enhancing environmental enforcement with near real-time monitoring: Likelihood-based detection of structural expansion of intensive livestock farms. *International Journal of Applied Earth Observation and Geoinformation* 103 (2021), 102463.

[11] Kenneth Ward Church and Valia Kordoni. 2022. Emerging Trends: SOTA-Chasing. *Natural Language Engineering* 28, 2 (2022), 249–269. https://doi.org/10.1017/S1351324922000043

[12] Sakshi Dhingra and Dharminder Kumar. 2019. A review of remotely sensed satellite image classification. *International Journal of Electrical & Computer Engineering (2088-8708)* 9, 3 (2019).

[13] David Freeman Engstrom, Daniel E Ho, Catherine M Sharkey, and Mariano-Florentino Cuéllar. 2020. Government by algorithm: Artificial intelligence in federal administrative agencies. *Report to the Administrative Conference of the United States* (2020).

[14] Environmental Protection Agency. 2014. Clean Water Act National Pollutant Discharge Elimination System Compliance Monitoring Strategy. https://www.epa.gov/sites/default/files/2013-09/documents/npdescms.pdf. [Online, Accessed May 18, 2022].

[15] Feng Gao and Xiaoyang Zhang. 2021. Mapping crop phenology in near real-time using satellite remote sensing: Challenges and opportunities. *Journal of Remote Sensing* 2021 (2021).

[16] Charles P Gerba and James E Smith. 2005. Sources of pathogenic microorganisms and their fate during land application of wastes. *Journal of environmental quality* 34, 1 (2005), 42–48.

[17] Kurt Glaze, Daniel E Ho, Gerald K Ray, and Christine Tsang. 2021. Artificial Intelligence for Adjudication: The Social Security Administration and AI Governance. (2021).

[18] Government Accountability Office. 2021. *Clean Water Act: EPA Needs to Better Assess and Disclose Quality of Compliance and Enforcement Data.*

[19] Environmental Working Group. 2016. Exposing Fields of Filth. https://www.ewg.org/research/exposing-fields-filth. []Online; Accessed May 11, 2022].

[20] Doug Gurian-Sherman. 2008. *CAFOs uncovered: The untold costs of confined animal feeding operations*. Vol. 1. JSTOR.

[21] Cassandra Handan-Nader and Daniel E Ho. 2019. Deep learning to map concentrated animal feeding operations. *Nature Sustainability* 2, 4 (2019), 298–306.

[22] Cassandra Handan-Nader, Daniel E Ho, and Larry Y Liu. 2021. Deep learning with satellite imagery to enhance environmental enforcement. In *Data Science Applied to Sustainability Analysis*. Elsevier, 205–228.

[23] Travis A Hanselman, Donald A Graetz, and Ann C Wilkie. 2003. Manure-borne estrogens as potential environmental contaminants: a review. *Environmental science & technology* 37, 24 (2003), 5471–5478.

[24] Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. 2015. Deep Residual Learning for Image Recognition. *arXiv preprint arXiv:1512.03385* (2015).

[25] Miyuki Hino, Elinor Benami, and Nina Brooks. 2018. Machine learning for environmental monitoring. *Nature Sustainability* 1, 10 (2018), 583–588.

[26] Daniel E Ho, Jennifer King, Russell C Wald, and Christopher Wan. 2022 (forthcoming). Building a National AI Research Resource. *Notre Dame Journal on Emerging Technologies* (2022 (forthcoming)).

[27] Carrie Hribar. 2010. Understanding concentrated animal feeding operations and their impact on communities. (2010).

[28] International Joint Commission. 2019. Oversight of Animal Feeding Operations for Manure Management in the Great Lakes Basin. (2019).

[29] Scott Jerger. 2004. EPA's New CAFO Land Application Requirements: An Exercise in Unsupervised Self-Monitoring. *Stan. Envtl. LJ* 23 (2004), 91.

[30] S. D. Klausner, P. J. Zwerman, and D. F. Ellis. 1976. Nitrogen and Phosphorus Losses from Winter Disposal of Dairy Manure. *Journal of Environmental Quality* 5, 1 (1976), 47–49.

[31] Bernard Koch, Emily Denton, Alex Hanna, and Jacob Foster. 2021. Reduced, Reused and Recycled: The Life of a Dataset in Machine Learning Research.

[32] Theodore W Lewis and Joseph C Makarewicz. 2009. Winter application of manure on an agricultural watershed and its impact on downstream nutrient fluxes. *Journal of Great Lakes Research* 35 (2009), 43–49.

[33] Jian Liu, Peter JA Kleinman, Helena Aronsson, Don Flaten, Richard W McDowell, Marianne Bechmann, Douglas B Beegle, Timothy P Robinson, Ray B Bryant, Hongbin Liu, et al. 2018. A review of regulations and guidelines related to winter manure application. *Ambio* 47, 6 (2018), 657–670.

[34] Xueping Liu, Wenfeng Zhang, Yuanan Hu, Erdan Hu, Xiande Xie, Lingling Wang, and Hefa Cheng. 2015. Arsenic pollution of agricultural soils by concentrated animal feeding operations (CAFOs). *Chemosphere* 119 (2015), 273–281.

[35] Michael A Mallin and Lawrence B Cahoon. 2003. Industrialized animal production—a major source of nutrient and microbial pollution to aquatic ecosystems. *Population and Environment* 24, 5 (2003), 369–385.

[36] Michael A Mallin, Matthew R McIver, Anna R Robuck, and Amanda Kahn Dickens. 2015. Industrial swine and poultry production causes chronic nutrient and fecal microbial stream pollution. *Water, Air, & Soil Pollution* 226, 12 (2015), 1–13.

[37] Susan Maroney, MaryJane McCool-Eye, Andrew Fox, and Christopher Burdett. 2020. Using object-based image analysis to map commercial poultry operations from high resolution imagery to support animal health outbreaks and events. *Geospatial Health* 15, 2 (2020).

[38] M Merkel. 2002. Raising a stink: Air emissions from factory farms. *Environmental Integrity Project* (2002).

[39] Anu Mittal. 2009. *Concentrated animal feeding operations: EPA needs more information and a clearly defined strategy to protect air and water quality from pollutants of concern.* DIANE Publishing.

[40] Lise R Montefiore, Natalie G Nelson, Amanda Dean, and Mahmoud Sharara. 2022. Reconstructing the historical expansion of industrial swine production from Landsat imagery. *Scientific reports* 12, 1 (2022), 1–12.

[41] Keeve E Nachman, Jay P Graham, Lance B Price, and Ellen K Silbergeld. 2005. Arsenic: a roadblock to potential animal waste management solutions. *Environmental Health Perspectives* 113, 9 (2005), 1123–1124.

[42] Amy O'Hara. 2018. US Data Access and the Commission for Evidence-based Policymaking. *International Journal of Population Data Science* 3, 4 (2018).

[43] Kelly A Patyk, Mary J McCool-Eye, David D South, Christopher L Burdett, Susan A Maroney, Andrew Fox, Grace Kuiper, and Sheryl Magzamen. 2020. Modelling the domestic poultry population in the United States: A novel approach leveraging remote sensing and synthetic data methods. *Geospatial Health* 15, 2 (2020).

[44] Inioluwa Deborah Raji, Emily M Bender, Amandalynne Paullada, Emily Denton, and Alex Hanna. 2021. AI and the everything in the whole wide world benchmark. *arXiv preprint arXiv:2111.15366* (2021).

[45] D Raj Raman, Elizabeth L Williams, Alice C Layton, Robert T Burns, James P Easter, Adam S Daugherty, Michael D Mullen, and Gary S Sayler. 2004. Estrogen content of dairy and swine wastes. *Environmental Science & Technology* 38, 13 (2004), 3567–3573.

[46] Clifford Rechtschaffen. 2003. Enforcing the Clean Water Act in the twenty-first century: Harnessing the power of the public spotlight. *Ala. L. Rev.* 55 (2003), 775.

[47] Joseph Redmon, Santosh Divvala, Ross Girshick, and Ali Farhadi. 2016. You only look once: Unified, real-time object detection. In *Proceedings of the IEEE conference on computer vision and pattern recognition*. 779–788.

[48] Joseph Redmon and Ali Farhadi. 2018. Yolov3: An incremental improvement. *arXiv preprint arXiv:1804.02767* (2018).

[49] Shaoqing Ren, Kaiming He, Ross Girshick, and Jian Sun. 2015. Faster r-cnn: Towards real-time object detection with region proposal networks. *Advances in neural information processing systems* 28 (2015).

[50] Vamshi Krishna Repala and Shiv Ram Dubey. 2019. Dual cnn models for unsupervised monocular depth estimation. In *International Conference on Pattern Recognition and Machine Intelligence*. Springer, 209–217.

[51] Caleb Robinson, Ben Chugg, Brandon Anderson, Juan M Lavista Ferres, and Daniel E Ho. 2022. Mapping industrial poultry operations at scale with deep learning and aerial imagery. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* (2022).

[52] Caleb Robinson, Anthony Ortiz, Juan M Lavista Ferres, Brandon Anderson, and Daniel E Ho. 2021. Temporal cluster matching for change detection of structures from satellite imagery. In *ACM SIGCAS Conference on Computing and Sustainable*

Societies. 138–146.

[53] Nithya Sambasivan, Shivani Kapania, Hannah Highfill, Diana Akrong, Praveen Paritosh, and Lora M Aroyo. 2021. "Everyone Wants to Do the Model Work, Not the Data Work": Data Cascades in High-Stakes AI. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 39, 15 pages. https://doi.org/10.1145/3411764.3445518

[54] MS Srinivasan, Ray B Bryant, Michael P Callahan, and Jennifer L Weld. 2006. Manure management and nutrient loss under winter conditions: A literature review. *Journal of soil and water conservation* 61, 4 (2006), 200–209.

[55] Planet Team. 2017. Planet Application Program Interface: In Space for Life on Earth. https://api.planet.com.

[56] Sofia Tilon, Francesco Nex, Norman Kerle, and George Vosselman. 2020. Post-disaster building damage detection from earth observation imagery using unsupervised and transferable anomaly detecting generative adversarial networks. *Remote sensing* 12, 24 (2020), 4193.

[57] USEPA. 2003. National Pollutant Discharge Elimination System permit regulation and effluent limitation guidelines and standards for concentrated animal feeding operations (CAFOs); final rule. *Fed. Regist.* 68, 29 (2003), 7176–7274.

[58] Jan Verbesselt, Achim Zeileis, and Martin Herold. 2012. Near real-time disturbance detection using satellite image time series. *Remote Sensing of Environment* 123 (2012), 98–108.

[59] Michiel Vlaminck, Rugen Heidbuchel, Wilfried Philips, and Hiep Luong. 2022. Region-Based CNN for Anomaly Detection in PV Power Plants Using Aerial Imagery. *Sensors* 22, 3 (2022), 1244.

[60] Kiri Wagstaff. 2012. Machine learning that matters. *arXiv preprint arXiv:1206.4656* (2012).

[61] Mark R Williams, Gary W Feyereisen, Douglas B Beegle, Robert D Shannon, Gordon J Folmar, and Ray B Bryant. 2011. Manure application under winter conditions: Nutrient runoff and leaching losses. *Transactions of the ASABE* 54, 3 (2011), 891–899.

[62] Yuxin Wu, Alexander Kirillov, Francisco Massa, Wan-Yen Lo, and Ross Girshick. 2019. Detectron2. https://github.com/facebookresearch/detectron2.

[63] Liyang Yu, Neng Wang, and Xiaoqiao Meng. 2005. Real-time forest fire detection with wireless sensor networks. In *Proceedings. 2005 International Conference on Wireless Communications, Networking and Mobile Computing, 2005.*, Vol. 2. Ieee, 1214–1217.

CLIMATE CHANGE

Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets

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The Paris Agreement's goal of limiting the increase in global temperature to 1.5° or 2°C above preindustrial levels requires rapid reductions in greenhouse gas emissions. Although reducing emissions from fossil fuels is essential for meeting this goal, other sources of emissions may also preclude its attainment. We show that even if fossil fuel emissions were immediately halted, current trends in global food systems would prevent the achievement of the 1.5°C target and, by the end of the century, threaten the achievement of the 2°C target. Meeting the 1.5°C target requires rapid and ambitious changes to food systems as well as to all nonfood sectors. The 2°C target could be achieved with less-ambitious changes to food systems, but only if fossil fuel and other nonfood emissions are eliminated soon.

The goal of the Paris Agreement is to limit average global temperature increases above preindustrial levels to "well below 2°C" and to pursue efforts to "limit increase to 1.5°C." Achieving either goal requires large and rapid reductions in greenhouse gas (GHG) emissions (*1*). To date, most efforts have focused on reducing GHG emissions from fossil fuel combustion in electricity production, transportation, and industry. Renewable energy sources, electric vehicles, improved efficiency, and other innovations and behavioral changes could eliminate most of these emissions, and carbon capture and sequestration could reduce atmospheric levels of previously emitted carbon. However, eliminating all emissions from these sectors may not be sufficient to meet the 1.5° and 2°C temperature targets. The global food system is also a major source of GHG emissions, emitting ~30% of the global total (*2*, *3*). Nevertheless, reducing food-related emissions has received less attention, perhaps because these emissions might seem to be an unavoidable environmental cost of feeding humanity.

The global food system generates GHG emissions from multiple sources. Major sources include land clearing and deforestation, which release carbon dioxide (CO_2) and nitrous oxide (N_2O); production and use of fertilizers and other agrichemicals, which emit CO_2, N_2O, and methane (CH_4); enteric fermentation during the production of ruminants (cows, sheep, and goats), which emits CH_4; production of rice in paddies, which emits CH_4; livestock manure, which emits N_2O and CH_4; and combustion of fossil fuels in food production and supply chains, which emits CO_2. In total, global food system emissions averaged ~16 billion tonnes (Gt) CO_2 equivalents $year^{-1}$ from 2012 to 2017 (*4*).

Here, we forecast GHG emissions from the global food system and assess whether they are compatible with the 1.5° and 2°C targets. We forecast emissions as a function of per capita diets (what is eaten and how much), the GHG intensity of various types of foods (emissions per unit of food produced, as estimated through life cycle assessment), and global population size. We assume that food systems continue to transition along trajectories of the past 50 years, which we refer to as business-as-usual (*5*, *6*). This business-as-usual forecast makes straightforward assumptions: (i) per capita dietary composition and caloric consumption continue to change as countries become more affluent (*5*); (ii) crop yields, which influence how much land is converted to cropland, increase along recent trajectories (*5*); (iii) global population increases along the United Nation's medium-fertility pathway (*7*); and (iv) the GHG intensity of foods (*8*) and the rates of food loss and waste (*9*) remain constant through time.

GHG emissions from the global food system largely occur from food production and from land being cleared for food production. Emissions from food production are calculated by pairing life cycle assessment estimates of the GHG emissions per unit of each type of food (*8*) with their forecasted total global demand, and these estimates include emissions from activities such as production of agricultural inputs, fertilizer application, and animal husbandry. Our estimates of emissions from supply chains do not include emissions from transportation, processing, packaging, retail, and preparation, which in total account for a minor fraction (~17%) of total food system emissions (*10*). Emissions from clearing land for food production are estimated by projecting crop yields, combining these with dietary projections to calculate annual rates of agricultural land-cover change, and pairing annual rates of agricultural land-cover change with Intergovernmental Panel on Climate Change (IPCC) Tier 1 estimates of GHG emissions from land clearing or carbon storage in biomass and soil after land abandonment (*11*, *12*).

We next determine the maximum allowable cumulative GHG emissions from all human activities from 2020 onward that are compatible with having a 67 or 50% chance of meeting the 1.5° and 2°C targets, on the basis of the thresholds set in the IPCC Special Report on Global Warming of 1.5°C (*13*). We call these the emissions limits. To accurately incorporate CH_4 into the cumulative emissions framework, we report emissions as global warming potential (GWP*) CO_2 warming-equivalents (CO_2-we) (*14*). We also show results with the more commonly used GWP100 (100-year GWP) metric in data S2. To have a 67% chance of meeting the 1.5° and 2°C targets, the cumulative emissions limits are 500 and 1405 Gt CO_2-we, respectively. For a 50% chance of meeting the targets, the emissions limits are 705 and 1816 Gt CO_2-we, respectively (see supplementary materials).

Our analysis suggests that reducing GHG emissions from the global food system will likely be essential to meeting the 1.5° or 2°C target. Our estimate of cumulative business-as-usual food system emissions from 2020 to 2100 is 1356 Gt CO_2-we (Fig. 1). As such, even if all non–food system GHG emissions were immediately stopped and were net zero from 2020 to 2100, emissions from the food system alone would likely exceed the 1.5°C emissions limit between 2051 and 2063 (date range reflects uncertainties in the 1.5°C emissions limit; see supplementary materials). Further, given our estimate of food system emissions, maintaining a 67% chance of meeting the 2°C target would require keeping cumulative nonfood emissions to <50 Gt CO_2-we in total over the next 80 years. This is slightly more than 1 year of current GHG emissions from non–food system activities (*4*). Maintaining a 50% chance of meeting the 2°C target would allow for 455 Gt CO_2-we in total from nonfood emissions, which is 9 years of current nonfood emissions (*4*). These general trends hold even if emissions from fossil fuel use in the global food system were also to be immediately halted (see supplementary materials).

We next explore how global food system GHG emissions might be reduced through five strategies that target food supply and demand: (i) globally adopting a plant-rich diet [here modeled as a diet rich in plant-based foods that contains moderate amounts of dairy, eggs,

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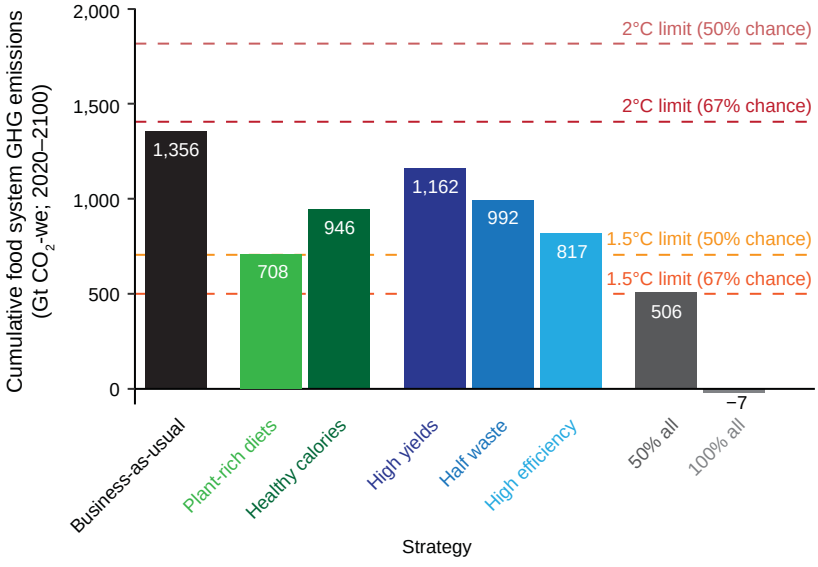

Fig. 1. Projected cumulative 2020 to 2100 GHG emissions solely from the global food system for business-as-usual emissions and for various food system changes that lead to emission reductions. Food system changes are gradually adopted between 2020 and 2050. Bars are colored by type of change to the food system: The black bar indicates business-as-usual emissions, green bars indicate changes to dietary patterns, blue bars indicate changes to food supply chains, and gray bars indicate combined changes of all five individual strategies. The plant-rich diet scenario is based on EAT-Lancet recommendations (*15*), the healthy calorie scenario contains ~2100 daily kilocalories per person, the high yields scenario involves yields that are 50% above current maximum potential yields, the half waste scenario has food loss and waste reduced by 50%, and the high efficiency scenario indicates a 40% reduction in GHG emissions per unit of food produced. The two rightmost columns indicate a global transition halfway (50% all) or entirely (100% all) to adoption by 2050 of all five strategies: plant-rich diet, healthy calories, high yields, half waste, and high efficiency changes. Horizontal lines indicate the maximum cumulative emissions from all sources (food and nonfood) compatible with a 50 or 67% likelihood of achieving the 2° (red) and 1.5°C (orange) temperature targets.

and meat, such as a Mediterranean diet or planetary health diet (*15*)]; (ii) adjusting global per capita caloric consumption to healthy levels; (iii) achieving high yields by closing yield gaps and improving crop genetics and agronomic practices; (iv) reducing food loss and waste by 50%; and (v) reducing the GHG intensity of foods by increasing the efficiency of production, such as by altering management regimes (e.g., precise use of nitrogen fertilizer and other inputs) or technological implementation (e.g., additives to ruminant feed). We also explore the potential GHG benefits of partial (50%) or complete (100%) adoption of all five strategies simultaneously. Other combinations of strategies and their levels of adoption are provided in data S2. Although we discuss food system transitions at the global scale, the magnitude and direction of the transitions will vary by country.

We find that cumulative food system GHG emissions from 2020 to 2100 can be reduced by 14 to 48% through changes in dietary composition and healthier caloric consumption, through increased crop yields, through decreased food loss and waste, or through increased emissions efficiency of food production, provided that these strategies are adopted individually and gradually such that they are fully adopted by 2050 (Fig. 1). If all five strategies were to be partially implemented together (50% adoption of each), cumulative emissions through 2100 could be reduced by 63% relative to business-as-usual. Full adoption of all five strategies could result in a food system with marginally negative net cumulative emissions because of lowered emissions and net carbon sequestration on abandoned croplands (Fig. 1).

GHG emissions from all human activities affect global climate. As such, to meet a given emissions limit, there is a tradeoff between food and nonfood emissions within a total cumulative budget: Higher emissions from the global food system necessitate lower emissions from other sectors, and vice versa. To illustrate how emissions from all human activities might be kept under the emissions limits, we consider them in the context of an increasingly decarbonized future in which all nonfood emissions and all food-related emissions from fossil fuel combustion decline linearly from current levels to zero by 2050 (*4*). This rate of reduction is approximately in line with the rates of decarbonization estimated to be needed to meet the 1.5°C target in global integrated assessment models (*16*). We find that in this increasingly decarbonized future, total global emissions from all sources (business-as-usual food plus nonfood) would exceed the 1.5°C limit within 11 years, and they would exceed the 2°C limit before the end of the century (Fig. 2A).

Assuming this linear reduction to decarbonization in 2050, meeting the 2°C target is plausible through the use of numerous food system strategies, provided that they are also adopted by 2050 (Fig. 2A). As is well known, dietary changes—such as the adoption of plant-rich diets—can greatly reduce emissions (*5*, *6*, *17*). Even in the absence of dietary changes, achieving either high yields, high agricultural efficiency, or a 50% reduction in food waste alone could also meet the 2°C limit, as could partial achievement of various strategies (Fig. 2A).

Meeting the 1.5°C target with this linear decarbonization by 2050 requires at least partial achievement of multiple food system strategies: None of the five individual strategies alone are sufficient. If full implementation of these food and nonfood emission changes were to be delayed by 25 years to 2075, then even 100% adoption of all five strategies would preclude meeting the 1.5°C target (Fig. 2B). For this case of slower implementation, the 2°C target could be met only by at least a 50% adoption of all five strategies, and not by any single strategy (Fig. 2B). This is because a slower adoption of food system strategies, a slower reduction of fossil fuel use in the food system, and a slower reduction in nonfood emissions each necessitates larger changes to the food system to meet targets.

The need for rapid reduction in GHG emissions from fossil fuels to meet the 1.5° or 2°C targets is widely acknowledged. We show that the same is true for food systems: Even if fossil fuel emissions were rapidly reduced, emissions from the global food system are on a trajectory that would prevent achievement of the 1.5° and 2°C targets before the end of the century. Our analyses also suggest there are many opportunities to meet the 1.5° or 2°C emission targets. Previous analyses have suggested that global food system emissions might increase by up to 80% from 2010 to 2050 (*5*, *6*, *17*). Our findings—consistent with these results (see supplementary materials)—improve on these forecasts by explicitly linking food systems to IPCC cumulative emissions limits (*13*), using a reporting method to include CH_4 in this framework (*14*), increasing the breadth of scenarios analyzed, allowing for different levels and different rates at which food system transitions occur, providing annual emissions estimates, and forecasting beyond 2050 to 2100.

We show that meeting the 1.5° and 2°C targets will likely require extensive and unprecedented changes to the global food system.

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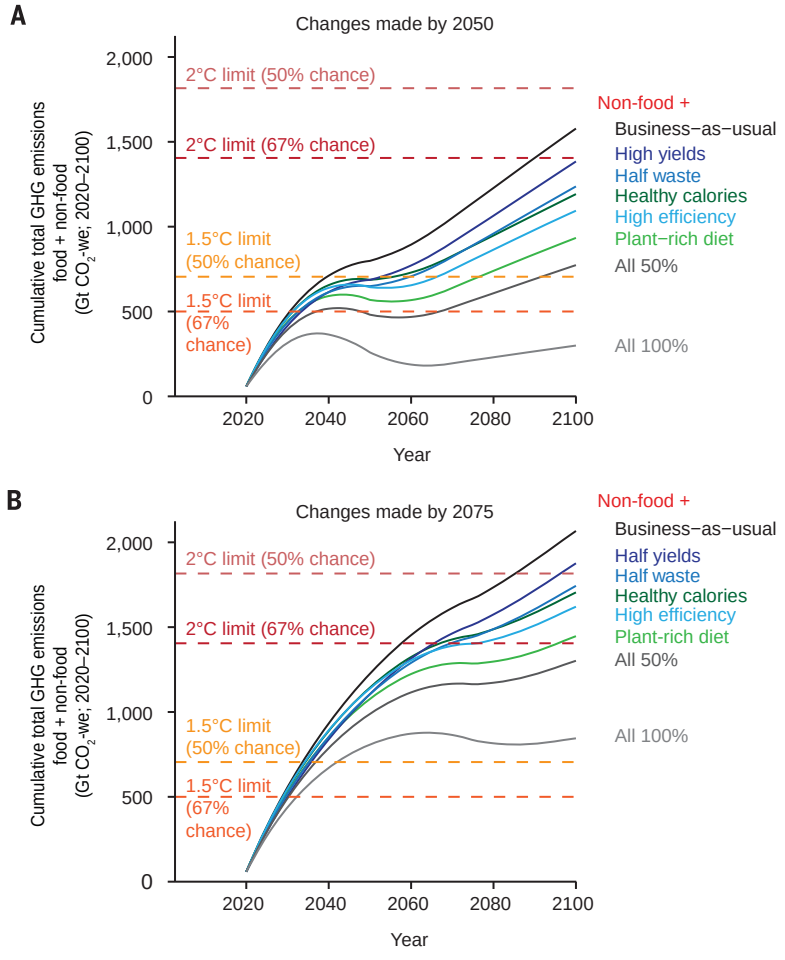

Fig. 2. Estimated GHG emissions from all human activities (food plus nonfood) for different food system changes and different rates of emissions reductions from fossil fuels and food systems. (**A** and **B**) Nonfood emissions are linearly reduced to zero from 2020 to 2050 (A) or from 2020 to 2075 (B). Solid curves show cumulative emissions from all human activities if different food system strategies were to be implemented. Fossil fuel emissions from within the food system are also assumed to be reduced at the same rate as for emissions from outside the food system. Horizontal dashed lines indicate maximum cumulative emissions from all sources (food and nonfood) compatible with a 50 or 67% likelihood of meeting the remaining 2° (red) and 1.5°C (orange) temperature targets.

Recent studies have provided insight into plausibly achievable ways to reduce food system GHG emissions. Large-scale field trials in China and the United States have shown that changes in farm management could reduce nitrogen fertilizer use and its associated GHG emissions while increasing farmer profits (*18*, *19*). Rapid increases in crop yields that decrease land clearing and its emissions have been achieved through access to improved seeds and fertilizers (*20*). Such increases in yields might also be achieved through the adoption of agroecological production practices—including cover crops, integrated pest management, and increased use of precision agriculture (*21*, *22*)—but will require different management interventions in different regions (*23*). Food awareness, reformulation, and labeling; changes in the food environment; and education and awareness campaigns have shifted consumer food purchases in numerous countries (*24*, *25*). Carbon taxation might also be effective (*26*). Food loss and waste could be reduced by improvements to infrastructure, such as grain storage and refrigeration, or by innovative methods to sell food that would otherwise be wasted (*9*). Food system changes that reduce GHG emissions may offer additional benefits (*27*), including progress toward targets set in the United Nations' Sustainable Development Goals (*28*), such as decreased nutrient pollution (*6*), reduced water pollution and scarcity (*6*), decreased land-use change (*5*, *6*, *17*), improved biodiversity outcomes (*29*), and, if dietary composition and caloric consumption are improved, reduced prevalence of obesity, diabetes, heart disease, and premature mortality (*30*).

Time is of the essence in addressing GHG emissions. Any delays will necessitate more ambitious and expeditious implementation of emissions reduction strategies if global temperature targets are to be met. We show that there are many opportunities to keep emissions from food systems and other activities within the global emissions limits for the 1.5° and 2°C targets. The global challenge of finding and implementing feasible, ethical, and equitable policies to reduce net GHG emissions will require the rapid adoption of coordinated solutions, both within and outside of the food system, that are tailored to the needs and customs of different countries and the communities within them.

REFERENCES AND NOTES

1. J. Rogelj, D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, M. V. Vilariño, in *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield, Eds. [Intergovernmental Panel on Climate Change (IPCC), 2018], pp. 93–174.
2. S. Vermeulen, B. M. Campbell, J. S. I. Ingram, *Annu. Rev. Environ. Resour.* **37**, 195–222 (2012).
3. C. Rosenzweig *et al.*, *Nat. Food* **1**, 94–97 (2020).
4. J. Gütschow, L. Jeffery, R. Gieseke, The PRIMAP-hist national historical emissions time series (1850-2016), version 2.0., GFZ Data Services (2019); https://doi.org/10.5880/pik.2019.001.
5. D. Tilman, M. Clark, *Nature* **515**, 518–522 (2014).
6. M. Springmann *et al.*, *Nature* **562**, 519–525 (2018).
7. United Nations Department of Economic and Social Affairs (UN DESA), "World Population Prospects: The 2017 Revision" (2017); www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html.
8. M. Clark, D. Tilman, *Environ. Res. Lett.* **12**, 064016 (2017).
9. J. Gustavsson, C. Cederberg, U. Sonesson, R. van Otterdijk, A. Meybeck, *Global Food Losses and Food Waste: Extent, Causes and Prevention* (Food and Agricultural Organization, 2011).
10. J. Poore, T. Nemecek, *Science* **360**, 987–992 (2018).
11. A. Ruesch, H. Gibbs, "New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000" (Carbon Dioxide Information Analysis Center, 2008); http://cdiac.ess-dive.lbl.gov.
12. T. Hengl *et al.*, *PLOS ONE* **12**, e0169748 (2017).
13. P. Forster, D. Huppmann, E. Kriegler, L. Mundaca, C. Smith, J. Rogelj, R. Séférian, in *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield, Eds. (IPCC, 2018), pp. 2SM-1–2SM-50.
14. M. Cain *et al.*, *npj Clim. Atmos. Sci.* **2**, 29 (2019).
15. W. Willett *et al.*, *Lancet* **393**, 447–492 (2019).
16. S. Roe *et al.*, *Nat. Clim. Chang.* **9**, 817–828 (2019).
17. B. Bajželj *et al.*, *Nat. Clim. Chang.* **4**, 924–929 (2014).
18. Z. Cui *et al.*, *Nature* **555**, 363–366 (2018).
19. S. Sela *et al.*, *Agron. J.* **108**, 1726–1734 (2016).
20. Z. Druilhe, J. Barreiro-Hurlé, "Fertilizer subsidies in sub-Saharan Africa" [ESA Working Paper 288997, Food and Agriculture Organization of the United Nations, Agricultural Development Economics Division (ESA), 2012]; https://doi.org/10.22004/ag.econ.288997.

Downloaded from https://www.science.org at Yale University on July 21, 2025

21. H. C. J. Godfray, T. Garnett, *Phil. Trans. R. Soc. B* **369**, 20120273 (2014).
22. G. Philip Robertson *et al*., *Bioscience* **64**, 404–415 (2014).
23. P. Pradhan, G. Fischer, H. van Velthuizen, D. E. Reusser, J. P. Kropp, *PLOS ONE* **10**, e0129487 (2015).
24. M. A. Colchero, J. Rivera-Dommarco, B. M. Popkin, S. W. Ng, *Health Aff.* **36**, 564–571 (2017).
25. J. Ranganathan, D. Vennard, R. Waite, B. Lipinski, T. Searchinger, P. Dumas, A. Forslund, H. Guyomard, S. Manceron, E. Marajo Petitzon, C. Mouël, P. Havlík, M. Herrero, X. Zhang, S. Wirsenius, F. Ramos, X. Yan, M. Phillips, R. Mungkung, "Shifting Diets for a Sustainable Future" (Installment 11 of Creating a Sustainable Food Future, World Resources Institute, 2016); www.wri.org/publication/shifting-diets.
26. M. Springmann *et al*., *Nat. Clim. Chang.* **7**, 69–74 (2016).
27. C. Mbow, C. Rosenzweig, L. G. Barioni, T. G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M. G. Rivera-Ferre, T. Sapkota, F. N. Tubiello, Y. Xu, in *Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, Eds. (IPCC, 2019), pp. 437–550.
28. United Nations General Assembly, "Transforming Our World: The 2030 Agenda for Sustainable Development" (UN, 2015); https://sustainabledevelopment.un.org/post2015/transformingourworld/publication.
29. D. Tilman *et al*., *Nature* **546**, 73–81 (2017).
30. M. Springmann *et al*., *Lancet Planet. Health* **2**, e451–e461 (2018).

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
References (*31*–*60*)
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BUSINESS ENERGY & OIL

California's Green-Energy Subsidies Spur a Gold Rush in Cow Manure

A lucrative state incentive to make natural gas from dairy waste is attracting companies from Amazon to Chevron

By Phred Dvorak Follow *Photographs by Jennifer Emerling for The Wall Street Journal*

Feb. 19, 2022 9:00 am ET

Clean Energy Fuels Corp., CLNE **0.99%** ▲ a major distributor of natural gas made from waste, found a way to boost its earnings by millions of dollars, virtually overnight.

All it had to do was switch the main biofuel it supplies to power cars and trucks in California—currently a type of natural gas produced with methane emissions from garbage—to a chemically identical gas produced from the manure of cows.

California's clean-fuels grading system gives cow-poop gas a much better score—and much higher subsidies—than landfill gas. So that simple substitution could net Clean Energy an additional $70 million in earnings before interest, taxes, depreciation and amortization by 2026, the company estimates.

Together with European energy giants BP PLC and TotalEnergies SE, Clean Energy is pouring hundreds of millions of dollars into gas production on dairy farms to milk that advantage. A host of developers, financiers and carbon-conscious corporations, from Chevron Corp. to Amazon.com Inc., AMZN **1.40%** ▲ are looking to buy or produce the fuel as well.

"It is like magic," said Andrew Littlefair, Clean Energy's president and chief executive, of the projected earnings boost.

The surging interest in dairy renewable natural gas, as it is called, shows how incentives can spur action to address the emissions linked to climate change—and sometimes unintended consequences as well. Until a few years ago, the gas, which is interchangeable with conventional natural gas and can replace dirtier fuels like diesel, was a niche product that was too expensive to make commercially.

Manure Power

Natural gas made from dairy manure scores the lowest—meaning it's the cleanest—on California's clean-fuels scale.

Carbon intensity scores for transportation fuels*

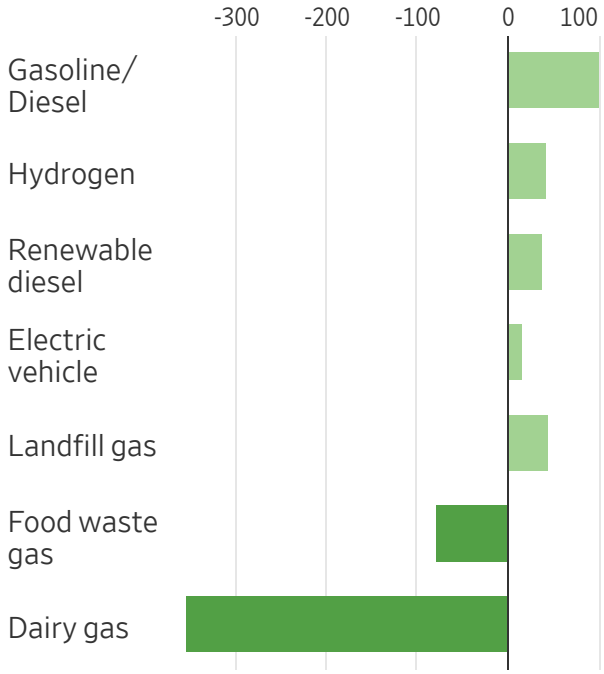

*Grams of carbon dioxide equivalent per megajoule of energy
Source: California Air Resources Board

Now, California's generous subsidies have prompted what some observers are dubbing a manure gold rush. One developer said he showed up at a dairy only to discover that the farmer had gotten more than 10 pitches for business tie-ups already. Others said competition for business has gotten so heated that some developers are promising to pay farmers a fixed amount per cow—a risky setup if the price of the California credits plummets.



David Ribiero, co-owner of Rib-Arrow Dairy in central California, said methane sales have finally become economically feasible.

Driving the boom is California's Low-Carbon Fuel Standard. The standard requires companies that sell transportation fuels in the state to lower their products' carbon intensity—the carbon dioxide

emitted during manufacture, distribution and consumption. Companies that exceed the carbon-intensity maximums have to buy offset credits, each of which represents a metric ton of emissions. Those with low-scoring fuels generate credits, whose price goes up and down depending on demand.

The lowest carbon-intensity scores go to fuels that keep warming gases out of the air—particularly methane, a greenhouse gas that can be 84 times more potent in trapping heat than carbon dioxide, according to the Intergovernmental Panel on Climate Change, the scientific group that helps the United Nations evaluate the state of research on the issue.

Other waste sources such as landfills produce methane, too. But California already requires landfills to curb methane emissions while farms don't have to, and thus they emit more. So capturing the methane from decomposing manure at dairies to make truck fuel cuts net emissions a lot, and reaps some of the best scores of all.

U.S. regulators haven't generally imposed controls on methane emissions from livestock, since they are tough to implement and politically sensitive.

California Bioenergy LLC, which develops projects to make energy out of manure, in 2016 received the first provisional carbon-intensity score—around negative 270—for a dairy-gas facility. Diesel by comparison has an average carbon-intensity score of more than 100. CalBio, as it is known, now has 41 dairy-gas projects in operation and another 60-odd projects in development.

Its latest project to go online is the 1,500-cow Rib-Arrow Dairy in central California, where manure is now flushed from the floor of the stalls into a covered lagoon, called a digester, so the methane can be collected for processing rather than released into the air. That raw biogas, which is around 60% methane and the remainder mostly carbon dioxide, is piped to a central facility that collects gas from a cluster of dairies in the area and purifies it for injection into the local utility's pipeline.

David Ribeiro, a third-generation co-owner of Rib-Arrow, said he had been approached by digester salesmen before, but that adding the gas sales to the environmental benefits finally made everything economically feasible: "We're like, 'Wow, this makes sense.'"

There are 116 such facilities currently operating in the U.S.—more than half of which went online last year—and another 121 planned or in construction, according to the Coalition for Renewable Natural Gas, a nonprofit that promotes gas made from waste. Analysts say thousands more dairies could support such plants, which can reduce foul odors in addition to capturing emissions.

The market is likely to remain small compared with the U.S.'s overall appetite for natural gas in homes, businesses and transport. Even in an optimistic scenario, biogas from manure would supply

only around 3% of today's demand by 2040, according to a 2019 study commissioned by the American Gas Foundation.

Still, money is pouring in from big companies looking to lower their carbon footprints quickly—as well as entrepreneurs smelling a business opportunity. Clean Energy said it is working on more than a billion dollars worth of deals through its dairy-gas joint ventures with BP and Total, and that it hopes to channel more than $2 billion in investment by 2026.

California-based Chevron has committed around $500 million to develop renewable natural-gas supply, starting with dairies. A Chevron investor presentation in September showed plans for a national network of as many as "190,000 milking cow equivalents" and forecast double-digit returns. Amazon has inked a deal with Clean Energy to buy biogas for its massive trucking fleet; it declined to comment.



At a California Bioenergy plant, methane is separated from carbon dioxide before it is injected into a local utility's pipeline.



The entire separation process happens over the course of a minute.

More than half of California's methane is released from dairy and livestock manure, and by cow burps. The state has vowed to lower greenhouse gas emissions by 40% compared with 1990 levels by 2030, and it is focusing on methane reductions in particular. It is also targeting a 20% reduction in the carbon intensity of its transportation fuel relative to 2010, and has so far managed to cut it by more than 7%.

"From our perspective, the program is working to drive private investment" to accomplish the state's environmental goals, said Matthew Botill, the division chief at California's Air Resources Board who oversees the state's low-carbon fuel standard and other climate change programs.

California officials said the program doesn't cost the state money because its market-based mechanism results in producers and consumers of higher-carbon fuels effectively paying the incentives to the producers and consumers of low-carbon fuels.

Oregon and the Canadian province of British Columbia are implementing similar fuel standards, and a number of other states are considering them, too. The federal government issues its own, less-lucrative, subsidies for low-carbon fuels.

California's aggressive incentive system is producing some odd results. One dairy that was already using digesters to collect methane and produce electricity from its manure—the 35,000-cow Threemile Canyon Farms in Oregon—got a relatively high carbon-intensity score of negative 189 when it shifted to making gas for California, since it had fewer emissions to reduce.

"The manure management practices on the farm were so good...that they were penalized a bit," said Ben Vitale, CEO of Resilient Infrastructure Group, which owns Threemile's gas plant.

Financiers at Cresta Fund Management, a Texas-based private-equity fund that has two renewable natural gas producers in its portfolio, said they have seen an increasing number of entrepreneurs with little experience in the area trying to raise money for dairy-gas projects.

"We had some authors pitch us," said John Skrinar, Cresta's director of sustainable investments. "The reality is, it's a lot more complicated than just show up, put a swimming pool in the ground, shovel a bunch of cow manure into it, and make a fortune."

At Rib-Arrow Dairy, water used in the methane-capture process is stored in this lagoon. The water will eventually be used for cow feed and fertilizer.

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Flooding results in livestock losses

brownfieldagnews.com/news/flooding-results-in-livestock-losses

June 25, 2024

News

Flooding results in livestock losses

By Mark Dorenkamp Filed Under: Ag Weather, Beef, Cattle, Livestock, Minnesota, News, USDA, weather



Flooding in the Upper Midwest is resulting in livestock losses.

Minnesota State Cattlemen's Association president Jake Thompson tells Brownfield the southwest corner of the state is most effected.

"With this drastic change in cool to hot and the water stresses, we did have a feedlot call that had fairly higher death loss due to some of this water and stress that they're dealing with in cattle and doing everything they can to minimize that."

He says impacted producers should contact their local FSA office.

“Depending on the size of operation and the amount of impact that’s happened, you could look at doing a livestock indemnity program.”

Thompson says even if threshold numbers aren’t reached, it’s still a good idea to reach out.

PNAS RESEARCH ARTICLE | EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES OPEN ACCESS

Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming

Gabrielle B. Dreyfus[a,b], Yangyang Xu[c,1], Drew T. Shindell[d], Durwood Zaelke[a,e], and Veerabhadran Ramanathan[f,g,1]

Contributed by Veerabhadran Ramanathan; received January 6, 2022; accepted March 22, 2022; reviewed by Valerie Masson-Delmotte and Venkatachalam Ramaswamy

The ongoing and projected impacts from human-induced climate change highlight the need for mitigation approaches to limit warming in both the near term (<2050) and the long term (>2050). We clarify the role of non-CO_2 greenhouse gases and aerosols in the context of near-term and long-term climate mitigation, as well as the net effect of decarbonization strategies targeting fossil fuel (FF) phaseout by 2050. Relying on Intergovernmental Panel on Climate Change radiative forcing, we show that the net historical (2019 to 1750) radiative forcing effect of CO_2 and non-CO_2 climate forcers emitted by FF sources plus the CO_2 emitted by land-use changes is comparable to the net from non-CO_2 climate forcers emitted by non-FF sources. We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of coemitted aerosols) and lead to temperatures exceeding 2 °C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2 °C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030 and reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this time frame. Our analysis demonstrates the need for a comprehensive CO_2 and targeted non-CO_2 mitigation approach to address both the near-term and long-term impacts of climate disruption.

climate mitigation | short-lived climate pollutants | fossil fuel radiative forcing | near-term warming | non-CO_2 climate effects

Significance

This study clarifies the need for comprehensive CO_2 and non-CO_2 mitigation approaches to address both near-term and long-term warming. Non-CO_2 greenhouse gases (GHGs) are responsible for nearly half of all climate forcing from GHG. However, the importance of non-CO_2 pollutants, in particular short-lived climate pollutants, in climate mitigation has been underrepresented. When historical emissions are partitioned into fossil fuel (FF)- and non-FF-related sources, we find that nearly half of the positive forcing from FF and land-use change sources of CO_2 emissions has been masked by coemission of cooling aerosols. Pairing decarbonization with mitigation measures targeting non-CO_2 pollutants is essential for limiting not only the near-term (next 25 y) warming but also the 2100 warming below 2 °C.

Global warming is causing climate disruption today. At about 1.1 °C warming above preindustrial temperature (1), these impacts are being felt sooner and more intensely than previously projected (2). The frequency and intensity of climate and weather extremes have increased due to human-induced climate changes (1), and impacts such as displacements due to extremes are expected to grow with additional global warming (2).

We make a distinction between near-term warming and long-term warming: Near-term warming refers to the warming from now until 2050, while long-term refers to the period beyond 2050. This distinction omits the "mid-term (2041 to 2060)" recently introduced in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) (1). When the focus is on long-term, decarbonization to reach net-zero carbon dioxide emissions should be the foremost goal. However, a new set of issues has emerged because of the link between warming and extreme weather (3) and the risk of crossing uncertain tipping points that increase with additional warming (1, 4).

Every region is experiencing extreme weather impacts from climate change (2, 5). The number of potentially fatal humid heat events doubled between 1979 and 2017 (6), while heat-related mortality in people over 65 y increased 53.7% (7). Such fatal humid heat events are expected to become common in the tropics at global average temperatures above 1.5 °C (8, 9). Increases in humid heat also reduce labor productivity, with current losses of annual gross domestic product up to 6% in tropical countries (7) and nonlinear increases under warming (10). Actions that limit warming to close to 1.5 °C would "substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*)" (2).

The critical need to curb near-term warming and limit warming to well below 2 °C requires broadening the zero carbon dioxide emissions approach, which focuses on mitigating the long-term warming, with other approaches that can quickly reduce the near-term warming by including non-CO_2 warming pollutants as an additional major

Author contributions: G.B.D., Y.X., D.T.S., D.Z., and V.R. designed research; G.B.D. and Y.X. performed research; G.B.D., Y.X., D.T.S., and V.R. analyzed data; and G.B.D., Y.X., D.T.S., D.Z., and V.R. wrote the paper.

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focus of climate mitigation actions. The science of non-CO_2 warming pollutants dates back to 1975 with the discovery of the supergreenhouse effect of chlorofluorocarbons (CFCs) (11) followed by the addition of methane (CH_4) and nitrous oxide (N_2O) in 1976 (12). A comprehensive review of non-CO_2 warming agents by a United Nations–commissioned group in 1985 (13) concluded that non-CO_2 greenhouse gases (GHGs) were contributing as much as CO_2 to warming and projected that for the period between 1980 and 2030 non-CO_2 gases were likely to continue contributing as much as CO_2 to warming. These findings and projections have been confirmed by the most recent IPCC reports (14–17). We summarize these in the next section.

Independently, a series of studies that began in the 1970s concluded that fossil fuels (FFs), while contributing to global warming through CO_2 emissions, were also leading to global dimming and resulting cooling by increasing atmospheric aerosol particles (18, 19). While the overall aerosol effect is strongly negative due to emissions of sulfates, nitrates, and some organics that primarily reflect sunlight, there are other aerosols such as black carbon (BC) and brown carbon that absorb sunlight and thus contribute to global warming. The findings of the three decades of studies have been confirmed by the most recent IPCC report, which concludes that as of 2019 the net radiative forcing from cooling aerosols is around −1.5 Wm^{-2} (excluding about +0.38 from the aerosol-radiation forcing from BC and its effect on surface albedo). The CO_2 radiative forcing is 2.16 Wm^{-2} and radiative forcing due to non-CO_2 GHGs and BC is 2.10 Wm^{-2} (15).

Despite the general recognition of the role of non-CO_2 pollutants in climate mitigation, their contribution to warming as well as their potential for near-term cooling has been underappreciated in part due to inconsistencies between representation of climate forcing between IPCC Working Group I (WGI: Physical Scientific Basis), which includes all pollutants, and Working Group III (WGIII: Mitigation of Climate Change), which focuses on CO_2 and the subset of GHGs covered under the Kyoto Protocol, hence excluding halogenated gases covered by the Montreal Protocol and both warming and cooling aerosols that are primarily coemitted with CO_2 from FF usage. As we discuss in the next section, since FF combustion is the primary source of CO_2 emissions and also the source of some non-CO_2 pollutants, the extent to which decarbonization strategies to reduce FF emissions also reduce non-CO_2 emissions is ambiguous in many mitigation studies due to study design, leading some to question the benefits of early and fast targeted action in reducing non-CO_2 emissions (20).

The focus on CO_2 underpins the concept of carbon budget, which has been used to construct decarbonization pathways to meet specified long-term warming levels (21). While it has long been known that the coincidental cancelling of non-CO_2 warming and aerosol cooling was unlikely to persist due to differences in their sources and residence times (22), few carbon-budget-based studies have included the tight linkage between CO_2 mitigation and reduction in cooling aerosol emissions until recently (23).

Many publications and reports by scientific agencies (24–32) highlighted the role of non-CO_2 for rapid near-term climate mitigation, specifically short-lived climate pollutants (SLCPs)—methane (CH_4), BC, hydrofluorocarbons (HFCs), and tropospheric ozone (O_3)—but these have not captured the attention of global mitigation actions, which still focuses largely on CO_2 emissions.

There are two primary objectives of this study: first, clarifying the role of non-CO_2 GHGs (short-lived and long-lived) and aerosols (warming and cooling) in the context of the need for near-term and long-term climate mitigation, and second, clarifying the net effect of the FF phaseout in decarbonization, which involves both cooling due to cutting CO_2 emissions and warming due to unmasking of cooling aerosols coemitted by FF use. Unless otherwise stated, we rely on forcing values in the IPCC WGI reports published in 2021 and 2013.

Contributions to Radiative Forcing: CO_2 vs. Non-CO_2 GHGs (Excluding Aerosols)

Previous reports of IPCC WGI have consistently found that CO_2 and non-CO_2 GHG and GHG precursor emissions contribute close to equal shares (52 to 57% for CO_2 and 43 to 48% for non-CO_2 GHG) to climate forcing in radiative forcing terms when excluding aerosols (*SI Appendix*, Table S1). These results are reproduced in Fig. 1 *A* and *B*. In contrast, IPCC WGIII states in the Fifth Assessment Report (AR5) that "CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emission increase from 1970 to 2010, with a similar percentage contribution for the period 2000–2010 .... Annually, since 1970, about 25% of anthropogenic GHG emissions have been in the form of non-CO_2 gases" (33). A similar statement was made by WGIII in the Fourth Assessment Report (AR4). However, these statements are inconsistent with WGI science and contribute to confusion for several reasons:

- First, GHG emissions considered by WGIII only include CO_2 (from FF use and forestry and other land use, [FOLU]), CH_4, N_2O, and HFCs and omit nonmethane tropospheric ozone precursors, CFCs, hydrochlorofluorocarbons (HCFCs), and other ozone-depleting substances covered by the Montreal Protocol (*SI Appendix*, Fig. S1). Taking into account these omitted non-CO_2 climate forcers using the EDGARv5.0 emissions database (34) for CO (as a proxy for nonmethane O_3 precursors) and National Oceanic and Atmospheric Administration and AGAGE (35) network data for CFC/HCFC/halon emissions, the average non-CO_2 GHGs and GHG precursors share over 1970 to 2010 is 39% (instead of the 25% quoted in WGIII reports) using the 100-y global warming potential (GWP_{100}) metric and 59% using GWP_{20}.
- Second, presenting the increase in emissions between two years (1970 and 2010) provides limited if not misleading insights into the actual forcing and climate impacts. We offer two examples, all of which adopt IPCC WGI estimates. 1) For the years 1993, 1998, 2005, 2011, and 2019, the percentage of CO_2 forcing (from all sources) compared with the total GHGs forcing ranges from 52 to 57% (*SI Appendix*, Table S1). The non-CO_2 GHGs contribute the balance of 43 to 48% (*SI Appendix*, Tables S1 and S2). 2) The contribution of the CO_2 forcing from just FFs to the total GHGs forcing is 38% for 2011 and 43% for 2019. The basic inference is that the WGIII finding of "CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emission increase from 1970 to 2010" cannot be used to infer the contribution of CO_2 or FFs to either the radiative forcing or the resulting climate changes.

In short, the conclusion by WGIII that CO_2 from FF combustion contributed 78% of the total GHG emissions increase from 1970 to 2010 significantly underrepresents the nearly equal contribution of non-FFs as well as that of non-CO_2 GHGs to the total radiative forcing, which are described in the next two sections. Revisiting this historical accounting puts

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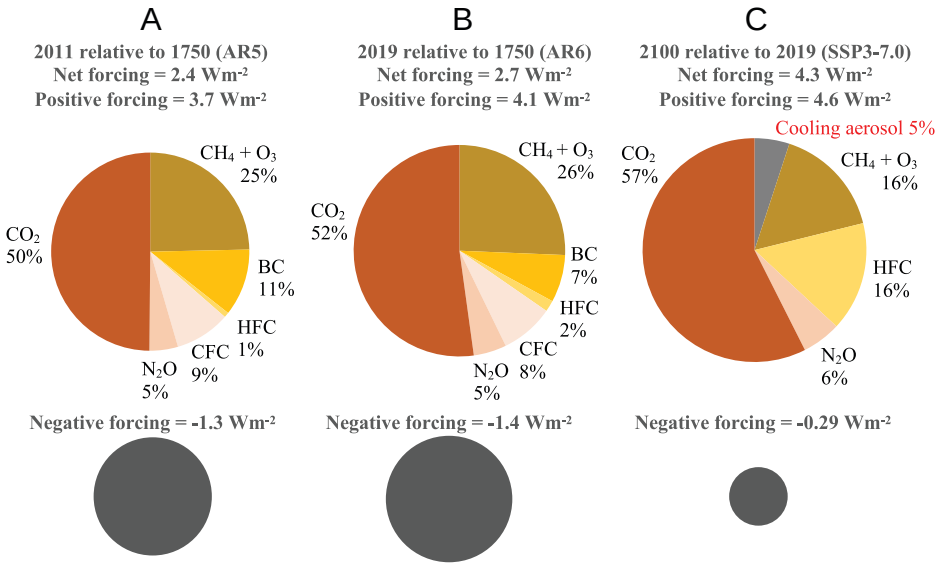

Fig. 1. Positive radiative forcing from long-lived GHGs (orange), short-lived GHGs, GHG precursors, and BC (aerosol–radiation interaction and snow albedo effects only) (yellow) and negative forcing from individual aerosol direct effects (aerosol–radiation interaction) and the total aerosol indirect effects (aerosol–cloud interaction) (separate gray pie) in (*A*) 2011 relative to 1750, from AR5 (14) and (*B*) 2019 relative to 1750, from AR6 (15). (*C*) The forcing at 2100 relative to 2019, under SSP3-7.0 emissions (49). Note the negative forcing due to assumed BC and CFC reduction and the positive forcing due to decline of cooling aerosols. Area of each pie chart is scaled to positive or negative forcing. See *SI Appendix*, Fig. S5 for bar chart version and *SI Appendix*, Table S6*A* for data.

into perspective the role of non-CO_2 emissions in the current global warming and serves as a reminder of the need to consider all sources of climate forcing when assessing mitigation strategies.

This comparison of WGI and WGIII approaches also further underscores the importance of separately accounting for short- and long-lived pollutant emissions, as discussed by Daniel et al. (36) and recently called for by Allen et al. (37). Reporting these pollutants separately allows for consideration not only of potential effects of mitigation measures by source and implications for coemissions but also an assessment of temperature impact on multiple time horizons of interest (1). With 1.5 °C expected to be crossed in the early 2030s (1, 38), Abernethy and Jackson (39) have advocated for choosing time horizons for GHG aggregation metrics consistent with temperature goals, specifically supporting the use of GWP_{20} over the GWP_{100}. A similar argument can be made in the context of the urgency to slow warming in the near term (2). In addition, common usage of aggregation metrics (e.g., GWP, GWP*, and global temperature potential) excludes very short-lived climate pollutants that are not well-mixed, such as aerosols and GHG precursors, but that can have significant implications for future warming (40, 41).

Contributions to Radiative Forcing: FFs vs. Non-FFs (Including Aerosols)

Here we clarify the historical contributions to present-day radiative forcing from FF and non-FF sources. Many heat-trapping gases and particles originate from both FF and non-FF sources, while others such as N_2O and halocarbons are primarily associated with non-FF sources. First, we calculate the relative share of emissions from FF and non-FF sources for GHGs alone, summing historical emissions pollutant by pollutant between 1850 and 2015 for each GHG based on source (42) and for future (after 2015) emissions using the FF coemission factors from Shindell and Smith (43) as described in *SI Appendix*. These shares are then applied to the total present-day radiative forcing in 2011 as in IPCC AR5 WGI (14) and 2019 as in IPCC AR6 WGI (15). Fig. 2 and *SI Appendix*, Table S2 show that for historical forcing (1750 to 2019) GHG from FF sources contributes about 53% of the total current GHG forcing, approximately the same as GHG forcing due to non-FF sources. However, if GHG emissions were to cease, residual forcing from long-lived GHG, predominantly FF CO_2, would dominate as shorter-lived pollutants would be rapidly removed.

Next, we consider warming and cooling aerosols. For forcing estimates related to aerosols, we distinguish effective radiative forcing (ERF) due to aerosol-radiation interaction (ERF_{ari}) for individual species from aerosol–cloud interaction (ERF_{aci}) considered separately as a lump-sum "indirect" forcing term associated with total aerosol emissions (*SI Appendix*). Previous studies have shown that the coemission of aerosols from FF combustion can result in warming or cooling with distinct temporal and spatial patterns (27, 44). Many studies have identified the importance of cooling aerosols—primarily sulfates (with SO_2 as the precursor), nitrates (NO, NO_2, and NH_3), and organic carbon—in masking GHG warming (1, 14). Fig. 1 shows the relative contributions of warming GHG, GHG precursors, and BC in comparison to the cooling from cooling aerosols relying on radiative forcing from historical emissions in recent IPCC reports, and how the relative contributions evolve in a reference scenario (SSP3-7.0) in 2100 relative to 2019.

The net forcings for all CO_2 and non-CO_2 FF (Fig. 2*A*) and non-FF non-CO_2 (Fig. 2*B*) sources are based on Hoesly et al. (42) for the period through 2015. For 2016 to 2019, we use the Shared Socioeconomic Pathways (SSP) scenario and adopt Shindell and Smith's (43) values for the coemission factors. We obtain similar results using radiative forcing values from AR6 WGI (*SI Appendix*, Table S3). For the radiative forcing from CO_2 emitted by FF as well as non-FF sources and non-CO_2 emitted by just FF, nearly half of the positive forcing (2.5 Wm^{-2}) in 2019 is masked by negative forcing of cooling aerosols (–1.1 Wm^{-2}), resulting in a net positive forcing of 1.4 Wm^{-2}. The forcing of cooling aerosols from non-FF non-CO_2 sources is only –0.2 Wm^{-2} compared to a positive forcing of 1.4 Wm^{-2}. Thus, the net forcing from non-FF non-CO_2 sources is 1.2 Wm^{-2} in 2019, or 45% of total net forcing when aerosols are included. The contribution to the net forcing from FFs (CO_2 and other

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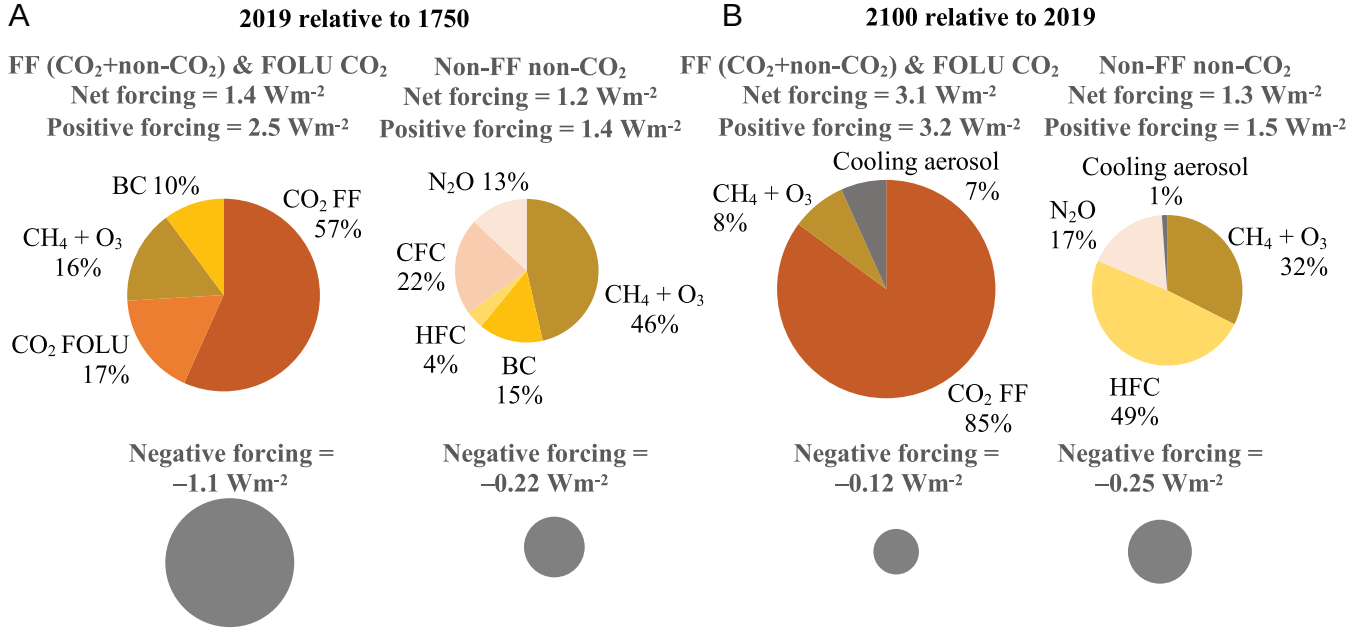

Fig. 2. (*A*) Contributions to 2019 radiative forcing from emissions by FF (CO_2+non-CO_2) sources and CO_2 from land-use changes (Forestry and Other Land Use, FOLU CO_2) compared with emissions from non-FF non-CO_2 sources based on ref. 42 and coemission factors from ref. 43 from this study, with similar results using radiative forcing values from AR6 WGI (*SI Appendix*, Table S3). (*B*) Contribution to the 2100 radiative forcing (relative to 2019) based on future emissions in SSP3-7.0 (49) partitioned by source using coemission factors from ref. 43. Area of each pie chart is scaled to positive or negative forcing. Data in *SI Appendix*, Table S6*B*.

GHGs) is 39% when aerosols are included and from non-FF sources is 61%.

The picture depicted above changes in the projection through 2100 under the limited climate policy SSP3-7.0 scenario. By 2100, around 70% of net forcing relative to 2019 is due to FF and other CO_2 emissions, emphasizing the importance of adopting decarbonization together with strategies targeting non-CO_2 to address near-term and long-term warming.

Contributions to Warming: CO_2 vs. Non-CO_2 and FFs vs. Non-FFs

The tendency to group CO_2 and non-CO_2 together irrespective of emission sources has contributed to a frequent misperception that CO_2, which comes predominantly from FF burning, is the only important contributor to observed warming. This misperception is understandable: Our model shows that out of the 1.01 °C warming simulated for 2015, CO_2 has contributed 0.98 °C (*SI Appendix*, Table S4). Thus, one can indeed claim that to the first order the observed global warming of ∼1 °C is primarily due to CO_2. However, a closer look reveals that the magnitude of warming by non-CO_2 GHGs coincidentally cancels the cooling by all (FF & non-FF sources) aerosols (45–47) (*SI Appendix*, Fig. S2). Indeed, our model shows that the combined cooling effects of aerosols including the indirect effects via enhancing cloud albedo (–1.15 °C) has masked an amount of warming that is almost equal to the total non-CO_2 warming of 1.17 °C. This leads to a facile but false assumption that most non-CO_2 forcings have canceled one another and will continue to do so in the future and obscures the significance of the residence time of the pollutants for both short- and long-term climate mitigation.

Uncovering the flaw in this reasoning requires correctly attributing the masking from cooling aerosols. Ignoring sources and aerosols, CO_2 would appear to contribute about 55% of GHG warming (*SI Appendix*, Table S4). Considering only FF sources, *SI Appendix*, Table S4 shows that the warming from FF emissions (GHGs and BC) of 1.07 °C in 2015 is mostly masked by cooling of 0.88 °C from cooling aerosols that are coemitted with FF emissions. In contrast, while the warming from non-FF emissions (GHGs and BC) is equivalent in magnitude at 1.08 °C, only 0.26 °C is masked by coemitted cooling aerosols. This analysis reveals that about 80% of warming realized in 2015 is attributable to non-FF sources due to masking by cooling aerosols coemitted from FF sources. As these aerosols fall out of the atmosphere, the future net warming contribution from FF sources under SSP3-7.0 begins to dominate by the 2060s due to the longer residence time of CO_2.

Accurately attributing past warming is key to mitigation actions going forward. As decarbonization measures reduce FF use they also reduce the coemitted cooling aerosols (primarily sulfates) and unmask the warming from accumulated GHGs in the atmosphere. In the following section we describe the implications of such unmasking for near- and long-term mitigation potential of decarbonization and clarify the essential role of strategies targeting non-CO_2 pollutants in limiting warming through 2050.

Mitigation Strategies in Time: Decarbonization and Targeted Mitigation

Reducing CO_2 emissions by shifting from FF to low-carbon energy sources is underway and needs to accelerate to achieve net-zero CO_2 emissions by midcentury or sooner consistent with the Paris temperature target (48). While getting to net-zero CO_2 emissions is critical and essential for stabilizing long-term warming, it also reduces coemitted cooling aerosols and causes weak near-term warming, which can be offset by reductions in non-FF pollutants (43). Few studies, however, have specifically quantified the contribution of measures targeting non-CO_2 independent from FF usage, such as the 16 measures in the 2011 UNEP/WMO Assessment (31).

Our analysis disentangles CO_2, SLCPs, and cooling aerosols by asking the following question: Under an aggressive climate

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mitigation scenario (such as the marker version of SSP1-1.9), what is the avoided warming due to decarbonization alone (i.e., reduction in FF usage) and when paired with non-decarbonization-related mitigation targeting non-CO_2 pollutants? We answer this question by explicitly accounting for the associated reductions in coemitted pollutants including cooling aerosols from each mitigation approach. As described in *SI Appendix*, we use SSP scenarios (49) and apply coemissions factors to partition emissions of individual pollutants into FF-related and non-FF-related (43). We consider three cases (Table 1): As a reference case we adopt the limited climate policy high-emission scenario SSP3-7.0, a middle case with only decarbonization-driven emissions reductions, and a "decarb+targeted" case including mitigation measures that go beyond decarbonization to target SLCPs and other non-CO_2 pollutants (based on SSP1-1.9). We construct the "decarb-only" case by partitioning the reduction in emissions in the "decarb+targeted" case relative to the baseline case into decarbonization-driven and other targeted measures. Our approach differs from ref. 43 in that we use the SSP3-7.0 scenario to quantify the nondecarbonization mitigation potential from methane and BC. This includes mitigation measures targeting the ∼10% of methane emissions from abandoned coal mines and wells due to fugitive emissions that are not directly affected by decarbonization-driven reductions in FF use (*SI Appendix*).

All emission pathways including total and individual forcing were converted to temperature trajectories using the energy balance climate model RXM (*SI Appendix*), which has been validated in our earlier studies with climate models used in IPCC assessments (27, 30, 50, 51) and observed warming trends for the 20th century (*SI Appendix*, Fig. S3). Both the equilibrium and the transient climate sensitivity of the RXM model used in our study is within a few percent of the central values recommended in AR6. Our results for the avoided warming in the "decarb+targeted" case (*SI Appendix*, Table S5) are consistent with the results for methane, ozone precursor, and HFC abatement reported in AR6 WGI (52), which also used SSP3-7.0 as a reference case and SSP1-1.9 as the mitigation case, but do not account for source partitioning. With RXM we find avoided warming of 0.3 °C by 2040 from SLCP mitigation compared to 0.1 to 0.4 °C in AR6. The impact of SLCP reductions in 2100 is 0.5 to 1.3 °C in AR6, compared to 1.7 °C in our scenarios, which likely reflects the more stringent HFC and N_2O reductions in our adapted mitigation scenario. Our methane mitigation benefit of ∼0.2 °C by 2050 is smaller than the ∼0.3 °C in a recent assessment based on similar abatement (38), suggesting that the sensitivity of RXM to methane is lower than that in the three-dimensions composition-climate models (but well within uncertainties) (*SI Appendix*).

Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s and no net avoided warming until the mid-2040s due to the reduction in coemitted cooling aerosols (Fig. 3*A*). By 2050, decarbonization measures result in very limited net avoided warming (0.07 °C), consistent with Shindell and Smith (43), but rise to a likely detectable 0.25 °C by 2060 and a major benefit of 1.4 °C by 2100 (*SI Appendix*, Table S5).

In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3 °C per decade (Table 1 and Fig. 3*B*), similar to the 0.2 °C to 0.25 °C per decade warming prior to 2020 (38, 53). Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events (54, 55).

By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26 °C, almost four times larger than the net benefit of decarbonization alone (0.07 °C) (*SI Appendix*, Table S5). These results are calculated using an average BC forcing at present of 0.33 Wm^{-2} relative to preindustrial (direct and snow albedo; *SI Appendix*), which is consistent with the AR6 range (0.30 ± 0.2 Wm^{-2} for ERF_{ari} and 0.38 Wm^{-2} including snow albedo effects) (56). Combining all targeted non-CO_2 measures results in a net avoided warming in 2060 of 0.43 °C. Pairing decarbonization measures with targeted measures can achieve 0.25 °C in total avoided warming, a level that is likely to be detected (57) over a decade earlier (∼2047) than

Table 1. Simulated warming rates and other key metrics under reference, decarbonization only, and decarb+targeted scenarios

Scenario	Warming rate, °C/decade (2020–2040)	Year when warming rate drops below 0.25 °C/decade	Year of peak warming rate	Year when crossing 1.5 °C warming	Year when crossing 2 °C warming	Warming in 2030 relative to 1850–1900, °C	Warming in 2050 relative to 1850–1900, °C
Reference: Limited climate policy, high emission (SSP3-7.0)	0.36 (0.34–0.38)	—	—	2031–2033	2045–2046	1.5 (1.4–1.5)	2.2
Decarbonization-driven: Scenario using decreasing FF primary energy as in SSP1-1.9 and associated emission factors to calculate decline in FF-related emissions compared to reference	0.37 (0.35–0.39)	2049–2052	2030	2030–2032	2045–2046	1.5 (1.4–1.5)	2.1
Decarbonization and Targeted measures: Aggressive climate policy, low emission (based on SSP1-1.9)	0.31 (0.29–0.32)	2035–2037	2023	2030–2033	—*	1.5 (1.4–1.5)	1.85 (1.8–1.9)

The range of years reflects the uncertainty in present-day forcings of BC and cooling aerosols.
*Peak temperature of 1.9 °C in 2060s before declining to 1.7 °C in 2100.

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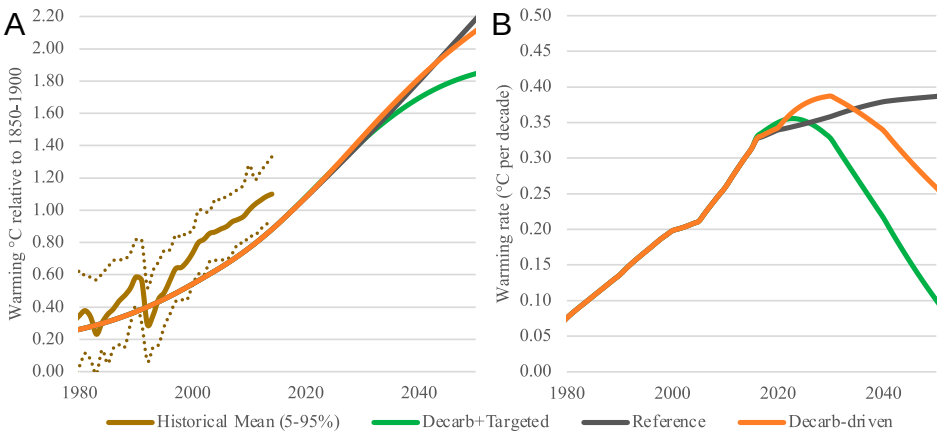

Fig. 3. (*A*) Historical and future temperature projections through 2050 calculated using the RXM energy balance model based on emissions scenarios from the SSP database (49) for reference scenario (SSP3-7.0), decarbonization-driven mitigation scenario (this study), and an "decarb+targeted" scenario including aggressive decarbonization and targeted SLCP mitigation (adapted from SSP1-1.9). Historical curve (past simulated warming) is from figure SPM8.a (47, 64). (*B*) Rate of warming (degrees Celsius per decade) in the reference SSP3, decarbonization only, and "decarb+targeted" mitigation cases.

decarbonization alone (2060; *SI Appendix*, Table S5). The avoided warming due to decarbonization begins to exceed that due to the targeted measures only after 2080 (*SI Appendix*, Fig. S4).

Only about 30% of the avoided warming from CH_4 over the period 2020 to 2040 is related to decarbonization measures (*SI Appendix*, Table S5). The larger portion of CH_4 reduction due to targeted measures may be due to a slower rate of reduction in natural gas usage in the marker SSP1-1.9 scenario (60% down in 2050 relative to 2015) compared with decrease in coal combustion (more than 90% down). Consistently, about two-thirds of non-CH_4-induced ozone mitigation is also due to non-CO_2 targeted measures rather than a direct consequence of decarbonization. These results are also consistent with UNEP/WMO (31), which found that measures to reduce methane and BC emissions cut warming in 2030 by half compared with a reference case and that aggressive CO_2 reductions, in themselves, did little to mitigate warming in the first 20 to 30 y, in part due to unmasking of coemitted cooling aerosol.

Fig. 3*A* shows that combining targeted mitigation strategies with decarbonization keeps warming below 2.0 °C, while decarbonization alone breaches 2.0 °C in 2045 in our scenario. Moreover, decarbonization alone increases the warming rate in the near term (Table 1). Notably, the warming rate in the decarbonization scenario would not drop below the current rate of warming until the 2040s (Fig. 3*B*). Pairing decarbonization with measures targeting SLCP slows the rate of warming a decade or two earlier than decarbonization alone.

Consideration of Uncertainties

The largest uncertainties in our analysis relate to the mitigation pathways chosen, both the reference limited climate policy scenario and the low-emission mitigation scenarios. While current CO_2 emissions commitments track closer to SSP2-4.5, the key insight of our study is not about additionality in terms of new policy measures. Rather, our study seeks to distinguish between mitigation policy focused on FF decarbonization alone versus decarbonization plus targeted measures. For this reason, we selected as a reference the high-emission scenario SSP3-7.0 and as a low-emission scenario SSP1-1.9, which are the same end-member scenarios as assessed in AR6 WGI (52).

The second major source of uncertainty is the nearly threefold uncertainty in climate sensitivity. All of the projected warming numbers presented here should be interpreted as median value with 50% probability. A third source of uncertainty relates to our use of constant FF coemission factors in constructing the decarbonization-driven scenario. Since this partitioning approach is most valid in the near term, we focus our analysis on the period through 2050. A fourth source of uncertainty relates to our limited understanding of the role of aerosols in climate forcing and feedbacks in future projections due to the following aspects: 1) the assumption of mixing of various aerosol species, especially the potential enhancement of BC forcing when accounting for the mixing with other reflective aerosols (58), 2) the future changes of background cloud field due to the slow feedback process to GHG warming (59, 60), and 3) the future changes of background aerosols from natural sources such as dust and sea salt due to climatic changes affecting the emission processes related to soil condition and wind stress over ocean surface and related cloud impacts (e.g., ref. 61).

Conclusions

This study clarifies as well as establishes the need for a comprehensive and inclusive CO_2 and non-CO_2 mitigation approach with distinct decarbonization and SLCP targets to address both the near-term and long-term impacts of climate disruption. A review of IPCC reports leads to the inference that non-CO_2 GHGs are responsible for nearly half of all current climate forcing from GHGs. When accounting for aerosols and coemissions by source, the inference from our analyses is that about 80% of the realized warming as of 2015 is attributable to non-FF sources due to FF GHG emissions being masked by coemission of short-lived cooling aerosols. However, the importance of non-CO_2 pollutants, in particular SLCPs, and their role in climate mitigation has been underappreciated due to misperception arising from inconsistencies between IPCC WGI and WGIII reports. The tendency to attribute impact to pollutants rather than sources and to group all non-CO_2 together regardless of emissions sources has further entrenched this misperception due to coincidental cancelling of warming and cooling pollutants and the false impression that they will continue to cancel out in the future. When historical emissions are partitioned into FF- and non-FF-related sources, we find that nearly half of the forcing from FF and other CO_2 emissions has been masked by coemission of cooling aerosols. As a result, close to half of net radiative forcing, as of now, is attributable to non-FF sources of methane, F-gases, BC, and N_2O. However, this

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is likely to change in the future as decarbonization policies reduce FF emissions of both warming GHGs and cooling aerosol.

By 2100, absent climate policy, FF will be the largest source (about 70%, mostly due to CO_2) for global warming and resulting impacts on planet and society. Even in the shorter term, FF emissions are the largest source of air pollution particles and ozone, which contribute to premature mortality of over 8 million people per year (45, 62). Tropospheric ozone also leads to crop losses of 100 million tons or more (63). As we have repeatedly emphasized in this study, achieving net-zero carbon dioxide emissions by 2050 is essential to limit global warming below 2 °C beyond 2050.

Pairing decarbonization with targeted SLCP mitigation measures is essential to simultaneously limit both near-term warming and long-term warming below 2 °C and thus reduce risks from crossing tipping points. Importantly, these two strategies are complementary and not interchangeable. Absent deep cuts in non-CO_2 emissions, CO_2 abatement alone is unable to keep warming below even the 2 °C threshold by 2050. Decarbonization measures alone achieve about a third of potential avoided warming from methane mitigation by 2050, less than half of SLCP mitigation potential, and none of the reductions from measures targeting N_2O. Nor can cutting methane emissions this decade replace the need for net-zero carbon dioxide by 2050 to stabilize the climate this century. Similarly, deeper CO_2 reductions this decade do not replace the need for methane and other SLCP reductions to slow warming in the near term. Aggregation metrics such as GWP and GWP* are designed in terms of warming impacts over multiple decades and are seldom used in ways that account for the important differences between strategies that can reduce warming in the near term.

Adopting a comprehensive mitigation approach that pairs rapid decarbonization with "strong, rapid and sustained reductions in CH_4 emissions" (1) as recommended in the Global Methane Assessment (32) and additional targeted SLCP mitigation responds to the call from WGII for urgent action to slow warming in the near term (2). For example, over 100 countries joined the Global Methane Pledge in November 2021, committing to a collective goal of reducing global anthropogenic methane emissions by at least 30% below 2020 levels by 2030. If achieved, this target, which is consistent with the reduction in the "decarb+targeted" scenario analyzed here, would avoid 0.2 °C by 2050 (*SI Appendix*, Table S5).

Data Availability. All study data are included in the article and/or *SI Appendix*.

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1. Intergovernmental Panel on Climate Change, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2021).
2. Intergovernmental Panel on Climate Change, *Climate Change 2022: Impacts, Adaptation and Vulnerability*, H.-O. Pörtner *et al.*, Eds. (Cambridge University Press, 2022).
3. S. C. Herring *et al.*, Explaining extreme events of 2016 from a climate perspective. *Bull. Am. Meteorol. Soc.* **99**, S1–S157 (2018).
4. T. M. Lenton *et al.*, Climate tipping points - Too risky to bet against. *Nature* **575**, 592–595 (2019).
5. J. M. Gutiérrez *et al.*, "Atlas" in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte *et al.*, Eds. (IPCC, 2021), pp. 1–196.
6. C. Raymond, T. Matthews, R. M. Horton, The emergence of heat and humidity too severe for human tolerance. *Sci. Adv.* **6**, eaaw1838, 1–8 (2020).
7. N. Watts *et al.*, The 2020 report of The Lancet Countdown on health and climate change: Responding to converging crises. *Lancet* **397**, 129–170 (2021).
8. Y. Xu *et al.*, Substantial increase in the joint occurrence and human exposure of heatwave and high-PM hazards over South Asia in the mid-21st century. *AGU Adv.* **1**, e2019AV000103 (2020).
9. Y. Zhang, I. Held, S. Fueglistaler, Projections of tropical heat stress constrained by atmospheric dynamics. *Nat. Geosci.* **14**, 133–137 (2021).
10. L. A. Parsons, D. Shindell, M. Tigchelaar, Y. Zhang, J. T. Spector, Increased labor losses and decreased adaptation potential in a warmer world. *Nat. Commun.* **12**, 7286 (2021).
11. V. Ramanathan, Greenhouse effect due to chlorofluorocarbons: Climatic implications. *Science* **190**, 50–52 (1975).
12. W. C. Wang, Y. L. Yung, A. A. Lacis, T. Mo, J. E. Hansen, Greenhouse effects due to man-mad perturbations of trace gases. *Science* **194**, 685–690 (1976).
13. V. Ramanathan *et al.*, Climate-chemical interactions and effects of changing atmospheric trace gases. *Rev. Geophys.* **25**, 1441–1482 (1987).
14. G. Myhre *et al.*, "Anthropogenic and natural radiative forcing" in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge University Press, 2013), pp. 659–740.
15. P. Forster *et al.*, "The Earth's energy budget, climate feedbacks, and climate sensitivity" in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte *et al.*, Eds. (Cambridge University Press, 2021), chap. 7.
16. P. Forster *et al.*, "Changes in atmospheric constituents and in radiative forcing" in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon *et al.*, Eds. (Cambridge University Press, 2007), chap. 2.
17. V. Ramaswamy *et al.*, "Radiative forcing of climate change" in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton *et al.*, Eds. (Cambridge University Press, 2001), chap. 6.
18. G. G. Persad, Y. Ming, V. Ramaswamy, The role of aerosol absorption in driving clear-sky solar dimming over East Asia. *J. Geophys. Res. Atmos.* **119**, 10,410–10,424 (2014).
19. V. Ramaswamy *et al.*, Radiative forcing of climate: The historical evolution of the radiative forcing concept, the forcing agents and their quantification, and applications. *Meteorol. Monogr.* **59**, 14.1-14.101 (2018).
20. J. Rogelj *et al.*, Disentangling the effects of CO2 and short-lived climate forcer mitigation. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 16325–16330 (2014).
21. J. Rogelj *et al.*, "Mitigation pathways compatible with 1.5°C in the context of sustainable development" in *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, V. Masson-Delmotte *et al.*, Eds. (IPCC, 2018), chap. 2.
22. H. D. Matthews, S. Solomon, R. Pierrehumbert, Cumulative carbon as a policy framework for achieving climate stabilization. *Philos. Trans.- Royal Soc., Math. Phys. Eng. Sci.* **370**, 4365–4379 (2012).
23. F. Feijoo *et al.*, Climate and carbon budget implications of linked future changes in CO2 and non-CO2 forcing. *Environ. Res. Lett.* **14**, 044007 (2019).
24. J. S. Wallack, V. Ramanathan, The other climate changers. *Foreign Affairs*, September–October 2009. https://www.foreignaffairs.com/articles/2009-09-01/other-climate-changers. Accessed 3 May 2022.
25. M. Molina *et al.*, Reducing abrupt climate change risk using the Montreal protocol and other regulatory actions to complement cuts in CO2 emissions. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 20616–20621 (2009).
26. S. C. Jackson, Climate change. Parallel pursuit of near-term and long-term climate mitigation. *Science* **326**, 526–527 (2009).
27. V. Ramanathan, Y. Xu, The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 8055–8062 (2010).
28. J. E. Penner *et al.*, Short-lived uncertainty? *Nat. Geosci.* **3**, 587–588 (2010).
29. D. Shindell *et al.*, Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335**, 183–189 (2012).
30. Y. Xu, V. Ramanathan, Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 10315–10323 (2017).
31. United Nations Environment Programme, World Meteorological Organization, "Integrated assessment of black carbon and tropospheric ozone" (United Nations Environment Programme, 2011).
32. United Nations Environment Programme, Climate and Clean Air Coalition, "Global methane assessment: Benefits and costs of mitigating methane emissions" (United Nations Environment Programme, 2021).
33. IPCC, "Summary for policymakers" in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer *et al.*, Eds. (Cambridge University Press, 2014), pp. 1–33.
34. M. Crippa *et al.*, "Fossil CO_2 and GHG emissions of all world countries: 2019 report" (European Commission Joint Research Centre Publications Office, 2019).
35. R. G. Prinn *et al.*, History of chemically and radiatively important atmospheric gases from the advanced global atmospheric gases experiment (AGAGE). *Earth Syst. Sci. Data* **10**, 985–1018 (2018).

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36. J. S. Daniel *et al.*, Limitations of single-basket trading: Lessons from the Montreal protocol for climate policy. *Clim. Change* **111**, 241–248 (2012).
37. M. R. Allen *et al.*, Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. *NPJ Clim. Atmos. Sci.* **5**, 5 (2022).
38. Y. Xu, V. Ramanathan, D. G. Victor, Global warming will happen faster than we think. *Nature* **564**, 30–32 (2018).
39. S. Abernethy, R. B. Jackson, Global temperature goals should determine the time horizons for greenhouse gas emission metrics. *Environ. Res. Lett.* **17**, 024019 (2022).
40. M. Dvorak *et al.*, When will the world be committed to 1.5 and 2.0°C of global warming? *Research Square* [Preprint] (2021). https://doi.org/10.21203/rs.3.rs-969513/v1 (Accessed 4 January 2022).
41. V. Ramanathan, Y. Feng, On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 14245–14250 (2008).
42. R. M. Hoesly *et al.*, Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the community emissions data system (CEDS). *Geosci. Model Dev.* **11**, 369–408 (2018).
43. D. Shindell, C. J. Smith, Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature* **573**, 408–411 (2019).
44. D. Shindell, G. Faluvegi, Climate response to regional radiative forcing during the twentieth century. *Nat. Geosci.* **2**, 294–300 (2009).
45. J. Lelieveld *et al.*, Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 7192–7197 (2019).
46. IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2013).
47. Intergovernmental Panel on Climate Change, "Summary for policymakers" in *Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2021), pp. 1–41.
48. IPCC, *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response To the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, V. Masson-Delmotte *et al.*, Eds. (Cambridge University Press, 2018).
49. K. Riahi *et al.*, The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Change* **42**, 153–168 (2017).
50. Y. Xu, D. Zaelke, G. J. M. Velders, V. Ramanathan, The role of HFCs in mitigating 21st century climate change. *Atmos. Chem. Phys.* **13**, 6083–6089 (2013).
51. R. Hanna, A. Abdulla, Y. Xu, D. G. Victor, Emergency deployment of direct air capture as a response to the climate crisis. *Nat. Commun.* **12**, 368 (2021).
52. V. Naik *et al.*, "Short-lived climate forcers" in *Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2021), chap. 6.
53. C. M. McKenna, A. C. Maycock, P. M. Forster, C. J. Smith, K. B. Tokarska, Stringent mitigation substantially reduces risk of unprecedented near-term warming rates. *Nat. Clim. Chang.* **11**, 126–131 (2021).
54. S. B. Power, F. P. D. Delage, Setting and smashing extreme temperature records over the coming century. *Nat. Clim. Chang.* **9**, 529–534 (2019).
55. E. M. Fischer, S. Sippel, R. Knutti, Increasing probability of record-shattering climate extremes. *Nat. Clim. Chang.* **11**, 689–695 (2021).
56. C. Smith *et al.*, "The Earth's energy budget, climate feedbacks, and climate sensitivity" in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte *et al.*, Eds. (Cambridge University Press, 2021), chap. 7.
57. B. H. Samset, J. S. Fuglestvedt, M. T. Lund, Delayed emergence of a global temperature response after emission mitigation. *Nat. Commun.* **11**, 3261 (2020).
58. H. Matsui, D. S. Hamilton, N. M. Mahowald, Black carbon radiative effects highly sensitive to emitted particle size when resolving mixing-state diversity. *Nat. Commun.* **9**, 3446 (2018).
59. M. O. Andreae, V. Ramanathan, Climate change. Climate's dark forcings. *Science* **340**, 280–281 (2013).
60. C. Heinze *et al.*, ESD Reviews: Climate feedbacks in the Earth system and prospects for their evaluation. *Earth Syst. Dyn.* **10**, 379–452 (2019).
61. K. D. Froyd *et al.*, Dominant role of mineral dust in cirrus cloud formation revealed by global-scale measurements. *Nat. Geosci.* **15**, 177–183 (2022).
62. K. Vohra *et al.*, Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environ. Res.* **195**, 110754 (2021).
63. D. Shindell, G. Faluvegi, P. Kasibhatla, R. Van Dingenen, Spatial patterns of crop yield change by emitted pollutant. *Earths Futur.* **7**, 101–112 (2019).
64. J. Fyfe, B. Fox-Kemper, R. Kopp, G. Garner, *Summary for Policymakers of the Working Group I Contribution to the IPCC Sixth Assessment Report - Data for Figure SPM.8 (v20210809)* (Cambridge University Press, 2021).

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July 1, 2025

New York State Department of Environmental Conservation
Mandatory Reporting Section
625 Broadway, 11th Floor
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Via email to air.regs@dec.ny.gov

Re: Comments on Proposed Part 253 related to Agriculture

On behalf of our thousands of supporters and members across New York State, the undersigned organizations submit these comments related to the reporting of agricultural greenhouse gas (GHG) emissions under Proposed Part 253.

The agricultural sector is a major source of GHG emissions in the world, the United States, and New York. Based on the Department of Environmental Conservation's (DEC's) 2024 Statewide GHG Emissions Report, total agricultural emissions in New York totaled about 21.49 million metric tons of carbon dioxide equivalent (CO2e), representing 5.8% of statewide emissions.[1] Troublingly, unlike other sectors, agricultural emissions are growing—overall agricultural emissions in New York were 37.2% higher in 2022 than 1990.[2] Moreover, agricultural emissions are often larger than understood. Recent evidence suggests that many models of agricultural emissions are overly conservative.

Commenters are encouraged that the proposed GHG reporting regulations would apply to several high-emitting segments of the agricultural sector, specifically the emissions from liquid storage of waste at concentrated animal feeding operations (CAFOs) and from the land application of agriculture lime and fertilizer. However, we urge DEC to make some adjustments to the proposed manure storage reporting requirements and to go further and require CAFOs to report enteric emissions and emissions from manure spreading in addition to emissions from manure storage.

I. CAFO emissions

An overwhelming 91% of New York's agricultural emissions come from livestock management practices.[3] The primary sources of these GHG emissions are manure management and enteric fermentation—a digestive process in cows and other ruminant animals that produces methane as

[1] DEC, *Agriculture, Forestry, and Other Land Use 2024 NYS Greenhouse Gas Emissions Report* 2 (2024), https://dec.ny.gov/sites/default/files/2024-12/sr3afolunysghgemissionsreport.pdf.
[2] *Id.*
[3] *Id.*

a by-product.[4] DEC's proposed reporting rules would require CAFOs that produce a threshold amount of waste that is stored as a liquid or a slurry to report the emissions from their manure storage systems. This is important because liquid manure storage produces far more emissions than dry systems. However, we suggest some changes to the proposed reporting requirements for this liquid waste to ensure complete and accurate reporting. In addition, the proposal's exclusive focus on manure storage emissions ignores other large sources of emissions from CAFOs, including enteric fermentation and land application of manure. CAFOs should be required to report these direct emissions in order to build a comprehensive picture of their emissions.

a. Manure emissions from liquid storage

Manure primarily emits methane and nitrous oxide when it decomposes anaerobically in waste pits.[5] Wet manure management systems cause particular harm, generating many times more methane than systems that store manure in dry form.[6] Indeed, the Environmental Protection Agency (EPA) recently recognized that "[i]n many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems" and that "the shift toward larger dairy cattle and swine facilities since 1990 has translated into an increasing use of liquid manure management systems, which have higher potential [methane] emissions than dry systems."[7]

This same trend is occurring in New York. From 1990 to 2022, nitrous oxide emissions from manure management nearly doubled while methane emissions more than tripled, largely as a result of increased liquid storage of dairy manure.[8] As of 2022, manure management was responsible for 4% of the state's methane emissions and 10% of its nitrous oxide emissions respectively.[9]

A recent study of GHG emissions at medium and large New York dairy farms found that manure management practices accounted for about 20% of farm-gate emissions.[10] It also found that

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[4] *See* EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020*, at 2-29, Tbl. 2-10 (2022), https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf.
[5] *See* Patricia M. Glibert, *From Hogs to HABS: Impacts of Industrial Farming in the US on Nitrogen and Phosphorus and Greenhouse Gas Pollution*, 150 Biogeochemistry 139, 157 (2020).
[6] *See* Olga Gavrilova et al., *Emissions from Livestock and Manure Management, in 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, at 10.67, Tbl. 10.17 (2019), https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch10_Livestock.pdf.
[7] EPA, *supra* note 4, at 5-12.
[8] DEC, *supra* note 1, at 6.
[9] *Id.*; DEC, *2024 Statewide GHG Emissions Report Summary Report*, at v (2024), https://dec.ny.gov/sites/default/files/2024-12/summaryreportnysghgemissionsreport.pdf.
[10] Olivia F. Godber et al., *Farm-Gate Greenhouse Gas Emission Intensity for Medium to Large New York Dairy Farms*, 108 J. Dairy Sci. 5039 (2025).

manure management practices explained the largest amount of variation in emissions among farms.[11] For these reasons, reporting of these emissions is crucial both to build understanding of emissions from New York's CAFOs and to inform future actions to reduce these emissions.

Under the proposed reporting requirements, CAFO operators would be subject to reporting requirements if they generated or imported a threshold amount of waste during the reporting year.[12] However, CAFOs that meet this waste threshold are eligible for "abbreviated reporting" if (1) they had fewer than 2,500 dairy cows or (2) they did not import a significant amount of waste and do not heat waste in liquid or slurry storages or anaerobic digestors or reactors using fossil fuels. Those few CAFOs that would be required to complete full reporting are also required to develop an Emissions Monitoring and Measurement Plan (EMMP).

Commenters overall support these reporting requirements, but we would like to make three specific points. First, we support the EMMP requirement for the largest CAFOs with anaerobic digesters or cover and flare systems and strongly urge DEC to keep this requirement. Second, we recommend that CAFOs of all sizes that use anaerobic digesters or cover and flare systems be required to report their full operational and activity data. Third, we recommend that the abbreviated reports include animal inventories.

i. The recommended emissions monitoring and measurement requirements are critical to improving understanding of CAFO manure storage emissions.

The proposed rule provides that liquid waste management facilities must develop an operation or facility-specific Emissions Monitoring and Measurement Plan (EMMP).[13] These requirements only apply to CAFOs that are not eligible for abbreviated reporting, meaning those with more than 2,500 dairy cows that also use an anaerobic digester or cover and flare system or that import a significant amount of outside waste.[14] Such monitoring and measurement is critical to develop a more accurate accounting of CAFO manure emissions. Indeed, field-based measurements of

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[11] *Id.*

[12] Note, the proposed rule sets the reporting threshold for liquid storage waste facilities, including CAFOs, based on the metric tons of waste imported to or generated at the facility annually. DEC, *Express Terms – Part 253 Mandatory Greenhouse Gas Reporting Program* 135–36 (2025), https://dec.ny.gov/sites/default/files/2025-03/part253expressterms.pdf. This conflicts with DEC's reporting program fact sheet, which provides that liquid storage waste facilities are required to report if wastes imported to or generated at the facility are in an amount that would generate 10,000 or more MT of CO2e per year. DEC, *Mandatory Greenhouse Gas Reporting Program Fact Sheet* 2 (2025), https://dec.ny.gov/sites/default/files/2025-03/ghgreportingfactsheet.pdf. We support using the thresholds based on the metric tons of waste imported to or generated at the facility.

[13] DEC, *Express Terms*, *supra* note 12, at 264–65.

[14] *Id.* at 265.

manure emissions often show that models underestimated methane emissions for most manure management practices.[15]

These emissions monitoring and measurement requirements would only apply to a small but very significant subset of CAFO facilities within the state. Of the 2,783 New York farms with a milk cow inventory reported in the 2022 United States Department of Agriculture (USDA) Census, only 39—or just 1.4%—had 2,500 or more dairy cows.[16] However, emissions monitoring and measurement requirements at CAFOs with 2,500 or more dairy cows would provide great insight into New York's CAFO emissions given that these facilities managed over 20% of the state's dairy cows.[17] There are several different options for measuring CAFO emissions, including using the tracer ratio method which releases a known tracer gas to mix with emitted gases then measuring downwind concentrations to estimate emission rates,[18] flux chambers that trap gases over a defined area,[19] and micrometeorological techniques such as eddy covariance which assess atmospheric gas fluxes over time.[20] Covered manure storage systems may also use gas flow meters to record biogas volume and gas chromatography or mass spectrometry to measure methane concentration.[21] These sources can also account for potential emission leaks using tools such as non-dispersive infrared (NDIR) cameras to visualize leaks and flux chambers for post-digestion monitoring.[22]

While more cost-effective monitoring and measurement technologies are continuing to develop, the largest CAFOs should be required to develop an EMMP to increase the usefulness and

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[15] Matthew N. Hayek & Scot M. Miller, *Underestimates of Methane from Intensively Raised Animals Could Undermine Goals of Sustainable Development*, 16 Env't Rsch. Letters 063006 (2021) (finding that atmospheric measurements taken above or downwind of animal production regions showed 39-90% higher methane emissions than model estimates); Justine J. Owen & Whendee L. Silver, *Greenhouse Gas Emissions from Dairy Manure Management: A Review of Field-Based Studies*, 21 Glob. Change Biology 550 (2014).
[16] USDA, *2022 Census of Agriculture – State Data, New York, Table 17. Milk Cow Herd Size by Inventory and Sales: 2022* (2024), https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_State_Level/New_York/st36_1_017_019.pdf.
[17] *Id.*
[18] R.W. Sneath et al., *Monitoring GHG from Manure Stores on Organic and Conventional Dairy Farms*, 112 Agric. Ecosystems & Env't 122 (2006).
[19] Kyu-Hyun Park, Claudia Wagner-Riddle & Robert Gordon, *Comparing Methane Fluxes from Stored Liquid Manure Using Micrometeorological Mass Balance and Floating Chamber Methods*, 150 Agric. & Forest Meteorology 175 (2010).
[20] *Id.*
[21] Nusrat Jahan Mumu et al., *Methodological Progress in the Measurement of Agricultural Greenhouse Gases*, 15 Carbon Mgmt. 2366527 (2024); J. Tauber et al., *Quantifying Methane Emissions from Anaerobic Digesters*, 80 Water Sci. Tech. 1654 (2019).
[22] Tauber, *supra* note 21.

accuracy of their reporting, to evaluate the efficacy of different touted manure methane reduction strategies, and to help improve data and modeling for other CAFO emissions.

ii. All CAFOs with digesters or cover and flare systems should report their full operational and activity data.

Anaerobic digesters capture some of the methane from animal manure storage to produce biogas, while cover and flare systems involve covering manure storage facilities with a gas-tight cover and then burning the collected biogas in a flare to convert methane to carbon dioxide. These systems are frequently touted as measures to reduce GHG emissions from the liquid storage of manure. However, information about the construction and operation of these systems is necessary to measure their impact.

The proposed reporting rule includes detailed reporting requirements about operational and activity data for anaerobic digesters and cover and flare systems, including information about the methane destruction devices, vents to the atmosphere, boilers and heaters used to operate the equipment, and the handling and disposal of the final waste products.[23] However, while this information is critical to understanding manure emissions from any CAFO facility that uses anaerobic digesters or cover and flare systems, the proposed reporting requirements only apply to facilities with 2,500 or more dairy cows. DEC does not offer any explanation for why this information would not be necessary to understand emissions from any CAFO that meets the waste threshold and uses an anaerobic digester or cover and flare system. Indeed, such information would be essential to understanding a CAFO's manure emissions even if it had fewer than 2,500 dairy cows, including farms that have no dairy cows but have a large number of other types of livestock.

iii. The abbreviated reporting should include animal inventories.

For CAFOs that have fewer than 2,500 dairy cows or that do not utilize anaerobic digesters or cover and flare systems, the abbreviated reporting requirements should include the total number and the average masses of each animal type whose manure went into storage. This information is important to make more accurate emission estimates because the waste characteristics of different animal types vary significantly.[24]

b. Enteric emissions

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[23] The reporting requirements provide that it is optional for anaerobic digesters and reactors to report the total mass of CH4 in generated biogas that is destroyed each year and the total mass of CH4 that is generated in biogas and emitted to the atmosphere through open-ended valves or lines. This data would be important to understand the total amount of emissions that come from these facilities. We urge DEC to require reporting of this information.

[24] Hongmin Dong et al., *Chapter 10: Emissions from Livestock and Manure Management, in 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, at 10.42 (2006), https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf.

Although manure storage emissions are an important piece of CAFO emissions, focusing solely on manure storage overlooks other large sources of direct CAFO emissions. Indeed, enteric emissions—or methane released during the digestive processes of ruminant animals like cows and sheep—are estimated to be more than twice the size of manure management emissions in New York[25] and constitute 10% of the state's total methane emissions.[26] Similar to New York's manure management emissions, enteric emissions in the state increased 15.8% from 1990 to 2022.[27] At the same time, enteric methane represents one of the most promising opportunities for mitigation in the livestock sector,[28] and comprehensive accounting that includes enteric emissions is essential for designing and encouraging the adoption of effective mitigation strategies. Enteric emissions can be estimated using information about animal species populations, body weights, nutrient requirements, and dietary information.[29] Excluding these sizeable emissions from reporting undercuts the credibility of the state's climate reporting program and emissions reductions goals.[30]

c. Manure land application emissions

Similarly, the reporting requirements for CAFOs should include the emissions that come from the land application of CAFO manure. Adding manure to soil increases the rate of natural soil microbial processes that emit nitrous oxide—a potent GHG with 264 times the global warming potential of carbon dioxide.[31] In New York, nitrous oxide emissions from application of soil amendments total 1.78 mmt CO2e,[32] the equivalent of nearly 2 billion pounds of coal burned.[33] Calculating the emissions from the land application of animal manure requires information on

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[25] DEC estimates that enteric emissions in 2022 were 13.51 mmt CO2e, while manure management emissions were 6.03 mmt CO2e. DEC, *supra* note 1, at 4. This was also seen in a recent study of on-farm emissions of New York medium and large dairies, which found that enteric emissions accounted for 45% of total farm emissions, while manure management accounted for 20% of emissions. Godber, *supra* note 10, at 5039.

[26] DEC, *2024 Statewide GHG Emissions Report Summary Report*, *supra* note 9, at v (reporting that New York's total methane emissions in 2022 equaled 128.94 mmt CO2e).

[27] DEC, *supra* note 1, at 5.

[28] Yuhong Lei et al., *A Review of Options and Costs for Mitigating GHG Emissions from the U.S. Dairy Sector*, 15 Atmosphere 926 (2024).

[29] Jessica Gilreath, Tryon Wickersham & Jason Sawyer, *Comparison of Methodologies Used to Estimate Enteric Methane Emissions and Warming Impact from 1920 to 2020 for U.S. Beef Production*, 14 Sustainability 17017 (2022).

[30] While ECL Section 75-0109(2)(b) provides that DEC is not *required* to impose requirements to control agricultural emissions from livestock, nothing precludes from DEC from doing so.

[31] DEC, *6 NYCRR Part 496 Statewide Greenhouse Gas Emission Limits* 3 (2020), https://dec.ny.gov/sites/default/files/2023-12/6nycrrpart496adopted2020.pdf.

[32] DEC, *supra* note 1, at 9 (reporting the combined emissions from multiple soil amendments, including manure as well as synthetic N fertilizer and biosolids).

[33] *Greenhouse Gas Equivalencies Calculator*, EPA, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (last updated Nov. 2024).

the number and types of animals producing manure, the weather conditions during spreading, the properties of the soil to which the manure is applied, and the amount of manure spread per unit area.[34] This information should be readily available because all farms with a CAFO permit as well as third-party CAFO manure appliers are required to comply with a Comprehensive Nutrient Management Plan and keep detailed records of manure application rates.[35] Given the size of these emissions as well as the ease in estimating them, CAFOs should be required to report emissions from the land application of their manure.

II. Fertilizer and lime emissions

a. Reporting fertilizer application emissions is critical.

The proposed reporting rule correctly covers emissions from the land application of lime and fertilizer. Synthetic fertilizers typically contain high concentrations of readily available nitrogen. Like organic manure application, when this nitrogen is applied to fields and not used by crops,[36] it fuels microbial processes emitting nitrous oxide. In fact, synthetic fertilizers are the primary source of anthropogenic nitrous oxide emissions[37] and are responsible for approximately 10.6% of global agricultural emissions.[38] The proposed rule would require suppliers of commercial fertilizer to report the annual quantity of nitrogen distributed to non-licensed persons and the resulting mass of nitrous oxide emissions that would result from land application. In addition, lime distributors would be required to report the annual quantity of lime distributed in New York and the resulting mass of emissions that would result from land application. We strongly support including this large source of emissions in the state's reporting program because it will help improve the completeness of the state's emissions accounting while incentivizing the adoption of more sustainable nutrient management practices.

b. There is an error in Equation 2.14-1.

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[34] *See* C.S. Snyder et al., *Review of Greenhouse Gas Emissions from Crop Production Systems and Fertilizer Management Effects*, 133 Agric. Ecosystems & Env't 247 (2009); K.A. Smith, *Changing Views of Nitrous Oxide Emissions from Agricultural Soil: Key Controlling Processes and Assessment at Different Spatial Scales*, 68 Eur. J. Soil Sci. 137 (2017).
[35] DEC, *ECL SPDES General Permit for Concentrated Animal Feeding Operations (CAFOs) Permit No. GP-0-22-001*, at 21 (2023), https://extapps.dec.ny.gov/docs/water_pdf/cafopermitgp022001.pdf; 6 N.Y. Comp. Codes R. & Regs. tit. 6, § 361-2.3(c) (2023).
[36] *See* Muhammad Anas et al., *Fate of Nitrogen in Agriculture and Environment: Agronomic, Eco-Physiological and Molecular Approaches to Improve Nitrogen Use Efficiency*, 53 Biological Rsch. 1, 3 (2020) (finding only 30.2 to 53.2% of nitrogen is taken up by crops).
[37] Smith, *supra* note 34.
[38] Stefano Menegat, Alicia Ledo & Reyes Tirado, *Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture*, 12 Sci. Reps. 1 (2022).

Commenters noticed that Equation 2.14-2, the equation provided for distributors of lime to calculate the carbon dioxide emissions that would result from land application in New York, appears to have an error. The left-hand side of the equation should say CO_2. It currently says CO_2-C, which is incorrect because the conversion factor (44/12) to go from CO_2-C to CO_2 is already included on the right-hand side of the equation.

III. Conclusion

Accurate and complete reporting of CAFO and fertilizer GHG emissions is essential to understanding and building strategies to address the largest sources of agricultural emissions. We applaud DEC for including liquid manure storage emissions and fertilizer application emissions in the proposed reporting requirements. At the same time, we strongly urge the state to adjust the reporting requirements in the ways discussed to include information necessary to build a full and valuable accounting of the state's agricultural GHG emissions.

Respectfully submitted,

Earthjustice
Natural Resources Defense Council (NRDC)
Northeast Organic Farming Association of New York (NOFA-NY)
NY Renews

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Emissions of nitrous oxide and methane after field application of liquid organic fertilizers and biochar

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ABSTRACT

The use of anaerobic digestates as fertilizer is proposed as a means to close agricultural nutrient cycles. However, digestates have higher inorganic nitrogen contents than raw manures, which could translate into increased emissions of potent greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4). To mitigate these emissions, the addition of biochar with high nutrient absorption capacity is suggested. To quantify the effects of anaerobic digestion and biochar amendment on N_2O and CH_4 emissions, we conducted a study over 33 months with four different crops (silage maize, winter wheat, winter barley, and forage grass). We measured soil parameters such as mineral nitrogen, moisture, and temperature. The N_2O emissions after application of digestates were generally similar to those observed after cattle slurry or mineral fertilizer application. The highest N_2O emissions were observed in the first year of the experiment during maize cultivation and were strongly influenced by high soil nitrate concentrations, which were likely linked to enhanced soil organic N mineralization after ley termination. The CH_4 emissions were mostly negative. The addition of biochar to co-digested manure before application at an annual rate of 2 t ha^{-1} had no effect on N_2O emissions but led to short-lived CH_4 peaks from organic fertilizers directly after spreading. We conclude that digestates do not promote larger N_2O emissions than mineral fertilizers or cattle slurry, and that biochar addition to digestates in small application quantities does not reduce N_2O emissions but bears the risk of CH_4 release.

1. Introduction

Reducing nitrous oxide (N_2O) emissions is a crucial part of optimizing agricultural management. Agricultural soils currently account for more than 50% of all human-generated N_2O emissions, making them the largest anthropogenic source of this potent greenhouse gas (GHG) (Tian et al., 2020). Research shows that nitrogen (N) fertilization is the main cause of high N_2O emissions from soils (Reay et al., 2012). However, N supply is vital for crop productivity. Organic fertilizers such as manures, if available, support long-term maintenance of soil organic carbon levels by supplying organic matter and can generate energy if subjected to anaerobic digestion (AD).

AD facilitates the recycling of organic materials and is therefore proposed as an option to close nutrient cycles while generating energy (Dahlin et al., 2015). In Switzerland, agricultural and non-agricultural organic wastes are processed via AD (Brändli et al., 2005). Agricultural digestates, derived from AD of about 80% liquid and solid animal manure, and around 20% non-agricultural co-substrate, such as food processing waste, have been extensively studied. In contrast, non-agricultural digestates, produced from municipal and industry waste such as organic household waste, food processing waste and green waste from gardens and public green areas, have received less attention in the literature (Nicholson et al., 2017). Due to the variation in feedstock materials and production methods applied in AD, digestate properties can be highly variable, resulting in different dynamics of soil mineral N (N_{min}) (Alburquerque et al., 2012) and affecting N_2O-producing soil microorganisms (Lazcano et al., 2021). Consequently, estimating N_2O emissions from digestate application is inherently complex. The higher ammonium (NH_4^+) content of digestates may allow the replacement of synthetic N fertilizers with digestates with a minimal

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yield penalty (Gutser et al., 2005). But this could potentially increase N_2O emissions due to higher substrate availability for the N_2O-producing microbial community. However, digestates have lower concentrations of easily degradable carbon (C) after AD (Nkoa, 2014), which can be used by denitrifiers as an energy source for the denitrification process and to produce N_2O, potentially reducing N_2O emissions (Stuchiner and von Fischer, 2022). Because of these complexities, prior studies have shown variable effects of AD on N_2O emissions. Some reported lower emissions compared to undigested manure (Sänger at al, 2010, Senbayram et al., 2009, Möller and Stinner, 2009), while others reported higher emissions (Eickenscheidt et al., 2014).

Biochar, a porous, C-rich end product of the pyrolysis of organic materials, has gained popularity as its application can improve soil properties and increase yields (Jeffery et al., 2017), potentially reduce both nitrate (NO_3^-) leaching and N_2O emissions (Borchard et al., 2018), as well as enhancing C- sequestration (Schmidt et al., 2021). At present, we do not have a full picture of the mechanisms by which biochar reduces N_2O emissions (Kammann et al., 2017), but several mechanisms have been proposed. Increased gas entrapment of N_2O in water-saturated soil pores may stimulate microbial N_2O reduction (Harter et al., 2016). The outer and inner (pore) surface of biochar can adsorb negatively charged functional groups such as NO_3^- (Hagemann et al., 2017) and the resulting N immobilization is a potential pathway which could result in lower N_2O emissions. This process might be more effective when biochar is combined with NH_4^+-rich digestates compared to raw manure. The mitigating effect of biochar on N_2O emissions was shown in two meta-analyses, with overall reductions of 54% (Cayuela et al., 2014) and 38% (Borchard et al., 2018) recorded. Yet, when evaluating field studies only, the potential of emissions reduction by biochar decreased to an average of 12% (Verhoeven et al., 2017). The effectiveness of biochar for reducing N_2O emissions further varies with soil type, application amount, feedstock used for production and pyrolysis conditions during production (Kammann et al., 2017). Moreover, biochar weathers in soil and thus changes its properties and functionality over time (Joseph et al., 2010), further complicating the prediction of its effects on N_2O emissions.

The magnitude of N_2O emissions from agricultural soils is influenced by various factors, including fertilizer N input, microbial community composition and functioning, soil properties, weather conditions, and agronomic management practices, such as tillage (Butterbach-Bahl et al., 2013; Oertel et al., 2016; Six et al., 2004). Therefore, the ability to reliably predict N_2O emissions in field studies will require long-term measurement campaigns and will not be a trivial task due to the temporal and spatial variability of abiotic conditions. However, these studies are critical due to the fact that the global warming potential of N_2O is 273 times that of CO_2. (IPCC, 2021).

Conversely, CH_4 emissions from well-aerated agricultural soils are generally small or negative (Hütsch, 2001). However, short-term CH_4 emission peaks after application of cattle slurry have been reported in Krauss et al. (2017). So far AD does not show a clear trend towards increasing or mitigating soil CH_4 emissions (Eickenscheidt et al., 2014; Wulf et al., 2002), which are also highly relevant given that the global warming potential of methane (CH_4) is 27 times that of CO_2 (IPCC, 2021).

The objective of this study was to evaluate the effects of agricultural and non-agricultural digestates, and small doses of biochar added to agricultural digestate, on N_2O and CH_4 emissions in organic agriculture. The study quantified N_2O and CH_4 emissions and associated soil and weather parameters during four consecutive cropping periods. The hypotheses were that (i) N_2O emissions from digestates are greater than from cattle slurry due to higher NH_4^+ contents in digestates, and (ii) adding biochar to agricultural digestate reduces N_2O emissions compared to digestate alone. Further, we expected (iii) smaller CH_4 emissions from digestates compared to cattle slurry, due to lower contents of readily degradable organic C compounds in digestates.

2. Material and methods

2.1. Study site, crop rotation and experimental setup

The study was conducted between March 2018 and December 2020 on an organic farm in the northwest of Switzerland (47°33′44.3″N 7°53′15.7″E, 330 m a.s.l.). The region has a temperate climate with an average annual rainfall of 1104 mm and a mean annual temperature of 10.8 °C (2004–2017) (data source: weather station, 47°34′10.8″N 7°53′54.4″E, Agrometeo, MeteoSwiss). The soil is a Haplic Luvisol with a silt-loam texture and an average pH ($CaCl_2$) of 5.6 (Table 1). Prior to establishing the trial in March 2018, a grass-clover ley was grown on the field, followed by a crop rotation of silage maize (*Zea mays L.*), winter wheat (*Triticum aestivum L.*) and winter barley (*Hordeum vulgare L.*). Cultivation measures are listed in Supplementary: Table S1. White mustard (*Sinapis alba L.*) was planted as an intercrop in between wheat harvest and barley sowing. Upon the harvest of the barley, a legume-grass mixture would traditionally follow, but was replaced by a forage grass mixture (*Lolium hybridum, Lolium perenne, Festuca perennis* and *Festuca pratensis*) in this experiment to avoid N inputs from symbiotic N fixation. The field was plowed to 20 cm depth, shortly before sowing of maize, wheat and barley. A cultivator was used to prepare the field before planting the forage grass mixture. Manual weeding (combining harrow/star cultivator) and seedbed preparations (rotary harrow) were conducted as needed.

The treatments consisted of an unfertilized control (NON), a mineral fertilized control (MIN, ammonium sulphate) and four liquid organic fertilizers: cattle slurry (SLU), agricultural slurry from an on-farm biogas plant (SLA), SLA amended with biochar (SLA+) and liquid digestate from a non-agricultural biogas plant (LID). The same amount of total N was applied in all treatments except NON in order to supply 140 kg N ha-1 to maize, 140 kg N ha-1 to winter wheat, 120 kg N ha-1 to winter barley and 50 kg N ha-1 to fodder grass. Plots of 9 m x 18 m were arranged in a split-plot design, and each treatment was replicated four times (Supplementary: Figure S2).

2.1.1. Environmental conditions

Average annual air temperature and rainfall over the measurement period of 33 months were 12.4 °C and 605 mm, respectively (weather station, 47°34′10.8″N 7°53′54.4″E, Agrometeo, Meteoschweiz). Due to drought conditions, maize plants received artificial irrigation of 54 mm water once in August 2018.

2.2. Fertilizers and biochar

The characteristics of the liquid fertilizers are presented in Table 2. SLU originated from two organic farms (Aemethof, Densbüren, Switzerland and Kiesholzhof, Wallbach, Switzerland) for the applications in maize, wheat and forage grass, but were highly diluted with rain water in spring 2020 and therefore sourced from a conventional farm (Paul Frey, Asp, Switzerland) for application in barley. SLA was produced in an agricultural biogas plant (Aemethof, Densbüren, Switzerland) using cattle slurry, and solid cattle and horse manure as the

Table 1
Selected soil characteristics (0–20 cm) before the start of the field experiment (February 2018). Means±standard deviations of all initial plots ($n = 32$).

Parameter	Unit	Mean±SD
Sand	%	23±13
Silt	%	47±8
Clay	%	28±5
pH_{CaCl2}		5.6±1
Total organic C	g kg^{-1}	15.3±1
Total N	g kg^{-1}	1.6±0.1
Microbial C	mg kg^{-1}	403±5
Microbial N	mg kg^{-1}	70±7

Table 2
Chemical characteristics of the liquid organic fertilizers and total volume added to a given crop.

Crop	Treatment	Volume	DM	C_{org}	N_{tot}	NH_4^+-N	NH_4^+-N:N_{tot}	C:N	pH
		[m^3]	[%]	[g (kg DM)$^{-1}$]	[g (kg DM)$^{-1}$]	[g (kg DM)$^{-1}$]			
Silage maize	SLU	74.1	4.4	433.2	41.0	20.0	0.49	10.6	7.3
	SLA	36.3	5.4	370.4	65.5	38.2	0.58	5.7	7.9
	SLA+	40.7	8.0	411.7	45.4	24.3	0.54	9.2	7.8
	LID	24.8	13.0	273.3	40.1	22.3	0.56	6.9	7.8
Winter wheat	SLU	91.5	3.4	425.2	47.9	23.2	0.48	8.9	7.2
	SLA	39.3	5.2	384.6	76.6	46.6	0.61	5.0	7.9
	SLA+	39.9	7.9	442.2	49.8	28.7	0.58	8.9	8.0
	LID	25.9	8.8	351.8	56.6	32.3	0.57	6.2	7.8
Winter barley	SLU	45.6	6.1	434.9	38.3	19.6	0.51	11.4	7.0
	SLA	22.0	6.0	362.8	85.2	57.5	0.67	4.3	8.1
	SLA+	22.5	9.3	362.8	52.2	27.5	0.53	7.3	8.2
	LID	23.4	8.7	364.7	56.5	33.2	0.59	6.5	7.8
Forage grass	SLU	64.6	3.1	390.3	43.5	19.7	0.45	9.0	7.8
	SLA	19.8	5.2	382.9	82.5	54.2	0.66	4.6	8.2
	SLA+	19.8	8.5	331.4	47.5	31.8	0.67	8.9	8.1
	LID	14.6	11.2	413.4	49.5	27.4	0.55	6.7	8.0

SLU: cattle slurry; SLA: agricultural slurry (from an on-farm biogas plant); SLA+ : agricultural slurry (from an on-farm biogas plant) and biochar (2 t ha-1 year-1); LID: non-agricultural digestate; DM: dry matter.

main feedstock and various food-processing wastes as co-substrates (perished cereals, residues from coffee capsule production, cocoa residues and remainders of herbs after extraction). SLA is the liquid fraction from solid-liquid separation after a 60-day digestion process at thermophilic (53 °C) conditions. For SLA+ , we added biochar to SLA to apply approximately 2 t ha^{-1} year^{-1}. LID was produced in a non-agricultural biogas plant (Biopower, Pratteln, Switzerland) from urban green cuttings and various organic wastes (from households, grocery shops, gastronomy and food processing). The mean residence time for AD was 15 days and the reaction was thermophilic (55 °C). LID refers to the liquid phase of the digested material. The certified biochar (European Biochar Certificate EBC) was obtained from tree and shrub cuttings (Verora AG, Edlibach, Switzerland) and characterized by on average 57–81% C, 0.65–0.75% N and an H/Corg ratio between 0.29 and 0.44. From the second application onwards, biochar was milled before application to slurry to allow homogeneous mixing.

Liquid organic fertilizers were stored in non-corrosive containers on the field site for about two weeks before fertilizer application. Fertilizers were analyzed for total N contents and batch-specific volumes needed to apply similar amounts of total N in each treatment were calculated. Granular ammonium sulphate was used as mineral fertilizer in the MIN treatment. The chosen N fertilization levels were 140 kg N ha^{-1} for maize and wheat, 120 kg N ha^{-1} for barley, and 80 kg N ha^{-1} for the establishment of forage grass. Applications were split into two equal applications, except for forage grass, where the first application was 50 kg N ha^{-1}, followed by an autumn application of 30 kg N ha^{-1}. Liquid fertilizers were applied by hand using watering cans to mimic drag hose spreading. To prevent crop limitation of P and potassium (K), NON and MIN received 20 kg P ha^{-1} (triple superphosphate in 2018; rock phosphate in 2019 & 2020) and 130 kg K ha^{-1} (potassium sulphate) annually. LID was lower in K compared to the agricultural fertilizers SLU, SLA and SLA+ , and therefore received an additional 70 kg K ha^{-1} (potassium sulphate; permitted in organic farming) applied to barley.

2.3. N_2O and CH_4 flux measurements

We quantified N_2O and CH_4 emissions over 33 months. Sampling took place weekly during the vegetation period, bi-weekly during winter, and daily or every second day for 7–14 days after fertilizer applications. Additional samples directly after spreading fertilizers were taken in barley and forage grass. Gas samples were collected with the static chambers method (two chambers per plot to allow for technical replication, resulting in 48 chambers in total). Chambers were designed according to international guidelines (Clough et al., 2020). Each circular chamber covered a basal area of 0.07 m^2 with a volume of 14 dm^3 (chamber height: 0.2 m, chamber diameter: 0.3 m). PVC rings were permanently inserted at 0.1 m soil depth and removed only during soil cultivation activities (Supplementary: Figure S1). Chambers were placed between crop rows during maize cultivation and included the crop for wheat, barley and grass. Gas samples were collected with a three-way-syringe system in pre-evacuated headspace vials with a volume of 12 ml (Labco Limited, Lampeter, United Kingdom), and closed with a double rubber septum. Samples were taken at 0, 10, 20 and 30 min after closing the chambers. Soil surface temperatures and chamber temperatures were recorded at the beginning and end of each sampling round. Gas samples were analyzed with a gas chromatograph (7890 A, Agilent Technologies, California, USA) equipped with an electron capture detector (μECD) to measure N_2O concentration and a flame ionization detector (FID) for CH_4 determination.

2.3.1. Calculations for N_2O and CH_4 emissions

Fluxes of N_2O and CH_4 were determined by taking into account the mean gas con- centrations (ppm), chamber air temperature (°C), as well as the area (m^2) and volume (L) of the chambers. Fluxes were then calculated for each chamber with the R package gasfluxes (Fuß, 2016). The *kappa.max* selection algorithm was used to select the method for flux trajectories (linear, robust-linear, Hutchinson- Mosier regression) for each flux individually based on the flux size and the measurement uncertainty (Hüppi et al., 2018, 2022). Fluxes were averaged between the two technical replicates per plot.

Cumulative N_2O and CH_4 emissions per hectare (area-scaled) were calculated for each cropping period (from tillage to tillage). Additional measurements taken directly after fertilizer applications, as displayed in Fig. 4 and Supplementary: Figure S2, were not included in the calculations of cumulative emissions. Due to different growing periods, the number of observations varied between crops, with 34 data points per treatment and replicate used to calculate the cumulative emissions from maize, 40 for wheat, 37 for barley, and 20 for forage grass.

Area-scaled N_2O emissions from NON (N_2O-$N_{control}$) were subtracted from fertilizer treatment emissions and divided by the corresponding amount of total N (N_{tot}) per fertilizer application to obtain fertilizer-based emission factors (EFs) as follows:

$$N_2O \quad EF1[\%] = \frac{N_2ON_{treatment} - N_2ON_{control}}{Fertilizer \quad N \quad input}$$

$$N_2O \quad EF2[\%] = \frac{N_2ON_{treatment}}{Fertilizer \quad N \quad input}$$

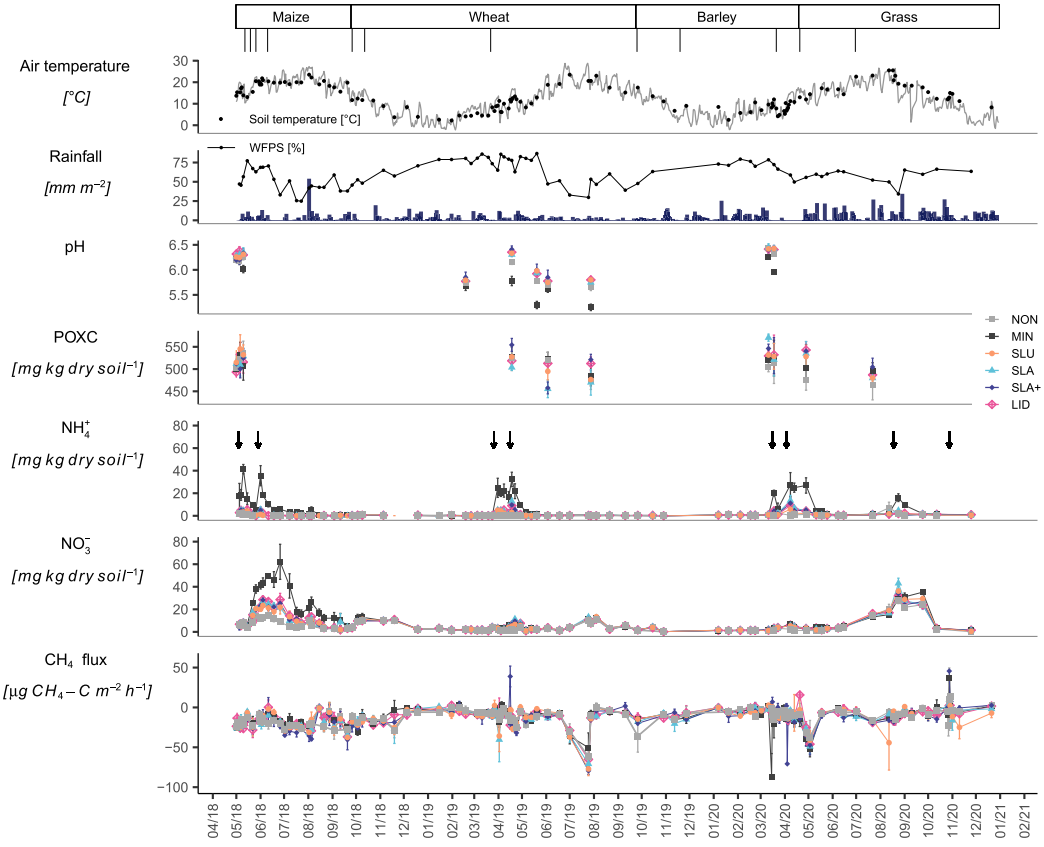

Fig. 1. Time series measurements of air temperature and rainfall (data Source: weather station, 47°34'10.8"N 7°53'54.4"E, Agrometeo, MeteoSwiss), averages across all treatments for soil temperature (−7 cm soil depth) and WFPS (0–20 cm) and treatment means fpr pH, POXC, NH_4^+, NO_3^- and soil-borne CH_4 emissions during a 33-month period with a crop rotation of silage maize, winter wheat, winter barley and forage grass (April 2018 to December 2020). Values represent treatment mean ±SEM ($n = 4$). For soil temperature and WFPS, values represent daily averages. Treatments: unfertilized control (NON); mineral fertilized control (MIN); cattle slurry (SLU); agricultural slurry from an on-farm biogas plant (SLA) and amended with biochar (SLA+) and liquid digestate from a non-agricultural biogas plant (LID). The arrows in the NH_4^+ panel represent fertilization events. Vertical lines above the first panel indicate soil cultivation measures

Data for EF2 and crop yields are listed in Supplementary: Table S3 and S1. By dividing area-scaled emission by grain yield (wheat, barley) or dry biomass yield (maize, grass), yield-scaled N_2O emission (g N_2O- N t^{-1} dry biomass for maize or grain in the case of cereals) were calculated (Venterea et al., 2011):

$$Yield-scaled\quad N_2O\quad emissions\quad [g\quad t^{-1}] = \frac{Area\quad scaled\quad N_2ON[kg\quad N_2ON\quad ha^{-1}]}{Yield/grain\quad yield\quad dry\quad matter[t\quad ha^{-1}]}$$

We did not calculate yield-scaled N_2O emission for forage grass because the growing period was not complete when the last measurement was taken. CO_2- equivalents for N_2O (Table 3) and CH_4 (Supplementary: Table S6) emissions were calculated according to the IPCC guidelines (IPCC, 2021).

2.4. Soil sampling

N_2O and CH_4 samplings were regularly accompanied by plot-specific soil sampling. Composite soil samples of eight cores (ø=2 cm) were taken from each plot to a depth of 20 cm and stored in cooling boxes for transport. Samples were passed through a 2 mm sieve and N_{min} was extracted from the fresh soil with a 0.01 M $CaCl_2$ solution (1:4 v/w), followed by filtration (pore size <2 µm) after shaking for 60 min. Contents of N_{min} were determined with a spectrophotometer (Smartchem450, AMS Alliance, Rome, Italy) according to Keeney and Nelson (1982) for NH_4^+ and using the method of Krom (1980) for NO_3^-. Gravimetric soil moisture was determined by drying the soil at 105 °C.

Soil WFPS was calculated as:

$$WFPS\quad [\%] = \frac{GWC\quad x\quad BD}{PO}\quad x100$$

with GWC = gravimetric water content [%], BD = soil bulk density [g cm^{-3}] and PO = soil porosity [%].

On selected dates, portions of the sieved soil were air-dried to measure the pH in $CaCl_2$ (1:2.5 $CaCl_2$). Bulk density was determined plot-wise before establishing the field trial and before sowing barley. Permanganate oxidizable C (POXC), which has been shown to represent a management-sensitive labile soil C fraction (Culman et al., 2012), was measured according to the method described by Weil et al. (2003) at ten time points in air-dried soil samples using a 0.2 M $KMnO_4$ solution.

2.5. Statistical analysis

Data analysis and production of graphs were conducted using R version 4.0.2 (R Development Core Team, 2021). The significance threshold was $p < 0.05$ for all statistical analyses. A linear mixed effects model was applied on log-transformed data using R-package *nlme* (Pinheiro et al., 2022). Negative N_2O fluxes were negligible and replaced by zeros. The time courses of N_2O fluxes (µg N_2O-N m^2 h^{-1}) were examined separately for each crop and combined across all crops for correlations with soil temperature (°C), WFPS (%) and contents of NO_3^- (mg kg^{-1}) and NH_4^+ (mg kg^{-1}) as fixed effects co-variates. Obtained model estimates (Table 4) represented the estimated increase of N_2O

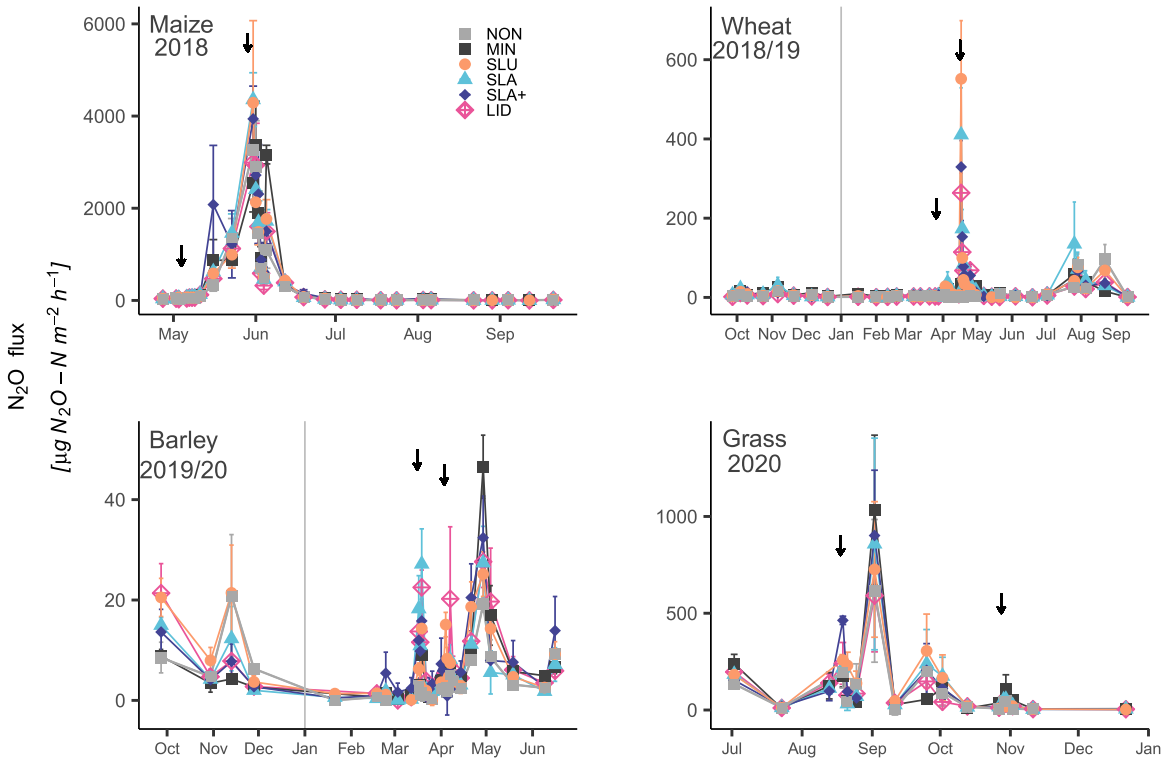

Fig. 2. Time series measurements of N_2O emissions from silage maize, winter wheat, winter barley, and forage grass. Values represent treatment mean ±SEM ($n = 4$). Scaling of the y-axis differs between panels. Arrows indicate the time points of fertilizer applications. Treatments: unfertilized control (NON); mineral fertilized control (MIN); cattle slurry (SLU); agricultural slurry from an on-farm biogas plant (SLA) and amended with biochar (SLA+) and liquid digestate from a non-agricultural biogas plant (LID).

fluxes (µg N_2O-N m^2 h^{-1}) by an increment of one unit of the explanatory variables (Soil temperature, WFPS, NO_3^- and NH_4^+ contents). For example, an estimate value of 1.5 for WFPS is to be interpreted as an increase of N_2O fluxes of 1.5 µg N_2O-N m^2 h^{-1} by an increase of 1% WFPS. The model accounted for treatments nested in split-plots and within replicated blocks as random factors in the analysis. Split-plots and blocks did not have a statistically significant impact on the data. Temporal correlation was included in the model. Soil pH and POXC were not included in this analysis because both parameters were sampled only on a few occasions.

We performed a linear mixed model followed by Tukey's Post Hoc test accounting for split plots nested in four replicates as random factors to examine differences between cumulative area-scaled N_2O and CH_4 emissions, yield- scaled N_2O emissions, EFs and CO_2-equivalents, firstly between crops and secondly between treatments within crops (Fig. 3; Table 3; Supplementary: Table S4 and Table S5). Data from cumulative area-scaled N_2O emission in barley was log-transformed to meet the criteria of normal distribution, while data from maize, wheat and barley was normally distributed. Statistical differences in wheat for area- and yield-scaled N_2O emission, EFs and CO_2-equivalents were further investigated with specified contrasts for comparison between SLU-MIN, SLU-NON, SLA-MIN and SLA-NON using the R-package *stats* (R Development Core Team, 2021).

Differences between snapshots of CH_4 (Fig. 4) and N_2O emissions (Supplementary: Figure S2) directly after fertilizer application were examined by a non-parametric test (Kruskal-Wallis test + pairwise Wilcoxon test) because the data did not fulfill the requirement of normal distribution despite log- transformation. Treatment differences and differences between sampling time points for soil pH and POXC were examined with an ANCOVA with split plots nested in four replicates as random factor (Supplementary: Table S3).

3. Results

3.1. Soil parameters

Soil temperature followed a seasonal pattern, and the overall highest value (25.5 °C) was recorded in maize in August 2018 and the lowest value (2.2 °C) in wheat in early February 2019 (Fig. 1). WFPS ranged between 25% and 86% and was not significantly different between treatments.

Soil pH ranged between 5.7 and 6.4 and was significantly lower in the MIN treatment compared to the organic fertilizers and NON (Fig. 1; Supplementary: Table S3). No consistent pattern was found for POXC contents, which ranged between 474 and 533 mg (kg dry soil)$^{-1}$.

Across all crops, soil NH_4^+ contents increased immediately following N input and showed a clear treatment distinction, with the highest concentrations in MIN. Much lower concentrations occurred in SLU, SLA, SLA+ and LID, and the lowest NH_4^+ contents were measured in NON after fertilizer application (Fig. 1).

Soil NO_3^- contents after fertilizer applications varied strongly over time, with the highest values of more than 50 mg (kg dry soil)$^{-1}$ measured in maize after the second application, and the lowest contents (< 20 mg (kg dry soil)$^{-1}$) in barley after the second application (Fig. 1). Clear treatment differences occurred in maize, where NO_3^- contents were about twice as high in MIN than in SLU, SLA, SLA+ and LID, and about three times as high as in NON. Fertilizer applications in wheat and barley induced much smaller NO_3^- peaks compared to maize. Increasing NO_3^- contents were also observed after management operations such as plowing, harrowing or sowing and also during fertilizer application in forage grass.

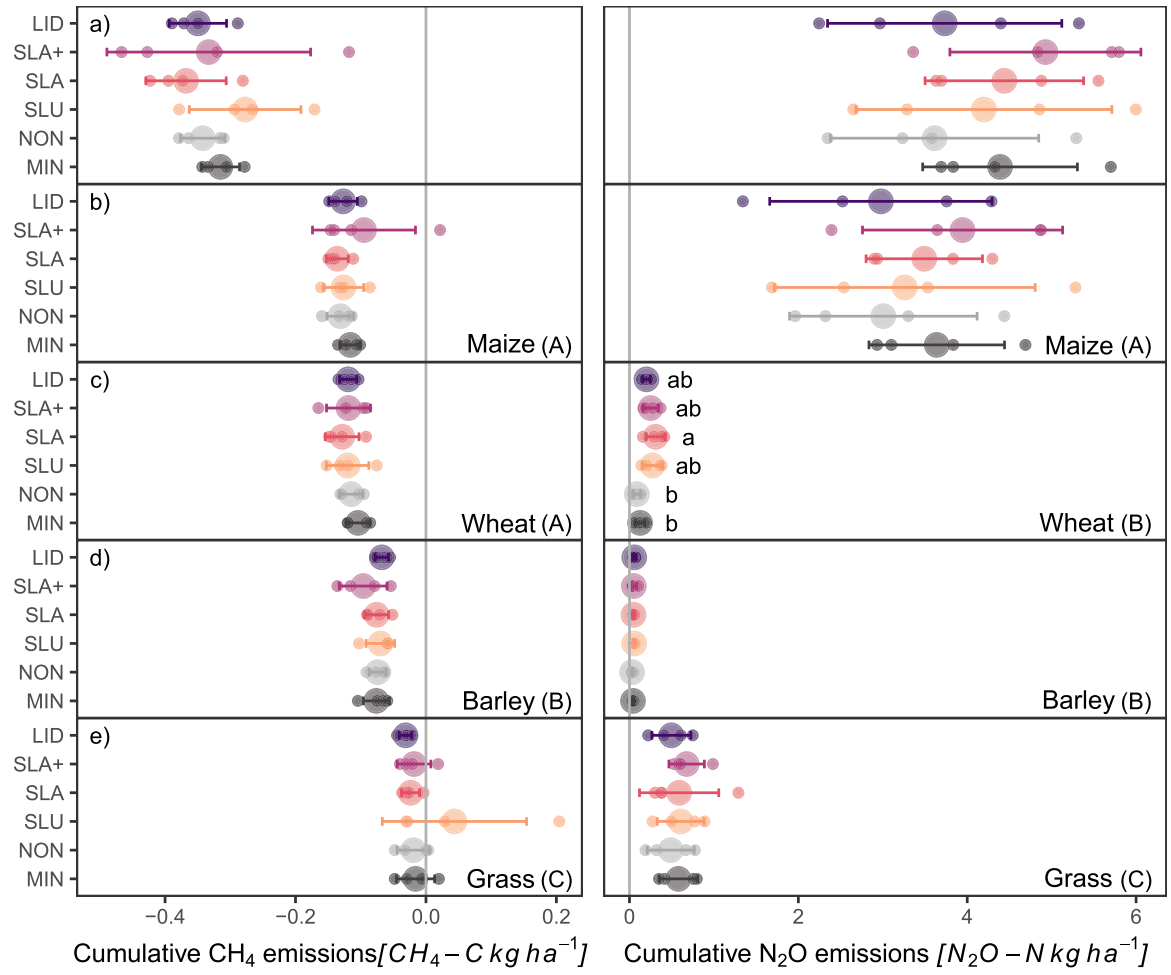

Fig. 3. Average cumulative CH_4 (left) and N_2O (right) emissions (big circles represent treatment means, small circles indicate replicates ($n = 4$)±SEM across 33 months ($n = 131$; upper panel) from silage maize ($n = 34$), winter wheat ($n = 40$), winter barley ($n = 37$) and forage grass ($n = 20$). Small letters indicate results from a linear mixed model and specified contrasts of N_2O emissions from winter wheat for comparison between SLU-MIN, SLU-NON, SLA-MIN and SLA-NON (Supplementary: Table S4). Capital letters express differences between crops (Supplementary: S4). Treatments: unfertilized control (NON); mineral fertilized control (MIN); cattle slurry (SLU); agricultural slurry from an on-farm biogas plant (SLA) and amended with biochar (SLA+) and liquid digestate from a non-agricultural biogas plant (LID).

3.2. N_2O fluxes

Fluxes of N_2O increased after fertilizer applications and management operations in combination with rainfall and heat, but were highly variable in magnitude between crops (Fig. 2). The N_2O emissions did not correspond well with N application amounts, and treatment differences were mostly small. N_2O emission from freezing and thawing in winter was negligible. Peak emissions of N_2O occurred after fertilizer applications and were remarkably high in maize (up to 4000 μg N_2O-N m^{-2} h^{-1}) compared to emission peaks from wheat, barley and grass, which were 10, 100 and five times lower, respectively (Fig. 2). N_2O emissions from maize rose after ley termination followed by fertilizer application under high soil temperature and moisture and after peaks did not return to the baseline flux in between fertilizer applications. Emissions during maize cultivation were at similar levels for all treatments.

The N_2O emissions peaked shortly after fertilizer application in wheat, decreased rapidly and peaked a second time immediately after the second fertilizer application (Fig. 2). Only the second N_2O peak showed a treatment effect, with higher emissions in SLU, SLA, SLA+ and LID compared to MIN and NON.

Two short-term N_2O peaks characterized emissions from barley immediately after fertilizer applications, which were followed by a larger peak about two weeks after the second fertilizer application (Fig. 2). After about 45 days, in early May 2020, N_2O emissions increased again in all treatments. During this time, soil temperatures rose significantly and rainfall occurred after prolonged drought (Fig. 1).

In forage grass, N_2O emissions already increased before fertilizer application (Fig. 2). Soil temperature and moisture were high in autumn 2020 (Fig. 1). With a time lag of about 10 days, N_2O emissions increased in forage grass after the first fertilizer application following a precipitation event (34 mm m^{-2}), while only a small increase was measured after the second fertilizer application. Soil temperatures were already lower during the second application at the end of October 2020.

3.3. Area-scaled and yield-scaled N_2O emission, emission factors and CO_2-equivalents

Area-scaled cumulative N_2O emissions throughout the experiment ranged from 0.03 kg N_2O-N ha^{-1} $crop^{-1}$ (NON treatment in barley) to 3.9 kg N_2O-N ha^{-1} $crop^{-1}$ (SLA+ treatment in maize) (Fig. 3; Supplementary B: Table S3). For maize, the emissions per area averaged across all treatments were 10 times higher (3.4±1.1 kg N_2O-N ha^{-1} $crop^{-1}$) and significantly different from wheat (0.2±0.1 kg N_2O-N ha^{-1} $crop^{-1}$) and forage grass (0.5±0.2 kg N_2O-N ha^{-1} $crop^{-1}$). Emissions from barley (0.04±0.02 kg N_2O-N ha^{-1} $crop^{-1}$) were significantly lower compared to the other crops.

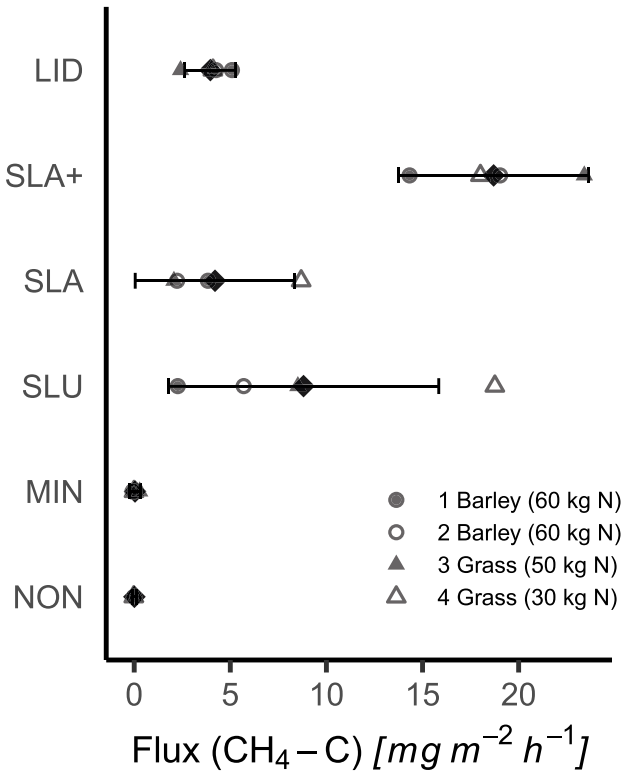

Fig. 4. Snapshot of CH_4 fluxes (mg CH_4-C m^2 h^{-1}) from measurements immediately after fertilizer applications at two time points in winter barley and two time points in forage grass. Black diamond shapes show treatment means ±SD ($n = 4$). Grey symbols represent individual values per sampling time point ($n = 4$). Letters indicate significant treatment differences (*Kruskal-Wallis chi-squared*=19.34, df=5, p = 0.002). NON: unfertilized control; MIN: mineral fertilizer; SLU: cattle slurry; SLA: agricultural digestate; SLA+ : agricultural digestate and biochar (2 t ha^{-1} $year^{-1}$); LID: non-agricultural digestate.

Fertilizer treatment affected N_2O emissions only during wheat (p=0.011), where area-scaled N_2O emissions in SLA+ were significantly higher than in MIN (p=0.098) (Fig. 3; Supplementary: Table S4). The EF1 for MIN in wheat was on average about four times lower than for SLU, SLA and SLA+ and three times lower than for LID (0.08%) (Table 3). Forage grass had an average EF1 of 0.12%. LID had the lowest treatment mean across the crops (0.01%). The average annual EF1 across all treatments was 0.13%. EFs that were additionally calculated without subtracting the emissions of the control (EF2) ranged between 2.20 and 2.65 for maize, 0.09–0.19 for wheat, 0.03–0.05 for barley and 0.57–0.82 for forage grass (Supplementary: Table S4).

Yield-scaled N_2O emissions based on aboveground biomass were highest from maize (177 g N_2O-N t^{-1}) (Table 3). Yield-scaled N_2O emissions based on grain yield were higher from wheat (59 g N_2O-N t^{-1}) compared to barley (12 g N_2O- N t^{-1}) (Supplementary: Table S5). We found treatment differences only in wheat, where yield-scaled N_2O emissions from SLA (83 g N_2O-N t^{-1}) were significantly higher than from MIN (32 g N_2O-N t^{-1}).

Annual averages of CO_2-equivalents did not significantly differ between fertilizer treatments and ranged between 0.58 t CO_2-equivalents ha^{-1} (LID) and 0.77 t CO_2-equivalents ha^{-1} (SLA+) (Table 3). Maize cropping produced on average 1 t CO_2-equivalents ha^{-1} more than the annual average.

3.4. Mixed effects model of drivers of N_2O emissions

Results from the linear mixed effects model across all crops showed that the most significant factor for increasing N_2O fluxes was soil temperature, followed by soil NO_3^- and NH_4^+ contents and soil WFPS (Table 4). In barley, N_2O fluxes correlated positively with soil temperature and NH_4^+ contents, but the effect of WFPS was significantly weaker compared to maize, wheat and forage grass. Barley was the only crop where soil NO_3^- contents did not correlate significantly positively with N_2O fluxes as there were no major N_2O emissions. Fluxes from forage grass were only significantly affected by rising soil NO_3^- contents. In maize, the influence of soil temperature, WFPS and NO_3^- but not NH_4^+ contents on N_2O was significant, however the effect for NO_3^- contents was smaller compared to the other crops. No significant relationships between N_2O emissions and fertilizer characteristics could be detected (Table 4; Supplementary: Table S7).

Table 3
Fertilizer-based emission factor (mean±SD), yield-scaled N_2O emissions (mean ±SD) for aboveground biomass (silage maize) and marketable grain yield of cereals (winter wheat and winter barley), and CO_2-equivalents (IPCC, 2021) (mean±SD). Small letters indicate results from a linear mixed model (n=4; p<0.05) and Tukey Post-Hoc test. Specified contrasts were applied in winter wheat for comparison between SLU-MIN, SLU-NON, SLA-MIN and SLA-NON.

Crop	Treatment	Fertilizer-based emission factors [%]	Yield-scaled N_2O emissions [g N_2O-N t^{-1}]	N_2O-CO_2-eq. emissions [t CO_2-eq. ha^{-1}]
Silage maize	NON	Not applicable	186±61a	1.29±0.4a
	MIN	0.45±0.50a	169±31a	1.56±0.3a
	SLU	0.19±1.00a	164±64a	1.40±0.6a
	SLA	0.37±0.45a	185±34a	1.50±0.3a
	SLA+	0.62±0.68a	207±61a	1.69±0.4a
	LID	<0	153±55a	1.28±0.5a
		F=0.3; p=0.84	F=0.4; p=0.84	F=0.4; p=0.82
Winter wheat	NON	Not applicable	34±17ab	0.04±0b
	MIN	0.03±0.04a	32±13b	0.05±0b
	SLU	0.13±0.07a	78±28ab	0.12±0ab
	SLA	0.14±0.06a	83±24a	0.13±0a
	SLA+	0.10±0.05a	67±23ab	0.11±0ab
	LID	0.08±0.03a	58±13ab	0.09±0ab
		F=2.2; p=0.12	F=3.3; p=0.03	F=4.3; p=0.01
Winter barley	NON	Not applicable	11±3a	0.01±0.01a
	MIN	0.01±0.01a	9±2a	0.02±0.00a
	SLU	0.02±0.01a	15±2a	0.02±0.00a
	SLA	0.02±0.01a	12±2a	0.02±0.00a
	SLA+	0.02±0.03a	11±6a	0.02±0.01a
	LID	0.02±0.01a	14±4a	0.03±01a
		F=0.5; p=0.71	F=0.94; p=0.48	F=1.2; p=0.35
Forage grass	NON	Not applicable	Not applicable	0.21±0.1a
	MIN	0.11±0.25a	Not applicable	0.25±0.1a
	SLU	0.13±0.27a	Not applicable	0.26±0.1a
	SLA	0.11±0.47a	Not applicable	0.25±0.2a
	SLA+	0.23±0.22a	Not applicable	0.29±0.1a
	LID	0.01±0.23a	Not applicable	0.21±0.1a
		F=0.2; p=0.93	Not applicable	F=0.2; p=0.94
Annual average	NON	Not applicable	Not applicable	0.56±0.2a
	MIN	0.15±0.14a	Not applicable	0.68±0.1a
	SLU	0.11±0.22a	Not applicable	0.65±0.2a
	SLA	0.15±0.17a	Not applicable	0.69±0.1a
	SLA+	0.22±0.15a	Not applicable	0.77±0.2a
	LID	0.02±0.21a	Not applicable	0.58±0.2a
		F=0.5; p=0.74	Not applicable	F=0.7; p=0.67

SLU: cattle slurry; SLA: agricultural slurry (from an on-farm biogas plant); SLA+: agricultural slurry (from an on-farm biogas plant) and biochar (2 t ha-1); LID: non-agricultural digestate.

Table 4
Linear mixed effects model of log-transformed N_2O fluxes [μg N_2O-N m^2 h^{-1}] and soil properties for all crops combined and for each crop separately (silage maize, winter wheat, winter barley, and forage grass). Soil properties comprise soil water-filled pore space [WFPS, %], soil temperature [°C] and nitrate and ammonium contents [mg kg^{-1}]. Estimates (E), 95%-confidence intervals and p values are shown. Replicates were included as random factors and temporal correlation was considered in the model.

	All crops			Maize			Wheat			Barley			Grass		
Predictors	E	CI	*p*	E	CI	*p*	E	CI	*p*	E	CI	*p*	E	CI	*p*
(Intercept)	0.26	0.09 – 0.73	0.01	0.86	0.30 – 2.46	0.782	0.07	0.03 – 0.17	< 0.001	12.38	3.18 – 48.19	< 0.001	10.37	1.93 – 55.76	0.007
WFPS	1.04	1.03 – 1.04	< 0.001	1.04	1.04 – 1.05	< 0.001	1.03	1.02 – 1.04	< 0.001	0.96	0.94 – 0.97	< 0.001	1	0.99 – 1.02	0.517
Soil temp	1.12	1.10 – 1.15	< 0.001	1.07	1.02 – 1.11	0.005	1.13	1.11 – 1.16	< 0.001	1.11	1.07 – 1.15	< 0.001	1	0.94 – 1.07	0.947
Nitrate	1.05	1.04 – 1.06	< 0.001	1.03	1.01 – 1.04	< 0.001	1.14	1.11 – 1.18	< 0.001	1.07	0.97 – 1.18	0.163	1.07	1.05 – 1.10	< 0.001
Ammonium	1.05	1.03 – 1.06	< 0.001	1.01	0.99 – 1.02	0.254	1.05	1.03 – 1.07	< 0.001	1.03	1.01 – 1.06	0.005	0.99	0.92 – 1.08	0.898

3.5. CH_4 fluxes

Daily CH_4 fluxes were mostly negative throughout the study period, except for a few peaks of up to 50 μg CH_4-C m^{-2} h^{-1} in SLA+ one day after fertilizer application (Fig. 1). However, when fluxes were quantified immediately after applying fertilizer in barley and forage grass, highly elevated CH_4 fluxes were recorded, especially in SLA+ but also in SLU, SLA and LID (Fig. 4). This was not observed for N_2O fluxes (Supplementary: Figure S2).

The sum of average cumulative CH_4 uptake excluding the peaks directly after fertilizer application was between − 0.28 kg CH_4-C ha^{-1} (SLU) and − 0.37 kg CH_4- C ha^{-1} (SLA) after 33 months of monitoring fluxes (Fig. 3). The CH_4 uptake was significantly higher in maize and wheat compared to barley ($p < 0.001$), and lowest in forage grass ($p < 0.001$) (Supplementary: Table S5). No significant treatment differences were observed. There was a trend for higher cumulative emissions in SLA compared to MIN (p=0.059) and SLU compared to NON (p=0.058) excluding the additional measurements directly after fertilizer applications (Fig. 3).

4. Discussion

This study was designed to quantify parameters related to N dynamics after fertilizer applications. Fertilization with digestates did not produce markedly different emissions in N_2O compared to cattle slurry (Fig. 3). This is supported by the absence of significant correlations of cumulative N_2O emissions with digestate composition (Supplementary: Table S7). As similar emissions were observed for all fertilizer treatments while applying a similar amount of N_{tot}, increased N availability after fertilizer application can at most only partially explain N_2O emission.

4.1. Management history and abiotic factors were the main drivers of N_2O fluxes

In April 2018, after plowing the ley mixture into the soil, maize was sown and fertilizer was applied, followed by repeated harrowing against weeds. Fertilizers were only applied when growing plants were present, e.g. 4- and 6-leaf stage in maize. The N_2O emissions recorded after fertilizer applications in maize were several magnitudes higher than emissions from wheat, barley and forage grass (Fig. 2; Fig. 3). A possible explanation is that soil management triggered soil microbial activity, causing mineralization of incorporated plant residues, and soil N surplus (>10 kg N ha^{-1}) prompts N_2O emission (Van Groenigen et al., 2010). The legacy effect of nitrogen fixing leys or green manures and associated incorporation of organic material is another driver for N_2O emissions in organic farming, which can explain the weak relationship between fertilizer N-input and N_2O emissions (Hansen et al., 2019; Skinner et al., 2014). In addition, maize cropping leaves part of the soil bare between the rows, and N demand of seedlings is low in the early growth stages, leaving more N for microbial processes. Conditions for spiking N_2O production were reached when soil temperature increased from about 15–20 °C, while at the same time WFPS was already above 60% and NO_3^- levels started rising (Fig. 1).

Forage grass cropping produced higher N_2O emissions compared to wheat and barley cropping due to heat and moisture, even though N-input levels were lower (Fig. 3). During barley cultivation, N_2O fluxes followed a distinct trajectory including peaks after fertilizer applications similar to other crops (Fig. 2). However, the magnitude of the N_2O fluxes from barley was much lower compared to the other crops (Fig. 3), which was attributed to a set of conditions potentially impeding N_2O production that occurred during barley cultivation. Baral et al. (2017) reported similarly low N_2O emissions from barley cultivation from the unfertilized control, which were not significantly different from treatments that had received mineral fertilizer or digestate. During fertilizer applications in barley in spring 2020, soil temperatures were very low (around 5–10 °C), and soil WFPS gradually decreased right after the first fertilizer application due to a lack of rainfall. This likely decreased soil nitrification and/or denitrification rates as shown in Fig. 1, resulting in less available substrate for N_2O production and subsequently lower N_2O emissions.

Fertilization with ammonium sulphate lowered soil pH below 6 (Supplementary Table S3), but, due to fewer data points compared to mineral N contents, soil temperature and WFPS, the possible effects on N_2O emissions were not resolved statistically. In most cases, WFPS, soil temperature and availability of soil N_{min} contents correlated significantly positively with N_2O fluxes (Table 4). This agrees with the literature (Oertel et al., 2016). Hot moments of N_2O formation occurred for all treatments, but the magnitude of the N_2O emissions seemed relatively unaffected by the course of NO_3^- contents later on. In our study, effects of fertilizer type on N_2O emissions were mostly masked by soil management history and abiotic factors.

4.2. N_2O emissions were mostly not affected by fertilizer type

We consistently observed similar N_2O emissions from digested and undigested organic fertilizers (Fig. 3), and hence no adverse effects of applying anaerobic digestates compared to cattle slurry could be detected. Wheat cultivation caused nearly 2.5-fold higher yield-scaled emissions for agricultural digestates compared to the unfertilized control and mineral fertilizer (Table 3). During winter wheat cultivation, low N_2O emissions from the mineral fertilizer treatment might stem from substrate limitation for soil microbial transformation pathways involving N cycling due to increased plant N-uptake (Supplementary: Table S2); for example, due to plant uptake of readily plant-available ammonium (Frick et al., 2022).

The effects of digested versus raw manure on N_2O emissions are inconsistent due to various chemical characteristics of digestates and soil. Various chemical characteristics of digestates and soil contribute to the complexity of N_2O responses (Oertel et al., 2016). The formation of N_2O from digestate application can be accelerated by higher NH_4^+ contents and higher pH after AD (Sänger et al., 2010; Senbayram et al., 2009; Eickenscheidt et al., 2014). On the other hand, some studies suggest that easily degradable C is critical for N_2O production (Baral et al., 2017; Köster et al., 2015; Petrova et al., 2021). Lower microbial-accessible C contents in digestates compared to raw manure can lead to increased N use efficiency and reduced N_2O emissions (Hansen et al., 2019). In a C-rich soil like the one at the experimental field site, differences in organic C contents between digestate (SLA=374 ±11 g C_{org} (kg DM) $^{-1}$) and raw manure (SLU=413±22 g C_{org} (kg DM) $^{-1}$) did not translate into statistically different POXC contents in the soil (Fig. 1; Supplementary: Table S3). The influence of degradable C in organic fertilizers may be more important when C is generally low in the soil. For example, it was observed that higher soil C_{org} contents tend to increase N_2O emissions (Eickenscheidt et al., 2014; Dietrich et al., 2020).

The values for EF1 in this study were consistently lower than the IPCC default value of 1% (Eggleston et al., 2006) and compared to the literature (Skinner et al., 2014; Walling and Vaneeckhaute, 2017). We obtained such low EFs because the calculation of EF1 foresees to subtract emissions from the control, which had not received any N. In the present study, the control, which had not received N input, produced similarly high N_2O emissions compared to the fertilized treatments. Thus, the N_2O emissions were largely unaffected by fertilizer N input and therefore, EF1 was very small. While high N_2O emissions in maize were observed, EF1 ranged from 0.01% (MIN) in barley to 0.62% (LID) in maize 3), with the annual average EF1 lowest for LID (EF1 =0.02%) but not significantly different from the other fertilizer treatments, which ranged between 0.11% and 0.15% with high variation. Since measurements in this study were carried out in a newly established field trial, substantial amounts of N may have been released during mineralization of crop residues and previously supplied manure. High N mineralization from soil organic matter can constitute a major source of N_2O emissions (Ammann et al., 2020) and consequently lower EF1. Therefore, high N_2O emissions in maize did not translate into a high EF1. Additionally, the relatively low clay content of 18% may have contributed to lower EF1 values, as clay-rich soil promotes larger EFs (van Groenigen et al., 2004).

Comparison of our results with the literature is limited because the calculation method for EFs varies between studies, often considering only fertilized plots. Therefore, we additionally calculated overall EFs (area-scaled N_2O emissions divided by fertilizer N-input; EF2) regardless of emissions from the control (NON). The overall values for EF2 in our study ranged between 0.74% and 0.91% annually and showed no fertilizer treatment effect (Supplementary: Table S4). These values are in line with Skinner et al. (2014) who reported a large range of EF2 (between 0.3% and 36%) from fields managed under organic farming. However, their calculation included emissions from crop residues and biological N fixation in addition to N from fertilizers. Walling and Vaneeckhaute (2017) reported EF2 values of applied N from synthetic fertilizers at 0.03–12.9%, from manures at 0.05–13.9% and from digestates at 0–5.1%, suggesting that digestates tend to have lower mean EF2 values, but higher variability.

Annual averages of CO_2-equivalents (Table 3) were slightly lower in our experiment (0.58–0.77 t CO_2-equivalents ha^{-1}) compared to on average 1.2 t CO_2- equivalents ha^{-1} as reported by Skinner et al. (2014) for arable land under organic farming.

4.3. Biochar amendment to digestate did not change N_2O emissions

Biochar had no significant effect on N_2O emissions in our study, likely due to the low application rate and limited interaction with the soil. A recent meta-analysis showed that reduction of N_2O emissions by biochar by 38% occurred at $>$ 10 t ha^{-1} biochar (Borchard et al., 2018). The field site in the present study receives 2 t ha^{-1} year^{-1} biochar and will therefore reach these inputs levels only 5 years after the beginning of the experiments. The results from Borchard et al. (2018) were furthermore obtained from a database consisting mainly of laboratory experiments, while our experiment was a field study. An absence of biochar effects on soil processes and properties in field experiments is not uncommon due to high (structural) heterogeneity in fields (Kammann et al., 2017) and associated large data variability (Hüppi et al., 2015; Verhoeven et al., 2017). We did not incorporate the biochar directly into the soil, but rather it was milled, added to SLA and spread onto the soil surface together with the fertilizer after a two week incubation period. Hence, the potential for biochar to interact with the soil, for example to increase the pore volume or the pH, was limited in our study. The biochar's molar H:C_{org} ratio of 0.29–0.44 also suggests limited effectiveness for mitigating N_2O emissions as biochars with an H:C_{org} ratio $<$ 0.3 mitigate N_2O emissions more effectively (Cayuela et al., 2015).

4.4. Net uptake of soil-borne CH_4 contrasts CH_4-release after fertilizer application

Cumulative area-scaled CH_4 uptake (Fig. 3) did not include the additional measurements (Fig. 4) which were conducted right after fertilizer applications in barley and forage grass. This decision was based on the lack of sufficient data to fully characterize the shape and origin of the additional CH_4 peaks. Without these additional fertilizer peaks, CH_4 fluxes were mostly negative and similar for all fertilizer treatments (Fig. 1). Although some studies have observed elevated CH_4 emissions from raw manure compared to digestates (Wulf et al., 2002; Clemens et al., 2006), no effects have been observed in other studies (Eickenscheidt et al., 2014). Across all fertilizer treatments, cumulative CH_4 uptake decreased over time, i.e. from crop to crop. This could be due to decreasing availability of organic C residues from previous ley termination for methanogenes.

The two additional measurements (Fig. 4) on the days of fertilizer applications in barley and forage grass revealed increased CH_4 fluxes from SLA+ and more moderately elevated CH_4 emissions from SLA and LID. Our study was not designed to capture non soil-borne CH_4 emissions. Possibly, dissolved CH_4 in SLA+ that remained bound to the surface of the biochar during storage was released upon fertilizer application. Alternatively, methanogens in the agricultural slurry might have been stimulated by biochar addition and incubation for about two weeks in the SLA+ treatment and dissolved CH_4 might then have been released upon fertilizer application. Methanogenesis during AD is inhibited by NH_4^+-N contents above 4000 mg L^{-1} (Czatzkowska et al., 2020; Zhang et al., 2019). Fertilizer NH_4^+ was presumably trapped within or adsorbed by the porous biochar structure allowing resumption of microbial CH_4 production. More research is needed to clarify the effect of biochar addition to liquid fertilizers on CH_4 emissions.

5. Conclusions

Based on a long-term field experiment and a multi-crop N_2O measurement campaign, our study shows that N_2O emissions were controlled by soil management history and abiotic factors rather than the type of N- fertilizer applied. Digestates did not increase N_2O emissions compared to cattle slurry. N_2O emissions from organic and mineral fertilizers were mostly similar. N_2O-EFs were generally low, because of large background emissions from the unfertilized plots. With respect to N_2O mitigation, we recommend reducing fertilizer N input to crops grown directly after ley termination as NO_3^- released by mineralization of soil organic N caused considerable N_2O emissions in all treatments. Biochar did not decrease N_2O emissions because of low application amounts. Biochar-amended agricultural digestate released CH_4 right after spreading. Therefore, measurements of CH_4 emissions during

digestate storage and spreading should be included in future field studies, especially when biochar is involved.

Author contributions

EB, NE, HMK, MK, JM and JM planned the experimental work and developed the methodological approach; NE, NV and FZ carried out the measurements; JS, HMK and EB guided and supervised the work; RH and MK provided advice on gas flux calculation and data analysis; NE analyzed the data and wrote the first draft; all authors commented on drafts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper..

Data Availability

The data will be made publicly available under the following link from Zenodo: 10.5281/zenodo.7633755.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108642.

References

Alburquerque, J.A., de la Fuente, C., Bernal, M.P., 2012. Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils. Agric. Ecosyst. Environ. 160, 15–22.

Ammann, C., Neftel, A., Jocher, M., Fuhrer, J., Leifeld, J., 2020. Effect of management and weather variations on the greenhouse gas budget of two grasslands during a 10-year experiment. Agric. Ecosyst. Environ. 292, 106814.

Baral, K.R., Labouriau, R., Olesen, J.E., Petersen, S.O., 2017. Nitrous oxide emissions and nitrogen use efficiency of manure and digestates applied to spring barley. Agric. Ecosyst. Environ. 239, 188–198.

Borchard, N., Michael, S., Cayuela, M.L., Kammann, C., Wrage-Mönnig, N., Estavillo, J., Fuertes-Mendizabal, T., Sigua, G., Spokas, K., Ippolito, J., Novak, J., 2018. Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: a meta-analysis. Sci. Total Environ. 651, 2354–2364.

Brändli, R.C., Bucheli, T.D., Kupper, T., Furrer, R., Stadelmann, F.X., Tarradellas, J., 2005. Persistent organic pollutants in source-separated compost and its feedstock materials–a review of field studies. J. Environ. Qual. 34 (3), 735–760.

Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern, S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philos. Trans. R. Soc. B 368 (1621), 20130122.

Cayuela, M.L., van Zwieten, L., Singh, B.P., Jeffery, S., Roig, A., Sanchez- Monedero, M. A., 2014. Biochar’s role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agric. Ecosyst. Environ. 191, 5–16.

Cayuela, M.L., Jeffery, S., van Zwieten, L., 2015. The molar H:Corg ratio of biochar is a key factor in mitigating N_2O emissions from soil. Agric. Ecosyst. Environ. 202, 135–138.

Clemens, J., Trimborn, M., Weiland, P., Amon, B., 2006. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. Agric. Ecosyst. Environ. 112 (2–3), 171–177.

Clough, T.J., Rochette, P., Thomas, S.M., Pihlatie, M., Christiansen, J.R., Thorman, R.E., 2020. Global research alliance N_2O chamber method- ology guidelines: design considerations. J. Environ. Qual. 49 (5), 1081–1091.

Culman, S.W., Snapp, S.S., Freeman, M.A., Schipanski, M.E., Beniston, J., Lal, R., Drinkwater, L.E., Franzluebbers, A.J., Glover, J.D., Grandy, A.S., Lee, J., Six, J., Maul, J.E., Mirsky, S.B., Spargo, J.T., Wander, M.M., 2012. Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. Soil Sci. Soc. Am. J. 76 (2), 494–504.

Czatzkowska, M., Harnisz, M., Korzeniewska, E., Koniuszewska, I., 2020. Inhibitors of the methane fermentation process with particular emphasis on the microbiological aspect: a review. Energy Sci. Eng. 8 (5), 1880–1897.

Dahlin, J., Herbes, C., Nelles, M., 2015. Biogas digestate marketing: qualitative insights into the supply side. Resour. Conserv. Recycl. 104, 152–161.

Dietrich, M., Fongen, M., Foereid, B., 2020. Greenhouse gas emissions from digestate in soil. Int. J. Recycl. Org. Waste Agric. 9 (1), 1–19.

Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (2006). Guidelines for National Greenhouse Gas Inventories. Technical report, Inter- governmental Panel on Climate Change (IPCC).

Eickenscheidt, T., Freibauer, A., Heinichen, J., Augustin, J., Drösler, M., 2014. Short-term effects of biogas digestate and cattle slurry application on greenhouse gas emissions affected by N availability from grasslands on drained fen peatlands and associated organic soils. Biogeosciences 11 (22), 6187–6207.

Frick, H., Oberson, A., Cormann, M., Wettstein, H.-R., Frossard, E., and Bünemann, E.K. (2022). Similar distribution of 15N labeled cattle slurry and mineral fertilizer in soil after one year. Nutrient Cycling in Agroecosystems.

Fuß, R. (2016). R package gasfluxes.

van Groenigen, J.W., Kasper, G.J., Velthof, G.L., van den Pol-van Dasselaar, A., Kuikman, P.J., 2004. Nitrous oxide emissions from silage maize fields under different mineral nitrogen fertilizer and slurry applications. Plant Soil 263 (1), 101–111.

Gutser, R., Ebertseder, T., Weber, A., Schraml, M., Schmidhalter, U., 2005. Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. J. Plant Nutr. Soil Sci. 168, 439–446.

Hagemann, N., Joseph, S., Schmidt, H.-P., Kammann, C.I., Harter, J., Borch, T., Young, R. B., Varga, K., Taherymoosavi, S., Elliott, K.W., McKenna, A., Albu, M., Mayrhofer, C., Obst, M., Conte, P., Dieguez-Alonso, A., Orsetti, S., Subdiaga, E., Behrens, S., Kappler, A., 2017. Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. Nat. Commun. 8 (1), 1089.

Hansen, S., Berland Frøseth, R., Stenberg, M., Stalenga, J., Olesen, J.E., Krauss, M., Radzikowski, P., Doltra, J., Nadeem, S., Torp, T., Pappa, V., Watson, C.A., 2019. Reviews and syntheses: review of causes and sources of N_2O emissions and NO_3 leaching from organic arable crop rotations. Biogeosciences 16 (14), 2795–2819.

Harter, J., Guzman-Bustamante, I., Kuehfuss, S., Ruser, R., Well, R., Spott, O., Kappler, A., Behrens, S., 2016. Gas entrapment and microbial N_2O reduction reduce N_2O emissions from a biochar-amended sandy clay loam soil. Sci. Rep. 6 (1), 39574.

Hüppi, R., Felber, R., Krauss, M., Six, J., Leifeld, J., Fuss, R., 2018. Restricting the nonlinearity parameter in soil greenhouse gas flux calculation for more reliable flux estimates. PLoS One 13 (7), e0200876.

Hüppi, R., Horváth, L., Dezső, J., Puhl-Rezsek, M., Six, J., 2022. Soil nitrous oxide emission and methane exchange from diversified cropping systems in Pannonian region. Front. Environ. Sci. 10, 277.

Hütsch, B.W., 2001. Methane oxidation in non-flooded soils as affected by crop production — invited paper. Eur. J. Agron. 14 (4), 237–260.

IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen,. Technical report, Intergov- ernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA.

Jeffery, S., Abalos, D., Prodana, M., Bastos, A.C., van Groenigen, J.W., Hungate, B.A., Verheijen, F., 2017. Biochar boosts tropical but not temperate crop yields. Environ. Res. Lett. 12 (5), 53001.

Joseph, S.D., Camps-Arbestain, M., Lin, Y., Munroe, P., Chia, C.H., Hook, J., van Zwieten, L., Kimber, S., Cowie, A., Singh, B.P., Lehmann, J., Foidl, N., Smernik, R.J., Amonette, J.E., 2010. An investigation into the reactions of biochar in soil. Soil Res. 48 (7), 501–515.

Kammann, C., Ippolito, J., Hagemann, N., Borchard, N., Cayuela, M.L., Estavillo, J., Fuertes-Mendizabal, T., Jeffery, S., Kern, J., Novak, J., Rasse, D., Saarnio, S., Schmidt, H.-P., Spokas, K., Wrage-Mönnig, N., 2017. Biochar as a tool to reduce the agricultural greenhouse-gas burden – knowns, unknowns and future research needs. J. Environ. Eng. Landsc. Manag. 25 (2), 114–139.

Keeney, D.R., Nelson, D.W., 1982. Nitrogen—inorganic forms 1. Methods of soil analysis: Part 2. Agron. Monogr. 643–698.

Köster, J.R., Cárdenas, L.M., Bol, R., Lewicka-Szczebak, D., Senbayram, M., Well, R., Giesemann, A., Dittert, K., 2015. Anaerobic digestates lower N_2O emissions compared to cattle slurry by affecting rate and product stoichiometry of denitrification – An N_2O isotopomer case study. Soil Biol. Biochem. 84, 65–74.

Krauss, M., Ruser, R., Müller, T., Hansen, S., Mäder, P., Gattinger, A., 2017. Impact of reduced tillage on greenhouse gas emissions and soil carbon stocks in an organic grass-clover ley - winter wheat cropping sequence. Agric. Ecosyst. Environ. 239, 324–333.

Krom, M.D., 1980. Spectrophotometric determination of ammonia: a study of a modified Berthelot reaction using salicylate and dichloroisocyanurate. Analyst 105, 305–316.

Lazcano, C., Zhu-Barker, X., Decock, C., 2021. Effects of organic fertilizers on the soil microorganisms responsible for N2O emissions: a review. *Microorganisms* 9 (5), 983.

Möller, K., Stinner, W., 2009. Effects of different manuring systems with and without biogas digestion on soil mineral nitrogen content and on gaseous nitrogen losses (ammonia, nitrous oxides). Eur. J. Agron. 30 (1), 1–16.

Nicholson, F., Bhogal, A., Cardenas, L., Chadwick, D., Misselbrook, T., Rollett, A., Taylor, M., Thorman, R., Williams, J., 2017. Nitrogen losses to the environment following food-based digestate and compost applications to agricultural land. Environ. Pollut. 228, 504–516.

Nkoa, R., 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. Agron. Sustain. Dev. 34 (2), 473–492.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., Erasmi, S., 2016. Greenhouse gas emissions from soils—A review. Chem. der Erde 76, 327–352.
Petrova, I.P., Pekrun, C., Mo ̈ller, K., 2021. Organic matter composition of digestates has a stronger influence on N_2O emissions than the supply of ammoniacal nitrogen. Agronomy 11 (11), 2215.
Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., and R, R.C.T. (2022). nlme: Linear and Nonlinear Mixed Effects Models.
R Development Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
Reay, D.S., Davidson, E.A., Smith, K.A., Smith, P., Melillo, J.M., Dentener, F., Crutzen, P. J., 2012. Global agriculture and nitrous oxide emissions. Nat. Clim. Change 2 (6), 410–416.
Sänger, A., Geisseler, D., Ludwig, B., 2010. Effects of rainfall pattern on carbon and nitrogen dynamics in soil amended with biogas slurry and composted cattle manure. J. Plant Nutr. Soil Sci. 173 (5), 692–698.
Schmidt, H.-P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T.D., Sa ́nchez Monedero, M.A., Cayuela, M.L., 2021. Biochar in agriculture – a systematic review of 26 global meta-analyses. GCB Bioenergy 13 (11), 1708–1730.
Senbayram, M., Chen, R., Mühling, K.H., Dittert, K., 2009. Contribution of nitrification and denitrification to nitrous oxide emissions from soils after application of biogas waste and other fertilizers. Rapid Commun. Mass Spectrom. 23 (16), 2489–2498.
Six, J., Ogle, S.M., Breidt, F., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob. Change Biol. 10 (2), 155–160.
Skinner, C., Gattinger, A., Muller, A., Mäder, P., Fliessbach, A., Stolze, M., Ruser, R., Niggli, U., 2014. Greenhouse gas fluxes from agricultural soils under organic and non-organic management–a global meta-analysis. Sci. Total Environ. 468–469, 553–563.
Stuchiner, E.R., von Fischer, J.C., 2022. Using isotope pool dilution to understand how organic carbon additions affect N_2O consumption in diverse soils. Glob. Change Biol. 28 (13), 4163–4179.
Tian, H., Xu, R., Canadell, J.G., Thompson, R.L., Winiwarter, W., Suntharalingam, P., Davidson, E.A., Ciais, P., Jackson, R.B., Janssens-Maenhout, G., Prather, M.J., Regnier, P., Pan, N., Pan, S., Peters, G.P., Shi, H., Tubiello, F.N., Zaehle, S., Zhou, F., Arneth, A., Battaglia, G., Berthet, S., Bopp, L., Bouwman, A.F., Buitenhuis, E.T., Chang, J., Chipperfield, M.P., Dangal, S.R.S., Dlugokencky, E., Elkins, J.W., Eyre, B. D., Fu, B., Hall, B., Ito, A., Joos, F., Krummel, P.B., Landolfi, A., Laruelle, G.G., Lauerwald, R., Li, W., Lienert, S., Maavara, T., MacLeod, M., Millet, D.B., Olin, S., Patra, P.K., Prinn, R.G., Raymond, P.A., Ruiz, D.J., van der Werf, G.R., Vuichard, N., Wang, J., Weiss, R.F., Wells, K.C., Wilson, C., Yang, J., Yao, Y., 2020. A comprehensive quantification of global nitrous oxide sources and sinks. Nature 586 (7828), 248–256.
Van Groenigen, J.W., Velthof, G.L., Oenema, O., Van Groenigen, K.J., Van Kessel, C., 2010. Towards an agronomic assessment of N_2O emissions: a case study for arable crops. Eur. J. Soil Sci. 61 (6), 903–913.
Venterea, R., Maharjan, B., Dolan, M., 2011. Fertilizer source and tillage effects on yield-scaled nitrous oxide emissions in a corn cropping system. J. Environ. Qual. 40, 1521–1531.
Verhoeven, E., Pereira, E., Decock, C., Suddick, E., Angst, T., Six, J., 2017. Toward a Better Assessment of Biochar-Nitrous Oxide Mitigation Potential at the Field Scale. J. Environ. Qual. 46 (2), 237–246.
Walling, E., Vaneeckhaute, C., 2017. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. J. Environ. Manag. 276 (3), 111211.
Weil, R., Stine, M., Gruver, J., Samson-Liebig, S., 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. Am. J. Altern. Agric. 18, 3–17.
Wulf, S., Maeting, M., Clemens, J., 2002. Application technique and slurry co-fermentation effects on ammonia, nitrous oxide, and methane emissions after spreading: II Greenhouse gas emissions. J. Environ. Qual. 31 (6), 1795–1801.
Zhang, M., Li, J., Wang, Y., Yang, C., 2019. Impacts of different biochar types on the anaerobic digestion of sewage sludge. RSC Adv. 9, 42375–42386.

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Atmospheric transport of particulate matter and particulate-bound agrochemicals from beef cattle feedlots: Human health implications for downwind agricultural communities

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HIGHLIGHTS

- Beef cattle feedlots are a major source of fugitive PM emissions.
- Particulate-bound agrochemicals transported >12 km downwind of large feedlots.
- Distance-decay indicates elevated levels of inhalable PM >12 km during diurnal peak.
- Agricultural post-application exposure to pyrethroids elevates child health risk
- Disproportionate impact in low-income, Hispanic and Latino communities

GRAPHICAL ABSTRACT

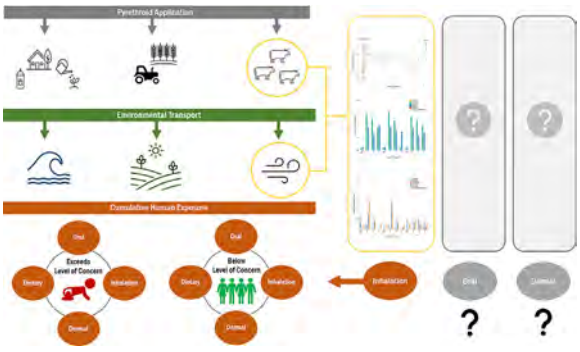

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ABSTRACT

Beef cattle feedlot particulate matter (PM) is a complex mixture of dust, animal waste, agrochemicals, and bioaerosols. However, no empirical data exist quantifying downwind residential exposure to PM or PM-bound agrochemicals. In the current study, authors investigated transport of PM and co-occurring insecticides and anthelmintics downwind of three feedlots in the Southern Great Plains (SGP) of North America from May–August 2022. PM collected on total suspended particulate (TSP) filters was analyzed via UHPLC-MS/MS for six pyrethroids and five macrocyclic lactones (MLs). Downwind TSP concentrations rapidly declined from 0.01 to ≤1.6 km (Monte Carlo mean ± SEM; 5049 ± 96.1 μg/m^3) and stabilized >1.6–12.4 km (1791 ± 9.9; μg/m^3). Distance decay >1.6 km indicated downwind PM exceeded levels of safe human exposure during diurnal peak periods. Pyrethroids and MLs were detected >LOQ in 96.2 and 98.1 % of downwind samples. Screening-level cumulative residential exposure indicates elevated pyrethroid risk (LOC = 1; RI = 0.173) to rural children (1–2 yrs) living near cropland operations in the SGP, with disproportionate co-exposure to feedlot PM and legacy pollution in low-income, Hispanic and Latino communities. Frequent occurrence and sustained transport of pyrethroids downwind of feedlots facilitate residue accumulation in outdoor residential areas that must also be quantified to assess the magnitude of daily average and lifetime-adjusted oral and dermal exposure in surrounding communities. Results significantly expand the known distribution of feedlot-derived PM and agrochemicals and highlight human exposure pathways unrecognized in residential human health assessments supporting pesticide registration and feedlot risk evaluation.

1. Introduction

Confined beef cattle feeding operations, hereafter "feedlots," have become standard practice in developed countries for rapidly increasing muscle

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mass and fat cover in beef cattle prior to slaughter (Smith, 2021). Feedlot cattle density can range from hundreds to over a hundred thousand head contained in open-air, earthen floor pens. In addition to loose soil, pen floor material contains a complex mixture of chemical and biological contaminants, including veterinary pharmaceuticals metabolized and excreted via feces and urine (Aust et al., 2008; Blackwell et al., 2014; Blackwell et al., 2015a; Blackwell et al., 2015b; Zhao et al., 2010), viral and bacterial pathogens (Alexander et al., 2011; Gaudino et al., 2022; Mosier, 2015; Qian et al., 2018), and pesticides (Modernel et al., 2013; Sadler et al., 2005; Yates et al., 2011). While it is well-documented that these facilities are detrimental to watersheds through off-site runoff of manure (Bicudo and Goyal, 2003; Sahoo et al., 2016), mounting evidence in the last two decades also implicates aerial dispersion of PM as a major transport pathway of agrochemicals beyond feedlot boundaries (Emert et al., 2023; McEachran et al., 2015; Peterson et al., 2017, 2020, 2021, 2022; Sandoz et al., 2018; Wooten et al., 2018). This is particularly problematic in arid and semi-arid regions, where dry pen floor material is aerosolized by cattle movement-driven mechanical disturbance (de Oro et al., 2021), which is then wind-transported downwind. Presently, U.S. EPA does not include particulate-bound emissions as an agrochemical transport pathway in environmental risk evaluation of feedlot facilities (U.S. EPA, 2004) or human health assessments supporting pesticide registration (U.S. EPA, 2012).

Downwind trajectories of suspended particulates are dependent upon atmospheric conditions and individual particle geometry (i.e., size and shape). More broadly, however, coarse PM size fractions (PM_{10}; ≤10–>2.5 μm) and larger debris settle out of suspension rapidly, exhibiting saltatory movement over smaller distances, but fine PM fractions ($PM_{2.5;}$ ≤2.5–>0.1 μm) are capable of atmospheric transport exceeding hundreds of kilometers (Chen et al., 2014; Jiménez-Vélez et al., 2009; Kallos et al., 2007; Perry et al., 1997). Particulate size fractions are also relevant to human exposure. PM_{10} is capable of deposition in the human respiratory tract, and $PM_{2.5}$ is capable of transport across the alveolar-capillary barrier deep in the lungs (Arias-Pérez et al., 2020). Chronic exposure to inhalable PM is linked to numerous adverse health outcomes including respiratory and cardiovascular diseases, cancers (Group I carcinogen; IARC, 2016), inflammation, adverse birth outcomes and overall lower life expectancies (Mukherjee and Agrawal, 2017). Rural communities in the US are particularly susceptible to adverse health outcomes, suffering from disparate mortality since 1986 (rural mortality penalty; James, 2014) due to socioeconomic and healthcare factors. Moreover, susceptibility to PM-associated disease is greater in children and older adults (Sacks et al., 2011). A 2014 meta-analysis of North American and European populations observed 8 and 9 % increased incidences of lung cancer per 10 $\mu g/m^3$ increase of outdoor PM_{10} and $PM_{2.5}$ exposure, respectively (Hamra et al., 2014). As such, inhalable PM in ambient air is hazardous to human respiratory health irrespective of its potential as an agrochemical transport vehicle.

Pyrethroid insecticides are the most frequently detected pesticide class in feedlot PM (Peterson et al., 2020) and have largely superseded older chemical classes (carbamates, organophosphates) used for control of external livestock and foliar cropland pests. Pyrethroids are neurotoxic, interacting with voltage-gated sodium ion channels to cause hyperpolarization of neuronal membranes, paralysis, and eventual death in target and non-target invertebrates (Bradberry et al., 2005; Soderlund, 2012; Todd, 2003). Pyrethroid exposure has recently been associated with a higher risk of all-cause and cardiovascular-specific human mortality (Bao et al., 2020), and agricultural workers and their children exposed to pyrethroids have a higher risk of impaired neurofunction (cognitive, motor, and behavioral; Lucero and Muñoz-Quezada, 2021). In humans living or working near pyrethroid pesticide applications in the previous five years, epigenome-wide association has identified differential methylation at CpG sites associated with Alzheimer's disease, diabetes, birth defects, and several cancers (n = 237; Furlong et al., 2020). Chronic exposure has been linked to primary ovarian insufficiency in Chinese women (Li et al., 2018) and male rat reproductive disfunction (oral; low total mixture dose = 0.0006 mg/kg/day, high total mixture dose = 0.0031 mg/kg/day; Ravula and Yenugu, 2021), including changes in fecundity and testicular genotoxicity (total mixture dose (oral) = 0.016 mg/kg/day; Priyanka et al., 2022). Prenatal exposure to pyrethroid mixtures is associated with adverse effects on human neurodevelopment (thyroid hormone function; Andersen et al., 2022), and irreversible adverse effects on follicular development and ovarian function in female rat offspring (total mixture dose (rat, oral) = 0.2 mg/kg/day; Song et al., 2022).

In addition to pyrethroids, macrocyclic lactones (MLs) including avermectins and milbemycins are the most frequently used veterinary anthelmintics, guarding livestock against both ecto- and endoparasites. Similarly, MLs are neurotoxic, interacting with GABA- and glutamate-gated chloride channels (Lumaret et al., 2012). Mammalian and avian nephrotoxicity, hepatotoxicity, and neurotoxicity are typically expressed in unit magnitudes exceeding mg/kg quantities for oral/dietary exposure (Salman et al., 2022), where 0.006–0.012 mg/kg oral ivermectin and 0.25 mg/kg oral moxidectin represent therapeutic doses for heartworm prevention in dogs (El-Saber Batiha et al., 2020). While human toxicity is typically low, avermectin $B1_{a,b}$ and derivatives are contraindicated for pregnant women due to potential developmental toxicity (avermectin B1; NOAEL = 0.075 mg/kg/day; MADL = 4.4 μg/day; OEHHA, 2011). Repeated sublethal exposure in medically important soil-transmitted helminths may also confer generational ML resistance (Moser et al., 2019; Prichard and Geary, 2019; Tinkler, 2020), an emerging public health concern in veterinary and human medicine (Freeman et al., 2019).

Hence, there were three objectives of the current study: 1) to determine the spatial extent and magnitude of PM transport downwind of large beef cattle feedlot facilities, 2) to quantify occurrence of pyrethroid insecticides and veterinary anthelmintics in feedlot-derived PM, and 3) to assess cumulative human health risk of agrochemicals in agriculture-adjacent communities downwind of feedlots. We first hypothesized that empirical distance decay of total suspended particulates (TSP) measured at three downwind locations could be used to characterize downwind PM transport. Secondly, we hypothesized that particulate-bound agrochemical transport extends beyond the spatial extent reported in previous literature (≤1 km), with potential additive impacts to downwind communities. Through the present objectives, we aim to better inform human and ecological risk assessments of feedlot facilities and feedlot-derived PM.

2. Materials and methods

2.1. Site description

The Southern Great Plains (SGP) region of North America encompasses portions of Colorado, Kansas, New Mexico, Oklahoma, and Texas (Fig. 1). The SGP contains the highest concentration of beef cattle in the U.S. (9.1 million head), centralized in the High Plains region of the Texas Panhandle (Fig. 1; 4.5 million hd; 15.6 % of US total beef cattle inventory; USDA NASS, 2023), where there are presently 135 active operations (U.S. EPA, 2023c). Nearly half (47.0 %) of the 1.3 million people living in the Texas High Plains reside in census tracts ≤12 km from large feedlot operations (≥1000 hd; mean animal unit capacity = 36,700 hd; (TCEQ, 2023; U.S. Census Bureau, 2020). Largely an agroecosystem, the regional burden of agrochemicals used for crop production already poses a risk to terrestrial and aquatic biodiversity (Brausch and Smith, 2009; Emert et al., 2023; Hanberry et al., 2021). Crops grown in the Texas panhandle primarily include cotton (4.9 million ac) and winter wheat (3 million ac), accounting for 70.9 % of all cultivated acreage in 2021 (Cropscape Data Layer; USDA NASS, 2022). In addition to mechanical disturbance of manure and exposed topsoil in feedlot pens, windborne soil erosion is considerable. The SGP is split along a continental dry line, where warm-dry air from the desert southwest meets warm-moist air from the Gulf of Mexico. Meteorological conditions along the dry line are a primary driver of high winds and tornadic weather systems frequently observed in Texas, Oklahoma, and Kansas in the spring

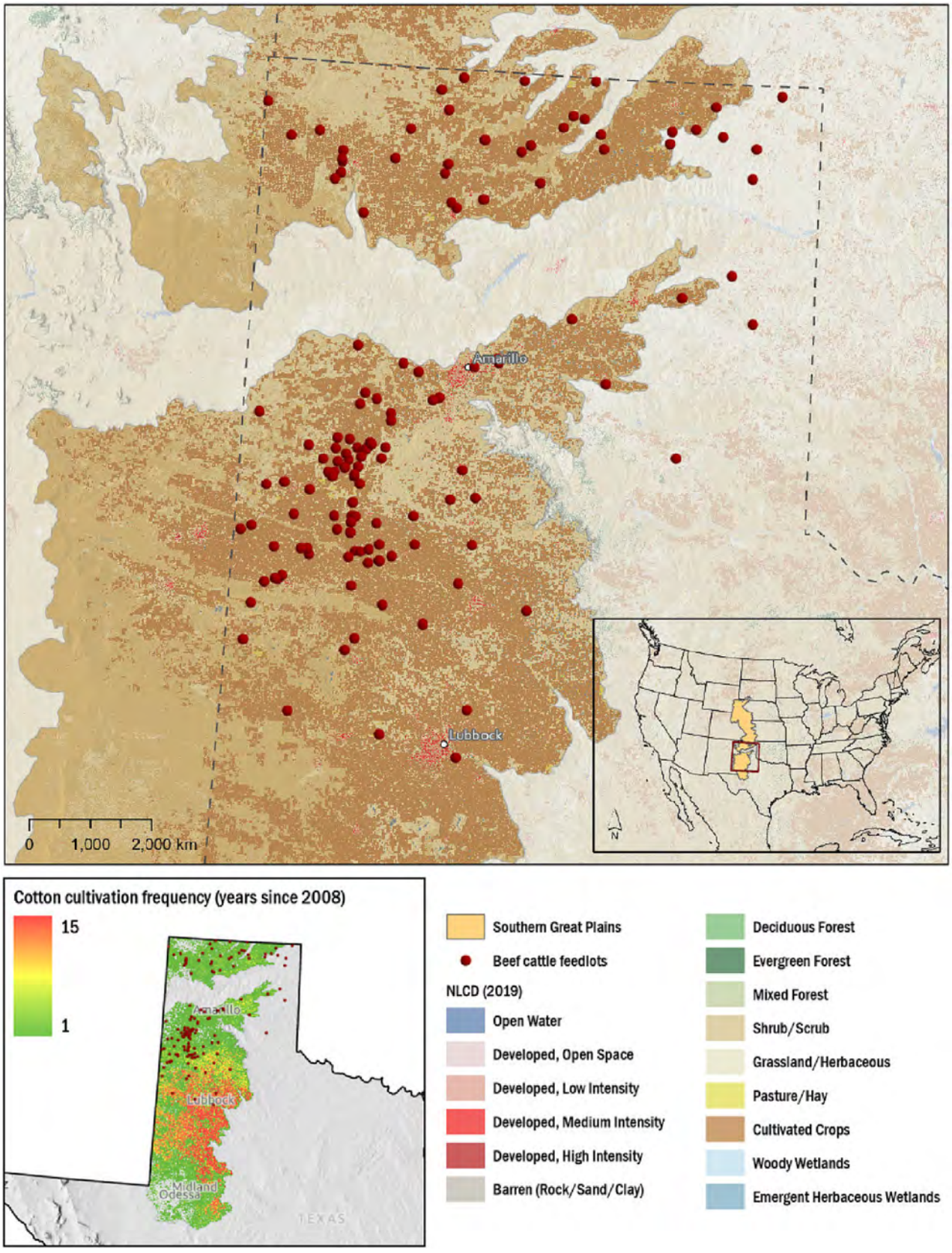

Fig. 1. Land cover map of sampling area in the Southern Great Plains (SGP) of North America highlighting active beef cattle feedlot facilities and cotton cultivation frequency in the Texas High Plains region; SGP land cover data layer derived from the National Land Cover Database (MRLC, 2023); active feedlots derived from U.S. EPA ECHO database (U.S. EPA, 2023c); cotton frequency layer derived from USDA NASS Cropscape Program (USDA NASS, 2022).

and early-summer season (Hoch and Markowski, 2005). As regional climate changes, prolonged periods of drought are projected to increase (Modala et al., 2017; Shafer et al., 2014), with subsequent increases in natural and anthropogenic PM emissions.

2.2. TSP collection

Total suspended particulates were collected upwind and downwind of three Texas feedlots (F1-F3; animal unit capacity = 75,000-82,500; Supplemental material SI1) over six events per feedlot (n = 18) from May–August 2022. To target peak PM emissions (Bonifacio et al., 2015; Guo et al., 2011), sample collection occurred in the evening 1.5 h before and after dusk on dates where no precipitation occurred at least 72 h prior to collection. One upwind and three downwind locations (D1-D3; >1–12.4 km) were selected based on public road access, wind speed and direction. Feedlots were located >20 km from the nearest neighboring facility to minimize upwind PM influence to the extent practicable. Glass fiber filters (10 cm; CF-902; HI-Q Environmental Products, San Diego, CA) were pre-weighed and sealed in air-tight containers and bagged prior to sampling. Four Hi-Q CF-902 digital portable high-volume air samplers (HI-Q Environmental Products, San Diego, CA) were used for TSP collection; two samplers were co-located at each sampling point for 30 min intervals, with samplers alternated for decontamination (70 % ethyl alcohol) between locations. Geographic coordinates were recorded at each sampled location. At the start of each 30 min interval, weather variables including air temperature and pressure, relative humidity, wind speed and direction were recorded from the nearest West Texas Mesonet station (WTM, 2022). At the end of each sampled interval, filters were placed in containers and bagged on ice until transport to the Texas Tech University Institute of Environmental and Human Health (TIEHH) where they were stored at −20 °C until extraction.

2.3. TSP distance decay model validation

A simplified physical model of distance decay was validated and incorporated for the purpose of estimating probabilistic downwind PM concentrations. Modeled TSP distance decay functions were compared using six candidate model distributions (four parameter logistic decay, two and three parameter exponential decay, four and five parameter biexponential decay, and Weibull decay), where the model of best fit was used for training and validation. Training and validation sets consisted of two of three feedlots (F1, F3), stratified by feedlot and downwind sample ID (D1-D3; 50 % training: 50 % validation). After model validation, predicted bagged mean TSP concentrations (n = 1000) for all feedlots were calculated, and final model prediction was assessed with the previously unincorporated third feedlot (F2) actual vs. predicted TSP concentrations. Monte Carlo simulations (n = 10,000) were then performed using the validated distance decay function with random noise ≤1 standard deviation from the mean.

2.4. Materials

Neat analytical standards (purity; 95–99.5 %) were acquired from Sigma-Aldrich (Burlington, MA; abamectin (ABA), cypermethrin (CYP), doramectin (DORA), eprinomectin (EPRIN), ivermectin (IVM), moxidectin (MOX), permethrin (PERM), tris (1-chloro-2-propyl) phosphate (TCPP)) and Chem Service (West Chester, PA; bifenthrin (BIF), λ-cyhalothrin (λ-CYH), esfenvalerate (ESFEN; *S,S*-fenvalerate), fenvalerate (FENV)). Magnesium sulfate and sodium chloride salts, high-performance liquid chromatography (HPLC) grade solvents (acetonitrile, acetone, methylene chloride, methanol, and water) and polytetrafluoroethylene (PTFE) syringe filters (0.45 μm, 30 mm; 0.22 μm, 13 mm) were purchased from Thermo Fisher Scientific (Waltham, MA).

2.5. Filter extraction and analysis

Sample extraction methodology was performed as described in Peterson et al. (2021). Briefly, TSP filters were weighed individually, and two filters per sampled location were placed in a 50-mL centrifuge tube to ensure sufficient sample mass for analysis. Filters were spiked with internal standard (TCPP), and 45 mL methylene chloride:acetone (1:1) was added, followed by heated sonication (40 °C) for 1 h. Supernatant was then syringe filtered (PTFE; 0.45 μm) into a secondary glass vial, and 40 mL acetonitrile:water (1:1) was added to the centrifuge tube. Tubes were capped and placed on an orbital shaker platform (Model MaxQ 4000, Thermo Scientific, Waltham, MA) for 18 h at 350 rpm. Next, tubes were centrifuged (10 min; 3100 rpm) and supernatant was decanted into a second 50-mL centrifuge tube. Magnesium sulfate (4 *g*) and sodium chloride (1 g) salts were added, and tubes were vortexed for 1 min followed by centrifugation for 10 min at 3100 rpm. The final supernatant was then combined with the initial supernatant in the glass vial, evaporated under a stream of nitrogen at 35 °C, and reconstituted in 1 mL acetonitrile. Extract was vortexed for 10 s and syringe filtered (PTFE; 0.22 μm) into amber chromatography vials for subsequent analysis via triple quadrupole liquid chromatography tandem mass spectrometry with electrospray ionization (Thermo TSQ Quantum Access Max, Thermo Scientific, Waltham, MA), as described in Peterson et al. (2020).

2.6. Quality assurance/quality control

Trip blanks and field blanks were collected once per day; trip blank filters remained sealed in coolers for the duration of each event, and field blanks were exposed to ambient air for 30 s. Matrix spikes and method blanks (approximate ratio; 10:1) were co-extracted, and additional clean filters were extracted for matrix-matched calibration standards. All analyte calibration curves were above minimum acceptable limits of linearity (R^2 > 0.995; RSD ≤20 %), and a signal-to-noise (S/N) ratio of 3:1 was used for quantitation of sample peaks. Limit of detection (LOD) and limit of quantitation (LOQ) were defined as 3.3σ/S and 10σ/S, respectively (σ = standard deviation of detector response; S = slope of calibration curve; ICH, 2021). No analytes were detected >LOQ in any trip blanks or field blanks. All samples were analyzed <5 months of collection.

2.7. Statistical analysis

Prior to multivariate analysis and probabilistic assessment, downwind TSP and agrochemical concentrations were normalized by upwind concentrations (denoted, hereafter, as ΔU), and transformed. If approximate normality of quantile residuals could not be achieved after transformation, non-parametric Friedman's with Bonferroni correction for multiple comparisons was performed with categorical distance classes (upwind, D1-D3). Analytes were excluded if detections >LOQ were <30 %. Where analytical detections were >30 %, non-detects were imputed as ½ LOD. Multicollinearity was assessed with robust

maximum likelihood (RML) estimation, and multivariate outliers were excluded if they exceeded the upper control limit (UCL) of Mahalanobis' distance or were identified as residual quantile outliers (Supplemental material S2). All predictor and response variables were then centered and scaled. Two levels of multicollinearity were addressed with partial least squares analysis (PLS), such that potential associations between diurnal weather gradients and intraseasonal weather gradients could be determined independently. K-fold cross-validation (k = 7) was employed to determine optimal number of model factors in each case. Retained factor scores from PLS were then incorporated with explanatory variables in canonical correlation analysis (CCA) for repeated measures. Empirical model selection of TSP distance decay was based on five selection parameters (corrected Akaike's Information Criterion (AICc), sum of square error (SSE), root mean square error (RMSE), and correlation coefficient (R^2). The best fit model function was used to perform Monte Carlo simulations (n = 10,000), and simulated values were backtransformed for interpretation. Daily weather (stations; n = 3) and wind rose observations (stations; n = 4) from May 1–August 31, 2022 were obtained from Weather Underground and NOAA Automated Surface Observing Systems (ASOS), respectively, where weather summaries, wind speed and directional probabilities from each station were collated. Parametric statistical analysis, model validation, and uncertainty analyses were performed in JMP Pro v16.0.0 (SAS Institute Inc.; Cary, NC). Non-parametric Friedman's tests were performed in IBM SPSS Statistical Software for Windows (Version 28.0. Armonk, NY; IBM Corp.)

2.8. Cumulative human health assessment

Cumulative short-term (non-carcinogenic) adult (≥16 yrs) and child (1–2 yrs) health assessments and aggregate adult lifetime (carcinogenic) health assessments of relevant agrochemicals were performed, where applicable, incorporating the most recent U.S. EPA screening-level cumulative (U.S. EPA, 2012) aggregate human health assessments (U.S. EPA, 2016, 2017b, 2019a, 2020a,b,c), and SOPs (U.S. EPA, 2005, 2012) as primary sources of methodology and exposure estimates. Feedlot-derived exposure scenarios were limited to parameters of the current study design, assuming 99.9th percentile of seasonal inhalation exposure from a single area source. Cumulative exposure considered all relevant dietary (99.9th percentile), oral, dermal, and inhalation exposure in adults and children (1–2 yrs) in SGP agricultural communities downwind of feedlot operations.

Daily average inhalation dose (ADD; mg/kg/day; Eq. (1)) or lifetime-adjusted average daily inhalation dose (LADD; mg/kg/day; Eq. (2)) were calculated as:

$$\mathrm{ADD} = \frac{\mathrm{Concentration}\ (\mathrm{mg/m^3}) \times \mathrm{IR} \times \left[1 - e^{[\,-\,\mathrm{AF}\,-\,\mathrm{ET}]}\right]}{\mathrm{BW}}, \tag{1}$$

and

$$\mathrm{LADD} = \frac{\mathrm{Concentration}\ (\mathrm{mg/m^3}) \times \mathrm{IR} \times \left[1 - e^{[\,-\,\mathrm{AR}\,-\,\mathrm{ET}]}\right]}{\mathrm{BW}} \times \mathrm{EF} \times \mathrm{LT}, \tag{2}$$

where IR = inhalation rate (m^3/h), AF = absorption factor, BW = body weight (kg), ET = exposure time, and LT = lifetime (years). Additionally, a cancer potency factor (Q_i^*) was applied to LADDs (Eq. (3)) to estimate incremental lifetime cancer risk (ILCR):

$$\mathrm{ILCR} = \mathrm{LADD} \times Q_i^* \tag{3}$$

Single compound margin of exposure (MOE; Eq. (4)) was then calculated individually as:

$$\mathrm{MOE} = \frac{\mathrm{Index\ POD}}{\mathrm{RpF} \times \mathrm{ADD}}, \tag{4}$$

where index POD = point-of-departure of index compound and RpF = relative potency factor. Cumulative risk indices (RI) were then calculated from U.S. EPA dietary, oral, dermal, and inhalation ADD (Eq. (5)) as:

$$\mathrm{RI} = \frac{1}{[1/[\mathrm{MOE}_{\mathrm{diet}\ 1}/\mathrm{LOC}] + [1/\mathrm{MOE}_{\mathrm{oral}\ 1}/\mathrm{LOC}] + [1/\mathrm{MOE}_{\mathrm{inhal.}\ 1}/\mathrm{LOC}] \ldots + [1/\mathrm{MOE}_{\mathrm{diet}\ n}/\mathrm{LOC}] + [1/\mathrm{MOE}_{\mathrm{oral}\ n}/\mathrm{LOC}] + [1/\mathrm{MOE}_{\mathrm{inhal.}\ n}/\mathrm{LOC}]]} \tag{5}$$

Levels of concern (LOCs) are based on lifestage-applicable uncertainty (UF_A, UF_H) and safety factors (FSQA SF; U.S. U.S. EPA, 2019a), where cumulative agrochemical RI's > 1 are unlikely to pose a human health risk to relevant subpopulations. Generic U.S. EPA recommended values (U.S. EPA, 2017a) were applied for body weight (kg), inhalation rate (m^3/h), averaging time (AT; adult, non-carcinogen), and lifetime (LT; adult, carcinogen). Exposure parameter values for adults and children (1–2 yrs) are listed in Table 1.

Table 1
Residential human health exposure parameters.

Parameters	Adult	Child, 1–2 yrs
Body weight (kg)[a]	80	11
Inhalation rate (m^3/h)[a]	0.64	0.33
Exposure time (ET; hrs/day)	8	8
Exposure frequency (EF; days/year; seasonal)	123 - *x wet days*	NA
Exposure duration (ED; life expectancy; years)[b]	78	NA
Averaging time (years; non-cancer)[b]	78	NA
Lifetime (LT; years; cancer)[b]	78	NA

NA = not applicable.
[a] U.S. EPA generic lifestage values (U.S. EPA, 2012).
[b] U.S. EPA post-application residential values (U.S. EPA, 2011).

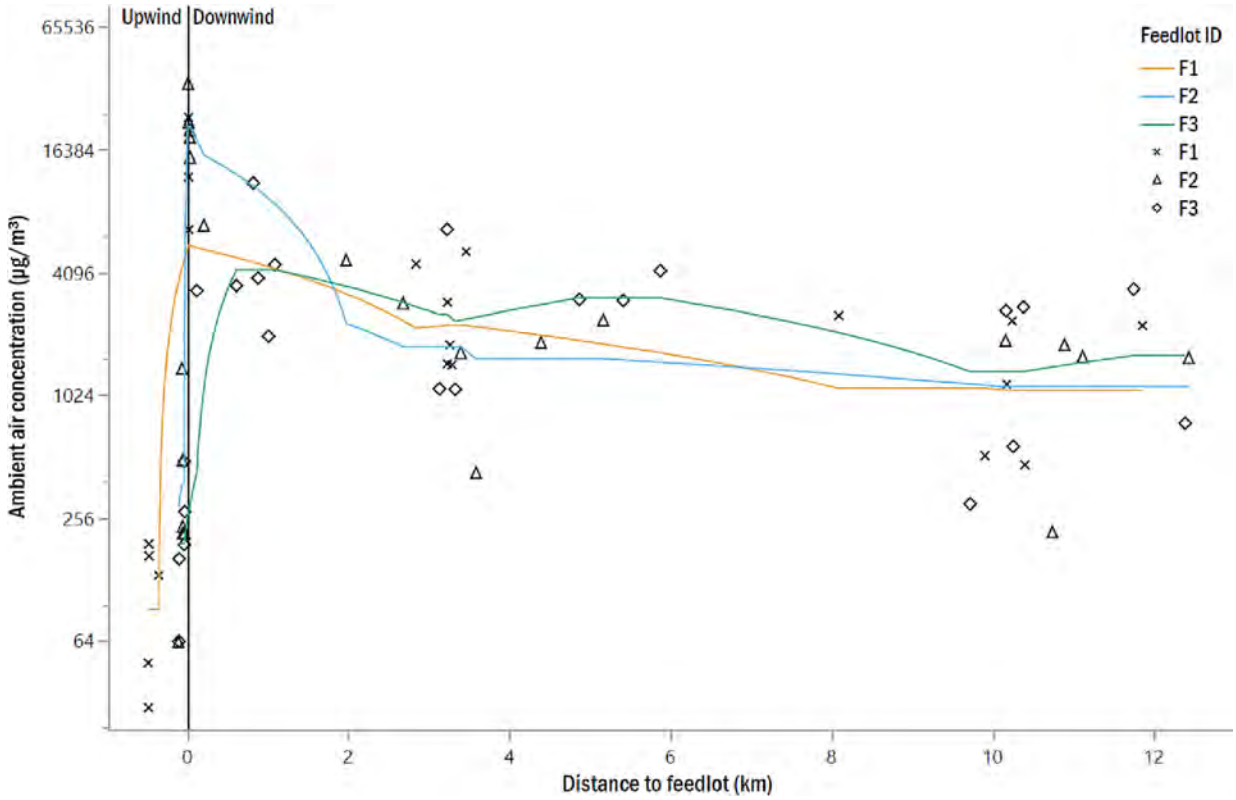

Fig. 2. Moving 5-point average of total suspended particulate (TSP) ambient air concentrations (µg/m^3) upwind and downwind of three feedlots (F1-F3) in the Southern Great Plains, Texas, USA.

2.9. Human demographics and environmental justice

To characterize exposure population demographics by census tract, authors used the U.S. EPA Environmental Justice screening tool (U.S. EPA, 2023d) and Enforcement and Compliance History Online (ECHO) interactive mapping tool (U.S. EPA, 2023c). Environmental justice (EJ) metrics were based on the Justice40 Initiative (2022) geospatial dataset, comprising seven areas of community development (climate change, energy, housing, transit, workforce, legacy pollution, and critical clean water/wastewater infrastructure). ArcGISPro (Version 3.1.0, ESRI, Inc.; Redland, CA) was also used to collate total and rural population demographics, cropland acreage, and environmental justice metrics in the Texas Panhandle High Plains region within 12-km geodesic feedlot buffers (rounded spatial extent of the current study).

3. Results

Non-normalized ambient air TSP concentrations (µg/m^3) are presented in Fig. 2. Summary statistics of non-normalized TSP concentrations and feedlot proximity are available in Supplemental material S3.

3.1. PM distance decay and Monte Carlo simulation

Monte Carlo-simulated distance decay serves to highlight the extent to which dust and organic debris remain airborne downwind of feedlots at a height of 2 m. Following model comparison (Supplemental material S4), a Weibull-distributed ΔU TSP distance decay function (Eq. (6)) was selected as the most appropriate model,

$$a*\left[1-\mathrm{Exp}\left[-\left[\frac{\text{Distance to feedlot (km)}}{b}\right]^{c}\right]\right] \quad (6)$$

where a = the asymptote, b = the inflection point, and c = the growth rate of the decay curve. Final model fit of actual vs. predicted TSP concentrations and Weibull distance decay curve are presented in Supplemental material S5a–b. After the model was validated and tested (Supplemental material S6a–b), the Weibull-distributed function was used to simulate Monte Carlo probabilistic point-density distribution presented in Fig. 3. Initial and simulated box-cox ($\lambda = -0.109$) transformed ΔU TSP and backtransformed ΔU TSP parameter estimates are presented in Supplemental material S7. The current distance decay model elucidated a rapid decline in TSP concentrations from 0 to 1.6 km (simulated mean ± SEM from 0 to 1.6 km = 5049 ± 96.1; 95 % CI: 4861–5238 µg/m^3) and subsequent trajectory stabilization >1.6–12.4 km (1791 ± 9.9, 95 % CI, 1773–1811 µg/m^3).

Seasonal exposure to downwind PM was greatest for residents living NNW-NNE of feedlot facilities in the Texas panhandle (Supplemental material SI8). From 1 May–31 August 2022, prevailing winds were observed from the SSW-SSE (40.8 %) with 31.4 % overall observations between 10.0 and 14.9 mph. Excluding wet days (n = 53; precipitation in the previous 72 h), 70 dry days were retained for expected seasonal agrochemical exposure frequency (EF).

3.2. Agrochemical occurrence

Of 11 agrochemical analytes included in the current study, four of six pyrethroids and all five MLs were detected in downwind TSP > LOQ (Fig. 4a–b). Pyrethroids were detected at the highest overall concentrations >LOQ in 96.2 % of downwind (grand mean = 3.4 ± 0.5 ng/m^3) and 27.8 % of upwind samples (grand mean = 1.2 ± 0.6 ng/m^3), with fenvalerate detected at the highest mean downwind concentration

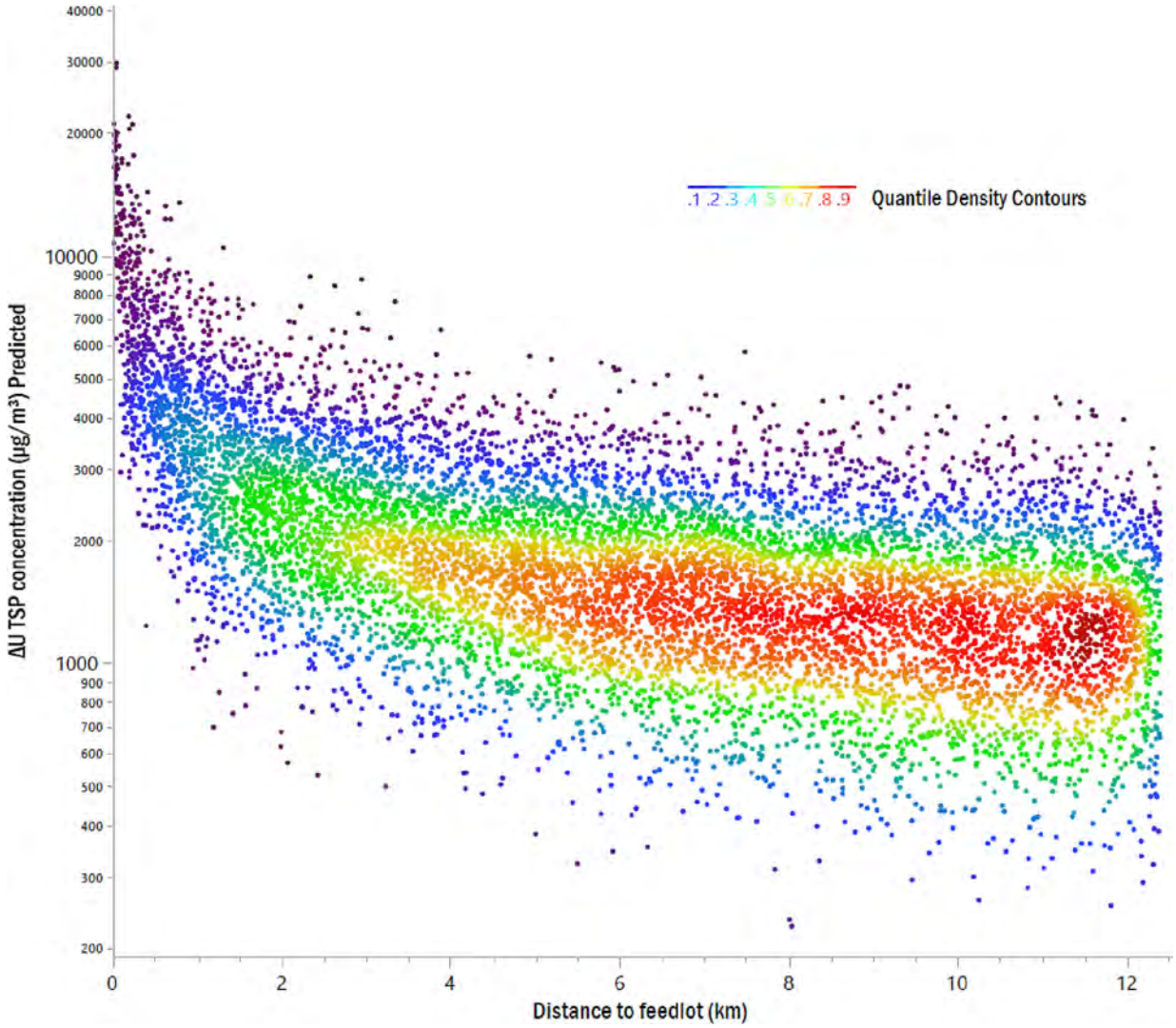

Fig. 3. Monte Carlo-simulated probability distribution of ΔU TSP concentrations (μg/m^3) downwind of three feedlots (F1-F3) in the Southern Great Plains, Texas, USA; quantile density contours highlight where each simulated ΔU TSP concentration falls within the overall probability distribution of concentrations from 0 to 12.4 km.

(5.9 ± 0.8 ng/m^3) followed by permethrin (1.1 ± 0.3 ng/m^3). Bifenthrin and λ-cyhalothrin were detected infrequently >LOQ in 5.6 and 3.7 % of all samples, respectively. Cypermethrin was not detected >LOQ in any samples, and esfenvalerate was detected only once in an upwind sample (F3; 2.8 ng/m^3). At least 1 ml was detected in 98.1 % of downwind (grand mean = 0.2 ± 0.04 ng/m^3) and 100.0 % of upwind samples (grand mean = 0.1 ± 0.04 ng/m^3). Among MLs, eprinomectin was detected at the highest mean downwind concentrations >LOQ (0.4 ± 0.2 ng/m^3) followed by ivermectin (mean = 0.3 ± 0.1 ng/m^3). Descriptive statistics of agrochemical occurrence and analytical quality assurance and control can be found in Supplemental material S9.

3.3. Parametric and non-parametric multivariate analyses

Multivariate analyses were performed to establish the underlying relationship between environmental predictor variables and downwind ambient air concentrations. PLS regression and CCA are constrained ordination methods that maximize explanatory covariance and correlation, respectively, between multiple predictor and dependent variables by projecting linear recombinations of original variables in factor space. Recombination in both cases serve to retain as much of the original variation in the dataset, while removing multicollinearity that may confound results. PLS regression was used as an initial method to parse out two levels of covariance in meteorological effects (diurnal and intraseasonal), and determine associations between each gradient individually. Results of initial PLS regression of meteorological variables are detailed in Supplemental materials S10–14, where associated scores along the Factor 1 and 2 axes preserved the greatest variation from the original dataset (Factor 1, X = 50.2 %, Y = 34.0 %; Factor 2, X = 49.8 %, Y = 6.2 %). PLS factor 1 and 2 scores, hereafter "intraseasonal weather variation" and "diurnal weather variation," respectively, were retained for use in CCA.

Final predictor variables included in CCA were downwind feedlot distance (km), intraseasonal variation, and diurnal variation, and response variables included ΔU TSP and ΔU ambient air concentrations of fenvalerate, permethrin, ivermectin, and moxidectin. Downwind concentrations, intraseasonal variation, and diurnal variation were not significantly different across feedlots (whole model F = 0.53; p = 0.715). Downwind concentrations were significantly correlated (eigenvalue = 1.48, canonical correlation = 0.772) with feedlot proximity (Fig. 5; univariate F = 10.9; $p < 0.0001$; fenvalerate > TSP > ivermectin > moxidectin > permethrin). Alternatively, intraseasonal and diurnal weather variation were not significant predictors across sampling events (intraseasonal F = 0.52, p = 0.759; diurnal F = 0.041, p = 0.907). Friedman's non-parametric tests (Supplemental material S15) established significant differences in abamectin, doramectin, and eprinomectin concentrations across all downwind distance classes (D1-D3) relative to upwind. Abamectin and

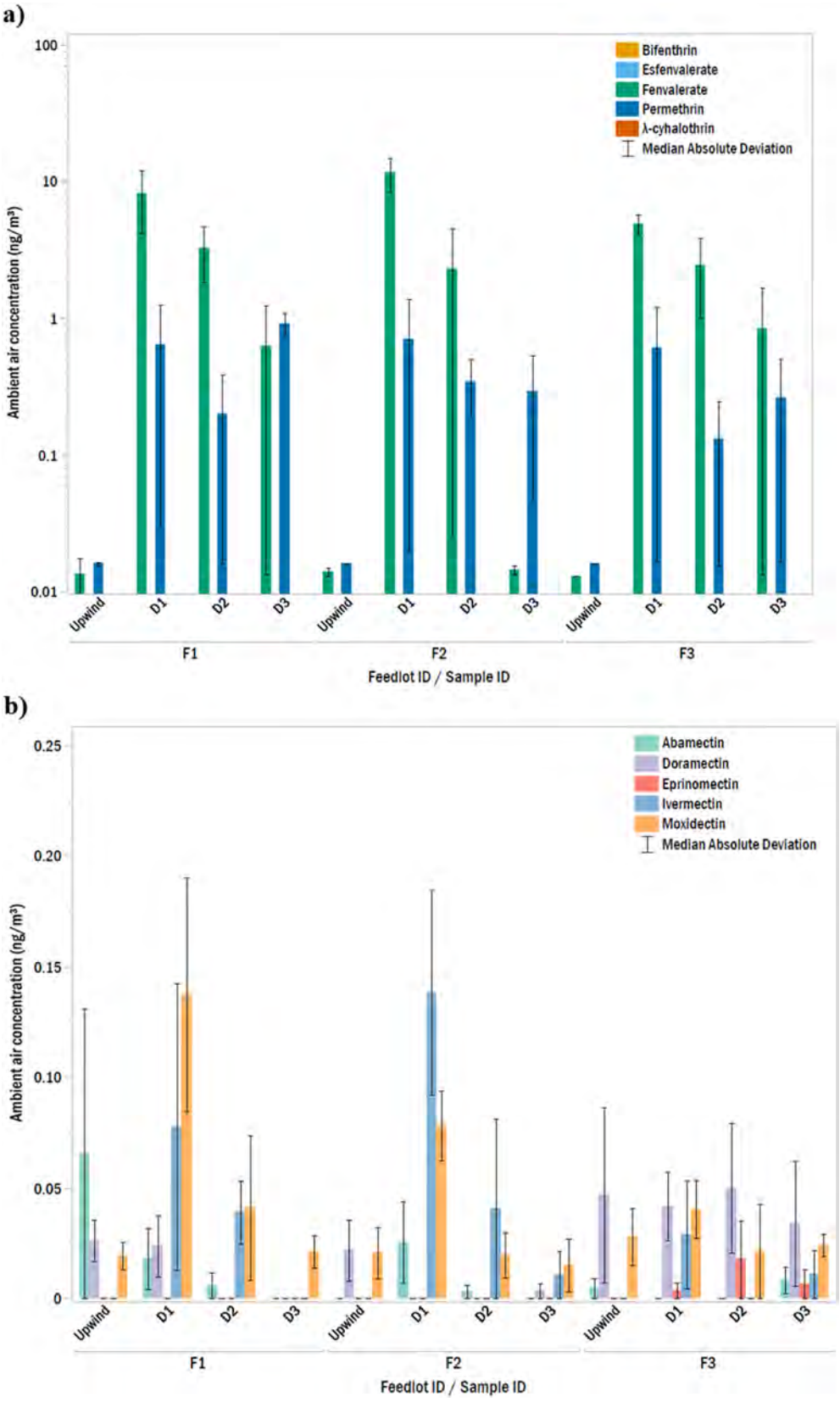

Fig. 4. a–b: Median ± median absolute deviation a) pyrethroid and b) macrocyclic lactone (ML) concentrations (ng/m^3) measured at one upwind and three downwind locations (D1-D3) at three feedlots (F1-F3; six evenings per feedlot) in the Southern Great Plains, Texas, USA; non-detect median for bifenthrin, esfenvalerate, and λ-cyhalothrin.

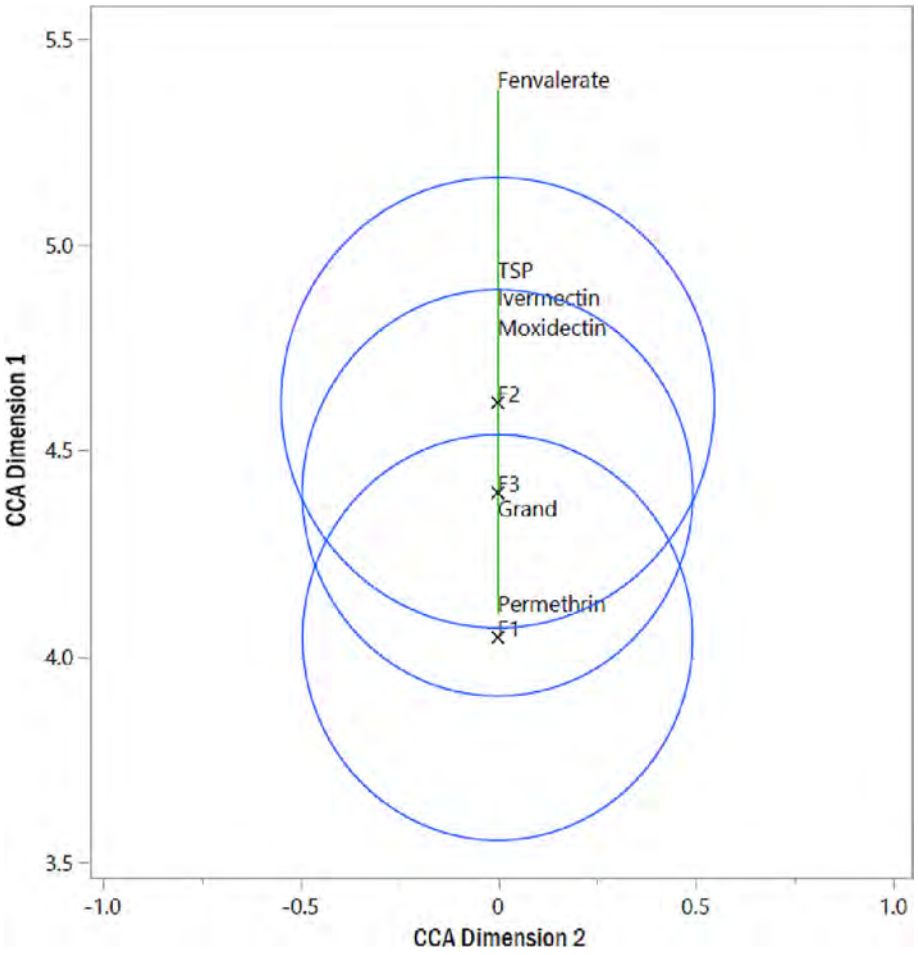

Fig. 5. Univariate canonical centroid plot; CCA Dimension 1 axis (vertical) represents a magnitude scale of association constrained to feedlot proximity; green biplot rays (overlapping; labels displayed at upper extent of each biplot ray) represent relative canonical correlation magnitude of response variables (greater absolute value = greater relative magnitude); blue centroids represent the 95 % confidence interval of point distributions observed across each feedlot (F1-F3); Grand = grand centroid value; TSP = total suspended particulates; Note: In a whole model centroid plot, the gradient distribution along CCA Dimension 2 axis (horizontal) would also represent a magnitude scale of association constrained to other significant predictors. In the univariate plot, the CCA Dimension 2 axis gradient distribution is not shown due to insignificance of all other predictors (diurnal and intraseasonal weather variation).

eprinomectin concentrations were significantly different across all feedlots, whereas a significant difference was observed in doramectin concentrations only between F1 and F2. However, due to low overall concentrations of ivermectin and moxidectin, and infrequent detections of abamectin, doramectin, and eprinomectin, MLs were excluded from cumulative exposure assessment.

3.4. Cumulative human health assessment

A cumulative residential human health assessment was performed for pyrethroids, including feedlot-derived inhalation exposure estimates for fenvalerate and permethrin, due to frequency of occurrence and ambient air concentrations in the current study. Feedlot-derived ML inhalation exposure estimates (99.9th percentiles) are also provided for reference in Supplemental material S16. Individual MOEs and cumulative RIs for pyrethroids are reported in Table 2. Post-application edge-of-field exposure to aerially-sprayed bifenthrin (assumed wind vector = 10 mph) was selected as a protective residential exposure scenario due to frequent use as a foliar treatment for cotton leafhoppers (Vyavhare and Kerns, 2022), the most prevalent and expensive foliar cotton pest in the Texas Panhandle in 2021 (100 % cotton acreage infested; 13 % of Texas cotton acreage reported as insecticide-treated; Cook and Threet, 2021). The pyrethroid index POD (11 mg/kg/day) was derived from deltamethrin and adjusted based on compound-specific relative potency factors (RpF; U.S. EPA, 2011). All remaining exposure estimates were based directly on U.S. EPA, 2011 residential and dietary exposure scenarios considered protective for cumulative exposure, except for residential handler and post-application exposure to backpack-sprayed turf treatment. Fluvinate, originally included in 2011, has since been discontinued, so the second highest turf exposure scenario was selected. Adult lifetime-adjusted average daily dose (mg/kg/day) and incremental lifetime aggregate cancer risk were also calculated for permethrin (Table 3; $Q_i^* = 9.567E^{-3}$), recently designated as a likely human carcinogen (U.S. EPA, 2017a).

3.5. Human demographics and environmental justice

Of the approximately 600 thousand Texas High Plains residents living ≤12 km from beef cattle feedlots, nearly a third (31.1 %) live in non-metropolitan census tracts, where federal PM monitors are absent, and co-occurring cropland exposure is likely (47.8 % co-occurrence of cropland acreage ≤12 km; 25.8 % co-occurrence of cotton acreage ≥1 growing seasons since 2008 (MRLC, 2023; USDA NASS, 2022).

Texas High Plains rural residents are a racial and ethnic minority-majority on average (54.0 %) and disproportionately Hispanic or Latino (43.3 %) compared to the overall regional (39.9 %) and national average (18.7 %; U.S. Census Bureau, 2020). In rural census tracts where feedlots are heavily concentrated (≥3 feedlots clustered ≤12 km), the Hispanic and Latino population are an overall ethnic majority (50.5 %) and

Table 2
Screening-level cumulative human health assessment (non-carcinogenic) of pyrethroids in agricultural communities downwind of feedlots; screening-level cumulative exposure estimates are intended to overestimate exposure from all possible co-occurring scenarios to provide an adequate margin of public safety.

Lifestage	Approved use (compound, scenario)	POD (mg/kg/day)	Rpf	Average daily dose (mg/kg/day)			Margin of exposure (MOE)				Risk Index[h]
				Dermal	Oral	Inhalation	Dermal[f]	Oral[f]	Inhalation[g]	Dietary[f]	
Adult (≥16 yrs)	Residential handler										1.72
	Garden (cypermethrin, backpack)[a]	11	0.19	6.7E-4	–	1.30E-5	8.64E4	–	4.45E6	–	
	Turf (cyfluthrin, hose-end)[a]	11	1.15	0.001	–	3.70E-5	8696	–	2.59E5	–	
	Pet (permethrin, shampoo)[a]	11	0.09	3.8E-4	–	1.00E-6	3.22E5	–	1.22E8	–	
	Post-application										
	Garden (cyhalothrin, backpack)[a]	11	1.63	0.007	–	–	964	–	–	–	
	Turf (cyfluthrin, TTR)[a]	11	1.15	0.003	–	–	2.16E4	–	–	–	
	Pet (cyphenothrin, spot on)[a]	11	0.15	0.001	–	–	6.67E4	–	–	–	
	Indoor fogger (cypermethrin)[a]	11	0.19	0.003	–	–	2.1E4	–	–	–	
	Crop, edge of field (bifenthrin, aerial)[b]	11	1.01	0.048	–	–	229	–	–	–	
	Feedlot-derived (fenvalerate)[d]	11	0.36	–	–	1.54E-07	–	–	1.98E8	–	
	Feedlot-derived (permethrin)[d]	11	0.09	–	–	1.37E-08	–	–	8.90E9	–	
	Dietary (food + water)[c,d]			–	–	–	–	–	–	5400	
Child (1–2 yrs)	Post-application										0.173
	Turf (cyfluthrin, TTR)[a]	11	0.15	0.003	5.0E-4	–	3986	1.9E4	–	–	
	Pet (cyphenothrin, spot on)[a]	11	0.15	0.003	4.9E-4	–	2.93E4	1.5E5	–	–	
	Indoor fogger (cypermethrin)[a]	11	0.19	0.003	0.012	–	1.93E4	4825	–	–	
	Crop, edge of field (bifenthrin, aerial)[b]	11	1.01	0.2[e]	–	–	54	–	–	–	
	Feedlot-derived (fenvalerate)[d]	11	0.36	–	–	5.78E-07	–	–	5.29E7	–	
	Feedlot-derived (permethrin)[d]	11	0.09	–	–	5.15E-08	–	–	2.37E9	–	
	Dietary (food + water)[c,d]			–	–	–	–	–	–	3000	

POD = point-of-departure.
RpF = relative potency factor.
LOC = level of concern, values ≤ LOC indicate exceedance.
[a] Average daily dose derived from U.S. EPA screening-level cumulative human health assessment of pyrethroids and pyrethrins (U.S. EPA, 2011).
[b] Average daily dose derived from U.S. EPA screening-level aggregate human health assessment of bifenthrin (U.S. EPA, 2020b).
[c] Combined margin of exposure (MOE) as reported in U.S. EPA (2011).
[d] 99.9th percentile.
[e] Child oral (hand-to-mouth) exposure combined with dermal exposure per U.S. EPA (2011, 2020c).
[f] Adult LOC = 100, child (1–2 yrs) LOC = 300.
[g] Adult LOC = 30, child (1–2 yrs) LOC = 90.
[h] Adult and child (1–2 yrs) LOC = 1.

communities on average are in the 82nd percentile for linguistic isolation, 67th percentile of individuals below 200 % of the federal poverty line, and 75th percentile of share of homes with no kitchen or indoor plumbing. By census tract, 66.4 % of rural feedlots are in communities comprising people of color above the national average (42.2 %; U.S. Census Bureau, 2020).

Of 110 active rural feedlots in the Texas High Plains, 55.5 and 72.7 % of facilities have been flagged at the state- and national-level, respectively, for co-location in census tracts where EJ indices exceed the 80th percentile (U.S. EPA, 2023c). Moreover, 60.0 and 77.3 % of rural feedlots exceed the 80th percentile at the state and national level, respectively, for ozone pollution within a 1-mile proximity. While no feedlots are subject to Clean Air Act inspections, 20.0 % of rural feedlots in the Texas High Plains have never been inspected for compliance across any environmental permitting program at the state or federal level, and 70 % have only been inspected once over the duration of the applicable facility permit.

Table 3
Post-application aggregate residential lifetime cancer risk of permethrin in agricultural communities downwind of feedlots in the Southern Great Plains, Texas, USA.

Exposure scenario	LADD (mg/kg/day)		ILCR[c]	
Feedlot-derived[a]	6.86E-10		6.56E-12	
	Lower	Upper	Lower	Upper
Indoor[b]	3.98E-06	3.27E-04	3.81E-08	3.13E-06
Outdoor[b]	9.51E-07	1.25E-04	9.10E-09	1.20E-06
Treated pet[b]	3.45E-04	4.18E-03	3.30E-06	4.00E-05
Treated fabric/clothing[b]	7.00E-04	5.12E-05	4.90E-07	6.70E-06
Aggregate	1.05E-03	4.68E-03	3.84E-06	5.10E-05

LADD = Lifetime-adjusted daily dose.
ILCR = incremental lifetime cancer risk.
[a] Inhalation exposure only.
[b] Aggregate values derived from ranges reported in U.S. EPA permethrin aggregate human health assessment (U.S. EPA, 2017a).
[c] ICLR = LADD multiplied by permethrin cancer potency factor (Qi* = 9.57E-3).

4. Discussion

4.1. Feedlot-derived PM

There has been a paucity of empirical data on the spatial extent and magnitude of PM transport beyond feedlot boundaries. Previous literature has indicated that TSP within and adjacent to feedlot pens is largely comprised of PM size fractions >10 μm ($PM_{2.5}$/TSP = 0.017–0.12, PM_{10}/TSP = 0.19–0.41; Blackwell et al., 2015b; Bonifacio et al., 2015; Sweeten et al., 1998). As such, most pen floor material subject to initial suspension is not capable of sustained atmospheric transport. However, due to considerable suspended mass overall, elevated levels of inhalable PM size fractions are frequently observed in and adjacent to cattle pens, and ratios of TSP concentrations ≥1.6–12.4 km vs. TSP concentrations at the asymptote (0.01 km; mean ratio = 0.039) are in good agreement with feedlot $PM_{2.5}$/TSP ratios reported in previous literature (Supplemental material S17). Presently, downwind distance decay modeling of feedlot TSP and previous literature suggest that non-inhalable and coarse particulate size fractions are primarily deposited ≤1.6 km downwind. Alternatively, this also suggests that downwind TSP concentrations >1.6–12.4 km (1791 ± 9.9; 95 % CI: 1773–1811 μg/m^3) are predominately composed of feedlot-derived $PM_{2.5}$ at levels that would significantly impact downwind residents during diurnal peak periods. Current estimates are supported by Hiranuma et al. (2011), who found that ground-level (2-m height) PM_{10} concentrations measured at a stationary air monitor 3.5 km downwind of a feedlot were reduced to approximately 8.5 % of concentrations measured at the

edge of cattle pens, whereas $PM_{2.5}$ concentrations did not significantly decrease across the same distance. This size-dependent pattern of PM transport and deposition has been observed across various applications and has been used extensively to characterize PM transport potential from roadways (Karner et al., 2010). Several indirect methods have been recommended to approximate PM size distribution when direct methods are cost-prohibitive or otherwise not feasible, including use of emissions factors for animal waste-producing facilities based on total pen area ($g/m^2/d$) and/or stocking density ($g/m^2/d$-1000 head; U.S. EPA, 2022a), estimation of transportable fractions from livestock operations on a county-wide basis (Pouliot et al., 2011), and multipliers to approximate $PM_{2.5}$ from PM_{10} concentrations (Pace, 2005). These estimation methods are particularly applicable to research in low-income, rural communities with disparate air quality monitoring infrastructure, as is the case in the current study.

While ambient air sampling in the current study was limited to TSP concentrations over a 3-hr time-from-sunset period given the concurrent objectives of quantifying agrochemical constituents and targeting peak diurnal emissions, no literature derived PM/TSP size ratio at any measured downwind distance would produce mean ambient air PM concentrations below National Ambient Air Quality Standards (NAAQS; U.S. EPA, 2023a). Prior to 1987, primary TSP NAAQS were 260 $\mu g/m^3$ (24-hr) and 75 $\mu g/m^3$ (annual). From 1987 to present, primary (health-based) and secondary (public welfare) NAAQS have instead been based on inhalable PM size fractions, with primary standards set in 2012 as 35 $\mu g/m^3$ (24-hr; one allowable exceedance of 98th percentile) and 12.0 $\mu g/m^3$ (annual; arithmetic mean) for $PM_{2.5}$ and primary and secondary standards of 150 $\mu g/m^3$ (24-hr) for PM_{10}. In January 2023, new U.S. EPA guidelines were proposed (U.S. EPA, 2023a), where primary $PM_{2.5}$ standards would be reduced to a range between 9.0 and 10 $\mu g/m^3$. Consequently, downwind residents who remain outdoors ≥30 min during diurnal peak periods are likely exposed to PM concentrations exceeding safe levels for human exposure.

4.2. Agrochemical occurrence

Trends of agrochemical occurrence in downwind PM are comparable to previous feedlot-adjacent sampling campaigns in the SGP region (Peterson et al., 2020). Usage of individual agrochemicals for beef cattle pest management will vary across feedlots, but pyrethroids and MLs have been consistently detected in feedlot PM. Upwind sampling was included in the current study to demonstrate comparative PM emissions and normalize downwind concentrations for analysis, a methodological approach commonly employed in near-source sampling campaigns. However, trace agrochemicals detected upwind >LOQ in the current study should not be misinterpreted as a measure of regional background concentrations. Because co-located upwind samplers were deployed near cattle pens (<0.5 km), resuspension of previously deposited feedlot PM must be factored into observations on the date of collection. While all pyrethroids of interest are used concurrently on croplands, abamectin is the only ML registered as an active ingredient for use in crop protection (U.S. EPA, 2017b; Vyavhare and Kerns, 2022), indicating that upwind detections of MLs are likely of feedlot origin.

4.3. Cumulative pyrethroid risk in downwind agricultural communities

Cumulative RIs for pyrethroids indicate elevated health risk for children 1–2 yrs. of age (LOC = 1; RI = 0.173) living near pyrethroid-treated cropland in the SGP. While U.S. EPA cumulative exposure and risk estimates are intended to be extremely conservative in lower-tiered assessments, they are only as conservative as the exposure scenarios considered. Under the tiered-assessment framework, single compound aggregate RIs above LOCs under the most protective scenarios will initiate a higher-tiered, refined assessment. However, because residential assessments do not include post-application exposure from surrounding agricultural operations, nor synergistic toxicity in any exposure scenario, risk estimates assumed to be protective are inadequate to address residential exposure in agricultural communities. Synergists such as piperonyl butoxide (PBO; Group C carcinogen; U.S. EPA, 2022b) are standard in pyrethroid product formulations (Gajendiran and Abraham, 2018), significantly increasing toxicity of individual active ingredients. Moreover, residential post-application exposure estimates of bifenthrin near cropland, while referenced regarding cotton pest usage, are derived from the same aerial max application rate (0.30 lb a.i./ac) for all crops treated with bifenthrin, except citrus and tobacco. Considering variable acreage, risk characterizations can be reasonably integrated for residential exposure across dominant bifenthrin-treated crops relevant to multiple agroecosystems.

It must also be intimated that feedlot-derived inhalation exposure to pyrethroids does not represent worst-case scenario cumulative residential exposure near feedlot operations, nor is it likely that inhalation is the primary route of residential exposure. PM-bound pyrethroid deposition is expected to contribute considerably to feedlot-derived exposure, as daily deposition facilitates the accumulation of pyrethroid residues in outdoor residential areas. Because these additional oral, dermal, and inhalation exposure scenarios cannot be adequately characterized in a singular study, they are not included. Instead, the present estimates represent a significant feedlot agrochemical transport mechanism wholly uncharacterized in human health assessments, and empirical estimates are the groundwork for incorporation of downwind scenarios in standard operating procedures for pesticide registration and feedlot risk evaluation. Previously, post-application inhalation exposure to pyrethroids has been assumed to be negligible beyond re-entry periods citing low volatilization and initial aerosol deposition (U.S. EPA, 2011). As demonstrated in the current study, these assumptions are incorrect when pyrethroid residues are subject to post-application mechanical re-suspension. Thus, inhalation exposure is subsequently driven by wind transport and aerodynamic properties of particulates to which compounds are sorbed, and all resulting downwind exposure routes must be considered.

4.4. Incremental lifetime cancer risk of pyrethroids

Lifetime cumulative cancer risk from possible human carcinogens (bifenthrin and cypermethrin; U.S. EPA, 2022b), and the more recently classified likely carcinogenicity of permethrin are also not included in U.S. EPA's most recent 2011 cumulative pyrethroid assessment. A Tier II epidemiology report was initiated in 2011 due to “moderately large” incidences of acute permethrin poisoning. In 2019, U.S. EPA summarily rejected any carcinogenic and non-carcinogenic health outcomes identified in epidemiologic studies (n = 62; U.S. EPA, 2019b) as lacking sufficient evidence to conclude a clear association or causal relationship with chronic, low-level pyrethroid exposure. Specifically, two studies investigated an association with pyrethroid exposure and incidence of acute lymphoid leukemia (ALL) and acute myeloid leukemia (AML) in Brazilian children (Ferreira et al., 2013; U.S. EPA moderate quality rank) and children residing in Shanghai, China (Ding et al., 2012; U.S. EPA low quality rank). Further epidemiological evidence of pyrethroid association with blood cancer precursors (MGUS; Hofmann et al., 2021) have since been reported. In concert with more recent prenatal in vivo studies (Priyanka et al., 2022; Song et al., 2022), conflicting conclusions on the weight of epidemiological evidence for health outcomes in children (Andersen et al., 2022), and prevalent incidences of acute permethrin exposure, the supporting literature for carcinogenic, reproductive, and neurodevelopmental pyrethroid risk to children deserves significantly greater regulatory consideration.

4.5. Human demographics and environmental justice

Through demographic characterization, authors aim to highlight subsections of the SGP in which communities are underserved and overburdened by pollution, and in which federal resource allocation would be particularly pertinent. Moreover, as state- and national-level EJ metrics are now readily available to stakeholders, permitting authorities, and policymakers, there is an additional degree of public transparency regarding the due consideration of sensitive populations in feedlot permitting

decisions. While informative, U.S. EPA EJ indices are presently limited by disparate rural PM monitoring in the SGP region and cannot accurately reflect close- or mid-range fugitive PM exposure in neighboring communities. Importantly, human exposure to feedlot PM, and co-exposure to pyrethroids used in both beef cattle and crop production, are of disproportionate concern for rural adults and children in low-income, minority communities. Furthermore, present demographic characterizations do not consider adult residential and occupational co-exposure frequently associated with farm operators and laborers, where a greater magnitude and frequency of pyrethroid exposure in resident and migrant workers is expected.

4.6. Feedlot-derived ML exposure

Macrocyclic lactones are not expected to pose an elevated human health risk based on minimal overlapping cropland use, but the indirect implication of ML resistance in soil-transmitted helminths also deserves careful consideration. Though outside of the present scope, atmospheric deposition of MLs may represent an environmental health risk to non-target invertebrates, particularly in soil microbial communities and dung beetles (de Souza and Guimarães, 2022; Sands and Noll, 2022). As such, the present quantification of downwind ML concentrations may also be used to supplement future ecological risk assessments. Lastly, agrochemical occurrence in PM is not limited to pesticides, and the potential for chronic exposure to complex mixtures of endocrine-disrupting compounds, including veterinary pharmaceuticals and bioaerosols downwind of feedlot facilities is an additional public and environmental health concern that must be addressed and regulated holistically.

4.7. Future directions

U.S. EPA's most recent risk evaluation of beef cattle feedlot facilities (U.S. EPA, 2004) does not incorporate foundational advancements in environmental impact research over nearly two decades. Federal exemptions have since been applied to all animal waste-producing facilities, with the most recent legislation in 2019 eliminating all hazardous air release reporting for beef cattle feedlots of any size (U.S. EPA, 2023b). The current regulatory landscape surrounding feedlot facilities in the U.S. has shifted the onus of proof to impacted populations, often disabling unincorporated rural communities from mounting viable evidence of environmental and public health impact. Agrochemical occurrence and distribution in downwind PM also underpins the considerable knowledge gap regarding human exposure near feedlot facilities, and actual year-round chronic exposure to feedlot-derived PM and agrochemicals, and associated human health risk of complex PM constituents, is expected to be significantly greater in areas where feedlot operations are heavily concentrated near municipalities. As agrochemicals registered for concurrent use in crop production already exert a chemical burden in agroecosystems, all relevant agricultural inputs must be considered to address cumulative daily intake. However, daily intake of pyrethroids in agriculture-intensive areas cannot be realistically predicted without comprehensive monitoring of fugitive feedlot emissions.

5. Conclusions

In this study, authors characterized agrochemical and PM transport downwind of feedlot facilities, significantly expanding the known distribution of feedlot-derived agrochemicals. Feedlot-derived PM concentrations in downwind ambient air reported in the current study likely exceed NAAQS thresholds of safe exposure to downwind residential communities, irrespective of agrochemical occurrence. Moreover, estimates of cumulative pyrethroid intake in downwind agroecosystems are well-above LOCs for children 1–2 yrs. of age. Due to the complex constituents of feedlot-derived PM, and extensive residential and commercial use of pyrethroids, potential non-carcinogenic and carcinogenic health risks to residents warrant more comprehensive and quantitative assessment. Importantly, atmospheric transport of PM-bound agrochemicals from feedlots is a major unrecognized transport pathway in environmental and human health assessments, and lack of monitoring and reporting of hazardous substance air releases at feedlots poses considerable challenges for risk characterization to sensitive receptors.

Acronyms

ADD	average daily dose
AICc	Corrected Akaike's information criterion for small sample sizes
CAA	Clean Air Act
FQPA	Food Quality Protection Act
FQPA SF	FQPA safety factor
GABA	gamma (γ)-aminobutryic acid
hd	head of cattle
ILCR	incremental lifetime cancer risk
IRIS	Integrated Risk Information System, U.S. EPA
LADD	lifetime-adjusted average daily dose
LOC	level of concern
LOD	limit of detection
LOQ	limit of quantitation
MGUS	monoclonal gammopathy of undetermined significance
MADL	maximum allowable dose level; Proposition 65, California Office of Environmental Health Hazard Assessment
Min.	minimum
Max.	maximum
MOA	mechanism of action
MOE	margin of exposure
MSE	mean square error
NAAQS	National Ambient Air Quality Standards
NOAEL	No-observed-adverse-effect level
PK	pharmacokinetic
PM	particulate matter
$PM_{2.5}$	particulate matter of aerodynamic equivalent diameter $\leq$ 2.5 μm
PM_{10}	particulate matter of aerodynamic equivalent diameter $\leq$ 10 μm
POD	point-of-departure
RpF	relative potency factor
RMSE	root mean square error
RI	risk index
SEM	standard error of the mean
SD	standard deviation
SSE	sum of squares error
U.S. EPA	United States Environmental Protection Agency
OPP	U.S. EPA Office of Pesticide Programs
SOP	standard operating procedure
USDA	United States Department of Agriculture
NASS	USDA National Agricultural Statistics Service
TSP	total suspended particulates
ΔU	upwind-normalized
UF_A	uncertainty factor, interspecies extrapolation
UF_H	uncertainty factor, interindividual variability (human)

CRediT authorship contribution statement

Amanda D. Emert: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Validation, Writing – original draft, Visualization. **Kerry Griffis-Kyle:** Supervision, Conceptualization, Writing – review & editing. **Frank B. Green:** Investigation, Writing – review & editing. **Philip N. Smith:** Supervision, Conceptualization, Resources, Project administration, Writing – review & editing.

Data availability

Location-censored raw data tables are available by request to the corresponding author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Alexander, T.W., Yanke, J.L., Reuter, T., Topp, E., Read, R.R., Selinger, B.L., McAllister, T.A., 2011. Longitudinal characterization of antimicrobial resistance genes in feces shed from cattle fed different subtherapeutic antibiotics. BMC Microbiol. 11 (1), 1–12. https://doi.org/10.1186/1471-2180-11-19/TABLES/4.

Andersen, H.R., David, A., Freire, C., Fernández, M.F., D'Cruz, S.C., Reina-Pérez, I., Fini, J.B., Blaha, L., 2022. Pyrethroids and developmental neurotoxicity - a critical review of epidemiological studies and supporting mechanistic evidence. Environ. Res. 214. https://doi.org/10.1016/J.ENVRES.2022.113935.

Arias-Pérez, R.D., Taborda, N.A., Gómez, D.M., Narvaez, J.F., Porras, J., Hernandez, J.C., 2020. Inflammatory effects of particulate matter air pollution. Environmental Science and Pollution Research 2020 27:34 27 (34), 42390–42404. https://doi.org/10.1007/S11356-020-10574-W.

Aust, M.O., Godlinski, F., Travis, G.R., Hao, X., McAllister, T.A., Leinweber, P., Thiele-Bruhn, S., 2008. Distribution of sulfamethazine, chlortetracycline and tylosin in manure and soil of Canadian feedlots after subtherapeutic use in cattle. Environ. Pollut. 156 (3), 1243–1251. https://doi.org/10.1016/J.ENVPOL.2008.03.011.

Bao, W., Liu, B., Simonsen, D.W., Lehmler, H.J., 2020. Association between exposure to pyrethroid insecticides and risk of all-cause and cause-specific mortality in the general US adult population. JAMA Intern. Med. 180 (3), 367–374. https://doi.org/10.1001/JAMAINTERNMED.2019.6019.

Bicudo, J.R., Goyal, S.M., 2003. Pathogens and manure management systems: a review. Environ. Technol. 24 (1), 115–130. https://doi.org/10.1080/09593330309385542.

Blackwell, B.R., Brown, T.R., Broadway, P.R., Buser, M.D., Brooks, J.C., Johnson, B.J., Cobb, G.P., Smith, P.N., 2014. Characterization of trenbolone acetate and estradiol metabolite excretion profiles in implanted steers. Environ. Toxicol. Chem. 33 (12). https://doi.org/10.1002/etc.2757.

Blackwell, B.R., Johnson, B.J., Buser, M.D., Cobb, G.P., Smith, P.N., 2015a. Transformation kinetics of trenbolone acetate metabolites and estrogens in urine and feces of implanted steers. Chemosphere 138. https://doi.org/10.1016/j.chemosphere.2014.10.091.

Blackwell, B.R., Wooten, K.J., Buser, M.D., Johnson, B.J., Cobb, G.P., Smith, P.N., 2015b. Occurrence and characterization of steroid growth promoters associated with particulate matter originating from beef cattle feedyards. Environ. Sci. Technol. 49 (14), 8796–8803. https://doi.org/10.1021/acs.est.5b01881.

Bonifacio, H.F., Maghirang, R.G., Trabue, S.L., McConnell, L.L., Prueger, J.H., Bonifacio, E.R., 2015. TSP, PM10, and PM2.5 emissions from a beef cattle feedlot using the flux-gradient technique. Atmos. Environ. 101, 49–57. https://doi.org/10.1016/j.atmosenv.2014.11.017.

Bradberry, S., Cage, S., Proudfoot, A., Vale, J., 2005. Poisoning due to pyrethroids. Toxicol. Rev. 24 (2), 93–106. https://doi.org/10.2165/00139709-200524020-00003.

Brausch, J.M., Smith, P.N., 2009. Pesticide resistance from historical agricultural chemical exposure in Thamnocephalus platyurus (Crustacea: Anostraca). Environ. Pollut. 157 (2), 481–487. https://doi.org/10.1016/J.ENVPOL.2008.09.010.

Chen, T.-F., Chang, K.-H., Tsai, C.-Y., 2014. Modeling direct and indirect effect of long range transport on atmospheric PM2.5 levels. Atmos. Environ. 89, 1–9. https://doi.org/10.1016/j.atmosenv.2014.01.065.

Cook, D.R., & Threet, M. 2021. Cotton Insect Losses - 2021. Cotton Insect Loss Estimates. Table 25. Cotton insect loss estimates for the High Plains area of Texas during 2021.

de Oro, L.A., Avecilla, F., Panebianco, J.E., Buschiazzo, D.E., 2021. PM10 emission from feedlots in soils with different texture: cattle trampling effect. Aeolian Res. 53, 100742. https://doi.org/10.1016/J.AEOLIA.2021.100742.

de Souza, R.B., Guimarães, J.R., 2022. Effects of avermectins on the environment based on its toxicity to plants and soil invertebrates—a review. Water Air Soil Pollut. 233 (7), 259. https://doi.org/10.1007/s11270-022-05744-0.

Ding, G., Shi, R., Gao, Y., Zhang, Y., Kamijima, M., Sakai, K., Wang, G., Feng, C., Tian, Y., 2012. Pyrethroid pesticide exposure and risk of childhood acute lymphocytic leukemia in Shanghai. Environ. Sci. Technol. 46 (24), 13480–13487. https://doi.org/10.1021/ES303362A.

El-Saber Batiha, G., Alqahtani, A., Ilesanmi, O.B., Saati, A.A., El-Mleeh, A., Hetta, H.F., Magdy Beshbishy, A., 2020. Avermectin derivatives, pharmacokinetics, therapeutic and toxic dosages, mechanism of action, and their biological effects. Pharmaceuticals 13 (8), 196. https://doi.org/10.3390/ph13080196.

Emert, A.D., Subbiah, S., Green, F.B., Griffis-Kyle, K., Smith, P.N., 2023. Atmospheric deposition of particulate matter from beef cattle feedlots is a likely contributor of pyrethroid occurrence in isolated wetland sediment: source apportionment and ecological risk assessment. Environ. Pollut. 316, 120493. https://doi.org/10.1016/J.ENVPOL.2022.120493.

Ferreira, J.D., Couto, A.C., Pombo-de-Oliveira, M.S., Koifman, S., 2013. In utero pesticide exposure and leukemia in Brazilian children <2 years of age. Environ. Health Perspect. 121 (2), 269–275. https://doi.org/10.1289/ehp.1103942.

Freeman, M.C., Akogun, O., Belizario, V., Brooker, S.J., Gyorkos, T.W., Imtiaz, R., Krolewiecki, A., Lee, S., Matendechero, S.H., Pullan, R.L., Utzinger, J., 2019. Challenges and opportunities for control and elimination of soil-transmitted helminth infection beyond 2020. PLoS Negl. Trop. Dis. 13 (4), e0007201. https://doi.org/10.1371/JOURNAL.PNTD.0007201.

Furlong, M.A., Paul, K.C., Yan, Q., Chuang, Y.-H., Cockburn, M.G., Bronstein, J.M., Horvath, S., Ritz, B., 2020. An epigenome-wide association study of ambient pyrethroid pesticide exposures in California's central valley. Int. J. Hyg. Environ. Health 229, 113569. https://doi.org/10.1016/j.ijheh.2020.113569.

Gajendiran, A., Abraham, J., 2018. An overview of pyrethroid insecticides. Frontiers in Biology 2018 13:2 13 (2), 79–90. https://doi.org/10.1007/S11515-018-1489-Z.

Gaudino, M., Nagamine, B., Ducatez, M.F., Meyer, G., 2022. Understanding the mechanisms of viral and bacterial coinfections in bovine respiratory disease: a comprehensive literature review of experimental evidence. Vet. Res. 53 (1), 70. https://doi.org/10.1186/S13567-022-01086-1.

Guo, L., Maghirang, R.G., Razote, E.B., Trabue, S.L., McConnell, L.L., 2011. Concentrations of particulate matter emitted from large cattle feedlots in Kansas. J. Air Waste Manage. Assoc. 61 (10), 1026–1035. https://doi.org/10.1080/10473289.2011.599282.

Hamra, G.B., Guha, N., Cohen, A., Laden, F., Raaschou-Nielsen, O., Samet, J.M., Vineis, P., Forastiere, F., Saldiva, P., Yorifuji, T., Loomis, D., 2014. Outdoor particulate matter exposure and lung cancer: a systematic review and meta-analysis. Environ. Health Perspect. 122 (9), 906–911. https://doi.org/10.1289/EHP/1408092.

Hanberry, B.B., DeBano, S.J., Kaye, T.N., Rowland, M.M., Hartway, C.R., Shorrock, D., 2021. Pollinators of the Great Plains: disturbances, stressors, management, and research needs. Rangel. Ecol. Manag. 78, 220–234. https://doi.org/10.1016/J.RAMA.2020.08.006.

Hiranuma, N., Brooks, S.D., Gramann, J., Auvermann, B.W., 2011. High concentrations of coarse particles emitted from a cattle feeding operation. Atmos. Chem. Phys. 11 (16), 8809–8823. https://doi.org/10.5194/acp-11-8809-2011.

Hoch, J., Markowski, P., 2005. A climatology of springtime dryline position in the U.S. Great Plains region. J. Clim. 18 (12), 2132–2137. https://doi.org/10.1175/JCLI3392.1.

Hofmann, J.N., Beane Freeman, L.E., Murata, K., Andreotti, G., Shearer, J.J., Thoren, K., Ramanathan, L., Parks, C.G., Koutros, S., Lerro, C.C., Liu, D., Rothman, N., Lynch, C.F., Graubard, B.I., Sandler, D.P., Alavanja, M.C., Landgren, O., 2021. Lifetime pesticide use and monoclonal gammopathy of undetermined significance in a prospective cohort of male farmers. Environ. Health Perspect. 129 (1), 017003. https://doi.org/10.1289/EHP6960.

IARC, 2016. List of Classifications – IARC Monographs on the Identification of Carcinogenic Hazards to Humans. World Health Organization, International Agency for Research on Cancer. https://monographs.iarc.who.int/list-of-classifications/.

ICH. 2021. *Q2(R1) Validation of Analytical Procedures: Text and Methodology*.

James, W.L., 2014. All rural places are not created equal: revisiting the rural mortality penalty in the United States. Am. J. Public Health 104 (11), 2122–2129. https://doi.org/10.2105/AJPH.2014.301989.

Jiménez-Vélez, B., Detrés, Y., Armstrong, R.A., Gioda, A., 2009. Characterization of African dust (PM2.5) across the Atlantic Ocean during AEROSE 2004. Atmos. Environ. 43 (16), 2659–2664. https://doi.org/10.1016/j.atmosenv.2009.01.045.

Justice40 Initiative. 2022. *Justice40 Tracts, November 2022* (1.0). Council on Environmental Quality, ESRI. https://www.arcgis.com/home/item.html?id=f95344889cab44bd84207052f44cb940

Kallos, G., Astitha, M., Katsafados, P., Spyrou, C., 2007. Long-range transport of anthropogenically and naturally produced particulate matter in the Mediterranean and North Atlantic: current state of knowledge. J. Appl. Meteorol. Climatol. 46 (8), 1230–1251. https://doi.org/10.1175/JAM2530.1.

Karner, A.A., Eisinger, D.S., Niemeier, D.A., 2010. Near-roadway air quality: synthesizing the findings from real-world data. Environ. Sci. Technol. 44 (14), 5334–5344. https://doi.org/10.1021/es100008x.

Li, C., Cao, M., Ma, L., Ye, X., Song, Y., Pan, W., Xu, Z., Ma, X., Lan, Y., Chen, P., Liu, W., Liu, J., Zhou, J., 2018. Pyrethroid pesticide exposure and risk of primary ovarian insufficiency in Chinese women. Environ. Sci. Technol. 52 (5), 3240–3248. https://doi.org/10.1021/ACS.EST.7B06689/ASSET/IMAGES/LARGE/ES-2017-066894_0002.JPEG.

Lucero, B., Muñoz-Quezada, M.T., 2021. Neurobehavioral, neuromotor, and neurocognitive effects in agricultural workers and their children exposed to pyrethroid pesticides: a review. Front. Hum. Neurosci. 15. https://doi.org/10.3389/fnhum.2021.648171.

Lumaret, J.-P., Errouissi, F., Floate, K., Römbke, J., Wardhaugh, K., 2012. A review on the toxicity and non-target effects of macrocyclic lactones in terrestrial and aquatic environments. Curr. Pharm. Biotechnol. 13 (6), 1004. https://doi.org/10.2174/138920112800399257.

McEachran, A.D., Blackwell, B.R., Hanson, J.D., Wooten, K.J., Mayer, G.D., Cox, S.B., Smith, P.N., 2015. Antibiotics, bacteria, and antibiotic resistance genes: aerial transport from cattle feed yards via particulate matter. Environ. Health Perspect. 123 (4), 337–343. https://doi.org/10.1289/ehp.1408555.

Modala, N.R., Ale, S., Goldberg, D.W., Olivares, M., Munster, C.L., Rajan, N., Feagin, R.A., 2017. Climate change projections for the Texas High Plains and Rolling Plains. Theor. Appl. Climatol. 129 (1–2). https://doi.org/10.1007/s00704-016-1773-2.

Modernel, P., Astigarraga, L., Picasso, V., 2013. Global versus local environmental impacts of grazing and confined beef production systems. Environ. Res. Lett. 8 (3), 035052. https://doi.org/10.1088/1748-9326/8/3/035052.

Moser, W., Schindler, C., Keiser, J., 2019. Drug combinations against soil-transmitted helminth infections. Adv. Parasitol. 103, 91–115. https://doi.org/10.1016/BS.APAR.2018.08.002.

Mosier, D., 2015. Review of BRD pathogenesis: the old and the new. Anim. Health Res. Rev. 24 (6). https://doi.org/10.1017/S1466252314000176.
MRLC, 2023. National Land Cover Database (NLCD) 2019 Data Layer. Consortium, Multi-Resolution Land Characteristics (MRLC). https://www.mrlc.gov/data.
Mukherjee, A., Agrawal, M., 2017. World air particulate matter: sources, distribution and health effects. Environ. Chem. Lett. 15 (2), 283–309. https://doi.org/10.1007/s10311-017-0611-9.
OEHHA. 2011. Proposition 65 Proposed Maximum Allowable Dose Level (MADL) for Reproductive Toxicity for Avermectin B1. http://oehha.ca.gov/prop65/CRNR_notices/admin_listing/intent_to_list/pdf_zip/Avermect
Pace, T.G. 2005. Examination of the Multiplier Used to Estimated PM2.5 Fugitive Dust Emissions from PM10. https://gaftp.epa.gov/air/nei/ei_conference/EI14/session5/pace.pdf
Perry, K.D., Cahill, T.A., Eldred, R.A., Dutcher, D.D., Gill, T.E., 1997. Long-range transport of north African dust to the eastern United States. J. Geophys. Res. 102 (D10), 225–236. https://doi.org/10.1029/97JD00260.
Peterson, E.M., Wooten, K.J., Subbiah, S., Anderson, T.A., Longing, S., Smith, P.N., 2017. Agrochemical mixtures detected on wildflowers near cattle feed yards. Environmental Science & Technology Letters 4 (6), 216–220. https://doi.org/10.1021/acs.estlett.7b00123.
Peterson, E.M., Green, F.B., Smith, P.N., 2020. Pesticides used on beef cattle feed yards are aerially transported into the environment via particulate matter. Environ. Sci. Technol. 54 (20), 13008–13015. https://doi.org/10.1021/ACS.EST.0C03603.
Peterson, E.M., Thompson, K.N., Shaw, K.R., Tomlinson, C., Longing, S.D., Smith, P.N., 2021. Use of nest bundles to monitor agrochemical exposure and effects among cavity nesting pollinators. Environ. Pollut. 286, 117142. https://doi.org/10.1016/J.ENVPOL.2021.117142.
Peterson, E.M., Green, F.B., Subbiah, S., Emert, A., Smith, P.N., 2022. Agrochemical occurrence on colocated wildflowers and wild bees collected near beef cattle feed yards and row crops. Integr. Environ. Assess. Manag. 18 (1), 163–173. https://doi.org/10.1002/IEAM.4436.
Pouliot, G., Simon, H., Bhave, P., Tong, D., Mobley, D., Pace, T., & Pierce, T. 2011. *Assessing the Anthropogenic Fugitive Dust Emission Inventory and Temporal Allocation Using an Updated Speciation of Particulate Matter* (pp. 585–589). doi: https://doi.org/10.1007/978-94-007-1359-8_97.
Prichard, R.K., Geary, T.G., 2019. Perspectives on the utility of moxidectin for the control of parasitic nematodes in the face of developing anthelmintic resistance. Int. J. Parasitol. Drugs Drug Resist. 10, 69. https://doi.org/10.1016/J.IJPDDR.2019.06.002.
Priyanka, P.P., Ravula, A.R., Yenugu, S., 2022. A mixture of pyrethroids induces reduced fecundity and increased testicular genotoxicity in rats. Andrologia 54 (11). https://doi.org/10.1111/and.14567.
Qian, X., Gu, J., Sun, W., Wang, X.J., Su, J.Q., Stedfeld, R., 2018. Diversity, abundance, and persistence of antibiotic resistance genes in various types of animal manure following industrial composting. J. Hazard. Mater. 344, 716–722. https://doi.org/10.1016/J.JHAZMAT.2017.11.020.
Ravula, A.R., Yenugu, S., 2021. Effect of oral administration of a mixture of pyrethroids at doses relevant to human exposure on the general and male reproductive physiology in the rat. Ecotoxicol. Environ. Saf. 208. https://doi.org/10.1016/J.ECOENV.2020.111714.
Sacks, J.D., Stanek, L.W., Luben, T.J., Johns, D.O., Buckley, B.J., Brown, J.S., Ross, M., 2011. Particulate matter–induced health effects: who is susceptible? Environ. Health Perspect. 119 (4), 446–454. https://doi.org/10.1289/ehp.1002255.
Sadler, R., Seawright, A., Shaw, G., Dennison, N., Connell, D., Barron, W., White, P., 2005. Bioaccumulation of organochlorine pesticides from contaminated soil by cattle. Toxicol. Environ. Chem. 87 (4), 575–582. https://doi.org/10.1080/02772240500414747.
Sahoo, P.K., Kim, K., Powell, M.A., 2016. Managing groundwater nitrate contamination from livestock farms: implication for nitrate management guidelines. Current Pollution Reports 2 (3), 178–187. https://doi.org/10.1007/S40726-016-0033-5/TABLES/6.
Salman, M., Abbas, R.Z., Mehmood, K., Hussain, R., Shah, S., Faheem, M., Zaheer, T., Abbas, A., Morales, B., Aneva, I., Martínez, J.L., 2022. Assessment of avermectins-induced toxicity in animals. Pharmaceuticals 15 (3), 332. https://doi.org/10.3390/ph15030332.
Sandoz, M.A., Wooten, K.J., Clendening, S.L., Hensley, L.L., Smith, L.R., Smith, P.N., 2018. Transport mechanisms for veterinary pharmaceuticals from beef cattle feedyards to wetlands: is aerial deposition a contributing source? Agric. Ecosyst. Environ. 252, 14–21. https://doi.org/10.1016/j.agee.2017.09.016.
Sands, B., Noll, M., 2022. Toxicity of ivermectin residues in aged farmyard manure to terrestrial and freshwater invertebrates. Insect Conserv. Divers. 15 (1), 9–18. https://doi.org/10.1111/icad.12526.
Shafer, M., Ojima, D., Antle, J. M., Kluck, D., McPherson, R. A., Peterson, S., Scanlon, B., & Sherman, K. 2014). *Ch 19: Great Plains. Climate Change Impacts in the United States: The Third National Climate Assessment* (J. M. Melillo, T. C. Richmond, & G. W. Yohe, Eds.; pp. 441–461). U.S. Global Change Research Program.
Smith, P.N., 2021. The meat of the matter: environmental dissemination of beef cattle agrochemicals. Environ. Toxicol. Chem. 40 (4), 965–966. https://doi.org/10.1002/etc.4965.
Soderlund, D.M., 2012. Molecular mechanisms of pyrethroid insecticide neurotoxicity: recent advances. Arch. Toxicol. 86 (2), 165. https://doi.org/10.1007/S00204-011-0726-X.
Song, J., Ma, X., Li, F., Liu, J., 2022. Exposure to multiple pyrethroid insecticides affects ovarian follicular development via modifying microRNA expression. Sci. Total Environ. 828, 154384. https://doi.org/10.1016/j.scitotenv.2022.154384.
Sweeten, J.M., Parnell Jr., C.B., Shaw, B.W., Auvermann, B.W., 1998. Particle size distribution of cattle feedlot dust emission. Transactions of the ASAE 41 (5), 1477–1481. https://doi.org/10.13031/2013.17297.
TCEQ. 2023. TCEQ - WQ General Permits Search. https://www2.tceq.texas.gov/wq_dpa/index.cfm
Tinkler, S.H., 2020. Preventive chemotherapy and anthelmintic resistance of soil-transmitted helminths – can we learn nothing from veterinary medicine? One Health 9, 100106. https://doi.org/10.1016/J.ONEHLT.2019.100106.
Todd, G.D., 2003. Toxicological profile for pyrethrins and pyrethroids. https://www.atsdr.cdc.gov/toxprofiles/tp155.pdf.
U.S. Census Bureau, 2020. 2020 U.S. Census Data. https://data.census.gov/.
U.S. EPA. 2004. Risk Assessment Evaluation for Concentrated Animal Feeding Operations. https://nepis.epa.gov/Exe/ZyPDF.cgi/901V0100.PDF?Dockey=901V0100.pdf
U.S. EPA, 2005. EPA/630/P-03/001F. Guidelines for Carcinogen Risk Assessment https://www.epa.gov/sites/default/files/2013-09/documents/cancer_guidelines_final_3-25-05.pdf.
U.S. EPA. 2011. Pyrethrins/*Pyrethroid Cumulative Risk Assessment.* https://www.regulations.gov/document/EPA-HQ-OPP-2011-0746-0003
U.S. EPA. 2012. Standard Operating Procedures for Residential Pesticide Exposure Assessment. https://www.epa.gov/sites/default/files/2015-08/documents/usepa-opp-hed_residential_sops_oct2012.pdf
U.S. EPA. 2016. DP No. D454372. Cyphenothrin. Updated Human Health Draft Risk Assessment in Support of Registration Review. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0842-0066
U.S. EPA, 2017a. DP No. 414137. Human Health Draft Risk Assessment for Registration Review, Permethrin. https://www.regulations.gov/document/EPA-HQ-OPP-2011-0039-0088.
U.S. EPA. 2017b. DP No. D442232. Avermectin Macrocyclic Lactones, Abamectin and Emamectin. Cumulative Screening Risk Assessment. https://www.regulations.gov/document?D=EPA-HQ-OPP-2015-0422-0019
U.S. EPA. 2019a. DP No. D453560. Cyfluthrins. Revised Human Health Draft Risk Assessment for Registration Review. https://www.regulations.gov/document/EPA-HQ-OPP-2010-0684-0114
U.S. EPA. 2019b. Pyrethroids: Tier II Epidemiology Report. https://www3.epa.gov/pesticides/EPA-HQ-OPP-2008-0316-DRAFT-0075.pdf
U.S. EPA, 2020a. DP no. D453647. Cypermethrin, zeta-cypermethrin, and alpha-cypermethrin. Revised human health risk assessment for registration review. https://www.regulations.gov/document/EPA-HQ-OPP-2012-0167-0145.
U.S. EPA, 2020b. DP no. 454914. Bifenthrin: revised occupational and residential exposure and risk assessment for registration review. https://www.regulations.gov/document/EPA-HQ-OPP-2010-0384-0282.
U.S. EPA, 2020c. DP No. D455077. Updated Human Health Draft Risk Assessment in Support of Registration Review, Esfenvalerate. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0301-0125.
U.S. EPA. 2022a. Chemicals Evaluated for Carcinogenic Potential by the Office of Pesticide Programs. https://www.epa.gov/risk/guidelines-carcinogen-risk-assessment
U.S. EPA. 2022b, July 14. National Air Emissions Monitoring Study (NAEMS). https://www.epa.gov/afos-air/national-air-emissions-monitoring-study
U.S. EPA, 2023a. Particulate Matter (PM) Standards - Table of Historical PM NAAQS. Environmental Protection Agency, U.S. https://www3.epa.gov/ttn/naaqs/standards/pm/s_pm_history.html.
U.S. EPA, 2023b. CERCLA and EPCRA Reporting Requirements for Air Releases of Hazardous Substances from Animal Waste at Farms. United States Environmental Protection Agency https://www.epa.gov/epcra/cercla-and-epcra-reporting-requirements-air-releases-hazardous-substances-animal-waste-farms.
U.S. EPA. 2023c. ECHO: Enforcement and Compliance History Online. https://echo.epa.gov/
U.S. EPA. 2023d. EJScreen: Environmental Justice Screening and Mapping Tool. https://www.epa.gov/ejscreen
USDA NASS, 2022. USDA National Agricultural Statistics Service cropland data layer. https://nassgeodata.gmu.edu/CropScape/.
USDA NASS. 2023, January 17. 2022 - Cattle, Cows, Beef - Inventory - Measured in Head - on Jan 1. U.S. Department of Agriculture, National Agricultural Statistical Services. https://app.usda-reports.penguinlabs.net/?crop=cattle_cows_beef&statistic=inventory_head&yearet=&year=2022.
Vyavhare, S.S., Kerns, D., 2022. Managing cotton insects in Texas. https://lubbock.tamu.edu/files/2022/07/managing-cotton-insects-in-texas.pdf.
Wooten, K.J., Sandoz, M.A., Smith, P.N., 2018. Ractopamine in particulate matter emitted from beef cattle feedyards and playa wetlands in the Central Plains. Environ. Toxicol. Chem. 37 (4), 970–974. https://doi.org/10.1002/ETC.4036.
WTM. 2022. West Texas Mesonet. https://www.mesonet.ttu.edu/
Yates, S.R., McConnell, L.L., Hapeman, C.J., Papiernik, S.K., Gao, S., Trabue, S.L., 2011. Managing agricultural emissions to the atmosphere: state of the science, fate and mitigation, and identifying research gaps. J. Environ. Qual. 40 (5), 1347–1358. https://doi.org/10.2134/jeq2011.0142.
Zhao, L., Dong, Y.H., Wang, H., 2010. Residues of veterinary antibiotics in manures from feedlot livestock in eight provinces of China. Sci. Total Environ. 408 (5), 1069–1075. https://doi.org/10.1016/J.SCITOTENV.2009.11.014.

Ammonia

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Overview

- Checklist of Sources, Site Evidence and Biological Effects
  - Consider Listing Ammonia as a Candidate Cause
  - Consider Contributing, Modifying and Related Factors as Candidate Causes
  - Consider Not Listing (Eliminating) Ammonia as a Candidate Cause

Ammonia (NH_3) is a common toxicant derived from wastes (see Figure 1), fertilizers and natural processes. Ammonia nitrogen includes both the ionized form (ammonium, NH_4^+) and the unionized form (ammonia, NH_3). An increase in pH favors formation of the more toxic unionized form (NH_3), while a decrease favors the ionized (NH_4^+) form. Temperature also affects the toxicity of ammonia to aquatic life.



Figure 1. Landfill settling pond.

Ammonia is a common cause of fish kills. However, the most common problems associated with ammonia relate to elevated concentrations affecting fish growth, gill condition, organ weights and hematocrit (Milne et al. 2000). Exposure duration and frequency strongly influence the severity of effects (Milne et al. 2000).

Ammonia in sediments typically results from bacterial decomposition of organic matter that accumulates in sediment. Sediment microbiota mineralize organic nitrogen or (less commonly) produce ammonia by dissimilatory nitrate reduction. Ammonia is especially prevalent in anoxic sediments because nitrification (the oxidation of ammonia to nitrite [NO_2^-] and nitrate [NO_3^-]) is inhibited. Ammonia generated in sediment may be toxic to benthic or surface water biota (Lapota et al. 2000).

Ammonia also exerts a biochemical oxygen demand on receiving waters (referred to as nitrogenous biological oxygen demand or NBOD). This occurs because dissolved oxygen is consumed as bacteria and other microbes oxidize ammonia into nitrite and nitrate. The resulting dissolved oxygen reductions can decrease species diversity and even cause fish kills.

Additionally, ammonia can lead to heavy plant growth (eutrophication) due to its nutrient properties (see the Nutrients module). Algae and macrophytes take up ammonia, thereby reducing aqueous concentrations.

Checklist of Sources, Site Evidence and Biological Effects

This module addresses ammonia as a proximate stressor with a toxic mode of action. Its nutrient properties are considered in the Nutrients module.

Ammonia should be a candidate cause when human sources and activities, site observations or observed biological effects support portions of the source-to-impairment pathways (see Figure 2).

The checklist below will help you identify key data and information useful for determining whether to include ammonia among your candidate causes. The list is intended to guide you in collecting evidence to support, weaken or eliminate ammonia as a candidate cause.
For more information on specific entries, go to the *When to List* tab.

Consider listing ammonia as a candidate cause when the following sources and activities, site evidence and biological effects are present:

Sources and Activities

- Impoundments
- Municipal waste treatment outfalls
- Septic seepage
- Industrial point sources
- Agricultural and urban runoff (fertilizer)
- Manure application
- Concentrated animal feeding operations
- Aquaculture
- Landfill leachate
- Atmospheric sources
- Riparian devegetation

<https://epa.gov/sites/default/files/2015-11/ammoniacd_sim_1000.jpg>

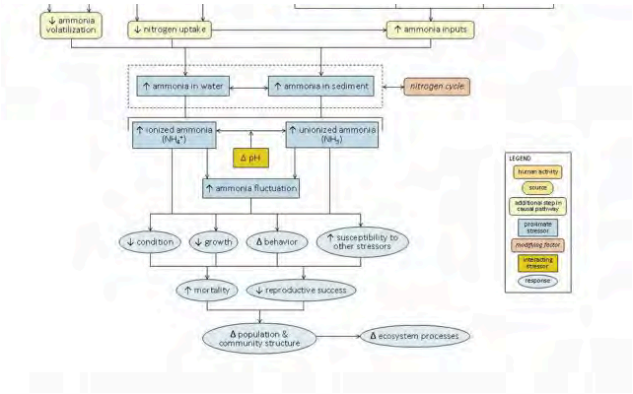

Figure 2. A simple conceptual diagram illustrating causal pathways, from sources to impairments, related to ammonia. Click on the diagram to view a larger version.

Site Evidence

- Slow-moving or stagnant water
- High density of fish
- Presence of organic waste
- Foul odor
- Presence of organic suspended solids or floc
- Alkaline, anoxic or warm water
- High plant production (e.g., algal blooms)

Biological Effects

- Reduction or absence of ammonia-sensitive species
- Physiological effects (e.g., decreased nitrogen excretion, decreased oxygen binding to hemoglobin)
- Behavioral effects (e.g., loss of equilibrium, hyperexcitability, increased breathing)

- Morphological effects (e.g., proliferation of gill lamellae, reduction of lymphoid tissue in the spleen, lesions in blood vessels, mucus secretion)
- Organismal and population effects (e.g., decreased growth and abundance, mass mortality)

Consider contributing, modifying and related factors as candidate causes when ammonia is selected as a candidate cause:

- **Temperature:** Toxicity of ammonia (as total ammonia) increases as temperature increases (U.S. EPA 1999).
- **pH:** Ammonia concentration and toxicity increases as pH increases, although less ammonia is required to produce toxic effects at lower pH (IPCS 1986, Wurts 2003).
- **Dissolved oxygen:** Oxygen is consumed as ammonia is oxidized (nitrification), and low oxygen levels increase ammonia levels by inhibiting nitrification.
- **Season:** Total ammonia-nitrogen concentration in surface waters tends to be lower during summer than during winter. This is due to uptake by plants and decreased ammonia solubility at higher water temperatures (IPCS 1986).
- **Ionic strength:** Tolerance to ammonia can increase with an increase in ionic strength or salinity (Sampaio et al. 2002).
- **Sediments:** Fine sediments tend to generate ammonia due to low oxygen levels and high organic matter.

Consider not listing (eliminating) ammonia as a candidate cause when you have the following evidence at your site:

- Concentrations measured continuously over time at the site are the same as or less than ammonia at sites without observed biological impairment (*lack of co-occurrence*).
- All life stages of ammonia-sensitive species are present at the site.

When to List

- Sources and Activities that Suggest Listing Ammonia as a Candidate Cause
- Site Evidence that Suggests Listing Ammonia as a Candidate Cause
- Biological Effects that Suggest Listing Ammonia as a Candidate Cause
- Site Evidence that Supports Excluding Ammonia as a Candidate Cause

Sources and Activities that Suggest Listing Ammonia as a Candidate Cause

The amount of ammonia in surface waters is influenced by many human activities in waterbodies and their associated watersheds. The more extensive the relevant sources and activities, the more likely it is that ammonia will reach concentrations that can impair surface waters.

- **Impoundments**: Impoundment of water may contribute to elevated ammonia concentrations. Lack of turbulence and mixing will decrease volatilization of ammonia, resulting in higher ammonia concentrations downstream. Thermal stratification in impoundments can lead to higher concentrations of ammonia in the hypolimnion which, with bottom-release dams, can result in increased ammonia in downstream waters.
- **Municipal waste treatment plants**: Municipal waste treatment plants and public-owned treatment works (POTWs) process domestic waste and are operated to comply with permit limits designed to protect receiving waterbodies from excess inputs of pollutants such as ammonia (Constable et al. 2003). However, during storms, excess flow may be diverted into combined sewer overflows (CSOs) that deposit untreated municipal waste directly into streams and lakes. Treatment plant failures also may result in high ammonia releases to streams (see Figure 3).
- **Septic seepage and failed package plants**: Seepage from failed septic tanks or their leach fields, and discharges from poorly–functioning package sewage treatment plants may contribute significant amounts of ammonia to streams and lakes.



Figure 3. Discharge from a wastewater treatment plant. Photo courtesy of USGS Toxic Substances Hydrology Program Photo Gallery

- **Industrial point source**: Certain industries release ammonia as a byproduct in their waste stream. These end-of-pipe discharges are regulated via permit limits to protect receiving waterbodies, but where the original system design is inadequate or problems in operation lead to inadequately treated discharges, increased ammonia concentrations result. This is especially an issue for industries that produce ammonia, aminated organic matter, or other nitrogenous wastes such as food processing (e.g., poultry, livestock, or seafood), pharmaceutical manufacturing (e.g., fermentation processes), paper mills, and flue gas treatment in coal-fired power plants.
- **Agricultural and urban runoff**: Runoff and leachate from agricultural, recreational (e.g., golf courses) or residential fertilizer use can directly increase the amount of ammonia in surface water (see Figure 4).
- **Manure application**: Manure containing ammonia and other nitrogenous compounds often is spread on fields and then washed into streams and other water bodies by rain or snow melt. Grazing livestock spread urine and manure on pastures and, where they have access to streams, they apply urine and manure directly to water.



Figure 4. Agricultural runoff. Photo courtesy of NOAA Ocean Service Education

- **Concentrated animal feeding operations**: Runoff from feedlots and other concentrated animal feeding operations can contain high levels of ammonia and other nitrogenous compounds.
- **Aquaculture**: Drainage from fish and shrimp farms is high in ammonia if not properly treated.
- **Landfills**: Leachate from landfills may contain high ammonia concentrations (Mancl and Veenhuizen 1991).
- **Atmospheric sources**: These sources include ammonia originating from agricultural practices and nitrogen oxide emissions from automobiles and industry (NOAA 2000). These are regionally important sources, but are seldom indicative of particular impairments.

- **Riparian devegetation**: The removal of vegetation from the banks of surface waters increases surface water runoff and water temperature and decreases woody debris input. Increased surface water runoff may increase the amount of ammonia directly entering the waterbody. Increased water temperature enhances the toxicity of ammonia. Reduced turbulence from less woody debris may decrease volatilization and oxygenation.
- **High plant production**: High algal or plant production can decrease ammonia by assimilation, increase ammonia by nitrogen fixation, or increase pH toxicity by CO_2 uptake, resulting in a shift to more unionized ammonia.

Site Evidence that Suggests Listing Ammonia as a Candidate Cause

In addition to observations of the sources discussed above, observational evidence at the site may suggest that high ammonia should be included as a potential candidate cause:



Figure 5. A flood control impoundment along Los Gatos Creek in Campbell, CA. Courtesy of USGS

Slow-moving water: Slow-moving or stagnant water (see Figure 5) may have high ammonia concentrations because of lack of turbulence and volatilization and greater accumulation of metabolic waste and decomposition products—including ammonia (WHO 1986).

High density of fish: Reduced stream flow may concentrate fish into pools or other refugia, concentrating waste excretion and elevating ammonia concentrations.

Presence of organic wastes: Organic wastes are the remains of any once-living organism or their excrement. Excrement and sewage are high in ammonia, so signs of such material in a waterbody may suggest ammonia as a candidate cause. In contrast, plant material is typically low in nitrogen, and associated decomposers may take up ammonia and reduce its aqueous concentration. Identifying the type of organic waste present in a waterbody will aid in identifying candidate causes. Excessive organic wastes in water may result in a grayish cast with visible sludge deposits in depositional areas.

Foul odor: Ammonia as a gas has a characteristically pungent odor (think of window and floor cleaners). Ammonia concentrations in streams are rarely high enough to exhibit this odor, but water that has a foul, septic or organic-waste smell may have relatively high concentrations of ammonia.

Suspended solids: Suspended solids from wastewater effluents or runoff can contain high ammonia or act as catalysts for bacterial growth promoting accumulation of ammonia. Identifying the type of suspended material present is important in identifying candidate causes.

Alkaline, anoxic or warm water: Water characteristics that promote ammonia formation (e.g., anoxia) or increase toxicity (e.g., high pH and temperature) are signs that ammonia may be a cause.

Biological Effects that Suggest Listing Ammonia as a Candidate Cause

Unionized ammonia is very toxic to aquatic animals, particularly fish, because it can readily diffuse across gill membranes (Sampaio et al. 2002). Ionized ammonia does not pass as easily through gill membranes, so it is appreciably less toxic than the unionized form (Camargo and Alonso 2006). In most fish, ammonia is excreted by passive diffusion of ammonia across the gills according to its partial pressure gradient (Wilson et al. 1998). Disruption of this gradient causes internal ammonia concentrations to increase, affecting internal organs, nervous system function, and respiration.

Reduction in ammonia-sensitive species and processes: Salmonids tend to be particularly sensitive in acute exposures associated with episodic sources. However, sensitivities to chronic exposures are less taxonomically consistent. In particular, the most sensitive fish genus used to derive the chronic water quality criterion is the sunfish (*Lepomis* spp.) (U.S. EPA 1999).

Early life stages of fish are more sensitive than juveniles or adults. Hence, effects are more likely to occur during seasons when early life stages are present.

Invertebrates, particularly arthropods, are generally less susceptible than fish. Hence, observations that fish are more affected than invertebrates are consistent with ammonia as a cause. However, recent information suggests that certain freshwater

mussels (Unionidae)—particularly the glochidia and juvenile stages—are very sensitive to ammonia (Newton and Bartsch 2006).

Unionized ammonia can cause toxicity to *Nitrosomonas* and *Nitrobacter* bacteria, inhibiting the nitrification process. This inhibition can result in increased ammonia accumulation in the aquatic environment, intensifying the level of toxicity to bacteria and aquatic animals (Carmargo and Alonso 2006).

Physiological, morphological and behavioral effects: Specific biotic effects suggesting that you consider ammonia as a candidate cause are described in Table 1. Please note, however, that observation of these effects does not confirm a causal relationship. In some cases the same observed effect could be caused by other stressors or multiple agents. If you suspect ammonia as the cause of observed biological impairments, then also consider pH, temperature, and low dissolved oxygen —stressors often associated with and contributing to ammonia concentrations.

Table 1. Physiological, Morphological and Behavioral Effects of Elevated Ammonia in Fish

Effects	Reference
Decreased respiratory function causing hyperventilation	Lease et al. 2003, Twitchen and Eddy 1994, IPCS 1986
Impairment of nerve function; peripheral and central nervous system effects causing hyperexcitability	Sampaio et al. 2002, Twitchen and Eddy 1994, IPCS 1986
Convulsions	Twitchen and Eddy 1994, IPCS 1986
Coma	Twitchen and Eddy 1994, IPCS 1986
Damage to gill epithelia causing asphyxiation	Lang et al. 1987
Proliferation of gill tissue	Lang et al. 1987

Effects	Reference
Stimulation of glycolysis and suppression of Krebs cycle, causing progressive acidosis and reduction in blood oxygen-carrying capacity	Camargo and Alonso 2007
Uncoupling of oxidative phosphorylation, causing inhibition of ATP production and depletion of ATP in the basilar region of the brain	Camargo and Alonso 2007, Sampaio et al. 2002
Disruption of blood vessels and osmoregulatory activity, causing stress to the liver and kidneys	Camargo and Alonso 2007, Sampaio et al. 2002, Bosakowski and Wagner 1994
Repression of immune system, causing increased susceptibility to bacteria and parasitic diseases	Camargo and Alonso 2007, Sampaio et al. 2002
Reduction of Na^+ to potentially fatally low levels	Twitchen and Eddy 1994

Organismal and population level effects: The above effects may lead to organismal and population level effects, including:

- Reduced growth rate
- Reduced feeding activity
- Reduced fecundity and reproductive success
- Decreased population size
- Increased mortality (e.g., fish kills)
- Increased fish fin erosion

Site Evidence that Supports Excluding Ammonia as a Candidate Cause

Advice on excluding ammonia as a candidate cause is limited to situations in which the physical and chemical characteristics of a site prevent ammonia from logically accounting for the impairment. Thus, a lack of obvious sources and site observations cannot be used to eliminate ammonia as a candidate cause. However, a lack of sources or other evidence may be used to defer consideration of ammonia if other candidate causes are supported.

Sources: Spillways, waterfalls and turbulent flows in streams and rivers naturally volatilize ammonia. Thus, high concentrations of ammonia are physically precluded by consistent volatilization from turbulence. However, ammonia concentrations will be affected if flow changes during the year, and this should be considered. Screening in these situations should be supplemented with measures of ammonia concentrations.

Site observations: We caution against using benchmarks of effects for excluding ammonia from your initial list of candidate causes, because different species have different ammonia tolerances and concentrations are seldom well-characterized. Table 2 provides example toxicity values for selected species with both acute and chronic values from the current Water Quality Criteria for Ammonia (U.S. EPA 1999).

Table 2. Representative Species Mean Acute Values[a] and Species Mean Chronic Values[b] Used to Derive Ambient Water Quality Criteria for Ammonia (U.S. EPA 1999)

Species	Mean Acute Value (mg N/L)	Mean Chronic Value (mg N/L)
Cladoceran, *Daphnia magna*	35.76	12.3
Clam, *Musculium transversum*	35.65	2.26
Fish, *Pimephales promelas*	43.55	3.09
Channel catfish, *Ictalurus punctatus*	34.44	8.84

Species	Mean Acute Value (mg N/L)	Mean Chronic Value (mg N/L)
[a] LC_{50} or EC_{50} means [b] Means of geometric means of NOECs and LOECs at pH = 8, 25°C		

Ways to Measure

The concentration of ammonia in water is measured as total ammonia and is usually reported in mg/L. The concentration of unionized ammonia (NH_3) is derived from well-established formulas (see link to calculator below). When differentiating between unionized and ionized ammonia, it is important to take into account the effects of temperature and pH (Eaton et al. 2005).

- **Ammonia probe**: A measuring probe is connected to an electronic ion meter that measures and displays the voltage resulting from ammonia, which is then converted to concentration using a standard curve.
- **Colorimeter**: One or more reagents are added in timed intervals to the sample, such that the intensity of the color produced is proportional to the ammonia that reacts with the reagent. This color absorbance then is measured using a colorimeter or spectrophotometer. Blanks and standards are used to generate a standard curve from which the sample absorbance reading is converted to ammonia concentration.

The fraction of unionized ammonia (NH_3) is not directly measured, but instead is calculated using measures of total ammonia, pH, temperature, and ionic strength (measured either in terms of total dissolved solids or conductivity). The American Fisheries Society has developed an ammonia calculator (Table 9 on the referenced web page should be downloaded) for this purpose. Once the required data are entered, the tool will calculate the amount of unionized ammonia in both mg/L and µg/L.

- Fish Hatchery Management Calculators - Table 9, Ammonia Calculator <https://fishculture.fisheries.org/resources/fish-hatchery-management-calculators/>

Conceptual Diagrams

- About Conceptual Diagrams
- Simple Conceptual Model Diagram

- Detailed Conceptual Model Diagram

About Conceptual Diagrams

Conceptual diagrams are used to describe hypothesized relationships among sources, stressors and biotic responses within aquatic systems.

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Simple Conceptual Model Diagram

Many human activities and associated sources can contribute to high ammonia concentrations in aquatic systems, which can lead to lethal and sub-lethal effects on aquatic organisms. Channel alteration can result in decreased nitrogen uptake within the stream, while decreases in riparian and watershed vegetation associated with agriculture and urbanization can reduce nitrogen uptake in the surrounding landscape. Channel alteration and water withdrawals can reduce ammonia volatilization due to changes in water velocities and depths.

<https://epa.gov/sites/default/files/2015-11/ammoniacd_sim_1000.jpg>

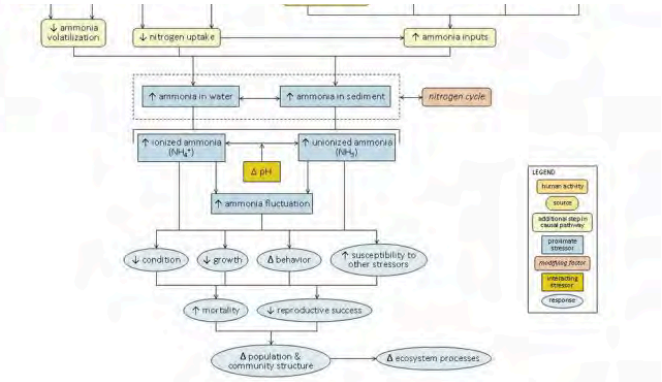

Figure 2. A simple conceptual diagram illustrating causal pathways, from sources to impairments, related to ammonia. Click on the diagram to view a larger version.

Sources associated with agriculture, urbanization, industry and aquaculture also can directly increase ammonia inputs to aquatic systems via four main transport pathways (or transport-defined sources): stormwater runoff, leakage or leachate into groundwater sources, atmospheric emissions and deposition, or direct effluent discharges (see Figure 6).

Ammonia is a key component of the nitrogen cycle in streams, where it may be dissolved in the water column or associated with sediments. At high

enough concentrations, ammonia can be toxic to aquatic organisms. In general, unionized ammonia (NH_3) is the form most toxic to aquatic biota. The relative contribution of unionized versus ionized forms to total ammonia concentrations depends on certain water quality criteria, most notably pH: as pH increases, so does the proportion of ammonia in its unionized form.

The Nitrogen Cycle in Streams

Increased ammonia concentrations or fluctuations within streams can result in decreased condition, decreased growth, altered behavior, increased susceptibility to other stressors, increased mortality, and decreased reproductive success in affected biota, and ultimately may alter population and community structure and ecosystem function (Figure 7).

Detailed Conceptual Model Diagram

<https://epa.gov/sites/default/files/2015-11/nitrogen_cycle.png>

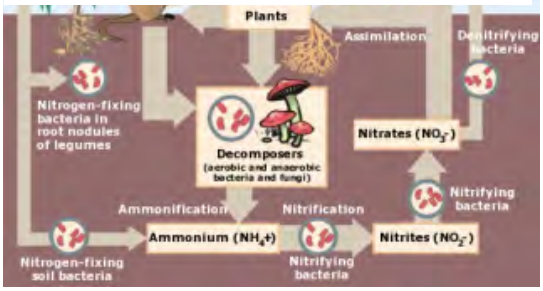

Figure 7. Illustration of the pathways of nitrogen.

High concentrations of ammonia in aquatic systems can have lethal and sub-lethal effects on aquatic organisms, potentially changing community structure and ecosystem function. This

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- Simple and Detailed Conceptual Diagrams <https://epa.gov/node/163779/>
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- Detailed Conceptual Diagram (PPT) (ppt) <https://www.epa.gov/sites/default/files/2016-04/ammonia_detailed_conceptual_diagram_ppt.ppt> (214 KB)

conceptual diagram (Figure 8) illustrates linkages between ammonia-related stressors (middle of diagram), the human activities and sources that can increase those stressors (top of diagram), and the biological responses that can result (bottom of diagram).

In some cases, additional steps leading from sources to stressors, modes of action leading from stressors to responses, and other modifying factors also are shown. This narrative generally follows the diagram top to bottom, left to right.

Linking Sources and Activities to Proximate Stressors

<https://epa.gov/sites/default/files/2015-11/ammoniacd_det_500.jpg>

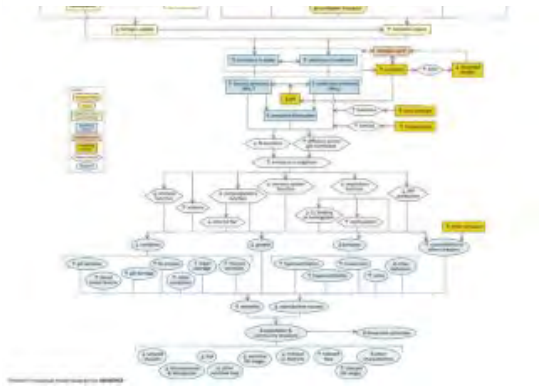

Figure 8. Example of a detailed conceptual diagram for ammonia. Click on the diagram to view a larger version.

Channel alteration can increase ammonia concentrations in several ways. Alterations that reduce channel complexity (e.g., piping or channelizing streams) can result in decreased nitrogen uptake. Impoundment of stream channels can result in decreased ammonia volatilization upstream of impoundments, due to decreased water velocities (and increased water depths). Reduced water flows downstream of impoundments (or in streams affected by water withdrawals) can limit habitat availability, crowding biota and concentrating ammonia-rich waste products.

Many human activities and land uses also decrease riparian and watershed vegetation, which may decrease the amount of nitrogen taken up by terrestrial plants, and further reduce channel complexity due to reduced woody debris inputs.

Certain human activities and land uses can directly introduce ammonia into aquatic systems, and in many cases ammonia-related impairments are only seen when these direct discharges are present. Sources associated with agriculture include animal wastes from concentrated animal feeding operations (CAFOs), other livestock operations, and aquaculture facilities, as well as fertilizers applied to cropfields.

Sources associated with urban and suburban development include fertilizers applied to golf courses and lawns; human wastes from sewer and septic systems and wastewater treatment plants; landfill wastes; and nitrogenous vehicle emissions.

Industries (e.g., coal-fired power plants and other industrial facilities) also may release ammonia to the environment. Ammonia from these sources can be introduced into aquatic systems via four main transport pathways (or transport-defined sources): stormwater runoff, leakage or leachate into groundwater sources, atmospheric emissions and deposition, or direct effluent discharges. Each of these transport-defined sources can lead to increased ammonia inputs into surface waters.

In streams, ammonia may be dissolved in the water column or associated with sediments. At non-toxic concentrations, ammonia acts as a nutrient and can stimulate microbial and plant production (see the nutrient module for more information on these pathways). Ammonia concentrations also will depend upon the nitrogen cycle, or the transformation of nitrogen among different oxidation states. This cycle is dependent on microbial activity and dissolved oxygen levels, so these factors play an important role in determining ammonia concentrations.

At high enough concentrations, ammonia can be toxic to aquatic organisms. In general, unionized ammonia (NH_3) is the form most toxic to aquatic biota. The relative contribution of unionized versus ionized forms to total ammonia concentrations depends on certain water quality criteria, most notably pH: as pH increases, so does the proportion of ammonia in its unionized form. Stressors such as ionic strength and temperature also may influence ammonia toxicity, through their effects on ammonia tolerance and toxicity.

Linking Proximate Stressors to Biological Responses

When ammonia concentrations or fluctuations increase within streams, ammonia concentrations within aquatic organisms may rise owing to reduced nitrogen excretion and increased diffusion of ammonia across gill membranes. Increases in internal ammonia concentrations can have several detrimental effects, including reduced immune, osmoregulatory, nervous system and respiratory function. For example, Na^+ efflux rates are elevated in the presence of ammonia, and fish must increase Na^+ influx to remain in Na^+ balance.

These different modes of action all may contribute to decreased condition, decreased growth, altered behavior and increased susceptibility to other stressors in affected biota. For example, increased ammonia concentrations may result in increased gill and organ damage, increased fin erosion, or increased mucous secretion in fish; possible changes in behavior include hyperexcitability, hyperventilation and convulsions.

Ultimately, these effects may result in changes in population and community structure and ecosystem function. For example, taxa particularly sensitive to unionized ammonia, such as unionid mussels and fish, may decrease, while more tolerant organisms become more dominant.

Literature Reviews

This section presents an annotated bibliography of references providing information on stressor-response relationships for ammonia, as well as general background information. This is not meant to be a comprehensive bibliography of references dealing with ammonia, but rather is meant to highlight a few references that may be especially useful.

- Camargo J, Alonso A (2006) Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. Environment International 32:831-849.

This paper discusses three major effects of inorganic nitrogen pollution, in the form of NH_4^+, NH_3, NO_2^-, HNO_2, and NO_3-, in detail: acidification of freshwater ecosystems without a large acid-neutralizing capacity, proliferation of primary producers causing eutrophication, and toxicity to aquatic vertebrates and invertebrates. The paper also describes human health and economic risks of inorganic nitrogen pollution.

- Camargo J, Alonso A (2007) Inorganic nitrogen pollution in aquatic ecosystems: causes and consequences. The Encyclopedia of Earth Web site.

This document discusses the effects of the increasing inorganic nitrogen pollution. The document explains about acidification of freshwater ecosystems, eutrophication, toxic algae, toxicity of inorganic nitrogen, in the form of NH_4^+, NH_3, NO_2^-, and NO_3^-, to aquatic organisms and its adverse effects on human health.

- Clement B, Merlin G (1995) The contribution of ammonia and alkalinity to landfill leachate toxicity to duckweed. Science of the Total Environment 170:71-79.

This study uses toxicity testing to determine if ammonia and alkalinity are major factors in the toxicity of landfill leachate to duckweed. Landfill leachate samples are collected and used in the toxicity tests with different pH values. In addition, some leachate samples were stripped of ammonia and used to help identify effects due to ammonia.

- Constable M, Charlton M, Jensen F, McDonald K, Craig G, Taylor K (2003) An ecological risk assessment of ammonia in the aquatic environment. Human and Ecological Risk Assessment 9(2):527-548.

This paper is a case study that investigates the potential for lethal and sub-lethal effects to a mix of vertebrate and invertebrate species in freshwater bodies in Canada. The Red River and Hamilton Harbor both have numerous municipal wastewater treatment plants discharging into them, and have shown high levels of ammonia in the past. The paper includes several aquatic community risk models that were designed to show species sensitivities to ammonia.

- Diamond J, Mackler D, Rasnake W, Gruber D (1993) Derivation of site-specific ammonia criteria for an effluent-dominated headwater stream. Environmental Toxicology and Chemistry 12:649-658.

This paper looks at the range of sensitivities to ammonia for several vertebrate and invertebrate species that inhabit the eastern shore of the United States. The study examined effects of pH and temperature on ammonia toxicity to native species.

- Environment Canada and Health Canada (2001) Priority Substances List Assessment Report for Ammonia in the Aquatic Environment <https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/environmental-contaminants/canadian-environmental-protection-act-1999-priority-substances-list-assessment-report-ammonia-aquatic-environment.html>. Minister of Public Works and Government Services, Canada. [Archived]

This document thoroughly discusses the basic properties, sources, and effects of ammonia to the aquatic environment of Canada.

- IPCS (International Programme on Chemical Safety) (1986) Environmental Health Criteria 54: Ammonia <http://www.inchem.org/documents/ehc/ehc/ehc54.htm>. United National Environment Programme, International Labour Organisation, World Health Organization.

This document gives an overall detailed review of ammonia. Its topics range from chemical properties to environmental and human exposure effects.

- Scott D, Lucas M, Wilson R (2005) The effect of high pH on ion balance, nitrogen excretion and behavior in freshwater fish from a eutrophic lake: a laboratory and field study. Aquatic Toxicology 73:31-43.

This paper focuses on the effect of summer blooms of cyanobacteria and increasing pH in the Slapton Ley, a freshwater hyper-eutrophic lake, to nonsalmonid species of fish. The summer blooms of cyanobacteria and increase in pH were said to be associated with intensification of effects from agriculture and wastewater treatment plants, in part due to NH_3.

- Stumm W, Morgan JJ (1996) Aquatic Chemistry. Wiley-Interscience, New York NY.

This standard text in limnochemistry provides a good explanation of the chemistry of ammonia in surface waters.

- U.S. EPA (1999) 1999 Update of Ambient Water Quality Criteria for Ammonia. U.S. Environmental Protection Agency, Washington DC. EPA-822-R-99-014. 153 pp.

This document provides an update to the 1998 update of the ambient water quality criteria for ammonia. It reviews acute and chronic toxicity of ammonia to freshwater organisms.

- Webster J, Mulholland P, Tank J, Valett M, Dodds W, Peterson B, Bowden W, Dahm C, Findlay S, Gregory S, Grimm N, Hamilton S, Johnson S, Marti E, McDowell W, Meyer J, Morrall D, Thomas S, Wollheim W (2003) Factors affecting ammonium uptake in streams: an inter-biome perspective. Freshwater Biology 48:1329-1352.

This paper discusses the Lotic Intersite Nitrogen eXperiment (LINX), which was an effort to find out how different physical, chemical, and biological process in streams affect ammonium uptake. The study looked at 11 stream sites, ranging from Alaska to Puerto

Rico. At each site ammonium was introduced at the upstream portion of the study reach. Timed samples were then collected at the downstream portion of the reach, and the data from all 11 regions were compared.

- Webster J, Swank W (1985) Within-stream factors affecting nutrient transport from forested and logged watersheds. in: Blackmon R (Eds). Proceedings of Forester and Water Quality: A Mid-South Symposium. University of Arkansas.

This paper describes nutrient uptake by means of autotrophic and heterotrophic processes, macroinvertebrate particle generation, and retention of dissolved and particulate nutrients by woody debris. The study focuses on the effect of logging and the resulting change in physical stream characteristics on nutrient input and uptake.

References

- Bosakowski T, Wagner EJ (1994) A survey of trout fin erosion, water quality, and rearing conditions at state fish hatcheries in Utah. Journal of the World Aquaculture Society 25(2):308-316.
- Camargo J, Alonso A (2006) Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. Environment International 32:831-849.
- Camargo J, Alonso A (2007) Inorganic nitrogen pollution in aquatic ecosystems: causes and consequences. The Encyclopedia of Earth Web site.
- Clement B, Merlin G (1995) The contribution of ammonia and alkalinity to landfill leachate toxicity to duckweed. Science of the Total Environment 170:71-79.
- Constable M, Charlton M, Jensen F, McDonald K, Craig G, Taylor K (2003) An ecological risk assessment of ammonia in the aquatic environment. Human and Ecological Risk Assessment 9(2):527-548.
- Diamond J, Mackler D, Rasnake W, Gruber D (1993) Derivation of site-specific ammonia criteria for an effluent-dominated headwater stream. Environmental Toxicology and Chemistry 12:649-658.
- Eaton AD, Clesceri LS, Rice EW, Greenberg AE, Franson MAH (Eds.) (2005) Standard Methods for the Examination of Water and Wastewater (21st edition). American Public Health Association, Washington DC.

- Environment Canada and Health Canada (2001) Priority Substances List Assessment Report for Ammonia in the Aquatic Environment <https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/environmental-contaminants/canadian-environmental-protection-act-1999-priority-substances-list-assessment-report-ammonia-aquatic-environment.html>. Minister of Public Works and Government Services, Canada.
- IPCS (International Programme on Chemical Safety) (1986) Environmental Health Criteria 54: Ammonia <http://www.inchem.org/documents/ehc/ehc/ehc54.htm>. United National Environment Programme, International Labour Organisation, World Health Organization.
- Lang T, Peters G, Hoffman R, Meyer E (1987) Experimental investigations on the toxicity of ammonia: effects on ventilation frequency, growth, epidermal mucous cells, and gill structure of rainbow trout Salmo gairdneri. Diseases of Aquatic Organisms 3:159-167.
- Lapota D, Duckworth D, Ward J (2000) Confounding Factors in Sediment Toxicology - Issue Papers 1-19. Space and Naval Warfare Systems Center, San Diego CA.
- Lease H, Hansen J, Bergman H, Meyer J (2003) Structural changes in gills of Lost River suckers exposed to elevated pH and ammonia concentrations. Comparative Biochemistry and Physiology, Part C 134:491-500.
- Mancl K, Veenhuizen M (1991) Avoiding Stream Pollution from Animal Manure. Ohio State University Extension. AEX-708-91.
- Milne I, Seager J, Mallett M, Sims I (2000) Effects of short-term pulsed ammonia exposure on fish. Environmental Toxicology and Chemistry 19(12):2929-2936.
- Newton N, Bartsch M (2006) Lethal and sublethal effects of ammonia to juvenile *Lampsilis* mussels (Unionidae) in sediment and water-only exposures. Environmental Toxicology and Chemistry 26:2057-2065.
- NOAA (2000) Atmospheric Ammonia: Sources and Fate. A Review of Ongoing Federal Research and Future Needs <https://www.esrl.noaa.gov/csd/aqrs/reports/ammonia.pdf> (PDF). Committee on the Environment and Natural Resources, Air Quality Research Subcommittee. 19 pp.
- Sampio L, Wasielesky W, Miranda-Filho K (2002) Effect of salinity on acute toxicity of ammonia and nitrate to juvenile *Mugil platanus*. Bulletin of Environmental Contamination and Toxicology 68:668-674.

- Scott D, Lucas M, Wilson R (2005) The effect of high pH on ion balance, nitrogen excretion and behavior in freshwater fish from a eutrophic lake: a laboratory and field study. Aquatic Toxicology 73:31-43.
- Stumm W, Morgan JJ (1996) Aquatic Chemistry. Wiley-Interscience, New York NY.
- Twitchen I, Eddy F (1994) Sublethal effects of ammonia to freshwater fish. in: Muller R, Lloyd R (Eds). Sublethal and Chronic Effects of Pollutants on Freshwater Fish. FAO and Fishing News Books, Oxford UK.
- U.S. EPA (1999) 1999 Update of Ambient Water Quality Criteria for Ammonia. U.S. Environmental Protection Agency, Washington DC. EPA-822-R-99-014. 153 pp.
- Webster J, Mulholland P, Tank J, Valett M, Dodds W, Peterson B, Bowden W, Dahm C, Findlay S, Gregory S, Grimm N, Hamilton S, Johnson S, Marti E, McDowell W, Meyer J, Morrall D, Thomas S, Wollheim W (2003) Factors affecting ammonium uptake in streams: an inter-biome perspective. Freshwater Biology 48:1329-1352.
- Webster J, Swank W (1985) Within-stream factors affecting nutrient transport from forested and logged watersheds. in: Blackmon R (Eds). Proceedings of Forester and Water Quality: A Mid-South Symposium. University of Arkansas.
- Wilson J, Iwata K, Iwama G, Randall D (1998) Inhibition of ammonia excretion and production in rainbow trout during severe alkaline exposure. Comparative Biochemistry and Physiology, Part B 121:99-109.
- Wurts W (2003) Daily pH cycle and ammonia toxicity. World Aquaculture 34(2):20-21.

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Last updated on February 7, 2025

Carbon Dioxide Emissions

epa.gov/ghgemissions/carbon-dioxide-emissions

January 7, 2025

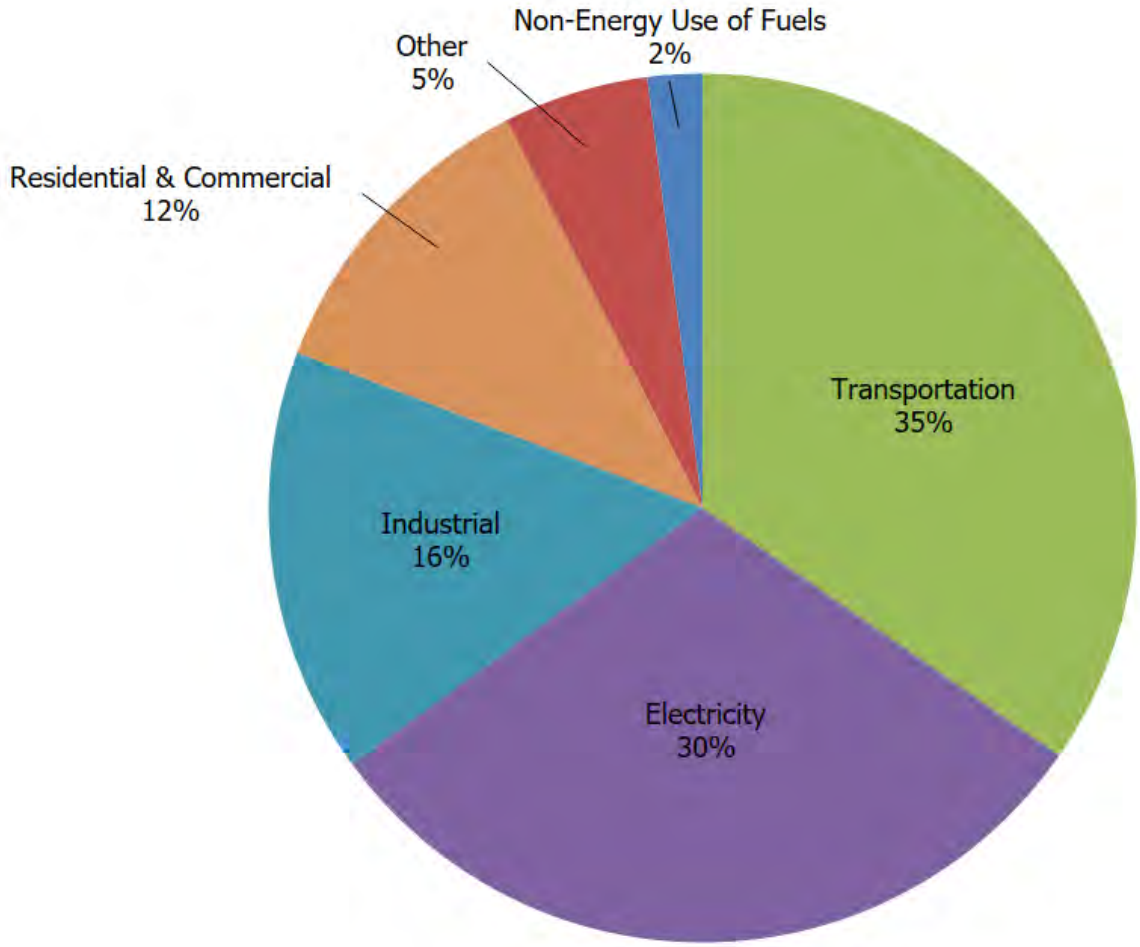

Properties of Carbon Dioxide

Chemical Formula: CO_2
Lifetime in Atmosphere: See reference[1]
Global Warming Potential (100-year): 1

On this page:

- Sources of Carbon Dioxide Emissions
- Carbon Dioxide Trends
- Reducing Carbon Dioxide Emissions

Sources of Carbon Dioxide Emissions

Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities. In 2022, CO_2 accounted for 80% of all U.S. greenhouse gas emissions from human activities.

Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle (the natural circulation of carbon among the atmosphere, oceans, soil, plants, and animals). Human activities are altering the carbon cycle, both by adding more CO_2 to the atmosphere and by influencing the ability of natural sinks, like forests and soils, to remove and store CO_2 from the atmosphere. While CO_2 emissions come from a variety of natural sources, human-related emissions are responsible for the increase that has occurred in the atmosphere since the industrial revolution.[2]

The main human activity that emits CO_2 is the combustion of fossil fuels (coal, natural gas, and oil) for energy and transportation. Certain industrial processes and land-use changes also emit CO_2. The main sources of CO_2 emissions in the United States are:

- **Transportation**. The combustion of fossil fuels such as gasoline and diesel to transport people and goods was the largest source of CO_2 emissions in 2022, accounting for 35% of total U.S. CO_2 emissions and 28% of total U.S. greenhouse gas emissions. This category includes domestic transportation sources such as highway and passenger vehicles, air travel, marine transportation, and rail.
- **Electricity**. Electricity is a key source of energy in the United States and is used to power homes, business, and industry. In 2022, the combustion of fossil fuels to generate electricity was the second largest source of CO_2 emissions in the nation, accounting for 30% of total U.S. CO_2 emissions and 24% of total U.S. greenhouse gas emissions. The types of fossil fuel used to generate electricity emit different amounts of CO_2. To produce a given amount of electricity, burning coal will produce more CO_2 than natural gas or oil.
- **Industry**. Many industrial processes emit CO_2 through fossil fuel consumption. Several processes also produce CO_2 emissions through chemical reactions that do not involve combustion, and examples include the production of mineral products such as cement, the production of metals such as iron and steel, and the production of chemicals. The fossil fuel combustion component of various industrial processes accounted for 16% of total U.S. CO_2 emissions and 13% of total U.S. greenhouse gas emissions in 2022. Many industrial processes also use electricity and therefore indirectly result in CO_2 emissions from electricity generation.
- **Land Use, Land-Use Change, and Forestry (LULUCF)**. In the United States, the management of forests and other land (e.g., cropland, grasslands, etc.) has acted as a net sink of CO_2, which means that more CO_2 is removed from the atmosphere, and stored in plants and trees, than is emitted. This carbon sink offset about 13% of total emissions in 2022.

Carbon dioxide is constantly being exchanged among the atmosphere, ocean, and land surface as it is both produced and absorbed by many microorganisms, plants, and animals. Emissions and removals of CO_2 by these natural processes, however, tend to balance over time, absent anthropogenic impacts. Since the Industrial Revolution began around 1750, human activities have contributed substantially to climate change by adding CO_2 and other heat-trapping gases to the atmosphere.

To find out more about the role of CO_2 in warming the atmosphere, visit the Climate Change Indicators page.

Carbon Dioxide Trends

Carbon dioxide emissions in the United States decreased by 1.5% between 1990 and 2022, excluding LULUCF sinks. Since the combustion of fossil fuel is the largest source of greenhouse gas emissions in the United States, changes in emissions from fossil fuel combustion have historically been the dominant factor affecting total U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population growth, economic growth, changing energy prices, new technologies, changing behavior, and seasonal temperatures. In 2022, the increase in CO_2 emissions from fossil fuel combustion corresponded with an increase in energy use as a result of economic activity rebounding after the height of the COVID-19 pandemic, in addition to an increase in coal use in the electric power sector.

Reducing Carbon Dioxide Emissions

The most effective way to reduce CO_2 emissions is to reduce fossil fuel consumption. Many strategies for reducing CO_2 emissions from energy are cross-cutting and apply to homes, businesses, industry, and transportation.

Strategy	Examples of How Emissions Can be Reduced
Energy Efficiency	Improving the insulation of buildings, traveling in more fuel-efficient vehicles, and using more efficient electrical appliances are all ways to reduce energy use, and thus CO_2 emissions. • See EPA's ENERGY STAR® program for more information on energy-efficient appliances and ways to save at home and work. • See EPA's and DOE's fueleconomy.gov site for more information on fuel-efficient vehicles. • Learn about EPA's motor vehicle standards that improve vehicle efficiency and save drivers money.

Strategy	Examples of How Emissions Can be Reduced
Energy Conservation	Reducing personal energy use by turning off lights and electronics when not in use reduces electricity demand. Reducing distance traveled in vehicles reduces petroleum consumption. Both are ways to reduce energy CO_2 emissions through conservation. Learn more about What You Can Do at Home, at School, in the Office, and on the Road to save energy and reduce your carbon footprint.
Fuel Switching	Producing more energy from renewable sources and using fuels with lower carbon contents are ways to reduce carbon emissions.
Carbon Capture and Sequestration (CCS)	Carbon dioxide capture and sequestration is a set of technologies that can potentially greatly reduce CO_2 emissions from new and existing coal- and gas-fired power plants, industrial processes, and other stationary sources of CO_2. For example, a CCS project might capture CO_2 from the stacks of a coal-fired power plant before it enters the atmosphere, transport the CO_2 via pipeline, and inject the CO_2 deep underground at a carefully selected and suitable subsurface geologic formation, such as a nearby abandoned oil field, where it is securely stored. Learn more about CCS.
Changes in Uses of Land and Land Management Practices	Learn more about Land Use, Land Use Change and Forestry Sector.

Examples of Reduction Opportunities for Carbon Dioxide

References

[1] Atmospheric CO_2 is part of the global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Some of the excess carbon dioxide will be absorbed quickly (for example, by the ocean surface), but some will remain in the atmosphere for thousands of years, due in part to the very slow process by which carbon is transferred to ocean sediments.

[2] IPCC (2021). Climate Change 2021: The Physical Science Basis. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y.

Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp.

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Development Document for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations

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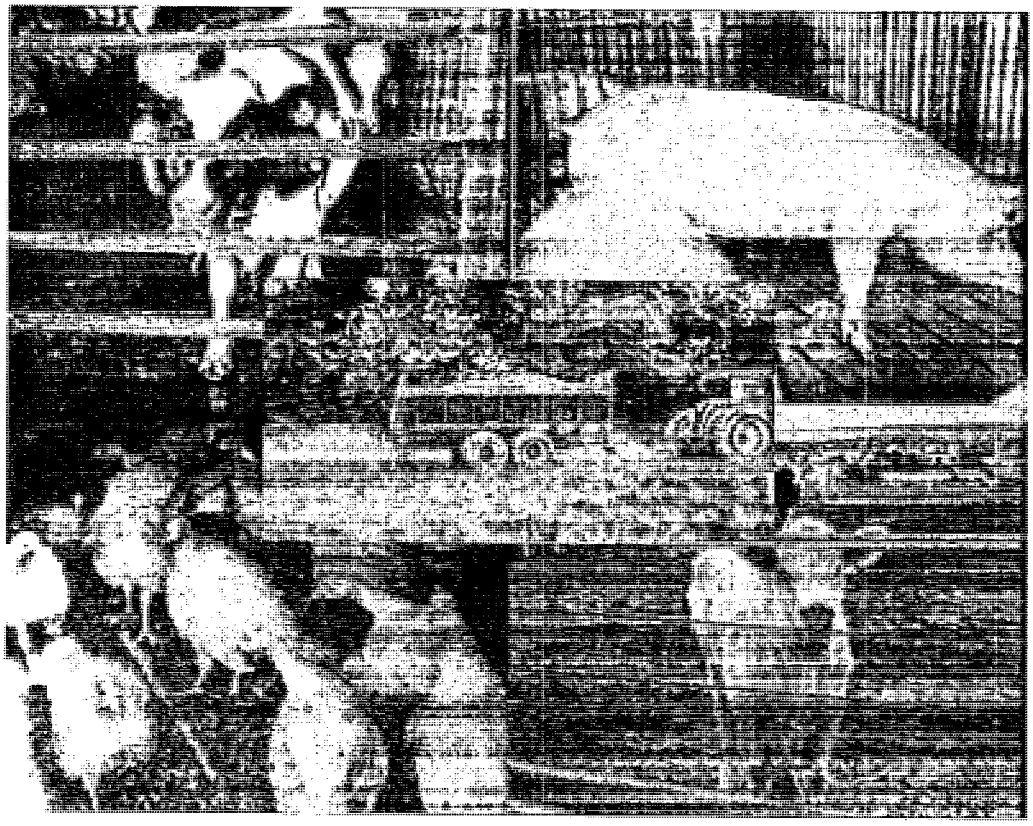

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CHAPTER 1

INTRODUCTION AND LEGAL AUTHORITY

1.0 INTRODUCTION AND LEGAL AUTHORITY

This chapter presents an introduction to the regulations that have been revised for the concentrated animal feeding operations (CAFOs) industry and describes the legal authority that the U.S. Environmental Protection Agency (EPA) has to revise these regulations. Section 1.1 describes the Clean Water Act (CWA), Section 1.2 reviews the Pollution Prevention Act (PPA), and Section 1.3 describes the Regulatory Flexibility Act (RPA).

1.1 Clean Water Act (CWA)

The Federal Water Pollution Control Act Amendments of 1972 established a comprehensive program to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (Section 101(a)). The CWA gives EPA the authority to regulate point source discharges (including CAFOs) into waters of the United States through the National Pollutant Discharge Elimination System (NPDES) permitting program. Under the CWA, EPA issues effluent limitations guidelines, pretreatment standards, and new source performance standards for point sources other than publicly owned treatment works (POTWs). Direct dischargers must comply with effluent limitations in NPDES permits, while indirect dischargers must comply with pretreatment standards.

These effluent limitations guidelines and standards "effluent guidelines" or "ELGs" are national regulations that establish limitations on the discharge of pollutants by industrial category and subcategory. For each category and subcategory guidelines address three classes of pollutants (1) conventional pollutants (i.e., total suspended solids (TSS), oil and grease, biochemical oxygen demand (BOD), fecal coliform bacteria, and pH); (2) priority pollutants (e.g., toxic metals such as lead and zinc, and toxic organic pollutants such as benzene) and (3) nonconventional pollutants (e.g., phosphorus). These technology-based requirements are subsequently incorporated into NPDES permits. The CWA provides that effluent guidelines may include numeric or nonnumeric limitations. Nonnumeric limitations are usually in the form of best management practices (BMPs). The effluent guidelines are based on the degree of control that can be achieved using various levels of pollution control technology, as outlined in Section 1.1.2.

On October 30, 1989, Natural Resources Defense Council, Inc., and Public Citizen, Inc., filed an action against EPA in which they alleged, among other things, that EPA had failed to comply with CWA Section 304(m). (See *Natural Resources Defense Council, Inc., et al.* v. *Reilly*, Civ. No. 89-2980 (RCL) (D.D.C.).) Plaintiffs and EPA agreed to a settlement of that action in a consent decree entered on January 31, 1992. The consent decree, which has been modified

several times, established a schedule by which EPA is to propose and take final action for 11 point source categories identified by name in the decree, and for eight other point source categories identified only as new or revised rules, numbered 5 through 12. After completing a preliminary study of the feedlots industry under the decree, EPA selected the swine and poultry portion of the feedlots industry as the subject for New or Revised Rule #8, and the beef and dairy portion of that industry as the subject for New or Revised Rule #9.

Under the decree, as modified, the Administrator was required to sign a proposed rule for both portions of the feedlots industry on or before December 15, 2000, and take final action on that proposal no later than December 15, 2002. As part of EPA's negotiations with the plaintiffs regarding the deadlines for this rulemaking, EPA entered into a settlement agreement dated December 6, 1999, under which EPA agreed to propose to revise the existing NPDES permitting regulations under 40 CFR Part 122 for CAFO by December 15, 2000. EPA also agreed to perform certain evaluations, analyses, or assessments and to develop certain preliminary options in connection with the proposed CAFO rules. (The Settlement Agreement expressly provides that nothing in the agreement requires EPA to select any of these options as the basis for its final rule.)

The remainder of this section describes the NPDES rules and the Effluent Limitations Guidelines and Standards as they apply to the CAFOs industry.

1.1.1 National Pollutant Discharge Elimination System

The NPDES permit program regulates the discharge of pollutants from point sources to waters of the United States. The term "point source" is defined in the CWA (Section 502(14)) as a discernible, confined, and discrete conveyance from which pollutants are or may be discharged. CAFOs are explicitly defined as point sources in Section 502(14). EPA promulgated the current NPDES regulations for CAFOs in the mid-1970s (see 41 FR 11458, March 18, 1976).

1.1.2 Effluent Limitations Guidelines and Standards

EPA promulgated effluent limitations guidelines and standards for the Feedlots Point Source Category in 1974 (40 CFR Part 412) (see 39 FR 5704, February 14, 1974). EPA is revising these regulations, as discussed above and in Chapter 2.

Effluent limitations guidelines and standards for CAFOs are being revised under the authority of Sections 301, 304, 306, 307, 308, 402, and 501 of the CWA, 33 U.S.C. 1311, 1314, 1316, 1317, 1318, 1342, and 1361. Effluent limitations guidelines and standards are summarized briefly below for direct and indirect dischargers.

Direct Dischargers

- Best Practicable Control Technology Currently Available (BPT) (304(b)(1) of the CWA) - In the guidelines for an industrial category, EPA defines BPT effluent limits for conventional, toxic, and nonconventional pollutants. In specifying BPT, EPA looks at a number of factors. EPA first considers the cost of achieving effluent reductions in relation to the effluent reduction benefits. EPA also considers the age of the equipment and facilities, the processes employed and any required process changes, engineering aspects of the control technologies, nonwater-quality environmental impacts (including energy requirements), and such other factors as EPA deems appropriate (CWA 304(b)(1)(B)). Traditionally, EPA establishes BPT effluent limitations based on the average of the best performances of facilities within the industry of various ages, sizes, processes, or other common characteristics. Where existing performance is uniformly inadequate, EPA may require higher levels of control than are currently in place in an industrial category if EPA determines that the technology can be practically applied.
- Best Available Technology Economically Achievable (BAT) (304(b)(2) of the CWA) - In general, BAT effluent limitations represent the best existing economically achievable performance of direct discharging plants in the industrial subcategory or category. The factors considered in assessing BAT include the cost of achieving BAT effluent reductions, the age of equipment and facilities involved, the processes employed, engineering aspects of the control technology, potential process changes, nonwater-quality environmental impacts (including energy requirements), and such factors as the Administrator deems appropriate. EPA retains considerable discretion in assigning the weight to be accorded to these factors. An additional statutory factor considered in setting BAT is economic achievability. Generally, the achievability is determined on the basis of the total cost to the industrial subcategory and the overall effect of the rule on the industry's financial health. BAT limitations may be based on effluent reductions attainable through changes in a facility's processes and operations. As with BPT, where existing performance is uniformly inadequate, BAT may be based on technology transferred from a different subcategory within an industry or from another industrial category. BAT may be based on process changes or internal controls, even when these technologies are not common industry practice.
- Best Conventional Pollutant Control Technology (BCT) (304(b)(4) of the CWA) - The 1977 amendments to the CWA required EPA to identify effluent reduction levels for conventional pollutants associated with BCT technology for discharges from existing industrial point sources. BCT is not an additional limitation, but replaces BAT for control of conventional pollutants. In addition to other factors specified in Section 304(b)(4)(B), the CWA requires that EPA establish BCT limitations after consideration of a two-part "cost-reasonableness" test. EPA explained its methodology for the development of BCT limitations in July 1986 (51 FR 24974). Section 304(a)(4) designates the following as conventional pollutants: biochemical oxygen demand (BOD_5), total suspended solids (TSS), fecal coliform, pH, and any additional pollutants

designated by the Administrator as conventional. The Administrator designated oil and grease as an additional conventional pollutant on July 30, 1979 (44 FR 44501).

- New Source Performance Standards (NSPS) (306 of the CWA) - NSPS reflect effluent reductions that are achievable based on the best available demonstrated control technology. New facilities have the opportunity to install the best and most efficient production processes and wastewater treatment technologies. As a result, NSPS should represent the greatest degree of effluent reduction attainable through the application of the best available demonstrated control technology for all pollutants (i.e., conventional, nonconventional, and priority pollutants). In establishing NSPS, EPA is directed to take into consideration the cost of achieving the effluent reduction and any nonwater-quality environmental impacts and energy requirements.

For the purposes of applying the new source performance standards, a source is a new source if it completes construction after the effective date of the final rule. See 40 CFR 122.2. Each source that meets this definition is required to achieve the newly promulgated NSPS upon commencing discharge.

However, the NSPS promulgated in 1974 continue to have force and effect for a limited universe of new sources; for this reason, in the final rule, EPA is including provisions at 40 CFR 412.35(d) and 412.46(e) addressing this limited universe. Specifically, the NSPS established in 1974 will continue to apply for a limited period of time to new sources that completed construction with the time period beginning ten years before the effective date of this rule and ending on the effective date of this rule. Thus, any direct discharging new source that completed construction during this ten year period is subject to the 1974 NSPS for ten years from the date it completed construction or during the period of depreciation or amortization of such facility, whichever comes first. See CWA section 306(d). After that ten-year period expires, the BPT, BCT, and BAT limitations established in this rule apply because they are more stringent than the 1974 NSPS.

Indirect Dischargers

- Pretreatment Standards for Existing Sources (PSES) (307(b) of the CWA) - PSES are designed to prevent the discharge of pollutants that pass through, interfere with, or are otherwise incompatible with the operation of POTWs. The CWA authorizes EPA to establish pretreatment standards for pollutants that pass through POTWs or interfere with treatment processes or sludge disposal methods at POTWs. Pretreatment standards are technology-based and analogous to BAT effluent limitations guidelines for removal of priority pollutants. EPA retains discretion not to issue such standards where the total amount of pollutants passing through a POTW is not significant.
- The General Pretreatment Regulations, which set forth the framework for the implementation of categorical pretreatment standards, are found at 40 CFR Part 403. Those regulations contain a definition of pass-through that addresses localized rather

than national instances of pass-through and establish pretreatment standards that apply to all domestic dischargers (see 52 FR 1586, January 14, 1987).

- Pretreatment Standards for New Sources (PSNS) (307(b) of the CWA) - Like PSES, PSNS are designed to prevent the discharges of pollutants that pass through, interfere with, or are otherwise incompatible with the operation of POTWs. PSNS are to be issued at the same time as NSPS. New indirect dischargers have the opportunity to incorporate into their facilities the best available demonstrated technologies. The Agency considers the same factors in promulgating PSNS as it considers in promulgating NSPS. EPA retains discretion not to issue such standards where the total amount of pollutants passing through a POTW is not significant.

1.2 Pollution Prevention Act

In the PPA of 1990 (42 U.S.C. 13101 et seq., Pub. Law 101-508, November 5, 1990), Congress declared pollution prevention a national policy of the United States. The PPA declares that pollution should be prevented or reduced at the source whenever feasible; pollution that cannot be prevented should be recycled in an environmentally safe manner whenever feasible; pollution that cannot be prevented or recycled should be treated; and disposal or other release into the environment should be chosen only as a last resort and should be conducted in an environmentally safe manner. This final regulation for CAFOs was reviewed for its incorporation of pollution prevention as part of EPA effort. Chapters 4 and 8 describe pollution prevention practices applicable to animal feeding operations (AFOs).

1.3 Regulatory Flexibility Act as Amended by the Small Business Regulatory Enforcement Fairness Act of 1996 (SBREFA)

In accordance with Section 603 of the RFA (5 U.S.C. 601 et seq.), EPA prepared an initial regulatory flexibility analysis (IRFA) that examined the impact of the proposed rule on small entities along with regulatory alternatives that could reduce that impact. The IRFA (available in Chapter 9 of *Economic Analysis of the Proposed Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations*) concluded that the economic effect of regulatory options being considered might significantly impact a substantial number of small livestock and poultry operations.

As required by Section 609(b) of the RFA, and as amended by SBREFA, EPA also conducted outreach to small entities and convened a Small Business Advocacy Review Panel to obtain the advice and recommendations of representatives of the small entities that potentially would be subject to the rule's requirements. Consistent with the RFA/SBREFA requirements, the panel evaluated the assembled materials and small entity comments on issues related to the elements of the IRFA. Participants included representatives of EPA, the Small Business Administration (SBA), and the Office of Management and Budget (OMB). Participants from the farming community included small livestock and poultry producers as well as representatives of the major commodity and agricultural trade associations. A summary of the panel's activities and

recommendations is provided in the *Final Report of the Small Business Advocacy Review Panel on EPA's Planned Proposed Rule on National Pollutant Discharge Elimination System (NPDES) and Effluent Limitations Guideline (ELG) Regulations for Concentrated Animal Feeding Operations* (April 7, 2000). This document is included in the public record.

For these regulated industries, SBA sets size standards for defining small businesses by amount of annual revenue generated, representing total facility revenue at the farm level (e.g., revenue from all sources including livestock, crop and other farm-related income at a livestock or poultry operation) and expressed as an average over a 3-year period. These size standards vary by North American Industry Classification System (NAICS) code; CAFOs are listed under NAICS 11 (Agriculture, Forestry, and Fishing). On June 7, 2001, SBA increased the size standards used to define small businesses for most agriculture sectors listed under NAICS 11 from $0.5 million to $0.75 million in average annual receipts (see 66 FR 30646). EPA estimates that the final revised regulations for the CAFOs industry affect approximately 6,300 small businesses; see the *Economic Analysis of the Final Revisions to the NPDES and the Effluent Guidelines for Concentrated Animal Feeding Operations* (hereafter referred to as the EA) for additional information.

CHAPTER 2

SUMMARY AND SCOPE OF FINAL REGULATION

2.0 SUMMARY AND SCOPE OF FINAL REGULATION

The final regulations described in this document include revisions of two regulations that ensure manure, litter, and other process wastewaters for CAFOs do not impair water quality. These two regulations are the NPDES described in Section 2.1 and the ELG for feedlots (beef, dairy, swine, poultry, and veal) described in Section 2.2, which establish the technology-based standards that are applied to CAFOs. Both regulations were originally promulgated in the 1970s. EPA revised these regulations to address changes that have occurred in the animal industry sectors over the last 25 years, to clarify and improve implementation of CAFO permit requirements, and to improve the environmental protection achieved under these rules by ensuring effective management of manure by primarily the largest CAFOs. EPA is not revising the ELG for the horse, sheep and lamb, or duck subcategories.

2.1 National Pollutant Discharge Elimination System

As noted in Chapter 1, CAFOs are "point sources" under the CWA. The regulation at 40 CFR 122.23 specifies which AFOs are CAFOs and, therefore, are subject to the NPDES program.

2.1.1 Applicability of the Final Regulation

The final rule retains the definition of an animal feeding operation (AFO) as it was defined in the 1976 regulation at 40 CFR 122.23(b)(1). An AFO means a lot or facility (other than an aquatic animal production facility) where the following conditions are met: (1) animals (other than aquatic animals) have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period, and (2) crops, vegetation, forage growth, or post-harvest residues are not sustained in the normal growing season over any portion of the lot or facility.

The 1976 NPDES regulation uses the term "animal unit," or AU, to identify facilities that are CAFOs. The term AUs is a metric unit established in the 1976 regulation that attempted to equate the characteristics of the wastes produced by different animal types. EPA has decided to eliminate the term animal unit in this final rule. The final regulation described in today's document retains the basic three-tier structure for determining what size AFOs are CAFOs, as well as retaining the existing conditions for defining which medium-sized AFOs are CAFOs. In the final rule, EPA discontinues the use of the term AU for defining these three size-based groups, and instead uses the actual number of animals to define certain AFOs as Large, Medium, and Small CAFOs.

Table 2-1 presents the thresholds for defining AFOs as Large, Medium, and Small CAFOs in each sector. All AFOs with more than the specified number of head or birds in the second column are defined as "Large CAFOs." AFOs with the specified number of animals in the third column are defined as "Medium CAFOs" only if they meet one of the two specified criteria governing the method of discharge (1) pollutants are discharged into waters of the United States through a man-made ditch, flushing system, or other similar man-made device; or (2) pollutants are discharged directly into waters of the United States which originate outside of and pass over, across, or through the facility or otherwise come into direct contact with the confined animals in the operation. Some AFOs in this middle size group may also be designated as CAFOs by EPA or the state NPDES permitting authority. AFOs with fewer than the number of animals in the last column would be defined as "Small CAFOs" only if they are designated by EPA or the state NPDES permitting authority.

Table 2-1. Summary of CAFO Size Thresholds for all Sectors.

Sector	Number of Head or Birds Confined at the AFO		
	Large CAFO	Medium CAFO[a]	Small CAFO[b]
Mature dairy cattle, whether milked or dry	>700	200 – 700	<200
Veal calves	>1,000	300 – 1,000	<300
Cattle other than mature dairy cows or veal calves. Cattle includes but is not limited to heifers, steers, bulls and cow/calf pairs.	>1,000	300 – 1,000	<300
Swine each weighing 55 pounds or more	>2,500	750 – 2,500	<750
Swine each weighing less than 55 pounds	>10,000	3,000 – 10,000	<3,000
Horses	>500	150 – 500	<150
Sheep or lambs	>10,000	3,000 – 10,000	<3,000
Turkeys	>55,000	16,500 – 55,000	<16,500
Laying hens or broilers (uses a liquid manure handling system)	>30,000	9,000 – 30,000	<9,000
Chickens other than laying hens (uses other than a liquid manure handling system)	>125,000	37,500 – 125,000	<37,500
Laying hens (uses other than a liquid manure handling system)	>82,000	25,000 – 82,000	<25,000
Ducks (uses other than a liquid manure handling system)	>30,000	10,000 – 30,000	<10,000
Ducks (uses a liquid manure handling system)	>5,000	1,500 – 5,000	<1,500

[a] Must also meet one of two criteria to be defined as a CAFO, or can be designated by the permitting authority.

[b] Must be designated by the permitting authority.

EPA considered a number of mechanisms for addressing animal types not explicitly covered in the 1976 regulation, specifically immature swine, heifers, and chickens utilizing dry manure handling systems. EPA selected the approach of counting the numbers of mature swine and numbers of immature swine separately, where either one of which could define the facility as a CAFO. Once a facility is defined as a CAFO for either age group of animals, all animals in confinement would be considered as part of the CAFO. Similarly, EPA selected phosphorus in the manure of 1,000 beef cattle for establishing 1,000 heifers as the threshold for a Large CAFO. See Section 2 of this Chapter for more information on EPA's analysis, and Chapter 6 for additional information on the manure and wastewater characteristics.

The final rule includes chicken operations that use "dry" or "wet" manure handling systems. As a result, the scope of the rule is expanded to include chicken operations with "dry" litter management systems. Similarly, EPA is establishing different thresholds for ducks raised in lots as opposed to ducks raised in confinement buildings. EPA's final evaluation concluded that 125,000 broilers and 82,000 layers produce an equivalent amount of manure phosphorus to 1,000 beef cows. The use of annual phosphorus production as the metric for establishing thresholds is consistent with the metric described above for swine and heifers. These analyses are discussed further in Section 2.2.

2.1.2 Summary of Revisions to NPDES Regulations

Overall, this final rule maintains many of the basic features and overall structure of the 1976 NPDES regulations with some important exceptions. First, EPA eliminated the 25-year, 24-hour storm permitting exemption for defining a CAFO. All Large CAFOs have a mandatory duty to apply for an NPDES permit. This removes the ambiguity of whether a Large facility needs to apply for an NPDES permit, even if it discharges only in the event of a large storm event. In the rare occasion that a Large CAFO has No Potential To Discharge (NPTD), the rule provides a process for the CAFO to make such a demonstration to the Director in lieu of obtaining a permit.

The second significant change is that AFOs with chickens are subject to the NPDES rule, regardless of the type of waste disposal system used or whether the litter or manure is managed in a wet or dry form. EPA maintained the existing size criteria for chicken operations with wet manure handling systems, and established different size criteria for chickens with dry manure handling systems based on broad type of chicken (i.e., chickens for meat (broilers) and chickens for eggs (layers)).

Third, under this final rule, all CAFOs covered by an NPDES permit are required to develop and implement a nutrient management plan. The plan would identify prohibitions and practices necessary to demonstrate compliance with any limitations or standards in the permit and, for Large CAFOs, applicable ELGs. This includes requirements to land-apply the manure and wastewater consistent with appropriate agricultural utilization. The plan must address the following nine minimum elements:

- Ensure adequate storage of manure and process wastewater, including procedures to ensure proper operation and maintenance of the storage facilities.
- Ensure proper management of mortalities (i.e., dead animals) to ensure that they are not disposed of in a liquid manure, storm water, or process waste water storage or treatment system that is not specifically designed to treat animal mortalities..
- Ensure that clean water is diverted, as appropriate, from the production area.
- Prevent direct contact of confined animals with waters of the United States.
- Ensure that chemicals and other contaminants handled on-site, are not disposed of in any manure, litter, process wastewater, or storm water storage or treatment system unless specifically designed to treat such chemicals and other contaminants.
- Implement appropriate site specific conservation practices, including as appropriate buffers or equivalent practices, to control runoff of pollutants to waters of the United States.
- Conduct appropriate testing of manure, litter, process wastewater, and soil.
- Land apply manure, litter or process wastewater in accordance with site specific nutrient management practices that ensure appropriate agricultural utilization of the nutrients in the manure, litter or process wastewater.
- Identify specific records that will be maintained to document the implementation and management of the minimum elements described above.

The discharge of manure, litter, or process wastewater to waters of the United States from a CAFO as a result of the application of that manure, litter, or process wastewater by the CAFO to land areas under its control is a discharge from that CAFO subject to NPDES permit requirements, except where it is an agricultural storm water discharge. If the manure, litter, or process wastewater has been applied in accordance with site specific nutrient management practices that ensure appropriate agricultural utilization of the nutrients in the manure, litter, or process wastewater a discharge of manure, litter, or process wastewater from land areas under the control of a CAFO is an agricultural stormwater discharge. "Appropriate agricultural utilization" includes, but is not limited to, land application of manure, litter, or process wastewater in accordance with site specific nutrient management practices.

In addition to new thresholds for chickens, the final rule establishes new, or clarifies existing, thresholds for veal calves, immature swine, cow/calf pairs, ducks that use other than a liquid manure handling system, and heifer operations, as described in Section 2.1.1. This final rule eliminates the formula for calculating whether an AFO is a CAFO due to the accumulation of several different animal types in confinement at one facility[1].

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[1]Previously, an AFO was defined as a CAFO if the number of slaughter steers and heifers multiplied by 1.0, plus the number of mature dairy cattle multiplied by 1.4, plus the number of swine over 55 pounds multiplied by 0.4, plus the number of sheep multiplied by 0.1, plus the number of horses multiplied by 2.0 was greater than 1,000.

In the final rule EPA requires that the CAFO owner or operator to maintain permit coverage for the CAFO until it is properly closed.

EPA requires certain records to be retained on site at the CAFO for 5 years. The specific record keeping, monitoring and reporting requirements of the final rule are as follows:

- A copy of the CAFO's site-specific nutrient management plan.
- All applicable records that will used document the implementation and management identified in the nutrient management plan.
- For Large CAFOs, any additional records specified in the ELGs (see Section 2.2).
- For Large CAFOs, a record of the date, recipient name and address, and approximate amount of manure, litter, or process wastewater transferred to another person.

In addition, the CAFO must submit to the permitting authority annual report that includes the following:

- The number and type of animals in, whether in open confinement or housed under roof (beef cattle, broilers, layers, swine weighing 55 pounds or more, swine weighing less than 55 pounds, mature dairy cows, dairy heifers, veal calves, sheep and lambs, horses, ducks, turkeys, other).
- Estimated amount of total manure, liter and process wastewater generated by the CAFO in the previous 12 months (tons/gallons).
- Estimated amount of total manure, litter and process wastewater transferred to other person by the CAFO in the previous 12 months (tons/gallons).
- Total number of acres for land application covered by the nutrient management plan.
- Total number of acres under control of the CAFO that were used for land application of manure, litter and process wastewater in the previous 12 months.
- Summary of all manure, litter and process wastewater discharges from the production area that have occurred in the previous 12 months, including date, time, and approximate volume.
- A statement indicating whether the current version of the CAFO's nutrient management plan was developed or approved by a certified nutrient management planner.

2.2 Effluent Limitations Guidelines and Standards

Effluent limitations guidelines and standards are national regulations that establish limitations on the discharge of pollutants by industrial category and subcategory. The final effluent limitations guidelines and standards establish the Best Practicable Control Technology Currently Available (BPT), Best Conventional Pollutant Control Technology (BCT), and the Best Availability

Technology Economically Achievable (BAT) limitations as well as New Source Performance Standards (NSPS) on discharges from the "production area" and the "land application areas" at CAFOs. The term "production area" means that part of an AFO that includes the animal confinement area, the manure storage area, the raw materials storage area, and the waste containment areas. The animal confinement area includes but is not limited to open lots, housed lots, feedlots, confinement houses, stall barns, free stall barns, milkrooms, milking centers, cowyards, barnyards, medication pens, walkers, animal walkways, and stables. The manure storage area includes but is not limited to lagoons, runoff ponds, storage sheds, stockpiles, under house or pit storages, liquid impoundments, static piles, and composting piles. The raw materials storage area includes but is not limited to feed silos, silage bunkers, and bedding materials. The waste containment area includes but is not limited to settling basins, and areas within berms and diversions which separate uncontaminated storm water. Also included in the definition of production area is any egg washing or egg processing facility, and any area used in the storage, handling, treatment, or disposal of mortalities. The term "land application areas" means land under the control of an AFO owner or operator, whether it is owned, rented, or leased, to which manure or process wastewater from the production area is or may be applied.

2.2.1 Applicability of the Final Regulation

EPA has subcategorized the CAFOs Point Source Category based primarily on animal production processes and waste handling and management practices. Large beef feedlots, dairies, and heifer operations typically have outdoor confinement lots where animals are housed for all or at least a portion of their time. The open outdoor lots expose large areas to precipitation, generating large volumes of storm water runoff contaminated with manure, bedding, feed, silage, antibiotics, and other process contaminants. In contrast, nearly all Large swine, poultry, and veal operations utilize total confinement housing. See Chapter 4 for more information on production practices, and Chapter 5 for a discussion of the basis considered for subcategorization. The final rule establishes new effluent limitations and guidelines for Subpart C, covering beef cattle, dairy cattle, and heifers; and Subpart D, covering veal calves, swine, and poultry (chickens and turkeys).

As described in Section 2.1, an AFO is a CAFO if the specific threshold for any one animal sector is met. Consistent with the final NPDES rule, the ELG eliminates the formula for calculating whether Subpart A applies due to the accumulation of several different animal types in confinement at one facility. The final ELG applicability of Subpart A thus only applies to horses and sheep. The final subcategories are listed and described in Table 2-2.

The ELG requirements for Subpart C (dairy and beef cattle other than veal) and Subpart D (swine, poultry, and veal) apply to those operations which are defined as Large CAFOs under the NPDES regulations described in Section 2.1. In the case of Medium or Small CAFOs, or CAFOs not otherwise subject to Part 412, effluent limitations will be established on a case-by-case basis by the permitting authority using best professional judgment (BPJ).

Table 2-2. Summary of Final ELG Subcategorization for CAFOs.

Subpart	Subcategory	Description
A	Horses and Sheep	CAFOs under 40 CFR 122.23 which confine more than 500 horses or 10,000 sheep.
B	Ducks	CAFOs under 40 CFR 122.23 which confine more than 5000 ducks.
C	Dairy and Beef Cattle Other than Veal	CAFOs under 40 CFR 122.23 which confine more than 700 mature dairy cows (either milking or dry) or 1000 cattle other than mature dairy cows or veal calves.
D	Swine, Poultry, and Veal	CAFOs under 40 CFR 122.23 which confine more than 2,500 swine each weighing 55 pounds or more, 10,000 swine each weighing less than 55 pounds, 30,000 laying hens or broilers when the facility uses a liquid manure handling system, 82,000 laying hens when the facility uses other than a liquid manure handling system, 125,000 chickens other than laying hens when the facility uses other than a liquid manure handling system, 55,000 turkeys, or 1,000 veal calves.

In 1974 when the original ELG was promulgated, stand-alone heifer operations were not considered a major livestock operation. However, due to the increased specialization of dairies over the past 25 years, these heifer operations have become more common and more abundant. While most heifers were maintained in pasture, many large dairies place the heifers in confinement at a feedlot. Therefore, EPA has specifically addressed heifer operations to address potential discharges to surface waters. Based on the similarity of the production (animal type and housing) and waste management processes for beef feedlots, dairies, and heifer operations, EPA developed a new subcategory, Subpart C, to address these types of operations under this rule.

Subpart D includes swine, poultry and veal calves, which are predominantly produced in confinement housing with little to no exposure to precipitation. Based on the information in the record, EPA is including operations with immature swine as CAFOs under Subpart D based on their production and waste handling practices. Immature swine operations were not specifically addressed in the 1974 ELG because immature swine were typically raised at a farrow-to-finish operation and not at a separate nursery operation like today. Although many large swine operations continue to have the full range of production phases at one location, these operations are no longer the norm. More frequently, in new operations, several specialized farms are integrated into a chain of production and marketing. Pigs begin in sowherds on one site, move to a nursery on another, and then move again to a finishing facility. Due to the increased construction and reliance on immature swine operations, EPA determined that these operations should be specifically addressed in the ELG.

The simplest approach for including immature swine is to count all swine, regardless of size and age. EPA determined counting all swine equally would increase the effective size of operations that have breeding functions by a factor of seven or more (based on the number of pigs per litter). While this approach would include nursery facilities, this approach also changes the existing basis without improving the regulation. Alternatively, all swine would be counted but a weighting factor could be used to distinguish animal sizes. This approach is inconsistent with EPA's attempt to simplify the regulations by removing mixed animal multipliers and animal unit calculations.

EPA selected the approach of counting the numbers of mature swine and numbers of immature swine separately, where either one of which could define the facility as a CAFO. EPA selected phosphorus in the manure as the metric for Large CAFO thresholds. EPA's analysis equates 2,500 mature swine (weighing over 55 pounds) to approximately 10,000 immature swine (weighing less than 55 pounds) on a phosphorus excreted basis. Once a swine facility is defined as a CAFO for either age group of animals, all animals in confinement would be considered as part of the CAFO. Because the immature operations use virtually the same animal production and waste management processes and are expected to use similar effluent reduction practices and technologies as mature swine operations, EPA has included these immature swine operations under Subpart D.

As discussed in Section 2.1, the final rule expands the scope of the rule to also address chicken operations with "dry" litter management systems. While liquid manure systems continue to be used by approximately 15 percent of the total laying industry (see Chapter 4), continuous flow watering systems have been largely discontinued in favor of more efficient water conserving methods (e.g., on-demand watering). Site visits and consultations with industry further suggest liquid manure handling systems are no longer constructed at laying hen operations.

EPA noted chickens raised for meat production are a different breed of chicken, have a different weight, eat a different diet, and are raised differently than those used for egg production. Therefore EPA considered a number of approaches to determine the final applicability thresholds. EPA evaluated the manure generated from chickens used for meat (broilers) and egg production (layers) and compared manure production to a 1,000 pound beef cow. EPA evaluated daily manure phosphorus production and annual phosphorus production, and determined annual production was more appropriate because annual production reflects the time birds are actually present and generating manure. The annual approach assumes 5 to 6 flocks of broilers are produced each year, for a total of 322 days of manure production in one year. In contrast, each layer flock is raised for either 80 weeks (non-molt flocks) or 105 weeks (molt flocks). Molt flocks go through two cycles of egg production, separated by a non-productive molting period (shedding of feathers and renewal of ovarian activity) induced by withholding food. Manure production greatly diminishes during the two-week molt period. Following the molt, egg production resumes to the end of the flock life. Furthermore, prior to egg-laying age, the bird will typically be raised for 19 weeks as a pullet. On average, layers are in production for 94 weeks. EPA's final evaluation concluded that 125,000 broilers and 82,000 layers produce an equivalent amount of manure phosphorus to 1,000 beef cows.

This rule addresses veal operations under Subpart D along with swine and poultry operations due to the similarity in animal production and waste management processes. See Chapter 5 for additional discussion of the industry subcategorization for this rule.

2.2.2 Summary of Revisions to Effluent Limitations Guidelines and Standards

Large CAFOs covered under Subpart C and Subpart D are required under this final rule to comply with the new effluent limitations guidelines and standards (see Table 2-3). The final guidelines establish BPT, BCT, BAT, and NSPS by requiring effluent limitations and standards and specific BMP that ensure that manure storage and handling systems are inspected and maintained adequately as described in the following subsections. Medium and Small CAFOs are not subject to the ELGs.

2.2.2.1 Land Application Best Practicable Control Technology

EPA set BPTs for land application applicable to any CAFO subject to Subparts C or D. These BMPs include the requirement to develop and implement a nutrient management plan that incorporates the following requirements based on a field-specific assessment:

- *Determination of application rates.* Application rates for manure, litter, and other process wastewater applied to land under the ownership or operational control of the CAFO must minimize phosphorus and nitrogen transport from the field to surface waters in compliance with the technical standards for nutrient management established by the Director. Such technical standards for nutrient management shall:
  - Include a field-specific assessment of the potential for nitrogen and phosphorus transport from the field to surface waters, and address the form, source, amount, timing, and method of application of nutrients on each field to achieve realistic production goals, while minimizing nitrogen and phosphorus movement to surface waters; and
  - Include appropriate flexibilities for any CAFO to implement nutrient management practices to comply with the technical standards, including consideration of multi-year phosphorus application on fields that do not have a high potential for phosphorus runoff to surface water, phased implementation of phosphorus-based nutrient management, and other components, as determined appropriate by the Director.
- *Manure and Soil Sampling.* Manure must be analyzed a minimum of once annually for nitrogen and phosphorus content, and soil analyzed a minimum of once every five years for phosphorus content. The results of these analyses are to be used in determining application rates for manure, litter, and other process wastewater.

- *Inspect land application equipment for leaks.* The operator must periodically inspect equipment used for land application of manure, litter, or process wastewater.
- *Setback requirements.* Manure, litter, and process wastewater may not be applied closer than 100 feet to any down-gradient surface waters, open tile line intake structures, sinkholes, agricultural well heads, or other conduits to surface waters unless one of the following compliance alternatives are used:
  - *Vegetated buffer compliance alternative.* As a compliance alternative, the CAFO may substitute the 100-foot setback with a 35-foot wide vegetated buffer where applications of manure, litter, or process wastewater are prohibited.
  - *Alternative practices compliance alternative.* As a compliance alternative, the CAFO may demonstrate that a setback or buffer is not necessary because implementation of alternative conservation practices or field-specific conditions will provide pollutant reductions equivalent or better than the reductions that would be achieved by the 100-foot setback.
- *Record keeping requirements for the land application areas.* Each CAFO must maintain on-site a copy of its site-specific nutrient management plan and the following information for a period of five years from the date they are created:
  - Expected crop yields.
  - The date(s) manure, litter, or process waste water is applied to each field.
  - Weather conditions at time of application and for 24 hours prior to and following application.
  - Test methods used to sample and analyze manure, litter, process waste water, and soil.
  - Results from manure, litter, process waste water, and soil sampling.
  - Explanation of the basis for determining manure application rates, as provided in the technical standards established by the Director.
  - Calculations showing the total nitrogen and phosphorus to be applied to each field, including sources other than manure, litter, or process wastewater.
  - Total amount of nitrogen and phosphorus actually applied to each field, including documentation of calculations for the total amount applied.
  - The method used to apply the manure, litter, or process wastewater.

- Date(s) of manure application equipment inspection.

2.2.2.2 Production Area Best Practicable Control Technology

EPA set BPTs for the production area that are applicable to any CAFO subject to Subparts C or D. Under BPT, EPA prohibits the discharge of manure, litter, or process wastewater pollutants into waters of the United States from the production area except overflow from containment facilities if caused by rainfall events and the facility is designed, constructed, operated, and maintained to contain all manure, litter, and process wastewater including the runoff and the direct precipitation from a 25-year, 24-hour rainfall event. The production area must also be operated in accordance with the additional measures and record keeping requirements described below. These requirements do not apply to discharges to ground water with a direct hydrologic connection to surface water, although the permit writer could establish such technology-based limitations on a case-by-case basis. BPT establishes the following additional measures and record keeping requirements for the production area (records are to be kept for five years from the time they are created):

- Weekly inspections of all storm water diversion devices, runoff diversion structures, and devices channelling contaminated storm water to the wastewater and manure storage and containment structure.
- Daily inspection of water lines, including drinking water or cooling water lines.
- Weekly inspections of the manure, litter, and process wastewater impoundments; the inspection will note the level in liquid impoundments as indicated by the depth marker.
- All open surface liquid impoundments must have a depth marker which clearly indicates the minimum capacity necessary to contain the runoff and direct precipitation of the 25-year 24-hour rainfall event.
- Any deficiencies found as a result of these inspections must be corrected as soon as possible.
- Mortalities must not be disposed of in any liquid manure or process wastewater system, and must be handled in such a way as to prevent the discharge of pollutants to surface water, unless alternative technologies are designed and approved to handle mortalities.
- Records documenting the inspections described above.
- Weekly records of the depth of the manure and process wastewater in the liquid impoundment as indicated by the depth marker.
- Records documenting any actions taken to correct deficiencies described above. Deficiencies not corrected within 30 days must be accompanied by an explanation of the factors preventing immediate correction.
- Records of mortalities management and practices used by the CAFO to meet the requirements described above.

- Records documenting the current design of any manure or litter storage structures, including volume for solids accumulation, design treatment volume, total design volume, and approximate number of days of storage capacity.
- Records of the date, time, and estimated volume of any overflow.

EPA set an alternative BPT, described in section 2.2.2.6 below, to encourage innovative technologies.

2.2.2.3 Best Control Technology

EPA set BCT requirements for Subparts C (dairy and beef cattle other than veal subcategories) and D (swine, poultry, and veal subcategories) the same as BPT. Table 2-3 shows the technology basis of BCT for these subcategories.

2.2.2.4 Best Available Technology

EPA set BAT requirements for Subparts C (dairy and beef cattle other than veal subcategories) and D (swine, poultry, and veal subcategories) the same as BPT. Table 2-3 shows the technology basis of BAT for these subcategories.

2.2.2.5 New Source Performance Standards

EPA set NSPS requirements equivalent to BPT requirements for Subpart C (dairy and beef cattle other than veal subcategories) and for the land application area of Subpart D (swine, poultry, and veal subcategories).

EPA set different NSPS requirements for the production area of Subpart D (swine, poultry, and veal subcategories). NSPS requirements for Subpart D prohibit the discharge of manure, litter, or process wastewater pollutants into waters of the United States from the production area. A facility designed, constructed, operated, and maintained to contain all manure, litter, and process wastewater including the runoff and the direct precipitation from a 100-year, 24-hour rainfall event will fulfill the requirement for no discharge. The production area must also be operated in accordance with the additional measures and record keeping requirements described earlier with the exception that all open surface liquid impoundments must have a depth marker which clearly indicates the minimum capacity necessary to contain the runoff and direct precipitation of the 100-year 24-hour rainfall event.

EPA set an alternative NSPS, described in Section 2.2.2.7 below, to encourage innovative technologies and whole-farm multi-media reductions.

For the purposes of applying the new source performance standards, a source is a new source if it commenced construction after the effective date of the final rule. See 40 CFR 122.2. Each source that meets this definition is required to achieve the newly promulgated NSPS upon commencing discharge.

Table 2-3. Summary of Technology Basis for Large CAFOs Covered by Part 412.

Technology Basis	BPT, BCT, and BAT		NSPS	
	Dairy and Beef Cattle other Than Veal Subcategory	Swine, Poultry, and Veal Subcategory	Dairy and Beef Cattle other Than Veal Subcategory	Swine, Poultry, and Veal Subcategory
Zero discharge with overflow provided if caused by rainfall events and the facility is designed, constructed, operated, and maintained to contain all manure, litter, and process wastewater including the runoff and the direct precipitation from a 25-year, 24-hour rainfall event.	✓	✓	✓	
Zero discharge with overflow provided if caused by rainfall events and the facility is designed, constructed, operated, and maintained to contain all manure, litter, and process wastewater including the runoff and the direct precipitation from a 100-year, 24-hour rainfall event.				✓
Development and implementation of a nutrient management plan; and maintain records.	✓	✓	✓	✓
Land application consistent with appropriate agricultural utilization.	✓	✓	✓	✓
Voluntary alternative performance standards for discharges from the production area that achieve equal or better pollutant reduction.	✓	✓	✓	
Voluntary superior environmental performance standards for technologies that achieve overall environmental performance across all media equal or superior to baseline NS.PS				✓
Daily and weekly inspections.	✓	✓	✓	✓
Depth marker for open surface liquid impoundments.	✓	✓	✓	✓
Corrective action.	✓	✓	✓	✓
Mortality handling requirements.	✓	✓	✓	✓
100-foot land application setback or equivalent compliance alternative.	✓	✓	✓	✓
Manure samples at least once per year.	✓	✓	✓	✓
Soil test every 5 years.	✓	✓	✓	✓
Record keeping.	✓	✓	✓	✓

However, the NSPS promulgated in 1974 continue to have force and effect for a limited universe of new sources; for this reason, in the final rule, EPA is including provisions at 40 CFR 412.35(d) and 412.46(e) addressing this limited universe. Specifically, the NSPS established in 1974 will continue to apply for a limited period of time to new sources that completed construction with the time period beginning ten years before the effective date of this rule and ending on the effective date of this rule. Thus, any direct discharging new source that completed construction during this ten year period is subject to the 1974 NSPS for ten years from the date it completed construction or during the period of depreciation or amortization of such facility, whichever comes first. See CWA section 306(d). After that ten-year period expires, the BPT, BCT, and BAT limitations established in this rule apply because they are more stringent than the 1974 NSPS.

EPA has determined that the ten-year period should apply to discharges from the both the CAFO production areas and land application areas even though the 1974 NSPS specifically addressed only discharges from the production area. This determination is based on the manner in which manure, litter, and other process wastewaters at CAFOs are generated and the waste management practices employed for these wastes. EPA recognizes that the land application BMPs established by this rule have the potential to alter the land application practices at the CAFO, which could affect waste management practices at the production area. Animal feeding strategies and waste management practices at the production area determine the form of the wastes (i.e., solid, liquid, or slurry) and the amount of nutrients and other pollutants present in the wastes. The timing of any application and the amount of nutrients (i.e., manure, litter, and other process wastewater) applied is determined by crop needs, irrigation requirements, and other factors such as the availability of manure spreading equipment and climate considerations. The land application BMPs established by this rule include a requirement to develop and implement a nutrient management plan, as well as a requirement to land-apply manure at rates based on technical standards for nutrient management established by the Director. Based on the information in the record, the land application BMPs established by this rule will lead to some changes in the ways CAFOs manage their land application areas. A number of CAFOs affected by this rule will need to reduce the amount of manure and other process wastewaters applied to cropland. As they develop their nutrient management plans some CAFOs may determine they should adjust the timing of manure applications. Since the CAFO must be able to store any wastes generated at the production area until able to land-apply the manure, significant changes in the amount of manure applied or the timing of manure application may affect waste management systems at the production area. Therefore, EPA determined that the ten-year period described above should apply to discharges from both the production areas and the land application areas at CAFOs.

If the production area and land application area wastestreams at CAFOs were more physically distinct, particularly if they were generated and remained distinct and severable throughout all steps of the waste generation and management (or could be managed in such a manner), and the NSPS requirements for the land application area did not significantly affect the waste management infrastructure at the production area, EPA likely would have determined that the ten-year "grandfathering" period would apply only to production area discharges and would not apply to discharges from the land application areas.

Rather than reproduce the 1974 NSPS in the newly revised rule, EPA is referring permitting authorities to the NSPS codified in the 2002 edition of the Code of Federal Regulations for use during the applicable ten-year period. (The 2002 edition of the Code of Federal Regulations presents the 1974 NSPS requirements.) This approach allows EPA to avoid reproducing in the new regulations the requirements of the 1974 NSPS that will soon become outdated.

2.2.2.6 Voluntary Alternative Performance Standards to Encourage Innovative Technologies

In addition to the production area effluent guidelines (baseline effluent guidelines), the final rule establishes provisions for the development of alternative performance standards for discharges from the production area for existing Large CAFOs and new large beef and dairy CAFOs. The BMPs described under BPT are applicable to all Large CAFOs (both existing and new sources), regardless of whether their NPDES permit limitations are based on the baseline effluent guidelines or the alternative performance standards.

The voluntary alternative performance standards will enable Large CAFOs to develop and implement new technologies and management practices that perform as well as or better than the baseline effluent guidelines at reducing pollutant discharges to surface waters from the production area. CAFOs will have the option to either accept NPDES permit limitations based on the baseline effluent guidelines, or may voluntarily request the permitting authority to establish an alternative BPT/BCT/BAT/NSPS performance standard as the basis for their technology-based NPDES permit limits. The specific requirements imposed by the alternative performance standard would be established by the NPDES permitting authority on the basis of BPJ.

Under this program, CAFOs will be allowed to discharge process wastewater that has been treated by technologies that the CAFO demonstrates will result in equivalent or better pollutant removal than would otherwise be achieved by the baseline effluent guidelines. These regulatory provisions are targeted toward the CAFO's wastewater discharges, but EPA encourages operations electing to participate in the alternative performance standards program to consider environmental releases holistically and also consider opportunities for achieving improvement in multiple environmental media. To demonstrate that an alternative control technology would achieve equivalent or better pollutant reductions than baseline effluent guidelines, the CAFO must submit a technical analysis, which includes calculating the quantity of pollutant reductions, on a mass-basis where appropriate, based on the site-specific modeled performance of a system designed to comply with the baseline effluent guidelines. The CAFO must also prepare a proposed alternative program plan including the results of the analysis; the proposed method for implementing new technologies and practices, including an approach for monitoring performance; and the results demonstrating that these technologies and practices perform equivalent to or better than the baseline effluent guidelines. This plan must be included with the CAFO's NPDES permit application or renewal, and will be incorporated into the permit upon approval by the permitting authority.

2.2.2.7 *Voluntary Superior EnvironmentalPerformance Standards for New Large Swine/Poultry/Veal CAFOs*

The NSPS requirements that apply to production area discharges at new Large swine, poultry, and veal CAFOs are more stringent than the NSPS established for other new sources and the BAT requirements for existing sources. EPA is endeavoring to ensure that this rule does not inadvertently discourage approaches that are superior from a multi-media environmental perspective. Therefore, for new sources subject to Subpart D (Large swine, poultry, and veal CAFOs), EPA is establishing alternative performance standards that provide additional compliance flexibilities specifically designed to encourage CAFOs to adopt innovative technologies for managing and/or treating manure, litter, and process wastewater. Specifically, alternative NPDES permit limitations based upon a demonstration that site-specific innovative or superior to the reductions achieved by baseline standards. The quantity of pollutants discharged from the production area must be accompanied by an equivalent or greater reduction in the quantity of pollutants released to other media from the production are (e.g., air emissions form housing and storage), the land application areas for all manure, litter, and process wastewater at on-site and off-site locations, or both. In making the demonstration that the innovative technologies will achieve an equivalent or greater reduction, the comparison of quantity of pollutants is to be made on a mass basis where appropriate.

In general, EPA expects CAFOs will conduct a whole-farm audit to evaluate releases that occur at the point to generation to minimize or eliminate waste production and air emissions, followed by an evaluation of the waste handling and management systems, and ending with an evaluation of land application and offsite transfer operations. The specific technologies that CAFOs will select and adopt to achieve the pollutant reductions are expected to be most effective for the particular operation. As part of the demonstration the CAFO will need to present information that describes how the innovative technologies will generate improvement across multiple environmental media. The Director has the discretion to request additional supporting information to supplement such a request where necessary. Such information could include criteria and data that demonstrate effective performance of the technologies and that could be used to establish the alternative NPDES permit limitations.

CHAPTER 3

DATA COLLECTION ACTIVITIES

3.0 DATA COLLECTION ACTIVITIES

EPA collected and evaluated data from a variety of sources during the course of developing the revised effluent limitations guidelines and standards for the CAFO industry. These data sources include EPA site visits, industry trade associations, the U.S. Department of Agriculture (USDA), published literature, previous EPA Office of Water studies of the Feedlots Point Source Category, and other EPA studies of AFOs. Each of these data sources is discussed below, and analyses of the data collected by EPA are presented throughout the remainder of this document.

The majority of the data EPA used to support development of the proposed effluent limitations guidelines and standards for the CAFO industry are from existing sources, including data from the USDA, industry, State agricultural extension agencies, and several land grant universities. As defined in the Office of Water 2002 Quality Management Plan, existing (or secondary) data are data that were not directly generated by EPA to support the decision at hand.

In keeping with the graded approach to quality management embodied in the Office of Water's quality management plan, EPA must assess the quality of existing data relative to their intended use. The procedures EPA used to assess existing data for use in developing effluent guideline limitations for CAFOs varied with the specific type of data. In general, EPA's assessment included:

- Reviewing a description of the existing data that explains who collected or produced the data and how the data were collected or produced (e.g., who collected the data, what data were collected; why were the data originally collected; when were the data collected; how were they collected; are the data part of a long-term collection effort, or was this a one-time effort; who else uses the data; what level of review by others have the data undergone).
- Specifying the intended use of the existing data relative to the CAFO final rule.
- Developing a rationale for accepting data from this source, either as a set of acceptance criteria, or as a narrative discussion.
- Describing any known limitations with the data and their impact on EPA's use of the data.

Brief descriptions of the data and their limitations are presented later in this document, as each data source is introduced.

In searching for existing data sources and determining their acceptability, EPA generally used a hierarchical approach designed to identify and utilize data with the broadest representation of the industry sector of interest. EPA began by searching for national-level data from surveys and studies by USDA and other federal agencies. When such survey or study data did not exist, EPA considered other data from federal agencies. An example of non-survey data considered are the USDA costs and capability data, which are based on a consensus of USDA experts.

Where national data did not exist, as the second tier, EPA searched for data from land grant universities. Such data are often local or regional in nature. EPA assessed the representativeness of the data relative to a national scale before deciding to use the data. When such data came from published sources, EPA gave greater consideration to publications in peer-reviewed professional journals compared to trade publications that do not have a formal review process.

The third tier was data supplied by industry. Prior to proposal, EPA requested data from a variety of industry sources, including trade associations and large producers. The level of review applied to data supplied by industry depended on the level of supporting detail that was provided. For example, if the industry supplied background information regarding how the data were collected, such as the number of respondents and the total number of potential respondents, EPA reviewed the results, compared them to data from other potential sources to determine their suitably for use in this rulemaking. If the data provided by industry originated from an identifiable non-industry source (e.g., a state government agency), EPA reviewed the original source information before determining the acceptability of the data. In a limited number of instances, EPA conducted site visits to substantiate information supplied by industry. In contrast, data supplied by industry without any background information were given much less weight and generally were not used by EPA. Further, some data that were supplied by industry prior to the proposal were included in the proposal for comment. In the absence of any negative comments, such data were relied on to a greater extent than data submitted by industry during the comment period itself.

3.1 Summary of EPA's Site Visit Program

EPA conducted approximately 116 site visits to collect information about AFOs and waste management practices. Specifically, EPA visited beef feedlots, dairies, and swine, poultry, and veal operations throughout the United States. A wide range of operations were visited including those demonstrating centralized treatment or new and innovative technologies. EPA chose the majority of facilities with the assistance of the following industry trade associations:

- National Pork Producers Council
- United Egg Producers and United Egg Association
- National Turkey Federation
- National Cattlemen's Beef Association

- National Milk Producers Federation
- Western United Dairymen

EPA also received assistance from environmental groups, such as the Natural Resources Defense Council and the Clean Water Network. The Agency contacted university experts, state cooperatives and extension services, and state and EPA regional representatives when identifying facilities for site visits. EPA also attended USDA-sponsored farm tours, as well as industry, academic, and government conferences.

Table 3-1 summarizes the number of site visits EPA conducted by animal industry sector, site locations, and size of animal operations.

Table 3-1. Number of Site Visits Conducted by EPA for the Various Animal Industry Sectors.

Animal Sector	Number of Site Visits	Location(s)	Size of Operations
Swine	30	NC, PA, OH, IA, MN, TX, OK, UT	900–1 million head
Poultry	6 (broiler)	GA, AR, NC, VA, WV, MD, DE, PA, OH, IN, WI	20,000–1 million birds
	12 (layer)		
	6 (turkey)		
Dairy	29	PA, FL, CA, WI, CO, VA	40–4,000 cows
Beef	30	TX, OK, KS, CO, CA, IN, NE, IA	500–120,000 head
Veal	3	IN	500–540 calves

EPA considered the following factors when identifying representative facilities for site visits:

- Type of animal feeding operation
- Location
- Feedlot size
- Current waste management practices

Facility-specific selection criteria are contained in site visit reports (SVRs) prepared for each facility visited by EPA. The SVRs are located in the administrative record for this rulemaking.

During the site visits, EPA typically collected the following types of information:

- General facility information including size and age of facility, number of employees, crops grown, precipitation information, and proximity to nearby waterways.

- Animal operation data including flock or herd size, culling rate, and method for disposing of dead animals.
- Description of animal holding areas such as barns or pens, and any central areas, such as milking centers.
- Manure collection and management information including the amount generated, removal methods and storage location, disposal information, and nutrient content.
- Wastewater collection and management information including the amount generated, runoff information, and nutrient content.
- Nutrient management plans and BMPs.
- Available wastewater discharge permit information.

This information, along with other site-specific information, is documented in the SVRs for each facility visited.

3.2 Industry Trade Associations

EPA contacted the following industry trade associations and representatives during the development of the proposed and promulgated rules.

US Poultry and Egg Association (USPOULTRY). USPOULTRY is described in their literature as dedicated to the growth, progress, and welfare of the poultry industry and all of its individual and corporate interests. All segments of the industry are represented, from producers of eggs, turkeys, and broilers to the processors of these products and allied companies which serve the industry. USPOULTRY sponsors the world's largest poultry industry show; scientific research; and a comprehensive, year-round educational program for members of the industry.

Capitol Link. Capitol Link represents the interests of many livestock organizations and acts as a liaison with federal agencies such as EPA. They frequently provide comments and data on proposed federal regulatory actions.

National Pork Producers Council (NPPC). NPPC is a marketing organization and trade association made up of 44 affiliated state pork producer associations. NPPC's stated purpose is to increase the quality, production, distribution, and sales of pork and pork products.

United Egg Producers and United Egg Association (UEP/UEA). UEP/UEA promotes the egg industry in the following areas: price discovery, production and marketing information, unified industry leadership, USDA relationships, and promotional efforts.

National Turkey Federation (NTF). NTF describes itself as the national advocate for all segments of the turkey industry, providing services and conducting activities that increase demand for its members' products.

National Chicken Council (NCC) and National Broiler Council (NBC). NCC is a trade association representing the vertically integrated companies that produce and process about 95 percent of the chickens sold in the United States. The association provides consumer education, public relations, and public affairs support, and is working to seek a positive regulatory, legislative, and economic environment for the broiler industry. The NCC's activities generally replace those activities conducted prior to proposal by the National Broiler Council.

National Cattlemen's Beef Association (NCBA). NCBA is a marketing organization and trade association for cattle farmers and ranchers, representing the beef industry.

National Milk Producers Federation (NMPF). NMPF is involved with milk quality and standards, animal health and food safety issues, dairy product labeling and standards, and legislation affecting the dairy industry.

American Veal Association (AVA). AVA represents the veal industry, advances the industry's concerns in the legislative arena, coordinates production-related issues affecting the industry, and handles other issues relating to the industry.

Western United Dairymen (WUD). WUD, a dairy organization in California, promotes legislative and administrative policies and programs for the industry and consumers.

Professional Dairy Heifer Growers Association (PDHGA). PDHGA is an association of heifer growers dedicated to growing high-quality dairy cow replacements. The association offers educational programs and professional development opportunities, provides a communication network, and establishes business and ethical standards for the dairy heifer grower industry.

All of the above organizations, along with several of their state affiliates, assisted EPA's efforts to understand the industry by helping with site visit selection, submitting supplemental data, and reviewing descriptions of the industry and waste management practices. These organizations also participated in and hosted meetings with EPA for the purpose of exchanging information. EPA also obtained copies of membership directories and conference proceedings, which were used to identify contacts and obtain additional information on the industry. Publications from trade associations were used to support cost methodologies.

3.3 U.S. Department of Agriculture

EPA obtained data from several agencies within the USDA, including the National Agricultural Statistics Service (NASS), the Animal and Plant Health Inspection Service (APHIS), Natural Resources Conservation Service (NRCS), and the Economic Research Service (ERS) in order to better characterize the CAFO industry. The collected data include statistical survey information and published reports. Data collected from each agency are described below.

3.3.1 National Agricultural Statistics Service

NASS is responsible for objectively providing accurate statistical information and data support services of structure and activities of agricultural production in the United States. Each year NASS conducts hundreds of surveys and prepares reports covering virtually every facet of U.S. agricultural publications. The primary source of data is the animal production facility. NASS collects voluntary information using mail surveys, telephone and in-person interviews, and field observations. NASS is also responsible for conducting a Census of Agriculture every 5 years. EPA gathered information from the following published NASS reports:

- *1997 Census of Agriculture*
- *Hogs and Pigs: Final Estimates 1993 - 1997*
- *Chickens and Eggs: Final Estimates 1994 - 1997*
- *Poultry Production and Value: Final Estimates 1994 - 1997*
- *Cattle: Final Estimates 1994 - 1998*
- *Milking Cows and Production: Final Estimates 1993 - 1997*

The information EPA collected from these sources is summarized below.

1997 Census of Agriculture

The Census of Agriculture is a complete accounting of U.S. agricultural production and is the only source of uniform, comprehensive agricultural data for every county in the nation. The census is conducted every 5 years. The Bureau of the Census conducted this activity until 1997, when the responsibility passed to NASS. The census includes all farm operations from which $1,000 or more of agricultural products are produced and sold. The most recent census occurred in late 1997 and is based on calendar year 1997 data.

The census collects information relating to land use and ownership, crops, livestock, and poultry. USDA maintains this database; EPA compiled data used for this analysis with the assistance of NASS staff. (USDA periodically publishes aggregated data from these databases and also compiles customized analyses of the data for members of the public and other government agencies. In providing such analyses, USDA maintains a sufficient level of aggregation to ensure the confidentiality of any individual operation's activities or holdings.)

EPA developed several size groups to allow tabulation of farm counts by farm size using different criteria than those used in the published *1997 Census of Agriculture*. EPA developed algorithms to define farm size in terms of capacity, or number of animals likely to be found on the farm at any given time. To convert sales of hogs and pigs and feeder pigs into an inventory, EPA divided total sales by the number of groups of pigs likely to be produced and sold in a given year. EPA estimates that the larger grower-finisher farms produce 2.8 groups of pigs per year.

Farrow-to-finish operations produce 2.0 groups of pigs per year. Nursery operations produce up to 10 groups per year. EPA developed data used to determine the groups of pigs produced per year from a survey conducted by APHIS (USDA,1999). For beef feedlots, EPA worked with staff from NASS and NCBA to estimate the number of groups of cattle produced per year at a CAFO, and the capacity of the operation based on the number of cattle sold. EPA estimates that beef feedlots produce between 1 and 2.5 groups of cattle per year, depending on the size of the operation (ERG, 2002).

Hogs and Pigs: Final Estimates 1993 - 1997

EPA used data from this report to augment the swine industry profile. The report presents information on inventory, market hogs, breeding herds, and pig crops, and specifically, the number of farrowings, sows, and pigs per litter. This report presents the number of operations with hogs; however, EPA did not use this information to estimate farm counts because the report provided limited data. Instead, as discussed earlier in this section, EPA used data provided by USDA based on the *1997 Census of Agriculture.*

Chickens and Eggs: Final Estimates 1994 - 1997

EPA used data from this report to augment the poultry industry profile. The report presents national and state-level data for the top-producing states on chickens and eggs including the number laid, and production for 1994 through 1997.

Poultry Production and Value: Final Estimates 1994 - 1997

EPA used data from this report to augment the poultry industry profile. The report presents national and state-level data for the top-producing states on production (number and pounds produced/raised), price per pound or egg, and value of production of broilers, chickens, eggs, and turkeys for 1994 through 1997.

Cattle: Final Estimates 1994 - 1998

EPA used data from this report to augment the beef industry profile. The report provides the number of and population estimates for beef feedlots that have a capacity of over 1,000 head of cattle, grouped by size and geographic distribution. This report also provides national and state-level data which include the number of feedlots, cattle inventory, and number of cattle sold per year by size class for the 13 top-producing beef states. In addition, the report presents the total number of feedlots that have a capacity of fewer than 1,000 head of cattle, total cattle inventory, and number of cattle sold per year for these operations. However, EPA did not use this report to estimate farm counts because it provided limited data. Instead, as discussed earlier in this section, EPA used data provided by USDA based on the *1997 Census of Agriculture.*

Milking Cows and Production: Final Estimates 1993 - 1997

EPA used data from this report to augment the dairy industry profile. The report presents national and state-level estimates of dairy cattle inventory and the number of dairy operations by size group. This particular report presents data for all dairy operations with over 200 mature dairy cattle in one size class. However, EPA did not use this report to estimate farm counts because it provided limited data. Instead, as discussed earlier in this section, EPA used data provided by USDA based on the *1997 Census of Agriculture.*

3.3.2 Animal and Plant Health Inspection Service National Animal Health Monitoring System (NAHMS)

APHIS provides leadership in ensuring the health and care of agricultural animals and plants, improving agricultural productivity and competitiveness, and contributing to the national economy and public health. One of its main responsibilities is to enhance the care of animals. In 1983, APHIS initiated NAHMS as an information-gathering program to collect, analyze, and disseminate data on animal health, management, and productivity across the United States. NAHMS conducts national studies to gather data and generate descriptive statistics and information from data collected by other industry sources. NAHMS has published national study reports for various food animal populations (e.g., swine, dairy cattle).

EPA gathered information from the following NAHMS reports:

- *Swine '95 Part I: Reference of 1995 Swine Management Practices*
- *Swine '95 Part II: Reference of Grower/Finisher Health & Management Practices*
- *Swine 2000 Part I: Reference of Swine Health and Management in the United States*
- *Layers '99 Parts I and II: Reference of 1999 Table Egg Layer Management in the U.S.*
- *Dairy '96 Part I: Reference of 1996 Dairy Management Practices*
- *Dairy '96 Part III: Reference of 1996 Dairy Health and Health Management*
- *Beef Feedlot '95 Part I: Feedlot Management Practices*
- *Feedlot '99 Part I: Baseline Reference of Feedlot Management Practices*
- *Equine '98 Parts I and II: Baseline Reference of 1998 Equine Health and Management*

EPA also collected information from NAHMS fact sheets, specifically the *Swine '95* fact sheets, which describe biosecurity measures, vaccination practices, environmental practices/ management, and antibiotics used in the industry. The information EPA collected from these reports is summarized below.

Swine '95 Part I: Reference of 1995 Swine Management Practices

This report (USDA APHIS, 1995b) provides references on productivity, preventative and vaccination practices, biosecurity issues, and environmental programs (including carcass disposal). The data were obtained from a sample of 1,477 producers representing nearly 91 percent of the U.S. hog inventory from the top 16 pork-producing states. Population estimates are broken down into farrowing and weaning, nursery, grower/finisher, and sows.

Swine '95 Part II: Reference of Grower/Finisher Health & Management Practices

This report (USDA APHIS, 1996a) provides additional references on feed and waste management, health and productivity, marketing, and quality control. The data were collected from 418 producers with operations having 300 or more market hogs (at least one hog over 120 pounds) and represent about 90 percent of the target population. NAHMS also performed additional analyses for EPA that present manure management information for the swine industry in two size classes (fewer than 2,500 marketed head and more than 2,500 marketed head) and three regions (Midwest, North, and Southeast) (USDA APHIS, 1999).

Swine 2000 Part I: Reference of Swine Health and Management in the United States

Swine 2000 (USDA APHIS, 2001) was designed to statistically sample from operations with 100 or more pigs. The study included 17 of the major pork-producing states that account for 94 percent of the U.S. pig inventory. Data for this report were collected from 2,328 operations. This report provides information on feed and waste management, health and productivity, animal management, and facility management. In addition to this report, NAHMS also performed additional analyses for EPA that present the percent of sites where pit holding was the waste management system used most by region and herd size for farrowing and grow/finish operations (USDA APHIS, 2002b).

Layers '99 Parts I and II: Reference of 1999 Table Egg Layer Management in the U.S.

The Layers '99 study (USDA APHIS, 2000b) is the first NAHMS national study of the layer industry. Data were obtained from 15 states, which account for over 75 percent of the table egg layers in the United States. Part I of this report summarizes the study results including descriptions of farm sites and flocks, feed, and health management. Part II of this report summarizes biosecurity, facility management, and manure handling practices.

Dairy '96 Part I: Reference of 1996 Dairy Management Practices and Dairy '96 Part III: Reference of 1996 Dairy Health and Health Management

These reports (USDA APHIS, 1996b and 1996c) present the results of a survey distributed to dairies in 20 major states to collect information on cattle inventories; dairy herd management practices; health management; births, illness, and deaths; housing; and biosecurity. The results represent 83 percent of U.S. milk cows, or 2,542 producers. The reports also provide national

data on cattle housing, manure and runoff collection practices, and irrigation/land application practices for dairies with more than, or fewer than, 200 mature dairy cattle. NAHMS provided the same information to EPA with the results reaggregated into three size classes (fewer than 500, 500 to 699, and more than 700 mature dairy cattle) and into three regions (East, West, and Midwest) (USEPA, 2002a).

Beef Feedlot '95 Part I: Feedlot Management Practices

This report (USDA APHIS, 1995a) contains information on population estimates, environmental programs (e.g., ground water monitoring and methods of waste disposal), and carcass disposal at small and large beef feedlots (fewer than and more than 1,000 head capacity). The data were collected from 3,214 feedlots in 13 states, representing almost 86 percent of the U.S. cattle-on-feed inventory.

Feedlot '99 Part I: Baseline Reference of Feedlot Management Practices

This report (USDA APHIS, 2000a) contains information on population estimates, environmental programs, and carcass disposal at beef feedlots. The data were collected from 1,250 feedlots in 12 states, representing 77 percent of all cattle on feed in the United States.

Equine '98 Parts I and II: Baseline Reference of 1998 Equine Health and Management

This report contains information on population demographics, as well as health and health management practices. Part II of the same report describes nutrition, pasture, housing, bedding, and manure management. NAHMS performed additional analyses for EPA to provide information on primary use and function by size class (USDA APHIS, 2002a).

3.3.3 Natural Resources Conservation Services

NRCS provides leadership in a partnership effort to help people conserve, improve, and sustain U.S. natural resources and the environment. NRCS relies on many partners to help set conservation goals, work with people on the land, and provide assistance. Its partners include conservation districts, state and federal agencies, NRCS Earth Team volunteers, agricultural and environmental groups, and professional societies.

NRCS publishes the *Agricultural Waste Management Field Handbook* (AWMFH) (USDA NRCS, 1992), which is an agricultural/engineering guidance manual that explains general waste management principles and provides detailed design information for particular waste management systems. The handbook presents specific design information on a variety of farm production and waste management practices at different types of feedlots. The handbook also provides runoff calculations under normal and peak precipitation as well as information on manure and bedding characteristics. NRCS also publishes Conservation Practice Standards for many waste handling and treatment operations. EPA used this information to develop its cost and environmental analyses. NRCS personnel also contributed technical expertise in the

development of EPA's estimates of compliance costs and environmental assessment framework by providing EPA with estimates of manure generation in excess of expected crop uptake.

NRCS also analyzed the census data that EPA used for its analysis. In the draft February 23, 2002 *Profile of Farms with Livestock in the United States: A Statistical Summary* (USDA, 2002), NRCS presents estimates of the number of CAFOs by animal sector and size group, as well as the number of head at these farms. EPA used these estimates to calculate the average number of head and the number of CAFOs by animal sector and size group. In the case of beef feedlots, NRCS used a turnover rate of 2.5 to estimate capacity for all size operations. EPA recalculated the number of head at these operations using the turnover rates discussed above.

Another NRCS report (USDA, 2000), *Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States* published in December 2000, provides background information on trends in animal agriculture and manure production based on information collected in the *1997 Census of Agriculture*. EPA used data on the percentage of farms with sufficient cropland, insufficient cropland, and no cropland to determine the number of CAFOs that require off-site transport of excess manure. EPA also used data from this report to determine the amount of excess manure at operations with an insufficient amount of cropland to agronomically land-apply all of the manure and wastewater generated on site.

Beginning in early 2002 the NRCS shared drafts of their report *Overview of Cost Analysis for Implementation of CNMPs On Animal Feeding Operations* with EPA. This report presents a cost analysis for planning, designing, implementing and following up on CNMPs on AFOs. The report also estimated the percentage of operations that have high, medium, and low requirements for the development and implementation of CNMPs. The scheduled release of the final document is October 2002. EPA used the data and appendices of information from these draft reports to refine baseline conditions for some portions of the CAFOs industry.

3.3.4 Agricultural Research Service (ARS)

ARS is the primary research agency working internally for the USDA. One of its many objectives is to heighten awareness of natural resources and the environment. EPA used information provided from ARS's *Agricultural Phosphorus and Eutrophication* report (USDA, 1999) to estimate the number of CAFOs that could be subject to a P-based regulation.

3.3.5 Economic Research Service (ERS)

ERS provides economic analyses on efficiency, efficacy, and equity issues related to agriculture, food, the environment, and rural development to improve public and private decision making. ERS uses data from the Farm Costs and Returns Survey (FCRS) to examine farm financial performance (USDA ERS, 1997). In this report, ERS grouped agricultural production in the United States into 10 broad geographic sectors: Pacific, Mountain, Northern Plains, Southern

Plains, Lake States, Corn Belt, Delta, Northeast, Appalachian, and Southern. EPA further consolidated the ten sectors into five regions in order to analyze aggregated Census of Agriculture data: Mid-Atlantic, South, Midwest, Central, and Pacific. These five aggregated regions are the geographic regions used throughout EPA's analyses.

ERS is also responsible for the Agricultural Resource Management Study (ARMS), USDA's primary vehicle for collecting information on a broad range of issues about agricultural resource use and costs, and farm sector financial conditions. The ARMS is a flexible data collection tool with several versions and uses. Information is collected via surveys, and provides a measure of the annual changes in the financial conditions of production agriculture.

3.4 Other Agency Reports

EPA used data from several EPA reports to develop emission factors used in the nonwater-quality impact analyses. The Office of Air Quality Planning and Standards (OAQPS) report entitled *Emissions from AFOs* (USEPA, 2001) summarizes data concerning air emissions from large AFOs including estimated emission factors. The Office of Air and Radiation report entitled *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2000* (USEPA, 2002b) provides methodologies for estimating methane and nitrous oxide emissions from manure management systems and agricultural land. The Office of Research and Development (ORD) provided literature summaries and possible approaches to quantifying pathogens in manure, their risks to human health, and potential reductions resulting from the various technology options and BMPs. ORD also provided the summary report *Regional/ORD Workshop on Emerging Issues Associated with Aquatic Environmental Pathogens* (September 5, 2001) and the memorandum *Human Health and Environmental Risks Associated with Runoff from Animal Feedlot Operations* (February 12, 2001).

3.5 Literature Sources

EPA performed several Internet and literature searches to identify papers, presentations, and other applicable materials to use in developing the proposed rule. Literature sources were identified from library literature searches as well as through EPA contacts and industry experts. Literature collected by EPA covers such topics as housing equipment, fertilizer and manure application, general agricultural waste management, air emissions, pathogens, and construction cost data. EPA used literature sources to estimate the costs of design and expansion of waste management system components at AFOs. EPA also used publicly available information from several universities specializing in agricultural research as well as existing computer models, such as the FarmWare Model that was developed by EPA's AgStar program, for industry profile information, waste management and modeling information, and construction cost data. The agency also reviewed industry magazines for useful information.

3.6 References

ERG, 2002. *Beef Production Cycles and Capacity*. Memorandum from D. Bartram to Feedlots Rulemaking Record. December 9, 2002.

USDA ERS. 1997. *Financial Performance of U.S. Commercial Farms, 1991-94*. U.S. Department of Agriculture Economic Research Service. AER-751. June 1997.

USDA APHIS. 1995a. *Part 1: Feedlot Management Practices*, National Animal Health Monitoring System. Fort Collins, CO. 1995.

USDA APHIS. 1995b. *Swine '95: Part 1: Reference of 1995 Swine Management Practices*, National Animal Health Monitoring System. Fort Collins, CO. October 1995.

USDA APHIS. 1996a. *Swine '95: Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices*, National Animal Health Monitoring System. Fort Collins, CO. June 1996.

USDA APHIS. 1996b. *Dairy '96 Part I: Reference of 1996 Dairy Management Practices*, National Animal Health Monitoring System. Fort Collins, CO. May 1996.

USDA APHIS. 1996c. *Dairy '96 Part III: Reference of 1996 Dairy Health and Health Management*, National Animal Health Monitoring System. Fort Collins, CO. May 1996.

USDA APHIS. 1999. *Re-aggregated Data from the National Animal Health Monitoring System's (NAHMS) Swine '95 Study*. Aggregated by Eric Bush of the U.S. Department of Agriculture, Animal and Plant Health Inspection System, Centers for Epidemiology and Animal Health. 1999.

USDA APHIS. 2000a. *Feedlot '99 - Part 1: Baseline Reference of Feedlot Management Practices*, National Animal Health Monitoring System. Fort Collins, CO. May 2000.

USDA APHIS. 2000b. *Part II: Reference of 1999 Table Egg Layer Management in the U.S.*, National Animal Health Monitoring System. Fort Collins, CO. January 2000.

USDA APHIS. 2001. *Part I: Reference of Swine Health and Management in the United States, 2000*, National Animal Health Monitoring System. Fort Collins, CO. August 2001.

USDA APHIS. 2002a. *Queries on Equine '98 run by Centers for Epidemiology and Animal Health*; prepared by Michael Durham; January 7, 2002.

USDA APHIS. 2002b. *Queries on Swine 2000 run by Centers for Epidemiology and Animal Health* prepared by Eric Bush; March 22, 2002; 2 pages.

USDA. 1992. *National Engineering Handbook: Agricultural Waste Management Field Handbook*, U.S. Department of Agriculture, Natural Resources Conservation Service. 1992.

USDA. 1999. *Agricultural Phosphorus and Eutrophication*. ARS-149. U.S. Department of Agriculture, Agricultural Research Service. 1999.

USDA. 2000. *Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States,* U.S. Department Agriculture, Natural Resources Conversation Service. December, 2000.

USDA. 2002. *Number Profile of Farms with Livestock in the United States: A Statistical Summary.* U.S. Department Agriculture, Natural Resources Conversation Service. February 4, 2002.

USEPA. 2001. *Emissions From Animal Feeding Operations (Draft).* U.S. Environmental Protection Agency Office of Air Quality Planning and Standards. August 15, 2001.

USEPA. 2002a. Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations. December 15, 2002. EPA-821-R-03-004.

USEPA. 2002b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2000.* EPA 430-R-02-003. U.S. Environmental Protection Agency Office of Atmospheric Programs. April 15, 2002.

CHAPTER 4

INDUSTRY PROFILES

4.0 INTRODUCTION

This chapter describes the current organization, production processes, and facility and waste management practices of the AFO and CAFO industries. Farm production methods, operation sizes, geographical distributions, pollution reduction activities, and waste treatment practices in use are described separately for the swine, poultry, beef, and dairy subcategories. Discussions of changes and trends over the past several decades are also provided.

Information on animal production was generally obtained from USDA 1997 Census of Agriculture, NASS, and information gathered from site visits and trade associations. For information obtained from the 1997 Census of Agriculture, EPA divided the U.S. into five production regions and designated them the South, Mid-Atlantic, Midwest, West, and Central Regions. Originally, the USDA ERS established ten regions so that it could group economic information. EPA condensed these regions into the five AFO regions because of similarities in animal production and manure handling techniques, and to allow for the aggregation of critical data on the number of facilities, production quantities, and financial conditions, which may otherwise not be possible due to concerns about disclosure[1]. The production regions are defined in Table 4-1. See the *Cost Report* for additional discussion of the sensitivity of EPA's models to the five AFO regions as used in the cost models.

4.1 Swine Industry Description

Swine feeding operations include facilities that confine swine for feeding or maintenance for at least 45 days in any 12-month period. These facilities do not have significant vegetation in the confinement area during the normal growing season, and include totally enclosed buildings, and open buildings with and without outside access. Swine pasture operations are generally not included. Facilities that have swine feeding operations may also include other animal and agricultural operations such as crop farming.

This section discusses the following aspects of the swine industry:

- 4.1.1: Distribution of the swine industry by size and region

[1]For example, USDA Census of Agriculture data are typically not released unless there is a sufficient number of observations to ensure confidentially. Consequently, if data were aggregated on a state basis (instead of a regional basis), many key data points needed to describe the industry segments would be unavailable.

- 4.1.2: Production cycles of swine
- 4.1.3: Swine facility types and management
- 4.1.4: Swine waste management practices
- 4.1.5: Pollution reduction
- 4.1.6: Waste disposal

Table 4-1. AFO Production Regions.

Region	States Included
Central	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Oklahoma, Texas, Utah, Wyoming
Midwest	Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin
Mid-Atlantic	Connecticut, Delaware, Kentucky, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, Tennessee, Vermont, Virginia, West Virginia
Pacific	Alaska, California, Hawaii, Oregon, Washington
South	Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, South Carolina

The swine industry is a significant component of the domestic agricultural sector, generating farm receipts ranging from $9.2 billion to more than $11.5 billion annually during the past decade (USDA NASS, 1998a). Total annual receipts from the sale of hogs average approximately 12 percent of all livestock sales and 5 percent of all farm commodity sales. Annual swine output ranks fourth in livestock production value after cattle, dairy products, and broilers. During 1997, more than 17 billion pounds of pork were processed from 93 million hogs. The retail value of pork sold to consumers exceeded $30 billion. The National Pork Producers Council estimates that the pork industry supports more than 600,000 jobs nationally (NPPC, 1999).

As described in the following sections, the swine industry has undergone a major transformation during the past several decades. Swine production has shifted from small, geographically dispersed family operations to large "factory farms" concentrated primarily in 10 states in the Midwest and the South. The number of hog operations, which approached 3 million in the 1950s, had declined to about 110,000 by 1997. The rate of consolidation has increased dramatically in the last decade, which has seen more than a 50 percent decline in the number of swine operations (USDA NASS, 1999a). All indications are that this trend toward consolidation is continuing.

Swine production has also changed dramatically in terms of the production process and the type of animal produced. The hog raised for today's consumer is markedly different from the one produced in the 1950s. Today's hogs contain approximately 50 percent less fat and are the result of superior genetics and more efficient diets. The average whole-herd feed conversion ratio (pounds of feed per pound of live weight produced) used to be between 4 and 5 and has steadily decreased with current averages between 3.6 and 3.8. The most efficient herds have whole-herd feed conversion ratios under 3.0 (NPPC, 1999). Hence, a well-run swine operation can currently produce a 250-pound hog using only 750 pounds of animal feed during its lifetime.

The domestic hog industry is increasingly dominated by large, indoor, totally confined operations capable of handling 5,000 hogs or more at a time (USDA NASS, 1999b, and USDA NASS, 1999c). These operations typically produce no other livestock or crop commodities. In addition, there has been greater specialization as more swine operations serve only as nursery or finishing operations.

Another growing trend in the industry is that more hogs are being produced under contract arrangement whereby large hog producers, typically referred to as integrators or contractors, establish production contracts with smaller growers to feed hogs to market weight. The producer-integrator provides management services, feeder pigs, food, medicine, and other inputs, while the grower operations provide the labor and facilities. In return, each grower receives a fixed payment, adjusted for production efficiency. These arrangements allow integrators to grow rapidly by leveraging their capital. For example, instead of investing in all the buildings and equipment required for a farrow-to-finish operation, the integrator can invest in specialized facilities, such as farrowing units, while the growers pay for the remaining facilities, such as the nurseries and finishing facilities (Martinez, 1999). Occasionally other forms of contracts may be used.

According to a survey conducted for the USDA, 11 percent of the nation's hog inventory at the end of 1993 was produced under long-term contracts. This percentage was expected to increase to 29 percent by 1998 (Martinez, 1999). The Mid-Atlantic region has the greatest proportion of contracted hogs, with more than 65 percent of grown at facilities where the grower does not own the hogs (USDA NASS 1999c).

These changes at both the industry and farm levels represent a significant departure from earlier eras, when hogs were produced primarily on relatively small but integrated farms where crop production and other livestock production activities occurred and where animals spent their complete life cycle. The following sections describe the current production and management practices of domestic swine producers.

4.1.1 Distribution of Swine Operations by Size and Region

EPA's 1974 CAFO Effluent Limitations Guidelines and Standards generally apply to swine feeding operations with more than 2,500 head, but count only those swine weighing more than 55

pounds. (See Chapter 2 for the definition of a CAFO, and Chapter 5 for a discussion of the basis for revisions to the swine subcategory.) Most data sources cited in this section do not distinguish swine by weight, but may provide other information that distinguishes sows and other breeding pigs, feeder pigs, litters, and market pigs. Where numbers of head are presented in the following sections, feeder pigs were not included in the counts unless specified in the text.

4.1.1.1 National Overview

The estimated number of domestic swine operations has continuously declined since the 1950s. As recently as 1970, there were more than 870,000 producers of swine. By 1997, this number had decreased to about 110,000 (USDA NASS, 1999b)[2]. The decline has been especially dramatic over the past decade. As shown in Table 4-2, the number of operations has steadily decreased over the years.

Table 4-2. Changes in the Number of U.S. Swine Operations and Inventory 1982-1997.

Year	Operations	Inventory
1982	329,833	55,366,205
1987	243,398	52,271,120
1992	191,347	57,563,118
1997	109,754	61,206,236

Source: USDA NASS, 1999b.

As the number of operations has decreased, however, hog inventories have actually risen due to the emerging market dominance by larger operations. Inventories increased from 55.4 million head in 1982 to 61.2 million head in 1997 (USDA NASS, 1999b).

4.1.1.2 Operations by Size Class

The general trend in the U.S. swine industry is toward a smaller number of large operations (Table 4-3). As the percentage of smaller producers decreases, there is a consistent increase in the percentage of herds with a total inventory of 2,000 or more head. The increase in the number of large operations has predominantly occurred in conjunction with extended use of total confinement operations, which separate the three production phases described in 4.1.2.

[2] USDA defines an operation as any place having one or more hogs or pigs on hand at any time during the year.

Table 4-3. Percentage of U.S. Hog Operations and Inventory by Herd Size.

Year	0-1,999 Head		2,000-4,999 Head		More Than 5,000 Head	
	Operations	Inventory	Operations	Inventory	Operations	Inventory
1982	99.3	85.7	0.6	9.5	0.1	4.8
1987	98.9	79.0	1.0	12.9	0.2	8.1
1992	97.9	68.7	1.6	15.2	0.4	17.0
1997	94.4	39.3	3.9	20.8	1.7	40.2

Source: USDA NASS, 1999b.

In terms of farm numbers, small operations still dominate the industry; however, their contribution to total annual hog production has decreased dramatically in the past decade. For example, operations with up to 1,999 head, which produced 85.7 percent of the nation's hogs in 1982, raised only 39.3 percent of the total in 1997. In contrast, in 1982, the 0.1 percent of operations that reported more than 5,000 head produced approximately 5 percent of the swine; in 1997 these large operations (1.7 percent of all operations) produced over 40 percent of the nation's hogs.

4.1.1.3 Regional Variation in Hog Operations

Swine farming has historically been centered in the Midwest Region of the United States, with Iowa being the largest hog producer in the country. Although the Midwest continues to be the nation's leading hog producer (five of the top seven producers are still in the Midwest), significant growth has taken place in other areas. Perhaps the most dramatic growth has occurred in the Mid-Atlantic Region, in North Carolina. From 1987 to 1997, North Carolina advanced from being the 12th largest pork producer in the nation to second behind only Iowa. Climate and favorable regulatory policies played a major role in the growth of North Carolina's swine industry.

North Carolina's winters are mild and summers are tolerable, and this has allowed growers to use open-sided buildings. Such buildings are less expensive than the solid-sided buildings made necessary by the Midwest's cold winters. Midwestern growers must also insulate or heat their buildings in the winter. Tobacco farmers, who found hogs a means of diversifying their operations, also fueled North Carolina's pork boom. The idea of locating production phases at different sites was developed in North Carolina. The state also has a much higher average inventory per farm than any of the states in the Corn Belt. Whereas Iowa had an average of fewer than 850 head per farm, North Carolina had an average of more than 3,200 head per farm in 1997. In recent years, significant growth has also occurred in the panhandle area of Texas and Oklahoma, Colorado, Utah, and Wyoming, in the Central Region; northern Iowa and southern Minnesota, in the Midwest Region.

Tables 4-4 through 4-7 present the distribution of different types of swine operations for the key producing regions. For the purposes of these tables, breeder operations, also known as farrowing operations, have large numbers of sows and sell or transfer the pigs when they have been weaned or grown to approximately 55 pounds (feeder pigs); some farrowing operations may also keep boars. Nursery operations receive weaned pigs and grow them to approximately 55 pounds. Grow-finish operations are operations that receive feeder pigs and grow them out to marketable weight; these pigs are often labeled "swine for slaughter." Combined operations perform all phases of production, known in the industry as "farrow-to-finish," or just the final two phases called "wean-finish." Note that no large independent nurseries are depicted by the 1997 census data. EPA is aware that several large nurseries have recently begun operation or are under construction. The considerable amount of growth in the Central (Southwest) Region that has occurred in the past 3 years is not reflected in the 1997 statistics presented in this section.

Table 4-4 shows the number of operations for six different size classes of facilities. Table 4-5 presents the average herd size by operation type, region, and operation size. Table 4-6 presents the percentage of total swine animal counts at combined and slaughter operations by region and operation size. Table 4-7 presents the distribution of different animal types in combined swine operations by region and operation size.

Table 4-4. Total Number of Swine Operations by Region, Operation Type, and Size in 1997.

Region[a]	Operation Type[b]	Number of Swine Operations (Operation Size Presented by Number of Head)						
		>0–750	>750–1,875	>1,875–2,500	>2,500–5,000	>5,000–10,000	>10,000	Total
Mid-Atlantic	combined	6,498	421	82	185	130	135	7,451
	slaughter	8,120	344	150	413	281	119	9,427
Midwest	combined	35,263	5,212	782	1,106	410	213	42,986
	slaughter	27,081	2,194	425	521	142	48	30,411
Other	combined	10,821	359	74	135	60	5	11,494
	slaughter	13,502	83	50	91	45	10	13,781
National	combined	52,582	5,992	938	1,426	600	393	61,931
	slaughter	48,703	2,621	625	1,025	468	177	53,619
	breeder	2,227		15			3	2,245
	nursery				83		0	83

[a] Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Other = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK, WA, OR, WA, OR, CA, AK, HI, AR, LA, MS, AL, GA, SC, FL.
[b] Operation type: combined = breeding inventory, finishing (average of inventory and sold/2.8), and feeders (sold/10); slaughter = finishing (average of inventory and sold/2.8); breeder = (inventory); and nursery = (feeders sold/10).
Source: USDA NASS 1999c.

Table 4-5. Average Number of Swine at Various Operations by Region Operation Type, and Size in 1997.

Region [a]	Operation Type [b]	Average Swine Animal Counts (Operation Size Presented by Number of Head)						
		>0– 750	>750– 1,875	>1,875– 2,500	>2,500– 5,000	>5,000– 10,000	>10,000	All Operations
Mid-Atlantic	combined	74	1,182	2,165	3,509	5,021	28,766	851
	slaughter	32	1,242	2,184	3,554	6,877	13,653	641
Midwest	combined	209	1,137	2,152	3,444	6,761	27,403	637
	slaughter	135	1,161	2,124	3,417	6,791	19,607	355
Other	combined	51	1,255	2,150	3,455	7,052	59,172	410
	slaughter	13	1,291	2,215	3,626	6,830	14,901	85
National	combined	160	1,147	2,153	3,453	6,413	31,509	621
	slaughter	84	1,176	2,146	3,491	6,846	15,338	336

[a] Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Other = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK, WA, OR, WA, OR, CA, AK, HI, AR, LA, MS, AL, GA, SC, FL.
[b] Operation type: combined = breeding inventory, finishing (average of inventory and sold/2.8), and feeders (sold/10); and slaughter = finishing (average of inventory and sold/2.8).
Source: USDA NASS, 1999c.

Table 4-6. Distribution of Swine Herd by Region, Operation Type, and Size in 1997.

Region [a]	Operation Type [b]	Percentage of Total Swine Animal Counts by Size Group (Operation Size Presented by Number of Head)						
		>0–750	>750– 1,875	>1,875– 2,500	>2,500– 5,000	>5,000– 10,000	>10,000	Total
Mid-Atlantic	combined	1.25	1.30	0.46	1.69	1.70	10.10	16.50
	slaughter	1.45	2.37	1.82	8.16	10.74	9.03	33.56
Midwest	combined	19.14	15.42	4.38	9.91	7.21	15.18	71.24
	slaughter	20.26	14.16	5.02	9.89	5.36	5.23	59.92
Other	combined	1.44	1.17	0.41	1.21	1.10	6.93	12.26
	slaughter	0.94	0.60	0.62	1.83	1.71	0.83	6.52
National	combined	21.83	17.88	5.25	12.81	10.01	32.21	100.00
	slaughter	22.65	17.13	7.45	19.88	17.80	15.09	100.00

[a] Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Other = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK, WA, OR, WA, OR, CA, AK, HI, AR, LA, MS, AL, GA, SC, FL.
[b] Operation type: combined = breeding inventory, finishing (average of inventory and sold/2.8), and feeders (sold/10); and slaughter = finishing (average of inventory and sold/2.8).
Source: USDA NASS, 1999c.

Table 4-7. Distribution of Animal Type in Swine Herds at Combined Facilities by Region, Operation Type, and Size in 1997.

Region [a]	Swine Type [b]	Percentage of Breeding, Finishing, and Feeder Hogs at Combined Facilities (Operation Size Presented by Number of Head)						
		>0–750	>750–1,875	>1,875–2,500	>2,500–5,000	>5,000–10,000	>10,000	All Operations
Mid-Atlantic	Breeding	19.84	17.38	15.59	17.68	16.66	17.19	17.31
	Finishing	73.96	71.74	72.46	65.56	59.02	58.55	61.61
	Feeder	6.20	10.88	11.95	16.75	24.32	24.25	21.08
Midwest	Breeding	17.85	16.14	16.55	15.88	15.23	14.65	16.18
	Finishing	78.33	79.59	76.66	76.38	77.77	80.32	78.59
	Feeder	3.82	4.26	6.80	7.73	7.00	5.03	5.23
Other	Breeding	22.47	19.95	19.54	18.38	20.84	17.54	18.74
	Finishing	73.03	61.02	69.00	71.39	64.45	78.57	73.89
	Feeder	4.48	19.04	11.46	10.23	14.71	3.90	7.37
National	Breeding	18.27	16.50	16.70	16.36	16.16	16.10	16.66
	Finishing	77.73	77.70	75.66	74.44	71.78	72.63	74.91
	Feeder	4.00	5.79	7.63	9.21	12.05	11.27	8.40

[a] Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Other = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK, WA, OR, WA, OR, CA, AK, HI, AR, LA, MS, AL, GA, SC, FL.
[b] Swine type: Breeding = inventory; finishing = average of inventory and sold/2.8; and feeder = sold/10.
Source: USDA NASS, 1999c.

USDA NRCS (2002) also provided information to EPA on the number of swine operations based on the following classifications as shown in Table 4.8:

- Operation size: >=2,500 head, 1,250-2,499 head, and 750-1,249 head.
- Land availability: No excess (Category 1 farms with sufficient crop or pastureland). Excess, with acres (Category 2 farms with some land, but not enough land to assimilate all manure nutrients). Excess, no acres (Category 3 farms with none of the 24 major crop types identified by NRCS).
- Location: Eleven states or groups of states.
- Nutrient basis: Applications are based on N or P application rates.

In Illinois for example, there are 72 facilities with more than 2,500 head with none of the 24 major crop types identified by NRCS for application of animal wastes. There are 34 operations (with 2,500 or more head) with some land in Illinois, but not enough land to assimilate all manure nutrients using N-based application rates, and 184 Illinois operations (with 2,500 or more head) with enough land to assimilate all manure nutrients using N-based application rates.

Table 4-8. Number of Swine Facilities as Provided by USDA Based on Analyses of 1997 Census of Agriculture Database.

Location	Land availability category	Operation Size and Nutrient Basis					
		>=2,500		1,250–2,499		750–1,249	
		N	P	N	P	N	P
AR, KS, OK	No excess	52	21	76	50	101	80
AR, KS, OK	Excess, no acres	66	66	36	36	22	22
AR, KS, OK	Excess, with acres	113	144	78	104	40	61
IL							
IL	Excess, no acres	72	72	45	45	39	39
IL	Excess, with acres	34	123	31	105	21	77
IN	No excess	179	107	254	205	387	346
IN	Excess, no acres	68	68	53	53	50	50
IN	Excess, with acres	35	107	29	78	36	77
IO	No excess	411	164	1,155	796	1,587	1,346
IO	Excess, no acres	211	211	183	183	235	235
IO	Excess, with acres	120	367	89	448	51	292
MI, WI	No excess	57	25	97	65	169	136
MI, WI	Excess, no acres	31	31	30	30	29	29
MI, WI	Excess, with acres	19	51	19	51	8	41
MN	No excess	225	97	386	272	523	430
MN	Excess, no acres	152	152	83	83	69	69
MN	Excess, with acres	50	178	28	142	28	121
MO	No excess	54	32	104	87	203	183
MO	Excess, no acres	17	17	18	18	25	25
MO	Excess, with acres	59	81	48	65	33	53
NC	No excess	194	15	83	23	56	21
NC	Excess, no acres	185	185	71	71	33	33
NC	Excess, with acres	630	809	157	217	45	80
NE	No excess	40	15	164	141	279	245
NE	Excess, no acres	81	81	49	49	82	82
NE	Excess, with acres	32	57	29	52	29	63
OH	No excess	45	23	98	61	202	154
OH	Excess, no acres	23	23	33	33	31	31
OH	Excess, with acres	12	34	17	54	29	77
other	No excess	184	87	244	145	404	289
other	Excess, no acres	132	132	99	99	102	102
other	Excess, with acres	157	254	104	203	78	193

Source: USDA NRCS, 2002.

4.1.2 Production Cycles of Swine

Swine production falls into three phases. Pigs are farrowed, or born, in farrowing operations. Sows are usually bred for the first time when they are 180 to 200 days old. Farrowing facilities range from pasture systems to completely confined housing systems. A sow's gestation period is about 114 days. Farrowings are typically 9 to 11 pigs per litter, with a practical range of 6 to 13. The highest death losses in the pig-raising cycle occur within 3 to 4 days of birth. The average number of pigs weaned per litter in 1997 was 8.67 (see Table 4-9). Producers incur significant expenses in keeping a sow, so the survival of each pig is critical to overall profitability. Sows

usually resume sexual activity within a week after a litter is weaned. Growers are able to roughly synchronize production by weaning all their baby pigs on the same day. When they do this, all the sows in a farrowing group become sexually active again at roughly the same time and may be bred again at the same time. The sows will then farrow at about the same time, over a period of about a week. In this way, growers are able to keep groups of pigs together as they move from one phase of production to another. Sows normally produce five to six litters before they are culled and sold for slaughter at a weight of 400 to 460 pounds.

Baby pigs are typically allowed to nurse from the sow, and then are relocated to a nursery, the second phase of swine production. In the nursery phase, pigs are weaned at 3 to 4 weeks of age and weigh 10 to 15 pounds. In the nursery, the pigs are raised to 8 to 10 weeks of age and 40 to 60 pounds. In practice, the weaning phase may take as few as 10 days, and may exceed 35 days.

During the third phase of production, growing pigs are raised to a market weight of 240 to 280 pounds. Finishing takes another 15 to 18 weeks, thus hogs are typically sent to market when they are about 26 weeks old (see Table 4-10). The growing and finishing phases were once separate production units, but are now combined in a single unit called grow-finish. In the growing–finishing unit, pigs are raised from 50 or 60 pounds to final market weight. The average grow-finish facility will produce approximately 2.8 turns (also called life cycles, herds, or groups) annually. Typically, finished pigs are from 166 to 212 days old. This results in a range of 2.4 to 3.4 turns (or groups) of pigs produced from the grow-finish unit per year. Average farrow-to-finish operations will produce 2.1 groups per sow per year. The range of annual turnover frequency at farrow-to-finish farms is from 1.8 to 2.5.

Table 4-9. Productivity Measures of Pigs.

Year	Number of Pigs Weaned per Litter	Per Breeding Animal per Year		Average Live Weight per Pig (pounds)
		Litters	Head to Slaughter	
1992	8.08	1.69	13.08	252
1993	8.13	1.68	13.06	254
1994	8.19	1.73	13.36	255
1995	8.32	1.68	13.64	256
1996	8.50	1.64	13.51	257
1997	8.67	1.72	13.79	260
Average	8.32	1.69	13.41	256

Source: NPPC, 1999.

Table 4-10. Age of Pigs Leaving Grow-Finish Unit in 1995.

Age of Pig on Leaving Grow-Finish Unit (days)	Percentage of Operations and Pigs	
	Percentage of Operations	Percentage of Pigs
120–160	12.5	12.2
160–165	16.7	12.6
166–180	49.6	45.8
181–209	16.3	24.9
210 or more	4.9	4.5
Weighted Average	173 days	175 days

Source: USDA APHIS, 1995.

In 1995, most operations had a farrowing facility, whereas slightly less than half of the facilities nationwide had a separate nursery facility. Most operations (85.6 percent) did have a finishing facility. Finishing operations get their pigs from on-site farrowing and nursery units (76.7 percent), off-site farrowing operations (10.2 percent), feeder pig producers under both contract and noncontract arrangements (13.8 percent), or livestock auctions or sales (5.9 percent). Large finishing operations (>10,000 head marketed) were more likely (56.3 percent) to get their pigs from off-site sources (USDA APHIS, 1995). Tables 4-11 and 4-12 present the frequency of the three major production phases by region and size. The sample profile of the *Swine '95* survey indicates that 61.9 percent of respondents were farrow-to-finish operations and that 24.3 percent were grow-finish operations. (At the time of writing, reports from the Swine 2000 survey did not provide equivalent statistics that allow comparisons based on region and operation size. Thus, Tables 4-11 and 4-12 present data from the *Swine '95* survey.)

Table 4-11. Frequency of Production Phases in 1995 on Operations That Marketed Less Than 5,000 Hogs in a 6-Month Period.

Production Phase	USDA APHIS Region[a]		
	Midwest	North	Southeast
Farrowing	76.6	68.6	69.3
Nursery	20.1	51	57.8
Finishing	78.8	79.7	93.4

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA APHIS, 1995

Table 4-12. Frequency of Production Phases in 1995 on Operations That Marketed 5,000 or More Hogs in a 6-Month Period.

Production Phase	USDA APHIS Region[a]		
	Midwest	North	Southeast
Farrowing	44.8	80.4	89
Nursery	75	67.1	97.4
Finishing	45.8	69.7	62.8

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA APHIS, 1995.

Although many large operations continue to have the full range of production phases at one facility, these operations are no longer the norm. More frequently, in new operations, several specialized farms are linked, or horizontally integrated, into a chain of production and marketing. Pigs begin in sowherds on one site, move to a nursery on another, and then move again to a finishing facility. Specialized operations can take advantage of skilled labor, expertise, advanced technology, streamlined management, and modern housing. However, the primary advantage of specialization is disease control. In a farrow-to-finish operation, a disease outbreak that begins in one phase of the operation can spread to the other phases. Physically separating the phases makes it easier to break this disease cycle. At the same time, separating phases spreads the cost of establishing swine operations, particularly if the different operations are owned by different persons.

Thus other categories of swine operations may comprise two or three of the three phrases described: combined farrow-nursery operations, which breed pigs and sell them at 40 to 60 pounds to finishing operations; wean-to-finish operations, which finish weaned pigs; and farrow-to-finish operations, which handle all phases of production from breeding through finishing. The emerging trend in the mid to late '90s was to produce pigs in two production phases rather than in three. In two-phase production, the weaned pigs may go straight into the grower building or finishing building, bypassing the nursery. The advantages of such practices are reduced transportation costs, lessened animal stress, and reduced animal mortality.

4.1.3 Swine Facility Types and Management

Table 4-13 summarizes the five major housing configurations used by domestic swine producers.

Although there are still many operations at which pigs are raised outdoors, the trend in the swine industry is toward larger confinement facilities where pigs are raised indoors. A typical confinement farrowing operation houses 3,000 sows, although some farrowing operations house as many as 10,000 sows at one location, and farms are being planned that will house as many as

15,000 sows at one location. Typical nursery operations are much smaller with a capacity of only about 1,500 head, but as stated earlier, separate nursery facilities are relatively uncommon.

Table 4-13. Summary of Major Swine Housing Facilities.

Facility Type[a]	Description	Applicability
Total confinement	Pigs are raised in pens or stalls in an environmentally controlled building.	Most commonly used in nursery and farrowing operations and all phases of very large operations. Particularly common in the Southeast.
Open building with no outside access	Pigs are raised in pens or stalls but are exposed to natural climate conditions.	Relatively uncommon but used by operations of all sizes.
Open building with outside access	Pigs are raised in pens or stalls but may be moved to outdoors.	Relatively uncommon, but used by some small to mid-sized operations.
Lot with hut or no building	Pigs are raised on cement or soil lot and are not confined to pens or stalls.	Used by small to mid-sized operations.
Pasture with hut or no building	Pigs are raised on natural pasture land and are not confined to pens or stalls.	Traditional method of raising hogs currently used only at small operations.

[a] These are the main facility configurations contained in the *Swine '95* Survey conducted by USDA APHIS, 1995.

The economic advantages of confined facilities have been the primary driving factor (especially at large operations) for farmers to abandon dry lot or pasture raising of hogs. Although controlled-environment buildings require a greater initial capital investment than traditional farm operations, labor costs per unit output are significantly reduced. Furthermore, these facilities allow for far greater control of the production process, protect both animals and workers from weather, and usually result in faster growth-to-market weight and better feed efficiency. Most controlled-environment facilities employ "all in, all out" production, in which pigs are moved in groups, and buildings are cleaned and disinfected between groups. It should be noted that the success of a controlled-environment operation is highly dependent on properly functioning ventilation, heating and cooling, and waste removal systems. A prolonged breakdown of any of these systems during extreme weather conditions can be catastrophic to the pig herd and economically devastating to the operator.

Facility requirements differ somewhat for each phase in a hog's life cycle, and hence farrowing, nursery, and growing-finishing facilities are configured differently. For example, farrowing operations require more intense management to ensure optimal production and reduce piglet mortality. A typical farrowing pen measures 5 by 7 feet, and the litter is provided with a protected area of approximately 8 square feet. The sow is relegated to a section of the pen and is separated from the piglets by low guard rails that reduce crushing but do not interfere with

suckling. Floors are usually slatted under or to the rear of the sow area to facilitate waste removal (NPPC, 1996).

Newly born piglets require special care because of their vulnerability to injury and disease. Nursery systems are typically designed to provide a warm, dry, and draft-free environment in which animal stress is minimized to promote rapid growth and reduce injury and mortality. Nursery rooms are regularly cleaned and sanitized to reduce the piglets' exposure to pathogens. Nursery buildings are cleaned and disinfected thoroughly between groups of pigs to prevent the transmission of disease from one herd to another. Nursery pens usually hold 10 to 20 pigs. Pigs are held in the nursery from weaning until they are 8 to 12 weeks old (NPPC, 1996).

Finishing pigs at tend to require less intensive management than piglets and can tolerate greater variations in environmental conditions without incurring health problems. In an environmentally controlled building, growing and finishing pens hold 15 to 40 pigs and allow about 6 square feet per pig. Overcrowding leads to stress and aggressive behavior and can result in reduced growth rates and injury. Slatted concrete floors are the most common (NPPC, 1996).

Smaller facilities tend to use open buildings, with or without access to the outside. Usually, hogs raised in these buildings are also confined to pens or stalls. Depending on the climate, the building might require ventilation and mist sprayer systems to prevent heat stress in the summer. Bedding might be needed during the winter months to protect the animals from the cold.

Hogs raised on dry lots or pasture require care and management similar to that for animals raised indoors, plus additional measures to protect the herds from extreme weather conditions. They must be provided with sufficient shade to reduce heat stress in the summer. Where natural shade is not available, facilities can be constructed to protect the herd from the sun in the summer and from wind and cold during the winter. Windbreaks are used under certain environmental conditions.

The most comprehensive information on swine facility and waste management systems currently in use by farm type, size, and state location was collected in conjunction with USDA's *Swine '95* study (USDA APHIS, 1995). Included in the study were 16 major pork-producing states that accounted for almost 91 percent of the U.S. hog inventory and more than 70 percent of the pork producers. The samples for the major swine-raising operations were statistically designed to provide inferences to the nation's swine population. Although the survey was conducted by APHIS and focused on swine health issues, it contains information on swine production and facility and waste management. Tables 4-14 and 4-15 present information on the housing types used in the farrowing phase. Tables 4-16 and 4-17 present information on the housing types used in the nursery phase. Tables 4-18 and 4-19 present information on the housing types used in the finisher phase. These tables clearly demonstrate that the larger facilities tend to use total confinement in all regions. (At the time of writing, reports from the Swine 2000 survey did not provide equivalent statistics that allow comparisons based on region and operation size. Thus Tables 4-14 through 4-19 present data from the *Swine '95* survey.)

Table 4-14. Housing Frequency (in percent) in 1995 of Farrowing Facilities at Operations That Marketed Fewer Than 5,000 Hogs in a 6-Month Period.

Facility Type	USDA APHIS Region[a]		
	Midwest	North	Southeast
Total Confinement	22.6	53.1	56
Open Building; no outside access	13.1	8.0	8.8
Open Building; outside access	25.7	33.8	31.2
Lot	16.2	3.2	1.1
Pasture	22.4	1.9	2.8

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA APHIS, 1995.

Table 4-15. Housing Frequency (in percent) in 1995 of Farrowing Facilities at Operations That Marketed 5,000 or More Hogs in a 6-Month Period.

Facility Type	USDA APHIS Region[a]		
	Midwest	North	Southeast
Total Confinement	98.3	100	100

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA APHIS, 1995.

Table 4-16. Housing Frequency (in percent) in 1995 of Nursery Facilities at Operations That Marketed Fewer Than 5,000 Hogs in a 6-Month Period.

Facility Type	USDA APHIS Region[a]		
	Midwest	North	Southeast
Total Confinement	52.3	55.4	62
Open Building; no outside access	9.1	11.5	8.8
Open Building; outside access	27.7	33.8	31.2
Lot	7.0	not available	3.7

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA.. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA APHIS, 1995.

Table 4-17. Housing Frequency (in percent) in 1995 of Nursery Facilities at Operations That Marketed 5,000 or More Hogs in a 6-Month Period.

Facility Type	USDA APHIS Region[a]		
	Midwest	North	Southeast
Total Confinement	99	100	96.4

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA; Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA APHIS, 1995.

Table 4-18. Housing Frequency (in percent) in 1995 of Finishing Facilities at Operations That Marketed Fewer Than 5,000 Hogs in a 6–Month Period

Facility Type	USDA APHIS Region[a]		
	Midwest	North	Southeast
Total Confinement	19.9	36.5	23.4
Open Building; no outside access	15.4	14.1	9.5
Open Building; outside access	24.5	42.1	55.9
Lot	17.1	4.6	9.3
Pasture	23.0	2.5	1.9

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA APHIS, 1995.

Table 4-19. Housing Frequency (in percent) in 1995 of Finishing Facilities at Operations That Marketed 5,000 or More Hogs in a 6-Month Period.

Variable	Region[a]		
	Midwest	North	Southeast
Total Confinement	96.8	95.5	83.9

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA APHIS, 1995.

4.1.4 Swine Waste Management Practices

Removal of manure from the animals' living space is critical for animal and farm worker well-being. Odor, gases, and dust carried by ventilation exhaust air are also affected by the waste management system used. Swine waste management systems can be separated into collection, storage, and treatment practices. An overview of the major practices in each of these areas is presented below, and more detailed information on waste collection, storage, and treatment practices is provided in Section 8 of this document. Although the practices described below do

not represent all of the waste management practices in use today, they are the predominant practices currently used at swine operations.

4.1.4.1 Swine Waste Collection Practices

Indoor raising of hogs requires that animals be physically separated from their waste products. Separation in larger facilities is usually accomplished through the use of concrete flooring with slots that allow the waste to drop below the living area and be transferred to a pit or trough beneath the pen. Smaller facilities hand clean pens to collect wastes.

The most frequently reported waste management system used in 1990 was hand cleaning (41.6 percent), which declined in use to 28.3 percent of operations in 1995 (USDA APHIS, 1995). This decrease in hand cleaning is highly correlated to the decrease in smaller facilities. Some facilities separate solid material from liquids before moving the material to storage. (A discussion of solid-liquid separation is presented in Section 8.) Slatted floors are now more commonly used to separate the manure from the animals at larger facilities. The waste is then deposited in an under-floor pit or gutter where it is stored or moved to another type of storage. There are two main types of under-floor collection practices in which the waste is moved for storage elsewhere.

- *Pit recharge.* Pit recharge is the periodic draining of the pit contents by gravity to storage, followed by recharging the pit with new or recycled water. Regular pit draining removes much of the manure solids that would otherwise settle and remain in the bottom of the pit. The regular dissolution of settled solids increases the likelihood the solids will be removed at the next pit draining. Recharge systems use a 16- to 18-inch-deep, in-house pit with 6 to 8 inches of water, which is emptied every 7 days to an anaerobic lagoon. Previously, 24-inch-deep pits were preferred, but now shallower pits are used with the hog slat system.
- *Flush.* Flush systems may use fresh water or recycled lagoon water for frequent removal of feces and urine from under-floor collection gutters or shallow pits. Like pit recharge systems, flush systems also improve animal health and performance as well as human working conditions in the swine houses by avoiding prolonged storage. Flush tanks with the capacity to release at least 1.5 gallons per 100 pounds of live animal weight per flush are placed at the end of the swine houses. Pit floors should be level from side to side, and wide pits should be divided into individual channels no wider than 4 to 5 feet. The floor slope for most flush systems is between 1 and 2 percent. Floors are flushed at least 1 to 12 times per day; the flush tanks are filled with new or recycled lagoon water before every flush. The flushed waste is collected and removed from the houses into storage through a system similar to that used in pit recharge systems.

4.1.4.2 Swine Waste Storage Practices

Waste storage is critical to the proper management of wastes from AFOs because manure nutrients are best applied to farmland only at certain times of the year, as determined by crops, climate, and weather. Storage practices include deep pits, anaerobic and aerobic lagoons, above

and belowground slurry storage (tanks or pits), and dry storage. Most large hog farms (more than 80 percent) have from 90 to 365 days of waste storage capacity (see Table 4-20).

Table 4-20. Percentage of Swine Facilities With Manure Storage in 1998.

Annual Marketed Head	0–3 months	3–6 months	6–9 months	9–12 months	None or NA
NR	3.2	3.7	3.2	7.4	82.5
0-1,000	31.9	27.2	12.3	17.4	11.3
1,000-2,000	14.9	38.0	20.7	19.4	7.1
2,000-3,000	10.1	35.4	21.9	28.1	4.4
3,000-5,000	5.8	33.5	22.8	32.6	5.3
5,000-10,000	6.1	2	22.1	35.6	7.0
10,000-20,000	4.7	26.4	21.1	40.9	6.8
20,000-50,000	6.0	23.5	22.8	39.2	8.6
50,000 +	4.0	19.5	28.7	28.0	19.8

NA = Not reported/available. Source: NPPC, 1998.

An overview of common waste storage practices is provided below; more detailed information can be found in Section 8 of this document.

- *Deep pit manure storage*. Many operations use pits that are 6- to 8-feet deep and provide for up to 6 months of storage under the house. Commonly, slurry is removed from the pit twice a year. The slurry is disposed of through direct surface application or subsurface injection, transferred to an earthen storage facility, or pumped to an above or belowground storage tank. This slurry system produces a waste stream with higher dry matter content (4 to 5 percent) and higher nutrient content than other liquid manure systems. The above and belowground storage systems conserve more N than other systems (N loss of only 10 to 30 percent). Operations use this system to avoid problems associated with lagoons such as odor, ammonia volatilization, and ground water impact resulting from leaking lagoons.
- *Lagoon Systems*. Lagoon systems can serve as both storage and treatment units. Anaerobic lagoons are the most common type of lagoon and are characterized by anaerobic decomposition of organic wastes. When properly designed an anaerobic lagoon will have a minimum total capacity that includes appropriate design treatment capacity, additional storage for sludge accumulation, and temporary storage for rainfall and wastewater inputs. A lagoon should also have sufficient freeboard and an indicator of the highest safe water level, to prevent the wastewater from overflowing the embankment.
- Lagoons usually fill to capacity within 2 to 3 years of startup due to the accumulated waste volume and, depending on the region, rainfall in excess of evaporation. When the

lagoon is full, water overflow will occur unless the operator is in a position to apply the excess water to the land. Lagoon water drawdown by irrigation or other methods is usually begun before the water reaches the maximum wastewater storage level. Several states require that liquid level indicators be placed in the lagoon to be sure that the liquid stays below the level required to contain the 24-hour, 25-year storm.

In addition to anaerobic lagoons, there are aerobic lagoons (which mix and aerate waste via mechanical aerators or ozone generators), two-stage lagoons (typically a constant volume covered treatment cell followed by a storage cell), and multistage cell lagoons. Technical information and a discussion of the advantages and disadvantages of these types of lagoons is presented in Section 8 of this document.

- *Settling and evaporation ponds*. Earthen ponds are used by some swine operations for solids separation. These ponds are designed to remove 40 percent of the total solids (in a 6 percent solids form) based on 3 months of storage. The material is then moved to another earthen pit, which serves as a drying bed, or flow is diverted to a parallel solids removal pond. The slurry dries to about 38 percent solids and 3-inch thickness within 6 months. The material is then moved with a front-end loader into a box-type spreader and applied to the land. Solids drying ponds and beds are not covered and therefore exposed to rainfall. A floating pump is located half the lagoon distance from the inlet, with a screen over the intake to protect sprinkler nozzles. The supernatant is pumped and used to irrigate fields. Another variation is to use a single lagoon followed by an evaporation pond that is 6 feet deep and as big as possible. Some evaporation ponds dry up during the summer. Because of odor problems, there is a trend away from the earthen pond for solids separation to either a single anaerobic lagoon or an anaerobic lagoon and an evaporation pond.

  Waste runoff storage. The systems described above can also be associated with operations that maintain hogs on an outside lot for at least part of the time. Such operations might also use housing similar to the systems described above, but allow outside access for the animals. Dry lot areas may be paved or dirt, and manure is stored in piles that are created by tractor or scraping systems. Although controls might be in place to contain manure from enclosed areas through use of a deep pit or lagoon, they are not generally protective of the outside environment. Other typical runoff controls include surface diversions to prevent rainwater from running onto the lot, or a crude settling basin with a slotted overflow.

- Other. Other types of waste management practices currently used include above and belowground tanks (possibly covered or aerated), and hoop housing/deep bedding systems.

USDA APHIS (2001) performed a survey of swine operations with 100 or more pigs. The study included 17 of the major pork-producing states that account for 94 percent of the U.S. pig inventory. Data for that survey were collected from 2,328 operations. The report provided information on feed and waste management, health and productivity, animal management, and facility management. In addition to this report, NAHMS also performed additional analyses for EPA that present the percent of sites where pit holding was the waste management system used

most by region and herd size for the farrowing and grow-finish phase (USDA APHIS, 2002a). Tables 4.21 and 4.22 indicate the percent of sites where pit holding was the waste management system used most.

Table 4-21. Percent of Sites Where Pit Holding was the Waste Management System used most by Region and Herd Size for Farrowing Phase.

States	Total Inventory (head)		
	Total	750–2500	>2500 +
Minnesota, Wisconsin, Michigan, Pennsylvania	37.3	50.3	49.3
Colorado, South Dakota, Nebraska, Kansas, Missouri	22.6	37.9	50.2
Iowa, Illinois, Indiana, Ohio	40.9	65.0	63.2
Texas, Oklahoma, Arkansas, North Carolina	16.0	14.4	23.9

Source: USDA APHIS, 2002a.

Table 4-22. Percent of Sites Where Pit Holding was the Waste Management System used most by Region and Herd Size for Grower-Finisher Phase.

States	Total Inventory (head)		
	Total	750–2500	>2500 +
Minnesota, Wisconsin, Michigan, Pennsylvania	59.9	77.5	83.3
Colorado, South Dakota, Nebraska, Kansas, Missouri	33.6	55.3	39.3
Iowa, Illinois, Indiana, Ohio	48.3	67.6	77.5
Texas, Oklahoma, Arkansas, North Carolina	27.7	26.3	37.5

Source: USDA APHIS, 2002a.

4.1.4.3 Swine Waste Treatment Practices

Many types of technology are used to treat swine wastes. These technologies work in a variety of ways to reduce the N, COD, and the volatile solids content of waste; or to change the form of the waste to make it more concentrated and thus easier to handle. The most common type of treatment practice is the anaerobic lagoon.

- *Lagoon treatment systems*. Lagoons designed to treat waste can reduce organic content and N by more than 50 percent (PADER, 1986). Anaerobic lagoons are generally preferred over aerobic lagoons because of their greater ability to handle high organic load. Nonetheless, incomplete anaerobic decomposition of organic material can result in offensive by-products, primarily hydrogen sulfide, ammonia, and intermediate organic acids, which can cause disagreeable odors. Therefore, proper design, size, and management are necessary to operate an anaerobic lagoon successfully.

  New lagoons are typically half filled with water before waste loading begins. Starting up during warm weather and seeding with bottom sludge from a working lagoon speeds establishment of a stable bacterial population. Proper lagoon maintenance and operation is absolutely necessary to ensure that lagoon liner integrity is not affected, that berms and embankments are stable, and the required freeboard and rainfall storage are provided.

Even when bacterial digestion is efficient, significant amounts of sludge accumulate in anaerobic lagoons. Although lagoons can be designed with enough storage to minimize the frequency of bottom sludge removals, at some point sludge accumulation will greatly diminish the treatment capacity of most lagoons. Without the proper treatment volume, anaerobic decomposition will be incomplete, and odors will usually become more pronounced. Inadequate maintenance of treatment volume is the single most common reason for the failure of lagoon treatment systems. The method used most frequently to remove sludge entails vigorous mixing of sludge and lagoon water by means of an agitator/chopper pump or propeller agitator. The operation of the agitator/chopper must be continuously monitored to prevent damage to the liner berms, or embankments, which could result in contamination of surface or ground water. The sludge mixture is then pumped through an irrigation system onto cropland.

Some lagoons are covered with a synthetic material. There can be multiple advantages to covering a lagoon. A cover will prevent rainfall from entering the system, which can result in additional disposal costs. Nitrogen volatilization is minimized, making the waste a more balanced fertilizer and potentially saving expenses for the purchase of N fertilizers. The EPA AgSTAR Program has demonstrated that biogas production and subsequent electricity generation from covered lagoons and digesters can be cost effective, help control odor, and provide for more effective nutrient management.

- *Digesters*. Conventional aerobic digestion is frequently used to stabilize biosolids at small municipal and industrial facilities as well as at some AFOs. Waste is aerated for relatively long periods of time to promote microbial growth. Substantial reductions in total and volatile solids, BOD, COD and organic N as well as some reduction in pathogen densities can be realized. Autoheated aerobic digesters use the heat released during digestion to increase reaction rates and allow for more rapid reduction of pathogens. The biosolids created by digesters concentrate solids, resulting in easier handling. Additional information on the operational considerations, performance, and advantages and disadvantages of digesters can be found in Section 8.

- *Sequencing batch reactors*. Manure is treated in sequence, typically in a vessel of metal construction. The vessel is filled, reacted (aeration cycled on and off), and then allowed to settle. Organic carbon and ammonia are reduced and P is removed through biosolids generation or chemical precipitation. The biosolids generated are in a concentrated form, allowing for ease in handling.

- *Other*. Many other practices are used separately or in combination with the practices listed above to treat swine wastes. Constructed wetland treatment cells, trickling filters, composting, oxidation ditches, are a few of the other ways to treat swine wastes. Systems being developed or under trial studies include Y- or V- shaped pits with scrapers for solid-liquid separation at the source, membrane filtration, chemical treatments, high-rise hog buildings, oligolysis, hydroponic cultivation, photosynthetic digesters, and closed loop water use systems using ultraviolet disinfection. Information on the operational considerations, performance, and advantages and disadvantages of these and other treatment practices can be found in Section 8.

4.1.4.4 Waste Management Practices by Operation Size and Geographical Location

The use of a particular waste management system is driven by the size of the operation and geographic considerations (e.g., climate). For example, operation of a confined facility with the use of a lagoon for treatment requires substantial capital investment. Below a certain number of head, such a system would be cost-prohibitive since the high start-up and maintenance costs of such a facility have to be spread over a large number of animals to ensure economic viability. Geographic considerations also play a role in waste management. Anaerobic lagoons are common in the Southeast, where factors such as land availability and climate conditions are favorable. Midwestern farms are more likely to use pit storage with slurry transport to above or belowground tanks. The *Swine '95* Survey (USDA APHIS, 1995) provides a detailed picture of swine management practices by operation type, size, and location. (At the time of writing, reports from the Swine 2000 survey did not provide equivalent statistics that allow comparisons based on region and operation size and is therefore not presented in this section.)

Waste Management Practice by Operation Size

As mentioned previously, large operations (greater than 2,000 head marketed in the past 12 months) are much more likely to use water for waste management than small operations. Small operations (less than 500 head) typically manage waste by hand cleaning or mechanical scraper/tractor. They also use pit-holding and flushing systems because of their relatively lower labor requirements. While larger operations also use pit storage and slurry storage in tanks, they are far more likely to move waste from the housing facility to a lagoon. Tables 4-23, 4-24, and 4-25 present the frequency of operations using the most common types of waste management systems for swine farrowing, nursery, and finishing phases, respectively. Table 4-26 presents the frequency of waste storage system use by size of operation. Table 4-27 presents the frequency of waste storage system use by region for operations that marketed 5,000 or more hogs in a 12-month period. It should be noted that the percentages do not add to 100 percent. This is because an operation may use more than one waste storage system. For example, many large facilities in the Southeast have below floor slurry storage that is then moved to lagoon storage.

Table 4-23. Frequency (in percent) of Operations in 1995 by Type of Waste Management System Used Most in the Farrowing Phase.

	Number of Hogs Marketed in Past 12 Months		
Variable	**<2,000**	**2,000–10,000**	**>10,000**
None	14.1	5.6	1.7
Pit-holding	24.4	53.9	49
Scraper/Tractor	12.3	3.6	6.0
Hand cleaned	39.7	0.6	0
Flush - under slats	4.6	20.8	39.3
Flush - gutter	3.0	2.7	2.6
Other	1.8	13	1.5

Source: USDA APHIS, 1995.

Table 4-24. Frequency (in percent) of Operations in 1995 by Type of Waste Management System Used Most in the Nursery Phase.

Variable	Number of Hogs Marketed in Past 12 Months		
	<2,000	2,000–10,000	>10,000
None	4.4	3.3	0
Pit-holding	32.3	55	48
Scraper/Tractor	18.5	3.9	1.7
Hand cleaned	31.7	1.6	0
Flush - under slats	8.7	19.6	10.2
Flush - gutter	2.1	1.7	3.4
Other	2.3	15	6.8

Source: USDA APHIS, 1995.

Table 4-25. Frequency (in percent) of Operations in 1995 by Type of Waste Management System Used Most in the Finishing Phase.

Variable	Number of Hogs Marketed in Past 12 Months		
	<2,000	2,000–10,000	>10,000
None	15.2	4.6	0
Pit-holding	22.1	53	45.3
Scraper/Tractor	25.5	8.6	11.4
Hand Cleaned	28.0	3.0	0
Flush - under slats	1.9	17.5	30.0
Flush - gutter	3.3	7.8	6.0
Other	4.0	5.5	7.4

Source: USDA APHIS, 1995.

Table 4-26. Frequency (in percent) of Operations in 1995 That Used Any of the Following Waste Storage Systems by Size of Operation.

Waste Storage System	Percentage of Operations by Number of Head Marketed for Slaughter		
	<2,000 Head	2,000–10,000 Head	>10,000 Head
Below-floor slurry	43.6	70.4	47.9
Aboveground slurry	4.1	10.3	8.3
Belowground slurry	17.3	25.6	26.8
Anaerobic lagoon with cover	2.2	0.5	2.0
Anaerobic lagoon without cover	17.4	29.2	81.8
Aerated lagoon	1.3	6.9	1.0
Oxidation ditch	2.9	0.1	0.0
Solids separated from liquids	4.1	5.9	4.7
Other	0.6	0.0	1.1

Source: USDA APHIS, 1995.

Table 4-27. Frequency (in percent) of Operations in 1995 That Used Any of the Following Waste Storage Systems by Region for Operations That Marketed 5,000 or More Hogs in a 12-Month Period.

Waste Storage System	USDA APHIS Region[a]		
	Midwest	North	Southeast
Below-floor slurry	21.5	28.5	85.7
Aboveground slurry	NA	NA	27.2
Belowground slurry	NA	NA	43.3
Anaerobic lagoon	91.2	4.8	33.3
Aerated lagoon	NA	X[b]	NA
Solids separated from liquids	NA	NA	14.4

[a] Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
The standard error for the aerated lagoons in the northern region as evaluated by NAHMS exceeds 21 percent and was therefore determined by NAHMS not to be statistically valid. Note that the aerated lagoon is reportedly found in roughly 70 percent of the operations in the north region.
Source: USDA APHIS, 1995.

With minor exceptions, there are consistent trends in operation management from one part of the country to another. The multisite model that separates production phases is being adopted across the country; finishing age and number of litters per year already tend to be the same from one part of the nation to another. With the exception of the Midwest, producers tend to farrow small groups of sows weekly (USEPA, 1998). In the Midwest, some producers farrow only twice a year, usually in the spring and fall. This is primarily done on smaller operations, where sows are maintained outdoors and then moved indoors for farrowing. The buildings in which pigs are housed in the Midwest tend to differ from those in more temperate parts of the country, and waste is managed differently in the Midwest than in other parts of the country. Confined, three-site operations predominate in the Southeast, South-Central, and West Regions, although there are some smaller outdoor operations in the South-Central and West Regions.

Most types of waste management systems are also similar across most regions with only minor deviations. For example, the pit-recharge systems with aboveground storage and land application are nearly identical among farms in the Midwest, the South-Central, and the Northeast Regions. The primary waste management system that has the most variation among and within regions is known as the hand wash system. Hand wash systems are found predominantly on operations with fewer than 500 pigs and most of those that use hand washing as their primary waste management system have fewer than 100 pigs. On these operations, it is in the farrowing house or nursery phases of production that hand washing is used to remove waste from the buildings. Either the wash water exits the building and enters the environment directly or a collection basin is located underneath or at one end of the building. In the case of collection, the wash water is stored and used for land application at a later time or is allowed to evaporate over time. Frequency of hand washing varies among operations from three times a day to once a week.

Another type of system identified as a primary waste management system on small operations in the Midwest and New England (USDA APHIS, 1995) uses a flat blade on the back of a tractor to

scrape or remove manure from feeding floors. The popularity of this system has apparently waned, and the it no longer represents a major means for removing wastes from swine feeding operations (NCSU, 1998a).

Swine Waste Management Systems in the Pacific Region

Descriptive information about the waste management systems in this region is provided in Table 4-28. In general, the region is characterized by operations with fewer than 500 pigs that use hand washing and dry lots as their primary waste management system. In contrast, the majority of pigs are raised on operations with more than 1,000 animals that use either deep pit/aboveground storage or pit recharge/lagoon.

Table 4-28. Distribution of Predominant Waste Management Systems in the Pacific Region[a] in 1997.

Farm Size (number of pigs)	Primary Waste Management System
Fewer than 500	1. Hand Wash/Dry Lots 2. Scraper/Aboveground Storage/Land Application
500 to 1,000	1. Hand Wash/Dry Lots 2. Deep Pit/Aboveground Storage/Land Application
More than 1,000	1. Deep Pit/Aboveground Storage/Land Application 2. Pit Recharge/Covered Anaerobic Lagoon/Irrigation

[a] Alaska, California, Hawaii, Oregon, and Washington.
Source: NCSU, 1998a.

Swine Waste Management Systems in the Central Region

Table 4-29 presents information for the Central Region. It is the fastest-growing area of swine production in the nation at the present time. As a result, large operations (>2,000 head) account for almost all of the swine in these states. As a group, these large operations appear to rely on evaporation from lagoons, aeration of anaerobic lagoons, or biogas production from lagoons as the main means for storing and treating swine waste.

Circle 4, one of the largest operations in the country, uses a pit-recharge system that is emptied about three times per week. Wastewater treatment is by a two-stage evaporative lagoon system. The primary stage is designed for treatment of volatile solids, with additional volume for 20 years of sludge storage. The exact treatment volume design is operation- (or complex-) specific and takes into consideration the diet, feed digestibility, and absorption and conversion efficiency of the animal for each group of confinement houses. The primary stage is sized on the basis of volume per input of volatile solids plus an additional volume for 20 years of sludge storage. The secondary stage lagoon volume and surface area are specified to allow evaporation of all excess water not required for pit recharge. Waste management plans call for sludge removal every 20 years. Because the operation has not reached its design life at this time, this system cannot be evaluated.

Table 4-29. Distribution of Predominant Waste Management Systems in the Central Region[a] in 1997.

Farm Size (number of pigs)	Primary Waste Management System
Fewer than 500	1. Hand Wash/Dry Lots
500 to 1,000	1. Flush or Pit Recharge/Anaerobic Lagoon/Irrigation 2. Deep Pit/Aboveground Storage/Land Application
More than 1,000	1. Flush or Pit Recharge/Aeration of Anaerobic Lagoon/Irrigation 2. Flush or Pit Recharge/Covered Anaerobic Lagoon/Land Application 3. Pit Recharge/Evaporation from Two-Stage System

[a]Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Oklahoma, Texas, Utah, Wyoming
Source: NCSU, 1998a.

Swine Waste Management Systems in the Mid-Atlantic Region

Table 4-30 summarizes descriptive information for the region. Only North Carolina and Pennsylvania grow a significant number of swine. The medium and large operations rely on either anaerobic lagoons and wastewater irrigation or aboveground storage and land application as their primary means of waste management. Operations in the remaining states typically have fewer than 500 animals each, and they use hand washing in conjunction with dry lots as their primary waste management system.

The design and operation of the anaerobic lagoon and irrigation system are different in the two key states. In Pennsylvania, lagoon loading rates are lower to accommodate the lower temperatures, and storage requirements must be increased to accommodate the longer inactive period during winter. Average yearly rainfall is about the same in the two states, with rainfall in excess of evapotranspiration requiring increased storage requirements.

Table 4-30. Distribution of Predominant Waste Management Systems in the Mid-Atlantic Region[a] in 1997.

Farm Size (number of pigs)	Primary Waste Management System
Fewer than 500	1. Hand Wash/Dry Lots 2. Gravity Drain/Collection Basin/Land Application
500 to 1,000	1. Deep Pit/Aboveground Storage/Land Application 2. Pit Recharge/Anaerobic Lagoons/Irrigation 3. Scraper/Aboveground Storage/Land Application
More Than 1,000	1. Deep Pit/Aboveground Storage/Land Application 2. Pit Recharge/Anaerobic Lagoons/Irrigation

[a]Connecticut, Delaware, Kentucky, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, Tennessee, Vermont, Virginia, and West Virginia.
Source: NCSU, 1998a.

Swine Waste Management Systems in the South Region

Table 4-31 summarizes descriptive information for the region. Large operations (more than 1,000 head) represent only a small fraction of the operations in the states of the region. The predominant waste management system is a flush or pit-recharge system for removal of waste

from buildings, an anaerobic lagoon for treatment and storage of waste, and reincorporation of treated wastewater back into the environment by irrigation. In these states, housing is usually enclosed, with ventilation and a concrete floor surface.

Table 4-31. Distribution of Predominant Waste Management Systems in the South Region[a] in 1997.

Farm Size (number of pigs)	Primary Waste Management System
Fewer than 500	1. Hand Wash/Dry Lots 2. Scraper System/ Aboveground Storage/Land Application
500 to 1,000	1. Flush or Pit Recharge/Anaerobic Lagoon/Irrigation
More Than 1,000	1. Flush or Pit Recharge/Anaerobic Lagoon/Irrigation

[a]Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, and South Carolina.
Source: NCSU, 1998a.

Swine Waste Management Systems in the Midwest Region

Table 4-32 summarizes descriptive information for this region. Small operations account for most of the operations in this region; however, recent construction of large units in Iowa, Minnesota, Missouri, and South Dakota indicate that the trend toward production in larger units seen in the southeastern United States is probably occurring in the Midwest Region as well. Primary waste management systems for operations with fewer than 500 pigs are hand wash coupled with dry lots with and without collection basins. In contrast, medium and large operations rely on storage of waste either under buildings with deep pits or in aboveground structures in conjunction with direct land application for crop production.

Table 4-32. Distribution of Predominant Waste Management Systems in the Midwest Region[a] in 1997.

Farm Size (number of pigs)	Primary Waste Management System
Fewer than 500	1. Hand Wash/Dry Lots 2. Hand Wash/Dry Lots and Collection Basin/Land Application 3. Deep Pit/Land Application
500 to 1,000	1. Deep Pit/Aboveground Storage/Land Application 2. Pit Recharge/Aeration of Anaerobic Lagoons/Irrigation 3. Deep Pit/Land Application
More than 1,000	1. Deep Pit/Aboveground Storage/Land Application 2. Pit Recharge/Covered Anaerobic Lagoon/Irrigation

[a]Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin.
Source: NCSU, 1998a.

4.1.5 Pollution Reduction

4.1.5.1 Swine Feeding Strategies

Swine producers use a variety of feed ingredients to achieve a balanced diet for a pig at each phase of the animal's development. Various grain products, including corn, barley, milo, and sometimes wheat, form the foundation of the growing pig's diet and supply most of the carbohydrates and fat. Oilseed meals, which foster muscle and organ development, are the primary source of protein (NPPC, 1999). Producers also supplement the basic diet with minerals and vitamins as needed. A pig's diet changes as the animal grows. For example, finishing pigs typically receive a diet containing 13 to 15 percent crude protein versus the 20 to 22 percent protein diet received by young pigs. The *Swine '95* survey indicates that more than 96 percent of grow-finish operations use multiple diets from time of entry to market weight. Almost 70 percent of the operations feed their pigs three or more diets during this phase.

Swine operations can use feeding strategies both to maximize growth rates and to reduce excretion of nutrients. The following feeding strategies can be used to reduce N and P manure content.

Grinding. Fine grinding and pelleting are simple but effective ways to improve feed utilization and decrease N and P excretion. By reducing the particle size, the surface area of the grain particles is increased, allowing for greater interaction with digestive enzymes. When particle size is reduced from 1,000 microns to 400 microns, N digestibility increases by approximately 5 to 6 percent. As particle size is reduced from 1,000 microns to 700 microns, excretion of N is reduced by 24 percent. The current average particle size is approximately 1,100 microns; the recommended size is between 650 and 750 microns. Reducing particle size below 650 to 750 microns greatly increases the energy costs of grinding and reduces the throughput of the mill. The use of so small a particle size will also increase the incidence of stomach ulcers in the hogs (NCSU, 1998b).

Amino Acid Supplemental Diets. Supplementing the diet with synthetic lysine to meet a portion of the dietary lysine requirement is an effective means of reducing N excretion by hogs. This process reduces N excretion because lower-protein diets can be fed when lysine is supplemented. Research studies have shown that protein levels can be reduced by 2 percent when the diet is supplemented with 0.15 percent lysine (3 pounds lysine-HC1/ton of feed) without negatively affecting the performance of grow-finish pigs. Greater reductions in protein are possible, but only if threonine, tryptophan, and methionine are also supplemented.

Table 4-33 shows the theoretical effect of feeding low-protein, amino acid-supplemented diets on N excretion of finishing pigs. Note that reducing the protein level from 14 to 12 percent and adding 0.15 percent lysine results in an estimated 22 percent reduction in N excretion. Reducing the protein further to 10 percent and adding 0.30 percent lysine, along with adequate threonine, tryptophan, and methionine, reduces the estimated N excretion by 41 percent.

Although it is currently cost-effective to use supplemental lysine and methionine, supplemental threonine and tryptophan are too expensive to use in widespread diets. However, because of rapid technological advances in fermentation procedures for synthesizing amino acids, the price of threonine and tryptophan will likely decrease in the next few years.

Table 4-33. Theoretical Effects of Reducing Dietary Protein and Supplementing With Amino Acids on Nitrogen Excretion by 200-lb Finishing Pig[a,b]

Diet Concentration	14 CP	12 CP + Lysine	10 CP + Lysine + Threonine + Tryptophan + Methionine
N balance			
N intake, g/d	67	58	50
N digested and absorbed, g/d	60	51	43
N excreted in feces, g/d	7	7	7
N retained, g/d	26	26	26
N excreted in urine, g/d	34	25	17
N excreted, total, g/d	41	32	24
Reduction in N excretion, %	----	22	41
Change in dietary costs, $/ton[b]	0	-0.35	+$14.50

[a]Assumes an intake of 6.6 lb/d and a growth rate of 1.98 lb/d. [b]Costs used L-Lysine HCl, $2.00/lb; corn, $2.50/bushel; SBM, $250/ton; L-Threonine, $3.50/lb; DL-Methionine, $1.65/lb; Tryptosine (70:15, Lys:Tryp) $4.70/lb.
Source: NCSU, 1998b.
g/d = grams/day

Phase Feeding and Split-Sex Feeding. Dividing the growth period into more phases with less spread in weight allows producers to meet the pig's protein requirements more closely. Also, since gilts (females) require more protein than barrows (males), penning barrows separately from gilts allows lower protein levels to be fed to barrows without compromising leanness and performance efficiency in gilts. Feeding three or four diets, compared with only two diets, during the grow-finish period would reduce N excretion by at least 5 to 8 percent (NCSU, 1998b).

Formulating Diets on an Available Phosphorus Basis. A high proportion (56 to 81 percent) of the P in cereal grains and oilseed meals occurs as phytate. Pigs do not use P in this form well because they lack significant amounts of intestinal phytase, the enzyme needed to remove the phosphate groups from the phytate molecule. Therefore, supplemental P is added to the diet to meet the pig's growth requirements.

Because some feedstuffs are high in phytate and because there is some endogenous phytase in certain small grains (wheat, rye, triticale, and barley), there is wide variation in the bioavailability of P in feed ingredients. For example, only 12 percent of the total P in corn is available, whereas 50 percent of the total P in wheat is available. The P in dehulled soybean meal is more available than the phosphorus in cottonseed meal (23 percent versus 1 percent), but neither source of P is as highly available as the P in meat and bone meal (66 percent), fish meal (93 percent), or dicalcium phosphate (100 percent) (NCSU, 1998b).

Supplementing Diets with Phytase Enzyme. Supplementing the diet with the enzyme phytase is an effective means of increasing the breakdown of phytate P in the digestive tract and reducing the P excretion in the feces. Using phytase allows one to feed a lower P diet because the unavailable phytate phosphorus in the grain and soybean meal is made available by the phytase enzyme to help meet the pig's P needs. Studies at Purdue University, the University of Kentucky, and in Denmark indicate that the inclusion of phytase increased the availability of P in a corn-soy diet threefold, from 15 percent to 45 percent.

A theoretical example of using phytase is presented in Table 4-34. If a finishing pig is fed a diet with 0.4 percent P (the requirement estimated by NRC, 1988, cited in NCSU, 1998b), 12 grams of P would be consumed daily (3,000 grams times 0.4 percent), 4.5 grams of P would be retained, and 7.5 grams of P would be excreted. Feeding a higher level of P (0.5, 0.6, or 0.7 percent) results in a slight increase in P retention but causes considerably greater excretion of P (10.3, 13.2, and 16.2 g/d, respectively). Being able to reduce the P to 0.3 percent in a diet supplemented with phytase would reduce the intake to 9 grams of P per day and would potentially reduce the excreted P to 4.5 g/day (a 37 percent reduction in P excretion versus NRC's estimate). The percent reduction in excreted P is even more dramatic (56 percent) when one compares the 4.5 grams with the 10.3 grams of P excreted daily by finishing pigs fed at the 0.5 percent P level typically recommended by universities and feed companies. Bone strength can be completely recovered by supplementing a low-P diet with 1,000 phytase units per kilograms of feed, while most of the grain and feed efficiency is returned to NRC levels. In addition to returning bone strength and growth performance to control levels, there is a 32 percent reduction in P excretion. A summary of 11 experiments (Table 4-35) indicates that all the growth rate and feed efficiency can be recovered with the dietary supplementation of 500 phytase units and reduced-P diets. Some analyses have suggested that a 50 percent reduction in excreted P by pigs would mean that land requirements for manure applications based on P crop uptake would be comparable to manure applications based on N.

Previously, phytase was too expensive to use as a feed additive. However, this enzyme can now be effectively produced by recombinant DNA techniques and the cost has decreased. A cost evaluation indicates that under certain conditions replacing dietary P of an inorganic P source (e.g., dicalcium phosphate) with the phytase enzyme would be cost neutral. Swine require that phytase supplements be fed at different levels based on the age of the pig (Table 4-36). The

Table 4-34. Theoretical Effects of Dietary Phosphorus Level and Phytase Supplementation (200-lb Pig).

Dietary P (%)	Phosphorus (g/d)			Change From Industry Average (%)
	Intake	Retained	Excreted	
0.70	21.0	4.8	16.2	+57
0.60	18.0	4.8	13.2	+32
0.50	15.0	4.7	10.3	0
0.40 (NRC, 1988)	12.0	4.5	7.5	-27
0.30	9.0	2.5	6.5	-37
0.30 + Phytase	9.0	4.5	4.5	-56

Source: Cromwell and Coffey, 1995, cited in NCSU, 1998b.

Table 4-35. Effect of Microbial Phytase on Relative Performance of Pigs.[a]

Growth Response	Negative Control	Positive Control	Effect of 500+ Phytase Units/kg
ADG	100	115 (+/- 6.5)	116.7 (+/ -10.6)
ADFI	100	105 (+/- 5.2)	107.6 (+/- 7.8)
Feed Conversion Ratio	100	93 (+/- 4.9)	93.2 (+/- 5.0)

[a]Eleven experiments with the negative control diets set at 100 percent and the relative change in pig growth performance to the control diets.
Source: Jongbloed et al., 1996, cited in NCSU, 1998b.

Table 4-36. Effect of Microbial Phytase on Increase in Phosphorus Digestibility by Age of Pigs and the Recommended Rates for Inclusion of Phytase in Each Phase.

	Nursery	Grower	Finisher	Gestation	Lactation
Approximate Increase (%)	13	17	17	7	20
Inclusion Level (Phytase Unit/lb)	454–385	385–227	27–113	227	227

Source: Jonbloed et al., 1996, cited in NCSU, 1998b.

different levels are based on phase of production and are likely related to the digestive enzymes and cecum of the younger pig being less developed.

4.1.5.2 Waste and Waste Water Reductions

Methods to reduce the quantity of wastewater generated at swine operations include advanced swine watering systems to reduce water spillage and recycling water in waste flush systems. The feeding strategies discussed in the previous section will also reduce the quantity of waste generated by ensuring that animals do not receive more feed than required for optimal growth. Additional information on feeding strategies for swine can be found in Chapter 8. Advanced swine breeding has resulted in animals that produce less waste per pound of meat produced.

Nipple water delivery systems reduce the amount of wastewater and are more healthy for the animals. Trough or cup waters are typically placed close to the floor of the pen. This allows the animal to spill water and add contaminates to the standing water. Nipple water delivery systems are placed higher in the pen and only deliver water to the animal when the animal is sucking on the nipple. Watering systems may also use water pressure sensors and automatic shutoff valves to reduce water spillage. The sensor will detect a sustained drop in water pressure resulting from a break in the water line. The sensor will then stop the water flow to the broken line and an alarm will sound. The operator can then fix the broken line and restore water to the animals with minimal water spillage. There is little information about the relative use of the various water delivery systems or the relative use of water pressure sensors and shutoff valves within the swine industry.

The use of recycled water in swine flush and pull plug waste management systems will also reduce the amount of wastewater generated at an operation. To obtain recycled water of

appropriate quality an operation can use a variety of methods to remove pollutants from the waste stream. Such methods include solid-liquid separation, digesters, and multiple-stage lagoon systems. Multiple-stage lagoon systems or the use of an initial settling basin will allow settling of solids and biological processes to occur that can result in high quality water. One large operation in Utah claims to have a completely closed system in which all wastewater is treated in a multiple-stage lagoon system and then recycled back to the manure flush system.

4.1.6 Waste Disposal

Waste is disposed in either a liquid or solid form. Handling and disposal in a solid form has several advantages the more concentrated the waste. Hauling costs are reduced as the water content is reduced; however, most operations prefer to handle and dispose of waste in a liquid form because of the reduced labor cost of handling the waste in this manner. Table 4-37 shows the percentage of operations that use or dispose of manure and wastes as unseparated liquids and solids. Tables 4-38 and 4-39 show the percentage of operations that are using the most common disposal methods by USDA APHIS region. (At the time of writing, reports from the Swine 2000 survey did not provide equivalent statistics that allow comparisons based on region and operation size and is therefore not presented in this section.)

Table 4-37. Percentage of Operations in 1995 That Used or Disposed of Manure and Wastes as Unseparated Liquids and Solids.

Operation Size	USDA APHIS Region[a]		
	Midwest	North	Southeast
Operations marketing fewer than 5,000 hogs in 12 months	92.3	99.1	97.7
Operations marketing 5,000 or more hogs in 12 months	100	19.6[b]	98.5

[a]Midwest = SD, NE, MN, IA, IL; North=WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
[b]The standard error on this measurement is 16.0, resulting in questions of its accuracy.
Source: USDA NAHMS, 1999.

Table 4-38. Percentage of Operations in 1995 That Marketed Fewer Than 5,000 Hogs in a 12-Month Period and That Used the Following Methods of Use/Disposal by Region.

Waste Disposal Method	USDA APHIS Region[a]		
	Midwest	North	Southeast
Placed on own land	97.9	98.5	96.8
Given away	NA	11.0	2.6

[a]Midwest=SD, NE, MN, IA, IL; North=WI, MI, IN, OH, PA; Southeast=MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA NAHMS, 1999.

Table 4-39. Percentage of Operations in 1995 That Marketed 5,000 or More Hogs in a 12-Month Period and That used the Following Methods of Use/Disposal by Region.

Waste Disposal Method	USDA APHIS Region[a]		
	Midwest	North	Southeast
Placed on own land	100	100	97.5
Sold	NA	NA	7.3
Given away	NA	NA	11.3

[a]Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA.
Source: USDA NAHMS, 1999.

Transport and land application of manure nutrients are necessary to realize the fertilizer benefit of such nutrients. Surface application and injection are common means of land application for slurry. Depending on the consistency of the manure, several types of equipment are available to apply the nutrients to the land. The common manure spreader is a low-maintenance, relatively inexpensive piece of equipment. The spreader is designed for solids and thick slurries; however, because of the characteristics of the equipment, the manure is hard to apply uniformly. This type of spreader requires loading equipment and usually takes longer to empty small loads. A flexible drag hose can be used on relatively flat landscapes. This system unloads the manure quickly, although it normally requires two tractors and a power unit on the pump. A flexible drag hose system is effective on regularly shaped fields, but the equipment is expensive. Tank wagon applications are used for liquid manure. The wagon is adaptable to either surface broadcast or injection, depending on the situation. Tank wagons apply liquid manure uniformly and are self-loading; however, the pump to discharge the manure requires a large amount of horsepower, which can be taxing on the tractor. Soil compaction is normally associated with tank wagons, and it usually takes longer to empty the storage facility. Tables 4-40 and 4-41 show the percentage of operations that disposed of manure and waste on owned or rented land using various methods. Operations may use more than one method, therefore columns do not add up to 100 percent.

Table 4-40. Method of Manure Application in 1995 on Land by Operations That Marketed Fewer Than 5,000 Hogs in a 12-Month Period.

Manure Application Method	USDA APHIS Region[a]		
	Midwest	North	Southeast
Irrigation	47.6	11.2	2.9
Broadcast	18.4	57.8	69.0
Slurry–surface	33.0	55.7	46.6
Slurry–subsurface	X[b]	26.6	22.9

[a]Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA.
[b]Operations in this region use this method, but NAHMS determined the standard error was too high to report statistically valid values.
Source: USDA NAHMS, 1999.

Table 4-41. Method of Manure Application in 1995 on Land by Operations That Marketed 5,000 or More Hogs in 12-Month Period.

Manure Application Method	USDA APHIS Region[a]		
	Midwest	North	Southeast
Irrigation	100	74.8	16.4
Broadcast	X[b]	X[b]	39.4
Slurry–surface	X[b]	6.3	68.1
Slurry–subsurface	X[b]	23.6	72.1

Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA.
[b]Operations in this region use this method, but NAHMS determined the standard error was too high to report statistically valid values.
Source: USDA NAHMS, 1999.

Most manure and waste is disposed of on land owned or rented by the operator, thus the amount of land available for land application of wastes is critical. Applying too much manure and waste to the same land year after year can result in a steady increase in the soil P content. Table 4-8 presents the number of swine operations with and without adequate crop and pastureland for manure application on an N- and P- basis at plant removal rates and operations that own no land. The operations that have no land were determined by running queries of the USDA 1997 Census of Agriculture data to identify facilities that did not grow any of the 24 major crops grown in the United States. Operations with no land available are assumed to haul their waste to land that can use the waste as a fertilizer resource.

Another waste product of swine farms is animal mortality. Mortalities are usually handled in an environmentally sound and responsible manner, but improper disposal may cause problems with odors, pathogens, biosecurity, and soil and water contamination. The 1995 USDA APHIS *Swine 95* study assessed the frequency of mortality disposal methods based on whether operations marketed more or fewer than 2,500 head in the prior 6 month period. (An operation that sold 2,500 head in the last 6 months corresponds roughly to an operation with 1,000 to 1,500 animal unit capacity.) Tables 4-42 and 4-43 show the percentage of operations by method of disposal for those operations which specified at least one pig had died in the 6 month period.

Table 4-42. Method of Mortality Disposal on Operations That Marketed Fewer Than 2,500 Hogs in a 6-Month Period in 1995.

Method of disposal	USDA APHIS Region[a]		
	Midwest	North	Southeast
Burial on operation	73.2	71.6	46.6
Burn on operation	9.1	7.2	15.2
Renderer entering operation	2.1	14.1	38.7
Renderer at perimeter of operation	2.7	4.2	8.7
Composting	10.3	6.4	13.0
Other	7.0	9.8	6.8

[a]Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA NAHMS, 1999.

Table 4-43. Method of Mortality Disposal on Operations That Marketed 2,500 or More Hogs in a 6-Month Period in 1995.

Method of Disposal	USDA APHIS Region[a]		
	Midwest	North	Southeast
Burial on operation	23.0	21.0	20.8
Burn on operation	9.9	10.2	17.1
Renderer entering operation	39.9	50.1	37.5
Renderer at perimeter of operation	27.9	23.2	31.4
Composting	X	X	11.1
Other	3.4	X	1.8

[a]Midwest = SD, NE, MN, IA, IL; North = WI, MI, IN, OH, PA; Southeast = MO, KY, TN, NC, GA. Only the 16 major pork states that accounted for nearly 91 percent of U.S. hog inventory were surveyed.
Source: USDA NAHMS, 1999.

4.2 Poultry Industry

Poultry feeding operations include facilities that confine chickens or turkeys for feeding or maintenance for at least 45 days in any 12-month period. These facilities do not have significant vegetation in the confinement area during the normal growing season, thus pasture and grazing operations are generally not included. Facilities at which poultry are raised may also include other animal and agricultural operations such as grazing, egg processing, and crop farming.

The specific poultry sectors are discussed in the following sections:

- 4.2.1: Broilers, roasters, and other meat-type chickens
- 4.2.2: Layers and pullets
- 4.2.3: Turkeys
- 4.2.4 Ducks

Up until the 1950s most of the nation's poultry production was conducted on small family farms in the Midwest. Midwestern states provided favorable climatic conditions for seasonal production of poultry and close proximity to major sources of grain feed. Eventually, with the improvement of the transportation and distribution systems, the poultry industry expanded from the Midwest to other regions. With the advent of climate-controlled systems, poultry production evolved to a year-round production cycle. By 1997, the value of poultry production exceeded $21.6 billion, and much of the poultry output was generated by corporate producers on large facilities producing more than 100,000 birds (USDA NASS, 1998a).

The poultry industry encompasses several subsectors including broilers, layers, turkeys, ducks, geese, and several other game fowl. This section focuses only on broilers, layers, and turkeys, which account for more than 99 percent of the annual farm receipts from the sale of poultry (USDA NASS, 1998a).

Together the annual sales of broilers, chicken eggs, and turkeys generate almost 10 percent of the value of all farm commodities. Although each of the poultry subsectors has experienced significant growth in output over the past two decades, broilers remain the dominant subsector, accounting for approximately 65 percent ($14.2 billion) of the $21.6 billion in poultry farm sales during 1997. Sales of eggs and turkeys accounted for 21 percent ($4.5 billion) and 13 percent ($2.9 billion), respectively. More than 15 million metric tons of poultry meat were produced in the U.S. during that year (USDA NASS, 1998c).

Poultry production (especially broiler production) is a highly integrated industry, and as a result, management strategies at the facility level tend to be more similar than in other sectors of AFOs. Contract growing began in the South during the 1930s, and by the 1950s the contracts had evolved to their current form. Thus, the integrated structure seen today was in place by the 1960s (Sawyer, 1971, cited in Aust, 1997). For example, more than 90 percent of all chickens raised for human consumption in the U.S. are produced by independent farmers working under contract with integrated chicken production and processing companies. The company provides some inputs such as the birds themselves, feed, medication, and monitoring of flock health by company service personnel. The farmer provides the grow-out buildings, electricity, water, fuel, bedding material ("litter"), and labor and management skills. The company provides the newly hatched chicks that the farmer raises to market age and weight, giving them the feed provided by the company. The farmer is paid largely on the basis of weight gained by the flock as compared with other flocks produced during the same span of time. When the birds reach market weight, the company picks them up and takes them to processing plants, where they are processed into food products. Most integrated companies are stand-alone chicken operations, although some also produce turkeys.

The poultry industry has continued to evolve in terms of the type and number of birds it produces. Genetically designed birds have been developed with the ability to mature quickly and reach market weight or lay eggs more rapidly. This has resulted in increased efficiency and overall poultry production. Facilities that grow the birds have incorporated the latest automated technology for the feed and watering systems as well as ventilation systems. The technological advances have transformed poultry raising into a modern, mechanized industry.

4.2.1 Broiler Sector

This section describes the following aspect of the broiler industry:

- 4.2.1.1: Distribution of the broiler industry by size and region
- 4.2.1.2: Production cycles of broilers
- 4.2.1.3: Broiler facility types and management4.2.1.4: Broiler waste management practices
- 4.2.1.5: Pollution reduction
- 4.2.1.6: Waste disposal

National Overview

Domestic broiler production has followed the same trend as swine and other livestock industries. Production has shifted from geographically diverse, small, family-run operations to large industrial production facilities concentrated in a few states. The number of broiler operations was quite stable between 1992 and 1997, with operations decreasing slightly from 23,949 broiler operations in 1992 to 23,937 operations in 1997, down less than 1 percent (USDA NASS, 1999b). However, between 1982 and 1992, more than 6,000 broiler operations, or 20 percent of the industry's producers, went out of business. As shown in Table 4-44, although the number of operations decreased over the past 20 years, total broiler production increased, with new large operations more than compensating for the small producers who have left the industry.

Table 4-44. Broiler Operations and Production in the United States 1982–1997.[a]

Year	Operations	Production
1982	30,100	3,516,095,408
1987	27,645	4,361,198,301
1992	23,949	5,427,532,921
1997	23,937	6,741,476,153

[a]Broilers are young chickens of the meat-type breeds, raised for the purpose of meat production. Estimates cover a 12-month period (Dec. 1 through Nov. 30) and exclude states with fewer than 500,000 broilers.
Source: USDA NASS, 1998a, 1998b.

4.2.1.1 Distribution of Broiler Operations by Size and Region

EPA's 1974 CAFO Effluent Limitations Guidelines and Standards generally apply to broiler operations with more than 100,000 birds and continuous overflow watering systems, and to broiler operations with 30,000 birds and a liquid manure system. (See Chapter 2 for the definition of a CAFO, and Chapter 5 for a discussion of the basis for revisions to the poultry subcategories.) Where numbers of birds are presented, all birds regardless of age (e.g., poult, laying age, or pullet) or function (i.e., breeder, layer, meat-type chicken) are included unless otherwise indicated in the text.

Large operations dominate broiler production. Although large production operations are characteristic of other livestock industries, such as the swine sector, the consolidation of the broiler industry began earlier and was well entrenched by the 1970s. By 1982, farms that produced fewer than 2,000 birds per flock numbered only 2,811, or about 5 percent of the total. This number decreased by two-thirds to about 1,000 farms a decade later (Abt, 1998). Compared with other livestock industries, such as swine, the broiler industry has the smallest proportion of small operators. For example, the smallest hog operations still accounted for more than 60 percent of all hog producers in 1992.

Regional Variation in Broiler Operations

Table 4-45 presents the 1997 distribution of broiler operations by region and operation size, and Table 4-46 presents the average flock size for these operations. In addition to being dominated by large producers, the broiler industry is concentrated in several states. Georgia, Arkansas, and Alabama, all in the South Region are some of the largest broiler-producing states. Table 4-47 presents the distribution of total chickens by region and operation size. It is important to note that

Table 4-45. Total Number of Broiler Operations by Region and Operation Size in 1997.

Region [a]	Number of Chicken Broiler Operations by Size Group [b] (Operation Size Presented by Number of Birds Spot Capacity)					
	>0-30,000	>30,000–60,000	>60,000–90,000	>90,000–180,000	>180,000	Total
Central	3,046	412	325	274	78	4,135
Mid-Atlantic	5,113	2,105	1,055	842	100	9,215
Midwest	7,910	207	96	141	43	8,397
Pacific	1,244	41	38	42	63	1,428
South	3,403	3,597	2,327	1,980	377	11,684
National	20,716	6,362	3,841	3,279	661	34,859

[a] Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL.
[b] Broilers are young chickens of the meat-type breeds, raised for the purpose of meat production. Estimates cover a 12-month period (Dec. 1 through Nov. 30) and exclude states with fewer than 500,000 broilers.
Source: USDA NASS, 1999c.

Table 4-46. Average Number of Chickens at Broiler Operations by Region and Operation Size in 1997.

Region [a]	Average Chicken Broiler Animal Counts [b] (Operation Size Presented by Number of Birds Spot Capacity)					
	>0–30,000	>30,000–60,000	>60,000–90,000	>90,000–180,000	>180,000	All Operators
Central	1,494	44,224	73,084	119,026	332,030	25,402
Mid-Atlantic	6,178	44,193	73,590	115,281	303,155	35,771
Midwest	830	47,357	75,821	118,611	414,945	6,933
Pacific	608	44,041	73,695	132,560	624,380	35,200
South	12,538	43,998	73,776	117,581	281,453	60,897
National	4,158	44,187	73,717	117,347	332,073	35,993

[a] Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL
[b] Broilers are young chickens of the meat-type breeds, raised for the purpose of meat production. Estimates cover a 12-month period (Dec. 1 through Nov. 30) and exclude states with fewer than 500,000 broilers.
Source: USDA NASS, 1999c.

Table 4-47. Distribution of Chickens by Region and Operation Size in 1997.

Region[a]	Percentage of Total Chicken Broiler Counts[b] (Operation Size Presented by Number of Birds Spot Capacity)					
	>0-30,000	>30,00060–000	>60,000–90,000	>90,000–180,000	>180,000	Total
Central	0.36	1.45	1.89	2.60	2.06	8.37
Mid-Atlantic	2.52	7.41	6.19	7.74	2.42	26.27
Midwest	0.52	0.78	0.58	1.33	1.42	4.64
Pacific	0.06	0.14	0.22	0.44	3.14	4.01
South	3.40	12.61	13.68	18.56	8.46	56.71
National	6.86	22.41	22.57	30.67	17.49	100.00

[a] Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL

[b] Broilers are young chickens of the meat-type breeds, raised for the purpose of meat production. Estimates cover a 12-month period (Dec. 1 through Nov. 30) and exclude states with fewer than 500,000 broilers.

Source: USDA NASS, 1999c.

operations with more than 90,000 birds accounted for more than 48 percent of the broilers even though they represented only 11.3 percent of the broiler operations. Operations with fewer than 30,000 birds represented almost 60 percent of the operations but accounted for less than 7 percent of the total birds.

USDA NRCS (2002) provided information to EPA on the number of broiler operations based on the following classifications as shown in Table 4-48:

- Operation size: > = 100,000 head, 50,000–99,999 head, and 30,000–9,999 head.
- Land availability: No excess (Category 1–farms with sufficient crop or pastureland). Excess, with acres (Category 2 farms with some land, but not enough land to assimilate all manure nutrients). Excess, no acres (Category 3 farms with none of the 24 major crop types identified by NRCS).
- Location:Ten states or groups of states.
- Nutrient basis:Applications are based on N or P application rates.

In Alabama for example, there are 98 facilities with more than 100,000 head with none of the 24 major crop types identified by NRCS for application of animal wastes. There are 268 operations (with 100,000 or more head) with some land in Alabama, but not enough land to assimilate all manure nutrients using N- based application rates and 274 operations (with 100,000 or more head) with some land in Alabama, but not enough land to assimilate all manure nutrients using P- based application rates. An undisclosed number of facilities have enough land (i.e., no excess manure).

Table 4-48. Number of Broiler Facilities as Provided by USDA Based on Analyses of 1997 Census of Agriculture Database.

Location	Land availability category	Operation Size and Nutrient Basis					
		>= 100,000		50,000–99,999		30,000–49,999	
		N	P	N	P	N	P
AL	No excess	d	d	34	15	39	32
AL	Excess, no acres	98	98	227	227	217	217
AL	Excess, with acres	268	274	666	685	412	419
AR	No excess	d	d	58	49	104	93
AR	Excess, no acres	69	69	155	155	226	226
AR	Excess, with acres	260	263	797	806	672	683
GA	No excess	d	d	17	6	14	10
GA	Excess, no acres	169	169	319	319	194	194
GA	Excess, with acres	382	387	494	505	250	254
KT, TN, VA, WV	No excess	d	d	34	17	23	15
KT, TN, VA, WV	Excess, no acres	58	58	169	169	129	129
KT, TN, VA, WV	Excess, with acres	187	201	304	321	149	157
MD, DE	No excess	d	d	106	31	103	38
MD, DE	Excess, no acres	62	62	275	275	294	294
MD, DE	Excess, with acres	38	73	146	221	107	172
MS	No excess	d	d	10	8	14	14
MS	Excess, no acres	72	72	172	172	70	70
MS	Excess, with acres	230	230	437	439	143	143
NC, SC	No excess	d	d	61	12	59	19
NC, SC	Excess, no acres	105	105	287	287	290	290
NC, SC	Excess, with acres	177	198	394	443	292	332
OK, MO, KS	No excess	d	d	19	12	30	29
OK, MO, KS	Excess, no acres	26	26	49	49	32	32
OK, MO, KS	Excess, with acres	124	126	248	255	171	172
TX, LA	No excess	d	d	23	21	9	8
TX, LA	Excess, no acres	53	53	117	117	41	41
TX, LA	Excess, with acres	231	231	312	314	86	87
other	No excess	d	d	41	11	45	17
other	Excess, no acres	113	113	162	162	112	112
other	Excess, with acres	100	104	190	220	99	127

Source: USDA NRCS, 2002.
d = data not disclosed

4.2.1.2 Production Cycles of Broilers

Broilers are usually grown for 42 to 56 days depending on the market weight desired. Female broilers can also be grown to lay eggs for replacement stock, and these females are called broiler breeders. Roasters are usually grown separated by sex, with the females being harvested at 42 days of age and the males given the space in the entire house until they are sent to market several weeks later (USEPA, 1998). Other meat-type chickens (capons, game hens) comprise less than 1 percent of chickens raised for meat. Since they are raised in a similar manner to broilers, albeit with different market weights and ages, they are not usually differentiated in the data.

Chickens are produced to meet specific requirements of the customer which can be a retail outlet, fast-food chain, or institutional buyer, among others. A broiler is considered any chicken raised

for meat products, though the industry further classifies chickens primarily by the size, weight, and age of the bird when processed.

- **Poussin** - Less than 24 days of age and about 1 pound or less.
- **Cornish Game Hens** - Less than 30 days of age and about 2 pounds.
- **Fast-food Broiler** - 2 pounds, 4 ounces to 3 pounds, 2 ounces (mostly 2 pounds, 6 ounces to 2 pounds, 14 ounces) and less than 42 days of age.
- **3's and Up** - 3 to 4 3/4 pounds and 40 to 45 days of age.
- **Broiler Roaster** - 5 to 6 pounds, hens usually 55 days.
- **Broiler for Deboning** - 5 to 6 pounds, males usually 47 to 56 days.
- **Heavy Young Broiler Roaster** - The typical roaster, 6 to 8 pounds, less than 10 weeks.
- **Capon** - 7 to 9 pounds, surgically desexed male broiler, 14 to 16 weeks.
- **Heavy Hens** - spent breeder hens, 5 to 5 ½ pounds, 15 months of age.

4.2.1.3 Broiler Facility Types and Management

The most common type of housing for broilers, roasters, pullets, and breeding stock is some type of enclosed housing with bedding derived from wood shavings, rice hulls, chopped straw, peanut hulls, or other products, depending on availability. The bedding absorbs moisture and dilutes the manure produced by the birds. Modern houses have an automatic feeding system to distribute the feed, a closed water system (automatic) to deliver the water for the birds, and a ventilation system to provide clean air. Some houses have side curtains that can be retracted to allow diffusion of air. Ventilation is typically provided using a negative-pressure system, with exhaust fans drawing air out of the house, and fresh air returning through ducts around the perimeter of the roof. The ventilation system uses exhaust fans to remove moisture and noxious gases during the winter season and excess heat during the summer. Advanced systems use thermostats and timers to control exhaust fans. These houses are also commonly integrated with an alarm signal to notify the operator of malfunctions and a back-up electric generator during power outages.

Broilers and Roasters. Houses for broilers and roasters are usually 40 feet wide and 400 to 500 feet long and typically designed for 25,000 to 30,000 broilers per flock. Older houses may be somewhat smaller, holding 20,000 to 25,000 birds. The houses contain an impermeable surface for the floor, typically clay. Wood shavings are initially added to the houses to a depth of approximately 4 inches. Between flocks, a small amount of litter referred to as cake (compacted and concentrated manure/litter mix) is removed and the remaining litter may be "top dressed" with an inch or so of new bedding material.

Pullets. Pullets are young chickens, usually less than 20 weeks of age, often raised for the purpose of egg production. Pullet houses are similar in construction to broiler houses. The houses are usually 40 to 45 feet in width and 300 to 500 feet in length. Most pullet houses are equipped with nipple, trough, or bell drinkers and often use mechanical feeders (drag chain, trough, or pan)

to distribute feed to the birds. Pullets are usually raised on a floor covered with a bedding source, 1 to 4 inches deep. This litter mixture is either removed after each flock (20 to 21 weeks) or used for a second flock. If the litter is used for a second flock, a small amount of litter as cake is removed and the remaining litter is top dressed with an inch or so of new bedding material. When the house is totally cleaned out, the litter is pushed to the center of the house and a front loader places it in a litter spreader for land application or disposal. Regular and thorough house cleaning is required to minimize disease transmission.

Breeders. Houses are usually 40 to 45 feet in width and 300 to 600 feet in length. Most of the breeder houses contain two rows of slats for the birds to roost. The slats are panels of wood elevated 18 to 24 inches and laid across supports. The slats are spaced 1 inch apart to allow the feces material to fall to the floor. Equipment can access the center section of the house to aid in the clean-out between flocks. These slats cover two-thirds of the entire length of the house along the outside walls, with the center one-third of the building containing bedding litter.

The center third of the house is covered with 2 to 6 inches of a bedding source before young breeder layers are placed in the breeder house. Drinkers, mechanical feeders, and nests are placed over the slat section of the house, which allows most of the manure produced by the birds to fall beneath the slat area, keeping the area accessible to the birds cleaner.

4.2.1.4 Broiler Waste Management Practices

This section summarizes waste management practices for broiler, breeding stock, pullets, and roaster production facilities. Manure as excreted by the birds has a high water content, most of which evaporates. A typical broiler house with capacity for 22,000 birds at a time will produce 120 tons of litter per year. The litter consists mainly of wood chips or other organic plant matter even after it has been in place for a year (NCC, 1999).

Litter Clean-out Schedules. The litter (bedding and manure) of broiler, pullet, and roaster houses is typically cleaned out completely once a year, although there is a trend toward less frequent complete clean-outs. Between flocks, the feeders, waterers, and brooding equipment are winched to the ceiling. A machine is often used to clean out any clumps of litter (termed caking out) that may build up around waterers and feeders. When the broiler or roaster house is completely cleaned out, the litter is typically removed with a front-end loader or bobcat to a spreader truck or flail-type spreader. Spreader trucks are similar to lime-spreading trucks, with a moving bed that empties onto large, round metal plates that distribute the litter for use as fertilizer nutrients for pasture and crops. The rate of application is controlled by the rate at which the moving bed empties and the speed of the truck (NCSU, 1998a).

The common clean-out frequency in broiler breeder houses is once a year. When the house is cleaned, all the equipment (including slats) is removed from the house to allow a front-end loader to push all of the manure to the center litter section of the house. Then a front-end loader places the mixture of manure and litter into a spreader for land application. A thorough cleaning after each flock (essentially once a year) removes pathogens that could be transferred to the next flock. After removal of all organic matter, the house is disinfected.

Litter Storage. Litter is removed from houses in large quantities during annual clean-out. Thus, operators that have land try to time the annual clean-out to coincide with the time land is available for litter application. If this approach is successful, the facility will need only enough storage for cake out during the rest of the year. Traditionally, operators stack litter outside, near the poultry houses or at the edge of fields for spreading in the spring.

However, an increasing number of states are imposing restrictions on the outdoor storage of waste, although the stringency of these requirements varies from state to state. For example, under Virginia's Poultry Waste Management Program, stockpiled poultry litter must be (1) covered, (2) located to prevent storm water runoff, and (3) separated a minimum of 3 feet from the seasonally high water table or by the use of an impermeable barrier. Maryland's requirements for outdoor storage are less restrictive and require only that storage be protected from rainfall and runoff. The state of Delaware, which is also an important producer of poultry, is less restrictive than Maryland and allows for uncovered storage of poultry litter (Hansen, 2000).

There are several methods for storing poultry litter ranging from open stock piles to roofed storage structures. The size and type of method employed varies with location and size of the operation as well as applicable regulations. Open stockpiles are the least expensive alternative, but pose the greatest risk of contaminating the surrounding environment. Contamination risk is reduced if these stockpiles are put on top of ground liners. Other storage structures include bunker-type storage structures, which are permanent aboveground concrete slabs with two parallel walls of concrete identical to those used for storing silage on livestock farms (Brodie et al., 2000). Storage structures with permanent roofs offer both advantages and disadvantages. These structures eliminate the need for plastic covers and reduce the risk of runoff contamination; however, they require a higher level of investment and higher maintenance costs than the other types of structures. Also if these roof structures are not high enough, compacting becomes more difficult and reduces the operator's ability to use the full capacity of the structure (Goan, 2000).

4.2.1.5 Pollution Reduction

New technologies in drinking water systems result in less spillage and are equipped with automatic shutoff valves that help ensure that broiler litter stays drier. Feeding strategies reduce the quantity of waste generated by ensuring that broilers do not receive more feed than required for optimal growth. State regulations have also driven many broiler operations to handle mortalities in ways other than burials such as rendering and composting, which are increasing (see Section 4.2.1.6).

Nipple water delivery systems reduce the amount of wasted water and are healthier for the animals. Trough or bell type watering devices allow the animal to spill water and add contaminants to the standing water. Nipple water systems deliver water only when the animal is sucking on the nipple. Watering systems may also use water pressure sensors with automatic shutoff valves to reduce water spillage. The sensor will detect a sustained drop in water pressure resulting from a break in the water line. The sensor will then stop the water flow to the broken

line and an alarm will sound. The operator can then fix the broken line and restore water to the animals with minimal water spillage.

Feeding strategies that reduce N and P can reduce the quantity of nutrients in the excreta. Dietary strategies designed to reduce N and P include enhancing the digestibility of feed ingredients, genetic enhancement of cereal grains and other ingredients resulting in increased feed digestibility, more precise diet formulation, and improved quality control. Although N and P are currently the focus of attention, these strategies also have the potential to decrease other nutrients. Phytase is commonly added to broiler feed. Phytase additions are expected to achieve a reduction in P excretion of 20 to 60 percent depending on the P form and concentration in the diet (NCSU, 1998b). Protein content, calcium, other mineral content, vitamin B, and other factors identified in the literature influence the effectiveness of phytase use in feed. Additional information on feeding strategies for broilers can be found in Chapter 8.

Feeding Strategies. P excretion can be reduced by improving the utilization of feed nutrients through genetic improvements in poultry or by improving the availability of nutrients in the feed ingredients through processing or genetics. Absorption of some minerals is relatively poor and is dependent on the chemical form in the feed or supplement.

4.2.1.6 Waste Disposal

This section summarizes waste disposal practices for poultry production facilities. The two major categories of poultry waste are manure or litter (manure mixed with bedding) and dead animals. There is little variation in manure characteristics, but the litter composition varies by storage, composting management, and other practices. Poultry litter can be disposed of in several ways including land application, animal feed, and incineration. Waste may be pelletized before its applied to the land. Pelletizing produces a more uniform product that is lighter, easily transported in bulk, and spread more uniformly. Additional information on pelletizing poultry wastes and other waste disposal methods can be found in Chapter 8.

Land Application of Poultry Litter. Land application of poultry litter recovers nutrients that otherwise would be lost, and improves crop yields. Poultry manure slowly releases its nutrients, so annual applications are possible. Composting and bagging a pelleted poultry manure fertilizer produces a marketable product for the commercial horticulture industry. One main obstacle to greater commercialization of poultry manure as a fertilizer product has been the inconsistency in product quality from one facility to another.

Where land application is employed, operators commonly use broadcast spreaders and flail-type spreaders for litter. Recommended application rates are based on the nutrient content of the litter, crop type and yield goals, and current soil conditions.

Many producers with cropland apply their litter to their own crops. However, as operations have increased in size and become more specialized, this option is becoming more limited. In some cases, poultry production provides supplemental income to an otherwise small or nonagricultural household with little or no land. Further exacerbating the problem of poultry litter disposal is the

fact that many areas of chicken production have a surplus of nutrient supply over crop needs (USDA NRCS, 1998). In these areas, poultry producers face difficulties in selling litter, giving litter away, or even paying local farmers to take the litter. Table 4-48 presents the number of broiler operations with and without adequate crop and pastureland for manure application on an N- and P- basis at plant removal rates and operations that own no land. The operations that have no land were determined by running queries of the USDA 1997 Census of Agriculture data to identify facilities that did not grow any of the 24 major crops grown in the United States. Operations with no land available are assumed to haul their waste to land that can use the waste as a fertilizer resource. More details on the national- and county-level nutrient balance are found in Chapter 6.

Use of Poultry Litter as Animal Feed. Data on the use of poultry litter as animal feed is inadequate to determine how prevalent it is as a waste disposal method. Anecdotal information indicates that use of poultry litter as a food supplement for beef herds may be common in the Mid-Atlantic and Southeast Regions.

Incineration of Poultry Wastes. Incineration of poultry wastes is not done on a large scale in the United States. The practice is being successfully implemented in the United Kingdom and is actively being investigated in this country. Additional information on centralized incineration of poultry wastes is presented in Chapter 8.

Disposal of Dead Animals. Concerns about possible ground water pollution from the burial of dead birds have caused the poultry industry to search for alternatives for dealing safely with dead stock. The most common methods of disposal of dead birds are composting, incineration, burial in deep pits, rendering, and disposal in landfills. Anecdotal information indicates that some broiler integrators have begun to distribute freezers to grower operations to store dead birds prior to picking them up for rendering. Technical information on practices for the disposal of dead animals is presented in Chapter 8. However, there is little information available on the relative use of these practices within the broiler industry.

4.2.2 Layer Sector

This section describes the following aspect of the layer industry:

- 4.2.2.1: Distribution of the layer industry by size and region
- 4.2.2.2: Production cycles of layers and pullets
- 4.2.2.3: Layer facility types and management
- 4.2.2.4: Layer waste management practices
- 4.2.2.5: Egg processing and wash water
- 4.2.2.6: Pollution reduction
- 4.2.2.7: Waste disposal

National Overview. Trends in the egg production subsector have paralleled those in other livestock industries—increasing overall production on fewer and larger farms. At the end of 1997, there were 69,761 operations with hens and pullets of laying age (layers 20 weeks and older) in the United States. This number represents a 19 percent decrease from the estimated 86,245 operations with egg-producing birds in 1992 (USDA NASS, 1999c). In the 10-year period from 1982 to 1992, the number of operations with hens and pullets declined from more than 212,000, a 60 percent decrease (Abt, 1998). Table 4-49 shows the number of operations and bird inventory for 1982, 1987, 1992, and 1997. The number of operations in each category of operation has decreased substantially while total production has increased. Table 4-49 also provides data on operations and inventory with birds below laying age. As with other sectors, specialization of production has gained a foothold, with a small but increasing number of operations producing only pullets.

Table 4-49. Operations With Inventory of Layers or Pullets 1982-1997.

Total Number of Farms with	1997		1992		1987		1982	
	Ops	Production	Ops	Production	Ops	Production	Ops	Production
Layers 20 weeks and older	69,761	313,851,480	86,245	301,467,288	141,880	316,503,065	212,608	310,515,367
Layer and pullets 13 weeks and older	72,616	366,989,851	88,235	351,310,317	144,438	373,577,186	215,812	362,464,997
Pullets between 13 and 20 weeks old	13,180	53,138,371	14,818	49,843,029	19,639	57,074,121	28,109	51,949,630
Pullets less than 13 weeks	5,122	51,755,985	4,938	44,567,993	6,753	47,409,798	8,726	40,705,085

Source: USDA NASS, 1999b.

One major difference between the layer and egg production sector and the broiler production sector is geographical distribution. Layer production, although primarily performed in 10 states, is much less geographically concentrated than the broiler industry. Hence, the key regions identified for the broiler industry in the previous section are not applicable to the layer and egg production sector. Overall, layer production has not increased as rapidly as has broiler production.

4.2.2.1 Distribution of Layer Operations by Size and Region

Layers are defined as chickens maintained for the production of table eggs. Eggs may be produced for human consumption in the shell form (sold in cartons) or may be used in the production of liquid, frozen, or dehydrated eggs. Laying hen operations include facilities that

confine chickens for feeding or maintenance for at least 45 days in any 12-month period. These facilities do not have significant vegetation in the confinement area during the normal growing season. Facilities that raise pullets are generally included. Egg washing and egg processing facilities located at the same site as the birds are generally included. Facilities that have laying hen or pullet feeding operations may also include animal and agricultural operations such as grazing and crop farming.

EPA's 1974 CAFO ELG generally apply to laying hen operations with more than 100,000 birds and with continuous overflow watering systems, and to laying hen operations with 30,000 birds and with a liquid manure system. (See Chapter 2 for the definition of a CAFO, and Chapter 5 for a discussion of the basis for revisions to the poultry subcategories.) Where numbers of birds are presented, all birds regardless of age (e.g., poult, laying age, or pullet) or function (i.e., breeder, layer, meat-type chicken) are included unless otherwise indicated in the text.

Table 4-50 presents the number of layer, pullet, and combined operations by size class as well as the average bird count at each type of operation. Table 4-51 presents the number of operations with laying hens by operation size and region. Data on the three types of operations were obtained through special queries of the 1997 Census of Agriculture (USDA NASS, 1999c). Each operation is uniquely characterized, thus the sum of all three provides the total number of operations with layers or pullets or both (75,172 total operations). Pullet operations were assumed to be evenly distributed so as to support layer operations. Table 4-52 presents the distribution of egg laying chickens by facility size and region. It is important to note that in 1997 the 326 largest operations with laying hens were less than one half of a percent of the total operations (70,857) but had over 55 percent of the laying hens. Table 4-53 presents the number of layer facilities and total USDA-based AUs using the 1997 Census of Agriculture (USDA NRCS, 2002).

Table 4-50. Number of Operations in 1997 and Average Number of Birds at Operations with Layers or Pullets or Both Layers and Pullets in 1997.

National Item	Number of Layer, Pullet, and combined Layer and Pullet Operations and Average Bird Counts (Operation Size Presented by Number of Birds Spot Capacity)					
	>0–30,000	>30,000–62,500	>62,500–180,000	>180,000–600,000	>600,000	Total
Layer Ops	57,413	528	419	146	25	58,531
Layer Count	926	43,621	103,048	311,189	1,013,318	
Pullet Ops [a]	3,694	516	61		44	4,315
Pullet Count	5,010	51,162	133,303		305,679	
Layer and Pullet Ops	12,011	67	93	91	64	12,326
Layer and Pullet Count	218	45,963	112,377	358,580	1,367,476	

[a] Pullet size ranges vary from the others: >0-30,000; >30,000-100,000; >100,000-180,000; and >180,000.
Source: USDA NASS, 1999c.

Table 4-51. Number of Operations in 1997 With Laying Hens by Region and Operation Size in 1997.

Region[a]	Number of Chicken Egg Laying Operations (Operation Size Presented by Number of Layers in Inventory)					
	>0–30,000	>30,000–62,500	>62,500–180,000	>180,000–600,000	>600,000	Total
Central	15,067	76	41	28	9	15,221
Mid-Atlantic	17,445	150	133	48	15	17,791
Midwest	23,069	123	182	78	39	23,491
Pacific	6,509	38	66	39	17	6,669
South	7,334	208	90	44	9	7,685
National	69,424	595	512	237	89	70,857

[a]Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL.
Source: USDA NASS, 1999c.

Table 4-52. Distribution of Chickens at Operations in 1997 With Laying Hens by Region and Facility Size.

Region[a]	Percentage of Total Chicken Egg Layer Counts (Operation Size Presented by Number of Layers in Inventory)					
	>0-30,000	>30,000–62,500	>62,500–180,000	>180,000–600,000	>600,000	Total
Central	1.62	1.12	1.27	3.08	2.29	9.38
Mid- Atlantic	5.51	2.21	4.41	4.77	5.24	22.14
Midwest	2.25	1.93	6.15	7.55	16.61	34.49
Pacific	0.26	0.57	2.27	3.75	4.79	11.65
South	9.29	2.79	3.04	4.48	2.79	22.34
National	18.92	8.62	17.14	23.63	31.69	100.00

[a]Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL.
Source: USDA NASS, 1999c.

Table 4-53. Layer Facility Demographics from the 1997 Census of Agriculture Database.

Size Class (EPA AUs)	Number of Operations	Total USDA AUs	Size Class Interval (Number of Head)	
			Lower	Upper
300-500	776	95,648	30,000	49,999
500-750	446	88,817	50,000	74,999
750-1000	238	69,379	75,000	99,999
>1000	671[a]	922,558	100,000	up
Total	2,131	1,176,402		

Source: USDA NRCS, 2002.

4.2.2.2 Production Cycles of Layers and Pullets

A layer is a sexually mature female chicken capable of producing eggs. Egg production can be divided into two types, table and hatching. Table eggs are used for consumption, and hatching eggs are used to supply broiler or layer production operations.

Traditionally, layers are kept through 1 year of egg production and sold for meat at 18 to 20 months of age. Depending on market conditions (relative price of eggs to hens), it has become increasingly common to recycle layers through more than 1 year of production (Bradley et al., 1998). Producers will recycle their flocks into a second or even a third cycle of lay. Flock recycling involves stopping the flock's egg production, allowing a suitable rest period, and then bringing the flock back into production. The entire process (called "force molting") of recycling layers takes approximately 4 to 5 weeks. Producers stop egg production by reducing the length of day (lighting) and feed supply. This period typically takes 2 to 4 weeks and involves a 7-day fast followed by a period during which the flock is fed a low calcium diet. After this "rest period," the flock is returned to normal lighting conditions and a nutritionally balanced diet to support egg production (UCD, 1998). Once the flock is brought back into production, most layers will meet or exceed original levels of egg production. Under this regime, the flock's life is extended for 6 to 12 additional months.

4.2.2.3 Layer Facility Types and Management

Litter-based Housing. A few litter and slat/litter houses are used to produce table eggs. These same housing systems are used for the breeders that produce fertile eggs for the production of hatching eggs, which eventually replace the current flock of egg layers.

Non-litter Based Housing. Layers are often raised in cages arranged in two or four decks. Cages have been the preferred way of housing table egg layers since the mid-1940s (Bradley et al., 1998). They are popular because they provide good sanitation. When the birds are caged, flock nutrition can be better managed and products (eggs) kept cleaner. Cages are designed to separate the layers from their own feces and thereby eliminate many of the feces-related parasite and health problems. Most commercial layer facilities employ one of the following designs.

High-rise Cage Systems. Cage systems are two-story poultry houses with cages for the laying hens in the top story suspended over the bottom story, where the manure is deposited and stored. The house structure itself is usually 40 to 60 feet wide and from 400 to 500 feet long. The watering system is a closed (noncontinuous flow) nipple or cup system. The ventilation system is designed so that the external air is brought into the top story, through the cages where the birds are located, and then over the manure in the bottom story, exiting through fans in the bottom story side wall. The ventilation system is designed to dry manure as it is stored. With proper management of waterers to prevent water leaking to the bottom story, layer waste commonly has a moisture content of 30 to 50 percent.

Scrape-out and Belt Systems. Housing facilities for scrape-out and belt manure removal cage systems are the same dimensions as high-rise units except they have only one story. Watering

systems in these operations are also closed, using nipple or cup waterers. Ventilation varies from fan-controlled to adjustable curtains in the side wall.

Cages in the scrape-out system are suspended over a shallow pit, which is scraped out to the end of the house by a small tractor or a pit scraper. Belt systems have a continuous belt under the different tiers of cages that moves the manure to the end of the house, where it is placed into a field spreader or some other suitable storage device. Some of the newer belt systems move air over the manure on the belt in an attempt to dry the manure before it is removed.

The manure from scrape-out and belt systems usually has a moisture content of between 70 and 85 percent. Therefore, the manure can be handled as a slurry, which is either injected or land applied to the land with a spreader that can handle the high-moisture manure.

Flush-Cage Housing. Housing, equipment, and ventilation in flush-cage housing are similar to the scrape-out system with the exception of how the manure is handled. Cages are suspended over a shallow pit as in the scrape-out system, but water is used to move the manure from under the cages to the end of the house, where the water and manure mixture is placed in an anaerobic lagoon. The water used to flush the manure pits is recycled from the lagoon. A variation of this system consists of solids separation by means of a primary lagoon and a secondary lagoon (NCSU, 1998a).

Although storage, management, and disposal practices are quite similar for broiler and layer operations, with the exception of layer operations using lagoon systems, there are regional differences in how operations manage waste. A survey conducted by the United Egg Producers during 1998 indicated significant regional differences in the way layer wastes are managed. These differences are shown in Table 4-54. This data was used with the data in Table 4-51 to estimate that the total number of layer operations that use water to move the wastes to a lagoon (referred to as wet layer systems) was approximately 3,100 operations.

Table 4-54. Summary of Manure Storage, Management, and Disposal.

Practice	Percentage of Region With Practice				
	Pacific	Central	Midwest	Mid-Atlantic	South
Storage sheds in addition to high-rise housing	0	0	10	0	0
Housing with 6-month or longer storage of dry manure	75	40	90	90	40
Export or sale of some or all of litter	100	40	100	75	50
Litter use other than land application (incineration, pelletization)	0	0	5	5	0
Farms with wet storage systems, such as lagoon	0	60	2	5	60

Source: UEP, 1998

4.2.2.4 Layer Waste Management Practices

Manure handling systems vary by region. In 1999 the USDA's APHIS completed the Layers '99 Study (USDA APHIS, 2000b), which looked at a 15-state target population to develop information on the nation's table egg layer population. The 15 states accounted for over 75 percent of the table egg layers in the United States on December 1, 1998. The information collected was summarized by four regions. The data collected on the manure-handling methods of layer facilities are presented in Table 4-55.

Table 4-55. Frequency of Primary Manure-Handling Method by Region.

Primary Manure-Handling Method	Great Lakes		Southeast		Central		West		All Farms	
	%	SE	%	SE	%	SE	%	SE	%	SE
High-rise (pit at ground level with house above	63.0	12.3	31.4	6.0	48.1	6.0	7.8	2.1	39.7	4.4
Deep pit below ground	0.0	--	0.0	--	6.4	3.9	7.3	2.5	2.9	1.0
Shallow pit (pit at ground level with raised cages)	23.4	9.6	19.9	7.3	1.6	1.2	24.1	7.2	18.9	4.4
Flush system to lagoon	0.0	--	41.0	5.9	0.0	--	12.0	3.6	12.5	2.5
Manure belt	13.6	6.7	4.3	2.1	20.2	4.9	5.2	1.5	10.6	2.7
Scraper system (not flush)	0.0	–	2.5	2.1	23.7	8.7	43.6	6.4	15.4	2.6
Total	100		100		100		100		100	

Great Lakes = IN, OH, and PA; Southeast = AL, FL, GA, and NC = Central = AR, IA, MN, MO, and NE; West = CA, TX, WA.
SE = Standard Error
Source: USDA APHIS, 2000b

4.2.2.5 Layer Egg Wash Water

The majority of eggs marketed commercially in the United States are washed using automatic washers. Cleaning compounds such as sodium carbonate, sodium metasilicate, or trisodium phosphate, together with small amounts of other additives, are commonly used in these systems. In addition, plants operating under the Federal Grading Service are required to rinse eggs with a sanitizer following washing (Moats, 1981). Wash water is contaminated with shell, egg solids, dirt, manure, and bacteria washed from the egg surface into the recycled water.

A study by Hamm et al. (1974), performed to characterize the wastewater from shell egg washers, calculated the pollutant load from 11 egg grading and egg breaking plants. Median waste concentrations in the wash waters at the grading plants were found to be 7,300 mg/L for COD, 9,300 mg/L for TSS, and 4,600 mg/L for volatile solids; median concentrations at the breaking plants were found to be 22,500 mg/L for COD, 27,000 mg/L for TSS, and 16,600 mg/L for volatile soilds.

Eggs may be washed either on or off farm. Operations that wash their eggs on farm may do so inline or offline. The frequency of egg processing by location is presented in Table 4-56. The frequency of egg processing by operation size is presented in Table 4-57. Eggs from over 80 percent of the operations are processed off site. Operations with fewer than 100,000 layers are more likely to have their eggs processed off site. Smaller poultry operations primarily haul their wash water to treatment centers or sell their eggs to larger operations for washing and processing (Thorne, 1999). On the other hand, larger egg production operations collect and store egg wash water on site in large tanks or lagoons for treatment and storage. This lagoon water may then be applied to fields using spray irrigation. These anaerobic lagoons are earthen structures designed to provide biological treatment and long-term storage of poultry layer waste. Treatment of waste occurs anaerobically, a process in which organic material is decomposed to carbon dioxide and water, while stabilized products, primarily humic substances, are synthesized. Where space is available, two-stage lagoons may be constructed for better wastewater treatment and greater management flexibility. The first stage contains only the treatment (permanent) volume and sludge volume while the second stage lagoon stores treated wastewater for irrigation and provides additional treatment that produces a higher quality effluent for recycling as flush water (Tyson, 1996).

Table 4-56. Percentage of Operations by Egg Processing Location and Region.

Primary Egg Processing Location	Great Lakes		Southeast		Central		West		All	
	%	SE	%	SE	%	SE	%	SE	%	SE
On farm in line	17.8	8.4	13.1	4.3	9.0	3.2	10.9	2.4	13.5	3.0
On farm off line	6.7	5.4	0.6	0.6	3.3	3.3	9.3	2.4	5.3	2.1
Off farm	75.5	8.1	86.3	4.4	87.7	4.5	79.8	3.6	81.2	3.2
Total	100	--	100	--	100	--	100	--	100	--

Regions: Great Lakes = IN, OH, and PA; Southeast = AL, FL, GA, and NC; Central = AR, IA, MN, MO, and NE; West = CA, TX, WA.
SE = Standard Error.
Source: USDA APHIS, 2000b.

Table 4-57. Percentage of Operations by Egg Processing Location and Operation Size.

Primary Egg Processing Location	Egg Laying Operations with <100,000 Layers		Egg Laying Operations with 100,000+ Layers	
	%	SE	%	SE
On farm in line	4.3	2.8	28.9	5.6
On farm off line	5.2	3.1	5.5	1.9
Off farm	90.5	4.1	65.6	6.0
Total	100	--	100	--

Regions: Great Lakes: IN, OH, and PA; Southeast: AL, FL, GA, and NC; Central: AR, IO, MN, MO, and NE; West: CA, TX, WA.SE = Standard Error.
Source: USDA NAHMS, 2000.

4.2.2.6 Waste and Wastewater Reductions

Methods to reduce the quantity of wastewater generated at layer operations include advanced watering systems to reduce water spillage and feeding strategies. The use of feeding strategies will reduce the quantity of waste generated by ensuring that animals do not receive more feed than required for optimal growth. Dietary strategies to reduce N and P content include developing more precise diets and improving the digestibility of feed ingredients through the use of enzyme additives and genetic enhancement of cereal grains. Information on feeding strategies for layer operations can be found in Chapter 8.

There are several types of water delivery systems used in layer operations. Nipple water delivery systems reduce the amount of wastewater and result in healthier birds. Trough or cup drinkers allow the bird to spill water and add contaminates to the standing water. Continual overflow watering systems reduce the health risk to the birds but produce a greater quantity of wastewater.

Nipple water delivery systems are placed in the cage and deliver water only when the bird is sucking on the nipple. Approximately 62 percent of all layer operations use nipple drinker systems (USDA APHIS, 2000b). However, for layer operations with more than 100,000 birds this number increases to approximately 81.5 percent (USDA NAHMS, 2000). Watering systems may also use water pressure sensors and automatic shutoff valves to reduce water spillage. The sensor will detect a sustained drop in water pressure resulting from a break in the water line. The sensor will then stop the water flow to the broken line and an alarm will sound. The operator can then fix the broken line and restore water to the animals with minimal water spillage. There is little information about the relative use of water pressure sensors within the layer industry.

4.2.2.7 Waste Disposal

Practices for the disposal of layer wastes are similar to those for other poultry litter. After removal from the housing facilities, waste can be directly applied to the land (if available), stored prior to final disposal, or pelletized and bagged for use as commercial fertilizer. Waste storage, application of litter, and other poultry waste disposal practices are discussed in detail in Section 4.2.1.6. The percentage of layer and pullet operations with and without enough land for application of manure on a N- and P- basis and operations with no land are shown in Tables 4-58 and 4-59. The facilities that have no land were determined by running queries of the USDA 1997 Census of Agriculture data to identify facilities that did not grow any of the 24 major crops grown in the United States.

Mortality and the disposal of dead hens is a potentially significant source of contamination at laying operations. A total of 6.5 percent of hens placed in the last completed flock (one flock per farm site) died by 60 weeks of age, and the overall average cumulative mortality was 14.6 percent (USDA APHIS, 2000b). The common methods of disposing of dead hens and frequency of use are presented in Table 4-60. Tables 4-61 and 4-62 present this information for operations with fewer than and more than 100,000 laying hens. Larger facilities are much more likely than smaller facilities to send dead birds to rendering plants (50.2 percent versus 21.1 percent). While

smaller facilities are more likely than larger facilities to bury their dead birds (45.6 percent versus 9.1 percent).

Table 4-58. Percentage of Layer Dominated Operations With Sufficient, Insufficient, and No Land for Agronomic Application of Generated Manure.

Capacity (Number of Birds)	Sufficient Land		Insufficient Land		No Land
	Nitrogen	Phosphorus	Nitrogen	Phosphorus	
1–29,999	12.2	9.2	49.1	53	41.1
30,000–59,999	6.8	1	60.3	65	33.2
60,000–179,999	6.2	0	52	62.2	36.8
180,000+	1.1	0	46.6	47.1	52.9
Total	10.5	6.9	49.5	57.5	38.8

Source: USDA NASS, 1999c.

Table 4-59. Percentage of Pullet Dominated Operations With Sufficient, Insufficient, and No Land for Agronomic Application of Generated Manure.

Capacity (Number of Birds)	Sufficient Land		Insufficient Land		No Land
	Nitrogen	Phosphorus	Nitrogen	Phosphorus	
1–29,999	11.6	5.9	47.3	53	41.1
30,000–59,999	11.9	1.7	54.9	65	33.2
60,000–179,999	14.1	1.1	49.2	62.2	36.8
180,000+	2	0	45.1	47.1	52.9
Total	11.6	3.7	49.5	57.5	38.8

Source: USDA NASS, 1999c.

Table 4-60. Frequency of Disposal Methods for Dead Layers for All Facilities.

Method of Disposal	Farm Sites		Dead Hens	
	Percent	Std Error	Percent	Std Error
Composting	15.0	(3.5)	11.7	(4.1)
Incineration	9.0	(2.9)	10.4	(4.5)
Covered deep pit	32.0	(5.8)	17.9	(4.3)
Rendering	32.0	(4.9)	41.4	(8.6)
Other	16.1	(3.6)	18.6	(5.4)
Total	--		100.0	

Source: USDA APHIS, 2000b.

Table 4-61. Frequency of Disposal Methods for Dead Layers for Facilities With <100,000 Birds.

Method of Disposal	Farm Sites		Dead Hens	
	Percent	Std Error	Percent	Std Error
Composting	13.9	4.7	13.4	7.5
Incineration	9.3	4.2	19.8	9.8
Covered deep pit	45.6	7.2	36.4	8.3
Rendering	21.1	4.5	19.7	6.0
Other	14.0	4.7	10.7	3.8
Total	--	--	100.0	--

Source: USDA NAHMS, 2000.

Table 4-62. Frequency of Disposal Methods for Dead Layers for Facilities With ≥ 100,000 Birds.

Method of Disposal	Farm Sites		Dead Hens	
	Percent	Std Error	Percent	Std Error
Composting	16.8	4.6	10.6	4.4
Incineration	8.7	3.3	4.6	2.5
Covered deep pit	9.1	2.2	6.5	2.5
Rendering	50.2	7.2	54.8	10.9
Other	19.7	5.8	23.5	8.7
Total	--	--	100.0	--

Source: USDA NAHMS, 2000.

4.2.3 Turkey Sector

This section describes the following aspects of the turkey industry:

- 4.2.3.1: Distribution of the turkey industry by size and region
- 4.2.3.2: Production cycles of turkeys
- 4.2.3.3: Turkey facility types and management
- 4.2.3.4: Turkey waste management practices
- 4.2.3.5: Pollution reduction
- 4.2.3.6: Waste disposal

National Overview

Turkey production has increased steadily over the past 2 decades and, as in the other poultry sectors, there has been a shift in production to fewer but larger operations. Between 1982 and 1997, almost 21 percent of the turkey operations went out of business (USDA NASS, 1998b). As

shown in Table 4-63, the number of turkey operations decreased from 12,708 operations in 1992 to 12,207 operations in 1997, a 4 percent decrease. The number of turkeys produced rose approximately 10 percent between 1992 and 1997. The number of hens held for breeding, however, decreased by almost 6 percent during the same period.

As in the broiler industry, most turkeys are produced under contract production arrangements. For each contract arrangement, an integrator company provides the birds, feed, medicines, bird transport, and technical help. The contract producer provides the production facilities and labor to grow the birds from hatchlings to market-age birds. In return, the contract producer receives a guaranteed price, which may be adjusted up or down based on the performance of the birds compared with that of other flocks produced or processed by the company during the same span of time. Some turkeys are raised by independent turkey producers. Even under this type of production, however, the independent producer may arrange for feed, poults, medical care, and possibly processing, through contracts. Finally, some turkeys are produced on farms owned by the integrator company. The integrator company may also be the company that processes the birds; however, some turkey integrators provide all services except the processing, which the integrator arranges with a processing company.

Table 4-63. Turkey Operations in 1997, 1992, 1987, and 1982 With Inventories of Turkeys for Slaughter and Hens for Breeding.

Total Farms With	1997		1992		1987		1982	
	Ops	Production	Ops	Production	Ops	Production	Ops	Production
Turkeys	6,031	307,586,680	6,257	279,230,136	7,347	243,336,202	7,498	172,034,935
Turkeys sold for slaughter	5,429	299,488,350	5,658	272,831,801	6,813	238,176,199	6,838	167,540,306
Turkey hens kept for breeding	747	8,098,330	793	6,398,335	761	5,160,003	1,040	4,494,629

Source: USDA NASS, 1998b.

4.2.3.1 Distribution of Turkey Operations by Size and Region

EPA's 1974 CAFO Effluent Limitations Guidelines and Standards generally apply to turkey operations with more than 55,000 birds. (See Chapter 2 for the definition of a CAFO, and Chapter 5 for a discussion of the basis for revisions to the poultry subcategories.) Where numbers of birds are presented, all birds regardless of age (e.g., poult, laying age, or pullet) or function (i.e., breeder, layer, meat-type birds) are included unless otherwise indicated in the text.

The consolidation of the turkey industry has mirrored that of other livestock industries. The number of turkey farms with fewer than 30,000 birds decreased from 5,113 in 1987 to only 3,378 in 1997 (USDA NASS, 1999b). Concurrently, the number of operations with more than 60,000 birds increased 26 percent from 1232 in 1987 to 1671 in 1997. Although these changes are not as dramatic as those for the swine or broiler industry, they are indicative of an industry that is undergoing a steady transformation into one dominated by large integrated operations.

Table 4-64 presents the number of turkey operations in 1997 by size and region. Table 4-65 presents the distribution of turkey production by size of operation and region. It is important to note that the 369 largest operations (2.7 percent) had 43.6 percent of the total turkey count. These tables reflect the use of 2.5 turns (flocks) per year. USDA NASS performed an analysis for EPA to estimate how variations in the estimated of number of turns per year would change the number of potential CAFOs (operations with more than 55,000 birds). This analysis showed that there would be only minor changes to the estimated number of CAFOs if the estimated number of turns was adjusted to two or three turns.

State-level data from the 1997 Census of Agriculture (USDA NASS, 1999b) indicate that states in the Midwest and Mid-Atlantic Regions account for more than 70 percent of all turkeys produced. Key production states (determined by number of turkeys produced) are North Carolina, Minnesota, Virginia, Arkansas, California, and Missouri. Other states with significant production include Indiana, South Carolina, Texas, Pennsylvania, and Iowa. Table 4-66 presents the number of turkey facilities and total USDA-based AUs using the 1997 Census of Agriculture (USDA NRCS, 2002).

Table 4-64. Number of Turkey Operations in 1997 by Region and Operation Size.

Region [a]	Number of Turkey Operations by Size (Operation Size Presented by Number of Birds Spot Capacity)				
	>0–16,500	>16,500–38,500	>38,500–55,000	>55,000	Total
Central	2,301	54	19	34	2,408
Mid-Atlantic	3,265	597	143	83	4,088
Midwest	4,016	493	121	142	4,772
Other	2,035	222	83	110	2,450
National	11,617	1,366	366	369	13,718

[a] Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Other = WA, OR, CA, AK, HI, AR, LA, MS, AL, GA, SC, FL.
Source: USDA NASS, 1999c.

Table 4-65. Distribution of Turkeys in 1997 by Region and Operation Size.

Region [a]	Percentage of Total Turkey Counts by Operation Size (Operation Size Presented by Number of Birds Spot Capacity)				
	>0–16,500	>16,500–38,500	>38,500–55,000	>55,000	Total
Central	0.64	1.22	0.80	5.20	7.85
Mid-Atlantic	4.93	13.18	5.73	7.15	30.99
Midwest	4.38	10.62	4.88	19.94	39.82
Other	1.48	5.18	3.35	11.34	21.34
National	11.43	30.20	14.75	43.62	100.00

[a] Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Other = WA, OR, CA, AK, HI, AR, LA, MS, AL, GA, SC, FL.
Source: USDA NASS 1999c.

Table 4-66. Turkey Facility Demographics from the 1997 Census of Agriculture Database.

Size Class (EPA AUs)	Number of Operations	Total USDA AUs	Size Class Interval (Number of Head)	
			Lower	Upper
300–500	875	360,475	16,500	27,499
500–750	478	306,632	27,500	41,249
750–1000	262	230,628	41,250	54,999
1000+	388	915,367	55,000	up
Total	2,003	1,813,102		

Source: USDA NRCS, 2002.

4.2.3.2 Production Cycles of Turkeys

The growth of a turkey is commonly divided into two phases: brooding and grow-out. The brooding phase is the period of the poult's life extending from 1 day to about 6 to 8 weeks. During this time, the poults are unable to maintain a constant body temperature and need supplemental heat. Brooder stoves are used to keep the ambient temperature at 90 to 95 °F when the poults arrive; thereafter, the producer decreases the temperature by 5 °F for the next 3 weeks until the temperature reaches 75 °F. Poults are extremely susceptible to disease and are typically administered special starter feeds containing antibiotics and a high percentage of protein. One difference between turkeys and broilers is that feeding strategies, such as the use of phytase to reduce P content in waste, are not employed with turkeys through the entire life cycle because phytase is thought by some to inhibit bone development in poults. As with the broiler industry, further research in diet, nutrition, and the complex relationships between calcium, vitamins, and P may overcome this limitation.

The grow-out phase is the period in a turkey's life between the brooding phase and the market or breeding phase. Depending on the sex of the birds, the grow-out phase typically lasts up to 14 weeks. Modern turkeys grow rapidly. A tom (male) poult weighs about ¼ pound at birth; at 22 weeks it weighs almost 37 pounds. Hens (females) are usually grown for 14 to 16 weeks and toms from 17 to 21 weeks before being marketed. Most operators start fewer toms than hens in a given house to allow more space for the larger birds.

4.2.3.3 Turkey Facility Types and Management

Market and breeder turkeys are raised in similar housing systems. Typically, young turkey poults are delivered to the operation on the day of, or the day after, hatching. The poults are placed in barns called brooder houses. The brooder houses for turkeys are usually as wide as broiler and pullet houses but are usually only 300 to 400 feet long. The houses have an impermeable floor surface made of either clay or cement. The floors are then covered with 3 to 4 inches of bedding.

As with broilers, ventilation is usually provided by a negative-pressure system, with exhaust fans drawing air out of the house and fresh air returning through ventilation ducts around the perimeter of the roof. Some turkey houses have side curtains that can be retracted to allow diffusion of air. More advanced ventilation systems use exhaust fans controlled by a thermostat

and timer. Brooding heaters are normally present in one-third to one-half of the house, for the early stages of development. As the poults get older, they are usually released into the other two-thirds or half of the house and remain there until they are of market age. In some operations the poults are moved to a specially designed grower house, where they stay until they are of market age. Some operations will move poults to range.

The construction of the housing facilities varies by region and depends on climatic conditions and production practices. Generally, in the southern and southeastern U.S. the houses are more open. The side walls of the houses are 6 to 8 feet high, with a 4- to 5-foot-wide opening covered by wires and curtains. Since moderate winters are normal in the South and Southeast, the curtains can contain the heat necessary to maintain a reasonable temperature within the commercial poultry houses. In the northern and central states, most houses have solid side walls and contain considerable insulation to combat the colder temperatures. These houses rely on exhaust fans or moveable solid side walls during the hot summer days to diminish the effects of heat stress on the birds.

These traditional systems are called two-age farms because two ages of birds can be on the farm at one time. Once the poults have been moved to the grower barn, the brooder house is totally cleaned out for another group of poults. This cleanup includes removal of all litter used during the brooding phase. The second group of poults occupies the brooder house while the first group of birds is still in the grower barn. Operations in the Shenandoah Valley area of Virginia and West Virginia are known to use a modification of the typical two-age management system. Under this system the houses are longer. Poults may occupy one end of the house, while an older group is being grown out at the other end. The birds do not have to be moved as often under this system.

The two-age farm system has served the turkey industry for more than 20 years. Currently, however, there are efforts to modify this system because of morbidity and mortality. The modifications are directed at raising older birds in facilities removed from the poults. This approach provides an opportunity to break any disease cycle that might put the birds, especially the younger ones, at increased risk (USEPA, 1998).

4.2.3.4 Turkey Waste Management Practices

For brooder facilities, the litter is removed after every flock of brooded poults. This practice is necessary to provide the next group of poults with clean bedding to achieve the lowest possible risk of disease exposure. Poult litter may be composted between flocks to control pathogens and then reused in the grow-out houses. For grower systems, the litter is removed once a year. In between flocks, cake is removed and the old litter may be top-dressed with a thin layer of new bedding. For single-age farms, the bedding in the brooding section is moved to the grower section. New bedding is put in the brooder section, and the facilities are prepared for the next group of poults.

4.2.3.5 Pollution Reduction

New technologies in drinking water systems result in less spillage and ensure that turkey litter stays drier. Feeding strategies will also reduce the quantity of waste generated by ensuring that turkeys do not receive more feed than required for optimal growth. State regulations have also driven many turkey operations to handle mortalities in ways other than burial such as rendering and composting, which are on the rise (see Section 4.2.3.6).

Nipple water delivery systems reduce the amount of wasted water and are healthier for the animals. Trough or bell type watering devices allow the animal to spill water and add contaminants to the standing water. Nipple water systems deliver water only when the animal is sucking on the nipple. Watering systems may also use water pressure sensors and automatic shutoff valves to reduce water spillage. The sensor will detect a sustained drop in water pressure resulting from a break in the water line. The sensor will then stop the water flow to the broken line and an alarm will sound. The operator can then fix the broken line and restore water to the animals with minimal water spillage.

Feeding strategies can be used to reduce the quantity of nutrients in the excreta. Dietary strategies designed to reduce N and P include enhancing the digestibility of feed ingredients, genetic enhancement of cereal grains and other ingredients resulting in increased feed digestibility, more precise diet formulation, and improved quality control. Although N and P are currently the focus of attention, these strategies also have the potential to decrease other nutrients. There is debate on the impacts of phytase feed supplements for turkey poults concerning bone growth and bone development. Phytase additions are expected to achieve a reduction in P excretion of 20 to 60 percent depending on the P form and concentration in the diet (NCSU, 1998b). Protein content, calcium, other mineral content, vitamin B, as well as other factors identified in the literature influence the effectiveness of phytase use in feed. Additional information on feeding strategies for turkeys can be found in Chapter 8.

4.2.3.6 Waste Disposal

Practices for the disposal of turkey litter are similar to those for other poultry litter. After removal from the housing facilities, waste can be directly applied to the land (if available), stored prior to final disposal, or pelletized and bagged for use as commercial fertilizer. Waste storage, application of litter, and other poultry waste management practices are discussed in detail in Section 4.2.1.4. The percentage of turkey operations with and without enough land for application of manure on a N- and P- basis and operations with no land are shown in Table 4-67. The facilities that have no land were determined by running queries of the USDA 1997 Census of Agriculture data to identify facilities that did not grow any of the 24 major crops grown in the U.S.

Disposal of dead birds can be handled through composting, incineration, burial in deep pits, rendering, and disposal in landfills. Technical information on practices for the disposal of dead animals is presented in Chapter 8; however, there is little information available on the relative use of these practices within the turkey industry.

Table 4-67. Percentage of Turkey Dominated Operations With Sufficient, Insufficient, and No Land for Agronomic Application of Generated Manure.

Capacity (Number of Birds)	Sufficient Land:		Insufficient Land:		No Land
	Nitrogen	Phosphorus	Nitrogen	Phosphorus	
1–16,499	15.6	5.9	52.5	62.2	31.8
16,500–38,499	6.8	0.3	65.4	71.9	27.9
38,500–54,999	4.1	0	65.5	69.9	30.4
55,000+	3	0	58.1	61.1	38.9
Total	9.4	2.4	59.5	66.5	31.1

Source: USDA NASS, 1999c.

4.2.4 Duck Sector

The specialized husbandry for ducks has limited expansion due to the fact that duck production "know-how" has tended to remain within families or in a limited number of large companies (Scott and Dean, 1991). Duck farms must also be located in close proximity to processing plants specially adapted to handle ducks. These factors, as well as the specialized market for duck meat in the United States, have played an important role in limiting the expansion of the duck industry.

4.2.4.1 Distribution of the Duck Industry by Size and Region

The 1992 Census of Agriculture reported an inventory of nearly 3.5 million ducks in the United States (Table 4-68). This represented more than a 26 percent drop from 1987. The number of farms dropped from about 25,000 operations in 1987 to about 16,000 operations in 1992.

Table 4-68. Duck Inventory and Sales.

Category		1987	1992
Total ducks	Inventory	4,538,716	3,339,659
	Number of farms	24,664	16,312
Duck sales	Sold	26,041,817	16,391,031
	Number of farms	4,262	3,038

Source: 1992 Census of Agriculture.

Ducks were first produced commercially in the United States on Long Island, New York. The major producers are now located in the Midwest and California. Indiana produces the majority of commercial ducks, followed by Wisconsin, California, New York, and Pennsylvania (Table 4-69).

Table 4-69. 1992 Regional Distribution of Commercial Ducks.

State	Inventory	Farms
Indiana	1,170,154	388
Wisconsin	695,109	653
California	526,610	806
New York	312,523	524
Pennsylvania	152,855	653

Source: 1992 Census of Agriculture.

Based on data provided to EPA by Maple Leaf Farms (2001), most duck operations tend to be relatively small. Table 4-70 presents the number of operations by size class based on data from five of the seven companies that raise ducks commercially.

Table 4-70. Distribution of Commercial Duck Operations by Capacity.

Number of Facilities	Capacity per Site
48	2,500–3,000
65	4,000–10,000
33	11,000–15,000
31	16,000–25,000
7	26,000–30,000
11	31,000–50,000
2	90,000
3	117,000
2	144,000
2	165,000
1	190,000

Source: Maple Leaf Farms, 2001.

4.3 Dairy Industry

Dairy AFOs include facilities that confine dairy cattle for feeding or maintenance for at least 45 days in any 12-month period, and do not have significant vegetation in the area of confinement. Dairies may also perform other animal and agricultural operations that are not covered by the existing dairy effluent guidelines including grazing, milk processing, and crop farming.

- Section 4.3.1: The distribution of dairy operations by size of operation and region in 1997
- Section 4.3.2: Dairy production cycles
- Section 4.3.3: Stand-alone heifer raising operations
- Section 4.3.4: Dairy facility management practices
- Section 4.3.5: Dairy waste management practices
- Section 4.3.6 lists the references used in this section

4.3.1 Distribution of Dairy Operations by Size and Region

Current effluent limitations guidelines and standards apply to dairy operations with 700 or more mature dairy cattle (both lactating and dry cows), where the animals are fed at the place of confinement and crop or forage growth or production is not sustained in the confinement area.

Information presented in this section comes from USDA, NASS 1997 Census of Agriculture data, and from site visits and trade associations. The 1993 to 1997 NASS reports on dairy

operations present the number of dairies by size class. Dairy operations with more than 200 mature dairy cattle are grouped in one size class; therefore, an analysis of dairy operations that fall under the current effluent guidelines regulations (i.e., those with more than 700 milking cows) cannot be completed with NASS data alone. Data from the 1997 Census of Agriculture provide some additional information on medium and large (more than 200 milking cows) dairy operations. Although the NASS and Census data do not match exactly, EPA has found that there is generally a good correlation between the two datasets. EPA used the Census data to estimate farm counts.

From 1988 to 1997, the number of dairies and milking cows in the U.S. decreased while total milk production increased. Improved feeding, animal health, and dairy management practices have allowed the dairy industry to continue to produce more milk each year with fewer milking cattle. Since 1988, the total number of milking cows has decreased by 10 percent and the total number of dairy operations has decreased by 43 percent, indicating a general trend toward consolidation (USDA NASS, 1995b; 1999d).

Between 1993 and 1997, the number of operations with fewer than 200 milking cows decreased, while the number of operations with 200 or more milking cows increased. Both NASS and the 1997 Census of Agriculture have collected data that quantify the changes by size class. Based on the NASS data, the number of operations with 200 or more milking cows increased by almost 7 percent between 1993 and 1997, while all smaller size classes decreased in numbers of operations. Table 4-71 shows the estimated distribution of dairy operations by size and region in 1997, and Table 4-72 shows the total number of milk cows and average cow herd size by size class in 1997. EPA derived the data in these tables from the Census data (ERG, 2000b).

According to Census of Agriculture data, of the 116,874 dairy operations across all size groups in 1997, Wisconsin had the most with 22,576 (19 percent), followed by Pennsylvania with 10,920 (9 percent), Minnesota with 9,603 (8 percent), and New York with 8,732 (7 percent). Table 4-73 presents the number of dairies by top-producing states for the following size groups:

- 1 to 199 milk cows
- 200 to 349 milk cows
- 350 to 700 milk cows
- more than 700 milk cows

Of the large dairies (more than 700 milking cows), California has the most operations (46 percent), and of the medium dairies (200 to 700 milking cows), California, New York, Wisconsin, and Texas have the most operations.

Table 4-74 shows the annual milk production in 1997 for the top-producing states. Although California has only 2,650 dairy farms in all, it is the largest milk-producing state in the U.S., according to NASS data and data received from the National Milk Producers Federation (National Milk Producers, 1999; USDA NASS, 1999d).

Table 4-71. Distribution of Dairy Operations by Region and Operation Size in 1997.

Region[a]	Number of Operations				
	0-199 Milk Cows	200-349 Milk Cows	350-700 Milk Cows	> 700 Milk Cows	Total
Central	9,685	593	433	404	11,115
Mid-Atlantic	32,490	870	487	81	33,928
Midwest	59,685	943	497	90	61,215
Pacific	2,875	722	725	786	5,108
South	5,001	253	170	84	5,508
National	109,736	3,381	2,312	1,445	116,874

[a] Centrl = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL.

Table 4-72. Total Milk Cows by Size of Operation in 1997.

Size Class	Number of Operations	Total Number of Milk Cows	Average Milk Cow Herd Size
0–199 Milk Cows	109,736	5,186,000	47
200–349 Milk Cows	3,381[a]	795,000	235
350–700 Milk Cows	2,312[a,b]	1,064,000	460
> 700 Milk Cows	1,445[b]	2,050,455	1,419
Total	116,874	9,095,455	78

[a] Estimated value. Published Census of Agriculture data show 4,881 dairies with 200-499 milk cows. Assumes approximately 70 percent have 200-349 milk cows and 30 percent have 350-500 milk cows.

[b] Estimated value. Published Census of Agriculture data show 1,379 dairies with 500-999 milk cows. Assumes approximately 60 percent have 500-699 milk cows and the remainder have 700-1,000 milk cows.

Table 4-73. Number of Dairies by Size and State in 1997.

Location	Size Class				Total
	1-199 Milk Cows	200-349 Milk Cows	350-700 Milk Cows	>700 Milk Cows	
California	969	471	547	663	2,650
Florida	495	51	58	62	666
Idaho	1,105	119	90	90	1,404
Michigan	3,743	144	81	22	3,990
Minnesota	9,379	135	75	14	9,603
New York	8,162	319	194	57	8,732
Pennsylvania	10,693	148	71	8	10,920
Texas	3,562	266	188	97	4,113
Washington	925	175	130	72	1,302
Wisconsin	22,041	333	171	31	22,576
Total United States	109,736	3,381	2,312	1,445	116,874

Table 4-74. Milk Production by State in 1997

Location	Total Milk Production (million pounds)	Milk Produced Per Cow (pounds)
California	27,582	19,829
Florida	2,476	15,475
Idaho	5,193	19,092
Michigan	5,410	17,680
Minnesota	9,210	16,186
New York	11,530	16,495
Pennsylvania	10,662	16,951
Texas	5,768	15,259
Washington	5,305	20,968
Wisconsin	22,368	16,057
Total United States	156,091	16,871

4.3.2 Dairy Production Cycles

The primary function of a dairy is the production of milk, which requires a herd of mature dairy cows that are lactating. In order to produce milk, the cows must be bred and give birth. Therefore, a dairy operation may have several types of animal groups present, including

- Calves (0 to 5 months)
- Heifers (6 to 24 months)
- Cows that are close to calving (close-up cows)
- Lactating dairy cows
- Dry cows
- Bulls

Most dairies operate by physically separating and handling their animals in groups according to age, size, milking status, or special management needs. This separation allows each group to be treated according to its needs. Section 4.3.2.1 presents a description of the typical mature dairy herd, and Section 4.3.2.2 discusses the immature animal groups that may also be present at the dairy.

4.3.2.1 *Milk Herd*

The dairy milk herd is made up of mature dairy cows that have calved at least once. These mature cows are either lactating or "dry" (not currently producing milk). After a cow has calved, the milk she initially produces (called "colostrum") contains higher amounts of protein, fat, minerals, and vitamins than normal milk. The colostrum is usually collected and fed to the calves. After about 4 days, the milk returns to normal and the cow rejoins the lactating cow herd.

After being milked for about 10 to 12 months after calving, the cows go through a dry period. These dry periods allow the cow to regain body condition and the milk secretory tissue in the udder to regenerate. The dairy industry has reported an average of 60.5 days of dry period per cow (USDA APHIS, 1996a).

Periodically, all dairies must cull certain cows that are no longer producing enough milk for that dairy. Cows are most often culled for the following reasons: reproductive problems, udder or mastitis problems, poor production for other reasons, lameness or injury, disease, or aggressiveness or belligerence. In 1995, an average of 24 percent of the herd was culled from all size operations (USDA APHIS, 1996a). Dairies in high milk-producing regions (e.g., California) have reported during site visits cull rates of up to 40 percent.

Some dairies decide when a cow is to be culled by determining a milk break-even level (pounds of milk per cow per day). Approximately 28 percent of dairies use this practice and reported an average milk break-even level of approximately 33 pounds per cow per day. The milk break-even levels ranged from 32.5 pounds per cow per day at small dairies (less than 100 head) up to 36.5 pounds per cow per day at larger dairies (200 or more head) (USDA APHIS, 1996a).

Nearly all culled cows (approximately 96 percent) are sent away for slaughter. Approximately 74 percent are sent to a market, auction, or the stockyards. Others (21 percent) are sold directly to a packer or slaughter plant, and the remaining 1 percent are sent elsewhere. Cows that are not sold for slaughter (approximately 4 percent) are usually sent to another dairy operation (USDA APHIS, 1996a).

4.3.2.2 Calves, Heifers, and Bulls

The immature animals at a dairy are heifers and calves. Typically, according to Census of Agriculture data, for dairies greater than 200 milking cows, the number of calves and heifers on site equals approximately 60 percent of the mature dairy (milking) cows. EPA assumes that there are an equal number of calves and heifers on site (30 percent each). Calves are considered to be heifers between the age of 6 months and the time of their first calving (between 25 and 28 months of age) (USDA APHIS, 1996a). Heifers tend to be handled in larger groups, and often they are divided for management purposes into a breeding group and a bred heifer group (Bickert et al., 1997). Heifers and cows are often bred artificially. They may be placed daily in stanchions for estrus (heat) detection with the aid of tail chalk or heatmount detectors. Heifers and cows in pastures or in pens without stanchions may be heat detected by observation and then bred in a restraining chute. Heifers that do not conceive after attempts with artificial insemination are often

placed in groups with a breeding-age bull to allow natural service of those animals. Approximately 45 percent of dairy operations do not keep bulls on site, and approximately 35 percent of dairy operations keep one bull on site for breeding (USDA APHIS, 1996a).

Cows and heifers that are at the end of their pregnancy are considered to be "periparturient" or "close-up cows." About 2 weeks before she is due, the heifer or cow is moved from her regular herd into a smaller pen or area where she can be observed and managed more closely. When the cow is very near to calving, she is often moved to an isolated maternity pen. Shortly after birth, the calves are separated from their mothers and are generally kept isolated from other calves or in small groups until they are about 2 months old. After the calves are weaned from milk (at about 3 months of age), they are usually moved from their individual pen or small group into larger groups of calves of similar age. Female calves are raised (as replacements) to be dairy cows at the dairy or sent to an off-site calf operation. Female calves (heifers) may also be raised as beef cattle. Male calves that are not used for breeding are either raised as beef cattle (see Section 4.4) or as veal calves (see Section 4.4.5).

4.3.3 Stand-Alone Heifer Raising Operations

Stand-alone, heifer-raising operations provide replacement heifer services to dairies. It has been estimated that 10 percent to 15 percent of all dairy heifers are raised by stand-alone heifer raisers (Gardner and Jordan 1999, personal communication). These heifer-raising operations often contract with specific dairies to raise those dairies' heifers for a specified period of time, and many also provide replacement heifers to any dairy needing additional cows. The age at which dairies send their animals to heifer-raising operations varies significantly (USDA APHIS, 1996a). Table 4-75 shows the percentage of dairies that use heifer- raising operations, the median age at which heifers are received by these facilities, and the amount of time that the heifers remain at these facilities.

Table 4-75. Characteristics of Heifer-Raising Operations.

Age of Heifer	Percentage of Dairies Using Heifer Raisers	Median Age of Heifer	Time That Heifers Remain on Site
0–4 months	41.2	1 week	12 months
4 months–breeding	47.1	6 months	15 months
Breeding–first calving	11.8	Breeding age	9 months

There are a number of advantages for dairies to use heifer-raising operations. Specifically, dairies using heifer-raising operations could expand their herd size by 25 percent or more within existing facilities, specialize in milking cows or raising crops, and obtain healthier and better producing milking cows. In addition, raising calves off the farm may reduce risks of transmission of diseases for which older cows are the main source of infection. Some disadvantages include an increased risk of introducing disease into the herd and a shortage of replacement heifers if the raiser's breeding results are less than adequate. Also, the costs associated with raising the heifers

could run higher than what the dairies are paying if labor, feed, and other resources are not allocated profitably (USDA APHIS, 1993).

Custom raising of dairy heifers is becoming more common as dairy herds increase in size and dairy farmers do not have facilities to raise all their heifers (Noyes, 1999). Throughout the U.S., the level of specialization is increasing for dairy farms; in fact, some large dairy farms raise no crops, purchase all of their feedstuffs, or do not raise replacement heifers for the milking herd. Herd owners for these dairies must use other strategies to obtain herd replacements. As a result, enterprises that specialize in raising dairy calves and heifers are found in many western states (Faust, 2000). It is also believed that the poor beef market in the last few years has caused some beef feedlots to add pens of dairy heifers or switch to heifers entirely (Cady 2000, personal communication).

Stand-alone heifer operations use two primary methods for raising their animals. One method is to raise heifers on pasture, usually in moderate to warm climates where grazing land is available. The second is to raise heifers in confinement (on dry lots, as for beef cattle). Confinement is commonly used at operations in colder climates or areas without sufficient grazing land (Jordan 1999, personal communication).

The actual number of stand-alone, heifer-raising operations, as well as the number of confined operations, is unknown. However, based on information supplied by industry representatives (e.g., Professional Dairy Heifer Growers Association), EPA estimates that there may be 5,000 heifer-raising operations in the United States; 300 to 400 operations with more than 1,000 head, 750 to 1,000 with more than 500 head, and 4,000 with fewer than 500 head (most of them with around 50 head) (Cady 2000, personal communication). Most large dairy heifer-raising operations (those with more than 1,000 head) are confinement-based while smaller operations are often pasture-based (see above). Table 4-76 shows EPA's estimate of confined heifer-raising operations by size and region (ERG, 2000a; 2000b).

Table 4-76. Distribution of Confined Heifer-Raising Operations by Size and Region in 1997.

	Number of Operations			
Region[a]	300–499 Heifers	500–1,000 Heifers	> 1,000 Heifers	Total
Central	25	250	180	455
Mid-Atlantic	0	0	0	0
Midwest	200	100	0	300
Pacific	25	150	120	295
South	0	0	0	0
National	250	500	300	1,050

[a] Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL.

The sizes of heifer-raising operations range from 50 head (typical "mom and pop" operations) to 25,000 head, and tend to vary geographically. The average size of a heifer operation located west of the Mississippi River is 1,000 to 5,000 head, while the average size in the upper Midwest, Northeast, and South is 50 to 200 head. Nationally, the median size of a dairy heifer-raising operation is approximately 200 head (Cady 2000, personal communication).

Stand-alone, heifer-raising operations are found nationwide with more heifer raisers located where cows are concentrated and in areas where the dairy industry is evolving toward more specialization (Bocher, 2000). EPA estimates that, of the number of heifers raised at stand-alone heifer operations, approximately 70 percent are managed in the West, 20 percent are managed in the South/Southeast, 7 percent are managed in the Northeast, and approximately 3 percent are managed in the upper Midwest. The upper Midwest is also believed to be the single largest growing region with respect to small heifer operations (see above).

4.3.4 Dairy Facility Management

This section describes factors that affect the facility management of a dairy operation including housing by type of animal, use of housing in the industry, flooring and bedding type, feeding and watering practices, milking operations, and rotational grazing.

4.3.4.1 Housing Practices

The purpose of dairy housing is to provide the animals with a dry and comfortable shelter, while providing the workers with a safe and efficient working environment. Optimal housing facilities accommodate flexibility in management styles and routines, enhance the quality of milk production, and allow for the protection of the environment, yet remain cost-effective (Adams et. al., 1995). The following subsections describe, housing for each type of animal group according to age, from milking cows to calves.

Milking Cows

The primary goal in housing lactating dairy cows is to provide an optimum environment for the comfort, proper nutrition, and health of the lactating cow for maximum milk productivity. It is also designed to allow for efficient milking processes. The most common types of lactating cow housing include freestalls, dry lots, tie stalls/stanchions, pastures, and combinations of these. The types of housing used for dry cows include loose housing and freestalls (Stull et al., 1998). These housing types are described in detail below.

- Freestalls - This type of housing provides individual resting areas for cows in freestalls or cubicles, which helps to orient the cow for manure handling. Freestalls provide the cows with a dry and comfortable place to rest and feed. The cows are not restrained in the freestalls and are allowed to roam on concrete alleys to feeding and watering areas. Manure collects in the travel alleys and is typically removed with a tractor or mechanical alley-scraper, by flushing with water, or through slotted openings in the floor (refer to Section 4.3.5 for a more detailed description of waste handling) (Adams,

1995). Recently, there has been a trend toward using freestalls to house dairy cows and many loose housing units have been converted to freestalls (Bickert, 1997).

- Dry lots - Dry lots are outside pens that allow the animals some exercise, but do not generally allow them to graze. The use of dry lots depends upon the farm layout, availability of land, and weather conditions. Also, milking cows are not likely to spend their entire time on a dry lot, as they need to be milked at least twice a day at a tiestall or in a milking parlor.
- Tie Stalls/Stanchions - Tie stalls or stanchions confine the cow to a single stall where she rests, feeds, and is often milked. The tie stall prevents the cow from moving out of her stall with a chained collar, but allows her enough freedom to get up and lie down without interfering with her neighbors. Tie stalls are also designed to allow the cows access to feed and fresh water in a natural grazing position (Adams, 1995). Cows that are housed in tie stalls may be let out at certain times each day (e.g., between milkings) to graze in a pasture. Tie stalls are the most predominant type of dairy cow housing for lactating cows (USDA APHIS, 1996a); however, this is true of older, smaller dairies. The current preference, particularly for medium and large dairies, is freestalls.
- Loose Housing - Barns, shades, and corrals are considered loose housing. The design of these facilities depends upon the number of cows, climate, and waste-handling techniques. Overcrowding in this type of housing can lead to health problems and may reduce access to feed, water, or resting areas for some subordinate animals. Loose housing that is hard-surfaced typically has at least a 4 percent slope, depending on soil type and rainfall (Stull et al., 1998).
- Pastures - Depending on the farm layout, availability of pastureland, and weather conditions, heifers or cows may spend part or most of their day in a pasture. Milking cows do not spend all of their day outside, since they are milked at least twice per day in a parlor or from a tie stall. On some farms, the cows may be contained outdoors during the day, but are housed in a tie stall or freestall overnight.

Close-Up Cows

The primary objective in housing for cows that are close to calving is to minimize disease and stress to both the cow and calf. Sod pastures are often used in warmer climates or during the summer; however, the pastures can become too muddy in the winter in some climates, requiring additional worker time to keep watch over the cows. Alternatively, the cows may be housed in multiple-animal or individual pens prior to calving. About 2 weeks before the cow is due (i.e., 2 weeks prior to freshening), she is moved to a close-up pen. The cow density in close-up pens is about one-half the density in lactating cow pens to allow the calving cows some space to segregate themselves from other cows if they go into labor, although calving in close-up pens is usually avoided.

When birth is very near, cows are moved to a maternity area for calving. If the climate is sufficiently mild, pastures can be used for a maternity area; otherwise, small individual pens are

used. Pens are usually designed to allow at least 100 square feet per cow and to provide a well-ventilated area that is not drafty (Stull et al., 1998).

Approximately 45 percent of all dairy farms have maternity housing apart from the housing used for the lactating cows. This feature is more prevalent in larger farms than in smaller farms. Approximately 87 percent of farms with 200 or more cows have separate maternity housing (USDA APHIS, 1996a).

Bulls

When bulls are housed on site at a dairy operation, they are typically kept in a pen or on pasture. If possible, bulls are penned individually with sufficient space for special care and to reduce fighting. When a bull is grazed on pasture, an electric fence is typically used to prevent the bull from escaping and causing danger (Bodman et al., 1987).

Heifers

According to information collected during site visits, the majority of heifers are kept on dry lots either on or off site. Heifers may also be kept in a pasture, in which the herd is allowed to move about freely and to graze. Pastures may be provided with an appropriate shelter. Heifer housing is typically designed for ease in:

- Animal handling for treatment (e.g., vaccinations, dehorning, pregnancy checks)
- Animal breeding
- Animal observation
- Convenient feeding, bedding, and manure handling (Bickert et al., 1997)

Weaned Calves (Transition Housing)

After calves are weaned, they are usually moved from individual pens or small group pens into housing for larger numbers of calves. This change causes a number of stresses due to new social interactions with other calves, competition for feed and water, and new housing. Therefore, the housing is designed such that the workers can monitor each calf's adjustment into the social group. Transition housing is used for calves from weaning to about 5 months of age. The most common types of housing used for weaned calves are calf shelters or superhutches, transition barns, and calf barns (Bickert et al., 1997). These types of housing are described below.

- Superhutches - Superhutches are open-front, portable pens that provide a feeder, water trough, and shelter for 5 to 12 calves. Superhutches typically provide 25 to 30 square feet per calf and can be moved in a field, dry lot, or pasture as needed to provide calves with a clean surface.

- Transition Barns - A transition barn is composed of a series of pens for groups of six to eight calves of up to 6 months old. Some transition barns are designed such that the back and end walls may be open or covered, depending on the weather conditions.
- Calf Barns - A calf barn combines both individual calf pens and transition barns within one building. The pens can be designed to be easily dismantled for waste removal, to minimize calf contact, or to provide draft protection (Bickert et al., 1997).

Calves

Sickness and mortality rates are highest among calves under 2 months of age; therefore, the housing for this group typically minimizes environmental stress by protecting the calves against heat, wind, and rain. Common calf housing types include individual animal pens and hutches, which are described below.

- Individual Pens - Pens are sized to house animals individually and separate them from others. Individual pens make it easier to observe changes in behavior, feed consumption, and waste production, which can indicate sickness. Calves may be raised in 2- by 4- foot expanded metal or slatted wood, elevated pens; however, these pens provide little shelter from drafts and cold in the winter (Stull, et al., 1998). Individual pens can be used inside a barn to provide isolation for each calf. Pens are typically 4- by 7- feet and removable. Solid partitions between pens and beyond the front of the pen prevent nose-to-nose contact between the calves. A cover over the back half of the pen gives the calf additional protection, especially in drafty locations. Pens can be placed on a crushed rock base or a concrete floor to provide a base for bedding (Bickert et al., 1997).
- Hutches - Hutches are portable shelters typically made of wood, fiberglass, or polyethylene and are placed in outdoor areas. Hutches allow for complete separation of unweaned calves since one calf occupies each hutch. One end of the hutch is open and a wire fence may be provided around the hutch to allow the calf to move outside. Lightweight construction materials improve hutch mobility and also allow for easier cleaning. Hutches are typically 4 feet by 8 feet by 4 feet and may be placed inside a shed or structure to provide protection from cold weather and direct sunlight (Bickert et al., 1997).

Use of Housing in Industry

Table 4-77 summarizes the relative percentages of U.S. dairies reporting various types of housing for their animals (USDA APHIS, 1996a). These data were collected in 1996 for activities in 1995 by USDA NAHMS. Note that some operations may have reported more than one type of housing being used for a particular group. The NAHMS data did not include housing type for dry cows. It is expected that dry cows are typically housed similarly to lactating cows (Stull et al., 1998).

Multiple age groups may be housed within a single building that allows for each group to be managed separately. Larger farms tend to place their animals in more than one building (Bickert et al., 1997). Superhutches, transition barns, calf barns, and loose housing were not specifically addressed in the NAHMS study, but may be considered specific types of multiple animal pens.

Dairies predominantly use some sort of multiple animal area for unweaned calves, weaned calves, and heifers.

Table 4-77. Percentage of U.S. Dairies by Housing Type and Animal Group in 1995.

Housing Type	Unweaned Calves	Weaned Calves and Heifers	Lactating Cows	Periparturient Cows
Dry lot	9.1	38.1	47.2	28.9
Freestall	2.5	9.7	24.4	5.6
Hutch	32.5	NA	NA	NA
Individual animal area	29.7	6.6	2.3	38.3
Multiple animal area	40.0	73.9	17.9	26.3
Pasture	7.4	51.4	59.6	41.9
Tie stall/stanchion	10.5	11.5	61.4	26.3

NA = Not applicable.

4.3.4.2 *Flooring and Bedding*

The flooring and bedding used in housing provide physical comfort for the cow, as well as a clean, dry surface to reduce the incidence of mastitis and other diseases. Tables 4-78 and 4-79 summarize the various types of flooring and bedding, respectively, that are used for lactating cows, as reported by U.S. dairies in the NAHMS study (USDA APHIS, 1996b).

The most predominantly used flooring is smooth concrete, reported by over 40 percent of the dairies. Other fairly common flooring types include grooved and textured concrete. The less common flooring types that were reported include slatted concrete, dirt, and pastures (USDA APHIS, 1996b). The flooring design is important in loose housing to maintain secure footing for the animals, as well as facilitate waste removal. The surfaces typically contain scarified concrete areas around water troughs, feed bunks, and entrances. Both hard-surface and dirt lots are sloped to allow proper drainage of waste and rainfall (Stull et al., 1998).

Table 4-78. Types of Flooring for Lactating Cows.

Type of Flooring	Percentage of Dairies Reporting
Smooth concrete	41.6
Grooved concrete	27.2
Textured concrete	16.2
Pasture	6.9
Dirt	5.8
Other	1.5
Slatted concrete	0.8

Table 4-79. Types of Bedding for Lactating Cows.

Type of Bedding	Percentage of Dairies Reporting
Straw and/or hay	66.9
Wood products	27.9
Rubber mats	27.0
Corn cobs or stalks	12.8
Sand	11.2
Shredded newspaper	6.7
Mattresses	4.7
Other	3.7
Composted manure	2.4
Rubber tires	1.0

More than one bedding type may be reported by a single dairy. The most commonly used bedding is straw or hay, or a combination of the two, while other common bedding includes wood products and rubber mats. Less frequently used are rubber tires, composted manure, mattresses, shredded newspaper, sand, and corn cobs and stalks (each reported by less than 13 percent of the dairies) (USDA APHIS, 1996b).

4.3.4.3 *Feeding and Watering Practices*

Feeding and watering practices vary for each type of animal group at the dairy. Most dairies deliver feed several times each day to the cows, and provide a continuous water supply. The type of feed provided varies with the age of the animal and the level of milk production to be achieved.

Milking cows - At dairies, mature cows are fed several times a day. Lactating cows are provided a balanced ration of nutrients including energy, protein, fiber, vitamins, and minerals (NRC, 1989). Dairies with greater than 200 milking cows typically feed a total mixed ration. In addition, most dairies in the U.S. feed grains or roughages (e.g., hay) that were grown and raised on the farm. Over half of all U.S. dairies reported that they pastured their dairy cows for at least 3 months of the year. Almost half of these dairies reported that grazing provided at least 90 percent of the total roughage for the cows while they were pastured (USDA APHIS, 1996a).

A lactating dairy cow consumes about 5 gallons of water per gallon of milk produced daily (Stull et al., 1998). Temperature can affect water consumption; therefore, actual consumption may vary. The predominant method for providing water to cows is from a water trough where more than one cow can drink at a time. Other watering methods frequently reported by small dairies (less than 200 cows) include automatic waterers for use by either individual cows or by a group of cows, at which only one cow drinks at a time (USDA APHIS, 1996b).

Heifers - Rations are balanced so heifers raised on site reach a breeding weight of 750 to 800 pounds by 13 to 15 months of age. Heifers are fed high-forage rations between breeding and calving, and are usually given enough manger space for all heifers to eat simultaneously (Stull et al., 1998).

Cows within 10 to 16 days of calving are normally fed as a separate group. They may be fed a few pounds of a grain concentrate mix in addition to forages. This practice avoids a sudden shift from an all-forage ration to a ration with a high proportion of concentrates, which is typical of that fed to cows in early lactation. If a postpartum cow is fed a total mixed ration, she may be fed about 5 pounds of long-stemmed hay in the ration for at least 10 days after calving to stimulate feed intake.

Calves - Calves are initially fed colostrum, the milk that is produced by the cow just prior to and during the first few days after calving. Colostrum contains more protein (especially immunoglobulins), fat, minerals, and vitamins than the milk normally produced, and less lactose (USDA BAMN, 1997). When calves are about 5 days old, their feed is switched to fresh whole milk or a milk replacer. Milk replacers are powdered products that contain predominantly dry milk ingredients. These are mixed with water to provide the optimum nutrition for the calf (Stull et al., 1998).

Calves are then weaned from a milk replacer or milk-based diet to a forage or concentrate diet. Calves are offered a starter ration in addition to milk or milk replacer when they are approximately 1 week old. Calves will consume 1 to 1.5 pounds of starter ration per day at weaning time, usually when they are 2 to 3 months old (Stull et al., 1998).

Because calves require more water than they receive from milk or milk replacer, water is typically available to them at all times.

4.3.4.4 Milking Operations

Lactating cows require milking at least twice a day and are either milked in their tie stalls or are led into a separate milking parlor. The milking parlors are often used in the freestall type of housing. The milking center typically includes other types of auxiliary facilities such as a holding area, milk room, and treatment area (Bickert, 1997).

Milking Parlor - Milking parlors are separate facilities, apart from the lactating cow housing, where the cows are milked. Usually, groups of cows at similar stages of lactation are milked at a time. The parlor is designed to facilitate changing the groups of cows milked and the workers' access to the cows during milking. Often, the milking parlors are designed with a worker "pit" in the center of a room with the cows to be milked arranged around the pit at a height that allows the workers convenient access to the cows' udders.

The milking parlor is most often equipped with a pipeline system. The milk is collected from the cow through a device called a "milking claw" that attaches to each of her four teats. Each milking claw is connected to the pipeline and the milk is drawn from the cow, through the claw, and into

the pipeline by a common vacuum pump. The pipeline is usually constructed of glass or steel and flows into a milk receiver. From the receiver, the milk is pumped through a filter and into a bulk tank where it is stored until collection.

The milking parlor is typically cleaned several times each day to remove manure and dirt. Large dairies tend to use automatic flush systems, while smaller dairies simply hose down the area. Water use can vary from 1 to 3 gallons per day per cow milked (for scrape systems) to 30 to 50 gallons per day per cow milked (for flush systems) in the dairy parlor and holding area (Loudon et al., 1985).

Milking at Tie Stalls - Cows that are kept in tie stalls may be milked from their stalls. The housing is equipped with a pipeline system that flows around the barn and contains ports where the milking claws may be "plugged in" at each stall. The workers carry the necessary udder and teat cleaning equipment as well as the milking claws from one cow to the next.

Approximately 70 percent of dairy operations reported that they milk the cows from their tie stalls, while only 29 percent reported that they used a milking parlor; however, more than half of the lactating cow population (approximately 55 percent) is milked in a milking parlor (USDA APHIS, 1996a; 1996b). Therefore, it can be interpreted that many of the large dairies are using milking parlors, while the smaller dairies are typically using tie stalls.

Holding Area - The holding area confines cows that are ready for milking. Usually, the area is enclosed and is part of the milking center, which in turn, may be connected to the barn or located in the immediate vicinity of the cow housing. The holding area is typically sized such that each cow is provided 15 square feet and is not held for more than 1 hour prior to milking (Bickert et al., 1997). The cows' udders may sometimes be washed in this area using ground-level sprinklers.

Milk Room - The milk room often contains the milk bulk tank, a milk receiver group, a filtration device, in-line cooling equipment, and a place to wash and store the milking equipment (Bickert et al., 1997). To enhance and maintain milk quality and to meet federal milk quality standards, it is cooled from the first milking to 40° F or less within 30 minutes. Some commonly used milk cooling devices include precoolers, heat exchangers, bulk tank coolers, and combinations of these. The cooling fluid used is typically fresh or chilled service water. This water is still clean and may then be used to water the animals (Bickert et al., 1997), or more commonly as milk parlor flush water.

Milking equipment cleaning and sterilizing processes are often controlled from the milk room. Typically, the milking equipment is washed in hot water (95 to 160 °F) in prerinse, detergent wash, and acid rinse cycles. The amount of water used by an automatic washing system, including milking parlor floor washes, can vary from 450 to 850 gallons per day (Bickert et al., 1997).

Treatment Area - Treatment areas are used on farms to confine cows for artificial insemination, postpartum examination, pregnancy diagnosis, sick cow examination, and surgery. A single stall or a separate barn can be used as a treatment area.

Other Areas of the Milking Center - Milking and processing equipment is typically stored in a utility room. This equipment may include:

- Milk vacuum pump
- Compressor
- Water heater
- Furnace
- Storage

A separate room may also be used to store cleaning compounds, medical supplies, bulk materials, replacement milking system rubber components, and similar products. The storage room is often separated from the utility room to reduce the deterioration of rubber products, and is typically designed to minimize high temperatures, light, and ozone associated with motor operation (Bickert et al., 1997).

4.3.4.5 Rotational Grazing

Intensive rotational grazing is known by many terms including intensive grazing management, short duration grazing, savory grazing, controlled grazing management, and voisin grazing management (Murphy, 1988). This practice involves rotating grazing cows among several pasture subunits or paddocks to obtain maximum efficiency of the pastureland. Dairy cows managed under this system spend all of their time, except time spent milking, out on the paddocks during the grazing season.

During intensive rotational grazing, each paddock is grazed quickly (1 or 2 days) and then allowed to regrow, ungrazed, until ready for another grazing. The recovery period depends on the forage type, the forage growth rate, and the climate, and may vary from 10 to 60 days (USDA, 1997). This practice is labor- and land-intensive as cows must be moved daily to new paddocks. All paddocks used in this system require fencing and a sufficient water supply. Many operations using intensive rotational grazing move their fencing from one paddock to another and have a water system (i.e., pump and tank) installed in each predefined paddock area.

The number of required paddocks is determined by the grazing and recovery periods for the forage. For example, if a pasture-type paddock is grazed for 1 day and recovers for 21 days, 22 paddocks are needed (USDA, 1997). The total amount of required land depends on a number of factors including the dry matter content of the pasture forage, use of supplemental feed, and the number of head requiring grazing. Generally, this averages out to one or two head per acre of pastureland (Hannawald 2000, personal communication). Successful intensive rotational grazing, however, requires thorough planning and constant monitoring. All paddocks are typically

monitored once a week. High-producing milk cows (e.g., more than 80 pounds of milk per day) need a large forage allowance to maintain a high level of intake. Therefore, they need to graze in pastures that have sufficient available forage or be fed stored feed (USDA, 1997).

Due to the labor, fencing, water, and land requirements for intensive rotational grazing, typically only small dairy operations (those with less than 100 head) use this practice (see above; USDA NRCS, 1996; CIAS, 2000a). Climate and associated growing seasons, however, make it very difficult for operations to use an intensive rotational grazing system throughout the entire year. These operations, therefore, must maintain barns or dry lots for the cows when they are not being grazed, or outwinter their milk cows. Outwintering is the practice of managing cows outside during the winter months. This is not a common practice as it requires farmers to provide additional feed (as cows expend more energy outside in the winter), provide windbreaks for cattle, conduct more frequent and diligent health checks on the cows, and keep the cows clean and dry so that they can stay warm (CIAS, 2000b).

There are two basic management approaches to outwintering: rotation through paddocks and "sacrifice paddocks." Some farms use a combination of these practices to manage their cows during the winter. During winter months, farmers may rotate cattle, hay, and round bale feeders throughout the paddocks. The main differences between this approach and standard rotational grazing practices are that the cows are not rotated as often and supplemental feed is provided to the animals. Deep snow, however, can cause problems for farmers rotating their animals in the winter because it limits the mobility of round bale feeders. The outwintering practice of sacrifice paddocks consists of managing animals in one pasture during the entire winter. There are several disadvantages and advantages associated with this practice. If the paddock surface is not frozen during the entire winter, compaction, plugging (tearing up of the soil), and puddling can occur. Due to the large amounts of manure deposited in these paddocks during the winter, the sacrifical paddocks must be renovated in the spring. This spring renovation may consist of dragging or scraping the paddocks to remove excess manure and then seeding to reestablish a vegetative cover. Some farmers place sacrifice paddocks strategically in areas where an undesirable plant grows or where they plan to reseed the pasture or cultivate for a crop (CIAS, 2000c).

Advantages of rotational grazing compared to conventional grazing include:

- Higher live weight gain per acre. Intensive rotational grazing systems result in high stocking density, which increases competition for feed between animals, forcing them to spend more time eating and less time wandering (AAFC, 1999).
- Higher net economic return. Dairy farmers using pasture as a feed source will produce more feed value with intensive rotational grazing than with continuous grazing (USDA NRCS 1996). Competition also forces animals to be less selective when grazing. They will eat species of plants that they would ignore in other grazing systems. This reduces less desirable plant species in the pasture and produces a better economic return (AAFC, 1999).
- Better land. Pastureland used in rotational grazing is often better maintained than typical pastureland. Intensive rotational grazing encourages grass growth and development of

healthy sod, which in turn reduces erosion. Intensive rotational grazing in shoreline areas may help stabilize stream banks and could be used to maintain and improve riparian habitats (PPRC, 1996).

- Less manure handling. In continuous grazing systems, pastures require frequent maintenance to break up large clumps of manure. In a good rotational system, however, manure is more evenly distributed and will break up and disappear faster. Rotational grazing systems may still require manure maintenance near watering areas and paths to and from the paddock areas (Emmicx, 2000).

Grazing systems are not directly comparable to confined feeding operations, as one system can not readily switch to the other; however, assuming all things are equal, intensive rotational grazing systems have a number of advantages over confined feeding operation. These include:

- Reduced cost. Pasture stocking systems are typically less expensive to invest in than livestock facilities and farm equipment required to harvest crops. Feeding costs may also be lowered.
- Improved cow health. Farmers practicing intensive rotational grazing typically have a lower cull rate than confined dairy farmers, because the cows have less hoof damage, and they are more closely observed as they are moved from one paddock to another (USDA, 1997).
- Less manure handling. Intensive rotational grazing operations have less recoverable solid manure to manage than confined operations. These include:
- Better rate of return. Research indicates that grazing systems are more economically flexible than the confinement systems. For example, farmers investing in a well-planned grazing operation will likely be able to recover most of their investment in assets if they leave farming in a few years. But farmers investing from scratch in a confinement operation would at best recover half their investments if they decide to leave farming (CIAS, 2000d).

There are a number of disadvantages associated with intensive rotational grazing compared with either conventional grazing or confined dairy operations. The major disadvantages are

- Limited applicability. Implementation of intensive rotational grazing systems depends upon available acreage, herd size, land resources (i.e., tillable versus steep or rocky), water availability, proximity of pasture area to milking center, and feed storage capabilities. Several sources indicate that this system is used by dairy farms with less than 100 cows. Typical confined dairy systems are often not designed to allow cows easy access to the available cropland or pastureland. Large distances between the milking center and pastureland will increase the cows expended energy and, therefore, increase forage demands.
- In most of the country, limited growing seasons prevent many operations from implementing a year-round intensive rotational grazing system. Southern states, such as Florida, can place cows on pasture 12 months of the year, but the extreme heat presents

other problems for cows exposed to the elements. Grazing operations in southern states typically install shade structures and increase water availability to cows, which in turn increases the costs and labor associated with intensive rotational grazing systems. Because most dairy operations cannot provide year-round grazing, they still must maintain barns and dry lot areas for their cows when they are not grazing, and dairy operations often prefer not to have to maintain two management systems.

- Reduced milk production levels. Studies indicate that dairy farmers using intensive rotational grazing have a lower milk production average than confined dairy farms (USDA NRCS, 1996). Lower milk production can offset the benefit of lower feed costs, especially if rations are not properly balanced once pasture becomes the primary feed source during warm months.
- Limited manure-handling options. Dairies using intensive rotational grazing systems may not be able to apply the wastewater and solid manure collected during the nongrazing seasons to their available pastureland as crops may not be growing.
- Increased likelihood of infectious diseases. Some infectious diseases are more likely to occur in pastured animals by direct or indirect transmission from wild animals or presence of an infective organism in pasture soil or water (Hutchinson, 1988).
- Limited flexibility. Intensive rotational grazing systems have limited flexibility for planning how many animals can be pastured in any one paddock. Available forage in a paddock can vary from one cycle to another because of weather and other conditions that affect forage growth rates. As a result, a paddock that was sized for a certain number of cows under adequate rainfall conditions will not be able to accommodate the same number of cows under drought conditions (USDA, 1997).

4.3.5 Dairy Waste Management Practices

Dairy waste management systems are generally designed based on the physical state of the waste being handled (e.g., solids, slurries, or liquids). Most dairies have both wet and dry waste management systems. Waste with 20 to 25 percent solids content can usually be handled as a solid while waste with less than 10 percent solids can be handled as a liquid (Loudon, 1985).

In a dry system, the manure is collected on a regular basis and stored where an appreciable amount of rainfall or runoff does not come in contact with it. Handling manure as a solid minimizes the volume of manure that is handled.

In a slurry or liquid system, manure is often diluted with water that typically comes from flushing system water, effluent from the solids separation system, or supernatant from lagoons. When dairy manure is handled and stored as a slurry or liquid, the milking center wastewater can be mixed in with the animal manure, serving as dilution water to ease pumping. If a gravity system is used to transfer manure to storage, milking center wastewater may be added at the collection point in the barn. Liquid systems are usually favored by large dairies for their lower labor cost and because the larger dairies tend to use automatic flushing systems.

4.3.5.1 Waste Collection

The collection methods for dairy manure vary depending on the management of the dairy operation. Dairy cows may be partially, totally, or seasonally confined. As previously mentioned, manure accumulates in confinement areas such as barns, dry lots, and milking parlors and in other areas where the herd is fed and watered. In wet climates, it is difficult to collect and store manure from unroofed areas as a solid, but it can be done if the manure is collected daily, stored in a roofed structure, and mixed with bedding. In arid climates, manure from unroofed areas can be handled as a solid if collection time can be flexible.

The following methods are used at dairy operations to collect waste:

- Mechanical/Tractor Scraper - Manure and bedding from barns and shade structures are collected normally by tractor or mechanical chain-pulled scrapers. Eighty-five percent of operations with more than 200 milking cows use a mechanical or tractor scraper (USDA APHIS 1996b). Tractor scraping is more common since the same equipment can be used to clean outside lots as well as freestalls and loose housing. A mechanical alley scraper consists of one or more blades that are wide enough to scrape the entire alley in one pass. The blades are pulled by a cable or chain drive that is set into a groove in the center of the alley. A timer can be set so that the scraper runs two to four times a day, or continuously in colder conditions to prevent the blade from freezing to the floor. Scrapers reduce daily labor requirements, but have a higher maintenance cost due to corrosion and deterioration.
- Flushing System - Manure can be collected from areas with concrete flooring by using a flushing system. A large volume of water is introduced at the head of a paved area, and the cascading water removes the manure. Flush water can be introduced from storage tanks or high-volume pumps. The required volume of flush water varies with the size of the area to be flushed and slope of the area. The total amount of flush water introduced can be minimized by recycling; however, only fresh water can be used to clean the milking parlor area. Flushing systems are predominantly used by large dairies with 200 or more head (approximately 27 percent) that tend to house the animals in a freestall-designed barn. These systems are much less common in dairies with fewer than 200 head (fewer than 5 percent reported using this system) (USDA APHIS, 1996b). These systems are also more common at dairies located in warmer climates.
- Gutter Cleaner/Gravity Gutters - Gutter cleaners or gravity gutters are frequently used in confined stall dairy barns. The gutters are usually 16 to 24 inches wide, 12 to 16 inches deep, and flat on the bottom. Either shuttle-stroke or chain and flight gutter cleaners are typically used to clean the gutters. About three-fourths (74 percent) of U.S. dairy operations with fewer than 100 milking cows and approximately one-third of U.S. dairy operations with 100 to 199 milking cows use a gutter cleaner (USDA APHIS, 1996b).
- Slotted Floor - Concrete slotted floors allow manure to be quickly removed from the animal environment with minimal labor cost. Manure falls through the slotted floor or is worked though by animal traffic. The waste is then stored in a pit beneath the floor or

removed with gravity flow channels, flushing systems, or mechanical scrapers. The storage of animal and milking center waste in a pit beneath slotted floors combines manure collection, transfer, and storage.

4.3.5.2 Transport

The method used to transport manure depends largely on the consistency of the manure. Liquids and slurries can be transferred through open channels, pipes, and in liquid tank wagons. Pumps can be used to transfer liquid and slurry wastes as needed; however, the greater the solids content of the manure, the more difficult it will be to pump.

Solid and semisolid manure can be transferred by mechanical conveyance or in solid manure spreaders. Slurries can be transferred in large pipes by using gravity, piston pumps, or air pressure. Gravity systems are preferred because of their low operating cost.

4.3.5.3 Storage, Treatment, and Disposal

Waste collected from the dairy operation is transported within the site to storage, treatment, and use or disposal areas. Typical storage areas for dairy waste include above and belowground storage tanks and storage ponds. Handling and storage methods used at dairy operations are discussed in detail in Section 8.2.

One common practice for the treatment of waste at dairies is solids separation. Mechanical or gravity solids separators are used to remove bulk solids from a liquid waste stream. This separation reduces the volume of solids entering a storage facility, which increases its storage capacity. Separation facilitates reuse of liquid in a flushing system which reduces clogging of irrigation sprinklers and waste volume going to treatment or land application sites. Manure slurry is often separated using mechanical separators, such as stationary screens, vibrating screens, presses, or centrifuges, all of which recover a relatively dry byproduct (Dougherty, 1998). Sedimentation by gravity settling is also used for solid/liquid separation.

Another common technology for the treatment of waste at dairies is an anaerobic lagoon. Anaerobic lagoons are biological treatment systems used to degrade animal wastes into stable end products. The advantage of anaerobic lagoons is their long storage times, which allow bacteria to break down solids. Disadvantages include odors produced during environmental or management changes, and sensitivity to sudden changes in temperature and loading rates. Anaerobic lagoons are designed to hold the following volumes: a minimum treatment volume (based on volatile solids loading), the volume of accumulated sludge for the period between sludge removal events, the volume of manure and wastewater accumulated during the treatment period, the depth of normal precipitation minus evaporation, the depth of the 25-year, 24-hour storm event, and an additional 1 foot of freeboard.

Typical manure and waste treatment technologies used at dairy operations are discussed in detail in Section 8.2.

The majority (approximately 99 percent) of small and large dairy operations (fewer than and more than 200 milking cows) dispose of their waste through land application (USDA APHIS, 1996b). The amount of cropland and pastureland that is available for manure application varies at each dairy operation. Generally, dairy operations can be categorized into three groups with respect to available cropland and pastureland: (1) those with sufficient land so that all manure can be applied without exceeding agronomic application rates, (2) those without sufficient land to apply all of their manure at agronomic rates, and (3) those without any available cropland and pastureland. Operations without sufficient land, or any land, often have agreements with other farmers allowing them to apply manure on their land. Depending on the size of the dairy operation, 1997 Census of Agriculture data indicate that the average age of cropland at dairies with at least 300 milking cows is approximately 350 acres, and the average age of pastureland is approximately 75 acres (Kellogg, 2000).

USDA conducted an analysis of the 1997 Census of Agriculture data to estimate the manure production at livestock farms (Kellogg, 2000). As part of this analysis, USDA estimated the number of confined livestock operations that produce more manure than they can apply on their available cropland and pastureland at agronomic rates for N and P, and the number of confined livestock operations that do not have any available cropland or pastureland. The analysis assumed land application of manure would occur on one of 24 typical crops or pastureland. Using the percentage of these facilities estimated by USDA against the total number of livestock facilities, one can also estimate the number of facilities that have sufficient cropland and pastureland for agronomic manure application. Table 4-80 summarizes the percentage of dairy operations that have sufficient, insufficient, and no land for manure application at agronomic application rates for N and P. EPA assumes that confined heifer operations have similar percentages.

Table 4-80. Percentage of Dairy Operations With Sufficient, Insufficient, and No Land for Agronomic Application of Generated Manure.

Size Class	Sufficient Land		Insufficient Land		No Land[a]
	Nitrogen Application	Phosphorus Application	Nitrogen Application	Phosphorus Application	
200–700 milking cows	50	25	36	61	14
> 700 milking cows	27	10	51	68	22

[a] No acres of cropland (24 crops) or pastureland.
Source: Kellogg, 2000.

4.4 Beef Industry

Beef feeding operations include facilities that confine beef cattle for feeding or maintenance for at least 45 days in any 12-month period. These facilities do not have significant vegetation on the beef feedlot during the normal growing season (i.e., the feedlot area does not include grazing operations). Facilities that have beef feedlot operations may also include other animal and agricultural operations not considered part of the feedlots, such as grazing and crop farming.

- This section discusses the following aspects of the beef industry:
- Section 4.4.1: Distribution of the beef industry by size of operation and region in 1997;
- Section 4.4.2: Beef production cycles
- Section 4.4.3: Beef feedlot facility management
- Section 4.4.4: Backgrounding operations
- Section 4.4.5: Veal operations
- Section 4.4.6: Cow-calf operations
- Section 4.4.7: Beef waste management practices

4.4.1 Distribution of the Beef Industry by Size and Region

EPA's current Effluent Limitations Guidelines and Standards apply to beef feedlot operations with 1,000 or more slaughter steers and heifers, where the animals are fed at the place of confinement and crop or forage growth or production is not sustained in the confinement area.

Information presented in this section comes from USDA NASS, 1997 Census of Agriculture data, and from site visits and trade associations. The 1994 to 1998 NASS reports on beef feedlots present annual estimates of beef operations that have a capacity of 1,000 head of cattle or more grouped in the following categories:

- Cattle inventory and calf crop
- Number of operations
- Inventory by class and size groups
- Monthly cattle on feed numbers
- Annual estimates of cattle on feed

NASS publishes only limited data for operations that have a capacity of fewer than 1,000 head of cattle (USDA NASS, 1999e). The 1997 Census of Agriculture collects information on cattle inventory and the number of cattle fattened for slaughter. NASS data on the number of beef feedlot facilites in each of EPA's size classes were limited; however, Census of Agriculture data provides the number of facilities by the number of head sold, or inventory. EPA used Census of Agriculture inventory data to estimate capacity. Then, EPA used these capacity data to estimate the percentage of total operations within each size class. These percentages were used with the NASS data to estimate total number of facilities in each size class. The capacity of a beef feedlot is the maximum number of cattle that can be held on site at any one time and can usually be determined by the amount of feedbunk space available for the cattle. On average, most beef feedlots operate at 80 to 85 percent of capacity over the course of a year, depending on market conditions (NCBA, 1999). In addition, most feedlots have cattle on site for 150 to 270 days (see Section 4.4.2); therefore, on average, the feedlot can run one and one half to two and one half turns of cattle each year. However, a feedlot may have anywhere from one to three and one half

turnovers of its herd per year. For example, some feedlots only have cattle on site during the winter months (one turnover) when crops cannot be grown, while other feedlots move cattle through the feedyard more quickly (three and one half turnovers).

EPA estimated the maximum capacity of beef feedlots reported in the 1997 Census of Agriculture using the reported sales of cattle combined with estimated turnovers and average feedlot capacity (ERG, 2000b).

Maximum Feedlot Capacity (Head) = Cattle Sales (Head) * Average Feedlot Capacity (%) / Turnovers

For example, a feedlot that sold 1,500 cattle in 1997 and is estimated to operate at 80 percent capacity with one and one half turnovers has an estimated maximum capacity of 800 head.

In 1997, there were approximately 2,075 beef feedlots with a capacity of more than 1,000 head in the United States. (USDA NASS, 1999e). These operations represent only about 2 percent of all beef feedlots. EPA estimates that there were approximately 1,000 additional beef feedlots with a capacity of between 500 and 1,000 head (another 1 percent of beef feedlots), 1,000 beef feedlots with a capacity of between 300 and 500 head, and another 102,000 beef feedlots with a capacity of fewer than 300 head. Table 4-81 shows the estimated distribution of these operations by size and region. Table 4-82 shows the estimated number of cattle sold during 1997 by size class. EPA derived these data from the 1997 Census of Agriculture data and NASS data (ERG, 2000b).

Table 4-83 presents the number of beef feedlots by top-producing states and nationally for the following eight size categories:

- up to 299 head
- 300 to 999 head
- 1,000 to 1,999 head
- 2,000 to 3,999 head
- 4,000 to 7,999 head
- 8,000 to 15,999 head
- 16,000 to 31,999 head
- 32,000 head and greater

The data in this table were obtained from NASS and were also derived from the 1997 Census of Agriculture data. Note that in some cases the feedlots from several size groups have been aggregated to avoid disclosing details on individual operations for some states.

As one would expect, the number of feedlots decreases as the capacity increases. For example, there are 842 feedlots in the 1,000 to 1,999 size category but only 93 in the greater than 32,000 size category. Of the 106,075 beef feedlots across all size groups in 1997, the Midwest Region has the most with 71,183 (67 percent). Nebraska and Iowa have the most large beef feedlots

(more than 1,000 head). Texas has the largest number of feedlots with a capacity of more than 32,000 head (41 percent).

Also included in the beef industry are veal operations, which are discussed in detail in Section 4.4.5. Veal operations are not specifically reported in the 1997 Census of Agriculture or NASS data. EPA conducted site visits to veal operations and requested distribution data from the industry to ultimately estimate the number of veal operations in the U.S., as shown in Table 4-84 (ERG, 2000b).

Table 4-81. Distribution of Beef Feedlots by Size and Region in 1997.

Region[a]	Feedlot Capacity					
	<300 Head	300–500 Head	500–1,000 Head	1,000–8,000 Head	>8000 Head	Total
Central	9,990	87	130	332	182	10,721
Mid-Atlantic	15,441	150	34	25	0	15,650
Midwest	68,235	685	810	1,236	217	71,183
Pacific	3,953	35	19	55	22	4,085
South	4,381	43	7	6	0	4,436
National	102,000[b]	1,000[b]	1,000	1,654	421	106,075

[a] Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL.
[b] Estimated value. Assumes 98 percent of feedlots with fewer than 1,000 head have a capacity of fewer than 300 head, and 99 percent of all feedlots with fewer than 1,000 head have a capacity of fewer than 500 head.

Table 4-82. Cattle Sold in 1997.

Size Class	Number of Facilities	Cattle Sold	Average Cattle Sold
<300 Head Capacity	102,000	2,362,000[a]	23
300–500 Head Capacity	1,000	600,000[b]	600
500–1,000 Head Capacity	1,000	1,088,000[b]	1,088
>1,000 Head Capacity	2,075	22,789,000	10,983
All Operations	106,075	26,839,000	253

[a] Estimated value. Value presented is the difference between total sales for all feedlots with fewer than 1,000-head capacity, and the estimated sales for feedlots with 300- to 1,000- head capacity.
[b] Estimated value. Calculated from using the midpoint of the size range (e.g., 400 head for the 300–500 size class) and an average turnover rate of one and one half herds a year.

Table 4-83. Number of Beef Feedlots by Size of Feedlot and State in 1997.[a]

Location	Feedlot Capacity							
	1–299 Head	300–999 Head	1,000–1,999 Head	2,000–3,999 Head	4,000–7,999 Head	8,000–15,999 Head	16,000–31,999 Head	32,000+ Head
Arizona	151	4	-	3[b]	-	-	3	3
California	885	25	4[b]	-	4	4	5	7
Colorado	1,374	70	54	46	32	23	11	8
Idaho	894	13	19	15	9	17[b]	-	-
Iowa	11,839	435	200	110[b]	-	-	-	-
Kansas	2,563	160	45	28	30	34	41	17
Nebraska	4,700	359	270	181	118	64	25	7
New Mexico	318	6	-	-	6[b]	-	4[b]	-
Oklahoma	1,840	21	3[b]	-	9	5	3	6
South Dakota	2,652	124	50	41	17	6[b]	-	-
Texas	3,556	49	8	13	28	25	35	38
Washington	1,166	8	7[b]	-	-	4	5[b]	-
Other States	70,062	726	191	85	36	8	5	-
United States	102,000	2,000	842	504	308	191	137	93

[a] The number of feedlots is the number of lots operating at any time during the year. The U.S. totals show the actual number of feedlots in each size group. The sum of the numbers shown by states under a specified size group may or may not add to the U.S. total for that size group because some states size groups are combined to avoid disclosing individual operations.
[b] Lots from other size groups are included to avoid disclosing individual operations.

Table 4-84. Distribution of Veal Operations by Size and Region in 1997.

Region[a]	Capacity		Total
	300–500 Calves	> 500 Calves	
Central	5	3	8
Mid-Atlantic	1	1	2
Midwest	119	81	200
Pacific	0	0	0
South	0	0	0
Total United States	125	85	210

[a] Central = ID, MT, WY, NV, UT, CO, AZ, NM, TX, OK; Mid-Atlantic = ME, NH, VT, NY, MA, RI, CT, NJ, PA, DE, MD, VA, WV, KY, TN, NC; Midwest = ND, SD, MN, MI, WI, OH, IN, IL, IA, MO, NE, KS; Pacific = WA, OR, CA, AK, HI; South = AR, LA, MS, AL, GA, SC, FL.

4.4.2 Beef Production Cycles

Beef feedlots conduct feeding operations in confined areas to increase beef weight gain, control feed rations, increase feeding efficiency, reduce feed costs, and manage animal health. Calves are often brought in from backgrounding operations to the feedlot (Section 4.4.4). Calves usually

begin the "finishing" phase when they reach 6 months of age or a weight of at least 400 pounds. Cattle are typically held on the feedlot for 150 to 180 days. As stated previously in this section, a beef feedlot may run anywhere from one to three and one half turnovers of its herd per year. The annual average steer weight at slaughter ranges from 1,150 to 1,250 pounds, while the annual average heifer weight at slaughter weight ranges from 1,050 to 1,150 pounds.

Some feedlots may bring in young calves at around 275 pounds and feed them on site for approximately 270 days. As a result, these feedlot operations have fewer turnovers of the herd per year. Based on site visits, this type of operation is typical at feedlots in southern California. Some operations may only bring in cattle during the winter months when no crops are being grown, also resulting in fewer turnovers of the herd per year. Other operations, the true "final finishing" operations, may bring cattle in at a heavier weight and require only approximately 100 days to feed cattle, resulting in more turnovers of the herd per year. These variations in turnovers often make it difficult to estimate farm counts if data only show cattle inventory.

4.4.3 Beef Feedlot Facility Management

This section describes factors that affect the facility management at a feedlot operation including the layout of feedlot systems, feeding and watering practices, water use and wastewater generation, and climate.

4.4.3.1 Feedlot Systems

Cattle traffic flow is an important factor in the design of a feedlot. These operations use separate vehicle and cattle traffic lanes when possible to minimize congestion, reduce the spread of parasites and disease, and promote drainage to make pen cleaning easier and to promote animal comfort and welfare. Outdoor feedlot systems comprise the following units which can be organized in various ways.

- Office - This is usually located on or near the main access road and has truck scales and facilities for sampling incoming feed. All bulk feed delivered to the lot enters at this point. Cattle trucks also use these scales for in and out weights (Thompson and O'Mary, 1983).
- Feed Mill - Truck traffic around the feed mill is typically heavy. A good design allows feed ingredients to be received while finished rations are trucked to the pens without traffic conflict. Feeding pens are often near the feed mill to reduce travel (Thompson and O'Mary, 1983).
- Pens - Pens are designed for efficient movement of cattle, optimum drainage conditions, and easy feed truck access. A typical pen holds 150 to 300 head but the size can vary substantially. Required pen space may range from 75 to 300 square feet of pen space per head, depending on climate (see Section 4.4.3.4). Space needs vary with the amount of paved space, soil type, drainage, annual rainfall, and freezing and thawing cycles.

- Large feedlots use cattle alleys behind the pens to keep the flow of cattle separate from the feed trucks. Smaller feedlots often use feeding alleys to move the cattle. The pens should allow for proper drainage of runoff to provide comfortable conditions. A grade of at least 3 percent is necessary to allow proper drainage in most areas (Thompson and O'Mary, 1983).
- Cattle Loading and Unloading Facilities - Feedlots locate these facilities to ensure the smooth flow of trucks to bring cattle in and out of the lot. Larger feedlots typically use two shipping areas, with the receiving area having hospital or separate processing facilities where cattle can receive various identification markers, vaccinations, and treatment for internal and external parasites, and are held until they are healthy enough to go to regular feeding pens (Thompson and O'Mary, 1983).
- Hospital Areas - These are facilities where cattle can be medically treated. Each facility normally has a squeeze chute, refrigerator, water, and medicine and equipment storage (Thompson and O'Mary, 1983). Approximately 10 percent of the cattle in a feedlot will be treated in hospital areas during the feeding period (NCBA, 1999).

The majority of beef feedlots are open feedlots, which are usually unpaved. These types of operations may use mounds in the pens to improve drainage and provide areas that dry quickly, because dry resting areas improve cattle comfort, health, and feed utilization. In open feedlots, protection from the weather is often limited to a windbreak near the fence in the winter and sunshade in the summer; however, treatment facilities for the cattle and the hospital area are usually covered. A concrete apron is typically located along feedbunks and around waterers, because these are heavy traffic areas (Bodman et al., 1987).

Open-front barns and lots with mechanical conveyors or fenceline bunks are common for feedlots of up to 1,000 head, especially in areas with severe winter weather and high rainfall. Confinement feeding barns with concrete floors are also sometimes used at feedlots in cold or high rainfall areas. These barns require less land and solve feedlot problems caused by drifting snow, severe wind, mud, lot runoff, and mound maintenance. Feeding is typically mechanical bunk feeding or fenceline bunks. Manure is usually scraped and piled in a containment area. If the barn has slotted floors, the manure is collected beneath slotted floors, and is scraped and stored or flushed to the end of the barn where it is pumped to a storage area for later application (Bodman et al., 1987).

4.4.3.2 Feeding and Watering Practices

At feedyards, all cattle are fed two or three times a day and are normally fed for 120 to 180 days, depending on their initial weight and type. Some operations may feed as long as 270 days if they receive young calves. Feedlots consider the following factors when determining feeding methods: the number of animals being fed; the type and size of grain and roughage storage; the equipment necessary to unload, meter, mix, and process feed; and the location and condition of existing feed storage (Bodman et al., 1987).

Beef feedlots use the following types of feeding methods:

- Fenceline feeding - Bunks are located along the side of a lot or pen. This method requires twice as much bunk length as bunks that feed from both sides, but the advantage is that feed trucks do not have to enter the pens with the cattle. Fenceline feedbunks have 6 to 14 inches of bunk space per head, and are typically used for feedlots with more than 100 head. Feedbunks are cleaned routinely to remove uneaten feed, manure, and other foreign objects.
- Mechanical bunk feeding - Bunks typically allow cattle to eat from both sides and are also used as pen dividers. This feeding method is common with continuous feed processing systems and small operations. Mechanical feedbunks are useful for feedlots of up to 500 head.
- Self-feeding - Feedlots use haystacks, feed from horizontal silos or plastic bags, and grain and mixed rations in bunks or self feeders with this feeding method. Portable silage and grain bunks are useful for up to 200 head (Bodman et al., 1987).

Twenty-four hour access to the water trough is required for the health of the animals and maximum production efficiency. Cattle water consumption varies, depending on such factors as animal size and season, and may range from 9 gallons per day per 1,000 pounds during winter to 18 gallons per day per 1,000 pounds during hot weather (Bodman et al., 1987). Typically, one watering space for each 200 head and a minimum of one watering location per pen of animals is provided (USDA NASS, 1999e). Some water may be required to add to the feed processing or to clean equipment.

4.4.3.3 Water Use and Wastewater Generation

The main source of wastewater to be managed is the runoff from rainfall events and snow melt. Surface runoff from rain and snow melt can transport manure, soil, nutrients, other chemicals (e.g., pesticides), and debris off the feedlot; therefore, it is important to divert clean water away from contact with manure, animals, feed processing and storage, and manure storage areas to reduce the total volume of contaminated wastewater. Runoff is affected by rainfall amount and intensity, feedlot maintenance practices, and soil type and slope. Runoff can be controlled by using diversions, sediment basins, and storage ponds or lagoons. Feedlots can also reduce the volume of runoff by limiting the size of confinement areas.

Typically, pens are constructed such that runoff is removed as quickly as possible, transported from the lot through a settling basin, and diverted into storage ponds designed to retain, at a minimum, the 24-hour, 25-year storm. Feedlots can reduce the runoff volume by preventing all runon water from entering clean areas and by diverting all roof runoff.

Only specially constructed barns use water to flush or transport manure. These barns are used by a very small percentage of the industry and typically at smaller feedlots.

4.4.3.4 Climate

Climate plays a large role in the design and operation of a feedlot. The metabolic requirement for maintenance of an animal typically increases during cold weather, reducing weight gain and increasing feed consumption to provide more net energy. Feed consumption typically declines under abnormally high temperatures, therefore reducing weight gain. Investigations in California have shown that the effects of climate-related stress could increase feed requirements as much as 33 percent (Thompson and O'Mary, 1983). As a result, waste (manure) generation would also increase.

In cold areas, feedlots typically provide a roof of some sort for the cattle. Sheltered cattle gain weight faster and more efficiently during winter than unsheltered cattle. Areas that receive substantial rainfall require mud control and paved feeding areas, since higher precipitation results in greater runoff volumes. In hot, semiarid areas, sun shades are typically provided for the cattle. A dry climate requires generally 75 square feet of pen space per head whereas a wet climate may require up to 400 square feet of pen space per head (Thompson and O'Mary, 1983). Feedlots typically use misting sprinklers or watering trucks to control dust problems in dry climates.

4.4.4 Backgrounding Operations

Backgrounding operations feed calves, after weaning and before they enter a feedlot using pasture and other forages. These operations allow calves to grow and develop bone and muscle without becoming fleshy or gaining fat covering. Weaned calves are typically sent to backgrounding operations to allow producers to:

- Develop replacement heifers.
- Retain rather than sell at weaning when prices are typically low.
- Use inexpensive home-grown feeds, crop residues, pasture, or a combination of these to put weight on calves economically.
- Put weight on small calves born late in the calving season before selling.
- Put minimal weight on calves during winter before grazing on pasture the following spring and summer.

Calves are normally kept at the operation from 30 to 60 days but can be kept up to 6 months (approximately 400 pounds) (Rasby et al., 1996). Typical diets consist of equal proportions of roughage and grains that produce a moderate gain of 2 to 2.5 pounds per day. Backgrounding operations typically keep calves on pasture during their entire stay; however, these operations may operate similarly to a beef feedlot, using pens to confine calves, and feedbunks to feed.

4.4.5 Veal Operations

Veal operations raise calves, usually obtained from dairy operations, for slaughter. Dairy cows must give birth to continue producing milk. Female dairy calves are raised to become dairy cows;

however, male dairy calves are of little or no value to the dairy operation. Therefore, these male dairy calves are typically sent to feedlots or veal operations. Calves are normally separated from the cows within 3 days after birth. Veal producers typically obtain calves through livestock auctions, although in some cases the calves may be taken directly from the dairy farm to the veal operation (Wilson et al., 2000).

The majority of veal calves are "special-fed" or raised on a low-fiber liquid diet until about 16 to 20 weeks of age, when they weigh about 450 pounds. Calves slated for "Bob" veal, which are marketed up to 3 weeks of age when they weigh about 150 pounds, constitute about 15 percent of the veal calves sold (USDA, 1998).

Calves are fed a milk-replacer diet composed of surplus dairy products including skim milk powder and whey powder. Their diet also includes plant- and animal-derived fats, proteins, and other supplements such as minerals and vitamins (Wilson et al., 2000). Calves spend their entire growing-out period on a liquid diet.

Veal calves are generally grouped by age in an environmentally controlled building. The majority of veal operations use individual stalls or pens. Floors are constructed of either wood slats or plastic-coated expanded metal, while the fronts and sides are typically wood slats. The slotted floors allow for efficient removal of waste. The back of the stall is usually open, and calves may be tethered to the front of the stall with fiber or metal tethers. Individual stalls allow regulation of air temperature and humidity through heating and ventilation, effective management and handling of waste, limited cross-contamination of pathogens between calves, individual observation and feeding, and, if necessary, examination and medical treatment (Wilson et al., 2000). The stalls provide enough room for the calves to stand, stretch, groom themselves, and lie down in a natural position.

Veal waste is very fluid, diluted by various volumes of wash water used to remove it from the building (see Section 6.4 for a discussion of veal manure characteristics). Therefore, manure is typically handled in a liquid waste management system. Manure, hair, and feed are regularly washed from under the stalls to reduce ammonia, odor, and flies in the room. Manure is typically washed out twice daily so that if the calf is having health problems, it is easily observed. Approximately 10 to 30 percent of the wastewater generated at a veal operation comes from scrubbing rooms and stalls after calves have been shipped to market.

The most common method for handling manure and wash water is using a sloping gutter under the rear of the stalls, allowing manure to continuously drain into a manure storage system. Tanks, pits, and lagoons are used to store manure until it is spread on fields. Storage pits may also be built directly under buildings; however, this produces higher levels of ammonia and other pit gases that require increased ventilation and higher fuel costs in the winter (Meyer, 1987).

4.4.6 Cow-Calf Operations

Cow-calf operations breed mature cows and yearling heifers with bulls to produce calves and can be located in conjunction with a feedlot, but they are more often stand-alone operations. A herd

of mature cows, some replacement heifers, and a few bulls are typically maintained at cow-calf operations on a year-round basis. Offspring calves remain with the cows until weaned and then may be held in different pastures to grow until they weigh between 650 to 750 pounds when they are sold to feedlots as yearlings. These operations may also sell their calves to backgrounding operations or dairy operations. Artificial insemination is not commonly used at cow-calf operations. Bulls are typically used for breeding and are placed with cows at the proper time to ensure spring calves.

The number of bulls required at a cow-calf operation depends on the number of cows and heifers, size and age of bulls, crossbreeding program, available pasture, and length of breeding season. One bull is typically provided for each set of 25 cows or heifers. Bulls are usually pastured away from the cows, and they may be penned separately from each other to prevent fighting (Bodman, 1987).

Outdoor calving requires clean, well-drained, and wind-protected pastures. Separate feed areas are provided for mature cows, first calf heifers, bulls, and calves (Loudon, 1985). In cold climates, a calving barn may be needed to reduce the risk of death. These barns typically include a loose housing observation area, individual pens, and a chute for holding and treating cows. Typically, a barn is provided for 5 percent to 10 percent of the cow herd in mild climates, and for 15 to 20 percent of the herd in more severe weather or during artificial insemination (Bodman, 1987).

4.4.7 Waste Management Practices

Waste from a beef feedlot may be handled as a solid or liquid; both management methods have advantages and disadvantages. Waste from a veal operation is handled as a liquid. Solid waste is typically found in calving pens and in open lots with good drainage. Semisolid waste has little bedding and no extra liquid is added. Waste treated as a solid has a reduced total volume and weight because it contains less water; therefore, its management may cost less and require less power.

Slurry waste has enough water added to form a mixture that can be handled by solids handling pumps. Liquid waste is usually less than 8 percent solids, and large quantities of runoff and precipitation are added to dilute it. Wastes treated as a liquid are easier to automate and require less daily attention; however, the large volumes of added water increase the volume of waste. As a result, the initial cost of the liquid-handling equipment is greater (USDA NRCS, 1992).

4.4.7.1 Waste Collection

Beef cattle are confined on unpaved, partially paved, or totally paved lots, and much of their manure is deposited around feedbunks and water troughs. Feedlots typically collect these wastes from the feedlot surface after shipping each pen of cattle (Sweeten, n.d.).

The following methods are used in the beef industry to collect waste:

- Scraping - This is the most common method of collecting solid and semisolid manure from both barns and open lots. Solids can be moved with a tractor scraper and front-end loader. A tractor scraper may be used in irregularly shaped alleys and open areas. Mechanical scrapers are typically used in the pit under barns with slotted floors and propelled using electrical drives attached by cables or chains. Tractors have fewer problems and work better on frozen manure; however, mechanical scrapers reduce labor requirements. Removing manure regularly reduces odor in enclosed areas. Scraping is common for medium and large feedlots (Loudon, 1985).
- Slotted Flooring - This term refers to slats and perforated or mesh flooring and is a method of rapidly removing manure from an animal's space. Most slats are reinforced concrete, but can be wood, plastic, or aluminum, and are designed to support the weight of the slats plus live load, which includes animals, humans, and mobile equipment. Manure drops between slats, which keeps the floor surface relatively clean. Wide slats (between 4 and 8 inches) are commonly used with 1.5 to 1.75 inches between slats (Loudon, 1985).

Flushing System - This type of system dilutes manure from beef feedlots with water to allow for automated handling. Diluting the manure increases its volume and therefore requires a larger capital investment for equipment and storage facilities. The system uses a large volume of water to flush manure down a sloped gutter to storage, where the liquid waste can be transferred to a storage lagoon or basin. The amount of water typically used for cleaning is 100 gallons per head at least twice a day. Grade is critical for the flush alleys as is amount of water used (Loudon, 1985). This system is not very common for large feedlots; however, this type of system is widely used at veal operations.

Waste collection is easiest on paved lots. On unpaved lots, cattle traffic tends to form a seal on the soil that reduces the downward movement of contaminated water; however, deep scraping can destroy the interface layer that forms between the manure and the soil and acts as a seal to decrease the chance of pollutants from entering the ground water.

To reduce the production of unnecessary waste, clean water can be diverted away from the feedlot area. For example, uncontaminated water can be directed away from the waste and carried outside of the feedlot area. Roof runoff can be managed using gutters, downspouts, and underground outlets that discharge outside the feedlot area. Unroofed confinement areas can include a system for collecting and confining contaminated runoff. Paved lots will generally have more runoff per square foot than unpaved lots, but due to a smaller total area, they will have less total runoff per animal.

4.4.7.2 Transport

Waste collected from the feedlot may be transported within the site to storage, treatment, and use or disposal areas. Solids and semisolids are typically transported using mechanical conveyance equipment, pushing the waste down alleys, and transporting the waste in solid manure spreaders. Flail-type spreaders, dump trucks, or earth movers may also be used to transport these wastes. Liquids and slurries, typically found at veal operations, are transferred through open channels,

pipes, or in a portable liquid tank. These wastes can be handled by relying on gravity or pumps as needed.

4.4.7.3 Storage, Treatment, and Disposal

Beef feedlot operations typically use a settling basin to remove bulk solids from the liquid waste stream, reducing the volume of solids before the stream enters a storage pond, thereby increasing storage capacity. A storage pond is typically designed to hold the volume of manure and wastewater accumulated during the storage period, the depth of normal precipitation minus evaporation, the depth of the 25-year, 24-hour storm event, and an additional 1 foot of freeboard. Solid manure storage can also range from simply constructed mounds to manure sheds that are designed to prevent runoff and leaching.

Beef feedlot operations may also use other types of technologies, such as composting or mechanical solids separation, when managing animal waste and runoff. Typical manure and waste handling, storage, and treatment technologies used at beef feedlots are discussed in detail in Section 8.2. The majority (approximately 83 percent) of beef feedlots dispose of their waste through land application (USDA APHIS, 2000a).

Veal operations typically use an underground storage pit or a lagoon for waste storage and treatment. Veal operations also typically dispose of their waste through land application.

The amount of cropland and pastureland that is available for manure application varies at each beef operation. Generally, operations in the beef industry can be categorized into three groups with respect to available cropland and pastureland: (1) those with sufficient land so that all manure can be applied without exceeding agronomic application rates, (2) those without sufficient land to apply all of their manure at agronomic rates, and (3) those without any available cropland and pastureland. Operations without sufficient land, or any land, often have agreements with other farmers allowing them to apply manure on their land. Depending on the size of the beef operation, 1997 Census of Agriculture data indicate that the average acreage of cropland at beef feedlots with at least 500 head is between 550 to 850 acres and the average acreage of pastureland is between 50 and 110 acres (Kellogg, 2000).

USDA conducted an analysis of the 1997 Census of Agriculture data to estimate the manure production at livestock farms. As part of this analysis, USDA estimated the number of confined livestock operations that produce more manure than they can apply on their available cropland and pastureland at agronomic rates for N and P and the number of confined livestock operations that do not have any available cropland or pastureland. The analysis assumed land application of manure would occur on 1 of 24 typical crop or pasturelands (Kellogg, 2000). Using the percentage of these facilities estimated by USDA against the total number of livestock facilities, one can also estimate the number of facilities that have sufficient cropland and pastureland for agronomic manure application. Table 4-85 summarizes the percentage of beef feedlots that have sufficient, insufficient, and no land for manure application at agronomic application rates for N and P. EPA assumes that all veal operations have sufficient land to apply their manure.

Table 4-85. Percentage of Beef Feedlots With Sufficient, Insufficient, and No Land for Agronomic Application of Manure.

Size Class	Sufficient Land		Insufficient Land		No Land[a]
	Nitrogen Application	Phosphorus Application	Nitrogen Application	Phosphorus Application	
300–1,000 head	84	62	9	31	7
1,000– 8,000 head	6	22	21	67	11
> 8,000 head	8	1	53	6	39

[a] No acreage of cropland (24 crops) or pastureland.
Source: Kellogg, 2000.

4.5 Horses

Today's horse industry is quite diverse, providing animals for pleasure, showing, breeding, racing, farm/ranch, and other uses. Because the horse industry is so diverse and much of the population is off farm, statistics on horse population sizes, distributions, and trends are much less available than they are for other agricultural livestock.

4.5.1 Distribution of the Horse Industry by Size and Region

In 1900, the Census of Agriculture indicated that 79 percent of all farms had horses, whereas by 1992 this percentage had dropped to 18 percent. Specifically, the 1992 Census of Agriculture reported 338,346 farms with 2,049,522 horses. The USDA estimates that up to 3 million of the approximately 5 million horses in the United States are raised off farms or on farms with too few animals to be reported in the Census data (USDA APHIS, 1996d). However, a study of equids (domestic horses, miniature horses, ponies, mules, donkeys, and burros) was recently completed for 28 states representing more than three-fourths of the U.S. horse and pony inventory on farms (USDA APHIS, 1998a). In addition, 133 race tracks participated in portions of this survey. Participation from and accounting for race tracks is important since some facilities are very large. The Lone Star Park at Grand Prairie, Texas, located near Dallas/Fort Worth, has accommodations for up to 1,250 horses. It is also believed that since mules, donkeys, and burros represented only 4.7 percent of the animals surveyed, this survey is useful for characterizing the horse sector.

For the surveyed states, 40.1 percent of the equids are located in Texas, Oklahoma, Louisiana, Maryland, Virginia, Kentucky, Tennessee, Alabama, Georgia, and Florida; 13.0 percent are located in Ohio, Pennsylvania, New Jersey, and New York; 20.7 percent are located in Kansas, Missouri, Illinois, Indiana, Michigan, Wisconsin, and Minnesota; and 26.2 percent are located in Montana, Wyoming, Colorado, New Mexico, Washington, Oregon, and California. More than 95 (96.3) percent of the operations have from 1 to 19 equids on the operation, representing 73 percent of all equids. Less than 4 (3.7) percent of operations have 20 or more equids, representing 27 percent of all equids. Overall, boarding/training and breeding operations account for 3.7 and 5.2 percent of the operations respectively, yet account for more than 10 percent of the equids. Race tracks account for 53.4 percent of the operations with 20 or more equids, followed

by boarding/training facilities (26.7 percent), breeding (22.7 percent), and farm/ranch (2.1 percent) (USDA APHIS, 1998a).

Farm or ranch use of equids represents 15.2 percent of all operations. Breeding as a primary use of equids represented 6.0 percent of operations. The categories of racing and showing/competition represented a total of 8.4 percent of all operations (USDA APHIS, 1998a).

According to the data presented in Table 4-86, pleasure was the primary use of equids on the largest percentage of operations regardless of region (66.8 percent). Larger percentages of operations in the Western and Southern Regions used equids primarily for farm/ranch work (20.6 and 18.4 percent, respectively) than in the Central (8.9 percent) and Northeast (5.7 percent) Regions. Outfitting, carriage horses, and teaching horses are examples of uses included in the other category. As shown in Tables 4-87 and 4-88, race tracks represent the primary use (more than 90 percent) at operations with 500 or more horses.

Table 4-86. Percent of Operations by Primary Use of Equids Present on January 1, 1998, and Region.

Primary Use of Equids	Southern	Northeast	Western	Central	All Operations
Pleasure	63.2	66.9	65.5	74.7	66.8
Showing/competition (not betting)	6.8	9.0	5.2	6.0	6.5
Breeding	6.3	6.3	3.5	7.9	6.0
Racing	2.7	2.9	1.0	0.9	1.9
Farm/ranch	18.4	5.7	20.6	8.9	15.2
Other	2.6	9.2	4.2	1.6	3.6
Total	100.0	100.0	100.0	100.0	100.0

Source: USDA APHIS, 1998a
Southern: Alabama, Florida, Georgia, Kentucky, Louisiana, Maryland, Oklahoma, Tennessee, Texas, and Virginia.
Northeast: New Jersey, New York, Ohio, and Pennsylvania.
Western: California, Colorado, Montana, New Mexico, Oregon, Washington, and Wyoming.
Central: Illinois, Indiana, Kansas, Michigan, Minnesota, Missouri, and Wisconsin.

Table 4-87. Percent of Operations by Primary Use of Equids Present on January 1, 1998, and Size Class.

Primary Use of Equids	<150 (n=2821)	150 - 499 (n=62)	500+ (n=21)
Pleasure	66.8	9.0	0.0
Showing/competition (not betting)	6.5	4.0	7.3
Breeding	6.0	53.3	0.0
Racing	1.9	13.5	92.7
Farm/ranch	15.2	16.6	0.0
Other	3.6	3.6	0.0
Total	100.0	100.0	100.0

Source: USDA APHIS, 2002b

Table 4-88. Percent of Operations by Primary Use of Equids Present on January 1, 1998, and Size Class.

Primary Function of Operation	<150 (n=2821)	150 - 499 (n=62)	500+ (n=21)
Boarding/training	3.7	17.6	7.3
Racetrack	0.0	6.7	92.7
Breeding farm	5.1	53.6	0.0
Farm/ranch	32.7	17.0	0.0
Residence with equids for personal use	54.7	0.0	0.0
Other	3.8	5.1	0.0
Total	100	100	100

Source: USDA AHPIS, 2002.

4.5.2 Waste Management Practices

Nationally, stalls are provided on two-thirds of operations (does not include race tracks). New England states provide stalls on 94.5 percent of their operations, while about one-half of operations in the western United States provide stalls. For those operations that do provide stalls, 71.3 percent had at least one stall per equid. About one-third (34.5 percent) of those operations with stalls clean them at least once a day, while 50.2 percent clean stalls once a week or less often. Straw, hay, wood shavings, chips, or sawdust are the most common type of bedding. Less than 40 (36.4) percent of operations indicate that they usually or sometimes compost manure or waste bedding on site. For those operations with more than 20 equids, the most common method of disposal was to apply the waste to fields where no animals graze (30.7 percent), followed by applying it to fields where livestock graze (29.7 percent), allowing manure/waste bedding to accumulate or leaving it to nature (15.1 percent), selling it or giving it away (11.5 percent), and hauling it away to someplace other than a landfill (8.9 percent) (USDA APHIS, 1998b).

Horse manure is usually handled as a solid. Many operations collect manure from stalls and paddocks regularly. This is usually done with a fork or shovel and a wheelbarrow, tractor-loader, or trailer. Daily maintenance of horses in a confined setting requires intense labor requirements to maintain sanitary conditions for the housed animals. Once manure and dirty bedding have been removed, wet areas might be treated with lime to maintain safe, clean, and odor-free conditions (Wheeler and Cirelli, 1995). Fresh bedding, typically composed of such materials as pine sawdust, peanut shells, peatmoss, rice hulls, and other absorbent materials, is added following removal of manure and soiled bedding to ensure clean, dry conditions. Simply adding fresh bedding and allowing manure and soiled bedding to accumulate in the horse stall results in dirty animals, provides excellent fly-breeding conditions, and may be unhealthy to horses (Graves, 1987). Depending on conditions, the runoff from paddocks, pens, corrals, and outdoor areas might need to be diverted to a settling basin or filter strip.

Manure management in pastures depends primarily on good distribution of manure across the pasture. Rotational grazing is a good option to avoid manure concentration in isolated spots in a

pasture. Additionally, avoiding grazing during rainy periods when soils are saturated is important to avoid soil compaction and manure runoff. Restricted access to streams avoids manure deposition in or near water bodies. Also, damaging the grass stand increases the potential for manure runoff from pastures. The risk of this can be reduced by refraining from excessive stocking rates that lead to overgrazing (Colorado State University, 1996).

4.5.2.1 Waste Storage

Manure is typically stockpiled prior to use, providing greater flexibility for land application. The Government of British Columbia (1998) recommends not to stockpile manure directly on the ground for long-term storage where there is high rainfall or water tables. The size of any storage facility would depend on the number of animals housed. A facility 12 feet wide by 12 feet long by 6 feet high can hold a year's worth of manure for a 1,000-pound animal (USDA, 1997).

For horse operations that employ confined operations, an on-site storage facility is considered the most efficient way to collect and contain manure. Manure storage facilities should receive as much attention and planning as any other aspect of a horse operation (B.C. Government, 1998). Storage facilities are permanent structures designed and operated to contain all manure until it can be applied as a fertilizer or removed for use elsewhere. Basic siting and sizing considerations of storage facilities from the B.C. Government (1998) include the following:

- Located at least 15 meters (50 feet) away from any watercourse and at least 30 meters (100 feet) away from wells or domestic water sources.
- Located so that clean surface runoff from adjacent areas is excluded.
- Sized to provide enough storage to prevent having to spread manure during the fall and winter or at any time runoff is likely to occur.
- Of watertight construction.
- Structurally sound (with possible consideration of professionally engineered designs for both earthen and concrete structures).
- Sized and located to contain all of the runoff expected from local climatic conditions, using figures from the worst precipitation in 25 years.
- Adequately fenced to prevent the accidental entry of humans, animals, or machinery.
- Located out of sight and downwind from public places and neighboring residences (where possible).
- Covered in areas of the province receiving more than 600 millimeters (24 inches) of rainfall between October and April.

4.5.2.2 Waste Treatment and Disposal

For smaller operations, composting is commonly used to treat horse manure. Composting produces a relatively dry end-product that is easily handled and reduces the volume of the manure (40 to 65 percent less volume and weight than the raw material). Ideal conditions for composting include a carbon-to-nitrogen (C:N) ratio between 25:1 and 30:1, a moisture content between 40 and 60 percent, and good aeration. Horse manure as excreted has a C:N ratio of 19:1. With the addition of bedding, the C:N ratio usually increases to a level ideal for composting. Under normal composting conditions, the internal temperature will increase to between 135 °F and 160 °F, killing most pathogens, parasites, and weed seed. Properly constructed and maintained compost piles or windrows will finish composting in as few as 90 days, though the average time is approximately 120 days. When the composting process is complete, the temperature cools naturally.

Compost can be reused on horse pastures. However, experience has shown in the absence of careful management, this practice can spread internal parasites. Composted manure/bedding can also be used as a surface for riding areas when mixed with sand and wood products. Shavings-based stall waste can often be used by nurseries and do not require a complete composting process. Table 4-89 shows the average rates of horse manure application for forages and should follow normal practices for minimizing runoff and leaching that are applicable for all manures.

Table 4-89. Average Manure Application Rates and Area Requirements for Forages.

Forage	Yield (tons/acre)	Horse Manure (tons/acre)	Land Base Needed (acres/horse/yr)
Alfalfa	4	30	0.3
Alfalfa-Grass	4	20	0.4
Bentgrass	2	21	0.4
Big Bluestem	3	10	0.9
Birdsfoot Trefoil	3	25	0.4
Bluegrass	2	19	0.5
Bromegrass	3	19	0.5
Little Bluestem	3	11	0.8
Orchard Grass	4	20	0.5
Red Clover	3	20	0.4
Reed Canary Grass	4	18	0.8
RyeGrass	4	22	0.3
Switchgrass	3	12	0.8

Source: Colorado State University, 1996.

4.6 References

Abt. 1998. *Preliminary study of the livestock and poultry industry: Appendices*. Abt Associates Inc., Cambridge, Massachusetts.

Adams, R. S., 1995. *Dairy reference manual*. 3rd ed. Northeast Regional Agricultural Engineering Service Cooperative Extension

AAFC. (Agriculture and Agri-Food Canada), 1999. *Farming for tomorrow: Conservation facts. Rotational grazing: The rest and recovery method of pasture management.* <http://aceis.agr.ca/pfra/land/fft10.htm>. Accessed February 2000.

Aust, P. 1997. *An institutional analysis of vertical coordination versus vertical integration: The case of the US broiler industry*. Michigan State University, Department of Agricultural Economics, East Lansing, Michigan.

B.C. Government. 1998. *Manure Management* Chapter 8, Horse Owner. Ministry of Agriculture and Food, Planning for Agriculture. British Columbia Government, Victoria, BC, Canada.

Bickert, W.G., G.R. Bodman, B.J. Holmes, D.W. Kammel, J.M. Zulovich, and R. Stowell. 1997. *Dairy freestall housing and equipment*. 6th ed. Midwest Plan Service, Agricultural and Biosystems Engineering Department

Bocher, L. W. 2000. *Custom heifer grower, specialize in providing replacements for dairy herds*, Hoard's Dairyman

Bodman, G.R., D.W. Johnson, D.G. Jedele, V.M. Meyer, J.P. Murphy, and H.L. Person. 1987. *Beef housing and equipment handbook*. 4th ed. Midwest Plan Service.

Bradley, F., D. Bell, R. Ernst, D. McMartin, and J. Milliam. 1998. *Animal care series: Egg-type layer flock care practices*. California Poultry Workgroup, University of California Cooperative Extension, University of California Publishing, Davis, California.

British Columbia Government. 1998. *Manure Management*. Chapter 8, Horse Owner. Ministry of Agriculture and Food, Planning for Agriculture. British Columbia Government.

Brodie, H.L. Carr, and C. Miller. 2000. *Structures for broiler litter manure storage.* <http://www.hermes.ecn.purdue.edu/cgi/convertwq?5343>. Accessed November 2000.

Cady, Roger. Personal communication, Monsanto Company and Founder of the Professional Dairy Heifer Growers Association. Personal communication, February 18, 2000.

CIAS. 2000a. *Grazing's potential: Predicting expansion's cost, profit*. Center for Integrated Agricultural Systems, <http://www.wisc.edu/cias/pubs/resbrief/030.html>. Accessed May 2000.

CIAS. 2000b. *Outwintering dairy cattle: Animal health issues*. Center for Integrated Agricultural Systems, <http://www.wisc.edu/cias/pubs/resbrief/027.html>. Accessed May 2000.

CIAS. 2000c. *Outwintering dairy cattle: Manure management issues*. Center for Integrated Agricultural Systems, <http://www.wisc.edu/cias/pubs/resbrief/028.html>, Accessed May 2000.

CIAS. 2000d. *Dairy grazing can provide good financial return*. Center for Integrated Agricultural Systems, <http://www.wisc.edu/cias/pubs/resbrief/050.html>. Accessed May 2000.

Colorado State University. 1996. *Management of Horse Manure: A Renewable Resource*. Colorado State University Cooperative Extension, Fort Collins, CO. December 1996.

Dougherty, M., L.D. Geohring, and P. Wright. 1998. *Liquid manure application systems,* Northeast Regional Agricultural Engineering Service, NRAES-89.

Emmicx, D.L. 2000. *ABC's of rotational grazing: Questions and answers*. <http://www.kingcd.org/stewardship/Ag%20Pr...ces/Pastures/ABCsofRotationalGrazing.html>. Accessed February, 2000.

ERG. 2000a. Stand alone dairy heifer raising operations. Memorandum from Birute Vanatta, Eastern Research Group, Inc. to Ron Jordan, U.S. Environmental Protection Agency.

ERG. 2000b. Facility counts for beef, dairy, veal, and heifer operations. Memorandum from Deb Bartram, Eastern Research Group, Inc., to the Feedlots Rulemaking Record.

Faust, M.A. 2000. *Dairy replacement heifer enterprises*. <Web address>. Accessed February 14, 2000.

Gardner, Don. South East District Director for the Professional Dairy Heifer Growers Association. Personal communication, December 9, 1999.

Goan, C. 2000. *Storage facilities for broiler litter*. <http://hermes.ecn.purdue.edu/cgi/convertwq?7146>. Accessed November 20, 2000.

Graves, R.E. 1987. *Animal Manure – Manure Management for Horses*. PENpages Number: 0870177. Pennsylvania State University Agricultural Engineering Department.

Hamm, D., G. Searcy, and A. Mercuri. 1974. A study of the waste wash water from egg washing machines. *Poultry Science* 53:191-197.

Hannawald, Jim. U.S. Department of Agriculture. Personal communication, April 4, 2000.

Hansen, D. 2000. State regulatory issues and implications: Eastern USA, in *Proceedings: 2000 National Poultry Waste Management Symposium*, Ocean City, Maryland.

Hutchinson, L.J. 1988. Animal health, pest management and environment. In *Proceedings of Pasture in the Northeast Region of the United States*. U.S. Department of Agriculture, Soil Conservation Service, Northeast National Technical Center, Chester, Pennsylvania.

Jordan, Larry. South East Regional Director for the Professional Dairy Heifer Growers Association. Personal communication, December 8, 1999.

Kellog, R. 2002. Profile of Farms with Livestock in the United States: A Statistical Summary; R. Kellogg; Feb 4, 2002; 31 pages.

Kellogg, R.L., C. Lander, D. Moffitt, and N. Gollehon. *Manure nutrients relative to the capacity of cropland and pastureland to assimilate nutrients: Spatial and temporal trends for the U.S.* April 27, 2000.

Loudon, T.L., D.D. Jones, J.B. Petersen, L.F. Backer, M.F. Brugger, J.C. Converse, C.D. Fulhage, J.A. Lindley, S.W. Nelvin, H.L. Person, D.D. Schulte, and R. White. 1985. *Livestock waste facilities handbook.* 2nd ed. Midwest Plan Service.

Maple Leaf Farms. 2001. Facility Distribution data gathered by Maple Leaf Farms; prepared by Dan Harper; June 29, 2001.

Martinez, S.W. 1999. *Vertical coordination in the pork and broiler industries: Implications for pork and chicken products.* Agriculture Economic Report No. 777. U.S. Department of Agriculture, Economic Research Service, Food and Rural Economics Division, Washington, DC.

Meyer, D. J. 1987. *Animal manure–Veal calf management.* <http://www.inform.umd.edu: 8080/EdRes/topic/ AgrEnv/ndd/watermgt/ANIMAL_MANURE_VEAL_CALF_MANAGEM.html>.

Moats, W.A. 1978. Factors Affecting Bacterial Loads on Shells of Commercially Washed Eggs. *Poultry Science* 60:2084-2090.

Murphy, B. 1988. Voisin grazing management in the Northeast. In *Proceedings of Pasture in the Northeast Region of the United States*. U.S. Department of Agriculture, Soil Conservation Service, Northeast National Technical Center, Chester, Pennsylvania.

NCBA. 1999. *Comments on the draft industry profile.* National Cattlemen's Beef Association.

NCC. 1999. Comments on EPA profile of broiler industry. National Chicken Council, Washington, DC.

National Milk Producers Federation submittal to U.S. Environmental Protection Agency on 3/1/99: State Level Milk Production.

NCSU. 1998a. *Draft of swine and poultry industry characterization, waste management practices and modeled detailed analysis of predominantly used systems*. North Carolina State University.

NCSU. 1998b. Nutritional strategies to reduce swine and poultry waste quantity and N and P in waste. North Carolina State University.

Noyes, T.E. 1999. *Heifer raising conference*. December 3, 1999. <http://www.ag.ohio-state.edu/~wayn/dairy/darnews.htm> Assessed.December 3, 1999.

NPPC. 1996. *Swine care handbook.* (National Pork Producers Council), <http://nppc.org/prod/swinecarehandbook.html>. Accessed August 17, 1999.

NPPC. 1998. *Environmental assurance program survey.*

NPPC. 1999. *Pork facts 1998/99.* (National Pork Producers Council), <http://nppc.org/prod/swinecarehandbook.html>. Accessed August 15, 1999.

NRC. 1989. *Nutrient requirements of dairy cattle*, 6th rev. ed. National Research Council.

PPRC. 1996. *Impacts of intensive rotational grazing on stream ecology and water quality.* Pacific Northwest Pollution Prevention Resource Center, <http://www.pprc.org/pprc/rpd/fedfund/usda/sare_nc/impactsi.html>. Accessed February, 2000.

PADER. 1986. *Swine manure management*. Pennsylvania Department of Environmental Resources, Harrisburg, Pennsylvania.

Rasby, R., I. Rush, and R. Stock. 1996. *Wintering and backgrounding beef calves*. <http://www.ianr.unl.edu/PUBS/BEEF/g1228.htm>.

Scott, M.L. and W.F. Dean. 1991. *Nutrition and Management of Ducks*. M.L. Scott of Ithaca, Ithaca, NY.

Stull, C.E., S. Berry, and E. DePeters. 1998. *Animal care series: Dairy care practices*. 2nd ed. Dairy Workgroup, University of California Cooperative Extension.

Sweeten, J. n.d. *Manure management for cattle feedlots*. Great Plains Beef Cattle Handbook. Cooperative Extension Service - Great Plains States.

Thompson, G.B. and C.C. O'Mary. 1983. *The feedlot*. 3rd ed. Lea & Febiger, Philadelphia, Pennsylvania.

Thorne, J. 1999. Proposed EPA Project XL: United egg producers. Capitolink LLC, Washington, DC.

Tyson, T. 1996. Planning and managing lagoons for poultry layer waste treatment. Alabama Cooperative Extension Service, Auburn, Alabama.

UCD. 1998. *Egg type- Layer flock care practices*. California Poultry Workgroup, University of California at Davis, Davis, California.

UEP. 1998. UEP (Egg Producers) Data Package. United Egg Producers. Submitted to USEPA.

USDA. (U.S. Department of Agriculture), *Safety of veal, from Farm to table.* <http://www.fsis.usda.gov/oa/pubs/veal/htm>. Accessed April 14, 1999.

USDA. 1997. *Horses: A Common Sense Approach*. U.S. Department of Agriculture. Spring. 1997.

USDA. 1997. Chapter 5: Management of grazing lands. In *National range and pasture handbook*. U.S. Department of Agriculture.

USDA APHIS. 1993. *National Dairy Heifer Evaluation Project, Contract heifer raising*. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado.

USDA APHIS. 1995. *Swine '95 Part 1: Reference of 1995 swine management practices*. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado.

USDA APHIS. 1996a. *National Animal Health Monitoring System, Part I: Reference of 1996 dairy management practices*. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado.

USDA APHIS. 1996b. *National Animal Health Monitoring System, Part III: Reference of 1996 dairy health and health management*. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado.

USDA APHIS. 1996c. *Swine '95 Part II: Reference of 1995 grower/finisher health and management*. U.S. Department of Agriculture, Animal and Plant Health Inspection Service. Fort Collins, Colorado.

USDA APHIS. 1996d. *The USDA's Role in Equine Health Monitoring.* <http://www.aphis.usda.gov/vs/ceah/cahm/>. U.S. Department of Agriculture, Animal and Plant Health Inspection Service.

USDA APHIS. 1998a. *National Animal Health Monitoring System, Part I: Baseline Reference of 1998 Equine Health and Management.* <http://www.aphis.usda.gov/vs/ceah/cahm/>. File eq98pt1.pdf accessed October 15, 1998. U.S. Department of Agriculture, Animal and Plant Health Inspection Service.

USDA APHIS. 1998b. *National Animal Health Monitoring System, Part II: Baseline Reference of 1998 Equine Health and Management.* <http://www.aphis.usda.gov/vs/ceah/cahm/>. File eq98pt2.pdf accessed October 15, 1998. U.S. Department of Agriculture, Animal and Plant Health Inspection Service.

USDA APHIS. 1999. *Swine '95 Reference of 1995 swine management practices*. Additional data queries run at the request of EPA for new region and size categories. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado.

USDA APHIS. 2000a. *National Animal Health Monitoring System, Part I: Baseline reference of feedlot management practices*. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado.

USDA APHIS. 2000b. *Part II: Reference of 1999 table egg layer management in the United States (Layer '99)*. U.S. Department of Agriculture, Animal Plant Health Inspection Service, Fort Collins, Colorado.

USDA APHIS. 2001. Part I: Reference of Swine Health and Management in the United States, 2000, United State Department of Agriculture National Animal Health Monitoring System, Fort Collins, Colorado.

USDA APHIS. 2002a. Queries run by Centers for Epidemiology and Animal Health prepared by Eric Bush; March 22, 2002; 2 pages. Centers for Epidemiology and Animal Health. U.S. Department of Agriculture (USDA), Animal Plant Health Inspection Service (APHIS), National Animal Health Monitoring System, Fort Collins, Colorado.

USDA AHPIS. 2002b. *Data aggregated from Equine ''98 data* by Michael Durham, Centers for Epidemiology and Animal Health. U.S. Department of Agriculture (USDA), Animal Plant Health Inspection Service (APHIS), National Animal Health Monitoring System, Fort Collins, Colorado.

USDA BAMN. 1997. *A guide to dairy calf feeding and management.* U.S. Department of Agriculture (USDA), Bovine Alliance on Management & Nutrition (BAMN) <http://www.aphis.usda.gov/vs/ceah/cahm/ File bamnfeed.htm>. Accessed

USDA ERS. 1997. *The U.S. Pork industry: As it changes, consumers stand to benefits* U.S. Department of Agriculture, Economic Research Service, Washington, DC.

USDA NAHMS. 1999. *Data aggregated from Swine '95 data*, U.S. Department of Agriculture, Animal Plant Health Inspection Service, National Animal Health Monitoring System, Centers for Epidemiology and Animal Health. Fort Collins, Colorado.

USDA NAHMS. 2000. *Data Aggregated from Layer 99 data* by Lindsey Garber, U.S. Department of Agriculture, Animal Plant Health Inspection Service, National Animal Health Monitoring System (NAHMS). Centers for Epidemiology and Animal Health. Fort Collins, Colorado.

USDA NASS. 1995a. *Milk: Final estimates 1988-1992*. Statistical Bulletin 909. U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Washington, DC.

USDA NASS. 1998a. *Agricultural statistics*. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

USDA NASS. 1998b. *Chickens and eggs final estimates 1994-97*. Statistical Bulletin No. 944. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

USDA NASS. 1998c. *Poultry production and value, final estimates 1994-97*. Statistical Bulletin No. 958. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

USDA NASS. 1999a. *Hogs and Pigs: Final estimates* 1993-1997. Statistical Bulletin Number 951. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

USDA NASS. 1999b. *1997 census of agriculture*. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

USDA NASS. 1999c. Queries run by NASS for USEPA on the 1997 Census of Agriculture data. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

USDA NASS. 1999d. *Milking cows and production: Final estimates 1993-1997*. Statistical Bulletin 952. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

USDA NASS. 1999e. *Cattle: Final estimates 1994-1998*. Statistical Bulletin 953. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

USDA NRCS. 1992. *Agricultural waste management field handbook, National engineering handbook (NEH)*, Part 651. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USDA NRCS. 1996. *Dairy farmer profitability using intensive rotational stocking: Better grazing management for pastures*. U.S. Department of Agriculture, Natural Resources Conservation Service, Grazing Lands Technology Institute. Washington, DC.

USDA NRCS. 1998. *Nutrients available from livestock manure relative to crop growth requirements*. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USEPA. 1998. Feedlot industry sector profile. Revised draft report. Prepared for U.S. Environmental Protection Agency by Tetra Tech, Inc., Fairfax, Virginia.

Vest, L. n.d. *Layer production*. Georgia Farm*A*Syst. Cooperative Extension Service, University of Georgia, College of Agricultural and Environmental Sciences. Athens, Georgia.

Wheeler, Gene, and A. Cirelli. 1995. *Animal Waste Management for the Horseowner*. Fact Sheet 95-11, University of Nevada Cooperative Extension, Lincoln, Nebraska.

Wilson, L.L., C.L. Stull, and T.L. Terosky. 2000. Scientific advancements and legislation addressing veal calves in North America. In: *Veal Perspectives to the Year 2000, Proceedings of an International Symposium,* LeMans, France, September 12 and 13, 1995, LeMans, France.

CHAPTER 5

INDUSTRY SUBCATEGORIZATION FOR EFFLUENT LIMITATIONS GUIDELINES AND STANDARDS

5.0 INTRODUCTION

The Clean Water Act requires EPA to consider a number of different factors when developing Effluent Limitations Guidelines and Standards (ELGs) for a particular industry category. These factors include the cost of achieving the effluent reduction, the age of the equipment and facilities, the processes employed, engineering aspects of the control technology, potential process changes, nonwater quality environmental impacts (including energy requirements), and factors the Administrator deems appropriate. One way EPA takes these factors into account is by breaking down categories of industries into separate classes of similar characteristics. The division of a point source category into groups called "subcategories" provides a mechanism for addressing variations among products, raw materials, processes, and other parameters that result in distinctly different effluent characteristics. Regulation of a category by subcategory ensures that each subcategory has a uniform set of effluent limitations that take into account technology achievability and economic impacts unique to that subcategory.

The factors that EPA considered in the subcategorization of the CAFO point source category include:

- Animal production processes
- Waste management and handling practices
- Wastes and wastewater characteristics
- Waste use practices
- Age of equipment and facilities
- Facility size
- Facility location

EPA evaluated these factors and determined that subcategorization of this point source category is necessary. Based on these evaluations, the CAFO point source category has been divided into four subcategories for the purpose of issuing effluent limitations. These four subcategories are:

- Subcategory A (Subpart A): Horses and sheep

- Subcategory B (Subpart B): Ducks
- Subcategory C (Subpart C): Dairy and beef cattle other than veal calves
- Subcategory D (Subpart D): Swine, poultry, and veal calves

Section 5.1 briefly discusses the background of the subcategorization of the CAFO point source category including the 1974 Feedlots ELG. Section 5.2 discusses the subcategorization basis of the CAFO industry.

5.1 Background

Under the 1974 rulemaking, EPA divided the point source category into two subcategories: (1) Subpart A - all subcategories except ducks, and (2) Subpart B - ducks on dry lots and wet lots. Subcategories addressed under Subpart A include

- Beef cattle, open lot
- Beef cattle, housed lot
- Dairy cattle, stall barn with milk room
- Dairy cattle, free stall barn with milking center
- Dairy cattle, cowyard with milking center
- Swine, open dirt or pasture lots
- Swine, housed with slotted floor
- Swine, open or housed with solid concrete floor
- Chickens, broilers housed
- Chickens, layers (egg production) housed
- Chickens, layer breeding and replacement stock housed
- Turkeys, open lot
- Turkeys, housed lot
- Sheep, open lot
- Sheep, housed lot
- Horses, stables

This subcategorization was developed primarily on the basis of animal type and production processes employed. Secondary criteria were product produced, prevalence of the production process employed, and characteristics of waste produced.

On January 21, 2001 (66 FR 2960), EPA published a proposal to revise and update the ELG for feedlots (beef, dairy, swine, and poultry operations) that included two new subcategories:

- Subpart C: Dairy and beef cattle, other than veal calves, including heifer operations.
- Subpart D: Swine, poultry, and veal calves.

This subcategorization scheme explicitly addressed immature cattle and swine weighing less than 55 pounds, which were not explicitly included in the previous subcategorization scheme, and established new subcategories for swine, poultry, and cattle operations (separate from horses and sheep). The proposal did not affect Subpart B, and retained Subpart A for horses and sheep.

5.2 Subcategorization Basis for the Final Rule

The CAFO industry has changed operational practices considerably in the past few decades since promulgation of the 1974 ELG. During the development of this revised ELG, EPA determined that the basis for subcategorization needed to reflect current industry trends. In developing the final CAFO rule, EPA used information from USDA, industry, EPA site visits, data from EPA enforcement and inspection efforts, and public comments to evaluate each of the statutory factors listed above in Section 5.0 as they affect the current industry. EPA also considered maintaining the basis of subcategorization used in the 1974 ELG and refining the performance expectations for these facilities. Based on these analyses, EPA retained the subcategorization scheme proposed on January 21, 2001. The subcategories are

- Subpart A: Horses and sheep.
- Subpart B: Ducks.
- Subpart C: Dairy and beef cattle, other than veal calves, including heifer operations.
- Subpart D: Swine, poultry, and veal calves.

The remainder of this section discusses the factors considered for the subcategorization of the CAFO industry and those that were selected as the basis of the final subcategories.

5.2.1 Animal Production, Manure Management, and Waste Handling Processes

Production processes in the CAFO industry include all aspects of animal husbandry, animal housing, and type of animal operation. The type of production process, including animal type and housing, was one of the primary levels of subcategorizing the industry in the 1974 ELG. Furthermore, the waste handling and manure management practices at CAFOs are closely tied to housing practices and support the rationale for using these processes as a basis for subcategorization. As discussed in Chapter 4, Large beef feedlots, dairies, and heifer operations typically have outdoor confinement lots where animals are housed for all or at least a portion of their time. Large beef, dairy, and heifer operations keep animals in confinement on outdoor lots

and generate and manage both solid manure and liquid process wastewater that are affected by climate, especially precipitation.

More specifically, the majority of Large beef feedlots are open feedlots, which are usually unpaved. These types of operations may use mounds in the pens to improve drainage and provide areas that dry quickly, because dry resting areas improve cattle comfort, health, and feed utilization, all of which contribute to efficient animal weight gain. In open feedlots, protection from the weather is often limited to a windbreak near the fence in the winter and sunshade in the summer; however, treatment facilities and hospital areas for the cattle are usually covered. Animals are fed two or three times daily, so a concrete apron is typically located along feedbunks and around waterers (i.e., heavy traffic areas). Wastes produced from beef feedlots include manure, bedding, spilled feed, and contaminated runoff. Unroofed confinement areas typically have a system for collecting and confining contaminated runoff. The runoff is typically managed in a storage pond and the manure from the open lots is often scraped and stacked into mounds or stockpiles. Beef feedlots typically use a settling basin to remove bulk solids from the liquid waste stream, reducing the volume of solids before the stream enters a storage pond.

The primary function of a dairy is the production of milk, which requires a herd of mature dairy cows that are lactating. In order to produce milk, the cows must be bred and give birth. Therefore, a dairy operation may have several types of animal groups present including calves, heifers, cows that are close to calving, lactating dairy cows, dry cows, and bulls. Animals at dairy operations may be confined in a combination of freestall barns, outdoor dry lots, tie stalls, or loose housing (barns, shades, and corrals). Some animals may be allowed access to exercise yards or open pastures. At dairies, the most common type of housing for lactating cows includes freestalls, dry lots, tie stalls/stanchions, pastures, and combinations of these. Freestalls are the housing systems used by practically all Large dairy operations. The cows are not restrained in the freestalls and are allowed to roam on concrete alleys to the feeding and watering areas. Manure collects in the travel alleys and is typically removed with a tractor or mechanical alley-scraper, by flushing with water, or through slotted openings in the floor (refer to Section 4.3.5 for a more detailed description of waste handling). Dry lots are outside pens that allow the animals some exercise, but do not generally allow them to graze. These milking cows are not likely to spend their entire time in a freestall or on a dry lot, as they need to be milked at least twice a day at a tiestall or in a milking parlor.

Most dairies have both wet and dry waste management systems. The dry waste (manure, bedding, and spilled feed) is typically collected from the housing and exercise areas by tractor scrapers and stored where an appreciable amount of rainfall or runoff does not come in contact with the waste. The wet waste (water from the barn and milking parlor cleaning operations, manure, and contaminated runoff) is typically stored in anaerobic lagoons. Like beef feedlots, dairies tend to use solid separators to remove bulk solids from a liquid waste stream. Waste associated with dairy production includes manure, contaminated runoff, milking parlor waste, bedding, spilled feed, and cooling water. Lactating cows require milking at least twice a day and are either milked in their tie stalls or are led into a separate milking parlor. The milking parlor is typically cleaned several times each day to remove manure and dirt via flushing or hosing and scraping.

Stand-alone, heifer-raising operations provide replacement heifer services to dairies. These heifer operations often contract with dairies to raise heifers for a specified period of time. Heifer-raising operations use two primary methods for raising their animals. One is to raise the cattle on pasture and the second is to raise heifers in confinement. These confined heifer operations tend to raise heifers in the same way that beef feedlots raise their cattle. The heifers are typically housed on unpaved open dry lots. Wastes produced from heifer operations include manure, bedding, and contaminated runoff. Unroofed confinement areas typically have a system for collecting and confining contaminated runoff. The runoff is typically managed in a storage pond and the manure from the open lots is often scraped and stacked into mounds or stockpiles. Heifer operations may also use a settling basin to remove bulk solids from the liquid waste stream.

In all cases, these open lots and outdoor pens expose large surface areas to precipitation, generating large volumes of storm water runoff contaminated with manure, bedding, feed, silage, antibiotics, and other process contaminants. Based on the similarity of the production, housing, and waste management processes for beef feedlots, dairies, and heifer operations, EPA developed a new subcategory, Subpart C, to address these operations under the revised ELG. EPA believes that these operations use similar technologies (e.g., storm water diversion, solid separation) to reduce effluent discharges from production areas given that all of these operations must manage storm water runoff from open lots as well as the storm water that contacts food or silage.

In contrast, nearly all Large swine, poultry, and veal calf operations use total confinement housing. These confinement buildings prevent contact of runoff and precipitation with the animals and manure. Furthermore, these operations are able to manage manure in a relatively dry form, or contain liquid wastes in storage structures such as lagoons, tanks, or under-house pits that are not greatly affected by precipitation. Operations using confinement housing differ most notably from operations using outdoor open lots in that they are constructed, or can be relatively easily configured, in a manner that prevents the generation of large volumes of contaminated storm water runoff. Thus they do not need to manage large, episodic volumes of storm water runoff. At most, operations using total confinement housing need only to manage the precipitation falling directly into manure-handling and storage structures (e.g., lagoon or open tank).

For example, swine operations may be categorized by six facility types based on the life stage of the animal in which they specialize: farrow-to-wean, farrow-nursery, nursery, grow-finish, farrow-to-finish, and wean-to-finish. Many operations have the traditional full range of pork production phases in one facility, known as farrow-to-finish operations. Most nursery and farrowing operations, as well as practically all large operations of any type, raise pigs in pens or stalls in environmentally controlled confinement housing. These houses commonly use slatted floors to separate manure and wastes from the animal. Swine waste includes manure, spilled feed, and water used to clean the housing area or dilute the manure for pumping. Most confinement hog operations use one of three waste handling systems: flush under slats, pit recharge, or deep under-house pits. The flushed manure and manure from pit recharge systems is typically stored in anaerobic lagoons or tanks while deep pit systems store manure under the confinement houses.

Based on the information in Chapter 4 as well as other information in the record, EPA is including operations with immature swine as CAFOs under Subpart D based on their production and waste-handling practices. Immature swine operations were not specifically addressed in the 1974 ELG because immature animals were typically raised at a farrow-to-finish operation and not at a separate operation like today. Although many large operations continue to have the full range of production phases at one facility, these are no longer the norm. Waste from immature operations is often flushed and managed in a lagoon or pit, just like operations that manage mature pigs. Due to the increased construction and reliance on immature swine operations, EPA maintains that these operations should be specifically addressed to ensure protection of surface water quality. Because the immature operations use virtually the same animal production and waste management processes and are expected to use similar effluent reduction practices and technologies as mature swine operations, EPA has included these immature operations under Subpart D.

Poultry operations can be classified into three individual sectors based on the type of commodity in which they specialize. These sectors include operations that breed or raise broilers, or young meat chickens, turkeys and turkey hens; and hens that lay shell eggs (layers). There are two types of basic poultry confinement facilities—those that are used to raise turkeys and broilers for meat, and those that are used to house layers. Both types use total confinement houses. Broilers and young turkeys are grown on floors on beds of litter shavings, sawdust, or peanut hulls, while layers are confined to cages suspended over a bottom story in a high-rise house, or over a pit, or a belt or scrape gutter. The majority of egg-laying operations use dry manure handling but some use liquid systems that flush waste to a lagoon. Poultry waste includes manure, poultry mortalities, litter, spilled water and feed, egg wash water, and also flush water at operations with liquid manure systems. Manure from broiler, breeder, some pullet operations, and turkey operations is allowed to accumulate on the floor where it is mixed with the litter. In the chicken houses, litter close to drinking water access forms a cake that is removed between flocks. The rest of the litter pack generally has low moisture content and is removed every 6 months to 2 years, or between flocks. The removed litter is stored in temporary field stacks, in covered piles, or in stacks within a roofed facility to help keep it dry.

Veal calf operations raise male dairy calves for slaughter. Veal calf are raised almost exclusively in confinement housing, generally using individual stalls or pens. Floors are constructed of either wood slats or plastic-coated expanded metal, while the fronts and sides are typically wood slats. The slotted floors allow for efficient removal of waste. Veal calves are raised on a liquid diet and their manure is highly liquid. Veal calf waste consists of manure, flushing water, and spilled liquid feed. Manure is typically removed from housing facilities by scraping or flushing from collection channels and then flushing or pumping into liquid waste storage structures, ponds, or lagoons. Veal calf manure is typically handled in a liquid waste management system like that used in swine operations and not like the outdoor stockpiled manure at beef feedlots. Veal calf operations maintain their animals in total confinement housing like swine and poultry operations as opposed to the outdoor lots used at most beef feedlots and dairies.

Nearly all Large swine, veal calves, and poultry operations confine their animals under roof, avoiding the use of open animal confinement areas that generate large volumes of contaminated storm water runoff. These operations differ most notably from beef and dairy operations in that they, in most cases, do not have to manage the large volumes of storm water runoff that must be collected at beef and dairy operations. While swine, veal calves, and certain poultry operations that manage wastes in uncovered lagoons must be able to accommodate precipitation, they are largely able to divert uncontaminated storm water away from the lagoons and minimize the volume of wastes they must manage. Furthermore, swine, poultry, and veal calf operations use similar technologies (e.g., reduction of fresh water use, storage of manure in covered or indoor facilities, recycle of flush water) to reduce effluent discharges.

Another basis for subcategorization is the type of production system in place. In the case of CAFOs that means the type of animal operation. For example, EPA considered whether the swine production pyramid of breeding, nursery, and finishing should be used as a basis of subcategorizing swine CAFOs, or whether subcategorization should be based on specific animal breeds, animal weights, type of feed, or other process-specific factors. In evaluating the information in the record, EPA determined there were too many life-cycle variables to allow reasonable subcategorization based on the type of production system, and that segmentation based on these variables was unlikely to result in substantially different effluent characteristics or effluent limitations for each subcategory. For example, such an approach as applied to chickens would result in over a dozen subcategorizations with considerable overlap. Yet the amount of litter and manure nutrients generated in 1 year by six flocks of broilers raised for 49 days each is not significantly different from that generated by seven flocks raised for 42 days (see Chapter 6 for additional information). Furthermore, such an operation could be subject to varying standards at different times of the year. EPA determined segmentation in this fashion would complicate rather than simplify the regulation.

5.2.2 Other factors

EPA analyzed data from USDA, universities, industries, and the literature on manure and waste characteristics for AFOs. Site-specific factors such as animal management, feeding regimens, and manure handling will affect the form and quantity of the final manure and waste products to some degree. However, for a given animal type, there is reasonably consistent manure generation, and similar pollutant generation. See Chapter 6 for more information. EPA considered, but rejected, basing subcategorization on the pollutant content of the wastes, in particular because this would not provide more effective control of CAFO discharges.

During the rulemaking, EPA evaluated subcategorization based on waste characteristics — one based on an expected nutrient content (e.g., P) of the manure or the mass of a particular nutrient. Although EPA believes that setting thresholds based on nutrient content of the manure may encourage the development of reduction strategies, it would not adequately reflect the form of the nutrient present in the manure (i.e., organic or inorganic, soluble fraction). Similarly, using the mass of the nutrient as the basis for subcategorization could possibly encourage manure

management and nutrient conservation. See Chapter 2 for a discussion on the merits of P production as a metric for establishing regulatory thresholds. EPA believes using this same approach for subcategorization creates difficulties. For example, such an approach would significantly increase the complexity of identifying CAFOs (e.g., a facility is a CAFO if it produces "x" pounds of P) and cost of implementing the ELG (by requiring rigorous sampling, additional recordkeeping, and more frequent reporting). Furthermore, while some practices can be used to affect manure generation and nutrient outputs, others are only effective for select animal species (such as adding phytase to feed), or may provide limited benefit to overall manure management at the operation (for example, smaller feed pellets increase digestibility and may decrease nutrient excretion in the manure but will also decrease solid-liquid separation efficiency). The nutrient mass excreted can also change based on feeding strategies, feed supplements, and the amount of time elapsed before sampling. See Chapter 8 for more information. These factors make it harder for the CAFO to manage, and difficult for the permitting authorities to implement the regulation. Therefore, EPA rejected both of these approaches due to their limitations, increased costs, and complexity.

EPA considered basing subcategorization on water use practices such as dairy, swine, and layer operations that employ technologies such as flush waste handling systems, deep pits, and scrapers. In considering these practices as a basis for subcategorization, EPA evaluated the cost for these sectors to comply with the various technology options, and concluded that water use practices did not prevent a facility from achieving the performance standards. (However, some technologies and practices for water use/reuse/recycle can be used to substantially reduce costs of certain technology options. See Chapter 8 and the Cost Report for more information.) EPA also determined that a subcategorization scheme based on water use practices could, in some cases, provide a disincentive for a facility to reduce fresh water consumption. Therefore, EPA did not select water use practices as a basis for subcategorization.

EPA evaluated the age of facilities as a possible means of subcategorization because older facilities may have different processes and equipment that could require the need for different or more costly control technologies to comply with regulations. EPA conducted site visits and consulted with EPA regions, enforcement officials, land grant and extension experts, and industry to collect information about AFOs and waste management practices. Specifically, EPA visited more than 115 beef feedlots; dairies; and swine, poultry, and veal calf operations throughout the United States. EPA visited a wide range of operations; including those demonstrating new and innovative technologies as well as old and new facilities were visited. EPA's analyses and site visits indicate that older facilities are similar to new facilities in a number of ways. Through retrofitting, expansions, and desire to maximize animal production, many older facilities have implemented technologies and practices used by the newer facilities in order to remain competitive. Even though confinement housing may have a 20- to 30-year useful life, modifications are continuously made to the internal housing structures at CAFOs such as replacement of floor materials, installation of new feeding systems, and improvements to drinking water equipment. These improvements and modifications are even more apparent at operations that have expanded the size of the facility. For example, many wet layer operations are retrofitting to dry manure systems, few, if any, Large swine facilities use open lots, and beef

feedlots are diverting clean storm water away from the feedlot and manure storage areas. These and other examples of modifications are documented in the record (See W-00-27, Section 5.3). EPA determined that the age of the facility does not have an appreciable impact on the wastewater characteristics, especially the total amount of nutrients to be managed, and was not considered as a basis for subcategorization.

EPA also considered subcategorization on the basis of facility size and analyzed several size groups for each major livestock sector. Within each size group, EPA considered the predominant practices, and developed cost models to reflect these baseline practices. EPA found that all Large CAFOs used similar practices, though the smaller the operation, the more diverse the range of practices employed. EPA also determined that farm size did not consistently influence the ability of the operation to achieve the desired performance standards for each technology option. Additionally, EPA did not find that CAFO size consistently influenced the ability of the facilities to achieve the performance standards for each technology option (see the Economic Analysis document for more information on impacts). Finally, pollution potential from all AFOs within a broad size range is approximately the same per unit of animal production for all sizes of facilities. Therefore, to minimize confusion, potential inconsistencies, and administrative burden, EPA determined that the ELG applies to anyone defined as a Large CAFO and did not select to subcategorize further on the basis of facility size.

With respect to geographic location, EPA analyzed key production regions for each major livestock sector and considered the predominant practices within each of these regions. Next EPA identified different treatment, storage, and handling practices based on geographic location, and developed cost models to reflect these baseline practices. EPA acknowledges that geographic considerations, especially temperature and rainfall, may affect manure storage and handling, yet the practices employed by the industry do not vary considerably within a region. For example, while pits or lagoons may be used with different frequencies in any given region, these two technologies are used all over the country. EPA could not draw clear distinctions for each locale that would form a basis for subcategorization. Furthermore, EPA's cost analysis shows location does not prevent an operation from meeting the performance standards. See the Cost Report for more information. Therefore, there is no need to develop subcategorization by location. This is further supported by reported compliance rates by each EPA region; compliance did not vary by region. Therefore, EPA concludes subcategorization by location is difficult to implement, largely impractical, and, even if selected, would not provide for additional control of discharges.

EPA also evaluated pollution-control technologies currently being used by the industry as a basis for establishing regulations. The treatability of waste was not a factor for categorization since wastes from CAFOs are concentrated and present in such quantities that no direct discharge from the production area is currently allowed. Pollution-control technologies are often complementary to or directly part of the production or manure management process, therefore the rationale for using such processes as a basis for subcategorization is further supported by the potential use of pollution-control technologies as a basis for subcategorization. However, EPA believes that the use of pollution-control technologies only to segment the industry may result in disincentives for new and innovative treatment technologies, especially the transfer of technologies between

animal sectors (for example, the recent application of high-rise housing to swine operations, a technology well established by layer hen operations). Although the current use of pollution-control technologies did assist EPA in identifying the best management practices addressed in the final ELG, EPA did not believe pollution-control technologies would serve as a better basis for subcategorization than the production of manure management processes.

Finally, EPA evaluated whether Nonwater Quality Impacts (NWQIs) could form a basis for subcategorization. NWQIs include changes in air emission and energy use at CAFOs such as those resulting from transportation of manure and wastes to off-site locations, and emissions of volatile organic compounds to the air. See the NWQI report for additional information. While NWQIs are of concern to EPA, the impacts are the result of individual facility practices and do not apply uniformly to different industry segments. To the extent there are similarities, these similarities do not lend themselves towards subcategorization of the industry in a way that provides better controls than the proposed approach. Therefore, NWQIs are not an appropriate basis for subcategorization.

CHAPTER 6

WASTEWATER CHARACTERIZATION AND MANURE CHARACTERISTICS

6.0 INTRODUCTION

This chapter describes waste streams generated by the animal feeding industry. Differences in waste composition and generation between animal types within each sector are highlighted.

The types of animal production and housing techniques determine whether the waste will be managed as a liquid, semisolid, or solid (Figure 6-1).The type of manure and how it is collected has a direct impact on the nutrient value of the waste, its value as a soil amendment, or other uses.

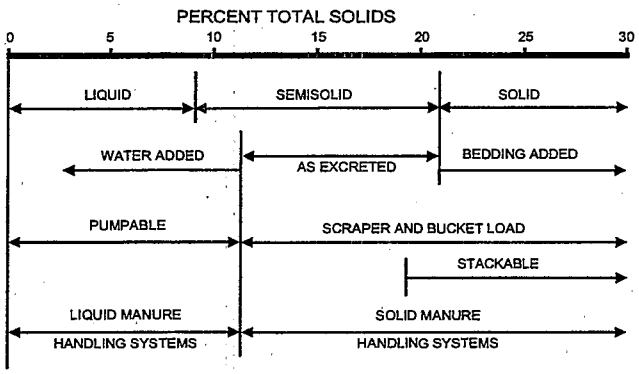

Figure 6-1.Manure characteristics that influence management options (after Ohio State University Extension, 1998).

6.1 Swine Waste

Swine waste contains numerous chemical and biological constituents such as nutrients, heavy metals, and pathogens that can potentially contaminate the environment. The composition of swine waste and the rate of its excretion by the pig varies with the stage of physical development, the pig's gender, and for females, whether she is farrowing. As noted in Chapter 4, during the course of their life cycle, pigs receive up to six different diets to maximize growth at each stage of physical development. Each diet is composed of a unique mix of nutrients and minerals, and these different diets are reflected in the different composition of manure generated.

Swine waste also undergoes physical and chemical changes after it has been excreted by the pig. For example, swine waste volume and composition change after the waste becomes mixed with water, feed, and bedding materials. Furthermore, microbial activity alters the chemical makeup of the waste by metabolizing organic matter and generating chemical by-products. Additional chemical changes can occur depending on how the waste is stored and whether it is treated.

For swine operations, typical manure-handling practices are designed to produce either a liquid or a semisolid. Thus, the nutrient component of manure usually becomes more dilute because of the addition of water used to aid in collection of the manure. In addition, ammonia volatilization reduces nitrogen (N) concentrations in both liquid and dry manure-handling systems. Phosphorus (P) concentrations increase in manure that is handled dry because the water content decreases.

As discussed in Chapter 4, swine manure is typically collected and stored by means of pit storage, lagoons, or a combination of the two. Most lagoons operate anaerobically. Aerated lagoons have received less attention because of their higher costs; however, their potential for decreased odor might increase their use. Svoboda (1995) achieved N removal, ranging from 47 to 70 percent (depending on aeration), through nitrification and denitrification in an aerobic treatment reactor using whole pig slurry. The proportion of P and potassium (K) typically remaining after storage is higher than N. However, up to 80 percent of the P in lagoons is found in the bottom sludge versus the water fraction (MWPS, 1993).

Jones and Sutton (1994) analyzed manure nutrient content in liquid manure pit and anaerobic lagoon samples just before land application. On a mass basis for pit storage, N decreases ranged from 11 to 47 percent; P, 9 to 67 percent; and K, 5 to 42 percent. In the water fraction of lagoons, N decreases ranged from 76 to 84 percent; P, 78 to 92 percent; and K, 71 to 85 percent. Nitrogen decreases in these two storage systems were primarily due to volatilization, whereas P and K decreases were due to accumulation in sludge. Boland et al. (1997) found that for deep pit systems almost four times as much land was needed when applying manure based on P rather than N, 2.5 times for tank storage, and 1.7 times for lagoon systems. These differences can be attributed to less ammonia volatilization in deep pit systems, and solids settling in lagoons.

A field study of Missouri swine lagoon surface-to-volume ratios found that large swine lagoons have significantly higher total N concentrations than small lagoons. This finding suggests that nutrient concentrations, and thus land application, of treated swine manure should be based on the design and performance characteristics of the lagoon rather than on manure production alone (Fulhage, 1998).

The use of evaporative lagoon systems has increased in arid regions. These systems rely on evaporation to reduce wastewater with pollutants accumulating in the lagoon sludge. This approach results in reduced or no land application of wastes. For example, due to a lack of adequate land disposal area in Arizona, Blume and McCleve (1997) increased the evaporation of wastewater from a 6,000-hog flush/lagoon treatment system by spraying the wastewater into the air. Although information on volatilization was not available, the evaporative increase from spraying and pond evaporation, versus pond evaporation alone, was 51 percent.

The following sections characterize swine waste in terms of generation rates, and chemical and biological contaminants. Differences between swine types and operations and changes to the waste after it leaves the pig are also characterized.

6.1.1 Quantity of Manure Generated

Table 6-1 shows the quantity of manure generated by different types of swine. Variation in these quantities can be attributed to different ages and sizes of animals within a group (USDA, 1992). Manure production can also vary depending on the digestibility of feed rations. For example, corn, which is 90 percent digestible, results in less total solids in manure than a less digestible feed such as barley, which is 70 percent digestible (USDA, 1992).

Table 6-1. Quantity of Manure Excreted by Different Types of Swine.

	Manure Mass (lb/yr/1,000 lb of animal mass)			
Type of Swine	**Maximum Reported**	**Minimum Reported**	**USDA 1998 Value**	
Grower-Finisher	44,327[a]	14,600[a]	Grower-Finisher 29,380[d]	Farrow to Finish 38,940[e]
Replacement Gilt	29,872[a]	11,972[a,b]		
Boar	31,527[a]	7,483[b]	Farrow 12,220[d]	
Gestating Sow	18,250[a]	9,928[b]		
Lactating Sow	32,120[a]	21,900[a,b]		
Sow and Litter	21,900[c]	21,900[c]		
Nursery Pig	54,142[a]	23,981[c]	---	

[a]NCSU, 1994.
[b]USDA, 1992.
[c]MWPS, 1993.
[d]USDA, 1998.
[e]Adapted from USDA, 1998.
---Not available.

As described in Chapter 3, there are three stages of swine production—farrow, nursery, and grower-finisher. Some swine operations encompass all three stages, whereas others specialize in just one. This section discusses the type of animal included in each operation and summarizes data on the quantity of manure produced by different operations.

Farrowing Operations

Farrowing operations include boars, gestating sows, lactating sows, and the sows' litters. Newborn pigs remain at the farrowing facility until they are weaned, which typically takes 3 to 4 weeks. Lactating sows and their litters produce the most manure, whereas boars produce the least. Manure production values for 1,000 lbs of animal in a farrowing operation range from 7,483 (USDA, 1992) to 32,120 lb/yr (NCSU, 1994), as shown in Table 6-2.

Nursery Operations

After farrowing and weaning, young pigs are moved to a nursery, when they reach approximately 15 pounds. They remain in the nursery for 7 to 8 weeks until they weigh approximately 60 pounds and are then transferred to a grower-finisher operation. Nursery pigs produce manure at

rates of 23,981 (MWPS, 1993) to 54,142 lb/yr per/1,000 lbs of animal (NCSU, 1994) (Table 6-2).

Table 6-2. Quantity of Nitrogen Present in Swine Manure as Excreted.

Operation Type	Nitrogen (lb/yr/1,000 lb of animal mass).		
	Maximum Reported	Minimum Reported	USDA 1998 Value
Farrow to Finish	NA	NA	220.0[c]
Grower-Finisher	228.8[a]	87.6[b]	166.0[d]
Farrow	214.0[a]	54.8[b]	81.0[d]
Nursery	224.1[a]	134.0[a]	—

[a]NCSU, 1994.
[b]USDA, 1992.
[c]Adapted from USDA, 1998.
[d]USDA, 1998.
NA Not available.

Grower-Finisher Operations

In a finishing operation pigs are raised to market weight, which is approximately 240 to 280 pounds. This third stage of swine production is typically 15 to 18 weeks long, after which finished hogs are sent to market at approximately 26 weeks of age. A grower-finisher operation raises pigs over a relatively long period of time, during which their weight changes substantially. This weight change affects the quantity of manure produced (USDA, 1992). Values for manure production from growing-finishing pigs range from 11,972 (USDA, 1992) to 44,327 lb/yr per 1,000 lbs of animal (NCSU, 1994) (Table 6-2).

Farrow-to-Finish Operations

A farrow-to-finish operation includes all three stages of swine production. Because of the large variability in animal types presented in this type of operation, manure production values vary widely, from 7,483 lb/yr per/1,000 lbs of animal for boars (USDA, 1992) to 54,142 lb/yr per 1,000 lbs of animal for nursery pigs (NCSU, 1994) (Table 6-1).

6.1.2 Description of Waste Constituents and Concentrations

Swine waste contains substantial amounts of N, P, K, pathogens, and smaller amounts of other elements and pharmaceuticals. This section provides a summary of the constituents of swine waste as reported in the literature. There is significant variability in the generation rates presented below. This variability can be attributed to different nutritional needs for swine in the same operation type (e.g., sows and boars), and for swine of different ages and sizes grouped in the same operation. Also, as shown earlier in Table 6-1, different types of swine produce different quantities of manure.

Nitrogen

Nitrogen is usually measured as total N or as total Kjeldhal nitrogen (TKN). Although TKN does not include nitrate-nitrogen (NO_3-N), it may be considered equal to total N because NO_3-N is present only in very small quantities in swine manure (0.051 to 1.241 lb/yr per 1,000 lbs of animal) (NCSU, 1994; USDA, 1998). Published values for N production in swine manure range from 54.8 (USDA, 1992) to 228.8 lb/yr per 1,000 lbs of animal (NCSU, 1994), as shown in Table 6-2. In general, boars produce the least amount of N per 1000 pounds of animal, and grower-finisher pigs produce the most.

Phosphorus

The quantity of P excreted in swine manure for different types of swine operations is shown in Table 6-3. Phosphorus content ranges from 18.3 (USDA, 1992) to 168.2 lb/yr per 1,000 lbs of animal (NCSU, 1994)—boars excrete the least amount of P in manure per 1000 pounds of animal, whereas grower-finisher pigs excrete the most.

Table 6-3. Quantity of Phosphorus Present in Swine Manure as Excreted.

	Phosphorus (lb/yr/1,000 lb of animal mass)		
Operation Type	**Maximum Reported**	**Minimum Reported**	**USDA 1998 Value**
Farrow to Finish	NA	NA	64.1[d]
Grower-Finisher	168.2[a]	29.2[b]	48.3[e]
Farrow	68.3[a]	18.3[b]	26.2[e]
Nursery	93.4[a,b]	54.6[c]	—

[a]NCSU, 1994.
[b]USDA, 1992.
[c]MWPS, 1993.
[d]Adapted from USDA, 1998.
[e]USDA, 1998.
NA Not available.

Potassium

Table 6-4 shows the range of measured K quantities in manure for each type of swine operation. Boars produce the least amount of K at 36.50 lb/yr per 1,000 lbs of animal (USDA, 1992), whereas grower-finisher pigs produce the most at 177.4 lb/yr per 1,000 lbs of animal (NCSU, 1994).

Table 6-5 shows differences in the quantity of nutrients in manure at different stages of storage and handling. The data show a decrease in nutrient quantities from a manure slurry, which is untreated, to lagoon liquid and finally to secondary lagoon liquid. Lagoon sludge contains less N and K but more P, than lagoon liquid , because tends to be associated with the particulate fraction of manure, and N and K are usually in dissolved form. Table 6-6 shows the percent of manure nutrient content as excreted that is retained using different manure management systems. Table 6-7 shows manure nutrient concentrations in pit storage and anaerobic lagoons.

Table 6-4. Quantity of Potassium Present in Swine Manure as Excreted.

Operation Type	Potassium (lb/yr/1,000 lb of animal mass)		
	Maximum Reported	Minimum Reported	USDA 1998 Value
Farrow to Finish	NA	NA	154.79[d]
Grower-Finisher	177.4[a]	47.45[b]	116.79[e]
Breeder	136.6[a]	36.50[b]	47.96[e]
Nursery	130.6[a]	103.88[c]	---

[a]NCSU, 1994.
[b]USDA, 1992.
[c]MWPS, 1993.
[d]Adapted from USDA, 1998.
[e]USDA, 1998.
NA Not available.

Table 6-5. Comparison of Nutrient Quantity in Manure for Different Storage and Treatment Methods.

Nutrient	Mean Quantity in Manure (lb/yr/1000 lb of animal mass)					Land-Applied Quantity After Losses[b]	
	Paved Surface Scraped Manure[a]	Liquid Manure Slurry[a]	Anaerobic Lagoon Liquid[a]	Anaerobic Secondary Lagoon Liquid[a]	Anaerobic Lagoon Sludge[a]	Farrow	Grower
Nitrogen	137.65	164.44	34.71	28.79	6.57	20.29	17.23
Phosphorus	61.05	51.28	6.06	4.47	6.18	22.12	17.11
Potassium	79.81	78.20	29.84	23.13	1.46	43.01	43.75

[a]NCSU, 1994.
[b]USDA, 1998.

Table 6-6. Percent of Original Nutrient Content of Manure Retained by Various Management Systems.

Management System	Nitrogen	Phosphorus	Potassium
Manure stored in open lot, cool humid region.	55-70	65-80	55-70
Manure liquids and solids stored in an uncovered, essentially watertight structure.	75-85	85-95	85-95
Manure liquids and solids (diluted less than 50%) held in waste storage pond.	70-75	80-90	80-90
Manure stored in pits beneath slatted floor.	70-85	90-95	90-95
Manure treated in anaerobic lagoon or stored in waste storage pond after being diluted more than 50%.	20-30	35-50	50-60

Source: Adapted from Jones and Sutton, 1994.

Metals and Other Elements

Other elements present in manure include the micronutrients calcium, chlorine, magnesium, sodium, and sulfur; and heavy metals such as arsenic, cadmium, iron, lead, manganese, and nickel. Many of these elements are found in swine feed; others, such as heavy metals, are found in pharmaceutical feed additives. Table 6-8 shows the range of quantities of these elements in manure as excreted, after storage, at different stages of treatment, and when it is land applied.

Swine manure contains many kinds of bacteria, several of which are naturally present in the digestive systems of the animals. Others are in the pigs' general environment and can be ingested

but are not a necessary component of digestion. Table 6-9 presents a summary of measured values of these bacteria in swine manure as excreted, and at various stages of treatment.

Table 6-7. Nutrient Concentrations for Manure in Pit Storage and Anaerobic Lagoons for Different Types of Swine.

Animal Type	Manure Produced 1000 gal/yr	Nitrogen (N) lb N/1000 gal/yr	Phosphorus (P) lb P/1000 gal/yr	Potassium (K) lb K/1000 gal/yr
Pit Storage				
Grower-Finisher	0.53	32.75	11.55	22.41
Lactating Sow	1.4	15.00	5.25	9.13
Gestating Sow	0.5	25.00	13.55	22.41
Nursery	0.13	25.00	8.44	18.26
Anaerobic Lagoon				
Grower-Finisher	0.95	5.60	1.639	3.486
Lactating Sow	2.10	4.10	0.874	1.660
Gestating Sow	0.90	4.40	1.857	3.320
Nursery	0.22	5.00	1.398	2.656

Source: Adapted from Jones and Sutton, 1994.

Table 6-8. Comparison of the Mean Quantity of Metals and Other Elements in Manure for Different Storage and Treatment Methods.

	Quantity produced in manure (lb/yr/1000 lb animal mass)					
Element	As Excreted	Paved Surface Scraped Manure[a]	Liquid Manure Slurry[a]	Anaerobic Lagoon Liquid[a]	Anaerobic Secondary Lagoon Liquid[a]	Anaerobic Lagoon Sludge[a]
Aluminum	1.340[a]	0.797	3.289	0.176	---	---
Arsenic	0.252[a]	---	0.003	0.004	---	---
Boron	1.132[b]-1.232[a]	0.239	0.086	0.042	0.037	0.004
Cadmium	0.010[a,b]	0.001	0.002	0.002	---	0.001
Calcium	120.45[b]-121.468[a]	117.932	48.433	7.547	6.459	6.373
Chlorine	93.335[a]-94.9[b]	90.615	27.073	18.571	---	0.378
Cobalt	0.014[a]	0.013	---	0.002	---	---
Copper	0.437[a]-0.438[b]	0.960	0.665	0.073	0.036	0.082
Chromium	---	---	---	---	---	0.007
Iron	5.84[b]-6.606[a]	16.858	4.643	0.486	0.292	0.713
Lead	0.030[a]-0.031[b]	0.019	---	0.033	---	0.007
Magnesium	25.55[b]-27.064[a]	33.766	16.884	2.461	1.587	1.837
Manganese	0.640[a]-0.694[b]	4.573	0.790	0.055	0.022	0.082
Molybdenum	0.010[a,b]	0.001	---	0.001	---	0.003
Nickel	0.029[a]	0.048	0.016	0.130	---	0.003
Selenium	---	---	---	0.000	---	---
Sodium	23.980[a]-24.455[b]	24.536	18.148	10.396	---	0.536
Sulfur	27.192[a]-27.74[b]	24.791	14.702	2.089	1.542	1.333
Zinc	1.825[b]-1.855[a]	2.414	2.210	0.191	0.036	0.212

[a]NCSU, 1994.
[b]ASAE, 1998.
NA Not available.

Table 6-9. Comparison of the Mean Concentration of Pathogens in Manure for Different Storage and Treatment Methods.

Type of Bacteria	Quantity Present in Manure (bacterial colonies per pound of manure)				
	Manure As Excreted	Paved Surface Scraped Manure	Liquid Manure Slurry	Anaerobic Lagoon Liquid	Anaerobic Lagoon Sludge
Enterococcus bacteria	3.128E+09	1.395E+09	3.839E+09	1.232E+06	---
Escherichia coliform bacteria	4.500E+07	5.400E+07	1.302E+08	---	---
Facultative bacteria	---	5.400E+11	5.164E+11	---	---
Fecal coliform bacteria	1.106E+09	4.800E+08	1.777E+07	2.502E+06	---
Fecal streptococcus bacteria	2.873E+10	---	2.276E+07	2.285E+06	---
Streptococcus bacteria	1.980E+08	2.205E+10	1.995E+10	---	---
Total aerobic bacteria	---	2.745E+11	1.269E+11	---	---
Total anaerobic bacteria	---	5.400E+11	1.092E+11	---	---
Total bacteria	---	---	---	3.885E+08	7.769E+09
Total coliform bacteria	2.445E+09	1.598E+09	9.551E+07	1.083E+07	---

Source: NCSU, 1994.
NA Not available.

Pharmaceuticals

To promote growth and to control the spread of disease, antibiotics and other pharmaceutical agents are often added to feed rations. Many of these chemicals are transformed or broken down through digestion and their components are excreted in manure. Table 6-10 lists several common pharmaceuticals added to swine feed and their frequency of use as reported in *Swine '95 Part I: Reference of 1995 Swine Management Practices* (USDA APHIS, 1995).

Table 6-10. Type of Pharmaceutical Agents Administered in Feed, Percent of Operations that Administer them, and Average Total Days Used.

Antibiotic/Agent in Feed	Percent Operations	Standard Error	Average Total Number Days	Standard Error
Chlortetracycline/Sulfathiazole/Penicillin	6.7	2.1	33.8	5.3
Chlorotetracycline/Sulfamethazine/Penicillin	6.4	2.0	23.6	3.6
Tylosin/Sulfamethazine	4.8	2.1	45.6	4.1
Carbadox	12.4	2.5	31.2	2.1
Lincomycin	4.3	1.4	60.3	17.6
Apramycin	2.8	1.2	50.9	22.7
Chlortetracycline	41.1	4.0	58.1	4.6
Oxytetracycline	9.6	2.2	39.2	6.6
Neomycin/Oxytetracycline	10.4	3.0	55.3	14.6
Tylosin	30.4	3.7	57.4	5.1
Bacitracin (BMD)	52.1	4.1	72.2	4.0
Virginiamycin	3.8	1.3	65.1	11.6
Zinc oxide	5.0	2.1	81.2	22.9
Copper sulfate	6.1	1.9	62.8	11.3
Other	4.6	2.2	97.6	11.8

Source: USDA APHIS, 1995.

Physical Characteristics

Tables 6-11 and 6-12 list several characteristics of swine manure as excreted by pigs, classified by different operation types, and with different types of storage and treatment methods.

Table 6-11. Physical Characteristics of Swine Manure by Operation Type and Lagoon System.

Characteristic	Physical Characteristics in Swine Manure (lb/yr/1000 lb unless otherwise noted)						
	Grower-Finisher as Excreted	Farrow as Excreted	Farrow Finish as Excreted	Liquid Manure Slurry[b]	Anaerobic Lagoon Sludge[b]	Anaerobic Lagoon Liquid[b]	Anaerobic Secondary Lagoon Liquid[b]
Manure	11,972[a]–33,830[b]	7,483[a]–27,313[b]	7,483[a]–39,586[b]	6,205	270	7,381	7,381
Urine	42.1[b]–49.0[b]	---	39.0[b]–74.0[b]	---	---	---	---
Density (lb/ft^3)	61.8[b]–62.8[b]	---	61.3–62.8	8.4	8.9	8.4	8.35
Moisture (%)	90[a]–91[a]	90[a]–97[a]	90[a]–97[a]	---	92[a]	100[a]	---
Total solids	3.28[a]–6.34[a]	1.9[a]–6.0[a]	1.9[a]–11.0[a]	---	7.60%[c]	0.25%[c]	---
Total dissolved solids	1.29[a]	---	1.29[a]	---	---	---	---
Volatile solids	2.92[a]–5.40[a]	1.00–5.40	1.00–8.80	---	379.89 [c] lb/1000 gal	10.00 [c] lb/1000 gal	---
Fixed solids	0.36[a]–0.94[a]	0.30[a]–0.60[a]	0.30[a]–1.80[a]	---	253.27 [c] lb/1000 gal	10.83 [c] lb/1000 gal	---
C:N ratio	6[a]–7[a]	3[a]–6[a]	3[a]–8[a]	---	8[a]	---	2[a]

[a]USDA, 1992.
[b]NCSU, 1994.
[c]USDA, 1996.
C Carbon

Table 6-12. Physical Characteristics of Different Types of Swine Wastes.

Physical Characteristic	lb/yr/1000 lb	lb/ 1000 gallons	
	Paved Surface Scraped Manure[a]	Feedlot Runoff Water[b]	Settling Basin Sludge[b]
Manure	21,089	---	---
Density (lb/ft^3)	62.4	---	---
Moisture (%)	---	98.50	88.8
Total solids	---	1.50	11.2

[A]NCSU, 1994
[b]USDA, 1996

6.2 Poultry Waste

Poultry wastes differ in composition between the three bird types addressed in this document — layers, broilers, and turkeys. Each bird type is raised for a specific role and is provided with a diet tailored to its nutritional needs. Hence, layers are fed diets to maximize egg production, whereas broilers are fed diets to promote growth and development. Within each subsector, however, variation in manure composition as excreted is quite small due to the high degree of integration, use of standardized feed, and total confinement (USEPA, 1999). However, there are differences in composition and quantity generated between operations due to variations in length and type of manure storage employed by the operation.

Broilers and turkeys have similar production regimes in terms of manure production, manure handling, and nutrient recovery. The floor of the house is covered with a bedding material that absorbs liquid. During the growth of the flock, continuous air flow removes ammonia and other gasses resulting in lower N content of the litter (manure and bedding). Another result of continuous air flow is a reduction in the moisture content of the litter over that of freshly excreted manure.

Manure produced by the laying industry typically includes no bedding. Two main types of manure handling are handling as excreted manure (with no bedding), and water-flushed collection. In high-rise cages or scrape-out/belt systems, manure is excreted onto the floor below with no bedding to absorb moisture. The ventilation system dries the manure as it is stored. Nutrients are more concentrated without bedding than with bedding. Flushing layer manure with water results in diluted nutrient concentrations, but increases the amount of waste that must be disposed.

As shown in Table 6-13, manure generation rates differ considerably between layers and broilers. The maximum reported generation rate for broilers is over 30 percent greater than for layers. Pullets have the lowest generation rate — almost half the rate of manure production for broilers, and only 70 percent of the production rate for layers.

Table 6-13. Quantity of Manure Excreted for Broilers.

Manure Mass (lb/yr/1,000 lb of animal mass)		
Minimum Reported	**Maximum Reported**	**USDA 1998 Value**
25,550[a]	31,025[b]	29,940[c]

[a]MWPS, 1993.
[b]ASAE, 1998.
[c]USDA, 1998.

6.2.1 Broiler Waste Characteristics

6.2.1.1 Quantity of Manure Generated

Manure production is frequently presented as volume or weight of manure produced per 1,000 pounds of animal mass. There is significant variation between the minimum and maximum reported values for manure generation in broilers. Table 6-13 contains the minimum, maximum, and 1998 USDA reported values for manure generation rates for broilers. The 1998 USDA reported values were used in EPA's analyses.

6.2.1.2 Description of Waste Constituents and Concentrations

Broiler waste contains N, P, K, and smaller amounts of other elements and pathogens. This section provides a summary of the constituents of broiler manure and litter as reported in the literature.

Table 6-14 shows selected physical and chemical characteristics for broiler manure as excreted, and after application of different storage practices. Manure quantity decreases under dry storage practices, especially when stored as a manure cake.

Table 6-14. Consistency of Broiler Manure as Excreted and for Different Storage Methods.

Physical Characteristic	Physical Characteristics of Manure (lb/yr/1,000 lb of animal mass unless otherwise noted)					
	As Excreted	Broiler Litter[d]	Broiler House Litter[c]	Broiler House Manure Cake[c]	Broiler Litter Stockpile[c]	Broiler-Roaster House Litter[c]
Manure/Litter	25,550[a]–31,025[b]	12,775	7,449	2,364	6,733	5,710
Density	63.0a–63.7[c]	---	31.7	34.3	33.1	29.0
Moisture	75d	24	---	---	---	---
Total solids	7,300d–8,030[b]	9,673	5,857	1,429	4,083	4,349
Volatile solids	5,475d–8,030[a]	7,811	4,666	1,110	2,903	3,349
Fixed solids	1,825[d]	1862	---	---	---	---
C:N ratio	8[d]	9	---	---	---	---

[a]ASAE, 1998.
[b]MWPS, 1993.
[c]NCSU, 1994.
[d]USDA, 1992.

Broilers excrete numerous nutrients including N, P, and K. As shown in Table 6-15, N is excreted at the highest rate of the three nutrients. In general, broilers produce more N and K per pound of bird than do layers, although K production rates are nearly equivalent on a time-averaged basis (USDA, 1998). These levels are altered when manure is stored or treated. Liquid manure volumes and nutrient concentrations are presented in Table 6-16 for raw and stored manure. Table 6-17 shows nutrient production as excreted and after loses. Storage as a manure

cake significantly reduces nutrient content, especially N. Table 6-18 shows metals in broiler manure as excreted and for different storage and treatment methods. Microbial populations are very active in broiler litter and include enterococcus, fecal coliform, salmonella, and streptococcus. Table 6-19 shows bacteria levels per pound of manure.

Table 6-15. Nutrient Quantity in Broiler Manure as Excreted.

Nutrient	Quantity Present in Manure (lb/yr/1,000 lb of animal mass)		
	Minimum Reported	Maximum Reported	Time-Averaged Value
Nitrogen	310.25[a]	401.50b,[c]	401.65[e]
Phosphorus	71.68[a]	124.10[b]	116.77[e]
Potassium	139.27[d]	167.90[b]	157.04[e]

[a]MWPS, 1993.
[b]USDA, 1992.
[c]ASAE, 1998.
[d]NCSU, 1994.
[e]USDA, 1998.

Table 6-16. Broiler Liquid Manure Produced and Nutrient Concentrations for Different Storage Methods.

Storage Method	Manure Produced (1000 gal/yr)	Nutrient Concentration (lb nutrient/1000 gal)		
		Nitrogen	Phosphorus	Potassium
Raw manure	0.006	130.4	36.3	44.3
Pit storage [a]	0.010	63.00	17.48	24.07
Anaerobic lagoon storage [b]	0.016	8.50	1.88	2.91

Source: MWPS, 1993 as presented by Jones and Sutton, 1994.
[a] Includes dilution water.
[b] Includes rainfall and dilution water.

Table 6-17. Nutrient Quantity in Broiler Manure Available for Land Application or Utilization for Other Purposes

Nutrient	Quantity Present in Manure As Excreted and After Losses (lb/yr/1,000 lb of animal mass)	
	As Excreted	After Losses[a]
Nitrogen	410.6	241.0
Phosphorus	116.8	99.0
Potassium	157.0	141.9

Source: USDA NRCS, 2000.
[a] Manure nutrient losses during collection, storage, treatment, and transfer include volatilization of nitrogen, spillage, and manure nutrients carried from the confinement facilities by rainfall and runoff. Only waste treatment technologies that are in common practice were considered in estimating these losses.

Table 6-18. Quantity of Metals and Other Elements Present in Broiler Manure as Excreted and for Different Storage Methods.

Element	Quantity Present in Manure and Litter (lb/yr/1,000 lb of animal mass)				
	As Excreted	Broiler House Litter[a]	Broiler House Manure Cake[a]	Broiler Litter Stockpile[a]	Broiler-Roaster House Litter[a]
Aluminum	---	4.901	---	---	---
Arsenic	---	0.176	---	---	---
Barium	---	0.148	---	---	---
Boron	0.795[a]	0.211	0.052	0.131	0.133
Cadmium	0.017[a]	0.012	0.002	0.001	0.014
Calcium	136.626[a]–149.650[b]	158.424	40.197	212.888	117.184
Chlorine	296.537[a]	47.694	---	51.803	---
Cobalt	---	0.007	---	---	---
Copper	0.331[a]–0.358[b]	1.984	0.481	0.968	1.389
Chromium	---	0.566	0.185	0.006	0.942
Iron	29.509[a]	4.381	1.420	5.991	4.553
Lead	0.033[a]	0.151	0.054	---	0.204
Magnesium	50.336[a]–54.750[b]	32.871	8.225	27.596	24.046
Manganese	2.378[a]	2.957	0.815	2.344	2.170
Mercury	---	0.001	---	---	---
Molybdenum	0.134[a]	0.003	0.001	0.002	0.002
Nickel	0.111[a]	0.427	0.217	0.008	0.352
Selenium	---	0.002	---	---	---
Silicon	---	5.323	---	---	---
Sodium	50.336[a]–54.750[b]	48.668	12.390	22.290	37.143
Strontium	---	0.339	---	---	---
Sulfur	28.763[a]–31.025[b]	45.749	10.876	33.892	39.229
Zinc	1.208[a]–1.314[b]	2.652	0.713	2.112	1.932

[a]NCSU, 1994.
[b]ASAE, 1998.

Table 6-19. Concentration of Bacteria in Broiler House Litter.

Parameter	Concentration of Bacteria (bacteria colonies/lb manure)
Total bacteria	4.775E+11
Total coliform bacteria	2.285E+06
Fecal coliform bacteria	7.758E+06
Streptococcus bacteria	6.728E+09
Salmonella	2.048E+06
Total aerobic bacteria	7.107E+09

Source: NCSU, 1994.

6.2.2 Layer Waste Characteristics

6.2.2.1 Quantity of Manure Generated

Manure production is frequently presented as volume or weight of manure produced per 1,000 pounds of animal mass. There is less variation between the minimum and maximum reported

values for manure generation in layers than in broilers. Table 6-20 contains the minimum, maximum, and 1998 USDA reported values for manure generation rates for layers. The 1998 USDA reported values for manure generation were used in EPA's analyses.

Table 6-20. Quantity of Manure Excreted for Layers.

Manure Mass (lb/yr/1,000 lb of animal mass)		
Minimum Reported	**Maximum Reported**	**USDA 1998 Value**
19,163[a]	23,722[b]	22,900[c]

[a]MWPS, 1993.
[b]NCSU, 1994.
[c]USDA, 1998.

6.2.2.2 Description of Waste Constituents and Concentrations

Layer waste contains N, P, K, and smaller amounts of other elements and pathogens. This section provides a summary of the constituents of layer manure as reported in the literature. Table 6-21 shows selected physical and chemical characteristics for layer manure as excreted, and after application of different storage and treatment practices. Manure quantity decreases under dry storage practices but increases significantly when converted to a slurry, or stored and treated in an anaerobic lagoon.

Table 6-21. Physical Characteristics of Layer Manure as Excreted and for Different Storage Methods.

	Physical Characteristics of Manure (lb/yr/1,000 lb of animal mass unless otherwise noted)						
Physical Characteristic	**As Excreted**	**High-Rise Litter[d]**	**Paved Surface Scraped Manure[b]**	**Unpaved Deep Pit Stored Manure[b]**	**Liquid Manure Slurry[b]**	**Anaerobic Lagoon Liquid[b]**	**Anaerobic Lagoon Sludge[b]**
Manure	19,163[a]–23,722[b]	14126	9877	32534	53598	9881	98805
Density (lb/ft^3)	60.0[a,c]–65.1[d]	62.4	51.3	7.8	8.4	8.4	8.4
Moisture (%)	74.8[a]–75.0[d]	---	---	---	---	---	---
Total solids	5,512[d]–6,019[b]	4979	5216	3646	265	1633	1633
Total suspended solids	2,477[b]	---	---	748	101	---	---
Volatile solids	3,942[d]–4,440[b]	3483	3137	2401	119	722	722
Volatile suspended solids	481[b]–4,380[c]	---	---	637	52	---	---
Fixed solids	1,570[d]	---	---	---	---	---	---
C:N ratio	7[d]	---	---	---	---	---	---

[a]MWPS, 1993.
[b]NCSU, 1994.
[c]ASAE, 1998.
[d]USDA, 1992.

Layers excrete numerous nutrients including N, P, and K. As shown in Table 6-22, N is excreted at the highest rate of these three nutrients. Nutrient concentrations of liquid manure are shown in Table 6-23. Table 6-24 shows nutrient production after application of storage or treatment practices. Table 6-25 shows metals in layer manure as excreted, and for different storage and treatment methods.

Table 6-22. Quantity of Nutrients in Layer Manure as Excreted.

Nutrient	Quantity Present in Manure (lb/yr/1,000 lb of animal mass)		
	Minimum Reported	Maximum Reported	Time-Averaged Value
Nitrogen	264.63[a]	315.43[b]	308.35[d]
Phosphorus	99.55[a]	113.15[c]	114.27[d]
Potassium	106.05[a]	124.10[c]	119.54[d]

[a]MWPS, 1993.
[b]NCSU, 1994.
[c]USDA, 1992.
[d]USDA, 1998.

Table 6-23. Annual Volumes of Liquid Layer Manure Produced and Nutrient Concentrations.

Storage Method	Manure Produced (1000gal/yr)	Nutrient (lb nutrient/1000 gal)		
		Nitrogen	Phosphorus	Potassium
Raw manure	0.011	110.2	35.4	37.7
Pit storage [a]	0.017	60.00	19.67	23.24
Anaerobic lagoon storage [b]	0.027	7.00	1.75	2.91

Source: MWPS, 1993 as presented by Jones and Sutton, 1994.
[a] Includes dilution water.
[b] Includes rainfall and dilution water.

Table 6-24. Nutrient Quantity in Layer Litter for Different Storage Methods.

Nutrient	Quantity Present in Manure and Litter (lb/yr/1,000 lb of animal mass)					
	High-Rise Litter[a]	Paved Surface Scraped Manure[b]	Unpaved Deep Pit Stored Manure[b]	Liquid Manure Slurry[b]	Anaerobic Lagoon Liquid[b]	Anaerobic Lagoon Sludge[b]
Nitrogen	199.44	165.79	238.42	42.35	24.63	24.63
Phosphorus	97.60	110.21	94.55	4.77	39.87	39.87
Potassium	114.40	107.96	114.40	54.75	9.60	9.60

[a]USDA, 1992.
[b]NCSU, 1994.

Table 6-25. Quantity of Metals and Other Elements Present in Layer Manure as Excreted and for Different Storage Methods.

Element	Quantity Present in Manure and Litter (lb/yr/1,000 lb of animal mass)						
	As Excreted	High-Rise Litter[c]	Paved Surface Scraped Manure[a]	Unpaved Deep Pit Stored Manure[a]	Liquid Manure Slurry[a]	Anaerobic Lagoon Liquid[a]	Anaerobic Lagoon Sludge[a]
Aluminum	9.987[a]	2.161	---	4.039	---	---	---
Arsenic	0.050[a]	---	---	---	0.002	---	---
Boron	0.651[a]–0.657[b]	0.157	0.178	0.125	0.059	0.041	0.041
Cadmium	0.014[a,b]	0.001	---	---	0.000	0.007	0.007
Calcium	474.500[b]–491.891[a]	288.598	375.753	138.050	6.945	55.653	55.653
Chlorine	204.400[b]–242.608[a]	28.394	---	27.554	21.777	---	---
Cobalt	0.029[a]	---	---	---	---	---	---
Copper	0.303[b]–0.308[a]	0.244	0.285	0.302	0.030	0.167	0.167
Chromium	---	0.114	0.188	---	0.002	---	---
Iron	21.900[b]–24.143[a]	2.936	14.008	7.089	0.387	5.727	5.727
Lead	0.270[b]–0.274[a]	0.135	0.656	---	0.005	0.023	0.023
Magnesium	51.100[b]–51.129[a]	58.577	28.306	16.495	2.188	13.629	13.629
Manganese	1.945[a]–2.227[b]	2.032	2.165	1.579	0.044	1.896	1.896
Mercury	---	---	---	---	0.000	---	---
Molybdenum	0.109[a]–0.110[b]	0.002	0.002	---	---	---	---
Nickel	0.091[a,b]	0.351	0.418	---	0.075	0.029	0.029
Selenium	0.010[a]	---	---	---	---	---	---
Sodium	36.500[b]–43.292[a]	19.646	16.268	20.082	11.755	3.958	3.958
Sulfur	51.053[a]–51.100[b]	49.971	23.554	16.762	3.918	8.414	8.414
Zinc	1.640[a]–6.935[b]	2.162	1.721	1.609	0.100	1.346	1.346

[a]NCSU, 1994.
[b]ASAE, 1998.
[c]USDA, 1992.

Microbial populations are quite active in layer litter and include enterococcus, fecal coliform, salmonella, and streptococcus. Table 6-26 shows bacteria levels per pound of manure. As shown in this table, converting the litter to a slurry substantially reduces the concentration of bacteria.

Table 6-26. Concentration of Bacteria in Layer Litter.

Type of Bacteria	Concentration in Manure (bacterial colonies/lb manure)	
	As Excreted	Layer Liquid Manure Slurry
Enterococcus bacteria	2.786E+13	---
Fecal coliform bacteria	1.552E+13	1.058E+06
Fecal streptococcus bacteria	3.375E+13	---
Salmonella	1.327E+10	---
Streptococcus bacteria	6.237E+13	---
Total aerobic bacteria	8.568E+15	---
Total bacteria	9.716E+16	---
Total coliform bacteria	1.835E+14	7.547E+06
Yeast	1.327E+15	---

Source: NCSU, 1994.

6.2.3 Turkey Waste Characteristics

Turkey operations usually separate and handle the birds in groups according to age, gender, size, or special management needs such as hatcheries or breeder farms. The types of animals are

- Poults (young turkeys)
- Turkey hens for slaughter
- Turkey toms for slaughter
- Hens kept for breeding

Although three major strains of turkeys are grown, the high degree of industry integration, standardized feed, and complete confinement has resulted in very little variation in manure characteristics. The exact quantity and composition of manure depends mostly on the specifics of farm management, such as precision feeding, control of wasted feed, and ammonia volatilization losses. Litter characteristics also vary according to material used for bedding.

6.2.3.1 Quantity of Manure Generated

Manure production is frequently presented as volume or weight of manure produced per 1,000 pounds of animal mass. Table 6-27 shows manure production as excreted for turkey hens for breeding and turkey hens and toms for slaughter.

Table 6-27. Annual Fresh Excreted Manure Production (lb/yr/1,000 lb of animal mass).

Animal Type	Range of Annual Manure Production Values	USDA 1998 Value
Turkeys for slaughter	15,914[a]-17,155[b]	16,360[c]
Hens for breeding		18,240[c]

[a]USDA, 1992.
[b]ASAE, 1998.
[c]USDA, 1998.

6.2.3.2 Description of Waste Constituents and Concentrations

Turkey waste contains N, P, K, and smaller amounts of other elements and pathogens. This section provides a summary of the constituents of turkey manure and litter as reported in the literature.

Composition of Manure

Exact manure composition depends on length and type of storage, as well as other management practices specific to each farm. Table 6-28 shows nutrients in turkey manure as excreted. Turkeys for slaughter produce more N and K in fresh, excreted manure, and breeding hens produce more P.

Table 6-28. Quantity of Nutrients Present in Fresh, Excreted Turkey Manure (lb/yr/1,000 lb of animal mass).

Animal Type	Nitrogen		Phosphorus		Potassium	
	Range Includes Minimum	Maximum Reported	Minimum Reported	Range Includes Maximum	Range Includes Minimum	Maximum Reported
Turkeys for slaughter	248.34[a]	270.1[b]	84[c]	96.77[a]	94.97[a]	102.20[b]
Hens for breeding	204.38[a]			120.48[a]	69.31[a]	

[a]USDA, 1998.
[b]USDA, 1992.
[c]ASAE, 1998.

Composition of Litter

The nutrient content of turkey litter is usually lower than that for broiler litter, and brooder litter contains less manure nutrients than grower house litter. Exact manure composition depends on length and type of storage, as well as other management practices specific to each farm. After stockpiling, litter may lose up to half of the total N excreted. When manure is combined with bedding materials, the waste litter absorbs water content from the manure. Table 6-29 displays the water absorption capacity of commonly used bedding materials. Because of different types of litter composition for turkey operations, nutrient quantities per ton of litter vary (Table 6-30).

Table 6-29. Water Absorption of Bedding.

Bedding Material	Pounds of Water Absorbed per Pound of Bedding
Wood	
Tanning Bark	4.00
Fine Bark	2.50
Pine	
Chips	3.00
Sawdust	2.50
Shavings	2.00
Needles	1.00
Hardwood Chips, Shavings or Sawdust	1.50
Corn	
Shredded Stover	2.50
Ground Cobs	2.10
Straw	
Flax	2.60
Oats	
Combined	2.50
Chopped	2.40
Wheat	
Combined	2.20
Chopped	2.10
Hay, Chopped Mature	3.00
Shells, Hulls	
Cocoa	2.70
Peanut, Cottonseed	2.50
Oats	2.00

Source: MWRA, 1993.

Table 6-30. Turkey Litter Composition in pounds per ton of litter.[a]

Manure Type	Nitrogen	Phosphorus	Potassium
Brooder house litter after each flock[b]	45	23	27
Grower house litter after annual cleanout[b]	57	31	33
Stockpiled litter[b]	36	30[e]-31	25[e]-27
Tom growout[c]	52	33	35
Hen growout[c]	73	38	38
Brood house[d]	51	14	27
Growout house[d]	65	28[e]-31	33[e]-38

[a]Zublena, 1993.
[b]NCSU, 1999.
[c]Pennsylvania
[d]Arkansas
[e]NCSU, 1994.
P_2O_5 converted to P by multiplication of 0.437.
K_2O converted to P by multiplication of 0.83.

In those cases where litter is recycled from the brooder barn and used in the growout barn, nutrient values of litter increase to roughly 60 pounds of available N and P per ton of litter. Table 6-31 presents some metal components of turkey litter.

Table 6-31. Metal Concentrations in Turkey Litter (pounds per ton of litter).

Manure type	Ca	Mg	S	Na	Fe	Mn	B	Mo	Zn	Cu
Turkey, brooder	28.0	5.7	7.6	5.9	1.4	0.52	0.047	0.00081	0.46	0.36
Turkey, grower	42.0	7.0	10.0	8.4	1.3	0.65	0.048	0.00092	0.64	0.51

Source: NCSU, 1998.

The physical characteristics and nutrient content of turkey manure and litter types are variable. As seen in Table 6-32, manure characteristics differ significantly from litter characteristics.

Fresh manure contains more nutrients than manure cakes, but litter from grower houses may exceed fresh manure K amounts. Table 6-33 shows metal quantities in excreted turkey manure and litter types by gender and age of bird.

Table 6-32. Waste Characterization of Turkey Manure Types (lb/yr/1,000 lb of animal mass).

Parameter	Turkey fresh manure	Turkey hen house manure cake[a]	Turkey tom house manure cake[a]	Turkey house litter[a]	Turkey poult (brooder) house litter[a]	Turkey breeder house litter[a]	Turkey stockpiled litter[a]
Manure	15,914[c]–17,155[d]	1905.3	1905.3	---	---	---	---
Litter	---	---	---	5960.5	6953.25	4967.65	5420.25
Volume (ft^3/yr/1000 lb)	251.85[c]	---	---	---	---	---	---
Density (lb/ft^3)	63[d]–63.49[a]	32.3	---	---	22.91	62.43	24.1
Total Solids (%wb)	4,179[a]–4,380[d]	1041.6	1041.6	4365.4	5527.96	3893.35	3316.90
Volatile Solids (%db)	3,205[a]–3,541[c]	845.2	845.3	3182.8	4297.07	-	-
TKN	226.3[d]–231.0[a]	42.74	42.74	165.13	138.12	87.97	85.67
NO_3–N	-	-	-	0.40	1.31		1.31
P	84.0[d]–87.8[a]	19.38	19.38	82.38	65.77	51.17	82.42
K	83.2[a]–87.6[d]	23.69	23.69	98.77	77.64	37.05	67.74

[a] NCSU, 1994.
[b] USDA, 1998.
[c] USDA, 1992.
[d] ASAE, 1998.

Table 6-33. Metals and Other Elements Present in Manure (lb/yr/1,000 lb of animal mass).

Metals/ Elements	Turkey fresh manure	Turkey hen house manure cake[a]	Turkey tom house manure cake[a]	Turkey house litter[a]	Turkey poult (brooder) house litter[a]	Turkey breeder house litter[a]	Turkey stockpiled litter[a]
Calcium	223.205[a]-230.0[b]	25.003	25.003	112.165	91.871	178.376	120.888
Magnesium	25.649[a]-26.6[b]	5.11	5.11	22.083	17.849	11.498	19.199
Sulfur	25.887[a]	5.986	5.986	25.477	21.207	18.287	20.039
Sodium	23.172[a]-24.0[b]	5.256	5.256	22.703	162.06	10.622	15.367
Chlorine	16.8407[a]	---	---	35.186	6.278	---	21.608
Iron	26.556[a]-27.4[b]	1.168	1.168	4.176	6.935	2.519	5.585
Manganese	0.853[a]-0.9[b]	0.548	0.5475	2.3725	1.825	1.059	2.044
Boron	0.452[a]	0.037	0.0365	0.146	0.146	0.073	0.110
Molybdenum	0.076[a]	0.001	0.001	0.004	0.003	---	0.003
Aluminum	---	0.694	0.694	2.263	5.037	---	---
Zinc	5.127[a]-5.5[b]	0.438	0.438	1.971	1.606	1.241	1.716
Copper	0.252[a]-0.3[b]	0.475	0.475	1.789	1.351	0.986	1.132
Cadmium	0.009[a]	---	---	0.001	0.001	---	0.001
Nickel	0.063[a]	---	---	0.018	0.007	---	0.007
Lead	0.190[a]	---	---	---	---	---	---

[a] NCSU, 1994.
[b] ASAE, 1998.

Data on bacterial concentrations in turkey manure or litter are generally sparse. However, Table 6-34 shows concentrations of fecal coliform and total bacteria for manure and litter. Land-applied quantities of turkey manure nutrients are shown in Table 6-35.

Table 6-34. Turkey Manure and Litter Bacterial Concentrations (bacterial colonies per pound of manure).

Bacteria Type	Excreted Manure	House Litter
Fecal coliform bacteria	1.31E+08	---
Total bacteria	---	2.53E+12

Source: NCSU, 1994.

Table 6-35. Turkey Manure Nutrient Composition After Losses–Land-Applied Quantities.

Animal	Manure Composition (lb/yr/1,000 lb of animal mass)		
	Nitrogen	Phosphorus	Potassium
Turkeys for slaughter	132.35 (116.0)	82.29 (14.5)	85.40 (9.6)
Hens for breeding	102.14 (102.2)	102.42 (18.1)	62.38 (6.9)

Source: USDA, 1998.
In parentheses are the differences between fresh, excreted manure content and after losses content.

6.2.4 Duck Wastes

The housing floor design and age of the ducks dictate the amount of area required to raise each bird. Age groups are kept isolated, either in separate buildings or in the same buildings with solid partitions between them. It is common for the female ducks and male drakes to be reared together. Breeding ducks are kept in breeder houses similar to turkey pole-barns. The mature ducks are typically bred at a ratio of one drake to five or six ducks.

6.2.4.1 *Quantity of Manure Generated*

The amount of manure produced depends on the number of birds, the amount and type of feed, and the age of the birds. Table 6-36 presents estimates for manure production by ducks. Table 6-37 presents the breakdown of nutrients available in the manure.

Table 6-36. Approximate Manure Production by Ducks.

Animal Type	Market Weight (Lbs)	Feed Eaten/Animal (lbs/year)	Manure Produced (lbs/year/animal)
Duck	7	114	22.8

Source: Jordan and Graves, 1996.

Table 6-37. Breakdown of Nutrients in Manure.

Animal Type	% Water	% N	% P	% K
Duck	61	1.1	1.45	0.5

Source: Florida Agricultural Information Retrieval System, 1998.

6.2.4.2 *Description of Waste Constituents and Concentrations*

Generally, ducks raised on small farms are housed in barns or poultry sheds with packed earthen or concrete floors. Bedding, such as straw or wood shavings, is used to dry the manure. The manure is removed manually or with power equipment at different intervals depending on the number of ducks and the season. The manure is then stored temporarily on a concrete pad or in a shed and then land applied. Some operations compost the manure.

Duck wastes in large operations are normally handled as a solid. Older barns or structures with solid floors accumulate a manure-litter mix that is removed between flocks with skid steers or front-end loaders. The solid manure is transported to a storage structure or directly applied to land.

6.3 Dairy Waste

This section describes the characteristics of dairy manure and waste. In this section, manure refers to the combination of feces and urine. Waste refers to manure plus other material, such as hair, bedding, soil, wasted feed, and water that is wasted or used for sanitary and flushing purposes. Due to the nature of dairy operations, however, even fresh manure may also contain small amounts of hair, bedding, soil, feed, and water.

6.3.1 Quantity of Manure Generated

Numerous analyses have estimated average manure quantities from dairy cattle. Four major data sources that contain mean values for dairy manure characteristics are identified below:

- ASAE Standard D384.1: *Manure Production and Characteristics*, 1999. This data source contains national fresh (as-excreted) manure characteristic values by animal type (e.g., dairy, beef, veal, swine).
- USDA, *Agricultural Waste Management Field Handbook (AWMFH)*, Chapter 4, 1996. This data source contains national manure characteristic values for fresh and managed manure (e.g., lagoon supernatant, feedlot runoff) by animal type including subtypes such as lactating and dry cows.
- NCSU, *Livestock Manure Production and Characterization in North Carolina*, 1994. This data source contains regional manure characteristic values for fresh and managed manure by animal type including subtypes.
- MWPS, *Livestock Waste Facilities Handbook*, 1985. This data source contains national fresh manure characteristic values by animal type and animal weight.

An analysis conducted by Charles Lander et al. of the USDA NRCS used a composite of three of these four data sources (Lander et al., 1998). Lander removed ASAE data before averaging to prevent double counting of the ASAE information that is included in the MWPS data. This

analysis assumed that the average weight of a lactating cow is 1,350 pounds. EPA used data from the Lander analyses in estimating compliance cost for beef feedlots and dairies to be consistent with other USDA data used in the costing analyses. Table 6-38 presents the fresh manure estimates from all of these data sources for mature lactating dairy cows and calves.

Table 6-38. Weight of Fresh Dairy Manure.

Data Source	Quantity of Manure (wet basis) (lb/day/1,000-lb animal)	
	Lactating Cow	Calf
ASAE Standard	86	ND
USDA *Agricultural Waste Management Field Handbook*	80	ND
NCSU, *Livestock Manure Production and Characterization in North Carolina*	87.3	65.8
MWPS *Livestock Waste Facilities Handbook*	86	ND
USDA Lander analysis	83.5	ND

ND No data.

6.3.2 Waste Constituents and Concentrations

The composition and concentration of dairy waste varies from the time that it is excreted to the time it is ultimately used as a fertilizer or soil amendment. Nutrients and metals are expected to be present in dairy waste due to the constituents of the feed.

6.3.2.1 Composition of Fresh Manure

Manure characteristics for dairy cattle are highly variable and can be affected by the following: animal size, breed, and age; management choices; feed ration; climate; and milk production. For example, dairy feeding systems and equipment often produce considerable feed waste, which in most cases is added to the manure. In addition, dairy stall floors are often covered with organic and inorganic bedding materials (e.g., hay, straw, wood shavings, sawdust, soil, sand, ground limestone, dried manure) that improve animal comfort and cleanliness. Virtually all of this material will eventually be pushed, kicked, and carried from the stalls and added to the manure, and their characteristics imparted into the manure (Lander et al., 1998). In addition, the nutrient content (N, P, and K) of dairy manure can vary significantly due to differences in voluntary feed intake, differing supplemental levels, and differing amounts of nutrients removed during milking (USDA, 1992). Table 6-39 presents averages for fresh mature dairy cow and heifer manure characteristics that are reported in the four major data sources identified in Section 6.3.1. Data are presented for 16 nutrients and metals found in fresh dairy manure. Nitrogen is present in manure in four forms: ammonium-N, nitrate-N, nitrite-N, and organic-N. The total N is the sum of these four components, while the TKN is the sum of the organic-N and ammonium-N.

Phosphorus is present in manure in inorganic and organic form and presented as total P. Colonies of the pathogens coliform and streptococcus bacteria have also been identified in dairy manure.

Table 6-39. Fresh Dairy Manure Characteristics Per 1,000 Pounds Live Weight Per Day.

Parameter	Mean (mature dairy cow/dry cow)			
	ASAE	USDA	NCSU	MWPS
Moisture (%)	87.2	87.5/88.4	ND	87.3
Total solids (lb)	12	10 9.5	12.15/9.5	12
Volatile solids (lb)	10	8.5/8.1	10/6.64	10
Biochemical oxygen demand (BOD), 5-day (lb)	1.6	1.6/1.2	1.82/0.98	1.6
Chemical oxygen demand (COD) (lb)	11	8.9/8.5	11.17/6.97	ND
pH	7	ND	7	ND
TKN (lb)	0.45	0.45/0.36	0.45/0.34	0.43
Ammonium-N (lb)	0.079	ND	0.84/0.14	ND
Total P (lb)	0.094	0.07/0.05	0.22/0.13	0.17
Orthophosphorus (lb)	0.061	ND	0.14/ND	ND
K (lb)	0.29	0.26/0.23	0.36/0.2	0.34
Calcium (lb)	0.16	ND	0.17/0.12	ND
Magnesium (lb)	0.071	ND	0.075/ 0.05	ND
Sulfur (lb)	0.051	ND	0.052	ND
Sodium (lb)	0.052	ND	0.064	ND
Chloride (lb)	0.13	ND	0.13	ND
Iron (lb)	0.012	ND	0.012	ND
Manganese (lb)	0.0019	ND	0.0019	ND
Boron (lb)	0.00071	ND	0.00073	ND
Molybdenum (lb)	0.000074	ND	0.000075	ND
Zinc (lb)	0.0018	ND	0.0019	ND
Copper (lb)	0.00045	ND	0.00047	ND
Cadmium (lb)	0	ND	0	ND
Nickel (lb)	0.0003	ND	0.00028	ND
Total coliform bacteria (colonies)	500	ND	1.09E11 (colonies/100gm)	ND
Fecal coliform bacteria (colonies)	7.2	ND	7.45E10 (colonies/100gm)	ND
Fecal streptococcus bacteria (colonies)	42	ND	4.77E11 (colonies/100gm)	ND

Sources: ASAE, 1999; USDA, 1996; NCSU, 1994; MWPS, 1985.
ND No data.

Lander et al. averaged values from the MWPS, USDA, and NCSU datasets for N, P, and K. In all cases, EPA compared the averaged values to ASAE's data and determined them to be comparable to the lactating cow numbers. As stated earlier in this section, the milking status of dairy cattle can affect the excreted levels of N, P, and K. Lactating cows are expected to have a higher nutrient content in their manure because they typically are fed a higher energy diet. Table 6-40 presents the nutrient values in dairy manure from Lander's analysis that were used in the estimation of compliance costs for beef feedlots and dairies.

Table 6-40. Average Nutrient Values in Fresh Dairy Manure.

Parameter	Dairy Cow (lb/day/1,000-lb animal) [a]
TKN	0.45
Total P	0.08
K	0.28

Source: Lander et al., 1998.
Lander's analysis relied on 1990 NCSU data, while the NCSU data presented in this report is from 1994.

The volatile solids content of dairy manure varies depending on the age and lactation of the cow. The volatile solids content of manure for mature dairy cattle can be calculated by using data for lactating and dry cows and is presented in USDA's AWMFH. EPA's analysis assumes the dairy herd is made up of 83 percent lactating and 17 percent dry cows at any given time. Therefore, the volatile solids content for mature dairy cows, using USDA data, was calculated as

(8.5 lb/day/1,000 animal x 83 percent) + (8.1 lb/day/1,000 animal x 17 percent) = 8.45 lb/day/1,000 animal

EPA used volatile solids data from USDA's AWMFH in the nonwater quality impact analyses to estimate emissions of methane.

6.3.2.2 Composition of Stored or Managed Waste

Dairy manure is often combined with large amounts of water and collected and stored in a number of different ways (see Section 4.3.5 for a detailed discussion of dairy waste management). This wastewater, therefore, has different physical properties than fresh manure. This section presents dairy waste values for waste from milking centers, and waste managed in lagoons.

Milking Centers

Approximately 15 percent of the manure generated at a dairy is produced in the milking center, which includes the milk room, milking parlor, and holding area. Milking centers that do not practice waste flushing use about 1 to 3 gallons of fresh water per day for each cow milked.

However, dairies that use flush cleaning and automatic cow washing use as much as 30 to 50 or more gallons pre day per cow (MWPS, 1985).

Waste associated with milking centers varies among the different rooms. Milk room waste typically consists of wash water associated with cleaning pipelines and holding tanks. This waste could be disposed of via septic tank systems, but many dairies include it in their manure waste management systems. Milk parlor waste typically consists of some manure and wash water from cleaning the milking equipment. Holding area waste generally contains more manure than the milk parlor and also contains wash water from cleaning the cows, and flush water from cleaning the area. Many dairies remove solids from milking center waste prior to storing the liquid waste in a lagoon. EPA used USDA data on milking center waste characteristics in the estimation of compliance costs for beef feedlots and dairies and NWQI analyses to calculate N loss during composting. Table 6-41 presents USDA data characterizing dairy waste from milking centers.

Table 6-41. Dairy Waste Characterization—Milking Centers.

Component	Units	Milking Center			
		Milk Room	Milk Room + Milk Parlor	Milk Room + Milk Parlor + Holding Area[a]	Milk Room + Milk Parlor + Holding Area[b]
Volume	ft^3/d/1,000#	0.22	0.6	1.4	1.6
Moisture	%	99.72	99.4	99.7	98.5
Total Solids	% wet basis	0.28	0.6	0.3	1.5
Volatile Solids	lb/1,000 gal	12.9	35	18.3	99.96
Fixed Solids	lb/1,000 gal	10.6	15	6.7	24.99
COD	lb/1,000 gal	25.3	41.7	ND	ND
BOD	lb/1,000 gal	ND	8.37	ND	ND
N	lb/1,000 gal	0.72	1.67	1	7.5
P	lb/1,000 gal	0.58	0.83	0.23	0.83
K	lb/1,000 gal	1.5	2.5	0.57	3.33
C:N ratio	unitless	10	12	10	7

Source: USDA/NRCS, 1992.
[a] Holding area scraped and flushed - manure removed via solids separator.
[b] Holding area scraped and flushed - manure included.
ND No data.

Lagoons

Lagoons that receive a significant loading of waste (e.g., from the holding area, freestall barn, and dry lots) generally operate in an anaerobic mode. Anaerobic dairy lagoon sludge accumulates at a rate of about 0.073 ft^3/lb of total solids. This is equivalent to about 266 ft^3/year per 1,000-lbs of lactating cow, assuming that 100 percent of the waste is placed in the lagoon (USDA, 1992).

Typically, storage or treatment reduces N in dairy manure by 30 to 75 percent through volatilization with only minor decreases in K and P. Although the values of K and P are low in the supernatant, which is removed on a regular basis, a disproportionate amount of the P and K is concentrated in the bottom sludge in lagoons and storage areas (Lander, 1999). EPA used USDA data on anaerobic lagoon waste characteristics in the estimation of compliance costs for beef feedlots and dairies and NWQI analyses. Table 6-42 presents USDA and NCSU data on dairy waste managed in lagoons.

Table 6-42. Dairy Waste Characterization—Lagoons.

Component	Units	Lagoon (USDA data/NCSU data)		
		Anaerobic - Supernatant	Anaerobic - Sludge	Aerobic - Supernatant
Moisture	%	99.75/ND	90/ND	99.95/ND
Total Solids	% wet basis	0.25/0.87	10/7.2	0.05/ND
Volatile Solids	lb/1,000 gal	9.16/52.4 % dry basis	383.18/56.7 % dry basis	1.67/ND
Fixed Solids	lb/1,000 gal	11.66/ND	449.82/ND	2.5/ND
COD	lb/1,000 gal	12.5/36.69	433.16/260.6	1.25/ND
BOD	lb/1,000 gal	2.92/7.8	ND	0.29/ND
N	lb/1,000 gal	1.67/4.86	20.83/19.16	0.17/ND
NH4-N	lb/1,000 gal	1.0/ND	4.17/ND	0.1/ND
P	lb/1,000 gal	0.48/2.76	9.16/41.8	0.08/ND
K	lb/1,000 gal	4.17/6.5	12.5/9.2	ND
C:N ratio	unitless	3/ND	10/ND	ND
Copper	lb/1,000 gal	ND/0.009	ND/0.46	ND
Zinc	lb/1,000 gal	ND/0.051	ND/0.74	ND

Sources: USDA NRCS 1992; NCSU, 1994.
ND No data.

6.3.2.3 Composition of Aged Manure/Waste

Dairy manure characteristics after excretion vary from operation to operation, and within the same operation during the year. Manure undergoes many changes after excretion including moisture change (dilution or consolidation), volatilization, oxidation, and reduction. These changes always affect the fresh manure characteristics. For example, it is estimated that as much as 50 to 60 percent of N in the urine portion of the manure can be lost during the first hours after excretion if some measure is not taken to preserve it (Lander, 1999). Phosphorus and potassium losses during storage are considered negligible except in open lots or lagoons. In open lots, about 20 to 40 percent of P and 30 to 50 percent of K can be lost by runoff and leaching. Up to 80 percent of the P in lagoons can accumulate in bottom sludges (USDA, 1998).

Characteristics of stored manure are either altered over time or conserved (mass). Nitrogen, for example, volatilizes as ammonia and is lost from the system. On the other hand, most of the compounds in manure (e.g., P, metals) remain in the manure over time and are considered to be conserved. Treating the manure often reduces the concentration of nonconservated elements, such as N and the organic compounds, thus reducing oxygen demands in further treatment (Lander, 1999).

Table 6-43 presents NCSU data on scraped dairy manure from a paved surface. NCSU data are used by EPA in the beef and dairy NWQI analyses.

Table 6-43. Dairy Manure Characteristics Per 1,000 Pounds Live Weight Per Day From Scraped Paved Surface.

Parameter	Unit	Value
Total solids	lb	13.7
Volatile solids	lb	11.5
TKN	lb	0.32
Ammonium-N	lb	0.077
Total P	lb	0.097
K	lb	0.22

6.4 Beef and Heifer Waste

This section describes the characteristics of beef and heifer manure and waste. In this section, manure refers to the combination of feces and urine, and waste refers to manure plus other material such as hair, soil, and spilled feed. Due to the nature of beef feedlots and heifer operations, however, even fresh manure may also contain small amounts of hair, soil, and feed.

6.4.1 Quantity of Manure Generated

Numerous analyses have estimated average manure quantities from beef cattle. Four major data sources that contain mean values for beef manure characteristics are identified below:

- American Society of Agricultural Engineers (ASAE) Standard D384.1: *Manure Production and Characteristics*, 1999. This data source contains national fresh (as-excreted) manure characteristic values by animal type (e.g., dairy, beef, veal, swine).
- USDA, *Agricultural Waste Management Field Handbook*, Chapter 4, 1996. This data source contains national manure characteristic values for fresh and managed manure (e.g., lagoon supernatant, feedlot runoff) by animal type including subtypes such as beef and heifer.

- North Carolina State University (NCSU), *Livestock Manure Production and Characterization in North Carolina*, 1994. This data source contains regional manure characteristic values for fresh and managed manure by animal type including subtypes.
- Midwest Plan Service-18 (MWPS): *Livestock Waste Facilities Handbook*, 1985. This data source contains national fresh manure characteristic values by animal type and animal weight.An analysis conducted by Charles Lander et al. of the USDA NRCS used a composite of three of these data sources (Lander et al., 1998). Lander removed ASAE data before averaging to prevent double counting of the ASAE information that is included in the MWPS data. Table 6-44 presents the fresh manure estimates from these five data sources for beef and heifer cattle.

Table 6-44. Weight of Beef and Heifer Manure.

Data Source	Quantity of Manure (wet basis) (lb/day/1,000-lb animal)		
	Steer, Bulls, and Calves	Beef Cows	Heifer
ASAE Standard	58	ND	ND
USDA *AWMFH*	55	63	82
NCSU *Livestock Manure Production and Characterization in North Carolina*	59	ND	68.4
MWPS *Livestock Waste Facilities Handbook*	60	63	ND
USDA Lander analysis	58	63	66

ND No data.

6.4.2 Waste Constituents and Concentrations

The composition and concentrations of beef and heifer waste varies from the time that it is excreted to the time it is ultimately used as a fertilizer or soil amendment. Nutrients and metals are expected to be present in beef and heifer waste due to the constituents of the feed.

6.4.2.1 Composition of "As-Excreted" Manure

Manure characteristics for beef and heifer cattle are highly variable and greatly influenced by the diet and age of the animals. Differences in weather, season, degree of confinement, waste collection systems, and overall management procedures used by feedlots across the nation add to the variability of manure characteristics in feedlots. The largest variable in fresh manure is moisture content, which significantly decreases over time. Another major variable is the ash content, which depends on the amount of soil entrained in the manure. Ash content also depends on the degree to which the manure has been degraded, which is a function of time since deposition, moisture conditions, temperature, and oxygen saturation (Sweeten et al., 1997). Ash content for fresh manure has been reported as 15.3 percent dry basis (Sweeten et al., 1995), while ash content for aged feedyard waste has been reported as high as 66 percent dry basis (TAES, 1996).

The N content of manure can begin to decrease rapidly after excretion. The urea-N part of the fecal protein rapidly converts to ammonia. Some measurements of ammonia concentrations in air around feedyards have indicated that about half of the N deposited in urine, or about one-fourth of the total N deposition of the feedlot surface, is lost to the atmosphere as ammonia gas (NH_3). The rate of ammonia emissions depends on temperature, pH, humidity, and moisture conditions, and has been found to nearly triple as manure dries after rainfall (Sweeten et al., 1997).

Table 6-45 presents data for 13 metals and nutrients found in fresh beef cattle manure, and Table 6-46 presents data on the constituents found in fresh heifer cattle manure. nitrogen is present in manure in four forms: ammonium-N, nitrate-N, nitrite-N, and organic-N. The total N is the sum of these four components, while the TKN is the sum of the organic-N and ammonium-N. phosphorus is present in manure in inorganic and organic forms and is presented as total P. Colonies of the pathogens coliform and streptococcus bacteria have also been identified in beef and heifer manure.

Table 6-45. Fresh Beef Manure Characteristics Per 1,000 Lbs. Live Weight Per Day.

Parameter	Mean (Beef)			
	ASAE	USDA	NCSU	MWPS
Moisture (%)	88.4	88.4	ND	88.4
Total solids (lb)	8.5	6.34	8.9	8.5
Volatile solids (lb)	7.2	5.74	7.3	7.2
BOD (5-day) (lb)	1.6	1.36	1.7	1.6
COD (lb)	7.8	5.86	7.9	ND
pH (lb)	7.0	ND	7.0	ND
TKN (lb)	0.34	0.30	0.36	0.34
Ammonium-N (lb)	0.086	ND	0.12	ND
Total P (lb)	0.092	0.10	0.22	0.25
Orthophosphorus (lb)	0.030	ND	0.07	ND
K (lb)	0.21	0.22	0.26	0.30
Calcium (lb)	0.41	ND	0.13	ND
Magnesium (lb)	0.049	ND	0.05	ND
Sulfur (lb)	0.045	ND	0.046	ND
Sodium (lb)	0.0030	ND	0.032	ND
Iron (lb)	0.0078	ND	0.0087	ND
Manganese (lb)	0.0012	ND	0.0012	ND
Boron (lb)	0.00088	ND	0.00095	ND
Molybdenum (lb)	0.000042	ND	0.000044	ND
Zinc (lb)	0.0011	ND	0.0010	ND
Copper (lb)	0.00031	ND	0.00033	ND
Total coliform bacteria (colonies)	29	ND	3E11 (colonies/100gm)	ND
Fecal coliform bacteria (colonies)	13	ND	1.3E11 (colonies/100gm)	ND
Fecal streptococcus bacteria (colonies)	14	ND	1.49E11 (colonies/100gm)	ND

Sources: ASAE, 1999; USDA, 1996; NCSU, 1994; MWPS, 1985
ND No data.

Table 6-46. Fresh Heifer Manure Characteristics Per 1,000 Lbs. Live Weight Per Day.

Parameter	Mean (Heifer)	
	USDA	NCSU
Moisture (%)	89.3	ND
Total solids (lb)	9.14	7.35
Volatile solids (lb)	7.77	5.34
BOD, 5-day (lb)	1.3	0.89
COD (lb)	8.3	5.67
TKN (lb)	0.31	0.23
Ammonium-N (lb)	ND	ND
Total P (lb)	0.04	0.38
Orthophosphorus (lb)	ND	ND
K (lb)	0.24	0.2
Calcium (lb)	ND	ND
Magnesium (lb)	ND	ND

Sources: USDA, 1996; NCSU, 1994.
ND No data.

EPA used beef waste characteristic data from USDA in the NWQI analyses. Lander et al. averaged values from the MWPS, USDA, and NCSU datasets for N, P, and K. EPA used Lander data in the estimation of compliance costs for beef feedlots and dairies. Table 6-47 presents Lander's averaged values for beef manure. EPA used USDA data in the estimation of compliance costs for heifer operations.

Table 6-47. Average Nutrient Values in Fresh (As-Excreted) Beef Manure.

Parameter	Beef (lb/day/1,000-lb animal)[a]
TKN	0.32
Ammonia	ND
Total P	0.098
K	0.23

Source: Lander et al., 1998.
[a] Lander's analysis relied upon 1990 NCSU data, while the NCSU data presented in this report is from 1994.
ND No Data.

6.4.2.2 Composition of Beef and Heifer Feedlot Waste

The characteristics of beef and heifer feedlot wastes vary widely because of differences in climate, rainfall, diet, feedlot surface, animal density, and cleaning frequency. Wasted feed and soil in unpaved feedlots is readily mixed with the manure because of animal movement and

cleaning operations (Arrington et al., 1981). Therefore, due to the incorporation of more solids and exposure to the elements, the moisture content of beef feedlot waste is significantly lower than for fresh beef manure.

Table 6-48 presents characteristics of beef waste collected from unpaved and paved feedlots (USDA, 1992). Most feedlots are unpaved. However, for paved lots, concrete is the most common paving material, although other materials (e.g., fly ash) have been used (Suszkiw, 1999). EPA used this USDA data in the NWQI analyses to calculate N losses during composting. Table 6-49 presents NCSU data on scraped beef manure from an unpaved surface.

Table 6-48. Beef Waste Characterization—Feedlot Waste.

Component	Units	Unpaved Lot[a]	Paved Lot[b]	
			High-Forage Diet	High-Energy Diet
Weight	lb/d/1000lb	17.5	11.7	5.3
Moisture	%	45	53.3	52.1
Total Solids	% wet basis	55	46.7	47.9
Total Solids	lb/d/1000lb	9.6	5.5	2.5
Volatile Solids	lb/d/1000lb	4.8	3.85	1.75
Fixed Solids	lb/d/1000lb	4.8	1.65	0.76
N	lb/d/1000lb	0.21	ND	ND
P	lb/d/1000lb	0.14	ND	ND
K	lb/d/1000lb	0.03	ND	ND
C:N ratio	unitless	13	ND	ND

Source: USDA NRCS, 1992.
[a] Dry climate (annual rainfall less than 15 inches); annual manure removal.
[b] Dry climate; semiannual manure removal.
ND No data.

Table 6-49. Beef Manure Characteristics Per 1,000 Lbs. Live Weight Per Day From Scraped Unpaved Surface.

Parameter	Unit	Value
Total solids	lb	9.4
Volatile solids	lb	5.3
TKN	lb	0.20
Ammonium-N	lb	0.38
Total P	lb	0.062
K	lb	0.14

Source: NCSU, 1994.

Sweeten, et al., compiled and compared feedlot waste data representing "as-collected" waste, composted waste, and stockpiled waste from one area of the country (Sweeten et al., 1997). The Sweeten report was used in the estimation of compliance costs for beef feedlots and dairies and the NWQI report for calculations using the moisture content of manure. The agency also used the report's levels of annual costs, volatile solids, and N content of composting to determine emissions for the nonwater quality impact analysis.

6.4.2.3 Composition of Aged Manure

Beef cattle feedlots typically scrape and remove the manure that is deposited on the ground about every 120 to 365 days, as opposed to dairies that scrape or remove manure as often as every day. During this "aging" process, nutrients are lost due to ammonia volatilization, runoff, and leaching. Mathers et al. determined average nutrient concentrations in aged manure ready for land application from 23 beef cattle feedlots in the Texas High Plains (Mathers et al., 1972). Since EPA has not identified national data on aged manure characteristics, these local data are presented in Table 6-50 to demonstrate the significant difference in characteristics of fresh and aged manure.

These data show that the aged beef manure N concentration is 40.3 percent of the fresh manure concentration, while P and K in aged manure are 50.9 percent and 64.5 percent, respectively, of their concentrations in fresh manure. N losses as high as 50 percent have been reported in aged beef manure due to temperature, moisture, pH, and C:N ratio. Phosphorus and K losses are primarily due to runoff but may also occur because of leaching.

Table 6-50. Percentage of Nutrients in Fresh and Aged Beef Cattle Manure.

Parameter	Unit	Fresh Manure	Aged Manure
Moisture	%	88	34
N	% dry basis	5.08	2.05
P	% dry basis	1.59	0.81
K	% dry basis	3.55	2.29

Source: Mathers et al. 1972.

6.4.2.4 Composition of Runoff from Beef and Heifer Feedlots

As with feedlot wastes, constituent characteristics of beef and heifer feedlot runoff also vary across the country. The factors that are responsible for runoff waste variations are similar to those for feedlot wastes (i.e., climate, rainfall, diet, feedlot surface, animal density, and cleaning frequency). Paved feedlots produce more runoff than unpaved lots, and areas of high rainfall and low evaporation produce more runoff than arid areas.

Numerous analyses characterizing the runoff from beef feedlots have been conducted on a local level. However, manure characteristics data collected at a local level may not be representative of

the beef industry as a whole. Since the constituent concentration of feedlot runoff varies among different areas of the country, this report presents only nationally available manure characteristics and regional estimates of feedlot runoff characteristics.

The USDA *AWMFH* characterizes both the supernatant and sludge from beef feedlot runoff lagoons. EPA used these data in the estimation of compliance costs for beef feedlots and dairies, and NWQI analyses. Table 6-51 presents these waste characteristics.

Table 6-51. Beef Waste Characterization—Feedlot Runoff Lagoon.

Component	Units	Runoff Lagoon	
		Supernatant	Sludge
Moisture	%	99.7	82.8
Total Solids	% wet basis	0.3	17.2
Volatile Solids	lb/1,000 gal	7.5	644.83
Fixed Solids	lb/1,000 gal	17.5	788.12
COD	lb/1,000 gal	11.67	644.83
N	lb/1,000 gal	1.67	51.66
NH_4-N	lb/1,000 gal	1.5	ND
P	lb/1,000 gal	ND	17.5
K	lb/1,000 gal	7.5	14.17
Copper	lb/lb	ND	1.94×10^{-4}
Zinc	lb/lb	ND	9.29×10^{-4}

Source: USDA NRCS, 1992; NCSU, 1994.
ND No data.

6.5 Veal Waste

This section describes the characteristics of veal manure and waste. In this section, manure refers to the combination of feces and urine, and waste refers to manure plus other material such as hair, soil, and spilled feed. Due to the nature of veal operations, however, even fresh manure may also contain small amounts of hair and feed.

This section discusses the following:

- Section 6.5.1: Quantity of manure generated; and
- Section 6.5.2: Waste constituents and concentrations.

6.5.1 Quantity of Manure Generated

National data on veal waste characteristics are available from the following three data sources:

- ASAE Standard D384.1: *Manure Production and Characteristics*, 1999. This data source contains national fresh manure characteristic values by animal type (e.g., dairy, beef, veal, swine).
- USDA, *AWMFH*, Chapter 4, 1996. This data source contains national manure characteristic values for fresh and managed manure (e.g., lagoon supernatant, feedlot runoff) by animal type including subtypes such as veal.
- NCSU, *Livestock Manure Production and Characterization in North Carolina*, 1994. This data source contains regional manure characteristic values for fresh and managed manure by animal type including subtypes.

Table 6-52 presents the average fresh manure characteristics for veal from these three data sources. EPA used USDA data in the estimation of compliance costs for veal operations.

Table 6-52. Average Weight of Fresh Veal Manure.

Data Source	Quantity of Manure (wet basis) (lb/day/1,000 lb animal)
ASAE Standard	62
USDA *AWMFA*	60
NCSU, *Livestock Manure Production and Characterization in North Carolina*	61.76

6.5.2 Waste Constituents and Concentrations

The composition and concentrations of veal waste vary from the time that it is excreted to the time it is ultimately used as a fertilizer or soil amendment. Nutrients and metals are expected to be present in veal waste due to the constituents of the feed. This section discusses the composition of fresh manure.

Table 6-53 presents data for nine metals and nutrients found in fresh veal manure. Veal manure is very fluid, with the consistency of a sloppy mortar mix, and is often diluted by large volumes of wash water (Meyer, 1987). The moisture content of fresh veal manure is approximately 98 percent (USDA, 1992).

Veal manure is typically stored in tanks, basins, and pits until it is pumped out onto the land as fertilizer. However, most of the fertilizer value of veal manure remains in the solids in a settling tank (Meyer, 1987). Over time, the most significant compositional change in veal manure, stored in pits, is the conversion of organic-N in fresh manure to ammonium-N and loss of total N to the

atmosphere in the form of ammonia. Much of the high ammonia loss is due to microbial degradation of the organic matter including total N components (Sutton et al., 1989). EPA used USDA data in the estimating compliance costs and NWQI analyses for veal operations.

Table 6-53. Fresh Veal Manure Characteristics Per 1,000 Lbs. Live Weight Per Day.

Parameter	Unit	Mean (Veal)		
		ASAE	USDA	NCSU
Moisture	%	97.5	97.5	ND
Weight	lb	62	60	61.8
Total solids	lb	5.2	1.5	4.0
Volatile solids	lb	2.3	0.85	2.1
BOD (5-day)	lb	1.7	0.37	0.83
COD	lb	5.3	1.5	1.5
pH	lb	8.1	ND	7.7
TKN	lb	0.27	0.20	0.24
Ammonium-N	lb	0.12	ND	0.11
Total P	lb	0.066	0.03	0.053
K	lb	0.28	0.25	0.27
Calcium	lb	0.059	ND	0.059
Magnesium	lb	0.033	ND	0.33
Sodium	lb	0.086	ND	0.16
Iron	lb	0.00033	ND	0.00033
Zinc	lb	0.013	ND	0.013
Copper	lb	0.000048	ND	0.000048

Source: ASAE, 1999; USDA, 1996; NCSD, 1994.
ND No data.

6.6 Horse Waste

The horse industry raises animals for diverse uses, including pleasure, showing, breeding, racing, farm/ranch, and other minor uses. Because the horse industry is so diverse and much of the population is off farm, statistics on horse production are less available than other livestock.

6.6.1 Quantity of Manure Generated

An average 1,000-pound horse generates approximately 9 tons of manure a year (51 pounds per day). The volume of this solid excrement ranges from 0.75 to 1.0 cubic foot per day. Urine production ranges from 2.25 to 8 gallons per day depending upon diet, activity, and environmental conditions (Wheeler and Cirelli, 1995). Depending on practices, substantial amounts of bedding are added to the wastes.

6.6.2 Horse Waste Characteristics

The characteristics of horse waste will vary by the type of diet fed to the animal, which can range from low-nutrient crops such as Bermuda grass to N-rich forages such as clover, in addition to supplemental feeding. Since horses, unlike ruminants, are limited in their ability to use forages of low nutritive value, feeding regimes require a greater level of management, especially for horses raised primarily in pastures.

6.7 References

Arrington, R.M., and C.E. Pachek. 1981. Soil Nutrient Content in Manures in an Arid Climate. In *Livestock Waste: A Renewable Resource, Proceedings of the Fourth International Symposium on Livestock Waste, 1980*, pp. 15-152. American Society of Agricultural Engineers, St. Joseph, Michigan.

ASAE. 1998. *ASAE Standards 1998, 45th ed.* American Society of Agricultural Engineers, St. Joseph, Michigan.

ASAE. 1999. *Manure Production and Characteristics*. American Society of Agricultural Engineers, St. Joseph, Michagan.

Barney, S., P. Davis, N.R. Deuel, F.E. Gilman, J. Hodson, B.A. Marriott, J.D. Minnick, T.F. Mitchell, J.R. Mitchell, E. Poole, and E.S. Taylor. 1990. *Good Neighbor Guide for Horse-Keeping: Manure Management.* New Hampshire Department of Environmental Services, University of New Hampshire Cooperative Extension, New Hampshire Department of Agriculture, U.S. Department of Agriculture, Soil Conservation Service.

Blume and McCleve. 1997. Disposal of Swine Wastewater Using Spray Nozzle. ASAE Paper No. 974072. Presented at the ASAE Annual International Meeting, American Society of Agricultural Engineers, Minneapolis, Minnesota, August 10-14, 1997.

Boland et. al. 1997. Analysis of Manure Management Systems and Phytase Adoption by Pork Producers. Livestock Environment 5, Volume 2. In *Proceedings of the Fifth International Symposium*, Bloomington, Minnesota, May 29-31, 1997, pp. 702-709.

Florida Agricultural Information Retrieval System. 1998. *Animal Manures.* <http://hammock.ifas.ufl.edu/txt/fairs/29659>. Accessed July 15, 1998.

Fulhage. 1998. Composting Dead Animals- The Missouri Experience. Presented at the ASAE Annual International Meeting. American Society of Agricultural Engineers, Orlando, Florida, July 12-16, 1998.

Graves, R.E. 1987. *Animal Manure – Manure Management for Horses*. PENpages Number: 0870177. Pennsylvania State University, Agricultural Engineering Department.

Jones, D. D., and A. Sutton. 1994. *"Treatment Options for Liquid Manure" in Liquid Manure Application Systems: Design, Management, and Environmental Assessment, Proceedings from the Liquid Manure Application Systems Conference*. Rochester, New York, Dec. 1-2, 1994.

Lander, C.H., D. Moffitt, and K. Alt. 1998. *Nutrients Available from Livestock Manure Relative to Crop Growth Requirements*. U.S. Department of Agriculture, Natural Resources Conservation Services, Washington, DC.

Lander, C.H. 1999. *Dairy Manure Characteristics*. National Milk Producers Federation submittal to EPA.

Loudon, T.L., et. al. 1985. *Livestock Waste Facilities Handbook*, 2nd ed. Midwest Plan Service.

Mathers, A.C., B.A. Stewart, J.D. Thomas, and B.J. Blair. 1972. *Effects of Cattle Feedlot Manure on Crop Yields and Soil Conditions*. Tech. Rep. No. 11, USDA Southwestern Great Plains Research Center Bushland, Texas.

Meyer, D. J. 1987. *Animal Manure—Veal Calf Management.* <http://www.inform.umd.edu:8080/EdRes/topic/AgrEnv/ndd/watermgt/ANIMAL_MANURE_VEAL_CALF_MANAGEM.html>.

MWPS (Midwest Planning Service). 1985. *Livestock Waste Facilities Handbook.*

MWPS. 1993. MWPS-18: *Livestock Waste Facilities Handbook.* 3rd ed. Midwest Plan Service, Iowa State University, Ames, Iowa.

NCSU. 1994. *Livestock Manure Production and Characterization in North Carolina*. North Carolina State University Cooperative Extension Service, Raleigh, North Carolina.

Suszkiw, J. 1999. *Low-Cost Way to Pave Feedlots*. Agricultural Research.

Sutton. A.L., M.D. Cunningham, J.A. Knesel, and D.T. Kelly. 1989. *Veal Calf Waste Production and Composition*. Applied Engineering in Agriculture, Vol 5, No. 1.

Svoboda. 1995. Nitrogen Removal from Pig Slurry by Nitrification and Denitrification. In

Proceedings of the Seventh International Symposium on Agricultural and Food Processing Wastes, organization, Chicago, Illinois, June 18-20, 1995 pp. 702-709.

Sweeten, J.M. and S.H. Amosson. 1995. *Total Quality Manure Management*, Texas Cattle Feeders Association. Chapter 4: Manure Quality and Economics.

Sweeten, J.M., S.H. Amosson, and B.W. Auvermann. 1997. Manure Quality and Economics. In Proceedings of Texas Biomass Energy Opportunities Workshop Series #1: Livestock Waste Streams: Energy and Environment. Texas A&M University Agricultural Research and Extension Center.

TAES. 1996. *Manure Analysis Summary—Coal Ash Surfacing vs Control Treatments for Beef Cattle Feedyards*. Result Demonstration Report. Texas Agricultural Extension Service.

USDA. 1992. *National Engineering Handbook: Agricultural Waste Management Field Handbook.* U.S. Department of Commerce, National Technical Information Service. Springfield, Virginia.

USDA. 1998. *Nutrients Available from Livestock Manure Relative to Crop Growth Requirements.* <http://www.nhq.nrcs.usda.gov/land/pubs/nlweb.html>. Accessed August 23, 1998.

USDA. 1999. 1997 Agricultural Resource Management Study (ARMS). U.S. Department of Agriculture, Economic Research Service.

USDA APHIS. 1995. *Swine '95 Part I: Reference of 1995 Swine Management Practices.* <http://www.aphis.usda.gov/vs/ceah/cahm/>. File sw95des1.pdf accessed October 15, 1998. U.S. Department of Agriculture, Animal and Plant Health Inspection Service.

USDA ARS. 1998. *Agricultural Uses of Municipal, Animal and Industrial Byproducts*. U.S. Department of Agriculture, Agricultural Research Service. <http://www.ars.usda.gov/is/np/agbyintro.htm>

USDA NRCS. 1992. *Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH)*, Part 651. U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS). <http://www.ncg.nrcs.usda.gov/awmfh.html>

Van Horn, H.H., G.L. Newton, R.A. Nordstedt, E.C. Krench, G. Kidder, D.A. Graetz, and C.F. Chambliss. 1998. *Circular 1016: Dairy Manure Management: Strategies for Recycling Nutrients to Recover Fertilizer Value and Avoid Environmental Pollution.* Dairy and Poultry Sciences Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

Zublena, J.P., Barker, Parker, and Stanislaw. 1993. *Soil Facts*. North Carolina Cooperative Extension Service.

CHAPTER 7

POLLUTANTS OF INTEREST

7.0 INTRODUCTION

Pollution generated at feedlot operations can arise from multiple sources. These sources, including animal waste, process wash waters, litter, animal carcasses, spills of pesticides, and pharmaceuticals, are the primary sources of potential environmental contamination.

Excreted animal waste contains undigested and partially digested feed, partially metabolized organic material, dead and living microorganisms from the digestive tract, cell wall material and other organic debris from the digestive tract, and excess digestive juices. Additional microorganisms may grow in the waste after it has been excreted. Depending on the type of feed provided to the animals and whether feed additives have been used, animal wastes can also contain pharmaceuticals (antibiotics and hormones), and trace inorganic elements.

Animal carcasses, which may contain pathogens, nutrients, and chemical toxicants, can pose an environmental problem, especially in the poultry industry where many operations have historically used burial as a means for disposal. For example, during 1990, several state agencies in Arkansas tested the management of dead-bird disposal pits and found high soil concentrations of ammonium (USEPA, 1999). Improper disposal of poultry carcasses has been implicated in ground water contamination; however, in recent years, greater regulation of animal disposal has reduced the risk of environmental contamination from buried animal carcasses. Arkansas, for example, has outlawed the use of dead-bird disposal pits. Other states have also issued guidelines or regulations for disposal of animal carcasses and require operators to use specific practices such as composting.

In the preliminary study on environmental impacts from animal feedlot operations, EPA (1998) identified and described the major animal waste constituents that can adversely affect the environment. Additional information on potential impacts can be found in the *Environmental Assessment of Proposed Revisions to the National Pollutant Discharge Elimination System Regulation and Effluent Limitations Guidelines for Concentrated Animal Feeding Operations* (USEPA, 2000). As demonstrated in Chapter 6, the physical and chemical characteristics of manure differ between animal sectors as well as within animal sectors. The following pollutants of interest identified by EPA in its preliminary feedlots study are described below:

- Nutrients (nitrogen, phosphorus)
- Total suspended solids (including sediment)
- Biochemical oxygen demand (BOD)

- Pathogen
- Chemical oxygen demand (COD)
- Other contaminants including salts, trace elements, and pharmaceuticals

Exposure pathways of contaminants in soil include direct ingestion, inhalation of dusts, ingestion of ground or surface water contaminated from migration of chemicals through soil or runoff from soil, dermal absorption, and ingestion of produce that has been contaminated through plant uptake (USEPA, 1996). Constituents in manure will have an impact on water quality if significant amounts reach surface or ground water. Management practices can reduce or block the potential transport of these constituents. Movement of constituents in manure is driven primarily by precipitation events, runoff and erosion of soluble and particulate components, leaching to ground water of soluble compounds, and wind erosion of dry material (USEPA, 2000).

7.1 Conventional Waste Pollutants

Biochemical Oxygen Demand

BOD is a measure of the oxygen-consuming requirements of organic matter decomposition. When animal waste is discharged to surface water, it is decomposed by aquatic bacteria and other microorganisms. Decomposing organic matter consumes oxygen and reduces the amount available for aquatic animals. Severe reductions in dissolved oxygen levels can lead to fish kills. Even moderate decreases in oxygen levels can adversely affect waterbodies through decreases in biodiversity as manifested by the loss of fish and other aquatic animal populations.

Total Suspended Solids

Suspended solids can clog fish gills and increase turbidity. Increased turbidity reduces penetration of light through the water column, thereby limiting the growth of desirable aquatic plants that serve as a critical habitat for fish, shellfish, and other aquatic organisms. Solids that settle out as bottom deposits can alter or destroy habitat for fish and benthic organisms. Solids also provide a medium for the accumulation, transport, and storage of other pollutants including nutrients, pathogens, and trace elements. Sediment-bound pollutants often have an extended interaction with the water column through cycles of deposition, resuspension, and redeposition.

Fecal Coliform Bacteria

Manure contains diverse microbial populations. Included are members of the normal gastrointestinal tract flora, such as members of the fecal coliform and fecal streptococcus groups of bacteria. These are the groups of bacteria commonly used as indicators of fecal contamination and the possible presence of pathogenic species. A discussion of pathogens found in the waste of AFOs is given in section 7.2.

7.2 Nonconventional Pollutants

Nutrients (Nitrogen, Phosphorus)

Because of its nutrient content, animal manure can serve as a valuable agricultural resource. In an area where the amount of nutrients in manure generated from AFOs is greater than the nutrient requirements of the crops grown in the area, excess land application has occurred, which can lead to increased nutrient runoff and seepage and subsequent degradation of water resources.

As noted in Chapter 6, wastes contain significant quantities of nutrients, particularly nitrogen (N) and phosphorus (P). Manure N occurs primarily in the form of organic-N and ammonia-N compounds. In its organic form, N is unavailable to plants. However, through bacterial decomposition, organic-N is transformed into ammonia, which is oxidized (by nitrification) to nitrite and ultimately to nitrate. Ammonia and nitrate are bioavailable and therefore have fertilizer value. These forms can also produce adverse environmental impacts when they are transported in excess quantities to the environment.

Ammonia. "Ammonia-N" includes the ionized form (ammonium) and the un-ionized form (ammonia). Ammonium is produced when microorganisms break down organic-N products in manure, such as urea and proteins. This decomposition can occur under aerobic or anaerobic conditions. Both forms are toxic to aquatic life, although the un-ionized form (ammonia) is much more toxic.

Ammonia is of environmental concern because it exerts a direct BOD on the receiving water. Ammonia can lead to eutrophication, or nutrient overenrichment, of surface waters. Ammonia itself is a nutrient and is also easily transformed to nitrate (another nutrient form of N) in the presence of oxygen. Although nutrients are necessary for a healthy ecosystem, the overabundance of nutrients (particularly N and P) can lead to nuisance algae blooms.

Nitrate. Nitrite is toxic to most fish and other aquatic species, but it usually does not accumulate in the environment because of its rapid conversion to nitrate in an aerobic environment. Nitrate is a valuable fertilizer because it is biologically available to plants. Excessive levels of nitrate in drinking water, however, can produce adverse human health and environmental impacts. For example, human infants exposed to high levels of nitrate can develop methemoglobinemia, commonly referred to as "blue baby syndrome" because the lack of oxygen can cause the skin to appear bluish in color. To protect human health, EPA has set a drinking water maximum contaminant level (MCL) of 10 mg/L for nitrate-N. N is the primary contributor to eutrophication in brackish and saline waters (USEPA, 2000).

N is interchanged among the atmosphere and organic matter and inorganic compounds in soil or water through the N cycle. The biological transformations of N that make up this process include N fixation, nitrate reduction, and denitification. Atmospheric nitrogen (N_2) can be bound by microorganisms with carbohydrates, water, and hydrogen to form ammonium and carbon dioxide

in the process of N fixation. Aquatic microorganisms with the ability to fix atmospheric nitrogen include photosynthetic bacteria, *Azotobacter*, and some species of *Clostridium*. In soil, *Rhizobium* can fix atmospheric nitrogen in the root nodules of leguminous plants. Ammonium can be further converted by *Nitromonas* and *Nitrobacter* bacteria into nitrite and nitrate, respectively, in the process of nitrate reduction. This process provides most plants with the form of N they are able to absorb (nitrate). Ammonium present in animal manure can also be converted into nitrate by these bacteria for use by plants. Denitrification is the process by which fixed N present in soil or water is returned to the atmosphere by bacteria in the form of N_2, allowing the N cycle to begin again (Manahan, 1991).

Phosphorus. Animal wastes contain both organic and inorganic forms of P. P occurs almost exclusively in the form of inorganic and organic phosphates in natural waters. Organic phosphate is phosphate associated with a carbon-based molecule such as plant or animal tissue. Phosphate not associated with organic matter is inorganic, which is the form required for uptake by plants. Animals can use organic or inorganic phosphate. Both organic and inorganic forms can be dissolved in water or suspended (attached to particles in the water column). Sources of P include soil and rocks, wastewater treatment plants, runoff from fertilized lawns and cropland, failing septic systems, runoff from animal manure storage areas, disturbed land areas, drained wetlands, water treatment, and commercial cleaning preparations (USEPA, 2002a). The majority of P binds to mineral and organic particles in manure and is subject to runoff and erosion more than leaching except in very sandy soils with low P-binding capacity (USEPA, 2000).

P is of concern in surface waters because it is a nutrient that can lead to eutrophication and the resulting adverse impacts—fish kills, reduced biodiversity, objectionable tastes and odors, increased drinking water treatment costs, and growth of toxic organisms. At concentrations greater than 1.0 mg/L, P can interfere with coagulation in drinking water treatment plants (Bartenhagen et al., 1994).

P is of particular concern in fresh waters, where plant growth is typically limited by phosphorous levels. Under high pollutant loads, however, fresh water may become nitrogen-limited (Bartenhagen et al., 1994). Thus, both N and P loads may contribute to eutrophication.

P is interchanged in an aquatic ecosystem through the P cycle. Inorganic P from various natural and human sources is taken up by plants and converted to organic P. Animals graze on plants and thereby take up organic P. Organic P is released to the ecosystem in animal feces and in decaying animals and plants, generally to the bottom of the lake or stream. Bacterial decomposition converts organic P into inorganic P in both dissolved and suspended forms. Inorganic P is returned to the water column, allowing the P cycle to begin again, when the bottom of the waterbody is disturbed by animals, human activity, chemical interactions, or water currents. In streams, P tends to move downstream over time because the current carries decomposing plant and animal material and dissolved P downstream. P is stationary in waterbodies only when taken it is taken up by plants or bound to particles that settle to the bottom of pools (USEPA, 2002a).

Chemical Oxygen Demand

COD is another measure of oxygen-consuming pollutants in water. The COD test differs from the BOD test in that it measures the amount of oxygen required to oxidize all organic matter present in a sample regardless of how biologically assimilable the organic matter is because it uses a strong chemical oxidizing agent instead of microorganisms to oxidize the organic compounds in a sample (Masters, 1997). BOD only measures the oxygen required to oxidize biologically degradable material present in a sample. The COD test is used to measure oxygen-consuming pollutants in water because all organic compounds, with few exceptions, can be oxidized by the action of strong oxidizing agents under acidic conditions. The measured value of COD is generally greater than BOD in a sample, although these values are similar in samples containing easily biodegradable material. Because the COD test can be performed more quickly than the BOD test, it is sometimes used to estimate BOD.

Pathogens

Manure contains diverse microbial populations. There are many examples that demonstrate that pathogens from manure can be a problem. Other studies show that manured fields do not pose a significant threat to surface waters. Most pathogens present in animal manure are from the gastrointestinal tract and can be divided into those pathogens that are highly host-adapted and not considered to be pathogenic to humans and those that are capable of causing infection in humans (zoonoses). For example, most *Salmonellae* are zoonoses, but *S. pulloram* and *S. gallinarum*, which might be present in poultry manures, are not. However, each of these species may be included in gross estimates of *Salmonella* densities. The pathogens that might be present in poultry and swine manures can also be divided into those microorganisms which are commonly present and those which are less common. For example in poultry manures, *Campylobacter jejuni* is commonly present while *Mycobacterium avium* is less common. These distinctions are important in assessing the potential public health risks associated with poultry and swine operations, as well as other animal feeding operations.

The interactions between pathogens, cattle, and the environment are not well understood but current literature suggests that dairy and beef cattle shed pathogens that are known to be infectious to humans. The threat posed by pathogens in animal manure is influenced by the source, pH, dry matter, microbial, and chemical content of the feces. Solid manure that is mixed with bedding material is more likely to undergo aerobic fermentation in which temperature increases reduce the number of viable pathogens. However, some pathogens grow under a wide range of conditions that makes their control very difficult. Quantifying the risk associated with these pathogens is thus challenging. Rapidly changing pathogen numbers, changes in the infective status of the host, and survivability of the pathogens all make it increasingly difficult to determine how much of a threat animal-excreted pathogens are to society. Moreover, methods of pathogen detection produce varying results, making it difficult to compare studies that use different analyses (Pell, 1997).

The most common pathogens and found in animal manures and capable of causing disease in humans are *Salmonella*, *Escherichia coli*, *Bacillus anthracis*, *Mycrobacterium paratuberculosis*, *Brucella abortus*, *Leptospira* spp., *Chlamydia* spp., *Rickettsia* spp., and *Listeria monocytogenes* (Epstein, 1998). In addition, *Cryptosporidium parvum* oocysts (the eggs of a protozoan parasite that can cause gastrointestinal illness in humans) found in calf and pig manure (USDA, 1996) and *Giardia* oocysts in young dairy cattle manure (Pell, 1997) appear to be infectious to humans.

Unlike biosolids, the bacterial content of animal manure is currently not regulated; however, the Federal Part 257 regulation does include provisions regarding general management of these materials to help ensure that practices will not impact threatened or endangered species or habitat be either a direct discharge or a nonpoint source of pollutants or contaminate underground drinking water sources (USEPA, 2000). Fecal coliform, fecal streptococci, *Escherichia coli*, and enterococci are commonly used indicators of human and animal fecal contamination. These bacteria are not harmful in themselves but they indicate the possible presence of pathogenic bacteria, viruses, and protozoa that live in human and animal digestive systems. Because it is difficult to test for the pathogens themselves, tests for indicator bacteria are used instead (USEPA, 2002b).

EPA now recommends that enterococci and *Escherichia coli* be used as indicators of fecal contamination in fresh water and enterococci be used as an indicator of fecal contamination in salt water; however, several states continue to use fecal coliform as their indicator water quality standard (USEPA, 2002b). Indicator bacteria can be used to determine whether surface waters have been contaminated from manure applied to nearby fields. In the past, fecal streptococci and fecal coliform were monitored together and a ratio of fecal coliform to streptococci was calculated to determine whether the contamination was of human or nonhuman origin; however, this ratio is no longer recommended by EPA (USEPA, 2002b).

The levels of fecal coliform and fecal streptococci bacteria have been measured in the manure of several livestock animal types. Fecal coliform bacterial densities were measured in units of colonies/1,000 kg live animal mass per day at densities of 45 ± 27 for sheep; 18 ± 12 for swine; 7.5 ± 2.0 for layer chickens; and 16 ± 28 for dairy cows. Fecal streptococci bacterial densities were measured in units of colonies/1,000 kg live animal mass per day at densities of 62 ± 73 for sheep; 530 ± 290 for swine; 16 ± 7.2 for layer chickens; and 92 ± 140 for dairy cows (ASAE, 1999).

For additional information on pathogens see the *Environmental and Economic Benefit Analysis* and the *Environmental Assessment*.

Other Potential Contaminants

Animal wastes can contain other chemical constituents that could adversely affect the environment. These constituents include salts trace elements and pharmaceuticals, including antibiotics. Although salts are usually present in waste regardless of animal or feed type, trace

elements and pharmaceuticals are typically the result of feed additives to help prevent disease or promote growth. Accordingly, concentrations of these constituents will vary with operation type and from facility to facility.

Salts and trace elements. Animal manure contains dissolved mineral salts. The major cations contributing to salinity are sodium, calcium, magnesium, and potassium; the major anions are chloride, sulfate, bicarbonate, carbonate, and nitrate. In land-applied wastes, salinity is a concern because salts can accumulate in the soil and become toxic to plants; they can also deteriorate soil quality by reducing permeability and contributing to poor tilth. Direct discharges and salt runoff to fresh surface waters contribute to salinization and can disrupt the balance of the ecosystem. Leaching salts can deteriorate ground water quality, making it unsuitable for human consumption. Trace elements such as arsenic, copper, selenium, and zinc are often added to animal feed as growth stimulants or biocides (Sims, 1995). When applied to land, these elements can accumulate in soils and become toxic to plants, and can affect human and ecological health.

Metals in potentially toxic concentrations in poultry, swine, and cow manures include arsenic, cadmium, copper, lead, molybdenum, nickel, selenium, and zinc (Overcash, et al., 1983). In promulgating standards for the disposal of sewage sludges by land application, EPA has established maximum allowable concentrations and cumulative loading limits for each of these metals as well as beryllium and mercury (Federal Register, 1989). It has generally been assumed that the metal concentrations in manure are well below those allowable for land application of wastewater treatment sludge; however, metal loadings may accumulate in cropland to which manure has been applied for many years.

Selenium and arsenic (as arsinilic acid) supplementation of complete feeds for poultry and swine is directly limited by EPA to 0.3 ppm and 90 ton of feed, respectively (21 CFR 573.920; 21 CFR 558.62). Copper and zinc are fed to swine as growth stimulants at levels significantly above nutritional requirements (Dritz et al., 1997). Arsenic is fed as a growth stimulant to broiler chickens. Drugs administered either prophylactically or therapeutically can also contain metals. Also, concentrated sources of macrominerals such as calcium might contain metals such as copper, manganese, and zinc, as well as other metals with no biological value. Copper and zinc in freshly excreted poultry and swine waste has been measured at concentrations between 12 and 15 mg/kg of total solids and between 42 and 310 mg/kg of total solids, respectively (Barker and Zublena, 1995).

Unlike poultry and swine, cattle are typically not fed excess amounts of metals because these metals do not have a growth-promoting effect on cattle. Zinc and copper in dry manure have been measured at concentrations of 50 mg/kg and 180 mg/kg, respectively in dairy cattle, and 25 mg/kg and 110 mg/kg, respectively in beef cattle. The differences in manure concentrations most likely occurred because enriched mineral supplements were supplied to the dairy cattle but not to the beef cattle (Nicholson, 1999).

Metals not essential for plant or animal nutrition are a concern because they do not degrade over time, they are relatively immobile, and they accumulate in the upper layers of the soil (Rutgers Cooperative Extension, 2000). Heavy metal concentrations in various fertilizers differ and large variabilities in concentration occur within the same fertilizer type. Researchers at Rutgers Cooperative Extension used measured metal concentrations in manure from existing studies to predict the concentrations of metals in soil after 100 years of application at rates of 6.2, 3.2, and 1.8 dry tons for dairy, poultry, and swine manure, respectively. From their model results, the researchers predicted that copper, lead, and zinc would persist in the soil.

According to a draft study performed by the Water Environment Research Foundation (WERF), farmers apply 120 million dry tons of animal manure on their farmlands annually. The draft WERF study results show that metal concentrations in swine and poultry manures are comparable to those in biosolids. The bioavailability and mobility of metals in soil is dependent on their form. Oxide-bound and organically bound metals largely remain immobile and are not absorbed by plants, while water soluble forms are more likely to be taken up by plants or to be carried off-site in runoff. The investigators for the WERF study are planning to perform more research on the metal leachability of manures, biosolids, and fertilizers (Spicer, 2002). This information will help to determine the impact of these heavy metals on humans and on the environment.

Researchers have found that aberrations and damage occurred in a high percentage of sperm cells from earthworms (*Eisenia fetida*) with elevated body burdens of heavy metals. The researchers exposed these earthworms to metals in their feed by placing them in cattle manure to which either 0.01 percent of lead or 1,000 micromoles/gram of manganese salts were added (Reinecke and Reinecke, 1997). High metal concentrations in soil may affect the ability of earthworms to reproduce and consequently affect soil fertility.

Heavy metals in soil can also adversely affect plant growth and survival and can accumulate in plants and subsequently affect the health of humans and animals who eat or use the plant products. Cadmium in soil is readily absorbed by tobacco, mushrooms, spinach, and other leafy vegetables. When tobacco is smoked, much of the cadmium is taken up by the human body. The National Research Council has recommended that the cadmium content of crops used to feed animals should be 0.5 mg/kg or less to reduce the cadmium concentration in meat (Cornell University, 1993). Symptoms of acute toxicity from ingestion of cadmium in humans include nausea, vomiting, and abdominal pain. Long-term effect of low-level exposure to cadmium are lung disease, emphysema, and kidney disease (Klaasen, 1996). Lead and arsenic are generally not absorbed by field crops; however, an accumulation of lead or arsenic in the soil may pose a risk to children and animals that might eat the soil (Klaasen, 1996). Lead exposure can adversely affect the nervous system, especially in children, which can lead to neurological, neurobehaviorial, and developmental impacts. Ingestion of large doses of arsenic (70 to 80 mg) can cause fever, anorexia, and heart arrhythmia, and can lead to death in humans. Long-term exposure to low concentrations of arsenic can cause adverse effects to the nervous system, peripheral vascular disease, and liver injury (Klaasen, 1996). Copper and zinc are toxic to plants

in large concentrations (Cornell University, 1993). Ingestion by humans of copper and zinc in soil in large enough quantities to cause toxicity is unlikely.

Antibiotics and hormones. A number of pharmacologic agents are used in the production of poultry and swine, among them a variety of antibiotics and hormones. Nonantibiotic antimicrobials, such as sulfonamides, and some antibiotics, such as streptomycin, are used primarily to cure existing infections (therapeutic use). However, most of the antibiotics used in both the swine and the poultry industries are used both therapeutically and nontherapeutically as feed additives to promote growth, to improve feed conversion efficiency, and to prevent disease (Mellon et al., 2001). When antibiotics are used for nontherapeutic uses the dosage rates are substantially lower than when they are administered for therapeutic use.

Mellon and other investigators (2001) estimate that 24.6 million pounds of antibiotics are used annually by livestock producers for nontherapeutic purposes, of which approximately 10.3 million pounds are used in hog production, 10.5 million pounds are used in poultry production, and 3.7 million pounds are used in cattle production. Tetracycline, penicillin, erythromycin, and other antibiotics are commonly used for these nontherapeutic purposes (Mellon, et al., 2001). The antibiotics in manure applied to soil can persist in soil for 1 day to several weeks or longer. The rate of inactivation of these antibiotics is related to the temperature of the soil and the chemical structure of the antibiotic (Gavalchin and Katz, 1994).

Despite the fact that there is little information in the literature about concentrations of antibiotics in poultry and swine manures, it is known that the primary mechanisms of elimination are in urine and bile (Merck and Company, 1998). Approximately 25 to 75 percent of antibiotics administered to feedlot animals could be excreted in the feces (Chee-Sanford, et al., 2001). The form excreted, the unchanged antibiotic or metabolites or some combination thereof, is antibiotic specific, as is the mass distribution among mechanisms of excretion. These compounds may pose risks to humans and the environment. For example, chronic toxicity may result from low-level discharges of antibiotics. For example, chronic toxicity may result from low-level discharges of antibiotics (Merck and Company, 1998).

Use of antibiotics in agriculture might contribute to antimicrobial resistance. The main route of transmission of drug resistance is considered to be consumption of contaminated food. Drug resistance can also be transmitted through natural waters and soil. Lagoons and pit systems are commonly used for waste disposal in animal agriculture operations. Antibiotic and antibiotic-resistant microorganisms have the potential to seep from these waste lagoons into ground water (Chee-Sanford, et al., 2001). The large quantities of antibiotics entering the environment from manure and other sources allow for survival of antibiotic-resistant strains of microorganisms that can start to predominate the microbial population, which can cause certain diseases in humans and animals to be more difficult to treat than they were in the past (Mellon, et al., 2001). For example, an outbreak of salmonellosis in humans has been linked to infection by antibiotic-resistant *Salmonella newport* (Gavalchin and Katz, 1994). Antibiotics introduced in soil through

manure application can also affect the bacterial populations of the soil (Gavalchin and Katz, 1994), which might lead to decreased soil fertility.

Specific hormones are used to increase productivity in the beef and dairy industries but hormones are not used in the poultry or swine industries. Thus, hormones present in poultry and swine manures are only in naturally occurring concentrations. U.S. farmers raise 36 million beef cattle per year of which two-thirds are given hormones. Some steer receive androgens to build their muscle mass and some cows receive female sex hormones to free up resources that would have otherwise been used for the reproductive cycle (Raloff, 2002).

A large portion of hormones passes through cattle in their feces. Waterborne androgen hormones have been detected in waterbodies downstream of animal feedlots. Investigators have found that male fish raised in water obtained from these waterbodies had significantly reduced testicle size in comparison to fish raised in water not containing these hormones, indicating that these waterborne hormones caused male fish to produce less testosterone and to be less fertile than male fish raised in water not containing these hormones. The investigators also suggested that these effects could have been caused by natural androgens and estrogens in manure in addition to or instead of being caused by the synthetic hormones given to the livestock (Raloff, 2002). Also, estrogen hormones in the environment have been implicated in the drastic reduction in sperm counts among men (Sharpe and Skakkebaek, 1993) and reproductive disorders in a variety of wildlife (Colburn et al., 1993).

Hormones in manure applied to soil might be degraded by soil bacteria and photochemical reactions. In addition, hormones might be leached by rain into lower soil horizons or washed directly into surface waters. Dissolved organic matter can bind steroids and enhance their solubility and mobility in the water (Schiffer, et al., 2001), increasing the potential of ground water and surface waters contamination by these compounds.

Schiffer and other investigators (2001) studied the residue and degradation of two growth promoting hormones used in cattle in the United States and Canada, trenbolone acetate and melegestrol acetate, in animal dung, liquid manure, and soil. The researchers found that trenbolone acetate concentrations were 5 to 70 times higher in solid manure than in liquid manure. Trenbolone acetate was determined to have a half-life of 267 days in liquid manure and was partially degraded in solid manure after 4.5 months of storage. The researchers found that trenbolone acetate was not detected in soil fertilized with liquid manure containing this hormone after 40 days; however, they did detect trenbolone acetate in soil 58 days after in had been fertilized with stored solid dung which contained lower concentrations of this hormone than the liquid manure. The researchers suggested that the trenbolone acetate might have adsorbed to the straw material present in the solid dung, which may have protected this hormone from leaching or degrading. The investigators also found that residues of melegestrol acetate in solid dung were more stable than trenbolone acetate because melegestrol acetate concentrations in dung did not decrease significantly after 4 months. They were able to detect melegestrol acetate in soil fertilized with solid manure from the spring until the end of cultivation (Schiffer, et al., 2001).

7.3 Priority Pollutants

The CWA requires states to adopt numeric criteria for priority toxic pollutants if EPA has published criteria guidance and if the discharge or presence of these pollutants could reasonably be expected to interfere with the designated uses of the state's waters. EPA currently lists a total of 126 toxic priority pollutants in 40 CFR 122, Appendix D. Other metal and organic chemicals, however, can cause adverse impacts.

Animal wastes may contain a variety of priority pollutants including the potentially toxic metals: arsenic, cadmium, chromium, copper, lead, molybdenum, nickel, selenium, and zinc (Overcash et al., 1983; ASAE, 1999). In promulgating standards for the disposal of sewage sludges by land application, EPA has established maximum allowable concentrations and cumulative loading limits for each of these metals. Although information about the concentrations of these metals in poultry and livestock manures, and its variability, is quite limited, it generally has been assumed that these concentrations are well below those allowable for land application of wastewater treatment sludges. However, the issue of cumulative loading has been raised periodically in light of long-term use of cropland for manure disposal, especially in areas where poultry and livestock production is concentrated (Sims, 1995).

Given the degree of vertical integration that has occurred in both the poultry and the swine industries, much of the feed manufacturing for these industries is controlled by integrators. Thus, information about the current use of trace mineral supplements in formulating both poultry and swine feeds is difficult to obtain because the integrators consider it proprietary. However, it appears to be a reasonable assumption that arsenic, copper, selenium, and zinc are typically added to poultry feeds and that copper, selenium, and zinc are common components of trace mineral premixes used in the manufacturing of swine feeds. It is probable that commonly used feed supplements also contain some manganese.

Feed amendments of selenium (0.3 part per million) and arsenic (90 grams per ton of feed) are regulated by the U.S. Food and Drug Administration (FDA) (Title 21, Part 573.920 of the Code of Federal Regulations). Levels of other trace minerals as feed supplements are regulated only indirectly by the FDA through maximum allowable concentrations in specified tissues at slaughter or in eggs.

Currently available information about metal concentrations in poultry and swine manures almost exclusively dates back to the 1960s and 1970s (Barker and Zublena, 1995). Kornegay's (1996) data are also somewhat dated, because they are averages over a 14-year period prior to 1992. When compared with Barker and Zublena's data for swine, Kornegay's data suggest that the concentrations of copper and zinc in swine manure have increased significantly over time. However, little is known about the current concentrations of trace metals in poultry and swine manures except that the variations in concentrations are substantial.

7.4 References

ASAE 1999. Manure production and characteristics. AS Data: AS D384.1. American Society of Agricultural Engineers, St. Joseph, Michigan.

Barker, J.C., and J.P. Zublena. 1995. Livestock manure assessment in North Carolina. In *Proceedings of the Seventh International Symposium on Agricultural and Food Processing Wastes,* American Society of Agricultural Engineers, St. Joseph, Michigan, pp. 98-106.

Bartenhagen, Kathryn, et al. 1994. *Water, Soil, and Hydro Environmental Decision Support System (WATERSHEDS)* NCSU Water Quality Group, <http://h20sparc.wq.ncsu.edu/info/phos.html. Accessed September 6, 1999.

Chee-Sanford, J.C., R.I. Aminov, I.J. Krapac, N. Garrigues-JeanJean, and R.I. Mackie. 2001. Occurrence and Diversity of Tetracycline Resistance Genes in Lagoons and Groundwater Underlying Two Swine Production Facilities. *Applied and Environmental Microbiology.* 67(4): 1494-1502.

Colburn, T., F.S. vom Sall, and A.S. Soto. 1993. Developmental effects of endocrine-disrupting chemicals in wildlife and humans. *Environmental Health Prospect,* 101:178. Cited in: Shore et al., 1995.

Dritz, S.S., R.D. Goodband, M.D. Tokach, and J.L. Nelessen. 1997. Feed Additive Guidelines for Swine. Kansas State University, Manhattan, Kansas.

Epstein, Eliot. 1998. Pathogenic health aspects of land application. *BioCycle.* September 1998:62-67.

Gavalchin, Jerrie and Stanley E. Katz. 1994. The Persistence of Fecal-Borne Antibiotics in Soil. *Journal of AOAC International,* 77(2): 481-485.

Klaasen. 1996. Casarett & Doull's Toxicology. 5th ed. The McGraw-Hill Companies, Inc., New York, New York.

Kornegay, E.T. 1996. Nutritional, environmental, and economic considerations for using phytase in pig and poultry diets. In *Nutrient Management of Food Animals to Enhance and Protect the Environment,* ed. E.T. Kornegay, pp. 277-302.

Manahan, Stanley E. 1991. *Environmental Chemistry.* 5th ed. Lewis Publishers, Inc., Chelsea, Michigan.

Masters, Gilbert M. 1997. *Introduction to Environmental Engineering and Science.* 2nd ed. Prentice-Hall, Inc., Upper Saddle River, New Jersey.

Mellon, Margaret, Charles Benbrook, and Karen Lutz Benbrook. 2001. *Hogging It. Estimates of Antimicrobial Abuse in Livestock.* Union of Concerned Scientists, Cambridge, Massachusetts.

Merck and Company, Inc. 1998. *The Merck Veterinary Manual.* 18th ed. Merck and Company, Inc., Whitehouse Station, New Jersey.

Nicholson, G.A. 1999. Heavy metal content of livestock feeds and animal manures in England and Wales. *Bioresource Technology* 70:1.

Overcash, M.R., F.J. Humenik, and J.R. Miner. 1983. *Livestock Waste Management.* Vol. I. CRC Press, Inc., Boca Raton, Florida.

Pell, Alice, 1997. Manure and Microbes: Public and Animal Health Problem? *Journal of Dairy Science* 80:2673-2681.

Raloff, Janet. 2002. Hormones: here's the beef. *Science News Online.* 161:1. http://www.sciencenews.org/20020105/bob13.asp. Accessed October 8, 2002.

Rutgers Cooperative Extension. 2000. Land Application of Sewage Sludge (Biosolids). #6: Soil Amendments and Heavy Metals. Rutgers Cooperative Extension, N.J. Agricultural Experiment Station, Rutgers, the State University of New Jersey, New Brunswick. https://www.rce.rutgers.edu/pubs/pdfs/fs956.pdf. Accessed October 4, 2002.

Schiffer, Bettina, Andreas Daxenberger, Karsten Meyer, and Heinrich H.D. Meyer. 2001. The fate of trenbolone acetate and melengestrol acetate after application as growth promoters in cattle: environmental studies. *Environmental Health Perspectives.* 109(11):1145-1151.

Sharpe, R.M., and N. Skakkebaek. 1993. Are Estrogens involved in falling sperm count and disorders of the male reproductive system? *Lancet* 341:1392. Cited in USEPA, 1998.

Sims, J.T. 1995. Characteristics of animal wastes and waste-amended soils: An overview of agricultural and environmental issues. In *Animal Wastes and the Land-Water Interface,* ed. K. Steele, pp. 1-13. CRC Lewis Publishers, Boca Raton, Florida.

Spicer, Steve. 2002. Fertilizers, Manure, or Biosolids? Water Environment & Technology. http://www.wef.org/pdffiles/biosolids/biosolids.pdf. Accessed October 4, 2002.

USDA. 1996. *Cryptospodium parvum* and cattle: implications for public health and land use restrictions. U.S. Department of Agriculture. http://www.nal.usda.gov/wqic/crptfac.html. Accessed October 4, 2002.

USEPA. 1996. *Soil Screening Guidance: User's Guide*. Publication 9355.4-23. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

USEPA. 1998. Appendix IV. Environmental data summary. In *Environmental impacts of animal feeding operations*. U.S. Environmental Protection Agency, Office of Water, Washington, DC. December 31, 1998.

USEPA. 1999. Success stories, Arkansas. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/owow/NPS/Success319/AR.html. December 31, 1998. Accessed September 7, 1999.

USEPA. 2000. *Environmental Assessment of Proposed Revisions to the National Pollutant Discharge Elimination System Regulation and Effluent Limitations Guidelines for Concentrated Animal Feeding Operations*. U.S. Environmental Protection Agency, Office of Wastewater Management, Washington, DC.

USEPA. 2002a. Monitoring and assessing water quality. 5.6 Phosphorus. U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds. http://www.epa.gov/owow/monitoring/volunteer/stream/vms56.html. August 27, 2002.

USEPA. 2002b. Monitoring and assessing water quality. 5.11 Fecal Bacteria. U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds. http://www.epa.gov/OWOW/monitoring/volunteer/stream/vms511.htm. August 27, 2002.

USFDA. 2002. The Use of Steroid Hormones for Growth Promotion in Food-Producing Animals. U.S. Food and Drug Administration Center for Veterinary Medicine. http://www.fda.gov/cvm/index/consumer/hormones.htm. Accessed October 8, 2002.

CHAPTER 8

TREATMENT TECHNOLOGIES AND BEST MANAGEMENT PRACTICES

8.0 INTRODUCTION

This chapter provides an overview of treatment technologies and best management practices (BMPs) for pollution prevention at animal feeding operations (AFOs), as well as for the handling, storage, treatment, and land application of wastes. The discussion focuses on technologies and BMPs currently implemented at domestic AFOs, but it also describes technologies and BMPs that are under research and development, are undergoing laboratory or field testing, or are used in other countries.

Many waste management technologies and BMPs are used by more than one animal sector, and information on them is presented in a general discussion form. However, the manner in which a particular technology or BMP is used or its degree of acceptance can vary among sectors. These differences are presented by animal sector where necessary.

8.1 Pollution Prevention Practices

Pollution prevention practices can be divided into feeding strategies that reduce the concentration of pollutants in waste and practices that reduce the amount of water used in the handling of wastes. Reduced water use or handling of wastes in a dry or drier form lowers the risk of pollutants entering surface waters. Reduced water use has the added benefit of making the waste less expensive to move from the facility site.

8.1.1 Feeding Strategies

Feeding strategies designed to reduce nitrogen (N) and phosphorus (P) losses include more precise diet formulation, enhancing the digestibility of feed ingredients, genetic enhancement of cereal grains and other ingredients resulting in increased feed digestibility, and improved quality control. These strategies increase the efficiency with which the animals use the nutrients in their feed and decrease the amount of nutrients excreted in the waste. With a lower nutrient content, more manure can be applied to the land and less cost is incurred to transport excess manure from the farm. Strategies that focus on reducing P concentrations, thus reducing overapplication of P and associated runoff into surface waters, can turn manure into a more balanced fertilizer in terms of plant requirements.

Feeding strategies that reduce nutrient concentrations in waste have been developed for specific animal sectors, and those for the swine, poultry and dairy industries are presented separately in

the following discussion. The application of these types of feeding strategies to the beef industry has lagged behind other livestock sectors and is not discussed here.

8.1.1.1 Swine Feeding Strategies

Practice: Precision Nutrition for Swine

Description: Current swine feed rations can result in overfeeding proteins and other nutrients to animals because they are designed to ensure that nutritional requirements are met and growth rate maintained. Precision nutrition entails formulating feed to meet more precisely the animals' nutritional requirements, causing more of the nutrients to be metabolized, thereby reducing the amount of nutrients excreted. For more precise feeding, it is imperative that both the nutritional requirements of the animal and the nutrient yield of the feed are fully understood.

When swine are fed typical diets, the P-use efficiency is on the order of 10 to 25 percent, while the N-use efficiency is on the order of 30 percent. These figures suggest that swine use these nutrients very inefficiently. An excess of N in the diet, principally from protein in feed, leads to inefficient utilization of nutrients. Phytate-phosphorus[1] (phytate-P), the most common form of P in feedstuffs (56 to 81 percent), is not well utilized by pigs because they lack intestinal phytase, the enzyme needed to remove the phosphate groups from the phytate molecule. Therefore, supplemental P is added to the diet to meet the pig's growth requirements, while phytate-P from the feed is excreted in the urine, thus increasing P concentrations in the manure. Because some feedstuffs are high in phytase, and because there is some endogenous phytase in certain small grains (wheat, rye, triticate, barley), there is wide variation in the digestibility of P in feed ingredients. For example, only 12 percent of the total P in corn is digestible whereas 50 percent of the total P in wheat is digestible. The P in dehulled soybean meal is more available than the P in cottonseed meal (23 versus 1 percent), but neither source of P is as highly digestible as the P in meat and bone meal (66 percent), fish meal (93 percent), or dicalcium phosphate (100 percent).

Application and Performance: Lenis and Schutte (1990) showed that the protein content of a typical Dutch swine ration could be reduced by 30 grams per kilogram without negative effects on animal performance. They calculated that a 1 percent reduction in feed N could result in a 10 percent reduction in excreted N. Monge et al. (1998) confirmed these findings by concluding that a 1 percent reduction in feed N yielded an 11 percent reduction in excreted N. According to Van Kempen and Simmins (1997), reducing the variation of nutrients in feed by using more appropriate quality control measures would reduce N waste by 13 to 27 percent. Experts believe that N losses through excretion can be reduced by 15 to 30 percent in part by minimizing excesses in diet with better quality control at the feed mill (NCSU, 1998).

Plant geneticists have produced strains of corn that contain less phytate-P (i.e., low-phytate corn) and are more easily digested than typical strains, resulting in less P excreted in manure. Allee

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[1]Most plant P occurs in the form of phytate, which is P bonded to phytic acid.

and Spencer (1998) found that hogs fed low-phytate corn excreted an average of 37 percent less P in manure, with no adverse effects on animal growth. In a study by Bridges et al. (1995), two weight classes of grow-finish pigs (66.1 and 101.7 kg) were given maize-soybean meal diets lower in protein and P to determine the reduction in N and P in pig waste when compared with pigs fed a conventional diet. Total N waste was reduced by 32 and 25 percent for the two weight classes, while total P excretion was reduced by 39 and 38 percent, respectively. The study also modeled the impact of reductions in dietary protein and P over the complete grow-finish period using the NCPIG model developed by the North Central Regional Swine Modeling Committee. Model results showed a reduction of approximately 44 percent in total N and P excretion compared with the conventional diet, with little impact on the time of production. In addition, the Fédération Européenne des Fabricants d'Adjuvants pour la Nutrition Animale in Belgium (FEFANA, 1992) calculated that the selection of highly digestible feedstuffs should result in a 5 percent reduction in total waste.

Advantages and Limitations: Precision feeding results in a higher feed efficiency (less feed used per pound of pig produced); however, any cost savings are at least partially offset by the cost of analyzing the nutrient content of feedstuffs. Consumer reaction to use of genetically modified crops to feed swine has not been determined yet.

Operational Factors: Precision feeding requires that feed manufacturers have the necessary equipment and procedures to create precision feeds within specified quality control limits. In general, feed manufacturers have traditionally limited quality control to measuring N, which correlates poorly with amino acid content in feedstuffs (van Kempen and Simmins, 1997). Precision feeding will also increase the costs and complexity of feed storage at the feeding operation.

Demonstration Status: Data on the frequency of use of precision nutrition are not available. Much of the information available on precision nutrition is derived from small-scale research experiments at the USDA and universities.

Practice: Multiphase and Split-Sex Feeding for Swine

Description: Multiphase feeding involves changing diet composition weekly instead of feeding only two different diets during the period from the 45-kg size to slaughter. Multiphase feeding is designed to better match the diet with the changing nutritional requirements of the growing animals.

Application and Performance: Feeding three or four diets during the grow-finish period instead of only two diets will reduce N excretion. According to models such as the Dutch Technical Pig Feeding Model by van der Peet-Schwering et al. (1993), multiphase feeding reduces N and P excretion by 15 percent. The modeling results have been confirmed by animal trials that showed a 12.7 percent reduction in N excretion in urine and a 17 percent reduction in P excretion.

Advantages and Limitations: Dividing the growth period into more phases with less spread in weight allows producers to meet more closely the pig's protein requirements. Also, because gilts

(females) require more protein than barrows (males), separating barrows from gilts allows lower protein levels to be fed to the barrows without compromising leanness and performance efficiency in the gilts.

Operational Factors: Multiphase and split-sex feeding require separate feeding areas and pens for the different types of animals. It is also more costly to produce a different feed every week.

Demonstration Status: The *Swine <95* report (USDA APHIS, 1995) showed that 96.2 percent of grow/finish operations fed two or more different diets. Of these operations, 63.4 percent progressed to a different diet based on animal weight, 5.3 percent changed diets based on either age or the length of time on the feed, and 30.0 percent based diet changes on equal consideration of weight and time. Of the 96.2 percent of grow-finish operations that fed more than one diet, 18.3 percent practiced split-sex feeding. Split-sex feeding is used much more frequently in medium (2,000–9,999 head) and large operations (10,000+ head) than in small operations (less than 2,000 head).

Practice: Improved Feed Preparation for Swine

Description: Milling, pelleting, and expanding are examples of technological treatments that improve the digestibility of feeds. By reducing the particle size, the surface area of the grain particles is increased, allowing greater interaction with digestive enzymes. NCSU (1998) reported that the industry average particle size was approximately 1,100 microns and that the recommended size is between 650 and 750 microns. Expanders and extruders are used mainly to provide flexibility in ingredient selection and to improve pellet quality rather than to improve nutrient digestion.

Application and Performance: As particle size is reduced from 1,000 microns to 700 microns, excretion of N is reduced by 24 percent. Vanschoubroek et al. (1971) reviewed many articles regarding the effect of pelleting on performance and found that not only did animals prefer pelleted feed over mash feed, but feed efficiency improved by 8.5 percent and protein digestibility improved by 3.7 percent with pelleted feed.

Advantages and Limitations: Although reducing particle size less than 650 to 750 microns can increase feed digestibility, it also greatly increases the costs of grinding and reduces the throughput of the feed mill. Smaller-sized particles can also result in an increased incidence of stomach ulcers in animals. In some cases, chemical changes resulting from the high temperatures created in grinding machines may decrease feed digestibility.

Operational Factors: A reduction in the particle size of the feed might result in manure with finer solids particles. This may affect the performance of manure management practices including possible effects on the efficiency of manure solid-liquid separators.

Demonstration Status: Data on the frequency of use of feed preparation techniques are not available.

Practice: Feed Additives for Swine

Description: Enzymes are commonly used in feed to improve the digestibility of nutrients. For example, plant P is often present in the form of phytate, which is digested poorly in swine, resulting in most of the P in feedstuffs being excreted in the manure. To prevent P deficiency, digestible P is added to swine rations, resulting in even more P in the manure. The enzyme additive phytase has been shown to improve P digestibility dramatically, and can be used to reduce the need for digestible P additives.

Other enzyme additives facilitate the retention of amino acids and digestive fluids, decreasing the amount of N excreted. Enzymes such as xylanases, beta-glucanases, and proteases upgrade the nutritional value of feedstuffs. Xylanases and beta-glucanases are enzymes used to degrade nonstarch polysaccharides (NSP) present in cereals such as wheat and barley. Swine do not secrete these enzymes and therefore do not have the capability to digest and use NSP. Because the NSP fraction traps nutrients that are released only upon partial degradation of the NSP fraction, addition of xylanase or beta-glucanase or both to cereal-containing diets can result in improvements in both digestibility and feed efficiency. In addition, supplementing the diet with synthetic lysine to meet a portion of the dietary lysine requirement is an effective means of reducing N excretion by pigs. This process reduces N excretion because lower-protein diets can be fed when lysine is supplemented. The use of other amino acid feed supplements is being tested.

Application and Performance: Mroz et al. (1994) showed that phytase increases P digestibility in a typical swine diet from 29.4 to 53.5 percent. They also demonstrated that phytase addition improved the digestibility of other nutrients in the feed such as Ca, Zn, and amino acids that are bound by phytase. For example, the addition of phytase to a commercial diet increased the digestibility of lysine by 2 percent while the digestibility of protein improved from 83.3 to 85.6 percent. Van der Peet-Schwering (1993) demonstrated that the use of phytase reduced P excretion by 32 percent in nursery pigs (a finding similar to the FEFANA [1992] predictions). Lei et al. (1993) found that feeding pigs 750 phytase units per gram of basal diet yielded a decrease in fecal P excretion of 42 percent without adverse health effects. This addition resulted in a linear improvement in phytate-P utilization. Graham and Inborr (1993) reported that enzyme additions improved the digestibility of protein in a wheat/rye diet by 9 percent.

Beal et al. (1998) used proteases on raw soybeans and observed a significant improvement in daily gain (+14.8 percent); feed efficiency, however, was improved by only 4.3 percent. Dierick and Decuypere (1994) saw a substantial improvement in feed efficiency when using proteases in combination with amylases and beta-glucanases, an improvement larger than that achieved with each enzyme individually. Studies have shown that protein levels can be reduced by 2 percent when the diet is supplemented with 0.15 percent lysine (3 pounds lysine-HCl per ton of feed) without harming the performance of grow-finish pigs.

Advantages and Limitations: Feed additives, especially synthetic amino acids and enzymes, increase the cost of feeding. Phytase, for example, was once too expensive to use as a feed

additive. This enzyme can now be produced at lower cost with recombinant DNA techniques. As technology improves, it is likely that the costs associated with other feed additives will decrease similarly.

Operational Factors: The level of phytase required in swine feed varies with the age of the animal. These different levels are likely determined by the development of digestive enzymes and intestines of the pig, with the younger pig being less developed. Lysine supplements can be used to achieve even greater reductions in the level of protein in diets, but only if threonine, tryptophan, and methionine are also supplemented.

Demonstration Status: The use of proteases in animal feeds is not widespread because of conflicting results from trials. With the advancement of enzyme-producing technology, as well as a better understanding of the role of enzymes in animal nutrition, proteases and other enzymes (e.g., pentosanases, cellulase, and hemicellulases, as tested by Dierick, 1989) are likely to play a greater role in animal nutrition. As their costs come down, the Amino Acid Council foresees an increased use of synthetic amino acids as a method of reducing N excretion as well as improving animal performance and decreasing feeding costs.

8.1.1.2 Poultry Feeding Strategies

Poultry operators have traditionally employed feeding strategies that focus on promoting animal growth rates or maximizing egg production. Feed additives have also been used to prevent disease and enhance bone and tissue development. As noted in Chapter 4, productivity has increased dramatically over the past several decades. The decrease in the average whole-herd feed conversion ratio (pounds of feed per pound of live weight produced) has translated into reduced feed input per bird produced. Smaller feed requirements can mean decreased manure output, but, until recently, development of better feeding strategies and advances in genetics have not focused on manure quality or quantity generated. Environmental issues associated with animal waste runoff have compelled the poultry industry to look for improved methods of waste prevention and management including feeding regimes that can reduce the nutrient content of manure.

Dietary strategies to reduce the amount of N and P in manure include developing more precise diets and improving the digestibility of feed ingredients through the use of enzyme additives and genetic enhancement of cereal grains.

Practice: Precision Nutrition for Poultry

Description: Precision nutrition entails formulating feed to meet the animals' nutritional requirements more precisely, causing more of the nutrients to be metabolized, thereby reducing the amount of nutrients excreted. For more precise feeding, it is imperative that both the nutritional requirements of the animal and the nutrient yield of the feed are fully understood. Greater understanding of poultry physiology has led to the development of computer growth models that take into account a variety of factors including strain, sex, and age of bird, for use in

implementing a nutritional program. By optimizing feeding regimes using simulation results, poultry operations can increase growth rates while reducing nutrient losses in manure.

Application and Performance: The use of improved feeds tailored to each phase of poultry growth has improved productivity significantly. Feed conversion ratios for broilers and turkeys have decreased steadily over the past several decades. Egg production productivity has also been boosted as operators have introduced improved nutrient-fortified feed.

Advantages and Limitations: Improved precision in feeding strategies offers numerous advantages including reduction of nutrients in animal manure and better feed conversion rates. Improved formulations are also cost-effective and reduce the probability of wasteful overfeeding of poultry.

Operational Factors: Precision nutrition requires detailed knowledge of poultry nutritional requirements and maintenance of detailed records to ensure that dietary adjustments are performed in a timely manner to maximize growth potential.

Demonstration Status: The use of precise nutrient formulations has already generated large increases in productivity in the poultry sector. Many of the poultry operations are under contract and receive feedstuffs with precise formulations from the integrator. Ongoing research will likely continue to result in productivity improvements.

Practice: Use of Phytase as a Feed Supplement for Poultry

Description: P, an essential element for poultry growth and health, is typically added to poultry feed mixes. However, because poultry are deficient in the enzyme phytase and cannot

break down the protein phytate, much of the P contained in feed cannot be digested (Sohail and Roland, 1999). Because poultry cannot produce phytase, up to 75 percent of the P contained in feed grains is excreted in manure (NCSU, 1999).

One feeding strategy used by poultry operators to reduce P levels in manure is to add microbial phytase to the feed mix.[2] This enzyme is produced by a genetically modified fungus, *Aspergillus niger*. The final enzyme product is usually available in two forms, a powder or a liquid (Miller, 1998). The phytase enzyme reduces P excretion by releasing the phytate-P contained in the cell walls of feed grains. The released P can then be absorbed by the bird's intestine and used for its nutrient value. A secondary beneficial effect of using phytase is that manure P content is further reduced because less inorganic P needs to be added to poultry diets (Edens and Simons, 1998).

Application and Performance: Phytase can be used to feed all poultry. P reductions of 30 to 50 percent have been achieved by adding phytase to the feed mix while simultaneously decreasing the amount of inorganic P normally added (NCSU, 1999).

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[2]As noted in Chapter 4, some experts believe phytase should not be provided to poults because of the enzyme's adverse effect on bone development in turkeys, while other experts believe it will enhance growth.

Advantages and Limitations: Addition of phytase to feed significantly reduces P levels in poultry manure. The high cost of phytase application equipment has discouraged more widespread use.

Operational Factors: Because phytase is heat-sensitive, it must be added to broiler and turkey feeds after the pelleting process (NCSU, 1999). The phytase is added by spraying it on the feed. This can result in uneven distribution and variable doses. Studies have shown that phytase efficacy is related to calcium, protein, and vitamin B levels in a complex manner. Further, phytase efficacy can be degraded by excess moisture, which can be a problem if mash (wet) feed is used for broilers (Miller, 1998). The shelf life of phytase is usually not a problem, because feed is typically consumed within 2 weeks or less at most operations.

Demonstration Status: Phytase is in use at many poultry operations. Application equipment for adding phytase to large volumes of feed is undergoing field testing.

Practice: Genetically Modified Feed for Poultry

Description: Using genetically modified animal feed offers poultry operators another way to reduce P levels in bird manure. In 1992, a research scientist at the USDA Agricultural Research Service developed a nonlethal corn mutant that stored most of its seed P as P rather than as phytate. The total P content in the mutant corn was the same as that found in conventional corn, except that there was a 60 percent reduction in phytic acid. The P released by the reduction in phytic acid P becomes available to the consuming animal as inorganic P (Iragavarapu, 1999).

Application and Performance: Genetically modified feed can be used for all poultry types. The potential for reducing P levels is quite large. One variety of corn with a high available P content has 35 percent of the P bound in the phytate form compared with 75 percent for normal corn (NCSU, 1999). Recent tests of a new hybrid corn, developed by USDA and the University of Delaware, demonstrated a 41 percent decrease in P levels in manure. Soluble P levels in waste decreased by 82 percent, compared with the amount produced by poultry fed a standard commercial diet (UD, 1999).

Advantages and Limitations: New hybrid varieties of grain can increase poultry utilization of plant P. Adding phytase to the modified feed further reduces manure P levels and can eliminate the need for nutrient supplements. The increased cost of feed and phytase additives might limit their use.

Operational Factors: The use of genetically modified feed would not differ from the use of conventional feed, although the increase in available nutrients in the feed would diminish the need for supplements.

Demonstration Status: Since its discovery in 1992, the mutant corn has been made available to commercial companies for further research, development, and commercialization of hybrid grains. Some hybrid varieties are currently used; others are in the research or demonstration stage. As more of these products are developed and prices are lowered, the use of hybrid grains combined with enzyme additives will likely increase.

Practice: Other Feeding Strategies to Reduce Nutrient Excretion for Poultry

Poultry operators use additives other than phytase to reduce manure nutrient content. These additives include synthetic amino acids and protease, and they are designed to facilitate more efficient digestion of N compounds and allow the use of smaller proportions of nutrients in feed while not adversely affecting animal growth rates and health. Researchers have also demonstrated that feed enzymes other than phytase can boost poultry performance and reduce manure production (Wyatt, 1995). Enzymes currently added to barley and wheat-based poultry feed in Britain and Europe include xylanases and proteases. Currently, the use of additives such as synthetic amino acids and enzymes could significantly increase feed costs. These costs, however could be expected to decrease over time as the technology matures and is more widely used by animal feed operators.

8.1.1.3 Dairy Feeding Strategies

Feeding strategies to reduce nutrient losses from dairy operations, primarily N and P, are focused on improving the efficiency with which dairy cows use feed nutrients. A more efficient use of nutrients for milk production and growth means that a smaller portion of feed nutrients ends up in manure. Elimination of dietary excess reduces the amount of nutrients in manure and is perhaps the easiest way to reduce on-farm nutrient surpluses (Van Horn et al., 1996). Reducing dietary P is the primary practice being used; however, a number of related management strategies also reduce nutrient levels in the manure by increasing the efficiency with which dairy cows use feed nutrients. These strategies include measuring the urea content of milk, optimizing feed crop selection, and exposing cows to light for a longer period of the day.

Practice: Reducing Dietary Phosphorus for Dairy Cattle

Description: Reducing the level of P in the diets of dairy cows is the primary and most important feeding strategy for reducing excess nutrients given because P plays a central role as a limiting nutrient in many soils; evidence indicates that dairy operators, as a whole, are oversupplying P in dairy diets; and there is an imbalance in the N to P ratio in cow manure, which favors reductions of P to produce a more balanced fertilizer. Reducing the amount of P in dairy diets has also been shown to reduce production costs and increase overall profitability.

The 2001 edition of the National Research Council's (NRC) nutrient requirements for dairy cows recommends dietary P levels of 0.32 to 0.44 percent of dry matter for dairy cows in lactation depending on breed and milk production rate (NRC, 2001). Dietary P in excess of these requirements has been shown to have no beneficial effect on animal health or production. Most excess P passes through the cows' systems and is excreted as manure, which is later applied to land. Rations, however, typically average 0.48 percent P or more (Satter and Wu, 2000). Supplemental feeding of dicalcium phosphate—often the second most expensive component in dairy cow diets—is the usual practice by which a dairy cow's rations achieve this level. A number of studies have addressed the adequacy of current dietary P recommendations. These studies include Steevens et al., 1971; Tamminga, 1992; McClure, 1994; and Chase, 1998.

Application and Performance: This practice should be applicable to all dairy operations. The amount of manure P resulting from a given level of dietary P is estimated using the following equation (Van Horn, 1991):

$$\text{Manure P} = 9.6 + 0\ .472 \times (\text{Intake P}) + 0.00126 \times (\text{Intake P})^2\ \text{B}\ 0.323 \times \text{Milk}$$

Manure and intake P are measured in grams, and milk production is measured in kilograms. Based on this formulation, assuming that each lactating cow produces on average 65 pounds of milk a day, Table 8-1 quantifies reductions in manure P resulting from reduced P intake (Keplinger, 1998). Four scenarios are considered: a 0.53 percent P diet, which is considered the baseline, and three reduced P diet scenarios. Comparing the 0.40 percent scenario against the baseline, P intake during lactation is reduced by 25 percent, while manure P is reduced by 29 percent. During the entire lactation period, manure P is reduced by 14.63 pounds per cow from the baseline level of 50.45 pounds per cow. For the entire year (lactation and nonlactation periods), manure P per cow is reduced by 27 percent.

Table 8-1. Per Cow Reductions in Manure P Resulting from Reduced P Intake During Lactation.

Percentage of P in Diet	Daily		Manure P (lb)		Reduction from Baseline (0.53%)		
	P Intake (lb)	Manure P (lb)	During Lactation	Entire Year	Amount (lb)	During Lactation	Entire Year
0.53	0.265	0.165	50.5	55.1	0.0	0	0
0.49	0.245	0.150	45.8	50.4	4.7	9	8
0.46	0.230	0.139	42.4	47.0	8.1	16	15
0.43	0.215	0.128	39.1	43.7	11.4	23	21
0.40	0.200	0.117	35.8	40.4	14.6	29	27

Advantages and Limitations: Supplemental feeding of dicalcium phosphate to dairy cows represents a substantial expense to dairy farmers—the second most expensive nutrient in a herd's mixed ration (Stokes, 1999). The economic advantages of reducing supplemental P, based on a study on the Bosque River watershed of Texas (Keplinger, 1998), suggest that a dairy operator who adopts a 0.40 percent P diet compared with the baseline 0.53 percent diet would save $20.81 per cow annually. A survey of scientific literature on the subject reveals no adverse impact on either milk production or breeding from reducing dietary P to NRC-recommended levels.

Another advantage to producers is the impact of reduced manure P on land application practices. Many states incorporate a P trigger in manure application requirements. For example, in Texas, state regulation requires waste application at a P rate (versus an N rate) when extractable P in the soil of an application field reaches 200 parts per million (ppm). Applying manure with a lower P concentration would slow and possibly eliminate the buildup of P in application fields, thereby delaying or eliminating the need to acquire or transform more land into waste application fields. When manure is applied at a P rate, greater quantities can be applied if it contains a lower P concentration. Thus, application fields would require less chemical N, because manure with

lower P concentrations is a more balanced fertilizer. In addition, reduced land requirements for waste application fields would represent substantial savings to dairy producers in cases in which a P application rate is followed.

Operational Factors: It is possible that factors such as climate, temperature, and humidity, as well as operation-specific factors, influence the effectiveness of steps taken to reduce dietary P; however, there are no published studies that address this issue. Dairy cows, for instance, are more prone to disease in moist climates and suffer heat stress in hot climates. Average milk production per cow varies greatly across geographic regions of the United States—averaging 21,476 pounds in Washington state versus only 11,921 pounds in Louisiana (USDA, 1999). Because dairy cow productivity and health are influenced by climate, it is likely that climate may also influence the effectiveness of nutrient-reducing feeding strategies, particularly those which depend on productivity gains. The magnitude and even the direction of the influence of factors such as temperature, humidity, and the like on nutrient-reducing feeding strategies, however, have not been established.

Demonstration Status: Dairy rations typically average 0.48 percent P or more (Satter and Wu, 2000), much higher than the NRC recommendation of 0.44 percent. A survey of milk producers in north Texas by a milk producers' organization indicated dietary P averaged 0.53 percent. A 1997 survey of professional animal nutritionists in the mid-South Region (Sansinena et al., 1999), indicates nutritionists' recommendations of dietary P averaged 0.52 percent, or 30 percent higher than the high end of NRC's current recommendation. Survey respondents cited several reasons for recommending final ration P in excess of NRC standards: almost half of the respondents (15 of 31) expressed a belief that lactating cows require more P than suggested by the NRC (Sansinena et al., 1999). The next most prevalent reason given was that a safety margin was required. Justifications for the safety margin included a lack of confidence in published ingredient P values and concern for variable P bioavailability in feed ingredients. Professional opinion also suggests that dietary P in dairy cow diets averages around 0.52 percent throughout the nation, although this percentage may be declining. Because of the heightened awareness of both the environmental benefits and the cost savings attainable by reducing P in dairy cow diets, some operators have adopted the NRC recommendation. Recent articles in dairy trade magazines have recommended adoption of the NRC standard for both environmental and economic benefits.

Practice: Milk Urea N Testing for Dairy Cattle

Description: There have been significant developments recently in the use of milk urea N (MUN) as a method for testing and fine-tuning dairy cow diets for protein feeding. Measured MUN concentrations are used as a proxy for the nutritional well-being of the cow.

Research has shown that mean MUN concentration levels from a group of cows should fall into specific ranges. By comparing the results of MUN tests with these ranges, the tests can be used as a monitoring tool to evaluate a herd's protein nutritional status. For cows fed at optimal dry matter intake, expected mean values of MUN concentrations range from 10 to 14 milligrams per deciliter (mg/dL) (Ferguson, 1999; Jonker et al., 1998). Field studies of MUN levels of dairy

herds in Pennsylvania (using a very large sample—312,005 samples) have reported average MUN concentrations of 14 mg/dL (Ferguson, 1999). Implicit in this level is that even allowing for the inherent large variability of MUN testing, the diets of some herds contain excess MUN levels that have no economic value; this also suggests that N in manure can be reduced by reducing excess N in dairy diets. The importance of reducing dietary protein levels is highlighted in a study (Van Horn, 1999) that estimates that for every 1 percent reduction in dietary protein, excretion of N may be reduced by 8 percent.

Application and Performance: This practice should be applicable to all dairy operations. The elimination of excess dietary protein with the use of the MUN test to evaluate protein levels in dairy cow feeds could reduce N levels in manure by 6 percent (Kohn, 1999). In addition, further methods to improve N utilization in dairy cows and raise the efficiency of feed delivery may be revealed by MUN testing.

Advantages and Limitations: Through MUN testing and the evaluation of other variables, farmers can identify which cows are eating too much protein, and fine-tune diets, thereby reducing N output in manure. Advantages of MUN testing are the possibilities of reducing ration costs by eliminating excess protein and improving the efficiency of feed delivery (Kohn, 1999). A disadvantage of animal group feeding strategies is that they become more difficult to set up and manage as group size decreases. The cost-effectiveness of custom feeding individual cows is as yet unproven.

Operational Factors: The large variability within and between herds and breeds of cows limits the usefulness of MUN testing, but it does not reduce the test's important role as a monitor of ration formulation.

Demonstration Status: This practice is primarily at the research stage and has not become widespread.

Practice: Diet Formulation Strategies for Dairy Cows

Description: Diet formulation strategies have received new examination. Alternative diet formulations to the NRC recommendations—notably the Cornell Net Carbohydrate and Protein model (CNCPS) (Sniffen et al., 1992)—that are more complicated than the NRC recommendations have been developed and suggest feeding about 15 percent less protein to a herd at the same level of production for certain conditions (Kohn, 1996). Evaluations of the CNCPS model's performance have been mixed, and further research is needed.

Theoretically, protected amino acid supplements have the potential to be part of an important strategy in increasing the efficiency of protein use by dairy cows, thereby reducing N losses. If amino acid supplements can be made effectively for dairy cows (avoiding rumen-associated problems), they could replace large portions of a dairy cow's protein intake. In theory, protected amino acid supplements could significantly reduce N intake and hence N levels in manure. In practice, the benefits of using protected amino acid supplements may not be as dramatic because the need to balance diet formulations may create limitations.

Application and Performance: This practice should be applicable to all dairy operations. Some evaluation of the alternative diet formulation suggested by the CNCPS implies a significant increase in milk production (from 24,100 pounds/cow per year to more than 26,000 pounds/cow per year) and a large reduction in N excretion (of about one-third) (Fox et al., 1995). More recent evaluations using two different large data sets (Kalscheur et al., 1997; Kohn et al., 1998) present mixed results, with the CNCPS performing better in some aspects and the NRC recommendations in others. Thus, results of the CNCPS evaluation should be considered preliminary. In theory, the use of protected amino acid supplements has great potential to improve nutrient efficiency. A typical lactating cow is assumed to require 1.1 pounds per day of N intake; by successfully substituting protected methionine and lysine for feed protein, this N intake and resulting manure N could be dramatically reduced (Dinn et al., 1996), but this research is preliminary.

Advantages and Limitations: Alternative diet formulations could improve nutrient efficiency. Information on limitations is unknown at this time, and EPA is continuing research in this area.

Operational Factors: The cost of preparing and storing multiple feed stuffs limits the use of this practice to the number of diets that the operator feels justifies the additional expense. Additional research on this practice is needed.

Demonstration Status: This practice is primarily at the research stage and has not become widespread.

Practice: Animal Feed Grouping for Dairy Cows

Description: Grouping strategies offer another method of realizing gains in nutrient efficiency. When grouping does not occur and the whole herd receives the same diet, cows may receive suboptimal diets and nutrient export to manure may be greater. Using grouping strategies to their greatest effect to improve nutrient efficiency would entail individualized diets. Feeding strategies already reviewed, such as the MUN concentration test, can be used in conjunction with grouping strategies or individual diets.

Application and Performance: This practice should be applicable to all dairy operations. Grouping strategies have been shown to reduce nutrient intakes and manure nutrients. When all the lactating cows are fed together according to current recommendations, they consume 7 percent more N and P, and 10 percent more nutrients are excreted in manure, compared with the individualized feeding strategy. Half of the gains of individualized diets could be achieved with two groups (Dunlap et al., 1997).

Advantages and Limitations: This practice could improve nutrient efficiency. Information on limitations is unknown at this time.

Operational Factors: As noted under diet formulation strategies, the cost of preparing and storing multiple feedstuffs limits the use of this practice to the number of diets that the operator

feels justifies the additional expense. Additional management input is also required in separating the animals into groups.

Demonstration Status: Dairy operations currently employ a range of grouping strategies (from no grouping to individual diets) to improve the efficiency of feed nutrients.

Practice: Optimizing Crop Selection

Description: Optimizing crop selection is another potential strategy for reducing nutrient losses in combination with dairy diets to meet annualized herd feed requirements with minimal nutrient losses. In whole-farm simulation of various crop strategies (corn silage, alfalfa hay, and a 50:50 mixture) the 50:50 mixture was judged to have performed best (when evaluated by N losses per unit of N in milk or meat) (Kohn et al., 1998). Converting dairy operations from confined to pasture operations is also considered a strategy for reducing nutrient loss on a per cow or operation basis. Kohn's model, however, found that a strategy of grazing versus confinement for lactating cows produced higher N loss per unit of milk produced because the decline in milk production was greater than the decline in manure nutrients (Kohn et al., 1998).

Application and Performance: This practice should be possible at operations that have sufficient land. In simulation of crop selection strategies involving whole-farm effects, mixed alfalfa hay and corn silage (50:50) was judged the best strategy for minimizing nutrient flows from the farm. Nitrogen losses were minimized to 2.9 units for every unit of N in meat or milk, compared with a loss of 3.5 units in the corn-based strategy, a 21 percent reduction (Kohn, 1999). Phosphorus accumulations did not tend to vary among the different strategies.

Advantages and Limitations: Optimal crop selection based on whole-farm effects suggests that the strategy that was most nutrient efficient in terms of N loss per unit of N in meat and milk is also the strategy that gains the most productivity from N; this strategy might, therefore, be the most cost-effective (Kohn et al., 1998). A grazing (versus confinement) strategy may or may not be cost-effective depending on the structure of individual dairy operations.

Operational Factors: Unknown at this time.

Demonstration Status: This practice is primarily at the research stage and has not come into widespread use.

Practice: Increasing Productivity

Description: The literature suggests that there are several feeding strategies that focus on increasing productivity as a route to nutrient efficiency. While the focus is on increased milk production, an important associated benefit of these strategies is that they result in greater milk production per unit of nutrient excreted. One approach involves exposing dairy cows to light for longer daily periods of the day through the use of artificial lighting. A longer daily photoperiod (18 hours light/6 hours dark) increases milk yields relative to those of cows exposed to the natural photoperiod (Dahl et al., 1996).

Application and Performance: This practice should be applicable at all operations that confine their animals. The artificial lighting technology to extend the daily photoperiod of dairy cows to 18 hours a day has been shown to be effective in increasing the nutrient efficiency of the farm. For an increase in milk production of 8 percent the herd's feed nutrients would be required to increase by only 4.1 percent, and N and P excretions would rise by only 2.8 percent when compared to a typical herd without artificial lighting (Dahl et al., 1996, 1998).

Advantages and Limitations: The artificial lighting technology is expected to be cost-effective. It is estimated that the initial investment in lighting can be recouped within 6 months. One observed advantage of milking three times a day rather than twice a day is that it reduces stress on the herd (Erdman and Varner, 1995). Because of the increased labor involved, the economic advantage of milking three times a day is variable and dependent on the individual farm (Culotta and Schmidt, 1988).

Operational Factors: To use this practice many dairy operations would need to install and operate additional lights.

Demonstration Status: This practice is primarily at the research stage and has not come into widespread use.

8.1.2 Reduced Water Use and Water Content of Waste

This section presents practices that reduce the water content in the waste stream. The production of a drier waste can be accomplished by three methods: (1) handling the waste in a dry form, (2) reducing the use of water at the AFO, or (3) separating the solid fraction of the waste from the liquid fraction. Most poultry operations currently handle their waste in a dry form, and this section generally does not apply to these operations.

Practice: Dry Scrape Systems *and the Retrofit of Wet Flush Systems*

Description: Scraper systems are a means of mechanically removing manure, and they can be used to push manure through collection gutters and alleys similar to those used in flush systems. For best results, scrapers should have a minimum depth of 4 inches in open gutters and 12 to 24 inches in underslat gutters (MWPS, 1993).

Retrofitting a wet flush system with a dry scrape system involves reconstructing the existing manure handling equipment within a livestock housing structure. A scraper blade replaces flowing water as the mechanism for removing manure from the floor of the structure.

In flush systems, large volumes of water flow down a sloped surface, scour manure from the concrete, and carry it to a manure storage facility. There are three basic types of flush systems: underslat gutters, narrow-open gutters, and wide-open gutters or alleys. Underslat gutters are used primarily in beef confinement buildings and swine facilities in which animals are housed on slats to prevent disease transmission as a result of animals coming into contact with feces. Narrow-open gutters are typically less than 4 feet wide and are used predominately in hog

finishing buildings. Wide-open gutters or alleys are most often seen in dairy freestall barns, holding pens, and milking parlors. The water used in a flush system can be either fresh or recycled from a lagoon or holding basin (Fulhage et al., 1993; MWPS, 1993).

Application and Performance: Removing manure with a scraper is appropriate for semisolid and slurry manure, as well as drier solid manure. The flush system is an appropriate means of removal for both semisolid and slurry manure. Retrofitting a flush system to a scraper system appears to be most feasible in underslat gutters and wide alleys. A major concern to be addressed is the discharge area of the scraper. Existing collection gutters, pumps, and pipes used in a flush system will likely be inadequate for handling the undiluted manure product.

Replacing a flush system with a dry scrape system dramatically reduces the amount of water used in manure handling and also reduces the tonnage of manure by decreasing dilution with water. There are several options for storing manure from a scrape system, including prefabricated or formed storage tanks, from which contaminants are less likely to seep.

Retrofitting a flush system with a scrape system will not treat or reduce pathogens, nutrients, metals, solids, growth hormones, or antibiotics. The concentrations of these components will actually increase with the decrease in water dilution.

Advantages and Limitations: In a building with a scrape system, the manure removed from the livestock housing area is in slurry or semisolid form (depending on species) and no water need be added. Compared with a wet flush system, the resulting manure product has a greater nutrient density and increased potential for further treatment and transportation to an area where the manure product is needed as a fertilizer. A large lagoon is usually necessary for storing and treating flush waste and water; handling manure in a drier form, on the other hand, significantly decreases the volume and tonnage of the final organic product. Although this is an important advantage when it is necessary to transport manure to areas where there is an increase in available land base, it can be a disadvantage in that an irrigation system would not be able to transport the thicker slurry that results from the use of a scrape system.

The greater volume of contaminated water and waste created in a flush system generally dictates that storage in a large lagoon is required. There are more options for storing manure removed with a scrape system. These storage alternatives may be more suited to practices that reduce odors (e.g., storage tank covers), more appropriate for areas with karst terrain or high water tables, and more aesthetically desirable.

The drawbacks of using a scrape system rather than a flush system include an increased labor requirement because more mechanical components need maintenance, a higher capital outlay for installation, an increased requirement for ventilation, and less cleanliness. Using a flush system to remove manure results in a cleaner and drier surface with less residual manure and less in-house odor, thus creating a better environment for livestock. Furthermore, alleys can be flushed without restricting animal access. As mentioned above, the discharge area of the scraper is a

concern. Existing pumps and pipes may be unable to handle the undiluted manure. Moreover, a completely new manure storage structure might be needed (Vanderholm and Melvin, 1990).

Operational Factors: Both the scrape and flush systems have disadvantages when used in open barns during winter months, but a scrape system is more likely to function properly at lower temperatures.

If alleys are straight with continuous curbs, alley scrapers can usually be installed, but alley lengths of up to 400 feet in dairy freestall barns may make installation of scraping systems impractical. Scrapers work best when they can be installed in pairs of alleys so the chain or cable can serve each and form a loop. It might be necessary to cut a groove into the concrete alley for the chain or cable to travel in. The decision of whether to cut a channel or let the chain rest on the pavement is best left to the manufacturer. It should be noted that maintenance requirements associated with the chain and cable will likely be high because of corrosion caused by continuous contact with manure. Hydraulic scrape units that operate on a bar and ratcheting blade are also available (Graves, 2000).

Demonstration Status: The use of scrape systems and the practice of retrofitting a flush system are not common in the livestock industry. Inquiries regarding the use of this practice have been made to manure management specialists, agricultural engineers, and manufacturers of scraper systems. Very few professionals indicated that they had any experience in the area or were aware of the practice being used. Those professionals willing to comment on the implications of retrofitting seemed to believe that it would be most feasible and advantageous on dairies (Graves, 2000; Jones, 2000; Lorimor, 2000; Shih, 2000).

Practice: Gravity Separation of Solids

Description: Gravity settling, separation, or sedimentation is a simple means of removing solids from liquid or slurry manure by taking advantage of gravitational forces. The engineering definition of a settling or sedimentation tank is any structure that is designed to retain process wastewater at a horizontal flow rate less than the vertical velocity (settling rate) of the target particles.

In agricultural applications, gravity settling is a primary clarification step to recover solids at a desired location where they can be managed easily, thereby preventing those solids from accumulating in a downstream structure where they would be difficult to manage. A wide range of gravity separation practices are used in agriculture including sand and rock traps, picket dams, and gravity settling basins designed to retain 1 to 12 months' accumulation of solids.

Settling tanks can be cylindrical, rectangular, or square. Agricultural settling tanks have been made with wood, metal, concrete, and combinations of materials. Some are earthen structures. In agriculture, gravity separation is sometimes accomplished without a recognizable structure including techniques such as a change in slope that allows particles to settle when the liquid velocity drops.

The critical design factor in sedimentation tanks is surface overflow rate, which is directly related to the settling velocity of particles in the wastewater (Loehr, 1977). Faster settling velocities allow for increased surface overflow rates, while slower settling velocities require decreased overflow rates to remove settleable particles. In "ideal" settling, the settling velocity (Vs) of a particle is equal to that particle's horizontal velocity (VH), where

$$VH = Q/DW$$

Q is the flow through the tank
D is the tank depth
W is the tank width

The ASAE has defined several types of gravity separation techniques (ASAE, 1998):

- Settling Channels: A continuous separation structure in which settling occurs over a defined distance in a relatively slow-moving manure flow. Baffles and porous dams may be used to aid separation by further slowing manure flow rates. Solids are removed mechanically once liquids are fully drained away.
- Settling Tank: A relatively short-term separation structure, smaller in size than a settling basin. The liquid is allowed to fully drain away for solids removal by mechanical means.
- Settling Basin: A relatively long-term separation structure, larger in size than a settling tank. Solids are collected by mechanical means once the liquids evaporate or have been drained away.

Application and Performance: Gravity separation is relatively common in the United States. Separation is used to reduce clogging of downstream treatment or handling facilities. Reduced clogging means improved lagoon function and better wastewater treatment. Most beef feedlots in the Midwest and Great Plains use gravity separation ponds to collect solids from rainfall runoff, thus improving the function of runoff collection ponds. Gravity separation basins are used across the country on hog farms to reduce solids accumulation in tanks or lagoons they discharge to. It is likely that more dairies with flush systems use gravity settling for solids recovery rather than mechanical separators to preserve lagoon capacity.

Table 8-2 shows the substantial range of treatment efficiencies for gravity settling of manure. The performance of a gravity separation basin depends on the design goal and ability of the operator to maintain the system in design condition. Performance will vary with animal type, animal feed, dilution water, flow rate, percent of capacity already filled with solids, temperature, and biological activity. The data ranges in Table 8-2 may be explained in part by the time span separating the studies. More recent studies show reduced solids recovery from swine manure. This may be partly due to the fact that animal diets have changed over the years, with feed more digestible and more finely ground these days. Further, feed is ground to different particle sizes that have different settling characteristics, thus potentially affecting separation basin performance. In addition, ruminants are fed materials that have different settling characteristics than those fed to nonruminants. Process variables such as overflow velocities are seldom

reported in the literature, but they are important determinants of separation basin performance. Extra water from processing or precipitation and already settled material will increase the flow rate across a settling basin, reducing settling time and solids capture. In many agricultural settling basins, biological activity resuspends some settled materials which then pass through the separator. At best, one can conclude from these data that gravity settling can recover in swine wastes a larger percentage of total solids (TS), volatile solids (VS), and total N (TN) than another separation technique reviewed for the practice, mechanical solid-liquid separation, that follows in this chapter.

Table 8-2. Performance of Gravity Separation Techniques.

Recovered in Separated Solids, Percent						
	TS	**VS**	**TN**	**P_2O_5**	**K**	**COD**
Swine (Moser et al., 1999)	39–65	45–65	23–50	17–50	16–28	25–55
Beef (Edwards et al.,1985; Lorimore et al., 1995) and Dairy (Barker and Young, 1985)	50–64	NA	32–84	20–80	18–34	NA

TS=Total solids; VS=volatile solids; TN=total nitrogen; P_2O_5=pyrophosphate; K=potassium, COD=chemical oxygen demand.

Because of short return times, pathogen reduction through settling is minimal; however, settling might reduce worm egg counts. No information is available on growth hormones in manure or on how settling might affect growth hormones that may be found in manure. Degradation of antibiotics usually hinders their detection in manure, and no information is available on the effect of settling on antibiotics in manure.

Taiganides (1972) measured 80 to 90 percent recovery of copper, iron, zinc, and P with settled swine solids. The study also reported that 60 to 75 percent of the sodium, K, and magnesium settled and was recovered.

Advantages and Limitations: The main advantage of gravity settling is the relatively low cost to remove solids from the waste stream. Recovering solids prevents the buildup of those solids in ditches, pipelines, tanks, ponds, and lagoons. Dairy solids consist mostly of fiber and can be composted and recycled as cow-bedding material, or they can be composted and sold as a soil amendment. Swine solids are finely textured, hard to compost aerobically, and rapidly degraded to odoriferous material if handled improperly. Beef solids collected from lot runoff can become odoriferous if left in a separation basin, but they can be composted for sale to crop farms, nurseries, or soil products companies.

Collected solids are a more concentrated source of nutrients than the separated liquid, resulting in decreased hauling costs per ton of nutrient. The separated liquid has a reduced nutrient content and can be applied to a smaller acreage than the original material.

Disadvantages of solids separation include the need to clean out the separator, the potential odor emitted from the basin, the odor produced by solids removed from the basin, and attraction of

insects and rodents to the separated solids. Additional costs are incurred when the solids and liquids from pig manure are managed separately.

Operational Factors: Solids separators do not function if they are frozen or experience horizontal flow rates higher than the solids settling rate. Solids tend to separate better at warmer temperatures.

Demonstration Status: Gravity separation is the most common solids separation technique in use in the United States.

Practice: Mechanical Solid-Liquid Separation

Description: Solids-liquid separation is used to recover solids prior to their entry into downstream liquid manure facilities. Solids recovery reduces organic loading and potential accumulation of solids and improves the pumping characteristics of animal manure. Mechanical separation equipment is used to reduce the space required for separation, to produce a consistent separated solid product amenable to daily handling, to produce a liquid product that is easily pumped for spreading, or to recover specific particle sizes for other uses such as bedding.

Mechanical separation equipment is readily available for animal wastes. Mechanical separators include static and vibrating screens, screw press separators, rotary strainers, vacuum filters, centrifugal separators, belt filter presses, and brushed screen/roller presses. Static screens are the most popular mechanical separators because they are inexpensive to buy, install, and operate. All other mechanical separation techniques are less common.

Static screens are usually mounted above grade on a stand to allow solids accumulation beneath. Barn effluent is typically pumped up to the screen, where the liquids pass through while the solids collect on the screen surface. Screens are typically inclined, causing accumulating solids to slide down from the screen toward collection. There are multiple configurations with different screen designs, screen materials, screen opening spacing, influent distribution, post-use washdown, and additional pressing of separated solids.

Vibrating screens are flat or funnel-shaped screens supported on springs and oscillated by an eccentric drive. The vibrations cause the solids to move from the screen for collection.

With screw presses, manure is pumped to the base of a turning open-flight auger that goes through a screen tube made of welded wire, wedge wire, perforated metal, or woven screen material. Solids collect on the screen, forming a matrix as the auger advances them. A tensioned opening restricts the flow of materials up the auger and out from the tube. The retained material is squeezed by the auger against the screen tube and tensioned opening until it overcomes the tension and exits. The matrix acts as a filter allowing the collection of finer particles than are collected by other types of screens. The auger wrings liquid from the separated solids by forcing material against the plug of material held by the tensioned opening and screen tube.

A rotary strainer is a slowly rotating, perforated cylinder mounted horizontally. Waste flows by gravity onto the cylinder at one end, where solids are scraped from the cylinder surface and moved to the exit end. Liquids pass through the screen for collection and removal (ASAE, 1998). Vacuum filters are horizontally mounted, rotating perforated cylinders with a cloth fiber cover. A vacuum is used to draw liquids from the wastewater. Wastewater flows onto the cylinder surface, liquids pass through the screen, and solids are scraped from the cloth at a separation point (ASAE, 1998).

A centrifugal separator, or centrifuge, is a rapidly rotating device that uses centrifugal force to separate manure liquids from solids. One type, a relatively low-speed design, uses a cylindrical or conical screen that can be installed vertically or horizontally. Manure is fed into one end, and solids are then contained by the screen, scraped from it, and then discharged from the opposite end. The liquid passes through the screen. A second type, a higher-speed decanter, uses a conical bowl in which centrifugal force causes the denser solids to migrate to the bowl exterior where they are collected. Less dense liquids are forced to the center for collection (ASAE, 1998).

A belt press is a roller and belt device in which two concentrically running belts are used to squeeze the manure as it is deposited between the belts. The belts pass over a series of spring-loaded rollers where liquids are squeezed out or through the belt, and remaining solids are scraped off at a belt separation point (ASAE, 1998).

Brush screen presses are rectangular containers with four vertical sides and a bottom consisting of two half-cylindrical screens lying side by side to provide two stages of separation. Within each screen rotates a multiple-brush and roller assembly that sweeps the manure across the screen. Manure is pumped into one side of the separator. The liquids are forced through the screen by the brush/roller while the solids are retained by the screen and pushed from the separator on the opposite side (ASAE, 1998).

Application and Performance: Mechanical separation is used to reduce clogging of downstream treatment or handling facilities. The use of this practice to preserve lagoon capacity by separating solids is relatively common among dairies using flush manure collection. Reduced clogging means improved lagoon function and better wastewater treatment. Mechanical separation of solids from manure, however, is relatively rare because of the added costs.

Table 8-3 shows the range of treatment efficiencies for the mechanical separation of manure. These systems do not perform as well as gravity separation, but they produce a more consistent product delivered as a solid for easy collection. Most manufacturers and owners are less concerned about the percentage of recovery or the properties of the recovered material than they are about the TS concentration of the separated solids. Performance will vary with animal type, animal feed, dilution water, flow rate, percent of capacity already full of solids, temperature, and biological activity. In general, pig manure has finer solids than cow manure, and recovery of pig manure constituents is in the low end of the ranges in Table 8-3, whereas cow manure constituent recovery is in the upper portion of the range.

Table 8-3. Summary of Expected Performance of Mechanical Separation Equipment.

Separation Technique	Recovered in Separated Solids, Percent				
	TS	VS	TN	P_2O_5	COD
Stationary screen	10–25	10–25	5–15	10–20	5–20
Vibrating screen	10–20	10–20	10–20	0–15	10–20
Screw press	20–30	20–30	10–20	20–30	20–40
Centrifuge	40–60	40–60	20–30	25–70	30–70
Roller drum	20–30	20–30	10–20	10–15	10–25
Belt press/screen	40–60	40–60	30–35	15–20	30–40

Source: Moser et al., 1999.

Pathogen reduction through mechanical separation is negligible. No information is available on growth hormones in manure or on the effect of mechanical separation on growth hormones that may be found in manure. Degradation of antibiotics usually hinders their detection in manure, and no information is available on the effect of mechanical separation on antibiotics in manure.

No significant information was found on the effect of mechanical separation on heavy metal content of either the solids or the liquids. Work in gravity separation suggests that metals are associated with fine particle sizes that would pass with the liquids through mechanical separation.

Static (stationary) screens are most commonly used for separating solids from dilute solutions with solids concentrations of 5 percent or less. The more dilute the solution, the more likely that discrete particles will be collected on the screen because there is less particle-versus-particle interference. The dilute solution also washes finer particles from larger, retained particles and through the screen.

Vibrating screens are used for separating solids from dilute solutions with solids concentrations of 3 percent or less. Vibrating screens will generally process more flow per unit of surface area than static screens because the vibrating motion moves the solids from the screen. Vibrating screens are more sensitive than static screens to variations in solids content and wastewater flow (Loehr, 1977).

Static screens and vibrating screens usually collect 10 to 15 percent of the TS from manure. An owner generally selects a screen that will not easily clog, or blind (i.e. one with larger screen spacing), instead of choosing an optimized screen and feed pump to avoid both screen blinding, when the slurry thickness changes, and the creation of a soggy solids pile.

Screw presses can handle thicker materials than most separators, and are used to separate manures that have between 0.5 and 12 percent TS. Chastain et al. (1998) noted, however, that a screw press did not separate well unless the TS content of the waste was above 5 percent. Because screw presses first allow the solids to form a matrix and catch fine solids, the percent solids recovery is generally greater than for other solids separators. The screw press is designed to produce drier solids (up to 35 percent). Solids recovery is dependent on the screen tube

openings and the setting of the retaining tension. The higher the tension is set, the harder the screw squeezes the separated material, and the more solids are forced out through the screen. Tighter settings for drier solids may significantly affect the useful life of both auger and screen.

Belt presses are expensive, require a trained operator, operate best with chemical addition, and cannot process rocks and barn parts found in manure. With or without chemical addition, however, they can do a good job of separating 40 percent or more of the TS. Nevertheless, the cost of belt presses, plus the extremely high cost of maintenance and the need for continuous operator presence, makes their use problematic.

The primary advantage of centrifugation over other separators appears to be in the reduction of total P, but centrifugation is also clearly more efficient than screening for removal of all constituents. Managed by trained operators, centrifuges will recover over 60 percent of the TS. Nevertheless, the large capital cost, the need for trained operators, and the high maintenance costs have made this equipment impractical for farm use.

Advantages and Limitations: The main advantages of mechanical separation are the consistent level of solids removal from the waste stream and the delivery of separated solids at a recovery location. Recovering solids prevents the buildup of those solids in ditches, pipelines, tanks, ponds, and lagoons. Dairy solids, which consist mostly of fiber, can be composted and recycled as cow bedding material. Dairy solids have also been composted and sold as a soil amendment. Swine solids are finely textured, hard to compost aerobically, and rapidly degraded to odoriferous material if handled improperly.

Collected solids are a more concentrated source of nutrients than the separated liquid, resulting in decreased hauling costs per ton of nutrient. The separated liquid has a reduced nutrient content and can be applied to a smaller acreage than the original material.

Disadvantages of solids separation include operation and maintenance requirements, potential odor production from collection basins and separated solids, and attraction of insects and rodents to the separated solids. Additional costs are incurred when the solids and liquids in swine manure are managed separately.

Operational Factors: Mechanical solids separators do not function if the manure or the face of the machine is frozen, but they can operate under a wide variety of other conditions.

Demonstration Status: Mechanical solids separation is being used at thousands of dairies and perhaps several hundred hog farms. Regarding specific technologies, static screens are most commonly used, whereas vibrating screens and rotary strainers are seldom used on farms today. Vacuum filters are infrequently used on farms because inorganic materials such as rocks and metal bits tend to rip the filter fabric. High capital and operating costs have limited farm use of centrifugal separators. Brush screen presses may occasionally be found on farms, but the low throughput rate has limited its use. Screw presses are in use at a few hundred dairy farms, but at a very limited number of swine farms in the United States.

Practice: Two-Story Hog Buildings

Description: The two-story, High-RiseJ hog building design (Menke et al., 1996) integrates manure collection, storage, and treatment in a single, enclosed facility. The building is designed to pen approximately 1,000 head of hogs on the second floor of a two-story building, with a dry manure collection and storage system on the first (ground) level. The second floor features solid side walls and totally slatted floors. The manure falls through the slats to the first floor area, which is covered with 12 to 18 inches of a dry bulking agent such as sawdust, oat or wheat straw, corn fodder, or shredded newspaper. The design includes sliding doors on the ground level to allow for tractor and loader access.

The building's unique, two-fold ventilation system maintains superior air quality in the swine holding area and dries the manure in the storage area (Figure 8-1). Clean air is pulled from the ceiling through continuous baffle inlets and is directed down over the swine vertically (with no horizontal, pig-to-pig air movement). Air exits the swine holding area through the floor slats and is pulled horizontally to the outside of the first-floor pit area by 14 computer-controlled ventilation fans mounted on the pit walls. This system prevents air from the manure pit from rising to the animal area. The second part of the ventilation system involves pumping air through the manure by floor aeration. PVC pipes with approximately 3,200 3/8-inch holes are installed before the concrete floor is poured. Two large fans on either end of the building force air through perforations in the concrete and into the composting mixture on the ground floor.

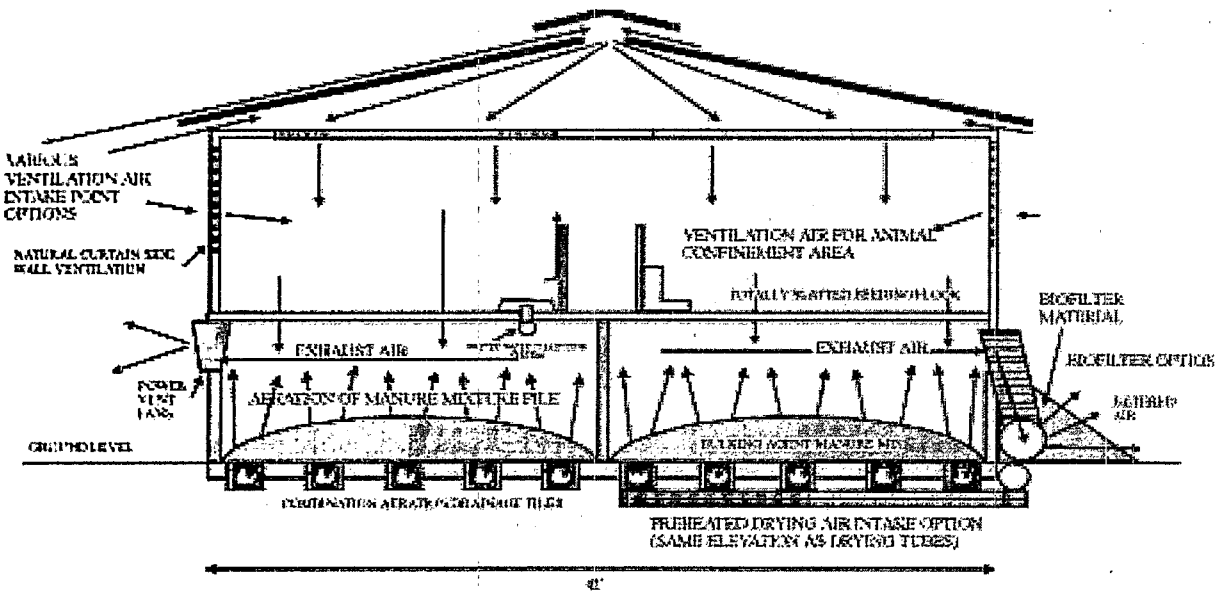

Figure 8-1. High-Rise Hog Building

Application and Performance: Management practices, swine care, and feeding are much the same as with conventional confinement. The High Rise facility is distinctive because it incorporates dry manure handling and storage into a traditional confinement production scenario. The system dries the manure mixture and maintains an aerobic environment to facilitate the composting process. Drying and homogeneity of the mixture are also facilitated by mixing with a tractor and loader or skid-steer loader. Frequency of mixing varies from once per production cycle to biweekly, depending on the saturation of bedding. The semicomposted bedding mixture is removed once per year and can be further composted, land applied, or sold. A typical 1,000-head unit produces 500 tons of semicomposted product per year.

The High Rise facility is best suited for areas where there is limited local land base for manure application; sandy, porous soils; limited water supply; or an existing market for compost or partially composted material.

The aerobic decomposition that occurs within the pit results in a significant volume reduction in the manure. In fact, initial trials have shown that loading the pit with 12 to 18 inches (approximately 11 tons) of bedding results in only 2.5 to 3 feet of manure to be removed at the end of 1 year. This is estimated as a 22 percent reduction in manure volume and a 66 percent reduction in manure tonnage (Envirologic, 1999; Mescher, 1999). These figures are based on a final product with 63 percent moisture. When compared with liquid/slurry hog manure that is approximately 90 percent moisture, this presents a great advantage in areas where there is a lack of local land base and manure must be transported more than 3 to 4 miles to alternative areas for application. Manure with 63 percent moisture is considered to be in dry form and can be hauled in a semi truck with an open trailer rather than in a liquid tanker pulled by a tractor.

The aerobic decomposition and drying that reduce the volume and tonnage of the final organic product do not result in a reduction of the overall nutrient content. In fact, with the exception of N and sulfur (some of which volatilizes) nutrients will be more concentrated in the resulting semicomposted product. The semicomposted manure is four times more concentrated than liquid manure from treatment lagoons.

The High-Rise facility incorporates both manure treatment and storage in a completely aboveground handling system. In addition, the ground-level manure storage area is enclosed in poured concrete. This is especially advantageous in sites with porous soils or fragmented bedrock. Such locations are unfit or, at the least, potentially dangerous areas for earthen basin and lagoon construction due to concerns regarding ground water contamination. Furthermore, belowground concrete pits have an increased potential for ground water pollution if leaking occurs in a region with porous soils or fragmented bedrock. The aboveground concrete manure storage of the High-Rise building allows visual monitoring for leakage.

Information is not currently available on the reduction of pathogens, heavy metals, growth hormones, or antibiotics in the manure product as it is removed from the High-Rise facility. However, research on some of these topics is currently underway. Based on the composition of the product, temperature readings within the manure pack, and knowledge of the composting

process, several speculations can be made. Destruction of pathogens in the composting process is a result of time and temperature. The higher the temperature within the manure pack, the less time it takes to eliminate pathogens. In general, the temperature within the manure pack needs to exceed the body temperature of the animal and pathogen destruction is most effective at 120 °F or higher. Temperature readings taken in the manure pack in the High-Rise facility ranged from only 45 to 78 °F (Keener, 1999). The predominant reason for the manure packs not reaching a high enough temperature is the continuous aeration provided. It is unlikely that there is a significant reduction of pathogens at this temperature. There may be some decrease in pathogen numbers due to the length of time (up to one year) the manure pack remains in the building. Further composting of the manure pack once it is removed from the High-Rise structure would allow the product to reach temperatures high enough for complete pathogen destruction.

The composting process has no effect on the quantity of heavy metals in the manure. Further, because of the decrease in volume and tonnage of the manure, heavy metals will be more concentrated. Composting does, however, influence the bioavailability of the metals, causing them to be less mobile. The extent to which the mobility of heavy metals is decreased in the semicomposted product removed from the High-Rise facility is unknown.

The degree to which growth hormones and antibiotics degrade during the composting process is unknown and is not widely studied.

Designers of the High-Rise facility claim a savings of 1.8 million gallons of water per 1,000 head of hogs annually when compared with a conventional pull-plug flush unit. This conservation results from using wet-dry feeders and eliminating the addition of water for manure removal and handling. A reduction in the amount of water used in the system results in less waste product to be handled.

Advantages and Limitations: As explained above, the dry manure handling system used in the High-Rise facility significantly decreases the volume and tonnage of the final organic product. This is an important advantage when transportation to areas where there is an increased land base for manure application is necessary. However, because the semicomposted product has greater concentrations of macronutrients, with the possible exception of N (which might volatilize), the number of acres needed to correctly apply the manure does not decrease. N volatilization during the composting process creates the possibility of upsetting the nutrient balance in manure. For example, if manure was applied to land with the application rate based on the amount of N in the manure, P and potassium could be applied at rates 10 times the recommended rate. This problem is eliminated if application rates are based on the P content of manure. Additional commercial N application might be necessary depending on the crop being produced.

Data from an initial trial show that the manure product removed from the High-Rise facility has a fertilizer value of about $19 per ton at 60.7 percent moisture, with an organic matter content of 29.8 percent. Secondary studies show that the manure mixture is of adequate content for further composting, which is necessary to sell manure commercially. These factors create an increased

opportunity to broker manure and possibly provide supplemental income to the swine production enterprise (Envirologic, 2000).

Observations and data resulting from the first year of study in the High-Rise structure indicate that there is a significant decrease in odor using the dry manure handling system. NH_3 measurements on the swine housing level averaged from 0 to 8 ppm, with an overall mean of 4.3 ppm and spikes of up to 12 ppm in times of decreased ventilation (winter months). In a conventional confinement building with a deep, liquid pit, ammonia levels of 20 to 30 ppm are commonplace. NH_3 levels on the ground level of the High-Rise building vary inversely with building ventilation and have exceeded a short-term exposure rate of 50 ppm in the winter. It must be realized, however, that the basement level is not occupied during normal conditions. Large sliding doors are opened when the facility is cleaned to let in fresh air and facilitate the entry of a tractor/loader. NH_3 levels external to the outside exhaust fans averaged 23.3 ppm, but quickly dissipated (Keener et al., 1999).

No hydrogen sulfide gas was detected in the swine holding area. Levels on the first floor were minimal (National Hog Farmer, 2000). Decreased levels of these potentially toxic gases improve air quality and prevent excessive corrosion in the building.

Producers who plan to build a High-Rise facility can expect a 15 percent increase in capital outlay compared to a 1,000-head, tunnel ventilation finisher with an 8-foot-deep pit. Cost projections prepared for the company that manufactures the High-Rise building indicate that reduced cost for manure handling and transportation offsets the additional building cost (Envirologic, 2000). Solid manure handling is less automated than many liquid manure handling systems. Although solid systems have lower capital costs, labor costs are higher than those associated with liquid systems. Labor costs are expected to be less than traditional scrape and haul systems because the slatted floors eliminate the need to scrape animal areas frequently.

In addition to the increased capital requirement, the cost of utilities is also elevated. Additional energy is needed to power the many ventilation fans. Electricity usage averages roughly twice that of a naturally ventilated confinement barn. Accounting for all of these factors, the cost of production in a High-Rise facility is approximately $180 per pig. This is 28 to 30 percent greater than the cost of production in a confinement structure with a shallow pit, and 15 to 18 percent greater than in a more conventional deep pit (Mescher et al., 1999).

The ventilation system that pumps air over the swine holding area keeps the swine and slats dry, resulting in cleaner swine and fewer injuries. Also, there is no flow of air from pig to pig, which helps prevent airborne transmission of disease. The combination of decreased moisture and exceptional air quality leads to improved animal health and decreased medication costs.

Data from a single High-Rise facility show that animal performance was the same or better than that of conventional facilities with respect to average daily gain, days to market, feed conversion, mortality, and the number of culls. In fact, the decreased number of days to market translates into 0.2 to 0.3 more production cycles per year, creating potential to increase profits significantly.

It is speculated that improvement in performance measures is due to better air quality (Envirologic, 2000).

Leachate from the manure mixture appears to be minimal if mixing is done on a regular basis. Rodents in the basement pit might become a problem if control measures are not taken.

Operational Factors: Artificial climate control and ventilation in the building make the High-Rise building appropriate in most climates . It is estimated that air in the building is exchanged every 10 to 15 seconds, providing an environment of uniform temperature and humidity throughout the building year-round. Over a 1-year span, the mean air temperature taken from several test areas within the building varied only ± 2 °F from the desired temperature. There were, however, differences of up to 10 °F between testing areas on the swine floor (Stowell et al., 1999). The building is equipped with a standard sprinkling system for use in hot summer months.

Demonstration Status: The High-Rise facility technology has been tested with finisher pigs since 1998 at a single research facility in Darke County, Ohio. The vendor has built four commercial grow-finish buildings since that time and they are currently in production in west central Ohio. The vendor is also developing prototypes for other phases of swine production using the same manure handling system.

Practice: Hoop Structures

Description: Hoop structures are low-cost, Quonset-shaped swine shelters with no form of artificial climate control. Wooden or concrete sidewalls 4 to 6 feet tall are covered with an ultraviolet and moisture-resistant, polyethylene fabric tarp supported by 12- to 16-gauge tubular steel hoops or steel truss arches placed 4 to 6 feet apart. Hoop structures with a diameter greater than 35 feet generally have trusses rather than the tubing used on narrower hoops. Some companies market hoops as wide as 75 feet. Tarps are affixed to the hoops using ropes or winches and nylon straps.

Generally, the majority of the floor area is earthen, with approximately one-third of the south end of the building concreted and used as a feeding area. The feeding area is designed with a slight slope (1 to 2 percent) to the outside of the building in case of a waterline break, and is raised 12 to 19 inches above the earthen floor to keep the feeding area clear of bedding material. Approximately 150 to 200 finisher hogs or up to 60 head of sows are grouped together in one large, deep-bedded pen. The building should be designed so that the group housing area provides approximately 12 square feet of space per finisher pig, or 27 square feet per sow.

Hoop structures are considered a new and viable alternative for housing gestational sows and grow-finish pigs. Gestational housing systems being used in the United States are modeled after conventional Swedish style, deep-bedded gestation and breeding housing. In Sweden today, deep-bedded housing systems with individual feeding stalls are the conventional method of dry sow housing. There are feeding stalls for each sow, with connecting rear gates and individually opening front gates, a deep-bedded area for the group-housed sows, and bedded boar pens. The

stalls are raised approximately 16 inches above the ground to accommodate the deep-bedding pack in the center.

In each production scenario, plentiful amounts of high quality bedding are applied to the earthen portion of the structure, creating a bed approximately 12 to 18 inches deep. The heavy bedding absorbs animal manure to produce a solid waste product. Additional bedding is added continuously throughout the production cycle. Fresh bedding keeps the bed surface clean and free of pathogens and sustains aerobic decomposition. Aerobic decomposition within the bedding pack generates heat and elevates the effective temperature in the unheated hoop structure, improving animal comfort in winter conditions.

Application and Performance: The hoop structure originated in the prairie provinces of Canada. Recently, interest in this type of structure has increased in Iowa and other states in the Midwest. Swine production in this type of facility is most prevalent for finishing operations, but is also used to house dry gestational sows. Other possible uses in swine production include gilt development, isolation facilities, housing for light pigs, breeding barns, farrowing, and segregated, early weaning swine development. A hoop structure is an appropriate alternative for moderately sized operations. An "all in, all out" production strategy must be used with finishing pigs.

The manure from hoop structures is removed as a solid with the bedding pack. The high volume of bedding used creates an increased volume of waste to be removed. Typically, a front-wheel assist tractor with a grapple fork attachment on the front-end loader is required to clean out the bedding pack. In a finishing production system, the bedding pack is removed at market time, usually two to three times per year. In gestational sow housing, slightly less bedding is required, and the bedding pack is typically removed one to four times a year depending on the stocking density and quality of bedding.

A limited amount of information is available on the manure characteristics, both inside the hoop and during consequent manure management activities. The manure content within the pack is highly variable. Dunging areas are quickly established when swine are introduced into the deep-bedded structure. These areas contain a majority of the nutrients within the pack. Results of an Iowa State University study are shown in Table 8-4. Samples were taken on a grid system at nine areas throughout the bedding pack (three samples along the west side of the building, three along the center, three along the east).

Temperatures throughout the bedding pack also varied greatly. Bedding temperature was highest in the sleeping/resting area where the moisture content is approximately 50 percent. Bedding temperatures were lowest in the wet dunging areas that contain 60 to 70 percent moisture. The lower temperatures were likely caused by anaerobic conditions that prevent oxidation of carbon and, therefore, reduce the amount of heat generated (Richard et al., 1997; and Richard and Smits, 1998).

Table 8-4. Examples of Bedding Nutrients Concentrations.

Bedding Nutrients by Location[a]				
Site	Total Moisture (percent)	Total Nitrogen (lb/ton)	Phosphorus (lb/ton)	Potassium (lb/ton)
West1	73.7	20	21	12
West2	75.2	22	22	12
West3	68.5	22	31	16
Center1	67.4	14	20	26
Center2	22.9	11	21	37
Center3	27.6	22	17	26
East1	68.5	29	24	29
East2	30.6	36	40	51
East3	73.5	16	13	15
Mean	56.4	21.3	23.2	24.8
Standard Deviation	22.3	7.6	7.6	13

[a] Adapted from Richard et al., 1997.

Richard et al. and Richard and Smits (1997, 1998) also examined the loss of N in the hoop structure bedding pack. One-third of the N was lost while swine were housed in the structure. This loss was hypothesized to be caused largely by NH_3 volatilization and possibly from nitrate leaching. An additional 10 percent reduction in N occurred as the bedding pack was removed from the hoop. This loss was also hypothesized as being a result of NH_3 volatilization. Additional N was lost during the composting process, with the amount lost corresponding to the specific composting process demonstrated. In general, the composting process that resulted in the greatest reduction of volume also had the greatest N loss (Richard and Smits, 1998).

N leaching potential was examined in yet another study at Iowa State University. The hoop facility used in this trial was located on hard-packed soil with a high clay-content. Following one production cycle, the surface NO_3-N was 5.5 times greater than the initial level. There was no significant change in NO_3-N at other depths ranging to 5 feet. Following a second production cycle, the NO_3-N levels at all depths to 5 feet increased three times compared with those taken following the initial production cycle (Richard et al., 1997). Nitrate was the only form of N tested.

The Medina Research Centre in Australia studied N and P accumulation in the soil beneath hoop structures. The hoop structures were constructed on Swan Coastal Plain sandy soils. Two trials were conducted in the same location approximately 6 weeks apart. In each trial there was no increase in the concentration of extractable P in the soil profile when compared with baseline data (Jeffery, 1996).

Advantages and Limitations: The quality of the work environment in a deep-bedded hoop structure is generally good. There is no liquid manure and therefore less odor than with conventional systems. The building structure and recommended orientation provide for a large

volume of naturally ventilated air. Also, because the manure is solid, storage requirements are minimized.

The high degree of variability within the bedding pack makes it difficult to predict nutrient content. Some areas can have a high fertilizer value, whereas others have high carbon and low N content. The latter can lead to N immobilization and result in crop stress if applied during or immediately prior to the growing season. For these reasons, it is desirable to mix the bedding pack to achieve a higher degree of uniformity. Some mixing will occur during the removal and storage of the manure. Treatments that allow for additional mixing, such as composting in windrows, appear to offer considerable benefits. Initial studies at Iowa State University found that composting improved uniformity, and provided for a 14 to 23 percent reduction in moisture and a 24 to 45 percent reduction in volume (Richard and Smits, 1998). It should be noted that bedding from gestational sow facilities is typically drier than that from finishing facilities. The lack of moisture is likely to limit the extent of composting unless additional manure or moisture is added.

Trials comparing a conventional confinement system to hoop structures have been performed at Iowa State University. The swine raised in the hoop structure experienced similar performance. Specifically, there was a low level of swine mortality (2.6 to 2.7 percent), comparable and acceptable average daily gain, and a slightly poorer feed efficiency (8 to 10 percent) for swine raised in the winter months (Honeyman et al., 1999). Poor feed efficiency in winter months is due to an increased nutrient/energy requirement to maintain body heat. These findings supported an earlier study by the University of Manitoba that found swine finished in hoop structures to have excellent health, similar rates of gain, poorer feed efficiency in colder months (10 to 20 percent), low swine mortality, and similar days to market (Conner, 1993). Moreover, similar results were found in a South Dakota State University study. Several researchers have identified proper nutrition for swine raised in hoops as an area needing further research.

With respect to housing dry gestational sows, providing a lockable feeding area for each sow affords similar advantages to those of traditional gestation crates. Producers have the ability to keep feed intake even, eliminate competition for feed, administer treatments and medication effectively, lock sows in for cleaning and bedding, and sort and transfer sows for breeding or farrowing through the front gates. Furthermore, group housing stimulates estrus (the period of time within a female's reproductive cycle in which she will stand to be bred), reduces stress to the sow, and alleviates many foot and leg problems common in sows. Fighting is minimized by the use of feeding stalls and introducing new sows at optimal times, such as farrowing. Concreting the deep-bedded section to prevent sows from rooting is an option, but it increases capital outlay (Honeyman et al.,1997).

Iowa State University has conducted demonstration trials on gestating sows in deep-bedded hoop structures. Conception rate, farrowing rate, number of swine born alive, and birth weight in groups gestated in the hoop structure were all excellent. The sow performance results indicate that hoop structures are an exceptional environment for gestating sows. It must be noted, however, that sow groups were not mixed and new sows were not introduced during the trial.

With respect to breeding, hot weather is of greater concern than cold weather. Excessive high temperatures can be detrimental to breeding performance. Boars exposed to elevated effective temperatures will experience poor semen quality for a 6- to 8-week period that begins 2 to 3 weeks following exposure. Sows are more tolerant to high temperatures, except during the first 2 to 3 weeks of gestation and the final 2 weeks prior to farrowing. Litter size and birth weight can be severely altered during these periods (Honeyman et al., 1997).

Iowa State University has also conducted preliminary trials with farrow-to-finish production, early weaned pigs, and wean-to-finish production. These studies concluded that, although each may be a viable alternative, many details must still be worked out before they all become successful consistently.

The hoop system offers several benefits with respect to animal welfare and behavior. Honeyman et al. (1997) stated that one of the most extreme stresses in livestock production results when an animal is prevented from controlling various aspects of its environment. This lack of control is apparent in many of today's conventional production systems and is responsible for an unduly high level of stress that affects general health, reproduction, and welfare. Production in a deep-bedded hoop structure allows each animal to control its own microenvironment by burrowing down into the bedding, huddling, or lying on top. Deep-bedded hoops also allow swine to root through and ingest some bedding at will. This is especially advantageous in dry-sow gestational housing. The behavior serves two purposes. First, swine have an inherent drive to root. Being able to do so prevents frustration, boredom, and, hence, aggression. Second, consumption of bedding material quiets any hunger the pig may feel. Increased genetic evolution has led swine to have an increased drive to eat. Gestating sows are typically fed a limited amount of feed, satisfying what is estimated to be only 30 to 50 percent of their appetite. Stereotypic behavior is indicative of a suboptimal environment and will ultimately have implications on an animal's general health and production. No evidence of stereotypic behavior is cited in any of the deep-bedded system studies (Honeyman et al., 1997).

The initial capital outlay for hoop structures is about 30 percent less than the capital requirement associated with a typical double-curtain swine finishing building (Harmon and Honeyman, 1997). Additionally, hoop structures are highly versatile and have many alternative uses (e.g., equipment storage) if production capacity is not needed. Production in hoop structures requires a greater amount of feed and large volumes of high quality bedding, however. Bedding is the key to successful production in hoop structures. These differences make the cost of production comparable to that of a traditional confinement setting.

Hoop structures are easy to construct with on-farm labor. In Iowa State University trials, hoop structures show no visible signs of deterioration after 4 years (Honeyman, 1995). The average useful life of a hoop structure is estimated to be 10 years (Brumm, 1997).

The amount of bedding used in the studies averages 200 pounds per finisher pig in each production cycle, with a greater amount of bedding being used in the winter months. It is estimated that approximately 1,800 pounds of high quality bedding per gestational sow are

needed each year (Halverson, 1998). The amount of labor is directly proportional to the amount of bedding and ranges from 0.3 to 0.6 hours per pig (Richard et al., 1997). A survey distributed to producers of finishing pigs in hoop structures and compiled by Iowa State University found actual labor requirements to average 0.25 hours per pig (Duffy and Honeyman, 1999). Labor requirements rely on many factors, including farm size, level of automation, and experience with the production system. Based on the trials conducted at each university, the labor requirement was considered to be reasonable and competitive with other finishing systems (Conner, 1993; Richard et al., 1997).

The large amount of bedding required in hoop structure production can limit its feasibility for some producers. Many types of bedding can be used. Corn stalks, oat straw, wheat straw, bean stalks, wood shavings, and shredded paper have all been used with some success, although shredded corn stalks are the most common. Selection of the appropriate bedding type is based on many factors. First, the availability of bedding must be considered. This is specific to geographical area but may also be limited by climate. An early snow or a wet fall could prevent stalk baling. Second, in several areas of the Midwest, federally mandated conservation plans on highly erodible land require residue to be left on the land. In such cases, harvesting corn and bean stalks may not be appropriate. Finally, bedding storage is an important consideration. Generally, bedding baled in the fall and used by the spring can be stored outdoors. Bedding needed for spring and summer use, however must be stored undercover in a well-drained area to avoid loss in quality and quantity.

Internal parasite control must be aggressive because swine are continually in contact with their feces. Several of the Iowa State University studies note that flies are a potential problem for hoop houses in warm months. Furthermore, rodent and bird problems may be difficult to control. Also, in the summer, incidental composting within the bedding pack can create unwelcome heat and may lessen the animals' comfort. It has not been determined whether there is severe potential for disease and parasite buildup in the soil beneath the hoop structure.

Operational Factors: Production in a hoop structure relies on bedding, intensive management, and keen husbandry for success. Climate control is a major factor in determining the feasibility of deep-bedded hoop structures. The recommended orientation of the buildings is north to south (depending on geographical area), to take advantage of the prevailing summer winds. Air enters the facility through spaces between the sidewall and the tarp and at the ends. Warm, moist air moves toward the top of the arch and is carried out the north end by natural currents. Various end structures are available that supply adjustable levels of ventilation. In the winter months, the north end is generally closed and the south is at least partially opened. If the ends are closed too tightly, high levels of humidity can become a problem. On average, the inside air temperature in the winter is only 5 to 8 °F warmer than outside temperatures. This is different from the effective temperature which the swine can alter by burrowing into the deep bedding. In summer months, both ends are left open. Ultraviolet resistant tarp and sprinklers inside the structure help to control the temperature within the structure. Air temperature in the summer averages 2 to 4 °F lower than outside temperature (Harmon and Xin, 1997). The length of the hoop structure also

has an effect on air temperature because of the rate of air exchange. Wider and longer hoop structures often have ridge vents to improve ventilation.

Demonstration Status: Hoop structures have been used successfully in the United States for housing finishing pigs and dry gestational sows. Grow-finish production is the most common use for hoop structures in swine production. Recently, there has been an increased interest in this type of production system in the Midwest, including the states of Iowa, Illinois, Minnesota, Nebraska, and South Dakota. It is estimated that more than 1,500 hoop structures have been built for swine production in Iowa since 1996 (Honeyman, 1999). Furthermore, initial demonstrations have been conducted with early weaned pigs and in farrow-to-finish production. Hoop structures are being used to house swine in at least seven Canadian provinces. Currently, more than 400 hoop structures are used for swine finishing in Manitoba (Conner, 1994).

Practice: Rotational Grazing

Description: Intensive rotational grazing is known by many terms, including intensive-grazing management, short duration grazing, savory grazing, controlled grazing management, and voisin-grazing management (Murphy, 1998). This practice involves rotating grazing cattle (both beef and dairy) among several pasture subunits or paddocks to obtain maximum efficiency of the pasture land. Dairy cows managed under this system spend all of their time not associated with milking out on the paddocks during the grazing season and beef cattle spend all of their time out on the paddocks during the grazing season. Intensive rotational grazing is rarely, if ever, used at swine and poultry operations. Nonruminants such as swine and poultry are typically raised in confinement because of the large number of animals produced and the need for supplemental feed when they are raised on pastures.

Application and Performance: Rotational grazing is applicable to all beef and dairy operations that have sufficient land. During intensive rotational grazing, each paddock is grazed quickly (1 or 2 days) and then allowed to regrow, ungrazed, until ready for another grazing. The recovery period depends on the forage type, the forage growth rate, and the climate, and may vary from 10 to 60 days (USDA, 1997). This practice is labor- and land-intensive as cows must be moved daily to new paddocks. All paddocks used in this system require fencing and a sufficient water supply. Many operations using intensive rotational grazing move their fencing from one paddock to another and have a water system (i.e., pump and tank) installed in each predefined paddock area.

The number of required paddocks is determined by the grazing and recovery periods for the forage. For example, if a pasture-type paddock is grazed for 1 day and recovers for 21 days, 22 paddocks are needed (USDA, 1997). The total amount of land required depends on a number of factors including the dry matter content of the pasture forage, use of supplemental feed, and the number of head requiring grazing. Generally, this averages out to one or two head per acre of pasture land for both beef and dairy cattle (Hannawale, 2000). Successful intensive rotational grazing, however, requires thorough planning and constant monitoring. All paddocks should be monitored once a week. High-producing milk cows (those producing over 80 lbs/day) need a

large forage allowance to maintain a high level of intake. Therefore, they need to graze in pastures that have sufficient available forage or be fed stored feed (USDA, 1997). It is also expected that beef cattle would need sufficient forage or stored feed to achieve expected weight gains.

The climate in many regions is not suitable for year round rotational grazing. Operations in these regions must maintain barns or dry lots for the cows when they are not being grazed or outwinter their cows. Outwintering is the practice of managing cows outside during the winter months. This is not a common practice because farmers must provide additional feed as cows expend more energy outside in the winter, provide windbreaks for cattle, conduct more frequent and diligent health checks on the cows, and keep the cows clean and dry so that they can stay warm (CIAS, 2000).

There are two basic management approaches to outwintering: rotation through paddocks and sacrifice paddocks. Some farms use a combination of these practices to manage their cows during the winter. During winter months, farmers may rotate cattle, hay, and round bale feeders throughout the paddocks. The main differences between this approach and standard rotational grazing practices are that the cows are not rotated as often and supplemental feed is provided to the animals. Deep snow, however, can cause problems for farmers rotating their animals in the winter because it limits the mobility of round bale feeders. The outwintering practice of "sacrifice paddocks" consists of managing animals in one pasture during the entire winter. There are several disadvantages and advantages associated with this practice. If the paddock surface is not frozen during the entire winter, compaction, plugging (tearing up of the soil), and puddling can occur. Due to the large amounts of manure deposited in these paddocks during the winter, the sacrificial paddocks must be renovated in the spring. This spring renovation may consist of dragging or scraping the paddocks to remove excess manure and then seeding to reestablish a vegetative cover. Some farmers place sacrifice paddocks strategically in areas where an undesirable plant grows or where they plan to reseed the pasture or cultivate for a crop (CIAS, 2000).

EPA conducted an analysis to estimate the manure reduction achievable with intensive rotational grazing at model beef and dairy operations (ERG, 2000a). Outwintering was not assumed to occur in this analysis. During the months that the cows from the model dairies and feedlots were assumed not to be on pasture, the amount of manure that must be managed is assumed to be equal to the amount produced at equal size confined dairy operations and beef feedlots. Table 8-5 presents the estimated range of months that intensive rotational grazing systems might be used at dairy farms and beef feedlots located in each of the five geographical regions included in this analysis.

It is estimated that approximately 15 percent of the manure generated by dairy cows is excreted in the milking center and 85 percent is excreted in the housing areas (i.e., barns, dry lots, pastures) (USDA NRCS, 1996). It is also estimated that 23 to 28 percent of the wastewater volume generated from a flushing dairy operation comes from the milking center and 72 to 77

Table 8-5. Amount of Time That Grazing Systems May Be Used at Dairy Farms and Beef Feedlots, by Geographic Region.

Region	Annual Use of Grazing Systems (months)
Pacific	3–12
Central	3–12
Midwest	3– 6
Mid-Atlantic	3– 9
South	9–12

percent (median of 75 percent) of the wastewater comes from flushing the barns (USEPA, 2000). All wastewater from a hose-and-scrape dairy system is generated at the milking center. Thus, dairies using intensive rotational grazing systems would manage 85 percent less solid manure and approximately 75 percent less wastewater (for flushing operations) than confined systems, during the months that the cows are on pasture.

All of the manure generated at beef feedlots using intensive rotational grazing systems would be excreted on the pasture during the months that the cows are grazing. No significant amounts of process wastewater are generated at beef feedlots. Thus, beef feedlots using intensive rotational grazing systems would manage 100 percent less solid waste during the months that the cows are on pasture.

Two model farm sizes were analyzed for dairy farms, assuming an average size of 454 (for medium-sized dairies) and 1,419 milking cows (for large-sized dairies). Both of these size groups are significantly larger than the 100 head or smaller operations expected to use intensive rotational grazing systems. Therefore, the specific model farm calculations are viewed as significantly overestimating the amount of collected manure and wastewater that could be reduced at typical intensive rotational grazing operations versus confined operations. For this reason, estimates on collected manure and wastewater reduction are presented on a per-head basis and model farm basis for the two dairy farm types (flushing, hose and scrape) included in EPA's ELG analysis for each of the five geographical regions.

Three model farm sizes were analyzed for beef feedlots, assuming an average size of 844 (for medium-sized feedlots), 2,628 (for large-sized feedlots), and 43,805 beef slaughter steer (for very large feedlots). Due to the slow weight gain associated with grazing operations for beef cattle and required number of pasture acres, beef feedlots of these sizes are not expected to use intensive rotational grazing systems. However, estimates on collected manure reductions are presented on a per-head basis and model farm basis for the three sizes of beef feedlots included in EPA's ELG analysis for each of the five geographical regions.

Table 8-6 presents the expected reduction in collected manure and wastewater for flush and hose-and-scrape dairy operations, by head, and by region. Table 8-7 presents the expected reduction in collected manure and wastewater for dairy operations by model farm, and by region. Table 8-8 presents the expected reduction in collected manure for beef feedlots, by head, and by region.

Table 8-9 presents the expected reduction in collected manure for beef feedlots by model farm, and by region.

Table 8-6. Expected Reduction in Collected Solid Manure and Wastewater at Dairies Using Intensive Rotational Grazing, per Head.

Farm Type	Region	Manure Reduction (lb/yr/head)	Wastewater Reduction (gal/yr/head)
Flush	Pacific	10,200–41,500	9,000–36,500
	Central	10,200–41,500	9,000–36,500
	Midwest	10,200–20,500	9,000–18,000
	Mid-Atlantic	10,200–30,700	9,000–27,000
	South	30,700–41,500	27,000–36,500
Hose and Scrape	Pacific	10,200–41,500	0
	Central	10,200–41,500	0
	Midwest	10,200–20,500	0
	Mid-Atlantic	10,200–30,700	0
	South	30,700–41,500	0

Table 8-7. Expected Reduction in Collected Solid Manure and Wastewater at Dairies Using Intensive Rotational Grazing, per Model Farm.

Farm Size (head)	Farm Type	Region	Manure Reduction (lb/yr/farm)	Wastewater Reduction (gal/yr/farm)
454	Flush	Pacific	4,630,800– 18,841,000	4,086,000– 16,571,000
		Central	4,630,800– 18,841,000	4,086,000– 16,571,000
		Midwest	4,630,800– 9,307,000	4,086,000– 8,172,000
		Mid-Atlantic	4,630,800– 13,937,800	4,086,000– 12,258,000
		South	13,937,800– 18,841,000	12,258,000–16,571,000
454	Hose & Scrape	Pacific	4,630,800– 18,841,000	0
		Central	4,630,800– 18,841,000	0
		Midwest	4,630,800– 9,307,000	0
		Mid-Atlantic	4,630,800– 13,937,800	0
		South	13,937,800– 18,841,000	0
1419	Flush	Pacific	14,473,800– 58,888,500	12,771,000– 51,793,500
		Central	14,473,800– 58,888,500	12,771,000– 51,793,500
		Midwest	14,473,800– 29,089,500	12,771,000– 25,542,000
		Mid-Atlantic	14,473,800– 43,563,300	12,771,000– 38,313,000
		South	43,563,300– 58,888,500	38,313,000– 51,793,500
1419	Hose and Scrape	Pacific	14,473,800– 58,888,500	0
		Central	14,473,800– 58,888,500	0
		Midwest	14,473,800– 29,089,500	0
		Mid-Atlantic	14,473,800– 43,563,300	0
		South	43,563,300– 58,888,500	0

Table 8-8. Expected Reduction in Collected Solid Manure at Beef Feedlots Using Intensive Rotational Grazing, per Head.

Region	Manure Reduction (lb/yr/head)
Pacific	5,040–20,167
Central	5,040–20,167
Midwest	5,040–10,080
Mid-Atlantic	5,040–15,120
South	15,120–20,167

Table 8-9. Expected Reduction in Collected Solid Manure at Beef Feedlots Using Intensive Rotational Grazing, per Model Farm.

Farm Size (head)	Region	Manure Reduction (lb/yr/farm)
844	Pacific	4,255,170–17,020,680
	Central	4,255,170–17,020,680
	Midwest	4,255,170–8,510,340
	Mid-Atlantic	4,255,170–12,765,510
	South	12,765,510–17,020,680
2628	Pacific	13,249,500–52,998,000
	Central	13,249,500–52,998,000
	Midwest	13,249,500–26,499,000
	Mid-Atlantic	13,249,500–39,748,500
	South	39,748,500–52,998,000
43805	Pacific	220,849,640–883,398,550
	Central	220,849,640–883,398,550
	Midwest	220,849,640–441,699,280
	Mid-Atlantic	220,849,640–662,548,910
	South	662,548,910–883,398,550

Advantages and Limitations: Compared with traditional grazing, intensive rotational grazing has been identified as environmentally friendly and, when managed correctly, is often considered better than conventional or continuous grazing. The benefits associated with intensive rotational grazing versus conventional grazing include:

- Higher live-weight gain per acre. Intensive rotational grazing systems result in high stocking density, which increases competition for feed between animals, forcing them to spend more time eating and less time wandering (AAC, 2000).
- Higher net economic return. Dairy farmers using pasture as a feed source will produce more feed value with intensive rotational grazing than with continuous grazing (CIAS,

2000). Competition also forces animals to be less selective when grazing. They will eat species of plants that they would ignore in other grazing systems. This reduces less desirable plant species in the pasture and produces a better economic return (AAC, 2000).

- Better land. Pastureland used in rotational grazing is often better maintained than typical pastureland. Intensive rotational grazing encourages grass growth and development of healthy sod, which in turn reduces erosion. Intensive rotational grazing in shoreline areas may help stabilize stream banks and could be used to maintain and improve riparian habitats (PPRC, 1996).
- Less manure handling. In continuous grazing systems, pastures require frequent maintenance to break up large clumps of manure. In a good rotational system, however, manure is more evenly distributed and will break up and disappear faster. Rotational grazing systems may still require manure maintenance near watering areas and paths to and from the paddock areas (Emmicx, 2000).

Grazing systems are not directly comparable with confined feeding operations, as one system can not readily switch to the other. However, assuming all things are equal, intensive rotational grazing systems might have some advantages over confined feeding operations. They are:

- Reduced cost. Pasture stocking systems are typically less expensive to invest in than livestock facilities and farm equipment required to harvest crops. Feeding costs may also be lowered.
- Improved cow health. Dairy farmers practicing intensive rotational grazing typically have a lower cull rate than confined dairy farmers, because the cows have less hoof damage, and they are more closely observed by the farmer as they are moved from one paddock to another (USDA, 1997).
- Less manure handling. Intensive rotational grazing operations have less recoverable solid manure to manage than confined operations.
- Better rate of return. Research indicates that grazing systems are more economically flexible than the confinement systems. For example, farmers investing in a well-planned grazing operation will likely be able to recover most of their investment in assets if they leave farming in a few years. But farmers investing from scratch in a confinement operation would at best recover half their investments if they decide to leave farming (CIAS, 2000).

The disadvantages associated with intensive rotational grazing compared with either conventional grazing or confined dairy operations include

- Limited applicability. Implementation of intensive rotational grazing systems is dependent upon available acreage, herd size, land resources (i.e., tillable versus steep or rocky), water availability, proximity of pasture area to milking center (for dairy operations), and feed storage capabilities. Typical confined dairy systems and beef

feedlots are often not designed to allow cows easy access to the available cropland or pastureland. Large distances between the milking center and pastureland will increase the dairy cow's expended energy and, therefore, increase forage demands.

In most of the country, limited growing seasons prevent many operations from implementing a year-round intensive rotational grazing system. Southern states such as Florida can place cows on pasture 12 months of the year, but the extreme heat presents other problems for cows exposed to the elements. Grazing operations in southern states typically install shade structures and increase water availability to cows, which in turn increases the costs and labor associated with intensive rotational grazing systems. Because most operations cannot provide year-round grazing, they still must maintain barns and dry lot areas for their cows when they are not grazing, and operations often prefer not to have to maintain two management systems.

- Reduced milk production levels. Studies indicate that dairy farmers using intensive rotational grazing have a lower milk production average than confined dairy farms (CIAS, 2000). Lower milk production can offset the benefit of lower feed costs, especially if rations are not properly balanced once pasture becomes the primary feed source during warm months.
- Reduced weight gain. Beef cattle managed in an intensive rotational grazing system would gain less weight per day than beef cattle managed on a feedlot unless they were supplied with extensive supplemental feed.
- Increased likelihood of infectious diseases. Some infectious diseases are more likely to occur in pastured animals due to direct or indirect transmission from wild animals or the presence of an infective organism in pasture soil or water (Hutchinson, 1998).
- Limited flexibility. Intensive rotational grazing systems have limited flexibility in planning how many animals can be pastured in any one paddock. Available forage in a paddock can vary from one cycle to another, because of weather and other conditions that affect forage growth rates. As a result, a paddock that was sized for a certain number of cows under adequate rainfall conditions will not be able to accommodate the same number of cows under drought conditions (USDA, 1997).

Operational Factors: As mentioned earlier, most dairy operations and beef feedlots cannot maintain year-round intensive rotational grazing systems. These systems are typically operated between 3 and 9 months of the year–with 12 months most likely in the southern states. Although outwintering is a possibility for year round grazing in more northern states, it is not a common practice.

Demonstration Status: Due to the labor, fencing, water, and land requirements of intensive rotational grazing, typically only small dairy operations (those with less than 100 head) use this practice (Hannawale, 2000; USDA NRCS, 2000; CIAS, 2000). Few beef feedlots practice intensive rotational grazing. Climate and associated growing seasons make it very difficult for operations to use an intensive rotational grazing system throughout the entire year.

Practice: Pasture-Based Systems at Swine Operations

Description: There are three main types of outdoor management systems at swine operations: pasture, open lots, and buildings with outside access. In pasture systems, crops are grown and the animals are allowed to forage for their own food. Open lots are generally nonvegetative areas where the animals are allowed to roam. These open lots are typically available to animals that are housed in buildings with outside access. The focus of this discussion is the pasture systems.

Application and Performance: This practice is applicable to any swine operation that has sufficient land. However, the practicality of the practice decreases with operation size. Wheaton and Rea (1999) found that the use of a good pasture containing such crops as alfalfa, clover, and grasses can support about eight to ten sows. Stocking rates, however, will depend upon soil fertility, quality of pasture, and time of year. The recommended stocking rates are (Wheaton and Rea, 1999):

- Sows with litters — 6 to 8 head per acre
- Pigs from weaning to 100 pounds — 15 to 30 head per acre
- Pigs from 100 pounds to market — 10 to 20 head per acre
- Gestating sows — 8 to 12 head per acre

Wheaton and Rea (1999) also found that pastured swine must receive 2 to 3 pounds of grain daily plus minerals and salt for proper weight gain. Adequate shade and water must also be provided to pastured swine. Swine can be very tough on pastures and soil. Therefore, it is recommended that producers rotate swine after each season and use the pasture for other animals or harvest hay for about 2 years before using it again for swine (Wheaton and Rea, 1999). All the waste produced by the animals while they are pastured is incorporated into the sod, and therefore requires minimal waste disposal.

Advantages and Limitations: A pasture-based system offers a number of advantages and disadvantages over confinement housing to swine producers. The advantages include (Wheaton and Rea, 1999)

- Lower feed costs on good pasture
- Exercise and nutrients for breeding sows
- Lower capital investment per production unit
- Good use of land not suitable for machine harvest
- Better isolation and disease control
- Decreased waste management handling
- Decreased cannibalism

The disadvantages include (Wheaton and Rea, 1999)

- Increased labor for animal handling, feeding, and watering
- Increased risk of internal parasites
- Increase labor for farrowing
- Increase animal production time to reach desired market weight
- Lack of environmental controls

Operational Factors: The increased labor costs associated with pasture-based swine operations are partially offset by decreased waste handling costs and reduced feed costs.

Demonstration Status: Data from the USDA's APHIS - Veterinary Service indicate pasture-based systems are used at 7.6 percent of farrowing operations, 1.5 percent of nurseries, and 6.7 percent of finishing operations (USDA APHIS, 1995). The percentage of pigs raised on such operations is about five times less than the number of operations, indicating these operations are generally smaller than other types of swine operations. NAHMS confirmed this with additional analysis of the *Swine '95* data, and indicated 7 to 8 percent of swine farms with fewer than 750 total head use pasture systems, but less than 1 percent of swine operations larger than 750 head use pasture systems (USDA NAHMS, 1999).

Practice: Pasture-Based Systems at Poultry Operations

Description: Pastured poultry refers to broilers, layers, and turkeys that are raised on pasture and feed. There are three basic methods for raising poultry on pasture: pasture pens, free range, and day range (Lee, 2000). Pasture pens are bottomless pens that hold layers, broilers, or turkeys, and are moved daily or as needed to give the poultry fresh pasture. This is the most commonly used pasture poultry method at present. To accommodate layers, nest boxes are fixed to the side of the pen. Approximately 30 to 40 hens can be housed in one typical pasture pen. Free range generally means a fenced pasture surrounding the barn or poultry shelter, and day range is similar to free range except that the birds are sheltered at night from predators and weather.

Application and Performance: The use of pasture pens has been documented at operations with 1,000 birds but is believed to be used most commonly at operations with fewer than 1,000 birds. Lee (2000) also indicates that pastured poultry operations require up to twice the amount of feed as confined poultry does to achieve the same weight gain and/or production goal. All wastes produced while the birds are on pasture is incorporated into the sod, and therefore results in minimal waste requiring disposal.

Advantages and Limitations: Some of the advantages associated with pastured poultry versus confinement housing are:

- Pasture pens are easy and inexpensive to build
- Controlled moves will harvest grass and help spread manure uniformly across the field

- Perimeter fencing is not required
- Diseases associated with confinement housing may be less likely to occur
- Waste management handling is reduced
- Pasture-raised birds may have a higher market value (Lee, 2000)

The limitations associated with pastured poultry include the following:

- The small pens hold relatively few poultry, compared with their cost
- Pens can trap heat, leading to heat stress
- The roof height of the pens is too low for turkeys to stretch and raise their heads to full height
- Pens may be difficult to move
- Pens offer only minimal protection from weather
- Birds often have to bed down at night in manure-soaked grass (Lee, 2000)

Operational Factors: Pasture-based poultry operations require increased labor for animal handling, feeding, and watering (Lee, 2000). This increased labor is partially offset by a decrease in waste management.

Demonstration Status: No data could be found to indicate the number of pasture-based poultry operations. However, the use of pasture pens is rarely observed at operations with more than 1,000 birds. Thus few if any pastured poultry operations confine sufficient numbers of birds to be defined as CAFOs on the basis of operation size.

8.2 Manure/Waste Handling Storage and Treatment Technologies

Manure is often used as a nutrient source and soil amendment, and can be used effectively by itself or along with other nutrient sources such as commercial fertilizer. In some cases surplus manure can be treated, processed, or repackaged to increase its value as a nutrient resource (such as compost, pelletized litter, or a fertilizer blend). When manure is generated in excess of what can be locally utilized either as a nutrient source or some other alternative use, it is often treated as a waste. EPA believes manure is most effectively used as a resource, and the use of the term waste in the following sections is not meant to imply to the contrary.

The term "waste" as it relates to AFOs includes manure, bedding material, spilt or waste feed, animal carcasses, and other by products. There are a variety of methods for handling, storing, and treating waste. Waste may be handled both in a solid form and through the use of water. As stated in earlier chapters, some facilities use water to move the waste away from the animals and then separate the solids from the liquids prior to storage, treatment, and disposal. Water may also be used for cleaning and disinfection, especially at dairies and egg-producing facilities. Storage and treatment of waste is done in the both the solid and liquid/slurry forms.

8.2.1 Waste Handling Technologies and Practices

Different practices are used to handle or move liquid and solid wastes, and the choice of practices depends on the type of housing configuration. Housing configurations include total confinement, which is the most common and used almost exclusively in the poultry industry and at larger swine operations, open buildings with or without outside access, and lots or pastures with a hut or with no buildings.

Practice: Handling of Waste in Solid Form

Description: The use of hoop houses for swine and high-rise hog houses to handle manure in a dry form was discussed in section 8.1. In facilities with open lots, manure accumulates on the ground as a solid that can be diluted by rainfall (mostly for beef and dairy, swine and poultry are mostly totally confined) or by spillage from watering areas. Whether the lot is paved, partially paved, or unpaved, manure is typically handled as a solid or slurry and is scraped with tractor scrapers or front-end loaders and stored in a pile (see Figure 8-2). There are several options for separating solid manure from the animals at confinement facilities. Solid, unslatted floors, both paved and unpaved, can be hand-scraped or scraped with a tractor or front-end loader into a pile, pit, or other storage facility. Sloped floors further aid in manure collection as animal traffic works the manure downslope. Other facilities use uncovered alley or gutter systems combined with hand scraping, automatic scraping, or sloped floors to collect manure. Scraped manure from underslat gutters, alleys, or shallow pits can be held temporarily in a pit or a deep collection gutter at one end of the building, from which it can be applied to the land or transferred to a more permanent storage structure.

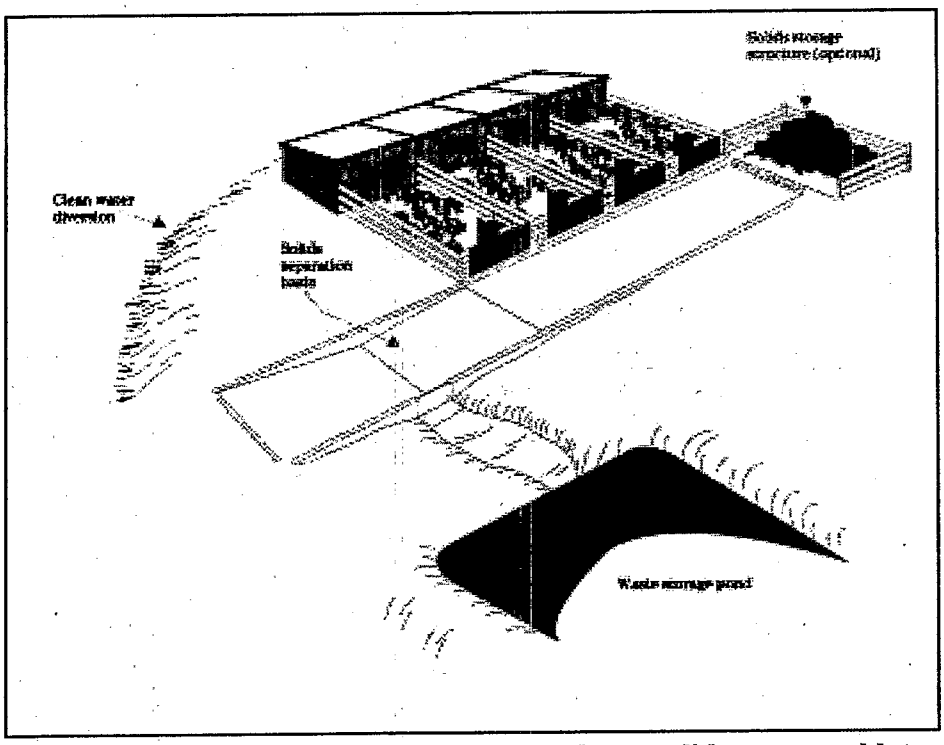

Figure 8-2. Manure scraped and handled as a solid on a paved lot operation (USDA NRCS, 1996).

Application and Performance: Solid systems are best suited for open lot facilities, especially in areas that have a dry climate because exposed manure is less likely to be diluted by excess rainfall. The choice of solid or liquid handling systems, however, has been historically based on operator preference with respect to capital investment, labor requirements, and available equipment and facilities.

Advantages and Limitations: Solid handling systems offer both advantages and disadvantages to facility operators. For instance, solid systems use equipment that is already present at the facility, such as tractors and front-end loaders. Tractors and front-end loaders are flexible, have fewer mechanical problems, are less subject to corrosion, and work well on frozen manure, but they require more labor than automatic scrapers. Solid systems are not as automated as liquid systems; although they involve little or no capital investment and require less maintenance, they require much more labor than mechanical scraper systems or flushing systems. An advantage to solid systems is that the volume of manure handled is much less than the volume associated with liquid systems, which translates into smaller storage facility requirements. Bedding can be used without concern for pumping or agitating equipment problems (which are a concern for liquid handling systems).

Operational Factors: The extent of paving on an open lot determines the care with which manure is removed. Unpaved lots develop an impervious layer from bacterial activity and hoof action, and this layer protects against soil loss and percolation of liquids. Also, scraping of unpaved surfaces incorporates sand and soil into the manure, which can cause problems with storage or treatment of the manure. If scraped manure is to be stacked, it may be necessary to add an appreciable amount of bedding to attain a more solid consistency.

Demonstration Status: Solid handling systems are fairly common at smaller swine operations. According to *Swine '95* (USDA APHIS, 1996a), removal of manure by hand is used most often in all types of operations (farrowing 38.2 percent, nursery 29.9 percent, and grow-finish 27.2 percent). Mechanical scrapers and tractors are also used for solids handling (farrowing 12.0 percent, nursery 17.6 percent, and grow-finish 24.9 percent).

Poultry waste is mostly handled as a dry litter, the exception being layer operations, particularly in the South Region (USDA NAHMS, 2000a).

Manure is often handled in solid form at smaller dairy farms. According to *Dairy '96* (USDA APHIS, 1996a), gutter cleaners are used most often to remove manure from dairy cow housing areas (63.2 percent). Mechanical scrapers or tractors are frequently used to clean alleys (57.7 percent). A number of dairies store manure in solid form; 79.2 percent of dairies with fewer than 100 cows and 59.5 percent of dairies with 200 or more cows are reported to use some form of solid waste storage (USDA APHIS, 1996b).

Scraping is the most common method of collecting solid and semisolid manure from beef barns and open lots. Solids can be moved with a tractor scraper and front-end loader. Mechanical scrapers are typically used in the pit under barns with slotted floors. Scraping is common for medium and large feedlots.

Practice: Teardrop, V- and Y-Shaped Pits With Scraper

Description: Confinement facilities have several manure collection options for separating manure liquids from manure solids. Several underfloor gutter systems that are applicable only to swine will be discussed. No comparable manure collection systems that separate liquids and solids are known for other animal species.

The reason for separating swine manure into solids and liquids is to concentrate pollutants and nutrients. Kroodsma (1985) installed a plastic 0.78 mm filter net under the floor of a pig house in which eight pigs were fed by wet feeders so that no excess water fell into the manure. Solids fell onto the screen and liquids passed through. The results showed that the relatively undisturbed feces contained about 80 percent of the BOD, COD, total solids (TS), P, calcium Ca, magnesium (Mg), and copper (Cu). Sixty per cent of the total TKN and forty percent of the K were also retained in the filter net. Thus, if solids can be recovered relatively intact, parameters such as nutrients will be concentrated.

Two gutter configurations that may be useful for swine operations are Y-shaped and V-shaped gutters under slatted floors (Tengman, et al., n.d.). The sloping sides of the gutters facilitate retention of solids and allow liquids to drain to the center collection area. Scrapers pull the solids to one end of the barn for solids handling, while liquids flow with gravity in the opposite direction for management in a liquid manure system.

V-shaped gutters are easier to build than Y-shaped gutters and may be easier to clean. Manure movement in V-shaped gutters is not substantially different than in Y-shaped gutters. The sideslope of Y- or V-shaped gutters should be 1:1 for farrowing operations and 3/4:1 for nurseries. A slope of 1:240 to 1:480 is recommended for the liquid gutter (Tengman, et al., n.d.).

Manure that is scraped from underslat gutters, alleys, or shallow pits can be held temporarily in a pit or a deep collection gutter at one end of the building, from which it can be applied to the land or transferred to a more permanent storage structure.

Application and Performance: The choice of a manure-handling system is based primarily on operator preference with respect to capital investment, labor requirements, and available equipment and facilities. Demonstration of the economic viability or the value of concentrating nutrients using the Y-shaped and V-shaped gutter is apparently lacking. No performance data was found from full-scale demonstration of the segregation of constituents including pathogens, metals, growth hormones, and antibiotics.

Advantages and Limitations: The advantage in using a Y-shaped or V-shaped scrape collection system would be the concentration of nutrients in the solids. Nutrients concentrated in solid form are cheaper to haul than in slurry form because water, which would increase the weight and volume, is not added. Disadvantages include reduced air quality in hog buildings over manure solids smeared on the collection slope, repair of cable scrapers in small spaces under slatted floors with hogs present, the need for the operator to manage both a compost or solids stacking operation with solids handling equipment and a liquid storage and application system with liquid handling equipment.

Operational Factors: Climate, temperature, and rainfall generally do not affect scraper systems in hog barns. If scraped manure solids are to be stacked or composted, it may be necessary to add an appreciable amount of bedding to attain a more solid consistency.

Demonstration Status: Underslat manure scrape and gutter systems to direct manure liquids and solids to different handling systems have been developed, but they are not commonly used.

Practice: Handling of Waste in Liquid Form

Description: Liquid handling systems are the alternative to scraping and hauling manure. They are especially common in confinement housing operations because it is easier to install automated systems inside new or existing structures and it is more difficult to maneuver tractors

or front-end loaders for scraping in small pens and tight corners. Excreted manure can be collected in shallow, narrow, open gutters or alleys, or it can collect under slats in gutters or pits for periodic flushing to a more permanent storage or treatment facility. The manure can also be directly applied to land without extended storage or treatment.

Slotted floors are an efficient method for removing manure from animal areas. Floors tend to be typically partially slotted over a pit or gutter. Feeding and resting areas are located on solid floors, and watering areas are placed over slotted floors. Manure is worked through the slats by hoof action and is stored beneath the slats until it is pumped or flushed to a lagoon. Fresh water can be used for flushing or water from a secondary lagoon can be recycled as flush water. An example of a slotted floor system is shown in Figure 8-3.

Application and Performance: Liquid manure systems are most frequently used for large animal facilities, where the automation of waste management systems is very important. They may also be preferred where water is abundant or when rainfall on open lots causes considerable dilution of manure solids. Liquid systems are especially appropriate when spray irrigation of nutrient-laden waters is the preferred method for fertilizing and watering crops.

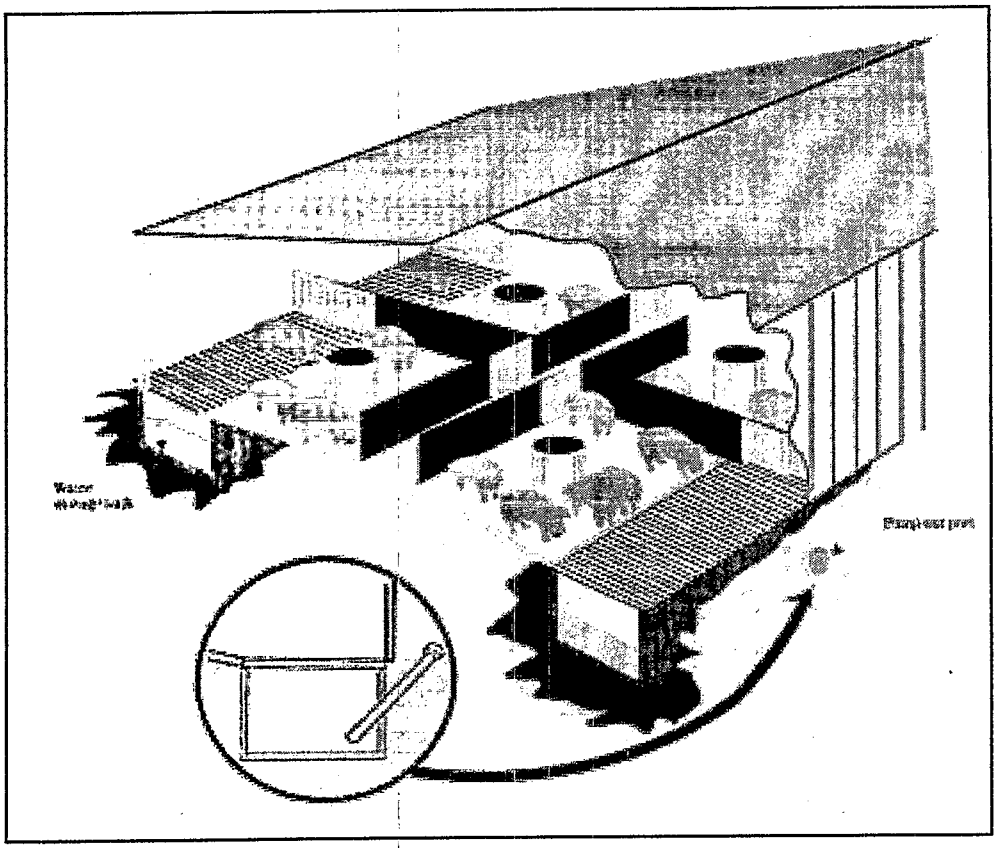

Figure 8-3. Fed hogs in confined area with concrete floor and tank storage liquid manure handling (USDA NRCS, 1996).

Advantages and Limitations: Flushing systems with liquid manure handling are less labor-intensive and more automated than solid handling systems, but the volume of manure and water to be stored, treated, and disposed of is greater. Flushing systems require large volumes of water to be pumped and stored in a sump until discharged by gravity flow or pumped to a lagoon. Consequently, where water is a valuable commodity, liquid systems might not be economical. This limitation can be offset by recycling flush water from treatment lagoons. Equipment needed for liquid systems, including sumps, pumps, agitators, choppers, and sprayers, brings with it high capital, operating, and maintenance costs, although savings may be seen in decreased labor costs. Manure consistency is very important in liquid handling systems because the equipment can be damaged by fibrous material (bedding), sand, or other foreign materials. Periodic cleanout of solids is necessary to maintain the capacity and proper functioning of storage structures and handling equipment.

Operational Factors: Slats can be made of wood, concrete, steel, aluminum, or plastic. Concrete is the most sturdy material, is the least corrodible, and handles the weight of larger animals, but it requires extra supports and the initial costs are higher than the costs of other materials. Wood is the least expensive material, but it can be chipped by the animals and needs to be replaced at least every 2 to 4 years. Plain steel and aluminum slats are subject to corrosion, but they can be galvanized or coated with paint or plastic to extend their life. Plastic slats, metal grates, expanded metal mesh, and stainless steel slotted planks are appropriate for swine farrowing and nursery operations that house smaller pigs. Openings between slats should be greater than 3/4 inch, up to 1 3/4 inches for swine operations.

Demonstration Status: The *Swine '95* report (USDA APHIS, 1996a) demonstrates that liquid systems, although not the most common type on a facility-by-facility basis, are still used fairly frequently. Flushing under slats accounts for 5.3 percent of farrowing, 9.4 percent of nursery, and 2.4 percent of grow-finish operations, whereas flushing with open gutter systems accounts for 3.0, 2.1, and 3.4 percent of each operation type, respectively. Liquid handling systems are becoming increasingly popular as larger operations become more prevalent, necessitating automated systems for manure handling.

Poultry waste is mostly handled as a dry litter, the exception being layer operations, particularly those in the South Region. Approximately 40 percent of the laying operations in the South use a flush system with a lagoon (USDA NAHMS, 2000).

Dairy '96 (USDA APHIS, 1996a) reports that a small number of dairy farms, 2.8 percent, use water to remove manure from alleys. However, over 90 percent of operations with 200 or more cows are reported to use liquid manure storage systems (USDA APHIS, 1996b). According to the NAHMS survey results (Garber, 1999), approximately 50 percent of all facilities with greater than 500 mature dairy cows employ flushing as a means of cleaning the housing area.

A flushing system dilutes manure from beef feedlots with water to allow for automated handling. The system uses a large volume of water to flush manure down a sloped gutter to storage, where the liquid waste can be transferred to a storage lagoon or basin. This system is not common for

large beef feedlots; however, this type of system is widely used at veal operations (Loudon, 1985). Based on EPA site visits, about 67 percent of veal operations flush manure to liquid lagoon storage systems.

Practice: Berms and Storm Water Diversions

Description: "Clean" storm water runoff from land surrounding livestock facilities can be diverted from barns, open animal concentration areas, and waste storage or treatment facilities to prevent mixing with wastewater. This is accomplished through earthen perimeter controls and roof runoff management techniques.

Earthen perimeter controls usually consist of a berm, dike, or channel constructed along the perimeter of a site. Simply defined, an earthen perimeter control is a ridge of compacted soil, often accompanied by a ditch or swale with a vegetated lining, located at the top or base of a sloping area. Depending on their location and the topography of the landscape, earthen perimeter controls can achieve one of three main goals: preventing surface runoff from entering a site, diverting manure-laden runoff created on site to off-site waste trapping devices, and intercepting clean storm water runoff and transporting it away from lagoons or belowground tanks. Therefore, diversions are used to protect areas from runoff and divert water from areas where it is in excess to locations where it can be stored, used, or released. Thus, it prevents the mixing of clean storm water with manure-laden wastewater, reducing the volume of wastewater to be treated.

Roof runoff management techniques such as gutters and downspouts direct rainfall from roofs away from areas with concentrated manure. Because these devices prevent storm water from mixing with contaminated water, they also reduce the volume of wastewater to be treated.

Application and Performance: Earthen perimeter controls or diversions are applicable where it is desirable to divert flows away from barns, open animal concentration areas, and waste storage or treatment facilities. They can be erected at the top of a sloping area or in the middle of a slope to divert storm water runoff around a feeding or manure storage site. However, unvegetated, earthen channels should not be used in regions of high precipitation because of potential erosion problems.

The design capacity of a channel is calculated using Manning's equation and is based on precipitation, slope, wetted perimeter, water cross-sectional area, and surface roughness. Water velocity is also a consideration in designing diversions to minimize erosion. Other types of diversions that can be used for runoff control include grassed waterways, which are natural or constructed channels that provide stable runoff conveyance, and lined waterways or outlets, which are lined channels or outlets reinforced with erosion-resistant linings of concrete, stone, or other permanent materials to provide additional stability.

Advantages and Limitations: When properly placed and maintained, earthen perimeter controls are effective for controlling the velocity and direction of storm water runoff. Used by themselves,

they do not have any ability to remove pollutants and thus must be used in combination with an appropriate sediment or waste trapping device at the outfall of the diversion channel. With these diversion techniques, storm water runoff is prevented from mixing with contaminated manure-laden wastewater and thus the volume of water for treatment is decreased; however, the concentrated runoff in the channel or ditch has increased erosion potential. To such erosion, diversion dikes must be directed to sediment trapping devices where erosion sediment can settle out of the runoff before being discharged. In addition, if a diversion dike crosses a vehicle roadway or entrance, its effectiveness may be reduced. Wherever possible, diversion dikes should be designed to avoid crossing vehicle pathways.

Operational Factors: The siting of earthen perimeter controls depends on the topography of the area surrounding a specific site. When determining the appropriate size and design of these diversion channels, the shape of the surrounding landscape and drainage patterns should be considered. Also, the amount of runoff to be diverted, the velocity of runoff in the diversion, and the erodibility of soils on the slope and within the diversion channel or swale are essential design considerations.

Both diversion channels and roof management devices must be maintained to remain effective. If vegetation is allowed to grow in diversions, the roughness increases and the channel velocity decreases which can cause channel overflow. Therefore, vegetation should be periodically mowed. In addition, the dike should be maintained at the original height, and any decrease in height due to settling or erosion should be remedied.

Roof management devices such as gutters and downspouts must be cleaned and inspected regularly to prevent clogging and to ensure its effectiveness.

Demonstration Status: The use of earthen perimeter techniques such as berms, diversions, and channels and the use of roof management techniques to divert storm water away from barns, open animal concentration areas, and waste storage or treatment facilities are well-accepted practices that prevent clean wastewater from mixing with manure-laden wastewater, thus reducing the volume of wastewater to be treated.

8.2.2 Waste Storage Technologies and Practices

The USDA NRCS recommends that storage structures be designed to handle the volume of manure produced between emptying events. The minimum storage period is based on the timing required for environmentally safe waste utilization considering climate; crops; soil; equipment; and local, state, and federal regulations. The design storage volume for liquid manure should account for manure, wastewater, precipitation and runoff (if uncovered), and other wastes that will accumulate during the storage period, such as residual solids that are not removed when liquids are pumped. Other general considerations are inlet designs, outlets or pumping access, and safety (such as fencing, odor and gas control, reinforcement against earth movements and hydrostatic pressure, use of a cover, and amount of freeboard).

Practice: Anaerobic Lagoons

Description: Anaerobic lagoons are earthen basins that provide storage for animal wastes while decomposing and liquefying manure solids. Anaerobic processes degrade high BOD wastes into stable end products without the use of free oxygen. Anaerobic lagoons are designed based on volatile solids loading rates (VSLR). Volatile solids are the wastes that will decompose. The volume of the lagoon consists of the following (see Figure 8-4):

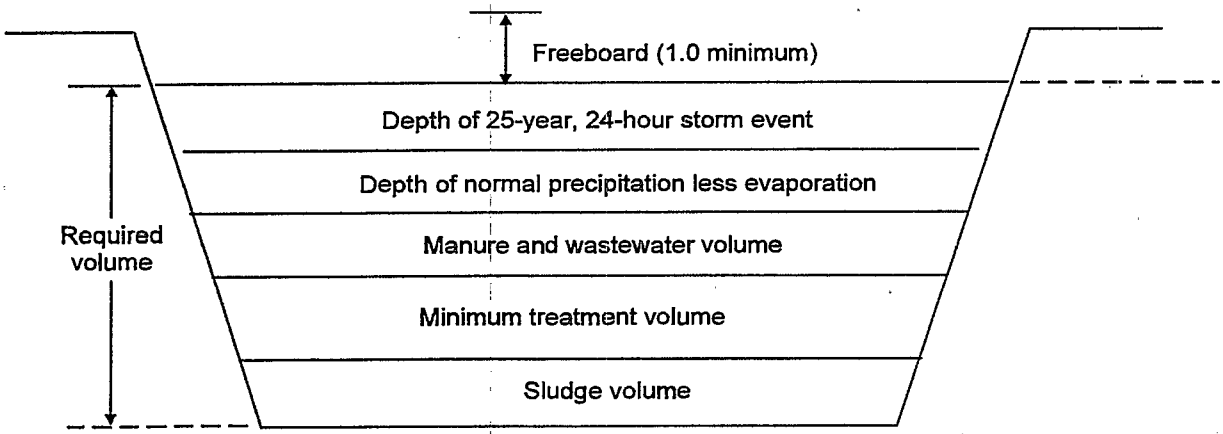

Figure 8-4. Cross section of anaerobic lagoons (USDA NRCS, 1998a)

1. Minimum Treatment Volume—The total daily volatile solids from all waste sources divided by the volatile solids loading rate for a particular region. The minimum treatment volume is based on the volatile solids loading rate, which varies with temperature and therefore with geographic location. Recommended volatile solids loading rates in the United States vary from 3 to 7 pounds per 1,000 ft^3 per day.

2. Sludge Volume—Volume of accumulated sludge between cleanouts. A fraction of the manure solids settles to the bottom of the lagoon and accumulates as sludge. The amount of sludge accumulation depends on the type and amount of animal waste.

3. Manure and Wastewater Volume—The volume of manure and wastewater transferred from feedlot operational facilities to the lagoon during the storage period. Lagoons are typically designed to store from 90 to 365 days of manure and wastewater.

4. Net Precipitation—Precipitation minus the evaporation during the storage period.

5. Design Storm—Typically a 25-year, 24-hour storm event.

6. Freeboard—A minimum of 1 foot of freeboard. Freeboard is the extra depth added to the pond as a safety factor.

7. Runoff—The runoff volume from lagoon berms. In general, lagoons should not receive runoff because runoff can shock the lagoon with an overload of volatile solids. Some runoff will enter the lagoons from the berms surrounding them.

Anaerobic lagoons should be at least 6 to 10 feet deep, although 8- to 20-foot depths are typical. Deeper lagoons require a smaller surface area, and they more thoroughly mix lagoon contents as a result of rising gas bubbles and minimize odors. Lagoons are typically constructed by excavating a pit and building berms around the perimeter. The berms are constructed with an extra 5 percent in height to allow for settling. The sides of the lagoon should be sloped with a 2:1 or 3:1 (horizontal:vertical) ratio. Lagoons can be designed as single-stage or multiple-stage (usually two stages). Two-stage lagoons require greater total volume but produce a higher quality lagoon effluent.

Lagoon covers can be used to control odor and collect biogas produced from the natural decomposition of manure. Covers are usually made of a synthetic material, and are designed to float on the surface of the lagoon. Often, because of the large size of the lagoon, the cover is constructed in multiple modules. Each module has flotation devices at the corners to help support the cover, and is tied down at the edge of the pond or lagoon. Covers typically have drains constructed in them to allow rainwater to drain through to the lagoon.

Lagoons are sometimes used in combination with a solids separator, typically for dairy waste. Solids separators help control the buildup of nondegradable material such as straw or other bedding materials. These materials can form a crust on the surface of the lagoon, which decreases its activity.

Application and Performance: Anaerobic lagoons provide effective biological treatment of animal wastes. Anaerobic lagoons can handle high pollutant loads while minimizing manure odors. Nondegradable solids settle to the bottom as sludge, which is periodically removed. The liquid is applied to cropland as fertilizer or irrigation water or is transported off site. Properly managed lagoons will have a musty odor. Anaerobic processes decompose faster than aerobic processes, providing effective treatment of wastes with high BOD, such as animal waste. Anaerobic lagoons are larger than storage ponds because additional volume is needed to provide biological treatment; however, since a constant oxygen concentration is not required, anaerobic lagoons are generally smaller than aerobic lagoons.

Lagoons reduce the concentrations of both N and P in the liquid effluent. P settles to the bottom of the lagoon and is removed with the lagoon sludge. Approximately 60 percent of the influent N is lost through volatilization to ammonia (Fulhage, 1998 Van Horn, 1999). Microbial activity converts the organic N to ammonia N. Ammonia N can be further reduced to elemental nitrogen (N_2) and released into the atmosphere. Lagoon effluent can be used for land application or flushing of animal barns, or can be transported off site. The sludge can also be applied to land

provided the soil is not saturated with nutrients. Information on the reduction of BOD, pathogens, and metals in lagoons is not available. Reductions in COD, TS, volatile solids (VS), total N, P, and K are presented in Table 8-10.

Table 8-10. Anaerobic Unit Process Performance.

Anaerobic Treatment	HRT	COD	TS	VS	TN	P	K
	days	Percent Reduction					
Pull plug pits	4–30	—	0–30	0–30	0–20	0–20	0–15
Underfloor pit storage	30–180	—	30–40	20–30	5–20	5–15	5–15
Open top tank	30–180	—	—	—	25–30	10–20	10–20
Open pond	30–180	—	—	—	70–80	50–65	40–50
Heated digester effluent prior to storage	12–20	35–70	25–50	40–70	0	0	0
Covered first cell of two cell lagoon	30–90	70–90	75–95	80–90	25–35	50–80	30–50
One-cell lagoon	>365	70–90	75–95	75–85	60–80	50–70	30–50
Two-cell lagoon	210+	90–95	80–95	90–98	50–80	85–90	30–50

HRT=hydraulic retention time; COD=chemical oxygen demand; TS=total solids; VS=volatile solids; TN=total nitrogen; P=phosphorus; K= potassium; — =data not available.

Source: Moser and Martin, 1999.

Advantages and Limitations: Anaerobic lagoons offer several advantages over other methods of storage and treatment. Anaerobic lagoons can handle high pollutant loads and provide a large volume for long-term storage. They stabilize manure wastes and reduce N content through biological degradation. Lagoons allow manure to be handled as a liquid, which reduces labor costs. If lagoons are located at a lower elevation than the animal barns, gravity can be used to transport the waste to the lagoon, which further reduces labor. Mild climates are most suitable for lagoons; cold weather reduces the biological activity of the microorganisms that degrade the wastes. Lagoons can experience spring and fall turnover, in which the more odorous bottom material rises to the surface. Foul odors can also result if biological activity is reduced or if there is a sudden change in temperature or pollutant loading rate.

Operational Factors: To avoid ground water and soil contamination, several factors must be considered. The lagoon should be located on soils with low to moderate permeability or on soils that can form a seal through sedimentation and biological action (USDA NRCS, 2000). Impervious barriers or liners are used to reduce seepage through the lagoon bottom and sides and are described in the following practice.

Lagoon inlets should be designed from materials that resist erosion, plugging, and freezing. Vegetation around the pond should be maintained to help stabilize embankments.

Lagoons must be properly maintained for effective treatment. The minimum treatment volume of the lagoon must be maintained. Lagoons work best when the influent flow is a steady, gradual flow rather than a large slug flow. The pH of the lagoon should be monitored. The optimum pH for lagoon treatment is about 6.5, which maximizes the activity level of the bacteria. Lime can be added to the lagoon to increase pH to this level. Also, since the rate of volatile solids decomposition is a function of temperature, the acceptable VSLR varies with climate. The loading rate should be monitored to ensure that it is appropriate to the region in which the lagoon is located.

Demonstration Status: Anaerobic lagoons without covers are used at 20.9 percent of all grow-finish swine operations. Of these, swine operations with 10,000 or more head use uncovered lagoons most frequently (81.8 percent) (USDA APHIS, 1996a). Lagoons are used on egg-laying farms in warmer climates. Beef facilities typically use storage ponds rather than lagoons. NAHMS estimates that 1.1 percent of dairies with more than 200 head use anaerobic lagoons with a cover and 46.7 percent use anaerobic lagoons without a cover (USDA APHIS, 1996b). The use of lined lagoons is dependent on site-specific conditions.

Practice: Lagoon Liners

Description: Lagoon liners are impervious barriers used to reduce seepage through the lagoon bottom and sides.

Application and Performance: Soil that is at least 10 percent clay can be compacted with a sheepsfoot roller to create a suitable impervious barrier. If the soil is not at least 10 percent clay, a liner or soil amendment should be used. There are also site conditions that may require seepage reduction beyond what is provided by compacting the natural soil. These conditions may include a shallow underlying aquifer, an underlying aquifer that is ecologically important or used as a domestic water source, or highly permeable underlying bedrock or soil. There are three options available to provide additional seepage reduction. First, the soil can be mixed with bentonite or a soil dispersant and then compacted. Clay can be imported from another area and compacted along the bottom and side walls. Last, concrete or synthetic materials such as geomembranes or geosynthetic clay liners can be used.

Advantages and Limitations: Concrete and synthetic liners are usually the most expensive.

Operational Factors: The method chosen to line the lagoon depends on the type of soil, site geography and location, available materials, and economics.

Demonstration Status: The use of lined lagoons depends on site-specific conditions.

Practice: Storage Ponds

Description: Waste storage ponds are earthen basins used to store wastes temporarily including runoff, solids (e.g., manure), and wastewater. The total volume of the pond consists of the following (see Figure 8-5):

1. Sludge Volume—Volume of accumulated sludge between cleanouts. A fraction of the manure solids settles to the bottom of the pond and accumulates as sludge. The amount of sludge accumulation depends on the type and amount of animal waste. For example, solids settling or solids separation prior to the storage pond reduces the rate of sludge accumulation.

2. Manure and Wastewater Volume—The volume of manure and wastewater from feedlot operational facilities transferred to the pond during the storage period. Ponds are typically designed to store from 90 to 270 days of manure and wastewater. The percentage of solids in the influent will depend on animal type and the waste management system.

3. Runoff—The runoff from the sites for the storage period (usually the drylot area at AFOs).

4. Net Precipitation—Precipitation minus the evaporation for the storage period.

5. Design Storm—Typically a 25-year, 24-hour storm event.

6. Freeboard—A minimum of 1 foot of freeboard. Freeboard is the extra depth added to the pond as a safety factor.

Ponds are typically rectangular in shape and are constructed by excavating a pit and building berms around the perimeter. The berms are constructed with an extra 5 percent in height to allow for settling. The sides of the pond are typically sloped with a 1.5:1 or 3:1 (horizontal:vertical) ratio.

Ponds are typically used in combination with a solids separator. Solids separators help control buildup of material such as straw or other bedding materials on the surface of the pond.

Pond covers can be used to control odor and collect biogas produced from the natural degradation of manure. Covers are usually made of a synthetic material, and are designed to float on the surface of the impoundment. Often, because of the large size of the pond, the cover is constructed in multiple modules. Each module has flotation devices at the corners to help support the cover, and is tied down at the edge of the pond. Covers typically have drains constructed in them to allow rainwater to drain through to the pond.

Application and Performance: Waste storage ponds are frequently used at AFO to contain wastewater and runoff from contaminated areas. Manure, process water, and runoff are routed to these storage ponds, where the mixture is held until it can be used for irrigation or transported off site. Solids settle to the bottom as sludge, which is periodically removed. The liquid is applied to cropland as fertilizer or irrigation water, or is transported off site.

Storage ponds hold wastewater and manure and are not intended to actively treat the waste. Because they do not require additional volume for treatment, storage ponds are smaller in size than treatment lagoons.

Ponds reduce the concentrations of both N and P in the liquid effluent. P settles to the bottom of the pond and is removed with the sludge. Influent N is reduced through volatilization to ammonia. Pond effluent can be used for land application or flushing animal barns, or it can be transported off site. The sludge can also be applied to the land provided the soil is not saturated with P.

Advantages and Limitations: Storage ponds provide a large volume for long-term waste storage and allow manure to be handled as a liquid. If ponds are located at a lower elevation than the animal barns, gravity can be used to transport the waste to the pond, which minimizes labor. Although ponds are an effective means of storing waste, no treatment is provided. Because ponds are open to the air, odor can be a problem.

Operational Factors: To avoid ground water and soil contamination, several factors must be taken into consideration. Impervious barriers or liners are used to reduce seepage through the pond bottom and sides. Soil that is at least 10 percent clay can be compacted with a sheepsfoot roller to create a suitable impervious barrier. If the soil is not at least 10 percent clay, a liner or soil amendment should be used. There are also site conditions that may require seepage reduction beyond what is provided by compacting the natural soil. Conditions may include a shallow underlying aquifer, an underlying aquifer that is ecologically important or used as a domestic water source, or highly permeable underlying bedrock or soil. There are three options available to provide additional seepage reduction. First, the soil can be mixed with bentonite or a soil dispersant and then compacted. Clay can be imported from another area and compacted along the bottom and side walls. Last, concrete or synthetic materials such as geomembranes or geosynthetic clay liners can be used. Concrete and synthetic liners are usually the most expensive. The method chosen to line the pond depends on the type of soil, site geography and location, available materials, and economics.

Pond inlets should be designed from materials that resist erosion, plugging, and freezing. Vegetation around the pond should be maintained to help stabilize embankments.

Demonstration Status: Ponds are a common method of waste storage for swine, beef, and dairy facilities and are used on poultry farms in warmer climates. Beef feedlots tend to use storage ponds for collection of runoff from the dry lots. EPA estimates that 50 percent of the medium-

size (300–1000 head) beef feedlots in all regions and 100 percent of the large-size (>1,000 head) beef feedlots in all regions have a storage pond for runoff. NAHMS estimates 27.8 percent of dairies use earthen storage basins (USDA APHIS, 1996b). The use of lined ponds depends on site-specific conditions.

Practice: Pit Storage

Description: Manure pits are a common method for storing animal wastes. They can be located inside the building underneath slats or solid floors, or outside and separated from the building. Typical storage periods range from 5 to 12 months, after which manure is removed from the pit and transferred to a treatment system or applied to land. There are several design options for pit storage. For example, shallow pits under slats provide temporary storage and require more frequent manure removal to longer-term storage or for land application. Pit recharge systems, which are common in the Midwest, involve regularly draining the pit contents to a lagoon and recharging the pit with fresh or recycled water. The regular dissolution of solids keeps the pits free of excessive buildup while providing temporary storage for manure. Pit recharge systems typically have level floors with an average depth of 12 inches of recharge water, 12 inches allowed for waste accumulation, and 12 inches of air space between the pit surface and the slatted floor.

Application and Performance: Because agitating and pumping equipment does not handle solid or fibrous materials well, manure with greater than 15 percent solids will require dilution. Chopper-type agitators may be needed to break up bedding or other fibrous materials that might be present in the pit.

Advantages and Limitations: Below-floor storage systems provide ease of collection and minimize volume (1.2 dilution versus 3.0 dilution for lagoon storage) while maximizing fertilizer value (1.7 times the N versus lagoon storage). Below-floor storage systems may cause a buildup of odors and gases and can be difficult to agitate and pump out. Remote storage avoids odor and gas buildup in animal housing areas and provides options for methane production and solids separation, but entails additional costs for transfer from the housing facilities to storage.

Operational Factors: Pits must have access for pumping equipment, and outside pits must be covered or fenced to prevent accidental entry into the pit. They should be designed to withstand anticipated hydrostatic, earth, and live loads as well as uplifting in high-water-table areas. Before the pit is filled with manure, water is typically added to prevent solids from sticking to the pit floor. Depths range from 3 to 4 inches under slatted floors and 6 to 12 inches if manure is scraped and hauled to the pit. Sand should not be used as a bedding material because it is incompatible with pumping systems. The pits should always be free of nails, lumber, or other foreign material that can damage equipment.

Demonstration Status: Pit holding is most commonly done at swine operations. *Swine '95* (USDA APHIS, 1996a) reports that pit holding accounts for 25.5, 33.7, and 23.2 percent of

farrowing, nursery, and grow-finish operations, respectively. Queries of the *Swine 2000* (USDA APHIS. 2002) data provided information on the use of pits by region, operation type, and size. Swine operations in the Midwest Region use pits most often, with 70.7 percent of the large and 67.7 percent of the medium grow-finish and 56.4 percent of the large and 54.9 percent of the medium farrow-to-finish operations using pits. Swine operations in the Mid-Atlantic Region use pits to a lesser degree, with 37.5 percent of the large and 26.3 percent of the medium grow-finish operations and 23.9 percent of the large and 14.4 percent of the medium farrow-to-finish operations using pits.

Below-floor slurry or deep pit storage is reported in *Dairy '96* (USDA APHIS, 1996b) at 7.9 percent of all dairy operations. Based on EPA site visits, about 33 percent of veal operations are believed to utilize pit storage systems. Beef feedlots do not typically utilize pit storage.

Practice: Belowground or Aboveground Storage Tanks

Description: Belowground and aboveground storage tanks are used as an alternative to under-building pit storage and earthen basins. Both aboveground and belowground tanks are commonly constructed of concrete stave, reinforced monolithic concrete, lap or butt joint coated steel, or spiral wound coated steel with concrete floors. Current assembly practices for aboveground storage facilities are primarily circular silo types and round concrete designs, but the structures may also be rectangular. Belowground storage can be located totally or partially below grade. All storage tanks must be engineered to withstand operational constraints including internal and external hydrostatic pressure, flotation and drainage, live loads from equipment, and loads from covers and supports. Belowground tanks should be surrounded by fences or guardrails to prevent people, livestock, or equipment from accidently entering the tank.

When located directly adjacent to the animal housing facility, belowground tanks are easily filled by scraping directly into the tank. In those situations where the storage tank is not adjacent to the animal housing facility, a collection pit or sump is necessary for loading. In these systems a large piston or pneumatic manure pump forces waste through a large-diameter underground pipe. Aboveground tanks at a lower grade than the livestock housing facility can often be gravity-fed through a similar underground pipe. The tank can be loaded from the top or bottom. Bottom loading in aboveground tanks is most appropriate for manure that forms a surface crust, such as cattle manure. The inlet pipe is usually located 1 to 3 feet above the bottom of the tank to prevent blockages from solids. An advantage to bottom loading is that it pushes solids away from the inlet pipe and distributes them more evenly. Top loading is suitable and most common for manures that do not crust (i.e., liquid swine manure); however, top loading in an aboveground system requires that manure be pumped against gravity. Figure 8-6 shows a typical aboveground storage tank.

Application and Performance: Aboveground or belowground tanks are suitable for operations handling slurry (semisolid) or liquid manure. This generally excludes open-lot waste which is inconsistent in composition and has a higher percentage of solids. Furthermore, because of the

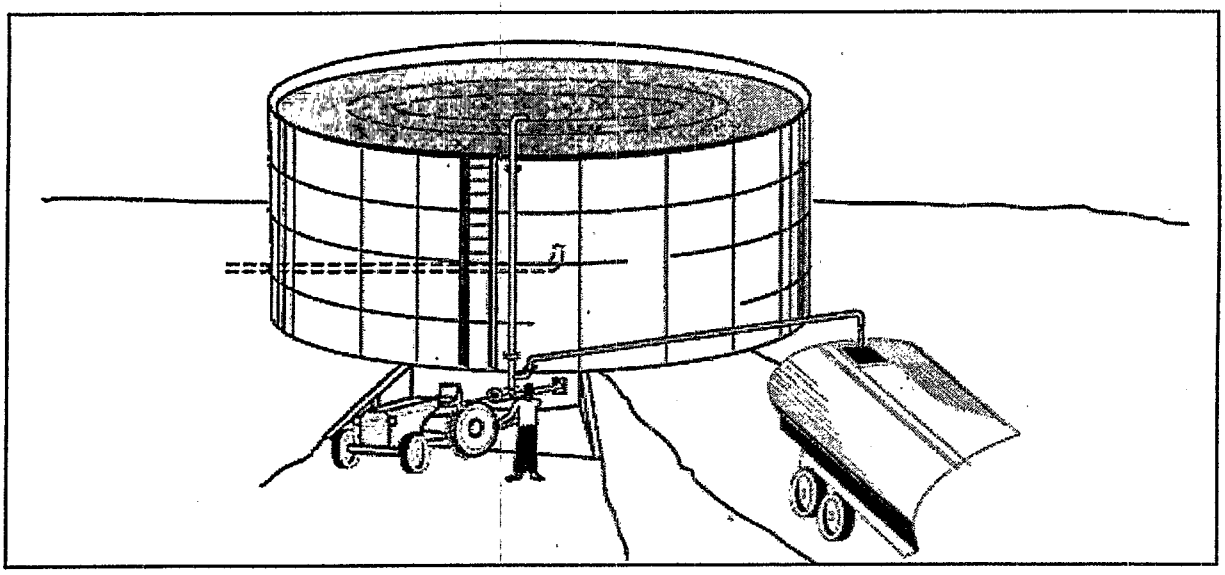

Figure 8-6. Aboveground waste storage tank (USDA NRCS, 1996).

high cost of storage volume, prefabricated storage tanks are generally used to contain only waste, but not runoff, from the livestock facility.

Below and aboveground storage tanks are appropriate and preferred alternatives in situations where the production site has karst terrain, space constraints, or aesthetics issues associated with earthen basins. Storing manure in prefabricated or formed storage tanks is especially advantageous on sites with porous soils or fragmented bedrock. Such locations may be unfit for earthen basins and lagoons because seepage and ground water contamination may occur. Construction of formed storage tanks often includes installation of a liner beneath the concrete to prevent seepage. Aboveground formed storage facilities allow visual monitoring for leaking. Aboveground tanks may exhibit unsightly leaks at seams, bolt holes, or joints, but these are usually quickly sealed with manure. In these storage systems the joint between the foundation and sidewall is the greatest concern. Leaching and ground water contamination can occur if the tank is not sealed properly.

Proper operational practices to maintain adequate storage tank capacity between land applications are critical. The holding volume of a storage tank consists of five fractions: residual volume, manure/waste storage volume (bedding, wasted feed, water added for manure handling), wash water volume, net rainfall and evaporation change, and freeboard capacity.

In general, large amounts of water are not added during the handling of manure that is stored in an above or belowground storage tanks. Installation costs usually dictate that capacity be limited to manure storage requirements. Thus, water conservation is often practiced by facilities that use

above or belowground storage tanks. For these facilities, recycling of wastewater is not an option because the manure is generally in slurry form with more than 4 percent solids.

Above and belowground storage tanks are simply storage facilities, and they do not facilitate treatment of the manure. Thus, there is little to no effect on the reduction of nutrients, pathogens, solids, heavy metals, growth hormones, or antibiotics. N in liquid manure is predominately in the inorganic form. This allows for some ammonia volatilization into the atmosphere and a reduction in the total amount of N.

Advantages and Limitations: When these systems are used, manure agitation is necessary before the contents of the storage structure are pumped into a tanker wagon for land application. Agitation ensures uniform consistency of manure and prevents the buildup of solids, thus maintaining the storage capacity of the tank. Agitation results in a more even distribution of nutrients in the manure prior to land application. It can be accomplished with high-horsepower, propeller-type agitators or by recirculating with a high-capacity pump. The length of time the manure needs to be agitated depends on the size of the storage tank, the volume of manure it contains, the percent of solids in the manure, and the type of agitator. Manure with up to 15 percent solids can be agitated and pumped. Because of the potential for agitation and pumping problems, only small amounts of chopped bedding are recommended for use in systems using storage tanks. Some types of agitators have choppers to reduce the particle size of bedding and solids. Dilution with additional water may be necessary to reduce agitation problems. One design variation places the pump in a sump outside the tank, using it for both agitation and pumpouts.

Manure in a storage tank undergoes some anaerobic decomposition, releasing odorous and potentially toxic gases, such as ammonia and hydrogen sulfide. Methane is also produced. Covers can be installed to interrupt the flow of gases up from the liquid surface into the atmosphere. Types of covers range from polyethylene, concrete, or geotextile to biocovers such as chopped straw. Various covers have been shown to reduce odors by up to 90 percent. Furthermore, particular types of covers can be used as methane reservoirs to collect and contain gases from the digestion process for disposal by flaring or converting to electrical power. Moreover, certain covers can prevent rainwater dilution and accumulation of airborne silts and debris. Finally, it is generally accepted that some types of covers control N volatilization into the atmosphere and maintain the N content of the manure.

The installation costs associated with prefabricated storage tanks are high when compared with other liquid manure-handling systems. Glass-lined steel tanks are typically associated with the highest cost. The useful life of the tanks depends on the specific manufacturer and the operator's maintenance practices. Once they have been installed, above and belowground storage tanks have a low labor requirement, especially when designed as a gravity feed system (Purdue Research Foundation, 1994).

Operational Factors: Specific storage structure designs will vary by state because of climate and regulatory requirements. Pumping manure during freezing conditions can be a problem unless all pipes are installed below the freezing level in the ground. Design considerations in these systems

include check valves if bottom loading is used, pumping power with respect to the maximum head, and pipe friction from the pump to the storage.

Demonstration Status: Belowground and aboveground storage tanks are in use nationwide in swine, poultry, and dairy operations. They are appropriate for use in all slurry-based manure-handling systems including those with shallow-pit flush systems, belt or scrape designs, or open-gutter flush systems.

Practice: Solid Poultry Manure Storage in Dedicated Structures

Description: In the broiler and turkey segments of the poultry industry, specially designed pole-type structures are typically used for the temporary storage of solid poultry manure; however, horizontal (bunker) silo-type structures are also used. Manure produced in "high-rise" houses for caged laying hens does not require a separate storage facility if handled as a solid.

A typical pole-type storage structure is 18 to 20 feet high and 40 feet wide. The length depends on the storage capacity desired but is usually a minimum of 40 feet. The structure will have a floor of either compacted soil or concrete, the latter being more desirable but much more expensive. The floor elevation should be at a height above grade that is adequate to prevent any surface runoff from entering the structure. A properly sited structure will be oriented parallel to the direction of the prevailing wind. Equipment access will be through the lee side, which will have no wall. The other three sides of the structure will have walls extending from the floor to a height of 6 to 8 feet. Experience has shown that a higher wall on the windward side of the building excludes precipitation more effectively. Walls may be constructed using pressure-treated lumber or reinforced concrete. Wooden trusses covered with steel sheets are most commonly used for roofing, although plywood roof decking covered with composition shingles is also an option. Manure is usually stacked to a height of 5 to 8 feet. Figure 8-7 shows three types of permanently covered solid manure storage structures.

Horizontal silo-type storage structures are also used for the temporary storage of solid poultry manure. These storage structures can be constructed using either post-and-plank or reinforced concrete walls on three sides. Equipment access will be through the lee side which will have no wall. Concrete walls can be poured in place or made with prefabricated sections that are manufactured for horizontal silo construction. Wall height can be from as low as 3 to 4 feet to as high as 8 to 10 feet if prefabricated concrete sections are used. Usually, there is a concrete floor.

Again, floor elevation should be sufficiently above grade to prevent surface runoff from entering the structure. With this type of storage structure, 6-mil or heavier plastic is typically used to cover the stored manure, but tarpaulins have also been used. As with horizontal silos, old tires

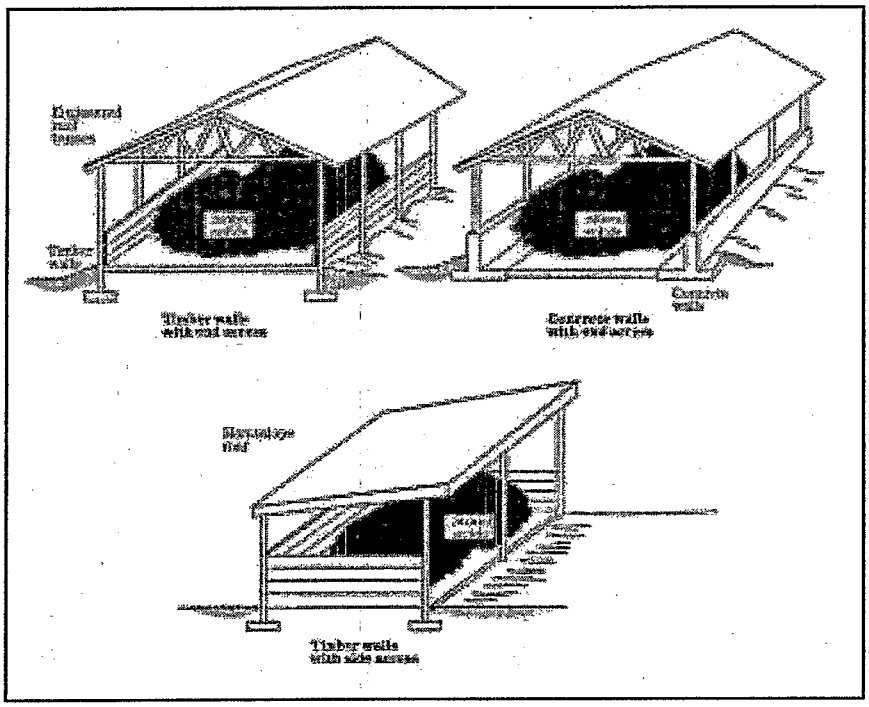

Figure 8-7. Roofed solid manure storage (USDA NRCS, 1996).

are commonly used to secure the cover, although ropes or cables can also be used. Manure is usually stacked to a height of 5 to 8 feet.

In the broiler industry, total cleanouts of production facilities occur only after a minimum of 1 year of production. A total cleanout frequency of 2 to 3 years is not uncommon. Total cleanouts may be more frequent for brood chambers, but the frequency depends on the cost and availability of bedding material, the incidence of disease, the concentration of gaseous ammonia within the production facility, and the policy of the integrator. Caked manure, also known as crust, is removed after every flock, typically a period of 49 days for 4- to 5-pound broilers. Usually, storage structures are designed only for the storage of this caked manure because most broiler growers view the cost of a structure large enough to store manure and litter from a total cleanout as prohibitively high. Because caked manure production varies with the type of bedding material, type of watering system, and climatic conditions, storage requirements may vary from farm to farm. Also, cake production increases with bedding age. Local experience is usually relied upon to estimate storage requirements.

In the turkey industry, total cleanouts of brooder facilities occur after every flock to control disease, but grow-out facilities are typically totally cleaned out only once a year. Again, most turkey growers consider the cost of storage of the manure and bedding from a total cleanout of grow-out facilities to be prohibitively high. Therefore, structures are typically sized only for the storage of manure and bedding from brooder houses.

Application and Performance: The temporary storage of solid poultry manure in a dedicated structure is applicable to all poultry operations at which birds are maintained on a bedding material. Thus, this practice is applicable to all broiler and turkey operations and the small fraction of egg-producing operations that do not house birds in cages. The combination of manure and bedding generated in these operations has a moisture content of less than 50 percent, usually 25 to 35 percent, and is handled as a solid. This practice is not necessary for caged laying hens in high-rise housing because the production facility has a manure storage capacity of 1 or more years.

When sized and managed correctly, storage of solid poultry manure in a dedicated structure will allow for the most efficient use of plant nutrients in the manure for crop production. This eliminates the potential for contamination of surface and ground waters resulting from open stacking of manure or spreading during the fall, winter, early spring, and after crop establishment, when there is no potential for crop uptake. When the stored manure is effectively protected from precipitation, odor and fly problems are minimal. Odor can be a problem, however, when the manure is removed from the storage structure and spread on cropland.

The storage of caked broiler litter and turkey brooder house manure and bedding reduces the potential impact of these materials on surface and ground water quality; however, a substantial fraction of the manure and bedding produced by these segments of the poultry industry is not stored because the associated cost is viewed as prohibitive. The material resulting from the total cleanout of broiler houses and turkey grow-out facilities is often stored temporarily in open piles or spread at inappropriate times of the year. Thus, storage, as currently practiced, is probably not as effective in reducing water quality impacts as is presently thought.

Advantages and Limitations: A correctly sized and managed storage structure allows application to cropland when nutrients will be most efficiently used, thus minimizing negative impacts on surface and ground waters as noted above. If application to cropland is not a disposal alternative, storage can facilitate off-site disposal other than application to cropland.

The principal disadvantage of storing solid poultry manure in a dedicated structure is the cost of the structure and additional material handling costs. Currently, sources of government assistance are available (e.g., cost-share funds available from local soil and water conservation districts) to partially offset construction costs and encourage the adoption of this practice.

Operational Factors: Spontaneous combustion in stored poultry manure has been a problem and has led to the recommendation that stacking height be limited to 5 to 8 feet to avoid excessive compaction. Fires in solid poultry manure storage structures, like silo fires, are extremely difficult to extinguish and often lead to the total loss of the structure.

Demonstration Status: Permanent covered structures for storage of solid manure are used extensively in the broiler and turkey segments of the poultry industry. In a 1996 survey of broiler growers on the Delmarva Peninsula, 232 of 562 respondents indicated that they used a permanent storage structure (Michele et al., 1996).

Practice: Concrete Pads

Description: Concrete pads are used as semi-impermeable surfaces upon which to place waste. The waste pile is often open to the environment, but it can be covered with a roof or plastic sheeting to minimize exposure to the elements. Pads are often sloped to a central location to allow for drainage of rainwater and runoff.

The design for concrete pads varies according to the type of waste it receives (wet or dry) Waste that includes settled solids from a settling basin or solids separator has a high moisture content. In this case, the concrete pad typically has at least two bucking walls to contain the waste and to facilitate the loading and unloading of waste onto the pile. The design height of the waste pile does not exceed about 4 feet, because of the semiliquid state of the waste. For operations with drier waste, the concrete pad typically does not have bucking walls, and the maximum height of the manure pile is 15 feet, because the manure is drier and can be stacked more easily.

Figure 8-8 illustrates the design of a concrete pad (MWPS,1993; USDA NRCS, 1996). Concrete pads are between 4 and 6 inches thick and are made of reinforced concrete to support the weight of a loading truck. The concrete pad is underlain by 4 inches of sand and 6 inches of gravel. The pad is sloped to divert storm water runoff from the pile to the on-site waste management facility, such as a lagoon or a pond. Bucking walls, made of reinforced concrete, are 8 inches thick and 3 to 4 feet tall.

Application and Performance: Concrete pads are used at AFOs to provide a surface on which to store solid and semisolid wastes that would otherwise be stockpiled directly on the feedlot surface. Manure scraped from dry lots and housing facilities and solids separated from the waste stream in a solids separator can be stored on a concrete pad.

The pads provide a centralized location for the operation to accumulate excess manure for later use on site (e.g., bedding, land application) or transportation off site. A centralized location for stockpiling the waste also allows the operation to better control storm water runoff (and associated pollutants). Rainwater that comes into contact with the waste is collected on the

concrete pad and is directed to a pond or lagoon and is thereby prevented from being released on the feedlot. The pad also provides an impermeable base that minimizes or prohibits seepage of rainfall, leaching pollutants or nutrients from the waste and infiltrating into the soil beneath it. The waste is not treated once it is on the concrete pad; the pad serves as a pollution prevention measure. However, with regular handling of the waste, the N loads in the waste will be released into the atmosphere through volatilization, and both N and P may be contained in runoff from the pile after storm events. Pathogen content, metals, growth hormones, and antibiotics loads are not expected to decrease significantly on the concrete pad unless the pile ages considerably.

Advantages and Limitations: An advantage to using a concrete pad for storage is to control runoff and prevent waste from contaminating the surrounding environment. When rainwater or

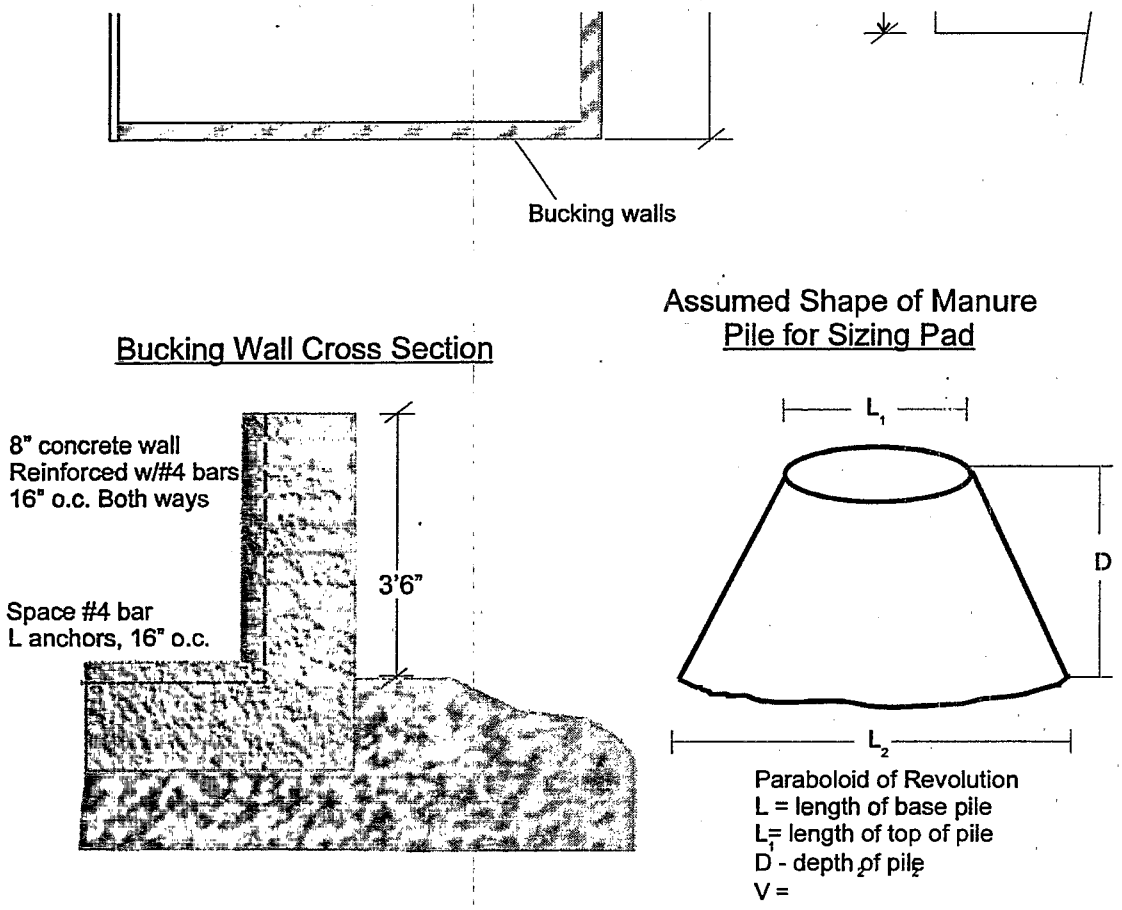

Figure 8-8 Concrete pad design.

precipitation comes into contact with the pile, the water may percolate through the pile, carrying pollutants along the way. The water may exit the pile as runoff and carry pollutants to surface waters or seep into the ground. The concrete pad and bucking walls minimize this potential seepage into and runoff onto the ground around the pile.

Depending on the duration of storage required, however, these pads can take up a very large area. An operation may not have sufficient area to install a concrete pad large enough to store waste in one place. It can also be expensive to construct a concrete pad large enough to accommodate the amount of waste that would accumulate over an appropriate storage time.

Waste stored on a concrete pad will still need to be further managed, either by land application or by transportation off site. There may be some odors from the pile on a concrete pad, but no more than would be expected from any manure stored in a pile.

Operational Factors: Operations that frequently transport their waste will require less storage volume than operations that have less frequent hauling schedules. Operations requiring less storage capacity will require a smaller pad area, resulting in lower capital costs.

Demonstration Status: Concrete pads are used relatively infrequently in the livestock industry. They are more commonly used in dairies than in poultry, beef or swine operations, because dairy waste is semisolid and bucking walls are needed to contain the waste effectively, given the higher moisture content. Waste from swine operations is generally too wet to stack on a pad, and beef and poultry waste is usually piled directly on the feedlot.

8.2.3 Waste Treatment Technologies and Practices

8.2.3.1 Treatment of Animal Wastes and Wastewater

Some treatment systems store waste as well as change the chemical or physical characteristics of the waste. Anaerobic lagoons are the most common form of treatment for AFOs. Other technologies use oxidation to break down organic matter. These include aerated lagoons and oxidation ditches for liquids and composting for solids.

Practice: Anaerobic Digesters for Methane Production and Recovery

Description: An anaerobic digester is a vessel that is sized both to receive a daily volume of organic waste and to grow and maintain a steady-state population of methane bacteria to degrade that waste. Methane bacteria are slow growing, environmentally sensitive bacteria that grow without oxygen and require a pH greater than 6.5 to convert organic acids into biogas over time. Anaerobic digestion can be simplified and grouped into two steps. The first step is easy to recognize because the decomposition products are volatile organic acids that have disagreeable odors. During the second step, methane bacteria consume the products of the first step and produce biogas—a mixture of carbon dioxide and methane—a usable fuel by product. A properly operating digester will produce a gas with minimal odor because methane bacteria from the second step reach a population large enough to rapidly consume the products of the first step. There are three basic temperature regimes for anaerobic digestion: psychrophilic, mesophilic, and thermophilic. Psychrophilic, or low-temperature, digestion is the natural decomposition path for manures at temperatures found in lagoons. These temperatures vary from about 38 to 85 °F (3 to 29 °C). The hydraulic retention time (HRT) required for stable operation varies from 90 days at low temperatures to 30 days at higher temperatures. Methane production will vary seasonally with the variation in lagoon temperature.

Maintaining a constant elevated temperature enhances methane production. Mesophilic digestion cultivates bacteria that have peak activity between 90 and 105 °F (32 to 40 °C). Mesophilic digesters operate at a retention period of 12 to 20 days. Thermophilic digesters promote bacteria that grow at between 135 to 155 °F (57 to 68 °C); these digesters operate with a retention time of 6 to 12 days.

Although there are many types of anaerobic digesters, only covered lagoons operating at ambient temperatures, complete-mix digesters, and plug-flow digesters can be considered commercially available, because they are the only ones that have been implemented successfully at 10 or more sites.

A cover can be floated on the surface of a properly sized anaerobic lagoon to recover methane. Ideally, the cover is floated on the primary lagoon of a two-cell lagoon system, with the primary lagoon maintained as a constant volume treatment lagoon and the second cell used to provide storage of treated effluent until the effluent can be properly applied to land. The lagoons are not heated, and the lagoon temperature and biogas production vary with ambient temperatures. Coarse solids, such as hay and silage fibers in cow manure, must be separated in a pretreatment step and kept from the lagoon. If dairy solids are not separated, they will float to the top and form a crust. The crust will thicken, reducing biogas production and eventually filling the lagoon.

A complete-mix digester is a biological treatment unit that anaerobically decomposes animal manures using controlled temperature, constant volume, and mixing. These digesters can accommodate the widest variety of wastes. Complete-mix digesters are usually aboveground, heated, insulated, round tanks; however, the complete-mix design has also been adapted to function in a heated, mixed, covered earthen basin. Mixing can be accomplished with gas recirculation, mechanical propellers, or liquid circulation. In Europe, some mixed digesters are operated at thermophilic temperatures; however, most of these are regional digesters that are built and operated by digester professionals. A complete-mix digester can be designed to maximize biogas production as an energy source or to optimize VS reduction with less regard for surplus energy. Either process is part of a manure management system, and supplemental effluent storage is required.

Plug-flow digesters are heated, unmixed, rectangular tanks. New waste is pumped into one end of the digester, thereby displacing an equal portion of older material horizontally through the digester and pushing the oldest material out through the opposite end. Lusk (1998) refers to a slurry-loop digester as a separate digester category, but this system, which is built in the shape of a horseshoe, functions by displacement in the same manner as a plug-flow digester.

Biogas formed in a digester bubbles to the surface and may be collected by a fixed rigid top, a flexible inflatable top, or a floating cover, depending on the type of digester. Biogas from a stable digester is saturated and contains 60 to 80 percent methane, with the balance as carbon dioxide and trace amounts of hydrogen sulfide (1,800 to 5,000 ppm H_2S). A collection system directs the virtually odorless biogas to gas-handling components. Biogas may be filtered for mercaptan and moisture removal before being pumped or compressed to operating pressure and then metered to equipment for use. Biogas that is pressurized and metered can be used as fuel for heating, adsorption cooling, electrical generation, or cogeneration.

Application and Performance: Properly designed anaerobic lagoons are used to produce biogas from dilute wastes with less than 2 percent total solids (98 percent moisture) including flushed dairy manure, dairy parlor wash water, and flushed hog manure. Complete-mix digesters can be

used to decompose animal manures with 3 to 10 percent TS. Plug-flow digesters are used to digest thick wastes (11 to 13 percent TS) from ruminant animals including dairy and beef animals. The plug-flow system operates best with scrape-collected, fresh dairy manure that contains low levels of dirt, gravel, stones, or straw.

Anaerobic digestion is one of the few manure treatment options that reduce the environmental impact of manure and produce a commodity—energy—that can be used or sold continuously. Digesters are used to stabilize manures to produce methane, while at the same time reducing odors.

Approximately 35 percent of the VS from dairy manure and 60 percent of the VS from swine or beef manure can be converted to biogas and removed from the manure liquid.

Table 8-11 summarizes the performance expected from anaerobic digesters. Anaerobic digesters will reduce BOD and TSS by 80 to 90 percent, and virtually eliminate odor. The digester will have minimal effect on the nutrient content of the digested manure passing through plug-flow or complete-mix digesters. Half or more of the organic N (Org-N) is converted into ammonia (NH_3-N). In lagoons, the concentrations of nutrients are reduced through settling, volatilization, and precipitation. With a cover in place, ammonia volatilization losses are eliminated, leaving only settling and precipitation as pathways for N loss. A small amount of the P and K will settle as sludge in most digesters.

Table 8-11. Anaerobic Unit Process Performance.

	Percentage Reduction						
Digester type	**HRT (days)**	**COD**	**TS**	**VS**	**TN**	**P**	**K**
Complete-mix	12–20	35–70	25–50	40–70	0	0	0
Plug-flow	18–22	35–70	20–45	25–40	0	0	0
Covered first cell of two-cell lagoon	30–90	70–90	75–95	80–90	25–35	50–80	30–50

Source: Moser and Martin, 1999.

The reductions of P, K, or other nonvolatile elements reported in the literature for covered lagoons are not really reductions at all. The material settles and accumulates in the lagoon, awaiting later management. Vanderholm (1975) reported P losses of up to 58 percent. Bortone et al. (1992) suggest that P accumulation in anaerobic lagoons may be due to high pH driving phosphate precipitation as $Ca(PO_4)_2$ and $Mg(PO_4)_2$. This is consistent with and supported by P mass losses documented in most lagoon studies. Water-soluble cations, such as Na, K, and ammonium N, tended to be distributed evenly throughout the lagoon. Humenik et al. (1972) found that 92 to 93 percent of the copper(Cu) and zinc(Zn) in anaerobic swine lagoon influent was removed and assumed to be settled and accumulated in sludge.

Pathogen reduction is greater than 99 percent in mesophilic and thermophilic digesters with a 20-day HRT. Digesters are also very effective in reducing weed seeds.

Advantages and Limitations: Some advantages of anaerobic digestion include the opportunity to reduce energy bills, produce a stabilized manure, recover a salable digested solid by-product, reduce odor and fly breeding, and produce a protein-rich feed from the digested slurry.

The energy from biogas can be used on site as a fuel or sold to a local utility company. On-site uses include the heating of the digester itself, fuel for boilers or electric generators, hot water production, and refrigeration. The equipment listed in Table 8-12 can use biogas in lieu of low-pressure natural gas or propane.

Table 8-12. Biogas Use Options.

Electrical generator	electricity for use or sale, heat recovery optional
Refrigeration compressors	cooling, heat recovery optional
Irrigation pumps	pumping, heat recovery optional
Hot water boiler	for space heat, hot water for process and cleanup
Hot air furnace	for space heat
Direct fire room heater	for space heat
Adsorption chiller	for cold water production, heat recovery optional

Dairy waste digesters partially decompose fibrous solids to a uniform particle size that is easily separated with a mechanical separator. The recovered solids are valuable for reuse as cow bedding or can be sold as a bagged or wholesale soil product.

Limitations include the costs associated with building and operating the digester. Furthermore, nutrient concentrations in the semisolid anaerobic digestion product are not reduced substantially unless they are then stored for several months. Therefore, the amount of land needed for land application of manure is greater than that needed for uncovered lagoons and other treatment practices.

Operational Factors: The successful operation of a properly designed digester is dependent upon two variables: feed rate and temperature. All other operational issues are related to ancillary equipment maintenance. Once a properly designed digester is operating, it will usually continue to function unless management oversight is lacking. Reactor capacity is maintained through periodic removal of settled solids and grit.

A sudden drop in biogas production or pH (from accumulation of organic acids) will indicate digester upset. Factors that decrease the efficiency of microbial processes and might result in digester upset include a change in temperature or feed rations, a change in manure loading rates, or the addition of large quantities of bacterial toxins. A normal ratio of alkalinity to volatile acids during a stable or steady-state anaerobic decomposition is 10:1. The known operating range is 4:1 to 20:1. (Metcalf and Eddy, 1979). An increase in volatile acids resulting in an alkalinity to volatile acid ratio of 5:1 indicates the onset of failure of methane-producing anaerobic digestion (unbalanced decomposition) (Chynoweth, 1998).

The level of hydrogen sulfide in the produced biogas can be controlled through either scrubbing or managed operation of equipment. Scrubbing is necessary for some gas uses but is generally expensive and maintenance intensive.

Demonstration Status: Anaerobic lagoons with covers were used at 1.8 percent of grow-finish operations in 1995 (USDA APHIS, 1999). Approximately 30 pig lagoons have been covered in the United States for odor control or methane recovery (RCM, 1999). The oldest continuously operating covered swine waste lagoon is at Roy Sharp's Royal Farms in Tulare, California. This system, which was installed in 1981, has been producing electricity with the recovered methane since 1983. Not all covered lagoon projects have beneficial uses for recovered methane; some farms either flare or release the gas.

The oldest complete-mix pig manure digester in the United States was built in 1972. Approximately 10 units are in operation today, 6 of which were built within the last 4 years. Many digesters are not operational, typically because the farm is no longer in the pig business. At least 16 operating plug-flow and slurry-loop digesters are currently operating in the United States (Lusk, 1998; RCM, 2000).

Practice: Single-Cell Lagoon With Biogas Generation

Description: In this practice, a cover is floated on the surface of a properly sized anaerobic lagoon to recover biogas (70 percent methane and 30 percent carbon dioxide). Anaerobic lagoons can produce biogas from any type of animal manure. The most successful arrangement consists of two lagoons connected in series to separate biological treatment for biogas production and storage for land application. A variable-volume, one-cell lagoon designed for both treatment and storage can be covered for biogas recovery; however, a single-cell lagoon cover presents design challenges due to the varying level of the lagoon surface.

In the early 1960s, the floating cover industry expanded beyond covering water reservoirs into floating covers for industrial wastewater lagoons. Covering industrial organic wastewater lagoons began as an odor control technique. Within the discovery that economic quantities of biogas could be recovered, cover systems were refined to collect and direct biogas back to the factory producing the organic waste. Lagoon design was optimized to provide both good BOD/COD reduction and a supply of usable biogas. Today, hundreds of industrial anaerobic lagoons have floating covers that optimize anaerobic digestion, control odor, and recover biogas. The industries that use such covers include pork processors and rendering plants in the United States. Lessons learned in the development of floating covers are incorporated into today's designs for animal waste facilities.

Psychrophilic, or low-temperature, digestion is the natural decomposition path for manures at the temperatures found in lagoons. These temperatures vary from about 38 to 85 °F (3 to 29 °C). The retention time required for stable operation varies from 120 days at low temperatures to 30 days

at the higher temperatures. Methane production varies seasonally with lagoon temperature. More methane is produced from warmer lagoons than from colder lagoons.

The USDA NRCS (1999) developed Practice Standard 360, Covered Anaerobic Lagoon, to guide floating cover design, installation, and operation. Many types of materials have been used to cover agricultural lagoons. Floating covers are not limited in dimension. A floating cover allows for some gas storage. Cover materials must have a bulk density near that of water and must be UV-resistant, hydrophobic, tear- and puncture-resistant, and nontoxic to aquatic aerobes and anaerobes.

Several types of material are used to construct floating covers, including high-density polyethylene, XR-5, polypropylene, and hypalon. Material is selected based on material properties (such as UV resistance), price, availability, installation, and service. Installation teams with appropriate equipment travel and install covers.

Biogas formed in a digester bubbles to the surface and is collected and directed by the cover to a gas use. Biogas from a stable covered lagoon is virtually odorless and saturated. It contains 70 to 85 percent methane; the balance is carbon dioxide and trace amounts of hydrogen sulfide (1,000 to 3,000 ppm H_2S). Biogas can be harmful if inhaled directly, corrosive to equipment, and potentially explosive in a confined space when mixed with air. When properly managed, the off-gas is as safe as any other fuel (e.g., propane) used on the farm. Safety concerns are more completely addressed in the *Handbook of Biogas Utilization* (Ross et al., 1996).

Biogas may be filtered for mercaptan and moisture removal. Biogas is usually pumped or compressed to operating pressure and then metered to the gas use equipment. Biogas can be used as fuel for heating, electrical generation, or cogeneration. Alternatively, it can simply be flared for odor control.

Application and Performance: Covered lagoons are used to recover biogas and control. Covers can be installed to completely cover the lagoon and capture clean rainwater. The uncontaminated rainwater can be safely pumped off, reducing the volume of lagoon liquid to be managed later.

Off-gases collected by an impermeable cover on an anaerobic manure facility are neither explosive nor combustible until mixed with air in proper proportions to support combustion. No reports of any explosions of biogas systems at animal production facilities were found.

Table 8-13 summarizes the performance expected from covered lagoons. Anaerobic digestion in a covered lagoon will reduce BOD and TSS by 80 to 90 percent. Odor is virtually eliminated.

Table 8-13. Anaerobic Unit Process Performance

		Percentage Reduction					
Digester type	HRT Days	COD	TS	VS	TN	P	K
Covered lagoon	30–90	70–90	75–95	80–90	25–35	50–80	30–50

Source: Moser et al., 1999.

The concentrations of nutrients are reduced through settling and precipitation in lagoons. Ammonia volatilization losses are virtually eliminated with a cover in place, leaving only settling and precipitation as pathways for N loss.

During anaerobic digestion, microbial activity converts half or more of the Org-N to NH_3-N. Cheng et al., (1999) found that 30 percent of the total TKN (which includes ammonia and organic N) entering the covered first cell of a two-cell lagoon was retained in that cell, probably as Org-N in slowly degradable organics in the sludge. A similar loss due to settling could be expected in a covered single-cell lagoon. A covered single-cell lagoon will not lose NH_3-N to the atmosphere; however NH_3-N will be volatilized from the uncovered second cell of a two-cell lagoon. Cheng et al., (1999) also reported that approximately 50 percent of the influent TKN was subsequently lost from the uncovered second cell of the system.

Reported reductions of P, K, or other nonvolatile elements through a covered lagoon are not really reductions at all. The material settles and accumulates in the lagoon awaiting later management. This is consistent with and supported by P mass losses documented in most lagoon studies. Humenik et al. (1972) found that 92 to 93 percent of the copper and zinc in anaerobic swine lagoon influent was removed and assumed to be settled and accumulated in sludge.

Cheng (1999) found pathogen reduction through a North Carolina covered lagoon to be 2 to 3 orders of magnitude. Martin (1999) determined that relationships between temperature and the time required for a one $\log_{10}$ reduction in densities of pathogens were consistently exponential in form. Although there is substantial variation between organisms regarding the time required for a one $\log_{10}$ reduction in density at ambient temperatures, this work suggests that variation in die-off rates among species decreases markedly as temperature increases. For example, the predicted time required for a one $\log_{10}$ reduction in fecal streptococcus density decreases from 63.7 days at 15 °C to 0.2 day at 50 °C. For *S. aureus*, the decrease is from 10.6 days at 15 °C to 0.1 day at 50 °C. Thus, for both storage and treatment at ambient temperature, an extended period of time is predicted for any significant reduction. A single-cell covered lagoon has a longer residence time than the covered first cell of a two-cell lagoon and should therefore have a greater reduction of pathogens. However, during pumpout of a single-cell lagoon, fresh influent can be short-circuited to the pumpout, carrying pathogens with it, whereas the covered first cell of a two-cell lagoon produces a consistent pathogen reduction without short-circuiting because the first cell's pathogen-destroying retention time is not affected when the second cell is pumped down.

Advantages and Limitations: The advantages of covered anaerobic lagoons are the reduction of lagoon odor, exclusion of rainfall from the lagoon, recovery of usable energy, reduction of ammonia volatilization, and reduction of methane emissions. There are also significant labor savings involved in handling manure as a liquid and being able to apply lagoon waters to the land through irrigation. Solids are broken down through microbial activity, and organic matter is stabilized when anaerobic digestion is complete, reducing the potential for production of noxious by products. A bank-anchored cover prevents the growth of weeds where the cover is placed. Finally, treated lagoon water can be recycled for flush water in confinement houses, resulting in cost savings in areas where water is scarce.

Limitations of covered anaerobic lagoons include the cost of installing a cover, which in 1999 varied from $0.37 to $1.65 per square foot (Martin, 1999), and the occasional need for cover maintenance such as rip repair, and rainfall pump off. The lagoons themselves can be large, depending on the size of the hog operation, and can require a significant amount of cover material. Spills and leaks to surface and ground water can occur if the lagoon capacity is exceeded, or if structural damage occurs to berms, seals, or liners. The treatment capacity of most lagoons is diminished by sludge accumulation, and sludge has to be removed and managed.

Operational Factors: Lagoons should be located on soils of low permeability or soils that seal through biological action or sedimentation, and proper liners should be used to avoid contamination of ground water. Proper sizing and management are necessary to effectively operate a covered anaerobic lagoon and maintain biogas production. The minimum covered lagoon capacity should include treatment volume, sludge storage, freeboard, and, if necessary, storage for seasonal rainfall and a 25-year, 24-hour rainfall event.

Temperature is a key factor in planning the treatment capacity of a covered lagoon. The lagoons are not heated, and the lagoon temperature and biogas production vary with ambient temperatures. Warm climates require smaller lagoons and have less variation in seasonal gas production. Colder temperatures will reduce winter methane production. To compensate for reduced temperatures, loading rates are decreased and hydraulic retention time is increased. A larger lagoon requires a larger, more costly cover than a smaller lagoon in a warmer climate.

The floating cover must be designed and operated in such a way as to keep it from billowing in windy conditions. Coarse solids, such as hay and silage fibers in cow manure, must be separated in a pretreatment step and kept from the lagoon. If dairy solids are not separated, they float and form a crust. The crust will thicken, reducing biogas production and eventually filling the lagoon.

Proper lagoon inspection and maintenance are necessary to ensure that lagoon liners and covers are not harmed by agitating and pumping, berms and embankments are stable, and the required freeboard and rainfall storage are provided. Sampling and analysis of the lagoon water are suggested to determine its nutrient content and appropriate land application rates.

Anaerobic lagoons accumulate sludge over time, diminishing treatment capacity. Lagoons must be cleaned out once every 5 to 15 years, and the sludge can be applied to land other than the spray fields receiving the lagoon liquid. Because crop P requirements are less than those for N, it takes more land to apply the sludge from lagoon cleanout than to apply liquid wastewater.

Demonstration Status: Floating-cover technology is well developed and readily available. Covering lagoons for odor control has been demonstrated in all sectors of the animal production industry. The installation of floating covers specifically for methane recovery is a less common, but well-known practice. There are at least 10 covered lagoon systems with biogas collection and combustion in the pig and dairy industries (Lusk, 1998; RCM, 2000).

Practice: Aerobic Treatment of Liquids

Description: Conventional aerobic digestion is a process used frequently at small municipal and industrial wastewater treatment plants for biosolids stabilization. It is a suspended growth process operating at ambient temperature in the stationary or endogenous respiration phase of the microbial growth curve. In the stationary phase, the exogenous supply of energy is inadequate to support any net microbial growth. Endogenous respiration occurs when the exogenous supply of energy is also inadequate to satisfy cell maintenance requirements, and a net decrease in microbial mass occurs. Operating parameters include a relatively long period of aeration, ranging from several days to more than 30 days depending on the degree of stabilization desired. Given the relatively long period of aeration, activated sludge recycling is not necessary and hydraulic detention and solids retention times are equal in continuous-flow systems. This is a major difference between aerobic digestion and the various variants of the activated sludge process including extended aeration (see "Secondary Biological Treatment" below). When aerobic digestion is used for biosolids stabilization, either the fill-and-draw or the continuous mode of operation can be used. With the fill-and-draw mode of operation, an option is to periodically cease aeration temporarily to allow settling and then decant the clarified liquid before resuming aeration. This approach also allows the reactor to be used as a biosolids thickener.

With conventional aerobic digestion, substantial reductions in TS, and VS, BOD, COD, and Org-N can be realized. Total N reduction can also be substantial, with either ammonia stripping or nitrification-denitrification serving as the primary mechanism, depending on the dissolved oxygen concentration of the mixed liquor. Actual process performance depends on a number of variables including solids retention time, temperature, and adequacy of oxygen transfer and mixing.

An aeration basin is typically used for the aerobic digestion of municipal and industrial wastewater biosolids. In contrast, several reactor types, including oxidation ditches and mechanically aerated lagoons, as well as aeration basins, have been used for the aerobic digestion of animal manures. Under commercial conditions, the oxidation ditch has been the most commonly used because it can be located in the animal housing unit under cages for laying hens or under slatted floors for swine. This eliminates the need for transport of manure to the treatment system.

It should be noted that since the oxidation ditch was originally developed to employ the activated sludge process used in municipal wastewater treatment, the term "activated sludge" has been used incorrectly on occasion to describe the aerobic digestion of swine, poultry, and other animal wastes. Aerobic digestion, not the activated sludge process, is employed in oxidation ditches, mechanically aerated lagoons, and aeration basins. Table 8-14 presents technologies that use aerobic digestion or the activated sludge process.

Table 8-14. Operational Characteristics of Aerobic Digestion and Activated Sludge Processes.

Process Modification	Flow Model	Aeration System	BOD Removal Efficiency (percent)	Remarks
Conventional	Plug flow	Diffused-air, mechanical aerators	85–95	Use for low-strength domestic wastes. Process is susceptible to shock loads.
Complete mix	Continuous-flow stirred-tank reactor	Diffused-air, mechanical aerators	85–95	Use for general application. Process is resistant to shock loads, but is susceptible to filamentous growths.
Step feed	Plug flow	Diffused air	85–95	Use for general application for a wide range of wastes.
Modified aeration	Plug flow	Diffused air	60–75	Use for intermediate degree of treatment where cell tissue in the effluent is not objectionable.
Contact stabilization	Plug flow	Diffused-air, mechanical aerators	80–90	Use for expansion of existing systems and package plants.
Extended aeration	Plug flow	Diffused-air, mechanical aerators	75–95	Use for small communities, package plants, and where nitrified element is required. Process is flexible.
High-rate aeration	Continuous-flow stirred-tank reactor	Mechanical aerators	75–90	Use for general applications with turbine aerators to transfer oxygen and control floc size.
Kraus process	Plug flow	Diffused air	85–95	Use for low-N, high-strength wastes.
High-purity oxygen	Continuous-flow stirred-tank reactors in series	Mechanical aerators (sparger turbines)	85–95	Use for general application with high-strength waste and where on-site space is limited. Process is resistant to slug loads.
Oxidation ditch	Plug flow	Mechanical aerators (horizontal axis type)	75–95	Use for small communities or where large area of land is available. Process is flexible.
Sequencing batch reactor	Intermittent-flow stirred-tank reactor	Diffused air	85–95	Use for small communities where land is limited. Process is flexible and can remove N and P.
Deep-shaft reactor	Plug flow	Diffused air	85–95	Use for general application with high-strength wastes. Process is resistant to slug loads.
Single-stage nitrification	Continuous-flow stirred-tank reactors or plug flow	Mechanical aerators, diffused-air	85–95	Use for general application for N control where inhibitory industrial wastes are not present.
Separate stage nitrification	Continuous-flow stirred-tank reactors or plug flow	Mechanical aerators, diffused-air	85-95	Use for upgrading existing systems, where N standards are stringent, or where inhibitory industrial wastes are present and can be removed in earlier stages.

Source: Metcalf and Eddy Inc., 1991.

Application and Performance: Conventional aerobic digestion is an option for all swine and poultry operations where manure is handled as a liquid or slurry, and it can be used with flushing systems using either mixed liquor or clarified effluent as flush water. With proper process design and operation, a 75 to 85 percent reduction in 5-day biochemical oxygen demand (BOD_5) appears achievable, with a concurrent 45 to 55 percent reduction in COD, and a 20 to 40 percent reduction in TS (Martin, 1999). In addition, a 70 to 80 percent reduction of the N in both poultry and swine wastes via nitrification-denitrification also appears possible. Total P is not reduced, but the soluble fraction may increase. As with aerobic digestion of biosolids, some reduction in pathogen densities may also occur depending on process temperature.

Advantages and Limitations: In addition to the potential for substantial reductions in oxygen-demanding organics and N, one of the principal advantages of aerobic digestion of poultry and swine manures is the potential for a high degree of odor control. Another advantage is the elimination of fly and other vermin problems.

Limitations include high energy requirements for aeration and mixing (e.g., pumps, blowers, or mixers for mechanical aeration). In addition, aerobic lagoons without mechanical aeration are generally shallow, requiring a very large land area to meet oxygen demands. The absence of a reduction in the volume of waste requiring ultimate disposal is another limitation. In certain situations, waste volume will be increased significantly. For example, use of an undercage oxidation ditch versus a high-rise type system to manage the waste from laying hens will substantially increase the waste volume requiring ultimate disposal. Also, management, maintenance, and repair requirements for aerobic digestion systems can be significant. For example, liquids and solids must be separated in a pretreatment step when aerated lagoons are used.

Operational Factors: Establishing and maintaining an adequate microbial population in aerobic digestion reactors is critical to ensure optimal process performance. Failure to do so will lead to excessive foam production, which has suffocated animals on slatted floors above in-building oxidation ditches. Failure to remove slowly biodegradable solids on a regular basis to maintain a mixed liquor total solids concentration of about 1 percent in fill-and-draw systems will lead to a substantial reduction in oxygen transfer efficiency and mixing. This results in reduced treatment efficiency and the potential for generation of noxious odors and release of poisonous gases, particularly hydrogen sulfide. Because ambient temperature determines process temperature, seasonal variation in process performance occurs.

Demonstration Status: Aerobic digestion has not been adapted to any significant degree by the poultry, dairy, or swine industries, although a number of research and demonstration scale studies were conducted in the late 1960s and early 1970s. Problems related to process and facilities design, together with the significant increase in electricity costs in the early to mid-1970s, led to a loss of interest in this animal waste treatment alternative. It is possible that no aerobic digestion systems for animal wastes are currently in operation in the poultry and swine industries.

Lagoons are the most popular method of treatment for livestock manure. Aerobic lagoons are commonly used for secondary treatment and storage of anaerobic lagoon wastes. Despite the advantages, however, aerobic lagoons are considered uneconomical for livestock manure treatment.

Practice: Autoheated Aerobic Digestion

Description: Autoheated aerobic digestion uses heat released during the microbial oxidation of organic matter to raise process temperature above ambient levels. This is accomplished by minimizing both sensible and evaporative heat losses through the use of insulated reactors and aeration systems with high-efficiency oxygen transfer. Mesophilic temperatures, 86 °F (30 °C) or higher, can typically be maintained even in cold climates, and thermophilic temperatures as high as 131 to 149 °F (55 to 65 °C) can be attained. Both ammonia stripping and nitrification-denitrification can be mechanisms of N loss at mesophilic temperatures; nitrification-denitrification is typically the principal mechanism if the aeration rate is adequate to support nitrification. Because both *Nitrosomas* and *Nitrobacter*, the bacteria that convert ammonium ions into nitrate, are mesophiles, N loss at thermophilic temperatures is limited to ammonia stripping. Typically, autoheated digestion reactors are operated as draw-and-fill reactors to minimize influent short-circuiting, especially when maximizing pathogen reduction is a treatment objective.

Application and Performance: Autoheated aerobic digestion is appropriate for all livestock and poultry operations where manure is handled as a slurry that has a minimum TS concentration of at least 1 to 2 percent, wet basis. At lower influent total solids concentrations, such as those characteristic of flushing systems, achieving process temperatures significantly above ambient levels is problematic because of an insufficient biological heat production potential relative to sensible and evaporative heat losses. As influent TS concentration increases, the potential for achieving thermophilic temperatures also increases. Influent TS concentrations of between 3 and 5 percent are necessary to attain thermophilic temperatures.

With proper process design and operation, the previously discussed reductions in BOD_5, COD, TS, and total N that can be realized with conventional aerobic digestion also can be realized with autoheated aerobic digestion (Martin, 1999). Autoheated aerobic digestion can also provide significant reductions in pathogen densities in a relatively short 1- to 2-day treatment period. Reductions realized are a function of process temperature. At a process temperature of 122 °F (50 °C) or greater, a minimum of at least a one $\log_{10}$ reduction in the density of most pathogens is highly probable, with two to three $\log_{10}$ reductions likely (Martin, 1999).

Advantages and Limitations: With respect to waste stabilization and odor control, the potential benefits of conventional and autoheated aerobic digestion are comparable. The principal advantages of autoheated aerobic digestion relative to conventional aerobic digestion from a process performance perspective are (1) higher reaction rates that translate into shorter detention times to attain a given degree of stabilization, and (2) more rapid reduction in densities of

pathogens. The time required to achieve comparable reductions in BOD_5, COD, TS, and total N is much shorter in autoheated than in conventional aerobic digestion. With autoheated aerobic digestion, these reductions occur within 1 to 3 days at thermophilic temperatures, whereas 15 days or more are required with conventional aerobic digestion at ambient temperatures. This translates directly into smaller reactor volume requirements.

The ability to provide rapid and substantial (at least a one $\log_{10}$) reductions in pathogen densities is one of the more attractive characteristics of autoheated aerobic digestion. This ability has been demonstrated in several studies of autoheated aerobic digestion of biosolids from municipal wastewater treatment, including a study by Martin (1999).

The high energy requirements for aeration and mixing are limitations of autoheated aerobic digestion. In addition, waste volume is not reduced through the treatment process. However, the requirement of a less dilute influent waste stream, as compared with conventional aerobic digestion, for example, to provide the necessary biological heat production potential translates into reduced ultimate disposal requirements.

Operational Factors: A foam layer covering the mixed liquor in autoheated aerobic digestion reactors is a common characteristic and serves to reduce both sensible and evaporative heat losses. It is necessary to control the depth of this foam layer to ensure that an overflow of foam from the reactor does not occur. Typically, mechanical foam cutters are used. Although autoheated aerobic digestion is less sensitive to fluctuations in ambient temperature than are other treatment processes, such as conventional aerobic digestion, some reduction in treatment efficiency can occur, especially during extended periods of extremely cold weather.

Demonstration Status: The feasibility of using autoheated aerobic digestion to stabilize swine manure has been demonstrated in several studies (Martin, 1999). Feasibility also has been demonstrated in several studies with cattle manure, including studies by Terwilliger and Crauer (1975) and Cummings and Jewell (1977). There does not appear to have been any comparable demonstration of feasibility with poultry wastes. Given the similarities in the composition of swine and poultry wastes, it is highly probable that autoheated aerobic digestion of poultry wastes is also technically feasible. Although no data are available, it is probable that this waste treatment technology is not currently being used in any segment of animal agriculture, primarily because of the associated energy cost.

Practice: Secondary Biological Treatment

Description: The activated sludge process is a widely used technology for treating wastewater that has high organic content. The process was first used in the early 1900s and has since gained popularity for treatment of municipal and industrial wastewater. Many versions of this process are in use today, but the fundamental principles are similar. Basically, the activated sludge process treats organic wastes by maintaining an activated mass of microorganisms that aerobically decomposes and stabilizes the waste.

Primary clarification or solids settling is the first step in the activated sludge process. Next, the organic waste is introduced into a reactor. Maintained in suspension in the reactor is a biological culture that converts the waste through oxidation and synthesis. The aerobic environment in the reactor is achieved using diffused or mechanical aeration, which also maintains a completely mixed state. After a specified period, the HRT, the mixture in the reactor is passed to a settling tank. A portion of the solids from the settling tank is recycled to the reactor to maintain a balance of microorganisms. Periodically, solids from the settling tank are "wasted" or discharged to maintain a specific concentration of microorganisms in the system. The solids are discharged according to a calculated solids retention time (SRT), which is based on the influent characteristics and the desired effluent quality. The overflow from the settling tank is discharged from the system.

Application and Performance: The activated sludge process is very flexible and can be used to treat almost any type of biological waste. It can be adapted to provide high levels of treatment under a wide range of operating conditions. Properly designed, installed, and operated activated sludge systems can reduce the potential pollution impact of feedlot waste because this technology has been shown to reduce carbon-, N-, and P-rich compounds.

In the activated sludge process, N is treated biologically through nitrification-denitrification. The supply of air facilitates nitrification, which is the oxidation of ammonia to nitrite and then nitrate. Denitrification takes place in an anoxic environment, in which the bacteria reduce the nitrate to nitrogen gas (N_2), which is released into the atmosphere. The activated sludge process can nitrify and denitrify in single- and double-stage systems.

P is removed biologically when an anaerobic zone is followed by an aerobic zone, causing the microorganisms to absorb P at an above-normal rate. The activated sludge technology most effective for removing P is the sequencing batch reactor (SBR) (see "Sequencing Batch Reactors," below).

N and P can both be removed in the same system. The SBR is also most effective for targeting removal of both N and P because of its ability to alternate aerobic and anaerobic conditions to control precisely the level of treatment.

Advantages and Limitations: An advantage of the activated sludge process is that it removes pollutants, particularly nutrients, from the liquid portion of the waste. Nutrient removal can allow more feedlot wastewater to be applied to land without overloading it with N and P. Furthermore, concentrating the nutrients in a sludge portion can potentially reduce transportation volumes and costs of shipping excess waste.

A disadvantage of an activated sludge system compared to an anaerobic lagoon is the relatively high capital and operating costs and the complexity of the control system. In addition, because pollutants will remain in the sludge, stabilization and pathogen reduction are necessary before disposing of it.

Because the activated sludge process does not reduce pathogens sufficiently, another way to reduce pathogens in both the liquid and solid portions of a waste may be appropriate prior to discharge or land application. The liquid effluent from an activated sludge system can be disinfected by using chlorination, ultraviolet radiation, or ozonation, which are the final steps in many municipal treatment systems.

Operational Factors: Many parameters can affect the performance of an activated sludge system. Organic loading must be monitored carefully to ensure that the microorganisms can be sustained in proper concentrations to produce a desired effluent quality. The principal factors in the control of the activated sludge process are:

- Maintaining dissolved oxygen levels in the aeration tank (reactor).
- Regulating the amount of recycled activated sludge from the settling tank to the reactor.
- Controlling the waste-activated sludge concentration in the reactor.

Ambient temperature can also affect treatment efficiency of an activated sludge system. Temperature influences the metabolic activities of the microbial population, gas-transfer rates, and settling characteristics of biological solids. In cold climates, a larger reactor volume may be necessary to achieve treatment goals because nitrification rates decrease significantly at lower temperatures.

Demonstration Status: Although activated sludge technologies have not been demonstrated on a full-scale basis in the animal feedlot industry, the process may treat such waste effectively. Studies have been performed on dairy and swine waste to determine the level of treatment achievable in an SBR (see "Sequencing Batch Reactors," below). The SBR is simpler, more flexible, and perhaps more cost-effective than other activated sludge options for use in the feedlots industry.

Practice: Sequencing Batch Reactors

Description: An SBR is an activated sludge treatment system in which the processes are carried out sequentially in the same tank (reactor). The SBR system may consist of one reactor, or more than one reactor operated in parallel. The activated sludge process treats organic wastes by maintaining an aerobic bacterial culture, which decomposes and stabilizes the waste. An SBR has five basic phases of operation, which are described below.

Fill Phase: During the fill phase, influent enters the reactor and mechanical mixing begins. The mixing action resuspends the settled biomass from the bottom of the reactor, creating a completely mixed condition and an anoxic environment. As wastewater continues entering the reactor, oxygen may also be delivered, converting the environment from anoxic to aerobic. Depending on the desired effluent quality, the oxygen supply can be operated in an "on/off" cycle, thus alternating the aerobic and anoxic conditions and accomplishing nitrification and denitrification.

React Phase: During the react phase, wastewater no longer enters the reactor. Influent to the system is instead either stored for later treatment in a single-reactor system or diverted to another reactor to begin treatment in a system with multiple reactors. Mechanical mixing continues throughout this phase. The oxygen supply may be operated in a cyclical manner, as described in the fill phase, to accomplish additional denitrification if necessary. Activated sludge systems, such as SBRs, depend upon developing and sustaining a mixed culture of bacteria and other microbes (i.e., the biomass) to accomplish the treatment objectives.

Settle Phase: During the settle phase, the oxygen supply system and mechanical mixer do not operate. This phase provides a quiescent environment in the reactor and allows gravity solids separation to occur, much like in a conventional clarifier.

Draw Phase: Following the treatment of a batch, it is necessary to remove from the reactor the same volume of water that was added during the fill phase. After a sufficient settling phase, the liquid near the top of the reactor is decanted to a predetermined level and discharged or recycled.

Idle Phase: The idle phase is a time period between batches during which the system does not operate. The duration of this unnecessary phase depends on the hydraulic aspects of the reactor. However, as a result of biological degradation and accumulation of inert materials from the wastewater, solids must be discharged from the reactor periodically to maintain a desirable level of mixed liquor suspended solids. This "sludge wasting" is done during the idle phase, or immediately following the draw phase.

Application and Performance: SBR technology could be applied to reduce the potential pollution impact of liquid manure waste from dairies because this technology has been shown to reduce carbon-, N-, and P-rich compounds. Removing these pollutants from the liquid portion of the waste could allow for greater hydraulic application to lands without exceeding crop nutrient needs. Concentrating the nutrients in the sludge portion could potentially reduce transportation volumes and cost of shipping excess waste. Although a proven technology for treatment of nutrients in municipal wastewater, available data does not exist showing SBRs to be effective in pathogen reduction.

Given the processes it employs, SBR treatment may allow treated dairy wastewater to be either applied to land or discharged to a stream if a sufficient level of treatment can be achieved. Further, the sludge from the wasting procedure could be applied to land, composted, or sent off site for disposal. Aqua-Aerobic Systems of Rockford, Illinois, (Aqua-Aerobics, 2000) estimates a sludge production rate of approximately 1.3 pounds of waste-activated sludge per pound of BOD_5 entering the system. The use of SBRs to treat dairy waste has been studied in the laboratory at both Cornell University and the University of California at Davis. Both studies have shown SBR technology to be effective in reducing pollutants in the liquid portion of dairy waste, although neither report included specific information on sludge characteristics or P removals (Johnson and Montemagno, 1999; Zhang et al., 1999).

In the Cornell study, diluted dairy manure was treated in bench-scale reactors (Johnson and Montemagno, 1999). Experiments were conducted to determine the operating strategy best suited for the diluted dairy manure. The study resulted in removals of 98 percent of ammonia (NH_3), 95 percent of COD, 40 percent of nitrate/nitrite (NO_3/NO_2), and 91 percent of inorganic N.

The University of California at Davis studied how SBR performance was affected by HRT, SRT, organic loading, and influent characteristics of dairy wastewater (Zhang et al., 1999). The highest removal efficiencies from the liquid portion of the waste were for an influent COD concentration of 20,000 mg/L (a COD concentration of 10,000 mg/L was also studied) and an HRT of 3 days (HRTs of 1 to 3 days were studied). With these parameters, laboratory personnel observed removal efficiencies of 85.1 percent for NH_3 and 86.7 percent for COD.

In addition, studies on SBR treatment of swine waste in Canada and of veal waste in Europe have demonstrated high removal rates of COD, N, and P (Reeves, 1999).

Advantages and Limitations: Technology currently used at dairies includes solids settling basins followed by treatment and storage of waste in an anaerobic lagoon. Lagoon effluent and solids are applied to cropland in accordance with their nutrient content, and excess water or solids are then transported off site. The SBR could replace treatment in an anaerobic lagoon, but there would still be a need for solids separation in advance of SBR treatment, as well as a pond or tank to equalize the wastewater flow. In fact, Aqua-Aerobics (2000) has indicated that solids removal and dilution of the raw slurry would be necessary to treatment in the SBR. Following the SBR, it is possible that some type of effluent storage would be required for periods when direct irrigation is not possible or necessary.

Use of an SBR is expected to be advantageous at dairies that apply a portion of their waste to land. The reduced level of nutrients in the liquid portion would allow for application of a greater volume of liquid waste, thereby reducing the volume of waste that must be transported off site and possibly eliminating liquid waste transport. An SBR is also beneficial in the handling of the solids portion of the waste because no periodic dredging is required as is the case with anaerobic lagoons. Disadvantages of an SBR system are the relatively high capital and operating costs, as well as the need to manage the nutrients that remain in the sludge.

Because the activated sludge process is not a generally accepted method of pathogen reduction, another means of reducing pathogens in both the liquid and solid portions of the dairy waste may be appropriate. Disinfection of the liquid effluent from the SBR could be accomplished through use of chlorination, ultraviolet radiation, or ozonation which are used as the final step in many municipal treatment systems. Composting has also been demonstrated as a means of reducing pathogens in organic solid waste and could be implemented for use with the SBR sludge.

Operational Factors: The five phases of SBR operation may be used in a variety of combinations in order to optimize treatment to address specific influent characteristics and effluent goals. N in the activated sludge process is treated biologically through the nitrification-denitrification process. The nitrification-denitrification process in the SBR is controlled through the timing and

cyclical pattern of aeration during the react phase. The supply of air causes nitrification, which is the oxidation of ammonia to nitrite and then nitrate. To accomplish denitrification, the air supply is shut off, creating an anoxic environment in which the bacteria ultimately reduce the nitrate to N_2, which is released to the atmosphere. The cycle can be repeated to achieve additional levels of denitrification. Some portion of the N in the influent to the SBR may also volatilize prior to treatment, and a portion may also be taken up by microorganisms that are present in the waste-activated sludge (Zhang et al., 1999).

P is removed when an anaerobic zone (or phase) is followed by an aerobic zone, causing the microorganisms to take up P at an above-normal rate. The waste-activated sludge containing the microorganisms is periodically "wasted" as described above. As such, the bulk of the P will be concentrated ultimately in the sludge portion with a minimal amount remaining in the liquid effluent.

N and P can both be removed in the same system. This dual removal is accomplished by beginning the fill phase without aeration, which creates an anoxic condition allowing for some denitrification as well as release of P from the cell mass to the liquid medium. There follows a period of aerated mixing, which will continue into the react phase, allowing for nitrification and uptake of P. The settle phase, in which no aeration occurs, is extended sufficiently to allow for additional denitrification. Again, these phases can be repeated or executed for varying durations in order to accomplish specific treatment goals.

Demonstration Status: Although the SBR technology has not been demonstrated on a full-scale basis in the dairy industry, SBRs are currently being evaluated for use at dairies because they generate a high volume of wastewater. Dairy wastewater treated in the SBR includes a combination of parlor and barn flush/hose water and runoff.

Cornell University is currently studying two pilot-scale SBR systems to further investigate the treatability of dairy waste (Johnson and Montemagno, 1999). No results from the pilot-scale study are yet available, although preliminary results for nutrient removal have been favorable and a full-scale system is being planned.

Practice: Solids Buildup in the Covered First Cell of a Two-Cell Lagoon

Description: This section addresses sludge accumulation, removal, and management in the first cell of a two-cell lagoon. The first cell may or may not be covered for methane recovery. Some sludge will be carried from the first cell to the second cell; however, the quantity is not significant compared with potential accumulations in the first cell. No quantitative information was found regarding the differences in the rate of accumulation of sludge in the first cell versus accumulation in a single-cell lagoon. The removal and management of sludge from the first cell of a two-cell lagoon will be the same as described for sludge cleaning from a single cell lagoon.

For the purpose of this section, sludge is material settled on the bottom of a lagoon receiving waste from any animal; it has a TS content greater than 10 percent, generally has a high angle of repose when dewatered, and will not readily flow to a pump. Sludge includes organic material not decomposed by lagoon bacteria, and inorganic material such as sand and precipitates. Sludge accumulation can eventually fill a lagoon.

Accumulated sludge is removed to restore lagoon treatment and storage capacities. Two general methods of sludge removal, slurry and solid, are described below. When managed as a slurry, sludge is resuspended with agitation and pumped to tankers or irrigation guns for land application. Slurry management is desirable when the sludge mixture can be pumped to an irrigation gun or hauled a short distance. Sludge removed from covered lagoons is removed as a slurry.

Sludge managed as a solid is excavated from the lagoon or pumped from the bottom as slurry to a drying area. Solid sludge is cheaper to haul than slurry because water, which increases the weight and volume, is not added. Solid sludge can be spread with conventional manure spreaders or dumped on fields and spread out and disced into the soil. In drier areas of the country, a lagoon may be withdrawn from service as a parallel lagoon is restored to service. The lagoon liquids are pumped off to field application and the sludge is allowed to dry. After 4 to 12 months, excavators, backhoes or bulldozers scrape, push, pull, or lift the material into trucks or wagons for hauling and spreading. Some lagoons are designed to be desludged by dragline bucket excavators while still in operation. Draglines work along the banks of these long, narrow lagoons, excavating sludge and either dropping it into trucks for hauling or depositing it on the lagoon embankment to dry for later hauling.

Application and Performance: Lagoon cleanout is applicable to all two-cell lagoons, regardless of location. Reported reductions of P, K, and other nonvolatile elements through a lagoon are not really reductions at all because these materials settle. N is considered volatile in the ammonia form, but some Org-N associated with heavier and nondegradable organics also settles into the lagoon sludge and stays, resulting in a high-Org-N fraction of total TKN in settled solids. The settled materials accumulate in the lagoon awaiting later disposal. Compared with lagoon liquids, lagoon sludges have higher concentrations of all pollutants that are not completely soluble. All reported data suggest that the sludge is more stable than raw manure based on its reduced VS/TS. VS are a portion of the TS that can be biologically destroyed, and as they are destroyed, the VS/TS ratio declines.

As anaerobic digestion of manure changes the solution chemistry in a lagoon, materials such as NH_3 and P form precipitates with Ca and Mg. Fulhage and Hoehne (1999) and Bicudo et al. (1999) both report concentrations of Ca, Mg, P, and K in lagoon sludge at 10 to 30 times that found in raw manure. Fulhage and Hoehne also reported that Cu and Zn settle and concentrate to 40 to 100 times the concentration found in lagoon liquid.

Martin (1999), in a review and analysis of factors affecting pathogen destruction, found that time and temperature controlled the die-off rate of pathogens. Sludge that has been in a lagoon for 10

years is expected to have very low concentrations of pathogens, and those would be associated with the most recent 90 to 180 days of settling.

Advantages and Limitations: The advantage of lagoon cleanout is that removal of sludge restores the volume of a first-cell lagoon that is necessary for design treatment capacity. One of the limitations is that sludge disposal is ignored in most NMPs. Sludge is a concentrated, nutrient-rich material. The nutrients in the sludge, if applied to the same cropland historically receiving lagoon liquids, could easily exceed the planned application rate of nutrients. P and other relatively insoluble nutrients are more concentrated than N in sludge and become the basis of planning proper use of the sludge.

Ideally, sludge will be managed as a high-value fertilizer in the year it is applied. As the sludge has a higher nutrient and, hence, cash value than liquid manure, hauling to remote farms and fields to replace commercial fertilizer application is possible and desirable. Proper management of applied sludge will result in successful crops and minimal loss of nutrients to surface or ground waters.

The cover is a limiting factor in covered lagoon cleanout. At least a portion of the cover is removed to allow equipment access. Removing a complete cover is usually not practical. Lacking complete access, covered lagoon cleanouts will not remove all of the sludge present. Therefore, more frequent cleanouts would be expected. Most covered lagoons have been developed with cleanout intervals of 10 to 15 years.

Operational Factors: The USDA allows for sludge accumulation by incorporating a sludge accumulation volume (SAV) in its lagoon design calculations. Table 8-15 shows USDA's ratios of sludge accumulated per pound of TS added to the lagoon. The higher the rate of sludge accumulation assumed in a design, the larger the lagoon volume required. There are no published data to compare sludge accumulation in the first cell of a two-cell lagoon versus accumulation in a single-cell lagoon. Anecdotal observations suggest that a first cell does not accumulate sludge faster than a single-cell lagoon as long as the first cell is sized to contain all of the treatment volume and SAV. In theory, a constant volume first cell should accumulate less sludge over time than a single-cell lagoon because the constant volume lagoon has a consistently higher microbial concentration than a single-cell lagoon. The higher concentration should result in the ability to consume new manure organic solids before they can settle to become sludge. Also in theory, a covered first cell would accumulate less sludge due to higher biological activity because a covered lagoon is a few degrees warmer than an uncovered lagoon.

Table 8-15. Lagoon Sludge Accumulation Ratios.

Animal Type	Sludge Accumulation Ratio
Layers	0.0295 ft^3/lb TS
Pullets	0.0455 ft^3/lb TS
Swine	0.0485 ft^3/lb TS
Dairy cattle	0.0729 ft^3/lb TS

Source: USDA NRCS 1996.

Information from various studies suggests that the USDA values may overestimate actual sludge accumulation rates. Table 8-16 shows a range of long-term sludge accumulation rates reported by various researchers. Field studies by both Fulhage and Hoehne (1999) and Bicudo et al. (1999) show lower accumulation rates than developed by Barth and Kroes (1985) and USDA NRCS (1996).

Table 8-16. Lagoon Sludge Accumulation Rates Estimated for Pig Manure.

Source	Sludge Accumulation Rate
Fulhage (1990)	0.002 m^3/kg LAW*
Bicudo (1999)	0.003 m^3/kg LAW*
Barth (1985)	0.008 m^3/kg LAW*
USDA (1992)**	0.012 m^3/kg LAW*

* LAW = live animal weight ** as calculated by Bicudo et al. (1999).

It is important to note that the accumulation rate of sludge is influenced by lagoon design, influent characteristics, site factors, and management factors. Lagoon design factors such as lagoon volume, surface fetch, and lagoon depth increase or decrease potential lagoon mixing. More lagoon mixing encourages greater solids destruction by increasing the opportunity for bacteria to encounter and degrade solids. Influent factors, including animal type and feed, determine the biodegradability of manure solids. Highly degradable manure solids are more completely destroyed, thus accumulating as sludge to a lesser degree. Site temperature and incident rainfall impact the biological performance of the lagoon. High temperature increases biological activity and solids destruction. High rainfall can fill the lagoon and reduce retention time, thus slowing biological destruction of solids. Management factors also affect sludge accumulation. Increasing animal population, adding materials such as straw or sand used for animal bedding, or adding process water will reduce the ability of a lagoon to destroy solids and, therefore, increase the rate of sludge accumulation. Properly managed solids separators can reduce the quantity of solids reaching the lagoon, hence reducing sludge accumulation.

Demonstration Status: First-cell cleanouts are common and have occurred since two-cell lagoons have been used. In many areas of the country, there are companies that specialize in lagoon cleaning.

Practice: Solids Buildup in an Uncovered Lagoon

Description: For the purpose of this section, sludge is material settled on the bottom of a lagoon receiving waste from any animal; it has a TS content greater than 10 percent, generally has a high angle of repose when dewatered, and will not readily flow to a pump. This definition is intended to distinguish sludge from a less concentrated layer of solids above the sludge surface that can be drawn off with conventional pumping. All lagoons accumulate settleable materials in a sludge layer on the bottom of the lagoon. Sludge includes organic material not decomposed by lagoon bacteria and inorganic material such as sand and precipitates. Over time the sludge accumulation decreases the active treatment volume of a lagoon and negatively impacts the lagoon

performance. Reduced treatment performance increases the rate of sludge accumulation. Sludge accumulations can eventually fill a lagoon.

Accumulated sludge is removed to restore lagoon treatment and storage capacities. Two general methods of sludge removal, slurry and solid, are described below.

When managed as a slurry, sludge is resuspended with agitation and pumped to tankers or irrigation guns for land application. Slurry management is desirable when the sludge mixture can be pumped to an irrigation gun or hauled a short distance.

Sludge managed as a solid is excavated from the lagoon. Solid sludge is cheaper to haul than slurry because water, which increases the weight and volume, is not added. Solid sludge can be spread with conventional manure spreaders or dumped on fields and spread out and disced into the soil. In drier areas of the country, a lagoon may be withdrawn from service when a parallel lagoon is restored to service. The lagoon liquids are pumped off to field application, and the sludge is allowed to dry. After 4 to 12 months, excavators, backhoes, or bulldozers scrape, push, pull, or lift the material into trucks or wagons for hauling and spreading. Some lagoons are designed to be desludged by dragline bucket excavators while still in operation. Draglines work along the banks of these long, narrow lagoons, excavating sludge and either dropping it into trucks for hauling or depositing it on the lagoon embankment to dry for later hauling.

Application and Performance: Lagoon cleanout is applicable to all operations that have lagoons, regardless of location. Reported reductions of P, K, and other nonvolatile elements through a lagoon are not really reductions at all. The material settles and accumulates in the lagoon, awaiting later disposal. Compared with lagoon liquids, lagoon sludges have higher concentrations of all pollutants that are not completely soluble. All reported data suggest that the sludge is more stable than raw manure based on its reduced VS/TS ratio. VS are a portion of the TS that can be biologically destroyed, and as they are destroyed, the VS/TS ratio declines. Some Org-N associated with heavier and nondegradable organics also settles into the lagoon sludge and stays, resulting in a high-organic N fraction of TKN in settled solids.

As anaerobic digestion of manure changes the solution chemistry in a lagoon, materials such as NH_3 and P form precipitates with Ca and Mg. Both Fulhage and Hoehne (1999) and Bicudo et al. (1999) report concentrations of Ca, Mg, P, and K in lagoon sludge at 10 to 30 times that found in raw manure. Fulhage and Hoehne also reported that Cu and Zn settle and concentrate to 40 to 100 times the concentration found in lagoon liquid.

Martin (1999), in a review and analysis of factors affecting pathogen destruction, found that time and temperature controlled the die-off rate of pathogens. Sludge that has been in a lagoon for 10 years is expected to have very low concentrations of pathogens, and those would be associated with the most recent 90 to 180 days of settling.

Advantages and Limitations: The advantage of lagoon cleanout is that removal of sludge restores the volume of a lagoon that is necessary for design treatment and storage capacities. One of the

limitations is that sludge disposal is ignored in most NMPs. Sludge is a concentrated, nutrient-rich material. The nutrients in the sludge, if applied to the same cropland historically receiving lagoon liquids, could easily exceed the planned application rate of nutrients. P and other relatively insoluble nutrients are more concentrated than N in sludge and become the basis of planning proper use and disposal of the sludge.

Ideally, sludge will be managed as a high value fertilizer in the year it is applied. As the sludge has a higher nutrient and, hence, cash value than liquid manure, hauling to remote farms and fields to replace commercial fertilizer application is possible and desirable. Proper management of applied sludge will result in successful crops and minimal loss of nutrients to surface or ground waters.

Operational Factors: The USDA allows for sludge accumulation by incorporating an SAV in its lagoon design calculations. Table 8-15 shows USDA's ratios of sludge accumulated per pound of TS added to the lagoon. The higher the rate of sludge accumulation assumed in a design, the larger the lagoon volume required.

Information from various studies suggests that the USDA values may overestimate actual sludge accumulation rates. Table 8-16 shows a range of long-term sludge accumulation rates reported by various researchers. Field studies by both Fulhage and Hoehne (1999) and Bicudo et al. (1999) show lower accumulation rates than were developed by Barth and Kroes (1985) and USDA NRCS (1996).

It is important to note that the accumulation rate of sludge is influenced by lagoon design, influent characteristics, site factors, and management factors. Lagoon design factors such as lagoon volume, surface fetch, and lagoon depth increase or decrease potential lagoon mixing. More lagoon mixing encourages greater solids destruction by increasing the opportunity for bacteria to encounter and degrade solids. Influent factors, including animal type and feed, determine the biodegradability of manure solids. Highly degradable manure solids are more completely destroyed, thus accumulate as sludge to a lesser degree. Site temperature and incident rainfall impact the biological performance of the lagoon. High temperature increases biological activity and solids destruction. High rainfall can fill the lagoon and reduce retention time, thus slowing biological destruction of solids. Management factors also affect sludge accumulation. Increasing the animal population, the addition of materials such as straw or sand used for animal bedding, or the addition of process water will reduce the ability of a lagoon to destroy solids and increase the rate of sludge accumulation. Properly managed solids separators can reduce the quantity of solids reaching the lagoon, thereby reducing sludge accumulation. Mixing a lagoon before land application will suspend some of the sludge solids, causing them to be pumped out sooner rather than later.

Demonstration Status: Lagoon cleanouts are common and have occurred since lagoons have been used. Companies that specialize in lagoon cleaning are found in many areas of the country.

Practice: Trickling Filters

Description: Trickling filters are currently being evaluated for use at AFOs to address the high concentrations of organic pollutants in AFO wastewater. The technology is a type of fixed-growth aerobic biological treatment process. Wastewater enters the circular reactor and is spread over media that support biological growth. The media are typically crushed rock, plastic-sheet packing, or plastic packing of various shapes. Wastewater contaminants are removed biologically.

The top surface of the media bed is exposed to sunlight, is in an aerobic state, contains microorganisms that are in a rapid growth phase, and is typically covered with algae. The lower portion of the bed is in an anaerobic state and contains microorganisms that are in a state of starvation (i.e., microorganism death exceeds the rate of reproduction). The biofilm covering the filter medium is aerobic to a depth of only 0.1 to 0.2 millimeters; the microbial film beneath the surface biofilm is anaerobic. As wastewater flows over the microbial film, organic matter is metabolized and absorbed by the film. Continuous air flow is necessary throughout the media bed to prevent complete anaerobic conditions (Viessman, 1993).

Components of a trickling filter include a rotary distributor, underdrain system, and filter medium. Untreated wastewater enters the filter through a feedpipe and flows out onto the filter media via distributor nozzles, which are located throughout the distributor. The distributor spreads the wastewater at a uniform hydraulic load per unit area on the surface of the bed. The underdrain system, typically consisting of vitrified clay blocks, carries away the treated effluent. The clay blocks have entrance holes that lead to drainage channels and permit the circulation of air through the media bed. Figure 8-9 below shows a cutaway of a typical trickling filter. Rock

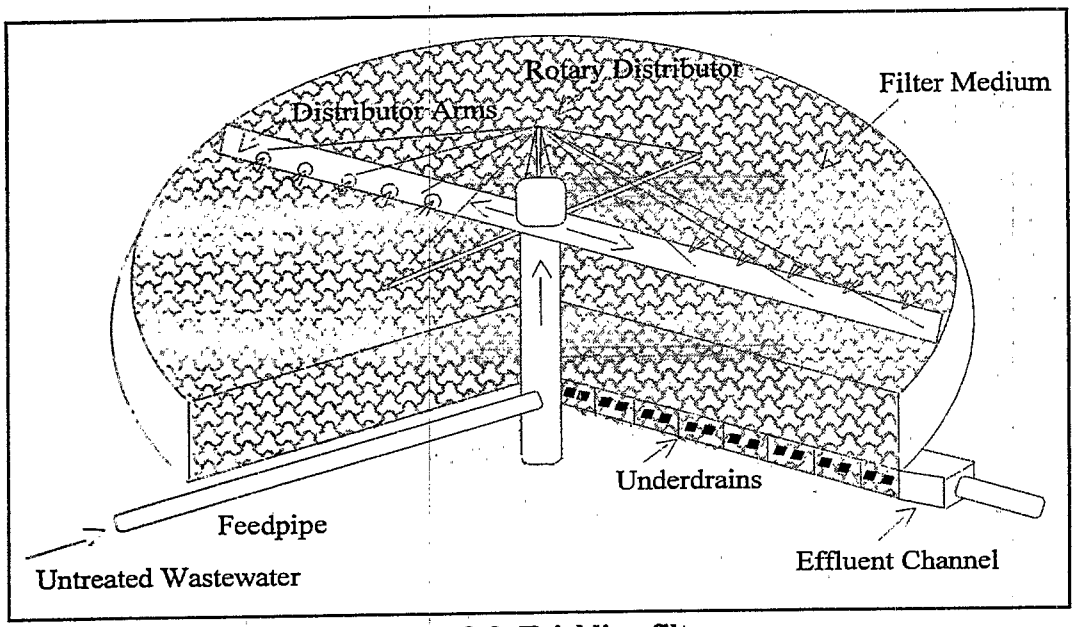

Figure 8-9. Trickling filter.

media beds can be up to 200 feet in diameter and 3 to 8 feet deep, with rock sizes ranging from 1 to 4 inches. Plastic media beds are narrower and deeper, ranging from 14 to 40 feet deep. These systems look more like towers than conventional rock-media systems. It is also common to have single- or two-stage systems for N removal. A two-stage system allows for greater flexibility because each stage can be operated independently and optimized accordingly. Flow capacity of trickling filters can range between 200 and 26,000 gallons per day; however, units can be installed in parallel to handle larger flows (AWT Environment).

Application and Performance: Traditionally, the trickling filter medium has been crushed rock or stone; however, this type of media occupies most of the volume in a filter bed, reducing the void spaces for air passage and limiting surface area for biological growth. Many trickling filters now use a chemical-resistant plastic medium because it has a greater surface area and a large percentage of free space. These synthesized media forms offer several advantages over naturally available materials, particularly in terms of surface contact area, void space, packing density, and construction flexibility (Viessman, 1993).

Although stone-media trickling filters are not as common, they are still used in shallow filters. BOD loads, expressed in terms of pounds of BOD applied per unit of volume per day, are typically 25 to 45 pounds per 1,000 ft^3 per day for single-stage stone filters and 45 to 65 pounds per 1,000 ft^3 per day for two-stage stone filters (based on the total media volume of both filters). The recommended hydraulic load ranges from 0.16 gallons per minute per ft^2 to 0.48 gallons per minute per ft^2 (Viessman, 1993).

Other shallow filters use random packing (e.g., small plastic cylinders, 3.5 x 3.5 inches), with a specific surface area of 31 to 40 ft^2/ft^3 and a void space of 91 to 94 percent. Deep filters use corrugated PVC plastic sheets that are 2 feet wide, 4 feet long, and 2 feet deep stacked on top of each other in a crisscross pattern. The specific surface area ranges from 26 to 43 ft^2/ft^3 and a void space of approximately 95 percent. The BOD loads for plastic media towers are usually 50 pounds per 1,000 ft^3 per day or greater with surface hydraulic loadings of 1 gpm/ft^2 or greater (Viessman, 1993).

A single or two-stage trickling filter can remove N through biological nitrification. The nitrification process uses oxygen and microorganisms to convert NH_3 to nitrite N, which is then converted to nitrate N by other microorganisms. Nitrate N is less toxic to fish and can be converted to N_2, which can be released to the atmosphere through denitrification, a separate anaerobic process following nitrification. Note that trickling filters are not capable of denitrifying.

A single-stage trickling filter removes BOD in the upper portion of the unit while nitrification occurs in the lower portion. A two-stage system removes BOD in the first stage while nitrification occurs in the second stage. Trickling filters do not typically remove P, but can be adapted to remove P from the wastewater effluent by chemical precipitation following BOD removal and nitrification (AWT Environment, ETI, 1998).

It is critical to have a properly designed trickling filter system. An improperly designed system can impact treatment performance and effluent quality. Media configuration, bed depth, hydraulic loading, and residence time all need to be carefully considered when designing a trickling filter system (Viessman, 1993).

In a study using municipal wastewater, the average BOD removal was greater than 90 percent and TSS removal was greater than 87 percent using a trickling filter. The average effluent BOD concentration was 13 mg/L, while the average effluent TSS concentration was 17 mg/L (AWT Environment). In another similar study that included municipal and dairy waste, BOD and TSS concentrations were slightly greater, but never exceeded 100 mg/L (Bio-Systems, 1999).

In another study using municipal wastewater and an anaerobic upflow filter prior to the trickling filter, the average effluent BOD and TSS concentrations both ranged from 5 to 10 mg/L, and the total N removal ranged from 80 to 95 percent. Pathogen reduction for this particular system is expected to be good, due to the upflow filter component. The estimated cost for this system is approximately $18,000 in annualized present day (Year 2000) costs (annualized over 20 years and not including design and permitting) (City of Austin, 2000).

Information on the reduction of pathogens, antibiotics, and metals in trickling filters is not available, but it is expected to be minimal based on engineering judgment.

Advantages and Limitations: An advantage of operating a trickling filter is that it is a relatively simple and reliable technology that can be installed in areas that do not have a lot of space for a treatment system. This technology is also effective in treating high concentrations of organics and nutrients. It can be cost-effective because it entails lower operating and maintenance costs than other biological processes, including less energy and fewer skilled operators. The wasted biomass, or sludge, can be processed and disposed of, although it contains high concentrations of nutrients. Finally, it also effectively handles and recovers from nutrient shock loads (ETI, 1998).

Disadvantages of operating a trickling filter are that additional treatment may be needed to meet stringent effluent limitations, the operation generates sludge that needs to be properly disposed of, poor effluent quality results if the system is not properly operated, and regular operator attention is needed. The system is susceptible to clogging from the biomass as well as odors and flies. The high solids content of CAFO waste would most likely require solids separation prior to treatment to also prevent clogging. Only the liquid waste may be treated in this system. In addition, a high investment cost may also prevent certain farms from installing this technology (ETI, 1998).

Operational Factors: Trickling filters are typically preceded by primary clarification for solids separation and are followed by final clarification for collection of microbiological growths that slough from the media bed. They can also be preceded by other treatment units such as septic tanks or anaerobic filters. Trickling filters effectively degrade organic pollutants, but can also be designed to remove N and P from the wastewater.

Trickling filters are relatively simple to operate, are lower in cost than other biological treatment processes, and typically operate at the temperature of the wastewater as modified by that of the air, generally within the 15 to 25°C range. A high wastewater temperature increases biological activity, but may result in odor problems. Cold wastewater (e.g., 5 to 10°C) can significantly reduce the efficiency BOD removal (Viessman, 1993).

Demonstration Status: Trickling filters are most commonly used to treat municipal wastewater, although the technology is applicable to agricultural wastewater treatment. They are best used to treat wastewaters with high organic concentrations that can be easily biodegraded. EPA was not able to locate any AFO facilities that currently operate trickling filters; however, based on the information gathered, several wastewater treatment vendors market this technology to such facilities.

Practice: Fluidized Bed Incinerators

Description: Fluidized bed incinerators (FBIs) are currently being evaluated for use at CAFOs given the high volume of manure they generate. The technology is typically used for wastewater sludge treatment (e.g., municipal sludge), but may be used for wastewater treatment. The main purpose of an FBI is to break down and remove volatile and combustible components of a waste stream and to reduce moisture. Its most prominent application to CAFO industries would be for animal waste disposal and treatment, because manure has a higher solids content than wastewater from CAFO operations.

An FBI is a vertical, cylindrical-shaped apparatus that requires media (typically sand), injected air, and an influent fuel to operate. An FBI contains three basic zones: a windbox, a sand bed, and a freeboard reactor chamber. Air enters the windbox and moves upward into the media bed through orifices called "tuyeres" at a pressure of 3 to 5 pounds per square inch. The injected air acts to fluidize the bed and to generate combustion. The term "fluidized bed" refers to the "boiling" action of the sand itself, which occurs when air is injected into the reactor. The fuel, or animal waste, directly enters the fluidized sand bed and is mixed quickly within the bed by the turbulent action. Any moisture in the animal waste evaporates quickly, and the sludge solids combust rapidly. Combustion gases and evaporated water flow upward through the freeboard area to disengage the bed material and to provide sufficient retention time to complete combustion. Gases and ash exit the bed out the top of the FBI. Exit gases may be used to preheat the injected air or may be recovered for energy. Exit ash is removed from exit gas in an air pollution device such as a venturi scrubber. Ash can either be disposed of or reused (typically as fertilizer) depending on its characteristics (Metcalf and Eddy Inc., 1991).

Prior to injection, the sand media is kept at a minimum temperature of 1300 °F and controlled at between 1400 and 1500 °F during treatment. This temperature range varies with specific design criteria. The FBI typically ranges in size from 9 to 25 feet in diameter; the media bed is typically 2.5 feet thick, when settled (Metcalf and Eddy Inc., 1991). The system has a capacity of up to 30 tons per hour (UNIDO, 2000). The combustion process is optimized by varying the animal waste

and air flow, with exit gas retention times greater than 1 second and solids retention times greater than 30 minutes (Versar, 2000). Figure 8-10 represents a typical FBI.

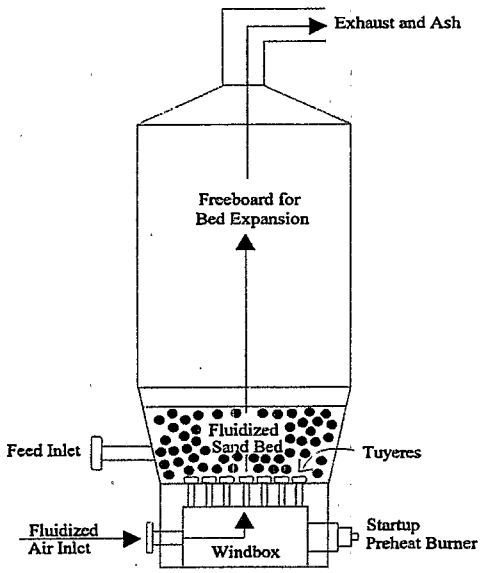

Figure 8-10. Fluidized bed incinerator.

Application and Performance: Animal waste enters the FBI and quickly combusts in the media bed. Organic constituents of the waste are burned to produce carbon dioxide and water, while volatile pollutants are evaporated and captured in the air control device. Solid material may be recycled through the system for further treatment. The ash contains many of the pollutants in the animal waste itself, although waste volume is reduced and most of the N in the waste is evaporated. The ash will still contain high levels of metals, P, and K.

The high temperature of the system typically eliminates the spread of pathogens, reducing biosecurity concerns. Similarly, any antibiotics or hormones remaining in the waste will also be broken down and reduced. Although FBIs operate at very high temperatures, they typically operate at lower temperatures than other types of incinerators, which results in lower air emissions, particularly of (NO_x) compounds and volatile organic compounds (VOCs).

Advantages and Limitations: Fluidized bed incineration is an effective and proven technology for reducing waste volume and for converting the waste to useful products (e.g., energy). Resulting ash may be used as an end-product fertilizer, or as an intermediate product used in manufacturing commercial fertilizers. Animal waste incineration eliminates aesthetic concerns (e.g., odors) as well as nuisance concerns (e.g., pest attraction) (Versar, 2000).

Although fluidized bed incineration is viewed as an efficient system, it is very sensitive to moisture content and fuel particle size. The higher the moisture content, the less efficient the system is because the moisture acts to depress the reactor temperature, thereby reducing combustion capabilities. Moisture can be reduced in animal waste by combining the waste with other biomass such as wood chips or straw. Air drying or dewatering the animal waste also reduces moisture content before treatment in the FBI. Blockages may often occur in input and output pipes triggering shut-down and maintenance (Versar, 2000).

Air emissions must also be considered when operating any type of incinerator. Organic and N compounds are easily removed from the waste; however, they are then emitted to the air, potentially creating a cross-media impact if not properly controlled. Furthermore, nutrients such as P, K, and metals typically remain in the ash and are not treated. Finally, FBIs entail high operating and maintenance costs, especially compared with other types of incinerators (Versar, 2000).

Operational Factors: As discussed above, FBIs are most sensitive to moisture content and fuel particle size. The less moist the influent fuel, the more efficient the system is. Acceptable influent moisture levels range from 15 to 20 percent. Fuel particle size should also be minimized to avoid clogging the system. Another consideration is that, depending on the metals concentrations and local regulations, the ash, if intended for disposal, may need to be handled as hazardous waste (Versar, 2000).

FBI costs depend on size and capacity. Capital costs can range from approximately $5 to $25 million for a 5-ton-per-hour and a 30-ton-per-hour FBI, respectively (UNIDO, 2000). FBIs are complex technologies and require operation by trained personnel. Because of this, FBIs are more economical for medium to large facilities, or when operated in cooperation with several businesses that are able to provide fuel sources. Therefore, FBIs may not be a cost-effective waste management technique for an individual farm, but, when operated on a larger scale, they may prove to be cost-effective. Capital and annual operating costs are generally higher for FBIs than for other types of incinerators because of the sensitive design parameters (e.g., moisture content and solid particle size). On the other hand, the system operates efficiently, and energy can usually be recovered from the process and may be sold to another party or used to reduce on-site operating costs.

Demonstration Status: ERG is not aware of any U.S. feedlots currently operating FBIs or sending animal waste to larger-scale municipal or private FBIs. According to information gathered for this program, FBIs are more commonly used in Europe and in Japan to treat animal waste, although some U.S. companies using waste-to-energy technology may be operating FBIs using animal waste with other fuel sources. FBIs are most commonly used in the United States to manage municipal sludge.

In a study done to assess the engineering and economic feasibility of using poultry litter as a fuel to generate electric power, researchers found that combusting poultry litter (combined with wood chips) can be an effective waste-to-energy technology (Versar, 2000). Although the study did not specifically evaluate fluidized bed incineration, the application and results are expected to be similar. The study found litter samples to have a heat content between 4,500 and 6,400 BTU per pound at approximately 16 percent moisture, which is a slightly higher content than the wood chips alone. The ash content of the litter was reported to be between 9 and 20 percent, which is significantly higher than the wood chips alone. However, although the air emissions data in this study were considered preliminary, they showed that the facility could trigger air permitting requirements. The study also found that poultry litter ash may be classified as hazardous waste under individual state regulations (Versar, 2000).

Practice: Constructed Wetlands

Description: Constructed wetlands (CWs) can be an important tool in the management of animal waste by providing effective wastewater treatment in terms of substantial removal of suspended solids, BOD_5, fecal coliform, and nutrients such as N and P. The treatment process in CWs

generates an effluent of better quality that can be applied on agricultural land or discharged to surface waters (CH2M Hill, 1997). Wastewater treatment in CWs occurs by a combination of mechanisms including biochemical conversions, settling/filtration, litter accumulation, and volatilization. Removal of pollutants in CWs is facilitated by shallow water depth (which maximizes the sediment-water interface), slow flow rate (which enhances settling), high productivity, and the presence of aerobic and anaerobic environments.

Wetland media (soil, gravel) and vegetation provide a large surface area that promotes microbial growth. Biochemical conversion of various chemical compounds through microbial activity is the main factor in the wetland treatment process. Through microbial activities, Org-N is converted to NH_3 (ammonification), which is used by plants as a nutrient; NH_3 is converted to nitrate and nitrite (nitrification), which is used by microbes and some plants for growth; and N is volatilized (denitrification) and is lost to the atmosphere (CH2M Hill, 1997). NH_3 may be removed through volatilization, uptake by plants and microbes, or oxidized to nitrate. Volatilization of NH_3 in CWs appears to be the most significant mechanism for N removal for animal waste treatment (Payne Engineering and CH2M Hill, 1997).

P removal is achieved mainly by fixation by algae and bacteria, plant uptake, and (Cronk, 1996) when oxidizing conditions promote the complexing of nutrients with iron and aluminum hydroxides (Richardson, 1985). Plant uptake of P is only a short-term sink because plant P is rapidly released after the death of plant tissues (Payne Engineering and CH2M Hill, 1997). Fixation of P by microbes ultimately results in the storage of P in the bottom sediments (Corbitt and Bowen, 1994), yet they may become saturated with P, resulting in an export of excess P (Richardson, 1985).

Rooted emergent aquatic plants are the dominant life form in wetlands (Brix, 1993) and are the only aquatic plants recommended for planting in CWs used for animal waste treatment (Payne Engineering and CH2M Hill, 1997). These aquatic plants have specialized structures that allow air to move in and out as well as through the length of the plant, have roots that allow adsorption of gases and nutrients directly from the water column, and are physiologically tolerant to chemical products of an anaerobic environment (Brix, 1993). For these reasons, emergent aquatic plants can survive and thrive in wetland environments. The most common emergent aquatic plants used in CWs for animal waste treatment are cattail (*Typha* spp.), bulrush (*Scirpus* spp.), and common reed (*Phragmites* spp.) (CH2M Hill and Payne Engineering, 1997).

Roles of emergent aquatic plants in the wastewater treatment process include the following:(1) providing a medium for microbial growth and a source of reduced carbon for microbial growth, (2) facilitating nitrification-denitrification reactions, (3) assimilating nutrients into their tissue, (4) facilitating entrapment of solids and breakdown of organic solids, and (5) regulating water temperature by shading the water (Payne Engineering and CH2M Hill, 1997). The vascular tissues of these plants move oxygen from overlying water to the rhizosphere and thus provide aerobic microsites (within the anaerobic zone) in the rhizosphere for the degradation of organic matter and growth of nitrifying bacteria (Brix, 1993). Dissolved nitrates, from nitrification, can then diffuse into the surrounding anaerobic zone where denitrification occurs. Furthermore,

wetland macrophytes remove small amounts (<5 percent) (Hammer, 1992) of nutrients, for nutritional purposes, by direct assimilation into their tissue. Removal of nutrients, however, increases slightly in CW systems that incorporate periodic harvesting of plants (Hammer, 1992) or may be considerably higher (67 percent) in specially designed systems that maximize influent-root zone contact (Breen, 1990).

The two principal types of CWs for treating wastewater are surface flow (SF) and subsurface flow (SSF) systems. The SF systems are shallow basins or channels, carefully graded to ensure uniform flow, planted with emergent vegetation, and through which water flows over the surface at relatively shallow (~30 cm) depths. The SSF systems consist of a trench or bed with a barrier to prevent seepage, and planted emergent vegetation growing in a permeable media (soil, gravel) designed such that the wastewater flows horizontally through the media with no open surface flow. The base media and plant roots provide large surface areas for biofilm growth and thus, functions somewhat like a rock trickling filter at a municipal wastewater treatment plant (Payne Engineering and CH2M Hill, 1997).

Some authors also refer to the SF system as the free water surface system, while the SSF type is also referred to as the vegetated rock-reed filter, vegetated submerged bed system, gravel-bed system, and root-zone system. Compared with SSF systems, the SF wetlands are capable of receiving a wider range of wastewater loads, have lower construction costs, and are relatively easy to manage (Payne Engineering and CH2M Hill, 1997). Additionally, mass removal of NH_3-N, the major form of N in animal wastewater (CH2M Hill and Payne Engineering, 1997), in SSF wetlands is significantly less compared with the SF type because there is less time and oxygen to support necessary nitrification reactions (USEPA, 1993). For these reasons, the SF system is the most commonly used wetland type for treating animal waste (Payne Engineering and CH2M Hill, 1997) and is the only one recommended for animal waste treatment by the USDA NRCS (USDA NRCS, 1991).

Application and Performance: A database, developed by CH2M Hill and Payne Engineering (1997), containing design, operational, and monitoring information from 48 livestock CW systems (in the United States and Canada), indicates that CWs have been and continue to be used successfully to treat animal waste including wastewater from dairy, cattle, swine, and poultry operations. The majority of CW sites included in the database have begun operations since 1992. SF systems constitute 84 percent of cells in the database, and the remainder consists of SSF or other wetland systems. Cattail, bulrush, and reed, in that order, dominate the aquatic vegetation planted in the surveyed CWs.

Typically, effluent from a CW treating animal waste is stored in a waste storage lagoon. Final dispersal occurs through irrigation to cropland and pastureland, though the potential for direct discharge of effluent exists. Direct discharge may, however, require a permit under the EPA's NPDES.

A performance summary of CWs used for treating animal waste indicates a substantial reduction of TSS (53 to 81 percent), fecal coliform (92 percent), BOD_5 (59 to 80 percent), NH_3-N (46 to 60

percent), and N (44 to 63 percent) for wastewater from cattle feeding, dairy, and swine operations (CH2M Hill and Payne Engineering, 1997). In a study by Hammer et al. (1993), swine effluent was treated in five CW cells, located below lagoons, that were equipped with piping that provided a control for variable application rates and water level control within each cell. Performance data indicate notable (70 to 90 percent) pollutant removal rates and reliable treatment of swine lagoon effluent to acceptable wastewater treatment standards for BOD_5, TSS, N, and P during the first year of the reported study.

Removal efficiency of N is variable depending on the system design, retention time, and oxygen supply (Bastian and Hammer, 1993). Low availability of oxygen can limit nitrification, whereas a lack of a readily available carbon source may limit denitrification (Corbitt and Bowen, 1994). Fecal coliform levels are significantly reduced (>90 percent) by sedimentation, filtration, exposure to sunlight, and burial within sediments (Gersberg et al., 1990). Compared with dairy systems, higher reduction of pollutants have been reported for swine wastewater treatment in CWs, probably because loading rates have tended to be lower at swine operations (Cronk, 1996).

Advantages and Limitations: In addition to treating wastewater and generating water of better quality, CWs provide ancillary benefits such as serving as wildlife habitat, enhancing the aesthetic value of an area, and providing operational benefits to farm operators and their neighbors (CH2M Hill, 1997). CWs, in contrast to natural wetlands, can be built with a defined (desired) composition of substrate (soil, gravel) and type of vegetation and, above all, offer a degree of control over the hydraulic pathways and retention times (Brix, 1993). An SF system is less expensive to construct than an SSF system, the major cost difference being the expense of procuring and transporting the rock or gravel media (USEPA, 1993). An SSF system, however, has the advantage of presenting an odor- and insect-free environment to local residents.

Major limitations include a need for relatively large, flat land areas for operation (Hammer, 1993), a possible decrease in SF system performance during winter in temperate regions (Brix, 1993), and a reduction in functional sustainability of the SSF systems if the pore spaces become clogged (Tanner et al., 1998). Other limitations include (1) an inadequacy of current designs of SF systems to store flood waters and use stored water to supplement low stream flows in dry conditions, and (2) potential pest problems and consequent human health problems from improperly designed or operated SF systems (Hammer, 1993). Moreover, because CW technology for animal waste treatment is not well established, long-term status and effects, including accumulation of elemental concentrations to toxic levels, are poorly documented. Further research is needed to better understand the nutrient removal mechanisms in CWs so that improved designs and operating criteria can be developed.

Operational Factors: Because untreated wastewater from AFOs has high concentrations of solids, organics, and nutrients that would kill most wetland vegetation, wastewater from AFOs is typically pretreated in a waste treatment lagoon or settling pond prior to discharge to a CW (Payne Engineering and CH2M Hill, 1997). Incorporating a waste treatment lagoon in the treatment process reduces concentrations of BOD_5 and solids considerably (>50 percent) and provides storage capacity for seasonal application to the wetlands (Hammer, 1993).

Figure 8-11 shows the typical components and a typical treatment sequence of a CW. Constructed wetlands may be built with cells that are parallel or in a series. Construction of cells needs to be determined by the overall topography as well as by the drainage slope of individual cells to maintain shallow water depth for the wetland plants (CH2M Hill and Payne Engineering, 1997). The land slope should be small (<0.5 percent), and the length-to-width ratios should be between 1:1 and 10:1, with an ideal ratio being 4:1 (USDA NRCS, 1991). Data for the surveyed CWs, reported by CH2M Hill and Payne Engineering (1997), indicate the following average design conditions: water depth of 38 cm; bottom slope of 0.7 percent; length-to-width ratio of 6.5:1; hydraulic loading rate of 4.7 cm/day; and a size of 0.03 hectare.

Design criteria for CWs for animal waste treatment are described in USDA NRCS (1991), including methods to determine the surface area of a proposed wetland. The NRCS *Presumptive Method* is based on an estimate of BOD_5 loss in the pretreatment process, which is used to calculate BOD_5 concentration in the pretreatment effluent. Size of the wetland is then determined based on a loading rate of 73 kg BOD_5/ha/day that would achieve a target effluent of <30 mg/L of BOD_5, <30 mg/L TSS, and <10 mg/L NH_3-N. The NRCS *Field Test Method* is based on

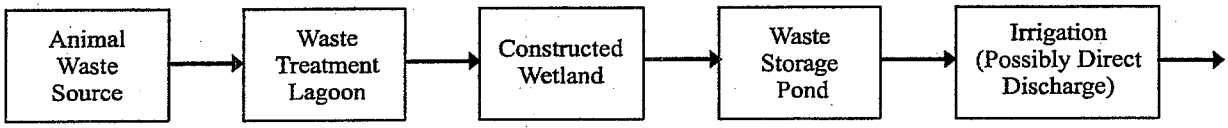

Figure 8-11. Schematic of typical treatment sequence involving a constructed wetland.

laboratory data for average influent BOD_5 concentration to the CW. The influent BOD_5 concentration, together with average temperature data, is used to determine the hydraulic residence time needed to obtain a desired effluent BOD_5 concentration.

Advances in research and technology of CW during the 1990s have provided additional information to allow modification of the USDA NRCS (1991) methods. CH2M Hill and Payne Engineering (1997) developed the *Modified Presumptive USDA-NRCS Method*, which takes into account pollutant mass loading and volume of water applied, and relates the results to a data table developed from existing CWs for animal waste treatment. The *Field Test Method #2* was also proposed by CH2M Hill and Payne Engineering (1997) based on the areal loading equation developed by Kadlec and Knight (1996), which includes rate constants specific to concentrated animal waste.

Operation and maintenance requirements for CWs include maintenance of water level in the wetland cells, monitoring water quality of influent and effluent, regular inspection of water conveyance and control structures to ensure proper flow, and maintenance of the embankments to avoid damage from rodents.

Demonstration Status: CWs have been demonstrated successfully as a management technology treatment for swine waste (Maddox and Kinglsey, 1990; Hammer et al., 1993) and dairy waste (Chen et al., 1995; Tanner et al., 1995; Schaafsma et al., 2000), and have been relatively less

successful in the treatment of poultry waste (Hill and Rogers, 1997). Results of several other successful case studies, performed in several regions of North America, are reported in DuBowy and Reaves (1994), DuBowy (1996), and Payne Engineering and CH2M Hill (1997).

Practice: Vegetated Filter Strips

Description: Vegetated filter strips are an overland wastewater treatment system. They consist of strips of land located along a carefully graded and densely vegetated slope that is not used for crops or pasture. The purpose of a vegetated filter strip is to reduce the nutrient and solids content of wastewater and runoff from AFOs. The filters are designed with adequate length and limited flow velocity to promote filtration, deposition, infiltration, absorption, adsorption, decomposition, and volatilization of contaminants. These filters consist of three parts: a sediment basin, a flow distribution device, and a filter strip area (Harner, 2000).

The wastewater is distributed evenly along the width of a slope in alternating application and drying periods. The wastewater may be applied to the slope by means of sprinklers, sprays, or gated, slotted, or perforated pipe. As the wastewater flows down the slope, suspended solids are deposited and some nutrients are absorbed into the vegetation. The effluent from the system is collected in a channel at the bottom of the slope and then discharged (see Figure 8-12).

Application and Performance: The design of a vegetated filter strip is typically based on the BOD concentration of the wastewater (Metcalf and Eddy, 1991). The total treatment area required is calculated from the hydraulic loading rate, assumed length of slope (generally 100 to 150 feet), and an operating cycle. The operating cycle and application rate can be varied to optimize the system. An operating cycle of 1 day is typical, with 8 to 12 hours of application and

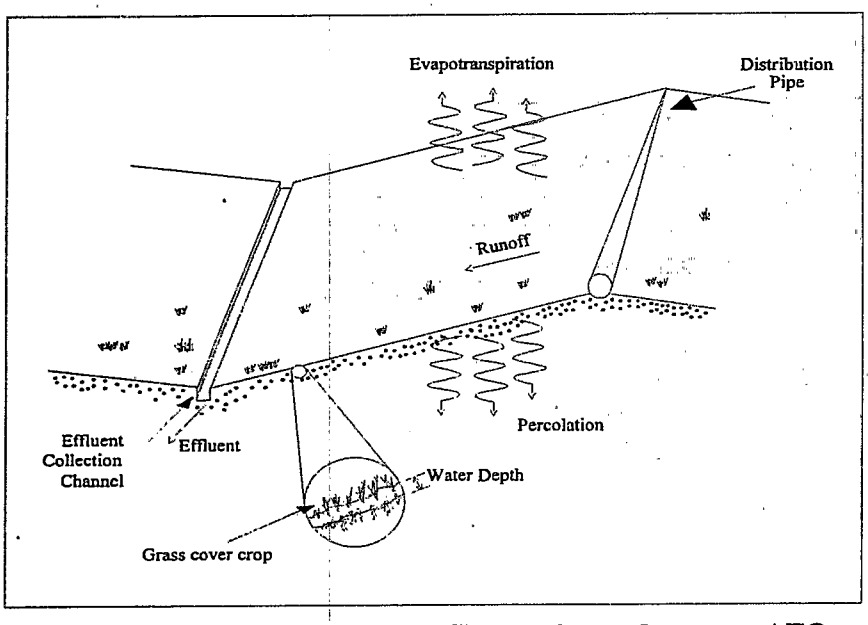

Figure 8-12. Schematic of a vegetated filter strip used to treat AFO wastes.

12 to 16 hours of drying. NH_3 removal from primary effluent can be expected to vary inversely with the ratio of application period to drying period. A properly designed system can remove up to 95 percent of NH_3. The application rate is critical for considering BOD removal because it is important to maintain aerobic conditions that are required for microbial decomposition. Too high an application rate can create anaerobic conditions because the oxygen transfer through natural aeration from the atmosphere will be insufficient.

The vegetative cover should be dense in growth, such as a grass, and well suited to the climatic conditions. The vegetation must be dense enough to slow the wastewater flow to allow adequate treatment and prevent erosion. Consideration should also be given to the nutrient uptake potential of the vegetation to maximize nutrient removal rates.

Proper grading is also critical to the design of a vegetated filter strip to prevent the channeling of wastewater and allow for efficient treatment. Sites with an existing slope of 2 to 6 percent are best suited for vegetated filter strips to keep regrading costs to a minimum without causing water to pond. The shape and area of the field being drained changes the filter strips effectiveness, as does the method of installation (Franti, 1997). It is best for runoff from areas of clean storm water to avoid passing through the filter. Allowing storm water into the filter strip could overwhelm the system causing inadequate filtration on the wastewater (Harner, 2000).

Vegetated filter strips are also best suited to sites that have low permeability soils to prevent wastewater from infiltrating the subsurface. In areas where soils are relatively permeable, it may be necessary to amend the existing soils or install an impermeable barrier.

Vegetated filter strips can be unsuccessful if the plants are not absorbing enough nutrients. Plants must be healthy, dense, swift growing, have fibrous roots to fight erosion, and be perennials. The plants must also endure being waterlogged and grow well in the spring and fall. The most effective type of plants to use are sod-forming grasses (Harner, 2000).

A study conducted to determine the effectiveness of milkhouse wastewater treatment using a vegetative filter strip at a dairy farm in Vermont (Clausen and Schwer, 1989) found that removals of TSS, total P, and TKN were 92 percent, 86 percent, and 83 percent, respectively. However, the total P concentration in the effluent was more than 100 times greater than the average P concentration of streams draining agricultural areas in the northeast. Moreover, only 2.5 percent of the total input of P, and 15 percent of the input of N were removed in the vegetation (Nebraska Cooperative Extension, 1997).

The EPA Chesapeake Bay Program studied the use of vegetative filter strips to reduce agricultural nonpoint source pollutant inputs to the bay (Dillaha et al., 1988). A series of nine experimental field plots were constructed, each containing a simulated feedlot source area and a vegetated filter strip of known length. A rainfall simulator was used to produce runoff, which was collected from the base of each vegetated filter strip. Analysis indicated that 81 to 91 percent of incoming sediment, 58 to 69 percent of the applied P, and 64 to 74 percent of the applied N were removed.

Advantages and Limitations: Compared with many treatment technologies, vegetated filter strips effectively reduce the nutrient and solids concentration of wastewater with relatively low construction and maintenance costs. This is particularly true for sites where available land is well suited for such a system.

However, to effectively treat high volumes of wastewater, such as from a milking parlor, excessive acreage may be required. In addition, because overland flow systems such as vegetated filter strips depend on microbiological activity at or near the surface of the soil, cold weather adversely affects their performance. Winter use of this in colder climates will therefore be limited and an appropriate amount of wastewater storage will be required. Storage is recommended when the average daily temperature is below 32 °F. The filter's performance is limited by the level and duration of rainfall and the type of vegetation (EPA, 2001).

Operational Factors: Maintenance of a vegetated filter strip consists of periodic removal of the vegetative growth, which contains many of the nutrients. The biomass has various potential uses—as forage, fiber, or mulch, for example. Sediment accumulation should be inspected (Harner, 2000). In addition, the slope needs to be periodically inspected and regraded to ensure a level flow surface and prevent channeling and erosion. When sparse plant coverage is observed, it should be reseeded. Undesirable plants in the filter should be managed (Harner, 2000).

Demonstration Status: Vegetated filter strips have been used to treat milkhouse wastewater in New York and North Carolina. They have also been used to treat a variety of other wastes including feedlot runoff.

Practice: Composting—Aerobic Treatment of Solids

Description: Composting is the aerobic biological decomposition of organic matter. It is a natural process that is enhanced and accelerated by the mixing of organic waste with other ingredients in a prescribed manner for optimum microbial growth. Composting converts an organic waste material into a stable organic product by converting N from the unstable NH_3 form to a more stable organic form. The end product is safer to use than raw organic material and one that improves soil fertility, tilth, and water holding capacity. In addition, composting reduces the bulk of organic material to be spread, improves its handling properties, reduces odor, reduces fly and other vector problems, and can destroy weed seeds and pathogens. There are three basic methods of composting: windrow, static pile, and in-vessel.

Windrow composting consists of placing a mixture of raw organic materials in long, narrow piles or windrows, which are agitated or turned on a regular basis to facilitate biological stabilization. Windrows aerate primarily by natural or passive air movement (convection and gaseous diffusion). Windrow composting is suitable for large quantities of organic material. For composting dense materials like manure mixtures, windrows are usually no more than 3 feet high and 10 to 20 feet wide. The equipment used for turning, ranging from a front-end loader to an automatic mechanical turner, determines the size, shape, and spacing of the windrows.

The **static pile method** consists of mixing the compost material and then stacking the mix on perforated plastic pipe or tubing through which air is drawn or forced. Forcing air (by suction or positive pressure) through the compost pile may not be necessary with small compost piles that are highly porous or with a mix that is stacked in layers with highly porous material. If layering is not practiced, the materials to be composted must be thoroughly blended before they are placed in a pile. The exterior of the pile is typically insulated with finished compost or other material. The dimensions of the static pile are limited by the amount of aeration that can be supplied by the blowers and by the stacking characteristics of the waste. The pile height generally ranges from 8 to 15 feet, and the width is usually twice the height. The spacing between individual piles is usually equal to about half the height.

The **in-vessel method** involves the mixing of manure or other organic waste with a bulking agent in a reactor, building, container, or vessel, and may involve the addition of a controlled amount of air over a specific detention time. This method has the potential to provide a high level of process control because moisture, aeration, and temperature can be maintained in some of the more sophisticated units (USDA, 1999).

Application and Performance: Composting is an accepted process for the biological stabilization of the organic material in waste, providing an alternative to long-term liquid and semisolid manure storage. It turns waste organic material (dead poultry, manure, garbage, and so forth) into a resource that can be used as a soil amendment and fertilizer substitute. Proper composting minimizes nutrient loss while killing pathogenic organisms by process generated heat. For example, two waste products from a municipal and a dairy source were composted in the lab under controlled temperature and air flow rates (Hall and Aneshansley, 1997). Researchers found that maintaining high and constant temperatures destroys pathogens and accelerates decomposition.

In general, only manure from confined animals is available for composting. Usually, manure must be dewatered or mixed with sawdust or wood chips to lower the moisture content, which may range from 60 to 85 percent. The presence of plant nutrients such as N, P, and K; the organic content; and the absence of significant levels of heavy metals makes animal manure a very attractive raw material for producing compost. In-vessel composting has been conducted successfully with dairy cattle manure, swine manure, horse manure, and poultry and turkey litter.

Advantages and Limitations: Compost and manure are both good soil conditioners that contain some fertilizer value. On a growing number of farms, however, manure is considered more of a liability than an asset. Animal waste generators may find themselves with surpluses of manure in the winter, yet lacking manure by spring planting. Odor complaints associated with manure are common in populated areas. Other concerns include polluted runoff from manure spread on frozen ground and nitrate contamination of wells.

Composting converts the nutrients in manure into forms that are less likely to leach into ground water or be carried away by surface runoff. Compost releases its nutrients more slowly than

commercial fertilizers, so it does not burn crops and can feed them over a longer period of time. The nutrient value of manure was demonstrated in a study in which five combinations of composted cattle feedyard manure and liquid phosphate were applied to provide 100 percent of the P requirement for corn (Auvermann and Marek, 1998). Five replicates were tested for each treatment. No significant difference was determined between corn yields in treatment-by-treatment comparisons, indicating that composted feedlot manure may be an adequate substitute for chemical fertilizers.

A well-managed composting operation generates few odors and flies, and the heat generated by the composting process reduces the number of weed seeds contained in the manure. Composting also reduces the weight, moisture content, and volatility of manure, making it easier to handle and store. Because of its storage qualities, compost can be held for application at convenient times of the year. Composted manure and composted manure solids can also be used as bedding material for livestock.

Different types of in-house, deep litter manure management systems were tested at a 100,000-chicken high-rise layer operation in Georgia (Thompson et al., 1998). Composting was conducted using raw manure, a manure and leaf mixture, and manure and wood chip mixture. The in-house composting was found to reduce the weight and volume of wastes more efficiently than conventional methods of stacking manure under the house. Wood chip and leaf manure both had lower moisture content and more concentrated nutrients compared with the raw manure.

Disposal is less of a problem for compost than for manure because there is usually someone willing to take the compost. One of the strongest incentives for composting is that a market exists for the product, especially in populated areas. Potential buyers include home gardeners, landscapers, vegetable farmers, garden centers, turf growers, golf courses, and ornamental crop producers. Bulk compost prices range from $7 to $50 per cubic yard, depending on the local market, compost quality, and the raw materials used.

Countering these advantages are several limitations. Managing and maintaining a composting operation takes time and money, and compost windrows and storage facilities for raw materials can take land, and possibly building space, away from other farming activities. When processing only small volumes of farm wastes, the equipment needed is probably already available on the farm, but composting may become a very capital- and labor-intensive task for larger operations. Farmers might need to invest in special composting equipment, which can cost anywhere from $7,000 to more than $100,000. The main equipment needed for composting on a moderate to large scale is machinery to construct, mix, and move material in a compost pile or windrow. A front-end loader and truck may be all that is required. Other equipment, such as chipping or shredding equipment, a windrow turner, screening equipment, aeration equipment, and a composting thermometer or temperature probe, might be needed as well.

Although the end product of composting is odor-free, the raw materials used to make compost may not be. Even the compost piles themselves, if not maintained properly, can become malodorous. Cold weather slows the composting process by lowering the temperature of the

composting material. Heavy precipitation adds water to the composting mix, and snow and mud can limit access to windrows.

There is also some ambiguity as to whether manure or compost provides crops with more N. Compost can contain less than half the N of fresh manure; however, the N in manure is less stable than that in compost. Farmers must apply more compost than manure to farmland to achieve the same results because compost nutrients are released very slowly. Generally, less than 15 percent of the N in compost is released in the first year.

Last, although compost is a salable product, selling compost involves marketing. This means searching out potential buyers, advertising, packaging, managing inventory, matching the product to the customer's desires, and maintaining consistent product quality.

In addition to these general limitations, there are specific limitations associated with composting different types of animal manure. Wastes containing excessively high water content, such as poultry manure from egg-laying operations and wet manure from free-stall dairy CAFOs, may require additional processing prior to composting. The conditions for optimal composting (see Operational Factors below for greater detail) are not always met with these wastes; for example, the water content is too high (usually greater than 70 percent), the biomass is poorly aerated, and the (Carbon:Nitrogen) ratio is often less than 15:1. In these cases, bulking agents such as wood chips or similar wood products are added to make the mix more suitable for efficient composting, but bulking agents must be purchased if not readily available on the farm. Table 8-17 summarizes some of the key advantages and disadvantages of composting.

Operational Factors: Because composting is a biological process, environmental factors influence organism activity, thus determining the speed of decomposition and the length of the composting cycle. The composting period typically lasts from 3 to 8 weeks for conventional composting methods under normal operating conditions. Users of some highly controlled mechanical systems claim to produce compost in as little as 1 week. The length of time depends upon many factors, including the materials used, temperature, moisture, frequency of aeration, and ultimate use of the material. Conditions that slow the process include lack of moisture, a high C:N ratio, cold weather, infrequent or insufficient aeration, and large or woody materials. A month-long "curing" period usually follows the active composting stage. Curing continues to stabilize the compost but at a much slower pace. At this stage, the compost can be stockpiled without turning or aeration and without the fear of odor problems (Rynk, 2000).

The characteristics of the raw organic material are the most important factors determining the quality of compost, including moisture content, C:N ratio, aeration, material particle size, and temperature. Acceptable and preferred ranges for nutrient balance (C:N ratio), moisture content, pH, and bulk density are provided in Table 8-18 (NREAS, 1992). Additional factors considered when formulating a raw organic material recipe are degradability, odor potential, and cleanness. For example, swine manure is very odorous and should not be composted on locations prone to odor complaints. Cleanness refers to the degree of contamination from unwanted materials (glass

and heavy metals), chemicals (pesticides), and organisms (human pathogens). If the compost is to be sold off site, the raw material content will greatly affect its market value.

Table 8-17. Advantages and Disadvantages of Composting.

Advantages of Composting	Disadvantages of Composting
Compost is an excellent soil conditioner.	Composting is labor and management intensive.
Compost is a salable product.	Selling compost involves marketing costs (advertising, packaging, management, customer service, and so forth).
Compost reduces the weight, moisture content, and activity of manure, making it easier to handle and store.	The composting site, raw materials storage, and compost storage require a large land area.
Composting converts the N content of manure into a more stable organic form. Manure that has been composted provides a better C:N ration in the soil, contains fewer weed seeds, and poses a lower risk of pollution and nuisance complaints (due to less odor and fewer flies).	Nutrients in compost are in complex form and, therefore, need to be mineralized for plant intake; thus a greater volume of compost is needed to meet crop demands.
Composting kills pathogens.	Effectiveness is weather dependent.
Compost is a suitable bedding substitute.	Large operations require expensive equipment.
Land-applied compost has proven to suppress soil-borne plant diseases without the use of chemical controls.	Odors can be a recurring problem.
Some farmers have begun accepting payment (referred to as "tipping fees") to compost off-site wastes.	Acceptance of off-site organic wastes may result in the operation being classified as commercial and increase compliance costs under zoning and environmental regulations.

Table 8-18. Desired Characteristics of Raw Material Mixes.

Characteristic	Reasonable Range	Preferred Range
C:N Ratio	20:1–40:1	25:–30:1
Moisture Content	40–65 percent	50–60 percent
pH	5.5–9	6.5–8.5
Bulk Density (lbs/y^3)	Less than 1,100	No preferred range

Source: NREAS, 1992.

The optimum **moisture content** for composting varies with particle size and aeration. At high moisture content, voids fill with liquids and aeration is hindered. Low moisture levels, on the other hand, retard or stop microbial activity, although some composting occurs with moisture as low as 25 percent. Depending on the raw materials, there is ultimately a 30 to 60 percent

reduction in volume of the compost material, much of it due to water loss. If the water content falls below 40 to 50 percent, water should be added and mixed into the composting feedstocks. Warm weather enhances water loss from compost windrows by surface evaporation. Increased turning also results in a higher evaporation rate. This can be an advantage if a drier compost is desired, but if the evaporation rate becomes too high, water should be added to reduce potential fire hazards.

Periods of high rainfall can also be a problem for windrow composting. Windrows usually absorb water from normal rainfall or snow without saturating the materials. If the windrows become wetter than desired, more turnings are required to evaporate the added moisture. Rain can also produce muddy conditions, making it difficult to operate turning equipment. Snow can halt operation altogether until plowed from equipment paths. In addition, puddles and standing water can lead to anaerobic conditions at the base of a windrow. It is important that the composting site has adequate drainage to compensate for periods of high rainfall.

C and N serve as nutrients for the microorganisms, and for efficient composting they should be available in the right balance. A good **C:N ratio** falls between 25:1 and 35:1, although recommendations vary based upon site-specific conditions. For example, a study by Virginia Polytechnic Institute and State University concluded that the best combination of straw and raw swine manure for composting has a C:N ratio of 16:1 and a moisture level of 50 to 70 percent (Collins and Parson, 1993). Above the optimum range of C:N ratio, the materials break down at a slower rate, while a lower ratio results in excess N loss. For example, a study of poultry litter composting as a function of the C:N ratio and the pH of the starting materials showed that NH_3 emissions decreased substantially as the C:N ratio increased through addition of short paper fiber (C:N ratio(> 200:1) to broiler litter (Ekinci et al., 1998). As composting progresses, the C:N ratio will fall gradually because the readily compostable carbon is metabolized by microorganisms and the N is converted to nitrate and organic forms.

In animal manure, the C:N ratio is usually 10:1 to 15:1. The C:N ratios for different manures vary: poultry litter 10:1, layer manure 5:1, cattle feedlot manure 13:1, dairy manure 18:1, swine feedlot manure 3:1, and horse stable manure 25:1. Bulking materials can be added to increase the C:N ratio in the compost pile. Typical bulking materials include grass clippings (C:N ratio of 12:1 to 25:1), hay (15:1 to 32:1), oak leaves (50:1), shrub and tree trimmings (50:1 to 70:1), straw, cornhusks, and cobs (50:1 to 100:1), pine needles (60:1 to 100:1), sawdust (150:1 to 700:1), wood chips (500:1 to 600:1), or newspaper (400:1 to 850:1). For example, dairy manure is a good substrate for composting because it breaks down quickly and supplies the microorganisms with most of the required nutrients, but it is also N-rich, excessively wet, and has a C:N ratio ranging from 12:1 to 18:1. Moisture content varies from about 75 percent for manure collected from stanchion barns to about 85 percent from free-stall operations, with the variability determined primarily by the amount of bedding used. To make dairy manure more suitable for composting, it must be mixed with bulking agents that can be easily incorporated into the composting mix by using them as bedding.

The feasibility of using sawdust and chopped fescue hay as a low-cost waste carbon source to compost with separated swine manure solids was investigated using 21-liter vessels and bin composting units (Hoehne et al., 1998). Manure and fescue hay produced the lowest C:N ratio in both small and large composting units. Temperature trends were used to indicate biological activity. Composting manure with a carbon source was recommended because the product was easy to transport, appropriate for transport through residential areas, and odor-stable, even though composting is labor intensive.

The rate of air exchange and effectiveness of aeration of windrows depends on the porosity of the windrow. For example, a wet, dense windrow containing manure is less porous than a windrow of leaves. Windrows that are too large may result in anaerobic zones occurring near the center and causing odors when the windrow is turned. Periodic turning of window compost piles exposes the decomposing material to the air and keeps temperatures from getting too high (exceeding 170 °F). The most important effect of turning is rebuilding the windrow's porosity. Turning fluffs up the windrow and restores pore spaces lost from decomposition and settling, thereby restoring oxygen within the pore spaces for microorganisms and improving passive air exchange. Turning also exchanges the material at the surface with material in the interior. The materials compost evenly and, as a result, more weed seeds, pathogens, and fly larvae are destroyed by the high temperatures. The minimum turning frequency varies from 2 to 10 days, depending on the type of mix, volume, and ambient air temperature. As the compost ages, the frequency of turning can be reduced.

A study in Ohio measured NH_3 concentrations from dairy manure and rice hulls composted with various aeration rates (Hong et al., 1997). Temperature and NH_3 concentrations peaked 48 days after aeration begins and then declined steadily, leveling off after 150 hours. The effect of intermittent aeration on composting swine waste was studied to determine changes in NH_3 emissions and dry matter loss (Hong et al., 1998). Continuous and intermittent aeration treatments were tested on composting hog manure amended with sawdust in pilot-scale 200-liter vessels. NH_3 emissions were 39 percent lower from the intermittent aeration treatments, and N losses as NH_3-N were 26 percent lower for continuous aeration and 14 percent lower for intermittent aeration. Dry solids loss and other physicochemical properties were similar between the two treatments. It was concluded that intermittent aeration may be a practical method of reducing N loss and NH_3 emissions when composting swine manure with sawdust.

Smaller particle size provides greater surface area and more access for the degrading organisms. It may be necessary to reduce by grinding the particle size of some material such as corn stalks. Windrow turning blends raw materials and breaks up particles into smaller pieces, thus accelerating biodegredation through increased surface area.

Heat produced during the composting process raises the temperature of the composting materials. Because the heat produced is directly related to the biological activity, temperature is the primary gauge of the composting process. During the first few days of composting, pile temperatures increase to between 104 and 158° F. This range enhances the growth and activity of the microorganisms. In addition, temperatures above 131° F kill most pathogens, fly larvae, and

weed seeds. The high temperature might be maintained for several days, until the microorganisms begin to deplete their food source or until moisture conditions become less than optimal. Mixing the composting feedstock brings more undecomposed food into contact with the microorganisms, replenishing their energy supply. Once the optimum moisture level is restored and the feedstocks have been remixed, the temperature increases again. After the readily decomposable material is depleted, the compost pile no longer heats upon remixing. The temperature continues to drop to ambient, and only very slow decomposition continues.

Although composting can be accomplished year-round, seasonal and weather variations often require operational adjustments. This is especially true for windrow composting. Cold weather can slow the composting process by increasing the heat loss from piles and windrows. The lower temperatures reduce the microbial activity, which decreases the amount of heat generated. To compensate for cold weather, windrows should be large enough to generate more heat than they lose to the environment, but not so large that the materials become excessively compacted. Windrows that are too small can lose heat quickly and may not achieve temperatures high enough to cause moisture to evaporate and kill pathogens and weed seeds.

Demonstration Status: Agricultural composting is experiencing a resurgence of activity, particularly in the northeastern United States. A growing number of farmers are now composting significant quantities of organic materials. These farmers have incorporated composting of a wide variety of organic wastes generated on and off farm into their normal operations. Some own large commercial enterprises; others are small "hobby" farms. A number operate otherwise traditional dairy enterprises, and several are organic vegetable growers. Some use all or most of the finished compost on the farm, and some produce compost and soil mixes as a primary agricultural product. Many use existing on-farm technology to manage the compost piles, and others have invested in specialized compost production equipment.

Several Massachusetts dairy farms have adopted composting as a manure management technique. In a study of five farms practicing composting in that state, it was found that three used the windrow method of composting, one used the passive method, and one experimented with several composting methods, finding the windrow method the most successful (Rynk, 2000). The Rosenholm-Wolfe Dairy Farm in Buffalo County, Wisconsin, has successfully produced compost for the commercial market using organic solids separated from manure that had been flushed from a 250-head, free-stall barn (Rosenow and Tiry, n.d.). The raw composting material has a C:N ratio of 30:1 and a moisture content of 60 percent, which is ideal for rapid production of a high-quality product using windrow composting.

A pilot project conducted at the Purdue Animal Science Research Center has shown that composting can be an efficient way to manage waste from dairy farms, hog farms, beef feedlots, and poultry operations at a lower cost than that associated with other waste management methods (*Purdue News,* August 1998). The composting site has 13 rows of compost material, each 5 feet tall, 10 feet wide, and 250 feet long. The rows are turned using a specialized windrow turner.

Three fundamental factors driving this renewed interest in composting are environmental and community constraints on traditional manure management options, increased understanding of the agronomic benefits of compost use, and rising disposal costs for such materials as municipal yard waste and food processing wastes, which might be managed for a profit in an agricultural setting. Despite growing interest, however, the environmental and possible economical benefits of composting are challenged by a variety of constraints. An agricultural composting study conducted by Cornell University (Fabian, 1993) concluded that governmental agencies need to take a number of steps to further encourage agricultural composting including minimizing regulatory constraints on farm-composted materials, encouraging local zoning to allow compost facilities as a normal agricultural operation, providing governmental assistance for composting equipment and site preparation, developing procurement guidelines for state agencies to use compost in preference to peat and topsoil, and supporting research and demonstration programs that explore new applications for compost in the agricultural sector.

Practice: Dehydration and Pelleting

Description: Dehydration is the process by which the moisture content of manure is reduced to a level that allows the waste to be used as a commercial product, such as fertilizer for horticulture.

Applicability and Performance: Dehydration has been used on a variety of animal waste products including poultry manure and litter. The output material (dried to about 10 percent moisture content) is an odorless, fine, granular material. With a moisture content of 10 to 15 percent, a slight odor may be noted. Crude protein levels of 17 to 50 percent have been reported in dried poultry waste (USEPA, 1974). The material can also be formed into pellets prior to drying. Pelleting can make the material easier to package and use as a commercial fertilizer.

Operational Factors: Manure is collected and dried from an initial moisture content of about 75 percent to a moisture content of 10 to 15 percent. The drying process is usually accomplished using a commercial drier. The input requirement for most commercial driers is that the raw material be mixed with previously dried material to reduce the average moisture content of the input mixture to less than 40 percent water.

The mixture is fed into a hammer mill, where it is pulverized and injected into the drier. An afterburner is generally incorporated to control offensive odors. The resultant dried material is either stockpiled or bagged, depending on the ultimate method of disposal selected. Units reported range in size from small portable units to systems capable of processing 150,000 tons per year (USEPA, 1974).

Advantages and Limitations: The drying of animal waste is a practiced, commercial technology with the dehydrated product sold as fertilizer, primarily to the garden trade. It is an expensive process that can be economical only where the market for the product exists at the price level necessary to support the process.

Development Status: The status of dehydrating animal manure is well established. Full-scale drying operations have been established with animal manure, in some cases since the late 1960s. A number of manufacturers offer a line of dehydration equipment specifically designed for this purpose. At least one large-scale facility, currently under construction on the Delmarva Pennisula, will be used to treat broiler manure.

Practice: Centralized Incineration of Poultry Waste

Description: Centralized incineration is an alternative method of disposing of excess poultry litter. Most poultry litter has energy content and combustion qualities similar to those of other biomass and commercially used alternative fuels (e.g., wood and refuse-derived fuels from municipal trash). Under a centralized incineration approach, poultry litter that is removed from the houses is collected and transported to a centralized facility that has been designed or retrofitted to burn poultry litter. The concentration of the poultry industry in several areas of the country and the dry composition of the manure facilitates litter transport, which is critical to the success of this alternative treatment technology. The centralized incineration unit could be located at a processing plant to provide power to the plant or at a stand-alone facility that would generate power for public use.

Application and Performance: Most of the nutrients in the litter would not be destroyed by combustion, but would be captured in the combustion ash and could be managed safely and economically. Consequently, the most immediate environmental benefit from burning litter is that its nutrients would not be applied to cropland and therefore would not run off into waterways.

Advantages and Limitations: The incineration of poultry litter to generate energy offers several clear advantages over current practices. The energy recovered by burning poultry litter would displace conventional fossil fuels and thereby avoid greenhouse gas emissions. The pollution control equipment required for major fuel burning units would likely minimize other combustion emissions when the manure is burned.

Limitations of using poultry litter as fuel include variability in litter composition, litter production rates, and litter caloric content. One of the most important determinants of the suitability of any substance as a fuel is its moisture content, and there is no guarantee that litter would undergo any sort of drying process prior to combustion. Moisture in a fuel represents a reduction in its heating value because some of its energy content must be used to vaporize the moisture, reducing the fuel's effective energy output. Poultry litter has a much lower British thermal unit (Btu) content, higher moisture content, and higher ash content than conventional fuels. It can pose greater operational problems (such as corrosion) and would probably be convertible to steam at a lower efficiency than conventional fuels. Moreover, because of its much higher ash content, litter will yield far more unburned residuals than other fuels. Metals, P, and K from the litter will concentrate in the residual ash; however, bottom ash and fly ash can be sold as fertilizer, contributing to the profitability of the technology.

Metals (e.g., Cu, arsenic, Zn) may be present in litter because they are added to poultry feed as a dietary supplement. Other metals may be unintentionally present in feed and bedding, or may be scraped from the floor of a poultry house when the litter is removed. Aluminum may be found in litter because alum is added to limit NH_3 volatilization, and aluminum sulfate is added to bind the P in litter, reducing P in runoff when applied to land. Metals in poultry litter can affect its suitability for combustion in several ways. First, the concentration of metals could affect the nature of air emissions from a poultry-fired boiler. Second, metals might pose a problem in the ash created from litter combustion. Most toxic metals concentrate significantly in combustion ash relative to the unburned litter.

Although litter combustion has significant environmental advantages, adverse environmental impacts might result from using poultry litter as a fuel source. Air emissions and treatment residuals result from the incineration of any fuel, however, and the chemical and physical properties of litter as a fuel do not suggest that burning litter would result in significantly worse pollution emissions than would burning conventional fuels. When compared with the combustion of conventional fuels, combustion of poultry litter produces fewer tons of NO_x, sulfur oxides (SO_x), and filterable particulate matter (PM) emissions at the boiler than coal or residual (No. 6) oil. In comparison with distillate fuel oil, litter has a less desirable emissions profile. A comparison with wood is mixed; litter shows lower emissions of carbon monoxide (CO), filterable PM, and methane, whereas wood shows lower emissions of NO_x, SO_x, and carbon dioxide (CO_2). Despite the high N content of poultry litter, burning litter should not increase NO_x emissions. NO_x emissions from combustion primarily depend on the nature of the combustion process itself (affecting the degree to which atmospheric N is oxidized) and only secondarily on the amount of N in the fuel. In fact, the high NH_3 levels in poultry litter may act to reduce much of the NO_x that is formed during combustion back into elemental N. This is the reaction that underlies most of the modern NO_x control technologies (selective catalytic and noncatalytic reduction) used in utility boilers.

SO_x formation in combustion processes depends directly on the sulfur content of the fuel. Therefore, SO_x emissions from burning poultry litter should be lower than those from high-sulfur fuels (residual oil or higher-sulfur coal) and higher than those from low-sulfur fuels (distillate oil, low-sulfur coal, wood, natural gas). The relatively high alkali (K and Na) content of litter and litter combustion ash may cause problems in the combustion system: a low ash melting point, which can lead to slagging and deposition of "sticky" ash on combustion surfaces, and high particulate emissions in the form of volatile alkali compounds. However, this high alkali ash content also has the likely benefit of reducing SO_x in the flue gas through a "scrubbing" effect. If the uncontrolled emissions from burning poultry litter appear likely to exceed emission standards, an appropriate air pollution control device would be installed at the unit, just as it would be at a conventional fuel-burning unit.

Costs for this technology include cleanout and storage/drying costs, as well as the cost of transporting the litter to the incineration facility. A fuel user might hire a contractor to remove litter from a poultry house and load it onto a truck for delivery, hire a contractor to load the litter and pay a grower for the litter and cleanout, or hire a contractor to get the litter from the shed and

load it onto a truck, paying the grower for the litter, cleanout, and storage. In addition, fuel users may also need to install new fuel-handling and management equipment and perform some redesign of the combustion process. Burning litter effectively might entail new plant construction, such as construction of a direct-fired biomass facility, retrofitting of an existing plant for direct firing poultry litter, or retrofitting of an existing cogeneration facility or boiler to co-fire poultry litter with conventional fuels (such as oil or coal). Most operations would also require a storage structure and litter supply system. The costs of retrofitting a processing plant boiler or feed mill boiler to co-fire litter do not appear excessive. The cost savings from burning litter would continue indefinitely and would increase as fuel users find more effective and efficient ways of burning litter.

Operational Factors: One of the first steps in using poultry litter as a fuel is to estimate the amount of litter produced by a feedlot. This amount is then compared with the quantity of litter that could be spread appropriately on local cropland to meet agricultural nutrient needs. The amount by which litter production exceeds the litter needed for crop nutrient purposes is the measure of the amount available for fuel. Several approaches are in use to project the volume of litter that a poultry operation will generate. The differing results of these approaches are mostly a function of the wide range of variables that affect poultry litter production—type of bird, feed and watering programs, bird target weight, type of bedding, litter treatment for NH_3 control, house type, crusting procedures, and cleanout schedules. One method uses a calculation of 10.8 lb of manure produced per broiler per year, another assumes an average of 35 lb of manure per 1,000 birds per day, and another assumes an average of 2.2 lb of litter per bird. Other more sophisticated methods apply a rate of litter produced per unit of bird weight produced. However, the most straightforward and commonly used calculation relies on an assumption of 1 ton of litter per 1,000 birds. It should be noted that since a significant portion of the weight of litter is water, having drier litter means fewer tons per bird. Therefore, the 1 ton of litter per 1,000 birds assumption should be treated strictly as a rough estimate.

The most important characteristic of litter with regard to its value as a fuel is its caloric content. Although the energy content of litter varies significantly, there is less variation after it is air-dried or oven-dried. For example, research conducted on the Btu content of several litter samples under varying moisture conditions showed that litter with a moisture content ranging from 0 to 30 percent had a caloric content ranging from 7,600 Btu per pound to 4,700 Btu per pound. Litter has a much lower caloric value than conventional fuels, but it has an energy content similar to that of several other commonly used alternative fuels. In addition, when litter is used as a fuel, its density affects the nature of the fuel feed systems and boiler configurations required. The density of litter also affects how the litter can be stored, handled, transported, and land-applied. Estimates of litter density vary widely, depending largely on the moisture content of the litter. Estimates range from 19 to 40 pounds per ft^3, with the average being roughly 30 pounds per ft^3.

Because poultry litter is quite variable with respect to several characteristics important to its use as a fuel, the fuel user must develop quality control and quality assurance guidelines to ensure that the litter is of consistent quality and well suited for combustion. Criteria for accepting litter may include acquiring only litter that has been covered in storage for some period of time to

avoid excessive moisture and increase Btu content per ton, or mixing a large quantity of litter on site prior to burning to reduce fluctuations in quality across individual loads of litter. One plant in operation in the United Kingdom employs the following measures: (1) litter shipments are examined for moisture content with infrared equipment, and shipments with excessive moisture are rejected; (2) core samples are taken and analyzed for moisture, ash, and Btu content; (3) based on the results of the analysis, the load is sorted into one of several storage pits; and (4) an overhead crane draws from the different storage pits in a manner providing an appropriate blend of wet and dry material, giving a reasonably constant caloric value when fed to the furnace.

Demonstration Status: This technology is not currently used in the United States for poultry waste; however, existing boilers could be retrofitted to co-fire litter with conventional fuels such as oil or coal, or litter could be burned in a direct-fired biomass facility to generate electricity, steam, or heat at power plants or in boilers at poultry processing plants to supplement energy needs. Other agricultural and silvicultural wastes such as bagasse, almond shells, rice hulls, and wood wastes are burned for energy recovery in scattered utility and industrial plants in the United States. In the United Kingdom, several medium-sized, profitable electric power plants are fueled by poultry litter. This indicates that centralized incineration of poultry waste has the potential to develop into a commercially viable alternative treatment technology for poultry growers.

A British company, Fibrowatt, conceived of, developed, and operates the electricity plants in the United Kingdom that use poultry litter as fuel. Fibrowatt's three plants (two operating, one under construction) are all new and are all electricity-generating plants rather than industrial boilers for steam heat or cogeneration facilities. Fibrowatt's litter storage and handling system is proprietary. The Fibrowatt plant at Eye in Suffolk, the first plant fueled by poultry litter, came on line in July 1992. The second plant, in Glanford at Humberside, came on line in November 1993. The third and largest plant is at Thetford in Norfolk, which was scheduled to begin operations in 1998.

The basic operations at the three plants are similar. Each plant is situated in the heart of a poultry-producing region. Trucks designed to minimize odor and the risk of biocontamination transport the litter from farms to the power plants. The trucks enter an "antechamber" to the litter storage structure, and the doors of the antechamber are closed before the truck unloads. Upon arrival, the litter is sampled for nearly 40 different traits including Btu content and moisture. The litter is stored and conditioned in a way that homogenizes the fuel. It is kept under negative pressure to control odor, and the air from the fans in the storage structure is directed to the boilers and used in combustion. The Glanford plant uses Detroit Air-jet spreader-stokers (reciprocating grate, solid-fuel combustors) to burn fuel. The Eye plant employs a stepped grate stoker. The boilers are Aalborg Ciserv three-pass, natural-circulation, single-drum water tube boilers. There are modifications to the ash removal process because the high alkali content of the litter can cause corrosion in the boiler. The steam from the boiler is passed to a turbo-alternator, and electricity is sold to the grid. The Fibrowatt plants are commercially viable in the United Kingdom because the prices Fibrowatt can charge for the electricity delivered to the grid are far higher than the prices charged in the United States. In addition, farmers are charged a disposal fee for their litter, and Fibrowatt is able to earn money on the ash produced by combustion,

which the plants collect and sell as concentrated fertilizer with a guarantee analysis. Theoretically, the process could be replicated in the United States, but a full-market study would be needed.

Poultry litter is not currently used as fuel in the United States; however, research into the feasibility of burning litter for electricity, steam, or heat is under way. Maryland Environmental Services (MES) has asked the Power Plant Research Program (PPRP), an arm of the Maryland Department of Natural Resources, to help investigate the possibility of burning poultry litter at the cogeneration plant at the Eastern Correctional Institute. In February 1998, Exeter Associates published a report for MES projecting the costs of various scenarios for using poultry litter at the plant. One of the recommendations in the report was that a full engineering study be done to obtain a better estimate of the costs involved. MES submitted a request for proposals on this basis in April 1998 and received bids from several companies. Among the companies that bid were Fibrowatt and two companies that build gasifiers. As of July 1998, the gasifier company bids had been rejected and the remaining bids were still under consideration. MES is determined to turn the cogeneration plant at the Eastern Correctional Institute into a working facility and is interested in a Fibrowatt-style system, the technology of which is proven and currently operational.

Other Technologies for the Treatment of Animal Wastes

Practice: Aquatic Plant Covered Lagoons

Aquatic plant covered lagoons provide low-cost wastewater treatment by removing suspended solids, BOD, N, and P in structures that are mechanically simple, relatively inexpensive to build, and low in energy and maintenance requirements (WPCF-TPCTF, 1990). Wastewater treatment occurs through a combination of mechanisms including biochemical conversion through plant-microbial reactions, plant uptake, settling, volatilization, and adsorption onto sediments. Free-floating aquatic plants such as duckweed (*Lemnaceae*), and water hyacinth (*Eichhornia crassipes*) grow rapidly (in a matter of days) and take up large amounts of nutrients from wastewaters (Reddy and De Busk, 1985). In addition, the extensive root system of water hyacinth provides a large surface area for microbial growth, which promotes degradation of organic matter and microbial transformation of N (Brix, 1993). Greater than 70 percent removal of pollutants by aquatic plant covered lagoons has been reported for domestic wastewater treatment (Orth and Sapkota, 1988; Alaerts et al., 1995; Vermaat and Hanif, 1998). Depending on the lagoon design, water depth, and retention time, effluent from hyacinth- and duckweed-covered lagoons can potentially meet secondary and sometimes advanced wastewater discharge standards for BOD, suspended solids, N, and P (Buddhavarapu and Hancock, 1991; Bedell and Westbrook, 1997).

In addition to providing wastewater treatment, nutrient uptake by water hyacinth and duckweed produces a protein rich biomass (Reddy and Sutton, 1984; Oron et al., 1988) that can be harvested and used as an agricultural fertilizer or a feed supplement (Oron, 1990). Furthermore, duckweed and hyacinths provide a dense cover that restricts algal growth by impeding sunlight at the water surface (Brix, 1993), reduces odor by preventing gaseous exchange, and acts as a

physical barrier to reduce the breeding of mosquitoes (Buddhavarapu and Hancock, 1991). Limitations of aquatic plant covered lagoons include a need for large treatment areas, pretreatment of wastewater in settling ponds, and floating grid barriers to keep plants from drifting (Brix, 1993). Cold temperature reduces the growth rate of floating plants (Brix, 1993). Although duckweed removes fewer nutrients than do water hyacinths (Reddy and De Busk, 1985), duckweed has higher protein and lower fiber, a faster growth rate, and lower harvesting costs (Oron, 1990), and can grow at temperatures as low as 1 to 3 °C (Brix, 1993). Duckweed prefers NH_3 over nitrate (Monselise and Kost, 1993), transforms nutrients to a protein-rich (25 to 30 percent) biomass (Oron, 1990), and selected duckweed species (*Lemna gibba*, *Lemna minor*) have been demonstrated to grow on undiluted swine lagoon effluent (Bergmann et al., 2000). For these reasons, duckweed is potentially effective in the treatment of animal waste. Further studies are needed to better understand the application and performance of aquatic plant covered lagoons for animal waste treatment.

Practice: Nitrification-Denitrification Systems—Encapsulated Nitrifiers

Description: Nitrification-denitrification refers to the biological conversion of ammonium first to nitrate, then to N_2. Many schemes for nitrification-denitrification have been researched including the use of nitrifying bacteria encapsulated in polymer resin pellets to speed up the reaction (Vanotti and Hunt, 1998). The theory is that elevated populations of nitrifying bacteria immobilized on resin pellets that are retained in a treatment system will convert more NH_3 to nitrate faster than free swimming bacteria. There is ample evidence that attached media systems that retain bacteria on their surface remove the target pollutants more effectively than bacteria that have to swim to their food and can be washed from the system.

Vanotti and Hunt demonstrated in the lab that an enriched solution of encapsulated nitrifiers in an oxygen-saturated solution at 30 °C, with 150 ppm BOD and 250 ppm TKN, could nitrify 90 percent of the NH_3 in a batch if sufficient alkalinity was added. The research also documented that a solution with encapsulated nitrifiers had more and faster nitrification than an aerated equivalent volume of anaerobic lagoon effluent with no nitrifiers added.

A pilot plant using imported pellets operating on anaerobic lagoon effluent followed the laboratory work. The effluent was first screened, and then introduced into a contact aeration treatment to reduce BOD. The aeration sludge was settled next, and then treated effluent was introduced into a nitrification tank in which another aeration blower was used to maintain a dissolved oxygen concentration of 3 milligrams per liter. The pH was maintained at 7.8 or greater with sodium hydroxide as necessary. The results of 3 months of operation were that, given adequate pretreatment, high nitrification rates of swine wastewater could be attained using enriched nitrifying populations immobilized on polymer resins.

Application and Performance: The technology specifically targets nitrification of NH_3, and could reduce the loss of NH_3-N to the atmosphere. When set up and operated properly, the treatment can convert 90 percent of the NH_3-N remaining in pretreated lagoon effluent to nitrate. A

nitrified farm effluent can be denitrified easily by either returning it to an anaerobic environment resulting in release of N_2. This technology will have little if any effect on pathogens, metals, growth hormones, or antibiotics. It can be assumed that most of these constituents were removed in the process of aerating the manure to reach oxygen-saturated conditions, which would enable the encapsulated nitrifiers to function.

Advantages and Limitations: A facility to support this process would be expensive to build, operate, and maintain. It is difficult to imagine this process being used on a farm. One area not considered is the sludge generated by aerobic pretreatment. Another limitation is the anaerobic lagoon pretreatment step used to reduce initial BOD and limit sludge production.

Operational Factors: Nitrifying bacteria are temperature sensitive, but the effect of temperature was not discussed by Vanotti. Rainfall and varying concentration should not affect performance; however, seasonal temperature variation may reduce nitrification.

Demonstration Status: NCSU has operated a pilot plant in Duplin County, North Carolina.

Disinfection—Ozonation and UV Radiation

Ozonation is commonly used to disinfect wastewater after biological treatment. Ozone is a highly effective germicide against a wide range of pathogenic organisms, including bacteria, protozoa, and viruses. It oxidizes a wide range of organics, can destroy cyanide wastes and phenolic compounds, and is faster-acting than most disinfectants. Moreover, unlike chlorine, ozone does not generate toxic ions in the oxidation process.

UV radiation is used primarily as a disinfectant. It inactivates organisms by causing a photochemical reaction that alters molecular components essential to cell function. It is very effective against bacteria and viruses at low dosages and produces minimal disinfection by-by products. To enhance the inactivation of larger protozoa, UV radiation is often considered in conjunction with ozone.

Disinfection measures such as ozonation and UV radiation are not commonly practiced in the United States for treatment of animal wastes. Animal wastewater would require primary and/or biological treatment prior to disinfection . Ozone is generally effective for aqueous waste streams with less then 1 percent organic content. Both processes are costly and require higher levels of maintenance and operator skill. Wastewater with high concentrations or iron, calcium, turbidity, and phenols may not be appropriate for UV disinfection. The effectiveness of UV disinfection is greatly hindered by high levels of suspended solids.

Vermicomposting

Composting is the controlled decomposition of organic materials and involves both physical and chemical processes (see Composting—Aerobic Treatment of Solids). During decomposition, organic materials are broken down through the activities of various invertebrates that naturally appear in compost, such as mites, millipedes, beetles, sowbugs, earwigs, earthworms, slugs, and

snails. Vermicomposting is accomplished by adding worms to enhance the decomposition process.

Vermicomposting uses "redworms" (*Eisenia foetida*), which perform best at temperatures between 50 and 70 °F. Bones, meats, fish, or oily fats should not be added to a worm compost box because of odors and rodent problems they could create. Successful operation requires a great amount of maintenance because the worms are highly sensitive to alterations in oxygen levels, temperature, moisture, pH, nutrients, and feed composition and volume. Heavy metals are not treated by any means of composting and can be toxic to the microorganisms and invertebrate population.

Farm-scale systems for vermicomposting have been developed. They tend to be simple systems using conventional, material-handling equipment. Labor and equipment are required to add material to the bed, remove composted material, separate the compost from the worms by screening, and process the compost and worms for their respective markets (the compost as a protein additive to animal feed, the worms as fish bait). Flies are a potential problem since this process occurs at a lower temperature than the general composting process. Pathogen destruction and drying are also reduced. A drying or heating step may be required to produce the desired compost.

Chemical Amendments

Chemical treatments have been applied to facility wastewater, animal waste, or directly to soils. A number of chemical amendments have been evaluated, mainly metal salts or by-products containing Al, Fe, or Ca, similar to methods used to remove P in municipal wastewater treatment. The P fixation capacity of soils is positively correlated with the Al content; Al and orthophosphate ions interact strongly to form either stable surface complexes or insoluble Al phosphate minerals (Moore and Miller 1994). Precipitation reactions with Fe and Ca form insoluble iron and calcium phosphates. Moore and Miller (1994) conducted laboratory studies of 100 different treatments with various Al, Fe, and Ca compounds at different rates and found that many of these compounds drastically reduced soluble P levels in poultry litter.

Amendments reported in the literature, mostly from laboratory or plot studies, include:

- **Water treatment residuals (WTR).** WTR, also known as alum sludge or alum hydrosolids (HS), are wastes generated from drinking water pretreatment. Peters and Basta (1996) added HS to soils previously treated with poultry litter and reported 50–60 percent reductions in Mehlich-III P. Haustein et al. (2000) found that high rates of both WTR and HiClay Alumina (HCA) applied directly to test plots decreased Mehlich-III soil test P levels due to the increased levels of soil Al.

- **Ferric Chloride ($FeCl_3$).** Ferric Chloride additions to poultry litter decreased P solubility at lower rates of about 20–50 g Fe/kg litter, but increased solubility at higher rates (Moore and Miller 1994). Barrow et al. (1997) reported that adding high levels of ferric chloride

to dairy wastewater improved sedimentation of P by almost 50 percent. Sherman et al. (2000) reported significant P removal from dairy flushwater using ferric chloride.

- **Coal combustion byproducts**. Stout et al. (1998) reported that addition of fluidized bed combustion flyash (FBC) and flue gas desulfurization product (FGD) to soils significantly reduced Mehlich-III P (45 percent), Bray-I P (50 percent), and water extractable P (72 percent) due to converting readily desorbable soil P to less soluble Ca-, Al-, or Fe-bound forms. Dao (1999) observed that application of Class C fly ash to cattle manure reduced water-extractable P by 85-93 percent and Mehlich-III P concentrations by up to 98 percent. FBC and FGD additions reduced water soluble inorganic P in by fresh dairy and swine manure by 50–80 percent (Toth et al. 2001a). Dou and Ferguson (2002) reported water soluble P reductions of 23–59 percent in swine and dairy manure treated with FBC and FGD. It should be noted that these byproducts can contain significant concentrations of heavy metals that may be toxic to plants and the loadings of these elements must be considered in the use of combustion byproducts.

- **Zeolite.** Lefcourt and Meisinger (2001) reported that addition of zeolite (primarily Si, AL, Na, and K oxides) to dairy slurry reduced soluble P content by over 50 percent.

- **Polyacrylamide (PAM).** PAM has been used to reduce sediment, nutrients, and pesticides in furrow-irrigated agriculture. In lab and field studies, PAM alone or in combination with Al and Ca reduced PO_4 by 47–64 percent in soil column leachate when manure was applied and by about 50 percent in water flowing over surface-applied cattle manure (Entry and Sojka 2000).

- **Limestone Dust.** Barrington and Gelinas (2002) reported precipitating about 93 percent of total P in swine manure into a sludge by the addition of 2 percent fine limestone dust.

- **Wollastonite.** Application of wollastonite (alkaline calcium and ferrous silicates) to soils has been proposed as a means to reduce P solubility in hydrologically sensitive areas (Willett et al. 1999). However, no experimental data have been reported.

By far, the most widely proposed and most thoroughly evaluated manure amendment is aluminum sulfate ($Al_2(SO_4)_3$), commonly called alum.

Alum Treatment

Although alum has been used for P precipitation in wastewater treatment for several decades, the use of alum additions to animal waste has been studied extensively only since the early 1990s. Applications have ranged from pretreatment of agricultural wastewaters, manure treatment, and soil amendment. While the majority of the studies have focused on effects on P solubility and runoff, significant effects on nitrogen volatilization and runoff of metals have also been documented.

Alum treatment for P control. Alum is thought to reduce soluble P through two mechanisms, formation of relatively insoluble aluminum phosphate compounds:

$$AL_2(SO_4)_3\text{-}14H_2O + 2H_3PO_4 \rightarrow 2AlPO_4 + 6H^+ + 3SO_4^{2-} + 14H_2O$$

or sorption of P by amorphous aluminum hydroxides:

$$AL(OH)_3 + H_3PO_4 \rightarrow AL(OH)_3\text{-}H_3PO_4$$

Over time, amorphous aluminum phosphate could be transformed to crystalline minerals such as variscite or wavellite, which are stable under acid conditions (Moore et al. 1998).

Much of the work on alum treatment has been done on poultry litter. Poultry litter is a particular problem because most P in litter occurs in the soluble form and intensive poultry production often occurs with a limited land base for waste application. Moore and Miller (1994) conducted early laboratory studies of alum additions to poultry litter and reported that alum additions decreased water soluble P from 2,000 to about 1 mg P/kg and concluded that treating litter prior to field application could significantly reduce soluble P runoff. In another study, the soluble P content of poultry litter amended with alum was reduced by up to 94 percent, from 2022 mg/kg to 111 mg/kg (Moore et al. 1995).

Shreve et al. (1995) evaluated the effects of alum treatment of poultry litter on runoff P and on forage production. Amending poultry litter with alum resulted in an 87 percent reduction in soluble P concentrations in runoff from plots compared with untreated litter in the first runoff event after application, and a 63 percent reduction for the second runoff event. Runoff soluble P load in the first runoff event was reduced 86 percent by alum addition. Litter application increased fescue yields, with yield having the greatest response to alum-amended litter, probably due to increased available N resulting from decreased NH_4 volatilization from the alum-treated litter. Based on these field trials, the authors concluded that alum treatment for poultry litter had significant promise for use as an environmental and economic management practice in the poultry industry.

A subsequent examination of long-term solubility of P in soils receiving treated poultry litter reported that after addition of litter containing 200 mg alum/kg, soil soluble P decreased from initial concentrations of 4.5-11.5 mg P/kg to about 1 mg P/kg after about 100 days over a wide pH range and remained low through nearly 300 days (Shreve et al. 1996).

Moore et al. (1997) determined the effect of alum treatment of poultry litter on phosphorus runoff from field-scale watersheds. Soluble reactive P concentrations in runoff averaged 1.05 and 3.23 mg P/L for the alum-treated and untreated litter, respectively; alum reduced soluble P runoff by 67 percent during the first year after application. Total P concentrations responded similarly (average 1.49 and 4.23 mg P/L for alum-treated and untreated litter, respectively). Soluble P concentrations averaged 74 percent lower from alum-treated litter runoff during the

second year after application. Overall, soluble reactive P concentrations were decreased 70 percent with alum.

Moore et al. (1997) also assessed agronomic rates of alum-treated poultry litter. The authors observed that application of normal poultry litter resulted in dramatic increases in water soluble P in soils, whereas application of alum-treated litter did not. Data showed that P bound by alum does not re-solubilize with time, indicating that litter application rates can be based on N, rather than P, if alum-treated litter is used, without risk of increasing soil test P levels. The study also found that the pH of soils fertilized with alum-treated litter was slightly higher than unfertilized soils, indicating that the use of alum in litter will not result in soil acidification.

Pre-treatment of poultry litter with alum significantly affects soil P as well as runoff. After three years of treating grass plots with alum-amended litter, no significant differences in soil water soluble P were observed when compared to the unfertilized control (Self-Davis et al. 1998, Moore et al. 2000). Water-soluble P levels in plots receiving untreated litter, however, increased each year. Alum-amended litter plots had significantly lower Mehlich-III P values compared to equivalently-managed untreated litter plots after two years of litter applications.

In an evaluation of treatment to fields already excessively high in soil test P, Haustein et al. (2000) applied water treatment residuals (WTR, composed of coagulated alum mixed with sand, silt, bacteria, and other compounds removed from raw water in the water treatment process) to grassed plots high in P. High rates of WRT (9–18 Mg/ha) decreased Mehlich-III soil test P levels 44–50 percent due to increased soil Al levels. Dissolved P in runoff from treated plots were less than or equal to levels in runoff from the control (no litter) plot.

A recent on-farm evaluation of alum as a poultry litter amendment showed that a poultry litter alum-treatment BMP can be effectively implemented under a wide range of real-world conditions (Sims and Luka-McCafferty 2002). Alum was applied over a 16-month period to 97 poultry houses on working poultry farms on the Delmarva peninsula, with 97 other houses serving as controls. Alum decreased water soluble P concentrations in litter by about 70 percent, from an average of 1475 mg P/kg in untreated litter to an average 405 mg P/kg in alum treated litter.

While the effects of alum treatment on P in other animal wastes have received considerably less evaluation, results seem to be similar to those observed with poultry litter. Alum addition to stockpiled and composted cattle waste reduced water-extractable P in the waste by 85–93 percent (Dao 1999). Sherman et al. (2000) demonstrated removals of 11–17 mg P/ mmol Al^{+3} added to flush waters containing 1 percent dairy manure solids. Alum has been shown to be very effective in reducing soluble P in dairy manure (Lefcourt and Meisinger 2000). Even a 0.4 percent addition rate reduced soluble P about 75 percent compared to the control; a 6.25 percent addition reduced soluble P by about 97 percent. Toth et al. (2001b) reported that alum addition significantly reduced soluble P in dairy manure (by 36–99 percent), and, to a lesser extent, in swine manure (7–80 percent). Addition of alum at 0.5 percent by volume to a swine waste settling basin improved P removal from the liquid fraction to 75 percent, compared to 38 percent without alum (Worley and Das 2000).

Addition of alum to horse bedding prior to application to grass plots decreased runoff soluble P concentrations by 97 percent, which was less than the mean soluble P concentration in runoff from control plots (Bushee et al. 1998). Alum addition to horse manure decreased P concentrations by >50 percent in plot runoff; runoff P concentrations from alum-treated application did not differ significantly from runoff from non-manured plots (Edwards et al. 1999).

Alum treatment effects on nitrogen. Ammonia (NH_3) volatilization from poultry litter results in accumulation of atmospheric NH_3 in the poultry house, which is detrimental to human and bird health and reduces poultry productivity. Ammonia loss from litter and other animal waste also reduces the N content of the manure and can contribute to both acid deposition and eutrophication (Kithome et al. 1999).

Numerous studies have confirmed that addition of alum to poultry litter can reduce NH_3 volatilization up to 99 percent (e.g., Moore et al. 1995, 1998, and 2000). Alum reduces NH_3 losses because the acid generated in the hydrolysis of alum reduces litter pH; the H^+ produced in this reaction will react with NH_3 to form non-gaseous NH_4^+, which can react with sulfate ions to form ammonium sulfate, a water-soluble fertilizer.

Moore et al. (1995) documented 36-99 percent reductions in NH_3 volatilization with alum application to poultry litter, noting that the preservation of N in the litter added to its fertilizer value. The authors attributed a lower poultry mortality rate in alum-treated litter due to decreased levels of atmospheric NH_3 in the house. Shreve et al. (1995) observed a higher forage yield with alum-treated litter compared to untreated litter, an effect they attributed to improved N content due to reduced NH_3 loss.

Moore et al. (1999, 2000) reported results of field trials where alum was applied to broiler litter. Alum applications lowered litter pH significantly during the entire growout period. Reductions in litter pH decreased NH_3 volatilization and resulted in significant reductions in atmospheric NH_3 in the alum-treated houses. Alum applications reduced NH_3 fluxes from litter by 97 percent for the first four weeks of the growout and by 75 percent for the full 6-week period. Additional benefits of the reduction of NH_3 loss included improved growth of broilers, improved feed conversion, lower mortality, and lower energy costs for ventilating and heating.

Addition of alum to poultry litter during composting has been shown to be effective in conserving nitrogen. Addition of 20 percent alum to poultry litter resulted in a 26 percent reduction in NH_3 loss (Kithome et al. 1999), resulting in a final compost significantly higher in total N and NH_4^+ compared to untreated compost.

In farm-scale evaluations of alum treatment, Sims and Luka-McCafferty (2002) reported that litters from alum-treated poultry houses had higher total N, NH_4-N concentrations and therefore a higher fertilizer value.

Again, relatively little work has been reported on alum amendment to other animal wastes for the reduction of ammonia volatilization. Lefcourt and Meisinger (2000) reported that the addition of 2.5 percent alum to dairy slurry reduced ammonia emissions by about 60 percent. In a laboratory test of potential amendments to reduce ammonia emissions from beef cattle feedlots, Shi et al. (2001) reported that alum application reduced NH_3 volatilization by up to 98 percent.

Alum treatment effects on metals. Poultry litter often contains significant concentrations of heavy metals such as As, Co, Cu, Mn, Se, and Zn. Trace metals are added to feed to prevent disease and improve feed conversion; most of the metals added pass directly through the bird, which leads to elevated metal levels in the manure. Research has indicated that the potential exists for nonpoint source metal pollution from fields receiving poultry litter (Moore et al. 1998).

Moore et al. (1997 and 1998) conducted plot studies to determine if alum treatment reduces metal runoff and uptake by plants from poultry litter; the authors present extensive data on alum effects on copper, zinc, arsenic, aluminum, selenium, and other elements. Concentrations and loads of water-soluble metals (Al, As, Ca, Cu, Fe, K, Mg, Na, and Zn) increased with increasing litter application rates, regardless of litter type. The metal of greatest concern was copper, which was found in high concentrations in runoff from untreated litter. Alum treatment significantly reduced concentrations of As, Cu, Fe, and Zn compared to untreated litter, but increased Ca and Mg levels. Reductions in trace metal runoff due to alum were thought to be related to reduction in concentrations of soluble organic carbon (SOC) due to alum treatment. The authors concluded that metal runoff from alum-treated litter is less likely to cause environmental harm than from untreated litter because the water quality impacts of Ca and Mg are far less than those caused by Cu, As, and Zn. The study also showed that aluminum runoff and uptake by plants was not affected by alum treatment.

Little work on the effects of alum on metals associated with other animal waste has been reported in the literature. Edwards et al. (1999) studied the runoff of metals from alum-treated horse manure and found few detectable effects on metals in runoff from manured plots. Runoff concentrations of Al, S, Ca, and K increased in response to alum.

Summary: Alum Treatment

Benefits of alum treatment. Alum treatment of animal waste, particularly poultry litter, has important beneficial effects as a P management BMP. These direct effects include:

- **Reduced P solubility in waste.** Reductions in water-soluble P content of poultry litter and other animal wastes of 70 to >90 percent have been cited (e.g., Moore and Miller 1994, Moore et al. 1995, Lefcourt and Meisinger 2000, Sims and Luka-McCafferty 2002). This effect has been documented from the laboratory to the farm scale.

- **Reduced soil P levels.** Use of alum-treated poultry litter significantly reduces soil P. For example, after three years of treating grass plots with alum-amended litter, no significant differences in soil water soluble P were observed when compared to the unfertilized control (Self-Davis et al. 1998, Moore et al. 2000). Alum-amended litter plots had significantly lower Mehlich-III P values compared to equivalently-managed untreated litter plots after two years of litter applications. Use of treated litter can also reduce soil test P on soils already excessively high in soil test P (Haustein et al. 2000).

- **Reduced runoff P.** Use of alum-treated animal waste can dramatically reduce P runoff losses compared to untreated waste. Reductions of about 60–90 percent in soluble P concentrations in runoff have been widely reported from alum-treated poultry litter and other animal wastes (Shreve et al. 1995, Moore et al. 1997, Bushee et al 1998). In several reported cases, P concentrations in runoff from land-applied alum-treated waste were not significantly different from P levels in runoff from un-manured land (Self-Davis et al. 1998, Edwards et al 1999, Moore et al. 2000).

- **Reduced ammonia loss.** Numerous studies have shown that addition of alum to poultry litter can reduce NH_3 volatilization up to 99 percent (e.g., Moore et al. 1995, 1998, and 2000). Reduction in ammonia loss from poultry litter not only reduces airborne ammonia inside the poultry house but improves the fertilizer value of the litter by conserving N. Higher N content in alum-treated litter has been widely documented (Shreve et al. 1995, Kithome et al. 1999, Sims and Luka-McCafferty 2002).

- **Reduced runoff losses of metals.** Alum amendment decreases litter pH and the solubility of metals such as As, Cu, and Zn, which should reduce the movement of these soluble forms into surface or ground waters (Sims and Luka-McCafferty 2002). Runoff losses of some trace metals that pose significant environmental risk (e.g., copper) have been shown to be lower from land application of alum-treated poultry litter, compared to conventional litter (Moore et al. 1997 and 1998).

These documented effects of alum treatment have led to the conclusion that alum treatment offers great promise as an animal waste management BMP, particularly for poultry production (Moore et al. 1999, Sims and Luka-McCafferty 2002). Long-term studies of alum use have reported few negative impacts. The aluminum-phosphate minerals formed when alum is added to manure are believed to be stable for geologic time periods (Moore at al. 1999). Soil acidfication from alum use does not appear to be a problem, as increases in soil pH have been reported with alum-treated litter (Moore et al. 1997, 2000).

At typical rates of addition, alum treatment would not be expected to raise soil Al content significantly for several centuries (Moore et al. 2000). Even then, alum additions would not generally increase Al concentrations in runoff because soil pH does not typically become low enough for Al to be soluble. Thus, increases in Al in runoff from application of alum-amended waste would not be expected (Moore et al. 1999, 2000). In one reported case, however, elevated

Al levels were found in runoff from plots that received high-aluminum water treatment residuals in direct application; this was attributed to washing of freshly applied material from the soil or plant surface (Haustein et al. 2000).

Moore et al (1997) reported no significant differences in aluminum levels in plants due to application of alum treated litter. This is expected because alum-treated litter contains only trace quantities of soluble Al; most Al in treated litter and soil occurs as insoluble minerals.

Treatment of poultry litter with alum has a number of potential indirect benefits, including:

- **Improved fertilizer value.** Reduction of N losses and decreases in soluble P changes the N:P ratio of the litter. If alum-treated litter is used, it may be possible to apply litter based on N needs of a crop, rather than P, without risk of increasing soil P levels. Improved fertilizer value could also increase the economic feasibility of animal waste export or transport to facilitate nutrient trading.

- **Odor control.** Reduction of ammonia volatilization from animal waste, particularly poultry litter, may offer significant benefits in reduction of odor problems with animal production.

- **Health and productivity.** The reduction of ammonia production in poultry litter by alum has many important benefits to human and bird health and to productivity. Reduced ammonia levels in poultry houses will reduce exposure of farm workers to harmful levels of ammonia. Reductions in flock mortality, improved weight gains and feed conversion, and reduction in incidence of disease have all been documented in response to alum treatment of litter in poultry houses (Moore et al. 1999). Reduction in energy costs due to decreases in need for ventilation and heating have also been documented in response to reduced ammonia levels.

- **Solids separation.** The ability of alum to precipitate P in liquid dairy or swine waste may facilitate solids separation for composting and manure transportation.

- **Recycling of byproducts.** Use of Al-based materials like alum hydrosolids, water treatment residue, or flyash are used for waste treatment may replace expensive landfill disposal of these byproducts.

In addition to the broad environmental benefits, alum use seems likely to be a cost-effective practice to poultry growers and integrators. Moore et al. (1999) estimated a benefit:cost ratio of 1.96 for alum treatment of poultry litter, accounting for the cost of the alum treatment and the savings associated with improved productivity, lower mortality, and lower energy costs.

Cautions. While the benefits of alum treatment of animal waste have been clearly documented and few serious environmental risks have been identified, a few qualifications and concerns remain that must be considered.

- The reported reduction in P loss in runoff due to alum treatment generally assumes that erosion from source areas is minimized. Erosion and soil loss would transport particulate P in runoff, which may pose a long-term threat to water quality despite reductions in solubility due to alum treatment.

- Alum amendment of animal waste must be done in the context of a sound nutrient management program. Use of alum treatment as a BMP would be of little value if nutrients continue to be applied in excess of crop requirements.

- The effectiveness of alum may be lower than reported for poultry litter in other wastes if more of the P is already in a stable (nonsoluble) form, e.g., biosolids.

- Alum treatment is not an unlimited solution to the problem of excessive P loading from animal waste. For example, even when high P soils were treated to reduce soil test P by about 50 percent, the level of plant-available P remaining in the soil was twice that required for maximum crop production (Haustein et al. 2000).

- Because alum treatment conserves N in animal waste, there may be an increased potential for N loss in runoff or leaching.

- Whereas alum-treated animal wastes are neutral or alkaline, untreated aluminum sulfate may result in undesirable soil acidification and lead to release of toxic levels of dissolved Al (Peters and Basta 1996).

- Alum dose must be carefully controlled; excess alum addition can increase soluble Al in manure slurries (Lefcourt and Meisinger 2001); excessive application of some alum could immobilize enough P so that crop yields suffer from induced P deficiency.

- Although most studies have indicated that P compounds formed with Al are quite stable, some authors have suggested that the effects of changing redox potential on long-term stability of these compounds should be evaluated (Shreve et al. 1996).

- Because Al solubility is controlled by pH, soil pH may need to be monitored in areas vulnerable to acid deposition or if alum-treated manure applications are discontinued and replaced by inorganic N fertilizers, which tend to reduce soil pH.

- While alum will decrease the solubility of elements such as P, As, Cu, and Zn, it will have little or no effect on the total quantity of these elements in the waste. Research is needed on long term stability, transformations, and potential mobility of P and trace

metals in soils amended with alum-treated animal waste (Sims and Luka-McCafferty 2002).

Chemical Treatment for Pathogen Reduction

Treatment of manure with lime (calcium hydroxide, calcium oxide) has been proposed as a means to reduce pathogens in animal waste. There is scant information in the scientific literature directly concerning animal waste treatment; most of the justification for this proposed treatment comes from the use of lime materials to reduce pathogens and odors in biosolids. It is important to note that the lime discussed here is not the same material as the limestone (calcium carbonate, "agricultural lime") that is used to raise the pH of agricultural soils.

Biosolids treatment

Federal regulations classify biosolids into two classes, based on pathogen content; these classes specify the degree of treatment the biosolids must receive before land application or disposal. To meet Class A requirements (very low pathogen concentrations), biosolids must be treated by thermal drying (80 °C, dried to ≥90 percent solids), composting (55 °C for three days, aerobic conditions), or lime stabilization. Lime stabilization to meet Class A requirements requires that pH be raised to ≥12 for 2 hours and be maintained at pH 11.5 for 22 hours, combined with high temperatures (70 °C for 30 minutes). Lime stabilizaton involves addition of dry quicklime (CaO) to raise the pH and temperature of the biosolids.

In a comparison of stabilization techniques, Rothberg, Bamburini & Winsor, Inc. (undated), cited a number of advantages of lime stabilization, including pathogen reduction to Class A levels, low capital cost, dilution of metals concentrations, fixing of metals under alkaline conditions, and value of end product as a soil liming agent. Disadvantages cited include high annual cost, odor problems for ammonia offgas, and product applicability to alkaline soils. Currently, almost 20 percent of biosolids in the U.S. are treated with lime.

Lime inhibits pathogens by controlling environmental conditions required for bacterial growth. At pH >12, cell membranes of microorganisms are destroyed; hydrated lime (calcium hydroxide) is capable of creating pH levels as high as 12.4 (NLA 2001). Furthermore, use of quicklime (calcium oxide) involves an exothermic reaction with water, potentially raising temperatures to levels inimical to microorganisms.

Lime as an agricultural disinfectant

Lime is reportedly used in Europe as a disinfectant for barn and milking center floors, for disease control in carcass disposal, and for disinfection of animal wastes (NLA 2001).

Cooper Hatchery, Inc. (1987) reported that total bacteria counts, molds, and coliform bacteria were decreased in turkey litter after three days of fermentation following addition of hydrated lime.

Shand and Associates (1998) conducted a project to test the effectiveness of a lime pasteurization process to partially dehydrate and stabilize organic wastes in the Fraser River Basin (Canada). Although no pathogen data were reported, it is interesting to note that addition of lime accelerated ammonia emissions from animal wastes (probably due to elevated pH in the waste). This ammonia offgassing has been cited as a possible agent of disinfection in alkaline treatment of waste (Logan 1999).

Hogan et al. (1999) reported that hydrated lime effectively inhibited bacteria in recycled dairy manure bedding in 1 day. Lime was effective on reducing gram-negative bacteria, coliform counts, *Klebsiella spp.*, and *streptococci.*

Logan (1999) reported mixed results of pathogen reductions in animal waste using a proprietary alkaline stabilization process; the process apparently did not use lime. Several different waste types were tested in a processing plant where alkaline materials (unspecified coal-burning byproducts) were mixed with animal waste. The process achieved reductions in fecal coliform of one to three orders of magnitude in digested dairy manure; however fecal coliform counts were still as high as 10^3–10^4/g after treatment. Alkaline treatment was effective in treating undigested manures, reducing fecal coliform counts from 10^6/g to 10^1/g in dairy manure and from 10^4/g to 10^1/g in beef manure. However, fecal streptococci, total aerobic bacteria, and gram-negative organisms were relatively unaffected by the treatment. Treatment of turkey manure was highly effective, reducing fecal coliform counts from 10^5/g to $<10^2$/g. The applicability of this proprietary, facility-based process to the farm scale was not addressed.

Given the lack of specific data on the ability of lime addition to reduce pathogen counts in animal waste, it is worth noting that environmental factors such as temperature, pH, moisture, nutrient supply, and solar radiation have significant effects on bacteria survival outside their host (Moore et al. 1988). Waste storage alone results in a significant reduction of bacteria numbers compared to those in fresh waste; reduction of 2–3 orders of magnitude in fecal coliform are typical with storage for 2–6 months (Patni et al. 1985, Moore et al. 1988). Microorganisms in land-applied waste are subject to mortality from high temperatures, dessication, UV light, and other stresses (Moore et al. 1988).

Summary: Lime Treatment

Given the lack of specific, objective literature on the subject, it is difficult to recommend the use of lime to reduce pathogens in animal waste at this time. More research is needed that specifically focuses on the effectiveness of lime treatment on reduction of indicator and pathogenic microorganisms in animal waste and on the practical application of lime addition at the farm scale as a practical BMP. There is insufficient data on these subjects at present.

Possible benefits of lime treatment:

- Proven effective and widespread use to achieve Class A biosolids standards

- Documented reductions of some microorganisms in some animal wastes
- Fixation of metals and phosphorus
- Odor control of hydrogen sulfide (NLA 2001)
- Potential value of end product in soil pH management

Major unknowns or possible disadvantages

- Little solid performance data specific to animal waste
- Possible ineffectiveness of alkaline treatment on some organism groups
- Variation in effectiveness on different waste types
- Acceleration of NH_3 generation reduces N content of final product and may pose environmental or health risks
- Unknown scalability to cost-effective farm management

Gasification

The fuel produced by gasification is viewed today as an alternative to conventional fuel. A gasification system consists of a gasifier unit, purification system, and energy converters (burners or internal combustion engines). The gasification process thermochemically converts biomass materials (e.g., wood, crop residues, solid waste, animal waste, sewage, food processing waste) into a producer gas containing carbon dioxide, hydrogen, methane and some other inert gases. Mixed with air, the producer gas can be used in gasoline and diesel engines with little modification.

Gasification is a complex process best described in stages: drying, pyrolysis, oxidation, and reduction. Biomass fuels have moisture contents ranging from 5 to 35 percent. For efficient operation of a gasification system, the biomass moisture content must be reduced to less than 1 percent. The second stage of the process, pyrolysis, involves the thermal decomposition of the dried biomass fuels in the absence of oxygen. The next stage, oxidation, produces carbon dioxide and steam. The last stage, reduction, produces methane and residual ash and unburned carbon (char).

Gasification is one of the cleanest, most efficient combustion methods known. It eliminates dependence on fossil fuel and reduces waste dumping. It extracts many substances, such as sulfur and heavy metals, in elemental form. Factors limiting the use of this process include stringent feed size and material-handling requirements. Process efficiency is strongly influenced by the physical properties of the biomass (surface, size, and shape), as well as by moisture content, volatile matter, and carbon content (see Pyrolysis below for additional limitations).

Gasification of animal wastes is still in the developmental stages. It is currently considered a better alternative to incineration for its lower NO_x emissions. However, this treatment option is limited to the AFOs that have a market in which to sell the excess power or heat generated by the

gasification unit. Without this advantage, such facilities would be inclined to resort to less expensive waste treatment technologies.

Pyrolysis

Pyrolysis is a major part of the gasification process described above. It is formally defined as chemical decomposition induced in organic material by heat in the absence of oxygen. Pyrolysis transforms organic materials into gaseous components, small quantities of liquid, and a solid residue (coke or char) containing fixed carbon and ash. Pyrolysis of organic materials produces combustible gases including carbon monoxide, hydrogen and methane, and other hydrocarbons. If the off-gases are cooled, liquids condense, producing an oil/tar residue and contaminated water.

Target contaminant groups for pyrolysis are volatile organic compounds and pesticides. The process is applicable for the separation of organics from refinery wastes, coal tar wastes, wood-treating wastes, creosote-contaminated soils, hydrocarbon-contaminated soils, mixed (radioactive and hazardous) wastes, synthetic rubber processing wastes, and paint waste.

Economic factors have limited the applicability of pyrolysis to the animal waste management field. There are also a number of handling factors that limit applicability. Pyrolysis involves specific feed size and material-handling requirements. The technology requires that the biomass be dried to low moisture content (<1 percent). Slight inconsistencies in moisture content and biomass properties (both physical and chemical) greatly increase operational costs. These considerations make it difficult to apply this technology to animal waste. Pyrolysis is not effective in either destroying or physically separating inorganics from the contaminated medium. Volatile metals may be removed as a result of the higher temperatures associated with the process but are not destroyed. Biomass containing heavy metals may require stabilization.

Pyrolysis is still an emerging technology. Although the basic concepts of the process have been validated, the performance data for this technology have not been validated according to methods approved by EPA and adhering to EPA quality assurance/quality control standards. Site characterization and treatability studies are essential for further refining and screening of this process. Pyrolysis has been considered for animal waste treatment as part of the gasification technology, but is currently not in high demand because of operation and maintenance costs.

Freeze Drying and Freeze Crystallization or Snowmaking

Freeze drying involves freezing the waste, which causes the solids and liquids to separate. When the frozen sludge melts, the liquid is easily drained away for reprocessing. The remaining sludge is high in solids, completely stabilized, and capable of being spread on land with conventional agricultural equipment. The process has proven to lower waste management costs by reducing waste volume.

Freeze crystallization, or snowmaking, is a treatment process in which wastewater is turned to snow, thus readily stripping volatile gases from water. Other contaminants are precipitated from

the water in a process called atomizing freeze-crystallization. Meltwaters may have a nutrient reduction of up to 60 percent, with almost 100 percent of pathogens killed (MacAlpine, 1997).

Both processes are scarcely utilized due to applicability limitations. These processes are suited only to colder climates. The freeze-drying process requires significant storage capacity, and facilities must be capable of storing up to 1 year's production of sludge on site.

Practice: Photosynthetic Purification

A proprietary new animal waste treatment technology, Photosynthetic Purification, uses the nutrients in concentrated animal waste to grow algae and photosynthetic bacteria that yield a harvestable crop (Biotechna, 1998). Photosynthetic Purification technology is reported to treat high-strength, high-moisture waste streams with minimal loss of manure nutrients and generate a clean effluent that can be recycled or safely discharged. The resultant biomass can be used as a high protein animal feed supplement. Nutritional value of the biomass is at least equivalent to that of soy protein. Along with producing a valuable biomass, the main advantage of this technology is that it reduces the potential environmental impact of land application or discharge of animal waste in regions with CAFOs. A possible disadvantage is that animal waste will need to be transported to a processing facility.

The technology has been under development by Biotechna Environmental (2000) Corporation (BE2000) since the early 1990s. Successful tests are reported to have been carried out at pilot scale in Ireland (1994-95), and Connecticut (1998). A laboratory-scale system and a full-scale commercial demonstration plant are planned. Photosynthetic Purification produces high-protein feed supplements and a range of other value added products for the feed and nonfood markets. Because of proprietary information and patent pending status, little information on this technology is currently available to the public.

Deep Stacking of Poultry Litter

Research dating back to the 1960s (Bhattacharya and Fontenot, 1965) has shown that poultry litter has significant nutritive value as a feedstuff for ruminants. Subsequently, concerns about the potential public health impacts of using poultry litter as well as other animal manures as feedstuffs emerged. The presence and impact of pathogens, such as species of Salmonella and Clostridium, in manures being used as feedstuffs was one of these concerns. There have been a number of reports from foreign countries of botulism in animals fed diets containing animal wastes (Fontenot et al., 1996).

For poultry litter, the response to this concern about potential pathogen transmission was the development of the practice known as deep or dry stacking (McCaskey, 1995). It consists simply of piling litter in a conical pile or stack after it is removed from a poultry house and is raised in temperature to a maximum of 140 °F (60 °C) by microbes. Litter with a moisture content exceeding 25 percent may reach temperatures above 140 °F if not covered to exclude air.

McCaskey et al. (1990) have shown that higher temperatures produce a material with a "charred" appearance and reduced nutritive value. They reported that excessively heated litter has about 50 percent of the dry matter digestibility of litter that has not been excessively heated. This estimate was based on the percentage of litter dry matter solubilized in rumen fluid after 48 hours. Also, it was observed that the amount of N bound to acid detergent fiber and considered not available approximately tripled in overheated litter.

The practice of deep stacking poultry litter enhances its value as a feedstuff for ruminants by reducing concern about possible pathogen transmission. However, deep-stacked poultry litter cannot be considered pathogen free because the stacked litter is not mixed out of concern that reaeration will create the potential for excessive heating. Thus, outer regions of the deep stacked litter might not reach the temperatures necessary for pathogen destruction. In reality, deep stacking is composting in which oxygen availability limits the temperature and the degree to which dry matter (VS) are destroyed.

When deep stacking is done in a roofed structure such as a litter storage shed or in covered piles, the potential water quality impacts are essentially nil; however, deep stacking in uncovered piles creates the potential for leaching and runoff losses of nutrients, oxygen-demanding organics, and pathogens, as well as producing a feedstuff with reduced nutritive value. Because of the heat generated, some NH_3 volatilization is unavoidable, but is probably no greater than the losses associated with land application. With proper management, odor is not a significant problem.

The impact of deep stacking on land application for litter disposal is a direct function of the ability to market poultry litter as a feedstuff. If such a market exists, on-site land application requirements are reduced or become unnecessary; however, the impact on a larger scale is less clear. Although the utilization of litter N by ruminants can be relatively high, much of the litter P consumed will probably be excreted. Thus, typical values for the P content of beef cattle manure might not be appropriate for developing nutrient management plans for beef operations that feed significant quantities of broiler litter. Also, total manure production by beef cattle fed poultry litter-amended rations may increase, depending on the dry matter digestibility and the ash content of the litter (Martin et al., 1983).

As with the temporary storage of solid poultry manure in a dedicated structure, fire due to spontaneous combustion is a risk associated with deep stacking of poultry litter. Thus, structure design to exclude precipitation and routine monitoring of litter temperature are important operational factors.

Although reliable data regarding the extent of the use of deep stacking are unavailable, anecdotal evidence indicates that the use of poultry litter as a feedstuff for beef cattle is fairly extensive in regions with significant broiler or turkey, and beef cattle production. Thus, it appears reasonable to assume that the use of deep stacking is also fairly extensive.

Practice: The Thermo Master™ process

Thermo Tech™ Technologies, Inc., is a Canadian corporation in the business of converting food wastes into a high-energy and high-protein animal feed supplement, and converting municipal wastewater treatment sludges into a fertilizer material. The company has constructed several organic waste conversion facilities, known as "Thermo Master™ Plants," that employ the company's proprietary microbial organic waste digestion technology. The technology is protected by U.S. and Canadian patents with patent applications pending in several other countries.

The Thermo Master™ process was originally developed to create an animal feed supplement from relatively high solids content food wastes such as fruit and vegetable processing wastes and wastes of animal origin including meat, dairy, and fish processing wastes. Animal manures and wastewater treatment sludges were also considered for conversion into a fertilizer material. The process has been modified to enable processing of materials with a lower solids content.

In the Thermo Master™ process, autoheated aerobic digestion is operated at the relatively short residence time of 30 hours to maximize single-cell protein production using the influent waste material as substrate. The effluent from the digestion process is then dried and pelletized.

The Thermo Master™ process could, in theory, be a viable method for poultry and swine carcass disposal. In addition to recovering nutrients for use as an animal feed supplement, the absence of any pollutant discharges is an attractive characteristic of this process. Given that the process operates at thermophilic temperatures, at least a two- to three-log $_{10}$ reduction in pathogen densities should be realized (Martin, 1999). The process, however, has never been used for animal carcass disposal.

As with rendering, the problems of preserving, collecting, and transporting carcasses could limit use of this disposal alternative. A more significant limitation is the lack of any operating Thermo Master™ plants in the United States. Only two plants are in operation as of April, 2000, and they are both located in Canada near Toronto, Ontario. A third, located near Vancouver, British Columbia, is being rebuilt following a fire. Even if new plants were to be constructed in the United States, it is likely that they would be located in or near major metropolitan areas given the nature of the primary sources of process feedstocks. This would exacerbate the problem of carcass transportation.

8.2.3.2 Mortality Management

Improper disposal of dead animals at AFOs can result in ground water contamination and health risks. Most mortality management is accomplished through rendering of the dead animals. Rendering involves heating carcass material to extract proteins, fats, and other animal components to be used for meat, bone, and meal. Beef and dairy operations handle mortality management almost exclusively through rendering operations. In most instances the rendering operation will pick up the dead animals, resulting in no environmental impact on the operation.

For this reason, the remainder of this section focuses on swine and poultry mortality management, and it will cover rendering, composting, and incineration.

Mortality Management: Swine

Large swine operations must dispose of significant numbers of dead pigs on a daily basis. For example, a 1,000 sow farrow-to-wean operation with an average of 22 piglets per litter and a prewean mortality rate of 12 percent will generate almost 16 tons of piglet carcasses per year, assuming an average weight of 6 pounds per carcass. Assuming an average sow weight of 425 pounds and a sow mortality rate of 7 percent per year, the total carcass disposal requirement increases to over 30 tons per year.

Improper disposal of swine carcasses can lead to surface or ground water contamination, or both, as well as noxious odors and the potential for disease transmission by scavengers and vermin. Historically, burial was the most common method of carcass disposal. Burial has been prohibited in many states, largely because of concerns regarding ground water contamination. The following subsections briefly describe and discuss the principal alternatives to burial for swine carcass disposal: composting, incineration, and rendering.

Practice: Composting

Description: Composting is the controlled decomposition or stabilization of organic matter (Gotaas, 1956). The process may be aerobic or anaerobic. If the composting mass is aerobic and suitably insulated, the energy released in the oxidation of organic carbon to carbon dioxide and water will produce a fairly rapid increase in the temperature of the composting mass. With suitable insulation, thermophilic temperature levels will be reached. The higher temperature increases the rate of microbial activity and results in quicker stabilization. Under anaerobic conditions, the rate of biological heat production is lower because fermentation generates less heat than oxidation, so the temperature increase in the composting mass is less rapid. Thermophilic temperature levels can still be attained with suitable insulation; however, the rate will be slower.

Application and Performance: Composting is a suitable method of carcass disposal for all swine operations. The compost produced can be spread on site if adequate land is available. Another recently cited disposal option for the compost is distribution or marketing as an organic fertilizer material or soil amendment. Thorough curing to preclude development of odor or vermin problems, and screening to remove bones are necessary to make marketing a viable option. Another requirement for composting as a method of swine carcass disposal is the availability of a readily biodegradable source of organic carbon, such as sawdust, wood shavings, or straw.

When carcass composting is managed correctly, potential negative impacts on water and air quality are essentially nonexistent, assuming proper disposal of the finished compost. Mismanagement, however, can lead to seepage from the composting mass. This seepage has high

concentrations of oxygen-demanding organics, N, and P; is a source of noxious odors; and attracts vermin.

Advantages and Limitations: One of the advantages of swine carcass composting is the relatively low capital cost of the necessary infrastructure. Depending on the volume of carcasses generated daily, one or more of a series of two composting bins are required. These bins should be located on a concrete pad in an open or partially enclosed shed-like structure. Critical to this capital cost advantage is the availability of a skid-steer or tractor-mounted, front-end loader for handling materials. Federal and, in some instances, state cost sharing has been used to encourage the construction and use of swine mortality composting facilities.

A recent comparison of carcass composting and incineration for disposal of poultry mortalities suggests that the lower capital cost of carcass composting is offset by higher labor costs (Wineland et al., 1998). The development of more fuel-efficient incinerators has made incineration more cost competitive in recent years.

While the temperatures that can be attained in a mass of composting carcasses (130 to 150 °F) will result in significant reductions in pathogen densities, finished swine mortality compost cannot be considered pathogen free. Therefore, appropriate biosecurity measures are necessary in the handling and ultimate disposal of the finished compost. Collection of carcasses by renderers presents a higher biosecurity risk, especially the risk of introducing disease from other operations. In contrast, the ash from carcass incineration is sterile.

Carcass composting in the swine industry appears to be best suited for the disposal of prewean and nursery mortalities because of the relatively small size of these carcasses. For larger animals (sows, gilts, boars, and feeder pigs), at least partial carcass dismemberment, an unpleasant task, is necessary.

Operational Factors: In the composting of swine mortalities, a single layer of carcasses or carcass parts is placed on a layer of the carbon source and finished compost or manure, followed by another layer of the carbon source and finished compost, and then carcasses. The pattern is repeated until a height of about 5 feet is reached. The pile is capped with a carbon source. Inadequate moisture will retard decomposition, whereas too much moisture will result in anaerobic conditions and process failure.

A proper facility is critical to the success of composting swine carcasses. As noted above, one or more of a series of two composting bins are required depending on the daily volume of carcasses generated. To maximize the rate of carcass decomposition and also to ensure complete decomposition of soft tissue, the composting mass should be transferred to a second bin after about 2 weeks of decomposition. This transfer process results in both mixing and aeration of the composting mass. Following an additional 2 weeks, the compost should be ready for storage and curing or ultimate disposal. While satisfactory decomposition can be realized without transfer and mixing, the time required is significantly longer.

Also critical to the success of composting swine carcasses is the initial combination of carcasses, a source of biodegradable carbon such as sawdust or chopped straw, a source of adapted microorganisms, and moisture. Although some cooperative extension publications recommend using manure as the source of an adapted microbial population, finished compost is equally suitable (Martin and Barczewski, 1996). The ratio, on a volume basis, of these ingredients should be 1 part carcasses, 1.5 parts of the carbon source, 0.5 to 0.75 part finished compost, and 0 to 0.5 part water. The objective is to create an initial C:N ratio of 20:1 to 30:1.

Demonstration Status: The first use of composting for animal carcass disposal occurred in the poultry industry during the 1980s (Murphy, 1988; Murphy and Handwerker, 1988). Since that time, this method of carcass disposal has also been adopted by the swine industry. It was estimated that 10.5 percent of swine operations use composting for mortality disposal (USDA APHIS, 1995).

Practice: Incineration

Description: Incineration or cremation is the reduction of swine carcasses to ash by burning at a high temperature under controlled conditions using specially designed equipment. Incineration temperatures can be as high as 3,500 °F, depending on equipment design. Incinerators using natural gas, propane, or No. 2 distillate fuel oil are available.

Application and Performance: Incineration of swine carcasses is applicable to all operations where the cost of the equipment required can be justified by the volume of carcasses generated.

The potential for surface or ground water contamination associated with incineration is minimal, provided that liquid fuel tanks are contained properly and residual ash is disposed of properly. The P, K, and other elements contained in the carcasses are concentrated in the ash. Because of the high temperature of incineration, this ash is pathogen-free if cross-contamination with carcasses is avoided.

Odors and other air quality concerns led to a significant decline in carcass incineration in the past. Newly designed equipment, however, incorporates secondary combustion of stack gases, essentially eliminating these problems. Yet the emission of low levels of some air pollutants is unavoidable, as with any combustion process. Improper operation of the incinerator (e.g., reducing process temperature by overloading) can result in unacceptably high air pollutant emissions.

Advantages and Limitations: One of the more attractive aspects of incineration relative to other swine carcass disposal options, such as composting and rendering, is the complete destruction of pathogens. Another advantage is the relatively small mass of residual material (ash) requiring some form of ultimate disposal, especially in comparison with composting. Moreover, incineration has a relatively low labor requirement.

The principal perceived limitation of incineration is cost. The initial investment required is relatively high. A recent comparison of incineration and composting costs for poultry carcass disposal, however, suggests that the former has become cost competitive with the latter because of lower labor costs and improvements in incinerator fuel efficiency (Wineland et al., 1998).

Another limitation of incineration for swine carcass disposal is fixed capacity. This can be problematic when disease or other factors such as heat stresses cause a sizable increase in the rate of mortality.

Operational Factors: Because of the fixed capacity of incineration equipment, incineration of swine carcasses must occur on a regular basis. Ideally, carcass incineration should occur at least on a daily basis to minimize the potential for disease transmission. Routine maintenance of incineration equipment is also important to ensure reliability and minimize emission of air pollutants. An air pollutant emissions permit, a siting permit, or both, may be required for an incinerator.

Demonstration Status: Incineration has been used in the swine industry as a method of carcass disposal for many years. With recent technological advances in incinerator fuel efficiency and odor control, a reversal in the shift away from incineration and to other carcass disposal options, such as composting, may occur. It was estimated that 12.5 percent of swine operations use incineration, described as burning, for mortality disposal (USDA APHIS, 1995).

Practice: Rendering

Description: Rendering is the process of separating animal fats and proteins, usually by cooking. The recovered proteins are used almost exclusively as animal feedstuffs, while the recovered fats are used both industrially and in animal feeds.

There are two principal methods of rendering (Ensminger and Olentine, 1978). The first and older method uses steam under pressure in large closed tanks. A newer and more efficient method is dry rendering, in which all of the material is cooked in its own fat by dry heat in open steam-jacketed drums until the moisture has been evaporated. One advantage of dry rendering is the elimination of a separate step to evaporate the moisture in the material being rendered. Cooking temperatures range from 240 to 290 °F. Rendering can be a batch or a continuous flow process.

The two basic protein feedstuffs derived from rendering are meat meal and meat and bone meal. The basis for this differentiation is P content (National Academy of Sciences, 1971). Meat meal contains a maximum of 4.4 percent P on an as-fed basis. Meat and bone meal contains a minimum of 4.4 percent P.

Application and Performance: Most of the animal fat and protein recovered by rendering is derived from meat and poultry processing, but rendering can also be used to recover these

products from swine carcasses. The ability to use rendering as a method of swine carcass disposal depends on the presence of a rendering facility servicing the area. Rendering plants are not widely distributed and are generally located near meatpacking and poultry processing plants. As the meatpacking and poultry processing industries have consolidated into fewer but larger operations, a similar pattern of consolidation in the rendering industry has also occurred. Because swine carcasses have minimal monetary value as a raw material for rendering, transportation only over limited distances can be justified economically.

Rendering is a capital-intensive process and requires careful process control to generate acceptable products. In addition, product volume has to be substantial to facilitate marketing. Because on-farm rendering is unlikely to be a viable option for swine carcasses, performance measures are not included.

Advantages and Limitations: For swine producers, disposal of mortalities by rendering has several advantages. One is that capital, managerial, and labor requirements are minimal in comparison with other carcass disposal options. A second advantage is the absence of any residual material requiring disposal, as is the case with both composting and incineration, albeit to a lesser degree. If carcass volume is adequate to justify daily pickup by the renderer, capital investment for storage is also minimal.

As discussed above, rendering is a feasible option for swine carcass disposal only if the swine production operation is located in an area serviced by a rendering plant. Also, not all rendering operations will accept mortalities, largely because of concerns about pathogens in the finished products.

Well-managed rendering operations will not accept mortalities more than 24 hours after death because of the onset of decomposition of fats and proteins, adversely affecting the quality of the final products. For swine operations that do not generate an adequate volume of carcasses to justify daily pickup by the renderer, carcass preservation by freezing, for example, is a necessity. While preservation of piglet carcasses by freezing may be justifiable economically, the cost of preserving larger animals is probably not justifiable because payment by renderers for carcasses is usually nominal at best. Typically, payment is no more than one to two cents per pound. Payment can be less, or there may even be a charge for removal, depending on transport distance.

Operational Factors: Since renderers usually pick up carcasses, stringent biosecurity precautions are essential to prevent disease transmission by vehicles and personnel serving several swine operations. Ideally, trucks should be disinfected before entering individual farms, and collection personnel should use disposable shoe coverings. Also, necessary carcass preservation measures should be employed to ensure that the renderer will continue to accept carcasses.

Demonstration Status: It was estimated that 32 percent of swine operations use rendering for mortality disposal, with 25.1 percent allowing the renderer to enter the operation and 6.9 percent placing carcasses at the perimeter of the operation for pickup (USDA APHIS, 1995).

Mortality Management: Poultry

Large poultry operations generate significant numbers of dead birds on a daily basis. For example, a flock of 50,000 broilers with an average daily mortality of 0.1 percent (4.9 percent total mortality) will result in approximately 2.4 tons of carcasses over a 49-day grow-out cycle (Blake et al., 1990). A flock of 100,000 laying hens averaging a 0.5 percent monthly mortality (6 percent annual mortality) will generate 11.25 tons of carcasses per year (Wineland et al., 1998). For a flock of 30,000 turkeys averaging 0.5 percent weekly mortality (9 percent total mortality), approximately 13.9 tons of carcasses will require disposal (Blake et al., 1990).

Improper disposal of poultry mortalities can lead to surface or ground water contamination, or both, as well as noxious odors and the potential for disease transmission by scavengers and vermin. The following subsections briefly describe and discuss the principal alternatives to burial used for dead bird disposal: composting, incineration, and rendering. Burial of dead birds has been prohibited in many states, principally because of concerns regarding ground water contamination. These alternatives for carcass disposal are also used in the swine industry and have been described in the previous section. Differences between the two sectors, however, are briefly noted.

Practice: Composting

Description: The general description of composting presented in the preceding section on swine mortality management also applies to poultry.

Application and Performance: As with swine, composting as a method of carcass disposal is suitable for all poultry operations. The compost produced can be spread on site if adequate land is available. Another disposal option for the compost is distribution or marketing as an organic fertilizer material or soil amendment. Thorough curing to preclude development of any odor or vermin problems and screening to remove bones are necessary to make marketing of carcass compost disposal a viable option. Another requirement for composting as a method of poultry carcass disposal is the availability of a readily biodegradable source of organic carbon such as sawdust, wood shavings, or straw.

When poultry carcass composting is managed correctly, potentially negative impacts on water and air quality are essentially nonexistent, assuming proper disposal of the finished compost. Mismanagement, however, can lead to seepage from the composting mass. This seepage has high concentrations of oxygen-demanding organics, N, and P; is a source of noxious odors; and attracts vermin.

Advantages and Limitations: As with swine carcass disposal, one of the advantages of poultry carcass composting is the relatively low capital cost of the necessary infrastructure, especially when compared with incineration. Depending on the volume of carcasses generated daily, one or more of a series of two composting bins are required. These bins should be located on a concrete

pad in an open or partially enclosed shed-like structure. Critical to this capital cost advantage is the availability of a skid-steer or tractor-mounted, front-end loader for handling materials. Federal and, in some instances, state and integrator cost sharing has been used to encourage the construction and use of poultry mortality-composting facilities.

A recent comparison of carcass composting and incineration for disposal of poultry mortalities suggests, however, that the lower capital cost of carcass composting is offset by higher labor costs (Wineland et al., 1998). The development of more fuel-efficient incinerators has made incineration more cost competitive in recent years.

While the temperatures that can be attained in a mass of composting carcasses (130 to 150 °F) will result in significant reductions in pathogen densities, finished poultry mortality compost cannot be considered pathogen-free. Therefore, appropriate biosecurity measures are necessary in the handling and ultimate disposal of the finished compost. Collection of carcasses by renderers presents a higher biosecurity risk, especially the risk of introducing disease from other operations. In contrast, the ash from carcass incineration is sterile.

Operational Factors: In the composting of poultry mortalities, a single layer of carcasses is placed on a layer of the carbon source and finished compost or litter, followed by another layer of the carbon source and finished compost, and then carcasses. The pattern is repeated until a height of about 5 feet is reached. The pile is capped with a carbon source. Inadequate moisture will retard decomposition, while too much moisture will result in anaerobic conditions and process failure.

A proper facility is critical to the success of composting poultry carcasses. As noted above, one or more of a series of two composting bins are required depending on the daily volume of carcasses generated. To maximize the rate of carcass decomposition and also to ensure complete decomposition of soft tissue, the composting mass should be transferred to a second bin after about 2 weeks of decomposition. This transfer process results in both mixing and aeration of the composting mass. Following an additional 2 weeks, the compost should be ready for storage and curing, or ultimate disposal. While satisfactory decomposition can be realized without transfer and mixing, the time required increases significantly.

Also critical to the success of composting poultry carcasses is the initial combination of carcasses, a source of biodegradable carbon such as sawdust, wood shaving, or chopped straw, a source of adapted microorganisms, and moisture. Although some cooperative extension publications recommend using litter or cake as the source of an adapted microbial population, finished compost is equally suitable (Martin and Barczewski, 1996). Martin et al. (1996) have suggested that use of cake be avoided. One recommendation, on a volume basis, is 1 part dead birds, 1.5 parts straw, 0.5 to 0.75 part litter, and 0 to 0.5 part water (Poultry Water Quality Handbook, 1998). Sawdust or shavings have been used successfully in place of straw. Basically, this same combination of materials is used for swine carcass composting. Again, the objective is to create an initial C:N ratio of 20:1 to 30:1.

Demonstration Status: The first use of composting for animal carcass disposal occurred in the poultry industry during the 1980s (Murphy, 1988; Murphy and Handwerker, 1988). Currently, composting for disposal of poultry mortalities is readily accepted by producers and used extensively. In a recent survey of broiler producers on the Delmarva Peninsula, 52.7 percent of 562 respondents reported using composting for dead bird disposal (Michel et al., 1996).

Practice: Incineration

Description: The general description of incineration presented in the preceding section on swine mortality management also applies to poultry.

Application and Performance: As with swine, the use of incineration for poultry carcass disposal is applicable to all operations where the cost of the equipment required can be justified by the volume of carcasses generated.

As with swine carcass incineration, the potential for surface or ground water contamination associated with incineration is minimal, provided that liquid fuel tanks are properly contained and residual ash is disposed of properly. The P, K, and other elements contained in the carcasses are concentrated in the ash. Because of the high temperature of incineration, this ash is pathogen-free if cross-contamination with carcasses is avoided.

Odors and other air quality concerns led to a significant decline in carcass incineration in the past. Newly designed equipment, however, incorporates secondary combustion of stack gases, essentially eliminating these problems. Yet the emission of low levels of some air pollutants is unavoidable, as with any combustion process. Improper operation of the incinerator (e.g., reducing process temperature by overloading) can result in unacceptably high air pollutant emissions.

Advantages and Limitations: One of the more attractive aspects of incineration relative to other poultry carcass disposal options, such as composting and rendering, is the complete destruction of pathogens. Another advantage is the relatively small mass of ash requiring some form of ultimate disposal, especially in comparison with composting. Moreover, incineration has a relatively low labor requirement.

The principal perceived limitation of incineration is cost. The initial investment required is relatively high. A recent comparison of incineration and composting costs for poultry carcass disposal, however, suggests that the former has become cost competitive with the latter because of lower labor costs and improvements in incinerator fuel efficiency (Wineland, et al., 1998).

Another limitation of incineration for poultry carcass disposal is fixed capacity. This can be problematic when disease or other factors such as heat stresses cause a sizable increase in the rate of mortality.

Operational Factors: Because of the fixed capacity of incineration equipment, incineration of poultry carcasses must occur on a regular basis. Ideally, carcass incineration should occur at least on a daily basis to minimize the potential for disease transmission. Routine maintenance of incineration equipment is also important to ensure reliability and minimize emissions of air pollutants. An air pollutant emissions permit, a siting permit, or both, may be required for an incinerator.

Demonstration Status: Incineration has been used to a limited degree in the poultry industry for carcass disposal for many years. In recent years, cost and odor problems resulted in a shift away from incineration to more seemingly attractive options such as composting. In a recent survey of broiler producers on the Delmarva Peninsula, only 3.3 percent of 562 respondents reported using incineration for dead bird disposal (Michel et al., 1996). Improvements in fuel efficiency and odor control, however, have renewed interest in this option for carcass disposal.

Practice: Rendering

Description: The general description of rendering presented in the previous section on swine mortality management also applies to poultry.

Application and Performance: As with swine, the ability to use rendering as a method of poultry carcass disposal depends on the presence of a rendering facility servicing the area. Because on-farm rendering is unlikely to be a viable option, performance measures are not included.

Advantages and Limitations: Rendering has the same advantages for poultry producers that it has for swine producers: (1) minimal managerial and labor requirements, and (2) the absence of any residual material requiring disposal.

Limitations include the need to preserve carcasses, because many operations will not generate a sufficient volume of carcasses to justify daily collection by a renderer. Several options have been demonstrated to be technically feasible for poultry carcass preservation. They include freezing, preservation using organic or mineral acids (Malone et al., 1998; Middleton and Ferket, 1998), preservation using sodium hydroxide (Carey et al., 1997), and lactic acid fermentation (Dobbins, 1988; Murphy and Silbert, 1990). All of these preservation strategies increase the cost of carcass disposal, and all but freezing increase labor requirements.

Another factor limiting the use of rendering for poultry carcass disposal is the problems that feathers create in the rendering process. Feathers absorb the fat separated by rendering and make the product difficult to handle and market. Feathers also dilute the nutritional and resulting market value of poultry by products meal, especially when used as a feedstuff for nonruminant animals which cannot digest feathers.

Although feathers can be removed by hydrolysis, cooking at high temperature under pressure degrades protein quality. It has been shown, however, that feathers can be removed successfully

up to 24 hours postmortem, using a batch scalding and picking system (Webster and Fletcher, 1998). Thus, renderers with feather-picking equipment can accept significant quantities of poultry mortalities without compromising product quality.

Operational Factors: As with swine, stringent biosecurity precautions are essential to prevent disease transmission by vehicles and personnel serving several poultry operations. Moreover, carcass preservation measures are generally necessary.

Demonstration Status: Overall, the use of rendering for disposal of poultry mortalities is minimal because of the necessity of carcass preservation and the problem of feathers described above. In a recent survey of broiler producers on the Delmarva Peninsula, none of the 562 respondents reported using rendering for dead bird disposal (Michel et al., 1996). One of the major broiler integrators, however, is currently evaluating the use of rendering after the grower preserves the carcasses by freezing. The integrator supplies the freezer and the grower pays for the electricity. Preliminary indications are that the growers are pleased with this approach.

8.3 Nutrient Management Planning

Nutrient management is a planning tool farmers use to control the amount, source, placement, form, and timing of the application of nutrients and soil amendments (USDA NRCS, 1999). Planning is conducted at the farm level because nutrient requirements vary with such factors as the type of crop being planted, soil type, climate, and planting season. The primary objective of a nutrient management plan (NMP) is to balance crop nutrient requirements with nutrient availability over the course of the growing season. By accurately determining crop nutrient requirements, farmers are able to increase crop growth rates and yields while reducing nutrient losses to the environment.

Proper land application of manure is dependent on soil chemistry, timing of application, and recommended guidelines for applying at agronomic rates (the amount of manure or commercial fertilizers needed to provide only the amount of a particular nutrient that will be used by a specific crop or crop rotation). Manure is an excellent organic fertilizer source and is a soil amendment that benefits a soil's chemical, physical, and biological properties. The predominant chemical benefit of manure to the soil is the supply of the major plant nutrients— nitrogen (N), phosphorus (P), and potassium (K). In addition, livestock manure supplies micronutrients and non-nutrient benefits such as organic matter, which are advantageous to plant growth. The organic matter increases the nutrient- and water-holding capacity of the soil and improves the physical structure. Finally, manure is a source of food and energy for soil microorganisms, which can directly and indirectly benefit the physical, chemical, and biological properties of the soil. The combination of these non-nutrient benefits to soil health has been found to boost corn yields by 7 percent, soybean yields by 8 percent, and alfalfa yields by 9 percent (Vetsch, 1999).

In spite of the benefits listed above, repeated applications of manure can elevate levels of N, P, K, and other micronutrients, as well as acidify soils and increase salinity. Excessive application of these nutrients can lead to surface runoff or leaching. Therefore, land application of manure, if improperly managed, can contribute to the degradation of surface water and ground water (Liskey et al., 1992). Excessive amounts of some nutrients in soils can also reduce crop yields (Brown, 1995).

More efficient use of fertilizer, animal manure, and process wastewater can result in higher yields, reduced input requirements, greater profits, and improved environmental protection. It is possible to further reduce fertilizer expenses and diminish water pollution by employing specific farming practices that help to reduce nutrient losses from manured fields. The best ways to conserve manure P and K are to apply only the amount of manure needed to meet the crop's nutrient needs, and to minimize transport of these nutrients from the field by using conservation practices that reduce erosion and runoff. These approaches also aid in preventing N losses, but N management must also include proper handling, storage, treatment, and timing of manure application and incorporation into the soil.

Sources of nutrients applied for crop production include commercial fertilizer, animal manure, and process wastewater. Nutrient application, manure management planning, erosion control, and other management practices are incorporated within what is referred to by USDA (and described in Section 8.3.1) as a "comprehensive nutrient management plan" or CNMP (USEPA, 1999b). EPA is not requiring all CAFO operators to develop and implement a CNMP. However, EPA recommends the use of USDA NRCS's *Comprehensive Nutrient Management Planning Technical Guidance* (National Planning Procedures Handbook Subpart E, Parts 600.50-600.54 and Subpart F, Part 600.75).

In 1999, the USDA NRCS published a National Conservation Practice Standard on Nutrient Management (Code 590) that provides guidance on managing the amount, source, placement, form and timing of the application of nutrients and soils amendments (e.g., manure). Several methods are presented for determining that proper nutrient application rates are used. Section 8.3.2.4 discusses some of these methods including: the P threshold, the P index, and soil testing. During the period 2001-2002, all states developed nutrient management standards that are in compliance with USDA's 590 standard. Most states developed a state-specific variation of the P index but the soil test method was used by one state to comply with the 590 standard (Landers personal communication, 2002).

8.3.1 Comprehensive Nutrient Management Plans (CNMPs)

As discussed in the USDA-EPA Unified National Strategy for Animal Feeding Operations (USEPA, 1999b), site-specific CNMPs may include some or all of the six components described below, based on the operational needs of the facility. Many of the CNMP components described in the strategy have been addressed in other parts of this document and are cross-referenced below. This section focuses on parts of component 2 (Land Application of Manure and Wastewater) and component 4 (Recordkeeping), however, all six of the CNMP components are presented here to illustrate what a CNMP may contain.

Component 1: Manure and Wastewater Handling and Storage: This portion of a CNMP, addressed more fully in Section 8.2, identifies practices for handling and storing manure to prevent water pollution. Manure and wastewater handling and storage practices should also consider odor and other environmental and public health concerns. Handling and storage considerations include the following:

- Clean water diversion. Siting and management practices should divert clean water from contact with feedlots and holding pens, animal manure, or manure storage systems. Clean water can include rain falling on the roofs of facilities, runoff from adjacent land, and other sources.
- Leakage prevention. Construction and maintenance of buildings, collection systems, conveyance systems, and permanent and temporary storage facilities should prevent leakage of organic matter, nutrients, and pathogens to ground or surface water.

- Adequate storage. Liquid manure storage systems should safely store the quantity and contents of animal manure and wastewater produced, contaminated runoff from the facility, and rainfall. Dry manure, such as that produced in broiler and turkey operations, should be stored in production buildings or storage facilities or otherwise stored in such a way as to prevent polluted runoff. The location of manure storage systems should consider proximity to water bodies, floodplains, and other environmentally sensitive areas.
- Manure treatments. Manure should be handled and treated to reduce the loss of nutrients to the atmosphere during storage; make the material a more stable fertilizer when applied to the land; or reduce pathogens, vector attraction, and odors, as appropriate.
- Management of dead animals. Dead animals should be disposed of in a way that does not adversely affect ground or surface water or create public health concerns. Composting and rendering are common methods used to dispose of dead animals.

Component 2: Land Application of Manure and Wastewater: Land application is the most common, and usually the most desirable, method of using manure and wastewater because of the value of the nutrients and organic matter they contain. Land application should be planned to ensure that the proper amount of nutrients are applied in a manner that does not adversely affect the environment or endanger public health. Land application in accordance with a CNMP should minimize the risk of adverse impacts on water quality and public health. Considerations for appropriate land application should include the following:

- Nutrient balance. The primary purpose of nutrient management is to achieve the level of nutrients (e.g., N and P) required to grow the planned crop by balancing the nutrients already in the soil and provided by other sources, with those which will be applied in manure, biosolids, and commercial fertilizer. At a minimum, nutrient management should prevent the application of nutrients at rates that will exceed the capacity of the soil and the planned crops to assimilate nutrients and prevent pollution. Soils, manure, and wastewater should be tested to determine nutrient content.
- Timing and methods of application. Care must be taken when applying manure and wastewater to the land to prevent them from entering streams, other water bodies, or environmentally sensitive areas. The timing and methods of application should minimize the loss of nutrients to ground or surface water and the loss of N to the atmosphere. Manure and wastewater application equipment should be calibrated to ensure that the quantity of material being applied is what was planned. These topics are discussed in Section 8.4.

Component 3: Site Management: Tillage, crop residue management, grazing management, and other conservation practices should be used to minimize movement to ground and surface water of soil, organic material, nutrients, and pathogens from lands to which manure and wastewater are applied. Forest riparian buffers, filter strips, field borders, contour buffer strips, and other conservation practices should be installed to intercept, store, and use nutrients or other pollutants

that might migrate from fields to which manure and wastewater are applied. Site management is addressed in Section 8.4.

Component 4: Recordkeeping: CAFO operators should keep records that indicate the quantity of manure produced and how the manure was used including where, when, and the amount of nutrients applied. Soil and manure testing should be incorporated into the recordkeeping system. The records should be kept after manure leaves the operation.

Component 5: Other Utilization Options: Where the potential for environmentally sound land application is limited, alternative uses of manure, such as sale of manure to other farmers, centralized treatment, composting, sale of compost to other users, and using manure for power generation may also be appropriate. Several of these options are described in Section 8.2. All manure use options should be designed and implemented in such a way as to reduce risks to human health and the environment, and they must comply with all relevant regulations.

Component 6: Feed Management: Animal diets and feed may be modified to reduce the amounts of nutrients in manure. Use of feed management activities, such as phase feeding, amino acid-supplemented low-protein diets, use of low-phytate-phosphorus grain, and enzymes such as phytase or other additives, can reduce the nutrient content of manure, as described in Section 8.1. Reduced inputs and greater assimilation of P by the animal reduce the amount of P excreted and produce a manure that has a N to P ratio closer to that required by crop and forage plants.

Other information that should be part of an NMP is provided in the USDA-NRCS Nutrient Management Conservation Practice Standard Code 590 (USDA NRCS, 1999). It includes aerial photographs or site maps; crop rotation information; realistic crop yield goals; sampling results for soil, manure, and so forth; quantification of all nutrient sources; and the complete nutrient budget for the crop rotation.

Practice: Developing a Comprehensive Nutrient Management Plan

Description: Effective nutrient management requires a thorough analysis of all the major factors affecting field nutrient levels. In general, a CNMP addresses, as necessary and appropriate, manure and wastewater handling and storage, land application of manure and other nutrient sources, site management, recordkeeping, and feed management. CNMPs also address other options for manure use when the potential for environmentally sound land application of manure is limited at the point where the manure is generated.

NMPs typically involves the use of farm and field maps showing acreage, crops and crop rotations, soils, water bodies, and other field limitations (e.g., sinkholes, shallow soils over fractured bedrock, shallow aquifers). Realistic yield expectations for the crops to be grown, soil and manure testing results, nutrient analysis of irrigation water and atmospheric deposition, crop nutrient requirements, timing and application methods for nutrients, and provisions for the proper calibration and operation of nutrient application equipment are all key elements of an NMP.

Application and Performance: CNMPs apply to all farms and all land to which nutrients are applied. Plans are developed by the grower with assistance, as needed, from qualified company staff, government agency specialists, and private consultants. To be effective, NMPs must be site-specific and tailored to the soils, landscapes, and management of the particular farm (Oldham, 1999).

A wide range of studies has found that implementation of nutrient management results in improved nutrient use efficiency, that is, providing for profitable crop production while minimizing nutrient losses and water quality impacts.

Numerous studies have reported significant decreases in N and P applications to cropland due to nutrient management, particularly in areas of concentrated livestock production. Significant reductions in nutrient losses in runoff or leaching often accompany reductions in inputs. However, nutrient management may yield other environmental benefits as well.

Nutrient management may affect N and P availability in soils even more than N and P losses. In a study of nutrient management on Virginia farms, average annual mineral N availability was reduced by 53 kg/ha, while N losses were reduced by 21 kg/ha; average annual phosphate availability was reduced by 29 kg/ha, while average P losses were reduced by only 4 kg/ha (VanDyke et al. 1999). By reducing available nutrients not used by the crop, nutrient management can also reduce immobilized N and P that are subject to loss with eroded sediment in subsequent years.

In rare cases, nutrient management may result in no net decrease (or even an increase) in some nutrient applications on a farm due to redistribution of manure or fertilizer among fields or to optimization of nutrient applications for crop production. In livestock operations, for example, fields nearest the waste storage facility may have received excessive amounts of manure while remote fields received little or none. In such cases, nutrient management will promote more uniform manure application, which will reduce potential water quality impacts by decreasing excessive nutrient levels on some fields and insuring an adequate nutrient supply for crop production on others.

Furthermore, in the process of nutrient management, the producer may discover that he/she had been under fertilizing and additional nutrients are required to produce a good crop. Existence of a healthy crop contributes to good erosion control and nutrient uptake, while poor crop cover would expose soil to erosion and perhaps leave unused nutrients in the soil for leaching or runoff.

Nutrient management can improve the overall efficiency in the use of resources for crop production. Use of animal waste effectively recycles nutrients that might otherwise become water pollutants. Effective use of manure nutrients can lead to reduced demands for commercial N and P fertilizers including reduced energy demands for natural gas intensive N fertilizers (Risse, et al. 2001). More efficient animal waste and fertilizer management may improve the efficiency of equipment and machinery use on the farm.

Numerous studies have shown that nutrient management can yield increased farm income as over-application of purchased nutrients is avoided and better use is made of animal waste for crop production.

Improved use of animal waste has significant benefits to the maintenance of soil quality. With a good NMP, adequate soil fertility and soil organic matter content are maintained on all farm fields. There are ample data to show that the use of animal waste to improve and maintain soil quality has produced substantial reductions in soil erosion (13 to77 percent) and runoff (1 to 68 percent) across the country (Risse and Gilley 2000)

Finally, efficient use of animal waste in an NMP may contribute to reductions in greenhouse gas emissions. Nitrous oxide and methane from manure and fertilizer account for about 5 percent of total U.S. emissions of greenhouse gasses, notably where nutrients are applied to cropland in excess of recommended amounts (USEPA, 1998). Improving management and use of animal waste could therefore reduce emissions of nitrous oxides and methane and increase organic carbon storage in soil (Ogg 1999).

Advantages and Limitations: A good NMP should help growers minimize adverse environmental impacts and maximize the benefits of using litter and manure. In a national survey of growers of corn, soybeans, wheat, and cotton, more than 80 percent of those who had used manure in the Northeast, southern plains, Southeast, and Corn Belt reported that they had reduced the amount of fertilizer applied to land receiving manure (Marketing Directions, 1998). Approximately 30 percent of the respondents reported that they had saved money through crop nutrient management, while more than 20 percent reported increased yields, about 18 percent claimed reduced fertilizer costs, and approximately 10 percent reported that profits had increased and the soil quality had improved. Despite the potential savings, some farmers are reluctant to develop NMPs because of the cost. Only 4 to 22 percent of respondents indicated that they have an NMP.

Proper crediting and application of hog manure has been reported to save $40 to $50 per acre in fertilizer expenses in Iowa (CTIC, 1998a). Similarly, injecting hog manure has resulted in savings of $60 to $80 per acre in Minnesota. Although savings vary from farm to farm, proper crediting and application of manure under a good NMP can result in considerable cost savings for producers.

When animal manure and litter are used as nutrient sources, those activities which affect the availability and characteristics of such sources need to be factored into the NMP. For example, an NMP in which poultry litter is used as a nutrient source should take into account the amount of litter to be removed and the time of removal so that sufficient land is available for proper land application. Alternatively, the plan would need to consider whether storage facilities are available for the quantity of material that must be handled prior to land application. Whenever possible, litter removal should be planned so that fresh litter, containing the maximum amount of nutrients, can be applied immediately to meet crop or forage plant needs.

The CNMP will need to be revisited and possibly revised if the livestock facility increases in size, or if there are changes in animal types, animal waste management, processes, crops, or other significant areas.

Nutrient management services are available in the major farming regions, and both low and high-tech options, such as precision agriculture, are available to producers. A CNMP is only as good as the information provided; the extent to which assumptions regarding yield, weather, and similar factors prove true; and the extent to which the plan is followed precisely.

Operational Factors: Climate, temperature, and rainfall are all critical factors to be considered in the development of an NMP. Since CNMPs are site-specific, the requirements of each CNMP will vary depending on the conditions at each facility.

Demonstration Status: A report on state programs related to AFOs indicates that 27 states already require the development and use of waste management plans (USEPA, 1999a). The complexity and details of these plans vary among states, but they typically address waste generated, application rate, timing, location, nutrient testing, and reporting provisions. Further, industry data and site visits conducted by EPA indicate that practically all CAFOs have some form of management plan in place.

8.3.2 Nutrient Budget Analysis

For animal operations at which land application is the primary method of final disposal, a well-designed NMP determines the land area required to accept manure at a set rate that provides adequate nutrients for plants and avoids overloading soils and endangering the environment. The four major steps of this process are as follows:

- Determine crop yield goals based on site-specific conditions (e.g., soil characteristics).
- Determine crop nutrient needs based on individual yield goals.
- Determine nutrients available in manure and from other potential sources (e.g., irrigation water).
- Determine nutrients already available in the soil.

These four steps constitute a nutrient budget analysis, which provides the operator with an estimate of how much animal waste can be efficiently applied to agricultural crops so that nutrient losses are minimized. Various organizations, including Iowa State University (ISU, 1995), USDA NRCS (1998b), and USEPA (1999b), have developed guidance on performing nutrient budget analysis. The Iowa State University guidance includes detailed worksheets for estimating nutrient needs versus supply from animal manure and other sources.

8.3.2.1 Crop Yield Goals

Practice: Establishing Crop Yield Goals

Description: Establishing realistic yield goals should be the first step of an NMP. The yield goal is the realistic estimate of crop that will be harvested based on the soil and climate in the area (USDA NRCS, 1995). Realistic yield goals can be determined through the following:

- Historical yield information (Consolidated Farm Service Agency-USDA).
- Soil-based estimates of yield potential (county soil survey books and current soil nutrient content reports).
- Farmer's or owner's records of past yields.
- Yield records from a previous owner.

Yield potential is based on soil characteristics and productivity. The soil's yield potential can be obtained from Soil Survey Reports, county extension agencies, or NRCS offices. As the equation below shows, individual yield goals are calculated by multiplying the total acreage of a certain soil type by the yield potential of that soil, then dividing that sum by the total acres in the field:

$$\frac{\text{Total Acreage} \times \text{Yield Potential}}{\text{Total Acres in the Field}} = \frac{(\quad)}{(\quad)} = \_\_\_\_\_ \text{ bu/acre (Individual Yield Goal)}$$

Application and Performance: Realistic yield goals apply to all farms and all land to which nutrients are applied. Yield goals can be developed by the grower with assistance, as needed, from qualified company staff, government agency specialists, and private consultants. To be effective, yield goals must be site-specific, tailored to the soils on each field.

How well this practice performs depends on both good science and good fortune. Farmers are typically encouraged to set yield goals 5 to 10 percent above the average yield for the past 5 years or so (Hirschi et al., 1997). The intent is allow the farmer to benefit from a good year, while still reducing waste in the event that an off year occurs. Hirschi reports, however, that a survey of farmers in Nebraska showed that only one in ten reached their yield goals, with a full 40 percent of the farmers falling more than 20 percent below their yield goals.

Estimation of realistic yield goals does not address direct treatment or reduction of any pollutants, but is essential to determining the proper manure and commercial fertilizer application rates.

Advantages and Limitations: Reliance on a realistic yield goal is, by its very nature, an advantage for farmers. The challenge is to establish a yield goal that is truly realistic. Farmers who rely on their own yield records should use an average from the past 5 to 7 years, recognizing that it is impossible to foretell growing seasons accurately (Oldham, 1999).

If yield goals are set too high, there is the risk that nutrients will be applied in excess of crop needs. This translates into increased expense, increased levels of nutrients in the soil, and increased risk to surface water and ground water (Hirschi et al., 1997). If yield goals are set too low, the crop yield may be diminished because of a lack of nutrients. Further, if the crop yield is low during a bumper crop year, the producer risks a substantial loss of profits.

Universities publish yield goal information for use by farmers in all states, providing a ready source of information in the absence of better, site-specific records. In addition, seed suppliers have yield information that can be shared with farmers including the results from local field trials.

Operational Factors: A key challenge in estimating crop yield is determining which historic yield data, industry data, and university recommendations are most appropriate for a given farm. Farmers need to recognize that exceptionally good years are rare (Hirschi et al, 1997). Assumptions regarding the year's weather are also key, and, because farming is a business, crop prices affect farmers' estimates of realistic yield as well.

If planting dates are affected by spring weather, yields may suffer, creating the potential for over application of nutrients. Similarly, extended droughts or wet periods may affect yields. Hail and other similar weather events can also harm crops, resulting in actual yields that fall short of even reasonable yield goals.

Demonstration Status: Estimation of crop yield is a basic feature of farming, although the methods used and accuracy of the estimates vary.

8.3.2.2 Crop Nutrient Needs

Practice: Estimating Crop Nutrient Needs

Description: Crop nutrient needs are the nutrients required by the crop and soil to produce the yield goal. Crop nutrient needs can be calculated for detailed manure nutrient planning. For AFOs, N and P are the primary nutrients of concern, and significant research has been conducted on specific crop requirements for these nutrients. In some cases, nutrient planning analyses also evaluate K requirements.

Crop nutrient needs can be estimated by multiplying the realistic yield goal by a local factor for each nutrient-crop combination. For example, N factors for corn are provided for three regions in Iowa (USDA NRCS, 1995). If the yield goal is 125 bushels per acre and the N factor is 0.90, the N need for corn is 112.5 pounds per acre (125 x 0.90).

Application and Performance: Estimation of crop nutrient needs is a practice that applies to all farms and all land to which nutrients are applied. These estimates can be developed by the grower with assistance, as needed, from qualified company staff, government agency specialists,

and private consultants. Nutrient uptake and removal data for common crops are available from the NRCS, the local extension office, and other sources (Oldham, 1999).

The accuracy of this calculation depends on the accuracy of the yield goal and nutrient factors for the crop. In the case of Iowa corn, for example, N factors vary from 0.90 to 1.22. A farmer preparing for a good year might add a 10 percent cushion to the yield goal of 125 bushels per acre used above, resulting in a revised yield goal of 137.5 bushels per acre. The N need increases to 123.75 pounds per acre, an increase of 10 percent as well. If the year turns sour and the yield is 112.5 bushels per acre (10 percent less), the excess N applied becomes 22.5 pounds per acre (123.75-101.25) instead of 11.25 pounds per acre (112.5-101.25), or 100 percent greater.

Estimation of crop nutrient needs does not address direct treatment or reduction of any pollutants, but is essential to determining the proper manure and commercial fertilizer application rates.

Advantages and Limitations: The determination of N needs should account for any N in the organic fraction of manure that is not available the first year, any N carryover from previous legume crops, N carryover from previous manure applications, and any commercial N that will be applied. The major factors determining the amount and availability of carryover N are the total amount of N applied, N uptake in the initial crop, losses to air and water, N concentration, C:N ratio, soil temperature, and soil moisture (Wilkinson, 1992).

In their analysis of nutrient availability from livestock, Lander et al. (USDA NRCS, 1998a) assumed that 70 percent of N applied in manure would be available to the crop. NH_3 volatilization, nitrate leaching, and runoff losses reduce the amount of available nutrient, and the percentage available also varies depending on soil temperature, soil moisture, organism availability, and the presence of other nutrients and essentials. When dry or liquid manure is incorporated immediately following application in the north-central region of the United States, about 50 percent of the N is available to the crop (Hirschi et al., 1997).

In North Carolina, it is estimated that half of the total N in irrigated lagoon liquid and 70 percent of the total N in manure slurries that are incorporated into the soil is available to plants (Barker and Zublena, 1996). Plant availability coefficients for N range from 25 percent (dry litter or semisolid manure broadcast without cultivation, and liquid manure slurry irrigated without cultivation) to 95 percent (injected liquid manure slurry and lagoon liquid), depending on form of the manure and method of application (Barker, 1996). For both P and K, the range is 60 to 80 percent, with the higher values for injection of liquid manure slurries and lagoon liquids, and application of lagoon liquids through broadcasting or irrigation with cultivation. The lower values in the range apply to broadcasting dry litter and semisolid manure with no cultivation. The results from plot studies conducted on Cecil sandy loam in Georgia indicate that carryover N from broiler litter should be factored into NMPs for periods longer than 3 years (Wilkinson, 1992).

In Ohio, only about one-third of the Org-N in animal manure is available to crops during the year it is applied (Veenhuizen et al., 1999). The P and K in the manure are available during the year they are applied, as are the equivalent amounts of fertilizer-grade P and K. Ohio State University Extension has published tables that show the estimated percentage of residual organic N that will be available in the 10 years after initial application.

In addition to Org-N in manure, other sources of N can be significant and are included in the calculation of N needs:

- Mineralization of soil organic matter
- Atmospheric deposition
- Residue mineralization
- Irrigation water

If appropriate, contributions from these sources should be subtracted from the total amount of N needed. A general value for calculating the N mineralized per acre from soil organic matter (SOM) is 40 pounds per year for each 1 percent of SOM. The amount of N from atmospheric deposition can be as much as 26 pounds per acre per year, but local data should be used for this estimate. Irrigation additions can be estimated by multiplying the N concentration (in parts per million) by the quantity of water applied (in acre-inches) by 0.227 (USDA NRCS, 1996a).

As discussed earlier, nutrient planning based on N levels alone could lead to excessive soil P levels, thereby increasing the potential for P to be transported in runoff and erosion. Soil P levels should be determined and compared with crop needs before manure or fertilizer containing P is applied. This can be accomplished by comparing annual P removal rates based on the type of crop planted with the amount of P applied the previous year. As with N, data are available for plant removal rates by specific crop.

Operational Factors: As noted above, the major factors determining the amount and availability of carryover N include losses to air and water, soil temperature, and soil moisture (Wilkinson, 1992). In addition, mineralization of soil organic matter, atmospheric deposition, residue mineralization, and irrigation water applications are all related to climate, temperature, and rainfall.

Demonstration Status: Estimation of crop nutrient needs is a basic feature of farming. The methods used vary, however, as does the accuracy of the estimates.

8.3.2.3 Nutrients Available in Manure

Manure is an excellent fertilizer because it contains at least low concentrations of every element necessary for plant growth. The most important macronutrients in manure are N, P, and K, all of which come from urine and feces. The chemical composition of manure when it is excreted from the animal is determined largely by the following variables:

- Species of animal
- Breed
- Age
- Gender
- Genetics
- Feed ration composition

The composition of manure at the time it is applied usually varies greatly from when it was excreted from the animal. The nutrients in manure undergo decomposition at varying rates influenced by the following factors:

- Climate (heat, humidity, wind, and other factors).
- Length of time the manure is stored.
- Amount of feed, bedding, and water added to manure before removal from the animal housing facility.
- Type of production facility.
- Method of manure handling and storage.
- Method and timing of land application.
- Use of manure/pit additives.
- Soil characteristics at time of application.
- Type of crop to which manure is applied.
- Net precipitation/evaporation in storage structure.
- Uncontrollable anomalies (e.g., broken water line).
- Ratio of nutrients that have been transformed or lost to the atmosphere or soil profile.

Given these many factors, it is nearly impossible to predict the nutrient content of manure in every animal production setting. Several state extension and university publications have attempted to predict nutrient contents for different species of animals at specific production phases. These book values are an educated guess at best and vary widely from state to state. It is imperative that livestock producers monitor the nutrient content of their manure on a consistent basis. Knowing the content of macronutrients in manure is an important step to proper land application.

Nitrogen

The total amount of N in manure is excreted in two forms. Urea, which rapidly hydrolyzes to NH_3, is the major N component of urine. Org-N, excreted in feces, is a result of unutilized feed, microbial growth, and metabolism in the animal.

$$\text{Total N} = NH_3 \text{ (ammonia)} + \text{Org-N}$$

The ratio of NH_3 to Org-N in the manure at the time of excretion is largely dependent on species, feed intake, and the other factors discussed above.

Before land application, inorganic N forms can be lost either to the atmosphere or into the soil profile, decreasing the nutrient value of the manure. Depending on the type of manure-handling and storage system and other factors described above, variable amounts of Org-N can be mineralized to inorganic forms, which then can be lost to the atmosphere or into the soil profile. N can be lost from manure in the following three ways:

1. NH_3 is volatilized into the atmosphere.
2. NO_3 (nitrate, a product of mineralization and nitrification) undergoes denitrification and is released into the atmosphere as N_2 (inert N gas).
3. NO_3 (nitrate, a water soluble form of N) is leached and carried down through the soil profile, where it is unavailable to plants.

Agitation of liquid manure prior to land application is extremely important. Solids will separate from still manure. The liquid will largely consist of the mineralized, inorganic forms of N, whereas the solid portions will contain the organic forms of N that are unavailable to plants. Proper agitation suspends the solids and helps ensure that the manure will be a more uniform and predictable fertilizer.

When manure is applied to land, the N content exists in two major forms, the ratio of which can be determined only by manure analysis. The amount of N that will be available to fertilize the plant will depend on the method and timing of application. The balance of the N available to the plant will be lost in one of the three ways described above or will remain immobilized in the organic form. It is generally agreed that 25 to 50 percent of N applied in the organic form will undergo mineralization and become available to plants in the first year. The remaining Org-N will mineralize and become available in subsequent years.

When manure is applied to the surface of land without incorporation into the soil, much of the inorganic N remains on the surface, is lost, and will never be available to the plant. Volatilization of NH_3 is the most significant loss factor and is greatest when drying conditions (dry, warm, sunny days) dominate. Field estimates of volatilization loss from surface-applied manure range from about 10 to 70 percent of NH_3-N applied (CAST, 1996).

When manure is incorporated into the soil, inorganic forms of N available to the plant are placed directly into the root zone and volatilization is minimized. The inorganic ammonia/ammonium is either taken up by the plant or converted to nitrate. The nitrate can then be taken up by the plant, denitrified, and released into the atmosphere as N gas, or carried by water through the root zone. In addition, the organic N fraction has more contact with soil microbes when incorporated, resulting in a greater rate of mineralization.

Phosphorus

The vast majority of P contained in manure is derived from the feces. Only small amounts of P are present in livestock urine. As with N, the amount of P excreted by an animal depends on several factors already discussed.

The introduction of water, bedding, and feed into the manure can affect both the nutrient concentration and the content of the manure product. Manure handling and storage have little influence on the P concentration. Any loss of P is a result of runoff from feedlots or solids settling in holding basins, storage tanks, or lagoons. This will not be a loss if it is collected and used later.

Most of the P is present in solid manure. As stated for N, proper agitation resuspends the solids and makes the manure a more uniform and predictable fertilizer.

Although method and timing of land application have little direct effect on the transformation of P to plant-available forms, they greatly influence the potential loss of P through runoff. Estimates of P vary widely (CAST, 1996); however, by current estimates, somewhere near 70 percent is available for plant uptake in the first year following manure application (Koelsch, 1997).

Potassium

In most species, K is equally present in both urine and feces. Similarly, the amount of K in manure is fairly constant between liquids and solids and is not influenced by agitation. As with the other macronutrients, the amount of K excreted by an animal depends on a multitude of factors already discussed.

As with P, the introduction of water, bedding, and feed to the manure can affect both the K concentration and the content of the manure product. Manure handling and storage have little influence on the K concentration. Any loss of K is a result of runoff from feedlots or solids settling in holding basins, storage tanks, or lagoons. This will not be a loss if it is collected and used later.

As for P, the method and timing of land application have little direct effect on the transformation of K to plant-available forms, but they greatly influence the potential loss of K through runoff.

Most of the K in manure is in the soluble form and is therefore readily available for plant uptake. Availability is estimated to be about 90 percent (Koelsch, 1997).

Swine-Specific Information

Swine excrete approximately 80 percent of the N and P and approximately 90 percent of the K in the feed ration (Sutton et al., 1996). Swine manure can be handled as a slurry, liquid (with the addition of wastewater), or solid (with the addition of large amounts of bedding).

Estimates of the nutrient content of swine manure classified by manure handling type and production phase are given in Table 8-19. The values were compiled from university, extension service, and government agency publications from around the United States. The wide range of values is due to the many factors discussed earlier in this section.

Table 8-19. Swine Manure Nutrient Content Ranges

Source	Units	Total N	NH_4	P	K
ASAE, 1998	pounds/ton	12.4	6.9	4.3	4.4
USDA NRCS, 1996a (farrow, storage tank under slats)	pounds/1,000 gal	29.2	23.3	15.0	23.3
USDA NRCS, 1996a (nursery, storage tank under slats)	pounds/1,000 gal	40.0	33.3	13.3	13.3
USDA NRCS, 1996a (grow/finish, storage tank under slats)	pounds/1,000 gal	52.5	—	22.5	18.3
USDA NRCS, 199a6 (breeding/gestation, storage tank under slats)	pounds/1,000 gal	25.0	—	10.0	17.5
USDA NRCS, 1996a (anaerobic lagoon liquid)	pounds/1,000 gal	2.9	1.8	0.6	3.2
USDA NRCS, 1996a (anaerobic lagoon sludge)	pounds/1,000 gal	25.0	6.3	22.5	63.3
USDA NRCS, 1998a (Breeding hogs, after losses)	pounds/ton	3.3	—	3.6	7.0
USDA NRCS, 1998a (Other types of hogs, after losses) [a]	pounds/ton	2.8	—	2.8	7.2
Jones and Sutton, 1994 (farrow, pit storage)	pounds/1,000 gal	15.0	7.5	5.2	9.1
Jones and Sutton, 1994 (nursery, pit storage)	pounds/1,000 gal	24.0	14.0	8.7	18.3
Jones and Sutton, 1994 (grow/finish, pit storage)	pounds/1,000 gal	32.8	19.0	11.5	22.4
Jones and Sutton, 1994 (breeding/gestation, pit storage)	pounds/1,000 gal	25.0	12.0	13.5	22.4
Jones and Sutton, 1994 (farrow, anaerobic lagoon)	pounds/1,000 gal	4.1	3.0	0.9	1.7
Jones and Sutton, 1994 (nursery, anaerobic lagoon)	pounds/1,000 gal	5.0	3.8	1.4	2.7
Jones and Sutton, 1994 (grow/finish, anaerobic lagoon)	pounds/1,000 gal	5.6	4.5	1.7	3.5
Jones and Sutton, 1994 (breeding/gestation, anaerobic lagoon)	pounds/1,000 gal	4.4	3.3	1.9	3.3
Reichow, 1995 (no bedding)	pounds/ton	10.0	6.0	3.9	6.6
Reichow, 1995 (bedding)	pounds/ton	8.0	5.0	3.1	5.8
NCSU, 1994 (paved surface scraped)	pounds/ton	13.0	5.6	5.8	7.6
NCSU, 1994 (liquid manure slurry)	pounds/1,000 gal	26.5	16.8	8.3	12.6
NCSU, 1994 (anaerobic lagoon liquid)	pounds/1,000 gal	4.7	3.8	0.8	4.0
NCSU, 1994 (anaerobic lagoon sludge)	pounds/1,000 gal	24.4	5.9	23.0	5.4

—Data not available.
[a] Selected for nutrient production calculations throughout this document.

Poultry-Specific Information

Excreted poultry manure has a moisture content of around 80 percent. It can be handled as a slurry or liquid, or in a dry form with added bedding (referred to as litter). Estimates of the nutrient content of chicken and turkey manure are given in Table 8-20. The values were compiled from university, extension service, and government agency publications from around the United States. The wide range of values is due to the many factors discussed earlier in this section.

Table 8-20. Poultry Manure Nutrient Content Ranges

Source	Units	Total N	NH_4	P	K
ASAE, 1998 (layer)	pounds/ton	26.3	6.6	9.4	9.4
USDA NRCS, 1996a (layer, anaerobic lagoon supernatant)	pounds/1,000 gal	6.3	4.6	0.8	8.3
USDA NRCS, 1996a (layer, anaerobic lagoon sludge)	pounds/1,000 gal	32.5	7.7	45.8	6.0
USDA NRCS, 1996a (layer with no bedding or litter)	pounds/ton	35.4		22.9	25.0
Jones and Sutton, 1994 (layer, pit storage)	pounds/1,000 gal	60.0	13.0	19.7	23.2
Jones and Sutton, 1994 (layer, anaerobic lagoon)	pounds/1,000 gal	7.0	5.5	1.7	2.9
NCSU, 1994 (layer paved surface scraped)	pounds/ton	28.2	14.0	13.8	16.2
NCSU, 1994 (layer unpaved deep pit storage)	pounds/ton	33.6	11.8	22.3	21.9
NCSU, 1994 (layer liquid manure slurry)	pounds/1,000 gal	57.3	36.8	22.7	27.5
NCSU, 1994 (layer anaerobic lagoon liquid)	pounds/1,000 gal	6.6	5.6	0.7	8.5
NCSU, 1994 (layer anaerobic lagoon sludge)	pounds/1,000 gal	20.8	6.5	33.7	8.1
ASAE, 1998 (broiler)	pounds/ton	25.9	—	7.1	9.4
USDA NRCS, 1996a (broiler litter)	pounds/1,000 gal	38.9	—	19.4	22.9
USDA NRCS, 1998a (broiler, as excreted)	pounds/ton	26.8	—	7.8	10.5
USDA NRCS, 1998a (broiler, after losses) [a]	pounds/ton	16.1	—	6.6	9.5
Jones and Sutton, 1994 (broiler, pit storage)	pounds/1,000 gal	63.0	13.0	17.5	24.1
Jones and Sutton, 1994 (broiler, anaerobic lagoon)	pounds/1,000 gal	8.5	5.0	1.9	2.9
NCSU, 1994 (broiler litter)	pounds/ton	71.4	12.0	30.3	38.7
NCSU, 1994 (stockpiled broiler litter)	pounds/ton	32.6	6.9	33.5	26.6
NCSU, 1994 (broiler house manure cake)	pounds/ton	45.5	11.8	23.0	29.9
ASAE, 1998 (turkey)	pounds/ton	26.4	3.4	9.8	10.2
USDA NRCS, 1996a (turkey litter)	pounds/1,000 gal	72.4	0.8	32.9	37.0
USDA NRCS, 1998a (turkeys for slaughter, as excreted)	pounds/ton	30.4	—	11.8	11.6
USDA NRCS, 1998a (turkeys for slaughter, after losses) [a]	pounds/ton	16.2	—	10.1	10.4
USDA NRCS, 1998a (turkey hens, as excreted)	pounds/ton	22.4	—	13.2	7.6
USDA NRCS, 1998a (turkey hens, after losses) [a]	pounds/ton	11.2	—	11.2	6.8
Jones and Sutton, 1994 (turkey tom, pit storage)	pounds/1,000 gal	53.0	16.0	17.5	24.4
Jones and Sutton, 1994 (turkey hen, pit storage)	pounds/1,000 gal	60.0	20.0	16.6	26.6
Jones and Sutton, 1994 (turkey tom, anaerobic lagoon)	pounds/1,000 gal	8.0	6.0	1.7	3.7
Jones and Sutton, 1994 (turkey hen, anaerobic lagoon)	pounds/1,000 gal	8.0	6.0	1.7	3.3
NCSU, 1994 (turkey house manure cake)	pounds/ton	44.8	20.1	20.3	24.8
NCSU, 1994 (stockpiled turkey litter)	pounds/ton	31.6	5.5	30.4	25.0

—Data not available.

[a] Selected for nutrient production calculations throughout this document

Dairy Specific Information

Because of the variety of housing and production options associated with dairies, many dairies have a combination of solid-, liquid-, or semisolid-based handling systems. Milking parlors commonly generate a large amount of wastewater from frequent flushing and cleaning of facilities and cows. Dry cows are often housed outdoors in open lots, while cows being milked may be kept in covered or completely enclosed freestall barns or holding pens.

Estimates of the nutrient content of dairy manure classified by manure handling type are given in Table 8-21. The values were compiled from university, extension service, and government agency publications from around the United States. The wide range of values is due to the many factors discussed earlier in this section.

Table 8-21. Dairy Manure Nutrient Content Ranges

Source	Units	Total N	NH_4	P	K
ASAE, 1998	pounds/ton	10.5	1.8	2.2	6.7
USDA NRCS, 1996a (as excreted, lactating cow)	pounds/ton	11.3	—	1.8	6.5
USDA NRCS, 1996a (as excreted, dry cow)	pounds/ton	8.8	—	1.2	5.6
USDA NRCS, 1996a (heifer)	pounds/ton	7.3	—	0.9	5.6
USDA NRCS, 1996a (anaerobic lagoon supernatant)	pounds/1,000 gal	1.7	1.0	0.5	4.2
USDA NRCS, 1996a (anaerobic lagoon sludge)	pounds/1,000 gal	20.8	4.2	9.2	12.5
USDA NRCS, 1996a (aerobic lagoon supernatant)	pounds/1,000 gal	0.2	0.1	0.1	—
USDA NRCS, 1998a (milk cows, as excreted)	pounds/ton	10.7	—	1.9	6.7
USDA NRCS, 1998a (milk cows, after losses)[a]	pounds/ton	4.3	—	1.7	6.0
USDA NRCS, 1998a (heifer & heifer calves, as excreted)	pounds/ton	6.1	—	1.3	5.0
USDA NRCS, 1998a (heifer & heifer calves, after losses)[a]	pounds/ton	1.8	—	1.1	4.5
Reichow, 1995 (dry without bedding)	pounds/ton	9.0	4.0	1.7	8.3
Reichow, 1995 (dry with bedding)	pounds/ton	9.0	5.0	—	—
Jones and Sutton, 1994 (mature cow, pit storage)	pounds/1,000 gal	31.0	6.5	6.6	15.8
Jones and Sutton, 1994 (heifer, pit storage)	pounds/1,000 gal	32.0	6.0	6.1	23.2
Jones and Sutton, 1994 (dairy calf, pit storage)	pounds/1,000 gal	27.0	5.0	6.1	19.9
Jones and Sutton, 1994 (mature cow, anaerobic lagoon)	pounds/1,000 gal	4.2	2.3	0.8	2.5
Jones and Sutton, 1994 (heifer, anaerobic lagoon)	pounds/1,000 gal	4.3	2.1	0.9	2.5
Jones and Sutton, 1994 (dairy calf, anaerobic lagoon)	pounds/1,000 gal	3.0	2.0	0.4	2.1
NCSU, 1994 (paved surface scraped)	pounds/ton	10.3	2.5	3.1	7.1
NCSU, 1994 (liquid manure slurry)	pounds/1,000 gal	22.0	9.2	6.0	16.6
NCSU, 1994 (anaerobic lagoon liquid)	pounds/1,000 gal	4.9	3.2	1.2	5.4
NCSU, 1994 (anaerobic lagoon sludge)	pounds/1,000 gal	19.2	6.2	18.3	7.7

—Data not available.
[a]Selected for nutrient production calculations throughout this document

Beef Cattle-Specific Information

Most beef cattle are produced in an open-lot setting, but some moderate-size operations produce beef in confinement. The nutrient content of feedlot manure is extremely difficult to quantify because of inconsistency in collection methods and content. Varying amounts of dirt, bedding, and precipitation are mixed with the bedding at different times of the year.

Estimates of the nutrient content of beef manure are given in Table 8-22. The ranges were compiled from university, extension service, and government agency publications from around the United States. The wide range of values is due to the many factors discussed earlier in this section.

Table 8-22. Beef Manure Nutrient Content Ranges

Source	Units	Total N	NH_4	P	K
ASAE, 1998	pounds/ton	11.7	3.0	3.2	7.2
USDA NRCS, 1996a (as excreted, high forage diet)	pounds/ton	10.5	—	3.7	8.1
USDA NRCS, 1996a (as excreted, high energy diet)	pounds/ton	10.2	—	3.2	7.1
USDA NRCS, 1996a (feedlot manure)	pounds/ton	24.0	—	16.0	3.4
USDA NRCS, 1998a (beef cows, as excreted)	pounds/ton	11.0	—	3.8	8.3
USDA NRCS, 1998a (beef cows, after losses)[a]	pounds/ton	3.3	—	3.2	7.4
USDA NRCS, 1998a (steers, calves, bulls, and bull calves, as excreted)	pounds/ton	11.0	—	3.4	7.9
USDA NRCS, 1998a (steers, calves, bulls, and bull calves, after losses)[a]	pounds/ton	3.3	—	2.9	7.1
USDA NRCS, 1998a (fattened cattle, as excreted)	pounds/ton	11.0	—	3.4	7.9
USDA NRCS, 1998a (fattened cattle, after losses)[a]	pounds/ton	4.4		2.9	7.1
Reichow, 1995 (dry without bedding)	pounds/ton	21.0	7.0	6.1	19.1
Reichow, 1995 (dry with bedding)	pounds/ton	21.0	8.0	7.9	21.6
Jones and Sutton, 1994 (pit storage)	pounds/1,000 gal	20.0	—	3.1	16.5
Jones and Sutton, 1994 (anaerobic lagoon)	pounds/1,000 gal	4.0	—	0.6	2.7
NCSU, 1994 (paved surface scraped)	pounds/ton	13.8	1.9	4.2	10.7
NCSU, 1994 (unpaved surface scraped)	pounds/ton	25.0	4.7	7.8	17.9
NCSU, 1994 (liquid manure slurry)	pounds/1,000 gal	35.0	14.6	9.9	61.6
NCSU, 1994 (anaerobic lagoon, liquid)	pounds/1,000 gal	3.4	2.3	0.8	4.1
NCSU, 1994 (anaerobic lagoon, sludge)	pounds/1,000 gal	38.2		25.7	12.1

—Data not available.
[a] Selected for nutrient production calculations throughout this document.

Practice: Manure Testing

Description: The nutrient composition of manure varies widely among farms because of differences in animal species and management, and manure storage and handling (Busch et al., 2000). The only method available for determining the actual nutrient content of manure for a particular operation is laboratory analysis. Typical laboratory reports show the moisture content and percentage of N, P, K, Ca, Mg, and Na, as well as the concentration (parts per million) of Zn, Fe, Cu, Mn (McFarland et al., 1998; USDA NRCS, 1996a). Other information, such as the pH and conductivity for liquid samples, is also provided.

Sampling should be performed as close as possible to the time of land application to limit error resulting from losses occurring during handling, storage, and application (Schmitt, 1999; Busch et al., 2000; Bonner et al., 1998; Sharpley et al., 1994). The best time to collect a representative manure sample is during the loading or application process (Schmitt, 1999), but the test results from such sampling cannot be used to plan the current manure applications. Sampling during hauling is considered more accurate and safer than sampling at storage structures (Busch et al., 2000). Subsamples should be collected from several loads and then composited into a single sample. This applies to liquid, solid, or semisolid systems. Because the nutrients in manure are not distributed evenly between the urine and feces portions, mixing is critical to obtaining a representative sample.

Barker and Zublena (1996) recommend that land-applied manure be sampled and analyzed twice annually for nutrient and mineral content. New sampling should be conducted whenever animal management practices change. For example, if there is a significant change in animal rations or operation management (e.g., a change in the size or type of animals raised), new sampling should be conducted. If manure is applied several times a year, samples should be taken during the period of maximum manure application. For example, if the manure that has accumulated all winter will be used as a nutrient source, sampling should be done before application in the spring.

For systems that are emptied or cleaned out once a year, it is recommended that sampling be conducted each time the manure is applied (Busch et al., 2000). This applies to uncovered lagoons, pits, basins, and stacking slabs. Manure from under-barn concrete pits or covered aboveground tanks will not vary as much between applications, unless the type of animal or another significant factor changes. Systems emptied twice a year or more might differ between application times, so a fall analysis might not be accurate for planning spring applications.

Application and Performance: Manure sampling is a practice that applies to all farms and all land on which manure is applied. The farmer or trained consultants can conduct the sampling.

Manure sampling does not address direct treatment or reduction of any pollutants, but is essential to determining the proper manure and commercial fertilizer application rates.

Advantages and Limitations: Manure analysis is the only way in which the actual nutrient content can be determined. Standardized tables of manure nutrient content do not reflect how variable the true nutrient content can be, but they can be useful in planning facilities and land application areas (Hirschi et al., 1997).

Convenient laboratory reports allow farmers to easily determine the pounds per ton of nutrients in solid manure, or pounds per acre-inch in liquid manure (McFarland et al., 1998). Laboratories are available at universities in most states, and lists of service providers can be obtained from county offices and the Internet.

Without manure analysis, farmers might buy more commercial fertilizer than is needed or spread too much manure on their fields (USDA NRCS, 1996a). Either practice can result in overfertilization, which, in turn, can depress crop yields and cut profits. Improper spreading of manure can also pollute surface and ground water.

Sampling from manure application equipment is quick, but the test results cannot be used to plan the current year's manure applications. Sampling before hauling allows use of the test results for the current year, but retrieving an accurate sample is difficult because the manure is not mixed. Further, there is the danger of falling into manure storage structures.

Operational Factors: Sample collection procedures vary considerably depending on manure form and storage, but all are intended to provide representative samples in a safe and convenient manner. Homogeneity is the key to simple sampling procedures, but the nutrient content of manure usually varies considerably within storage structures and stockpiles. For this reason, agitation of liquid manure and mixing of solid manure are generally recommended prior to sampling. Alternatively, several samples can be taken from different locations and depths within a lagoon, pit, or manure stack. Sampling each of several loads of hauled manure is another option to address spatial variability of manure nutrient content. The process of agitating and loading manure is believed to provide mixing that ensures representative sampling (Busch et al., 2000).

The number of samples to be taken for suitable results depends on the variability of the manure sampled (Busch et al., 2000). One sample may be adequate for agitated liquid slurries and lagoon liquids, whereas three or more samples may be needed for stacked solids. It is recommended that one sample be taken per poultry house.

Hirschi et al. (1997) recommend taking solid manure samples from several locations in a manure stack or on a feedlot, mixing them together in a tied, 1-gallon plastic bag, placing that bag inside another bag, and then freezing the sample before shipping to a laboratory for analysis. Busch et al. (2000) say that 10 to 20 subsamples should be taken from different depths and locations using a pitchfork or shovel. In Texas, five to seven random subsamples are recommended (McFarland et al., 1998). The subsamples are placed in a pile and mixed before a composite sample is taken.

Busch et al. (2000) recommend that samples be taken from the manure in the tank or spreader box on its way to the field for application. For solid manure, samples should be collected from application equipment using a pitchfork, shovel, or plastic glove, avoiding large pieces or chunks of bedding. The sample taken to the lab should be a mixture of manure taken from several (5 to 10) loads representing the beginning, middle, and end of the application process. Subsamples should be mixed thoroughly, prior to filling a sample jar three-fourths full, allowing room for gas expansion. Jars should be cleaned and sealed in a plastic bag, and samples should be frozen before being mailed.

Bonner et al. (1998) suggest that samples can be collected by using catch pans in the field as the material is applied to the land. Samples from multiple pans are mixed to form the overall sample, and a 1-liter plastic bottle is filled halfway to allow for gas expansion. Samples should be frozen or kept cold until delivered to a laboratory.

Rather than sampling from the lagoon or pit, samples can be retrieved with a plastic pail or a coffee can on a pole from the top of the spreader or from the bottom unloading port (Busch et al., 2000). Sampling should be done immediately after filling.

Hirschi et al. (1997) recommend agitating or mixing liquid manures prior to sampling unless it is more practical to take samples from several areas within a lagoon or pit and then mix them. To sample from lagoons and storage facilities, a plastic container attached to a pole or rod is recommended (Bonner et al., 1998; McFarland et al., 1998; Busch et al., 2000). Alternatively, a ½- or ¾-inch PVC pipe can be pushed into the manure to a depth no closer than 1 foot from the bottom (Busch et al., 2000). The sample can be secured by placing a hand over the top of the pipe and pulling the pipe up. Samples should be taken from 5 to 10 locations around the lagoon, covering several depths to include solids. After mixing the samples in a bucket, a representative sample is then taken to a laboratory for analysis.

Demonstration Status: Manure sampling is practiced widely across the United States, but many farmers still do not test manure or employ an N credit from manure when determining commercial fertilizer needs (Stevenson, 1995). A 1995 survey of 1,477 swine producers showed that 92 percent of operations had not had their manure tested for nutrients within the past 12 months (USDA APHIS, 1995). Approximately 6 percent had tested their manure for nutrients once during the past 12 months, while another 1.5 percent had tested it twice. These findings are supported by a crop nutrient management survey in which only 2 to 17 percent of respondents in various regions stated that they factored manure nutrient values into their NMPs (Marketing Directions, 1998).

8.3.2.4 Nutrients Available in Soil

A major problem in using organic nutrient sources such as animal waste is that their nutrient content is rarely balanced with the specific soil and crop needs. For example, the N:P ratio in applied manure is usually around 3 or less, whereas the ratio at which crops use nutrients typically ranges from 5 to 7. Therefore, when manure is applied at rates based solely on N

analysis and crop need for N, P is applied in excess of crop needs. Because the amounts of P added in manure exceed the amounts removed by crops, continuous use of manure can result in accumulations of excess P in the soil, increasing the potential for P to be transported in runoff and erosion (Sharpley et al., 1999).

A recent change of emphasis in NMPs has been to base manure application rates on both P and N needs. Different soil types can accommodate different P concentrations before experiencing significant P export in runoff. The amount of P that a soil can hold depends on the availability of binding sites. For example, a clayey soil will tend to be able to retain more P than a sandy soil because clays have a greater surface area and typically contain a greater proportion of iron, which has a strong affinity for P. Table 8-23 demonstrates the variability of the P-binding capacity of several soils. P bound to soils is primarily in a particulate form; however, as a soil becomes saturated with P, the finite number of binding sites will be overwhelmed and P can be released into runoff or ground water in a soluble form.

Table 8-23. Maximum P-Fixation Capacity of Several Soils of Varied Clay Contents.

Soil Great Group (and series)	Location	Percent clay	Maximum P fixation (mg P/ kg soil)
Evesboro (Quartzipsamment)	Maryland	6	125
Kitsap (Xerochrept)	Washington	12	453
Matapeake (Hapludult)	Maryland	15	465
Newberg (Haploxeroll)	Washington	38	905

Source: Brady and Weil, 1996.

P Threshold - The concept of a P threshold (TH) has been developed to identify soil P levels at which soluble losses of P in runoff become significant. The recently revised USDA NRCS nutrient management policy (Part 402) addressing organic soil amendments, such as manures, proposes that for soils with a known P TH the following P manure application rates apply:

- If soil P levels are below 75 percent of the P TH, N-based manure application is allowed.
- If soil P levels are between 75 percent and 150 percent of the P TH, manure application rates should be based on the amount of P estimated to be removed by the crop.
- If soil P levels are between 150 percent and 200 percent of the P TH, manure application rates should be based on one-half the amount of the P estimated to be removed by the crop.
- If soil P levels are greater than twice (200 percent) the P TH, no manure should be added to the soil.
- When no soil-specific TH data are available, P application should be based on soil P test levels.

- If the soil P test level is low or medium, the application rate of organic soil amendments (e.g., manure) can be based on the soil's N content.
- If the soil P level is high, the manure application rate should be based on 1.5 times the P estimated to be removed by the crop.
- If the soil P level is very high, the manure application rate should be based on the P estimated to be removed by the crop.
- If the soil P level is excessive, no manure should be applied.

Phosphorus Index The concept of a P index is still evolving, but it is a tool that assesses the potential risk of P movement to water bodies. Both natural (e.g., rainfall, soil type, slope) and human (e.g., farming practices) factors influence the transformation and ultimate fate of P in the agricultural landscape. The P index looks at site-specific characteristics to identify where corrective soil and water conservation practices can be used to reduce the movement of P into surface water and thus reduce the threat of eutrophication. These characteristics are assigned a value based upon the site vulnerability and are weighted according to their assumed relative effect on potential P loss. Table 8-24 presents a list of nine site characteristics that may be used

Table 8-24. The P index.

Site characteristic (Weighting factor)	Loss rating (value)				
	None	Low (1)	Medium (2)	High (4)	Very high (8)
Soil erosion (1.5)	N/A	<5 tons/acre	5 to 10 tons/acre	10 to 15 tons/acre	>15 tons/acre
Irrigation erosion (1.5)	N/A	Infrequent irrigation on well-drained soils	Moderate irrigation on soils with slopes <5%	Frequent irrigation on soils with slopes of 2 to 5%	Frequent irrigation on soils with slopes of >5%
Soil runoff class (0.5)	N/A	Very low or low	Medium	Optimum	Excessive
Distance from watercourse (1.0)	> 1,000 ft	1,000 to 500 ft	500 to 200 ft	200 to 30 ft	<30 ft
Soil test P (1.0)	N/A	Low	Medium	Optimum	Excessive
P fertilizer application rate, lb P/acre (0.75)	None applied	<15	16 to 40	41 to 65	>65
P fertilizer application method (0.5)	None applied	Placed with planter deeper than 2 inches	Incorporated immediately before crop	Incorporated >3 months before crop or surface applied <3 months before crop	Surface applied to pasture or applied >3 months before crop
Organic P source application rate, lb P/acre (1.0)	None applied	<15	16 to 40	41 to 65	>65
Organic P source application method (0.5)	None applied	Injected deeper than 2 inches	Incorporated immediately before planting	Incorporated >3 months before crop or surface applied <3 months before crop	Surface applied to pasture or applied >3 months before crop

Source: USDA ARS, 1999.

to develop a P index (USDA ARS, 1999). Also presented are suggested weighting factors and loss ratings. The USDA continues to perform extensive research on factors that may be used in the development of a P index. Most states have developed customized P indexes to account for site-specific conditions that influence both soluble P losses and particulate P losses resulting from erosion.

The vulnerability of the site to P loss is estimated by multiplying the ratings value for each characteristic by the weighting factor and then summing all the weighted values to produce the P index for the site. Table 8-25 presents generalized interpretation of the P index. Site-specific factors will have a large impact on P loss. USDA recommends that efforts by farmers, extension agronomists, and soil conservation specialists be coordinated to identify management options that can reduce P loss to surface waters. Management options recommended by USDA include soil testing, soil conservation, and nutrient management. Actions become progressively proactive as the P index of a site increases.

For instance, an area prone to P transport, such as a field rich in P located on erodible soils adjacent to a reservoir, would receive a high score identifying the importance of implementing a management program. Such a site would need a comprehensive long-term P management plan including no application of fertilizer or manure for 3 or more years. Fields with a lower P index would require less severe management options and manure and fertilizer application programs could be developed accordingly.

Table 8-25. Generalized Interpretation of the P index.

P index	General vulnerability to P loss
< 8	**Low** potential for P loss. If current farming practices are maintained, there is a low probability of adverse impacts on surface waters.
8 to 14	**Medium** potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the probability of P loss.
15 to 32	**High** potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and P management plans are needed to minimize the probability of P loss.
> 32	**Very high** potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss.

Source: USDA ARS, 1999.

Practice: Soil Testing

Description: Soil testing, an important tool for determining crop nutrient needs, evaluates the fertility of the soil to determine the basic amounts of fertilizer and lime to apply (USDA NRCS, 1996a). Soil tests should be conducted to determine the optimum nutrient application of N and P,

pH, and organic matter. Typical laboratory reports show soil pH, P, K, Ca, Mg, Zn, and Mn levels, plus fertilizer and lime recommendations (USDA NRCS, 1996a). Special analyses for organic matter, nitrate-N, and soluble salts can be requested.

The best time to sample soil is after harvest or before fall or spring fertilization. Late summer and fall are best because K test results are most reliable at these times (Hirschi et al., 1997). The worst time to sample is shortly after the application of lime, commercial fertilizer, or manure, or when the soil is extremely wet. Samples are usually composited to determine a general application rate for a specific field or field section. The goal is to obtain a representative view of the field conditions. This can be achieved by sampling in areas that have similar soil types, crop rotation, tillage type, and past fertility programs. In addition, soil samples should be taken at random in a zigzag pattern, making sure to avoid irregularities in the land (e.g., fence lines, very wet areas) to get samples that accurately portray the landscape. Two weaknesses of random sampling in a zigzag pattern are the assumptions that the composite sample is representative of the entire field and that the result of the sampling produces an average value for the field (Pocknee and Boydell, 1995). Samples can be gathered and composited over smaller areas to determine distinct treatment options. To evaluate the variability of the land, the grid method of dividing the field into 5-acre plots can also be used. Treatment decisions can be made by balancing labor requirements, environmental concerns, and economics.

Grid-cell sampling and grid-point sampling are two sampling methods used on farms where precision farming is practiced. In grid-cell sampling, an imaginary grid is laid over the sampling area and soil cores are taken randomly within each cell, bulked, and mixed. A subsample is then taken from the composite sample for analysis. This approach is considered similar to the random sampling method, with the exception that the sampled area is divided up into many smaller "fields." In grid-point sampling, a similar imaginary grid is used, but the soil cores are taken from within a small radius of each grid intersection, bulked, mixed, and subsampled for analysis. Each of these methods has its limitations. Grid-cell sampling is very time-intensive because most of the field needs to be covered in the sampling process, whereas grid-point sampling will not work well unless grid sizes are very small. Thus, both methods tend to be expensive because of the labor involved. A newer method, directed sampling, is based on spatial patterns defined by some prior knowledge about a field. Sampled areas are divided into homogeneous soil units of varying size. Factors such as field management history, soil maps, soil color, yield maps, topography, and past soil tests are combined and analyzed using a geographic information system (GIS) to determine optimal sampling patterns.

Sampling equipment for grid sampling includes four-wheelers and trucks equipped with global positioning system (GPS) capabilities and mechanized sampling arms (Pocknee and Boydell, 1995). Costs for custom service range from $7 to $15 per acre, including soil sampling, analysis of standard elements, and mapping.

Recommendations regarding sampling frequency range from once a year to once every 4 years. In Arizona, soil sampling for residual nitrate content analysis is recommended prior to planting

annual crops (Doerge et al., 1991). For sandy soils in North Carolina, sampling is recommended once every 2 to 3 years; testing once every 4 years is suitable for silt and clay loam soils (Baird et al., 1997). A minimum frequency of once every 4 years is generally recommended in the central United States (Hirschi et al., 1997). In Mississippi, soil samples should be taken once every 3 years or once per crop rotation (Crouse and McCarty, 1998).

Application and Performance: Soil sampling is a practice that applies to all farms and all land to which nutrients are applied. The farmer or trained consultants can conduct the sampling.

Soil sampling does not address direct treatment or reduction of any pollutants, but is essential to determining the proper manure and commercial fertilizer application rates.

Advantages and Limitations: Soil analysis is the only way in which the actual nutrient content can be determined. N testing has not been consistently reliable because N is highly mobile in soil, but drier parts of the Corn Belt have had some success with both the early spring nitrate-N test and the pre-sidedress N test (Hirschi et al., 1997). There is also some evidence that the pre-sidedress test is most helpful on soils to which manure has been applied.

A late spring N test ensures that the proper amount of N was applied to the crops. Because this test is used to make site-specific adjustments of application rates, following the recommendations provided by this test can help achieve expected crop yields. For example, where N is too high, the late spring N test will indicate that additional N application is not needed by the crop and may contaminate water supplies. Records should be kept and adjustments made to N applications on future crops.

Without soil analysis, farmers might buy more commercial fertilizer than is needed or spread too much manure on their fields (USDA NRCS, 1996a). Either practice can result in overfertilization, which, in turn, can depress crop yields and cut profits. Improper spreading of manure also can pollute surface and ground water.

Convenient laboratory reports allow farmers to easily determine the pounds of nutrients per acre of soil (McFarland et al., 1998). Recommendations based on soil testing results are developed using crop response data from within a state or region with similar soils, cropping systems, and climate (Sims et al., 1998). For this reason, it is important to send samples to a laboratory that is familiar with the crops, soils, and management practices that will be used on the particular farm. The better the information provided to laboratories for each soil sample—such as previous fertilizer use, management plans, and soil series—the greater the potential for receiving a better recommendation. Laboratories are available at universities in most states, and lists of service providers can be obtained from county offices and the Internet.

Operational Factors: Soil samples can be taken with a probe, auger, or spade and collected in a clean bucket. Probes and augers are preferred because they provide an equal amount of soil from each depth (Crouse and McCarty, 1998). For uniform fields, one sample is satisfactory, but most

fields are not uniform in treatment, slope, soil type, or drainage, and so should be divided into small areas of 5 to 10 acres each for sampling (USDA NRCS, 1996a). It is recommended that a soil map be used to guide sampling, and a separate, composite soil sample should be taken for each distinct kind of land, soil texture, soil organic matter, fertility level, and management unit (Crouse and McCarty, 1998). The samples should be taken from 20 or more places in the field, using a zig-zag pattern (USDA NRCS, 1996a). Samples should not be taken from unusual areas such as turn rows, old fence rows, old roadbeds, eroded spots, areas where lime or manure have been piled, or in the fertilizer band of row crops. A soil auger, soil tube, or spade can be used for sampling at the plow depth for cropland (6 to 8 inches or more) and at 2 to 4 inches for pasture. Samples should be placed in a clean plastic pail, mixed thoroughly with all clods broken up, and then sent to a laboratory in a 1/2-pint box for analysis.

Recommendations regarding the appropriate field size to be sampled vary somewhat, as shown in Table 8-24.

Table 8-24. Recommended Field Size for Soil Sampling.

Location	Field Size	Comments	Source
Arizona	40 acres or less	15–20 subsamples	Doerge et al., 1991
Hawaii	2–5 acres	5–10 subsamples	Hue et al., 1997
Minnesota	5–20 acres	15–20 subsamples	Rosen 1994
North Carolina	20 acres or less	15–20 subsamples	Baird et al., 1997
Texas	10–40 acres	10–15 subsamples	McFarland et al., 1998
U.S.	20–30 acres	20–25 subsamples	Sims et al., 1998
U.S.	5–10 acres	20 or more subsamples	USDA NRCS, 1996a

Sampling for the early spring nitrate-N test involves taking soil samples in 1-foot increments down to a depth of 2 to 3 feet in early spring, while the pre-sidedress N test calls for sampling from the top 1 foot of soil when corn is 6 to 12 inches tall (Hirschi et al., 1997). Guidelines on interpretation of early spring nitrate tests vary across states.

P soil tests are based on the chemical reactions that control P availability in soils (Sims et al., 1998). These reactions vary among soils, so a range of soil tests is available in the United States, including the Bray P1 (used in the North Central and Midwest Regions), Mehlich 3 (in widespread use in the United States), Mehlich 1 (Southeast and Mid-Atlantic), Morgan and Modified Morgan (Northeast), and Olsen and AB-DTPA (West and Northwest).

Demonstration Status: Soil testing is widely practiced in the United States. In a national survey of corn, soybeans, wheat, and cotton growers, 32 to 60 percent of respondents said that they perform soil testing (Marketing Directions, 1998).

8.3.2.5 Manure Application Rates and Land Requirements

Practice: Determining Manure Application Rates and Land Requirements

Description: The final step of a nutrient management analysis is to determine the amount of manure that can be applied to field crops to meet crop needs while simultaneously preventing excessive nutrient losses. This step involves using the information developed in the nutrient budget analysis to compare crop nutrient requirements with the supply of nutrients provided per unit volume of animal waste. Soil testing helps in determining the rates at which manure should be applied by establishing which nutrients are already present in the soil and available to the crop. Testing manure identifies the amount and types of nutrients it contains and helps to ensure that nutrients are not overapplied to the land. Depending on the cropping system, different amounts of nutrients will be required for optimum production. This final analysis allows the operator to determine how much land acreage is required to apply the animal manure generated or, conversely, how much manure can be applied to the available acreage. These final calculations are illustrated in Figures 8-13 and 8-14.

Determine land area needed for manure application.

Total pounds of usable nutrients available and pounds of nutrients available to plants in each gallon have been calculated. This information should be used to calculate the number of acres you need for manure application.

From nitrogen planning:
Net usable nitrogen available _____ lb
Net nitrogen amount ÷ _____ lb N/acre
Land area needed for spreading nitrogen: = _____ acres

From phosphorus planning:
Net usable P_2O_5 available: _____ lb
Total P_2O_5 needs: ÷ _____ lb P_2O_5/acre
Land area needed for spreading P_2O_5: = _____ acres

Acres required:
Greater of the two above values (a or b): _____

Adapted from Iowa State University, 1995.

Figure 8-13. Example procedure for determining land needed for manure application.

Determine manure volume to apply.

Total annual volume of manure:		_____ gal or T
Land area required for spreading:	÷	_____ acres
Manure volume used on field:	=	_____ gal or T/acre

If the field is smaller than the acres calculated above, calculate the manure to apply to this field:

Land area in field:		_____ acres
Manure volume to apply :	x	_____ gal or T/acre
Manure volume used on field:	=	_____ gal or T

Determine the number of gallons or tons of manure remaining to be spread:

Total annual volume of manure:		_____ gal or T
Manure volume used on field:	–	_____ gal or T
Manure volume remaining:	=	_____ gal or T

Manure volume remaining:		_____ gal or T
Manure volume to apply :	÷	_____ gal or T/acre
Additional land area for spreading:	=	_____ acres

Adapted from Iowa State University, 1995.

Figure 8-14. Example calculations for determining manure application rate.

Figure 8-13 illustrates that two possible strategies for determining the correct agronomic application rate of manure are (1) applying enough manure to ensure the proper amount of N is available to the crop, and (2) applying manure based on desired amounts of P, then adding commercial N and K to make up the differences in crop needs. Depending on the frequency of application, the first method might increase the risk of oversupplying P and K, thereby potentially adversely affecting soil and water quality (Dick et al., 1999). For this reason, the strategy requiring the greater land area for spreading is selected in the analysis illustrated by Figure 8-13.

Application and Performance: Determining manure application rates and land requirements applies to all farms and all land to which manure is applied. This analysis does not address direct treatment or reduction of any pollutants, but is essential to determining the proper manure and commercial fertilizer application rates.

Advantages and Limitations: Without this analysis, farmers may buy more commercial fertilizer than is needed or spread too much manure on their fields (USDA NRCS, 1996a). Either practice can result in overfertilization, which, in turn, can depress crop yields and cut profits. Improper spreading of manure also can pollute surface and ground water.

In cases where there is inadequate land to receive manure generated on the farm, alternative approaches to handling the manure, described elsewhere in this document, need to be considered.

Operational Factors: Although the correct manure application rate is determined by soil and manure nutrient composition, as well as the nutrient requirements for the crop system, further consideration should be given to soil type and timing of application. Attention to these factors aids in determining which fields are most appropriate for manure application. Before applying manure, operators should consider the soil properties for each field. Coarse-textured soils (high sand content) accept higher liquid application rates without runoff because of their increased permeability; however, manure should be applied frequently and at low rates throughout the growing season because such soils have a low ability to hold nutrients, which creates a potential for nitrate leaching (NCSU, 1998). Fall applications of animal manure on coarse-textured soils are generally not recommended. Fine-textured soils (high clay content) have slow water infiltration rates, and therefore application rates of manure should be limited to avoid runoff. Application on soils with high water tables should be limited to avoid nitrate leaching into ground water (Purdue University, 1994).

Demonstration Status: A 1995 survey of 1,477 swine producers showed that 92 percent of operations had not had their manure tested for nutrients within the past 12 months (USDA APHIS, 1995). Approximately 6 percent had tested their manure for nutrients once during the past 12 months, while another 1.5 percent had tested it twice. These findings are supported by a crop nutrient management survey in which only 2 to 17 percent of respondents in various regions stated that they factored manure nutrient value into their NMPs (Marketing Directions, 1998). Like manure testing, analysis of land requirements and application rates is practiced widely across the United States, but many farmers still do not test manure or employ an N credit from manure when determining commercial fertilizer needs (Stevenson, 1995).

8.3.3 Recordkeeping

The key to a successful nutrient management system is sound recordkeeping. Such a recordkeeping regime should include the following:

Practice: Recordkeeping

Description: Recordkeeping for a CNMP includes recording manure generation; field application (amount, rate, method, incorporation); the results and interpretation of manure, soil, and litter analysis; visual inspections of equipment and fields; manure spreader calibration worksheets; manure application worksheets (nutrient budget analyses); and related information on a monthly or more frequent basis.

Application and Performance: Recordkeeping applies to all farms and all land to which nutrients are applied. Recordkeeping does not address direct treatment or reduction of any pollutants, but is essential to tracking the results of activities associated with nutrient management.

Advantages and Limitations: Without recordkeeping, farmers will have little ability to determine what works and does not work with regard to on-farm nutrient management. Failure to learn from past successes and mistakes may cause farmers to continue in an endless loop of buying more commercial fertilizer than is needed, spreading too much manure on their fields, and realizing smaller profits than would otherwise be obtainable. For example, tracking manure sampling locations, dates, and methods will help establish a firm basis for adjusting sampling frequencies to provide an accurate assessment of manure nutrient content (Busch et al., 2000).

Recordkeeping can seem to be nothing but a burden unless tools are provided with which farmers can analyze the information for their own benefit. Fortunately, a great number of tools are currently available from universities and industry to help farmers use their records to make better business decisions. For example, MAX (Farming for Maximum Efficiency Program) is a program designed to help farmers look at their profit margins, rather than just their yields (CTIC, 1998b). MAX software is provided to cooperators to help them document their savings.

Operational Factors: Recordkeeping can be performed using pencil and paper, personal computers, portable computers, or GIS-based systems.

Demonstration Status: Recordkeeping of some form is conducted on all farms as a matter of business.

8.3.4 Certification of Nutrient Management Planners

Practice: Training and Certification for Nutrient Management Planners

Description: CNMPs should be developed or modified by a certified specialist. Certified specialists are persons who have a demonstrated ability to develop CNMPs in accordance with applicable USDA and state standards and are certified by USDA or a USDA-sanctioned organization. Certified specialists would include individuals who have received certifications through a state or local agency, third-party organization approved by NRCS, or NRCS personnel. In addition, USDA develops agreements with third-party vendors similar to the 1998 agreement with the Certified Crop Advisors (CCAs) and consistent with NRCS standards and specifications

(or state standards if more restrictive)[1]. CCAs provide technical assistance to producers in nutrient management, pest management, and residue management. The purpose of using a certified specialist is to ensure that CNMPs are developed, reviewed, and approved by persons who have the appropriate knowledge and expertise to ensure that plans fully and effectively address the core components of CNMPs, as appropriate and necessary, and that plans are appropriately tailored to the site-specific needs and conditions of the farm. Because of the multidisciplinary nature of CNMPs, it is likely that a range of expertise will be needed to develop an effective CNMP (e.g., professional engineer, crop specialist, soil specialist).

Application and Performance: Certification of nutrient management planners applies to all farms and all land to which nutrients are applied. Farmers may seek certification themselves or choose to seek assistance from certified professionals when developing their NMPs.

Certification provides no direct treatment or reduction of any pollutants, but is essential to ensuring that CNMPs developed and implemented are effective in preventing pollution.

Advantages and Limitations: Without certification, those who develop CNMPs might not have the skills or knowledge necessary to develop cost-effective plans. This could result in both water pollution and less-than-optimal farm profits.

If a producer chooses to attain certification, a time commitment is required, and training and travel expenses may be incurred. Course fees of $25 and 1 day of time lost are considered reasonable estimates of costs based on a review of both state training programs for nutrient management and pesticide certification costs provided by various state extension services. The major advantage of becoming certified is that the farmer will be able to develop his or her own CNMPs without the need for outside technical assistance. Certification would ultimately provide benefits with regard to time commitments, convenience, and expense.

Farmers who choose not to obtain certification will need to purchase services from those who are certified.

Operational Factors: Producers might need to travel within their state to attain certification.

Demonstration Status: Some states already have certification programs in place for nutrient management planning, which can provide an excellent foundation for CNMP certification programs. In addition, USDA develops agreements with third-party vendors similar to the 1998 agreement with the CCAs.

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[1]Third-party vendor certification programs may include, but are not limited to, (1) the American Society of Agronomy's certification programs including Certified Crop Advisors (CCA) and Certified Professional Agronomists (CPAg), Crop Scientists (CPCSc), and Soil Scientists (CPSSc), (2) land grant university certification programs, (3) National Alliance of Independent Crop Consultants (NAICC), and (4) state certification programs.

8.4 Land Application and Field Management

Two important factors that affect nutrient loss are field application timing and application method.

8.4.1 Application Timing

The longer manure remains in the soil before crops take up its nutrients, the more likely those nutrients will be lost through volatilization, denitrification, leaching, erosion and surface runoff. Timing of application is extremely important. To minimize N losses, a good BMP is to apply manure as near as possible to planting time or to the crop growth stage during which N is most needed. Because of regional variations in climate, crops grown, soils, and other factors, timing considerations vary across regions.

Spring is the best time for land application to conserve the greatest amount of nutrients. Available nutrients are used during the cropping season. Nutrient losses are still possible, however, because the likelihood of wet field conditions may result in export by surface runoff or leaching. Spring applications result in less time for organic decomposition of manure (an issue for manure with a low percentage of moisture) and the release of some nutrients. Four main considerations often prevent manure application in the spring. First, a livestock producer might not have sufficient storage capacity for an entire year of manure and might be forced to apply at multiple times during the year. Second, time constraints and labor availability for farmers and applicators during the spring season make it difficult to complete manure application. Third, time constraints are complicated further if there are wet field conditions. Finally, applying manure in the spring creates a potential for greater soil compaction which can cause yield loss. Field equipment, such as heavy manure tanks, compacts the soil and can alter soil structure and reduce water movement. Tillage to break up this compaction is not a viable option in reduced-till cropping systems. Freezing and thawing cycles in winter months lessen the effect of compaction caused during fall application.

Conversely, fall application usually results in greater nutrient losses (25 to 50 percent total N loss, depending on soil type, climate, and crop) than spring application, especially when the manure is not incorporated into the soil (MWPS, 1993). These N losses are a result of NH_3 volatilization and conversion to nitrate, which may be lost by denitrification and leaching. However, fall applications allow soil microorganisms time to more fully decompose manure and release previously unavailable nutrients for the following cropping season. This is especially advantageous for solid manure, which contains high levels of organic matter. When temperatures are below 50 °F, microbial action of the soil slows and prevents nitrification, thereby immobilizing some of the nutrients. In the fall, manure is best applied to fields to be planted in winter grains or cover crops. If winter crops are not scheduled to be planted, manure should be applied to fields that require nutrients in the subsequent crop year or have the most existing vegetation or crop residues, or to sod fields to be plowed the next spring.

Summer application is suitable for small-grain stubble, noncrop fields, or little-used pastures. Manure can also be applied effectively to pure grass stands or to old legume-grass mixtures, but not on young stands of legume forage. Summer application allows a farmer or applicator to spread out the workload of a busy spring and fall.

Winter is the least desirable application time, for both nutrient utilization and pollution prevention. Late fall or winter applications might be desirable because of greater labor availability and better soil trafficability. Although there may be significant losses of available N, the Org-N fraction will still contribute to the plant-available N pool. The potential for nutrient runoff is an environmental concern for applications that cannot be incorporated, especially during winter. Winter applications of manure should include working the manure into the soil either by tillage or by subsurface injection, thereby reducing runoff potential. In northern areas where frozen soil and snow cover are common conditions, winter manure application should be avoided. Winter manure application is prohibited in a number of northern states and in most Canadian provinces. There may be some limited local justification for winter manure application, such as reduced NH_3 volatilization and odor problems (Steenhuis et al., 1979), reduced runoff due to a mulching effect of solid manure (Young and Holt, 1977; Clausen, 1990), enhanced die-off of some microorganisms in freeze-thaw cycles (Kibbey et al., 1978; Stoddard et al., 1998), avoidance of soil compaction, and simplified farm management schedules. However, considerable research has demonstrated that runoff from manure application on frozen or snow-covered ground has a high risk of water quality impact.

Extremely high runoff N and P concentrations have been reported from plot studies of winter-applied manure: 23.5 – 1086.0 mg TKN/L and 1.6 – 15.4 mg total P/L (Thompson et al., 1979; Melvin and Lorimor, 1996). In two Vermont field studies, Clausen (1990, 1991) reported 165 to 224 percent, increases in total P concentrations, 246 to 1480 percent, increases in soluble P concentrations, 114 percent increases in TKN concentrations, and up to 576 percent increases in NH_3-N following winter application of dairy manure. Mass losses of up to 22 percent of applied N and up to 27 percent of applied P from winter-applied manure have been reported (Midgeley and Dunklee, 1945; Hensler et al., 1970; Phillips et al., 1975; Converse et al., 1976; Klausner et al., 1976; Young and Mutchler, 1976; Clausen, 1990 and 1991; Melvin and Lorimer, 1996). Much of this loss can occur in a single storm event (Klausner et al., 1976). Such losses may represent a significant portion of annual crop nutrient needs.

On a watershed basis, runoff from winter-applied manure can be an important source of annual nutrient loading to water bodies. In a Wisconsin lake, 25 percent of annual P load from animal waste sources was estimated to arise from winter spreading (Moore and Madison, 1985). In New York, snowmelt runoff from winter-manured cropland contributed more P to Cannonsville Reservoir than did runoff from poorly managed barnyards (Brown et al., 1989). Clausen and Meals (1989) estimated that 40 percent of Vermont streams and lakes would experience significant water quality impairments from the addition of just two winter-spread fields in their watersheds.

Winter application of manure can increase microorganism losses in runoff from agricultural land compared to applications in other seasons (Reddy et al., 1981). Cool temperatures enhance survival of fecal bacteria (Reddy et al., 1981; Kibby et al., 1978). Although some researchers have reported that freezing conditions are lethal to fecal bacteria (Kibby et al., 1978; Stoddard et al., 1998), research results are conflicting. Kudva et al. (1998) found that *E. coli* can survive >100 days in manure frozen at –20 °C. Vansteelant (2000) observed that freeze/thaw of soil/slurry mix only reduced *E. coli* levels by about 90 percent. Studies have found that winter-spreading of manure does not guarantee die-off of *Cryptosporidium* oocysts (Carrington and Ransome, 1994; Fayer and Nerad, 1996). Finally, because incorporation or injection of manure is impossible in winter applications, filtration and adsorption through soil contact, important mechanisms for attenuating microorganism losses (Gerba et al., 1975; Patni et al., 1985), is prevented.

There are several additional disadvantages to winter manure application. Runoff from winter-spread fields, whether during winter thaws or in spring snowmelt, would occur before the growing season when riparian buffers or vegetated filter strips are relatively inactive and ineffective in removing pollutants from runoff before delivery to surface waters. In cases where winter spreading is carried out because of lack of adequate manure storage, the loss of management flexibility makes good nutrient management difficult.

Although several studies have reported little water quality impact from winter-spread manure (Klausner, 1976; Young and Mutchler, 1976; Young and Holt, 1977), such findings typically result from fortuitous circumstances of weather, soil properties, and timing/position of manure in the snowpack. The spatial and temporal variability and unpredictability of such factors makes the possibility of ideal conditions both unlikely and impossible to predict.

8.4.2 Application Methods

Manure can be handled as a liquid (less than 4 percent solids), semisolid or slurry (4 to 20 percent solids), or solid (greater than 20 percent solids). The amount of bedding and water dilution influence the form, as do the species and production phase of the animals. Consequently, the manure form dictates the way manure will be collected, stored, and finally applied to land (MWPS, 1993).

Liquid manure and slurry manure are applied using similar methods, but equipment needs for the two manure forms may vary depending on percentage of solids content. Chopper pumps may be necessary to reduce the particle size of bedding or feed. Agitation of liquid manure is extremely important prior to land application. Inadequate agitation results in inconsistent nutrient content and makes the manure difficult to credit as a valuable fertilizer source. A lack of uniform application can also lead to nutrient excesses and deficiencies, yield loss, and increased incidence of ground and surface water contamination. Furthermore, insufficient agitation can cause a buildup of solids in the storage tank and lead to decreased capacity. A disadvantage to liquid manure-handling systems is that they may require the addition of water for collection of the manure, increasing the amount of material that must be handled and applied.

The liquid-based manure is applied to fields by means of tank wagons, drag-hose systems, or irrigation systems. Tank wagons can either broadcast manure (surface apply) or inject it into the soil. The method of injection, and the corresponding level of disturbance to the soil surface, is extremely variable. With the proper implement type, disruption to the soil surface and residue cover can be minimal and appropriate for reduced-tillage operations. Depending on the specific implement chosen, injection is the preferred method in reduced-till or no-till cropping systems. Soil incorporation occurs immediately and crop residues are left on the surface to act as a mulch. The amount of exposed soil surface is minimized, resulting in reduced erosion. Injection systems can reduce odor by 20 to 90 percent (Hanna, 1998). There is less nutrient loss to air and diminished runoff as well. For injection, a liquid manure spreader or "umbilical" system, and equipment to deposit manure below the soil surface are necessary. Injection requires more horsepower, fuel, and time than broadcasting. Liquid-based manure can also be pumped from a tanker or storage facility located adjacent to the field through a long flexible hose. This umbilical or drag-hose system is feasible for both broadcasting and injecting manure. Irrigation equipment applies liquid manure pumped directly from storage (usually lagoons). Wastewater and manure can be applied by means of sprinkler or surface (flood) irrigation.

Solid manure is broadcast using box-type or open-tank spreaders. Spreader mechanisms include paddles, flails, and augers. Rate calibration of box spreaders is often difficult, resulting in less uniform application, difficulty crediting fertilizer values, nutrient excesses and deficiencies resulting in yield loss, and increased potential for ground and surface water contamination.

Surface application, or broadcasting, is defined as the application of manure to land without incorporation. Simply applying manure to the soil surface can lead to losses of most of the available N, depending on soil temperature and moisture. N is lost through volatilization of NH_3 gas, denitrification of nitrates, and leaching. Volatilization losses are greatest with lower humidity and with increases in time, temperature, and wind speed. High- moisture conditions can carry water-soluble nitrates through the soil profile and out of the plant root zone, potentially causing ground water contamination. University extension services generally recommend a certain correction factor (Table 8-25). Environmental conditions such as temperature, wind, and humidity influence this factor. Generally, P and K losses are negligible, regardless of application method. However, some P and K is lost through soil erosion and runoff.

Table 8-25. Correction Factors to Account for Nitrogen Volatilization Losses During Land Application of Animal Manure.

Application Method	Correction Factor
Direct injection	0.98
Broadcast and incorporation within 24 hours	0.95
Broadcast and incorporation after 24 hours	0.80
Broadcast liquid, no incorporation	0.75
Broadcast dry, no incorporation	0.70
Irrigation, no incorporation	0.60

Source: Adapted from Iowa State University Extension PM-1811, November 1999.

Solid and liquid manures can be incorporated into the soil by tillage in a row-crop system. Incorporation increases the amount of N available for crops by limiting volatilization, denitrification, and surface runoff. Incorporation also reduces odor and encourages mineralization of Org-N by microbial action in the soil, thereby increasing the amount of N readily available to the plants. Although incorporation by tillage makes the nutrients less susceptible to runoff, the resulting reduction in crop residue can increase sediment runoff. If manure nutrients are to be fully used, incorporation should be performed within 12 to 24 hours of land application.

8.4.3 Manure Application Equipment

Livestock producers and custom manure applicators consider six predominant criteria when choosing an application system: (1) the amount of land to be covered/fertilized, (2) the amount of manure to be spread, (3) water content and consistency of the manure, (4) the frequency of application and importance of timeliness, (5) soil trafficability, and (6) distance between storage and the field to be treated. The fundamental classes of application equipment are solid waste spreaders, liquid waste tankers, umbilical systems, and liquid waste irrigation systems. Table 8-26 presents the advantages and disadvantages of the different application systems.

Table 8-26. Advantages and Disadvantages of Manure Application Equipment.

Application Method	Description	Advantages	Disadvantages
Solid			
Box spreader	Common box spreader with aprons, paddles, or hydraulic push system. Depending on size, can be pulled by as small as a 15-hp tractor.	Equipment readily available. Mobile. Equipment relatively inexpensive. High solids content allows less total volume to be handled.	Limited capacity. High labor and time requirement. Fairly difficult to achieve uniform application. Significant nutrient loss and odor if not incorporated immediately. Moderate risk of soil compaction. Uneven applications when conditions are windy.
Flail spreader	V-bottom spreader with chains attached to a rotating shaft to sling the manure out of the top or side of the tank. Can be pulled by 30- to 90-hp tractor.	Wide, even application. Spreads solid, frozen, chunky, slurry, semisolid, or bedded manure. Low maintenance because of few moving parts.	Moderate risk of soil compaction. Higher cost and power requirements than box spreader. Significant nutrient loss and odor if not incorporated immediately. Uneven applications when conditions are windy.
Hopper spreader	V-bottom spreader with large auger across bottom of spreader. Manure spread by impeller on side.	Wide, even application.	Moderate risk of soil compaction. Higher cost and power requirements than box spreader. Significant nutrient loss and odor if not incorporated immediately. Uneven applications when conditions are windy.

Application Method	Description	Advantages	Disadvantages
Liquid (Broadcast)			
Tank spreader	Mounted tank shoots manure in widespread pattern. Can be on one side, both sides, or directly behind spreader. Also can have drop hoses. Spreading width of 15 to 25 feet. Capacity of 1,000 to 5,000 gallons.	Simple to manage. Less costly than injectors. Requires less hp than injectors.	Great nutrient loss and odor possibilities. Uneven applications when conditions are windy. Air contact results in some nutrient loss. High risk of soil compaction.
Tractor-pulled flexible hose (drag-hose)	Manure is pumped from the storage facility or tanker at the edge of the field through hose pulled by tractor. Tractor-mounted unit consists of pipe, nozzle, and deflector plate. Spread pattern similar to that of broadcast tank spreader.	Simple design. Relatively inexpensive. Low power required to pull hose. Low risk of soil compaction.	Great nutrient loss and odor possibilities. Uneven applications when conditions are windy. Air contact results in some nutrient loss. May be limited by distance from storage to fields and by terrain.
Liquid (Injection)			
Tank spreader	Front- or rear-mounted tank. Soil is opened and manure deposited below surface by variable methods. Capacity of 1,000 to 5,000 gallons.	Odor is minimized. Nutrients not lost to atmosphere. Nutrients can be placed near plant's root zone in a standing crop. Depending on implement type, soil surface and residue disturbed minimally.	Pulling injectors require more horsepower. Operation difficult in stony soil. More expensive than broadcasting. High risk of soil compaction. Increased application time as compared with broadcasting.
Tractor-pulled flexible hose (drag-hose)	Manure is pumped from storage facility or tanker at the edge of the field through hose pulled by tractor and fed into injectors. Injectors must be lifted from ground to turn. Rigid, swinging pipe on equipment prevents hose damage by tractor. 150- to 200-hp tractor needed.	Odor controlled during spreading. N retained. Requires less power than tanker injection systems. Low soil compaction risk.	Some manure may be spilled at end of runs. May be limited by distance from the storage to fields and by terrain. Increased application time as compared with broadcasting by drag-hose.
Irrigation			
Surface irrigation	Manure transported to application site through rigid irrigation pipes. Manure spread on field via gated pipes or open ditches.	Low initial investment. Low energy requirements. Little equipment needed. Little soil compaction. Few mechanical parts. Timely manure application.	Moderate labor requirement. High degree of management skill needed. Limited to slopes of less than 2 percent. May be limited by distance to field. High odor levels possible. Difficult to control runoff and achieve uniform application. Significant nutrient loss if not incorporated immediately.

Application Method	Description	Advantages	Disadvantages
Hand-moved sprinklers	Manure transported through rigid irrigation pipe, including a mainline and one or more aluminum pipe laterals. One parcel irrigated at a time. Pipe is disassembled and moved by hand to next parcel.	Low initial investment. Few mechanical parts. Low power requirement. Adapts to field shape. Little soil compaction. Timely manure application.	High labor requirement. Sprinklers can clog. Significant nutrient loss if not incorporated immediately. High odor levels possible. Uneven distribution in windy conditions.
Towline sprinklers	Manure transported through rigid irrigation pipe, including a mainline and one or more aluminum pipe laterals. One parcel irrigated at a time. Laterals are stronger and are moved using a tractor.	Low initial investment. Requires less labor than hand-move sprinklers. Few mechanical parts. Low power requirement. Little soil compaction. Timely manure application.	Not adaptable to irregular field shapes because of fixed laterals. Sprinklers can clog. Require tractor lanes for towing in tall crops. Significant nutrient loss if not incorporated immediately. High odor possible. Uneven distribution in windy conditions.
Stationary big gun	Manure transported through rigid irrigation pipes. Single large gun sprays manure in a circle. Must be moved by hand.	Moderate labor requirement. Few mechanical parts. Adaptable to irregular land area. Requires less pipe than small sprinklers. Big nozzle allows spreading of manures with more solids. Little soil compaction. Timely manure application.	Moderate to high initial investment. High power requirement. Uneven distribution in windy conditions. Significant nutrient loss if not incorporated immediately. High odor possible.
Towed big gun	Manure transported through rigid irrigation pipes. Functions like a towline system with the laterals replaced by a big gun.	Few mechanical parts. Requires less labor than hand-move or stationary gun systems. Requires less pipe than small sprinklers. Big nozzle allows spreading of manures with more solids. Little soil compaction. Timely manure application.	Moderate to high initial investment. High power requirement. Uneven distribution in windy conditions. Less adaptable to land area. Requires tractor driving lanes. Significant nutrient loss if not incorporated immediately. High odor possible.
Traveling gun	Manure transported through rigid irrigation pipes. Irrigation gun travels across field, spreading manure in semicircular pattern. Hard or soft hose types available. Soft hose system is less expensive.	Lowest labor requirement of all sprinkler systems. Big nozzle allows spreading of manures with more solids. Little soil compaction. Less energy required than tank spreader. Timely manure application.	High initial costs. May be limited by distance to field. Uniform application difficult in very windy conditions. Possibility of high odor levels. Significant nutrient loss if not incorporated immediately. Environmental damage likely if not supervised. High odor possible.

Sources: MWPS, 1993; and Bartok, 1994.
hp = horsepower

Practice: Solid Manure Application with Spreaders

Description: Solid and semisolid manure can be applied to land using box, V-bottom, or flail spreaders. Spreaders are either tractor-pulled or mounted on trucks, depending on the load capacity. The manure is discharged from the rear, side, or bottom of the spreader with the aid of paddles, flails, chains, or augers (MWPS, 1993).

Application and Performance: Solid waste application methods are appropriate for manure containing 20 percent or more solids (MWPS, 1993). Spreaders are most appropriate for smaller operations with frequent manure removal from small areas (USDA NRCS, 1996a).

Advantages and Limitations: Spreaders are relatively inexpensive but have a limited load capacity. They require power to operate and, because of the open-air application method, often present odor problems during and after application. In addition, calibration can be difficult and create a problem with uniform application and nutrient crediting. Most spreaders must be filled using a tractor front-end loader. Smaller spreaders require a greater time investment because of the number of return trips to the manure source for refilling. Increasing spreader capacity reduces the time investment but increases the risk of soil compaction. V-box bottom spreaders can achieve a more uniform application than box spreaders but require more power and investment.

Operational Factors: Spreaders are constructed of treated wood or steel and include a plastic or fiberglass interior lining to assist with loading and unloading. The spreaders can rot or rust, depending on the construction material, and tractor front-end loaders can damage the spreader and lining during loading. To prevent deterioration and damage, operators should load the spreader carefully, clean and lubricate it regularly, and protect it from the weather.

Demonstration Status: Of grow-finish swine operations that dispose of waste on owned or rented land, 57.8 percent use broadcast/solid spreader methods. Only 13.7 percent of large grow-finish operations (marketing more than 10,000 head) use broadcast/solid spreader methods (USDA APHIS, 1996a).

On dairy farms with fewer than 100 milk cows, 90.6 percent broadcast manure with a solid spreader. As herd size increases, solid handling is less common. Solid handling is most common in the northeastern and midwestern areas of the United States (USDA APHIS, 1997).

Fewer than 1 in 7 producers with fewer than 100 milk cows incorporate manure into soil within 24 hours of application. This ratio increases with herd size to more than one-third of producers with more than 500 cows incorporating manure into the soil in less than 24 hours (USDA APHIS, 1997).

Practice: Liquid Manure Application With Tankers

Description: Manure is applied to the soil surface or injected into the soil using spreader pump tankers or vacuum tankers. The spreader pump tanker is composed of a tank and pump mounted on a truck or wagon and requires a separate pump to load the manure. The vacuum tanker is mounted in a similar fashion but includes a pump that both loads and unloads the manure. Tankers usually include an agitating device (either auger or pump type) to keep solids suspended. Chopper pumps may be needed to prevent malfunctions caused by clogging with manure solids or fibrous material. A gated opening at the rear bottom of the tank either discharges the manure into a spinner for broadcasting or directs it through hoses to an injection device.

Application and Performance: Tankers are used for spreading slurry and liquid manure with less than 10 percent solids. Tankers are appropriate for moderate- to large-size operations. Thorough agitation prior to and during tanker loading is necessary to limit inconsistency of manure.

Tankers using injection systems can decrease runoff by causing minimal soil surface disturbance and maintaining a residue cover.

Advantages and Limitations: Broadcast tankers use less power and are less expensive than injector tankers but result in greater nutrient loss and odor problems. Tankers with injector systems decrease the loss of N and odorous gases to the atmosphere, and place nutrients near the plant's root zone where they are needed. Depending on the specific injector system, there is a significant decrease in disturbance to the soil surface and residue, limiting the potential for erosion. The weight of both types of tanker spreaders can cause soil compaction.

Operational Factors: Tankers must be cleaned and repaired regularly and should be protected from the weather. Vacuum pumps, moisture traps, pipe couplers, tires, and power shafts must be maintained regularly. Sand, often used in dairy freestall barns, can cause damage to the pumps. A vacuum tanker used for swine manure typically lasts 10 years (USDA NRCS, 1996a).

Demonstration Status: Slurry surface application is practiced at 46.0 percent of all grow-finish operations that apply wastes to land, while subsurface injection of slurry is practiced at 21.9 percent of these operations (USDA APHIS, 1996a).

Slurry surface application is practiced at 44.6 percent of dairy farms having more than 200 milk cows. Subsurface slurry application is practiced at only 8.6 percent of dairy operations of the same size (USDA APHIS, 1997).

Practice: Liquid Manure Application With a Drag-Hose System

Description: The drag-hose system pumps manure from the manure storage tank, or from a portable tank adjacent to the field, through a supply line that can be up to 3 miles long. The supply line attaches to a flexible hose that is pulled across the field by a tractor. Manure is fed

through the hose to applicator implements similar to the types found on tankers. The manure can be broadcast or injected.

Application and Performance: Drag-hose systems are used for spreading slurry and liquid manure with less than 10 percent solids. They are appropriate for moderate- to large-size operations. Up to 40 acres of a field can be covered before the hoses must be repositioned. Thorough agitation prior to and during pumping is necessary to limit inconsistency of manure.

Use of certain injection systems can decrease runoff and erosion by causing minimal soil surface disturbance and maintaining residue cover.

Advantages and Limitations: The drag-hose system eliminates the need for repeated trips with a wagon or tanker to the manure storage site. It takes more initial setup time, but overall it has a smaller fuel and labor requirement than other spreader systems. Another benefit is decreased soil compaction and decreased road traffic. The weight of the liquid-based manure is dispersed over a much greater surface area and there is less equipment weight.

The person using a drag-hose system must be careful not to cut the line or break the umbilical cord during manure application.

For application rates under or around 2,000 gallons per acre, a drag-hose may not be practical because a certain amount of pressure is needed to keep the hose from collapsing.

Operational Factors: The application of drag-hose systems is limited by the distance the supply lines can travel, as well as by terrain.

Demonstration Status: Drag-hose systems are becoming increasingly popular as consolidation takes place in livestock production. It should be noted that the demonstration figures given in the tanker section also pertain to and include swine and dairy operations using the drag-hose system for slurry application.

Practice: Liquid Waste Application by Irrigation

Description: Irrigation systems use pipes to transfer liquid manure and wastewater from the containment facility (usually a lagoon) to the field. Wastewater can be transferred to the field through portable or stationary pipes or through an open ditch with siphon tubes or gated pipe. Manure is applied to the land using either a sprinkler or surface irrigation system.

Sprinkler systems most often used for manure disposal include handmove sprinklers, towlines, and big guns (MWPS, 1993). Surface irrigation systems include border, furrow, corrugation, flood, and gated pipe irrigation (MWPS, 1993). Descriptions of individual irrigation systems are included in Table 8-26.

Application and Performance: Irrigation systems are increasingly used by hog operations that spread over a million gallons of wastewater per year (USDA NRCS, 1996a). Most irrigation systems can handle manure that contains up to 4 percent solids (MWPS, 1993). Solid separation practices may be necessary to achieve this level.

Irrigation system selection varies according to the percentage of solids present in the manure, the size of the operation, the labor and initial investment available, field topography, and crop height.

Advantages and Limitations: Irrigation systems minimize soil compaction, labor costs, and equipment needed for large operations, and espread the manure more quickly than tank spreaders. Also, irrigation makes it possible to move large quantities of manure in a short time period. Finally, irrigation systems can be used to transport water during dry periods, and they are especially effective if crop irrigation systems are already in place.

However, N is easily lost to volatilization and denitrification if not incorporated into the soil. Odor from the wastewater can create a nuisance. Other problems that might alter the viability of the irrigation system include windy conditions that reduce the uniformity of spreading and increase odor problems off-site, the fact that soils might not be permeable enough to absorb the rapidly applied liquid, and a crop height that prevents application (MWPS, 1993; USDA NRCS, 1996a).

Although irrigation systems can reduce the overall labor cost of large spreading operations, labor communication and coordination are needed for initiating, maintaining, and ceasing an irrigation cycle. System operators must agitate manure before and during pumping to keep solids in suspension. Surface irrigation application must be closely monitored to control runoff and application uniformity. Pipes must be flushed with clean water after manure is applied to prevent clogs. Irrigation pipes are susceptible to breakage and should be regularly inspected.

Operational Factors: Single-nozzle sprinklers perform better where wind is a problem. Also, one large nozzle is less likely to plug than two smaller nozzles with the same flow capacity.

Demonstration Status: Irrigation of swine wastewater is practiced at 12.8 percent of grow-finish operations which dispose of their waste on owned or rented land. Nearly 80 percent of grow-finish operations with more than 10,000 head use irrigation for land application of manure.

Land application of wastewater by irrigation is also common at large dairy operations; 40.5 percent of producers with more than 200 cows used irrigation for manure application.

Practice: Center Pivot Irrigation

Description: Center pivots are a method of precisely irrigating virtually any type of crop (with the exception of trees) over large areas of land. In a center pivot, an electrically driven lateral assembly extends from a center point where the water is delivered, and the lateral circles around

this point, spraying water. A center pivot generally uses 100 to more than 150 pounds of pressure per square inch (psi) to operate and therefore requires a 30- to 75-horsepower motor.

The center pivot system is constructed mainly of aluminum or galvanized steel and consists of the following main components:

- Pivot: The central point of the system around which the lateral assembly rotates. The pivot is positioned on a concrete anchor and contains various controls for operating the system including timing and flow rate. Wastewater from a lagoon, pond, or other storage structure is pumped to the pivot as the initial step in applying the waste to the land.
- Lateral: A pipe and sprinklers that distribute the wastewater across the site as it moves around the pivot, typically 6 to 10 feet above the ground surface. The lateral extends out from the pivot and may consist of one or more spans depending on the site characteristics. A typical span may be from 80 to 250 feet long, whereas the entire lateral may be as long as 2,600 feet.
- Tower: A structure located at the end point of each span that provides support for the pipe. Each tower is on wheels and is propelled by either an electrically driven motor, a hydraulic drive wheel, or liquid pressure, which makes it possible for the entire lateral to move slowly around the pivot.

The center pivot is designed specifically for each facility, based on wastewater volume and characteristics, as well as site characteristics such as soil type, parcel geometry, and slope. The soil type (i.e., its permeability and infiltration rate) affects the selection of the water spraying pattern. The soil composition (e.g., porous, tightly packed) affects tire size selection as to whether it allows good traction and flotation. Overall site geometry dictates the location and layout of the pivots, the length of the laterals, and the length and number of spans and towers. Center pivots can be designed for sites with slopes of up to approximately 15 percent, although this depends on the type of crop cover and methods used to alleviate runoff. Figure 8-15 presents a schematic of a central pivot irrigation system.

Application and Performance: Using a center pivot, nutrients in the wastewater, such as N and P, can be efficiently applied to the cropland to meet crop needs. With a known nutrient concentration in the wastewater, the animal waste can be agronomically applied to cropland very precisely by appropriately metering the flow based on crop uptake values. Agronomic application helps reduce runoff of pollutants from cropland and overapplication of nutrients to the soil.

Center pivot irrigation does not provide wastewater treatment. Nutrients, pathogens, and other pollutants simply pass through and are distributed by the center pivot.

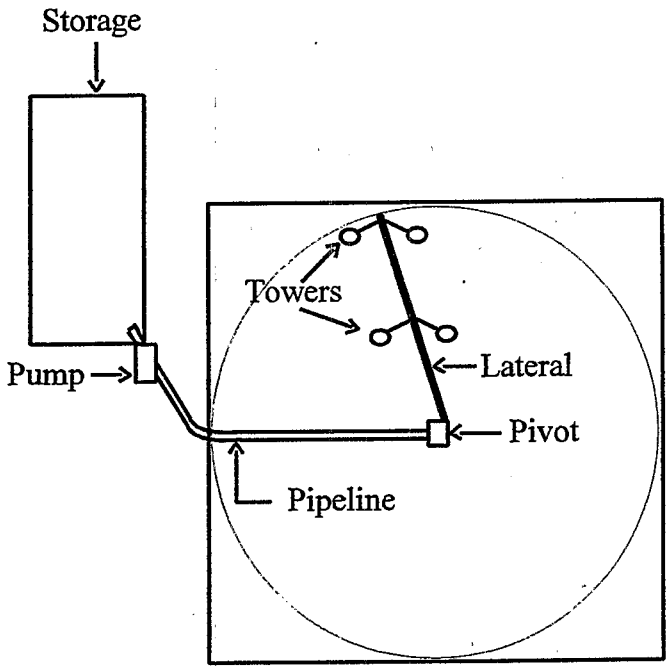

Figure 8-15. Schematic of a center pivot irrigation system.

Operational Factors: According to one manufacturer (Valley Industries), center pivot systems can be designed to handle wastes containing up to 5 percent solids. Thus, it may be necessary to have a solids removal step (e.g., settling basin or mechanical separator) prior to wastewater storage and subsequent land application. It is also a good practice to flush the pipes with clean water following waste application to prevent clogging of pipes and sprinkler nozzles.

Salt accumulation in the soil may be an issue, especially in drier climates. Salt concentrations in the wastewater and soil should be monitored to determine if salinity is a problem at a particular site.

Odor may also be a problem when using a center pivot to apply liquid animal wastewater to the land. However, techniques can be implemented to reduce the dispersion of the waste stream into the wind, such as positioning the sprinklers closer to the ground, using low-trajectory sprinklers, and using low-pressure sprinklers. Proper timing of application based on environmental conditions (i.e, monitoring wind velocity and direction) can also help reduce odor problems.

Application efficiency (i.e., the percentage of the total water pumped that reaches the ground or plant surface) depends primarily on climatic factors such as ambient temperature, relative

humidity, and wind velocity and direction. A typical application efficiency is about 90 percent, provided that at least 1 inch of water is applied.

Advantages and Limitations: As noted above, a center pivot is an effective means of distributing liquid animal waste and supplying nutrients to cropland at agronomic rates. The center pivot design is fairly flexible and can be adapted to a wide range of site and wastewater characteristics. Center pivots are also advantageous because they can distribute the wastewater quickly, uniformly, and with minimal soil compaction. Center pivots have low operating labor costs compared with manual application methods.

One limitation of a center pivot system is the relatively high capital investment it entails. Other limitations may result from sloped lands, high solids content of waste, and potential odor problems. Center pivots are also vulnerable to high winds and lightning. Additionally, swine waste is fairly corrosive so the waste either needs to be treated to reduce its corrosivity or system components such as piping need to be corrosion-resistant (e.g., galvanized or lined pipe). Another concern with center pivot spraying is N loss through volatilization, which is estimated to be as high as 25 percent (USDA NRCS, 1996a).

Demonstration Status: Center pivots have been in operation in the United States since the 1950s. In the 1970s, center pivots started to become popular as a means of land-applying wastewater from municipal, industrial, and agricultural sources. Today, center pivots are widely used in agriculture including land application of wastewater from swine, beef, and dairy facilities.

Practice: Calibration of Application Equipment

Description: Three conditions must be addressed to ensure that application rates are accurate (Schmitt and Rehm, 1998). First, analysis of a properly collected manure sample is needed to quantify nutrient content. Second, the rate of manure being applied to the field must be known and kept constant; calibration must be conducted for all manure applications. Third, the application or spread pattern of the manure must be uniform throughout the field.

Manure spreaders can discharge manure at varying rates, depending on forward travel speed, power take-off speed, gear box settings, discharge opening, width of spread, overlap patterns, and other parameters (USDA NRCS, 1996a). Calibration defines the combination of settings and travel speed needed to apply manure at a desired rate.

The actual rate at which a spreader applies manure will differ from the manufacturer's estimates, so calibration is necessary to ensure accurate manure application (Hirschi et al., 1997). Two basic methods, the load-area method and weight-area method, can be used for calibration (USDA NRCS, 1996a). In the load-area method, the amount of manure in a loaded spreader is measured and the rate is determined based on the number of loads needed to cover a known area of land. In the weight-area method, manure spread over a small surface is weighed, and the weight per unit area is calculated. Although there are only two basic calibration methods, a variety of specific

calibration procedures are available, many of which require knowledge of the tank's or spreader's load size (Hirschi et al., 1997).

For solid systems, the spreader can be weighed before and after going to the field to determine the weight of manure spread (Schmitt and Rehm, 1998). Using the width of the spread manure and the distance traveled per load, the weight of manure applied per acre can be calculated. Alternatively, the rate per acre can be estimated using the weight of a full load as determined with a scale, the number of loads per field, and the field acreage. A third method is to lay a tarp or sheet of strong plastic in a field and make a pass over it with the spreader. The manure deposited on the tarp or sheet of plastic is then collected and weighed. Using the area of the tarp or plastic sheet, the weight of manure applied per unit area can be determined. Because of the small area involved in this method, there is high variability, so multiple samples should be collected. Knowledge of the variability in application rate, however, is useful information when one considers that uniform application is desired.

For liquid systems, calibration requires that the manure be measured in gallons per acre. The best way to determine the volume applied is to weigh the tank before and after spreading the manure and then to divide by the density of liquid manure (8.3 lb/gallon) (Schmitt and Rehm, 1998). Combining this information with the width of the spread pattern and the distance the tank travels before emptying the tank will provide the data necessary to determine the application rate. A second option for liquid systems that does not involve a scale is to fill the tank, count the number of loads applied uniformly per unit area of field, and then calculate the volume per acre using the known volume of a filled tank.

Manure application rates must often be adjusted to match the recommended rate (Schmitt and Rehm, 1998). The most common method of changing the application rate is to change the speed at which the spreader is driven across the field. Solid manure equipment may also have an adjustment that changes the chain speed in the box, thereby changing the application rate. Liquid manure application equipment may have valve opening adjustments to alter the rate. Because the flow rate may change from the beginning to the end of a tank of liquid manure, some equipment uses pressurized tanks, flow pumps, and newer distributor designs to address the problem of variable flow. Once equipment is adjusted or driving rates are changed to achieve new application rates, recalibration is necessary to maintain the accuracy in calculating application rates.

A wide range of water measurement devices is available including some that primarily measure rate or volume of flow, and some that primarily measure rate of flow (USDA NRCS, 1997). A suitable measuring device, calibrated in the laboratory or field, can be used to determine total application volume, which, combined with the measured nutrient concentration in the applied liquid, can be used to determine the quantity of nutrients applied to the receiving land. Dividing the quantity of nutrients by the land acreage provides the nutrient application rate. Rain gauges can be used in the field to check the uniformity of application of sprinkler systems.

Application and Performance: Calibration is a practice that applies to all farms and all land on which manure is applied, and it can be performed by the producer with little training.

Calibration of manure application equipment provides no direct treatment or reduction of any pollutants, but it is essential to accurate application of manure.

Planning manure application based on plant P requirements may result in application rates below the capability of some manure-spreading equipment. However, a general consensus among selected extension service specialists and equipment manufacturers indicates that box spreaders and liquid spreaders can be reliably calibrated to application rates as low as 2 to 3 tons/acre and 1,500 to 2,000 gallons/acre, respectively (Tetra Tech, 2001). This will allow for P-based application of manure under most conditions.

Advantages and Limitations: Calibrating manure applicators helps to ensure that applications are adequate for crop needs, but not excessive and a source of water quality problems (USDA NRCS, 1995).

Calibration of spreaders should take less than 1 hour (Hirschi et al., 1997).

Operational Factors: Agitation of liquid manure is extremely important prior to land application. Inadequate agitation results in inconsistent nutrient content and makes the manure difficult to credit accurately as a valuable fertilizer source. A lack of uniform application can also lead to nutrient excesses and deficiencies, yield loss, and increased incidence of ground and surface water contamination.

Solid manure is broadcast using box-type or open-tank spreaders. Spreader mechanisms include paddles, flails, and augers. Rate calibration of box spreaders is often difficult, resulting in less uniform application, difficulty crediting fertilizer values, nutrient excesses and deficiencies resulting in yield loss, and increased potential for ground and surface water contamination.

Windy conditions can affect the uniformity of applications with sprinklers. System operators must agitate manure before and during pumping to keep solids in suspension. Surface irrigation application must be closely monitored to control runoff and application uniformity.

Demonstration Status: Calibration of manure spreaders is a topic that has been addressed in technical guidance and extension service publications across the United States. Information regarding the extent to which farmers calibrate manure applicators was not found, but information regarding the extent to which manure is sampled is probably indicative of the maximum extent to which calibration is practiced.

Manure sampling is practiced widely across the United States, but many farmers still do not test manure or employ an N credit from manure when determining commercial fertilizer needs (Stevenson, 1995). A 1995 survey of 1,477 swine producers showed that 92 percent of operations

had not had their manure tested for nutrients within the past 12 months (USDA NAHMS, 1999). Approximately 6 percent had tested their manure for nutrients once during the past 12 months, while another 1.5 percent had tested it twice. These findings are supported by a crop nutrient management survey in which only 2 to 17 percent of respondents in various regions stated that they factored manure nutrient value into their NMPs (Marketing Directions, 1998).

Practice: Transportation of Waste Off Site

Description: Animals at an AFO generate a large amount of liquid and semi-solid waste every day. This waste is rich in nutrients and can be applied to cropland as fertilizer. Often, there are more nutrients present in the waste than can be used by the crops on site. In this case, or in the case where the operation has no cropland, the waste must be transported off site to a facility that can manage the waste properly.

Application and Performance: At an agronomic application rate, some facilities will be able to apply all produced animal waste to on-site cropland. However, some AFOs do not have sufficient land to accommodate all of the waste on site. These facilities must transport the waste off site using farm equipment or by hiring a contractor to haul the waste away. Hiring a contractor is a viable option for operations that do not have the capital to purchase their own trucks to haul excess waste.

Transportation does not "treat" the waste; however, it does move the waste off the farm. By transporting the waste off site, the operation prevents potential pollution by limiting the time that waste remains on the feedlot, and thereby reduces the likelihood of nutrients, pathogens, and other pollutants being carried from the stockpile by rainfall, runoff, seepage, or volatilization.

The cost of transporting waste off site is determined by the quantity and consistency of the waste as well as the distance the waste must be transported to be managed properly. Semisolid or liquid manure can be more expensive to haul because it requires a tanker truck for transport and is heavier due to a higher moisture content. Solid waste is easier to handle and is therefore less expensive to transport. Because the amount of manure transported off site is dictated by the amount that is applied to on-site cropland, it is expected that facilities will apply semisolid or liquid waste to fields before they apply solid waste. The distance manure must be hauled to be properly managed depends on the proximity of operations that need additional nutrients.

Advantages and Limitations: One advantage of transportation as a waste management practice is not having to treat and dispose of the waste on site. Excess waste at one operation can be transported to and used as fertilizer at another operation, distributing the nutrient load among cropland at multiple facilities. In addition, in some cases the operation owner is able to sell the waste to a compost or fertilizer facility or another farm operation. This income can potentially offset the cost of the transportation.

It is important to consider the potential nonwater-quality impacts that result from increased diesel truck traffic. EPA assumes that some facilities do not currently apply at agronomic rates, and therefore, there will be an increase in excess waste once operations begin applying agronomically. This increase in excess waste requires an increase in truck traffic, causing an increase in exhaust emissions from the trucks transporting the waste.

Operational Factors: There are three operational factors considered in determining transportation practices: the amount of waste to be transported, type of waste to be transported (semisolid or liquid), and the distance from the operation to the off-site destination. The amount of waste to be transported per year determines the size of the trucks that are required and the time that is spent hauling the waste. The consistency of the waste determines the type of truck that is used and the cost of handling that waste. The distance of the off-site facility from the operation determines how far the waste must be hauled and the cost of transporting the waste. The regional location of the operation also plays a role in determining how frequently the waste needs to be transported (e.g., if there are seasons in which the waste is not applied, due to climate or crop cycles).

Demonstration Status: It is not known what portion of AFOs have their waste hauled by contractors and what portion opt to own and operate their own vehicles. It is assumed that each operation chooses the most economically beneficial option, which in most cases is to contract-haul the waste off site.

Beef: Eleven percent of beef feedlots across the country currently sell excess manure waste, and 27 percent give away their manure waste. Approximately 3 percent of beef operations currently pay to have manure waste hauled off site (USDA APHIS, 2000).

Dairy: In 1997, 23 percent of dairies with more than 200 head give away some portion of their manure waste, and 18 percent sold or received compensation for their manure waste (USDA APHIS, 1997).

Poultry: Most poultry operations are currently transporting their waste off site. Nationwide, broiler operations transport about 95 percent of their waste. The percentage of layer operations transporting waste varies by region: 40 percent in the Central Region, 100 percent in the Midwest Region, 75 percent in the Mid-Atlantic Region, 95 percent in the Pacific Region, and 50 percent in the South Region (USDA NAHMS, 2000).

Swine: Four to 6 percent of swine operations currently transfer some manure off site (USDA APHIS 1995), while 23 percent of small swine operations and 54 percent of large swine operations do not have enough land to apply agronomically under an N-based application scenario (Kellogg et al., 2000).

8.4.4 Runoff Control

Fields to which manure is to be applied should have an appropriate conservation management system in place to prevent nutrients from leaving the landscape. In the event of mismanaged

manure application, such as applying manure prior to an unexpected rainfall, conservation practices that reduce soil erosion and water runoff, including grassed waterways, sediment basins, and buffers, can help to minimize the transport of nutrients off-site.

Susceptibility to erosion and the rate at which it occurs depend on land use, geology, geomorphology, climate, soil texture, soil structure, and the nature and density of vegetation in the area. Soil erosion can be caused by wind or water and involves the detachment of soil particles, their transport, and their eventual deposition away from their original position. Movement of soil by water occurs in three stages: (1) soil particles, or aggregates, are detached from the soil surface when raindrops splash onto the soil surface or are broken loose by fast-moving water; (2) the detached particles are removed or transported by moving water; and (3) the soil particles fall out of suspension when the water velocity slows, and are deposited as sediment at a new site.

Soil erosion caused by water is generally recognized in four different forms: sheet erosion, rill erosion, ephemeral erosion, and gully erosion. Erosion occurs during or immediately after rainstorms or snowmelt. Sheet erosion is the loss of a uniform, thin layer of soil by raindrop splash or water runoff. The thin layer of topsoil, about the thickness of a dime, disappears gradually, making soil loss visibly imperceptible until numerous layers are lost.

Rill erosion often occurs in conjunction with sheet erosion and is a process in which numerous channels, a few inches deep, are formed by fast-flowing surface water. The detachment of soil particles results from the shear stress that water exerts on the soil. The shear stress is related to the velocity of water flow. Therefore, when water gains velocity on steeper and longer slopes, rill erosion increases. Sheet and rill erosion carry mostly fine-textured small particles and aggregates. Fine-textured particles contain the bulk of plant-available nutrients, pesticides, and other absorbed pollutants because there is more surface area per given volume of soil.

Ephemeral erosion occurs when concentrated water flows through depressions or drainage areas. The water forms shallow channels that can be erased by tillage practices. Ephemeral erosion is a precursor to gully erosion if left untreated.

Once rills become large enough to restrict vehicular access, they are referred to as gullies. Gully erosion results from the removal of vast amounts of topsoil and subsoil by fast-flowing surface water through depressions or drainage areas. Gully erosion detaches and transports soil particles that are the size of fine to medium sand. These larger soil particles often contain a much lower proportion of absorbed nutrients, organic material, and pollutants than the fine-textured soil particles from sheet and rill erosion.

It is not practical to prevent all erosion, but the preferred strategy is to reduce erosion losses to tolerable rates. In general terms, tolerable soil loss, sometimes referred to as T, is the maximum rate of soil erosion that can occur while still maintaining long-term soil productivity. These tolerable soil loss levels determined by USDA NRCS are based on soil depth and texture, parent

material, productivity, and previous erosion rates. The levels range from 1 to 5 tons/acre/year (2 to 11 metric tons/hectare/year). The strategies for controlling erosion involve reducing soil detachment and reducing sediment transport.

Surface water runoff contains pollutants including nutrients (e.g., N and P) and some pathogens. Excessive manure application can cause increased nitrate concentration in water. If the rate of manure application exceeds plant or crop N needs, nitrates may leach through the soil and into ground water. Nitrates in drinking water are the cause of methemoglobinemia ("blue baby syndrome").

Agricultural nonpoint source pollutants, such as those contained in manure, can migrate off the field and into surface water through soil erosion. Excessive nutrients attached to the sediment and carried into surface water bodies can cause algae blooms, fish kills, and odors. Combinations of BMPs can be used to protect surface water by reducing the amount of nutrient-rich sediment that is detached and transported away from a field.

A BMP is a practical, affordable strategy for conserving soil and water resources without sacrificing profitability. BMPs that reduce soil erosion are part of a broader integrated soil management system that improves overall soil health and water quality. In addition, BMPs benefit crop production in a variety of ways such as improved drainage, improved moisture-holding capacity, pest management, and ultimately, long-term profitability.

Runoff Control Practices

Livestock manure can be a resource if managed correctly. A large proportion of livestock manure is returned to the land as organic fertilizer. Unfortunately, if manure is handled incorrectly, it can become a source of pollution that ends up in streams or lakes. The nutrients in animal manure, especially P and N, can cause eutrophication of water.

Eutrophication is a natural process that takes place in all surface water bodies. The natural process is accelerated by increased sediment and nutrient loading in the water. It is characterized by an aquatic environment rich in nutrients and prolific plant production (algae). As a result of nutrient enrichment, the biomass of the water body increases and eventually produces a noxious environment that accelerates algae growth, leading to a reduction in water quality.

The transport of manure nutrients to streams and lakes is very similar to the transport of nutrients from commercial fertilizers. N is water-soluble and moves largely with the flow of water. Injecting or incorporating manure into the land however, significantly reduces the amount of N transported with runoff. Yet N can still move with ground water or subsurface water flow.

Reducing P levels in surface water is the best way to limit algae growth. Most of the P transported by surface water is attached to sediment particles. Therefore, reducing soil erosion is essential to protecting water quality.

Manure from properly managed grazing animals has little detrimental effect on water quality. In a grazing system, 100 percent of the manure generated by the grazing animal is applied to the land daily. In addition, the runoff from a well-managed grazing system carries very little sediment or nutrients; however, manure from feedlots or overgrazed pastures is more susceptible to runoff and sediment delivery (Hatfield, 1998).

Practices to Reduce Soil Detachment

The most effective strategy for keeping soil on the field is to reduce soil detachment. Crop canopy and crop residue on the soil surface protect against soil detachment by intercepting falling raindrops and dissipating their energy. In addition, a layer of plant material on the ground creates a thick layer of still air next to the soil to buffer against wind erosion. Keeping sufficient cover on the soil is therefore a key factor to controlling both wind and soil erosion.

Conservation practices, such as no-tillage, preserve or increase organic matter and soil structure. No-tillage reduces soil detachment and transport and results in improved water infiltration and surface stability. No-tillage also increases the size of soil aggregates, thereby reducing the potential of wind to detach soil particles.

Combinations of the following practices can be used to effectively reduce soil detachment by wind or water erosion:

- Conservation tillage (including mulch-tillage, no-tillage, strip-tillage, and ridge-tillage)
- Cover crops
- Contour stripcropping/contour buffer strips
- Crosswind trap strips
- Crosswind ridges
- Crosswind stripcropping
- Crop rotation (including small grains, grasses, and forage legumes)
- Chemical fallow or no fallow
- Grassed waterways
- Pasture management
- Shelterbelts/field windbreaks

Practices to Reduce Transport Within the Field

Sediment transport can be reduced in several ways including the use of vegetative cover, crop residue, and barriers. Vegetation slows runoff, increases infiltration, reduces wind velocity, and traps sediment. Strips of permanent vegetation (e.g., contour strip cropping and contour grass

strips) slow runoff and trap sediment. Contour farming creates rough surfaces that slow surface water velocity and reduce transport of sediment.

Reductions in slope length and steepness reduce sediment-carrying capacity by slowing velocity. Terraces and diversions are common barrier techniques that reduce slope length and slow, or stop, surface runoff.

By decreasing the distance across a field that is unsheltered from wind, or by creating soil ridges and other barriers, sediment transport by wind can be reduced.

Combinations of the following practices can be used to effectively reduce soil transport by wind or water erosion:

- Buffers
  - Shelterbelts/field windbreaks
  - Contour strip cropping/contour buffer strips
  - Riparian buffers
  - Filter strips
  - Grassed waterways
  - Field borders
  - Crosswind trap strips
  - Contour or cross slope farming
- Conservation tillage, (including mulch-tillage, no-tillage, strip-tillage, and ridge-tillage)
- Crop rotation (including grains, grasses and forage legumes)
- Chemical fallow or no fallow
- Cover crops
- Crosswind ridges
- Crosswind stripcropping
- Diversions
- Ponds
- Sediment basins
- Terraces

Practices to Trap Sediment Below the Field or Critical Area

Practices are also typically needed to trap sediment leaving the field before it reaches a wetland or riparian area. Deposition of sediment is achieved by practices that slow water velocity and

increase infiltration. Combinations of the following practices can be used to effectively trap sediment below the field or critical area:

- Contour strip cropping/contour buffer strips
- Crosswind traps strips
- Crosswind stripcropping
- Diversions
- Filter strips
- Grassed waterways
- Ponds
- Riparian buffers
- Sediment basins
- Shelterbelts/field windbreaks
- Terraces
- Wetlands

Practices That Have Multiple Functions to Reduce Detachment, Transport, and Sediment Delivery

Many conservation practices have multiple functions. Table 8-27 identifies the primary functions of each practice.

Considerations in BMP Selection

The selection of the most effective BMPs to protect water quality depends on the objectives of the farmer and the specific site conditions of individual fields. The best combination of BMPs for any specific field depends on factors such as the following:

- Rainfall—more rainfall means more erosion potential.
- Soil type—some soils erode more easily than others.
- Length of slope—a longer slope has increased potential for erosion due to increased runoff energy.
- Steepness of slope—steep slopes erode more easily than gradual slopes.
- Ground cover—the more the soil is covered with protective grasses, legumes, or crop residues, the better the erosion control.

Table 8-27. Primary Functions of Soil Conservation Practices.

Conservation Practice	Detachment	Transport	Sedimentation
Chemical fallow or no fallow	O	O	
Conservation Tillage (mulch-till, ridge-till, strip-till, and no-till)	X / O	X / O	
Contour or Cross Slope		X	
Contour Stripcropping/Contour Buffer Strips	X	X	X
Cover Crops	X	X	
Crop Rotation (including small grains, grasses, and forage legumes)	X	X	
Crosswind Trap Strips	O	O	O
Crosswind Ridges	O	O	
Crosswind Stripcropping	O	O	O
Diversions		X	X
Field Borders		X	
Filter Strips		X	X
Grassed Waterways	X	X	X
Ponds		X	X
Riparian Buffers		X	X
Sediment Basins		X	X
Shelterbelts/Field Windbreaks	O	O	O
Terraces		X	X
Wetlands			X

Note: X = water erosion; O = wind erosion

Other factors to consider include:

- Type of farm operation.
- Size of the field or farm.
- Nutrient levels of manure.
- Nutrient requirements of crops.
- Proximity to a waterway (stream, lake), water source (drinking water well), or water of the state.
- Relationship of one erosion control practice to other supporting conservation practices.
- Conservation plan if required by USDA NRCS.
- Economic feasibility.

Agricultural nonpoint source runoff management practices that protect natural resources generally have two principal goals: (1) to reduce runoff volume, and (2) to contain and treat agricultural runoff. An effective runoff control system meets both of these goals by integrating several practices in a way that meets the needs of the particular management system. Strategies for controlling erosion involve reducing soil detachment, reducing sediment transport, and trapping sediment before it reaches a water body.

Soil erosion can be reduced by using a single conservation practice or a combination of practices. The following section explains conservation practices that can be used separately or in combination to reduce manure runoff and improve water quality.

Practice: Crop Residue Management

Description: Tillage operations influence the amount and distribution of plant residues on or near the soil surface. In the past, the preferred system, conventional tillage, was designed to bury as much residue and leave the soil surface as smooth as possible, which unfortunately led to significant soil erosion. In contrast, residue management systems are designed to leave residue on top of the soil surface to increase infiltration and reduce erosion. In general, the more residue left on the soil surface, the more protection from erosion the soil has. The amount of crop residue left after planting depends on the original amount of residue available, the tillage implements used, the number of tillage passes, and the depth and speed at which tillage was performed.

Crop residue management has been designated by many terms since its inception. The NRCS and the Conservation Technology Information Center (CTIC) have adopted the following terms and definitions.

- Conventional-till: Tillage types that leave less than 15 percent residue cover after planting. Generally this involves plowing or intensive (numerous) tillage trips.
- Reduced-till: Tillage types that leave 15 to 30 percent residue cover after planting.
- Conservation tillage: Any tillage and planting system that leaves 30 percent, or more, of the ground covered after planting with the previous year's crop residues. Conservation tillage systems include mulch-till, no-till, strip-till, and ridge-till.
- Mulch-till: Full-width tillage that disturbs the entire soil surface is performed prior to and during planting. Tillage tools such as chisels, field cultivators, discs, sweeps, or bands are used. Weed control is accomplished with herbicides and/or cultivation.
- No-till and strip-till: The soil is left undisturbed from harvest to planting except strips up to one-third of the row width (strips may involve only residue disturbance or may include soil disturbance). Planting or drilling is accomplished using disc openers, coulter(s), row cleaners, in-row chisels, or roto-tillers. Weeds are controlled primarily with herbicides. Cultivation may be used for emergency weed control. Other common terms used to describe no-till include direct seeding, slot planting, zero-till, row-till, and slot-till.

- Ridge-till: The soil is left undisturbed from harvest to planting except for strips up to one-third of the row width. Planting is completed on the ridge and usually involves the removal of the top of the ridge. Planting is completed with sweeps, disc openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weeds are controlled with herbicides (frequently banded) and/or cultivation. Ridges are rebuilt during cultivation (CTIC, 1998a).

No-till, strip-till, and ridge-till provide the most soil conservation protection.

Application and Performance: Plant residues can aid in soil erosion control. Residues can protect the soil from the time of rowcrop harvest through the time the succeeding crop has developed sufficiently to provide adequate canopy protection. Conservation tillage reduces soil erosion by reducing detachment. It also reduces transport by minimizing soil crusting and increasing infiltration, which reduces runoff. The residue acts as small dams, slowing the movement of water across the field and reducing its ability to carry soil particles.

Conservation tillage increases the size of soil aggregates, which reduces the potential of wind to detach soil particles and thereby reduces wind erosion. The residue also slows the wind speed at ground level, reducing its ability to carry soil particles.

Advantages and Limitations: Benefits other than soil conservation that can be gained include the following:

- Reduced tillage costs
- Reduced labor
- Reduced runoff
- Reduced fuel use
- Reduced machinery wear
- Reduced PM in air from wind erosion
- Increased soil moisture
- Improved surface water quality
- Increased water infiltration
- Decreased soil compaction
- Improved soil tilth
- Increased populations and diversity of wildlife
- Increased sequestration of greenhouse gases (carbon dioxide)

Normally, the cost of changing from a conventional tillage system to a conservation tillage system is minimal if current equipment can be adapted. The cost of changing is associated with the purchase of additional attachments for equipment and depends on the type of conservation tillage to be done (no-till, ridge-till, mulch-till, and so forth). The incremental cost of these attachments may range from $1.00 to $3.00/acre/year. However, if equipment is impossible to adapt or needs extreme adaptations, the investment in changing to a conservation tillage system can become significant.

Intensive overall management is critical to the success of a no-tillage or ridge-tillage system. Constraints and challenges within the system should be considered before choosing a no-tillage or ridge-tillage method. The most successful system needs a strong commitment from a knowledgeable manager. Management considerations and system constraints include the following:

- Manure application and the need to incorporate.
- Alternative methods or equipment modifications for nutrient placement.
- The need to apply or incorporate lime.
- Planter and harvesting attachments need to be correctly installed and maintained.
- Critical timing of field operations.
- Greater reliance on herbicides for weed control.
- Shifts in weed populations and weed varieties.
- Increased N requirements due to an increase in residue that has a high C:N ratio.
- Delays in spring field operations due to cold, wet soils.
- Delayed seed germination due to cold, wet soils.

Conservation tillage can be used on cropland fields where excess sheet and rill erosion and wind erosion are a concern. Conservation tillage is most effective when used with other supporting conservation practices such as grassed waterways, contouring, and field borders.

Operational Factors: In the northern areas of the United States where soil temperatures stay colder for longer periods of time, no-till may not be as well adapted as some of the other conservation tillage systems. In these areas strip-till or ridge-till may be better options.

Demonstration Status: Conservation tillage is used across the United States and in conjunction with all the major crops.

Practice: Crop Rotation

Description: Crop rotation is the practice of alternating high-residue crops with low-residue crops on the same piece of land, from year to year. Although crop rotations can vary significantly, a typical rotation giving significant erosion protection could include high-residue-producing crops like small grains and hay, and low-residue-producing row crops like corn and soybeans. A typical rotation using these crops would be corn-soybeans-corn-small grain-hay-hay.

Application and Performance: The soil conservation purpose of a crop rotation is to alternate crops that have high erosion potential with crops that have low erosion potential because it is the average soil loss over time that is critical. It is expected that in those years when low-residue crops are planted, significant erosion may occur. However, in years when high-residue crops are planted, very little erosion will occur. Therefore, the average rate of soil erosion throughout the rotation sequence will be significantly lower than it would be if only low-residue crops had been planted. A rotation of corn-soybeans-corn-small grain-hay-hay could be expected to reduce soil erosion by 50 percent as compared with just corn and soybeans, depending on the tillage system (Renard et al, 1997).

Advantages and Limitations: Weather conditions, unexpected herbicide carryover, and marketing considerations may result in a desire to change a scheduled crop rotation. Since most farmers want to balance production acres of different crops, they need to have the flexibility of changing the rotations in one field because of an unexpected condition in another field.

Operational Factors: Crop rotation can be used where sheet and rill erosion is a problem on cropland. Crop rotation works best with other supporting conservation practices such as conservation tillage, contouring, and grassed waterways. A market or use for the small grains or hay is needed before farmers will adopt the use of crop rotation.

Demonstration Status: The use of crop rotations is generally adopted in those regions that have dairy herds because of the need for hay.

Practice: Contouring and Cross-Slope Farming

Description: Contour farming is the practice of tilling, planting, and cultivating crops around a slope on a nearly level line that slowly grades water to a nonerosive area that can handle concentrated flow. In gentle rains, the contoured rows are able to slowly grade the water to a nonerosive area such as a grassed waterway or field border. In heavier rains, when the water runs over the tops of the rows, the rows serve as mini dams to slow the water. Slowing the water allows for more infiltration of water into the soil profile and reduces sediment transport in the field.

On some slopes, strict contour farming that results in sharp turns and endless point rows is impractical. Farm machinery may be too large to accommodate the tight turns and numerous point

rows and increases the amount of time required to complete field operations. In this case, an alternative to contouring is cross-slope farming, which allows greater deviation from the contour line. Although cross-slope makes farming easier, it is generally only half as effective as contouring in reducing soil erosion.

In some areas of the country, using a rollover plow on the contour is beneficial to turn the soil uphill while performing conventional tillage. By using a rollover plow on the contour, soil is mechanically moved up-slope.

To allow for the removal of water in a concentrated flow, waterways need to be seeded, or shaped and seeded.

Application and Performance: Contouring can reduce soil erosion by 25 to 50 percent and cross-slope farming can reduce soil erosion by 10 to 25 percent depending on slope length, slope steepness, field roughness, and row grade (Renard et al, 1997).

Advantages and Limitations: Because contouring and cross-slope farming slow the runoff of water, water infiltration is increased and soil erosion is reduced. The increased water infiltration may also mean more available subsoil moisture during the growing season. Horsepower requirements may also be lower when farming on the contour or cross-slope.

On longer slopes, both contouring and cross-slope farming become less effective and should then be used in combination with a supporting conservation practice such as terraces or contour strip cropping.

The major disadvantage of contouring, and to a lesser extent cross-slope farming, is the increased time needed to perform the tilling, planting, spraying, cultivating, and harvesting operations. Contouring may require 25 to 50 percent more time as compared with farming straight rows. Cross-slope farming may require 10 to 25 percent more time as compared to farming straight rows. This increased time leads to higher labor, fuel, and equipment costs on a per acre basis.

Operational Factors: Contouring or cross-slope farming can be used on most slopes on which row crops are planted.

Demonstration Status: Contouring or cross-slope farming is widely adopted across the United States.

Practice: Contour Stripcropping/Contour Buffer Strips

Description: Contour stripcropping is a system of growing crops in approximately even-width strips or bands on the contour. The crops are arranged so that a strip of meadow or close- growing crop is alternated with a strip of row crop. Contour stripcropping combines the soil protection of both contouring and crop rotation. The widths of rowcrop strips should equal the widths of the

hay or small grain strips. The strips of hay or small grain slow water flow and trap sediment from the row crop strips above them.

Contour buffer strips can be used when a higher percentage of row crop acres are needed. A contour buffer strip system allows for the hay or small grain strips to be narrower than the strips of row crop. Because a contour buffer strip system results in more row crop acres, it is less effective than contour strip cropping in reducing soil erosion.

The strip width depends on the steepness of the slope and the management practices being used. It is also designed to accommodate the width of equipment (planters, sprayers, and harvesters). An even number of equipment passes along each strip which improves field operation efficiency by starting and finishing a pass at the same end of the field. Grassed field borders and grassed waterways are an integral part of any stripcropping system. They provide access lanes and safe areas for concentrated water runoff.

Application and Performance: Contour stripcropping is very effective in reducing sheet and rill erosion. It can reduce soil loss by as much as 75 percent, depending on the type of crop rotation and the steepness of the slope. Depending on the width of the grass strip and the row crop strip, and the steepness of the slope, contour buffer strips can reduce sheet and rill erosion by as much as 75 percent or as little as 20 percent (Renard et al., 1997).

Advantages and Limitations: Choosing to use contour stripcropping or contour buffer strips is an excellent conservation practice for a farmer who can use small grains or hay. Instead of planting one entire field to small grains or hay and another entire field to row crops, strips of hay or grain can be alternated, thereby reducing soil erosion.

Effective stripcropping systems require strips that are wide enough to be farmed efficiently. If possible, consolidation of fields may be necessary. The major disadvantage of using contour stripcropping or contour buffer strips as an erosion control practice is the same as that of contouring: increased time to perform the field operations (e.g., tillage, planting, spraying, and harvesting). These practices may require 25 to 50 percent more time than farming straight rows. Increased time used in field operations leads to higher labor, fuel, and equipment costs on a per acre basis.

Operational Factors: Contour stripcropping and contour buffer strips can be used where sheet and rill erosion are a problem in cropland, and they work best with other supporting conservation practices such as conservation tillage and grassed waterways. The use of contour stripcropping and contour buffer strips is practical only if there is a market or use for the small grains or hay.

Demonstration Status: The use of crop rotations is generally adopted in those regions that have dairy herds, beef cattle, or sheep because of the need for hay.

Practice: Grassed Waterways

Description: Grassed waterways are areas planted to grass or other permanent vegetative cover where water usually concentrates as it runs off a field. They can be either natural or man-made channels. Grass in the waterway slows the water as it leaves the field. Grassed waterways can serve as safe outlets for graded terraces, diversions, and contour rows. They can also serve as passageways for water that enters a farm from other land located higher in the drainage basin. Grassed waterways significantly reduce gully erosion and aid in trapping sediment.

Application and Performance: Grassed waterways protect the soil from erosion at points of concentrated water flow. They are designed to safely carry runoff water from the area that drains into them to a stable outlet. Small waterways are designed in a parabolic shape and are built wide enough and deep enough to carry the peak runoff from a 24-hour storm that would be expected to occur once every 10 years.

The decision to mow or not to mow grassed waterways depends on supporting conservation practices and other management concerns. To increase the lifespan of the waterway, it is best to mow or clip the grass in the waterway. If grasses are allowed to grow, the flow rate of the waterway is slowed, increasing the rate of sedimentation in the waterway, which in turn increases the cost of maintaining the waterway. If waterways are clipped, however, water flows faster and the sediment is carried farther down slope before being dropped out. If manure is applied in the waterway drainage area, grassed waterways should not be mowed. To prevent excessive sedimentation in the unmowed waterways, other supporting conservation practices, such as contouring, conservation tillage, or barrier systems, should be in place.

Advantages and Limitations: The goal of a waterway design is to protect against soil loss while minimizing siltation and gullying in the waterway. Gullies can form along the side of a waterway if the water does not enter the waterway or if the runoff spills out of the waterway and runs parallel to it. This can be caused by inadequate design (too shallow or too narrow) or inadequate maintenance, and in some cases by flooding. Even under the best conditions, grassed waterways tend to either silt in or develop channels or gullies. Timely maintenance and repairs can prevent major reconstruction. Silt can be cleaned out and small gullies can be filled in. However, if the waterway is damaged too badly, it will need to be completely reshaped and reseeded. Often heavy equipment such as a bulldozer or a scraper is required.

Grassed waterways permanently take land out of cereal and row crop production, but they can be harvested for forage production if the farmer has a use or market for the forage and the equipment to harvest the forage.

The cost of waterway construction depends on the depth and width of the waterway. It ranges from $1.50 to $3.50 per linear foot, with mulch and seed. In addition to the construction cost, there is a maintenance cost. The cost to maintain a waterway is highly variable depending on drainage area size, soil type, grade of the waterway, and level of control of soil erosion above the

waterway. Some waterways can function for 10 years without maintenance, whereas others need maintenance on a yearly basis.

Operational Factors: Grassed waterways can be used where ephemeral erosion and gully erosion are a problem.

Demonstration Status: Grassed waterways are used across the United States and in conjunction with all the major crops.

Practice: Terraces

Description: Terraces are earthen structures that run perpendicular to the slope and intercept runoff on moderate to steep slopes. They transform long slopes into a series of shorter slopes. On shorter slopes, water velocity is slower and therefore has less power to detach soil particles. Terraces slow water, catch water at intervals down slope, and temporarily store it in the terrace channel.

Depending on the soil type, the water can either infiltrate into the ground or be delivered into a grassed waterway or an underground tile. Terraces are spaced to control rill erosion and to stop ephemeral gullying. Terrace spacing is determined by several factors including soil type, slope, and the use of other supporting conservation practices such as conservation tillage and crop rotation. When more than one terrace is placed on a hillside, it is best to construct the terraces parallel to each other and at spacings that are multiple widths of field equipment. This approach helps eliminate short rows and improves the efficiency of field operations.

Application and Performance: Terraces reduce the rate of runoff and allow soil particles to settle out.

Advantages and Limitations: One of the biggest advantages of terraces is that they are permanent conservation practices. A farmer usually does not adopt terracing one year and decide the next year not to use it, unlike such management practices as conservation tillage or contouring. In almost all cases, terraces will not be removed until they have exceeded their life expectancy of 20 years.

A disadvantage of terraces is that they are built with heavy construction equipment and the soil structure around the terrace can be permanently altered. Terraces are built by pushing soil up, which usually requires a bulldozer. Compaction on the lower side of the terrace is always a concern and can last for years after the terrace is constructed.

Terraces can permanently remove land from production. The amount of land removed from production depends on the terrace system installed, but it normally ranges from 0 to 5 percent of the overall land base. The cost to install terraces ranges between $0.75 and $3.00 per linear foot, including seeding. In many cases terraces also require either a tile line or a waterway as an outlet

for the water. The cost of installing tile can range from $.75 to $1.50 per linear foot. Waterway costs are covered in the section on grassed waterways. It can cost in the range of $100 to $165 to protect 1 acre of land with terraces and suitable outlets. In addition to construction costs, there are always maintenance costs. If excessive rains occur, terraces will overtop and require maintenance. The sediment collected in terrace channels should be cleaned out periodically, at least every 10 years, or sooner, depending on the sedimentation rate. Maintenance also includes removing trees and shrubs from the terrace and repairing rodent damage.

In addition to the loss of cropland and cost of construction and maintenance, terraces are laid out on the contour, which can increase the time, fuel, and equipment costs associated with field operations. See the section on contouring and cross-slope farming for costs associated with contouring.

Operational Factors: Terraces can be used when sheet, rill, or ephemeral erosion are a concern.

Demonstration Status: Terraces are widely adopted across the United States.

Practice: Field Borders

Description: A field border is a band or strip of perennial vegetation, usually grass or legume, established at the edge of a field. From a soil conservation standpoint, field borders are used to replace end rows that run up and down a hill. Sometimes field borders replace end rows all the way around the field, and other times they are used where slope length and steepness present a concern for soil erosion. Field borders can be used in fields that are contoured, cross-sloped, contour stripcropped, contour buffer stripped, or terraced.

Application and Performance: Field borders reduce detachment, slow transport, and help reduce sediment load in water.

Advantages and Limitations: Field borders reduce acres of cereal crops or row crops in production. However, if the field border is planted to forage, it can be harvested, as long as the farmer has the proper equipment and a use or market for the crop. The cost of seeding an acre of field borders is approximately $50 to $70 per acre.

Operational Factors: Field borders can be used with all crops and in all regions of the United States.

Demonstration Status: Field borders are commonly used as a conservation practices in combination with other practices.

Practice: Sediment Basin

Description: A sediment basin is a barrier structure constructed to collect and store manure, sediment, or other debris.

Application and Performance: Sediment basins are constructed to accumulate and temporarily store water runoff. For controlling manure runoff, sediment basins may be used in two types of settings, to capture feedlot or field runoff. As runoff accumulates and water is slowly discharged through an outlet, soil particles settle out and are trapped in the basin. Frequently, a filter strip is positioned as a secondary treatment practice below the sediment basin to catch the additional sediment flowing through the outlet. Sediment basins reduce the transport of soil and manure by flowing water.

Advantages and Limitations: The construction cost of sediment basins is quite variable, depending on the steepness of the land and the size of the drainage area flowing into the basin. However, basins are normally a cost-effective practice to capture sediment.

On-site erosion control cannot be achieved with sediment basins, because they do little to stop detachment and transport of soil.

Operational Factors: Sediment basins can be used with all crops and in all regions of the United States.

Demonstration Status: Sediment basins are commonly used as conservation practices in all cropland systems.

Practice: Cover Crops

Description: A cover crop is a crop of close-growing grass, legumes, or small grain grown primarily for seasonal protection and soil improvement. These crops are also known as green manure crops. Cover crops are usually grown for 1 year or less, except where there is permanent cover (e.g., orchards). They increase vegetative and residue cover during periods when erosion energy is high, and especially when primary crops do not furnish adequate cover. Cover crops may be established by conventional or conservation tillage (no-till or mulch-till) methods or by aerial seeding.

Cover crops should be planted immediately after harvest of a primary crop to maximize the erosion control benefits. Recommended seeding dates vary from year to year and depend on soil type, local climatic conditions, field exposure, and the species of cover crop being grown.

Application and Performance: Cover crops control erosion during periods when the major crops do not furnish adequate cover. Since cover crops provide a quick canopy, they reduce the impact of raindrops on the soil surface, thereby reducing soil particle detachment. Cover crops also slow the surface flow of water, reducing transport of sediment and increasing water infiltration. Cover crops can add organic material to the soil; they improve water infiltration, soil aeration, and soil quality. In addition, cover crops can control plant nutrients and soil moisture in the root zone. If a legume crop is used as a cover crop, it will provide N for the next year's crop.

Actively growing cover crops use available nutrients in the soil, especially N, thus preventing or decreasing leaching or other loss. These nutrients may then become available to the following crop during the decaying process of the green manure.

Advantages and Limitations: Cover crops increase transpiration. In areas of the United States where moisture is limited, cover crops may use up too much of the available soil moisture. Loss of available soil moisture may reduce the yield of the primary crop planted after the cover crop, reducing profits.

Preparing a seedbed and drilling in a winter cereal crop costs $40 to $45 per acre. Broadcast seeding after harvest, followed by a tillage pass that levels the soil surface, costs $35 per acre. Broadcast seeding prior to harvest costs $15 per acre.

Operational Factors: Cover crops can be used when major crops do not furnish adequate cover and sheet and rill erosion is a problem.

Demonstration Status: Cover crops are used throughout the United States.

Practice: Filter Strip/Riparian Buffer

Description: Filter strips are strips of grass used to intercept or trap field sediment, organics, pesticides, and other potential pollutants before they reach a body of water.

Riparian buffers are streamside plantings of trees, shrubs, and grasses that can intercept contaminants from both surface water and ground water before they reach a stream.

Application and Performance: Filter strips and riparian buffers are designed to intercept undesirable contaminants such as sediment, manure, fertilizers, pesticides, bacteria, pathogens, and heavy metals from surface and subsurface flows of water to a water body. They provide a buffer between a contaminant source and water bodies. Buffers and filter strips slow the velocity of water, allowing soil particles to settle out.

Advantages and Limitations: Buffer strips and riparian buffers reduce the acreage in cereal crops or row crops, but they can be harvested for forage production if the farmer has a use or market for the forage and the equipment to harvest the forage. Depending on whether the filter strip or riparian buffer strip is seeded to grass or planted to trees, the cost of seeding can range from $50 to $500 per acre.

Operational Factors: Buffer strips and riparian buffers can be used with all crops and in all regions of the United States.

Demonstration Status: Filter strips and riparian buffers have been widely promoted and adopted throughout the United States with programs like the Conservation Reserve Program (CRP).

Practice: Crosswind Trap Strips, Crosswind Ridges, Crosswind Stripcropping, and Shelterbelts/Field Windbreaks

Description: Crosswind trap strips are rows of perennial vegetation planted in varying widths and situated perpendicular to the prevailing wind direction. They can effectively prevent wind erosion in cropping areas with high, average annual wind speeds.

Crosswind ridges are formed by tillage or planting and are aligned across the prevailing wind erosion direction. The ridges reduce wind velocity near the ground, and the soil particles that do start to move are trapped in the furrows between the ridge crests.

Crosswind stripcropping is growing crops in strips established across the prevailing wind direction and arranged so that the strips susceptible to wind erosion are alternated with strips having a protective cover that is resistant to wind erosion.

A shelterbelt or field windbreak is a row (or rows) of trees, shrubs, or other plants used to reduce wind erosion, protect young crops, and control blowing snow. Shelterbelts also provide excellent protection from the elements for wildlife, livestock, houses, and farm buildings. Field windbreaks are similar to shelterbelts but are located along crop field borders or within the field itself. In some areas of the country, they may also be called hedgerow plantings.

Application and Performance: These practices are designed to reduce soil erosion by increasing the soil roughness and reducing the wind speed at the soil surface.

Advantages and Limitations: The same practices that reduce wind erosion also reduce moisture loss. Snow is more likely to stay on the field than to blow off, thereby increasing soil moisture. A drawback to crosswind trap strips, shelterbelts, and field windbreaks is that they take cropland out of production. Also, they are a physical barrier to operations such as manure application with an umbilical cord system.

Operational Factors: These practices can be used anywhere that wind erosion is a concern in row crops.

Demonstration Status: These practices are used where row crops are planted in the Plains states.

8.5 References

AAC. 2000. *Farming for Tomorrow: Conservation Facts. Rotational Grazing: The Rest and Recovery Method of Pasture Management.* <http://aceis.agr.ca/pfra/land/fft10.htm>. Accessed 2/11/00. Agriculture and Agri-Food Canada.

ASAE. 1998. *Standards, 45th Edition, Standards, Engineering Practices and Data.* American Society of Agricultural Engineers, St. Joseph, Michigan.

Baird, J.V., S.C. Hodges, and M.R. Tucker. 1997. *Careful soil sampling—the key to reliable soil test information.* Publication AG-439-30, North Carolina Cooperative Extension Service, North Carolina State University, Raleigh, North Carolina.

Barker, J.C. 1996. *Livestock waste sampling, analysis, and calculation of land application rates.* Publication Number EBAE 111-84, North Carolina Cooperative Extension Service, North Carolina State University, Raleigh, North Carolina.

Barker, J.C., and J.P. Zublena. 1996. *Components of a complete manure management plan.* Publication Number EBAE 185-93, North Carolina Cooperative Extension Service, North Carolina State University, Raleigh, North Carolina.

Barrington, S. and J. B. Gelinas. 2002. Precipitating swine manure phosphorous using fine limestone dust. Paper No. 02-609, AIC 2002 Meeting, July 14-17, Saskatoon, Saskatchewan, Canada.

Barrow, J.T., H.H. Van Horn, D.L. Anderson, and R.A. Norstedt. 1997. Effects of Fe and Ca additions to dairy wastewaters on solids and nutrient removal by sedimentation. *Appl. Eng. in Agric.* 13(2):259-267.

Barth, C.L. and J. Kroes. 1985. Livestock Waste Lagoon Sludge Characteristics, In *Agricultural Waste Utilization and Management, Proceedings of the Fifth International Symposium on Livestock Wastes*, pp.660-671. ASAE. St. Joseph, Michigan.

Bartok, J.W. 1994. *Fertilizer and manure application equipment.* NRAES-57. Northeast Regional Agricultural Engineering Service, Cooperative Extension, Ithaca, New York.

Beal, J.D., P.H. Brooks, and H. Schulze. 1998. *The effect of the addition of a protease enzyme to raw or autoclaved soya bean on the growth performance of liquid fed grower/finisher pigs.* Abstract submitted for the Brit. Soc. Anim. Sci. meetings.

Berry, J.T., and N. Hargett. 1984. *Fertilizer summary data.* Tennessee Valley Authority, National Fertilizer Development Center, Mussel Shoals, Alabama.

Bicudo, J., D. Schmidt, C. Jacobson, K. Janni. 1999. *Nutrient Content and Sludge Volumes in Single Cell Recycle Anaerobic Swine Lagoons in North Carolina*, Transactions of the ASAE. Vol.42(4): 1087-1093.

Blake, J.P. and J.B. Hess. 2001. Litter Treatments for Poultry. ANR-1199. Alabama Cooperative Extension System, Auburn University, Auburn, Alabama. http://www.aces.edu/department/extcomm/publications/anr/anr-1199/anr-1199.html

Bonner, J., R.B. Moore, and J. Thomas. 1998. *Managing animal waste nutrients*. Mississippi State University Extension Service, Mississippi State University, Jackson, Mississippi.

Brady, N.C., and R.R. Weil. 1996. *The nature and properties of soils*. 11th ed. Macmillan Publishing Company, New York, New York.

Bridges, T.C.; L.W. Turner, G.L. Cromwell, and J.L. Pierce. 1995. Modeling the effects of diet formulation on nitrogen and phosphorus excretion in swine waste. *Applied Engineering in Agriculture* 11: 5, 731-739.

Brown, K.W. 1995. *Agronomy 616-Land disposal of waste*. Vol.1. Texas A&M University, College Station, Texas.

Brown, M.P., P. Longabucco, M.R. Rafferty, P.D. Robillard, M.F. Walter, and D.A. Haith. 1989. Effects of animal waste control practices on nonpoint-source phosphorus loading in the West Branch of the Delaware River watershed. *J. Soil and Water Conserv.* 44(1):67-70.

Brumm, M.C., J. D. Harmon, M. C. Honeyman, and J. Kliebenstein. 1997. Hoop Structures for Grow-Finish Swine. *Agricultural Engineers Digest* 41: 1-16. February 1997.

Busch, D., T. Wagar, and M. Schmitt. 2000. *Livestock manure sampling*. FO-6423-GO, College of Agricultural, Food, and Environmental Sciences, University of Minnesota Extension Service, St. Paul, Minnesota.

Bushee, E.L., D.R. Edwards, and P.A. Moore. 1998. Quality of runoff from plots treated with municipal sludge and horse bedding. *Trans. ASAE* 41(4):1035-1042.

Carrington, E.G. and M.E. Ransome. 1994. *Factors influencing the survival of* Cryptosporidium *oocysts in the environment*. Report No. FR 0456. Foundations for Water Research. Marlow, Bucks.

CAST. 1996. *Integrated animal waste management*. Task Force Report No. 28. Council for Agricultural Science and Technology, Ames, Iowa.

Chase, L. E. 1998. "Phosphorus nutrition of dairy cattle" Mid-South Ruminant Nutrition Conference, Dallas, Texas, sponsored by Texas Animal Nutrition Council and the Texas Agricultural Extension Service. May 7-8, 1998.

Chastain, J., W. Lucas, J. Albrecht, J. Pardue, J. Adams, and K. Moore. 1998. *Solids and Nutrient Removal from Liquid Swine Manure using a Screw Press Separator.* Paper No. 98-4110. American Society of Agricultural Engineers, St. Joseph, Michigan.

Cheng, J., J. Pace, K. D. Zering, J. C. Barker, K. F. Roos, and L. M. Saele. 1999. Evaluation of Alternative Swine Waste Treatment Systems in Comparison with Traditional Lagoon System. Paper to be presented at Livestock Waste Management Symposium, American Society of Agricultural Engineers, Des Moines, Iowa, October 2000.

CIAS. 2000. *Dairy Grazing Can Provide Good Financial Return.* Center for Integrated Agricultural Systems. <http://www.wisc.edu/cias/pubs/resbrief/050.html> Accessed May 29, 2000.

Clausen, J.C. 1990. Winter and Fall application of manure to corn land. Pages 179 – 180 in Meals, D.W. 1990. LaPlatte River Watershed Water Quality Monitoring and Analysis Program: Comprehensive Final Report. Program Report No. 12. Vermont Water Resource Research Center, University of Vermont, Burlington.

Clausen, J.C. 1991. Best manure management effectiveness. Pages 193 – 197 in Vermont RCWP Coordinating Committee. 1991. St. Albans Bay Rural Clean Water Program, Final Report. Vermont Water Resources Research Center, University of Vermont, Burlington

Clausen, J.C. and D.W. Meals. 1989. Water quality achievable with agricultural best management practices. *J. Soil and Water Conserv.* 44(6):593-596.

Conner, M. 1994. Update on alternative housing for pigs. *Manitoba Swine Seminar Proceedings* 8: 93-96.

Conner, M. 1993. Evaluation of a biotech housing for feeder pigs. *Manitoba Swine Update.* July 1993. 5(3)1.

Cooper Hatchery, Inc. 1987. The Efficiency of Hydrated Lime Used in Turkey Litter Sanitation Procedures. PSA Annual Meeting, 10-14 Aug., Oregon State University, Corvallis, OR.

Converse, J.C., G.D. Bubenzer, and W.H. Paulson. 1976. Nutrient losses in surface runoff from winter spread manure. *Trans. ASAE* 19:517-519.

Crouse, K., and W. McCarty. 1998. *Soil testing for the farmer.* Extension Agronomy, Mississippi State University, Jackson, Mississippi.

CTIC. 1998a. *Crop Residue Management Survey Executive Summary.* <http://www.ctic.purdue.edu/Core4/CT/CTSurvey/Method.PDF>. Conservation Technology Information Center, Purdue University, West Lafayette, Indiana. Accessed March 31, 2000.

CTIC. 1998b. *The 1998 MAX report.* Conservation Technology Information Center, Purdue University, West Lafayette, Indiana.

Culotta, C. P., and G. H. Schmidt. 1988. An Economic Evaluation of Three Times Daily Milking of Dairy Cows. *Journal of Dairy Science* 71: 1960.

Cummings, R.J., and W.J. Jewell. 1977. Thermophilic Aerobic Digestion of Dairy Waste. In *Food, Fiber, and Agricultural Residues*, ed. R.C. Loehr, pp. 637-657. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan.

Dahl, G. E., J. P. Chastain and R. R. Peters. 1998. Manipulation of photoperiods to increase milk production in cattle: biological, economic and practical considerations. In *Proceedings of the Fourth International Dairy Housing Conference*, J. P. Chastain ed., American Society of Agricultural Enginineers, St. John's, Michigan.

Dahl, G.E., T.H. Elsasser, A.V. Capuco, R.A. Erdman and R.R. Peters. 1996. Long day photoperiod that stimulates milk yield and also increases circulating insulin-like growth factor-1 (IGF-1). FASEB J. 10: A751.

Dao, T.H. 1999. Coamendments to modify phosphorus extractability and Nitrogen/Phosphorus ratio in feedlot manure and composted manure. *J. Environ. Qual.* 28:1114-1121.

Dick, W.A., D.J. Eckert, J.W. Johnson. 1999. *Land application of poultry litter.* ANR-4-98. Ohio State University Extension Fact Sheet, School of Natural Resources, Columbus, Ohio.

Dierick and Decuypere. 1994: referenced by Close, W.H. 1996. Nutritional management of swine is ever-evolving challenge. *Feedstuffs*, 22 Jan.:16-19,46-47

Dinn, N. E. , L. J. Fisher, J. A. Shelford and J. Paul. 1996. The use of the Cornell net carbohydrate and protein system and rumen protected lysine and methionine to reduce nitrogen excretion of lactating dairy cows. *J. Dairy Sci.* 79: (Suppl 1) 129.

Doerge, T.A., R.L. Roth, and B.R. Gardner. 1991. *Nitrogen fertilizer management in Arizona.* College of Agriculture, University of Arizona, Tucson, Arizona.

Dou, Z. and J.D. Ferguson. 2002. Using chemical amendments to reduce phosphorus solubility in animal manure. University of Pennsylvania, School of Veterinary Medicine, http://cahpwww.vet.upenn.edu/cahpinfo/ppl/dou/chemamen.html

Dunlap, T. F., R. A. Kohn and K. F. Kalscheur. 1997. Effect of animal grouping strategies on nutrient losses from the dairy farm. *J. Dairy Sci.* 80: (Suppl. 1) 246.

Edens F. and C. Simons. 1998. *Use of Phytase in Poultry diets to Reduce Phosphorus Excretion.* North Carolina State University, Department of Poultry Sciences, and Center for Applied Poultry Research, Netherlands.

Edwards, D.R., P.A. Moore, S.R. Workman, and E.L. Bushee. 1999. Runoff of metals from alum-treated horse manure and municipal sludge. *J. Am. Water Resour. Assoc.* 35(1):155-165.

Emmicx, D.L. 2000. *State Grasslands Specialist, New York State. ABC's of Rotational Grazing: Questions and Answers.* <http://www.kingcd.org/stewardship/Ag%20Pr...ces/Pastures/ABCsofRotationalGrazing.html>. Accessed February 11, 2000.

Entry, J.A. and R.E. Sojka. 2000. The efficacy of polyacrylamide and related compounds to remove microorganisms and nutrients from animal wastewater. *J. Environ. Qual.* 29:1905-1914.

Envirologic Corporation. 2000. *High-Rise™ Hog Facilities.* Informational packet distributed by Fort Recovery Equipment Systems, Inc. Received March 27, 2000.

Erdman, R. A. and M. Varner. 1995. Fixed yield responses to increased milking frequency. *J. Dairy Sci.* 78: 1199.

Fayer, R. and T. Nerad. 1996. Effects of low temperature on viability of *Cryptosporidium parvum* oocysts. *Appl. and Environ. Microbiol.* 62(4):1431-1433.

Ferguson, J. D. 1999. *Typical concentrations of urea found in milk.* <http://www.dhia.psu.edu/munnews>.

Fox, D.G., M.C. Barry, R.E. Pitt, D.K. Roseler, and W.C. Stone. 1995. "Application of the cornell net carbohydrate and protein system for cattle consuming forage" *J. Anim. Sci.* 73: 267.

Franti, T.G. 1997. *Vegetative Filter Strips for Agriculture.* NF 97-352. Nebraska Cooperative Extension.

Fulhage C. 1998. *Gaseous Emissions from Manure Management Systems - An Overview.* Presented at 1998 American Society of Agricultural Engineers Annual Meeting, Orlando, Florida. 1998.

Fulhage, C. and J. Hoehne. 1999. *Manure Nutrient Content and Variability in Missouri Swine Lagoons*. Paper. No. MC99-104. Presented at 1999 American Society of Agricultural Engineers Mid-Central Meeting, St. Joseph, Michigan. April 20-May 1, 1999.

Fulhage, C.D., and D.L. Pfost. 1993. *Flushing Systems for Dairies*. WQ308. Department of Agriculture Engineering, University of Missouri-Columbia, Columbia, Missouri. July 15.

Garber, L. 1999. USDA NAHMS Center for Animal Health Monitoring facsimile sent August 1999.

Gerba, D., C. Wallis, and J. Mellnick. 1975. Fate of wastewater bacteria and viruses in soil. *J. Irr. Drain. Div. ASCE* 101:157-174.

Graham, H. and J. Inborr. 1993. Feed enzymes: mode of action and application to heat processed poultry feeds. Amandus Kahl Seminar

Graves, R. 2000. Department of Agriculture Engineering, Penn State University, University Park, Pennsylvania. E-mail correspondence. April 2.

Hallberg, G.R. 1991. *A progress review of Iowa's agricultural-energy-environmental initiatives: nitrogen management in Iowa*. Technical Information Series 22, Iowa Department of Natural Resources, Iowa City, Iowa.

Halverson, M. 1998. Management in Swedish Deep-Bedded Swine Housing System: Background and Behavioral Considerations. Managing Manure in Harmony with the Environment Conference and Proceedings, Ames, Iowa, February 10-12 1998: 155-158.

Hanna, M. 1998. *Incorporate manure to reduce odor and maintain residue cover*. Iowa Manure Matters Odor Nutrient Management Newsletter. Summer 1998. Iowa State University, Ames, Iowa.

Hannawale, J. 2000. Telephone conversation with Jim Hannawale, USDA, on April 4, 2000.

Harmon, J., H. Xin. 1997. *Thermal Performance of a Hoop Structure for Finishing Swine*. ASL-R1391. 1996 Swine Research Reports: 104-106. Iowa State University Extension, Ames, Iowa.

Harmon, J., M. Honeyman. 1997. *Hoop Structures- Research on Performance and Operation*. <http://www.ae.iastate.edu/aen189.htm>. Accessed March 15, 2000.

Harner, J.P., J. P. Murphy, D. L. Devlin, W. H. Fick, G.L. Kilgore. 2000. *Vegetative Filter Strip Systems for Animal Feeding Operations*. Kansas State University Agricultural Experiment Station and Cooperative Extension Service.

Hatfield, J.L. 1998. *Evaluation of the potential environmental implications of animal manure.* National Soil Tilth Laboratory, Ames, Iowa.

Haustein, G.K., T.C. Daniel, D.M. Miller, P.A. Moore, and R.W. McNew. 2000. Aluminum-containing residuals influence high-phosphorus soils and runoff water quality. *J. Environ. Qual.* 19:1954-1959.

Hensler, R.F., R.J. Olsen, S.A. Witzel, O.J. Attoe, W.H. Paulson, and R.F. Johannes. 1970. Effect of method of manure handling on crop yields, nutrient recovery, and runoff losses. *Trans ASAE* 13(6):726-731.

Hirschi, M., R. Frazee, G. Czapar, and D. Peterson. 1997. *60 ways farmers can protect surface water.* North Central Regional Extension Publication 589, University of Illinois, Urbana-Champaign, Illinois.

Hogan, J.S., V.L. Bogacz, L.M. Thompson, S. Romig, P.S. Schoenberger, W.P. Weiss, and K.L. Smith. 1999. Bacterial counts associated with sawdust and recycled manure bedding treated with commercial conditioners. *J. Dairy Sci.* 82:1690-1695.

Honeyman, M. 1999. *An Overview of Swine System Options.* Proceedings: Swine System Options For Iowa 1999, February 17, 1999. Iowa State University, Ames, Iowa.

Honeyman, M. 1996. *Hoop Structures with Deep Bedding for Grow-finish Pigs.* ASL-R1392. 1996 Swine Research Reports: 107:110. Iowa State University Extension, Ames, Iowa.

Honeyman, M., J. Harmon, D. Lay, and T. Richard. 1997. *Gestating Sows in Deep-bedded Hoop Structures.* ASL-R1496. 1997 Swine Research Reports. Iowa State University Extension, Ames, Iowa.

Honeyman, M., J. Harmon, A. Penner, and C. Jorgenson. 1999. *Performance of Finishing Pigs in Hoops and Confinement During Summer and Winter.* ASL-R1682. 1999 Swine Research Reports. Iowa State University Extension, Ames, Iowa.

Hue, N.V., R. Uchida, and M.C. Ho. 1997. *Testing your soil—why and how to take a soil-test sample.* AS-4. Agronomy and Soils, Cooperative Extension Service, College of Tropical Agriculture & Human Resources, University of Hawaii, Manoa, Hawaii.

Humenick, F., A.A. Szogi, P.G. Hunt, J.M. Rice, and G.R. Scalf. 1972. *Constructed Wetlands for Swine Wastewater Treatment.* Waste Management Research, Proceedings of the 1972 Cornell Agricultural Waste Management Conference. Cornell University and USEPA. pp. 41-353.

Hutchinson, L.J. 1988. *Animal Health, Pest Management and Environment.* U.S. Department of Agriculture, Soil Conservation Service, Northeast National Technical Center, Chester, Pennsylvania.

Iowa State University. 1999. *Managing Nutrients for Crop Production.* PM-1811. Iowa State University Extension, Ames, Iowa.

Iragavarapu, R., and T. Doerge. 1999. *Manure Phosphorus - Problems Regulations, and Crop Genetic Solutions.* <http://www.pioneer.com/usa/nutrition/ manure_phosphorus _availability_99.html>. Accessed September 20, 1999

ISU (Iowa State University). 1995. *Land application for effective manure nutrient management.* Pm-1599. October 1995. Iowa State University Extension, Ames, Iowa.

Jeffery, R. 1996. *Nitrogen and Phosphorus Accumulation in the Soil Profile Beneath an Alternative Housing System for Pigs*, Report No 2. Pig Research and Development Corporation, Medina Research Centre, February 27, 1996, Greenwood, Washington.

John, R.E. 1991. *Alternative Animal Products: The Industry. University of Maryland National Dairy Database.* <http://www.inform.umd.edu/EdRes/Topic/AgrEnv/ndd/feeding/ALTERNATIVE_ANIMAL_PRODUCTS_THE_INDUSTRY.html>. Accessed September 24, 1999.

Johnson, D.E., G.M. Ward and J. Torrent. 1992. "The environmental impact of bovine somatotropin use in dairy cattle." *J. Environ. Qual.* 21: 157.

Johnson, K.P., and C.D. Montemagno. 1999. *An Analysis of Dairy Waste Treatment Using Sequencing Batch Reactors.* Cornell University, Department of Agricultural and Biological Engineering.

Jones, D.D. 2000. Department of Agriculture and Biosystems, Purdue University, West Lafayette, IN. E-mail correspondence. March 31.

Jonker, J.S., R.A. Kohn and R.A. Erdman. 1998. Using Milk Urea Nitrogen to Predict Nitrogen Excretion and Utilization Efficiency in Lactating Dairy Cows. *J. Dairy Sci.* 81:2681.

Kalscheur, K.F., R.A Kohn, R.A. Erdman, and J.H. Vandersall. 1997. Evaluation of Diet Formulation Models Using Low Protein Corn-based Diets. *J. Dairy Sci.* 80: (Suppl. 1) 162.

Keener, H., D. Elwell, T. Menke, and R. Stowell. 1999. *Design and Management of High-Rise™ Hog Facility Manure Drying Bed.* ASAE Paper 994108. ASAE, St. Joseph, Michigan.

Keplinger, K. 1998. Cost savings and environmental benefits of dietary P reductions for dairy cows in the Bosque river watershed. Working paper, Texas Institute for Applied Environmental Research.

Kibby, H.J., C. Hagedorn, and E.L. McCoy. 1978. Use of Fecal Streptococci as indicators of pollution in soil. *Appl. and Environ. Microbiol.* 35(4):711-717.

Kithome, M., J.W. Paul, and A.A. Bomke. 1999. Reducing nitrogen losses during simulated composting of poultry manure using adsorbents or chemical amendments. *J. Environ. Qual.* 28:194-201.

Klausner, S.D., P.J. Zwerman, and D.F. Ellis. 1976. Nitrogen and phosphorus losses from winter disposal of dairy manure. *J. Environ. Qual.* 5(1):47-49.

Knowlton, K. F., and R. Kohn. 1999. "We've got to stop overfeeding phosphorus" *Hoard' Dairyman*, Vol. 144, no. 11, June.

Koelsch, R. 1997. *Determining crop available nutrients from manure.* G97-1335A. NebGuide, Cooperative Extension Publication. Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska.

Kohn, R. A., K. F. Kalscheur and M. Hanigan. 1998. "Evaluation of Models for Balancing the Protein Requirements of Dairy Cows," *J. Dairy Sci.* 81: 3402.

Kohn, R.A. 1999. *The Impact of Dairy Herd Management on Nutrient Losses to Water Resources.* <http://www.inform.umd.edu/ManureNet/herdeffic>.

Kroodsma, W. 1985. Separation as a Method of Manure Handling and Odours Reduction in Pig Buildings. *In Odour Prevention and Control of Organic Sludge and Livestock Farming.* Elsevier Applied Science Publishing, London, England.

Kudva, I.T., K. Blanch, and C.J. Hovde. 1998. Analysis of *Escherichia coli* O157:H7 in ovine or bovine manure and manure slurry. *Appl. and Environ. Microbiol.* 64(9):3166-3174.

Langland, M.J., and D.K. Fishel. 1996. *Effects of agricultural best-management practices on the Brush Run Creek headwaters, Adams County, Pennsylvania, prior and during nutrient management.* Report 95-4195, U.S. Geological Survey, Water Resources Investigations Lemoyne, Pennsylvania.

Lee, A. 2000. *What Is Pastured Poultry?* <http://www.lionsgrip.com/pastured.html>. Accessed December 4, 2000.

Lefcourt, A.M. and J.J. Meisinger. 2001. Effect of adding alum or zeolite to dairy slurry on ammonia volatilization and chemical composition. *J. Dairy Sci.* 84:1814-1821.

Lei, X.G., P.K. Ku, E.R. Miller, and M.T. Yokoyama. 1993. Supplementing corn-soybean meal diets with microbial phytase linearly improves phytate phosphorus utilization by weaning pigs. *Journal of Animal Science* 71(12): 3359-3367.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. *Journal of Production Agriculture*: 6(4): 483-486.

Lenis, N.P., and J.B. Schutte. 1990. Aminozuurvoorziening van biggen en vleesvarkens in relatie tot stikstofuitscheiding. In *Mestproblematiek: aanpak via de voeding van varkens en pluimvee* eds. A.W. Jongbloed and J. Coppoolse; pp. 79-89. Onderzoek inzake de mest en ammoniakproblematiek in de veehouderij 4, Dienst Landbouwkundig Onderzoek, Wageningen, Netherlands.

Liskey, R.K., J.B. Franzini, D.L. Freyberg, and G. Tchobanoglous. 1992. *Water Resources*, 4th ed. McGraw-Hill, New York, New York.

Loehr, R. 1977. *Pollution Control for Agriculture.*, Academic Press, Inc., New York, New York.

Logan, T. 1999. Alkaline Stabilization of Animal Wastes. Annual Report. N-Viro International, Inc. <http://www.nviro.com/facility references/facs/Beltsville99report.pdf>.

Lorimor, J. 2000. Department of Agriculture and Biosystems Engineering, Iowa State University, Ames, Iowa.. E-mail correspondence. April 4.

Lusk, P. 1998. *Methane Recovery from Animal Manures: The Current Opportunities Casebook.* NREL/SR-580-25145. National Renewable Energy Lab, Golden, Colorado. September 1998

Marketing Directions. 1998. *Nutrient management research.* Conservation Technology Information Center, West Lafayette, Indiana.

Martin, J.H., Jr. 1999. Pathogen Reduction-Temperature Relationships. Unpublished report prepared for the Engineering Analysis Division, U.S. Environmental Protection Agency, Washington, DC by ICF, Inc., (need to insert City, State).

McClure, T.J. 1994. *Nutritional and Metabolic Infertility in the Cow.* CAB International, Oxon, United Kingdom.

McFarland, M.L., T.L. Provin, and S.E. Feagley. 1998. *Managing crop nutrients through soil, manure and effluent testing.* L-5175, Texas Agricultural Extension Service, Texas A&M University System, College Station, Texas.

Meals, D.W., J.D. Sutton, and R.H. Griggs. 1996. *Assessment of progress of selected water quality projects of USDA and state cooperators*. U.S. Department of Agriculture, National Resources Conservation Service, Washington, DC.

Melvin, S. and J. Lorimor. 1996. *Effects of winter manure spreading on surface water quality. 1996 Research Report.* <http://www.nppc.org/Research/ 96Reports/ 96Melvin-manure.html>.

Menke, T., R. Mackin, H. Keener, M. Veenhuizen, and Organic Resource Technologies, Inc. 1996. An Integrated Method of Managing the Residuals of Swine Production. A demonstration project/study proposal. March 21, 1996.

Mescher, T., T. Menke, R. Stowell, M. Veenhuizen, and H. Keener. 1999. *Design, Performance, and Economics of a High-Rise™ Swine Finishing Building*. ASAE Paper 994107. ASAE, St. Joseph, Michigan.

Metcalf & Eddy, Inc. 1991. edited by G. Tchabanoglous. *Wastewater Engineering: Treatment, Disposal, And Reuse*, 3rd ed. McGraw-Hill Book Co., New York, New York.

Michele, D., J.R. Bacon, C.M. Gempesaw, and J.H. Martin. 1996. *Nutrient management by Delmarva poultry growers: A survey of attitudes and practices*. University of Delaware, Newark, Delaware.

Midgeley, A.R. and D.E. Dunklee. 1945. *Fertility runoff losses from manure spread during the winter*. University of Vermont, Agric. Exp. Station, Bulletin 523.

Mignotte-Cadiertues, B., A. Maul, A. Huyard, S. Capizzi, and L. Schwartzbrod. 2000. The effect of liming on the microbiological quality of urban sludge. *Water Sci. and Technol.* 43(12): 195-200. [abstract only]

Monge, H., P.H. Simmins, and J. Weigel. 1998. Reduction du taux proteique alimentaire combinee avec differents rapports methionine:lysine. Effet sur le bilan azote du porc maigre en croissance et en finition. *Journees de la Recherce Porcine en France* 29:293-298.

Moore, J.A., J. Smyth, S. Baker, J.R. Miller. 1988. Evaluating Coliform concentrations in runoff from various animal waste management systems. Special Report 817, Agricultural Experiment Stations, Oregon State University, Corvallis, OR.

Moore, I.C., and F.W. Madison. 1985. Description and application of an animal waste phosphorus loading model. *J. Environ. Qual.* 14(3):364-368.

Moore, P.A. and D.M. Miller. 1994. Decreasing phosphorus solubility in poultry litter with aluminum, calcium, and iron amendments. *J. Environ. Qual.* 23:325-330.

Moore, P.A., T.C. Daniel, D.R. Edwards, and D.M. Miller. 1995. Effect of chemical amendments on ammonia volatilization from poultry litter. *J. Environ. Qual.* 24:293-300.

Moore, P.A., G.A. Aiken, T.C. Daniel, D.R. Edwards, J.T. Gilmour, D.W. Kennedy, and T.J. Sauer. 1997. Agricultural and Environmental Effects of Treating Poultry Litter with Aluminum Sulfate. Final Report to U.S. Poultry & Egg Association, USDA-ARS Poultry Production and Product Safety Research Unit, University of Arkansas, Fayetteville, AR.

Moore, P.A., T.C. Daniel, J.T. Gilmour, B.R. Shreve, D.R. Edwards, and B.H. Wood. 1998. Decreasing metal runoff from poultry litter with aluminum sulfate. *J. Environ. Qual.* 27:92-99.

Moore, P.A., T.C. Daniel, and D.R. Edwards. 1999. Reducing phosphorus runoff and improving poultry production with alum. *Poultry Sci.* 78(5):692-698.

Moore, P.A., T.C. Daniel, and D.R. Edwards. 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. *J. Environ. Qual.* 29:37-49.

Moser, M., Dr. J. Martin, A. Martin, R.P. Mattocks. 1999. Pig Manure Solids Separation. Unpublished report prepared by ICF Inc. for the Engineering Analysis Division, U.S. Environmental Protection Agency, Washington DC.

Moser, M.A., and A. Martin. 1999. Anaerobic Manure Management. Unpublished report prepared for the Engineering Analysis Division, U.S. Environmental Protection Agency, Washington, DC.

Mroz, Z., A.W. Jongbloed, and P.A. Kemme. 1994. Apparent digestibility and retention of nutrients bound to phytate complexes as influenced by microbial phytase and feeding regimen in pigs. *J. Anim. Sci.* 72:126-132.

Murphy, B. 1988. *Voisin Grazing Management in the Northeast.* U.S. Department of Agriculture, Soil Conservation Service, Northeast National Technical Center, Chester, Pennsylvania. Proceedings of the Pasture in the Northeast Region of the United States.

MWPS. 1993. *Livestock Waste Facilities Handbook.* 3rd ed. MidWest Plan Service, Iowa State University, Ames, IA.

National Lime Association (NLA). 2001. Comments of the National Lime Association on CAFO Proposed Rule, Docket #OW-00-27, July 30, 2001.

National Research Council. 2001. *Nutrient Requirements of Dairy Cattle: Seventh Revised Edition.*

NCSU. 1998. *EPA national guidelines for swine and poultry waste management.* North Carolina State University, Raleigh Durham, North Carolina.

NCSU. 1999. Nitrogen and Phosphorus Excretion in Poultry Production. Unpublished. February 1999. North Carolina State University, Animal Waste Management Program

Ogg, C. 1999. Benefits from managing farm produced nutrients. *Journal of the American Water Resource Association* 35(5):1015 –1021.

Oldham, L. 1999. *Nutrient management.* Mississippi State University Extension Service, Mississippi State University, Jackson, Mississippi.

Patni, N.K., H.R. Toxopeus, and P.Y. Jui. 1985. Bacterial quality of runoff from manured and non-manured cropland. *Trans. ASAE* 28():1871-1884.

Pennsylvania State University. 1992. *Nonpoint source database.* Department of Agricultural and Biological Engineering, Pennsylvania State University, University Park, Pennsylvania.

Peters, J.M. and N.T. Basta. 1996. Reduction of excessive bioavailable phosphorus in soils by using municipal and industrial wastes. *J. Environ. Qual.* 25:1236-1241.

Phillips, P.A., A.J. MacLean, F.R. Hore, F.J. Sowden, A.D. Tenant, and N.K. Patni. 1975. *Soil water and crop effects of selected rates and times of dairy cattle liquid manure applications under continuous corn.* Engineering Research Service Contribution No. 540. Agriculture Canada, Ottawa, Ontario.

Pocknee, S., and B. Boydell. 1995. *Soil sampling for precision farming.* National Environmentally Sound Production Agriculture Laboratory, College of Agricultural and Environmental Sciences, University of Georgia, Athens, Georgia.

PPRC. 1996. *Impacts of Intensive Rotational Grazing on Stream Ecology and Water Quality.* <http://www.pprc.org/pprc/rpd/fedfund/usda/sare_nc/impactsi.html>. Accessed February 11, 2000.

Purdue Research Foundation. 1994. *Manure Storage - Storage Facilities.* <http://abe.www.ecn.purdue.edu/~epados/farmstead/ manure/src/credits.htm>. Accessed September 15, 1999.

Purdue University. 1994. *Poultry Manure Management Planning.* Purdue University, Cooperative Extension Service, West Lafayette, Indiana.

RCM, Inc. 2000. File date. RCM Inc., Berkeley, California.

RCM, Inc. 1999. File date. RCM Inc., Berkeley, California.

Reddy, K.R., R. Khaleel, and M.R. Overcash. 1981. Behavior and transport of microbial pathogens and indicator organisms in soils treated with organic wastes. J. *Environ. Qual.* 10(3):255-266.

Reeves, P.L., K.P. Johnson, and C.D. Montemagno. 1999. *Biological treatment of dairy manure using sequencing batch reactors: Improving profitability through innovative design.* Cornell University, Ithaca, New York

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. *Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE).* Agricultural Handbook No. 703. U.S. Department of Agriculture, Washington, DC.

Richard T., S. Smits. 1998. *Management of Bedded-Pack Manure from Swine Hoop Structures: 1998 Results.* ASL-R1595. 1998 Swine Research Reports. Iowa State University Extension, Ames, Iowa.

Richard, T., J. Harmon, M. Honeyman, and J. Creswell. 1997. *Hoop Structure Bedding Use, Labor, Bedding Pack Temperature, Manure Nutrient Content, and Nitrogen Leaching Potential.* ASL-R1499. 1997 Swine Research Reports. Iowa State University Extension, Ames, Iowa.

Risse, M., J. Gaskin, H. Zhang, J. Gilley, A. Franzluebbers, J. P. Campbell, Sr., D. Radcliffe, B. Tolner. 2001. Land application of manure provides numerous benefits. Proceedings of *International Symposium of Animal Production and Environment.* North Carolina State University. Research Triangle Park, North Carolina, October 3-5, 2001.

Risse, L. M. and J. E. Gilley. 2000. *Manure impacts on runoff and soil loss.* Animal, Agricultural, and Food Processing Wastes. ASAE. Des Moines, Iowa. October 9-11, 2000. pp. 578-587.

Ross, C.C., et al. 1996. *Handbook of Biogas Utilization*, 2nd ed, U.S. Department of Energy, Southeastern Regional Biomass Energy Progam, Tennessee Valley Authority, Muscle Shoals, Alabama.

Rothberg, Bamburini & Winsor, Inc. n.d. *Biosolids Stabilization, Which "Class A" Stabilization is Most Economical?* Engineering Analysis by Rothberg, Bamburini & Winsor, Inc., Denver, CO, Bulletin No. 334, National Lime Association, Arlington, VA.

Sansinena, M., L.D. Bunting, S.R. Stokes, and E.R. Jordan. 1999. *A survey of trends and rationales for dietary phosphorus recommendations among mid-south dairy nutritionists* Mid-South Ruminant Nutrition Conference, Irving, Texas.

Satter, L.D., Z. Wu. *Balancing the Animal's Nutritional Needs with Environmental Stewardship*, Advances in Dairy Technology. 2000.

Schmitt, M., and G. Rehm. 1998. *Fertilizing Cropland with Poultry Manure*. FO-5881-GO. University of Minnesota, St. Paul, Minnesota.

Schmitt, M.A. 1999. *Manure management in Minnesota*. FO-3553-GO. College of Agricultural, Food, and Environmental Sciences, University of Minnesota Extension Service, St. Paul, Minnesota.

Self-Davis, M.L., P.A. Moore, T.C. Daniel, and D.R. Edwards. 1998. Use of aluminum sulfate to reduce soil test phosphorus levels in soils fertilized with poultry litter. p. 341-345 In J.P. Blake and P.H. Patterson (ed.) Proc. 1998 Nat. Poult. Waste Manage. Symp., Springdale, AR. 19-21 Oct. 1998, Auburn Press, Auburn, AL.

Sharpley, A.N. 1995. Identifying sites vulnerable to phosphorus loss in agricultural runoff. Journal of Environmental Quality, 24(5): 947-951.

Sharpley, A.N., S.C. Chapra, and R. Wedepohl. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. *Journal of Environmental Quality* 23(3): 437-446.

Sharpley, A.N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 1999. *Agricultural phosphorus and eutrophication*. ARS-149. U.S. Department of Agriculture, Agricultural Research Service, Pasture Systems & Watershed Management Research Laboratory, University Park, Pennsylvania.

Sherman, J.J., H.H. Van Horn, and R.A. Norstedt. 2000. Use of flocculants in dairy wastewaters to remove phosphorus. *Appl. Eng. in Agric.* 16(4):445-452 [abstract only]

Shi, Y., D.B. Parker, N.A. Cole, B.W. Auvermann, and J.E. Mehlhorn. 2001. Surface amendments to minimize ammonia emissions from beef cattle feedlots. *Trans. ASAE* 44(3):677-682.

Shih, J. 2000. North Carolina Department of Poultry Science, North Carolina State University, Raleigh, NC. E-mail correspondence. April 6.

Shreve, B.R., P.A. Moore, T.C. Daniel, D.R. Edwards, and D.M. Miller. 1995. Reduction of phosphorus in runoff from field-applied poultry litter using chemical amendments. *J. Environ. Qual.* 24:106-111.

Shreve, B.R., P.A. Moore, D.M. Miller, T.C. Daniel, and D.R. Edwards. 1996. Long-term phosphorus solubility in soils receiving poultry litter treated with aluminum, calcium and iron amendments. *Commun. Soil Sci. Plant Anal.* 27(11/12):2492-2510.

Sims, J.T. and N.J. Luka-McCafferty. 2002. On-farm evaluation of aluminum sulfate (alum) as a poultry litter amendment: effects on litter properties. *J. Environ. Quality* 31: in press.

Sims, J.T., S. Hodges, and J. Davis. 1998. Principles of soil testing for phosphorus. In *SERA-17, Soil testing for phosphorus: Environmental uses and implications*, Southern Cooperative Series Bulletin #389.

Sniffen, C.J., J.D. O'Connor, P.J. Van Soest, D.G. Fox and J.B. Russell. 1992. "A Net Carbohydrate and Protein System for Evaluating Cattle Diets: Ii. Carbohydrate and Protein Availability" *J. Anim. Sci.* 70: 3562.

Sohail S. and D. Roland. 1999. *Phytase Enzyme Proving Helpful to Poultry Producers and Environment. Highlight of Agricultural Research.* <http://www.ag.auburn.edu /aaes/information/highlights/spring99/phytase.html>. Accessed September 21, 1999.

Steenhuis, T.S., G.D. Bubenzer, and J.S. Converse. 1979. Ammonia volatilization of winter spread manure. *Trans. ASAE* 22: 153-157.

Steevens, B.J., L.J. Bush, J.D. Stout, and E.I. Williams. 1971. "Effects of varying amounts of calcium and phosphorus in rations for dairy cows" *J. Dairy Sci.* 54:655.

Stevenson, G.R. 1995. Watershed management and control of agricultural critical source areas. In *Animal waste and the land-water inteface*, K. Steele ed., pp. 273-281, CRC Press, Inc., Baton Rouge, Louisiana.

Stokes, S.R. 1999. Addressing Environmental Concerns Associated with the Dairy Industry, Report to the Bosque River Advisory Council, personal collection, July 8.

Stout, W.L., A.N. Sharpley, and H.B. Pionke. 1998. Reducing soil phosphorus solubility with coal combustion by-products. *J. Environ. Qual.* 27:111-118.

Stowell, R., D. Elwell, B. Strobel, H. Keener, and T. Menke. 1999. *Airflow and Air Quality within a High-Rise™ Hog Facility.*

Sutton, A., D. Jones, E. Collins, L. Jacobs, and S. Melvin. 1996. *Swine Manure as a Plant Resource.* PIH-25. Oklahoma State University Cooperative Extension Service, Stillwater, OK. February.

Tammiga, S. 1992. Nutrition management of dairy cows as a contribution to pollution control. *J. Dairy Science.* 75:345.

Tengman, C.L., H.L. Person, and D.R. Rozeboom. n.d. *Immediate liquid-solid separation of swine manure below slats using sloped pit floors to concentrate phosphorus in the solids.* Michigan State University, Department of Animal Science, East Lansing, Michigan.

Terwillger, A.R., and L.S. Crauer. 1975. Liquid Composting Applied to Agricultural Wastes. In *Managing Livestock Wastes*, pp. 501-505. American Society of Agricultural Engineers, St. Joseph, Michigan.

Thompson, D.B., T.L. Loudon, and J.B. Gerrish. 1979. Animal manure movement in winter runoff for different surface conditions. in. *Best Management Practices for Silviculture and Agriculture.* eds. R.C. Loeher et al., pp. 145-157. Ann Arbor Science, Ann Arbor, Michigan.

Toth, J.D., G. Zhang, Z. Dou, and J.D. Ferguson. 2001a. Reducing phosphorus solubility in animal manures using chemical amendments. *J. Anim. Sci.* 79(Supplement 1): 255.

Toth, J.D., G. Zhang, Z. Dou, and J.D. Ferguson. 2001b. Reducing readily soluble phosphorus forms in animal manures using chemicals. Poster presentation. University of Pennsylvania School of Veterinary Medicine, Center for Animal Health and Productivity. <http://cahpwww.vet.upenn.edu/nutrimgt/poster/poster1.html>.

UD. 1999. *Changes for chicken? New Hybrid Corn Helps Reduce Phosphorus in Poultry Litter.* <http://www.eurekalert.org/releases/udel-cfc0824999.html>. Accessed September 10, 1999.

USDA Agricultural Research Service. 1998. Manure and Byproduct Utilization National Program Annual Report FY 1998. <http://www.nps.ars.usda.gov/programs/programs.htm?npnumber=206&docid=245>.

USDA APHIS. 1995. *Swine '95 Part I: Reference of 1995 Grower/Finisher Health and Management.* U.S. Department of Agriculture, animal and Plant Health Inspection Service, Fort Collins, Colorado <http://www.aphis.usda.gov/vs/ceah/cahm/>. File sw95des2.pdf accessed October 15, 1998.

USDA APHIS. 1996a. *Environmental Practices/Management by U.S. Pork Producers. Swine '95 Part II: Reference of 1995 Grower/Finisher Health and Management.* U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado <http://www.aphis.usda.gov/vs/ceah/cahm/>. Accessed April 4, 2000.

USDA APHIS. 1996b. *National Animal Health Monitoring System, Part III: Reference of 1996 Dairy Health and Health Management Practices.* U.S. Department of Agriculture, Animal and Plant Health Inspection Service. Fort Collins, Colorado

USDA APHIS. 1996c. *APHIS Info Sheet: Waste Handling Facilities and Manure Management on U.S. Dairy Operations.* U.S. Department of Agriculture, Animal and Plant Health Inspection Service. Fort Collins, Colorado.

USDA APHIS. 1997. *Waste Handling Facilities and Manure Management on U.S. Dairy Operations*. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado. <http://www.aphis.usda.gov/vs/ceah/cahm/>. Accessed April 4, 2000.

USDA APHIS. 2002. Queries of *Swine 2000* prepared by Eric Bush; U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Fort Collins, Colorado. March 22, 2002. 2 pages.

USDA NAHMS. 2000. *Part I: Baseline Reference of Feedlot Management Practices*. U.S. Department of Agriculture, National Animal Health Monitoring System, Washington, DC.

USDA NRCS. 1995. *Nutrient management for better crops, more profit, and clean water*. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USDA NRCS. 2000. *Field Office Technical Guide No. IA-208. IA-208*. U.S. Department of Agriculture, Natural Resources Conservation Service. Des Moines, Iowa.

USDA NRCS. 1999. *National Handbook of Conservation Practices*. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USDA NRCS. 1998a. *Nutrients available from livestock manure relative to crop growth requirements*. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington DC.

USDA NRCS. 1998b. *Nutrient Management*. Conservation Practice Standard, Code 590. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USDA NRCS. 1996. *Agricultural waste management field handbook, Part 651*. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USDA. 1997. Management of Grazing Lands. In *National Range and Pasture Handbook*. U.S. Department of Agriculture, Washington, DC.

USEPA. 1998. *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. EPA-230-R-97-002, U.S. Environmental Protection Agency, Washington, D.C.

USEPA. 1999. *Unified National Strategy for Animal Feeding Operations*. U.S. Department of Agriculture and U.S. Environmental Protection Agency, Washington, DC.

USEPA. 2000. *Cost Model Report for Beef and Dairy Operations Developed for the Effluent Limitations Guidelines*. Office of Water, U.S. Environmental Protection Agency, Washington, DC.

USEPA. 2001. *National Management Measures to Protect and Restore Wetlands and Riparian Areas for the Abatement of Nonpoint Source Pollution*. EPA 841-B-01-001. Office of Water, U.S. Environmental Protection Agency, Washington, DC.

Van der Peet-Schwering, C. 1993. *Effect microbieel fytase in het voer op de opfokresultaten van gespeende biggen*. Praktijkonderzoek varkenshouderij. Proefstation voor de Varkenshouderij, Rosmalen.

VanDyke, L.S., J.W. Pease, D.J. Bosch, and J.C. Baker. 1999. Nutrient management planning on four Virginia livestock farms: Impacts on net income and nutrient losses. *J. Soil and Water Conserv.* 54(2):499-505.

Van Horn, H.H., G.L. Newton and W.E. Kunkle. 1996. "Ruminant nutrition from an environmental perspective: factors affecting whole-farm nutrient balance" *J. Anim. Sci.* 74: 3082.

Van Horn, H.H., G.L. Newton, R.A. Nordstedt, E.C. French, G. Kidder, D.A. Graetz, and C.F. Chambliss. 1998. *Dairy Manure Management: Strategies for Recycling Nutrient to Recover Fertilizer Value and Avoid Environmental Pollution*. Florida Cooperative Extension Service, Institute of Food and Agricultural Services, University of Florida, Gainesville, Florida.

Van Horn, H.H. 1999. *"Options in Managing Manure Phosphorus"* Florida Ruminant Nutrition Symposium, Gainesville, Florida, Jan 14-15.

Vanschoubroeck, F., L. Coucke, and R. van Spaendonck. 1971. The quantitative effect of pelleting feed on the performance of piglets and fattening pigs. *Nutr. Abstr.* Rev. 41:1-9.

Vansteelant, JY. 2000. Personal communication, Institut National de la Recherche Agronimique, Thonon les Bains, France.

Veenhuizen, M.A., D.J. Eckert, K. Elder, J. Johnson, W.F. Lyon, K.M. Mancl, and G. Schnitkey. 1999. *Ohio livestock manure and wastewater management guide*, Bulletin 604, Extension Service, Ohio State University, Columbus, Ohio.

Vetsch, J. Fertility and Management Issues. Lecture Notes. June 23, 1999. Rippey, Iowa.

Willett, I.R., T. Steenhuis, and T. Walter. 1999. Wollastonite as an amendment to decrease losses of phosphorus from hydrologically sensitive areas. http://instruct1.cit.cornell.edu/Courses/nsfreu/runophos.html

Worley, J.W. and K.C. Das. 2000. Swine manure solids separation and composting using alum. *Appl. Eng. Agric.* 16(5):555-561. [abstract only]

Young, R.A. and R.F. Holt. 1977. Winter-applied manure: effects on annual runoff, erosion, and nutrient movement. *J. Soil and Water Conserv.* 32(5):219-222.

Young, R.A. and C.K. Mutchler. 1976. Pollution potential of manure spread on frozen ground. *J. Environ. Qual.* 5(2):174-179

Wheaton, H.N. and J.C. Rea. 1999. *Forages for Swine*. Publication No. G2360. University Extension, University of Missouri-Columbia.

Wilkinson, S.R. 1992. Nitrogen carryover from broiler litter applied to coastal bermudagrass. In *National livestock, poultry and aquaculture waste management - proceedings of the national workshop*. Kansas, Missouri. American Society of Agricultural Engineers. July 29-31, 1991, pp. 166-170.

Zhang, Ruihong, Li, Xiujing, Tao, Jun. 1999. Treatment of Dairy Wastewater with Sequencing Batch Reactor Systems (ASAE Paper No. 994069), written for presentation at the 1999 ASAE Annual International Meeting in Toronto, Canada, July 1999.

CHAPTER 9

ESTIMATION OF REGULATED OPERATIONS AND UNFUNDED MANDATES

9.0 INTRODUCTION TO NPDES PROGRAM

Under the National Pollutant Discharge Elimination System (NPDES) permit program, all point sources that discharge pollutants to waters of the United States must apply for an NPDES permit and may discharge pollutants only under the terms of that permit. Such permits include nationally established technology-based effluent discharge limitations. In the absence of national effluent limitations, NPDES permit writers must establish technology-based limitations and standards on a case-by-case basis, based on the permit writer's best professional judgment.

In addition to the technology-based effluent limits, permits may also include water quality-based effluent limits where technology-based limits are not sufficient to ensure compliance with the water quality standards or to implement a Total Maximum Daily Load (TMDL). Permits may include specific BMPs to achieve effluent limitations, typically included as special conditions. In addition, NPDES permits normally include monitoring and reporting requirements, as well as standard conditions that apply to all permits (such as duty to properly operate and maintain equipment).

EPA's analysis of the final rule includes estimates of the incremental costs and benefits of changes in the NPDES permit regulations in 40 CFR 122. To obtain incremental values, EPA developed estimates of the number of regulated operations for a baseline compliance scenario and a compliance scenario based on the final rule. Section 9.1 describes how EPA derived baseline estimates. Section 9.2 provides the estimates of the number of operations affected under the final rule. Section 9.3 provides estimates of the new expenditures states are expected to incur when they implement the final rule.

9.1 Industry Baseline Compliance with 1976 Regulations

EPA promulgated the original NPDES regulations for CAFOs in 1976. For the purposes of this analysis, EPA assumes that all operations covered by the 1976 regulations are currently in compliance with the existing regulatory program. This assumption generates the baseline number of regulated operations estimated for the final rule.

More specifically, EPA assumes that all operations are fully complying with the existing regulations because they fall into one of two categories. The first category consists of those operations that are defined or designated as CAFOs and that have in fact obtained a permit. EPA

assumes, for purposes of costing the new regulations, that these CAFOs are in full compliance with their existing permits. The second category consists of all of the other unpermitted AFOs. EPA assumes that these operations do not need a permit because they do not meet the definition of a CAFO. For example, they might not meet the criteria for being defined as a Medium CAFO, or for Large CAFOs they might meet the criteria, but are excluded from the definition because they do not discharge except in the event of a 25-year, 24-hour storm. In reality, however, there are probably a number of unpermitted operations that are subject to the regulations and should have a permit (for example, they incorrectly claim they are a "no discharge" facility, as discussed in the preamble).

The following sections present EPA's approach and assumptions for estimating the population of AFOs that are subject to permitting under the 1976 NPDES CAFO permitting regulations. The universe of AFOs and CAFOs is discussed by livestock category, size of operation, and production region. EPA's assumptions about what is needed to comply with the current CAFO regulations are consistent with EPA's views as stated in its 1995 CAFO guidance manual, *Guidance Manual on NPDES Regulations for Concentrated Animal Feeding Operations* (USEPA, 1995; USEPA, 1999).

9.1.1 Total Medium and Large Animal Feeding Operations

EPA's estimates of Large and Medium AFOs by livestock category are provided in Table 9-1. The breakdowns by size are based the following animal thresholds, which are from the 1976 NPDES CAFO regulation. The discussion in this section pertains to which operations in these categories are considered effectively regulated by the 1976 rule.

Large operations that stable or confine more than:

- 1,000 beef cattle
- 700 mature dairy
- 2,500 swine over 55 pounds
- 55,000 turkeys
- 500 horses
- 5,000 ducks
- 30,000 laying hens or broilers using liquid manure systems

Medium operations that stable or confine:

- 300 to 1,000 beef cattle
- 200 to 700 mature dairy

- 750 to 2,500 swine over 55 pounds
- 16,500 to 55,000 turkeys
- 150 to 500 horses
- 1,500 to 5,000 ducks
- 9,000 to 30,000 laying hens or broilers using liquid manure systems

AFO estimates for additional animal categories that will be regulated under the final rule have also been included in Table 9-1 to provide a summary of all Medium and Large AFOs potentially regulated as CAFOs. In addition to breakdowns by livestock or poultry category and facility size, Table 9-1 shows that the primary livestock or poultry sectors have been divided into five production regions consistent with development of the Cost Models. The designation and use of production regions allows for the aggregation of critical data on the number of facilities, production quantities, and financial conditions, which might otherwise not be possible because of concerns about disclosure[1]. The facilities listed below as medium AFOs include all AFOs in that size range and are not limited to those facilities that may be defined or designated under current conditions or the final rule.

Table 9-1. Total 1997 Facilities with Confined Animal Inventories by Livestock or Poultry Sector, Operation Size, and Region.

Sector	Region	Medium Operations	Large Operations
Beef	Central	326	557
	Mid-Atlantic	100	11
	Midwest	2,198	1,124
	Pacific	44	74
	South	14	0
	Total	2,682	1,766
Dairy	Central	1,034	401
	Mid-Atlantic	1,407	103
	Midwest	1,503	96
	Pacific	1,406	759
	South	430	91
	Total	5,780	1,450
Swine	Central	153	82
	Mid-Atlantic	905	1,220
	Midwest	8,484	2,431
	Pacific	31	15

[1] For example, USDA Census of Agriculture data are not typically released unless there is a sufficient number of observations to ensure confidentially. Consequently, if data were aggregated on a state basis (instead of a regional basis), many key data points needed to describe the industry segments would be unavailable.

	South	328	176
	Total	9,901	3,924
Layer	Central	301	143
	Mid-Atlantic	394	211
	Midwest	346	312
	Pacific	110	125
	South	819	321
	Total	1,970	1,112
Broiler	Central	694	164
	Mid-Atlantic	2,892	413
	Midwest	411	56
	Pacific	184	15
	South	6,221	984
	Total	10,402	1,632
Turkey	Central	67	36
	Mid-Atlantic	692	88
	Midwest	574	149
	Pacific	110	45
	South	172	70
	Total	1,615	388
Heifers[1]	Central	195	145
	Mid-Atlantic	0	0
	Midwest	395	0
	Pacific	134	97
	South	0	0
	Total	724	242
Veal[1]	Central	3	0
	Mid-Atlantic	1	0
	Midwest	53	12
	Pacific	0	0
	South	0	0
	Total	57	12
Horses	Total	1,123	195
Ducks	Total	71	21
Grand Total		34,325	10,742

[1]New livestock category in the final rule.

9.1.2 Baseline Compliance Estimates

The following subsections describe the livestock or poultry categories that EPA assumes are in full compliance with current NPDES regulations for CAFOs. In general, the large operations shown in Table 9-1 are currently defined as CAFOs, unless they are exempt because they have no discharges except in the event of a 25-year, 24-hour storm. Therefore, subsequent estimates of large operations currently in compliance include the large AFOs shown in Table 9-1. The exception for large layer and broiler operations is discussed below. The medium operations in Table 9-1 may be defined as CAFOs if either of the following conditions apply:

- Pollutants are discharged into navigable waters through a man-made ditch, flushing system, or other similar man-made device (the "MMD discharge" condition).
- Pollutants are discharged directly into waters of the United States, which originate outside of and pass over, across, or through the facility, or otherwise come into direct contact with the animals confined in the operation (the "direct contact" condition).

The number of medium operations meeting either condition is not known with any great degree of certainty. EPA derived estimates of the medium livestock operations that might meet either condition based on the best available information from USDA Extension personnel, state water quality staff, industry representatives, and other stakeholders, and BPJ judgement. The estimates are generally based on best estimates of the share of operations that might meet at least one condition. EPA multiplied these percentages by the estimate of total medium operations to derive the number of CAFOs for the medium category. In some instances, information supported different percentages across regions. The following sections provide EPA's estimates of the number of medium CAFOs under current regulations.

9.1.2.1 Beef

The beef industry is concentrated in the Midwest Region. The second largest production area is the Central Region.

EPA's estimates of the number of medium-size beef AFOs with a direct discharge or stream running through part of the production area were developed through various contacts with state agricultural and environmental personnel and USDA contacts. There are very limited data addressing these criteria, and opinions vary even within production regions. Information obtained from key states in each region indicates that the share of AFOs potentially meeting either criterion ranges from approximately 3 percent (Funk, 2002) to less than 6 percent in the Midwest (Lawrence, 2002). The share is less than 10 percent in the Central and Pacific Regions (Johnson, 2002), and close to 0 percent in the Mid-Atlantic and South Regions (Kniffen, 2002; Sadler, 2002). Using conservative values to account for some uncertainty regarding conditions in other states, EPA assumed that 6 percent of Medium AFOs in the Midwest Region would meet the CAFO definition and that 10 percent would meet it in the Central and Pacific Regions. The assumption for the Mid-Atlantic and South should be close to zero, but EPA assumed a nonzero

value to allow for the possibility of some Medium CAFOs in the states not contacted. There are 114 Medium AFOs in these regions and EPA assumed that 4 percent of regional AFOs would meet the CAFO definition, which generates approximately 5 CAFOs throughout both regions. Table 9-2 reports the number of Medium CAFOs that EPA estimates may be defined as CAFOs under the 1976 NPDES CAFO regulations, by region, based on these assumptions.

Table 9-2. Regulated Beef Feeding Operations by Size Category Assuming Full Compliance.

Region	Total	Medium Facilities	Large Facilities
Central	590	33	557
Mid-Atlantic	15	4	11
Midwest	1,255	131	1,124
Pacific	79	5	74
South	1	1	0
Total	1,940	174	1,766

9.1.2.2 Dairy

Compared to other livestock categories, dairies are relatively evenly distributed across all regions except the South. The large dairies tend to be concentrated in the Central and Pacific Regions, while the Midwest and Mid-Atlantic have the most medium dairies. Many of these dairies were designed and built on or near waters of the United States and, therefore, have direct contact. Others have some type of MMD discharge. Estimates for the percentage of dairies in the Midwest Region with direct contact or MMD discharge have a large range. Bickert (1999) estimated less than 10 for each criteria and Groves (1999) estimated a range of 25 percent to 75 percent for the direct contact criterion and almost zero percent for the MMD discharge. Holmes (1999) estimated that 15 percent of operations would have direct contact and 40 to 50 percent would have an MMD discharge. EPA assumed that, on average, 45 percent for the medium-size dairies throughout the Midwest would meet either criterion. This estimate places greater weight on the estimates of Holmes (<20 percent across criteria) and Bickert (55 to 65 percent across criteria). EPA assumed a slightly higher percentage of 55 percent for the Mid-Atlantic to reflect a higher propensity for direct contact in that region. According to Johnson (1999), less than 10 percent of medium-size operations in California will have either direct contact or an MMD discharge. EPA assumed that 10 percent of operations throughout the Pacific Region would be defined CAFOs. EPA assumed that the CAFO share in the Central Region is 20 percent, and 35 percent in the South. These are BPJ estimates based on the belief that operations in these regions are less likely than Midwest operations to meet either criterion, but more likely than Pacific Region operations.

Table 9-3 reports EPA's estimates of medium dairy CAFOs. Nationwide, approximately one-third of all medium operations are defined as CAFOs. Table 9-3 also shows that all large operations should be effectively regulated by the existing requirements either because they have a

discharge permit or because they have no discharge except in the event of the 25-year, 24-hour storm event.

Table 9-3. Regulated Dairy Feeding Operations by Size Category Assuming Full Compliance.

Region	Total	Medium Facilities	Large Facilities
Central	608	207	401
Mid-Atlantic	877	774	103
Midwest	773	677	96
Pacific	900	141	759
South	241	150	91
Total	3,399	1,949	1,450

9.1.2.3 Swine

The swine industry is heavily concentrated in the Midwest. This is particularly true for medium-size operations. The Mid-Atlantic is the second largest production region, followed by the South Region.

Table 9-4 shows that all large swine AFOs are assumed to be effectively regulated under the 1976 NPDES CAFO regulations because they are either permitted or exempt because they have no discharges except in the event of a 25-year, 24-hour storm. Based on contacts with USDA Extension personnel, EPA assumes that approximately 15 percent of facilities in this size category (across all regions) have direct contact or use an MMD (Greenless, et al., 1999; Steinhart, 1999).

Table 9-4. Regulated Swine Operations by Size Category Assuming Full Compliance.

Region	Total	Medium Operations	Large Operations
Central	105	23	82
Mid-Atlantic	1,355	135	1,220
Midwest	3,704	1,273	2,431
Pacific	20	5	15
South	225	49	176
Total	5,409	1,485	3,924

9.1.2.4 Layers

Under the 1976 NPDES CAFO regulations, a layer operation is defined as a large CAFO if it confines more than 30,000 birds and uses a wet manure management system, or if it maintains

more than 100,000 birds using continuous overflow watering and has the potential to discharge pollutants to waters of the U.S. EPA recognizes that continuous overflow watering is an outdated technology that has fallen out of favor in the layer industry. Therefore, EPA's estimates of the effectively regulated baseline large CAFO operations is based on those that use a wet manure management system.

The estimates of large layer CAFOs include operations with actual wet manure-handling systems and operations that create a crude wet manure-handling system. Currently, as many as 60 percent of the operations in the South and Central Regions use a wet manure-handling system, whereas only 0 to 5 percent of the operations use a wet system in the other regions.

As noted in EPA's 1995 permitting guidance, dry poultry operations are subject to the NPDES regulations if they establish a "crude liquid manure system" by stacking manure or litter in an outside area unprotected from rainfall and runoff. Including these operations as defined large CAFOs brings the total for the South and Central Regions to approximately 70 percent of large operations and approximately 7 percent of operations in other regions. These additions based on storage practices are based on conversations with industry personnel, who indicate that layer operations generally have long-term (> 6 months) storage, after which the manure is either sold or land applied (Funk, 1999; Jacobson, 1999; Patterson, 1999; Thomas, 1999; Tyson, 1999; York, 2000). The large CAFO estimates in Table 9-5 reflect the number of operations having either type of wet manure system.

For medium-size operations, either the MMD discharge or the direct contact condition must apply for operations that either have a wet manure-handling system or create a crude one. The regulated medium-size layer operations in Table 9-5 reflect combined estimates for both types of operations.

For operations with wet manure-handling systems, EPA obtained estimates from experts in the five states that have the largest regional shares of operations. These estimates indicate that the CAFO conditions are rarely met, bordering on 0 percent of operations in any region (Carey, 2002; Ramsey, 2002; Parsons, 2002; Hopkins, 2002; Johnson, 2002, Earnst, 2002, and Solainian, 2002). EPA derived a share estimate by assuming a worst-case average of two CAFOs per state, the total of 10 CAFOs equals approximately 3 percent of the 349 Medium AFOs in these states. Applying this percentage to all medium-sized wet layer AFOs generates a total CAFO estimate of 24.

Similarly, experts for key states in the Central, Mid-Atlantic, Midwest, and South Regions indicated that very few, if any, medium-sized dry operations stored manure outside of the production houses in a manner that might meet either of the CAFO conditions (Carey, 2002; Ramsey, 2002; Parsons, 2002; Hopkins, 2002; Jones, 2002; and Solainian, 2002). Rather than assume there are no Medium CAFOs in these regions, EPA derived a share estimate by assuming that an average of two operations per state stored manure outside (i.e., eight total in the four states) and in all cases the practice led to either a direct contact condition or an MMD condition.

The resulting number of CAFOs accounts for 2 percent of medium-sized AFOs in these states. EPA applied this percentage to all AFOs in these regions. EPA used a slightly higher estimate of 5 percent for the Pacific Region based on information provided by Johnson (2002) and Earnst (2002). These assumptions generate a total of 26 Medium CAFO operations.

Table 9-5. Regulated Layer Operations by Size Category Assuming Full Compliance.

Region	Total	Medium Operations	Large Operations
Central	107	8	99
Mid-Atlantic	26	8	18
Midwest	28	7	21
Pacific	13	5	8
South	259	22	237
Total	433	50	383

9.1.2.5 Broilers

Under the 1976 NPDES CAFO regulations, broiler operations with more than 30,000 birds are defined as CAFOs only if they use a liquid manure-handling system; operations with 9,000 to 30,000 birds and a liquid manure-handling system would also need to meet either the MMD discharge or the direct contact condition to be defined a CAFO. Because few, if any, broiler operations use a liquid manure-handling system, the only way by which a broiler operation is defined as a CAFO currently is if, through its manure-handling practices, it creates a form of liquid manure-handling system (Carey, 1999). As noted, dry poultry operations may establish a "crude liquid manure system" by stacking litter in an outside area unprotected from rainfall or runoff. This analysis assumes that at most 10 percent of the large broiler operations and 5 percent of the medium operations stack litter temporarily, in a manner consistent with EPA's interpretation of a liquid manure handling system and, therefore, would be defined as CAFOs (York, 2000). Furthermore, EPA assumed that no broiler operations would otherwise have direct contact with waters of the U.S. (WOUS) or an MMD based on information provided by regional experts (Carey, 1999; Gale, 1999; Lory, 1999; Patterson, 1999; Thomas, 1999; Tyson, 1999). Table 9-6 presents regulated broiler operation numbers.

Table 9-6. Regulated Broiler Operations by Size Category Assuming Full Compliance.

Region	Total	Medium Operations	Large Operations
Central	51	35	16
Mid-Atlantic	186	145	41
Midwest	26	20	6
Pacific	11	9	2
South	409	311	98
Total	683	520	163

9.1.2.6 Turkeys

EPA assumes turkey operations with more than 55,000 birds (1,000 AUs) are in compliance, being either permitted or exempt because they have no discharges except in the event of a 25-year, 24-hour storm. The only other turkey AFOs subject to the NPDES program are those having between 16,500 and 50,000 birds and an MMD discharge; no operations meet the direct contact conditions. Because virtually all turkey operations use dry litter systems (Battaglia, 1999; Carey, 1999; Jones, 1999), the only that have the potential to discharge are those operations that have established a crude liquid manure system through the use of waste management practices that allow contact between manure and rainwater. EPA assumed that 5 percent of the medium operations in the South Region and 2 percent in the other regions have established crude liquid systems. Table 9-7 presents the number of turkey feeding operations in full compliance by region and size.

Table 9-7. Regulated Turkey Operations by Size Category Assuming Full Compliance.

Region	Total	Medium CAFOs	Large CAFOs
Central	38	2	36
Mid-Atlantic	102	14	88
Midwest	160	11	149
Pacific	47	2	45
South	78	8	70
Total	425	37	388

9.1.2.7 Designated Operations

A medium facility that is not defined a CAFO may be designated a CAFO under the 1976 NPDES CAFO regulations if a permit authority determines that it is a significant contributor of pollutants to waters of the United States. A small facility can be designated a CAFO only if pollutants are discharged into navigable waters through a man-made ditch, flushing system or other similar man-made device, or pollutants are discharged directly into WOUS that originate outside of and pass over, across, or through the facility, or otherwise come into direct contact with the animals confined in the operation.

EPA has historically made very limited use of the designation provisions of the NPDES CAFO regulation that was promulgated in 1976. It is understood that only a few operations have been designated CAFOs over a 25-year span of existing NPDES CAFO regulations. Because the final rule does not alter the conditions for designation, EPA assumes that designation will continue to occur in a limited number of cases where an AFO does not meet the regulatory definition of a CAFO, but is determined to be a significant contributor of pollutants to WOUS based on site-specific conditions.

EPA does not possess any location-specific information regarding which AFOs may meet the conditions for designation. Furthermore, EPA expects that many of these operations that have conditions that might make them candidates for designation would be able to seek out technical assistance through voluntary programs to alter those conditions and avoid designation. These two factors make estimating future designations difficult, but the ability to prevent being designated a CAFO should minimize the number of designations.

Based on the limited use of this provision under the current regulation and the ability of operators to address conditions that might lead to designation, EPA assumed no more than 0.5 percent of all medium AFOs would be designated CAFOs. Table 9-8 shows the estimates of designated Medium CAFOs under the current rule by sector.

Designation would in almost all cases be the tool of last resort to address small operations that are found to be significant contributors of pollutants. Most, if not all, of these operations would be able to avoid designation through technical assistance offered by USDA and other voluntary programs. Although a lack of empirical data regarding discharge conditions at small operations makes it difficult to derive designation estimates, EPA believes designation of Small CAFOs will occur in only a very limited number of cases, if at all. Given this, EPA assumed a very small number of designations be assigned to each sector for the purposes of estimating cost and burdens for the final rule.

Table 9-8 Estimated Small and Medium Designated CAFOs over a 5-Year Period by Sector.

Sector	Medium Designated CAFOs	Small Designated CAFOs
Beef	13	2
Dairy	28	2
Swine	50	2
Layer	8	2
Broiler	50	2
Turkey	8	2
Heifers	3	0
Total	160	12

9.1.2.8 Summary of Baseline Compliance Estimates by Size and Type

The estimated number of regulated AFOs based on an assumption of full compliance with the existing regulations is presented in Table 9-9. The estimates include the large and medium beef, dairy, swine, broiler, layer, and turkey operations that are CAFOs by definition or that meet the 25-year, 24-hour storm exemption and the medium-size operations that potentially meet either the MMD discharge or the direct contact condition. The estimates also include the 195 horse operations that have 500 or more horses and, therefore, meet the definition of a large CAFO, and 157 large duck operations that meet current CAFO definitions. The horse CAFOs comprise 50 farms, 45 racetracks, and 100 fairgrounds (Tetra Tech, 2002). EPA does not have information to

indicate that any of the 1,123 medium horse AFOs will meet either condition to be CAFOs by definition, and EPA does not expect any medium or small horse AFOs to be designated CAFOs. For ducks, EPA assumed that all facilities greater that 5,000 head were either permitted or claimed the storage exemption. EPA assumed no duck operations in the medium category met the current definition of a CAFO. Finally, the estimates in Table 9-9 include the medium and small designated CAFOs.

Table 9-9. Summary of Effectively Regulated Operations by Size and Livestock Sector

Livestock Category	Total	Defined CAFOs		Designated CAFOs	
		Medium CAFOs	Large CAFOs[1]	Medium	Small
Beef	1,955	174	1,766	13	2
Dairy	3,429	1,949	1,450	28	2
Swine	5,461	1,485	3,924	50	2
Layer	443	50	383	8	2
Broiler	735	520	163	50	2
Turkey	435	37	388	8	2
Horse	195	0	195	0	0
Duck	157	0	157	0	0
Heifers	3	0	0	3	0
Total	12,813	4,215	8,426	160	12

[1]Includes permitted CAFOs and Large AFOs that are in current compliance because they do not discharge except in the instance of the 25-year, 24-hour storm event.

This summary of animal operations that should currently have NPDES permits does not correspond with the number of NPDES permits issued to date. Most sources place the estimate of the number of operations covered by NPDES permits at approximately 4,100 (SAIC, 1999).

There are two main reasons for the large disparity between these numbers. First, many of the large operations opt out of the NPDES program because they claim they do not discharge except in the event of a 25-year, 24-hour storm. Second, many authorized states have declined to issue NPDES permits for CAFOs, relying instead on regulatory mechanisms other than the NPDES program to regulate CAFOs.

9.2 Affected Entities under the Final Rule

The final rule will increase the number of regulated operations as well as the number of operations needing to obtain an NPDES permit, which will include newly covered operations and large operations currently claiming the storm exemption. It will also affect the permit requirements of facilities already operating under permit coverage.

9.2.1 Final Rule Provisions that Affect the Number of Regulated Operations

EPA estimates that the final rule increases the potential number of regulated entities by about 2,500 facilities. These facilities are predominantly large, dry poultry operations. Operations that confine immature animals are the second largest component of change. EPA assumes that the number designated under the 1976 rule, assuming full compliance, will be same as the number designated under the final rule. The new sectors and size threshold changes in the final rule that affect the number of regulated operations are:

Large operations that stable or confine:

- 1,000 heifers
- 1,000 veal
- 10,000 small swine under 55 pounds
- 82,000 layers using other than a liquid manure-handling system
- 125,000 broilers using other than a liquid manure handling system
- 30,000 ducks (dry operations)

Medium operations that stable or confine:

- 300 to 1,000 heifers
- 300 to 1,000 veal
- 3,000 to 10,000 small swine under 55 pounds
- 25,000 to 82,000 layers using other than a liquid manure-handling system
- 37,500 to 125,000 broilers using other than a liquid manure-handling system
- 10,000 to 30,000 ducks (dry operations)

In addition, the following revisions to 40 CFR 122 in the final rule may affect currently and newly regulated operations:

- Clarify the definition of an AFO
- Eliminate the 25-yr, 24-hr storm exemption
- Implement duty-to-apply requirement
- Eliminate the mixed animal multiplier
- Include facility closure requirements.

9.2.2 Number of Operations Required to Apply for Permit

The primary impact on the number of NDPES permits issued to CAFOs will come from the addition of dry poultry operations; stand-alone, immature animal operations; and operations previously exempt due to the 25-yr, 24-hr storm provision. As a result of removing the storm exemption, all of the large beef, dairy, swine, wet layer, turkey, and horse AFOs reported in Section 9.1 are considered CAFOs and will need to obtain a permit except in cases where the permitting authority makes a determination that there is no potential to discharge. Table 9-10 provides a summary of the total expected permitted facilities by sector based on the final rule. Many of the estimates are the same as those in Table 9-9. Additions are explained below.

Table 9-10. Summary of CAFOs by Livestock Sector and Region Required to Apply for Permit.

Livestock Category	Total	Defined CAFOs		Designated CAFOs	
		Medium CAFOs	Large CAFOs	Medium	Small
Beef	1,955	174	1,766	13	2
Dairy	3,429	1,949	1,450	28	2
Swine	5,461	1,485	3,924	50	2
Layer	1,172	50	1,112	8	2
Broiler	2,204	520	1,632	50	2
Turkey	435	37	388	8	2
Heifers	475	230	242	3	0
Veal	16	4	12	0	0
Horse	195	0	195	0	0
Duck	25	4	21	0	0
Total	15,367	4,453	10,742	160	12

The inclusion of all poultry operations, regardless of manure handling system, brings in all large broiler and dry layer feeding operations. The number of large broiler CAFOs increases from 163 to 1,632. The medium broiler CAFO estimate is unchanged from the baseline estimate because the dry operations that met the medium CAFO conditions before will continue to meet those conditions. Similarly, the number of large layer CAFOs increases from 383 to 1,112, but the Medium CAFO estimates are unchanged because the conditions that define CAFOs in this size category have not changed.

The thresholds for duck operations with dry manure-handling systems were changed from 5,000 to 30,000 ducks for large operations, and from 1,500 to 10,000 ducks for medium operations. These changes were based on data EPA received from Purdue University, The Indiana Poultry Association, and duck producers. The threshold for duck operations with wet manure-handling systems is has not changed and remains 5,000 ducks for large operations and 1,500 ducks for

medium operations. Because almost all operations use dry manure-handling systems, the number of large duck CAFOs under the revised size thresholds of the final rule is 21. EPA assumed that the share of medium dry duck operations that meet either the MMD discharge or direct contact condition is the same as the broiler share. Thus, there are four Medium duck CAFOs.

Finally, final rule provisions for stand-alone, immature animal operations adds 488 newly regulated large and medium operations. The Large CAFOs comprise 242 heifer operations and 12 veal operations. EPA assumes that the incidence of medium-sized veal and heifer CAFOs would be the same as the regional percentages in the baseline descriptions for beef and dairy, respectively. These assumptions add 230 medium heifer CAFOs and four medium veal CAFOs to the estimate of regulated operations under the final rule.

9.3 Unfunded Mandates

This section provides EPA's estimates of the new expenditures States are expected to incur when they implement the final rule. These administrative expenditures are based primarily on estimates of the amount of labor time needed to incorporate new regulatory requirements into existing State NPDES programs and to administer CAFO permits on an annual basis. EPA obtained the labor burden estimates used in this analysis from various sources including communications with staff at EPA regional offices and a small sample of State agencies, previous NPDES-related cost and burden analyses, and comments on the proposed rule. Then EPA asked State agency and EPA regional staff to evaluate whether those estimates were appropriate for administering NPDES permits for CAFOs.

EPA's cost analysis presumes that States issue fewer than 100 percent of the permits because EPA has responsibility for issuing permits in States that do not have approved NPDES programs. For informational purposes, this section will also show cost estimates pertaining to EPA's portion of the NPDES permits for CAFOs.

EPA estimated administrative costs for States with approved NPDES programs (hereafter "approved States") for four categories of activities:

- NPDES rule modification
- NPDES program modification request
- implementation for general permits
- implementation for individual permits.

Rule modification is a one-time activity in which approved States modify their NPDES programs to incorporate the new requirements contained in the final rule. EPA received substantial comment in this area at proposal and believes that this analysis fully recognizes the types of

activities that would be required and their associated burden. Specific actions will vary across States because CAFO permitting practices vary widely. Forty-three States have approved NPDES base programs through which CAFO permits can be issued.[2] EPA's State Compendium (2001) demonstrates that State permitting programs for CAFOs vary substantially. Some State programs utilize a combination of NPDES and non-NPDES permits while others issue only one or the other type of permit to CAFOs.

Rule modification may involve a variety of activities such as reviewing the final rule requirements, revising regulatory or statutory language, conducting public outreach to solicit inputs or make the public aware of program changes, conducting formal public notification hearings to solicit comments on draft changes, and finalizing and publishing regulatory statutory revisions. For some approved States, rule modification may be as simple as incorporating the final rule by reference. For others, regulatory changes may require a lengthy stakeholder process or changes to state statutes.

Information provided by State agencies suggests that the labor hours required to develop or modify regulations may range from 0.10 full time equivalents (FTEs) to 1.57 FTEs.[3] Hammerberg (2002) indicated that Maryland completes approximately two major rules and several minor rules per year with a staff of three, which suggests a range of 0.25 to 1.0 FTEs per rule depending on the level of complexity. Consistent with the lower end of this range, Allen (2002) agreed with a midpoint estimate of 750 hours or 0.36 FTEs and Coats (2002) provided an estimate of 500 hours or 0.20 FTEs for States in EPA Region 2. At the high end, Sylvester (2002) estimated that a final rule similar to the proposed rule would require 1.57 FTEs to implement in Wisconsin, with approximately one-third of the time devoted to initial drafting, one-third to hearings, and one-third to responding to comments and finalizing the rule. EPA believes that the final CAFO rule is less complex than the proposed rule and most States are not likely to require this level of effort to implement rule revisions. In particular, the final rule will not change the definition of a medium-size CAFO or the designation criteria for small CAFOs, and it will not require the ELG be applied to medium-size CAFOs. Also, it will not require CAFOs to have certified permit NMPs or that those plans be submitted to permitting authorities along with permit applications. Therefore, EPA placed greater weight on the Maryland and EPA Region 2 estimates than the Wisconsin estimate to derive a weighted average of 0.41 FTEs or approximately 850 hours (0.45×0.20 FTE + 0.45×0.36 FTE + 0.10×1.57 FTE).

Following rule development, the approved States will need to request EPA approval for the modifications made to their NPDES programs in response to the final rule. These applications consist of a narrative program description including enforcement and compliance plans; a legal

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[2] Six States—Alaska, Arizona, Idaho, Massachusetts, New Hampshire, and New Mexico—do not have approved NPDES programs. A seventh state, Oklahoma, has an approved base program, but is not authorized to administer the CAFO portion of the NPDES program; EPA Region 6 has responsibility for CAFO permits.

[3] One FTE is equivalent to 2,080 hours.

certification that the State has authority to implement the program (Attorney General's statement); a compilation of relevant statutes, regulations, guidance, and tribal agreements; and copies of permit application forms, permit forms and reporting forms. In general, the amount of labor time required to prepare the application will vary. EPA's labor hour estimate is based on program modification and approval burdens in an active NPDES ICR ("NPDES and Sewage Sludge Management State Program Requirements," OMB NO. 2040-0057, EPA ICR 0168.07), which estimates 250 hours per State to prepare and submit a request for NPDES Program Modification under 40 C.F.R. Part 123.62. Allen (2002) and Sylvester (2002) concurred with this estimate, but Coats (2002) noted that 80 hours might be sufficient.

Table 9-11 summarizes EPA's labor assumptions for these one-time costs and provides unit expenditure estimates based on an hourly loaded wage rate of $29.78 (in 2001 dollars).[4]

Table 9-11. State Administrative Costs for Rule Development and NPDES Program Modification Requests. (costs in 2001 dollars)

Administrative Activity	Unit Hours	Labor Cost	O&M Cost[1]
State Administrative Costs			
Rule Development	850 per State	$25,310	$2,120
NPDES Program Modification Requests	250 per State	$7,450	

1. States may incur public notification costs twice (i.e., for draft and final rules) while revising their regulations. The O&M cost estimate is based on the same assumption of $1,000 per public notice that was used for the proposed rule. That estimate assumed that public notices would be placed in four newspapers and each notice cost $250. The $1,000 was converted from 1999 dollars to 2001 dollars using the Consumer Price Index (1000 × 177.1/166.6 = 1060) (BLS, 2002a). This estimate is consistent with a cost estimate for public notification expenses provided by Tilley and Kirkpatrick (2002).

Approved States will incur annual costs to administer their permit programs. To administer State general permits, permitting authorities will need to:

- Update their general permits to incorporate final rule requirements.
- Review Notice of Intent (NOI) forms submitted by CAFO operators seeking coverage under a general permit.

[4] This estimate was based on the mean hourly wage rate of $20.53 for Conservation Scientists (SOC 19-1031) employed in the public sector (BLS, 2001) because employees in this occupation will most likely conduct permit review and facility inspections, which account for most of the burden hours. The rate was escalated from 2000 dollars to 2001 dollars using the Employment Cost Index, which indicates a 3.6 percent increase in wages and salaries for state and local government workers from December 2000 to December 2001 (BLS, 2002c). Then, the escalated wage rate ($21.27 = $20.53 × 1.036) was converted to a loaded wage rate using a total compensation-to-wage ratio of 1.4, which was the ratio in 2001 for all state and local workers (BLS, 2002b).

- Inspect CAFOs covered by the general permit.
- Review annual reports submitted by CAFOs covered by general permits.

To administer individual permits, State agencies will need to:

- Review application forms (i.e., Forms 1 and 2B)
- Request public comment prior to issuing a permit
- Conduct public hearings, as needed
- Inspect CAFOs covered by individual permits
- Review annual reports submitted by CAFOs covered by individual permits.

To update their general permits, the 43 approved States will need to revise the general permit conditions affected by the final rule (or develop a general permit for CAFOs in the 21 approved States that currently do not have such permits). For example, general permits will need to specify the method(s) that the permit authority is requiring the CAFO owner or operator to use to calculate the rate of appropriate manure application as a special condition, as well as incorporate the NMP requirements listed in 40 C.F.R. 122.42(e)(1). They may also need to reflect changes to animal thresholds between large, medium, and small CAFOs if current permits use the AU approach in the CAFO definition.

EPA estimated that States may need 300 hours to revise their general permits to reflect new provisions of the final rule. Information provided by State contacts indicated that initial general permit development was a contentious process that took two (Allen, 1999) to four years (KauzLoric, 1999) to complete. EPA does not believe that the changes necessitated by the final rule (e.g., adding the NMP requirements; adding new recordkeeping or reporting requirements; switching from size thresholds based on AU to animal counts; and altering the ELG, BPJ, or special conditions where necessary) will require the same magnitude of effort as initial permit development. Furthermore, EPA will develop a model permit that States can adopt in whole or part to minimize the costs of permit revisions. Sylvester (2002) estimated that revising Wisconsin's general permit may take 456 hours and Coats (2002) estimated that States in Region 2 would need 160 hours to revise their general permits. EPA's estimate of 300 hours or 0.14 FTE is the approximate midpoint between these estimates. Allen (2002) considered EPA's 300-hour estimate to be acceptable.

Revised general permits will be subject to public comment. EPA estimated costs for the proposed rule based on public notice, comment review, and response requiring 160 hours or 0.08 FTE. Comments from State employees in South Dakota (Pirner, 2001) and Illinois (Willhite, 2001) indicated that costs would be higher because the process for selecting the type of facilities

that may be eligible under a general permit will be contentious. Subsequent information obtained by EPA indicates a wide range of time from as little as 100 hours (Coats, 2002) to as much as 968 hours (Sylvester, 2002); Allen (2002) considered EPA's revised estimate of 180 hours to be acceptable. EPA assumed that the 180-hour estimate reflects labor requirements for the 22 States that already provide general NPDES permit coverage for CAFOs (US EPA, 2001) because these States have already resolved the applicability issue, which should not be substantially affected by the final rule. For the 21 States with approved programs that do not currently provide coverage under a general permit, EPA used the high estimate of 968 hours provided by Sylvester (2002) to incorporate additional time for the decision making process regarding which CAFOs would qualify for general permit coverage. The weighted average across all 43 States is approximately 570 hours ($0.51 \times 180 + 0.49 \times 968$) or 0.27 FTE.

Finally, States may conduct hearings regarding general permit revisions (or development for the States that do not provide general permit coverage for CAFOs). For the proposed rule, EPA derived costs for 240 hours based on the assumption that a State holds four hearings, each requiring 60 hours of labor time. Allen (2002) and Coats (2002) considered that assumption acceptable. Sylvester (2002) recommended an alternative estimate of 616 hours based on 12 hearings requiring 48 staff hours each plus an additional 40 hours for material preparation. For the final rule, EPA assumed that its original 240-hour estimate is sufficient for the 22 States that only need to revise existing general permits, and that the 21 States that do not provide general permit coverage for CAFOs will conduct additional hearings. For those States, EPA used the 616-hour estimate. The weighted average across all States is approximately 420 hours ($0.51 \times 240 + 0.49 \times 616$).

Adding together the three labor estimates for general permit development, EPA obtained a total estimate of 1,290 hours per general permit. For the 22 States that already provide general permit coverage, aggregate hours would be 720 hours. For the 21 States that would need to provide general permit coverage and determine which CAFOs are eligible, aggregate hours would be approximately 1,880 hours. It is possible that some of the States not currently providing general permit coverage will continue to rely solely on individual permits for CAFOs. Thus, EPA's cost analysis assumption that all 43 States will incur general permit revision costs provides an upper bound cost estimate.

CAFOs seeking coverage under a State's (or EPA's) general permit will submit completed NOI forms that the permitting authority will need to review and make a determination of coverage. For the proposed rule, EPA estimated that NOI review would require 1 hour. Comments indicated that the labor requirement would be substantially higher. For example, a Wisconsin State employee (Bazzell, 2001) indicated an expected expenditure of approximately 100 hours to review the NOI and accompanying documents. Ohio employees (Jones, et al., 2001) indicated that the estimates provided in the proposed rule did not allow time to ensure that the facilities were meeting all permit conditions. Willhite (2001) also indicated that costs for review of the NOI would be substantially higher. EPA believes that much of the concern regarding its proposed rule estimate centered on review of the proposed permit nutrient plan. For example, 60

hours of the 96-hour Wisconsin estimate pertained to reviewing the content of the NMP (Sylvester, 2002); 32 hours were allocated for review and approval of manure storage and runoff management systems, and 4 hours for general review for completeness of information. The final rule does not require a CAFO to submit this plan with the permit application, so this concern does not pertain to the final rule.

Nevertheless, EPA has revised the information requirements for the NOI and subsequently increased its estimate of the amount of time required for review. The final rule requires the following information be provided on the revised NOI and Form 2B: name and address of operator; manure storage mode and capacity; physical location including latitude and longitude of the production area; number of animals by type; estimated amount of manure generated per year; acreage available for agricultural use of manure, or litter and wastewater (under the control of the owner or operator); estimated amount of manure, or litter and wastewater to be transferred off site; and date for development of NMP, and expected date for full implementation. Reviews of the revised NOI forms to ensure completeness and accuracy of this required information should not take longer than 4 hours. This estimate is consistent with the one provided by Sylvester (2002). Furthermore, Allen (2002), Coats (2002), and Domingo (2002) indicated four hours would be adequate for NOI review. The annual reports that CAFOs are now required to submit (regardless of permit type) will contain updates for some of the information provided on the NOI form. Consequently, EPA assumed that the State burden to review an annual report, enter data as needed, and maintain CAFO records is the same as the NOI review estimate—4 hours.

EPA assumed that compliance inspections for CAFOs covered by a general permit would require an average of 16 hours, which includes 6 hours for round-trip travel time, 2 hours to prepare for the inspection, 4 hours to conduct the on-site portion of the inspection, and 4 hours for reporting and record keeping. This estimate is slightly greater than the recommendation of 12 hours made by Sylvester (2002), which included 8 hours for the inspection and travel time and 4 hours for reporting and data entry. EPA's estimate also equals the average of two inspection burden estimates in an active NPDES ICR ("Pollutant Discharge Elimination System and Sewage Sludge Management State Programs," OMB NO. 2040-0057, EPA ICR 0168.07). The reconnaissance inspection has a burden estimate of 8 hours and the compliance evaluation inspection has a burden estimate of 24 hours. On average, CAFO inspections will require less time than a typical compliance evaluation inspection, which includes inspection of effluent and receiving waters and discharge monitoring records. A reconnaissance inspection often does not include review of onsite records. Thus, a CAFO inspection that includes review of onsite records in addition to a visual inspection of the operation will most likely require more than eight hours.

State administration costs for individual permits include 100 hours per permit to review Forms 1 and 2B, issue public notices, and respond to comments. EPA increased this estimate from the 70 hours used in its analysis of the proposed rule in response to comments (Muldener, 2001). Sylvester (2002) and Allen (2002) concurred with this estimate; Harsh (2002) thought it might be low, but Coats (2002) considered it to be twice the time needed.

EPA estimated that the hearing time for an individual permit would require 200 hours based on estimates from Washington State (KauzLoric, 1999), which indicated that a hearing required approximately 100 to 150 hours of State employee time. Using BPJ, EPA assumed an average of two hearings per permit and an average requirement of 100 hours per hearing. This is higher than the estimate per hearing provided by Sylvester (2002). Nevertheless, Sylvester agreed with the estimate, as did Coats (2002) and Allen (2002). Harsh (2002) provided an alternative estimate of 22 to 33 hours. EPA decided to retain an average estimate of 200 hours because some individual permits may attract numerous participants and require multiple hearings.

EPA assumed that the inspection time and annual report review and subsequent recordkeeping costs for operations with individual permits would be the same as operations with general permits. The average inspection time will most likely be the same because most of the 16-hour estimate is spent on activities that will not vary across permit types. Similarly, the annual report content requirements are the same for all CAFOs regardless of permit type. Thus, the labor requirement is 4 hours.

Table 9-12 summarizes EPA's assumptions for general permit administration and Table 9-13 provides the assumptions used to develop State costs for individual permits. The same State wage rate is used to estimate unit costs. These tables also provide unit cost estimates for EPA, which is the permitting authority in some States.[5]

States may also need to undertake enforcement actions, but EPA has adopted the standard analytical assumption of full compliance for the purposes of estimating State and private sector expenditures. Given CAFO costs that reflect full compliance assumptions, there should be no need for enforcement actions. Therefore, this analysis excludes enforcement costs.

Although, the overall unit costs for permitting are generally higher than those used in proposal, due to a decrease in the universe of potential permittees under the final rule, States will incur much smaller permitting costs compared to either of the regulatory alternatives considered for EPA's proposed rule. For the proposed rule, EPA coproposed the following:

- A three-tier alternative in which all Tier 2 facilities would be required to either apply for an NPDES permit or submit certification that they did not meet any conditions necessitating a permit.

- A two-tier alternative that lowered the threshold for AFOs that were automatically defined as CAFOs from 1000 AU to 500 AU.

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[5] EPA used an hourly wage rate for a GS12, Step One Federal employee to estimate the cost of EPA staff. The U.S. Office of Personnel Management 2001 General Schedule reported a base annual salary of $51,927. EPA divided this by 2,080 hours to obtain an hourly rate of $24.96. Multiplying this rate by 1.6 to incorporate typical Federal benefits (OPM, 1999), EPA obtained a final hourly rate of $39.94 .

Table 9-12. State and Federal Administrative Costs Associated With General Permits. (costs in 2001 dollars)

Administrative Activity	Unit Hours	Labor Cost	O&M Cost[1]
State Administrative Costs			
General Permit Development	1,290 per State	$38,420	$1,060
- Revise Permit	300 per State		
- Public Notice/Response to Comments	570 per State		
- Public Hearing(s)	420 per State		
Review and Approval of NOIs	4 per CAFO	$120	
Review Annual Reports	4 per CAFO	$120	
Facility Inspections	16 per CAFO	$480	
Federal Administrative Costs[2]			
Review and Approval of NOIs	4 per CAFO	$160	
Review Annual Reports	4 per CAFO	$160	
Facility Inspections	16 per CAFO	$640	

1. States may incur public notification costs for the general permit. The O&M cost estimate is based on the same assumption of $1,000 per public notice that was used for the proposed rule. That estimate assumed that public notices would be placed in four newspapers and each notice cost $250. The $1,000 was converted from 1999 dollars to 2001 dollars using the Consumer Price Index (1000 × 177.1/166.6 = 1060) (BLS, 2002a). This estimate is consistent with a cost estimate for public notification expenses provided by Tilley and Kirkpatrick (2002).

2. EPA employees will incur the same hourly burden for these activities as their State counterparts.

Table 9-13. State and Federal Administrative Costs Associated with Individual Permits. (in 2001 dollars)

Administrative Activity	Unit Hours	Labor Cost	O&M Cost[1]
State Administrative Costs			
Application Review/Public Notification/Response to Comments	100 per CAFO	$2,980	$1,060
Public Hearing	200 per CAFO	$5,960	$1,060
Review Annual Reports	4 per CAFO	$120	
Facility Inspections	16 per CAFO	$480	
Federal Administrative Costs[2]			
Application Review/Public Notification/Response to Comments	100 per CAFO	$3,990	$1,060
Public Hearing	200 per CAFO	$7,990	$1,060
Review Annual Reports	4 per CAFO	$160	
Facility Inspections	16 per CAFO	$640	

1. States may incur public notification costs for each individual permit and hearing. The O&M cost estimate is based on the same assumption of $1,000 per public notice that was used for the proposed rule. That estimate assumed that public notices would be placed in four newspapers and each notice cost $250. The $1,000 was converted from 1999 dollars to 2001 dollars using the Consumer Price Index (1000 × 177.1/166.6 = 1060) (BLS, 2002a). This estimate is consistent with a cost estimate for public notification expenses provided by Tilley and Kirkpatrick (2002).

2. EPA employees will incur the same hourly burden for these activities as their State counterparts.

EPA estimated that 31,930 facilities would be affected under the proposed three-tier option. Under the proposed two-tier option, 25,540 facilities would have required NPDES permits. Based on the provisions of the final rule, EPA estimates that approximately 15,400 operations will require a permit. This estimate includes more than 10,700 large CAFOs, almost 4,500 medium operations defined as CAFOs, and almost 200 designated CAFOs. Because States incur most of their program costs through ongoing permit administration, EPA's final rule will be more cost effective and less burdensome than either of its proposed alternatives.

Of the 15,400 CAFOs requiring NPDES permits, EPA estimates that approximately 13,000 should have permits or meet the 25-year, 24-hour exemption under the 1976 regulations. EPA estimates, however, that only 4,100 permits have been issued, which implies that the permitting impact above the actual compliance baseline is approximately 11,300 permits.

EPA also recognizes that the final rule may affect permit conditions for those CAFOs that already have (or should have) permits. This could affect state costs for issuing permits and conducting inspections. Furthermore, revisions to the permit application forms may increase State review time as well as increase the time it takes producers to complete the forms. Thus, States may incur incremental costs for the baseline CAFOs that do (or should) have NPDES permits now. To simplify the analysis, EPA estimated an upper-bound impact that includes total permitting and inspection costs for all 15,400 CAFOs, although States are already incurring some portion of cost on 4,100 CAFOs. Actual new expenditures, therefore, will be lower than EPA's estimate suggests.

Operators or owners of a large CAFO may submit documentation that there is no potential to discharge in lieu of applying for a permit. The permitting authority would need to review the documentation and make a determination of whether there is a potential to discharge. Although there are no estimates of how many operations may pursue this option, given the stringent requirements, EPA believes that few, if any, operations will claim no potential to discharge. Therefore, EPA's cost analysis assumes that all CAFOs obtain NPDES permits. If any operation chooses to request a no-potential-to-discharge determination, then presumably doing so is as cost effective or more cost effective in the long run than obtaining a permit. Therefore, EPA concludes that its analysis may overstate costs should any CAFOs obtain an exemption based on no potential to discharge.

As noted above, only the approved States will incur costs. To derive State costs, EPA needed to estimate how often the States activities would occur. First, EPA estimated that 97 percent of the permitted CAFOs are located in these States based on its analysis of USDA livestock operation data. Second, EPA assumed that 70 percent of these CAFOs will request coverage under a State general permit (or EPA's general permit). The remaining 30 percent will obtain individual permits. EPA believes that the split between the two permit types is conservative (i.e., tending to overestimate costs) because the permit conditions for CAFOs are amenable to the use of a general permit. In particular, there are no facility-specific discharge limits that would require individual permitting. Third, EPA assumed that 12 percent of individual permits will require

public hearings. The hearing percentage for individual permits is an average of estimates provided for Kansas (4 to 8 percent) and Indiana (15 to 20 percent). Finally, using best professional judgement, EPA assumed that each CAFO is inspected once within each 5-year permit period, which implies an annual inspection rate of 20 percent. The final rule contains no inspection frequency requirements and for NPDES purposes, this is a relatively high inspection rate because CAFOs fall into the category of nonmunicipal, minor dischargers, which have an annual inspection rate closer to 1 percent. States have indicated, however, that they inspect CAFOs more frequently to ensure compliance with multiple State requirements (US EPA, 2001). Although these frequent inspections may not be necessary to ensure NPDES compliance, inspectors can assess NPDES compliance status. Consequently, EPA increased its inspection rate estimate from 10 percent (used in the proposed rule) to 20 percent to reflect at least one NPDES-related inspection per CAFO every 5 years. This inspection rate includes the inspection required to designate a small or medium AFO, a CAFO.

Table 9-14 shows how the total estimate of 15,400 CAFOs and preceding assumptions generate the CAFO estimates for each of the permit-related costs shown in Tables 9-12 and 9-13. NPDES permits are valid for up to 5 years. Thus, States incur application review costs for each CAFO once every five years. To derive average annual costs, EPA assumed these costs would be incurred for 20 percent of total CAFOs each year. The annual CAFO column in Table 9-14 reflects this assumption.

Table 9-14. Derivation of CAFO Estimates Used to Calculate Annual Administrative Costs.[1]

Category	Total	Annual[1]
Total CAFOs	15,400	3,080
State-Issued Permits[2]	14,923	2,985
• General Permits	10,446	2,089
– Inspections	2,089	2,089
• Individual Permits	4,477	895
– Hearings	537	107
– Inspections	895	895
EPA-Issued Permits[2]	477	95
• General Permits	334	67
– Inspections	67	67
• Individual Permits	143	29
– Hearings	17	3
– Inspections	29	29

Detail may not add to totals because of independent rounding. The total CAFO estimate has been rounded to the nearest hundred for the purpose of this UMRA analysis.

1. Annual CAFO estimates for permit review costs equal total divided by 5 because permits are renewed every 5 years. Annual CAFO estimates for inspections equal 20 percent of total CAFOs.

2. EPA estimated the number of CAFOs in the 43 states with approved NPDES programs based on its analysis of USDA livestock operation data. EPA used this estimate to split total CAFOs between those receiving State-issued permits and EPA-issued permits.

To obtain the annual State costs reported in Table 9-15, EPA multiplied the one-time unit costs in Table 9-11 by the number of States expected to incur those costs. These one-time costs were then annualized over 5 years at a 7 percent discount rate.[6] Recurring annual permitting and inspection costs were derived by multiplying the unit costs in Tables 2 and 3 by their respective annual CAFO estimates in Table 9-14. Total annual State administrative costs are the sum of annualized one-time costs and annual permitting costs. The annual cost estimate for all States is $8.5 million. Federal costs for administering a portion of permits are shown in Table 9-16 for information purposes.

Table 9-15. Annual State Administrative Costs. (in 2001 dollars)

Administrative Activity	Unit Cost	Units	Total Cost ($millions)
Up-front State Costs			
Rule Development[1]	$27,430	43 States	$1.18
NPDES Program Modification Request	$7,450	43 States	$0.32
General Permit Development[1]	$39,480	43 States	$1.70
		Up-front Total	**$3.20**
		Annualized up-front Costs[2]	**$0.73**
Average Annual Implementation Costs for Permits and Inspections			
Review and Approve NOIs for General Permits	$120	2,089 CAFOs per year	$0.25
Review Applications/Public Notices/Respond to Comments for Individual Permits[1]	$4,040	895 CAFOs per year	$3.61
Public Hearings for Individual Permits[1]	$7,020	107 CAFOs per year	$0.75
Review Annual Reports (General and Individual Permits)	$120	14,923 CAFOs per year	$1.78
Facility Inspections (General and Individual Permits)	$480	2,984 CAFOs per year	$1.42
		Annual Permit Costs	**$7.81**
		Total Annual Costs	**$8.54**

Detail may not add to totals due to independent rounding.
1. Includes O&M costs.
2. Total up-front costs annualized over 5 years at a 7 percent discount rate.

[6] Assuming a 5-year annualization period generates a conservative annual estimate that tends to overstate costs because it treats these one-time activities as though they recur every five years, which is unlikely to be the case.

Table 9-16. Federal Administrative Costs. (in 2001 dollars)			
Administrative Activity	**Unit Cost**	**Units**	**Total Cost ($millions)[1]**
Average Annual Implementation Costs for Permits and Inspections			
Review and Approve NOIs for General Permits	$160	67 CAFOs per year	$0.01
Review Applications/Public Notices/Respond to Comments for Individual Permits[2]	$3,990	29 CAFOs per year	$0.15
Public Hearings for Individual Permits[2]	$7,990	3 CAFOs per year	$0.03
Review Annual Reports (General and Individual Permits)	$160	477 CAFOs per year	$0.08
Facility Inspection (General and Individual Permits)	$640	95 CAFOs per year	$0.06
		Annual Permit Costs	**$0.32**

Detail may not add to totals due to independent rounding.
1. EPA used an hourly wage rate for a GS12, Step One Federal employee to estimate the cost of the Agency staff. The U.S. Office of Personnel Management (OPM, 2001) General Schedule reported a base annual salary of $51,927 in 2001. EPA divided this by 2,080 hours to obtain an hourly rate of $24.96. Multiplying this rate by 1.6 to incorporate typical Federal benefits (OPM, 1999), EPA obtained a final hourly rate of $39.94.
2. Includes O&M costs.

New State expenditures as a result of the final rule are expected to differ across States. Although all approved States will incur up-front costs to revise their rules and implement programs, States with more CAFOs will incur more annual costs. EPA estimated that almost 50 percent of permitted CAFOs are located in seven States: approximately 9 percent in both Iowa and North Carolina; approximately 6 percent in both Georgia and California; and between 5 and 6 percent in each of Nebraska, Minnesota, and Texas. Thus, these States are likely to incur much higher annual costs than other States. State costs will also vary depending on the rate at which they utilize general versus individual permits.

States can use existing sources of financial assistance to revise and implement the final rule. Section 106 of the CWA authorizes EPA to provide federal assistance (from Congressional appropriations) to States, Tribes, and interstate agencies to establish and implement ongoing water pollution control programs. Section 106 grants offer broad support to States to administer programs to prevent and abate surface and ground water pollution from point and nonpoint sources. States may use the funding for a variety of activities including permitting, monitoring, and enforcement. Thus, State NPDES permit programs represent one type of State program that can be funded by Section 106 grants. The total appropriation for Section 106 grants for fiscal year 2002 was $192,476,900. On average, eligible States may receive between $60,000 to $9,000,000 of the total appropriation.

9.4 References

Allen, P. 1999. Environmental Program Manager, Maryland Department of Environment, Water Management Administration. Personal communication on May 19 with R. Johnson, DPRA, Arlington, Virginia.

Allen, P. 2002. CAFO Rule State NPDES Burden Estimates. E-mail message on July 26 to T. Cannon, SAIC, Reston, Virginia.

Battaglia, R. 1999. Department of Animal and Veterinary Science, University of Idaho. Personal communication on April 6 with R. Johnson, DPRA, Alexandria, Virginia.

Bazzell, D. 2001. Public Comment Submitted in Response to EPA's CAFO Rule. Wisconsin Department of Natural Resources. Doc# CAFO201450.

Bickert, W. 1999. Dairy Housing Extension Specialist, Michigan State University. Personal communication on May 18 with R. Johnson, DPRA, Alexandria, Virginia.

Bureau of Labor Statistics (BLS). 2002a. Consumer Price Index-All Urban Consumers. www.bls.gov.

Bureau of Labor Statistics (BLS). 2002b. Employer Cost for Employee Compensation. www.bls.gov. (Series Id. CCU310000290000D, Total compensation, Public Administration, State and local government)

Bureau of Labor Statistics (BLS). 2002c. Employment Cost Index. www.bls.gov. (Series Id: ECU20003A, Wages and salaries, State and local government)

Bureau of Labor Statistics (BLS). 2001. 2000 National Industry-Specific Occupational Employment and Wage Estimates. www.bls.gov. (SIC 902 - State Government)

Carey, J.B. 2002 . Texas A&M, Poultry Science Department. Personal communication on October 18 with S. Ragland, SAIC, Lakewood, Colorado.

Carey, J.B. 1999. Swine and Poultry Survey. E-mail message on April 16 to DPRA, Arlington, Virginia.

Coats, A. 2002. State/regional respondent burden estimates. E-mail EPA from EPA Region 2 on July 24 to T. Cannon, SAIC, Reston, Virginia.

Domingo, D. 2002. State/regional respondent burden estimates. E-mail EPA from EPA Region 10 on July 24 to T. Cannon, SAIC, Reston, Virginia.

Earnst, R. 2002. Poultry Specialist, University of California Davis. Personal communication on October 15 with T. Doley, SAIC, Reston, Virginia.

Funk, T. 2002. Agricultural Engineer and Extension Specialist, University of Illinois. Personal communication on October 15 with T. Doley, SAIC, Reston, Virginia.

Funk, T. 1999. FYI. E-mail message on November 23 to DPRA, Arlington, Virginia.

Gale, J.A. 1999. UT—response. E-mail message on May 5 to DPRA, Arlington, Virginia.

Greenless, W., et al. 1999. Completed Survey—Iowa. E-mail message on April 27 to DPRA, Alexandria, Virginia.

Groves, R. 1999. Penn State University Dairy Extension. Personal communication on May 14 via E-mail message to R. Johnson, DPRA, Arlington, Virginia.

Hammerberg, E. 2002. Maryland Department of the Environment. Personal communication on March 8 with C. Simons, DPRA, Virginia.

Harsh, J. 2002. Kansas Department of Health and Environment. Personal communication on July 31 with T. Cannon, SAIC, Reston, Virginia..

Holmes, B. 1999. Farm Structures Extension Specialist, University of Wisconsin Extension. Personal communication on May 14 with R. Johnson, DPRA, Arlington, Virginia.

Hopkins, O. 2002. Missouri Department of Natural Resources, Water Pollution Control Program. Personal communication on October 18 with T. Doley, SAIC, Reston, Virginia.

Jacobson, L.D. 1999. Survey Response—MN. E-mail message on April 14 to DPRA, Arlington, Virginia.

Johnson, D. 2002. California NRCS, Eng. Section. Personal communication on October 15 with T. Doley, SAIC, Reston, Virginia.

Johnson, D. 1999. Responses from Calif. regarding dairies and water. E-mail message on May 17 to DPRA, Arlington, Virginia.

Jones, C.; Speck, S.; Daily, F. 2001. Public Comment Submitted in Response to EPA's CAFO Rule. Ohio Department of Agriculture; Ohio Department of Natural Resources; Ohio EPA. Doc# CAFO201851.

Jones, D. 1999. Department of Agricultural & Bio Engineering, Purdue University. Personal communication on April 25 with R. Johnson, DPRA, Alexandria, Virginia.

Jones, D. 2002. Department of Agricultural & Bio Engineering, Purdue University. Personal communication on October 18 with T. Doley, SAIC, Reston, Virginia.

KauzLoric, P. 1999. Dairy Program Coordinator, Washington Department of Ecology, Water Quality Program. Personal communication on May 11 with R. Johnson, DPRA, Virginia.

Kniffen, D. 2002. Extension Agent, Pennsylvania State University. Personal communication on October 18 with T. Doley, SAIC, Reston, Virginia.

Lawrence, J. 2002. Director of Beef Center, Iowa State University. Personal communication on October 18 with T. Doley, SAIC, Reston, Virginia.

Lory, J.A. 1999. Feeding Operations. E-mail message on April 16 to DPRA, Arlington, Virginia.

Muldener, K. 2001. Public Comment Submitted in Response to EPA's CAFO Rule. Kansas Department of Health and Environment. Doc# CAFO202366.

Parsons, G. 2002. Inspector, Missouri Department of Natural Resources. Personal communication on October 17 with S. Ragland, SAIC, Lakewood, Colorado.

Patterson, P. 1999. Penn State Poultry Science Dept. Personal communication on November 11 with J. DeSantis, DPRA, Arlington, Virginia.

Pirner, S. 2001. Public Comment Submitted in Response to EPA's CAFO Rule. South Dakota Departments of Environment and Natural Resources and Department of Agriculture. Doc# CAFO201739.

Ramsey, D. 2002. Division of Water Quality, North Carolina Division of Environmental Management. Personal communication on October 15 with T. Doley, SAIC, Reston, Virginia.

Sadler, M. 2002. South Carolina Bureau of Water - Industrial Permits Division. Personal communication on October 14 with T. Doley, SAIC, Reston, Virginia.

Science Applications International Corp. (SAIC). 1999. Aggregated ARMS financial data received by USDA, ERS, and spreadsheet versions of files converted by M. Beljak. May 7.

Solainian, J. 2002. Arkansas Department of Environmental Quality. Personal communication on October 16 with T. Doley, SAIC, Reston, Virginia.

Steinhart, T. 1999. Answers to recent questions—Iowa. E-mail message on April 15 to DPRA. Arlington, Virginia.

Sylvester, S. 2002. Wisconsin Department of Natural Resources. Personal communication. August 1, 2002.

Tetra Tech. 2002. Methodology for determining the potential number of duck and horse CAFOs in the United States. Memorandum on July 3 to C. White and G. Kibler, U.S. Environmental Protection Agency from B. Kurapatskie and G. Mallon.

Thomas, J. 1999. Completed Survey—MS. E-mail message on April 15 to DPRA, Arlington, Virginia.

Tilley, M., and Kirkpatrick B. 2002. Arkansas Department of Environmental Quality. Personal communication on March 12 with B. Crowley, DPRA, Virginia.

Tyson, T.W. 1999. Survey response—Alabama. E-mail message on April 22 to DPRA, Arlington, Virginia.

U.S. Environmental Protection Agency (US EPA). 2001. *State Compendium: Programs and Regulatory Activities Related to Animal Feeding Operations*. U.S. Environmental Protection Agency, Washington, D.C.

U.S. Environmental Protection Agency (US EPA). 1999. *State Compendium: Programs and Regulatory Activities Related to Animal Feeding Operations*. U.S. Environmental Protection Agency, Washington, D.C.

U.S. Environmental Protection Agency (US EPA). 1995. *Guidance Manual on NPDES Regulations for Concentrated Animal Feeding Operations*. EPA 833-B-95-001. U.S. Environmental Protection Agency, Washington, D.C.

U.S. Office of Personnel Management (OPM). 2001. *Government Pay Tables, 2001.* http://www.seemyad.com/gov/USAPAY.htm

U.S. Office of Personnel Management (OPM). 1999. *Work Years and Personnel Costs: Fiscal Year 1998*. OMSOE-OWI-98-12. Washington, D.C.: U.S. Office of Personnel Management.

Willhite, M. 2001. Public Comment Submitted in Response to EPA's CAFO Rule. Illinois EPA. Doc# CAFO202080.

York, K. 2000. Soil & Water Division, Smithville USDA Service Center. Personal communication on March 2 with J. Blair, DPRA, Arlington, Virginia.

CHAPTER 10

TECHNOLOGY OPTIONS CONSIDERED

This section describes the combinations of treatment technologies and best management practices (BMPs) that EPA configured as technology options for consideration as bases for the Concentrated Animal Feeding Operation (CAFO) effluent limitations guidelines and standards (ELGs). EPA developed technology options for the following:

- Best practicable control technology currently available (BPT);
- Best conventional pollutant control technology (BCT);
- Best available technology economically achievable (BAT); and
- New source performance standards (NSPS).

Technology bases for each option for each regulation were selected from the treatment technologies and BMPs described in Chapter 8. Sections 10.1 through 10.4 discuss the regulatory options that were considered for each of the regulations listed above.

10.0 INTRODUCTION

The regulations applicable to Large CAFOs are ELGs which are applied to individual operations through National Pollutant Discharge Elimination System (NPDES) permits issued by EPA or authorized states under Section 402 of the Clean Water Act (CWA). For Large CAFOs under Subparts C and D, the final ELG regulations prohibit the discharge of manure, litter, and other process wastewater, except for allowing discharge when rainfall causes an overflow from a facility designed, maintained, and operated to contain all process wastewaters, including storm water, plus runoff from the 25-year, 24-hour rainfall event.

All of these regulations are based upon the performance of specific technologies but not require the use of any specific technology.

10.1 Best Practicable Control Technology Currently Available (BPT)

The BPT effluent limitations control conventional, priority, and nonconventional pollutants when discharged from CAFOs to surface waters of the United States. Generally, EPA determines BPT effluent levels based upon the average of the best existing performances by plants of various sizes, ages, and unit processes within each industrial category or subcategory. In industrial categories where present practices are uniformly inadequate, however, EPA may determine that BPT requires higher levels of control than any currently in place if the technology to achieve those levels can be practicably applied.

In addition, CWA Section 304(b)(1)(B) requires a cost assessment for BPT limitations. In determining the BPT limits, EPA must consider the total cost of treatment technologies in relation to the effluent reduction benefits achieved. This inquiry does not limit EPA's broad discretion to adopt BPT limitations that are achievable with available technology unless the required additional reductions are "wholly out of proportion to the costs of achieving such marginal level of reduction." See Legislative History, op.cit. p. 170. Moreover, the inquiry does not require the Agency to quantify benefits in monetary terms. See e.g., American Iron and Steel Institute v. EPA, 526 F. 2d 1027 (3rd Cir., 1975).

In balancing costs against the benefits of effluent reduction, EPA considers the volume and nature of expected discharges after application of BPT, the general environmental effects of pollutants, and the cost and economic impacts of the required level of pollution control. In developing guidelines, the CWA does not require or permit consideration of water quality problems attributable to particular point sources, or water quality improvements in particular bodies of water. Therefore, EPA has not considered these factors in developing the final limitations. See Weyerhaeuser Company v. Costle, 590 F. 2d 1011 (D.C. Cir. 1978).

10.1.1 BPT Options for the Subpart C Subcategory

EPA incorporated the following BMPs into all BPT technology options:

Production Area BMPs

- Perform weekly inspections of all storm water diversion devices, runoff diversion structures, animal waste storage structures, and devices channeling contaminated storm water to the wastewater and manure storage and containment structure;
- Perform daily inspections of all water lines, including drinking water or cooling water lines;
- Install depth markers in all surface and liquid impoundments (e.g., lagoons, ponds, tanks) to indicate the design volume and to clearly indicate the minimum capacity necessary to contain the 25-year, 24-hour rainfall event, including additional freeboard requirements;
- Correct any deficiencies found as a result of daily and weekly inspections as soon as possible;
- Do not dispose of mortalities in liquid manure or storm water storage or treatment systems, and mortalities must be handled in such a way as to prevent discharge of pollutants to surface water; and
- Maintain on-site a complete copy of the records specified in 40 CFR 412.37(b) and (c). These records must be maintained for 5 years and if requested, be made available to the permitting authority.

Land Application BMPs

- Land-apply manure, litter, and other process wastewaters in accordance with a nutrient management plan that establishes application rates for each field based on the nitrogen requirements of the crop, or on the phosphorus requirements where necessary because of soil or other field conditions.
- Account for other sources of nutrients when establishing application rates, including previous applications of manure, litter, and other process wastewaters; residual nutrients in the soil; nitrogen credits from previous crops of legumes; and application of commercial fertilizers, biosolids, or irrigation water.
- Collect and analyze manure, litter, and other process wastewaters annually for nutrient content, including nitrogen and phosphorus.
- Calibrate manure application equipment annually.
- Applications of manure, litter, and other process wastewaters are prohibited within 100 feet of any down-gradient surface waters, open tile line intake structures, sinkholes, agricultural well heads, or other conduits to surface waters. As a compliance alternative to the 100-foot setback, the CAFO may elect to establish a 35-foot vegetated buffer where application of manure, litter, or other process wastewaters is prohibited. The CAFO may also demonstrate to the permitting authority that a setback or vegetated buffer is unnecessary because implementation of alternative conservation practices or site-specific conditions will provide pollutant reductions equivalent to or better than the reductions that would be achieved by the 100-foot setback.
- Maintain on-site the records specified in 40 CFR 412.37(b) and (c). These records must be maintained for 5 years and if requested, be made available to the permitting authority.

In addition, BPT options for Subpart C operations (dairy and beef cattle other than veal which includes heifer operations) include the following technology bases:

Option 1: Zero discharge from a facility designed, maintained, and operated to hold manure, litter, and other process wastewaters, including direct precipitation and runoff from a 25-year, 24-hour rainfall event. In addition, determine the maximum allowable nitrogen-based application rates based on the nitrogen requirement of the crop to be grown and realistic crop yields that reflect the yields obtained for the given (or similar) field in prior years. Manure, litter, and other process wastewater applications must not exceed the nitrogen-based application rate.

Option 1A: The same elements as Option 1, with the addition of storage capacity for the chronic storm event (10-year, 10-day storm) above any capacity necessary to

hold manure, litter, and other process wastewaters, including direct precipitation and runoff from a 25-year, 24-hour rainfall event.

Option 2: The same elements as Option 1, except nitrogen-based agronomic application rates are replaced by phosphorus-based agronomic application rates when dictated by site-specific conditions. In addition, at least once every three years, collect and analyze representative soil samples for phosphorus content from all fields where manure, litter, and other process wastewaters are applied.

Options 3A/3B: The same elements as Option 2, plus ground-water monitoring, concrete pads, synthetically lined lagoons and/or synthetically lined storage ponds for operations located in environmentally sensitive areas such as karst terrain where ground water contamination is likely and an assessment of the ground water's hydrologic link to surface water for all other operations.

Options 3C/3D: The same elements as Option 2, plus permeability standards for lagoons and storage ponds for operations located in environmentally sensitive areas such as karst terrain. No additional requirements are placed on operations not located in environmentally sensitive areas.

Option 4: The same elements as Option 2, plus costs for additional surface water monitoring.

Option 5A: The same elements as Option 2, plus implementation of a drier manure management system (i.e., composting).

Option 6: For Large dairy operations only, the same elements as Option 2, plus implementation of anaerobic digestion with energy recovery.

Option 7: The same elements as Option 2, plus timing restrictions on land application of animal waste to frozen, snow-covered, or saturated ground.

In addition to the technology options described above, EPA conducted several sensitivity analyses of costs include the requirement that all operations use a phosphorus-based agronomic rate as opposed to only when dictated by site-specific conditions, and all recipients of manure from a CAFO prepare nutrient management plans.

10.1.2 BPT Options for the Subpart D Subcategory

BPT options for Subpart D operations (swine, poultry, and veal calves) are the same as those described in Section 10.2.1 for Subpart C operations for Options 1, 1A, 2, 3A/3B, 3C/3D, 4, and 7. Option 5A is replaced by Option 5 and Option 6 is modified to address the operations under Subpart D. Descriptions of Options 5 and 6 for Subpart D operations are described below.

Option 5: The same elements as Option 2, but based on zero discharge with no overflow under any circumstances (i.e., total confinement and covered storage).

Option 6: For Large swine operations, the same elements as Option 2, plus implementation of anaerobic digestion with energy recovery.

10.2 Best Conventional Pollutant Control Technology (BCT)

BCT limitations control the discharge of conventional pollutants from direct dischargers. Conventional pollutants include BOD, TSS, oil and grease, and pH. BCT is not an additional limitation, but rather replaces BAT for the control of conventional pollutants. To develop BCT limitations, EPA conducts a cost reasonableness evaluation, which consists of a two-part cost test: 1) the POTW test, and 2) the industry cost-effectiveness test.

In the POTW test, EPA calculates the cost per pound of conventional pollutants removed by industrial dischargers in upgrading from BPT to a BCT candidate technology and then compares this to the cost per pound of conventional pollutants removed in upgrading POTWs from secondary to tertiary treatment. The upgrade cost to industry, which is represented in dollars per pound of conventional pollutants removed, must be less than the POTW benchmark of $0.25 per pound (in 1976 dollars). In the industry cost-effectiveness test, the ratio of the incremental BPT to BCT cost, divided by the BPT cost for the industry, must be less than 1.29 (i.e., the cost increase must be less than 29 percent).

In developing BCT limits, EPA considered whether there are technologies that achieve greater removals of conventional pollutants than for BPT, and whether those technologies are cost-reasonable according to the BCT Cost Test. In each subcategory, EPA considered the same technologies and technology options when developing BCT options as were developed for BPT.

10.3 Best Available Technology Economically Achievable (BAT)

The factors considered in establishing a BAT level of control include: the age of process equipment and facilities, the processes employed, process changes, the engineering aspects of applying various types of control techniques to the costs of applying the control technology, non-water quality environmental impacts such as energy requirements, air pollution and solid waste generation, and such other factors as the Administrator deems appropriate (Section 304(b)(2)(B) of the Act). In general, the BAT technology level represents the best existing economically achievable performance among facilities with shared characteristics. BAT may include process changes or internal plant controls which are not common in the industry. BAT may also be transferred from a different subcategory or industrial category.

In each subcategory, EPA considered the same technologies and technology options when developing BAT options as were developed for BPT.

10.4 New Source Performance Standards (NSPS)

NSPS under Section 306 of the CWA represent the greatest degree of effluent reduction achievable through the application of the best available demonstrated control technology for all pollutants (i.e., conventional, nonconventional, and toxic pollutants). NSPS are applicable to new industrial direct discharging facilities. Congress envisioned that new treatment systems could meet tighter controls than existing sources because of the opportunity to incorporate the most efficient processes and treatment systems into plant design. Therefore, Congress directed EPA, in establishing NSPS, to consider the best demonstrated process changes, in-plant controls, operating methods, and end-of-pipe treatment technologies that reduce pollution to the maximum extent feasible.

In each subcategory, EPA considered the same technologies and technology options when developing NSPS options as were developed for BPT. In addition, at proposal, EPA considered a zero discharge option with no exception for storm overflows, based on maintaining animals in total confinement.

CHAPTER 11

MODEL FARMS AND COSTS OF TECHNOLOGY BASES FOR REGULATION

This section describes the methodology used to estimate engineering compliance costs associated with implementing the regulatory options for the concentrated animal feeding operations (CAFOs) industry. The information contained in this section provides an overview of the methodology and assumptions built into the cost models. More detailed information on the cost methodology and specific technologies and practices is contained in the *Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations* (2002).

The following information is discussed in this section:

- Section 11.1: Overview of cost methodology;
- Section 11.2: Development of model farm operations;
- Section 11.3: Design and cost of waste and nutrient management technologies;
- Section 11.4: Development of frequency factors;
- Section 11.5: Summary of estimated industry costs by regulatory option; and
- Section 11.6: References.

11.1 Overview of Cost Methodology

To assess the economic impact of the effluent limitations guidelines and standards on the CAFOs industry, EPA estimated costs associated with regulatory compliance for each of the regulatory options described in Section 10. The economic burden is a function of the estimated costs of compliance to achieve the requirements, which may include initial fixed and capital costs, as well as annual operating and maintenance (O&M) costs. Estimation of these costs typically begins by identifying the practices and technologies that can be used to meet a particular requirement. The Agency then develops a cost model to estimate costs for their implementation.

EPA used the following approach to estimate compliance costs for the CAFOs industry:

- EPA collected data from published research, meetings with industry organizations, discussions with USDA cooperative extension agencies, review of USDA's Census of Agriculture data, and site visits to swine, poultry, beef, veal, and dairy CAFOs. These data were used to define model farms and to determine waste generation and nutrient

concentration, current waste and nutrient practices, and the viability of waste management technologies for the model farms.

- EPA identified candidate waste and nutrient management practices and grouped appropriate technologies into regulatory options. These regulatory options serve as the bases of compliance cost and pollutant loading calculations.
- EPA developed technology frequency factors to estimate the percentage of the industry that already implements certain operations or practices required by the regulatory options (i.e., baseline conditions).
- EPA developed cost equations for estimating capital costs, initial fixed costs, and 3-year recurring costs, 5-year recurring costs, and annual O&M costs for the implementation and use of the different waste and nutrient practices targeted under the regulatory options. Cost equations were developed from information collected during the site visits, published information, vendor contacts, and engineering judgment.
- EPA developed and used computer cost models to estimate compliance costs and nutrient loads for each regulatory option.
- EPA used output from the cost model to estimate total annualized costs and the economic impact of each regulatory option on the CAFOs industry (presented in the *Economic Analysis*).

Table 11-1 presents the regulatory options and the waste and nutrient management components that make up each option.

Table 11-1. Summary of Regulatory Options for CAFOs

Technology or Practice	Options									
	1	1A	2	3A/ 3B	3C/ 3D	4	5	5A	6	7
Feedlot best management practices (BMPs), including storm water diversions, lagoon/pond depth markers, periodic inspections, and records	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mortality handling requirements (e.g., rendering, composting)[1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Nutrient management planning and recordkeeping (sample soils once every 3 years, sample manure twice per year)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Land application limited to nitrogen-based agronomic	✓	✓								
Land application limited to phosphorus-based agronomic application rates where dictated by site-specific conditions, and nitrogen-based application elsewhere			✓	✓	✓	✓	✓	✓	✓	✓
No manure application within 100 feet of any surface water, tile drain inlet, or sinkhole	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ground water requirements, including assessment of hydrologic link, monitoring wells (four per facility), impermeable pads under storage, impermeable lagoon/pond liners, and temporary/modified storage during upgrade				✓						
Ground water requirements including performance based standards for lagoons					✓					
Additional capacity for 10-year, 10-day chronic storm event		✓								
Surface water monitoring requirement, including four total grab samples upstream and downstream of both feedlot and land application areas, 12 times per year. One composite sample collected once per year at stockpile and surface impoundments. Samples are analyzed for nitrogen, phosphorus, and total suspended solids.						✓				
Drier manure technology basis[2,3]							✓	✓		
Anaerobic digestion									✓	
Timing requirements for land application (resulting in regional variation in storage periods)										✓

[1] There are no additional compliance costs expected for beef and dairy operations related to mortality handling requirements.
[2] Option 5 mandates "drier waste management." For beef feedlots and dairies, this technology basis is composting. For swine, poultry and veal operations, drier systems include covered lagoons.
[3] Option 5B mandates "no overflow" systems. For swine operations, the technology basis is high-rise housing for hogs, and for poultry operations the technology basis is dry systems.
(ERG, 2000a; Tetra Tech, Inc., 2000a)

11.2 Development of Model Farm Operations

For the purpose of estimating total costs and economic impacts, EPA calculated the costs of compliance for CAFOs to implement each of the regulatory options being considered. These costs reflect the range of capital costs, annual operating and maintenance costs, start-up or first year costs, as well as recurring costs that may be associated with complying with the regulations. EPA traditionally develops either facility-specific or model facility costs. Facility-specific

compliance costs require detailed process information about many, if not all, facilities in the industry. These data typically include production, capacity, water use, wastewater generation, waste management operations (including design and cost data), monitoring data, geographic location, financial conditions, and any other industry-specific data that may be required for the analyses. EPA then uses each facility's information to determine how the potential regulatory options will impact that facility, and to estimate the cost of installing new pollution controls.

When facility-specific data are not available, EPA develops model facilities to provide a reasonable representation of the industry. Model facilities are developed to reflect the different characteristics found in the industry, such as the size or capacity of operations, types of operation, geographic locations, modes of operation, and types of waste management operations. These models are based on data gathered during site visits, information provided by industry members and their trade associations, and other available information. EPA estimates the number of facilities that are represented by each model. Cost and financial impacts are estimated for each model farm, then industry-level costs are calculated by multiplying model farm costs by the number of facilities represented by each particular model. Because of the amount and type of information that is available for the CAFOs industry, EPA has chosen a model-facility approach to estimate compliance costs.

EPA estimated compliance costs using a representative facility approach based on more than 1,700 farm-level models that were developed to depict conditions and to evaluate compliance costs for select representative CAFOs. The major factors used to differentiate individual model CAFOs include the commodity sector, the farm production region, the facility size (based on herd or flock size or the number of animals on site), and performance of the operation. EPA's model CAFOs primarily reflect the major animal sector groups, including beef cattle, dairy, hog, broiler, turkey, and egg laying operations. Practices at other subsector operations are also reflected by the cost models, such as replacement heifer operations, veal operations, flushed caged layers, and hog grow-finish and farrow-to-finish facilities. Model facilities with similar waste management and production practices were used to depict operations in regions that were not separately modeled.

Another key distinguishing factor incorporated into EPA's model CAFOs is the availability of cropland and pastureland to apply manure nutrients to land. For this analysis, nitrogen and phosphorus rates of land application are evaluated for three categories of cropland use: Category 1 CAFOs that have sufficient land for all on-farm nutrients generated, Category 2 CAFOs that have insufficient land, and Category 3 CAFOs that have no land. The number of CAFOs within a given category of land availability is drawn from 1997 USDA data and varies depending on which nutrient (nitrogen or phosphorus) is used as the basis to assess land application and nutrient management costs. For Category 2 and 3 CAFOs, EPA evaluated additional technologies that may be necessary to balance on-farm nutrients. These technologies may also be used to reduce off-site hauling costs associated with excess on-farm nutrients. Such technologies may include best management practices (BMPs) and various farm production technologies, such

as feed management strategies, solid-liquid separation, composting, anaerobic digestion, and other retrofits to existing farm technologies.

EPA's model CAFOs also take into account such production factors as climate and farmland geography, as well as land application and waste management practices and other major production practices typically found in the key producing regions of the country. Required practices under existing state regulations are also taken into account. Model facilities reflect major production practices used by larger confined animal farms, generally those with more than 300 animal units. Therefore, the models do not reflect pasture and grazing type farms, nor do they reflect typical costs to small farms. EPA's cost models also reflect cost differences within sectors depending on manure composition, bedding use, and process water volumes.

11.2.1 Swine Operations

EPA developed the parameters describing the model swine farms using information from the National Agriculture Statistics Service (NASS), site visits to swine farms across the country, discussions with the National Pork Producers Council, and the USDA Natural Resources Conservation Service (NRCS). Dscriptions of the various components that make up the model farms are presented in the following discussion, and the sources of the information used to develop that piece of the model farm are noted.

11.2.1.1 Housing

Swine are typically housed in total confinement barns, and less commonly in other housing configurations such as open buildings with or without outside access and pastures (USDA, 1995). On many farms, small numbers of pigs (fewer than the number covered by this regulation) are raised outdoors; however, the trend in the industry is toward larger confinement farms at which pigs are raised indoors (North Carolina State University, 1998). For these reasons, the model swine farm is assumed to house its animals in total confinement barns.

11.2.1.2 Waste Management Systems

The characteristics of waste produced at an operation depends on the type of animals that are present. In farrow-to-finish operations, the pigs are born and raised at the same facility. Therefore, the manure at a farrow-to-finish farm has the characteristics of mixed excreta from varying ages. In grow-finish facilities, young pigs are first born and cared for at a nursery in another location, and then brought onto the finishing farm. Therefore, the manure at a grow/finish farm has characteristics of older pigs 7 weeks to slaughter weight. These are the two predominant types of swine operations in the United States from the size classes that would be covered under the final rule.

Swine houses with greater than 750 head typically store their wastes in pits under the house or flush the wastes to outside lagoons. Slatted floors or flush alleys are used to separate manure and

wastes from the animal. It is common to allow manure to collect in a pit and wash the pit one to six times per day with water to move the waste to a lagoon. The waste is stored in the lagoon until it is applied to land or transported off site. Storing the waste in an anaerobic lagoon provides some treatment during storage, conditioning the wastewater for later land application, and reducing odors (NCSU, 1998). EPA developed model farms for farrow-to-finish and grow/finish operations in the Mid-Atlantic and Midwest regions that are assumed to use pits or flush alleys and anaerobic lagoon storage.

In the Midwest, a deep pit storage system is more common. Deep pit systems start with several inches of water in the pit, and the manure is collected and stored under the house until it is pumped out for field application, typically twice a year. This system uses less water, creating a manure slurry that has higher nutrient concentrations than the flush system described earlier. A survey of swine operations in 2000 shows that both lagoons and deep pits are commonly used for waste storage in the Midwest region (USDA APHIS, 2002). For purposes of developing the cost models, EPA estimated, from the USDA APHIS (2002) data, the percentage of farrow-to-finish and grow/finish operations in the Mid-Atlantic and Midwest regions that use pit storage. EPA developed model farms for farrow-to-finish and grow/finish operations in the Mid-Atlantic and Midwest regions that are assumed to use pit storage pumped twice per year.

Although not present in the statistics that were available to the EPA at the time of this analysis, EPA recognizes the increasing number of large swine operations in the Central region. Many of these larger operations in the Central region use evaporative lagoons instead of traditional anaerobic lagoons found in the Mid-Atlantic and Midwest. Thus, EPA developed model farms for large facilities in the Central region and assumed evaporative lagoons are used for waste storage.

EPA's swine model farms under Option 5 assume that all lagoons are covered with a synthetic cover. Facilities that use deep pit storage are not assumed to need any additional practices to comply with Option 5.

Figure 11-1 presents these waste management systems used for the model swine farms in this cost model.

11.2.1.3 Size Group

The general trend in the U.S. swine industry is toward a smaller number of large operations that have a larger number of animals on site. The number of smaller facilities, which tend to house the animals outdoors, has significantly decreased over the past 10 years (North Carolina State University, 1998). The trend in the larger operations is toward extended use of confinement operations.

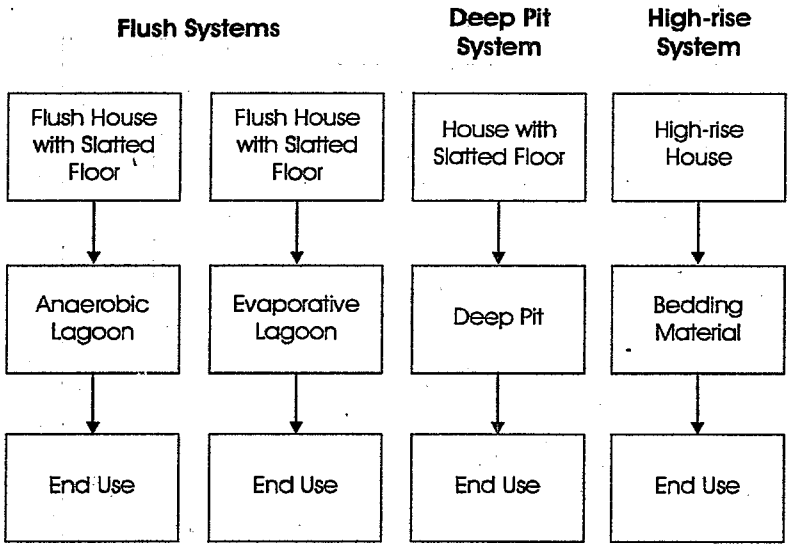

Figure 11-1. Swine Model Farm Waste Management System

For this regulation, five size groups were modeled for each type of model farm. The size groups are provided in Table 11-2.

Table 11-2. Number of Swine per Facility based on Modeled Region, Land Availability Category, Operation Size for Phosphorus-Based Application of Manure

Region	Land Availability Category	Medium 1	Medium 2	Medium 3	Large 1	Large 2
Central	No excess	NA	NA	NA	2,500	6,037
Central	Excess, with acres	NA	NA	NA	3,304	9,890
Central	Excess, no acres	NA	NA	NA	4,999	34,944
Mid-Atlantic	No excess	883	1,346	1,888	2,500	6,390
Mid-Atlantic	Excess, with acres	964	1,496	2,077	4,134	12,375
Mid-Atlantic	Excess, no acres	976	1,477	2,051	4,424	14,929
Midwest	No excess	863	1,311	1,885	2,500	5,094
Midwest	Excess, with acres	926	1,415	1,965	2,878	9,172
Midwest	Excess, no acres	976	1,522	2,114	4,463	16,636

NA - Not applicable.

11.2.1.4 Region

Data from site visits and North Carolina State University's draft *Swine and Poultry Industry Characterization* indicate that the predominant type of waste management system at swine operations varies from region to region (NCSU, 1998). EPA decided to develop model farms for the Mid-Atlantic and Midwest regions because over 93 percent of the facilities with more than750 head were located in these two regions in 1997 (USDA NASS, 1999). EPA added additional model farms in the Central region based on comments received on the proposed rule that many large facilities had recently located in states in the Central region.

As previously mentioned, flush-to-lagoon waste storage systems are more common in the Mid-Atlantic region while deep-pit storage systems are common in the Midwest. Given the regional variances in waste management systems, other variations in farming practices (e.g., crop rotations), and differences in climate, swine operations with both type of waste storage systems were modeled in both regions. Large swine operations that use evaporative lagoons for waste storage were modeled in the Central region. Operations located in other regions were split among the modeled regions to fully account for operations in a given size class. Allocating operations from one region to another was necessary since the census data could not be obtained for all desired regions and size groups (USDA NASS, 1999).

11.2.2 Poultry Operations

EPA developed four model farms to represent poultry operations in the United States. The model farms are broiler, turkey, dry layer, and wet layer operations. EPA developed the parameters describing the model poultry farms using information from NASS, site visits to poultry farms across the country, and the USDA NRCS. A description of the various components of each model farm is presented in the following discussion, and the sources of the information used to develop each piece of the model farm are noted.

11.2.2.1 Housing

Broilers and turkeys are typically housed in long barns (approximately 40 feet wide and 400 to 500 feet long; NCSU, 1998) and are grown on the floor of the house. The floor of the barn is covered with a layer of bedding, such as wood shavings, and the broilers or turkeys deposit manure directly onto the bedding. Approximately 4 inches of bedding are initially added to the houses and top dressed with about 1 inch of new bedding between flocks.

Layers are typically confined in cages in high-rise housing or shallow pit flush housing. In a high-rise house, the layer cages are suspended over a bottom story, where the manure is deposited and stored. EPA used this configuration to model housing for dry layer model farms. In shallow pit flush housing, a single layer of cages is suspended over a shallow pit. Manure drops directly into the pit, where it is flushed out periodically using recycled lagoon water. EPA used this configuration to model housing for wet layer model farms.

These poultry housing systems are considered typical systems in the poultry industry (NCSU, 1998). Therefore, the cost model uses these farm housing systems in the model farms.

11.2.2.2 Waste Management Systems

Manure from broiler and turkey operations accumulate on the floor where it is mixed with bedding, forming litter. Litter close to drinking water forms a cake that is removed between flocks. The rest of the litter in a house is removed periodically (6 months to 2 years) from the barns, and then transported off site or applied to land. Typically, broiler and turkey operations are completely dry waste management systems (NCSU, 1998). Therefore, EPA used this waste management configuration in modeling both broiler and turkey model farms.

Layer operations may operate as a wet or a dry system. Approximately 12 percent of layer houses use a liquid flush system, in which waste is removed from the house and stored in a lagoon (USDA APHIS, 2000). Operations that use this type of waste management system are referred to as wet layers. The remaining layer operations typically operate as dry systems, with manure stored in the house for up to a year. A scraper is used to remove waste from the collection pit or cage area (NCSU, 1998). Operations that use this type of waste management system are referred to as dry layers. The lagoon wastewater and dry manure are stored until they are applied to land or transported off site. Figure 11-2 presents the waste management systems for poultry.

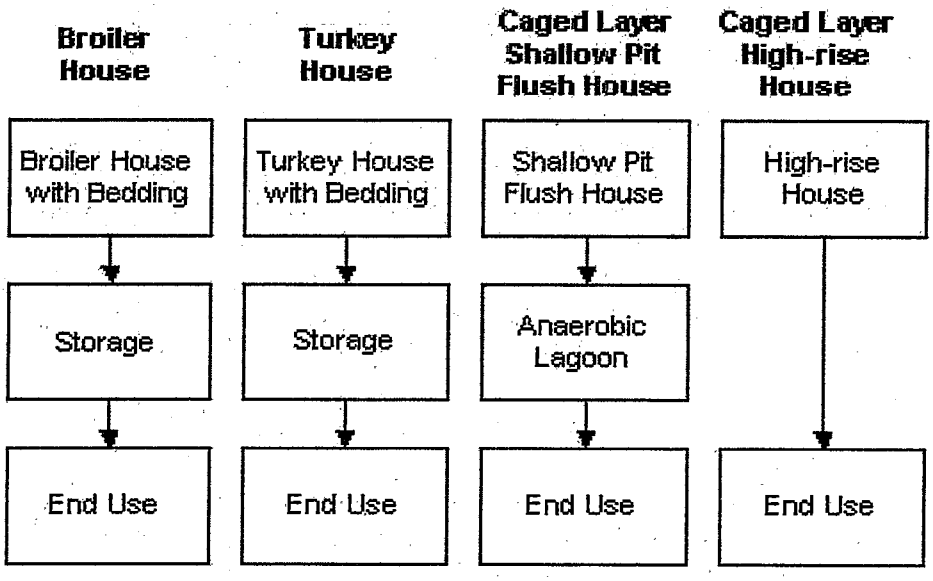

Figure 11-2. Poultry Model Farm Waste Management System

11.2.2.3 Size Group

For the final regulation, EPA modeled four size groups for broiler and dry layer operations, two size groups for wet layer operations, and four size groups for turkey operations. The size groups are presented in Tables 11-3, 11-4, and 11-5.

Table 11-3. Number of Broilers per Facility Based on Modeled Region, Land Availability Category, Operation Size for Phosphorus-Based Application of Manure.

Region	Land Availability Category	Medium 1	Medium 2	Medium 3	Large 1	Large 2
Mid-Atlantic	No excess	39,642	55,618	85,355	125,000	219,247
Mid-Atlantic	Excess, with acres	39,851	58,110	89,171	132,696	326,246
Mid-Atlantic	Excess, no acres	39,609	56,176	86,342	149,292	385,154
South	No excess	38,845	53,886	82,820	125,000	219,247
South	Excess, with acres	39,427	57,644	88,596	135,091	312,224
South	Excess, no acres	39,419	57,557	88,516	132,017	325,838

Table 11-4. Average Head Count for Layer Operations.

Size Class	Size Class Interval (Number of Head)		Average Head Count per Operation
	Lower	Upper	
Dry Layer Operations			
Medium 1	25,000	49,999	36,068
Medium 2	50,000	74,999	61,734
Medium 3	75,000	81,999	78,546
Large 1	82,000	599,999	291,153
Large 2	≥600,000		856,368
Wet Layer Operations			
Medium 1	9,000	29,999	19,500
Large 1	≥30,000		146,426

Table 11-5. Turkey Facility Demographics from the 1997 Census of Agriculture Database.

Size Class	Size Class Interval (Number of Head)		Average Head Count per Operation
	Lower	Upper	
Medium 1	16,500	27,499	22,246
Medium 2	27,500	41,249	34,640
Medium 3	41,250	54,999	47,534
Large 1	≥55,000		127,396

Source: USDA NRCS, 2002.

11.2.2.4 Region

Data from site visits and North Carolina State University's draft *Swine and Poultry Industry Characterization* indicate that the predominant type of waste management system at poultry operations varies from region to region (NCSU, 1998). Most of the broiler operations in the United States are located in the South and Mid-Atlantic regions, while most of the egg-laying operations are located in the Midwest and South regions. Therefore, the model broiler farm reflects the South and Mid-Atlantic regions, and the model layer farm reflects the Midwest and South regions. State-level data from the 1997 Census of Agriculture indicate that states in the Midwest and Mid-Atlantic regions of the United States account for over 70 percent of all turkeys produced. For this reason, model turkey farms are located in the Mid-Atlantic and Midwest regions (USDA NASS, 1999).

11.2.4 Dairy Operations

EPA developed two model farms to represent medium- and large-sized dairies in the United States: a flush dairy and a hose/scrape dairy. EPA developed the parameters describing the dairy model farms from information from USDA, 1997 Agricultural Census data, data collected during site visits to dairy farms across the country, meetings with USDA extension agents, and meetings with the National Milk Producers Federation and Western United Dairymen. Description of the various components that make up the model farms are presented below, with the sources of the information used to develop each piece of the model farm.

11.2.4.1 Housing

To determine the type of housing used at the model farm, the type of animals on the farm were considered. In addition to the mature dairy herd (including lactating, dry, and close-up cows), there are often other animals on site at the dairy, including calves and heifers. The number of immature animals (i.e., calves and heifers) at the dairy is proportional to the number of mature cows in the herd, but further depends on the farm's management. For example, the dairy may house virtually no immature animals on site and obtain their replacement heifers from off-site operations, or the dairy could have close to a 1:1 ratio of immature animals to mature animals. Site visits suggest the trend that the largest dairy managers want to focus on milk production only, and prefer not to keep heifers on site.

Typically, according to Census of Agriculture data, for dairies greater than 200 milking cows, the number of calves and heifers on site equals approximately 60 percent of the mature dairy (milking) cows (USDA, 1997). EPA assumes that there are an equal number of calves and heifers on site (30 percent each) at the dairy model farms. Based on this information, the number of calves on site is estimated to be 30 percent of the number of mature cows on site, as are the number of heifers on site. The percentage of bulls is typically small (USDA, 1997), as most dairies do not keep them on site. For this reason, EPA assumed that their impact on the model

farm waste management system is insignificant, and did not consider bulls in the dairy model farm.

The most common types of housing for mature cows include freestall barns, tie stalls/stanchions, pasture, drylots, and combinations of these (Stull, 1998). Based on site visits, most medium- to large-sized dairies (>200 mature dairy cattle) house their mature dairy cows in freestall barns; therefore, it is assumed that mature dairy cows are housed in freestall barns for the dairy model.

The most common types of calf and heifer housing are drylots, multiple animal pens, and pasture (USDA, 1996c). Based on site visits, most medium- to large-sized facilities use drylots to house their heifers and calves; therefore, it is assumed that calves are housed in hutches on drylots and heifers are housed in groups on drylots at dairies described in the model. EPA calculated the size of the drylot for the model farm using animal space requirements suggested by Midwest Plan Service (MWPS, 1995).

11.2.4.2 Waste Management Systems

Waste is generated in two main areas at dairies: the milking parlor and the housing areas. Waste from the milking parlor includes manure and wash water from cleaning the equipment and the parlor after each milking. Waste from the confinement barns includes bedding and manure for all barns, and wash water if the barns are flushed for cleaning. Waste generated from the drylots includes manure and runoff from any precipitation that falls on the drylot.

Based on site visits, most dairies transport their wastewater from the parlor and flush barns to a lagoon for storage and treatment. Some dairies use a solids separator (either gravity or mechanical) to remove larger solids prior to the wastewater entering the lagoon. Solids are removed from the separator frequently to prevent buildup in the separator, and they are stockpiled on site. Solid waste scraped from a barn is typically stacked on the feedlot for storage for later use or transport. Solid waste on the drylot is often mounded on the drylot for the cows and is later moved for transport or land application. Wastewater in the lagoon is held in storage for later use, typically as fertilizer on cropland either on or off site. Figure 11-4 presents the waste management systems used for model dairy farm.

The amount of waste generated at a dairy depends on how the operation cleans the barn and parlor on a daily basis. Some dairies clean the parlor and barns by flushing the waste (a flush dairy); others use less water, hosing down the parlor and scraping the manure from the barns (a hose/scrape dairy). EPA estimated the percentage of total dairies that operate as a flush dairy or a hose/scrape dairy using USDA data (USDA APHIS, 1996). Both flush and hose/scrape dairy systems are modeled separately as two model facilities.

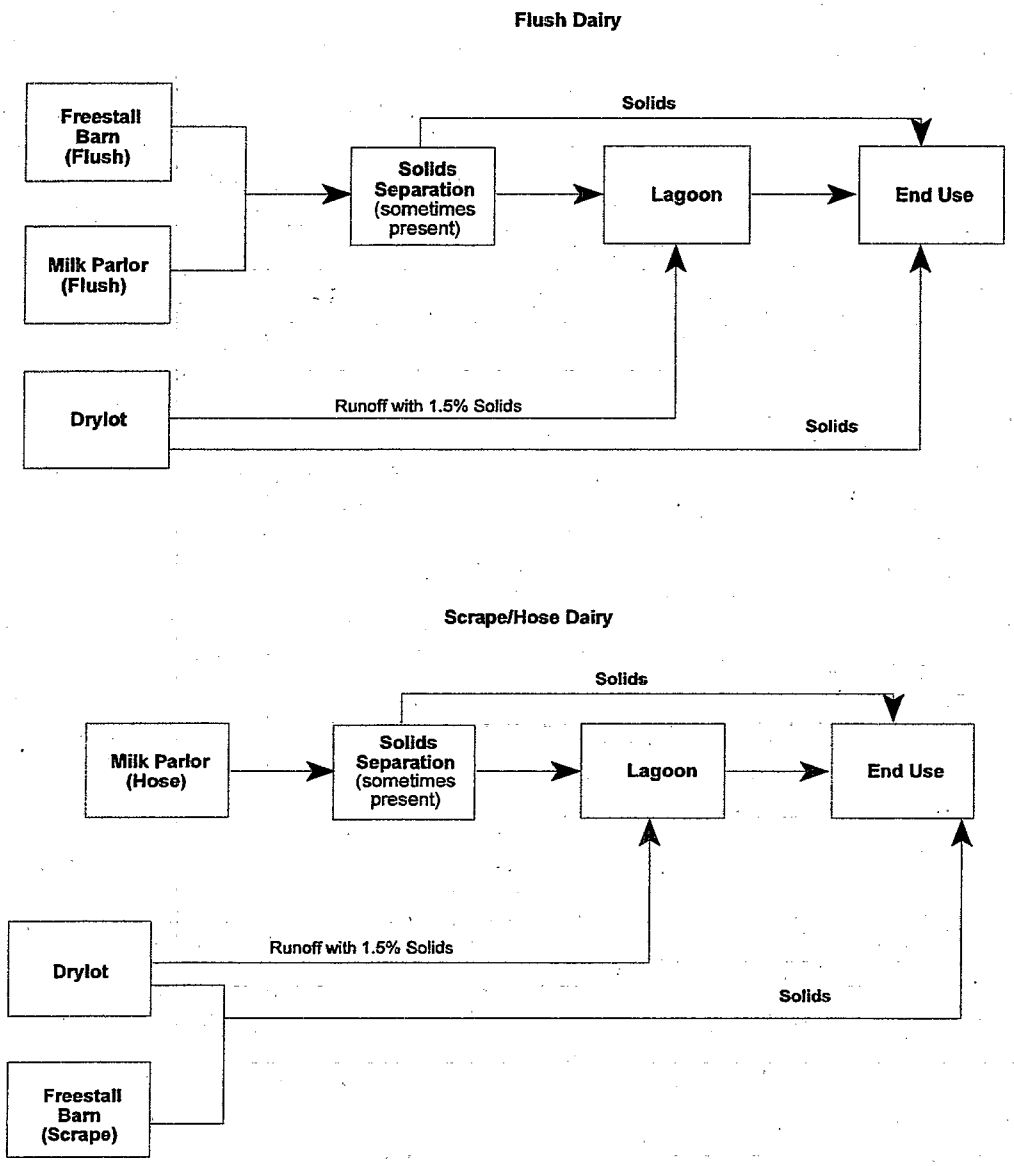

Figure 11-4 Dairy Model Farm Waste Management Systems

11.2.4.3 Size Group

Data collected during site visits indicate that dairies operate differently depending on their size. For example, larger dairies tend to already have lagoon storage, while moderate-sized dairies may have only a small amount of storage. Also, because feedlots with more than 700 animals are already regulated under the current rule, it was assumed for the cost model that these facilities are already in compliance with many of the components of the final rule. Therefore, four different size groups were used to model dairy operations with more than 200 animals. The size groups are presented in Table 11-6.

Table 11-6. Size Classes for Model Dairy Farms.

Size Class	Size Range	Average Head
Medium 1	200-349	250
Medium 2	350-524	425
Medium 3	525-699	600
Large 1	≥ 700	1,430

11.2.4.4 Region

Data from site visits indicate that dairies in varying regions of the country have different characteristics. These differences are primarily related to climate. For example, a dairy in the Pacific region receives a greater amount of rainfall annually than a dairy in the Central region; therefore, the Pacific dairy produces a higher amount of runoff to be contained and managed. Because operating characteristics may change between regions, dairies are modeled in five distinct regions of the United States: Central, Mid-Atlantic, Midwest, Pacific, and South.

11.2.5 Beef Feedlots and Heifer Operations

EPA developed one type of model farm to represent medium- and large-sized beef feedlots and heifer operations in the United States. The parameters describing the beef and heifer model farm were developed from information from USDA, data collected during site visits to beef feedlots across the country, meetings with USDA extension agents, the National Cattlemen's Beef Association, and the National Milk Producers Federation, and discussions with the Professional Heifer Growers Association. Descriptions of the various components that make up the model

farm are presented below, with the sources of the information used to develop that piece of the model farm referenced.

11.2.5.1 Housing

The vast majority of beef feedlots and heifer operations in the United States house their cattle on drylots (USDA, 1995a). Some smaller operations use confinement barns at beef feedlots. However, since the majority of operations, including most new ones, use open lots, EPA used drylots as the housing for the beef and heifer model farm. Some operations raise their heifers on pasture, but because this regulation addresses only confined operations, the heifer model farm accounts only for animals housed on drylots. The size of the drylot is calculated using animal space requirements suggested by Midwest Plan Service (MWPS, 1995).

11.2.5.2 Waste Management System

Based on site visits, the drylot is the main area where waste is produced at beef feedlots and heifer operations. Waste from the drylot includes solid manure, which has dried on the drylot, and runoff, which is produced from precipitation that falls on the drylot and open feed areas.

Most beef operations in the United States divert runoff from the drylot to a storage pond (USDA, 1995a). Heifer operations typically operate like beef feedlots (Cady, 2000). As such, EPA assumed that runoff from the drylot is channeled to a storage pond at both beef and heifer operations. Some operations use a solids separator (typically an earthen basin) to remove solids from the waste stream prior to the runoff entering the pond. Solid waste from the drylot is often mounded on the drylot to provide topography for the cattle and is later moved from the drylot for transportation off site or land application on site (USDA, 1995a).

The beef and heifer model farm was developed following these typical characteristics of beef feedlots and heifer operations. Figure 11-5 presents the waste management system used as part of the beef and heifer model farm.

11.2.5.3 Size Group

Data collected during site visits indicate that beef feedlots and heifer operations operate differently depending on their size. For example, larger feedlots frequently have solid separators prior to a holding pond, while moderate sized facilities are less frequently equipped with solids separators. Moreover, feedlots with more than 1,000 beef cattle are already regulated under the current rule. EPA, therefore, assumes that these facilities are already in compliance with many components of the final rule. To account for these differences, five different size groups were used to model beef feedlots with more than 300 animal units and four different size groups were used to model heifer operations with more than 300 animals. The size groups are presented in Tables 11-7 and 11-8.

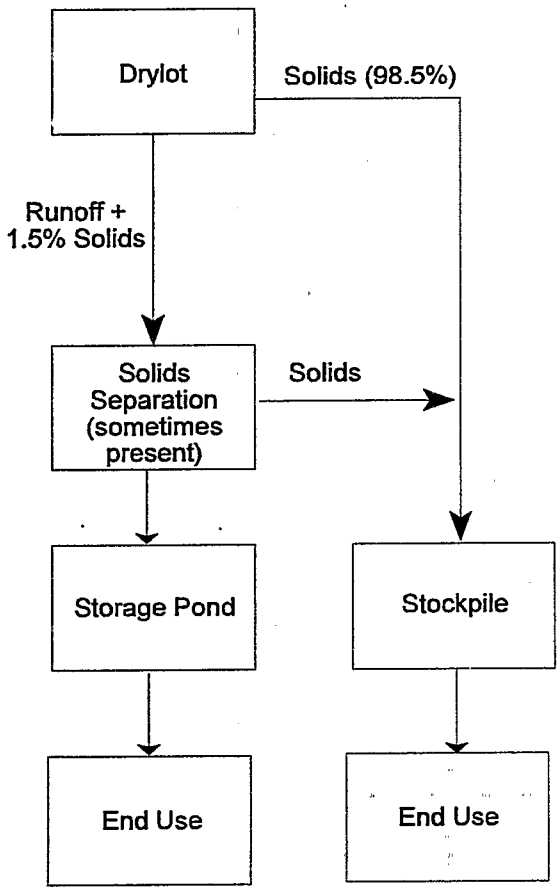

Figure 11-5. Beef and Heifer Model Farm Waste Management System

Table 11-7. Size Classes for Model Beef Farms

Size Class	Size Range	Average Head
Medium 1	300-499	370
Medium 2	500-749	552
Medium 3	750-999	766
Large 1	1,000-7,999	1,839
Large 2	≥ 8,000	25,897

Table 11-8. Size Classes for Model Heifer Farms

Size Class	Size Range	Average Head
Medium 1	300-499	400
Medium 2	500-749	625
Medium 3	750-999	875
Large 1	≥ 1,000	1,500

11.2.5.4 Region

Data from site visits indicate that beef feedlots in varying regions of the country have different characteristics. These differences are primarily related to climate. For example, a beef feedlot in the Midwest region receives a greater amount of rainfall annually than a beef feedlot in the Central region; therefore, the Midwest feedlot produces a greater volume of runoff to be contained and managed. Because operating characteristics may change between regions to accommodate these climatological differences, beef feedlots are modeled in five diverse regions of the United States: Central, Mid-Atlantic, Midwest, Pacific, and South, as described in Section 1.1. Data from USDA indicate that heifer operations are located in similar areas as beef feedlots and would have similar characteristics as the beef feedlots.

11.2.6 Veal Operations

EPA developed one model farm to represent medium- and large-sized veal operations in the United States. The parameters describing the veal model farm are developed from information collected during site visits to veal operations in Indiana and discussions with the American Veal Association. Descriptions of the various components that make up the model farm are presented below, with the sources of the information used to develop that piece of the model farm referenced.

11.2.6.1 Housing

Veal calves are generally grouped by age in environmentally controlled buildings. The majority of veal operations in the United States utilize individual stalls or pens with slotted floors, which allow for efficient removal of waste (Wilson, 1995). Because this type of housing is the predominant type of housing used in the veal-producing industry, individual stalls in an environmentally controlled building is designated as the housing for the veal model farm.

11.2.6.2 Waste Management Systems

Based on site visits, the only significant source of waste at veal operations is from the veal confinement areas. Veal feces are very fluid; therefore, manure is typically handled in a liquid

waste management system. Manure and waste that fall through the slotted floor are flushed regularly out of the barn. Flushing typically occurs twice daily. Most veal operations have a lagoon to receive and treat their wastewater from flushing, although some operations have a holding pit system in which the manure drops directly into the pit. The pit provides storage until the material can be land applied or transported off site. Wastewater in the lagoon is held in storage for later use as fertilizer off site.

EPA developed the veal model farm used in the cost model from these general characteristics. The animals are totally confined; therefore, the only source of wastewater is from flushing the manure and waste from the barns. Direct precipitation is also collected on the lagoon surface, if the lagoon is uncovered. Figure 11-6 presents a diagram of the veal model farm waste management system.

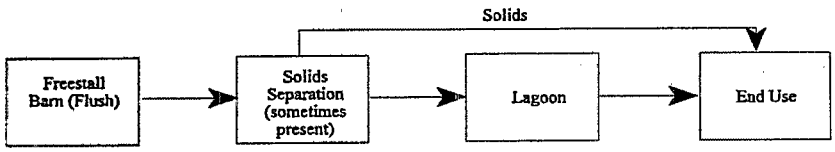

Figure 11-6. Veal Model Farm Waste Management System

11.2.6.3 Size Group

The veal industry standard operating procedures do not vary significantly based on the size of the operation, according to data collected during site visits and discussions with the American Veal Association (Crouch, 1999). The size groups are presented in Table 11-9.

Table 11-9. Size Classes for Model Veal Farm

Size Class	Size Range	Average Head
Medium 1	300-499	400
Medium 2	500-749	540
Medium 3	≥750	1080

11.2.6.4 Region

The American Veal Association indicates that veal producers are located predominantly in the Midwest and Central regions (Crouch, 1999); therefore, only these two regions are modeled as part of the veal model farm.

11.3 Design and Cost of Waste and Nutrient Management Technologies

Two separate models were created to estimate compliance costs associated with regulatory options for CAFOs: one model to generate beef, dairy, heifer, and veal costs, and another model to generate swine, broiler, turkey, and layer costs. The cost models calculate model farm costs in three major steps:

1) Costs are calculated for each technology or practice that makes up each regulatory option for each model farm, based on model farm characteristics, including number of head, waste characteristics, and facility characteristics.

2) The costs for each technology or practice are then weighted for the entire model farm population, using frequency factors to indicate the portion of the model farm population that will incur that cost. These frequency factors define the performance of a model farm as having low, medium, or high requirements to comply with the regulatory option.

3) The weighted costs for each model farm population are summed, resulting in an average model farm cost for each model population in each performance category.

The resulting model farm cost represents the average cost that all of the operations within that model population are expected to incur within a performance category. The compliance costs that a single model farm incurs may be more or less than this average cost; however, the performance categories are expected to encompass the approximate range of compliance costs.

The cost estimates generated contain the following types of costs:

- **Capital costs** - Costs for facility upgrades (e.g., construction projects);
- **Fixed costs** - One-time costs for items that cannot be amortized (e.g., training);
- **Annual operating and maintenance (O&M) costs** - Annually recurring costs, which may be positive or negative. A positive O&M cost indicates an annual cost to operate, and a negative O&M cost indicates a benefit to operate, due to cost offsets;
- **Three-year recurring O&M costs** - O&M costs that occur only once every three years;

- **Five-year recurring O&M costs** - Application fees and reporting costs that occur only once every five years; and

- **Annual fertilizer costs** - Costs for additional commercial nitrogen fertilizer needed to supplement the nutrients available from manure application.

These costs provide the basis for evaluating the total annualized costs, cost effectiveness, and economic impact of each regulatory option.

The following sections discuss the six primary components of the costing methodology:

- Manure and nutrient production at each operation;
- Cropland acreage;
- Nutrient management planning;
- Facility upgrades;
- Land application; and
- Off-site transportation of manure.

Further detail on the cost methodology and data inputs to the cost model may be found in the *Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (2002).*

11.3.1 Manure and Nutrient Production

The manure produced at each model farm provides the basis for the design of the technology components and model farm parameters, including determining farm acreage, nutrient management practices, equipment sizes, and the agronomic rate of applying waste to land. The quantity and characteristics of the waste for each model farm are calculated from values provided in the *Agricultural Waste Management Field Handbook* and the *Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States* (USDA NRCS, 1996; USDA NRCS, 2000).

The quantity of manure generated from a feedlot operation depends on the animal type and the number of mature and immature animals that are present. Nutrient production at each model farm is calculated using waste characteristics data for excreted manure for each animal type. The mass production of each of these nutrients is calculated using the average weight of the animal while housed at the model farm, the waste concentration data, and the number of animals on site.

11.3.2 Available Acreage

Data on the amount of cropland and pastureland available to facilities for land application of manure are limited. Therefore, EPA classified the model farms into three categories that define how much land they have available and how the operation ultimately manages its waste:

- **Category 1:** Facilities with sufficient land to apply all of their generated manure at appropriate agronomic rates. No manure is transported off site.
- **Category 2:** Facilities without sufficient land to apply all of their generated manure at appropriate agronomic rates. The excess manure after agronomic application is transported off site.
- **Category 3:** Facilities without any available land for manure application. All of the manure is transported off site regardless of the regulatory options considered by EPA.

EPA defines Category 1 operations as having a sufficient amount of land, and at a minimum, the available land equals the amount of land required to agronomically apply all of the manure generated at the operation. Category 2 acreages are based on a 2000 USDA analysis that calculated the amount of nutrients present in manure that exceeded the amount that could be applied agronomically (Kellogg, 2000). EPA assumes Category 3 operations have no available land.

11.3.2.1 Agronomic Application Rates

Under all regulatory options considered, all operations are required to implement nitrogen-based agronomic application rates when applying animal waste or wastewater. Under Options 2 through 7, however, operations that are located in areas with certain site conditions (e.g., phosphorus-saturated soils) are required to follow more stringent phosphorus-based agronomic application rates. Costs for nitrogen-based application are different than costs for phosphorus-based application. These costs are weighted for a model farm using a "nutrient-based application factor" to account for these different costs, based on the percent of facilities in that region that would apply on a phosphorus-basis verses a nitrogen-basis. The nutrient-based application factors vary according to the type of facility (beef, dairy, swine, or poultry).

Agronomic application rates are calculated using crop yields, crop uptakes, and crop utilization factors. These crops vary by region and animal type. EPA selected representative crops for each model farm by contacting USDA state and county cooperative extension services and incorporating data from USDA's *Agricultural Waste Management Field Handbook* (USDA NRCS, 1996). EPA does not expect crops to vary significantly based on the size of the animal operation. Because veal operations are located predominantly in the Midwest, EPA developed only one set of crop assumptions for veal that reflect the Midwest region.

$$\text{Crop N Requirements (lb/acre)} = \text{Crop Yield (tons/acre)} \times \text{Crop Uptake (lb/ton)}_{\text{nitrogen}}$$

$$\text{Crop P Requirements (lb/acre)} = \text{Crop Yield (tons/acre)} \times \text{Crop Uptake (lb/ton)}_{\text{phosphorus}}$$

The average annual nitrogen and phosphorus crop removal and application rates were calculated by dividing the total crop requirements over the time to complete a full crop rotation. The cost model estimates that 70 percent of the nitrogen and 100 percent of the phosphorus in cattle manure that is applied to land is available for crop uptake and utilization over time (Lander, 1998); therefore, the agronomic application rate is calculated as the total crop nutrient requirements divided by the appropriate utilization factor.

$$\text{Manure Application Rate}_{\text{Nitrogen}}\ (\text{lb/acre}) = \text{Total Crop Nitrogen Requirements (lb/acre)} \div 70\%$$

$$\text{Manure Application Rate}_{\text{Phosphorus}}\ (\text{lb/acre}) = \text{Total Crop Phosphorus Requirements (lb/acre)} \div 100\%$$

When more than one crop is present, the agronomic rate is presented as the average of the individual agronomic rates for each crop. These agronomic rates for nitrogen- and phosphorus-based application scenarios are used as inputs to the cost model.

11.3.2.2 Category 1 Acreage

Category 1 acreages are calculated using the agronomic application rates, number of animals, manure generation estimates, nutrient content of the manure, and manure recoverability factors:

$$\text{Category 1 Acreage} = \frac{\#\text{Animals} \times \text{Manure Generation (tons/head)} \times \text{Nutrient Content (lbs/ton manure)} \times \text{Recoverability Factor}}{\text{Agronomic application rate (lb/acre)}}$$

EPA defines recoverability factors as the percentage of manure, based on solids content, that it would be practical to recover. Recoverability factors are developed for each region, using USDA state-specific recoverability factors, and are based on the assumption that the decrease in nutrient value per ton of manure mirrors the reduction in solids content of the recoverable manure (Lander, 1998).

11.3.2.3 Category 2 Acreage

Category 2 acreages are calculated using Category 1 acreages, the estimate of excess manure from USDA's analysis, and acres required to apply excess manure to land (Kellogg, 2000):

Average Excess Nutrients (lbs/yr)	=	Excess Nutrients (lbs/yr)÷Number of Category 2 Facilities
Excess Acreage (acres)	=	Average Excess Nutrients (lbs/yr)÷Agronomic Application Rate (lb/acre)
Category 2 Acreage (acres)	=	Category 1 Acreage - Excess Acreage

11.3.3 Nutrient Management Planning

To minimize the release of nutrients to surface and ground waters, confined animal feeding operations must prevent excess application of manure nutrients on cropland through the process of nutrient management planning. Confined animal feeding operations apply manure nutrients to the land in the form of solid, liquid, or slurry. Manure is also stored prior to application in

stockpiles, tanks, pits, storage ponds, or lagoons. Confined animal feeding operations prevent excess application by developing and abiding by appropriate manure application rates that are designed to add only the nutrients required by the planned crops at the expected yields. Nutrient management planning may also minimize releases of nutrients by specifying the timing andlocation of manure application.

Six nutrient management practices are evaluated as part of the costing methodology:

1. **Nutrient management plan** - a practice in which a documented plan is developed for each facility to ensure agronomic application of nutrients on cropland and management of waste on site. The plan includes costs for development of the plan, manure sampling and analysis (collecting samples from solid and liquid waste before each land application period), soil sampling and analysis (once every 3 years), hydrogeologic assessment for facilities located in ground water protection areas, periodic inspections of on-site facility upgrades, identification and protection of crop setback areas to protect waterfront areas, calibration of the manure spreader before each application period, and ongoing recordkeeping and recording. The plan is updated at least once every 5 years.

2. **Surface water monitoring** - a practice in which surface water samples are periodically collected and analyzed for indications of contaminated runoff into adjacent waters. Costs account for twelve sampling events per year, including four grab samples and one quality assurance sample per event, measuring for nitrate-nitrite, total Kjeldahl nitrogen, total phosphorus, and total suspended solids.

3. **Ground water assessment** - a practice for facilities to conduct a hydrogeologic assessment to determine if a direct hydrogeologic link exists between ground water and surface water.

4. **Ground water monitoring** - a practice for operations where ground water has a direct hydrogeologic link to surface water. Costs include installation of four 50-foot ground water wells and the collection of a sample from each well twice annually for indications of ground water contamination from the feedlot operation.

5. **Feeding strategies** - a practice in which the animal feed is monitored and adjusted to reduce the quantity of nutrients that are excreted from the animal. Costs include feeding strategies to reduce nitrogen and phosphorus in excrement from poultry and swine.

6. **Timing restrictions** - a practice in which manure is only land applied during times that the land and crops are most amenable to nutrient utilization. Costs for this practice are calculated for all animal sectors.

Further detail on the design of each practice may be found in the *Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (2002).*

11.3.4 Facility Upgrades

Section 8.0 of this report describes treatment technologies and facility upgrades that are presented as part of this cost methodology. These facility upgrades include:

- Anaerobic digestion with energy recovery;
- Anaerobic lagoons;
- Field runoff controls;
- Lagoon covers;
- Lined manure storage;
- Liners for lagoons and ponds;
- Litter storage sheds;
- Manure composting equipment;
- Recycle flush water;
- Retrofit options;
- Screen solid-liquid separation;
- Sludge removal;
- Solids separation (settling basin);
- Storage ponds; and
- Storm water diversions (berms).

An overview of the costs and applicability of each of these upgrades to each of the animal sectors is presented below:

- **Anaerobic digestion with energy recovery**: Option 6 requires the use of anaerobic digestion for Large dairy and swine CAFOs, prior to discharge to a storage lagoon. The digester is designed to receive waste from all flushing, hose, and scrape operations, and combines this waste into a reactor to produce methane for energy use at the operation. Covered lagoon digesters are costed for large flush dairies and swine operations, and complete mix digesters are costed for large hose dairies. Runoff from the dairy feedlot is collected separately into a storage pond or lagoon.

- **Anaerobic lagoons:** Costs for anaerobic lagoons are included for facilities that collect mixtures of water and manure, such as dairies, veal operations, swine, and wet layer operations. Lagoons receive wastewater from flush barns, flush and hose milking parlors (for dairies), and runoff from drylots. They are designed to include process wastewater, plus the capacity for the 25-year, 24-hour storm event and average rainfall for the storage period.
- **Field runoff controls:** Under all options, costs are included to implement and maintain setbacks along waterbodies contained within land-applied cropland for all animal operations. The size and therefore the cost of the setback were calculated based on national estimates of land area and stream miles and the average size and cost of filter strips (USEPA, 2000; USEPA, 1993).
- **Lagoon covers:** Under Option 5, the regulation requires that facilities have zero potential for discharge from the feedlot. This requirement may be met by covering liquid storage basins and preventing direct precipitation from entering and adding to the storage volume. Swine, wet layers, and veal operations under Option 5 have costs for lagoon covers.
- **Lined manure storage:** The cost model includes costs for the installation and maintenance of concrete pads as part of the waste management system for beef, heifer, and dairy operations under Option 3. The pads are designed to store waste from drylots, separated solids, and scraped manure.
- **Liners for lagoons and ponds:** Under the ground water options, operations that store animal waste (e.g., runoff and/or process water) in a lagoon or pond are required to have a liner in place if they are located in an area where ground water has a hydrogeologic connection to surface water. The liner is composed of two parts: a synthetic portion and a clay portion. The liner is designed to cover the floor of the pond or lagoon, including sloped sidewalls. Costs are calculated for all animal sectors to install liners in their lagoons and ponds.
- **Litter storage sheds:** Litter storage is included in the costing for all dry poultry operations. Requirements for poultry litter storage structures are similar to those for mortality composting facilities in that they require a roof, foundation, and floor, and suitable building materials for side walls.
- **Manure composting equipment:** EPA designed windrow composting systems to treat and manage manure waste from drylots, separated solids, and scraped manure under Option 5A for beef, dairy, and heifer operations. Mortality composting systems are designed for swine and poultry operations to manage mortality waste under all options.
- **Recycle flush water:** In liquid-based systems, fresh water can be used for flushing or water from a secondary lagoon can be recycled as flush water. This technology is applied to Category 2, lagoon-based swine operations for all Options except Option 5.

- **Retrofit options:** In addition to the use of lagoon covers to comply with the requirements of Option 5, EPA investigated retrofitting swine and wet layer systems to replace lagoons as the waste management practice. Retrofitting to a "scraper system" was assessed for swine and wet layers facilities. In addition, retrofitting to a high-rise and hoop house for swine operations was assessed.
- **Screen solid-liquid separation:** The cost model includes costs for swine operations to install and operate screen separation. Screens are used to separate the solids from the liquids, allowing the solids to be handled more economically.
- **Sludge removal:** Sludge must be removed from lagoons periodically to keep storage capacity available. The cost model accounts for sludge cleanout annually for beef feedlots, dairies, and heifer operations and once every five years for liquid-based swine operations for all considered options.
- **Solids separation (settling basin):** The cost model includes solids separation as part of facility upgrades for beef and dairy operations, to facilitate the management of manure waste by separating the solid portion from the liquid portion. EPA costed earthen separators for beef feedlots, where runoff is the largest expected flow through the separator, and concrete-lined separators for dairy operations, where large amounts of flush water are expected through the separator. Concrete is used to prevent erosion of the side slopes of the separator.
- **Storage ponds:** The cost model includes costs for storage ponds for facilities that collect runoff from the feedlot, such as beef facilities in which the cattle are confined on dry lots, and as a holding pond for effluent from an anaerobic digester in Option 6. The storage pond receives waste from drylot runoff only and is designed to include capacity for the 25-year, 24-hour storm event and average rainfall for the storage period. Under Option 1A, the cost model also includes capacity for the 10-year, 10-day storm event.
- **Storm water diversions (berms):** Under all regulatory options, EPA requires that all animal operations contain any runoff collecting in potentially contaminated areas. EPA assumes that Large CAFOs already have stormwater diversions in place, because it is required by the current regulation.

EPA calculated costs for facility upgrades using design specifications in combination with cost estimates for each portion of the upgrade (e.g., excavation, compaction, gravel fill, etc.). Design specifications were obtained from various sources, including the Natural Resources Conservation Service (Conservation Practice Standards), the Midwest Plan Service, the *Agricultural Waste Management Field Handbook*, and other engineering design sources. EPA combined these design specifications with model-farm information, such as the animal type, manure generation, housing methods, and the type of farm, to calculate the required size of the component as well as the materials and labor required to construct and operate the upgrade. Then, cost-estimation guides, including *Means Building Construction Cost Data*, *Means Heavy Construction Cost Data*, *Richardson's*, EPA's *FarmWare* Model, and vendor-supplied cost data, were used to determine the costs for each of these items that comprise the upgrade.

11.3.5 Land Application

The cost model calculates costs for land application of manure and other waste for those operations that have land, but are not currently applying their waste. Based on site visits, EPA estimates that all beef, dairy, veal, and heifer operations that have land already have equipment to apply dry waste. However, some facilities are assumed to need liquid land application equipment as well. Land application costs are based on installation and operation of a center pivot irrigation system, or a traveling gun system, based on vendor supplied cost data (Zimmatic, Inc., 1999, Rifco, Inc., 2001). For swine and poultry operations, EPA estimated (based on site visits) that all facilities already land apply their waste, and no additional costs would be incurred under the regulatory options.

11.3.6 Off-Site Transport of Manure

Animal feeding operations use different methods of transportation to remove excess manure waste and wastewater from the feedlot operation. The costs associated with transporting excess waste off site were calculated using two methods: contract hauling waste or purchasing transportation equipment. For poultry and swine operations, EPA based transportation costs on operations contract hauling their waste. For beef and dairy operations, EPA based transportation costs on either contract hauling or purchasing equipment to self-haul waste (whichever was least expensive).

Contract Hauling

EPA evaluated contract hauling as a method for the transport of manure waste off site. In this method, the animal feeding operation hires an outside company to transport the excess waste. This method is advantageous to facilities that do not have the capacity to store excess waste on site, or the cropland acreage to agronomically apply the material. In addition, this method is useful for facilities that do not generate enough excess waste to warrant purchasing their own waste transportation trucks.

No capital costs are associated with contract hauling; only the operating cost to haul the waste. For beef and dairy operations, EPA calculated a set rate per mile for solid waste and for liquid waste, using vendor-supplied quotations and the average hauling distance for each region (ERG, 2000b; Tetra Tech, Inc., 2000b). For swine and poultry operations, EPA extracted costs for contract hauling solid waste and liquid waste from multiple published articles (Tetra Tech, Inc., 1999).

Purchase Equipment

Another method evaluated for the transport of manure waste off site was purchasing transportation equipment. In this method, the feedlot owner is responsible for purchasing the necessary trucks and hauling the waste to an off-site location. Depending on the type of waste to

be transported, a solid waste truck, a liquid tanker truck, or both types of trucks would be required. In addition, the feedlot owner is responsible for determining a suitable location to transport the waste, as well as all costs associated with loading and unloading the trucks, driving the trucks to the off-site location, and maintaining the trucks. EPA did not base compliance costs for swine and poultry operations on purchasing transportation equipment, and therefore no costs are calculated for these facilities under this transportation option.

The capital and annual costs associated with the purchase and operation of a truck for waste transport depend on the type of waste (solid or liquid) and quantity of waste to be transported. The cost model includes an evaluation on the amount of solid and/or liquid waste the operation will ship off site, and a determination of the capital costs based on that information. Annual costs are also calculated using the quantity of liquid or solid waste, as well as the hauling distance, maintenance costs, labor, fuel rates, and other parameters (ERG, 2000b).

11.4 Development of Frequency Factors

EPA recognizes that most individual farms are currently implementing certain waste management techniques or practices that are called for in the regulatory options considered. Only costs that are the direct result of the regulation are included in the cost model. Therefore, costs already incurred by operations are not attributed to the regulation.

To reflect baseline industry conditions, EPA developed technology frequency factors to describe the percentage of the industry that already implements particular operations, techniques, or practices required by the final rule. In some cases, these frequency factors are based on an assumed performance category (i.e., high, medium, and low performance) as estimated by USDA. EPA also developed ground water control frequency factors based on the location of the facility and current state requirements for permeabilities of waste management storage units. In addition, EPA developed nutrient basis frequency factors describing the distribution of farms that would apply manure to soils on a nitrogen or phosphorus basis, land availability frequency factors describing the distribution of farms with and without sufficient cropland to land apply the manure and wastewater generated at the farm, and transportation frequency factors describing the distribution of farms transporting excess manure and wastewater off site.

Some technologies included in the cost model, including composting and anaerobic digestion, were assumed not to be present under baseline industry conditions. Therefore, EPA assumed all of the facilities incur the cost of implementing the technologies and did not develop frequency factors for these technologies.

EPA estimated frequency factors based on the sources below (each source was considered along with its limitations):

- **EPA site visit information** - This information was used to assess general practices of animal feeding operations and how they vary between regions and size classes.

- **Observations from industry experts** - Experts on animal feeding operations were contacted to provide insight into operations and practices, especially where data were limited or not publicly available.
- **USDA Agricultural Phosphorus and Eutrophication document (USDA, 1999)** - This source provides information on the phosphorus content in state soils using the soil test P. EPA used this information to determine the percentage of facilities in each state that would require nitrogen-based versus phosphorus-based application rates.
- **USDA, Animal Plant and Health Inspection Service (APHIS)/National Animal Health Monitoring System (NAHMS)** - This source provides information on animal housing practices, facility size, and waste system components sorted by size class and region. These data have limited use because of the small number of respondents in the size classes of interest.
- **State Compendium: Programs and Regulatory Activities Related to AFOs** - This summary of state regulatory programs was used to estimate frequency factors based on current waste-handling requirements that already apply to animal operations in various states and in specific size classes. Operations located in states whose requirements meet or exceed the option requirements would already be in compliance and would not incur any additional cost.
- **USDA, Estimation of Private and Public Costs Associated with Comprehensive Nutrient Management Plan Implementation: A Documentation** - This source provides frequency factors for three performance-based categories of facilities (low-performing; medium-performing, and high-performing) for a series of "representative" farms defined by USDA in eight USDA defined regions. USDA defined high performers to be 25 percent of the facilities, medium performers to be 50 percent of the facilities, and low performers to be 25 percent of the facilities.

11.5 Summary of Estimated Model Farm Costs by Regulatory Option

A summary of the estimated regulatory compliance costs is provided in the following tables. Capital, fixed, annual, three-year recurring costs, and five-year recurring costs are included for each animal sector for Options 1, 2, and 5. Costs are presented in 1997 dollars.

- Table 11-10: Summary of Industry Costs for Option 1
- Table 11-11: Summary of Industry Costs for Option 2
- Table 11-12: Summary of Industry Costs for Option 5

Table 11-10. Summary of Industry Costs for Option 1

Animal Type	Manure Type	Operation Type	Capital	Annual	Fixed	3-YearRecurring	5-YearRecurring
Beef	Solid/Liquid	Beef	$66,271,376	$8,689,062	$4,305,153	$592,050	$2,530,516
Dairy	Solid/Liquid	Flush	$262,639,714	$45,358,315	$2,626,098	$183,113	$894,258
Dairy	Solid/Liquid	Hose	$33,153,994	$4,072,126	$2,461,447	$2,798,726	$739,387
Heifers	Solid/Liquid	Heifers	$13,452,388	$1,319,976	$694,719	$204,401	$82,858
Veal	Liquid	Flush	$0	$30,553	$38,948	$2,422	$10,090
Chicken	Liquid	LW	$9,118,438	$1,296,980	$132,432	$19,525	$81,264
Chicken	Solid	BR	$93,407,347	$4,060,985	$2,184,684	$74,888	$1,009,264
Chicken	Solid	LA	$32,664,307	$1,746,196	$356,844	$51,695	$247,758
Swine	Evapor	FF	$108,469	$150,883	$84,495	$3,970	$35,289
Swine	Evapor	GF	$111,079	$154,573	$86,411	$4,054	$36,036
Swine	Liquid	FF	$5,308,843	$1,686,581	$844,688	$30,149	$241,083
Swine	Liquid	GF	$4,017,456	$1,135,603	$527,369	$22,505	$171,891
Swine	Pit	FF	$360,663	$1,497,912	$889,058	$30,374	$272,588
Swine	Pit	GF	$334,852	$1,720,540	$957,771	$38,814	$329,614
Turkey	Solid	SL	$31,170,087	$1,668,463	$701,880	$27,143	$450,698

Table 11-11. Summary of Industry Costs for Option 2.

Animal Type	Manure Type	Operation Type	Capital	Annual	Fixed	3-YearRecurring	5-Year Recurring
Beef	Solid/Liquid	Beef	$96,942,128	$38,651,376	$7,672,585	$1,496,851	$9,179,452
Dairy	Solid/Liquid	Flush	$147,690,591	$115,353,998	$3,188,393	$334,556	$2,017,898
Dairy	Solid/Liquid	Hose	$35,758,320	$8,280,186	$3,066,584	$2,961,250	$1,916,937
Heifers	Solid/Liquid	Heifers	$16,559,995	$2,305,508	$842,928	$243,437	$312,186
Veal	Liquid	Flush	$0	$30,553	$38,948	$2,422	$10,090
Chicken	Liquid	LW	$14,047,475	$1,491,472	$144,601	$22,435	$93,337
Chicken	Solid	BR	$93,515,959	$4,120,237	$2,303,023	$83,562	$1,127,487
Chicken	Solid	LA	$32,642,246	$1,929,765	$333,911	$47,230	$224,575
Swine	Evapor	FF	$109,151	$151,249	$128,484	$8,945	$79,289
Swine	Evapor	GF	$112,054	$155,285	$131,852	$9,178	$81,337
Swine	Liquid	FF	$6,645,012	$1,803,879	$1,358,438	$86,947	$6,894,239
Swine	Liquid	GF	$4,934,234	$1,196,853	$855,210	$61,344	$5,231,336
Swine	Pit	FF	$505,620	$13,907,671	$1,398,631	$82,198	$781,926
Swine	Pit	GF	$454,228	$19,817,425	$1,538,482	$101,262	$910,429
Turkey	Solid	SL	$31,276,907	$2,864,728	$835,304	$35,254	$584,319

Table 11-12. Summary of Industry Costs for Option 5.

Animal Type	Manure Type	Operation Type	Capital	Annual	Fixed	3-Year Recurring	5-Year Recurring
Chicken	Liquid	LW	$22,224,957	$1,711,084	$200,193	$35,781	$148,929
Chicken	Solid	BR	$184,992,580	$4,120,237	$2,303,023	$83,562	$1,127,487
Chicken	Solid	LA	$32,642,246	$1,929,765	$333,911	$47,230	$224,575
Swine	Evapor	FF	$43,483,000	$1,830,320	$138,485	$10,060	$89,300
Swine	Evapor	GF	$44,603,942	$1,877,631	$142,109	$10,321	$91,605
Swine	Liquid	FF	$341,161,677	$10,805,902	$1,458,059	$98,623	$838,708
Swine	Liquid	GF	$250,152,138	$7,850,690	$920,791	$69,564	$552,835
Swine	Pit	FF	$37,452,731	$12,278,113	$1,398,631	$82,198	$781,926
Swine	Pit	GF	$46,434,556	$18,034,408	$1,538,482	$101,262	$910,429
Turkey	Solid	SL	$31,276,907	$2,864,728	$835,304	$35,254	$584,319
Veal	Liquid	Flush	$1,036,004	$82,351	$38,948	$2,422	$10,090

11.6 References

Bocher, Lori Ward. 2000. Custom Heifer Grower... Specialize in Providing Replacements for Dairy Herds. Hoards Dairyman. January 10, 2000.

Cady, Dr. Roger. 2000. Telephone conversation with Dr. Roger Cady, Monsanto Company and Founder of the Professional Dairy Heifer Growers Association, February 18, 2000.

Crouch, Alexa. 1999. Telephone conversation with Alexa Crouch, American Veal Association, October 14, 1999.

ERG. 2000a. Cost Methodology Report for Beef and Dairy Animal Feeding Operations. prepared for U.S. Environmental Protection Agency, Office of Water. Washington, D.C. December 2000.

ERG. 2000b. Transportation of Waste Off Site for Beef and Dairy Cost Model. Memorandum prepared for U.S. Environmental Protection Agency, Office of Water. Washington, D.C. December 2000.

Kellogg, Robert, Charles H. Lander, David Moffitt, and Noel Gollehon. 2000. Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the U.S. Washington, D.C.

Lander, C.H., D. Moffitt, and K.Alt. 1998. Nutrients Available from Livestock Manure Relative to Crop Growth Requirements. Resource Assessment and Strategic Planning Working Paper 98-1.

Midwest Plan Service. 1987. Beef Housing and Equipment Handbook. Fourth Edition, MWPS-6, February 1987.

North Carolina State University. 1998. Draft Swine and Poultry Industry Characterization, Waste Management Practices and Model Detailed Analysis of Predominantly Used Systems. Prepared for Environmental Protection Agency (WA 1-27), September 30, 1998.

Stull, Carolyn E., Steven Berry, and Ed DePeters. eds. 1998. Animal Care Series: Dairy Care Practices. 2nd ed. Dairy Workgroup, University of California Cooperative Extension. June 1998.

Tetra Tech, Inc. 2000a. Cost Model for Swine and Poultry Sectors. Prepared for U.S. Environmental Protection Agency, Office of Water. Washington, D.C. November 2000.

Tetra Tech, Inc. 2000b. Revised Transportation Distances for Category 2 and 3 Type Operations. Memorandum prepared for U.S. Environmental Protection Agency, Office of Water. Washington, D.C. January 7, 2000.

Tetra Tech, Inc. 1999. Costs of Storage, Transportation, and Land Application of Manure. Memorandum prepared for U.S. Environmental Protection Agency, Office of Water. Washington, D.C. February 1999.

USDA APHIS. 2000. Part II: Reference of 1999 Table Egg Layer Management in the United States (Layer 99). United States Department of Agriculture (USDA), Animal Plant Health Inspection Service (APHIS). Fort Collins, CO.

USDA APHIS. 1996a. National Animal Health Monitoring System, Part I: Feedlot Management Practices. http://www.aphis.usda.gov/vs/ceah/cahm/ File cofdes1.pdf. U.S. Department of Agriculture, Animal and Plant Health Inspection Service. Washington, D.C.

USDA APHIS. 1996b. Swine '95: Part II: Reference of 1995 Grower/Finisher Health and Management. U.S. Department of Agriculture, Animal and Plant Health Inspection Service. Washington, D.C.

USDA APHIS. 1996c. National Animal Health Monitoring System, Part 1: Reference of 1996 Dairy Management Practices. U.S. Department of Agriculture, Animal and Plant Health Inspection Service. Washington, D.C.

USDA APHIS. 1995. Swine '95: Part I: Reference of 1995 Swine Management Practices. U.S. Department of Agriculture, Animal and Plant Health Inspection Service. Washington, D.C.

USDA NASS. 1999. Queries run by NASS for USEPA on the 1997 Census of Agriculture data. United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), Washington, DC.

USDA NRCS. 2000. Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States. U.S. Department of Agriculture (USDA), National Resources Conservation Service (NRCS), Washington, D.C.

USDA NRCS. 1996. Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. U.S. Department of Agriculture, Natural Resources Conservation Service. Washington, D.C.

USEPA. 2000. Water Quality Conditions in the United States. EPA#841-F-00-006. U.S. Environmental Protection Agency, Office of Water. Washington, D.C.

USEPA. 1993. Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters. Office of Water. EPA840-B-92-002. U.S. Environmental Protection Agency, Office of Water. Washington, D.C..

Zimmatic, Inc. 1999. Cost Estimate for Center Pivot Irrigation Systems, <http://www.Zimmatic.com>.

CHAPTER 12

POLLUTANT LOADING REDUCTIONS FOR THE REVISED EFFLUENT LIMITATIONS GUIDELINES FOR CONCENTRATED ANIMAL FEEDING OPERATIONS

12.0 INTRODUCTION

Section 301(d) of the Clean Water Act (CWA) directs Environmental Protection Agency (EPA) to periodically review and revise, if necessary, Effluent Limitations Guidelines and Standards (ELGs) promulgated under CWA Sections 301, 304, and 306. Animal feeding operations (AFOs) have been identified as a major source of pollutants impairing surface water and ground water in the United States; therefore, EPA is revising the existing effluent guidelines for AFOs. The final regulation requires beef, dairy, veal, heifer, poultry, and swine AFOs to handle their manure in a more environmentally sound manner including upgrading facilities to reduce the runoff potential from feedlots, limiting land application of manure based on nitrogen (N) and phosphorus (P) agronomic rates, and encouraging other technologies (e.g., treatments that lower environmental impact or reduce the manure water content).

12.1 Computer Model Simulations

To support its rule revision, EPA performed computer model simulations of 13,500 different Sample Farms representing land application of manure by AFOs. Each Sample Farm represents various combinations of animal type, farm size, location, soil type, waste management and storage, incorporation technique, etc. For each Sample Farm, EPA estimated edge-of-field pollutant loadings (in pounds per year per acre of cropland) to serve as a basis for summing the national average annual pollutant reductions over a 25-year period of analysis. In sum, the interaction of these AFO facilities with the environment is based on approximately 228 million simulated days of Sample Farm performance. In addition to edge-of-field load reductions, EPA's assessment incorporated pollutant loadings from feedlots and manure storage structures, representing discharges from AFO production areas. These discharges generally include runoff from the feedlot or manure storage areas due to precipitation events, but also include, where actual discharge data was available, a limited number of discharges attributed to storage system failures and improper management.

The *Pollutant Loading Reductions for the Revised Effluent Limitations Guidelines for Concentrated Animal Feeding Operations*, or "Loads Report", describes the methods used by EPA to analyze these AFO and environment interactions, generate total pollutant loads, and then calculate potential pollutant load reductions associated with revisions to the existing CAFO

ELGs. These load reductions form the basis of potential benefits attributed to each technology option. Note, potential benefits associated with estimated national pollutant loads reductions are detailed in *Environmental and Economic Benefit Analysis of Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations* (or "Benefits Document"), and the economic impacts of rule revisions for each option is documented in *Economic Analysis of the Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations* ("Economic Analysis").

Finally, since this loads analysis reflects load reductions over a range of NPDES-permitting scenarios that could define CAFOs at different thresholds, all AFOs with more than 300 AUs were evaluated. Variations in farm size were also selected to correspond to different potential applicability thresholds for the revised ELG. These farm size variations allow load reductions to be calculated for the subset of AFOs defined as CAFOs, as well as the subset of CAFOs for which the ELG would apply. See the *Cost Report* for more information on the size thresholds evaluated.

12.2 Delineation of Potentially Affected Farm Cropland

EPA's loads assessment estimates the national sediment, nutrient, pathogen, and metals loadings to surface waters and ground water under the current effluent limitations guidelines (also called "pre-revised regulation" or "baseline") and after the implementation of various effluent limitations guidelines technology options (also referred to as "post-regulation" scenarios). EPA's national assessment starts with estimates of manure generation consistent with the methodology published by USDA in the 2002 "*Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients.*" The next step estimates of fertilizer-based (both manure and synthetic) edge-of-field loads. See Section III.H of the Loads Report for more information.

Key to assessing the edge-of-field pollutant loads is a reasonable representation of land application of manure to croplands. Croplands are the primary destination for AFO generated manure (including treated or processed manure such as compost or pelletized litter). Analytical and mathematical models can be used to estimate pollutant loading from agricultural areas by simulating the physical, chemical, and biochemical processes that govern the transport of water and sediment. For example, field-scale models such as Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Knisel et al., 1993) and Erosion-Productivity Impact Calculator (EPIC) (Sharpley and Williams, 1990) provide estimates of pollutants in runoff and sediments that are leaving the field boundaries. Field-scale models permit a detailed assessment of pollutant load generation and the influence of various management technologies, but generally require detailing of variation in soil and crop type. In total, EPA used 13,500 different Sample Farms as inputs to GLEAMS to calculate the edge-of-field loads.

To provide a consistent basis for comparison, EPA evaluated pollutant loads at both AFO and non-AFO facilities for a cropland area totaling 21 million acres nationally. EPA used P-based

fertilization, i.e., fertilization of cropland by applying manure at a P-based rate to calculate 21 million total acres for this analysis. In general, P-based fertilization at agronomic levels using manure requires about seven times the acreage needed than when applying manure N-based. Within the 21 million acres are multiple categories of AFO and non-AFO farms that reflect differences in fertilizer requirements and, therefore, application rates. Note, EPA's postrevision options do not affect the total generation of manure (i.e., production rates are constant), but rather the management of the AFO manure nutrients generated. Figure 12-1 indicates how, for baseline and three technology options (potential revised effluent guidelines technology options are described below), EPA maintained a constant total of 21 million acres in its assessment, to enable evaluation of AFO and non-AFO acres.

Additional information on the characterization of cropland acres potentially affected by EPA's rule revision is provided in Table 12-1. Category I AFO manure generation does not exceed the agronomic fertilizer requirements of their cropland acreage. Therefore, Category I farms are generally less affected by the various regulatory scenarios for land application. Category II AFOs have insufficent cropland to make full use of the manure they generate, so under baseline they either overapply manure to their croplands (a common occurrence according to site visits, compliance reports, literature, and state inspection reports in EPA's record). In most cases, this results in application rates 2 or 3 times the N application rate. For a limited number of sample

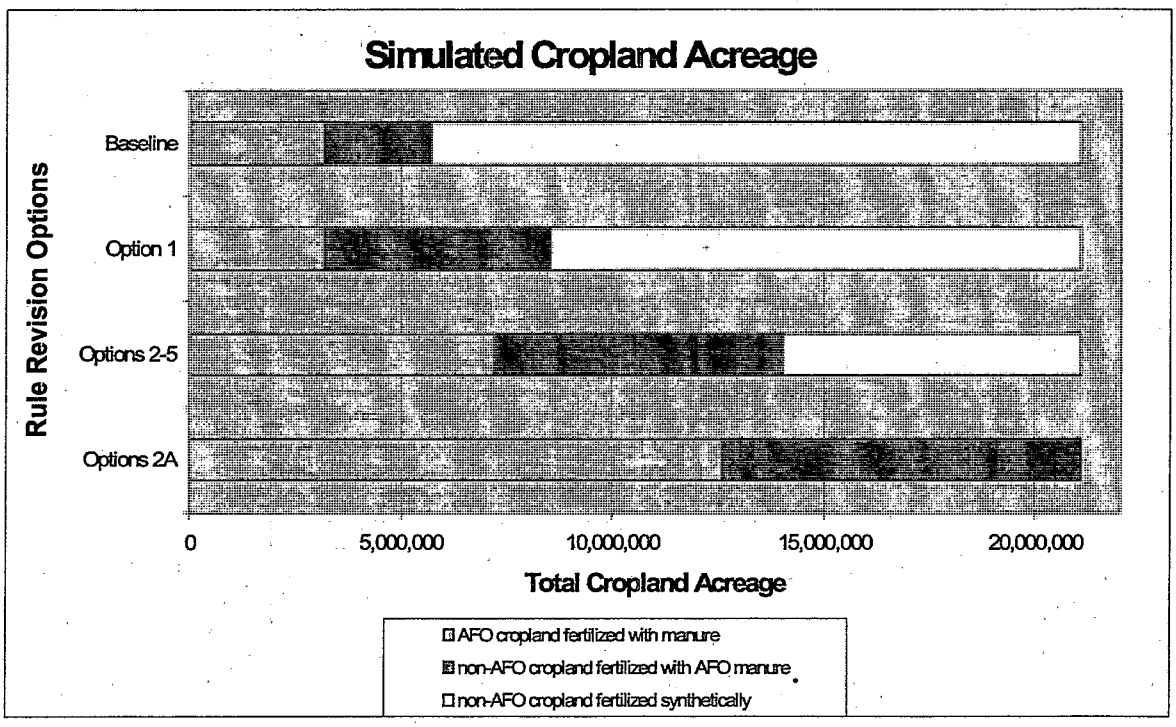

Figure 12-1. Delineation of cropland potentially affected by rule revisions

Table 12-1. Characterization of Farm Cropland Potentially Affected by Rule Revision, Based on Farm Conditions.

Farm Condition	Agronomic Limit based on Crop Selection	Baseline Acres (Prerevision)	Option 1 Acres	Option 2–5 Acres	Option 2A Acres
Category I - AFO cropland where manure is applied at agronomic rates.					
	N-based	1,415,812	1,415,812	784,137	0
	P-based	0	0	1,976,708	4,893,744
Category II - AFO cropland for facilities where manure application exceeds agronomic rates.					
	N-based within AFO facilities	1,755,734	1,755,734	910,503	0
	P-based within AFO facilities	0	0	3,571,789	7,840,241
	N-based for off-site non-AFO facilities	350,284	3,171,869	4,543,510	6,137,784
Category III - AFO farms with no land for manure application (Values are for non-AFO acreage receiving manure from AFOs).*					
	N-based	2,165,781	2,165,781	2,165,781	2,165,781
Total national acres in N-based condition (AFO manure fertilized)		5,687,611	8,509,196	8,403,931	8,303,565
Total national acres in P-based condition (AFO manure fertilized)		0	0	5,548,497	12,733,985
Non-AFO farms using commercial fertilizer (Used to ensure an consistent total acreage for cropland when comparing rule-revision options).					
	N-based and P-based	15,387,767	12,566,182	7,122,950	37,837
Total National Acreage Simulated		21,075,378	21,075,378	21,075,378	21,075,387

* Farms without available acreage to dispose of manure are assumed to disperse their manure to croplands of non-AFO farms at a rate less than five times N-based agronomic levels.

farms (34 out of 435 models), this would result in manure application at rates several times higher than the N rate. These higher manure application rates are likely to negatively affect crop responses. Based on land grant university application rates and the lower limit application attainable by certain land application designed for more concentrated animal manure (such as the limitations of poultry litter with broadcast spreaders), EPA set a limit of five (5) times the N rate for manure application rates at Category II operations. In the small number of cases where the Category II operations still had excess manure, the excess manure was transferred offsite to non-AFO cropland. Note that although 8 percent of the Sample Farms fall under this description, the number of CAFOs represented by these Sample Farms is small, such that these farms account for less than 4 percent of the total national loads. Finally, Category III AFO facilities have 10 or fewer acres of cropland, and all of the manure is transferred offsite to non-AFO croplands. The above described conditions for the three Categories of land availability comprise "baseline" conditions.

All manure transferred offsite is always assumed to be land-applied at an N-based rate. This assumption results in conservative (i.e. lower bound) estimates of load reductions, because load reductions are higher under P-based application rates, and some non-AFOs may be willing to accept manure and land apply manure at less than N-based rates. However, this assumption is deemed appropriate for this analysis as EPA expects very few non-AFO farms (such as row crop farmers) would accept manure as a fertilizer substitute if that farmer had to travel the same croplands more than once for fertilizer applications (i.e., once for manure applied at a P rate and once for supplemental N fertilizer to meet total crop requirements for N) . This analysis does not reflect alternative uses of manure because the processed, treated, or value-added manure is still ultimately land-applied (examples include compost, pelletized litter, digested manure, residual ash after incineration, etc.).

12.3 Modeled Changes from Baseline

For the post-regulation scenarios described below, departure from baseline conditions entails decreasing the over application of manure by linking application rates to crop requirements. As shown in Table 12-1, EPA's assessment differentiates between N-based and P-based fertilized cropland. Under the options considered, use of AFO manure at agronomic rates results in a decrease in synthetic (commercial) fertilizer needed to sustain crop yields on non-AFO cropland acres. This reduction in synthetic fertilizer affects the total estimated national pollutant loads, as detailed below. Note that application of manure on an agronomic N basis generally results in an overapplication of P, which over time can result in the buildup of soil P levels and increase P in the runoff. High levels of P in runoff is known to cause deleterious effects in surface waters. Additionally, application of manure at agronomic P rates results in a deficit of N. When assessing rule revisions, EPA assumed crops would receive the necessary commercial fertilizer to fulfill the total crops' N requirements. EPA also considered direct application to field surfaces versus incorporation of the manure. These two application methods have been shown to have quite different effects on sediment and nutrient transport, so this methodology considers the frequency of both application methods and the subsequent changes in loads.

Based on the farm categories defined in Table 12-1, Table 12-2 outlines what the rule-revision options entail in terms of nutrient application for AFO and non-AFO acres. Table 12-2 indicates how potential options establish requirements for agronomic fertilizing that is either N-based or P-based, and changes the categorization of cropland acres under management. In particular, the number of Category I farms (i.e. farms with sufficient cropland to assimilate all manure produced on the farm) under N-based application rates is lower than the number of Category I farms under P-based application rates. The total number of farms under all scenarios remains constant.

Technology Option 1 establishes manure application standards that prohibit application of manure in excess of the agronomic N rate. This scenario differs from baseline conditions in the decrease (about 3 million acres) in cropland receiving manure in excess of crop nitrogen requirements, and in the increased use of manure instead of synthetic fertilizer at non-AFO cropland. In other words, Category I farms continue to apply manure at a N based rates,

Category III farms continue to transfer manure offsite, and Category II farms will spread manure over more acres. Options 2 through 5 establish manure application rates based on the limiting nutrient, either N or P. EPA used soil P test maps and USDA data to determine the percent of facilities in each state that would require N-based versus P-based application rates. This approach is based on a recent informal NRCS survey where 49 out of 50 states (all states except Idaho) reported an intention to use the Phosphorus Index (PI) to meet the NRCS Nutrient Management Standard 590.

Table 12-2. Overview of Regulatory Options.

Description of Assessed Regulatory Condition	Description of Major Features	
	AFO Acreage (On site)	Non-AFO Acreage
Baseline (prerevised regulatory baseline)	Category I, II, and III land receiving manure at N- to 5N-based rates or commercial fertilizer	Manure applied at agronomic N-based rate. Cropland not receiving manure has commercial fertilizer applied as needed to track a fixed total acreage.
Option 1	Category I, II, and III land receives manure at N-based rates or commercial fertilizer	
Options 2—5	Category I, II, and III land receives manure at N- or P-based rates depending on current soil P levels or commercial fertilizer	
Option 2a	Category I, II, and III land receives manure at P- based rates or commercial fertilizer	

Under Option 2 there are fewer Category I farms and correspondingly more Category II farms. The Category I farms apply commercial fertilizer N in addition to the manure to meet the total crop requirements for N. In addition, because P is used as the limiting nutrient for Options 2 through 5, an additional 6 million acres (8 million acres of cropland in total) are affected by a change in application rates at Category II facilities. Under Option 2A, all AFOs are assumed to apply manure to onsite cropland at the P-based rate with supplemental N added to bring the N applied to the crop removal rate. Option 2A was done as a sensitivity analysis to determine the upper bound load changes if all onsite manure was applied on a P-basis. Under Option 2, from 12 percent to 60 percent (on average roughly half) of all AFOs apply manure at a P-based rate, while the remaining AFOs continue to apply at a N-based rate identical to Option 1. See Chapter 1 of the *Loads Report* for a more detailed description of the model.

12.4 Methodology for Production Area Loads

EPA established a separate methodology for computing runoff and other discharges from the production area. EPA assumes CAFOs subject to the current ELG are in full compliance, therefore there are no runoff load reductions for these facilities. Medium size facilities (AFOs less than 1,000 AUs) may have runoff from the feedlot or manure storage areas. For purposes of this analysis, EPA assumes liquid waste storage facilities (ponds and lagoons) are designed in accordance with the NRCS Code 313 Waste Storage Facility or NRCS Code 359 Waste Treatment Lagoon. The storage capacity (days of storage) for each type of AFO is based on

USDA NAHMS data, site visits, and inspection/compliance reports. EPA then uses 25-year daily weather station precipitation and evaporation data from the county the Sample Farm is located in to represent the climate. Weather, manure generation, and process wastewater are tracked daily for 25 years to estimate the average annual overflow for each Sample Farm. Note that many Sample Farms, especially swine, poultry, and dairy operations, experienced no overflows using this methodology. The complete methodology and an example of the calculations for liquid storage overflows may be found in *Methodology for Estimating BAT Overflow from a Liquid Waste Storage Facility* in Appendices B and C of the *Loads Report*. In a similar manner, the runoff from stacked manure or uncovered litter stockpiles is calculated. See the *Loads Report* for more information.

Next, EPA reviewed available state inspection and discharge reports and university studies to determine the frequency of discharges occurring each year that are not attributable to precipitation at the time of the discharge. For example, one North Carolina study identified the probability of occurrence of permit violations on swine facilities in three North Carolina counties and identified the engineering and management factors that may relate to their occurrence. These discharges are generally infrequent, and when distributed across all Sample Farms, the load reductions attributable to these discharges are small. However, since many discharges are not thoroughly documented in state inspection/compliance reports, EPA believes the methodology is conservative and understates total discharges.

Finally, EPA evaluated the contribution of pollutants to surface waters through ground water with a direct hydrologic connection. Comprehensive studies conducted in North Carolina (Sheffield 2002) and Iowa (ISU 1999) conclude that all liquid impoundments leak, though the rate of leakage varies by soil type and liner construction (if any). Most studies of the lagoon leakage estimated ground water loads by simulating transport of pollutants through ground water aquifers. For its Sample Farm models, EPA assumed that 2,000 pounds per acre per year leaked from manure storage structures lined with silt loam soils. This reference value was used to develop direct and indirect manure storage structure leakage loadings for other soil types (i.e., soil permeability) based on work by Clapp and Hornberger (1978). However, these leakage values are for ammonium, which is not mobile in soils. For ammonium to mobilize, oxygen must be present to oxidize the ammonium to nitrate. Once nitrate is formed it can leach into ground water. Because soil under lagoons generally remains wet and anaerobic, only the outer fringe of the lagoon plume may oxidize and leach. Therefore, EPA assumed that 10 percent of the ammonia-nitrogen that reaches groundwater by leaching from the bottom of the manure storage structure reaches ground water in the form of nitrate-nitrogen. Sobecki and Clipper (1999) determined how many manure storage structures had direct seepage losses by evaluating the ground water pollution potential of AFO manure storage structures according to AFO region land characteristics. For these structures with a direct surface link, pollutant loads were assumed to directly connect with surface water and it was assumed that no ground water aquifer pollutant assimilation took place. See the *Loads Report* for more information.

12.5 Converting Site-specific Loads to National Loads

Each Sample Farm model represents a single combination of animal type, farm size, manure application technique, manure application rate, and farm location. Each Sample Farm model is also evaluated across the three categories of land availability and several soil types. EPA's estimate of the annual national total pollutant load was calculated by assigning the per farm pollutant loads from the suite of Sample Farm models to every AFO facility nationwide. Thus each Sample Farm model represents the behavior of a small fraction of the total AFO population. Sample Farm loads were subsequently extrapolated to the AFO region (See Chapter 4 for a description of EPA's regions) and eventually to national pollutant loads.

To orchestrate the feeding of sample model data into GLEAMS, EPA developed a processor (using the FORTRAN programming language), referred to as the Loadings Estimate Tool (LET). This program extracts data from several large databases, forms an input data file suitable for GLEAMS, feeds the data into GLEAMS, and then regulates GLEAMS output. LET also integrates pollutant loadings estimates from open-air feedlots, manure piles, runoff, and leaking lagoons, to estimate the average annual total pollutant loadings. These per facility production area pollutant loads or per acre land application loads were multiplied by the number of facilities specific to that particular state, farm size, animal type, and waste management system to obtain regional pollutant loads. These regional pollutant loads were then summed to obtain national pollutant loads. The following tables provide a summary of results for each pollutant parameter evaluated.

Tables 12-3 through 12-8 reflect the edge-of-field pollutant loads for Large CAFOs, and Tables 12-9 through 12-14 show the edge-of-field pollutant load reductions for Large CAFOs. Tables 12-15 through 12-20 reflect the edge-of-field loads from all Medium AFOs. Tables 12-21 through 12-26 show the edge-of-field load reductions from the permitted Medium AFOs *only*. No edge-of-field pollutant reductions occurred from the unpermitted Medium AFOs

Table 12-3. Edge-of-field nitrogen loads from Large CAFOs in millions of pounds per year.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	106	60	58	51	58
Dairy	45	31	30	27	30
Swine	89	87	85	75	110
Poultry	189	159	152	150	147
Total	428	338	325	304	345

Table 12-4. Edge-of-field phosphorous loads from Large CAFOs in millions of pounds per year.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	105	89	82	82	82
Dairy	19	16	14	14	14
Swine	26	26	22	22	18
Poultry	80	71	61	61	59
Total	230	202	178	178	173

Table 12-5. Edge-of-field sediment loads from Large CAFOs in millions of pounds per year.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	14,374	12,850	12,850	12,850	12,850
Dairy	2,351	2,225	2,225	2,225	2,225
Swine	3,726	3,726	3,583	3,583	4,311
Poultry	15,042	15,011	14,776	14,776	14,731
Total	35,493	33,813	33,434	33,434	34,118

Table 12-6. Edge-of-field *Fecal coliform* loads from Large CAFOs in 10^{19} colony forming units.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	437	424	423	423	423
Dairy	54	53	53	53	53
Swine	139	139	70	70	1
Poultry	64	57	29	29	0.7
Total	695	672	576	576	478

Table 12-7. Edge-of-field *Fecal streptococcus* loads from Large CAFOs in 10^{19} colony forming units.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	196	190	190	190	190
Dairy	214	206	207	207	207
Swine	4,103	4,087	2,068	2,068	39
Poultry	576	150	89	89	29
Total	5,089	4,633	2,554	2,554	465

Table 12-8. Edge-of-field metals loads from Large CAFOs in millions of pounds per year.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	2.8	2.7	2.6	2.6	2.6
Dairy	2.5	2.4	2.3	2.3	2.3
Swine	3.5	3.5	3.4	3.4	3.7
Poultry	11.2	10.9	10.7	10.7	10.6
Total	20.0	19.5	18.9	18.9	19.2

Table 12-9. Edge-of-field nitrogen load reductions from Large CAFOs in millions of pounds per year. Numbers in ( ) indicate negative values.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	45.2	47.9	54.3	47.9
Dairy	14.1	14.7	17.9	14.7
Swine	0.3	4.0	13.6	(21.3)
Poultry	29.9	36.4	38.1	41.6
Total	89.6	103.0	123.8	82.9

Table 12-10. Edge-of-field phosphorous load reductions from Large CAFOs in millions of pounds per year.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	15.6	23.1	23.1	23.1
Dairy	3.2	5.0	5.0	5.0
Swine	0.1	4.7	4.7	8.1
Poultry	8.5	19.2	19.2	20.4
Total	27.4	52.1	52.1	56.5

Table 12-11. Edge-of-field sediment load reductions from Large CAFOs in millions of pounds per year. Numbers in ( ) indicate negative values.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	1,524	1,524	1,524	1,524
Dairy	126	126	126	126
Swine	0	143	143	(585)
Poultry	31	266	266	311
Total	1,681	2,059	2,059	1,376

Table 12-12. Edge-of-field *Fecal coliform* load reductions from Large CAFOs in 10^{19} colony forming units.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	14.0	14.0	14.0	14.0
Dairy	1.3	1.3	1.3	1.3
Swine	0.5	69.1	69.1	138.0
Poultry	6.8	35.0	35.0	63.2
Total	22.7	119.5	119.5	216.6

Table 12-13. Edge-of-field *Fecal streptococcus* load reductions from Large CAFOs in 10^{19} colony forming units.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	6	6	6	6
Dairy	8	7	7	7
Swine	16	2,035	2,035	4,064
Poultry	426	487	487	547
Total	456	2,535	2,535	4,624

Table 12-14. Edge-of-field metals load reductions from Large CAFOs in millions of pounds per year. Numbers in ( ) indicate negative values.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	0.14	0.22	0.22	0.22
Dairy	0.03	0.14	0.14	0.14
Swine	0.01	0.13	0.13	(0.23)
Poultry	0.33	0.55	0.55	0.63
Total	0.51	1.04	1.04	0.76

Table 12-15. Edge-of-field nitrogen loads from Mediums CAFOs in millions of pounds per year.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	24	23	23	23	23
Dairy	60	56	55	53	55
Swine	101	101	100	98	102
Poultry	173	172	172	172	172
Total	358	353	351	347	353

Table 12-16. Edge-of-field phosphorous loads from Mediums CAFOs in millions of pounds per year.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	17	17	17	17	17
Dairy	24	23	22	22	22
Swine	22	22	21	21	20
Poultry	79	78	78	78	78
Total	141	140	137	137	136

Table 12-17. Edge-of-field sediment loads from Mediums CAFOs in millions of pounds per year.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	4,582	4,580	4,562	4,562	4,562
Dairy	2,885	2,882	2,827	2,827	2,827
Swine	3,910	3,910	3,890	3,890	3,898
Poultry	20,094	20,092	20,088	20,088	20,087
Total	31,470	31,464	31,367	31,367	31,374

Table 12-18. Edge-of-field *Fecal coliform* loads from Mediums CAFOs in 10^{19} colony forming units.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	22	10	10	10	10
Dairy	44	36	36	36	36
Swine	240	240	222	222	204
Poultry	40	40	40	40	39
Total	346	325	307	307	289

Table 12-19. Edge-of-field *Fecal streptococcus* loads from Mediums CAFOs in 10^{19} colony forming units.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	10	4	4	4	4
Dairy	254	201	201	201	201
Swine	7,057	7,055	6,530	6,530	6,003
Poultry	1,177	1,125	1,124	1,124	1,124
Total	8,498	8,385	7,859	7,859	7,332

Table 12-20. Edge-of-field metals loads from Mediums CAFOs in millions of pounds per year.

Sector	Baseline	Option 1	Option 2	Option 3	Option 5
Cattle	0.4	0.4	0.4	0.4	0.4
Dairy	3.4	3.4	3.3	3.3	3.3
Swine	2.9	2.9	2.9	2.9	2.8
Poultry	8.9	8.9	8.9	8.9	8.9
Total	15.7	15.7	15.6	15.6	15.6

Table 12-21. Edge-of-field nitrogen load reductions from Medium CAFOs in millions of pounds per year.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	0.17	0.22	0.22	0.22
Dairy	4.59	5.03	7.34	5.03
Swine	0.03	0.98	3.11	(0.59)
Poultry	0.81	0.88	0.90	0.95
Total	5.60	7.10	11.56	5.60

Table 12-22. Edge-of-field phosphorous load reductions from Medium CAFOs in millions of pounds per year.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	0.05	0.27	0.27	0.27
Dairy	1.33	2.55	2.55	2.55
Swine	0.01	0.70	0.70	1.50
Poultry	0.26	0.72	0.72	0.73
Total	1.66	4.24	4.24	5.05

Table 12-23. Edge-of-field sediment load reductions from Medium CAFOs in millions of pounds per year.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	1	20	20	20
Dairy	3	57	57	57
Swine	0	20	20	12
Poultry	2	6	6	7
Total	6	104	104	96

Table 12-24. Edge-of-field *Fecal coliform* load reductions from Medium CAFOs in 10^{19} colony forming units.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	12.1	12.1	12.1	12.1
Dairy	8.2	8.2	8.2	8.2
Swine	0.1	17.9	17.9	35.8
Poultry	0.1	0.5	0.5	0.8
Total	20.4	38.6	38.6	56.9

Table 12-25. Edge-of-field *Fecal streptococcus* load reductions from Medium CAFOs in 10^{19} colony forming units.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	5	5	5	5
Dairy	54	54	54	54
Swine	2	527	527	1,054
Poultry	52	53	53	54
Total	113	639	639	1,166

Table 12-26. Edge-of-field metals load reductions from Medium CAFOs in thousands of pounds per year.

Sector	Option 1	Option 2	Option 3	Option 5
Cattle	0.9	1.9	1.9	1.9
Dairy	23.2	80.3	80.3	80.3
Swine	0.1	18.5	18.5	42.4
Poultry	6.1	9.6	9.6	10.6
Total	30.2	110.2	110.2	135.1

12.6 References

Clapp, R.B., and G.M. Hornberger. 1978. Empirical equations for some hydraulic properties. *Water Resources Research* 14:601-604.

Iowa State University. 1999. Earthen Waste Storage Structures in Iowa. A Study for the Iowa Legislature. Iowa State University, Publication Number EDC-186.

Knisel, W.G., F.M. Davis, R.A. Leonard, and A.D. Nicks. 1993. *GLEAMS: Groundwater Loading Effects of Agricultural Management Systems,* Version 2.10.

Sharpley, A.N., and J.R. Williams. 1990. *EPIC-Erosion/Productivity Impact Calculator: 1. Model Documentation.* USDA Tech. Bull. No. 1786. U.S. Department of Agriculture, Washington, DC.

Sheffield, R.E. 2002. The relationship of engineering and management factors on the occurrence of regulatory and water quality violations on selected NC swine farms. North Carolina State University, Department of Biological and Ag5ricultural Engineering, Raleigh, NC.

Sobecki, T.M., and M. Clipper. 1999. Identification of Acreage of U.S. Agricultural Land with a Significant Potential for Siting of Animal Waste Facilities and Associated Limitations from Potential of Ground Water Contamination. Draft 12/15/99, U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USDA. 2000. Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the U.S. U.S. Department of Agriculture, Washington, DC.

CHAPTER 13

NON-WATER QUALITY IMPACTS

13.0 INTRODUCTION

Eliminating or reducing one form of pollution may create or aggravate other environmental problems. Sections 304(b) and 306 of the Clean Water Act (CWA) require that the U.S. Environmental Protection Agency (EPA) consider the non-water quality environmental impacts (NWQI) of effluent limitations guidelines and standards. This chapter presents the methodology and estimates from EPA's NWQI analysis of seven primary regulatory options that were considered for concentrated animal feeding operations (CAFOs), including beef (includes heifer) operations, dairies, veal, swine, broiler, layer, and turkey operations. These impacts include:

- Air emissions from the animal production area, including animal housing and manure storage and treatment areas;
- Air emissions from application of manure to land;
- Air emissions from vehicles, including those involved in off-site transport of manure and in on-site composting operations; and
- Energy impacts from land application activities, the use of digesters, and the transportation of manure.

Typically, NWQI also include estimates of the generation of solid waste. Because manure is considered a by-product of animal feeding operations and is not regulated directly, the solid waste NWQI of the manure are not considered. In addition, although the chemical content of the manure may change, the amount of manure generated is not expected to change under any of the regulatory options being considered; therefore, this chapter does not discuss solid waste NWQI.

The remainder of this chapter contains the following information:

- Section 13.1 presents an overview of the analysis and pollutants;
- Section 13.2 discusses the methodology for estimating air emissions from animal feeding operations;
- Section 13.3 discusses the methodology for estimating air emissions from land application activities;
- Section 13.4 discusses the methodology for estimating air emissions from vehicles;
- Section 13.5 discusses the methodology for estimating energy impacts;

- Section 13.6 summarizes the industry-level non-water quality impacts for Large and Medium CAFOs; and
- Section 13.7 lists the references used in this section.

EPA's Office of Air Quality Planning and Standards also conducted an in-depth study of air emissions from animal feeding operations and prepared a draft report in August 2001. The National Academy of Sciences subsequently reviewed this report, and since that time, EPA has updated the available data used to develop air emission factors. This chapter presents results based on available data and methodologies developed as of September 2002. A more detailed description of the analysis is provided in the report *Non-Water Quality Impact Estimates for Animal Feeding Operations* (ERG, 2002a).

13.1 Overview of Analysis and Pollutants

A number of factors affect the energy use at and the pollutant emissions from CAFOs. Most of the substances emitted are the products of microbial processes that decompose the complex organic constituents in manure. The microbial environment determines which substances are generated and at what rate. This section describes the chemical and biological mechanisms that affect the formation and release of emissions.

The pollutants included in this analysis are:

- Ammonia. Ammonia is a by-product of the microbial decomposition of the organic nitrogen compounds in manure. Nitrogen occurs as both unabsorbed nutrients in manure and as either urea (mammals) or uric acid (poultry) in urine. Urea and uric acid hydrolyze rapidly to form ammonia and are emitted soon after excretion. Urea plus ammonia nitrogen from urine usually accounts for 40 to 50 percent of the total nitrogen excreted in manure (Van Horn et al., 1994).

  Ammonia continues to form during the microbial breakdown of manure under both aerobic and anaerobic conditions. Because it is highly soluble in water, ammonia accumulates in manure handled as liquids and semisolids or slurries, but volatilizes rapidly with drying from manure handled as solids. In aqueous solution, ammonia reacts with acid to form ammonium, which is not gaseous. The chemical equilibrium in an acid environment promotes rapid conversion of ammonia to ammonium with little release of ammonia to the atmosphere. Because most animal manure, lagoons, and feedlot surfaces have a pH greater than 7.0 (i.e., a nonacidic environment), ammonia is rapidly lost to the atmosphere. Consequently, ammonia losses from animal manure can easily exceed 50 percent (Van Horn et al., 1994).

- Nitrous oxide. Nitrous oxide can also be produced from the microbial decomposition of organic nitrogen compounds in manure. Unlike ammonia, however, nitrous oxide is emitted only under certain conditions. Nitrous oxide is emitted only if nitrification occurs and is followed by denitrification. Nitrification is the microbial oxidation of

ammonia to nitrites and nitrates, and the process requires an aerobic environment. Denitrification is most commonly a microbially mediated process where nitrites and nitrates are reduced under anaerobic conditions. The principal end product of denitrification is dinitrogen gas (N_2). However, small amounts of nitrous oxide as well as nitric oxide also can be generated under certain conditions. Therefore, for nitrous oxide emissions to occur, the manure must first be handled aerobically and then anaerobically.

Research indicates that aerobic manure storage, such as composting, produces more nitrous oxide than anaerobic storage, such as lagoons (AAF Canada, 2000). In general, manure that is handled as a liquid tends to produce less nitrous oxide than manure that is handled as a solid. The quantity of nitrous oxide generated is typically small and varies significantly depending on environmental conditions such as pH, drainage, and plant uptake.

- Methane. With respect to livestock emissions, methane is produced in the normal digestive processes of animals and during the decomposition of animal manure. This analysis assesses only the amount of methane produced in manure decomposition. Livestock manure is principally composed of organic material. When this organic material decomposes in an anaerobic environment, methanogenic bacteria, as part of an interrelated population of microorganisms, produce methane. Methane is insoluble in water. Thus, methane volatilizes from solution as rapidly as it is generated. Concurrent with the generation of methane is the microbially mediated production of carbon dioxide, which is only sparingly soluble in water. The mixture of these two gases is commonly referred to as biogas.

  The principal factors affecting methane emission from animal manure are the methane-producing potential of the waste and the portion of the manure that decomposes anaerobically. The second factor depends on the biodegradability of the organic fraction and how the manure is managed. When manure is stored or treated as a liquid (e.g., in lagoons, ponds, tanks, pits), it tends to decompose anaerobically and produce a significant quantity of methane. When manure is handled as a solid (e.g., in stacks or pits) or when it is deposited on pastures and rangelands, it tends to decompose aerobically, producing little or no methane (IPCC, 2000).

- Hydrogen sulfide. Hydrogen sulfide is produced and subsequently emitted from animal manure only under anaerobic conditions and results from the mineralization of organic sulfur compounds and the reduction of the more oxidized inorganic forms of sulfur, including sulfites and sulfates. In animal manure, the principal organic sulfur compounds are the sulfur amino acids, and the principal sources of inorganic sulfur are minerals, such as copper and zinc, which are added to diets to correct nutritional deficiencies or to serve as growth stimulants. High concentrations of hydrogen sulfide can be released by agitation and pumping of liquid wastes. Although only small amounts of hydrogen sulfide are produced in a manure tank compared with the other

major gases, this gas is heavier than air and becomes more concentrated in the tank over time. Research has determined that hydrogen sulfide production from animal feeding operations depends on the average outside air temperature, the size of the housing or waste management areas, the air retention time in the housing areas, and the daily sulfur intake of the animals.

- Criteria air pollutants. Criteria air pollutants are those pollutants for which a national ambient air quality standard has been set. Animal feeding operations that transport their manure off site and/or compost their manure on site use equipment (e.g., trucks, tractors) that release criteria air pollutants when operated. These pollutants are also released when biogas, generated from energy recovery systems for anaerobic digesters, is used for fuel (e.g., in an engine or flared). The criteria air pollutants included in this analysis are volatile organic compounds, nitrogen oxides, particulate matter, sulfur dioxide, and carbon monoxide.

- Energy usage. CAFOs also use energy when transporting manure off site, applying manure to land, and performing on-site operations such as composting. In some cases, the CAFO may generate energy from capturing and using biogas. Energy usage included in this analysis is expressed in kilowatt hours (kW-hr) and in consumed fuel (gallons). Energy use also includes production of fertilizer. Though CAFOs do not generate commercial fertilizer, the manure is used as a fertilizer replacement. Since the criteria air pollutants analysis reflects NWQI due to increased hauling distances and spreading of manure, an energy usage NWQI estimate is used to reflect national reductions in fertilizer consumption. This analysis of reductions in commercial fertilizer use are included in the memorandum entitled "Commercial Fertilizer Analysis" (ERG, 2002).

Where possible, the NWQI estimates for each regulatory option are presented in relation to the baseline conditions under which animal feeding operations generate air emissions and use energy (i.e., prior to implementation of a regulatory option). In some cases, however, there were insufficient data to quantify baseline NWQI. In these cases, the impacts presented in this chapter reflect only the change in impacts expected to result from implementation of the regulatory options from baseline.

13.2 Air Emissions from Animal Feeding Operations

Animal feeding operations generate various types of animal wastes, including manure (feces and urine), waste feed, water, bedding, dust, and wastewater. Air emissions are generated from the decomposition of the wastes from the point of generation through the management and treatment of these wastes on site. The rate at which emissions are generated varies as a result of a number of operational variables (e.g., animal species, type of housing, waste management system) and weather conditions (e.g., temperature, humidity, wind, time of release).

EPA evaluated air releases from animal confinement areas and manure management systems under baseline conditions and seven regulatory options considered by the Agency. Little data

exist to allow for a complete analysis of all possible compounds; therefore, this analysis focused on the release of ammonia, hydrogen sulfide, and greenhouse gases (methane and nitrous oxide) from animal confinement areas and manure management systems and certain criteria air pollutants (carbon monoxide, nitrogen oxides, and volatile organic compounds) from energy recovery systems.

This section summarizes the methodology used for the following air emission calculations from the animal feeding operation:

- Section 13.2.1 - Ammonia and hydrogen sulfide from animal confinement areas and manure management systems;
- Section 13.2.2 - Greenhouse gases from animal confinement areas and manure management systems; and
- Section 13.2.3 - Criteria air pollutants from energy recovery systems.

A detailed description of the data inputs and equations used to calculate these air emissions is provided in the report *Non-Water Quality Impact Estimates for Animal Feeding Operations* (ERG, 2002a).

13.2.1 Ammonia and Hydrogen Sulfide Emissions From Animal Confinement Areas and Manure Management Systems

Animal housing and manure management systems produce ammonia and hydrogen sulfide emissions. Nitrogen is the primary component of animal waste most likely to generate air emissions. Total nitrogen comprises organic nitrogen, ammonia, nitrite, and nitrate. The primary form of nitrogen emissions from animal feeding operations to the atmosphere occurs as ammonia. For this analysis, EPA calculated emissions of ammonia for drylots, confinement houses, ponds and lagoons, and composted manure.

Hydrogen sulfide is produced by anaerobic decomposition of organic wastes such as animal manure. High concentrations can be released by agitation and pumping of liquid wastes. Research has determined that hydrogen sulfide production from animal feeding operations depends on the average outside air temperature, the size of the housing or waste management areas, the air retention time in the housing areas, and the daily sulfur intake of the animals. EPA estimated hydrogen sulfide emissions for confinement houses operating deep-pit systems, as these are production areas with anaerobic conditions.

The Agency based emission rates of ammonia and hydrogen sulfide on the emission factor and the amount of nitrogen or sulfur in the excreted manure. Emission factors depend upon the animal species as well as the type of animal confinement and manure management area. Because only swine emission factors for hydrogen sulfide have been published in the literature, EPA transferred these data to other animal types.

Livestock may be confined in a number of different ways that impact the type and amount of ammonia emissions. Some animals are housed in traditional confined housing (e.g., tie stall barns, freestall barns), while others are confined in outdoor areas (e.g., drylots, paddocks). Studies have shown that the method of confinement directly affects the emission of ammonia (Jacobson et al., 2000). Management of waste within the confinement area (e.g., litter system, deep-pit, freestall) also influences emissions of both ammonia and hydrogen sulfide. For instance, deep-pit systems are associated with a higher nitrogen emission factor because waste remains in the pit for a longer period of time, increasing ammonia volatilization.

Anaerobic lagoons and waste storage ponds are major components of the waste management systems at many animal feeding operations. These systems rely on microbes that biodegrade organic nitrogen to ammonium and ammonia. The ammonia continuously volatilizes from the surface of lagoons and ponds. The high sulfur content of swine, dairy, veal, and layer waste also results in hydrogen sulfide emissions from lagoons. Settling basins, used as a technology basis for several regulatory options, are estimated to remove 50 percent of manure solids at an operation. The remaining 50 percent reach the pond or lagoon. It is assumed that these basins remove approximately 12 percent of nitrogen and 50 percent of sulfur; therefore, 88 percent of the nitrogen and 50 percent of the sulfur excreted in manure enters the storage pond or lagoon.

The seven regulatory options, based on the implementation of different types of waste management systems, influence whether emissions of ammonia and/or hydrogen sulfide will increase or decrease when compared to baseline.

13.2.2 Greenhouse Gas Emissions from Animal Confinement Areas and Manure Management Systems

Manure management systems, including animal confinement areas, produce methane (CH_4) and nitrous oxide (N_2O) emissions. Data used to estimate greenhouse gas emissions include: animal weight, volatile solids excretion rate, nitrogen excretion rate, maximum methane-producing potential, runoff solids generation, and manure composted. The maximum methane-producing potential is the maximum volume of methane that can be produced per kilogram of volatile solids and is based on the type of animal and its diet. The methane and nitrous oxide emissions were estimated based on the guidance developed for international reporting of greenhouse gas emissions (IPCC, 2000) and used by EPA's Office of Air and Radiation.

Methane production is directly related to the quantity and quality of waste, the type of waste management system used, and the temperature and moisture of the waste (EPA, 1992). In general, manure that is handled anaerobically will produce more methane, while manure that is handled aerobically produces little methane. For example, liquid and slurry systems result in higher methane production because they promote anaerobic conditions. Certain animal populations, such as beef cattle on feedlots, may produce more methane if they are fed higher energy diets. Methane is also produced from the digestive processes of ruminant livestock as a result of enteric fermentation. However, because the regulatory options do not establish

requirements dictating specific feeding strategies that affect diet, the effect on enteric fermentation methane emissions is difficult to predict and is not discussed further.

Nitrous oxide is produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine. The emission of nitrous oxide from manure management systems is a function of the nitrogen content of the manure, as well as the length of time the manure is stored and the specific type of system used. In general, the amount of nitrous oxide emitted from manure management systems tends to be small because conditions are often not suitable for nitrification to occur; however, when nitrous oxide is generated, manure that is handled as a liquid tends to produce less nitrous oxide than manure handled as a solid. The amount of emitted nitrous oxide depends upon the nitrogen excreted by the animal, and emission factors are assumed not to vary regionally.

13.2.3 Criteria Air Emissions From Energy Recovery Systems

Criteria air pollutants are those pollutants for which a national ambient air quality standard has been set. The criteria pollutants evaluated as non-water quality impacts from energy recovery systems include oxides of nitrogen (NOx), which are precursors to ozone, as well as carbon monoxide (CO) and sulfur dioxide (SO_2). These criteria pollutants are formed from the flaring and combustion of biogas.

NOx emissions result from the oxidation of nitrogen compounds in biogas and from thermal formation during the flaring and combustion processes. No emission factors incorporate both situations; therefore, EPA estimated emissions using an emission factor for each situation and a subsequent calculation estimating the amount of volatilized ammonia oxidized to NOx. EPA calculated sulfur dioxide emissions under the assumption that the sulfur compounds in biogas are completely oxidized in both the flare and gas turbines and estimated carbon monoxide emissions associated with the incomplete combustion of methane and other organic compounds.

Criteria pollutant air emissions from flaring and energy recovery systems are expected under Options 5 and 6. Under Option 5, anaerobic lagoons at all swine, chicken, and veal operations are modeled as covered, and the biogas is vented to a flare. Option 6 is based on the implementation of anaerobic digestion systems with energy recovery for Large swine operations and dairies. Options 5 and 6 greatly reduce the emissions of methane through the capture of biogas; however, flaring the biogas or using it in an energy recovery system will increase emissions of the criteria pollutants NOx, SO_2, and CO. These pollutants are generated from oxidation of nitrogen (from NH_3), sulfur (from H_2S), and carbon compounds (from organics and methane).

13.3 Air Emissions from Land Application Activities

Applying animal manure from animal feeding operations to cropland generates air emissions. These emissions result primarily from the volatilization of ammonia at the point the material is applied to land (Anderson, 1994). Additional emissions of nitrous oxide are released from

cropland when nitrogen applied to the soil undergoes nitrification and denitrification. Loss through denitrification depends upon the oxygen levels of the soil to which manure is applied. Low oxygen levels, resulting from wet, compacted, or warm soil, increase the amount of nitrate-nitrogen released into the air as nitrogen gas or nitrous oxide (OSUE, 2000). However, a study by Sharpe and Harper (1997), which compared losses of ammonia and nitrous oxide from the sprinkler irrigation of swine effluent, concluded that ammonia emissions contributed more to airborne nitrogen losses. This analysis of air emissions from land application activities focuses on the volatilization of nitrogen as both ammonia and nitrous oxide and quantified both on- and off-site emissions.

The amount of nitrogen released into the environment from the land application of animal waste is affected by the rate and method by which it is applied, the quantity of material applied, and site-specific factors such as air temperature, wind speed, and soil pH. There were insufficient data to quantify the effect of site-specific factors; therefore, they were not addressed in this analysis.

Ammonia emissions depend on the ammonia volatilization rate and the amount of manure applied on and off site. The ammonia volatilization rates used to estimate total ammonia emissions are animal-specific and are based on the application method and the rate of incorporation. Ammonia losses were calculated separately for beef feedlots, dairies, and poultry and swine operations, and total emissions were estimated by summing the volatilization from solid and liquid application. Nitrous oxide emissions were calculated based on the methodology described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*, EPA 236-R-02-003 (EPA, 2002). This methodology estimated that 1.25 percent of the nitrogen that is land applied, but does not volatilize to ammonia, will be emitted as nitrous oxide, and that one percent of the nitrogen that volatilizes as ammonia will eventually become nitrous oxide. Like ammonia, the total amount of nitrous oxide emitted on and off site was calculated by summing the emissions resulting from both solid and liquid waste application.

Although ammonia volatilization may be reduced by implementing application techniques aimed at conserving nitrogen, this is not required by any regulatory option. However, Option 5, which mandates total confinement and covered lagoon storage, results in an increased concentration of applied nitrogen and elevated ammonia and nitrous oxide emissions from land application activities. The composting requirement of Option 5A is expected to result in increased emissions of ammonia and nitrous oxide, due to drier manure handling and windrow turning.

13.4 Air Emissions From Vehicles

Animal feeding operations that transport their manure off site and/or compost their manure on site use equipment (e.g., trucks, tractors) that release criteria air pollutants when operated. The NWQI analysis evaluated the increased emissions from off-site transportation and from composting manure on site.

Criteria air emissions from the off-site transportation of animal manure were evaluated for each of the regulatory options considered by EPA, as all options will result in an increase of off-site transportation of manure at some operations. The analysis examined three types of facilities: Category 1 operations have sufficient cropland to apply all manure on site; Category 2 operations do not have enough cropland to apply all waste on site and may or may not currently transport waste; and Category 3 operations have no cropland and currently transport all manure off site. Because Category 1 operations emit no criteria air pollutants from vehicles at baseline, nor will any regulatory option induce them to do so, there are no current or projected emissions in criteria air emissions for this category. Category 2 operations, however, incur costs for transporting more manure off site, leading to an increase in the amount of criteria air pollutants generated by these operations. Although Category 3 facilities currently transport their manure, a regulation that requires phosphorous-based rather than nitrogen-based application may cause facilities to transport their excess manure a further distance; therefore, there may also be an increase in the amount of criteria air pollutants generated by these operations for options that require phosphorus-based application. EPA calculated air emission estimates for the off-site transportation of manure from all Category 2 facilities, as well as from Category 3 facilities that are expected to follow phosphorus-based application.

Two different waste transportation options were also analyzed. One considered the cost of purchasing trucks to transport waste, and the other evaluated the cost of paying a contractor to haul the waste off site. Because of the different methods used to estimate the costs of the two transportation options, two methods were used to calculate air emissions. Criteria pollutant emissions from operations purchasing waste transportation vehicles were based on an estimate of the number of trucks purchased and the annual number of miles traveled. Contract hauling emissions were based on an estimate of the annual amount of waste generated, the annual number of miles traveled, and truck sizes.

Transportation emissions are reported as the incremental increase in criteria air pollutants from baseline for Category 2 and Category 3 operations. Additional criteria air pollutants are released in all cases.

Farm equipment used for on-site composting activities also affects the generation of air emissions. Composting of waste can result in a reduction in transportation air emissions if the volume or weight of material composted is reduced; however, the mere use of composting equipment contributes to criteria air emissions. Option 5A for beef (includes heifer) operations and dairies is based on all operations composting their waste; therefore, criteria air emissions from on-site composting of manure were estimated only for these CAFOs under Option 5A. The amount of waste composted was based on the amount of excreted semisolid waste. Pollutant emissions were determined using vehicle emission factors and miles traveled along the length of the windrow. On-site emissions of criteria air pollutants due to composting activities increase under Option 5A for all for beef (includes heifer) operations and dairies.

13.5 Energy Impacts

Certain regulatory options evaluated for animal feeding operations entail the use of different waste management systems and land application practices that may increase or decrease energy usage. Energy impacts related to land application for animal feeding operations were evaluated under baseline conditions and under the seven regulatory options considered by EPA. Energy impacts related to the use of anaerobic digesters were evaluated for all Large dairies and swine operations under Option 6.

Some beef (includes heifer) operations and dairies do not currently collect and land apply their liquid waste. The regulatory options implementing a no-discharge policy would force these operations to collect and land apply their liquid waste using pivot irrigation systems or traveling guns, depending on the amount of acreage available for application. As a result of the addition of these application systems, the energy requirements of these operations would increase.

Transporting manure off site and composting manure on site requires the use of equipment such as trucks and tractors. The fuel consumption resulting from using these vehicles contributes to the energy impacts associated with land application activities. The estimation of fuel consumption by transportation vehicles used the number of miles traveled per year and the vehicle fuel efficiency as data inputs.

Option 6 includes the use of anaerobic digesters with energy recovery to manage animal waste for the Large dairies and swine operations. Digesters require a continuous input of energy to operate the holding tank mixer and the engine that converts captured methane into energy (Jewell, 1997). The energy required to continuously operate these devices and the amount of energy generated by the system have been determined from EPA's *FarmWare* model. CAFOs using anaerobic digesters with energy recovery systems are expected to have a net decrease in electricity use.

13.6 Industry-Level NWQI Estimates

This section summarizes the industry-level NWQI estimates for each of the regulatory options considered by EPA. To evaluate the impact of the regulation on NWQI, model farm emissions were extrapolated to the population of animal feeding operations covered by the rule. Industry-level impacts for each animal sector (i.e., beef (includes heifer), dairy, veal, swine, and poultry) were estimated for Medium and Large CAFOs throughout the United States. Large facilities are considered CAFOs if they fall within the size range presented in Table 13-1. Medium AFOs are defined as CAFOs only if they fall within the size range presented in Table 13-1 and they meet one of the two specific criteria governing the method of discharge: (1) pollutants are discharged through a man-made ditch, flushing system, or other similar man-made device; or (2) pollutants are discharged directly into waters of the United States that originate outside the facility and pass over, across, or through the facility or otherwise come into direct contact with the confined animals.

Table 13-1. Summary of Size Thresholds for Large and Medium CAFOs.

Sector	Large	Medium[a]
Mature dairy cattle	More than 700	200 - 700
Veal calves	More than 1,000	300 - 1,000
Cattle or cow/calf pairs	More than 1,000	300 - 1,000
Swine (weighing 55 pounds or more)	More than 2,500	750 - 2,500
Swine (weighing less than 55 pounds)	More than 10,000	3,000 - 10,000
Turkeys	More than 55,000	16,500 - 55,000
Chickens (liquid manure handling system)	More than 30,000	9,000 - 30,000
Chickens other than laying hens (other than a liquid manure handling system)	More than 125,000	30,000 - 125,000
Laying hens (other than a liquid manure handling system)	More than 82,000	25,000 - 82,000

[a] Must also meet one of two criteria to be defined as a CAFO.

13.6.1 Summary of Air Emissions for Beef (Includes Heifer) Operations and Dairies

Tables 13-2 and 13-3 present estimates for Large CAFOs, and Tables 13-8 and 13-9 present estimates for Medium CAFOs.

Option 1

Option 1 is expected to result in a change in precursor pollutant (i.e., ammonia and hydrogen sulfide) emissions from CAFOs. Total ammonia emissions from beef (includes heifer) operations and dairies, including both the production area and land application activities, decrease under Option 1. Production area emissions decrease due to the added step of solids separation in waste management. Option 1 also requires agronomic application of manure, litter, and other process wastewater on site, which results in decreased application of manure nitrogen to cropland on site and decreased on-site land application ammonia emissions. However, off-site application of manure nitrogen increases, which also increases the off-site land application ammonia emissions. Hydrogen sulfide emissions from the production area decrease for dairies also because of the practice of solids separation, which allows for increased aerobic decomposition and the inhibition of hydrogen sulfide formation.

In addition, Option 1 is expected to result in a change in greenhouse gas emissions. For Large beef (includes heifer) and dairy CAFOs, methane emissions decrease due to the added step of solids separation in the waste management system. The separated solids are stockpiled rather than held in waste storage ponds or anaerobic lagoons. This drier method of manure handling reduces anaerobic conditions and the potential for volatile solids to convert to methane. This approach also results in greater conversion of nitrogen to nitrous oxide; thus, nitrous oxide emissions from dairies increase. For Medium beef (includes heifer) CAFOs, methane emissions increase due to increased liquid storage from baseline.

Due to the requirement under Option 1 to apply manure, litter, and other process wastewater at nitrogen-based agronomic rates, CAFOs with insufficient land on which to apply their waste at these rates will transport the excess manure off site. Due to this increase in transportation, emissions of criteria air pollutants increase from baseline for beef (includes heifer) and dairy CAFOs.

Options 2-4 and 7

Options 2-4 and 7 also result in changes to precursor and greenhouse gas emissions as discussed for Option 1. However, these options require manure, litter, and other process wastewater to be applied at agronomic rates for phosphorus for some operations.

Therefore, criteria air emissions increase compared to baseline and Option 1 due to an increase in the amount of manure nutrients transported off site.

Option 5A

Option 5A requires the implementation of composting at beef (includes heifer) and dairy CAFOs. Under Option 5A, ammonia emissions increase for these operations. Ammonia volatilizes rapidly from drying manure, resulting in an increase in emissions as more manure is handled as a solid rather than a liquid or slurry. In addition, composting practices release more emissions than stockpiles because the windrows are turned regularly, exposing more manure to the air. Stockpiles tend to form outer crusts that reduce the potential for volatilization.

Under a composting option, production area methane emissions increase as a result of the addition of organic material to the waste prior to composting. This material decomposes and contributes to increased methane emissions compared to other options and baseline. Nitrous oxide emissions also increase for these operations, as aerobic storage enhanced by windrow turning promotes the release of this gas.

Option 5A also results in an increase in criteria air emissions. The practice of composting requires turning equipment, which consumes fuel and generates additional air emissions. However, this increase is not as large as the increase under Options 2-4, 6, and 7. The additional criteria pollutants emitted by composting equipment is partially offset by reductions in transportation emissions, resulting from a decrease in the weight and/or volume of the composted material.

Option 6

Under Option 6, emissions of pollutants do not differ from Option 2 for all beef (includes heifer) CAFOs, and for Medium dairy CAFOs. However, for Large dairy CAFOs, this option results in changes to greenhouse gas and criteria air emissions. Methane and nitrous oxide emissions from the production area of Large dairy CAFOs decrease substantially, due to the addition of an

anaerobic digester with energy recovery. Generated methane is collected as biogas and converted to energy, and nitrous oxide is oxidized during the combustion process. Emissions of nitrogen oxides, carbon monoxide, and sulfur dioxide increase due to combustion of the biogas.

13.6.2 Summary of Air Emissions for Swine, Poultry, and Veal Operations

Tables 13-4 through 13-7 present estimates for Large swine, poultry, and veal CAFOs, and Tables 13-10 through 13-13 present estimates for Medium swine, poultry, and veal CAFOs.

Option 1

Emissions of precursor pollutants and greenhouse gases do not change for veal, swine, and poultry operations under Option 1, as this option does not result in changes to the production area waste management procedures. However, criteria air pollution increases for swine and poultry operations due to the nitrogen-based application requirements and the associated increases in transportation of manure nutrients off site. Emissions for veal operations do not change from baseline because it is assumed that they have adequate cropland to apply all waste on site and consequently do not transport any manure.

Options 2-4 and 7

Under these options, emissions of precursor pollutants and greenhouse gases do not change from baseline for all veal, swine, and poultry operations, as waste handling practices are not expected to change.

As in Option 1, there is no increase in criteria air pollutant emissions for veal operations because they are not expected to transport manure off site. However, there is an increase in these pollutant emissions for swine and poultry operations when compared to baseline and Option 1 because of the increased transport of waste necessitated by the phosphorus-based application requirement.

Option 5

Option 5 requires zero discharge, with no allowance for overflow. It is expected that operations will implement total confinement and covered storage, in addition to the requirements of Option 2, for all swine, poultry, and veal operations. Under this option, ammonia emissions decrease for veal, swine, and chicken operations. Usually, ammonia in the effluent from the covered lagoon is released upon exposure to air. Option 5, however, is based on covered storage at all times; thus, depending on the application methods (e.g., if the waste is incorporated into the soil), ammonia emissions could substantially decrease. The use of a covered lagoon lowers the production area ammonia emissions. It should be noted, however, that ammonia emissions increase from material applied to land both on site and off site. Ammonia emissions from turkey operations do not change compared to baseline. Emissions of hydrogen sulfide decrease for veal and swine and drop to zero for wet-layer operations due to the practice of covered storage.

Methane and nitrous oxide emissions from the production area decrease for all veal, chicken, and swine operations as a result of total confinement and covered storage. However, nitrous oxide emissions increase from material applied to land both on site and off site.

Veal operations emit a larger quantity of nitrogen oxides, carbon monoxide, and sulfur dioxide compared with baseline and all other options due to flaring. Wet layer and swine operations also emit additional criteria air pollutants compared to baseline because of this practice. However, compared to Options 2-4 and 7, these operations emit a smaller amount of VOCs, nitrogen oxides, particulate matter, and carbon monoxide but a larger amount of sulfur dioxide. For turkey operations, criteria air emissions increase from baseline to the same level that results from Options 2-4, 6 and 7.

Option 6

Under Option 6, emissions of precursor pollutants do not differ from Option 2 for all veal and poultry CAFOs and for Medium swine CAFOs. However, for Large swine CAFOs, this option results in changes to greenhouse gas and criteria air emissions. Methane and nitrous oxide emissions from the production area of Large swine CAFOs decrease substantially, due to the addition of an anaerobic digester with energy recovery. Generated methane is collected as biogas and converted to energy, and nitrous oxide is oxidized during the combustion process. Emissions of nitrogen oxides, carbon monoxide, and sulfur dioxide increase due to combustion of the biogas.

13.6.3 Energy Impacts

The regulatory options evaluated for CAFOs are based on the use of certain waste management systems and land application practices that may impact electricity and fuel usage. Both energy usage indicators were estimated in relation to baseline, with electricity usage in units of megawatt-hours per year (MW-hr/yr) and fuel usage in gallons.

Increased electricity usage occurs at beef (includes heifer) and dairy CAFOs under all options. Surface runoff from the feedlot must be collected and stored before it can be land applied. These additional measures require an increase in electricity expenditures. Because veal, poultry, and swine are confined in houses, these operations do not experience elevated electricity demands, as there are no additional runoff controls expected. In addition, the land application of waste consumes electricity during the operation of the irrigation system. It is assumed that swine and poultry operations already land apply their waste and therefore do not experience additional electricity needs. However, some beef (includes heifer) operations and dairies do not currently collect and land apply their liquid waste, and a zero discharge policy would likely result in these operations collecting and land applying this waste using new irrigation systems. As a result, the energy requirements of these operations are expected to increase.

Under Option 1, all operations except veal operations experience an increase in fuel usage due to the requirement that manure be land applied according to agronomic rates for nitrogen. This

requirement is expected to result in excess manure nutrients being transported to off-site land application sites. This fuel usage grows under Options 2-4, 6 and 7 because of the more stringent phosphorus-based requirement and the resultant increase in the amount of manure to be transported. Veal operations are assumed to apply all waste on site no matter the option and thus do not incur additional energy costs.

Under Option 5, swine and chicken operations use less fuel as a result of the total confinement and covered storage requirements. Fuel consumption at veal and turkey operations does not change from baseline under any option.

Under Option 5A, which requires composting at beef (includes heifer) and dairy CAFOs, fuel usage by transportation vehicles decreases due to a decrease in the weight and/or volume of the waste. Nevertheless, because of the fuel demands of the composting equipment, total fuel usage at beef and heifer operations increases compared to other options. Because all beef (includes heifer) waste is deposited on the drylot, a large amount of waste is available for composting. The additional fuel usage of composting equipment at these operations offsets the decrease from lower transportation fuel requirements. At dairies, however, much of the manure is in liquid and slurry form and less solid waste can be composted. Consequently, the energy demands of the composting equipment do not outweigh the energy saved from a reduction in transportation, and the overall fuel usage for dairies decreases under Option 5A.

Overall electricity use decreases at those operations that use anaerobic digesters under Option 6. Large swine and dairy CAFOs that digest their waste and recover and use the biogas to operate an engine generate excess energy, which can be sold or used to operate other machinery.

Table 13-2. NWQI for Beef (Includes Heifers) - Large CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	385,256	383,154	383,154	383,154	383,154		505,713	383,154	383,154
Hydrogen Sulfide (H_2S)	NC	NC	NC	NC	NC		NC	NC	NC
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.93	0.86	0.86	0.86	0.86		1.13	0.86	0.86
Nitrous Oxide (N_2O)	7.72	7.72	7.72	7.72	7.72		7.93	7.72	7.72
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	1.4	18.6	18.6	18.6		18.7	18.6	18.6
Nitrogen Oxides (NOx)	Baseline	29.3	387.5	387.5	387.5		389.8	387.5	387.5
Particulate Matter (PM)	Baseline	1.0	12.9	12.9	12.9		13.0	12.9	12.9
Carbon Monoxide (CO)	Baseline	7.6	103.8	103.8	103.8		104.4	103.8	103.8
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC		NC	NC	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	37,986	37,986	37,986		38,257	37,986	37,986
Fuel Usage (gallons/yr)	Baseline	178,069	2,280,586	2,280,586	2,280,586		2,295,467	2,280,586	2,280,586

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-3. NWQI for Dairy - Large CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	151,595	147,591	147,591	147,591	147,591		162,576	147,591	147,591
Hydrogen Sulfide (H_2S)	5,986	3,611	3,611	3,611	3,611		3,611	3,611	3,611
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	5.85	3.60	3.60	3.60	3.60		3.68	0.02	3.60
Nitrous Oxide (NOx)	1.46	1.95	1.95	1.95	1.95		2.72	0.56	1.95
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	42.4	90.8	90.8	90.8		88.7	90.8	90.8
Nitrogen Oxides (NOx)	Baseline	850.3	1820.1	1820.1	1820.1		1779.0	1841.3	1820.1
Particulate Matter (PM)	Baseline	26.5	56.8	56.8	56.8		55.5	56.8	56.8
Carbon Monoxide (CO)	Baseline	240.5	514.3	514.3	514.3		502.7	519.7	514.3
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC		NC	20.1	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	14,430	14,430	14,430		14,430	(1,009,331)	14,430
Fuel Usage (gallons/yr)	Baseline	4,682,297	10,031,078	10,031,078	10,031,078		9,805,490	10,031,078	10,031,078

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-4. NWQI for Veal - Large CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	149	149	149	149	149	104		149	149
Hydrogen Sulfide (H_2S)	10	10	10	10	10	2		10	10
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.001	0.001	0.001	0.001	0.001	0.00002		0.001	0.001
Nitrous Oxide (N_2O)	0.0017	0.0017	0.0017	0.0017	0.0017	0.0021		0.0017	0.0017
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Nitrogen Oxides (NOx)	Baseline	Baseline	Baseline	Baseline	Baseline	0.41		Baseline	Baseline
Particulate Matter (PM)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Carbon Monoxide (CO)	Baseline	Baseline	Baseline	Baseline	Baseline	0.36		Baseline	Baseline
Sulfur Dioxide (SO_2)	Baseline	Baseline	Baseline	Baseline	Baseline	0.41		Baseline	Baseline
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Fuel Usage (gallons/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-5. NWQI for Swine - Large CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	183,732	183,732	183,732	183,732	183,732	109,037		183,732	183,732
Hydrogen Sulfide (H_2S)	13,036	13,036	13,036	13,036	13,036	2,150		13,036	13,036
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	12.46	12.46	12.46	12.46	12.46	2.27		0	12.46
Nitrous Oxide (NOx)	0.29	0.29	0.29	0.29	0.29	0.52		0.20	0.29
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	1.9	32.8	32.8	32.8	16.9		31.5	32.8
Nitrogen Oxides (NOx)	Baseline	38.5	655.4	655.4	655.4	404.7		700.8	655.4
Particulate Matter (PM)	Baseline	1.2	20.4	20.4	20.4	10.5		19.6	20.4
Carbon Monoxide (CO)	Baseline	10.9	185.9	185.9	185.9	154.1		196.8	185.9
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC	66.0		66.0	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		(2,217,565)	Baseline
Fuel Usage (gallons/yr)	Baseline	210,840	3,593,589	3,593,589	3,593,589	1,855,656		3,459,148	3,593,589

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-6. NWQI for Chickens - Large CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	205,038	205,038	205,038	205,038	205,038	200,755		205,038	205,038
Hydrogen Sulfide (H_2S)	1,146	1,146	1,146	1,146	1,146	0		1,146	1,146
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	1.19	1.19	1.19	1.19	1.19	0.27		1.19	1.19
Nitrous Oxide (N_2O)	2.30	2.30	2.30	2.30	2.30	2.40		2.30	2.30
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	1.9	7.5	7.5	7.5	6.9		7.5	7.5
Nitrogen Oxides (NOx)	Baseline	41.0	161.7	161.7	161.7	152.7		161.7	161.7
Particulate Matter (PM)	Baseline	1.5	5.8	5.8	5.8	5.4		5.8	5.8
Carbon Monoxide (CO)	Baseline	10.4	40.8	40.8	40.8	39.8		40.8	40.8
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC	2.6		NC	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Fuel Usage (gallons/yr)	Baseline	256,763	1,015,976	1,015,976	1,015,976	952,584		1,015,976	1,015,976

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-7. NWQI for Turkeys - Large CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	35,599	35,599	35,599	35,599	35,599	35,599		35,599	35,599
Hydrogen Sulfide (H_2S)	NC	NC	NC	NC	NC	NC		NC	NC
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.09	0.09	0.09	0.09	0.09	0.09		0.09	0.09
Nitrous Oxide (N_2O)	1.05	1.05	1.05	1.05	1.05	1.05		1.05	1.05
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	0.2	1.6	1.6	1.6	1.6		1.6	1.6
Nitrogen Oxides (NOx)	Baseline	4.6	35.3	35.3	35.3	35.3		35.3	35.3
Particulate Matter (PM)	Baseline	0.2	1.3	1.3	1.3	1.3		1.3	1.3
Carbon Monoxide (CO)	Baseline	1.2	8.8	8.8	8.8	8.8		8.8	8.8
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC	NC		NC	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Fuel Usage (gallons/yr)	Baseline	29,706	225,701	225,701	225,701	225,701		225,701	225,701

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-8. NWQI for Beef (Includes Heifers) - Medium CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	3990	3964	3964	3964	3964		5386	3964	3964
Hydrogen Sulfide (H_2S)	NC	NC	NC	NC	NC		NC	NC	NC
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.012	0.013	0.013	0.013	0.013		0.016	0.013	0.013
Nitrous Oxide (N_2O)	0.08	0.08	0.08	0.08	0.08		0.10	0.08	0.08
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	0.012	0.067	0.067	0.067		0.070	0.067	0.067
Nitrogen Oxides (NOx)	Baseline	0.3	1.4	1.4	1.4		1.5	1.4	1.4
Particulate Matter (PM)	Baseline	0.009	0.049	0.049	0.049		0.051	0.049	0.049
Carbon Monoxide (CO)	Baseline	0.07	0.37	0.37	0.37		0.39	0.37	0.37
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC		NC	NC	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	1,640	2,821	2,821	2,821		2,822	2,821	2,821
Fuel Usage (gallons/yr)	Baseline	1,613	8,668	8,668	8,668		9,071	8,668	8,668

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-9. NWQI for Dairy - Medium CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	39,837	39,185	39,185	39,185	39,185		48,337	39,185	39,185
Hydrogen Sulfide (H_2S)	1,068	598	598	598	598		598	598	598
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.97	0.64	0.64	0.64	0.64		0.67	0.64	0.64
Nitrous Oxide (N_2O)	0.585	0.589	0.589	0.589	0.589		0.818	0.589	0.589
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	0.9	4.3	4.3	4.3		4.0	4.3	4.3
Nitrogen Oxides (NOx)	Baseline	18.4	87.5	87.5	87.5		82.8	87.5	87.5
Particulate Matter (PM)	Baseline	0.6	2.8	2.8	2.8		2.7	2.8	2.8
Carbon Monoxide (CO)	Baseline	5.1	24.1	24.1	24.1		22.7	24.1	24.1
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC		NC	NC	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	970	4,228	4,228	4,228		1,667	4,228	4,228
Fuel Usage (gallons/yr)	Baseline	103,764	498,686	498,686	498,686		473,028	498,686	498,686

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-10. NWQI for Veal - Medium CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	12	12	12	12	12	8		12	12
Hydrogen Sulfide (H_2S)	0.7	0.7	0.7	0.7	0.7	0.2		0.7	0.7
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.0001	0.0001	0.0001	0.0001	0.0001	0.000001		0.0001	0.0001
Nitrous Oxide (N_2O)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002		0.0001	0.0001
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Nitrogen Oxides (NOx)	Baseline	Baseline	Baseline	Baseline	Baseline	0.04		Baseline	Baseline
Particulate Matter (PM)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Carbon Monoxide (CO)	Baseline	Baseline	Baseline	Baseline	Baseline	0.04		Baseline	Baseline
Sulfur Dioxide (SO_2)	Baseline	Baseline	Baseline	Baseline	Baseline	0.04		Baseline	Baseline
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Fuel Usage (gallons/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-11. NWQI for Swine - Medium CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	10,596	10,596	10,596	10,596	10,596	7,090		10,596	10,596
Hydrogen Sulfide (H_2S)	616	616	616	616	616	183		616	616
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.68	0.68	0.68	0.68	0.68	0.19		0.68	0.68
Nitrous Oxide (N_2O)	0.02	0.02	0.02	0.02	0.02	0.03		0.02	0.02
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	0.0	0.6	0.6	0.6	0.3		0.6	0.6
Nitrogen Oxides (NOx)	Baseline	0.6	11.9	11.9	11.9	7.5		11.9	11.9
Particulate Matter (PM)	Baseline	0.0	0.4	0.4	0.4	0.2		0.4	0.4
Carbon Monoxide (CO)	Baseline	0.2	3.4	3.4	3.4	3.1		3.4	3.4
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC	1.6		NC	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Fuel Usage (gallons/yr)	Baseline	3,266	65,369	65,369	65,369	31,852		65,369	65,369

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-12. NWQI for Chickens - Medium CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	6,287	6,287	6,287	6,287	6,287	6,276		6,287	6,287
Hydrogen Sulfide (H_2S)	3.1	3.1	3.1	3.1	3.1	0.0		3.1	3.1
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.040	0.040	0.040	0.040	0.040	0.038		0.040	0.040
Nitrous Oxide (N_2O)	0.1427	0.1427	0.1427	0.1427	0.1427	0.1430		0.1427	0.1427
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	0.07	0.43	0.43	0.43	0.43		0.43	0.43
Nitrogen Oxides (NOx)	Baseline	1.47	9.40	9.40	9.40	9.47		9.40	9.40
Particulate Matter (PM)	Baseline	0.05	0.34	0.34	0.34	0.43		0.34	0.34
Carbon Monoxide (CO)	Baseline	0.37	2.33	2.33	2.33	2.32		2.33	2.33
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC	0.11		NC	NC
Baseline + Energy Usage[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Fuel Usage (gallons/yr)	Baseline	9,404	60,024	60,024	60,024	59,844		60,024	60,024

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

Table 13-13. NWQI for Turkeys - Medium CAFOs

NWQI	Baseline	Regulatory Option							
		Option 1	Option 2	Option 3	Option 4	Option 5	Option 5A	Option 6	Option 7
AIR EMISSIONS									
Precursor Pollutants (tons per year)									
Ammonia (NH_3)	603	603	603	603	603	603		603	603
Hydrogen Sulfide (H_2S)	NC	NC	NC	NC	NC	NC		NC	NC
Greenhouse Gases (Tg/yr CO_2 - Equiv)									
Methane (CH_4)	0.002	0.002	0.002	0.002	0.002	0.002		0.002	0.002
Nitrous Oxide (N_2O)	0.018	0.018	0.018	0.018	0.018	0.018		0.018	0.018
Criteria Air Pollutants (tons per year)[a]									
Volatile Organic Compounds (VOCs)	Baseline	0.00	0.04	0.04	0.04	0.04		0.04	0.04
Nitrogen Oxides (NOx)	Baseline	0.09	0.82	0.82	0.82	0.82		0.82	0.82
Particulate Matter (PM)	Baseline	0.00	0.03	0.03	0.03	0.03		0.03	0.03
Carbon Monoxide (CO)	Baseline	0.02	0.20	0.20	0.20	0.20		0.20	0.20
Sulfur Dioxide (SO_2)	Baseline	NC	NC	NC	NC	NC		NC	NC
BASELINE + ENERGY USAGE[a]									
Electricity Usage (MW-hr/yr)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline
Fuel Usage (gallons/yr)	Baseline	596	5,213	5,213	5,213	5,213		5,213	5,213

NC - Not calculated.

[a]Energy estimates reflect the incremental change in usage from baseline.

13.7 References

AAF Canada. 2000. Estimates of Emissions--Reducing Nitrous Oxide Emissions. In *The Health of Our Air*. Agriculture and Agri-Food Canada. <http://res2.agr.ca/research-recherche/science/Healthy_Air/2d8.html>. October 10.

Anderson, B. 1994. *Animal Manure as a Plant Resource.* <http://www.agcom.purdue.edu/AgCom/Pubs/ID/ID-101.html>. Purdue University. July 5, 2000.

EPA. 1992. Global Methane Emissions From Livestock and Poultry Manure. EPA/400/1-91-048. U.S. Environmental Protection Agency, Washington, DC.

EPA 2002. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000. EPA/236/R-02-003. U.S. Environmental Protection Agency, Washington, DC.

ERG. 2002. Commercial Fertilizer Analysis. Memorandum prepared for U.S. Environmental Protection Agency, Engineering and Analysis Division, Washington, DC. December.

ERG. 2002a. *Non-Water Quality Impact Estimates for Animal Feeding Operations.* Prepared for U.S. Environmental Protection Agency, Engineering and Analysis Division, Washington, DC. December.

IPCC. 2000. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Chapter 4, Agriculture. Intergovernmental Panel on Climate Change, NGGIP..

Jacobson, L. D., R. Moon, J. Bicudo., K. Janni, S. Noll, G. Shurson, J. Zhu, D. Schmidt, P. McGinley, R. Nicolai, C. Clanton, K. Davis, L. Brosseau, J. Bruns, C. Pijoan, T. Blaha, B. Curgan, and K. Draeger. 2000. *Generic Environmental Impact Statement on Animal Agriculture: A Summary of the Literature Related to Air Quality and Odor.* Prepared for Minnesota Department of Agriculture, Environmental Quality Board, St. Paul Minnesota.

Jewell, W.J., P.E. Wright, N.P. Fleszar, G. Green, A. Safinski, and A. Zucker. 1997. *Evaluation of Anaerobic Digestion Options for Groups of Dairy Farmers in Upstate New York.* Department of Agriculture and Biological Engineering, College of Agriculture and Life Sciences. Cornell University, Ithaca, NewYork. June.

OSUE. 2000. *Selecting Forms of Nitrogen Fertilizer.* <http://www2.ag.ohio-state.edu/~ohioline/agf-fact/0205.html>. Ohio State University Extension. July 5.

Sharpe, R.R., and L.A. Harper. 1997. Ammonia and Nitrous Oxide Emissions from Sprinkler Irrigation Applications of Swine Effluent. *Journal of Environmental Quality* 26:1703-1706.

Van Horn, H.H., A.C. Wilkie, W.J. Powers, and R.A. Nordstedt. 1994. Components of Dairy Manure Management Systems. *Journal of Dairy Science* 77:7.

CHAPTER 14

GLOSSARY

aeration	the process of bringing air into contact with a liquid by one or more of the following methods: (1) spraying the liquid in the air, (2) bubbling air through the liquid, and (3) agitating the liquid to promote absorption of oxygen through the air liquid interface
aerobic	having or occurring in the presence of the free oxygen
aerobic lagoon	a holding and/or treatment pond that speeds up the natural process of biological decomposition of organic waste by stimulating the growth and activity of bacteria that degrade organic waste in an oxygen-rich environment
Ag Census	the census of agriculture conducted every 5 years; a major source of information about the structure and activities of agricultural production at the national, state, and county levels
agitation	thorough mixing of liquid or slurry manure at a storage structure to provide a more consistent fertilizer material and allow the producer to empty as much of the storage as possible
agronomic rates	the land application of animal wastes at rates of application that provide the crop or forage growth with needed nutrients for optimum health and growth
air emissions	release of any pollutant into the air
ammonia volatilization	the loss of ammonia gas to the atmosphere
anaerobic	the absence of molecular oxygen, or capable of living and growing in the absence of oxygen, such as anaerobic bacteria
anaerobic lagoon	a holding and/or treatment pond that speeds up the natural process of biological decomposition of organic waste by stimulating the growth and activity of bacteria that degrade organic waste in an oxygen-depleted environment

animal feeding operation (AFO)	a lot or facility (other than an aquatic animal production facility) where animals have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period, and the animal confinement areas do not sustain crops, vegetation, forage growth, or postharvest residues in the normal growing season. Two or more animal feeding operations under common ownership are a single animal feeding operation if they adjoin each other or if they use a common area or system for the disposal of wastes.
APHIS	Animal and Plant Health Inspection Service, United States Department of Agriculture
baffle	a device (as a plate, wall, or screen) to deflect, check, or regulate flow (fluid, light, or sound)
barrow	a castrated male pig
berm	a narrow shelf, path, or ledge typically at the top or bottom of a slope; a mound or wall of earth
best available technology (BAT)	the best available technology that is economically achievable established under 301(b) and 402 of the Federal Water Pollution Control Act as amended, also known as the Clean Water Act, found at 33 USC 1251 et seq. The criteria and standards for imposing technology-based treatment requirements are listed in 40 CFR 125.3.
best conventional technology (BCT)	the best conventional pollutant control technology that is economically achievable established under 301(b) and 402 of the Federal Water Pollution Control Act as amended, also known as the Clean Water Act, found at 33 USC 1251 et seq. The criteria and standards for imposing technology-based treatment requirements are listed in 40 CFR 125.3.
best management practice (BMP)	a practice or combination of practices found to be the most effective, practicable (including economic and institutional considerations) means of preventing or reducing the amount of pollution generated
bioavailability	the degree and rate at which a substance is absorbed into a living system or is made available at the site of physiological activity
biochemical oxygen demand (BOD)	an indirect measure of the concentration of biodegradable substances present in an aqueous solution. Determined by the amount of dissolved oxygen required for the aerobic degradation of the organic matter at 20 °C. BOD_5 refers to that oxygen demand for the initial 5 days of the degradation process

biogas	a mixture of methane and carbon dioxide produced by the bacterial decomposition of organic wastes and used as a fuel
biosecurity	a defensive health plan and hygiene procedures that can help keep an animal feeding operation disease free
biosolids	solid organic matter recovered from a sewage treatment process and used especially as fertilizer
BPJ	best professional judgement
BPT	best practicable technology
broadcasting	method of application (seed or fertilizer) to the soil surface
broilers	chickens of either sex specifically bred for meat production and marketed at approximately 8 weeks of age
carcass-weight	weight of the dead body of an animal, slaughtered and gutted
certified specialist	someone who has been certified to prepare Comprehensive Nutrient Management Plans (CNMPs) by USDA or a USDA sanctioned organization
compaction	an increase in soil bulk density, limiting both root penetration, and water and nutrient uptake induced by tillage- and vehicular-traffic
composting	a process of aerobic biological decomposition of organic material characterized by elevated temperatures that, when complete, results in a relatively stable product suitable for a variety of agricultural and horticultural uses
concentrated animal feeding operation (CAFO)	an "animal feeding operation" that meets the criteria in 40 CFR Part 122, Appendix B, or an operation designated as a significant contributor of pollution pursuant to 40 CFR 122.23
costing	a systematic method or procedure used to develop the estimated costs of a technology or practice
cover crop	a close-growing crop, whose main purpose is to protect and improve the soil and use excess nutrients or soil moisture during the absence of the regular crop, or in the nonvegetated areas of orchards and vineyards

crop removal rate	the application rate for manure or wastewater which is determined by the amount of phosphorus which will be taken up by the crop during the growing season and subsequently removed from the field through crop harvest. Field residues do not count towards the amount of phosphorus removed at harvest.
crop rotation	a planned sequence of crops
denitrification	the chemical or biological reduction of nitrate or nitrite to gaseous nitrogen, either as molecular nitrogen (N_2) or as an oxide of nitrogen (N_2O)
detention pond	a basin whose outlet has been designed to detain the storm water runoff from a design storm (e.g., 25 year/24 hour storm) for some minimum time to allow particles and associated pollutants to settle
digestion	the process whereby organic matter breaks down into simpler and/or more biologically stable products, e.g., ammonia to organic nitrogen
disking	cultivating with an implement that turns and loosens the soil with a series of discs
dry lots	open feedlots sloped or graded from 4 to 6 percent to promote drainage away from the lot to provide consistently dry areas for cattle to rest
effluent	the liquid discharge from a waste treatment process
endogenous	growing or produced by growth from deep tissue (e.g., plant roots)
ephemeral erosion	a shallow, concentrated flow path that develops as a response to a specific storm and disappears as a result of tillage or natural processes
erosion	the wearing away of the land surface by water, wind, ice, or other geologic agents and by such processes as gravitational creep
ERS	Economic Research Service, United States Department of Agriculture
evapotranspiration	the loss of water from an area by evaporation from the soil or snow cover and transpiration by plants
farrowing	the act of giving birth to pigs by the sow
farrow-to-finish	contains all three hog production phases: farrow, nursery, finish
fecal coliform	the bacterial count (Parameter 1) at 40 CFR 136.3 in Table 1A, which also cites the approved methods of analysis.

feedlot	a concentrated, confined animal or poultry growing operation for meat, milk, or egg production, or stabling, in pens or houses wherein the animals or poultry are fed at the place of confinement and crop or forage growth or production is not sustained in the area of confinement, and is subject to 40 CFR 412
fertilizer value	the value of noncommercial fertilizer (e.g., manure)
flushing system	a system that collects and transports or moves waste material with the use of water, such as in washing of pens and flushing of confinement livestock facilities
freeboard	the height above the recorded high-water mark of a structure (as a dam) associated with the water
FRN	federal registrar notice
frequency factor	the regional compliance of animal feeding operations with BMPs associated with a nutrient management plan, facility upgrades, or strategies to reduce excess nutrients
FORTRAN	one of the most widely used programming languages for solving problems in science and engineering
gilt	a young or immature female pig
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
ground water	water filling all the unblocked pores of underlying material below the water table
hen	a mature female chicken
incorporation	mixing manure into the soil, either by tillage or by subsurface injection, to increase manure nutrient availability for use by crops
injection	a tillage implement that cuts into the soil depositing liquid or slurry
integrators	poultry companies, under contract with growers, who supply birds, feed, medicines, transportation, and technical help
irrigation	application of water to lands for agricultural purposes (Soil Conservation Society of America, 1982)

lagoon	an all-inclusive term commonly given to a water impoundment in which organic wastes are stored or stabilized, or both. Lagoons may be described by the predominant biological characteristics (aerobic, anaerobic, or facultative), by location (indoor, outdoor), by position in a series (primary, secondary, or other), and by the organic material accepted (sewage, sludge, manure, or other)
land application	application of manure, sewage sludge, municipal wastewater, and industrial wastes to land for reuse of the nutrients and organic matter for their fertilizer and soil conditioning values
land application area	any land under the control of the CAFO operator, whether it is owned, rented, or leased, to which manure and process wastewater is or may be applied
layer	a mature hen that is producing eggs
leaching	(1) the removal of soluble constituents, such as nitrates or chlorides, from soils or other material by the movement of water; (2) the removal of salts and alkali from soils by irrigation combined with drainage; (3) the removal of a liquid through a non-watertight artificial structure, conduit, or porous material by downward or lateral drainage, or both, into the surrounding permeable soil
load	quantity of substance entering the receiving body
macronutrient	a chemical element required, in relatively large amounts, for proper plant growth
manure	the fecal and urinary excretions of livestock and poultry
micronutrient	a chemical element required, in relatively small amounts, for proper plant growth
mulch	any substance that is spread on the soil surface to decrease the effects of raindrop impact, runoff, and other adverse conditions and to retard evaporation
NAHMS	National Animal Health Monitoring System, United States Department of Agriculture
NASS	National Agricultural Statistics Service, United States Department of Agriculture

new source	a source that is subject to subparts C or D of 40 CFR 412 and, not withstanding the criteria codified at 40 CFR 122.29(b)(1): (i) is constructed at a site at which no other source is located; or (ii) replaces the housing including animal holding areas, exercise yards, and feedlot, waste handling system, production process, or production equipment that causes the discharge or potential to discharge pollutants at an existing source; or (iii) constructs a production area that is substantially independent of an existing source at the same site. Whether processes are substantially independent of an existing source, depends on factors such as the extent to which the new facility is integrated with the existing facility; and the extent to which the new facility is engaged in the same general type of activity as the existing source.
nitrification	the biochemical transformation by oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) or nitrate (NO_3^-)
nitrogen	a chemical element, commonly used in fertilizer as a nutrient, that is also a component of animal wastes. Plant available nitrogen forms include nitrate (NO_3^-) and ammonium (NH_4^+).
no-till	a planting procedure that requires no tillage except that done in the immediate area of the crop row
NRCS	Natural Resource Conservation Service, United States Department of Agriculture
NSPS	New Source Performance Standards are uniform national EPA air emission and water effluent standards that limit the amount of pollution allowed from new sources or from modified existing sources
nutrient management	a planning tool used to control the amount, source, placement, form, and timing of the application of nutrients and soil amendments (USDA, 1999)
nutrient management plan	an approach for managing the form, rate, timing, and method of application of nutrients, including nutrients from biosolids, being applied to the soil in a manner that provides adequate plant nutrition but minimizes the environmental impact of these nutrients
nutrient removal rate	the removal of nutrients in harvested material on a per acre basis
NWPCAM	National Water Pollution Control Assessment Model
organic matter	the organic fraction of the soil exclusive of undecayed plant and animal residue

overflow	the process wastewater discharge resulting from the filling of wastewater or liquid manure storage structures to the point at which no more liquid can be contained by the structure
permit nutrient plan (PNP)	a plan developed in accordance with 40 CFR 412.33 (b) and §412.37. This plan shall define the appropriate rate for applying manure or wastewater to crop or pasture land. The plan accounts for soil conditions, concentration of nutrients in manure, crop requirements and realistic crop yields when determining the appropriate application rate.
phosphorus	one of the primary nutrients required for the growth of plants. Phosphorus is often the limiting nutrient for the growth of aquatic plants and algae.
phosphorus level	a system of weighing a number of measures that relate the potential for phosphorus loss due to site and transport characteristics. The phosphorus index must at a minimum include the following factors when evaluating the risk for phosphorus runoff from a given field or site: (1) Soil erosion. (2) Irrigation erosion. (3) Run-off class. (4) Soil phosphorus test. (5) Phosphorus fertilizer application rate. (6) Phosphorus fertilizer application method. (7) Organic phosphorus application rate. (8) Method of applying organic phosphorus.
phosphorus threshold (TH level)	a specific soil test concentration of phosphorus established by states. The concentration defines the point at which soluble phosphorus may pose a surface runoff risk.
photoperiod	the time between sunrise and sunset
phytase	an enzyme effective at increasing the breakdown of phytase phosphorus in the digestive tract and reducing the phosphorous excretion in the feces
point source	the release of a contaminant or pollutant, often in concentrated form, from a conveyance system, such as a pipe, into a waterbody
porous dam	a runoff control structure that reduces the rate of runoff so that solids settle out in the settling terrace or basin. The structure may be constructed of rock, expanded metal, or timber arranged with narrow slots.

potassium	one of the primary nutrients required for the growth of plants
poult	a young, immature turkey
precipitation	a deposit on the earth of hail, mist, rain, sleet, or snow; *also* : the quantity of water deposited
pretreatment	a process used to reduce, eliminate, or alter the nature of wastewater pollutants from nondomestic sources before they are discharged into publicly owned treatment works
process wastewater	water directly or indirectly used in the operation of the CAFO for any or all of the following: spillage or overflow from animal or poultry watering systems; washing, cleaning, or flushing pens, barns, manure pits, or other CAFO facilities; direct contact swimming, washing or spray cooling of animals; litter or bedding; dust control; and stormwater which comes into contact with any raw materials, products or by-products of the operation.
production area	that part of the CAFO that includes the animal confinement area, the manure storage area, the raw materials storage area, and the waste containment areas. The animal confinement area includes but is not limited to open lots, housed lots, feedlots, confinement houses, stall barns, free stall barns, milkrooms, milking centers, cowyards, barnyard, exercise yards, animal walkways, and stables. The manure storage area includes but is not limited to lagoons, sheds, under house or pit storage, liquid impoundments, static piles, and composting piles. The raw materials storage area includes but is not limited to feed silos, silage bunkers, and bedding materials. The waste containment area includes but is not limited to settling basins, and areas within berms, and diversions which separate uncontaminated stormwater . Also included in the definition of production area is any egg washing or egg processing facility.
production phase	the animal life cycles grouped into discreet categories based on age and maturity
protease	any of numerous enzymes that hydrolyze proteins and are classified according to the most prominent functional group (as serine or cysteine) at the active site
PSES	Pretreatment Standards for Existing Sources
PSNS	Pretreatment Standards for New Sources
pullet	an immature female chicken

reduced-till	a management practice whereby the use of secondary tillage operations is significantly reduced
residue cover	unharvested material left on the soil surface designed to reduce water and wind erosion, maintain or increase soil organic matter, conserve soil moisture, stabilize temperatures, and provide food and escape cover for wildlife
RFA	Regulatory Flexibility Analysis
rill erosion	an erosion process in which numerous small channels of only several centimeters in depth are formed; occurs mainly on recently cultivated soils
runoff	the part of precipitation or irrigation water that appears in surface streams of waterbodies; expressed as volume (acre-inches) or rate of flow (gallons per minute, cubic feet per second)
SBA	Small Business Administration
SBREFA	Small Business Regulatory Enforcement Fairness Act
setback	a specified distance from surface waters or potential conduits to surface waters where manure and wastewater may not be land applied. Examples of conduits to surface waters include, but are not limited to, tile line intake structures, sinkholes, and agricultural well heads.
sheet erosion	soil erosion occurring from a thin, relatively uniform layer of soil particles on the soil surface; also called interrill erosion
side-dressing	the application of fertilizer alongside row crop plants, usually on the soil surface. Nitrogen materials are most commonly side-dressed.
sludge	settled sewage solids combined with varying amounts of water and dissolved materials that are removed from sewage by screening, sedimentation, chemical precipitation, or bacterial digestion
slurry	a thin mixture of a liquid and finely divided particles
soil test phosphorus	the measure of the phosphorus content in soil as reported by approved soil testing laboratories using a specified analytical method
sow	a mature female hog
spreader	a farm implement used to scatter fertilizer
supernatant	the liquid fraction in a lagoon

surface runoff	the portion of precipitation on an area that is discharged from the area through stream channels
surface water	all water whose surface is exposed to the atmosphere (Soil Conservation Society of America, 1982)
suspended solids	(1) undissolved solids that are in water, wastewater, or other liquids and are largely removable by filtering or centrifuging; (2) the quantity of material filtered from wastewater in a laboratory test, as prescribed in APHA Standard Methods for the Examination of Water and Wastewater or similar reference
tanker	a vehicle constructed to transport bulk liquids
tom	a male turkey
total suspended solids (TSS)	the weight of particles that are suspended in water. Suspended solids in water reduce light penetration in the water column, can clog the gills of fish and invertebrates, and are often associated with toxic contaminants because organics and metals tend to bind to particles. Differentiated from total dissolved solids by a standardized filtration process whereby the dissolved portion passes through the filter.
USDA	United States Department of Agriculture
volatilization	the loss of gaseous components, such as ammonium nitrogen, from animal manure
waste management system	a combination of conservation practices formulated to appropriately manage a waste product that, when implemented, will recycle waste constituents to the fullest extent possible and protect the resource base in a nonpolluting manner
wastewater	the spent or used water from a home, a community, a farm, or an industry that contains dissolved or suspended matter
water quality	the excellence of water in comparison with its intended use or uses

Health and Environmental Effects of Particulate Matter (PM)

Health Effects

The size of particles is directly linked to their potential for causing health problems. Small particles less than 10 micrometers in diameter pose the greatest problems, because they can get deep into your lungs, and some may even get into your bloodstream.

Exposure to such particles can affect both your lungs and your heart. Numerous scientific studies have linked particle pollution exposure to a variety of problems, including:

- premature death in people with heart or lung disease
- nonfatal heart attacks
- irregular heartbeat
- aggravated asthma <https://epa.gov/asthma>
- decreased lung function
- increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing.

People with heart or lung diseases, children, older adults, minority populations, and low socioeconomic status populations are the most likely to be affected by particle pollution exposure, either because they are more sensitive or may have higher exposures.

- AirNow <https://www.airnow.gov/> can help you monitor air quality near you, and protect yourself and your family from elevated PM levels.

Environmental Effects

Visibility impairment

Fine particles ($PM_{2.5}$) are the main cause of reduced visibility (haze) in parts of the United States, including many of our treasured national parks and wilderness areas. Learn more about visibility and haze <https://epa.gov/visibility>

Environmental damage

Particles can be carried over long distances by wind and then settle on ground or water. Depending on their chemical composition, the effects of this settling may include:

- making lakes and streams acidic
- changing the nutrient balance in coastal waters and large river basins
- depleting the nutrients in soil
- damaging sensitive forests and farm crops
- affecting the diversity of ecosystems
- contributing to acid rain effects <https://epa.gov/acidrain/effects-acid-rain>.

Materials damage

PM can stain and damage stone and other materials, including culturally important objects such as statues and monuments. Some of these effects are related to acid rain effects on materials <https://epa.gov/acidrain/effects-acid-rain#materials>.

Further Reading

Particle Pollution and Your Health (txt) (2 pp, 320 KB): Learn who is at risk from exposure to particle pollution, what health effects you may experience as a result of particle exposure, and simple measures you can take to reduce your risk.

How Smoke From Fires Can Affect Your Health <https://www.airnow.gov/air-quality-and-health/fires-and-your-health/>: It is important to limit your exposure to smoke -- especially if you may be susceptible.

EPA research on airborne particulate matter <https://epa.gov/air-research>: EPA supports research that provides the critical science on PM and other air pollutants to develop and implement Clean Air Act regulations that protect the quality of the air we breathe.

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C. Integrated Approaches

Minnesota



Air Emissions Planning

Minnesota Pollution Control Agency's (MPCA) Animal Feedlot or Manure Storage Area Permit Application (feedlot permit application), used for both NPDES and State Disposal System (SDS) permits, requires applicants to identify odor control strategies currently used at the feedlot and at least one possible additional odor control strategy for animal holding areas and liquid and solid manure storage areas, as stated in the feedlot permit application form provided by MPCA. Identification of air emission control strategies on the feedlot permit application satisfies the requirement of Minn. R.7020.0505 subp. 4 item B (1) for air emissions plans for animal holding areas and manure storage areas.

The air emissions plan is an enforceable component of Minnesota's NPDES CAFO permit and SDS pemits. By signing the feedlot permit application the applicant certifies that if ambient air quality monitoring during a MPCA complaint response indicates an exceedance of the Hydrogen Sulfide Standard[1], the permittee will implement the air emissions plan as required by the permit and submit a report, at MPCA's request, documenting that one of the following best management practices (BMPs) will be implemented to control air emissions:

Liquid manure storage areas

- Chemical additions
- Natural crusting
- Straw cover
- Treatment of escaping air
- Synthetic cover (i.e., High-density polyethylene [HDPE])

Solid manure storage areas

- Synthetic cover
- Frequent manure removal
- Frequent land application
- Incineration
- Composting

The permittee's report must provide evidence that the selected technology will control air emissions, state when the technology will be installed and fully operational, and report temporary measures to minimize emissions prior to installation of the selected control technology. The permittee must immediately implement the air emission control BMPs upon MPCA approval. The air emissions plan becomes effective when MPCA issues permit coverage, not upon signing the application.

Programmatic Framework

The Minnesota Ambient Hydrogen Sulfide Air Quality Standards were promulgated in 1969 (MPCA n.d.a). MPCA was directed to monitor and identify livestock facility violations of the state ambient air quality standards for hydrogen sulfide through Minnesota Statutes 116.0713 (Supp. 1997). To regulate the odor produced from feedlots, it was necessary to identify a quantifiable component that could be regulated. H_2S had been identified to be a significant component of feedlot odors and was also a quantifiable gas with a known toxicology. H_2S was also known to be a human health concern. Minnesota Department of Health (MDH) monitored ambient air quality in the vicinity of large swine facilities in

[1] Minnesota's air pollution standard for hydrogen sulfide (H_2S) is a 30-minute average of 30 parts per billion (ppb) twice in five days, or a 30-minute average of 50 ppb twice per year.

1995 and 1996. H_2S levels appeared to exceed state standards and were characterized as a human health concern. Data collected indicated that H_2S was the primary compound of concern in livestock odors (MPCA 1998). MPCA's *Statement of Need and Reasonableness (SONAR) In the Matter of Proposed Amendments to Minnesota Rules Relating to Animal Feedlots, Storage, Transportation, and Utilization of Animal Manure* proposed the inclusion of an air emissions plan in permit applications for facilities with 1,000 or more animal units to control and reduce air emissions. Smaller feedlots also must comply with the H_2S standard, with the exception of certain times during pumpout.

MPCA is authorized to implement the air emissions plan requirement found in Minn. R.7020.0505 subp. 4 item B (1) pursuant to the 2015 Minnesota Statutes:

- Chapter 115 Water Pollution Control; Sanitary Districts, Section 03 Powers and Duties; and
- Chapter 116 Pollution Control Agency, Section 07 Powers and Duties.

MPCA is required to monitor feedlots for H_2S and to take enforcement action when needed pursuant to the 2015 Minnesota Statutes 116.0713 Livestock Odor.

Minnesota Administrative Rules
7020.0505 PERMIT APPLICATIONS AND PROCESSING PROCEDURES

Subp. 4. **Content of permit application.**

B. In addition to the requirements of item A [required information for permit application], a permit application for an animal feedlot capable of holding 1,000 animal units or more or a manure storage area capable of holding the manure produced by 1,000 animal units or more must contain:

4. B. (1) an air emission plan that includes:

(a) methods and practices that will be used to minimize air emissions resulting from animal feedlot or manure storage area operations including manure storage area start-up practices, loading, and manure removal;

(b) measures to be used to mitigate air emissions in the event of an exceedance of the state ambient hydrogen sulfide standard; and

(c) a complaint response protocol describing the procedures the owner will use to respond to complaints directed at the facility, including:

i. a list of each potential odor source at the facility;

ii. a determination of the odor sources most likely to generate significant amounts of odors; and

iii. a list of anticipated odor control strategies for addressing each of the significant odor sources…

Implementation

Approximately 1,300 Minnesota CAFOs have completed air emissions plans when submitting the feedlot permit application. Inspection and enforcement of a CAFO's air emissions plan is largely driven by complaints received by MPCA. If a complaint is received about air emissions from a CAFO, MPCA staff may visit the facility. If MPCA staff believe the odor could be H_2S-related or have received a high frequency of complaints, they will collect instantaneous H_2S level readings using a hand-held meter,

called a Jerome Meter. Continuous air monitoring (CAM) may be required at the facility, depending on exceedance detected by a Jerome meter, number and nature of complaints, whether or not the actions required by the permit air emissions plan are implemented and effective, and site conditions. MPCA will only make a compliance determination on H_2S with CAM data.

If the H_2S emissions are not reduced, the MPCA may take enforcement action, which may include an administrative penalty order (APO) or stipulation agreement (MPCA n.d.b; MPCA n.d.c). An APO assigns a monetary penalty and a schedule of actions the violator must follow to return to compliance. A stipulation agreement is a negotiated settlement used when actions needed to correct the problem may take longer than 30 days to complete or if the violations warrant a civil penalty greater than $20,000. (MPCA n.d.c). According to MPCA, within the past 15 years, MPCA has only encountered 3 or 4 enforcement cases.

Results

According to the MPCA, the number of odor complaints has been reduced as a result of CAFOs that have implemented their air emissions plans.

References

MPCA (Minnesota Pollution Control Agency). n.d.a. Ambient Air Quality & Feedlots: Minnesota's Regulations, Program, Procedures, and Experiences. http://dnr.wi.gov/topic/AirQuality/documents/bmp/File7.pdf. Accessed February 12, 2016.

MPCA (Minnesota Pollution Control Agency). n.d.b. *Frequently asked questions about livestock odor*. https://www.pca.state.mn.us/quick-links/frequently-asked-questions-about-livestock-odor. Accessed February 10, 2016.

MPCA (Minnesota Pollution Control Agency). n.d.c. *Enforcement*. https://www.pca.state.mn.us/regulations/enforcement. Accessed February 10, 2016.

MPCA (Minnesota Pollution Control Agency). 1998. *Legislative Report of the Feedlot Hydrogen Sulfide Program*. http://archive.leg.state.mn.us/docs/pre2003/mandated/980083.pdf. Accessed February 12, 2016.

EPA: Greenhouse Gases Threaten Public Health and the Environment / Science overwhelmingly shows greenhouse gas concentrations at unprecedented levels due to human activity

epa.gov/archive/epapages/newsroom_archive/newsreleases/08d11a451131bca585257685005bf252.html

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Release Date: 12/07/2009
Contact Information: Cathy Milbourn, Milbourn.cathy@epa.gov, 202-564-7849, 202-564-4355; En español: Lina Younes, younes.lina@epa.gov, 202-564-9924, 202-564-4355 **EPA: Greenhouse Gases Threaten Public Health and the Environment**
Science overwhelmingly shows greenhouse gas concentrations at unprecedented levels due to human activity **WASHINGTON** – After a thorough examination of the scientific evidence and careful consideration of public comments, the U.S. Environmental Protection Agency (EPA) announced today that greenhouse gases (GHGs) threaten the public health and welfare of the American people. EPA also finds that GHG emissions from on-road vehicles contribute to that threat.

GHGs are the primary driver of climate change, which can lead to hotter, longer heat waves that threaten the health of the sick, poor or elderly; increases in ground-level ozone pollution linked to asthma and other respiratory illnesses; as well as other threats to the health and welfare of Americans.

“These long-overdue findings cement 2009’s place in history as the year when the United States Government began addressing the challenge of greenhouse-gas pollution and seizing the opportunity of clean-energy reform,” said EPA Administrator Lisa P. Jackson. “Business leaders, security experts, government officials, concerned citizens and the United States Supreme Court have called for enduring, pragmatic solutions to reduce the greenhouse gas pollution that is causing climate change. This continues our work towards clean energy reform that will cut GHGs and reduce the dependence on foreign oil that threatens our national security and our economy.”

EPA’s final findings respond to the 2007 U.S. Supreme Court decision that GHGs fit within

the Clean Air Act definition of air pollutants. The findingsdo not in and of themselves impose any emission reduction requirements but rather allow EPA to finalize the GHG standards proposed earlier this year for new light-duty vehicles as part of the joint rulemaking with the Department of Transportation.

On-road vehicles contribute more than 23 percent of total U.S. GHG emissions. EPA's proposed GHG standards for light-duty vehicles, a subset of on-road vehicles, would reduce GHG emissions by nearly 950 million metric tons and conserve 1.8 billion barrels of oil over the lifetime of model year 2012-2016 vehicles.

EPA's endangerment finding covers emissions of six key greenhouse gases – carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride – that have been the subject of scrutiny and intense analysis for decades by scientists in the United States and around the world.

Scientific consensus shows that as a result of human activities, GHG concentrations in the atmosphere are at record high levels and data shows that the Earth has been warming over the past 100 years, with the steepest increase in warming in recent decades. The evidence of human-induced climate change goes beyond observed increases in average surface temperatures; it includes melting ice in the Arctic, melting glaciers around the world, increasing ocean temperatures, rising sea levels, acidification of the oceans due to excess carbon dioxide, changing precipitation patterns, and changing patterns of ecosystems and wildlife.

President Obama and Administrator Jackson have publicly stated that they support a legislative solution to the problem of climate change and Congress' efforts to pass comprehensive climate legislation. However, climate change is threatening public health and welfare, and it is critical that EPA fulfill its obligation to respond to the 2007 U.S. Supreme Court ruling that determined that greenhouse gases fit within the Clean Air Act definition of air pollutants.

EPA issued the proposed findings in April 2009 and held a 60-day public comment period. The agency received more than 380,000 comments, which were carefully reviewed and considered during the development of the final findings.

Information on EPA's findings: https://www.epa.gov/climatechange/endangerment.html

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Recent additions

12/23/2014	EPA Announces Availability of $2.7 Million in Environmental Education Local Grants
12/23/2014	EPA, Coast Guard Extend Pollution Control Agreement with Royal Caribbean: New advanced technologies allow industry to comply with emission standards, reduce costs
12/23/2014	EPA to Hold Public Hearings in California, Texas and D.C. on Proposed Smog Standards
12/23/2014	Nominations for EPA New England's Annual Environmental Merit Awards-Deadline is January 30, 2015
12/22/2014	XTO Energy, Inc. to Restore Areas Damaged by Natural Gas Extraction Activities

Sources and Solutions: Agriculture

Farmers apply nutrients on their fields in the form of chemical fertilizers and animal manure, which provide crops with the nitrogen and phosphorus necessary to grow and produce the food we eat. However, when nitrogen and phosphorus are not fully utilized by the growing plants, they can be lost from the farm fields and negatively impact air and downstream water quality.

Watch

The U.S. Department of Agriculture's YouTube Channel: **Preventing Runoff Into The Mississippi River**

This excess nitrogen and phosphorus can be washed from farm fields and into waterways during rain events and when snow melts, and can also leach through the soil and into groundwater over time. High levels of nitrogen and phosphorus can cause eutrophication of water bodies. Eutrophication can lead to hypoxia (“dead zones”), causing fish kills and a decrease in aquatic life. Excess nutrients can cause harmful algal blooms (HABs) in freshwater systems, which not only disrupt wildlife but can also produce toxins harmful to humans.

Fertilized soils, as well as livestock operations, are also vulnerable to nutrient losses to the air. Nitrogen can be lost from farm fields in the form of gaseous, nitrogen-based compounds, like ammonia and nitrogen oxides. Ammonia can be harmful to aquatic life if large amounts are deposited from the atmosphere to surface waters. Nitrous oxide is a potent greenhouse gas.



Applying fertilizers in the proper amount, at the right time of year and with the right

There are many ways that farmers can reduce nutrient losses from their operations[1], including, but not limited to[2].

method can significantly reduce how much fertilizer reaches water bodies.

- **Adopting Nutrient Management Techniques:** Farmers can improve nutrient management practices by applying nutrients (fertilizer and manure) in the right amount, at the right time of year, with the right method and with the right placement.[3,4]
- **Using Conservation Drainage Practices:** Subsurface tile drainage is an important practice to manage water movement on and through many soils, typically in the Midwest. Drainage water can carry soluble forms of nitrogen and phosphorus, so strategies are needed to reduce nutrient loads while maintaining adequate drainage for crop production. Conservation drainage describes practices including modifying drainage system design and operation, woodchip bioreactors, saturated buffers, and modifications to the drainage ditch system. [5,6]
- **Ensuring Year-Round Ground Cover:** Farmers can plant cover crops[7] or perennial species[8] to prevent periods of bare ground on farm fields when the soil (and the soil and nutrients it contains) are most susceptible to erosion and loss into waterways.
- **Planting Field Buffers:** Farmers can plant trees, shrubs and grasses along the edges of fields; this is especially important for a field that borders water bodies. Planted buffers can help prevent nutrient loss from fields by absorbing or filtering out nutrients before they reach a water body.[9]
- **Implementing Conservation Tillage:** Farmers can reduce how often and how intensely the fields are tilled. Doing so can help to improve soil health, and reduce erosion, runoff and soil compaction, and therefore the chance of nutrients reaching waterways through runoff.[10]

- **Managing Livestock Access to Streams:** Farmers and ranchers can install fence along streams, rivers and lakes to block access from animals to help restore stream banks and prevent excess nutrients from entering the water.[11]
- **Engaging in Watershed Efforts:** The collaboration of a wide range of people, stakeholders and organizations across an entire watershed is vital to reducing nutrient pollution to our water and air. Farmers can play an important leadership role in these efforts when they get involved and engage with their State governments, farm organizations, conservation groups, educational institutions, non-profit organizations, and community groups.



Keeping animals and their waste out of streams keeps nitrogen and phosphorus out of the water and protects stream banks.

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[1] Reducing Nutrient Loss: Science Shows What Works <https://store.extension.iastate.edu/product/reducing-nutrient-loss-science-shows-what-works>

[2] USDA Natural Resource Conservation Service Conservation Practice Standards <https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/cp/ncps/> are the best available baseline nationally for implementation of these practices.

[3] Pennsylvania Nutrient Management Program <https://extension.psu.edu/programs/nutrient-management>

[4] Best Management Practices for Agricultural Nutrients <https://content.ces.ncsu.edu/best-management-practices-for-agricultural-nutrients>

[5] Transforming Drainage <https://transformingdrainage.org/>

[6] Conservation Drainage for the Midwest <https://engineering.purdue.edu/watersheds/conservationdrainage/index.html>

[7] Cover Crops - Keeping Soil in Place While Providing Other Benefits

[8] Research shows perennials would reduce nutrient runoff to the Gulf of America's dead zone <https://phys.org/news/2016-07-perennials-nutrient-runoff-gulf-mexico.html>

[9] Buffers and Vegetative Filter Strips <https://epa.gov/sites/production/files/2015-07/documents/2006_8_24_msbasin_symposia_ia_session4-2.pdf>

[10] Conservation tillage <http://asi.ucdavis.edu/programs/sarep/about/copy_of_what-is-sustainable-agriculture/practices/conservation-tillage>

[11] Stream Bank Fencing: Green Banks, Clean Streams <https://extension.psu.edu/programs/nutrient-management/educational/best-management-practices/stream-bank-fencing-green-banks-clean-streams>

Last updated on March 20, 2025

Sources of Greenhouse Gas Emissions

epa.gov/ghgemissions/sources-greenhouse-gas-emissions

December 29, 2015

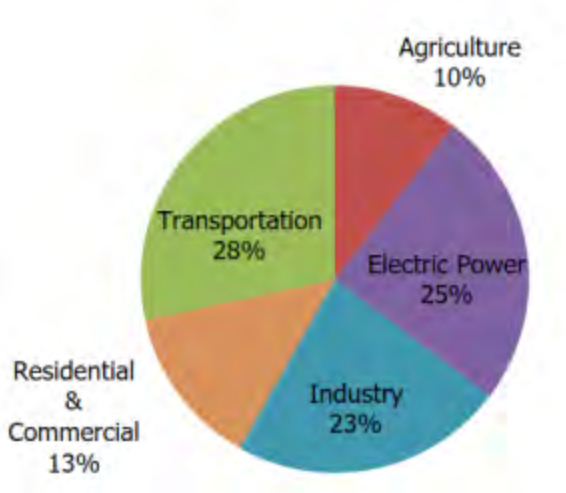

On this page:

- Sources of Greenhouse Gas Emissions: Overview
- Greenhouse Gas Emissions Trends: All Sources

Sources of Greenhouse Gas Emissions: Overview

Greenhouse gases trap heat and make the planet warmer. Human activities are responsible for almost all of the increase in greenhouse gases in the atmosphere over the last 150 years.[1] The largest source of greenhouse gas emissions from human activities in the United States is from burning fossil fuels for electricity, heat, and transportation.

EPA tracks total U.S. emissions by publishing the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. This annual report estimates the total national greenhouse gas emissions and removals associated with human activities across the United States by source, gas, and economic sector.

Total emissions in 2022 are 6,343.2 Million Metric Tons of CO_2 equivalent. Percentages may not add up to 100% due to independent rounding. Greenhouse gas emissions from the commercial, residential, and industrial sectors increase substantially when indirect emissions from electricity end-use are included, due to the relatively large share of electricity use by buildings (e.g., heating, ventilation, and air conditioning; lighting; appliances and plug load) and use of electricity for powering industrial machinery. More information is also in the electricity end-use emissions section of the Electric Power sector page.

Land Use, Land-Use Change, and Forestry in the United States is a net sink and offsets 13% of these greenhouse gas emissions. This net sink is not shown in the above diagrams. All emission estimates are sourced from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*.

What are the primary sources of U.S. greenhouse gas emissions and sinks in each economic sector?

- **Transportation** – Greenhouse gas emissions from transportation primarily come from burning fossil fuel for cars, trucks, ships, trains, and planes. Over 94% of the fuel used for transportation is petroleum based, which includes primarily gasoline and diesel and results in direct emissions.[2] The transportation sector is the largest source of direct greenhouse gas emissions and second largest source when indirect emissions from electricity end-use are allocated across sectors. The transportation sector is an end-use sector for electricity but currently represents a relatively low percentage of total electricity use. Indirect emissions from electricity are less than 1 percent of direct emissions.
- **Electricity production** – Electric power includes emissions from electricity production used by other end use sectors (e.g., industry). In 2022, 60% of our electricity comes from burning fossil fuels, mostly coal and natural gas.[3]
- **Industry** – Greenhouse gas emissions from industry primarily come from burning fossil fuels for energy, as well as greenhouse gas emissions from certain chemical reactions necessary to produce goods from raw materials. Industrial emissions are the third largest source of direct emissions. If indirect emissions from electricity use are allocated to the industrial end-use sector (e.g. to power industrial buildings and equipment), industrial activities account for a much larger share of U.S. greenhouse gas emissions as shown above.
- **Commercial and Residential** – Greenhouse gas emissions from the commercial and residential sector come from fossil fuels burned for heat and the use of gases for refrigeration and cooling in buildings, and non-building specific emissions such as the handling of waste. The commercial and residential sector emissions increase substantially when indirect emissions from electricity end-use are included, largely because buildings use 75% of the electricity generated in the US (e.g., for heating, ventilation and air conditioning; lighting; appliances, and plug loads).[4] When emissions from electricity use are distributed to the commercial and residential end-use sector, commercial and residential activities account for a much larger share of U.S. greenhouse gas emissions as shown above.
- **Agriculture** – Greenhouse gas emissions from agriculture come from livestock such as cows, agricultural soils, and rice production. Indirect emissions from electricity use in agricultural activities (e.g., powering buildings and equipment) are about 5 percent of direct emissions.

- **Land Use and Forestry** – While not shown in the figure, land areas can act as a sink (absorbing CO_2 from the atmosphere) or a source of greenhouse gas emissions. In the United States, since 1990, managed forests and other lands are a net sink, i.e., they have absorbed more CO_2 from the atmosphere than they emit, offsetting 13% of total gross greenhouse gas emissions.

See Emissions Information and Reduction Strategies by Source

Electric Power Transportation Industry Commercial/Residential

Agriculture Land Use/Forestry

Greenhouse Gas Emissions Trends: All Sources

- Since 1990, gross U.S. greenhouse gas emissions have decreased by just over 3%. From year to year, emissions can rise and fall due to changes in the economy, the price of fuel, and other factors.
- In 2022, U.S. greenhouse gas emissions increased 0.2% compared to 2021 levels. In 2020, there was a sharp decline in emissions largely due to the impacts of the coronavirus (COVID-19) pandemic on travel and other economic activity. In 2021 and 2022, the increase in total greenhouse gas emissions was driven largely by an increase in CO_2 emissions from fossil fuel combustion due to the continued rebound in economic activity after the height of the COVID-19 pandemic.
- In 2022, CO_2 emissions from fossil fuel combustion increased by 8% relative to 2020 and 1% relative to 2021. CO_2 emissions from natural gas consumption increased by 5% relative to 2021. CO_2 emissions from coal consumption decreased by 6% from 2021. The increase in natural gas consumption and emissions in 2022 is observed across all sectors except for U.S. Territories, while the coal decrease in primarily in the electric power sector. Emissions from petroleum use increased by less than 1% in 2022.

References

1. IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. .

2. IPCC (2022): Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
3. U.S. Energy Information Administration (2023). *Electricity Explained – Basics*
4. National Renewable Energy Laboratory (2023). NREL Researchers Reveal How Buildings Across United States Do—and Could—Use Energy. Shoemaker, Susannah.

Explanation of Units

A million metric tons of CO_2: What does that mean?

A million metric tons equals about 2.2 billion pounds, or 1 trillion grams. For comparison, a small car is likely to weigh a little more than 1 metric ton. Thus, a million metric tons are roughly the same mass as 1 million small cars.

The U.S. GHG Inventory uses metric units for consistency and comparability with other countries. For reference, a metric ton is slightly more (approximately 10%) than a U.S. "short" ton.

Greenhouse gas emissions are often measured in carbon dioxide (CO_2) *equivalent*. To convert emissions of a gas into CO_2 equivalent, its emissions are multiplied by the gas's Global Warming Potential (GWP). The GWP takes into account the fact that many gases are more effective at warming Earth than CO_2, per unit mass.

The GWP values appearing in the Overview of Greenhouse Gases and Sources of Greenhouse Gas web pages reflect the values used in the U.S. GHG Inventory, which are drawn from the IPCC's Fifth Assessment Report (AR5). For further discussion of GWPs and an estimate of greenhouse gas emissions using updated GWPs, see Annex 6 of the U.S. GHG Inventory and the IPCC's discussion on GWPs (pdf) (106 pp, 7.7MB).

The Effects: Dead Zones and Harmful Algal Blooms

Dead zones are areas of water bodies where aquatic life cannot survive because of low oxygen levels. Dead zones are generally caused by significant nutrient pollution, and are primarily a problem for bays, lakes and coastal waters since they receive excess nutrients from upstream sources.

Watch

YouTube: Dead Zones



Harmful algal blooms cause thick, green muck that impacts clear water, recreation, businesses and property values.

Excess nitrogen and phosphorus cause an overgrowth of algae in a short period of time, also called algae blooms. The overgrowth of algae consumes oxygen and blocks sunlight from underwater plants. When the algae eventually dies, the oxygen in the water is consumed. The lack of oxygen makes it impossible for aquatic life to survive. The largest dead zone in the United States – about 6,500 square miles – is in the Gulf of America and occurs every summer as a result of nutrient pollution from the Mississippi River Basin.

When some types of algae blooms are large and produce chemicals, or toxins, the event is called a harmful algal bloom. Harmful algal blooms can occur in lakes, reservoirs, rivers, ponds, bays and coastal waters, and the toxins they produce can be harmful to human health and aquatic life. Harmful algal blooms are mainly the result of a type of algae called cyanobacteria, also known as blue-green algae.

Elevated nutrient levels and algal blooms can also cause problems in drinking water in communities nearby and upstream from dead zones. Harmful algal blooms release toxins that contaminate drinking water, causing illnesses for animals and humans.

Last updated on February 5, 2025

Understanding Global Warming Potentials

epa.gov/ghgemissions/understanding-global-warming-potentials

January 12, 2016



Greenhouse gases (GHGs) warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space; they act like a blanket insulating the Earth. Different GHGs can have different effects on the Earth's warming. Two key ways in which these gases differ from each other are their ability to absorb energy (their "radiative efficiency"), and how long they stay in the atmosphere (also known as their "lifetime").

Starting in 1990, the Intergovernmental Panel on Climate Change (IPCC) (pdf) has used the Global Warming Potential (GWP) to allow comparisons of the global warming impacts of different gases. Specifically, the GWP is a measure of how much energy the emission of 1 ton of a gas will absorb over a given period of time, relative to the emission of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years.

GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases (e.g., to compile a national GHG inventory), and allows policymakers to compare emissions reduction opportunities across sectors and gases.

- CO_2, by definition, has a GWP of 1 regardless of the time period used, because it is the gas being used as the reference. CO_2 remains in the climate system for a very long time: CO_2 emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years.

- Methane (CH_4) is estimated to have a GWP of 27 to 30 over 100 years. CH_4 emitted today lasts about a decade on average, which is much less time than CO_2. But CH_4 also absorbs much more energy than CO_2. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. The CH_4 GWP also accounts for some indirect effects, such as the fact that CH_4 is a precursor to ozone, and ozone is itself a GHG.
- Nitrous Oxide (N_2O) has a GWP 273 times that of CO_2 for a 100-year timescale. N_2O emitted today remains in the atmosphere for more than 100 years, on average. (Learn why EPA's U.S. Inventory of Greenhouse Gas Emissions and Sinks uses a different value.)
- Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) , and nitrogen trifluoride (NF_3) are sometimes called high-GWP gases because, for a given amount of mass, they trap substantially more heat than CO_2. The GWPs for these gases can be in the thousands or tens of thousands. Once emitted, PFCs, SF_6, and NF_3 persist in the atmosphere for hundreds or thousands of years.

Learn more about the main GHGs on our Overview page. Explore the questions and answers below to learn more about global warming potentials (GWPs).

Frequently Asked Questions

- Why does the IPCC definition of GWP differ from the definitions used in ISO (e.g., 14044 and 21930:2017) and related Environmental Product Declarations and Product Category Rules?
- Why do GWPs change over time?
- Why are GWPs presented as ranges?
- What GWP estimates does EPA use for GHG emissions accounting, such as the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (Inventory) and the Greenhouse Gas Reporting Program?
- Are there alternatives to the 100-year GWP for comparing GHGs?

The International Organization for Standardization (ISO) community differs in its definition and use of the term Global Warming Potential (GWP) from that used by IPCC (pdf). This ISO approach is applied in Environmental Production Declaration (EPD), Product Category Rules (PCR), Buy Clean Policies, and related programs. This definition and use are inconsistent with how GWP is defined by the IPCC and used in many international GHG accounting efforts, including national reporting by Parties to the UNFCCC and Paris Agreement.

The ISO and relevant communities use the term "GWP" as an impact category to refer to the embodied greenhouse gases of a specific product or product-level GHG emission intensities (see, e.g., ISO 21930:2017). This specific use of GWP by the EPD community refers to the total greenhouse gas emissions directly associated with the production of a product, including the upstream activities of extraction and transport of raw materials. This type of calculation can also be described with terms such as "embodied GHG equivalent" or "GHG footprint." The product GWP measure is reported in CO_2-equivalents per functional unit in EPDs, PCRs, etc. However, the ISO calculation of CO_2-equivalents requires the use of the original GWP as defined by IPCC, thereby making the EPD/ISO GWP inherently confusing as it uses both meanings of the term GWP simultaneously.

To reduce confusion, the use of the term "Global Warming Potential" or "GWP" that fall outside the IPCC definition or use—i.e., a measure of the relative climate impact of a given greenhouse gas relative to the impact of carbon dioxide (as defined on this page)—should include a definition of the non-IPCC usage of the term to distinguish it from the original established IPCC definition. In the case of how ISO and relevant communities use the term GWP, it should be clearly explained that the specific meaning in that context refers to "embodied GHG equivalent," "embodied GHG emissions," or "carbon equivalent footprint," as applicable. This context is especially important if the document uses both different meanings of the term "GWP" such as in the ISO/EPD context.

EPA and other organizations will update the GWP values they use occasionally. This change can be due to updated scientific estimates of the energy absorption or lifetime of the gases or to changing atmospheric concentrations of GHGs that result in a change in the energy absorption of 1 additional ton of a gas relative to another.

In the most recent report by the Intergovernmental Panel on Climate Change (IPCC), multiple methods of calculating GWPs were presented based on how to account for the influence of future warming on the carbon cycle. For this web page, we are presenting the range of the lowest to the highest values listed by the IPCC.

EPA considers the GWP estimates presented in the most recent IPCC scientific assessment to reflect the state of the science. In science communications, EPA will refer to the most recent GWPs. The GWPs listed above are from the IPCC's Sixth Assessment Report, published in 2021.

EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (Inventory) complies with international GHG reporting standards under the United Nations Framework Convention on Climate Change (UNFCCC). UNFCCC guidelines now require the use of the GWP values from the IPCC's Fifth Assessment Report (AR5), published in 2013. The Inventory also presents emissions by mass, so that CO_2 equivalents can be calculated using any GWPs, and emission totals using more recent IPCC values are presented in the annexes of the Inventory report for informational purposes.

The data collected by EPA's Greenhouse Gas Reporting Program is generally reported in mass units of greenhouse gas and is used in the Inventory. The Reporting Program generally uses GWP values from the IPCC's Fourth Assessment Report (AR4) to determine whether facilities exceed reporting thresholds and to publish data in CO2 equivalent values. The Reporting Program collects data about some industrial gases that do not have GWPs listed in the AR4; for these gases, the Reporting Program uses GWP values from other sources, such as the AR5.

EPA's CH_4 reduction voluntary programs also use CH_4 GWPs from the AR5 report for calculating CH_4 emissions reductions through energy recovery projects, for consistency with the national emissions presented in the Inventory.

The United States primarily uses the 100-year GWP as a measure of the relative impact of different GHGs. However, the scientific community has developed a number of other metrics that could be used for comparing one GHG to another. These metrics may differ based on timeframe, the climate endpoint measured, or the method of calculation.

For example, the 20-year GWP is sometimes used as an alternative to the 100-year GWP. Just like the 100-year GWP is based on the energy absorbed by a gas over 100 years, the 20-year GWP is based on the energy absorbed over 20 years. This 20-year GWP prioritizes gases with shorter lifetimes, because it does not consider impacts that happen more than 20 years after the emissions occur. Because all GWPs are calculated relative to CO_2, GWPs based on a shorter timeframe will be larger for gases with lifetimes shorter than that of CO_2, and smaller for gases with lifetimes longer than CO_2. For example, for CH_4, which has a short lifetime, the 100-year GWP of 27–30 is much less than the 20-year GWP of 81–83. For CF_4, with a lifetime of 50,000 years, the 100-year GWP of 7380 is larger than the 20-year GWP of 5300.

Another alternate metric is the Global Temperature Potential (GTP). While the GWP is a measure of the heat absorbed over a given time period due to emissions of a gas, the GTP is a measure of the temperature change at the end of that time period (again, relative to CO_2).The calculation of the GTP is more complicated than that for the GWP, as it requires modeling how much the climate system responds to increased concentrations of GHGs (the climate sensitivity) and how quickly the system responds (based in part on how the ocean absorbs heat).

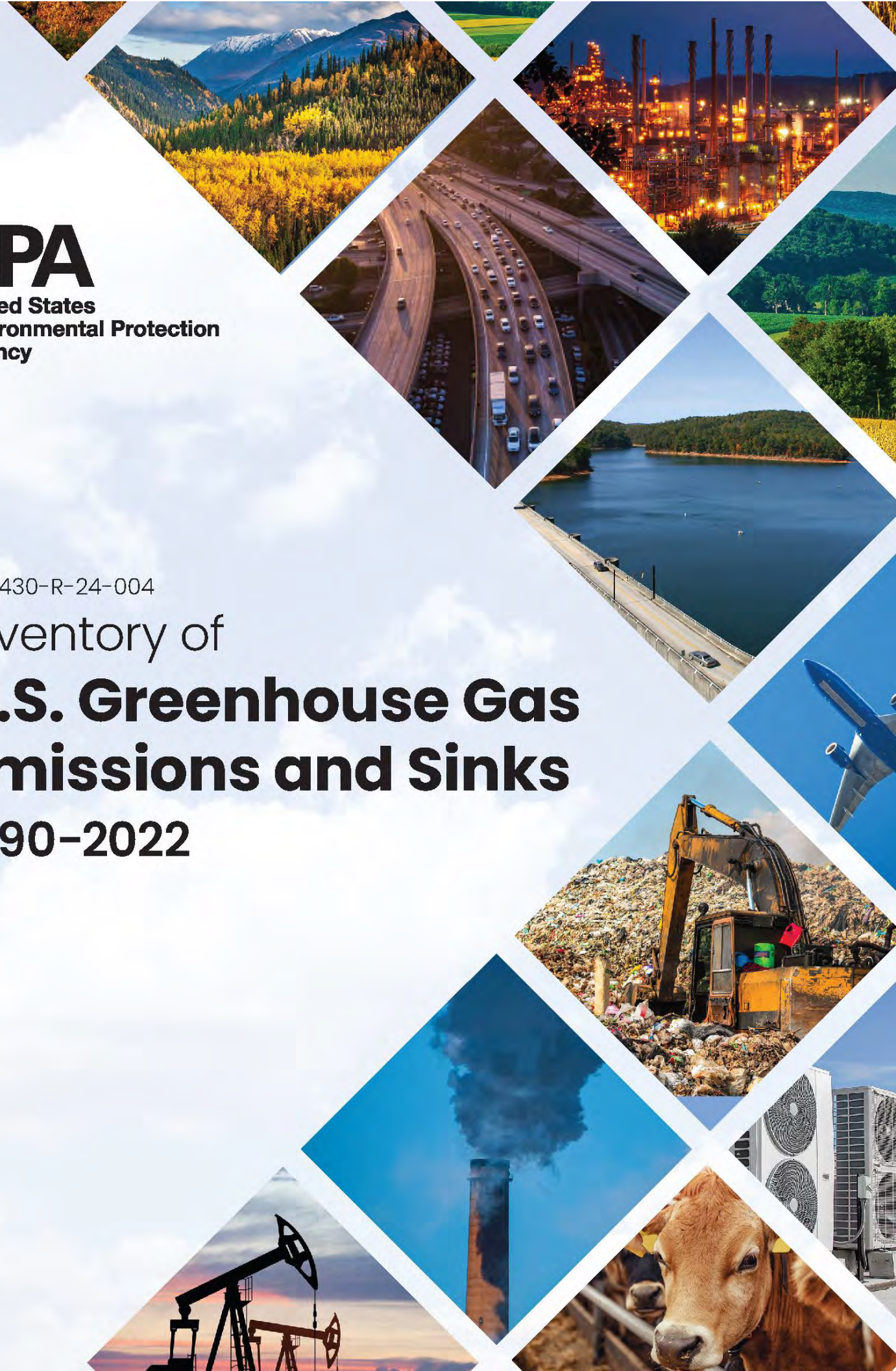

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Inventory of
U.S. Greenhouse Gas Emissions and Sinks
1990–2022

Front cover photo credit for cow and digester: Vanguard Renewables.

HOW TO OBTAIN COPIES

You can electronically download this document on the U.S. EPA's homepage at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

All data tables of this document for the full time series 1990 through 2022, inclusive, will be made available within 4-6 weeks after publication of the final report online at the link mentioned in the citation below.

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For more information regarding climate change and greenhouse gas emissions, see the EPA web site at https://www.epa.gov/ghgemissions.

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Preface

The United States Environmental Protection Agency (EPA) prepares the official U.S. Inventory of Greenhouse Gas Emissions and Sinks to fulfill annual existing commitments under the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). National greenhouse gas (GHG) inventory reports are to be submitted each year by April 15.

In an effort to engage the public and researchers across the country, the EPA has instituted an annual public review and comment process for this document. The draft document was announced via Federal Register Notice and published for a 30-day comment period on the EPA Greenhouse Gas Emissions and Removals web site from February 14 through March 15, 2024, and comments received during the public review period are posted to the docket EPA-HQ-OAR-2024-0004. Comments received after the closure of the public comment period will be considered for the next edition of this annual report. Responses to comments are typically posted to EPA's website 2-4 weeks following publication of the final report in April 2024.

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Executive Summary

An inventory that identifies and quantifies a country's anthropogenic[1] sources and sinks of greenhouse gas emissions and removals is essential for addressing climate change. This *Inventory* adheres to both (1) a comprehensive and detailed set of methodologies for estimating national sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent format that enables Parties to the Paris Agreement and United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different greenhouse gases emissions and removals to climate change.

The United States is party to both the 1992 UNFCCC and the 2015 Paris Agreement. The Paris Agreement set a global temperature goal – holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5°C – that articulates with greater precision States' views on what is necessary to meet the UNFCCC's objective of "stabiliz[ing] … greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[2]

The United States is committed to submitting a national inventory of anthropogenic emission sources and removals by sinks of greenhouse gases by April 15 of each year. The United States has prepared this report, in conjunction with Common Reporting Tables (CRTs) that accompany this report, consistent with its obligations under those agreements.

This Executive Summary provides the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2022. The structure of this report is consistent with requirements under the Paris Agreement and the UNFCCC on national greenhouse gas inventory reporting, as discussed in Box ES-1. Throughout this report, emission and sink estimates are grouped into five reporting sectors (i.e., chapters): Energy, IPPU, Agriculture, Land Use, Land-Use Change, and Forestry (LULUCF), and Waste. In describing trends (Chapter 2), emissions and sinks are also summarized according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. See Box 2-1 for more information on how economic sectors are defined.

Box ES-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines)* and, where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories

[1] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[2] See Paris Agreement, Article 2.1(a); UNFCCC, Article 2.

under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in this *Inventory* does not preclude alternative examinations (e.g., economic sectors). Rather, this *Inventory* presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP), which is complementary to the U.S. Inventory.[3] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[4] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for reporting year 2011.[5] Methodologies used in EPA's GHGRP are consistent with the 2006 IPCC Guidelines. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and removals (e.g., the GHGRP excludes emissions from the agricultural, land use, and forestry sectors), it is an important input to the calculations of national-level emissions in this *Inventory*.

The GHGRP dataset provides not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and subcategories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. See Annex 9 for more information on specific uses of GHGRP data in the Inventory (e.g., use of Subpart W data in compiling estimates for natural gas systems).

ES.1 Background Information

Greenhouse gases absorb infrared radiation, trapping heat in the atmosphere and making the planet warmer. The most important greenhouse gases directly emitted by human activities include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several fluorine-containing halogenated substances (HFCs, PFCs, SF_6 and NF_3). Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. From the pre-industrial era (i.e., ending about 1750) to 2022, concentrations of these greenhouse gases have increased globally by 49.5, 161.9, and 24.3 percent, respectively (IPCC 2013; NOAA/ESRL 2024a, 2024b, 2024c). This annual report estimates the total national greenhouse gas emissions and removals associated with human activities across the United States.

[3] On October 30, 2009, EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[4] See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

[5] See https://ccdsupport.com/confluence/pages/viewpage.action?pageId=322699300.

Global Warming Potentials

The IPCC developed the global warming potential (GWP) concept to compare the ability of a greenhouse gas to trap heat in the atmosphere relative to another gas. A GWP is a quantified measure of the relative globally averaged radiative forcing impacts of emissions of a particular greenhouse gas over time. The GWP of a greenhouse gas is defined as the ratio of the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram of the gas, relative to that of the reference gas CO_2 (IPCC 2021); therefore, CO_2-equivalent emissions are provided in million metric tons of CO_2 equivalent (MMT CO_2 Eq.) for non-CO_2 greenhouse gases.[6,7] All estimates are provided throughout the main report in both CO_2 equivalents and unweighted units, while estimates for all gases in this Executive Summary are presented in units of MMT CO_2 Eq. Emissions by gas in unweighted mass kilotons are also provided in the Trends chapter and individual sector chapters of this report, and in the CRTs that are included in the submission to the UNFCCC.

Recent decisions under the Paris Agreement[8] and the UNFCCC[9] require Parties to use 100-year GWP values from the IPCC *Fifth Assessment Report* (AR5) for calculating CO_2-equivalents in their national reporting (IPCC 2013) by the end of 2024. This reflects updated science and ensures that national greenhouse gas inventories reported by all nations are comparable. This report reflects CO_2-equivalent greenhouse gas emission totals using 100-year AR5 GWP values. A comparison of emission values with the IPCC *Sixth Assessment Report* (AR6) (IPCC 2021) values can be found in Annex 6.1 of this report. The 100-year GWP values used in this report are listed below in Table ES-1.

Table ES-1: Global Warming Potentials (100-Year Time Horizon) Used in this Report

Gas	GWP
CO_2	1
CH_4[a]	28
N_2O	265
HFCs	up to 12,400
PFCs	up to 11,100
SF_6	23,500
NF_3	16,100
Other Fluorinated Gases	See Annex 6

[a] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to production of CO_2 is not included. See Annex 6 for additional information.
Source: IPCC (2013).

[6] Carbon comprises 12/44 of carbon dioxide by weight.

[7] One million metric ton is equal to 10^{12} grams or one teragram.

[8] See Annex to decision 18/CMA.1, available online at https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[9] See paragraphs 1 and 2 of the decision on common metrics adopted at the 27th UNFCCC Conference of Parties (COP27), available online at https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2022, total gross U.S. greenhouse gas emissions were 6,343.2 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).[10] Total gross U.S. emissions decreased by 3.0 percent from 1990 to 2022, down from a high of 15.2 percent above 1990 levels in 2007. Gross emissions increased from 2021 to 2022 by 0.2 percent (14.4 MMT CO_2 Eq.). Net emissions (including sinks) were 5,489.0 MMT CO_2 Eq. in 2022. Overall, net emissions increased by 1.3 percent from 2021 to 2022 and decreased by 16.7 percent from 2005 levels as shown in Table ES-2. Between 2021 and 2022, the increase in total greenhouse gas emissions was driven largely by an increase in CO_2 emissions from fossil fuel combustion across most end-use sectors due in part to increased energy use from the continued rebound of economic activity after the height of the COVID-19 pandemic. In 2022, CO_2 emissions from fossil fuel combustion increased by 1.0 percent relative to the previous year and were 1.1 percent below emissions in 1990. Carbon dioxide emissions from natural gas use increased by 5.2 percent (84.8 MMT CO_2 Eq.) from 2021, while CO_2 emissions from coal consumption decreased by 6.1 percent (58.6 MMT CO_2 Eq.) from 2021 to 2022. The increase in natural gas consumption and associated emissions in 2022 is observed across all sectors except U.S. Territories, while the coal decrease is due to reduced use in the electric power sector. Emissions from petroleum use also increased by 0.9 percent (19.0 MMT CO_2 Eq.) from 2021 to 2022. Carbon sequestration from the Land Use, Land-Use Change, and Forestry (LULUCF) sector offset 14.5 percent of total emissions in 2022.

Figure ES-1 and Figure ES-2 illustrate the overall trends in total U.S. emissions by gas and annual percent changes, and Table ES-2 provides information on trends in gross U.S. greenhouse gas emissions and sinks for 1990 through 2022. Unless otherwise stated, all tables and figures provide total gross emissions and exclude the greenhouse gas fluxes from the LULUCF sector. For more information about the LULUCF sector, see Section ES-3.

[10] The gross emissions total presented in this report for the United States excludes emissions and removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and removals from LULUCF.

Figure ES-1: U.S. Greenhouse Gas Emissions and Sinks by Gas

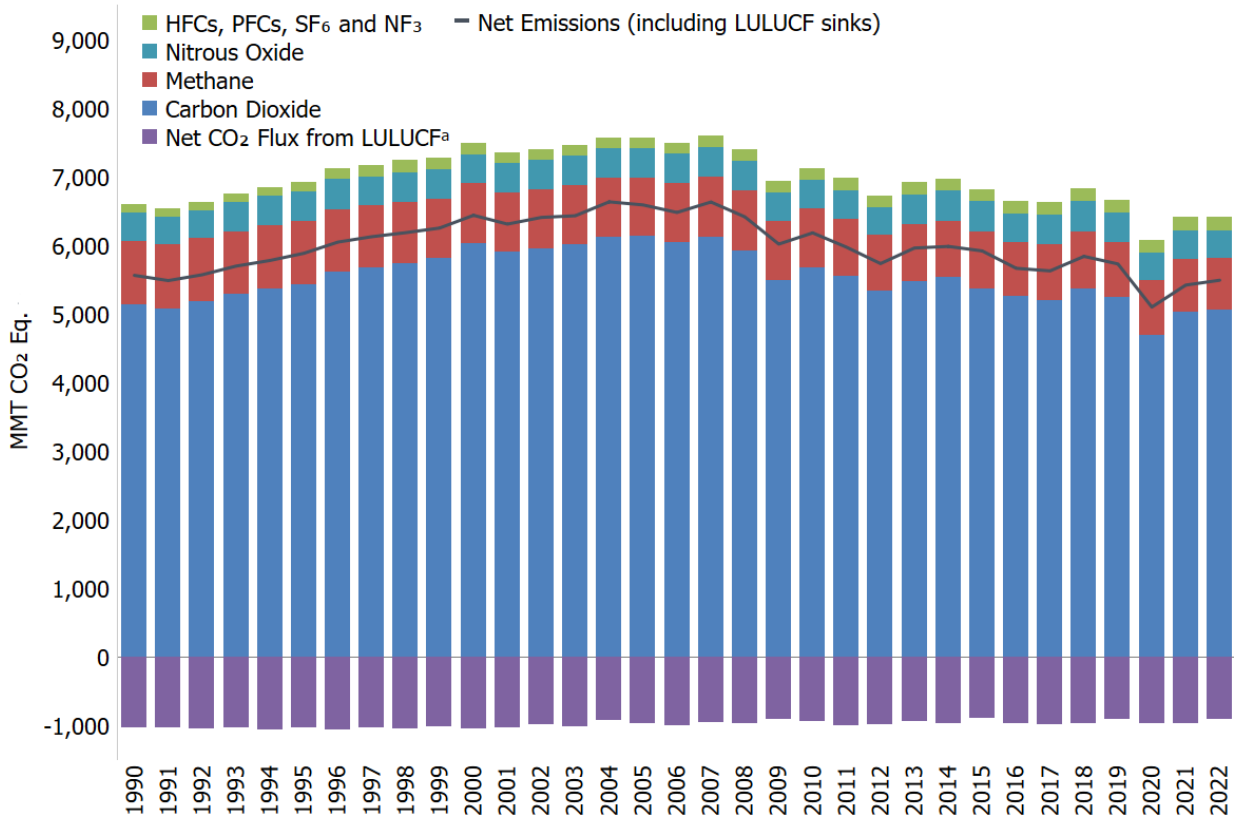

[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	5,131.6	6,126.9	5,362.2	5,234.5	4,689.0	5,017.2	5,053.0	-1.5%
CH_4 (excludes LULUCF sources)[a]	871.7	795.4	771.5	754.3	735.3	720.5	702.4	-19.4%
N_2O (excludes LULUCF sources)[a]	408.2	419.2	439.5	416.4	391.2	398.2	389.7	-4.5%
HFCs	47.7	121.7	163.9	168.2	170.3	177.0	182.8	282.9%
PFCs	39.5	10.2	7.4	7.3	6.6	6.3	6.7	-83.1%
SF_6	37.9	20.2	7.6	8.4	8.1	8.5	7.6	-80.0%
NF_3	0.3	1.0	0.7	1.1	1.3	1.1	1.1	238.3%
Total Gross Emissions (Sources)[a]	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Emissions[b]	58.0	68.9	62.8	58.0	68.4	72.9	67.6	16.5%
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4	10.0%
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1	88.3%
LULUCF Carbon Stock Change[c]	(1034.7)	(976.6)	(978.3)	(921.6)	(972.8)	(983.4)	(921.8)	-10.9%
LULUCF Sector Net Total[d]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] Gross emissions totals do not include CH_4 and N_2O emissions from LULUCF. LULUCF CH_4 and N_2O emissions are included in net emission totals.

[b] LULUCF emissions subtotal of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[c] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[d] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) are emissions presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Figure ES-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions and Sinks Relative to the Previous Year

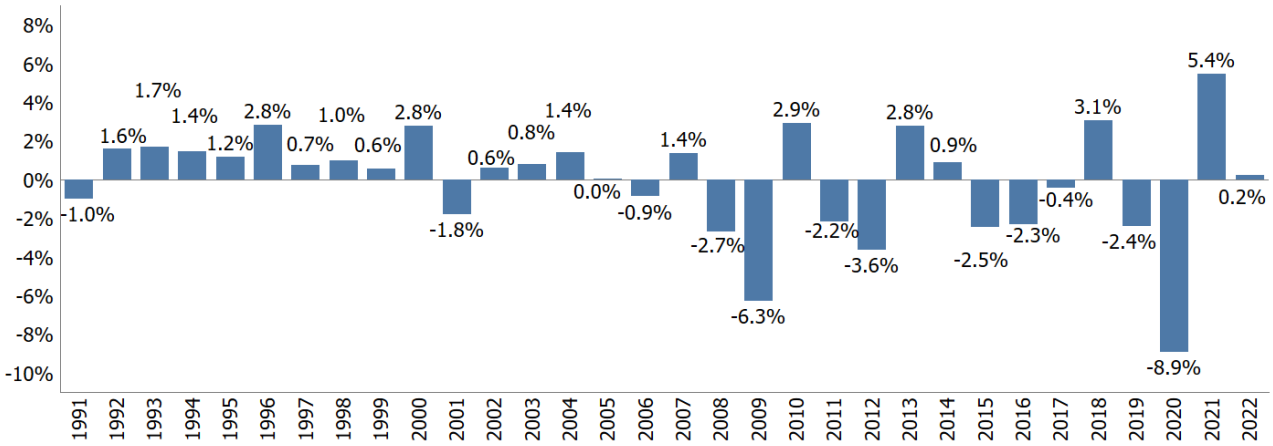

Improvements and Recalculations Relative to the Previous Inventory

Each year, some emission and removal estimates in the *Inventory* are recalculated and revised to incorporate improved methods and/or data. The most common reason for recalculating U.S. greenhouse gas emission estimates is to update recent historical data. Changes in historical data are generally the result of changes in data supplied by other U.S. government agencies or organizations, as they continue to make refinements and improvements. These improvements are implemented consistently across the previous *Inventory's* time series, as necessary, (i.e., 1990 to 2021) to ensure that the trend is accurate.

Collectively, all methodological changes and historical data updates made in the current *Inventory* resulted in an annual average decrease of 114.8 MMT CO_2 Eq. (1.9 percent) for net emissions.

Figure ES-3: Impacts of Recalculations on Net Emissions

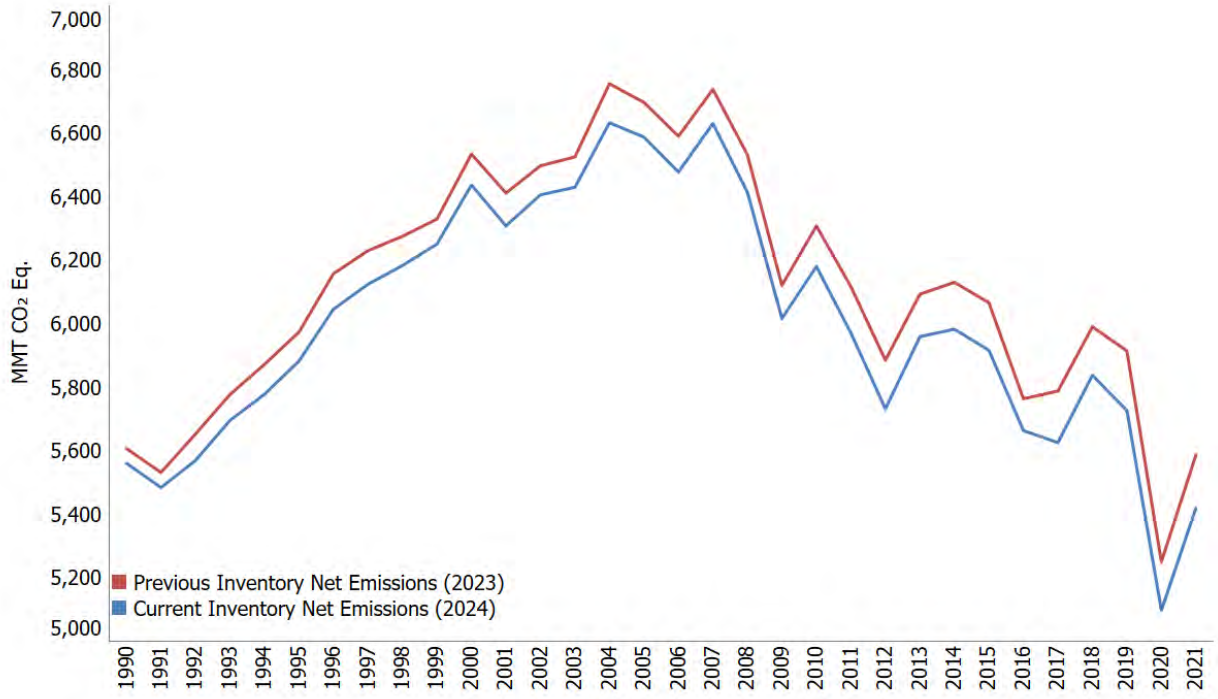

Below are categories with methodological and data-related recalculations resulting in an average change of greater than 2.0 MMT CO_2 Eq. over the time series.

- Forest land remaining forest land: changes in forest carbon stocks (CO_2)
- Land converted to grassland: changes in all ecosystem carbon stocks (CO_2)
- Land converted to cropland: changes in all ecosystem carbon stocks (CO_2)
- Grassland remaining grassland: changes in all ecosystem carbon stocks (CO_2)
- Non-energy use of fuels (CO_2)
- Land converted to settlements: changes in all ecosystem carbon stocks (CO_2)
- Fluorochemical production (HFCs)
- Fossil fuel combustion (CO_2)
- Cropland remaining cropland: changes in all ecosystem carbon stocks (CO_2)
- Agricultural Soil Management (N_2O)
- Petroleum Systems (CH_4)
- Wetlands Remaining Wetlands: changes in soil carbon stocks in coastal wetlands (CO_2)

In addition, the current *Inventory* includes new categories not included in the previous *Inventory* that improve completeness of the national estimates: CO_2 emissions from ceramics production and non-metallurgical magnesia production within other process use of carbonates category, fluorinated gases from fluorochemical production other than HCFC-22 within the fluorochemical production category, and managed forest land in Hawaii and several U.S. Territories. This report also now includes SF_6 and PFCs from product uses.

In each *Inventory*, the results of all methodological changes and historical data updates and the inclusion of new sources and sink estimates are summarized in the Recalculations and Improvements chapter (Chapter 9). For more detailed descriptions of each recalculation including references for data, please see the respective source or sink category description(s) within the relevant report chapter (the Energy chapter [Chapter 3], the Industrial Processes and Product Use [IPPU] chapter [Chapter 4], the Agriculture chapter [Chapter 5], the Land Use, Land-Use Change, and Forestry [LULUCF] chapter [Chapter 6], and the Waste chapter [Chapter 7]).

Emissions and Sinks by Greenhouse Gas

Figure ES-4 illustrates the relative contribution of the greenhouse gases to total gross U.S. emissions in 2022, weighted by GWP. The primary greenhouse gas emitted by human activities in the United States is CO_2, representing 79.7 percent of total greenhouse gas emissions. The largest source of CO_2 and of overall greenhouse gas emissions is fossil fuel combustion, primarily from transportation and power generation. Methane (CH_4) emissions account for 11.1 percent of emissions. The major sources of methane include enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of wastes in landfills. Agricultural soil management, wastewater treatment, stationary sources of fuel combustion, and manure management are the major sources of N_2O emissions. Emissions of substitutes for ozone depleting substances are the primary contributor to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions are primarily attributable to electronics manufacturing, fluorochemical production, and primary aluminum production. Electrical equipment systems account for most sulfur hexafluoride (SF_6) emissions. The electronics industry and fluorochemical production are the only sources of nitrogen trifluoride (NF_3) emissions. U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in forests, trees in urban areas, agricultural soils, landfilled yard trimmings and food scraps, and coastal wetlands, which together offset 14.5 percent of gross total emissions in 2022 (as reflected in Figure ES-1). The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

Figure ES-4: 2022 Total Gross U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)

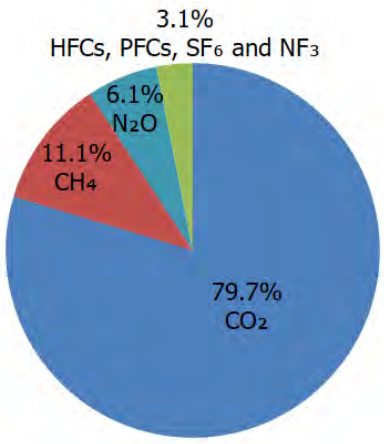

Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from the figure above.

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, global carbon fluxes among these various reservoirs are roughly balanced.[11]

Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen 49.5 percent (IPCC 2013; NOAA/ESRL 2024a), principally due to the combustion of fossil fuels for energy. Globally, an estimated

[11] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

33,423 MMT of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2022, of which the United States accounted for approximately 14.1 percent.[12]

Overall CO_2 emissions have decreased by 1.5 percent since 1990 and increased by 0.7 percent since 2021, consistent with trends in fuel combustion emissions. Within the United States, fossil fuel combustion accounted for 93.0 percent of CO_2 gross emissions in 2022. Nationally, the transportation sector was the largest emitter of CO_2 in 2022 followed by electric power generation. There are 27 additional sources of CO_2 emissions included in the *Inventory* (see [Table 2-1 in Trends]). Although not illustrated in Table ES-4, changes in land use and forestry practices can also lead to net CO_2 emissions (e.g., through conversion of forest land to agricultural or urban use) or to a net sink for CO_2 (e.g., through net additions to forest biomass). See more on these emissions and removals in Table ES-4.

Figure ES-5: 2022 Sources of CO_2 Emissions

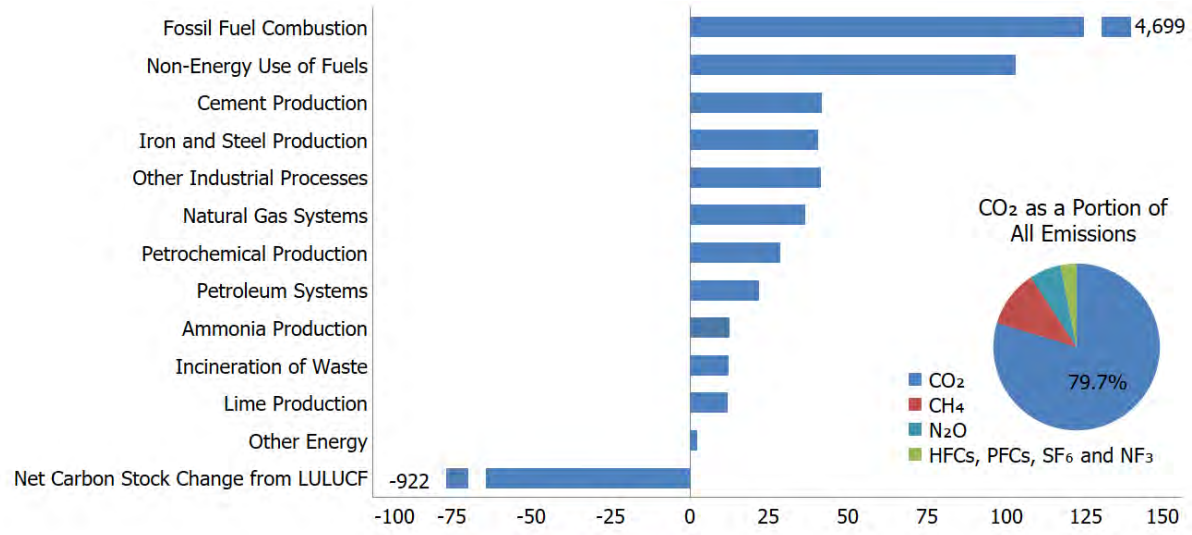

Note: "Other Industrial Processes" includes emissions from aluminum production, carbide production and consumption, carbon dioxide consumption, ferroalloy production, glass production, lead production, magnesium production, other process uses of carbonates, phosphoric acid production, substitution of ozone depleting substances, soda ash production, titanium dioxide production, urea consumption for non-agricultural purposes, and zinc production. "Other Energy" includes emissions from abandoned oil and gas wells and coal mining.

Between 1990 and 2022, CO_2 emissions from fossil fuel combustion decreased by 1.1 percent; emissions decreased by 18.2 percent (1,044.7 MMT CO_2 Eq.) from 2005 levels; and from 2021 to 2022, these emissions increased by 1.0 percent (45.1 MMT CO_2 Eq.).

Historically, changes in emissions from fossil fuel combustion have been the driving factor affecting U.S. emission trends. Important drivers include changes in demand for energy and a general decline in the overall carbon intensity of fuels combusted for energy in recent years by non-transport sectors of the economy. Between 2019 and 2021, changes in economic activity and travel due to the COVID-19 pandemic and the subsequent recovery had significant impacts on energy use and fossil fuel combustion emissions.

The five major fuel-consuming economic sectors are transportation, electric power, industrial, residential, and commercial and are described below. Carbon dioxide emissions are produced by the electric power sector as fossil fuel is consumed to provide electricity to one of the other four economic sectors, or "end-use" sectors. In Figure

[12] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *Global energy-related CO_2 emissions, 1990-2022 – Charts.* Available at: https://www.iea.org/reports/co2-emissions-in-2022 (IEA 2022).

ES-6, electric power emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity use (i.e., indirect fossil fuel combustion). Greenhouse gas emissions from the commercial and residential and industry increase substantially when indirect emissions from electricity end-use are distributed, due to the relatively large share of electricity use by buildings (e.g., heating, ventilation, and air conditioning; lighting; and appliances) and use of electricity for powering industrial machinery.

Figure ES-6: 2022 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

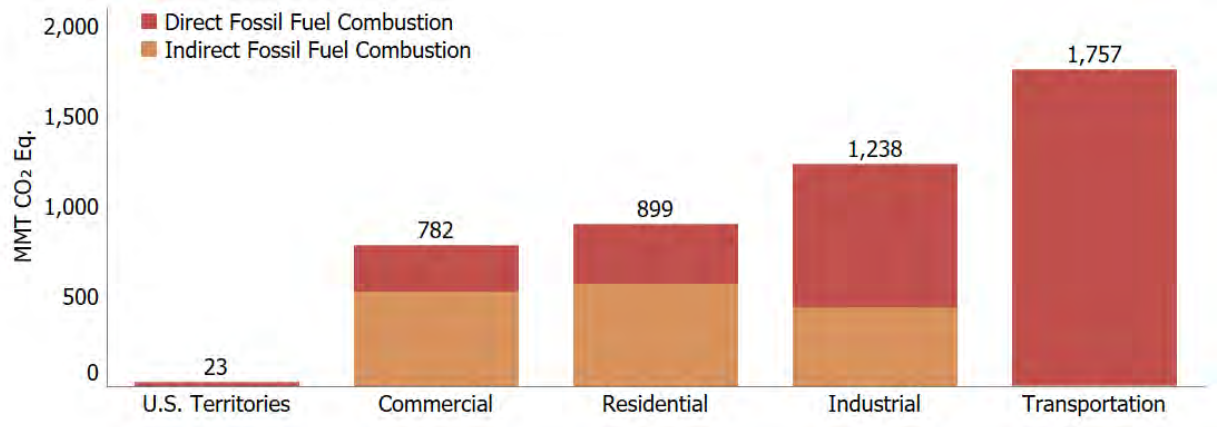

Transportation End-Use Sector. Transportation activities accounted for 37.4 percent of U.S. CO_2 emissions from fossil fuel combustion in 2022, with the largest contributors being light-duty trucks (36.8 percent), followed by medium- and heavy-duty trucks (23.0 percent) and passenger vehicles (20.6 percent). In terms of the overall trend from 1990 to 2022, total transportation CO_2 emissions increased due largely to increased demand for travel, which was a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. While an increased demand for travel has led to generally increasing CO_2 emissions since 1990, improvements in average new vehicle fuel economy since 2005 have slowed the rate of increase of CO_2 emissions. In 2022, petroleum-based products supplied 94.3 percent of the energy consumed for transportation, primarily from gasoline consumption in automobiles and other highway vehicles (51.9 percent).

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels[13] and indirectly from the generation of electricity that is used by industry, accounted for 26.3 percent of CO_2 emissions from fossil fuel combustion in 2022. Approximately 64.7 percent of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from the use of electricity for motors, electric furnaces, ovens, lighting, and other applications. Total direct and indirect emissions from the industrial sector have declined by 20.8 percent since 1990. This decline is due to structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements. From 2021 to 2022, total energy use in the industrial sector increased by 1.8 percent due to an increase in total industrial production and manufacturing output.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 19.1 and 16.6 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2022 including indirect emissions from electricity. The residential and commercial sectors relied heavily on electricity for meeting energy demands, with 62.9 and 66.9 percent, respectively, of their emissions attributable to electricity use for building -related activities such as lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking. Total direct and indirect emissions from the residential sector have decreased by 3.4 percent since 1990, and total direct and indirect emissions from the commercial sector have increased by 2.1 percent since 1990. From 2021 to 2022, an increase in heating degree

[13] This does not include fossil fuels used as feedstocks and reductants, which are reported under IPPU emissions.

days (7.9 percent) increased energy demand for heating in the residential and commercial sectors; also, a 4.3 percent increase in cooling degree days compared to 2021 increased demand for air conditioning in the residential and commercial sectors. Combined, this resulted in a 2.5 percent increase in residential sector energy use. From 2021 to 2022, energy use in the commercial sector increased by 4.7 percent.

Electric Power. The United States relies on electricity to meet a significant portion of its energy demands. Electricity generators used 30.5 percent of U.S. energy from fossil fuels and emitted 32.6 percent of the CO_2 from fossil fuel combustion in 2022. The type of energy source used to generate electricity, and the mix of electric generation resources used to meet demand, are the main factors influencing emissions.[14] Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54.1 percent of generation in 1990 to 20.3 percent in 2022.[15] This corresponded with an increase in natural gas generation and non-fossil fuel renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 10.7 percent of electric power generation in 1990 and increased over the 33-year period to represent 38.8 percent of electric power generation in 2022. Wind and solar generation (in kWh) represented 0.1 percent of electric power generation in 1990 and increased over the 33-year period to represent 14.2 percent of electric power generation in 2022. Between 2021 and 2022, coal electricity generation decreased by 10.2 percent, natural gas generation increased by 4.0 percent, and renewable energy generation increased by 7.6 percent.

Across the time series, changes in electricity generation and the carbon intensity of fuels used for electric power have a significant impact on CO_2 emissions. While CO_2 emissions from fossil fuel combustion in the electric power sector have decreased by 15.8 percent since 1990, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, decreased by 27.6 percent during that same timeframe. This decoupling of the level of electric power generation and the resulting CO_2 emissions is shown in Figure ES-7.

[14] In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not included in the electricity sector totals and trends discussed in this section. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[15] Values represent electricity *net* generation from the electric power sector. See Table 7.2b Electricity Net Generation: Electric Power Sector of EIA (2024).

Figure ES-7: Electric Power Generation and Emissions

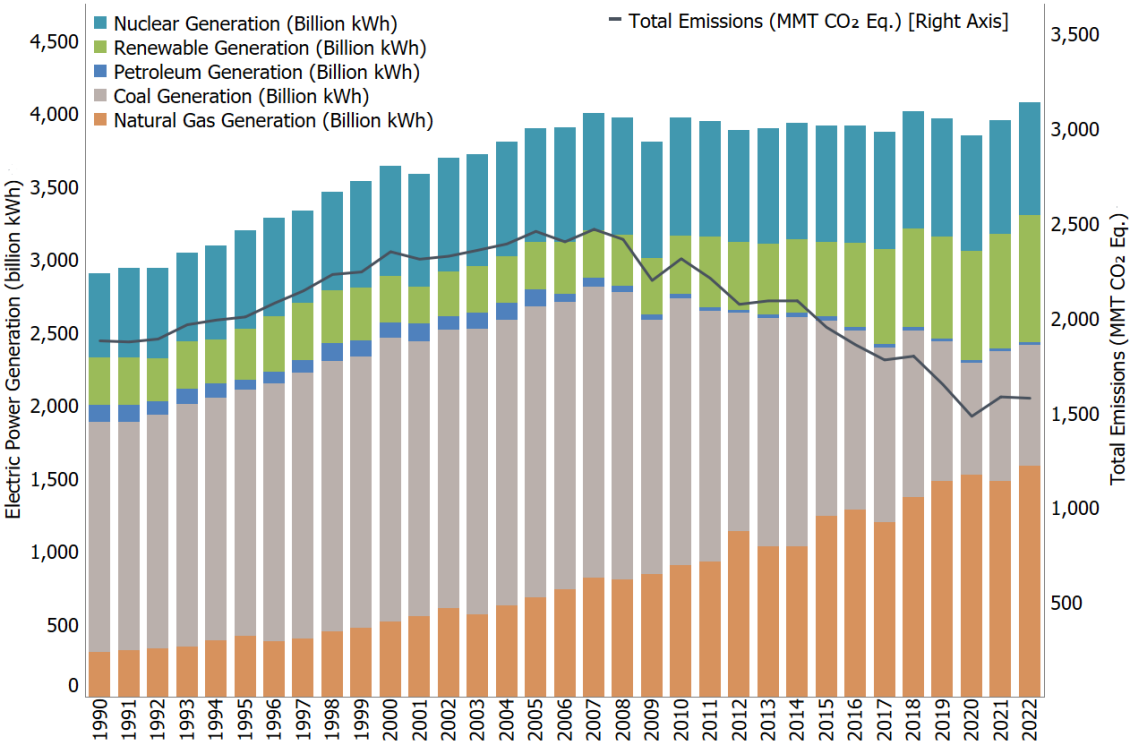

Other significant CO_2 trends included the following:

- Carbon dioxide emissions from natural gas and petroleum systems combined accounted for 1.2 percent of CO_2 emissions and 0.9 percent of total gross emissions in 2022. These emissions increased by 39.1 percent (16.4 MMT CO_2 Eq.) from 1990 to 2022. This increase is due primarily to increases in the production segment, where flaring emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time.
- Carbon dioxide emissions from iron and steel production and metallurgical coke production accounted for 0.8 percent of CO_2 and 0.6 percent of total gross emissions. Emissions decreased by 61.2 percent (64.1 MMT CO_2 Eq.) from 1990 through 2022. This decrease was primarily due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- Total carbon stock change (i.e., net CO_2 removals) in the LULUCF sector decreased by 10.9 percent between 1990 and 2022. This decrease was primarily due to a decrease in the rate of net carbon accumulation in forest carbon stocks and cropland remaining cropland, as well as an increase in emissions from land converted to settlements.

Methane Emissions

Methane (CH_4) is significantly more effective than CO_2 at trapping heat in the atmosphere: by a factor of 28 over a 100-year time frame based on the IPCC *Fifth Assessment Report* estimate (IPCC 2013). Over the last 250 years, the concentration of CH_4 in the atmosphere increased by 161.9 percent (IPCC 2013; NOAA/ESRL 2024b). Within the United States, the main anthropogenic sources of CH_4 include enteric fermentation from domestic livestock, natural gas systems, landfills, domestic livestock manure management, flooded land, coal mining, and petroleum systems (see Figure ES-8).

Figure ES-8: 2022 Sources of CH_4 Emissions

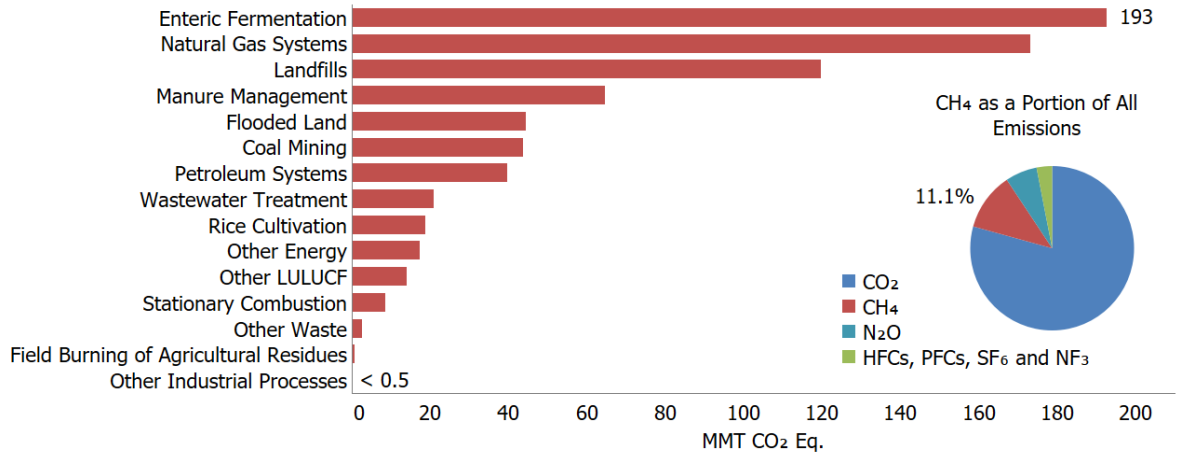

Note: "Other Energy" includes CH_4 emissions from abandoned oil and gas wells, abandoned underground coal mines, incineration of waste, and mobile combustion. "Other Waste" includes CH_4 emissions from anaerobic digestion at biogas facilities and composting. "Other Industrial Processes" includes CH_4 emissions from carbide production and consumption, ferroalloy production, iron and steel production and metallurgical coke production, and petrochemical production. "Other LULUCF" includes the CH_4 reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, coastal wetlands remaining coastal wetlands, and land converted to coastal wetlands.

Overall, CH_4 emissions in the United States in 2022, including LULUCF CH_4 emissions, accounted for 760.8 MMT CO_2 Eq., representing a decrease of 17.7 percent (164.0 MMT CO_2 Eq.) since 1990 and 2.8 percent decrease (21.8 MMT CO_2 Eq.) since 2021. Significant trends for the largest sources of anthropogenic CH_4 emissions include the following:

- Enteric fermentation was the largest anthropogenic source of CH_4 emissions in the United States in 2022, accounting for 27.4 percent of total CH_4 emissions and 3.0 percent of total gross emissions. Emissions have increased by 5.2 percent (9.5 MMT CO_2 Eq.) since 1990. This increase in emissions from 1990 to 2022 generally follows the increasing trends in cattle populations.
- Natural gas systems were the second largest anthropogenic source category of CH_4 emissions in the United States in 2022, accounting for 24.6 percent of total CH_4 emissions and 2.7 percent of total gross emissions. Emissions have decreased by 20.9 percent (45.7 MMT CO_2 Eq.) since 1990, largely due to decreases in emissions from distribution, transmission, and storage.
- Landfills were the third largest anthropogenic source of CH_4 emissions in the United States in 2022, accounting for 17.1 percent of total CH_4 emissions and 1.9 percent of total gross emissions and representing a decrease of 39.4 percent (78.0 MMT CO_2 Eq.) since 1990, with small year-to-year increases. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series.[16]

Nitrous Oxide Emissions

Nitrous oxide (N_2O) is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy, industrial, and waste management fields. While total N_2O emissions are much lower than CO_2 emissions, N_2O is 265 times more powerful than CO_2 at trapping heat in the atmosphere over a 100-year time frame (IPCC 2013). Since 1750, the global atmospheric concentration of N_2O has

[16] Carbon dioxide emissions from landfills are not included specifically in summing waste sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs and decay of disposed wood products are accounted for in the estimates for LULUCF.

risen by 24.3 percent (IPCC 2013; NOAA/ESRL 2024c). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, wastewater treatment, stationary fuel combustion, manure management, fuel combustion in motor vehicles, and nitric acid production (see Figure ES-9).

Figure ES-9: 2022 Sources of N_2O Emissions

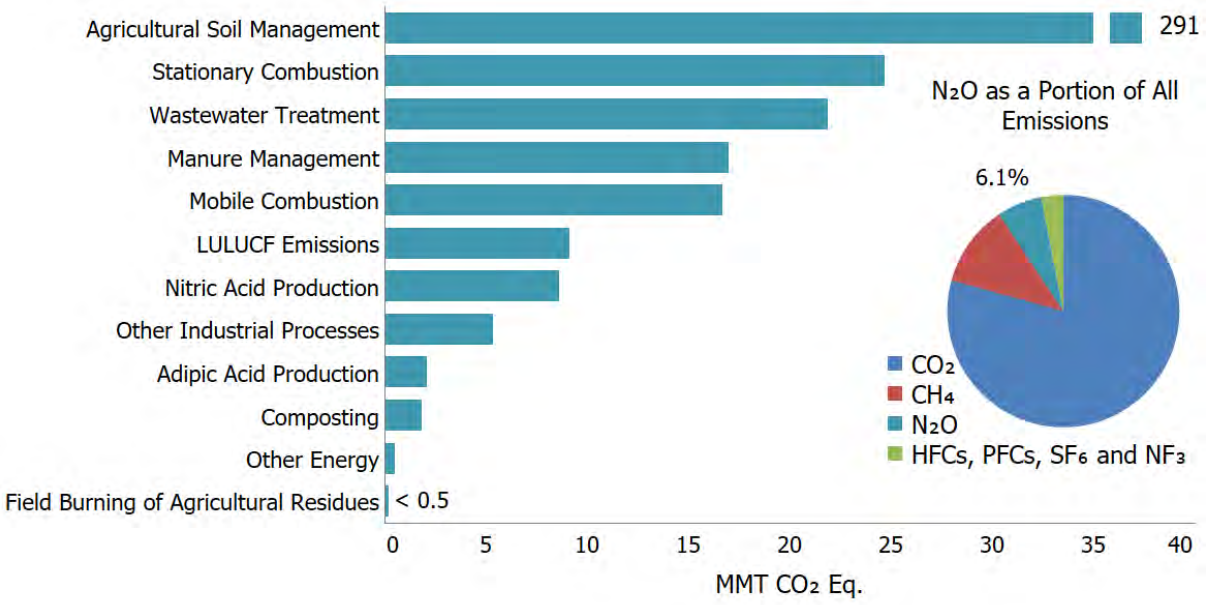

Note: "Other Industrial Processes" includes N_2O emissions from caprolactam, glyoxal, and glyoxylic acid production; the electronics industry; and product uses. "Other Energy" includes N_2O emissions from petroleum systems, natural gas systems, and incineration of waste. LULUCF emissions include N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, coastal wetlands remaining coastal wetlands, forest soils, and settlement soils.

Overall, N_2O emissions in the United States in 2022, including LULUCF N_2O emissions, accounted for 398.8 MMT CO_2 Eq., representing a decrease of 3.4 percent (14.2 MMT CO_2 Eq.) since 1990 and a decrease of 2.5 percent (10.1 MMT CO_2 Eq.) since 2021. Significant trends for the largest sources of anthropogenic N_2O emissions include the following:

- Agricultural soils were the largest anthropogenic source of N_2O emissions in 2022, accounting for 74.6 percent of N_2O emissions and 4.6 percent of total gross greenhouse gas emissions in the United States. These emissions increased by 0.7 percent (2.0 MMT CO_2 Eq.) from 1990 to 2022 but fluctuated during that period due to annual variations in weather patterns, fertilizer use, and crop production.
- Stationary combustion was the second largest source of anthropogenic N_2O emissions in 2022, accounting for 6.3 percent of N_2O emissions and 0.4 percent of total gross U.S. greenhouse gas emissions in 2022. Stationary combustion emissions peaked in 2007 and steadily decreased until 2020. Emissions increased in 2021 and 2022. Stationary combustion emissions have increased by 10.6 percent (2.4 MMT CO_2 Eq.) since 1990.
- Wastewater treatment, both domestic and industrial, was the third largest anthropogenic source of N_2O emissions in 2022, accounting for 5.6 percent of N_2O emissions and 0.3 percent of total gross greenhouse gas emissions in the United States in 2022. Emissions from wastewater treatment increased by 48.2 percent (7.1 MMT CO_2 Eq.) since 1990 as a result of growing U.S. population and protein consumption.

HFC, PFC, SF_6, and NF_3 Emissions

Hydrofluorocarbons (HFCs) are synthetic chemicals that are used as alternatives to ozone depleting substances (ODS), which are being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. Hydrofluorocarbons do not deplete the stratospheric ozone layer and therefore have been used as alternatives under the Montreal Protocol.

Perfluorocarbons (PFCs) are emitted from the production of electronics and aluminum and also (in smaller quantities) from their use as alternatives to ODS. Sulfur hexafluoride (SF_6) is emitted from the manufacturing and use of electrical equipment as well as the production of electronics and magnesium. NF_3 is emitted from electronics production. HFCs are also emitted during production of HCFC-22 and electronics (see Figure ES-10).

HFCs, PFCs, SF_6, and NF_3 are potent greenhouse gases. In addition to having very high GWPs, SF_6, NF_3, and PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere once emitted. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated (IPCC 2021).

Figure ES-10: 2022 Sources of HFCs, PFCs, SF_6, and NF_3 Emissions

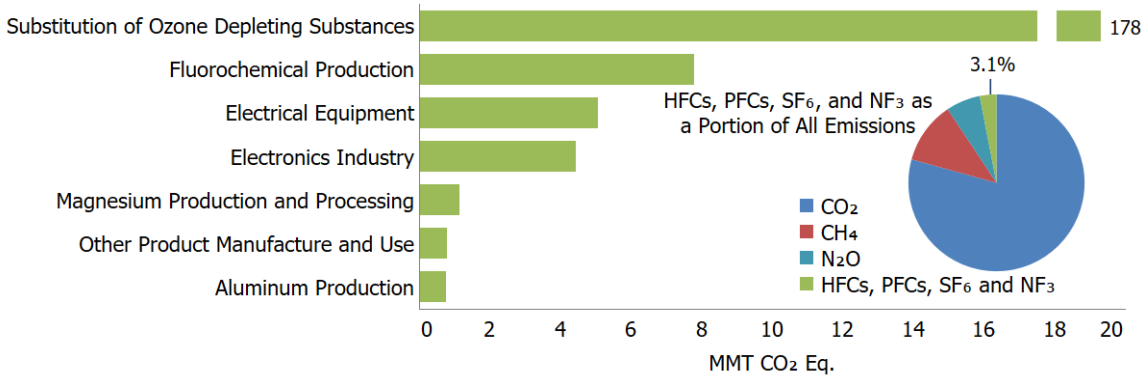

Some significant trends for the largest sources of U.S. HFC, PFC, SF_6, and NF_3 emissions include the following:

- Hydrofluorocarbon and perfluorocarbon emissions resulting from their use as substitutes for ODS (e.g., chlorofluorocarbons [CFCs]) are the largest share of fluorinated emissions (89.9 percent) in 2022 and have been consistently increasing, from small amounts since 1990. This increase over the time series was largely the result of efforts to phase out CFCs and other ODS in the United States.
- Sulfur hexafluoride emissions from electrical equipment decreased by 79.4 percent (19.6 MMT CO_2 Eq.) from 1990 to 2022. There are two factors contributing to this decrease: (1) a sharp increase in the price of SF_6 during the 1990s and (2) a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.
- HFC, PFC, SF_6, and NF_3 emissions from fluorochemical production decreased by 89.0 percent (63.2 MMT CO_2 Eq.) from 1990 to 2022 due to a reduction in the HFC-23 emission rate from HCFC-22 production (kg HFC-23 emitted/kg HCFC-22 produced), the imposition of emissions controls at production facilities, and a decrease in SF_6 production (due to the cessation of production at the major SF_6 production facility in 2010).
- PFC emissions from aluminum production decreased by 96.1 percent (18.5 MMT CO_2 Eq.) from 1990 to 2022, due to both industry emission reduction efforts and lower domestic aluminum production.

ES.3 Overview of Sector Emissions and Trends

Figure ES-11 and Table ES-3 aggregate emissions and sinks by the sectors defined by the UNFCCC and Paris Agreement reporting guidelines and methodological framework in the IPCC guidelines to promote comparability across countries. Over the 33-year period of 1990 to 2022, total emissions from the Energy and Waste sectors decreased by 3.4 percent (181.2 MMT CO_2 Eq.) and 29.3 percent (69.1 MMT CO_2 Eq.) respectively. Emissions from the Industrial Processes and Product Use and Agriculture sectors grew by 3.9 percent (14.4 MMT CO_2 Eq.), and 7.7 percent (42.2 MMT CO_2 Eq.), respectively. Over the same period, the overall net flux from LULUCF (i.e., the net sum of all CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.) decreased by 12.5 percent (122.5 MMT CO_2 Eq.) and resulted in a removal of 854.2 MMT CO_2 Eq. in 2022.

Figure ES-11: U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector

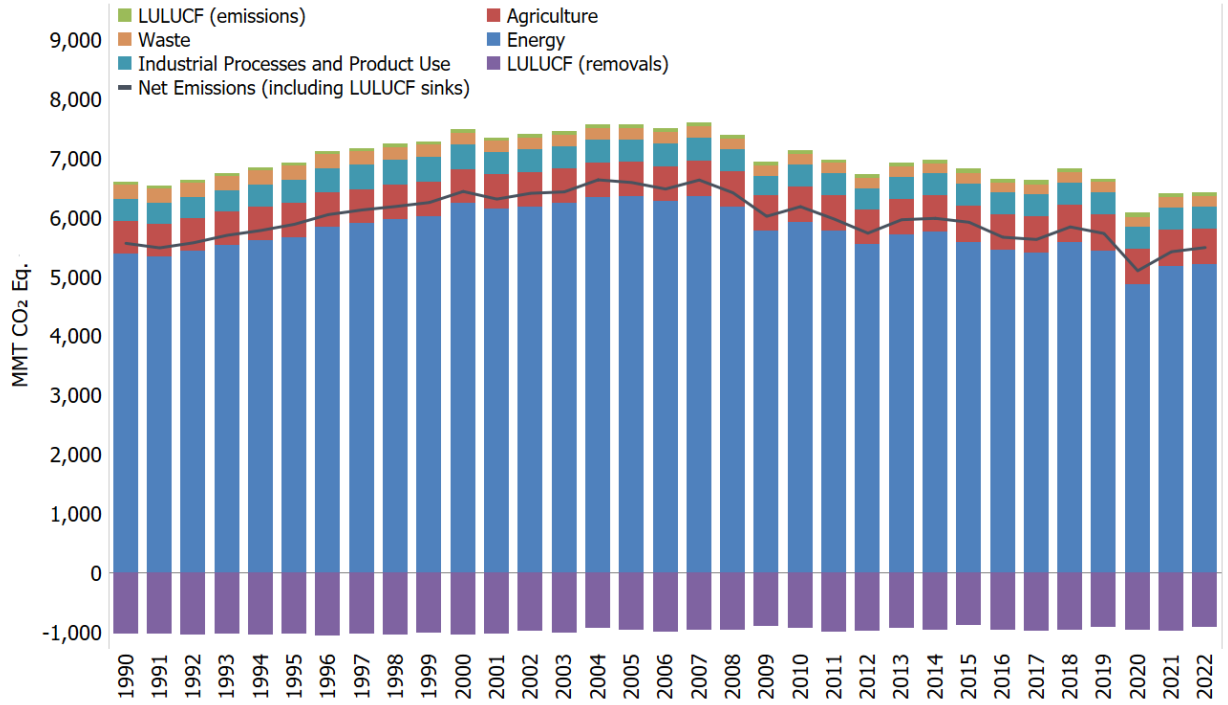

Table ES-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector (MMT CO_2 Eq.)

UNFCCC/IPCC Sector	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Energy	5,381.0	6,349.5	5,570.0	5,422.4	4,862.6	5,173.3	5,199.8	-3.4%
Industrial Processes and Product Use	368.8	371.3	367.2	371.9	367.9	381.6	383.2	3.9%
Agriculture	551.1	581.8	642.4	620.1	599.7	604.8	593.4	7.7%
Waste	235.9	192.0	173.2	175.8	171.7	169.2	166.9	-29.3%
Total Gross Emissions[a] (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[b]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)[c]	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] Total emissions without LULUCF.

[b] The LULUCF sector net total is the sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

[c] Net emissions with LULUCF.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

The Energy chapter contains emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and the use of fossil fuels for non-energy purposes. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2022. Energy-related activities are also responsible for CH_4 and N_2O emissions (40.2 percent and 10.8 percent of total U.S. emissions of each gas, respectively).[17] Overall, emission sources in the Energy chapter account for a combined 82.0 percent of total gross U.S. greenhouse gas emissions in 2022. Emissions from energy increased by 0.5 percent (26.5 MMT CO_2 Eq.) since 2021, but they have decreased by 3.4 percent (181.2 MMT CO_2 Eq.) since 1990.

In 2022, 83.0 percent of the energy used in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 17.0 percent came from other energy sources, such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-12).

Figure ES-12: 2022 U.S. Energy Consumption by Energy Source (Percent)

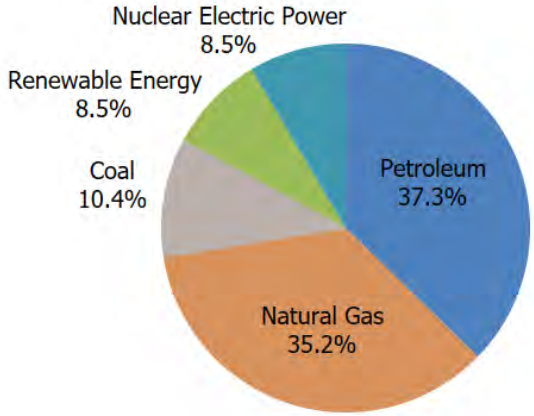

Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter contains greenhouse gas emissions generated and emitted as the byproducts of non-energy-related industrial processes, which involve the chemical or physical transformation of raw materials and can release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). These processes include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., other uses of carbonates, other uses of soda ash not associated with glass manufacturing, ceramics production, and non-metallurgical magnesia production), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, other fluorochemical production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption. Most of these industries also emit CO_2 from fossil fuel combustion which, in line with UNFCCC/IPCC sectoral definitions, is included in the Energy sector.

[17] The contribution of energy non-CO_2 emissions is based on gross totals and excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related CH_4 and N_2O including LULUCF non-CO_2 emissions is 37.1 percent and 9.8 percent respectively.

This chapter also contains emissions resulting from the release of HFCs, PFCs, SF_6, and NF_3 and other man-made compounds used in industrial manufacturing processes and by end-consumers (e.g., residential and mobile air conditioning). These industries include electronics manufacturing, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by electronics industry and anesthetic and aerosol applications, PFCs and SF_6 are emitted in other product use, and CO_2 is consumed and emitted through various end-use applications. In 2022, emissions resulting from use of the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) by end-consumers was the largest source of IPPU emissions and accounted for 46.5 percent of total IPPU emissions.

IPPU activities are responsible for 3.3, less than 0.5, and 4.1 percent of total U.S. CO_2, CH_4, and N_2O emissions respectively as well as for all U.S. emissions of fluorinated gases including HFCs, PFCs, SF_6 and NF_3. Overall, emission sources in the IPPU chapter accounted for 6.0 percent of U.S. greenhouse gas emissions in 2022. IPPU emissions have increased by 0.4percent (1.6 MMT CO_2 Eq.) since 2021 and by 3.9 percent (14.4 MMT CO_2 Eq.) since 1990, mostly due to increased use of ODS substitutes (e.g., HFCs).

Agriculture

The Agriculture chapter contains information on anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and some agricultural CO_2, CH_4, and N_2O fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry chapter).

Several agricultural activities contribute directly to emissions of greenhouse gases including the following sources: agricultural soil management, enteric fermentation in domestic livestock, livestock manure management, rice cultivation, urea fertilization, liming, and field burning of agricultural residues.

In 2022, agricultural activities were responsible for 9.4 percent of total gross U.S. greenhouse gas emissions. Agriculture sector emissions decreased by 11.4 MMT CO_2 Eq. (1.9 percent) since 2021 and have increased by 42.2 MMT CO_2 Eq. (7.7 percent) since 1990, mostly from trends in enteric fermentation and manure management. Methane, N_2O, and CO_2 are greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented 36.6 percent of total CH_4 emissions from anthropogenic activities in 2022. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to U.S. N_2O emissions in 2022, accounting for 74.6 percent of total N_2O emissions. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities.

Land Use, Land-Use Change, and Forestry

The LULUCF chapter contains emissions and removals of CO_2 and emissions of CH_4 and N_2O from managed lands in the United States. Consistent with the *2006 IPCC Guidelines*, emissions and removals from managed lands are considered to be anthropogenic, while emissions and removals from unmanaged lands are considered to be natural.[18] The share of managed land in the United States is approximately 95 percent of total land included in the Inventory.[19] More information on the definition of managed land used in the *Inventory* is provided in Chapter 6.

Overall, the *Inventory* results show that managed land is a net sink for CO_2 (C sequestration). The primary drivers of fluxes on managed lands include forest management practices, tree planting in urban areas, the management of agricultural soils, lands remaining and lands converted to reservoirs and other constructed waterbodies, landfilling

[18] See http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_01_Ch1_Introduction.pdf.

[19] The current land representation does not include land in U.S. Territories, but there are planned improvements to include these regions in future *Inventories*. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2 in Chapter 6 of this report.

of yard trimmings and food scraps, and activities that cause changes in carbon stocks in coastal wetlands. The main drivers for forest carbon sequestration include forest growth and increasing forest area (i.e., afforestation), as well as a net accumulation of carbon stocks in harvested wood pools. The net sequestration in settlements remaining settlements, which occurs predominantly from urban forests (i.e., settlement trees) and landfilled yard trimmings and food scraps, is a result of net tree growth and increased urban forest area, as well as long-term accumulation of carbon from yard trimmings and food scraps in landfills.

The LULUCF sector in 2022 resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 CO_2 Eq.[20] The removals of carbon offset 14.5 percent of total gross greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 represented 1.2 percent of net greenhouse gas emissions.[21] Carbon dioxide removals from carbon stock changes are presented in Table ES-4 along with CH_4 and N_2O emissions for LULUCF source categories.

Between 1990 and 2022, total carbon sequestration in the LULUCF sector decreased by 10.9 percent, primarily due to a decrease in the rate of net carbon accumulation in forests and in cropland remaining cropland, as well as an increase in CO_2 emissions from land converted to settlements. The overall net flux from LULUCF (i.e., net sum of all CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.) resulted in a removal of 854.2 MMT CO_2 Eq. in 2022.

Flooded lands were the largest source of CH_4 emissions from the LULUCF sector and the fifth largest source overall net CH_4 emissions in 2022. Forest fires were the second largest source of CH_4 emissions, followed by coastal wetlands remaining coastal wetlands. Forest fires were the largest source of N_2O emissions from the LULUCF sector in 2022.

Table ES-4: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Forest Land Remaining Forest Land[a]	(968.8)	(860.1)	(863.4)	(807.0)	(846.3)	(823.9)	(771.7)
Land Converted to Forest Land[b]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland[c]	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland[d]	24.6	24.9	29.7	28.9	17.1	11.5	14.0
Land Converted to Grassland[c]	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands[e]	36.8	39.4	38.2	38.1	38.1	38.1	38.1
Land Converted to Wetlands[e]	7.2	1.8	0.7	0.7	0.7	0.7	0.7
Settlements Remaining Settlements[f]	(109.1)	(115.2)	(131.0)	(131.5)	(131.8)	(132.3)	(132.3)
Land Converted to Settlements[c]	57.2	77.1	71.4	70.2	68.8	68.2	68.2
LULUCF Carbon Stock Change[g]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Emissions[h]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1
LULUCF Sector Net Total[i]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products, emissions from fires on both forest land remaining forest land and land converted to forest land, emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land, and CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[20] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[21] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[b] Includes the net changes to carbon stocks stored in all forest ecosystem pools.
[c] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.
[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.
[e] Estimates include CH_4 emissions from flooded land remaining flooded land and land converted to flooded land.
[f] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.
[g] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land use conversion categories.
[h] LULUCF emissions subtotal includes the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Emissions values are included in land-use category rows.
[i] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Waste

The Waste chapter contains emissions from waste management activities (except the incineration of waste, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic greenhouse gas emissions from waste management activities, accounting for 71.8 percent of total greenhouse gas emissions from waste management activities, and 17.1 percent of total U.S. CH_4 emissions.[22] Additionally, wastewater treatment accounted for 25.6 percent of total Waste sector greenhouse gas emissions, 3.0 percent of U.S. CH_4 emissions, and 5.6 percent of U.S. N_2O emissions in 2022. Emissions of CH_4 and N_2O from commercial composting are also included in this chapter, accounting for 1.5 percent (2.6 MMT CO_2 Eq.) and 1.1 percent (1.8 MMT CO_2 Eq.) of overall waste sector emissions, respectively. Anaerobic digestion at biogas facilities generated CH_4 emissions, accounting for less than 0.05 percent of emissions from the Waste sector. Overall, emission sources in the Waste chapter accounted for 2.6 percent of total gross U.S. greenhouse gas emissions in 2022. Waste sector emissions decreased by 1.4 percent (2.3 MMT CO_2 Eq.) since 2021 and by 29.3 percent (69.1 MMT CO_2 Eq.) since 1990.

ES.4 Other Information

Emissions and Sinks by Economic Sector

In addition to the Paris Agreement and UNFCCC sectors and methods defined by the IPCC, this report also characterizes emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture.[23] Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. For more information on trends in the Land Use, Land-Use Change, and Forestry sector, see Section ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks.

[22] Landfills also store carbon, due to incomplete degradation of organic materials such as harvest wood products, yard trimmings, and food scraps, as described in the Land Use, Land-Use Change, and Forestry chapter of the Inventory report. Also, the estimated total methane emissions used to estimate contribution excludes methane emissions from the LULUCF sector.

[23] The agriculture economic sector includes emissions from fossil fuel combustion and electricity use within the agricultural sector.

Figure ES-13 shows the trend in emissions by economic sector from 1990 to 2022, and Table ES-5 summarizes emissions from each of these economic sectors.

Figure ES-13: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors

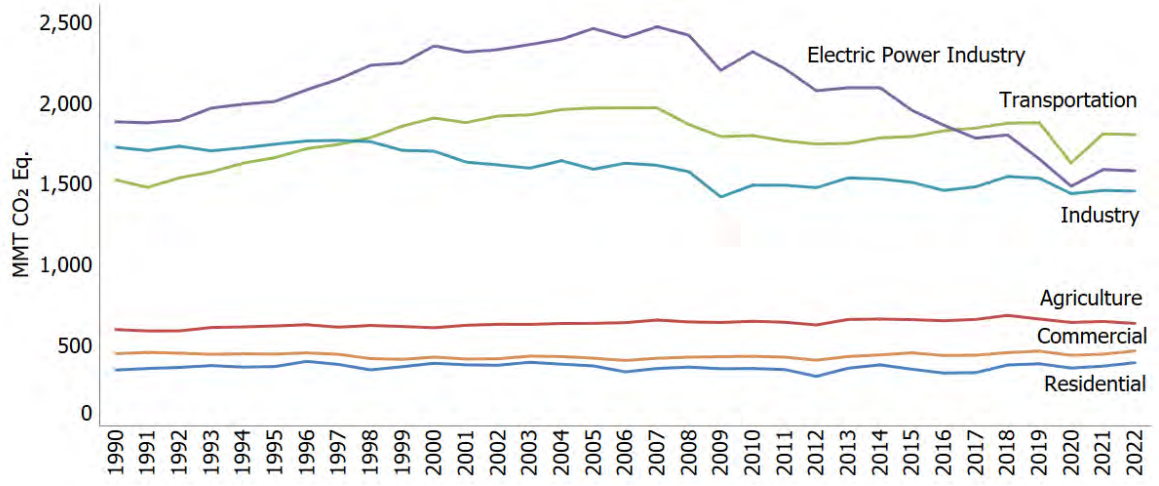

Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table ES-5: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)

Economic Sectors	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Transportation	1,521.4	1,965.9	1,871.6	1,874.6	1,625.3	1,805.5	1,801.5	18.4%
Electric Power Industry	1,880.2	2,457.4	1,799.2	1,650.8	1,482.2	1,584.4	1,577.5	-16.1%
Industry	1,723.3	1,587.3	1,541.9	1,531.8	1,435.9	1,455.8	1,452.5	-15.7%
Agriculture	595.9	634.3	683.5	661.0	640.0	645.9	634.0	6.4%
Commercial	447.0	418.9	453.5	462.6	436.9	443.7	463.7	3.7%
Residential	345.6	371.2	376.8	384.2	358.0	369.6	391.3	13.2%
U.S. Territories	23.4	59.7	26.3	25.1	23.4	23.9	22.7	-3.1%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[a]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) emissions are presented without LULUCF. Total net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Using this categorization, emissions from transportation activities accounted for the largest portion (28.4 percent) of total gross U.S. greenhouse gas emissions in 2022. Electric power accounted for the second largest portion (24.9 percent) of U.S. greenhouse gas emissions in 2022, while emissions from industry accounted for the third largest portion (22.9 percent). Emissions from industry have in general declined over the past decade, due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and energy efficiency improvements.

The remaining 23.8 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 10.0 percent of U.S. emissions; unlike other economic sectors, agricultural sector

emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation. An increasing amount of carbon is stored in agricultural soils each year, but this CO_2 sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for 7.3 percent and 6.2 percent of emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in carbon stocks in coastal wetlands.

Electricity is ultimately used in the economic sectors described above. Table ES-6 presents greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power generation are allocated to the economic sectors in which the electricity is used). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electric power were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity for each end-use sector (EIA 2024).[24] These source categories include CO_2 from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO_2 and N_2O from incineration of waste, CH_4 and N_2O from stationary sources, and SF_6 from electrical equipment systems.

When emissions from electricity use are distributed among these end-use sectors, industrial activities and transportation account for the largest shares of U.S. greenhouse gas emissions (29.5 percent and 28.5 percent, respectively) in 2022. The commercial and residential sectors contributed the next largest shares of total gross U.S. greenhouse gas emissions in 2022 (15.8and 15.3 percent, respectively). Emissions from the commercial and residential sectors increase substantially when emissions from electricity use are included, due to their relatively large share of electricity use for energy (e.g., lighting, cooling, appliances). Figure ES-14 shows the trends in these emissions by sector from 1990 to 2022.

Table ES-6: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed by Economic Sector (MMT CO_2 Eq.)

Economic Sectors	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Industry	2,397.3	2,302.9	2,017.1	1,974.8	1,823.5	1,877.8	1,872.9	-21.9%
Transportation	1,524.6	1,970.8	1,876.5	1,879.5	1,629.5	1,810.6	1,807.8	18.6%
Commercial	1,002.5	1,241.1	1,074.3	1,030.5	931.5	976.8	1,002.6	0.0%
Residential	958.0	1,247.7	1,035.9	984.0	919.5	958.0	973.5	1.6%
Agriculture	631.1	672.6	722.7	696.3	674.4	681.6	663.6	5.2%
U.S. Territories	23.4	59.7	26.3	25.1	23.4	23.9	22.7	-3.1%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[a]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

[24] U.S. Territories consumption data that are obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to Territories data.

Figure ES-14: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors

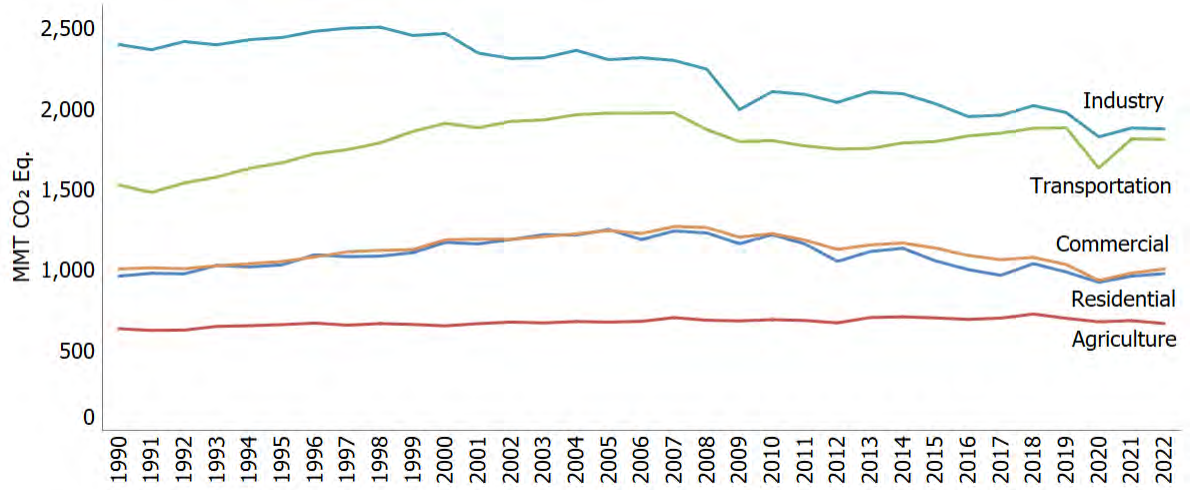

Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Box ES-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total (gross) greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) aggregate energy use, because energy-related activities are the largest sources of emissions; (2) energy use per capita as a measure of efficiency; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

Table ES-7 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have declined at an average annual rate of 0.01 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use and fossil fuel consumption, and overall gross domestic product (GDP), and national population (see Figure ES-15). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use, and fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.9 percent since 2005. Since 2005, GDP and national population, generally, continued to increase while energy has decreased slightly—noting 2020 was impacted by the COVID-19 pandemic.

Table ES-7: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2018	2019	2020	2021	2022	Avg. Annual Growth Rate Since 1990[a]	Avg. Annual Growth Rate Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	103	101	92	97	97	-0.1%	-0.9%
Energy Use[c]	100	119	118	117	107	113	115	0.5%	-0.2%
GDP[d]	100	159	201	206	201	213	217	2.5%	1.9%
Population[e]	100	118	130	131	132	132	133	0.9%	0.7%

+ Absolute value does not exceed 0.05 percent.
[a] Average annual growth rate.
[b] Gross total GWP-weighted values.
[c] Energy content-weighted values (EIA 2024).
[d] GDP in chained 2017 dollars (BEA 2024).
[e] U.S. Census Bureau (2024).

Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product (GDP)

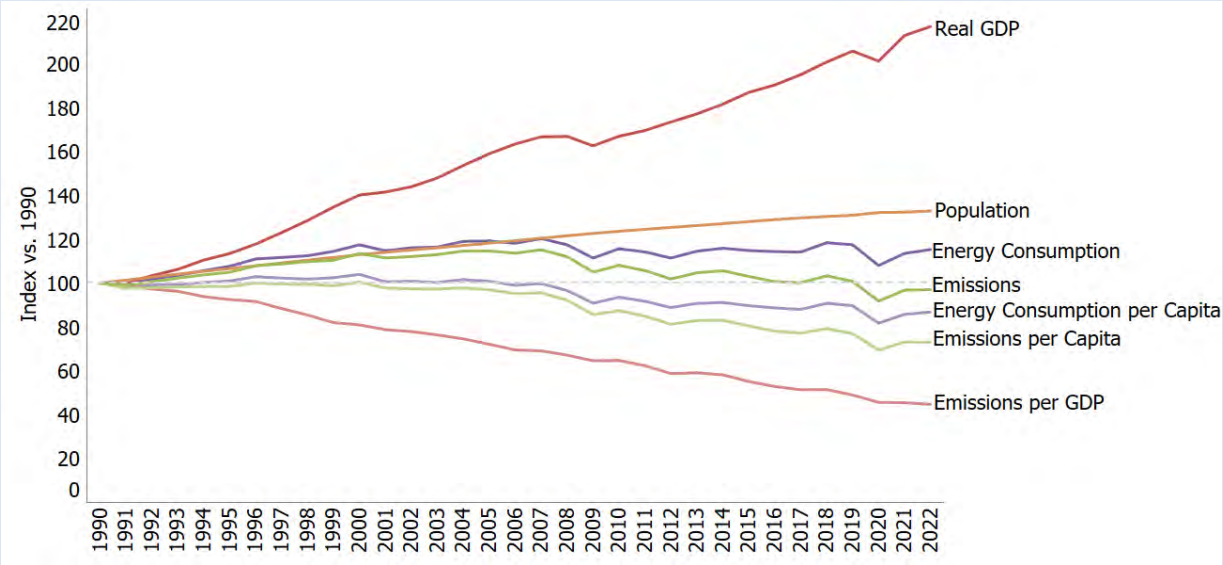

Source: BEA (2024), U.S. Census Bureau (2024), and emission estimates in this report.

Key Categories

The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) defines key categories as "inventory categories which individually, or as a group of categories (for which a common method, emission factor and activity data are applied) are prioritized within the national inventory system because their estimates have a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or

the level of uncertainty in emissions or removals."[25] A key category analysis identifies priority source or sink categories for focusing efforts to improve overall Inventory quality. In addition, a qualitative review of key categories and non-key categories can also help identify additional source and sink categories to consider for improvement efforts, including reducing uncertainty.

Figure ES-16 presents the 2022 key categories identified by the Approach 1 level assessment, including the LULUCF sector. A level assessment using Approach 1 identifies all source and sink categories that cumulatively account for 95 percent of total (i.e., gross) emissions in a given year when assessed in descending order of absolute magnitude.

For a complete list of key categories and more information regarding the overall key category analysis, including approaches accounting for uncertainty and the influence of trends of individual source and sink categories, see the Introduction chapter, Section 1.5, and Annex 1.

[25] See Chapter 4 "Methodological Choice and Identification of Key Categories" in IPCC (2006) and IPCC (2019). See http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html and https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch04_MethodChoice.pdf.

Figure ES-16: 2022 Key Categories (Approach 1 including LULUCF)[a]

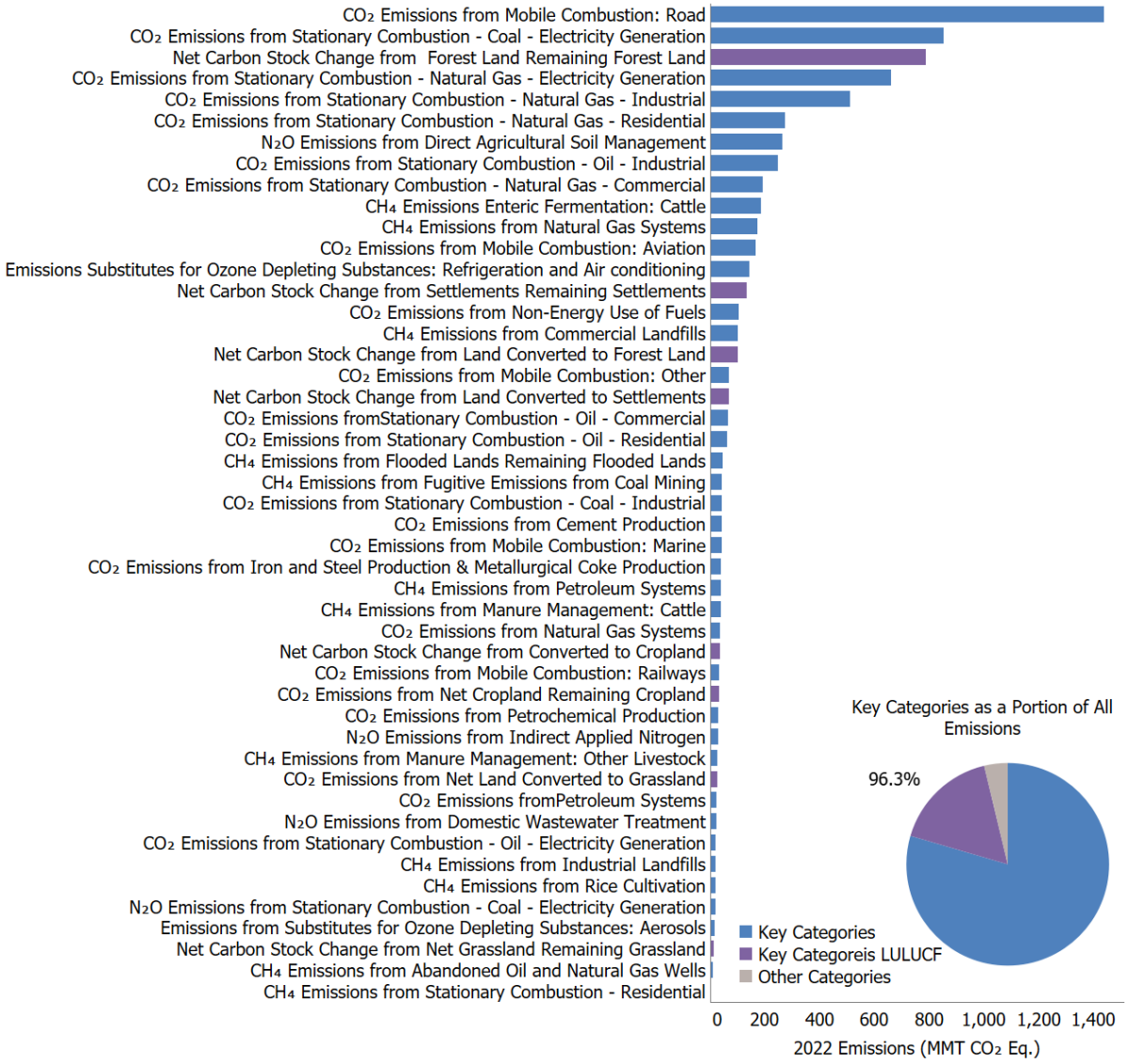

Note: For a complete list of key categories and detailed discussion of the underlying key category analysis, see Annex 1. Bars indicate key categories identified using Approach 1 level assessment including the LULUCF sector. The absolute values of net CO_2 emissions from LULUCF are presented in this figure but reported separately from gross emissions totals. Refer to Table ES-4 for a breakout of emissions and removals for LULUCF by source/sink category.

Quality Assurance and Quality Control (QA/QC)

The United States seeks continuous improvements to the quality, transparency, and usability of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. To assist in these efforts, the United States implemented a systematic approach to QA/QC. The procedures followed for the Inventory have been formalized in accordance with the U.S. Inventory QA/QC plan, and the UNFCCC reporting guidelines and *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The QA process includes expert and public reviews for the Inventory estimates and this report.

Box ES-3: Use of Ambient Measurements Systems for Validation of Emission Inventories

In following Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC, as well as relevant decisions under those agreements to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally accepted methods in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines) and, where appropriate, its supplements and refinements.[26] Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[27] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used to assess estimates or potentially be incorporated into the Inventory in a manner consistent with this *Inventory* report's transparency of its calculation methodologies, and the ability of inverse modeling techniques to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

The *2019 Refinement to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1 General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that emission estimates derived from atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC [2019] Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC [2019] Volume 1, Chapter 6). Further, it identified fluorinated gases as particularly suitable for such comparisons due their limited natural sources, their generally long atmospheric lifetimes, and well-understood loss mechanisms, which makes it relatively more straightforward to model their emission fluxes from observed mass quantities. Unlike emissions of CO_2, CH_4, and N_2O, emissions of fluorinated greenhouse gases are almost exclusively anthropogenic, meaning that the fluorinated greenhouse gas emission sources included in this Inventory account for the majority of the total U.S. emissions of these gases detectable in the atmosphere. This evaluation approach is also useful for gases and sources with larger uncertainties in available bottom-up inventory methods and data, such as emissions of CH_4, which are primarily from uncertain biological (e.g., enteric fermentation) and fugitive (e.g., natural gas production) activities.

In this *Inventory*, EPA includes the results from current and previous comparisons between fluorinated gas emissions inferred from atmospheric measurements and fluorinated gas emissions estimated based on bottom-up measurements and modeling. These comparisons, performed for HFCs and SF_6 respectively, are described under the QA/QC and Verification discussions in Chapter 4, Sections 4.25 Substitution of Ozone Depleting Substances and 4.26 Electrical Equipment, in the IPPU chapter of this report.

Consistent with the *2019 Refinement*, a key element to facilitate such comparisons is a spatially-explicit (or gridded inventory as an input to inverse modeling. To improve the ability to compare methane emissions from the national-level greenhouse gas inventory with observation-based estimates , a team of researchers from U.S. EPA, SRON Netherlands Institute for Space Research, Harvard University, and Lawrence Berkely National Laboratory and other coauthors developed a time series of anthropogenic methane emissions maps with 0.1° x 0.1° (10 km x 10 km) spatial resolution and monthly temporal resolution for the contiguous United States.[28] The gridded methane inventory is designed to be consistent with the U.S. EPA *Inventory of U.S. Greenhouse Gas*

[26] See http://www.ipcc-nggip.iges.or.jp/public/index.html.

[27] See http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf.

[28] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Emissions and Sinks estimates, which presents national totals for different source types.[29] The development of this gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Finally, in addition to the use of atmospheric concentration measurement data for comparison with Inventory data, information from top-down studies is directly incorporated in the natural gas systems calculations to quantify emissions from certain well blowout events.

Uncertainty Analysis of Emission and Sink Estimates

Uncertainty assessment is an essential element of a complete inventory of greenhouse gas emissions and removals because it helps to inform and prioritize inventory improvements. Recognizing the benefit of conducting an uncertainty analysis, the UNFCCC reporting guidelines follow the recommendations of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), Volume 1, Chapter 3 and require that countries provide single estimates of uncertainty for source and sink categories. In addition to quantitative uncertainty assessments, a qualitative discussion of uncertainty is presented for each source and sink category identifying specific factors affecting the uncertainty surrounding the estimates provided in accordance with UNFCCC reporting guidelines. Some of the current estimates, such as those for CO_2 emissions from energy-related combustion activities, are considered to have low uncertainties. This is because the amount of CO_2 emitted from energy-related combustion activities is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel, and for the United States, the uncertainties associated with estimating those factors are relatively small. For some other categories of emissions and sinks, however, inherent variability or a lack of data increases the uncertainty or systematic error associated with the estimates presented. Finally, an analysis is conducted to assess uncertainties associated with the overall emissions, sinks, and trends estimates. The overall uncertainty surrounding total net greenhouse gas emissions is estimated to be -6 to +6 percent in 1990 and -5 to +6 percent in 2022. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -3 to +4 percent in 1990 and -2 to +4 percent in 2022.

[29] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

1. Introduction

This report presents an inventory of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 2022 compiled by the United States government. A summary of source and sink category estimates is provided in Table 2-1, Table 2-2, andTable 2-4 by gas and IPCC sector in the Trends in Greenhouse Gas Emissions and Sinks chapter. The emission and sink estimates in these tables are presented throughout the main report in both CO_2 equivalents (CO_2 Eq.[30] and unweighted units). This report also discusses the methods and data used to calculate the emission and sink estimates.

The United States is party to both the 1992 UNFCCC and the 2015 Paris Agreement. The Paris Agreement set a global temperature goal–holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5°C–that articulates with greater precision States' views on what is necessary to meet the UNFCCC's objective of "stabiliz[ing] … greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[31]

The United States is committed to submitting a national inventory of anthropogenic emissions sources and removals by sinks of greenhouse gases by April 15 of each year. The United States has prepared this report, in conjunction with Common Reporting Tables (CRTs) that accompany this report, consistent with its obligations under those agreements.

In 1988, preceding the creation of the UNFCCC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation (IPCC 2021). The Paris Agreement and the UNFCCC require use of methods from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and encourages Parties to use the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* and *the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The recently released *2019 Refinement* clarify and elaborate on the existing guidance in the *2006 IPCC Guidelines*, along with providing updates to default values of emission factors and other parameters based on updated science. This report applies both the *2013 Supplement* and updated guidance in the *2019 Refinement* to improve accuracy and completeness of the *Inventory*. For more information on specific uses, see Section 1.4 of this chapter on Methodology and Data Sources.

[30] More information is provided in the Global Warming Potentials section of this chapter on the use of IPCC *Fifth Assessment Report* (AR5) GWP values.

[31] See Paris Agreement, Article 2.1(a); UNFCCC, Article 2.

Box 1-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC, as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and, where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in this *Inventory* does not preclude alternative examinations (e.g., economic sectors). Rather, this *Inventory* presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP), which is complementary to the U.S. *Inventory*.[32] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[33] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories[34] subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for the 2011 reporting year. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines*. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and removals (e.g., the GHGRP excludes emissions from the Agriculture and Land Use, Land-Use Change, and Forestry sectors), it is an important input to the calculations of national-level emissions in this *Inventory*.

Data presented in this *Inventory* report and EPA's GHGRP are complementary. The GHGRP dataset continues to be an important resource for the *Inventory*, providing not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines* (e.g., higher tier methods). GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. EPA uses annual GHGRP data in several categories to improve the national estimates presented in this *Inventory*, consistent with IPCC methodological guidance. See Annex 9 for more information on specific uses of GHGRP data in the *Inventory* (e.g., natural gas systems).

1.1 Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal, oil, and natural gas, along with deforestation, land-use changes, and other activities have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere (IPCC 2021). These gases in the atmosphere absorb some of the energy

being radiated from the surface of the Earth that would otherwise be lost to space, essentially acting like a blanket that makes the Earth's surface warmer than it would be otherwise.

Greenhouse gases are necessary to life as we know it. Without greenhouse gases to create the natural heat-trapping properties of the atmosphere, the planet's surface would be about 60 degrees Fahrenheit cooler than present (USGCRP 2017). Carbon dioxide is also necessary for plant growth. With emissions from biological and geological sources, there is a natural level of greenhouse gases that is maintained in the atmosphere. Human emissions of greenhouse gases and subsequent changes in atmospheric concentrations alter the balance of energy transfers between space and the earth system (IPCC 2021). A gauge of these changes is called radiative forcing, which is a measure of a substance's total net effect on the global energy balance for which a positive number represents a warming effect, and a negative number represents a cooling effect (IPCC 2021). IPCC concluded in its most recent scientific assessment report that it is "unequivocal that human influence has warmed the atmosphere, ocean and land" (IPCC 2021).

As concentrations of greenhouse gases continue to increase from man-made sources, the Earth's temperature is climbing above past levels. The Earth's average land and ocean surface temperature has increased by about 2.0 degrees Fahrenheit from the 1850 to 1900 period to the decade of 2011 to 2020 (IPCC 2021). The last four decades have each been the warmest decade successively at the Earth's surface since at least 1850 (IPCC 2021). Other aspects of the climate are also changing, such as rainfall patterns, snow and ice cover, and sea level. If greenhouse gas concentrations continue to increase, climate models predict that the average temperature at the Earth's surface is likely to increase between 0.27 to 9.99 degrees Fahrenheit (0.15 to 5.55 degrees Celsius) relative to 1995 to 2014 levels by the end of this century, depending on the emissions scenario and the responsiveness of the climate system (IPCC 2021).

For further information on greenhouse gases, radiative forcing, and implications for climate change, see the recent scientific assessment reports from the IPCC,[35] the U.S. Global Change Research Program (USGCRP),[36] and the National Academies of Sciences, Engineering, and Medicine (NAS).[37]

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 2021).

Naturally occurring greenhouse gases include water vapor, CO_2, CH_4, N_2O, and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in

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[32] On October 30, 2009, EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[33] See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

[34] See https://www.ccdsupport.com/confluence/pages/viewpage.action?pageId=322699300

[35] See https://www.ipcc.ch/report/ar6/wg1/.

[36] See https://nca2018.globalchange.gov/.

[37] See https://www.nationalacademies.org/topics/climate.

national greenhouse gas inventories.[38] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several other substances that influence the global radiation budget but are short-lived and therefore not well-mixed, leading to spatially variable radiative forcing effects. These substances include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed from chemical reactions in the atmosphere of precursor pollutants, which include volatile organic compounds (VOCs), CH_4, and nitrogen oxides (NO_x), in the presence of ultraviolet light (sunlight).

Aerosols are extremely small particles or liquid droplets suspended in the Earth's atmosphere that are often composed of sulfur compounds, carbonaceous combustion products (e.g., black carbon), crustal materials (e.g., dust) and other human-induced pollutants. They can affect the absorptive characteristics of the atmosphere (e.g., scattering incoming sunlight away from the Earth's surface, or, in the case of black carbon, absorbing sunlight) and can play a role in affecting cloud formation and lifetime, as well as the radiative forcing of clouds and precipitation patterns.

CO_2, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities (such as fossil fuel combustion, cement production, land-use, land-use change, and forestry, agriculture, or waste management), however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes, except when directly or indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

Table 1-1: Global Atmospheric Concentration, Rate of Concentration Change, and Atmospheric Lifetime of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.730 ppm	0.270 ppm	0.01 ppt	34.1 ppt
Atmospheric concentration	419 ppm[a]	1.912 ppm[b]	0.336 ppm[c]	11.02 ppt[d]	85.5 ppt[e]
Rate of concentration change	2.28 ppm/yr[f]	8.83 ppb/yr[f,g]	1.01 ppb/yr[f]	0.32 ppt/yr[f]	0.81 ppt/yr[f]
Atmospheric lifetime (years)	See footnote[h]	11.8	109[i]	About 1,000[j]	50,000

[a] The atmospheric CO_2 concentration is the 2022 annual average at the Mauna Loa, HI station (NOAA/ESRL 2024a). The global atmospheric CO_2 concentration, computed using an average of sampling sites across the world, was 417 ppm in 2022.

[b] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024b).

[c] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024c).

[d] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024d).

[e] The 2019 CF_4 global mean atmospheric concentration is from the Advanced Global Atmospheric Gases Experiment (IPCC 2021).

[f] The rate of concentration change for CO_2 is an average of the rates from 2007 through 2022 and has fluctuated between 1.5 to 3.0 ppm per year over this period (NOAA/ESRL 2024a). The rate of concentration change for CH_4, N_2O, and SF_6, is the average rate of change between 2007 and 2022 (NOAA/ESRL 2024b; NOAA/ESRL 2024c; NOAA/ESRL 2024d). The rate of concentration change for CF_4 is the average rate of change between 2011 and 2019 (IPCC 2021).

[g] The growth rate for atmospheric CH_4 decreased from over 10 ppb/year in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 13.22 ppb/year (NOAA/ESRL 2024b).

[38] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

[h] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[i] This table reports the "perturbation lifetime" for both CH_4 and N_2O, which takes into account the interactions between emissions of the gas and its own atmospheric residence time.

[j] The lifetime for SF_6 was revised from 3,200 years to about 1,000 years based on recent studies (IPCC 2021).

Source: Pre-industrial atmospheric concentrations and atmospheric lifetimes for CH_4, and N_2O, are from IPCC (2021), pre-industrial atmospheric concentration for SF_6, is from Rigby (2010), and pre-industrial atmospheric concentration for CF_4 is from Meinhausen (2017).

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of global warming potentials (GWPs), which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Water vapor is the largest contributor to the natural greenhouse effect. Water vapor is fundamentally different from other greenhouse gases in that it can condense and rain out when it reaches high concentrations, and the total amount of water vapor in the atmosphere is in part a function of the Earth's temperature. While some human activities such as evaporation from irrigated crops or power plant cooling release water vapor into the air, these activities have been determined to have a negligible effect on global climate (IPCC 2021). The lifetime of water vapor in the troposphere is on the order of 10 days. Water vapor can also contribute to cloud formation, and clouds can have both warming and cooling effects by either trapping or reflecting heat. Because of the relationship between water vapor levels and temperature, water vapor and clouds serve as a feedback to climate change, such that for any given change in other greenhouse gas concentrations, the total temperature change is greater than would happen in the absence of water vapor. Aircraft emissions can create contrails, which may also develop into contrail-induced cirrus clouds, with complex regional and temporal net radiative forcing effects that currently have a low level of scientific certainty (IPCC 2021).

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 419 ppmv in 2022, a 50 percent increase (IPCC 2021; NOAA/ESRL 2024a).[39, 40] The IPCC states that "Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities" (IPCC 2021). The predominant source of anthropogenic CO_2 emissions is the combustion of fossil fuels. Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2. In its *Sixth Assessment Report*, the IPCC determined that of the 2.0 degrees of observed warming, the best estimate is that 1.9 degrees of that are due to human influence, with elevated CO_2 concentrations being the most important contributor to that warming (IPCC 2021).

Methane (CH_4). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes and treatment of wastewater. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a byproduct of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 162 percent since 1750, from a pre-industrial value of about 730 ppb to 1,912 ppb in 2022[41] although the rate of increase decreased to near zero in the early 2000s, and has recently increased again to

[39] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2021).

[40] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750 to 1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 2021).

[41] This value is the global 2022 annual average mole fraction (NOAA/ESRL 2024b).

about 8.83 ppb/year. The IPCC has estimated that about half of the current CH_4 flux to the atmosphere (and the entirety of the increase in concentration) is anthropogenic, from human activities such as agriculture, fossil fuel production and use, and waste disposal (IPCC 2021).

Methane is primarily removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, creating a feedback that increases the atmospheric lifetime of CH_4 (IPCC 2021). Methane's reactions in the atmosphere also lead to production of tropospheric ozone and stratospheric water vapor, both of which also contribute to climate change. Tropospheric ozone also has negative effects on human health and plant productivity.

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste incineration; and biomass burning. The atmospheric concentration of N_2O has increased by 24 percent since 1750, from a pre-industrial value of about 270 ppb to 336 ppb in 2022,[42] a concentration that has not been exceeded during at least the last 800 thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2021).

Ozone (O_3). Ozone is present in both the upper stratosphere,[43] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[44] where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as CFCs, have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 2021). The depletion of stratospheric ozone and its radiative forcing remained relatively unchanged since 2000 for the last two decades and is starting to decline; recovery is expected to occur shortly after the middle of the twenty-first century (WMO/UNEP 2018).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO_2 and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds and CH_4 mixing with NO_x in the presence of sunlight. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable (IPCC 2021).

Halocarbons, Sulfur Hexafluoride (SF_6), and Nitrogen Trifluoride (NF_3). Halocarbons are, for the most part, man-made chemicals that have direct radiative forcing effects and could also have an indirect effect. Halocarbons that contain chlorine (CFCs, HCFCs, methyl chloroform, and carbon tetrachloride) and bromine (halons, methyl bromide, and hydrobromofluorocarbons) result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although most CFCs and HCFCs are potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is a greenhouse gas but which also shields the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap

[42] This value is the global 2022 annual average (NOAA/ESRL 2024c).

[43] The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

[44] The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

was placed on the production and importation of HCFCs by non-Article 5 countries, including the United States,[45] beginning in 1996, and then followed by intermediate requirements and a complete phase-out by the year 2030. While ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC, they are reported in this Inventory under Annex 6.2 for informational purposes.

HFCs, PFCs, SF_6, and NF_3 are not ozone depleting substances. The most common HFCs are, however, powerful greenhouse gases. Hydrofluorocarbons are primarily used as replacements for ozone depleting substances but are also emitted as a byproduct of the HCFC-22 (chlorodifluoromethane) manufacturing process. Other contributing sources to HFC emissions include the electronics industry and magnesium production and processing. Currently, these emissions have a small aggregate radiative forcing impact, but it was anticipated that without further controls their contribution to overall radiative forcing would increase, the ERF (effective radiative forcing) of halogenated gases increased by 3.5 percent between 2011 and 2019 primarily due to a decrease in atmospheric mixing-ratios of CFCs and an increase in their replacements (IPCC 2021). On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and which gives EPA authority to phase down HFC production and consumption (i.e., production plus import, minus export), through an allowance allocation program, promulgate certain regulations for purposes of maximizing reclamation and minimizing releases of HFCs and their substitutes from equipment, and facilitate the transition to next-generation technologies through sector-based restrictions, which will lead to lower HFC emissions over time. On October 31, 2022, the United States also ratified the Kigali Amendment to the Montreal Protocol, committing to continued phase down of HFCs. Perfluorocarbons, SF_6, and NF_3 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, SF_6, and NF_3 is also small, but they have a significant growth rate, extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2021).

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect. Warming effects can occur due to reactions leading to the formation of ozone in the troposphere, but cooling effects can occur due to the role of NO_x as a precursor to nitrate particles (i.e., aerosols) and due to destruction of stratospheric ozone when emitted from very high-altitude aircraft.[46] Additionally, NO_x emissions are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 2021). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Non-methane Volatile Organic Compounds (NMVOCs). Non-methane volatile organic compounds include substances such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

[45] Article 5 of the Montreal Protocol covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

[46] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere that are either directly emitted into or are created through chemical reactions in the Earth's atmosphere. Aerosols or their chemical precursors can be emitted by natural events such as dust storms, biogenic or volcanic activity, or by anthropogenic processes such as transportation, coal combustion, cement manufacturing, waste incineration, or biomass burning. Various categories of aerosols exist from both natural and anthropogenic sources, such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, volcanic aerosols, industrial dust, and carbonaceous[47] aerosols (e.g., black carbon, organic carbon). Aerosols can be removed from the atmosphere relatively rapidly by precipitation or through more complex processes under dry conditions.

Aerosols affect radiative forcing differently than greenhouse gases. Their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation (and to a lesser extent scattering, absorption, and emission of terrestrial radiation); and indirectly by increasing cloud droplets and ice crystals that modify the formation, precipitation efficiency, and radiative properties of clouds (IPCC 2021). Despite advances in understanding of cloud-aerosol interactions, the contribution of aerosols to radiative forcing are difficult to quantify because aerosols generally have short atmospheric lifetimes, and have number concentrations, size distributions, and compositions that vary regionally, spatially, and temporally (IPCC 2021).

The net effect of aerosols on the Earth's radiative forcing is believed to be negative (i.e., net cooling effect on the climate). In fact, aerosols contributed a cooling influence of up to 1.4 degrees, offsetting a substantial portion of greenhouse gas warming (IPCC 2021). Because aerosols remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[48] Not all aerosols have a cooling effect. Current research suggests that another constituent of aerosols, black carbon, has a positive radiative forcing by heating the Earth's atmosphere and causing surface warming when deposited on ice and snow (IPCC 2021). Black carbon also influences cloud development, but the direction and magnitude of this forcing is an area of active research.

Global Warming Potentials

A GWP is a quantified measure of the relative globally averaged radiative forcing impacts of emissions of a particular greenhouse gas over time (see Table 1-2). It is defined as the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram (kg) of the gas, relative to that of the reference gas CO_2 (IPCC 2021). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in CO_2 equivalent (CO_2 Eq.).[49] For example, the relationship between a kg of emissions of a gas and a kg of CO_2 Eq. emissions can be expressed as follows and also adapted to other units (e.g. metric tons, etc.):

[47] Carbonaceous aerosols are aerosols that are comprised mainly of carbon and hydrogen. Those carbonaceous aerosols with more hydrogen are classified as "organic carbon", and are generally reflective, while the aerosols that are nearly pure carbon are classified as "black carbon" (also referred to as "soot") and can absorb light (IPCC 2021).

[48] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer lasting negative forcing effect (i.e., a few years) (IPCC 2021).

[49] Carbon comprises 12/44^{ths} of carbon dioxide by weight.

Equation 1-1: Calculating CO_2 Equivalent Emissions

$$\text{kg } CO_2 \text{ Eq.} = (\text{kg emission of gas}) \times (\text{GWP})$$

where,

kg CO_2 Eq.	= kilograms of CO_2 equivalent
kt	= kilograms (equivalent to a thousand metric grams)
GWP	= Global warming potential

GWP values allow for a comparison of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±40 percent.

All estimates are provided throughout the report in both MMT CO_2 equivalents and unweighted units. Recent decisions under the UNFCCC require Parties to use 100-year GWP values from the IPCC *Fifth Assessment Report* (AR5) for calculating CO_2-equivalent emissions in their national reporting by the end of 2024.

> *…Decides that, until it adopts a further decision on the matter, the global warming potential values used by Parties in their reporting under the Convention to calculate the carbon dioxide equivalence of anthropogenic greenhouse gas emissions by sources and removals by sinks shall be based on the effects of greenhouse gases over a 100-year time horizon as listed in table 8.A.1 in appendix 8.A to the contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,[50] excluding the value for fossil methane.*[51]

This reflects updated science and ensures that national greenhouse gas inventories reported by all nations are comparable. In preparation for upcoming UNFCCC requirement,[52] this report reflects CO_2-equivalent greenhouse gas totals using 100-year AR5 GWP values. A comparison of emission values with the previously used 100-year GWP values from IPCC *Fourth Assessment Report* (AR4) (IPCC 2007), and the IPCC *Sixth Assessment Report* (AR6) (IPCC 2021) values can be found in Annex 6.1 of this report. The 100-year GWP values used in this report are listed below in Table 1-2.

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. Parties to the UNFCCC have not agreed upon GWP values for these gases that are short-lived and spatially inhomogeneous in the atmosphere.

Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) Used in this Report

Gas	Atmospheric Lifetime	GWP[a]
CO_2	See footnote[b]	1
CH_4[c]	12.4	28
N_2O	121	265

[50] Intergovernmental Panel on Climate Change. 2013. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change. TF Stocker, D Qin, G-K Plattner, et al. (eds.). Cambridge and New York: Cambridge University Press. Available at http://www.ipcc.ch/report/ar5/wg1.

[51] See paragraphs 1 and 2 of the decision on common metrics adopted at the 27th UNFCCC Conference of Parties (COP27), available online at https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

[52] See Annex to decision 18/CMA.1, available online at https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf The Paris Agreement reporting guidelines also clarified use of the 100-year GWPs listed in table 8.A.1 in Annex 8.A of Chapter 8 of the *Fifth Assessment Report* (AR5) of the Intergovernmental Panel on Climate Change, excluding the value for fossil methane. United Nations Framework Convention on Climate Change, see paragraph 25 of Decision 5/CMA.3 available online at https://unfccc.int/sites/default/files/resource/CMA2021_L10a2E.pdf.

HFC-23	222	12,400
HFC-32	5.2	677
HFC-41[d]	2.8	116
HFC-125	28.2	3,170
HFC-134a	13.4	1,300
HFC-143a	47.1	4,800
HFC-152a	1.5	138
HFC-227ea	38.9	3,350
HFC-236fa	242	8,060
CF_4	50,000	6,630
C_2F_6	10,000	11,100
C_3F_8	2,600	8,900
c-C_4F_8	3,200	9,540
SF_6	3,200	23,500
NF_3	500	16,100
Other Fluorinated Gases		See Annex 6

[a] 100-year time horizon.
[b] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.
[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.
[d] See Table A-1 of 40 CFR Part 98
Source: IPCC (2013).

Box 1-2: The IPCC Sixth Assessment Report and Global Warming Potentials

In 2021, the IPCC published its *Sixth Assessment Report* (AR6), which updated its comprehensive scientific assessment of climate change. Within the AR6 report, the GWP values of gases were revised relative to previous IPCC assessment reports, e.g., the IPCC *Fifth Assessment Report* (AR5) (IPCC 2014). Although the AR5 GWP values are used throughout this report, consistent with UNFCCC reporting requirements, it is straight-forward to review the changes to the GWP values and their impact on estimates of the total GWP-weighted emissions of the United States. In the AR6, the IPCC used more recent estimates of the atmospheric lifetimes and radiative efficiencies of some gases and updated background concentrations. The AR6 now includes climate-carbon feedback effects for non-CO_2 gases, improving the consistency between treatment of CO_2 and non-CO_2 gases. Indirect effects of gases on other atmospheric constituents (such as the effect of methane on ozone) have also been updated to match more recent science.

Table 1-3 presents the new GWP values, relative to those presented in the AR5, using the 100-year time horizon common to Paris Agreement and UNFCCC reporting.[53] Updated reporting guidelines under the Paris Agreement require the United States and other countries to shift to use of the IPCC *Fifth Assessment Report* (AR5) (IPCC 2013) 100-year GWP values (without feedbacks) for national inventory reporting.[54] All estimates provided throughout this report are also presented in unweighted units. For informational purposes, emission estimates that use 100-year GWPs from other recent IPCC Assessment Reports are presented in detail in Annex 6.1 of this report.

[53] See Decision 7/CP.27 included in https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

[54] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement.

Table 1-3: Comparison of 100-Year GWP values

100-Year GWP Values				Comparisons to AR5	
Gas	AR5[a]	AR5 with feedbacks[b]	AR6[c]	AR5 with feedbacks[b]	AR6[c]
CO_2	1	1	1	NC	NC
CH_4[d]	28	34	27	6	(1)
N_2O	265	298	273	33	8
HFC-23	12,400	13,856	14,600	1,456	2,200
HFC-32	677	817	771	140	94
HFC-41	116	141	135	25	19
HFC-125	3,170	3,691	3,740	521	570
HFC-134a	1,300	1,549	1,530	249	230
HFC-143a	4,800	5,508	5,810	708	1,010
HFC-152a	138	167	164	29	26
HFC-227ea	3,350	3,860	3,600	510	250
HFC-236fa	8,060	8,998	8,690	938	630
CF_4	6,630	7,349	7,380	719	750
C_2F_6	11,100	12,340	12,400	1,240	1,300
C_3F_8	8,900	9,878	9,290	978	390
c-C_4F_8	9,540	10,592	10,200	1,052	660
SF_6	23,500	26,087	24,300	2,587	800
NF_3	16,100	17,885	17,400	1,785	1,300

NC (No Change)

[a] The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

[b] The GWP values in this column are from the AR5 report but include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime.

[c] The GWP values in this column are from the AR6 report.

[d] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. Including the indirect effect due to the production of CO_2 resulting from methane oxidation would lead to an increase in AR5 methane GWP values by 2 for fossil methane and is not shown in this table.

Note: Parentheses indicate negative values.

Sources: IPCC (2021), IPCC (2013), IPCC (2007), IPCC (2001), IPCC (1996).

1.2 National Inventory Arrangements

The U.S. Environmental Protection Agency (EPA), in cooperation with other U.S. government agencies, prepares the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. A wide range of agencies and individuals are involved in supplying data to, planning methodological approaches and improvements, reviewing, or preparing portions of the Inventory—including federal and state government authorities, research and academic institutions, industry associations, and private consultants.

Within EPA, the Office of Atmospheric Protection (OAP) is the lead office responsible for the emission and removal calculations provided in the Inventory, as well as the completion of the National Inventory Report including the Common Reporting Tables (CRTs). EPA's Office of Transportation and Air Quality (OTAQ) and Office of Research and Development (ORD) are also involved in calculating emissions and removals for the Inventory. The U.S. Department of State (DOS) serves as the overall national focal point to the Paris Agreement and the UNFCCC, and EPA's OAP serves as the National Inventory Focal Point for this report, including responding to technical questions and comments on the U.S. Inventory. EPA staff coordinate the annual methodological choice, activity data collection, emission and removal calculations, uncertainty assessment, QA/QC processes, and improvement

planning at the individual source and sink category level. EPA's inventory coordinator manages overall compilation of the entire *Inventory* into the proper reporting format for submission under the Paris Agreement and the UNFCCC and is responsible for the synthesis of information along with the consistent application of cross-cutting IPCC good practice across the *Inventory*.

Several other government agencies contribute to the collection and analysis of the necessary underlying activity data used in the Inventory calculations via formal (e.g., interagency agreements) and informal relationships, in addition to the calculation of estimates integrated in the report (e.g., U.S. Department of Agriculture's U.S. Forest Service and Agricultural Service, National Oceanic and Atmospheric Administration, Federal Aviation Administration, and Department of Defense). Other U.S. agencies provide official data for use in the *Inventory*. The U.S. Department of Energy's Energy Information Administration provides national fuel consumption data and the U.S. Department of Defense provides data on military fuel consumption and use of bunker fuels. Other U.S. agencies providing activity data for use in EPA's emission calculations include: the U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, and the Federal Aviation Administration. Academic and research centers also provide activity data and calculations to EPA, as well as individual companies participating in voluntary outreach efforts with EPA. EPA engages with agencies regularly on data needs and improvements to ensure sufficient activity collection for annual compilation of estimates. Finally, EPA as the National Inventory Focal Point, in coordination with the U.S. Department of State, officially submits the *Inventory* under the Paris Agreement and the UNFCCC each April by the reporting deadline.

Figure 1-1: National Inventory Arrangements and Process Diagram

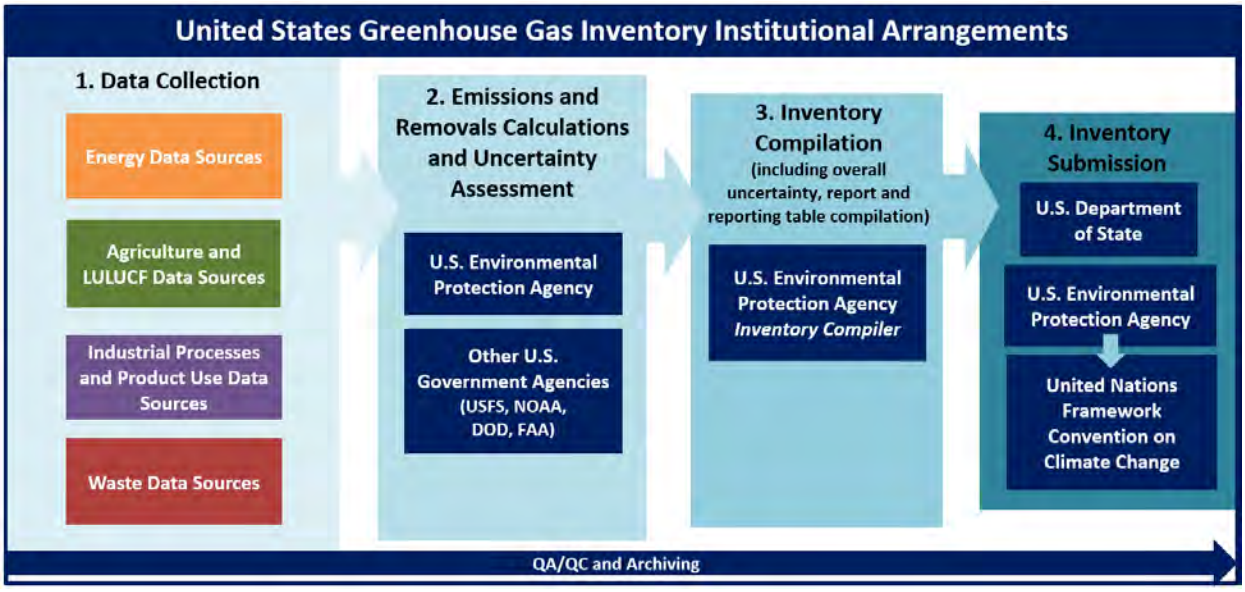

Overview of Inventory Data Sources by Source and Sink Category

Energy	Agriculture and LULUCF	IPPU	Waste
U.S. Energy Information Administration	USDA U.S. Forest Service Forest Inventory and Analysis Program (FIA)	EPA Greenhouse Gas Reporting Program (GHGRP)	EPA Greenhouse Gas Reporting Program (GHGRP)
U.S. Department of Commerce – Bureau of the Census	USDA Natural Resource Conservation Service (NRCS)	U.S. Geological Survey (USGS) National Minerals Information Center	EPA Office of Land and Emergency Management (OLEM)
U.S. Department of Defense – Defense Logistics Agency	USDA National Agricultural Statistics Service (NASS) and Agricultural Research Service (ARS)	American Chemistry Council (ACC)	EPA Clean Watershed Needs Survey (CWNS)
U.S. Department of Homeland Security	EPA Office of Research and Development (ORD)	American Iron and Steel Institute (AISI)	American Housing Survey
U.S. Department of Transportation - Federal Highway Administration	U.S. Fish and Wildlife Service	U.S. International Trade Commission (USITC)	Data from research studies, trade publications, and industry associations
U.S. Department of Transportation - Federal Aviation Administration	U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS)	Air-Conditioning, Heating, and Refrigeration Institute	
U.S. Department of Transportation & Bureau of Transportation Statistics	Association of American Plant Food Control Officials (AAPFCO)	Data from other U.S. government agencies, research studies, trade publications, and industry association	
U.S. Department of Labor – Mine Safety and Health Administration	National Oceanic and Atmospheric Administration (NOAA)	UNEP Technology and Economic Assessment Panel (TEAP)	
U.S. Department of Energy and its National Laboratories	EPA Office of Land and Emergency Management (OLEM)		
EPA Acid Rain Program	USDA Farm Service Agency		
EPA MOVES Model	U.S. Geological Survey (USGS)		
EPA Greenhouse Gas Reporting Program (GHGRP)	U.S. Department of the Interior (DOI) - Bureau of Land Management (BLM)		
U.S. Department of Labor – Mine Safety and Health Administration	EPA Office of Land and Emergency Management (OLEM)		
American Association of Railroads	Alaska Department of Natural Resources		
American Public Transportation Association	U.S. Department of Commerce – Bureau of the Census		
U.S. Department of Interior - Bureau of Ocean Energy Management	Data from research studies, trade publications, and industry associations		
Federal Energy Regulatory Commission			
Data from research studies, trade publications, and industry associations			

Note: This table is not an exhaustive list of all data sources.

1.3 Inventory Preparation Process

This section describes EPA's approach to preparing the annual U.S. *Inventory*, which includes both the National Inventory Document (NID) and Common Reporting Tables (CRTs). The inventory coordinator at EPA, with support from the cross-cutting compilation staff, is responsible for coordinating aggregation of all emission and removal estimates, conducting the overall uncertainty analysis of *Inventory* emissions and trends over time, and ensuring consistency and quality throughout the NID and CRTs. Emission and removal calculations, including associated uncertainty analysis for individual sources and/or sink categories are the responsibility of individual source and sink category leads, who are most familiar with each category, underlying data, and the unique national circumstances relevant to its emissions or removals profile. Using IPCC methodological decision trees and suggested good practice guidance, the individual leads determine the most appropriate methodology and collect the relevant activity data to use in the emission and removal calculations, based upon their expertise in the source or sink category, as well as coordinating with researchers and expert consultants familiar with the sources and sinks. Each year, the coordinator oversees a multi-stage process for collecting information from each individual source and sink category lead to compile all information and data for the *Inventory*.

Methodology Development, Data Collection, and Emissions and Sinks Estimation

Source and sink category leads at EPA coordinate the collection of input data (e.g., activity data and other information) and, as necessary, evaluate or develop the estimation methodology for the individual source and/or sink categories. Because EPA has been leading preparation of the *Inventory* for many years, for most source and sink categories, the methodology for the previous year is applied to the new "current" year of the *Inventory*, and inventory analysts collect any new data or update data that have changed from the previous year. If estimates for a new source or sink category are being developed for the first time, or if the methodology is changing for an existing category (e.g., the United States is implementing improvement efforts to apply a higher tiered approach for that category), then the source and/or sink category lead will develop and implement the new or refined methodology, gather the appropriate activity data and other information (e.g., emission factors or in some cases direct emission measurements) for the entire time series, and conduct any further category-specific review with involvement of relevant experts from industry, government, and universities (see Chapter 9 and Box ES-3 on EPA's approach to recalculations).

Once the methodology is in place and the data are collected, the individual source and sink category leads calculate emission and removal estimates. The individual leads then update or create the relevant national inventory document text and accompanying annexes for the *Inventory*. Source and sink category leads are also responsible for completing the relevant sectoral background tables of the CRTs, conducting quality control (QC) checks, preparing relevant category materials for QA, or expert reviews, category-level uncertainty assessments, and reviewing data for publication in EPA's GHG Data Explorer.[55]

The treatment of confidential business information (CBI) in the *Inventory* is based on EPA internal guidelines, as well as regulations[56] applicable to the data used. EPA has specific procedures in place to safeguard CBI during the inventory compilation process. When information derived from CBI data is used for development of inventory calculations, EPA procedures ensure that these confidential data are sufficiently aggregated to protect confidentiality while still providing useful information for analysis. For example, within the Energy and Industrial

[55] See https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

[56] 40 CFR Part 2, Subpart B titled "Confidentiality of Business Information" which is the regulation establishing rules governing handling of data entitled to confidentiality treatment. See https://www.ecfr.gov/cgi-bin/text-idx?SID=a764235c9eadf9afe05fe04c07a28939&mc=true&node=sp40.1.2.b&rgn=div6.

Processes and Product Use (IPPU) sectors, EPA has used aggregated facility-level data from the Greenhouse Gas Reporting Program (GHGRP) to develop, inform, and/or quality-assure U.S. emission estimates. In 2014, EPA's GHGRP, with industry engagement, compiled criteria that would be used for aggregating its confidential data to shield the underlying CBI from public disclosure.[57] In the *Inventory*, EPA is publishing only data values that meet the GHGRP aggregation criteria.[58] Specific uses of aggregated facility-level data are described in the respective methodological sections within those chapters. In addition, EPA uses historical data reported voluntarily to EPA via various voluntary initiatives with U.S. industry (e.g., EPA Voluntary Aluminum Industrial Partnership (VAIP)) and follows guidelines established under the voluntary programs for managing CBI.

Data Compilation and Archiving

The inventory coordinator at EPA with support from the data/document manager collects the source and sink categories' descriptive text and annexes, and also aggregates the emission and removal estimates into a summary data file that links the individual source and sink category data files together. This summary data file contains all of the essential data in one central location, in formats commonly used in the *Inventory* document. In addition to the data from each source and sink category, other national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Trends chapters of the *Inventory* report (e.g., GDP, population, energy use). Similarly, the recalculation analysis and key category analysis are completed in a separate data file based on output from the summary data file. The uncertainty estimates for each source and sink category are also aggregated into uncertainty summary data files that are used to conduct the overall *Inventory* uncertainty analysis (see Section 1.7). A Microsoft SharePoint work site, maintained within EPA's IT infrastructure by the inventory coordinator, provides a platform for facilitating collaboration on the national inventory report preparation during each compilation phase, but also the efficient storage and archiving of electronic document and data files each annual cycle. Previous final published inventories are also maintained on a report archive page on EPA's Greenhouse Gas Emissions website.[59]

National Inventory Document (NID) Preparation

The NID is compiled from the sections developed by each individual source or sink category lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions and removals from all sources and sinks discussed in the chapters. Also at this time, the Executive Summary, Introduction, Trends in Greenhouse Gas Emissions and Removals, and Recalculations and Improvements chapters are drafted, to reflect the trends and impact from improvements for the time series of the current *Inventory*. The analysis of trends necessitates gathering supplemental data, including annual climate, economic activity and gross domestic product, population, atmospheric conditions, and the annual use of electricity, energy, fossil and non-fossil fuels. Changes in these data are used to explain the trends observed in greenhouse gas emissions in the United States. Furthermore, specific factors that affect individual sectors are researched and discussed. Many of the factors that affect emissions are included in the *Inventory* document as separate analyses or side discussions in boxes within the text. Finally, the uncertainty analysis and key category analysis are compiled and updated in the report as part of final analysis steps. Throughout the report text boxes are also created to provide additional documentation (e.g., definitions) and/or examine the data aggregated in different ways than in the remainder of the document, such as a focus on transportation activities or emissions from electricity generation. The document is prepared to align with the Paris Agreement and UNFCCC reporting guidelines for National Inventory Reports while also reflecting national circumstances.

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[57] Federal Register Notice on "Greenhouse Gas Reporting Program: Publication of Aggregated Greenhouse Gas Data." See pp. 79 and 110 of notice at https://www.gpo.gov/fdsys/pkg/FR-2014-06-09/pdf/2014-13425.pdf.

[58] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

[59] See https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-archive.

Common Reporting Tables (CRTs) Compilation

The CRTs are compiled from individual time series input data sheets completed by each individual source or sink category lead, which contain emissions and/or removals and activity data, estimates, methodological and completeness notations and associated explanations. The inventory coordinator and cross-cutting compilation staff import the U.S. category and subcategory background data into the UNFCCC's Enhanced Transparency Framework Reporting Tools to export CRTs, assuring consistency and completeness across all sectoral tables. The summary reports for emissions and removals, methods, and emission factors used, the summary tables indicating completeness of estimates (i.e., notation key NE/IE tables), the recalculation tables, and the emission and removal trends tables are automatically compiled by the online reporting software and reviewed by the inventory coordinator with support from the cross-cutting compilation staff. Internal automated quality checks within the software, as well as checks by the cross-cutting and category leads, are completed for the entire time series of CRTs before submission.

QA/QC and Uncertainty

Quality assurance and quality control (QA/QC) and uncertainty analyses are guided by the QA/QC and inventory coordinators, who help maintain the QA/QC plan and the overall uncertainty analysis procedures (see sections on QA/QC and Uncertainty, below) in collaboration with the broader inventory compilation team. The QA/QC coordinator works closely with the Inventory coordinator and source and sink category leads to ensure that a consistent QA/QC plan is implemented across all inventory categories. Similarly, the inventory coordinator ensures the uncertainty analysis is implemented consistently across all categories. The inventory QA/QC plan, outlined in Section 1.6 and Annex 8, is consistent with the quality assurance procedures outlined by EPA and IPCC good practices. The QA/QC and uncertainty findings also inform overall improvement planning, and specific improvements are noted in the Planned Improvements sections of respective categories. QA processes are outlined below.

Expert, Public, and UNFCCC/Paris Reviews

The compilation of the *Inventory* includes a two-stage review or QA process, in addition to international technical expert review following submission of the report under the UNFCCC and Paris Agreement. EPA publishes responses to comments received during both expert and public reviews with the publication of the final report on its website.[60] Responses to UNFCCC and Paris reviews are included in Annex 8 of this document.

During the first stage of review, i.e., the 30-day expert review period, a first draft of updated sectoral chapters are sent to technical experts who are not directly involved in preparing estimates. The purpose of the expert review is to provide an objective review of the methodological approaches and data sources used in the current *Inventory*, especially for sources and sinks which have experienced any changes since the previous *Inventory*. Expert review follows good practices from EPA's Peer Review handbook, i.e., the review is organized by sector, and reviewers are provided a guidance memo and charge questions to facilitate their review.[61] Expert reviewers include other federal agency staff, researchers, industry experts, and others who have technical knowledge of the data, industry, and methods. EPA reviews and updates expert participation and outreach on an annual basis prior to each expert review cycle. Experts are identified in various ways; for example, many reach out to EPA with technical feedback and are added to the expert reviewer list. Reviewers are also identified through direct outreach by inventory staff based on expertise. Currently, EPA's expert list includes nearly 300 experts across all sectors. Once comments are received, they are reviewed by the source or sink lead and addressed in several ways. For example, comments suggesting methodological clarifications may be incorporated into methodological discussions prior to the next

[60] See https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

[61] See https://www.epa.gov/osa/peer-review-handbook-4th-edition-2015.

review phase, while comments citing new literature or data will be noted for review as part of planned improvements.

Following expert review, a second draft of the document, including cross-cutting synthesis chapters, is released for a 30-day public review through a notice in the U.S. Federal Register. The entire draft *Inventory* document is published on the EPA website. The public review period is open to the entire U.S. public. Comments are submitted and tracked using an online electronic docket that is accessible to the general public as well. Similar to expert review, some comments received may require further discussion with commenters, other experts and/or additional research. Specific *Inventory* improvements requiring further analysis as a result of comments are noted in the relevant category's Planned Improvement section.

As mentioned above, following completion and submission of the report under the UNFCCC and the Paris Agreement, the report also undergoes review by an international team of independent experts for adherence to UNFCCC/Paris reporting guidelines and consistency with IPCC methodological guidance.[62] Feedback from all review processes that contribute to improving inventory quality over time are described within each planned improvement section and further in Annex 8. See also the Improvement Planning process discussed below.

Final Submittal and Publication under the Paris Agreement and the UNFCCC

After the final revisions to incorporate any comments from the Expert Review and Public Review periods, EPA prepares the final NIR, which includes the NID and the accompanying CRTs for electronic reporting. Prior to submission, EPA's Office of Atmospheric Protection briefs senior leadership on reporting findings and improvements since the previous report, along with an overview of feedback from the expert and public review processes.

EPA, as the National Inventory Focal Point, sends the official submission of the U.S. *Inventory* under the Paris Agreement and the UNFCCC using the UN's reporting software, coordinating with the U.S. Department of State, the overall UNFCCC focal point. Concurrently, the report is also published on EPA's website.[63] On EPA's website, users can also visualize and download the current time-series estimates from the GHG Inventory Data Explorer Tool,[64] and also download more detailed data presented in tables within the report and report annex in CSV format.

Improvement Planning

Each year, several emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised, through the use of better methods and/or data with the goal of improving inventory quality and reducing uncertainties, including the transparency, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006) and its *2019 Refinement*, which state, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is *good practice* to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors." The EPA's OAP coordinates improvement planning across all sectors and also cross-cutting analyses based on annual review and input from the technical teams leading compilation of each sector's estimates, including

[62] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/review-process.

[63] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

[64] See https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

continuous improvements to the overall data and document compilation and QA/QC processes. Planned improvements are identified through QA/QC processes (including completeness checks), the key category analysis, and the uncertainty analysis. The inventory coordinator, with input from EPA source and sink category leads, maintains a log of all planned improvements, by sector and cross-cutting, tracking the category significance, specific category improvement, prioritization, anticipated time frame for implementation of each proposed improvement, and status of progress in implementing improvement. Improvements for significant or key categories are usually prioritized across all improvements unless effort would require disproportionate levels of effort and resources relative to improvements for other key categories to address.

1.4 Methodology and Data Sources

Emissions and removals of greenhouse gases from various source and sink categories have been estimated using methodologies that are consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and its supplements and refinements. To a great extent, this report makes use of published official economic and physical statistics for activity data, emission factors and other key parameters as inputs to the methods applied. Depending on the category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, or commodity produced, etc. Emission factors are factors that relate quantities of emissions to an activity. For more information on data sources see Section 1.2 above, Box 1-1 on use of GHGRP data, and categories' methodology sections for more information on other data sources. In addition to official statistics, the report utilizes findings from academic studies, trade association surveys and statistical reports, along with expert judgment, consistent with the *2006 IPCC Guidelines*.

The methodologies provided in the *2006 IPCC Guidelines* represent foundational methodologies for a variety of source and sink categories, and many of these methodologies continue to be improved and refined as new research and data become available. This report uses those IPCC methodologies when applicable, and supplements them with refined guidance, other available country-specific methodologies and data where possible (e.g., EPA's GHGRP). For example, as noted earlier in this chapter, this report does apply recent supplements and refinements to *2006 IPCC Guidelines* in estimating emissions and removals from coal mining, wastewater treatment and discharge, low voltage anode effects (LVAE) during aluminum production, drained organic soils, and management of wetlands, including flooded lands. Choices made regarding the methodologies and data sources used are provided in the Methodology and Time-Series Consistency discussion of each category within each sectoral chapter of the report, applying higher tiered methods when feasible, especially for key categories consistent with methodological decision trees. Where additional detail is helpful and necessary to explain methodologies and data sources used to estimate emissions, complete documentation is provided in the annexes as indicated in the methodology sections of those respective source categories (e.g., Annex 3.13 for forest land remaining forest land and land converted to forest land). Methods used for key categories (discussed below) are summarized in Annex 1.

1.5 Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) and *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019) define key categories as "inventory categories which individually, or as a group of categories (for which a common method, emission factor and activity data are applied) are prioritized within the national inventory system because their estimates have a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the level of uncertainty in emissions or removals. Whenever the term *key category* is used, it

includes both source and sink categories."[65] A key category analysis identifies source or sink categories for focusing efforts to improve overall Inventory quality, including additional review when feasible.

The *2006 IPCC Guidelines* (IPCC 2006) and its *2019 Refinement* (2019) define several approaches, both quantitative and qualitative, to conduct a key category analysis and identify key categories both in terms of absolute level and trend, along with consideration of uncertainty. This report employs all approaches to identify key categories for the United States. The first approach, Approach 1, identifies significant or key categories without considering uncertainty in its calculations. An Approach 1 level assessment identifies all source and sink categories that cumulatively account for 95 percent of total level, i.e., total emissions (gross) in a given year when assessed in descending order of absolute magnitude. The level analysis was performed twice, including and excluding sources and sinks from the land use, land-use change, and forestry (LULUCF) sector categories. Similarly, an Approach 1 trend analysis can identify categories with trends that significantly influence overall trends by identifying all source and sink categories that cumulatively account for 95 percent of the sum all the trend assessments (e.g., percent change relative to national trend) when sorted in descending order of absolute magnitude.

The next method, Approach 2, was then implemented to identify any additional key categories not already identified from the Approach 1 level and trend assessments by considering uncertainty. The Approach 2 analysis differs from Approach 1 by incorporating each category's uncertainty assessments in its calculations and was also performed twice, including and excluding LULUCF categories. An Approach 2 level assessment identifies all sources and sink categories that cumulatively account for 90 percent of the sum of all level assessments when sorted in descending order of magnitude. Similarly, an Approach 2 trend analysis can identify categories whose trends contribute significantly to overall trends weighing the relative trend difference with the category's relative uncertainty assessment for 2022.

For 2022, based on the key category analysis, excluding the LULUCF sector and uncertainty, 34 categories accounted for 95 percent of emissions. Four categories account for 55 percent of emissions: CO_2 from road transport-related fuel combustion, CO_2 from coal-fired electricity generation, CO_2 from gas fired electricity generation, and CO_2 from gas-fired industrial processes. When considering uncertainties, additional categories such as emissions from substitutes for ozone depleting substances in aerosols were also identified as a key category. In the trend analysis, 32 categories were identified as key categories, and when considering uncertainties, 7 additional categories were identified as key. The trend analysis shows that CO_2 emissions from coal-fired electricity generation, in addition to CO_2 from gas fired electricity generation, CO_2 from road transport related combustion, and HFC and PFC emissions from substitutes for ozone depleting substances in the refrigeration and air conditioning sector are also significant with respect to trends over the time series.

When considering the contribution of the LULUCF sector to 2022 emissions and removals, 42 categories accounted for 95 percent of emissions and sinks, with the most significant category from LULUCF being net CO_2 emission from forest land remaining forest land. When considering uncertainties and the contribution of the LULUCF sector, additional categories such as net CO_2 emissions from grassland remaining grassland were also identified as a key category. In the trend analysis, 40 categories were identified as key, and when considering uncertainties, 2 additional categories were identified as key.

Finally, in addition to conducting Approach 1 and 2 level and trend assessments as described above, a qualitative assessment of the source and sinks categories was conducted to capture any additional key categories that were not identified using the previously described quantitative approaches. For this *Inventory*, no additional categories were identified using qualitative criteria recommend by IPCC, but EPA continues to review its qualitative assessment on an annual basis. Find more information on the key category analysis, including the approach to disaggregation of inventory estimates, see Annex 1 to this report.

[65] See Chapter 4 Volume 1, "Methodological Choice and Identification of Key Categories" in IPCC (2006) and IPCC (2019). See http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Table 1-4: Summary of Key Categories for the United States (1990 and 2022) by Sector

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
Energy										
1.A.3.b Transportation: Road	CO_2	◉	•	◉	•	◉	•	◉	•	1,438.1
1.A.1 Stationary Combustion - Coal - Electricity Generation	CO_2	◉	•	◉	•	◉	•	◉	•	851.5
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	CO_2	◉	•	◉	•	◉	•		•	659.3
1.A.2 Stationary Combustion - Natural Gas - Industrial	CO_2	◉	•	◉	•	◉	•	◉	•	510.4
1.A.4.b Stationary Combustion - Natural Gas - Residential	CO_2	◉	•	◉	•	◉	•	◉		272.0
1.A.2 Stationary Combustion - Oil - Industrial	CO_2	◉	•	◉	•	◉	•	◉	•	247.6
1.A.4.a Stationary Combustion - Natural Gas - Commercial	CO_2	◉	•	◉	•	◉	•	•	•	192.3
1.A.3.a Transportation: Aviation	CO_2	◉	•	◉	•	◉		◉		165.6
1.A.5 Non-Energy Use of Fuels	CO_2	◉		◉		◉	•	◉		102.8
1.A.3.e Transportation: Other	CO_2	◉	•	◉	•		•			69.3
1.A.4.a Stationary Combustion - Oil - Commercial	CO_2	◉	•	◉	•					65.1
1.A.4.b Stationary Combustion - Oil - Residential	CO_2	◉	•	◉	•					62.1

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.2 Stationary Combustion - Coal - Industrial	CO_2	◉	•	◉	•	◉	•	○	•	43.0
1.A.3.d Transportation: Domestic Navigation	CO_2	◉		◉						40.9
1.B.2 Natural Gas Systems	CO_2	◉		◉						36.5
1.A.3.c Transportation: Railways	CO_2	◉		◉						32.5
1.B.2 Petroleum Systems	CO_2	•	•	•	•		•		•	22.0
1.A.1 Stationary Combustion - Oil - Electricity Generation	CO_2	◉	•	◉	•	○	•		•	20.5
1.A.5 Stationary Combustion - Oil - U.S. Territories	CO_2	○		○						17.0
1.A.5.b Transportation: Military	CO_2		•		•					4.8
1.A.4.a Stationary Combustion - Coal - Commercial	CO_2		•		•					1.4
1.A.4.b Stationary Combustion - Coal - Residential	CO_2						•			NO
1.B.2 Natural Gas Systems	CH_4	◉	•	◉	•	◉	•	◉	•	173.1
1.B.1 Fugitive Emissions from Coal Mining	CH_4	◉	•	◉	•	◉	•	◉	•	43.6
1.B.2 Petroleum Systems	CH_4	◉	•	◉	•	◉	•	◉		39.6
1.B.2 Abandoned Oil and Natural Gas Wells	CH_4					◉		◉		8.5
1.A.4.b Stationary Combustion - Residential	CH_4					◉	•	◉	•	4.3
1.A.1 Stationary Combustion - Coal - Electricity Generation	N_2O					◉		•		18.2
1.A.3.b Transportation: Road	N_2O	○	•	○	•					8.9

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	N_2O						•			3.4
Industrial Processes and Product Use										
2.A.1 Cement Production	CO_2	◉		◉	•					41.9
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CO_2	◉	•	◉	•	◉	•	○	•	40.7
2.B.8 Petrochemical Production	CO_2	◉	•	◉	•					28.8
2.B.3 Adipic Acid Production	N_2O		•		•					2.1
2.F.1 Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	•	•	•	•	•	•	•	•	144.6
2.F.4 Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs		•		•	•	•	•	•	17.0
2.F.2 Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs		•		•					11.7
2.B.9 Fluorochemical Production	PFCs, HFCs, SF_6, NF_3	○	•	○	•	○	•	○	•	7.8
2.G Electrical Equipment	PFCs, SF_6	○	•	○	•		•		•	5.1
2.C.3 Aluminum Production	PFCs	○	•	○	•					0.8
Agriculture										
3.A.1 Enteric Fermentation: Cattle	CH_4	◉	•	◉	•	◉	•	◉	•	185.9
3.B.1 Manure Management: Cattle	CH_4	•	•	•	•	•	•		•	37.7
3.B.4 Manure Management: Other Livestock	CH_4	◉		◉		•				27.0
3.C Rice Cultivation	CH_4	◉		•		◉		◉		18.9

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
3.D.1 Direct Emissions from Agricultural Soil Management	N_2O	◉		◉		◉		◉		262.5
3.D.2 Indirect Emissions from Applied Nitrogen	N_2O	◉		◉		◉	•	◉		28.3
Waste										
5.A Commercial Landfills	CH_4	◉	•	◉	•	◉	•	◉	•	100.9
5.A Industrial Landfills	CH_4	•		•		•	•			18.9
5.D Domestic Wastewater Treatment	CH_4					○				13.6
5.D Domestic Wastewater Treatment	N_2O	•		•		◉	•	◉	•	21.4
Land Use, Land-Use Change, and Forestry										
4.E.2 Net Emissions from Land Converted to Settlements	CO_2			◉	•			◉	•	68.2
4.B.2 Net Emissions from Land Converted to Cropland	CO_2			◉	•			◉	•	35.1
4.C.2 Net Emissions from Land Converted to Grassland	CO_2			◉	•			◉	•	25.6
4.C.1 Net Emissions from Grassland Remaining Grassland	CO_2			○	•			◉	•	13.4
4.B.1 Net Removals from Cropland Remaining Cropland	CO_2			•	•			◉	•	(31.7)
4.A.2 Net Removals from Land Converted to Forest Land	CO_2			◉				◉		(100.3)
4.E.1 Net Removals from Settlements Remaining Settlements	CO_2			◉	•			◉	•	(134.8)

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
4.A.1 Net Removals from Forest Land Remaining Forest Land	CO_2			◉	•			◉	•	(787.0)
4.D.1 Flooded Lands Remaining Flooded Lands	CH_4			◉						44.2
Subtotal of Key Categories Without LULUCF[b]										**6,169.7**
Total Gross Emissions Without LULUCF										**6,343.2**
Percent of Gross Total Without LULUCF										**97%**
Subtotal of Key Categories With LULUCF[c]										**5,285.4**
Total Net Emissions With LULUCF										**5,488.9**
Percent of Net Total With LULUCF										**96%**

NO (Not Occurring)

[a] Symbols correspond to the year(s) in which a category is key: 1990 = ○; 2022 = •; 1990 and 2022 = ◉.

[b] Subtotal includes key categories from Level Approach 1 Without LULUCF, Level Approach 2 Without LULUCF, Trend Approach 1 Without LULUCF, and Trend Approach 2 Without LULUCF.

[c] Subtotal includes key categories from Level Approach 1 With LULUCF, Level Approach 2 With LULUCF, Trend Approach 1 With LULUCF, and Trend Approach 2 With LULUCF.

Note: Parentheses indicate negative values (or sequestration).

1.6 Quality Assurance and Quality Control (QA/QC)

As part of efforts to achieve its stated goals for inventory quality, transparency, and credibility, the United States has developed a quality assurance and quality control plan designed to check, document, and improve the quality of its inventory over time. QA/QC activities on the *Inventory* are undertaken within the framework of the U.S. *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC plan) *for the U.S. Greenhouse Gas Inventory: Procedures Manual for QA/QC and Uncertainty Analysis*.

Key attributes of the QA/QC plan are summarized in Figure 1-2. These attributes include:

- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving QA/QC implementation and related information, as well as to guide the implementation of QA/QC and the analysis of uncertainty
- *Implementation of Procedures:* guidance on application of QA/QC procedures throughout the whole Inventory development process from initial data collection, through preparation of the emission and removal estimates, to publication of the *Inventory,* consistent with the *2006 IPCC Guidelines*.
- *Quality Assurance (QA):* process for implementing expert and public reviews for both the inventory estimates and the Inventory report (which is the primary vehicle for disseminating the results of the inventory development process). The expert technical review conducted by the UNFCCC supplements these QA processes, consistent with the QA good practice and the *2006 IPCC Guidelines* (IPCC 2006). See Section 1.3 for more details on these QA processes.
- *Quality Control (QC)*: application of *General (Tier 1) and Category-specific (Tier 2)* quality controls and checks, as recommended by *2006 IPCC Guidelines* (IPCC 2006), along with consideration of secondary data and category-specific checks (additional Tier 2 QC) in parallel and coordination with the uncertainty assessment; the development of protocols and templates, which provides for more structured communication and integration with the suppliers of secondary information
- *General (Tier 1) and Category-specific (Tier 2) Checks:* quality controls and checks, as recommended by *IPCC Good Practice Guidance* and *2006 IPCC Guidelines* (IPCC 2006)
- *Record Keeping:* provisions to track which procedures have been followed, the results of the QA/QC, uncertainty analysis, and feedback mechanisms for corrective action based on the results of the investigations which provide for continual data quality improvement and guided research efforts moving forward.
- *Multi-Year Implementation*: tracking the application of more involved QA/QC procedures which may take more than one cycle to fully implement, especially for category-specific QC, prioritizing key categories in conjunction with improvement planning (see Section 1.3).
- *Interaction and Coordination:* promoting communication within the EPA, across federal agencies and departments, state government programs, and research institutions and consulting firms involved in supplying data or preparing estimates for the *Inventory*. The QA/QC Management Plan itself is intended to be revised and reflect new information that becomes available as the program develops, methods are improved, or additional supporting documents become necessary.

Figure 1-2: Summary of Key QC Processes from U.S. QA/QC Plan

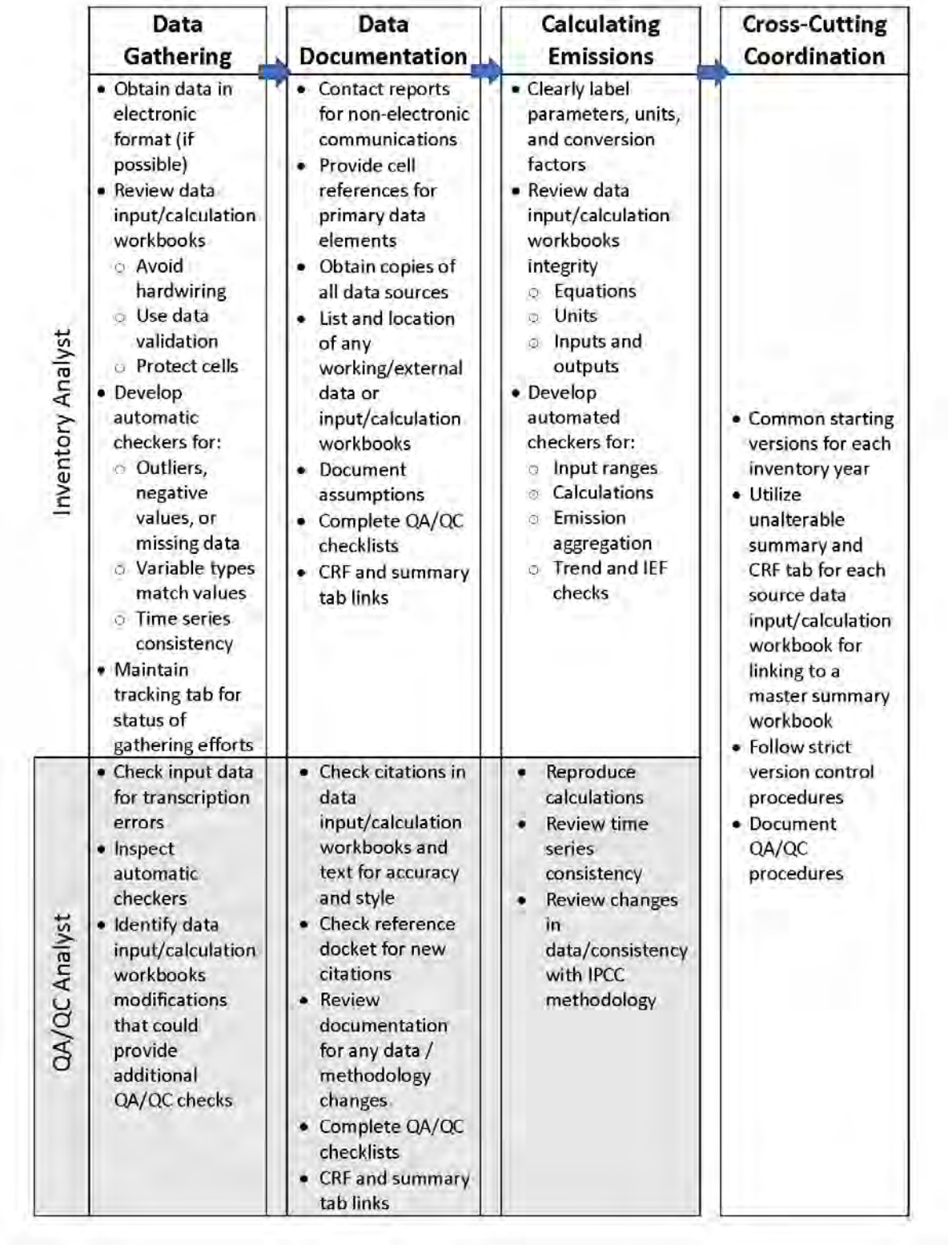

Box 1-3: Examples of Verification Activities

Consistent with IPCC guidance for national greenhouse gas inventories, verification activities include comparisons with emission or removal estimates prepared by other bodies and comparisons with estimates derived from fully independent assessments, e.g., atmospheric concentration measurements. Verification activities provide information to improve inventories and are part of the overall QA/QC system.

Use of Lower Tier Methods. The Paris Agreement/UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology for purposes of verification. This estimation method uses alternative methodologies and different data sources than those contained in that section of the Energy chapter. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys (see Annex 4 of this report). The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

Use of Ambient Measurements Systems for Validation of Emission Inventories. In following the Paris Agreement and UNFCCC reporting requirements to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally accepted methods provided by the IPCC.[66] Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[67] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used to assess estimates or potentially be incorporated into the *Inventory* in a manner consistent with this *Inventory* report's transparency of its calculation methodologies, and the ability of inverse modeling to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

The *2019 Refinement to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1 General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that emission estimates derived from atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC [2019] Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC [2019] Volume 1, Chapter 6). Further, it identified fluorinated gases as particularly suitable for such comparisons due their limited natural sources, their generally long atmospheric lifetimes, and well-understood loss mechanisms, which makes it relatively more straightforward to model their emission fluxes from observed mass quantities. Unlike emissions of CO_2, CH_4, and N_2O, emissions of fluorinated greenhouse gases are almost exclusively anthropogenic, meaning that the fluorinated greenhouse gas emission sources included in this Inventory account for the majority of the total U.S. emissions of these gases detectable in the atmosphere. This evaluation approach is also useful for gases and sources with larger uncertainties in available bottom-up inventory methods and data, such as emissions of CH_4, which are primarily from uncertain biological (e.g., enteric fermentation) and fugitive (e.g., natural gas production) activities.

In this *Inventory*, EPA includes the results from current and previous comparisons between fluorinated gas

[66] See http://www.ipcc-nggip.iges.or.jp/public/index.html.

[67] See http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf.

emissions inferred from atmospheric measurements and fluorinated gas emissions estimated based on bottom-up measurements and modeling. These comparisons, performed for HFCs and SF_6 respectively, are described under the QA/QC and Verification discussions in Chapter 4, Sections 4.25 Substitution of Ozone Depleting Substances and 4.26 Electrical Equipment in the IPPU chapter of this report.

Consistent with the *2019 Refinement*, a key element to facilitate such comparisons is a spatially-explicit (or gridded) emissions inventory as an input to inverse modeling. To improve the ability to compare methane emissions from the national-level greenhouse gas inventory with observation-based emission estimates, a team of researchers from U.S. EPA, SRON Netherlands Institute for Space Research, Harvard University, and Lawrence Berkely National Laboratory developed a time series of annual anthropogenic methane emissions maps with 0.1° x 0.1° (~10km x 10km) spatial resolution and monthly temporal resolution for the contiguous United States.[68] The gridded methane inventory is designed to be consistent with the *U.S. EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks* estimates, which presents national totals for different source types.[69] The development of this gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Finally, in addition to use of atmospheric concentration measurement data for comparison with Inventory data, information from top-down studies is directly incorporated in the Natural Gas Systems calculations to quantify emissions from certain well blowout events.

In addition, based on the national QA/QC plan for the *Inventory*, some sector, subsector and category-specific QA/QC and verification checks have been applied. These checks follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific documentation and data files associated with individual sources. For each greenhouse gas emissions source or sink category included in this *Inventory*, a minimum of general or Tier 1 QC analysis has been undertaken. Where QC activities for a particular category go beyond the minimum general checks and include category-specific checks (Tier 2) or include verification, further explanation is provided within the respective source or sink category text. Similarly, responses or updates based on comments from the expert, public and the international technical expert reviews (e.g., UNFCCC) are also addressed within the respective source or sink category sections in each sectoral chapter and Annex 8.

The quality control activities described in the U.S. QA/QC plan occur throughout the inventory process; QA/QC is not separate from, but is an integral part of, preparing the *Inventory*. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. In addition, quality assurance occurs during the expert review and the public review, in addition to the UNFCCC expert technical review. While all phases significantly contribute to improving inventory quality, the public review phase is also essential for promoting the openness of the inventory development process and the transparency of the inventory methods and underlying input data sources.

The QA/QC plan guides the process of ensuring inventory quality by describing data and methodology checks, developing processes governing peer review and public comments, and developing guidance on conducting an analysis of the uncertainty surrounding the emission and removal estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time.

[68] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

[69] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

1.7 Uncertainty Analysis

Emissions and removals calculated for the U.S. Inventory reflect best estimates for greenhouse gas source and sink categories in the United States and are continuously revised and improved as new information becomes available. Uncertainty assessment is an essential element of a complete and transparent emissions inventory because it helps inform and prioritize Inventory improvements. For the U.S. Inventory, uncertainty analyses are conducted for each source and sink category as well as for the uncertainties associated with the overall emission (current and base year) and trends estimates. These analyses reflect the quantitative uncertainty in the emission (and removal) estimates associated with uncertainties in their input parameters (e.g., activity data and EFs) and serve to evaluate the relative contribution of individual input parameter uncertainties to the overall Inventory, its trends, and each source and sink category.

The overall level and trend uncertainty estimates for total U.S. greenhouse gas emissions was developed using the IPCC Approach 2 uncertainty estimation methodology (assuming a Normal distribution for Approach 1 estimates), which employs a Monte Carlo stochastic simulation technique. The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for both individual and combined source categories. Approach 2 quantifies uncertainties based on a distribution of emissions (or removals), built-up from repeated calculations of emission estimation models and the underlying input parameters, randomly selected according to their known distributions. Approach 2 methodology is applied to each individual source and sink category wherever data and resources are permitted and is also used to quantify the uncertainty in the overall Inventory and its Trends. Source and sink chapters in this report provide additional details on the uncertainty analysis conducted for each source and sink category. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the overall emission (base and current year) and trends estimates. Consistent with IPCC (IPCC 2006), the United States has ongoing efforts to continue to improve the overall Inventory uncertainty estimates presented in this report.

The United States has also implemented many improvements over the last several years to reduce uncertainties across the source and sink categories and improve Inventory estimates. These improvements largely result from new data sources that provide more accurate data and/or increased data coverage, as well as methodological improvements. Following IPCC good practice, additional efforts to reduce Inventory uncertainties can occur through efforts to incorporate excluded emission and sink categories (see Annex 5), improve estimation methods, and collect more detailed, measured, and representative data. Individual category chapters and Annex 7 both describe current ongoing and planned Inventory and uncertainty analysis improvements. Consistent with IPCC (2006), the United States has ongoing efforts to continue to improve the category-specific uncertainty estimates presented in this report, largely prioritized by considering improvements categories identified as significant by the Key Category Analysis.

Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions in 1990 (base year) and 2022 are shown below in Table 1-5 and Table 1-6, respectively. The overall uncertainty surrounding the Total Net Emissions is estimated to be -6 to +6 percent in 1990 and -5 to +6 percent in 2022. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -3 to +4 percent in 1990 and -2 to +4 percent in 2022.

Table 1-5: Estimated Overall Inventory Quantitative Uncertainty for 1990 (MMT CO_2 Eq. and Percent)

Gas	1990 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Greenhouse Gas Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Greenhouse Gas Estimate[a] (%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,131.6	5,008.2	5,348.2	-2%	4%	5,098.2	88.0
CH_4[d]	871.7	731.3	948.4	-16%	9%	701.5	56.3
N_2O[d]	408.2	349.7	513.0	-14%	26%	434.8	41.6
PFC, HFC, SF_6, and NF_3[d]	125.5	108.6	152.9	-13%	22%	207.3	11.6
Total Gross Emissions	**6,536.9**	**6,354.3**	**6,792.8**	**-3%**	**4%**	**6,441.8**	**113.3**
LULUCF Emissions[e]	57.9	55.2	61.9	-5%	7%	68.7	1.7
LULUCF Carbon Stock Change Flux[f]	(1,034.7)	(1,296.1)	(845.3)	25%	-18%	(957.3)	116.7
LULUCF Sector Net Total[g]	**(976.7)**	**(1,237.7)**	**(787.8)**	**27%**	**-19%**	**(888.6)**	**116.7**
Net Emissions (Sources and Sinks)	**5,560.2**	**5,247.0**	**5,882.2**	**-6%**	**6%**	**5,553.3**	**161.4**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 1990.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[f] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 1-6: Estimated Overall Inventory Quantitative Uncertainty for 2022 (MMT CO_2 Eq. and Percent)

Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Greenhouse Gas Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Greenhouse Gas Estimate[a] (%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,053.0	4,937.3	5,257.7	-2%	4%	5,095.2	81.9
CH_4[d]	702.4	604.3	803.1	-14%	14%	703.8	52.0
N_2O[d]	389.7	324.6	490.2	-17%	26%	399.5	42.3
PFC, HFC, SF_6, and NF_3[d]	198.1	182.8	217.5	-8%	10%	199.5	9.0

Total Gross Emissions	**6,343.2**	**6,190.3**	**6,604.8**	**-2%**	**4%**	**6,397.9**	**106.3**
LULUCF Emissions[e]	67.5	64.3	73.2	-5%	8%	68.6	2.3
LULUCF Carbon Stock Change Flux[f]	(921.8)	(1,158.6)	(748.7)	26%	-19%	(957.5)	105.3
LULUCF Sector Net Total[g]	**(854.3)**	**(1,090.3)**	**(680.5)**	**28%**	**-20%**	**(888.8)**	**105.3**
Net Emissions (Sources and Sinks)	**5,488.9**	**5,216.2**	**5,801.9**	**-5%**	**6%**	**5,509.0**	**150.6**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 2022.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[f] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The uncertainty for 2022 is similar to the uncertainty for 1990, though slightly lower. There have been some improvements in significant categories which do not necessarily reduce uncertainties as also acknowledged in the IPCC 2006 IPCC GL, p. 3.13 (e.g., improvements to estimates for Agricultural Soil Management over time, implications of methodological choice). For example, the 95 percent uncertainty bounds for nitrous oxide emissions from Agricultural Soil Management were increased from –25 percent to 29 percent in 1990 to –30 percent to 72 percent in 2022. Methodological and data quality improvements were also made for HFCs, PFCs, SF_6 and NF_3 this year but the uncertainties for these sources also slightly increased, better representing the limitations of existing emissions estimates. The methods and data for fossil fuel combustion categories, the most significant source, has not changed significantly and neither have uncertainties. It is also worth noting that some of the improvements to shift to use of GHGRP have been in less significant categories within the inventory (e.g., for IPPU). So, the overall uncertainty for latest year reflects these offsetting effects and trends within the uncertainty assessment.

In addition to the estimates of uncertainty associated with the current and base year estimates, Table 1-7 presents the estimates of inventory trend uncertainty. The *2006 IPCC Guidelines* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2022) *Inventory* estimates. However, for purposes of understanding the concept of trend uncertainty, the trend is defined in this Inventory as the percentage change in the gross emissions (or net emissions) estimated for the current year, relative to the gross emission (or net emissions) estimated for the base year. The uncertainty associated with this trend is referred to as trend uncertainty and is reported as between -8 and 8 percent at the 95 percent confidence level between 1990 and 2022. This indicates a range of approximately -8 percent below and 8 percent above the trend estimate of -1.3 percent. See Annex 7 for trend uncertainty estimates for individual source and sink categories by gas.

Table 1-7: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent)

Gas	Base Year Emissions[a]	2022 Emissions	Emissions Trend	Trend Range[b]	
	(MMT CO_2 Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO_2	5,131.6	5,053.0	-2%	-6%	3%
CH_4	871.7	702.4	-19%	-32%	2%
N_2O	408.2	389.7	-5%	-30%	51%
HFCs, PFCs, SF_6, and NF_3	125.5	198.1	58%	32%	95%
Total Gross Emissions[c]	**6,536.9**	**6,343.2**	**-3%**	**-7%**	**3%**
LULUCF Emissions[d]	57.9	67.5	17%	6%	30%
LULUCF Carbon Stock Change Flux[e]	(1,034.7)	(921.8)	-11%	-35%	21%
LULUCF Sector Net Total[f]	**(976.7)**	**(854.3)**	**-13%**	**-37%**	**21%**
Net Emissions (Sources and Sinks)[c]	**5,560.2**	**5,488.9**	**-1.3%**	**-8%**	**8%**

[a] Base Year is 1990 for all sources.

[b] The trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5th percentile value and the upper bound corresponding to 97.5th percentile value.

[c] Totals exclude emissions for which uncertainty was not quantified.

[d] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[e] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[f] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

1.8 Completeness

This report, along with its accompanying CRTs, serves as a thorough assessment of the anthropogenic sources and sinks of greenhouse gas emissions for the United States for the time series 1990 through 2022. This report is intended to be comprehensive and includes the vast majority of emissions and removals identified as anthropogenic, consistent with IPCC methods and the Paris Agreement and UNFCCC reporting guidelines. In general, sources or sink categories not accounted for in this *Inventory* are excluded because they are not occurring in the United States and its territories, or because data are unavailable to develop an estimate and/or the categories were determined to be insignificant[70] in terms of overall national emissions per the Paris Agreement and UNFCCC reporting guidelines.

The United States is continually working to improve upon the understanding of such sources and sinks currently not included and seeking to find the data required to estimate related emissions and removals, focusing on categories that are anticipated to be significant. See Chapter 9 on Improvements and Recalculations for more

[70] See paragraph 32 in the Annex to Decision18/CMA.1 of the Paris Agreement reporting guidelines on national inventories that state "…emissions from a category should only be considered insignificant if the likely level of emissions is below 0.05 per cent of the national total GHG emissions, excluding LULUCF, or 500 kilotonnes of carbon dioxide equivalent (kt CO_2 eq), whichever is lower. The total national aggregate of estimated emissions for all gases from categories considered insignificant shall remain below 0.1 per cent of the national total GHG emissions, excluding LULUCF. Parties should use approximated activity data and default IPCC emission factors to derive a likely level of emissions for the respective category."

information on completeness and improvements implemented this cycle. As such improvements are implemented, new emission and removal estimates are quantified and included in the *Inventory*, improving completeness of national estimates. For a list of sources and sink categories not included and more information on significance of these categories, see Annex 5 and the respective category sections in each sectoral chapter of this report.

1.9 Organization of Report

In accordance with the Paris Agreement and UNFCCC reporting guidelines, this *Inventory* is grouped into five sector-specific chapters consistent with the Paris Agreement Common Reporting Tables (CRT),[71] listed below in Table 1-8. In addition, the U.S. *Inventory* submission includes chapters on Trends in Greenhouse Gas Emissions, Other information, and Recalculations and Improvements to be considered consistent with the suggested outline or national inventory documents submitted under the Paris Agreement and UNFCCC.

Table 1-8: CRT/IPCC Sector Descriptions

Chapter (CRT and UNFCCC/IPCC Sector)	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and non-energy use of fossil fuels.
Industrial Processes and Product Use	Emissions resulting from industrial processes and product use of greenhouse gases.
Agriculture	Emissions from agricultural activities except fuel combustion, which is addressed under Energy.
Land Use, Land-Use Change, and Forestry	Emissions and removals of CO_2, and emissions of CH_4, and N_2O from land use, land-use change, and forestry.
Waste	Emissions from waste management activities.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/CRT/IPCC Sector: Overview of emissions and trends for each CRT/IPCC defined sector.

CRT Source or Sink Category: Description of category pathway and emission/removal trends based on IPCC methodologies, consistent with the Paris Agreement and UNFCCC reporting guidelines.

Methodology and Time-Series Consistency: Description of analytical methods (e.g., from *2006 IPCC Guidelines,* or country-specific methods) employed to produce emission estimates and identification of data references, primarily for activity data and emission factors, and a discussion of time-series consistency.

Uncertainty: A discussion and quantification of the uncertainty in emission estimates.

QA/QC and Verification: A discussion on steps taken to QA/QC and verify the emission estimates, consistent with the U.S. QA/QC plan, and any key QC findings.

Recalculations Discussion: A discussion of any data or methodological changes that necessitate a recalculation of previous years' emission estimates, and the impact of the recalculation on the emission estimates, if applicable.

Planned Improvements: A discussion on any category-specific planned improvements, if applicable.

[71] See paragraph 50 in the Annex to Decision 18/CMA.1

Special attention is given to CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-9.

Table 1-9: List of Annexes

ANNEX 1 Key Category Analysis	
ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion	
2.1.	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
2.2.	Methodology for Estimating the Carbon Content of Fossil Fuels
2.3.	Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels
ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories	
3.1.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion
3.2.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions
3.3.	Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption
3.4.	Methodology for Estimating CH_4 Emissions from Coal Mining
3.5.	Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
3.6.	Methodology for Estimating CH_4 Emissions from Natural Gas Systems
3.7.	Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste
3.8.	Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
3.9.	Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
3.10.	Methodology for Estimating CH_4 Emissions from Enteric Fermentation
3.11.	Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
3.12.	Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Lands (Cropland and Grassland)
3.13.	Methodology for Estimating Net Carbon Stock Changes in Forest Land Remaining Forest Land and Land Converted to Forest Land
3.14.	Methodology for Estimating CH_4 Emissions from Landfills
ANNEX 4 IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion	
ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included	
ANNEX 6 Additional Information	
6.1.	Global Warming Potential Values
6.2.	Ozone Depleting Substance Emissions
6.3.	Greenhouse Gas Precursors: Mapping of NEI categories to the Inventory
6.4.	Constants, Units, and Conversions
6.5.	Chemical Formulas
ANNEX 7 Uncertainty	
7.1.	Overview
7.2.	Methodology and Results
7.3.	Reducing Uncertainty
7.4.	Planned Improvements
7.5.	Additional Information on Uncertainty Analyses by Source
ANNEX 8 QA/QC Procedures	
8.1.	Background
8.2.	Purpose
8.3.	Assessment Factors
8.4.	Responses During the Review Process
ANNEX 9 Use of Greenhouse Gas Reporting Program (GHGRP) in Inventory	

2. Trends in Greenhouse Gas Emissions and Removals

2.1 Overview of U.S. Greenhouse Gas Emissions and Sinks Trends

In 2022, total gross U.S. greenhouse gas emissions were 6,343.2 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).[1] Total gross U.S. emissions decreased by 3.0 percent from 1990 to 2022, down from a high of 15.2 percent above 1990 levels in 2007. Gross emissions increased from 2021 to 2022 by 0.2 percent (14.4 MMT CO_2 Eq.). Net emissions (i.e., including sinks) were 5,489.0 MMT CO_2 Eq. in 2022. Overall, net emissions increased by 1.3 percent from 2021 to 2022 and decreased by 16.7 percent from 2005 levels, as shown in Table 2-1. Between 2021 and 2022, the increase in total greenhouse gas emissions was driven largely by an increase in CO_2 emissions from fossil fuel combustion across most end-use sectors due in part to increased energy use from the continued rebound of economic activity after the height of the COVID-19 pandemic. The CO_2 emissions from fossil fuel combustion increased by 1.0 percent from 2021 to 2022, including a 5.0 percent increase in residential sector emissions, 8.9 percent increase in commercial sector emissions, 0.1 percent decrease in transportation sector emissions, 2.6 percent increase in industrial emissions, and 0.6 percent decrease in electric power sector emissions. Carbon sequestration in the Land Use, Land-Use Change, and Forestry (LULUCF) sector offset 14.5 percent of total emissions in 2022.

Figure 2-1 and Figure 2-2 illustrate the overall trend in total U.S. emissions and sinks since 1990, by gas and by annual percentage changes relative to the previous year.

[1] The gross emissions total presented in this report for the United States excludes emissions and sinks from removals from LULUCF. The net emissions total presented in this report for the United States includes emissions and sinks from removals from LULUCF.

Figure 2-1: U.S. Greenhouse Gas Emissions and Sinks by Gas

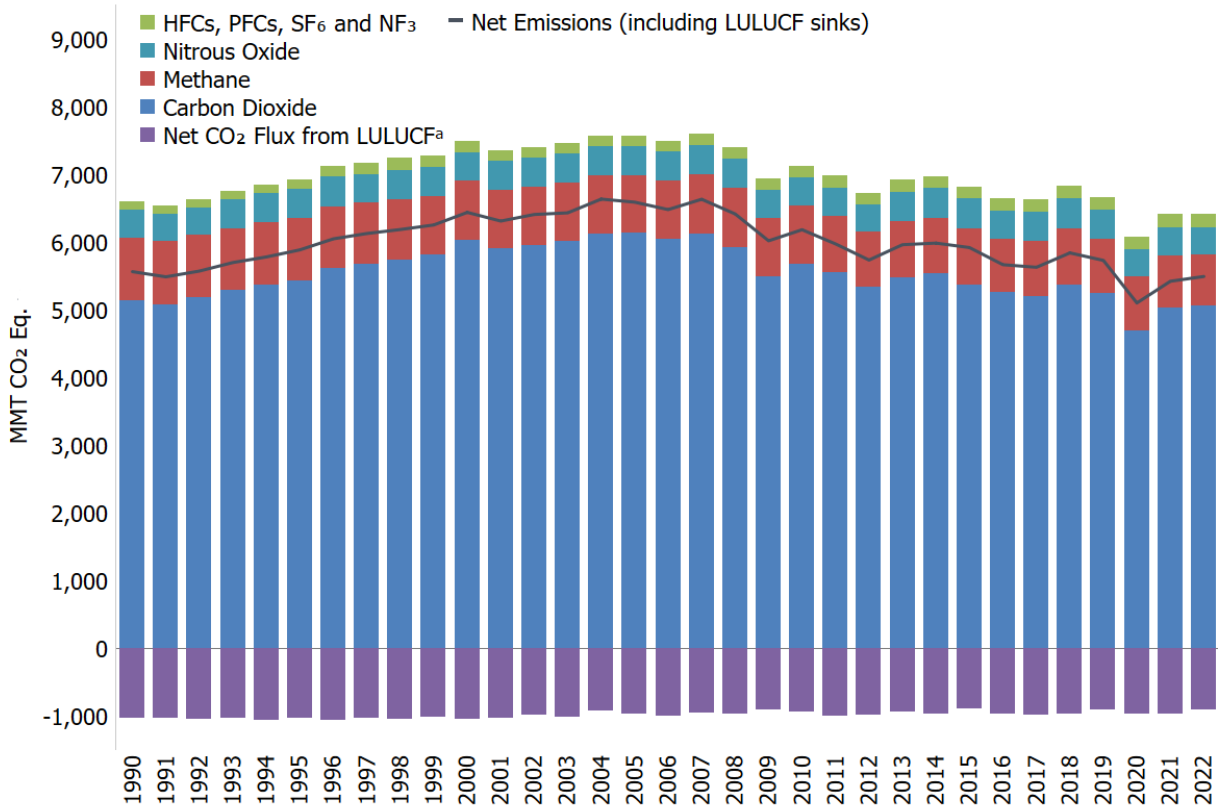

[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Figure 2-2: Annual Percentage Change in Gross U.S. Greenhouse Gas Emissions Relative to the Previous Year

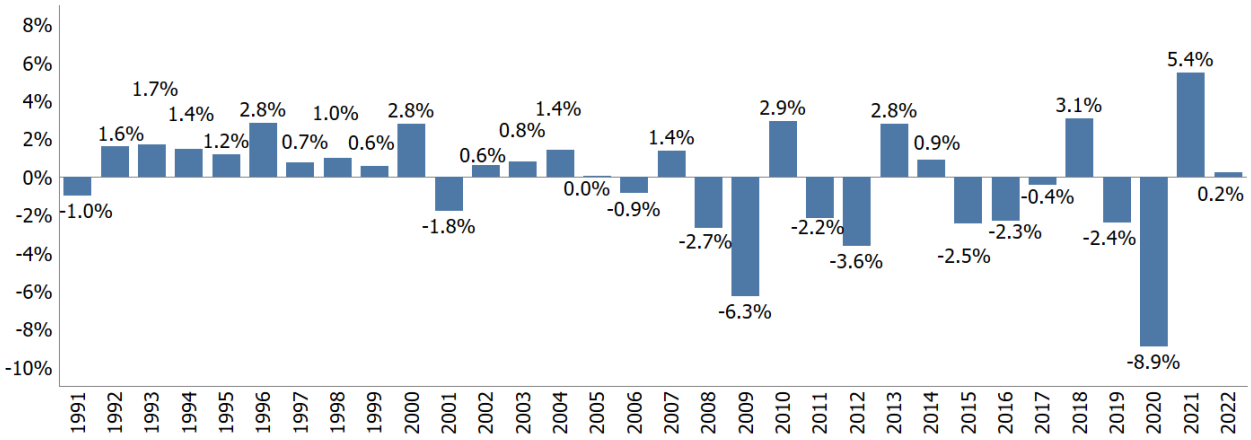

Emissions and Sinks by Gas

Figure 2-3 illustrates the relative contribution of each gas to total gross U.S. greenhouse gas emissions in 2022, in CO_2 equivalents (i.e., weighted by global warming potential). The primary greenhouse gas emitted by human activities in the United States is CO_2, representing 79.7 percent of total greenhouse gas emissions. The largest source of CO_2—and of overall greenhouse gas emissions—is fossil fuel combustion, primarily from transportation and power generation. Methane (CH_4) emissions account for 11.1 percent of emissions. The major sources of methane include enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of waste in landfills. Agricultural soil management, wastewater treatment, stationary sources of fuel combustion, and manure management are the major sources of N_2O emissions. Ozone depleting substance (ODS) substitute emissions were the primary contributor to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions were attributable primarily to fluorochemical production and electronics manufacturing. Electrical equipment accounted for most sulfur hexafluoride (SF_6) emissions. Nitrogen trifluoride (NF_3) emissions were approximately evenly split between electronics manufacturing and fluorochemical production.

Figure 2-3: 2022 Gross Total U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)

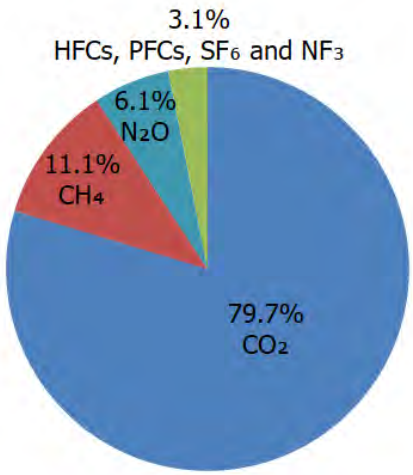

Note: Emissions and removals from LULUCF are excluded from the figure above.

From 1990 to 2022, total emissions of CO_2 decreased by 1.5 percent (78.6 MMT CO_2 Eq.), total emissions of methane (CH_4) decreased by 19.4 percent (169.3 MMT CO_2 Eq.), and total emissions of nitrous oxide (N_2O) decreased by 4.5 percent (18.4 MMT CO_2 Eq.). During the same period, emissions of fluorinated gases including HFCs, PFCs, SF_6, and NF_3 rose by 57.9 percent (72.7 MMT CO_2 Eq.). Rapidly growing emissions of HFCs drove this trend, overwhelming decreases in emissions of PFCs and SF_6. Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6, and NF_3 are significant because many of them have extremely high global warming potentials (GWPs), and, in the cases of PFCs, SF_6, and NF_3, very long atmospheric lifetimes. U.S. greenhouse gas emissions were partly offset by carbon sequestration in managed forests, trees in urban areas, agricultural soils, landfilled yard trimmings, and coastal wetlands. These were estimated to offset 14.5 percent (921.8 MMT CO_2 Eq.) of total gross emissions in 2022.

Table 2-1 provides information on trends in emissions and sinks from all U.S. anthropogenic sources and sinks in weighted units of MMT CO_2 Eq., while unweighted gas emissions and sinks in kilotons (kt) are provided in Table 2-2.

Table 2-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Gas (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**5,131.6**	**6,126.9**	**5,362.2**	**5,234.5**	**4,689.0**	**5,017.2**	**5,053.0**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*
Electric Power Sector	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Magnesium Production and Processing	0.1	+	+	+	+	+	+
Biomass and Biodiesel Consumption[a]	*237.9*	*245.4*	*336.0*	*333.1*	*295.7*	*303.0*	*305.4*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
CH_4[c]	**871.7**	**795.4**	**771.5**	**754.3**	**735.3**	**720.5**	**702.4**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+

Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O[c]	**408.2**	**419.2**	**439.5**	**416.4**	**391.2**	**398.2**	**389.7**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Natural Gas Systems	+	+	+	+	+	+	0.2
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**
Substitution of Ozone Depleting Substances	0.3	99.5	157.9	162.1	166.2	172.6	178.1
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	+	+
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	+	+
Electrical Equipment	0.0	+	0.0	+	+	+	+
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8
SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6
Fluorochemical Production	5.8	3.3	+	+	+	+	+
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**
LULUCF Emissions[c]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1
LULUCF Carbon Stock Change[e]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Sector Net Total[f]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

[e] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[f] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) emissions are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Table 2-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Gas (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**5,131,650**	**6,126,864**	**5,362,191**	**5,234,488**	**4,688,969**	**5,017,202**	**5,053,019**
Fossil Fuel Combustion	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
Transportation	*1,468,944*	*1,858,552*	*1,813,135*	*1,816,636*	*1,572,820*	*1,753,546*	*1,751,286*
Electric Power Sector	*1,819,951*	*2,400,057*	*1,753,432*	*1,606,721*	*1,439,566*	*1,540,933*	*1,531,680*
Industrial	*876,468*	*847,640*	*810,472*	*809,807*	*761,986*	*780,453*	*801,064*
Residential	*338,568*	*358,898*	*338,940*	*342,905*	*314,795*	*318,034*	*334,065*
Commercial	*228,293*	*227,130*	*246,297*	*251,749*	*229,264*	*237,528*	*258,733*
U.S. Territories	*20,010*	*51,857*	*25,923*	*24,813*	*23,279*	*23,772*	*22,575*
Non-Energy Use of Fuels	99,104	124,988	118,382	106,474	97,757	111,624	102,808
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884
Iron and Steel Production & Metallurgical Coke Production	104,740	70,082	42,863	43,095	37,724	41,873	40,672
Natural Gas Systems	32,427	26,312	32,768	38,525	36,719	35,780	36,470
Petrochemical Production	20,075	26,882	27,200	28,483	27,926	30,656	28,788
Petroleum Systems	9,585	10,210	34,777	45,498	28,937	24,140	21,967
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610
Incineration of Waste	12,900	13,254	13,339	12,948	12,921	12,476	12,357
Lime Production	11,700	14,552	13,106	12,112	11,299	11,870	12,208
Other Process Uses of Carbonates	7,103	8,472	7,938	8,973	9,012	8,583	10,384
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	6,113	6,150	5,805	6,600	7,053
Urea Fertilization	2,417	3,504	4,936	5,034	5,132	5,229	5,327
Carbon Dioxide Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000
Liming	4,690	4,351	2,240	2,203	2,887	2,387	3,268
Coal Mining	4,606	4,169	3,139	2,992	2,197	2,455	2,474
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704
Titanium Dioxide Production	1,195	1,755	1,541	1,340	1,340	1,474	1,474
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446
Ferroalloy Production	2,152	1,392	2,063	1,598	1,377	1,567	1,327
Zinc Production	632	1,030	999	1,026	977	1,007	947
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Lead Production	516	553	527	531	450	439	428
Carbide Production and Consumption	243	213	184	175	154	172	210
Abandoned Oil and Gas Wells	7	7	8	8	8	8	8
Substitution of Ozone Depleting Substances	+	1	3	3	4	4	4
Magnesium Production and Processing	129	4	2	2	3	3	3
Biomass and Biodiesel Consumption[a]	*237,946*	*245,421*	*335,971*	*333,057*	*295,695*	*303,014*	*305,417*
International Bunker Fuels[b]	*103,634*	*113,328*	*124,279*	*113,632*	*69,638*	*80,180*	*98,241*
CH_4[c]	**31,131**	**28,408**	**27,553**	**26,941**	**26,262**	**25,731**	**25,084**
Enteric Fermentation	6,539	6,722	7,028	7,045	7,010	7,017	6,878
Natural Gas Systems	7,813	7,505	6,795	6,741	6,439	6,235	6,183
Landfills	7,063	5,275	4,512	4,595	4,431	4,359	4,277
Manure Management	1,398	1,964	2,418	2,382	2,390	2,373	2,312
Coal Mining	3,860	2,552	2,110	1,892	1,648	1,595	1,558
Petroleum Systems	1,765	1,723	2,108	1,865	1,904	1,737	1,415
Wastewater Treatment	811	809	763	755	748	738	743
Rice Cultivation	677	735	711	558	664	653	674
Stationary Combustion	345	313	344	351	285	286	307
Abandoned Oil and Gas Wells	279	294	301	302	303	306	303
Abandoned Underground Coal Mines	288	264	247	237	232	224	225
Mobile Combustion	258	154	101	102	91	92	93
Composting	15	75	90	91	92	92	92
Field Burning of Agricultural Residues	19	23	22	23	22	22	22
Anaerobic Digestion at Biogas Facilities	+	+	+	1	+	+	+
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*3*	*3*	*3*
N_2O[c]	**1,540**	**1,582**	**1,658**	**1,571**	**1,476**	**1,503**	**1,471**
Agricultural Soil Management	1,090	1,110	1,258	1,191	1,102	1,124	1,097
Stationary Combustion	84	115	95	84	78	83	93
Wastewater Treatment	56	68	80	81	84	83	83
Manure Management	50	57	63	63	64	65	64
Mobile Combustion	145	140	67	72	61	63	63
Nitric Acid Production	41	38	32	34	31	30	33
N_2O from Product Uses	14	14	14	14	14	14	14
Adipic Acid Production	51	24	35	18	28	25	8
Composting	1	6	7	7	7	7	7
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	5	5	4	5	5
Incineration of Waste	2	1	1	1	1	1	1
Electronics Industry	+	+	1	1	1	1	1

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Field Burning of Agricultural Residues	1	1	1	1	1	1	1
Natural Gas Systems	+	+	+	+	+	+	1
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*4*	*3*	*2*	*2*	*3*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	M	M	M	M	M	M	M
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
SF_6 and PFCs from Other Product Use	101	83	178	173	167	138	172
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Electrical Equipment	+	+	0	+	+	+	+
SF_6	**2**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	1	1	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
SF_6 and PFCs from Other Product Use	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+
NF_3	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.
M (Mixture of multiple gases)
NO (Not Occurring)
[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.
[b] Emissions from international bunker fuels are not included in totals.
[c] LULUCF emissions of LULUCF CH_4 and N_2O are reported separately from gross emissions totals. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.
[d] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.
Notes: Totals by gas may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Emissions and Sinks by UNFCCC/IPCC Sector

Emissions and removals of all gases can be summed from each source and sink category into a set of five sectors defined by the Paris Agreement and UNFCCC reporting guidelines and methodological framework provided by the Intergovernmental Panel on Climate Change (IPCC). Figure 2-4 and Table 2-3 illustrate that over the 33-year period of 1990 to 2022, total emissions from the Energy and Waste sectors decreased by 3.4 percent (181.2 MMT CO_2 Eq.) and 29.3 percent (69.1 MMT CO_2 Eq.), respectively. Emissions from Industrial Processes and Product Use and Agriculture grew by 3.9 percent (14.4 MMT CO_2 Eq.) and 7.7 percent (42.2 MMT CO_2 Eq.), respectively. Over the same period, total carbon sequestration in the LULUCF sector decreased by 12.5 percent (122.5 MMT CO_2), and emissions from the LULUCF sector increased by 16.5 percent (9.6 MMT CO_2 Eq.).

Figure 2-4: U.S. Greenhouse Gas Emissions and Sinks by IPCC Sector

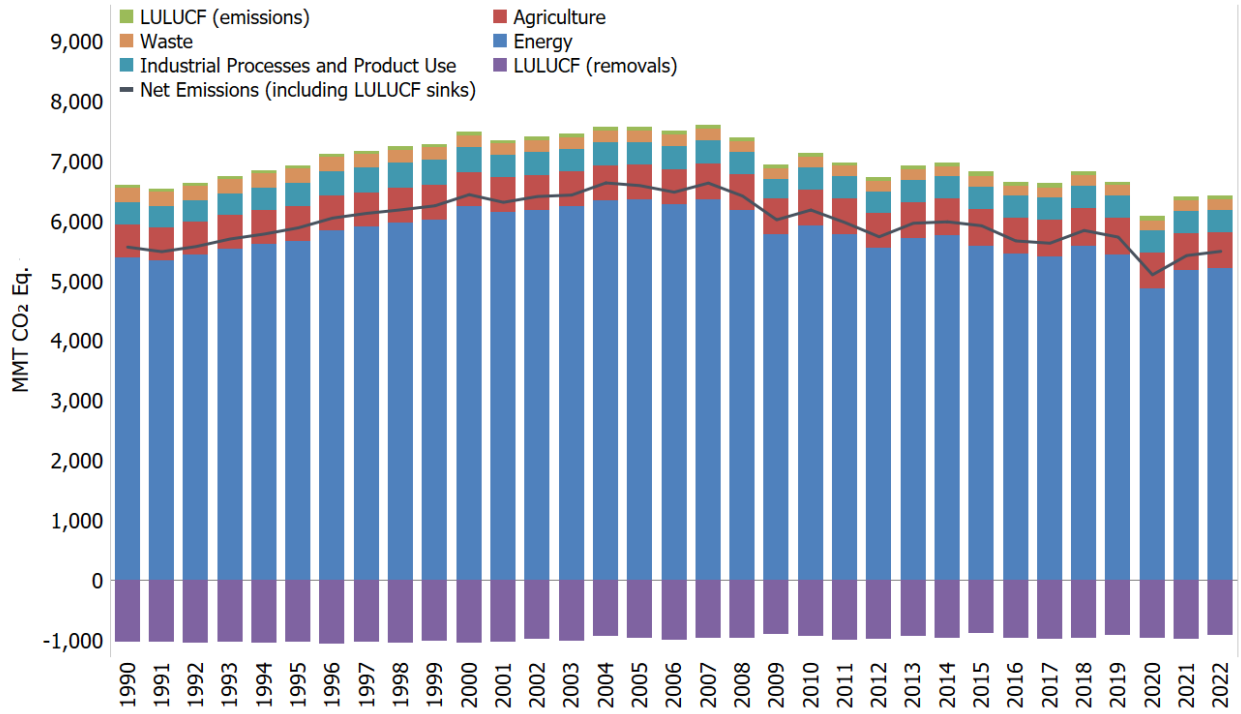

Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector/Category (MMT CO_2 Eq.)

UNFCCC/IPCC Sector/Category	1990	2005	2018	2019	2020	2021	2022
Energy	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Natural Gas Systems	251.2	236.5	223.0	227.3	217.0	210.4	209.7
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Petroleum Systems	59.0	58.5	93.8	97.8	82.3	72.8	61.6
Coal Mining	112.7	75.6	62.2	56.0	48.3	47.1	46.1
Stationary Combustion[a]	32.0	39.3	34.7	32.0	28.5	30.1	33.3
Mobile Combustion	45.6	41.3	20.5	21.9	18.7	19.4	19.3
Incineration of Waste	13.3	13.6	13.7	13.3	13.3	12.8	12.7
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Biomass and Biodiesel Consumption[b]	*237.9*	*245.4*	*336.0*	*333.1*	*295.7*	*303.0*	*305.4*
International Bunker Fuels[c]	*104.6*	*114.3*	*125.3*	*114.6*	*70.3*	*80.9*	*99.1*
Industrial Processes and Product Use	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**
Substitution of Ozone Depleting Substances	0.3	99.5	157.9	162.1	166.2	172.7	178.1
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.8	70.1	42.9	43.1	37.7	41.9	40.7
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
Fluorochemical Production	70.9	30.0	8.7	9.3	6.9	7.1	7.8

Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Electrical Equipment	24.7	11.9	5.0	6.1	5.9	6.0	5.1
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Electronics Industry	3.3	4.5	4.8	4.5	4.5	4.8	4.7
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Aluminum Production	26.1	7.2	2.9	3.3	3.2	2.5	2.2
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Magnesium Production and Processing	5.7	3.0	1.1	1.0	0.9	1.2	1.2
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
SF_6 and PFCs from Other Product Use	1.4	1.5	0.9	0.8	0.7	0.5	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Manure Management	52.5	70.2	84.3	83.5	83.8	83.6	81.7
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
Field Burning of Agricultural Residues	0.7	0.8	0.8	0.9	0.8	0.8	0.8
Waste	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Wastewater Treatment	37.5	40.7	42.5	42.7	43.2	42.7	42.7
Composting	0.7	3.6	4.3	4.3	4.4	4.4	4.4
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+
Total Gross Emissions[d] (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**
LULUCF Sector Net Total[e]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**
Forest Land	(1,069.0)	(960.2)	(963.8)	(907.3)	(946.6)	(924.2)	(872.0)
Cropland	40.4	2.9	14.2	12.0	20.5	2.9	3.4
Grassland	59.8	46.7	54.9	54.3	45.8	36.0	39.6
Wetlands	44.0	41.2	38.9	38.9	38.8	38.8	38.8
Settlements	(51.9)	(38.1)	(59.7)	(61.4)	(63.0)	(64.1)	(64.1)
Net Emission (Sources and Sinks)[f]	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Includes CH_4 and N_2O emissions from fuel combustion.

[b] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[c] Emissions from international bunker fuels are not included in totals.

[d] Total emissions without LULUCF.

[e] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[f] Net emissions with LULUCF.

Notes: Total (gross) emissions are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

Emissions from energy-related activities come from two main categories: 1) direct emissions associated with fuel use (i.e., fossil fuel combustion, non-energy use of fossil fuels and waste combustion), and 2) fugitive emissions mainly from coal, natural gas, and oil production. Energy emissions also include some categories that are not added to Energy sector totals but are instead presented as memo items, including international bunker fuels and biomass emissions. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions from 1990 through 2022. Fossil fuel combustion is the largest source of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 2-5). Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered in detail in the Energy chapter (see Chapter 3).

In 2022, 83.0 percent of the energy used in the United States on a Btu basis was produced through the combustion of fossil fuels. The remaining 17.0 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy. A discussion of specific trends related to CO_2 and other greenhouse gas emissions from energy use is presented here with more detail in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (40.2 percent and 10.8 percent of gross total U.S. emissions of each gas, respectively).[2] Table 2-4 presents greenhouse gas emissions from the Energy chapter by source and gas.

Figure 2-5: Trends in Energy Sector Greenhouse Gas Sources

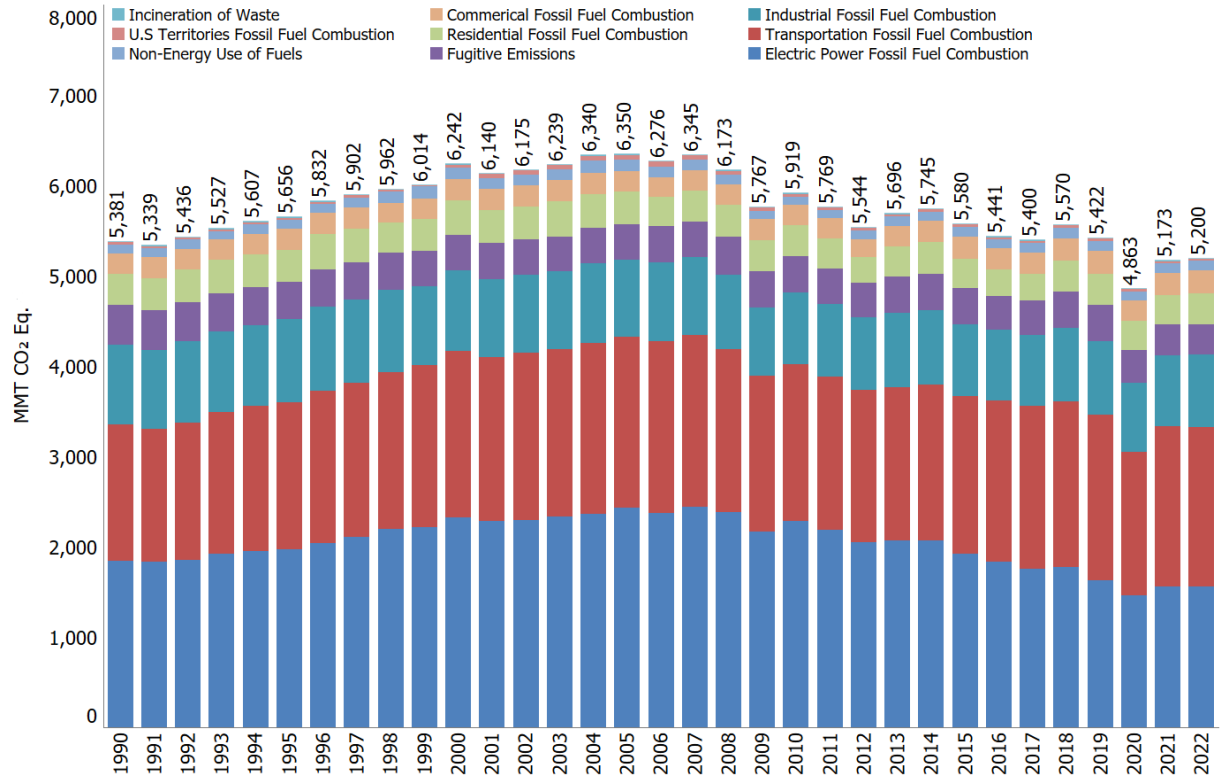

[2] The contribution of energy non-CO_2 emissions is based on gross totals so excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related CH_4 and N_2O including LULUCF non-CO_2 emissions, is 37.1 percent and 9.8 percent, respectively.

Table 2-4: Emissions from Energy by Gas (MMT CO_2 Eq.)[3]

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**4,910.9**	**5,923.1**	**5,190.6**	**5,059.1**	**4,520.2**	**4,840.7**	**4,875.5**	**-0.7%**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4	-1.1%
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*	*19.2%*
Electricity Generation	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*	*-15.8%*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*	*-8.6%*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*	*-1.3%*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*	*13.3%*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*	*12.8%*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8	3.7%
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5	12.5%
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0	129.2%
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4	-4.2%
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5	-46.3%
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+	13.0%
Biomass-Wood[a]	*215.2*	*206.9*	*220.0*	*217.7*	*190.6*	*192.5*	*195.3*	*-9.2%*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*	*-5.2%*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*81.9*	*82.6*	*71.8*	*79.1*	*79.6*	*1783.2%*
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*	*100.0%*
Biomass-MSW[a]	*18.5*	*14.7*	*16.1*	*15.7*	*15.6*	*15.3*	*14.9*	*-19.8%*
CH_4	**409.0**	**358.5**	**336.2**	**321.7**	**305.3**	**293.3**	**282.4**	**-31.0%**
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1	-20.9%
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6	-59.6%
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6	-19.8%
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6	-10.8%
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5	8.8%
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3	-21.8%
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6	-63.8%
Incineration of Waste	+	+	+	+	+	+	+	-17.9%
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*-51.8%*
N_2O	**61.2**	**67.9**	**43.2**	**41.6**	**37.1**	**39.2**	**41.9**	**-31.5%**
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7	10.6%
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7	-56.5%
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3	-17.9%
Natural Gas Systems	+	+	+	+	+	+	0.2	3,204.7%
Petroleum Systems	+	+	+	+	+	+	+	282.0%
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*	*1.4%*
Total	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**	**-3.4%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines*, the Paris Agreement and the UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

[3] The full time series data is available in Common Reporting Tables (CRTs) included in the U.S. Paris Agreement and UNFCCC submission and in CSV format available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Fossil Fuel Combustion CO_2 Emissions

As the largest contributor to U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 74.6 percent of CO_2-equivalent total gross emissions on average across the time series. Within the United States, fossil fuel combustion accounted for 93.0 percent of CO_2 emissions in 2022. Emissions from this source category include CO_2 associated with the combustion of fossil fuels (coal, natural gas, and petroleum) for energy use. Fossil fuel combustion CO_2 emissions decreased by 1.1 percent (52.8 MMT CO_2 Eq.) from 1990 to 2022 and were responsible for most of the decrease in national emissions during this period. Similarly, CO_2 emissions from fossil fuel combustion have decreased by 18.2 percent (1,044.7 MMT CO_2 Eq.) since 2005. From 2021 to 2022, these emissions increased by 1.0 percent (45.1 MMT CO_2 Eq.).

Historically, changes in emissions from fossil fuel combustion have been the main factor influencing U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion since 1990 are affected by many long-term and short-term factors, including population and economic growth, energy price fluctuations and market trends, technological changes, carbon intensity of energy fuel choices, and seasonal temperatures. On an annual basis, the overall consumption and mix of fossil fuels in the United States fluctuates in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives. For example, coal consumption for electric power is influenced by factors such as the relative price of coal and alternative sources, the ability to switch fuels, and longer-term trends in coal markets. Fossil fuel combustion CO_2 emissions also depend on the type of fuel consumed or energy used and its carbon intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, reduces CO_2 emissions because of the lower carbon content of natural gas (see Table 3-12 in Chapter 3 for more detail on electricity generation by source and see Table A-19 in Annex 2.1 for more detail on the carbon content coefficient of different fossil fuels).

Overall CO_2 emissions from electric power generation decreased by 36.2 percent from 2005 to 2022 (see Figure 2-7), reflecting the continued shift in the share of electric power generation from coal to natural gas and renewables since 2005. Carbon dioxide emissions from coal combustion for electric power generation gradually increased between 1990 and 2007, then began to decrease at a faster rate from 2008 to 2022. Carbon dioxide emissions from natural gas combustion for electric power generation remained relatively constant, with a slight increase between 1990 and 2009, then began to consistently increase between 2010 and 2022.

Petroleum use is another major driver of CO_2 emissions from fossil fuel combustion, particularly in the transportation sector, which has represented the largest source of CO_2 emissions from fossil fuel combustion since 2017. Emissions from petroleum consumption for transportation (including bunker fuels) decreased by 0.1 percent from 2021 to 2022. Fuel economy of light-duty vehicles is an important factor in transportation sector CO_2 emissions trends. The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from about 29.6 percent of new vehicle sales in 1990 to 48.0 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period and has slowed the rate of increase of CO_2 emissions.

Trends in CO_2 emissions from fossil fuel combustion by end-use sector are presented in Table 2-5 and Figure 2-6 based on the underlying U.S. energy consumer data collected by the U.S. Energy Information Administration (EIA). Figure 2-7 further describes trends in direct and indirect CO_2 emissions from fossil fuel combustion by end-use sector. Estimates of CO_2 emissions from fossil fuel combustion are calculated from these EIA "end-use sectors" based on total fuel consumption and appropriate fuel properties described below.[4]

- *Transportation.* EIA's fuel consumption data for the transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another.
- *Electric Power.* EIA's fuel consumption data for the electric power sector are composed of electricity-only and combined-heat-and-power (CHP) plants within the North American Industry Classification System (NAICS) 22 category whose primary business is to sell electricity, or electricity and heat, to the public.

[4] Additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report.

(Non-utility power producers are included in this sector as long as they meet the electric power sector definition.)

- *Industry.* EIA statistics for the industrial sector include fossil fuel consumption that occurs in the fields of manufacturing, agriculture, mining, and construction. EIA's fuel consumption data for the industrial sector consist of all facilities and equipment used for producing, processing, or assembling goods. (EIA includes generators that produce electricity and/or useful thermal output primarily to support on-site industrial activities in this sector.)
- *Residential.* EIA's fuel consumption data for the residential sector consist of living quarters for private households.
- *Commercial.* EIA's fuel consumption data for the commercial sector consist of service-providing facilities and equipment from private and public organizations and businesses. (EIA includes generators that produce electricity and/or useful thermal output primarily to support the activities at commercial establishments in this sector.)

Table 2-5: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,472.0**	**1,863.3**	**1,817.9**	**1,821.4**	**1,576.9**	**1,758.6**	**1,757.4**
Combustion	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3
Electricity	3.0	4.7	4.8	4.8	4.1	5.0	6.1
Industrial	**1,562.9**	**1,584.0**	**1,311.8**	**1,275.3**	**1,171.8**	**1,225.6**	**1,238.0**
Combustion	876.5	847.6	810.5	809.8	762.0	780.5	801.1
Electricity	686.4	736.3	501.3	465.5	409.8	445.1	437.0
Residential	**931.3**	**1,214.9**	**981.2**	**926.7**	**860.1**	**890.3**	**899.4**
Combustion	338.6	358.9	338.9	342.9	314.8	318.0	334.1
Electricity	592.7	856.0	642.3	583.7	545.3	572.2	565.3
Commercial	**766.0**	**1,030.1**	**851.3**	**804.4**	**709.6**	**756.1**	**782.0**
Combustion	228.3	227.1	246.3	251.7	229.3	237.5	258.7
Electricity	537.7	803.0	605.0	552.7	480.3	518.5	523.3
U.S. Territories[a]	**20.0**	**51.9**	**25.9**	**24.8**	**23.3**	**23.8**	**22.6**
Total	**4,752.2**	**5,744.1**	**4,988.2**	**4,852.6**	**4,341.7**	**4,654.3**	**4,699.4**
Electric Power	**1,820.0**	**2,400.1**	**1,753.4**	**1,606.7**	**1,439.6**	**1,540.9**	**1,531.7**

[a] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands) is included in this report.

Notes: Combustion-related emissions from electric power are allocated based on aggregate national electricity use by each end-use sector. Totals may not sum due to independent rounding.

Figure 2-6: Trends in CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector and Fuel Type

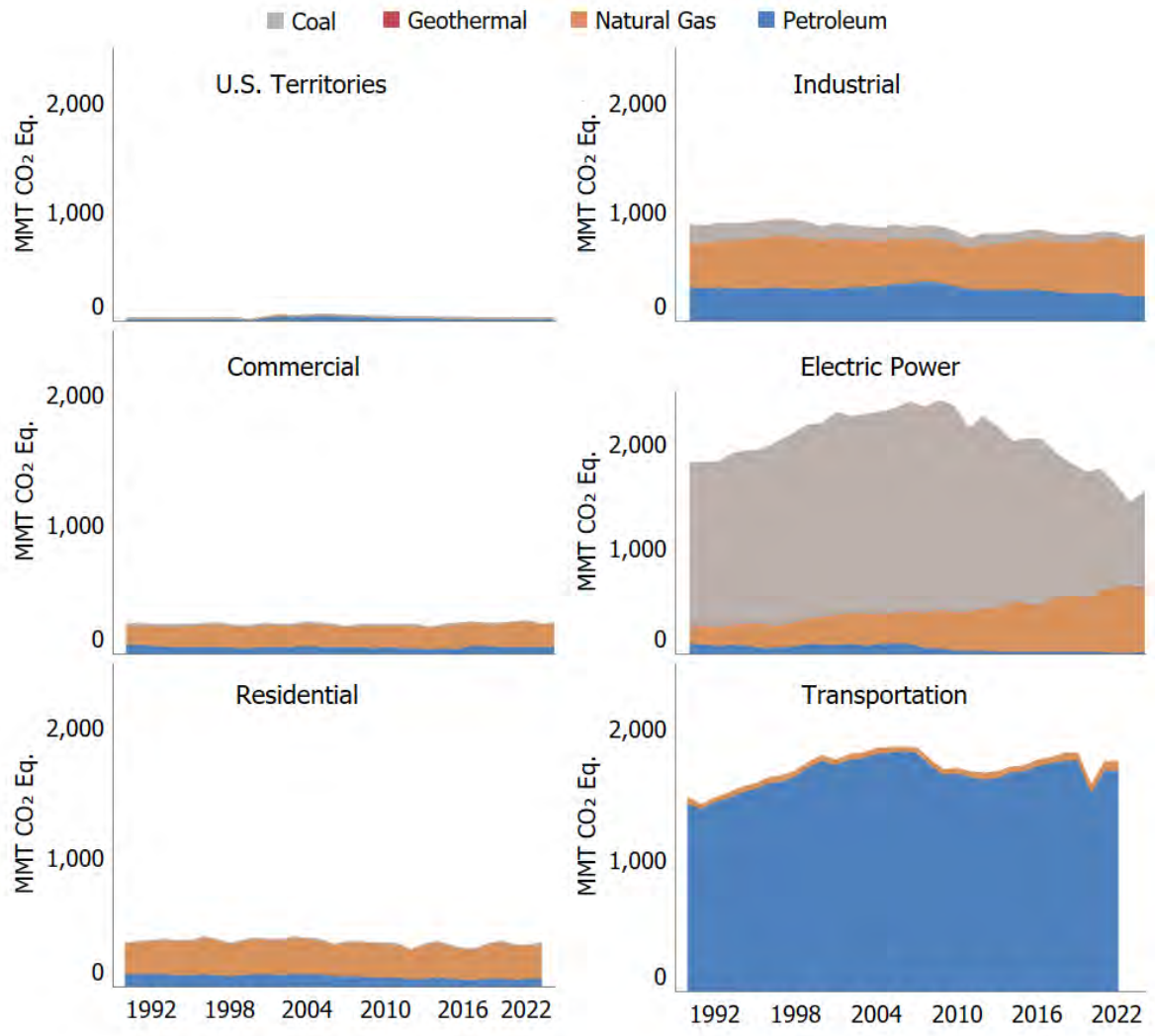

Note: Fossil fuel combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation. Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Figure 2-7: Trends in End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

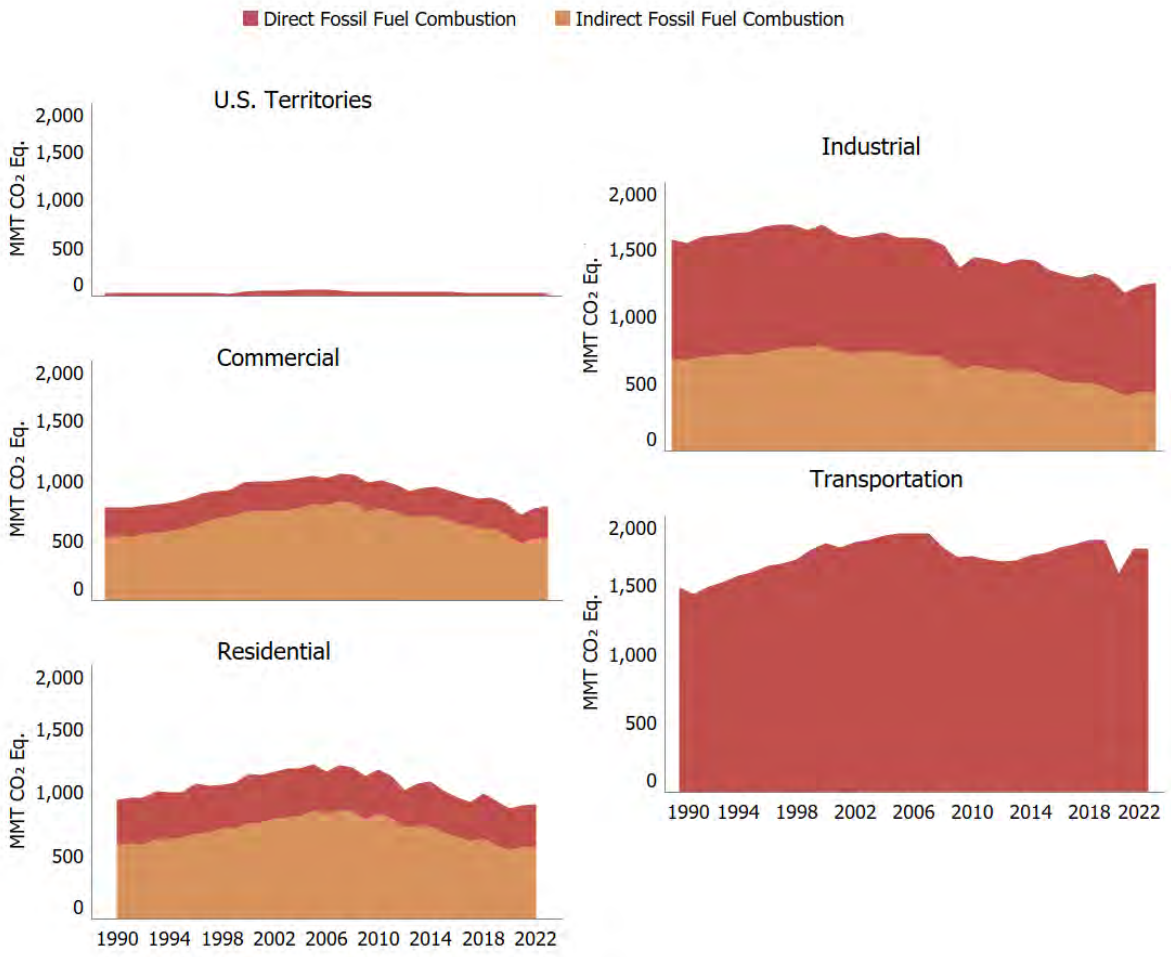

Electric power was the second largest end-use emitter of CO_2 in 2022 (surpassed by transportation in 2017); electric power generators used 30.5 percent of U.S. energy from fossil fuels and emitted 32.6 percent of the CO_2 from fossil fuel combustion in 2022. CO_2 emissions from the fossil fuel combustion in the electric power sector decreased by 0.6 percent between 2021 and 2022 due to changes in the mix of electric generation resources. Between 2021 and 2022 overall electricity generation increased by 3 percent, coal electricity generation decreased by 10.2 percent, natural gas generation increased by 4.0 percent, and renewable energy generation increased by 7.6 percent. Changes in electricity demand and the carbon intensity of fuels used for electric power generation have a significant impact on CO_2 emissions. Carbon dioxide emissions from fossil fuel combustion from the electric power sector have decreased by 15.8 percent since 1990, and the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, has decreased by 27.6 percent during that same timeframe. This decoupling of electric power generation and the resulting CO_2 emissions is shown below in Figure 2-8.

Figure 2-8: Electric Power Generation (Billion kWh) and Emissions (MMT CO_2 Eq.)

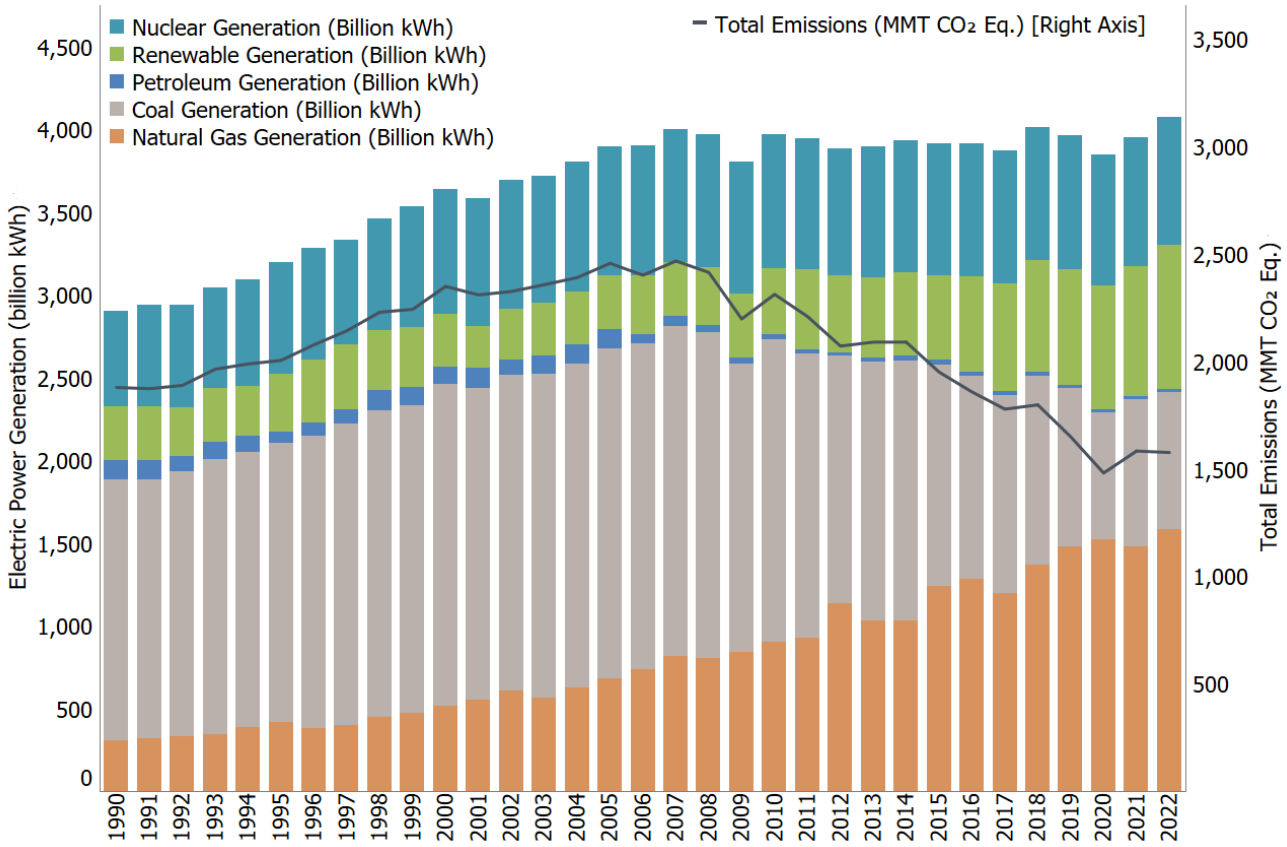

Electric power CO_2 emissions can also be allocated to the end-use sectors that use electricity, as presented in Table 2-5. With electricity CO_2 emissions allocated to end-use sectors, the transportation end-use sector represents the largest source of fossil fuel combustion emissions accounting for 1,757.4 MMT CO_2 Eq. in 2022 or 37.4 percent of total CO_2 emissions from fossil fuel combustion, a 0.1 percent decrease since 2021. The industrial end-use sector accounted for 26.3 percent of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions, an increase of 1.0 percent since 2021. From 2021 to 2022, total energy use in the industrial sector increased by 1.8 percent due to an increase in total industrial production and manufacturing output. The residential and commercial end-use sectors accounted for 19.1 and 16.6 percent, respectively, of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions. Both of these end-use sectors were heavily reliant on electricity for meeting building-related energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances contributing 62.9 and 66.9 percent of emissions from the residential and commercial end-use sectors, respectively. From 2021 to 2022, an increase in heating degree days (7.9 percent) increased energy demand for heating in the residential and commercial sectors; also, a 4.3 percent increase in cooling degree days compared to 2021 increased demand for air conditioning in the residential and commercial sectors. As a result, CO_2 emissions from the residential and commercial end-use sectors when including allocated electricity emissions increased by 1.0 and 3.4 percent since 2021, respectively.

Other Energy Sector Trends

Energy sector emissions increased by 0.5 percent since 2021 and decreased by 3.4 percent since 1990. Other notable trends in emissions from energy source categories (Figure 2-6 and Figure 2-7) over the 33-year period from 1990 through 2022 included the following:

- Emissions (CH_4, CO_2, and N_2O) from oil and gas systems decreased by 13.0 percent (38.8 MMT CO_2 Eq.) since 1990 and decreased by 4.2 percent (11.8 MMT CO_2 Eq.) from 2021 to 2022. Natural gas systems CH_4 emissions have decreased by 20.9 percent (45.7 MMT CO_2 Eq.) since 1990, due to a decrease in emissions from the distribution, transmission and storage, processing, and exploration segments. The decrease in distribution emissions is due mainly to reduced emissions from pipeline and distribution station leaks, and the decrease in transmission and storage emissions is due mainly to reduced compressor station emissions (including emissions from compressors and leaks). Over the same time period (i.e., since 1990), methane emissions from the natural gas production segment increased due to increased gathering and boosting emissions. Between 2021 and 2022, methane emissions from natural gas systems decreased 0.8 percent, due to a decrease in emissions from production segment pneumatic controllers. Petroleum systems CH_4 emissions decreased by 19.8 percent (9.8 MMT CO_2 Eq.) since 1990 and 18.5 percent between 2021 and 2022. This decrease is due primarily to decreases in emissions from offshore platforms, tanks, and pneumatic controllers. Carbon dioxide emissions from natural gas and petroleum systems increased by 39.1 percent (16.4 MMT CO_2) from 1990 to 2022 and decreased by 2.5 percent between 2021 and 2022. This increase since 1990 is due primarily to increases in the production segment, where emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time. The decrease in emissions between 2021 and 2022 and is also due primarily to the production segment, where flaring emissions decreased for associated gas and tanks.
- Methane emissions from coal mining decreased by 59.6 percent (64.4 MMT CO_2 Eq.) from 1990 through 2022 and by 2.3 percent between 2021 and 2022 primarily due to a decrease in the number of active mines and annual coal production over the 1990 to 2022 time period. Between 2021 and 2022, the number of mines and coal production increased.
- Nitrous oxide emissions from mobile combustion decreased by 56.5 percent (21.7 MMT CO_2 Eq.) from 1990 through 2022 and by 0.7 percent (0.1 MMT CO_2 Eq.) between 2021 and 2022, primarily as a result of national vehicle criteria pollutant emissions standards and emission control technologies for on-road vehicles.
- Nitrous oxide emissions from stationary combustion were the third largest source of anthropogenic N_2O emissions in 2022, accounting for 6.3 percent of N_2O emissions and 0.4 percent of total gross U.S. greenhouse gas emissions in 2022. Stationary combustion emissions peaked in 2007 and have steadily decreased since then.
- Carbon dioxide emissions from non-energy uses of fossil fuels increased by 3.7 percent (3.7 MMT CO_2 Eq.) from 1990 through 2022 but decreased by 7.9 percent (8.8 MMT CO_2 Eq.) between 2021 and 2022. Emissions from non-energy uses of fossil fuels were 102.8 MMT CO_2 Eq. in 2022, which constituted 2.0 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- Carbon dioxide emissions from incineration of waste decreased slightly by 4.2 percent (0.5 MMT CO_2 Eq.) from 1990 through 2022, as the volume of scrap tires and other fossil carbon-containing materials in waste decreased. Emissions decreased 0.9 percent (0.1 MMT CO_2 Eq.) between 2021 and 2022, consistent with trends across the time series.

Industrial Processes and Product Use

Greenhouse gases can be generated and emitted by industry in two different ways. First, they are generated and emitted as the byproducts of many non-energy-related industrial activities. For example, industrial processes can chemically or physically transform raw materials, which often release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). In the case of byproduct emissions, the emissions are generated by an industrial process itself, and are not directly a result of energy consumed during the process.

Second, industrial manufacturing processes and use by end-consumers also release HFCs, PFCs, SF_6, and NF_3 and other man-made compounds. In addition to the use of HFCs and some PFCs as substitutes for ozone depleting substances (ODS), fluorinated compounds such as HFCs, PFCs, SF_6, NF_3, and others are also emitted through use by

a number of other industrial sources in the United States. These industries include the electronics industry, electrical equipment, and magnesium metal production and processing. In addition, N_2O is used in and emitted by the electronics industry and anesthetic and aerosol applications, PFCs and SF_6 are emitted from other product use, and CO_2 is consumed and emitted through various end-use applications.

Emission sources in the Industrial Processes and Product Use (IPPU) chapter accounted for 6.0 percent of U.S. greenhouse gas emissions in 2022. Emissions from the IPPU sector increased by 3.9 percent from 1990 to 2022. The use of HFCs as substitutes for ODS is the largest source of emissions in this sector, contributing 46.5 percent of IPPU emissions in 2022 and driving growth since 1990. From 2021 to 2022, total emissions from IPPU increased 0.4 percent between 2021 and 2022. Despite the sectoral increase in emissions, emissions from adipic acid production decreased by almost 70 percent, emissions from ferroalloy production decreased by over 10 percent, and emissions from aluminum production, petrochemical production and zinc production decreased by between 5 and 10 percent. Figure 2-9 presents greenhouse gas emissions from IPPU by source category.

Figure 2-9: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

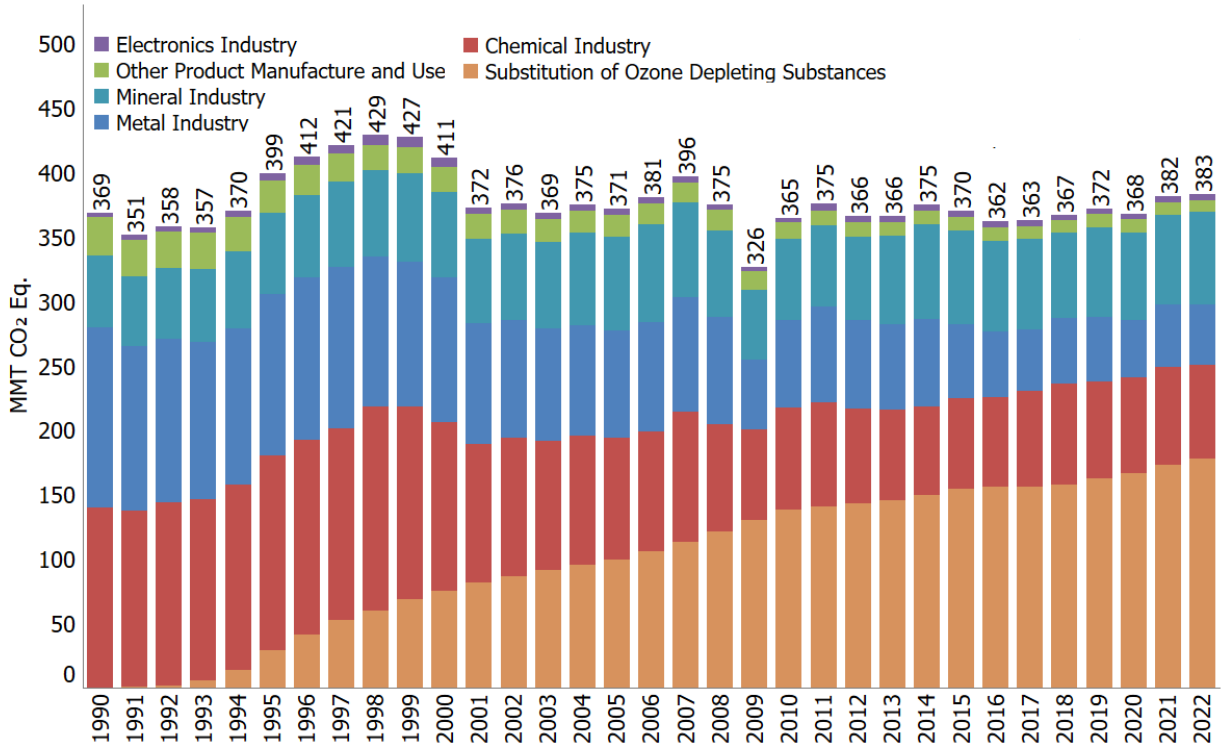

Table 2-6: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**213.7**	**195.9**	**164.4**	**168.2**	**160.7**	**168.8**	**168.9**	**-20.9%**
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9	25.1%
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7	-61.2%
Iron and Steel Production	*99.1*	*66.2*	*41.6*	*40.1*	*35.4*	*38.6*	*37.7*	*-62.0%*
Metallurgical Coke Production	*5.6*	*3.9*	*1.3*	*3.0*	*2.3*	*3.2*	*3.0*	*-47.3%*
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8	43.4%
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6	-12.5%

Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2	4.3%
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4	46.2%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1	86.4%
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0	239.7%
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0	-13.6%
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7	19.0%
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5	23.3%
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4	-78.8%
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3	-38.3%
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9	49.9%
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8	-45.0%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4	-17.1%
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2	-13.7%
Substitution of Ozone Depleting Substances[a]	+	+	+	+	+	+	+	28,664.2%
Magnesium Production and Processing	0.1	+	+	+	+	+	+	-97.7%
CH_4	**0.1**	**+**	**+**	**+**	**+**	**+**	**+**	**-48.9%**
Carbide Production and Consumption	+	+	+	+	+	+	+	-38.5%
Ferroalloy Production	+	+	+	+	+	+	+	-45.2%
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+	-67.8%
Petrochemical Production	+	+	+	+	+	+	+	-21.7%
N_2O	**29.6**	**22.2**	**23.1**	**18.7**	**20.8**	**19.7**	**16.1**	**-45.7%**
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6	-20.2%
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8	-0.4%
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1	-84.5%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3	-10.5%
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3	720.0%
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**	**282.9%**
Substitution of Ozone Depleting Substances[a]	0.3	99.5	157.9	162.1	166.2	172.6	178.1	70,357.0%
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3	-90.9%
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3	74.0%
Magnesium Production and Processing	NO	NO	0.1	0.1	0.1	+	+	100.0%
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**	**-83.1%**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0	-83.1%
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7	7.8%
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8	-96.1%
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2	39.4%
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+	100.0%
Electrical Equipment	+	+	NO	+	+	+	+	-99.2%
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**	**-80.0%**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1	-79.4%
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1	-80.0%
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8	47.0%

SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6	-53.0%
Fluorochemical Production	5.8	3.3	+	+	+	+	+	-100.0%
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**	**238.3%**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6	1313.8%
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5	72.7%
Total	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**	**3.9%**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

Note: Totals may not sum due to independent rounding.

IPPU sector emissions increased 0.4 percent since 2021 and 3.9 percent since 1990. Some significant trends in U.S. emissions from IPPU source categories over the 33-year period from 1990 through 2022 included the following:

- HFC and PFC emissions resulting from the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) increased from small amounts in 1990 to 178.1 MMT CO_2 Eq. in 2022 (an increase of 70,357 percent).
- Combined CO_2 and CH_4 emissions from iron and steel production and metallurgical coke production decreased by 2.9 percent from 2021 to 2022 to 40.7 MMT CO_2 Eq. and declined overall by 61.2 percent (64.1 MMT CO_2 Eq.) from 1990 through 2022, due to restructuring of the industry. The trend in the United States has been a shift toward fewer integrated steel mills and more electric arc furnaces (EAFs). EAFs use scrap steel as their main input and generally have lower on-site emissions.
- Carbon dioxide emissions from petrochemical production increased by 43.4 percent between 1990 and 2022, from 20.1 MMT CO_2 Eq. to 28.8 MMT CO_2 Eq. The increase in emissions is largely driven by the production of ethylene more than doubling over that period.
- Carbon dioxide emissions from ammonia production have decreased by 12.5 percent (1.8 MMT CO_2 Eq.) since 1990. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia from year to year. Emissions from ammonia production have increased since 2016, due to the addition of new ammonia production facilities and new production units at existing facilities. Agricultural demands continue to drive demand for nitrogen fertilizers and the need for new ammonia production capacity.
- Carbon dioxide emissions from cement production increased by 25.1 percent (8.4 MMT CO_2 Eq.) from 1990 through 2022. Emissions rose from 1990 through 2006 and then fell until 2009, due to a decrease in demand for construction materials during the economic recession. Since 2010, CO_2 emissions from cement production have risen by 33.2 percent.
- HFC, PFC, SF_6, and NF_3 emissions from fluorochemical production decreased by 89.0 percent (63.2 MMT CO_2 Eq.) from 1990 to 2022 due to a reduction in the HFC-23 emission rate from HCFC-22 production (kg HFC-23 emitted/kg HCFC-22 produced), the imposition of emissions controls at production facilities, and a decrease in SF_6 production due to the cessation of production at the major SF_6 production facility in 2010.
- PFC emissions from aluminum production decreased by 96.1 percent (18.5 MMT CO_2 Eq.) from 1990 to 2022, due to both industry emission reduction efforts and lower domestic aluminum production.
- SF_6 emissions from electrical equipment decreased by 79.4 percent (19.6 MMT CO_2 Eq.) from 1990 to 2022 due to a sharp increase in the price of SF_6 during the 1990s and industry emission reduction efforts.

Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, liming, urea fertilization, and field burning of agricultural residues. Methane and N_2O are the primary greenhouse gases emitted by agricultural activities, with

small amounts of CO_2 also emitted.[5] Carbon stock changes from agricultural soils are included in the LULUCF sector.

In 2022, agricultural activities were responsible for emissions of 593.4 MMT CO_2 Eq., or 9.4 percent of total U.S. greenhouse gas emissions. Agricultural soil management activities, such as the application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to agricultural-related emissions (49.0 percent) and were the largest source of U.S. N_2O emissions in 2022, accounting for 74.6 percent. Methane emissions from enteric fermentation and manure management represented 27.4 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2022. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities. Figure 2-10 and Table 2-7 illustrate agricultural greenhouse gas emissions by source and gas.

Figure 2-10: Trends in Agriculture Sector Greenhouse Gas Sources

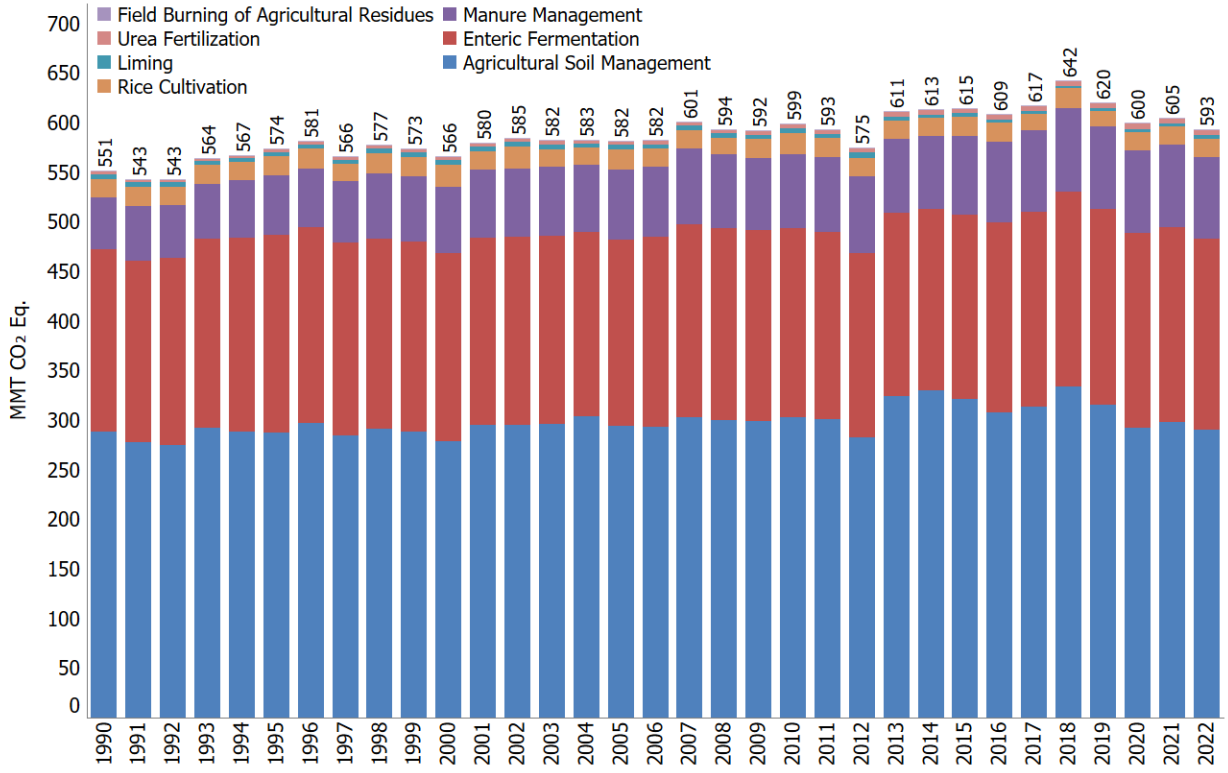

[5] The contribution of agriculture non-CO_2 emissions is based on gross totals and excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of agriculture CH_4 and N_2O including LULUCF non-CO_2 emissions, is 40.5 percent and 48.3 percent, respectively.

Table 2-7: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**7.1**	**7.9**	**7.2**	**7.2**	**8.0**	**7.6**	**8.6**	**21.0%**
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3	120.4%
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3	-30.3%
CH_4	**241.7**	**264.4**	**285.0**	**280.2**	**282.4**	**281.8**	**276.8**	**14.5%**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6	5.2%
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7	65.3%
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9	-0.4%
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6	14.4%
N_2O	**302.3**	**309.5**	**350.2**	**332.6**	**309.2**	**315.3**	**308.0**	**1.9%**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8	0.7%
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0	27.2%
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2	15.5%
Total	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**	**7.7%**

Note: Totals may not sum due to independent rounding.

Agriculture sector emissions decreased by 1.9 percent since 2021 and increased by 7.7 percent since 1990. Some significant trends in U.S. emissions from Agriculture source categories (Figure 2-10) over the 33-year time series from 1990 through 2022 included the following:

- Agricultural soils are the largest anthropogenic source of agriculture-related emissions and of N_2O emissions in the United States, accounting for 74.6 percent of N_2O emissions and 4.6 percent of total emissions in the United States in 2022. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2022, and overall emissions were 0.7 percent (2.0 MMT CO_2 Eq.) higher in 2022 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.
- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2022, enteric fermentation CH_4 emissions were 27.4 percent of total CH_4 emissions, which represents an increase of 5.2 percent (9.5 MMT CO_2 Eq.) since 1990. This increase in emissions from enteric fermentation from 1990 to 2022 generally follows the increasing trends in cattle populations. For example, from 1990 to 1995, emissions increased and then generally decreased from 1996 to 2004, mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Emissions increased from 2005 to 2007, as both dairy and beef populations increased. Research indicates that the feed digestibility of dairy cow diets decreased during this period. Emissions decreased again from 2008 to 2014 as beef cattle populations again decreased. Emissions increased from 2014 to 2022, consistent with an increase in beef cattle population over those same years. CH_4 emissions from enteric fermentation decreased by 2.0 percent (3.9 MMT CO_2 Eq.) from 2021 to 2022, however, largely driven by a decrease in beef cattle populations.
- Manure management is the fourth largest anthropogenic source of CH_4 and N_2O emissions in the United States and accounted for 13.8 percent of Agriculture sector emissions in 2022. Emissions from manure management increased by 55.6 percent between 1990 and 2022. This includes an increase of 65.3 percent (25.6 MMT CO_2 Eq.) for CH_4 and an increase of 27.2 percent (3.6 MMT CO_2 Eq.) for N_2O. The majority of the increase observed in CH_4 emissions resulted from swine and dairy cattle manure, where emissions increased by 37.2 and 108.7 percent, respectively, from 1990 to 2022. From 2021 to 2022, CH_4 emissions from manure management decreased by 2.6 percent, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

- Liming and urea fertilization are the only sources of CO_2 emissions reported in the Agriculture sector. All other CO_2 emissions and removals (e.g., carbon stock changes from the management of croplands) are included in the LULUCF sector. Liming emissions increased by 36.9 percent relative to 2021 and decreased by 30.3 percent (1.4 MMT CO_2 Eq.) relative to 1990, while urea fertilization emissions increased by 1.9 percent relative to 2021 and 120.4 percent (2.9 MMT CO_2 Eq.) relative to 1990.

Land Use, Land-Use Change, and Forestry

When humans alter the terrestrial biosphere through land use, changes in land use, and land management practices, they also influence the carbon stock fluxes on these lands and cause emissions of CH_4 and N_2O. Overall, managed land is a net sink for CO_2 (carbon sequestration) in the United States. The primary driver of fluxes on managed lands is from management of forest lands, but also includes trees in settlements (i.e., urban areas), afforestation, conversion of forest lands to settlements and croplands, the management of croplands and grasslands, flooded lands, and the landfilling of yard trimmings and food scraps. The main drivers for net forest sequestration include net forest growth, increasing forest area, and a net accumulation of carbon stocks in harvested wood pools. The net sequestration in settlements remaining settlements is driven primarily by carbon stock gains in urban forests (i.e., settlement trees) through net tree growth and increased urban area, as well as long-term accumulation of carbon in landfills from additions of yard trimmings and food scraps.

The LULUCF sector in 2022 resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 MMT CO_2 Eq. (Table 2-8).[6] This represents an offset of 14.5 percent of total (i.e., gross) greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 were 67.6 MMT CO_2 Eq. and represented 1.2 percent of net greenhouse gas emissions.[7] Between 1990 and 2022, total net carbon sequestration in the LULUCF sector decreased by 10.9 percent, primarily due to a decrease in the rate of net carbon accumulation in forests and cropland remaining cropland, as well as an increase in CO_2 emissions from land converted to settlements.

Flooded land remaining flooded land was the largest source of CH_4 emissions from LULUCF and the fifth largest source overall of net CH_4 emissions in 2022, totaling 44.2 MMT CO_2 Eq. (1,579 kt of CH_4). Forest fires were the second largest source of CH_4 emissions from LULUCF in 2022, totaling 9.1 MMT CO_2 Eq. (327 kt of CH_4). Forest fires were the largest source of N_2O emissions from LULUCF in 2022, totaling 5.7 MMT CO_2 Eq. (22 kt of N_2O). Figure 2-11 and Table 2-8 illustrate LULUCF emissions and removals by land-use category and gas.

[6] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[7] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

Figure 2-11: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

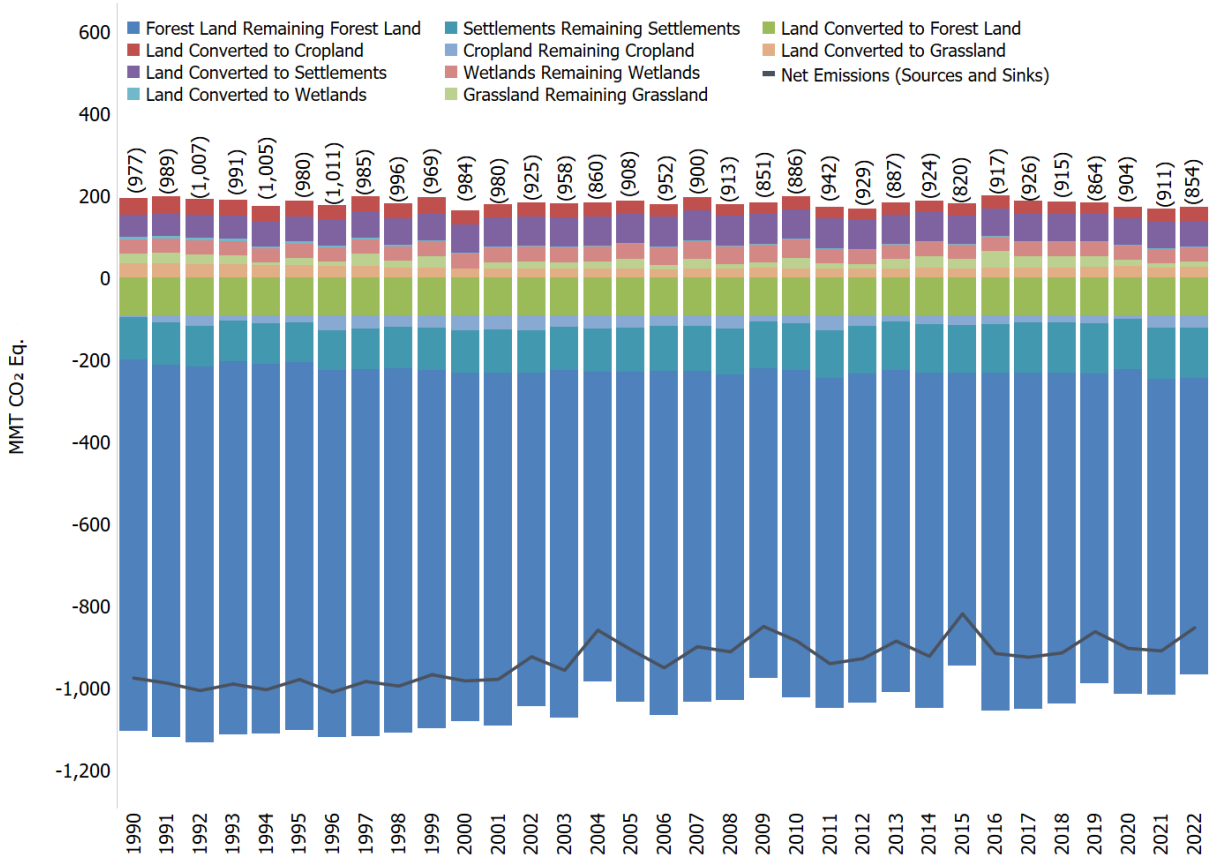

Table 2-8: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Forest Land Remaining Forest Land	**(968.8)**	**(860.1)**	**(863.4)**	**(807.0)**	**(846.3)**	**(823.9)**	**(771.7)**	**-20.3%**
Changes in Forest Carbon Stocks[a]	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)	-19.3%
Non-CO_2 Emissions from Forest Fires[b]	5.8	15.4	9.7	5.7	15.3	19.9	14.8	153.9%
N_2O Emissions from Forest Soils[c]	0.1	0.4	0.4	0.4	0.4	0.4	0.4	455.1%
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0%
Land Converted to Forest Land	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**	**0.1%**
Changes in Forest Carbon Stocks[e]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)	0.1%
Cropland Remaining Cropland	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**	**529.0%**
Changes in Mineral and Organic Soil Carbon Stocks	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)	529.0%
Land Converted to Cropland	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**	**-22.7%**
Changes in all Ecosystem Carbon Stocks[f]	45.4	34.5	31.9	31.4	29.3	34.9	35.1	-22.7%
Grassland Remaining Grassland	**24.6**	**24.9**	**29.7**	**28.9**	**17.1**	**11.5**	**14.0**	**-43.1%**

Changes in Mineral and Organic Soil Carbon Stocks	24.4	24.1	28.6	28.5	16.1	10.6	13.4	-45.2%
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.8	1.1	0.3	1.1	0.9	0.6	184.1%
Land Converted to Grassland	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**	**-27.3%**
Changes in all Ecosystem Carbon Stocks[f]	35.3	21.8	25.2	25.4	28.7	24.5	25.6	-27.3%
Wetlands Remaining Wetlands	**36.8**	**39.4**	**38.2**	**38.1**	**38.1**	**38.1**	**38.1**	**3.6%**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.6	0.6	0.5	0.6	-45.7%
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+	-47.0%
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(10.8)	(10.1)	(11.1)	(11.1)	(11.1)	(11.1)	(11.1)	2.8%
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3	3.4%
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1	14.9%
CH_4 Emissions from Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2	4.7%
Land Converted to Wetlands	**7.2**	**1.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**-90.3%**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)	-97.0%
CH_4 Emissions from Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2	-38.9%
Changes in Land Converted to Flooded Land	3.6	0.6	0.3	0.3	0.3	0.3	0.3	-91.7%
CH_4 Emissions from Land Converted to Flooded Land	2.9	0.4	0.2	0.2	0.2	0.2	0.2	-92.6%
Settlements Remaining Settlements	**(109.1)**	**(115.2)**	**(131.0)**	**(131.5)**	**(131.8)**	**(132.3)**	**(132.3)**	**21.2%**
Changes in Organic Soil Carbon Stocks	9.9	10.1	14.4	14.6	15.1	15.4	15.4	56.0%
Changes in Settlement Tree Carbon Stocks	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)	43.4%
N_2O Emissions from Settlement Soils[h]	2.1	3.1	2.4	2.5	2.5	2.5	2.5	22.8%
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(13.4)	(13.1)	(12.8)	(12.5)	(11.8)	-52.0%
Land Converted to Settlements	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**	**19.1%**
Changes in all Ecosystem Carbon Stocks[f]	57.2	77.1	71.4	70.2	68.8	68.2	68.2	19.1%
LULUCF Carbon Stock Change[i]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**	**-10.9%**
LULUCF Emissions[j]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**	**16.5%**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4	10.0%
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1	88.3%
LULUCF Sector Net Total[k]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**	**-12.5%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.
[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.
[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.
[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.
[h] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.
[i] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land-use conversion categories.
[j] LULUCF emissions subtotal includes the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, and land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils. Emissions values are included in land-use category rows.
[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Overall CH_4 and N_2O emissions from LULUCF decreased by 7.3 percent from 2021 and increased by 16.5 percent since 1990 while total net sequestration decreased by 10.9 percent since 1990 and 6.3 percent from 2021. Other trends from 1990 to 2022 in emissions from LULUCF categories (Figure 2-11) over the 33-year period included the following:

- Annual carbon sequestration by forest land (i.e., annual carbon stock accumulation in the five ecosystem carbon pools and harvested wood products for forest land remaining forest land and land converted to forest land) has decreased by 17.5 percent since 1990. This is primarily due to decreased carbon stock gains in land converted to forest land and the harvested wood products pools within forest land remaining forest land.
- Annual carbon sequestration from settlements remaining settlements (which includes organic soils, settlement trees, and landfilled yard trimmings and food scraps) has increased by 21.2 percent over the period from 1990 to 2022. This is primarily due to an increase in urbanized land area in the United States with trees growing on it.
- Annual emissions from land converted to settlements increased by 19.1 percent from 1990 to 2022 due primarily to carbon stock losses from forest land converted to settlements and mineral soils carbon stocks from grassland converted to settlements.

Waste

Waste management and treatment activities are sources of CH_4 and N_2O emissions (see Figure 2-12 and Table 2-9). Overall, emission sources accounted for in the Waste chapter generated 166.9 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions in 2022. In 2022, landfills were the largest source of waste emissions, accounting for 71.8 percent of waste-related emissions. Landfills are also the third-largest source of U.S. anthropogenic CH_4 emissions, generating 119.8 MMT CO_2 Eq. and accounting for 17.1 percent of total U.S. CH_4 emissions in 2022.[8] Additionally, wastewater treatment generated emissions of 42.7 MMT CO_2 Eq. and accounted for 25.6 percent of waste emissions, 3.0 percent of U.S. CH_4 emissions, and 5.6 percent of U.S. N_2O emissions in 2022. Emissions of CH_4 and N_2O from composting are also accounted for in this chapter, generating emissions of 2.6 MMT CO_2 Eq. and 1.8 MMT CO_2 Eq., accounting for 1.5 and 1.1 percent of Waste sector emissions, respectively. Anaerobic digestion

[8] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land Use, Land-Use Change, and Forestry chapter.

at biogas facilities generated CH_4 emissions of less than 0.05 MMT CO_2 Eq., accounting for less than 0.05 percent of emissions from the Waste sector.

Figure 2-12: Trends in Waste Sector Greenhouse Gas Sources

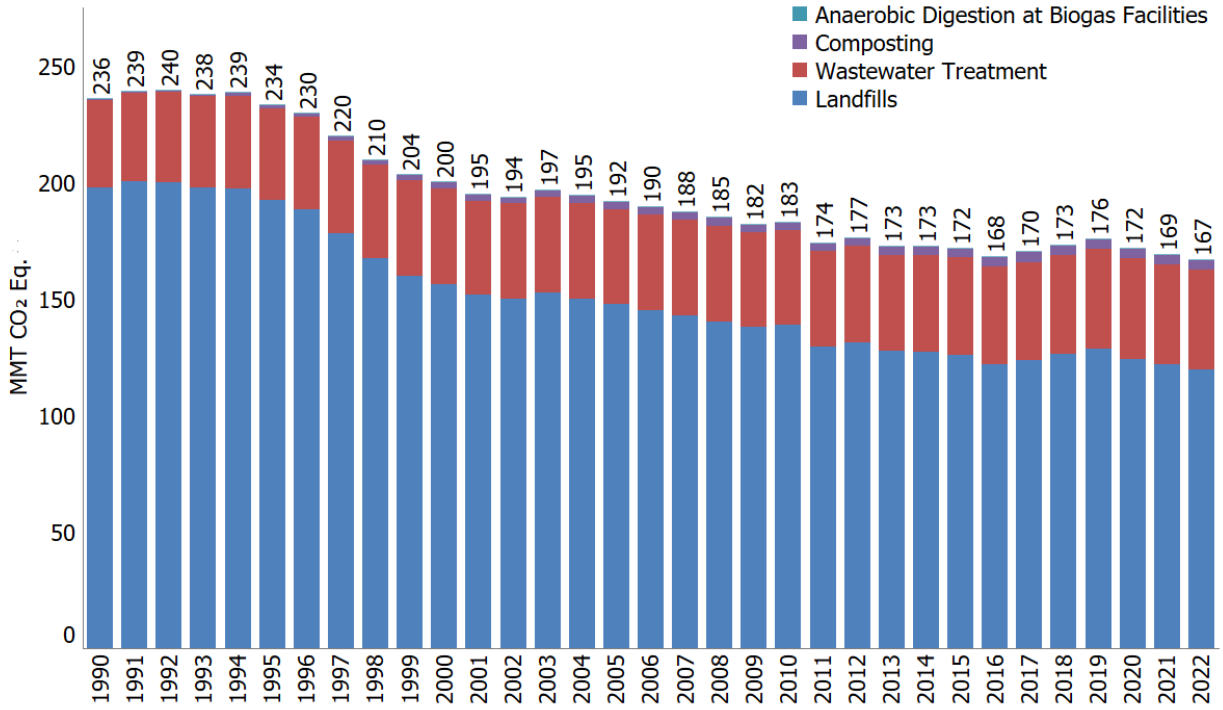

Table 2-9: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CH_4	**220.9**	**172.4**	**150.2**	**152.4**	**147.6**	**145.3**	**143.2**	**(35.2%)**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8	(39.4%)
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8	(8.4%)
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6	504.8%
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+	1,109.3%
N_2O	**15.1**	**19.5**	**23.0**	**23.4**	**24.1**	**23.9**	**23.7**	**57.4%**
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9	48.2%
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8	504.8%
Total	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**	**(29.3%)**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Waste sector emissions decreased by 1.4 percent since 2021 and 29.3 percent since 1990. Some notable trends in U.S. emissions from Waste source categories (Figure 2-12) over the 33-year period from 1990 through 2022 included the following:

- Net CH_4 emissions from landfills decreased by 78.0 MMT CO_2 Eq. (39.4 percent), with small increases occurring in interim years. This downward trend in emissions coincided with increased landfill gas

collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in municipal solid waste (MSW) landfills over the time series.

- CH_4 and N_2O emissions from wastewater treatment decreased by 8.4 percent (1.9 MMT CO_2 Eq.) and increased by 48.2 percent (7.1 MMT CO_2 Eq.), respectively. Methane emissions from domestic wastewater treatment have decreased since 1999 due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems. N_2O emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.
- Combined CH_4 and N_2O emissions from composting have increased by 504.8 percent (3.7 MMT CO_2 Eq.) since 1990. The growth in composting since the 1990s is attributable to primarily four factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings and food waste in landfills; (2) an increase in yard trimming collection and yard trimming drop-off sites provided by local solid waste management districts; (3) an increased awareness of the environmental benefits of composting; and (4) loans or grant programs to establish or expand composting infrastructure.

2.2 Emissions and Sinks by Economic Sector

In addition to the Paris Agreement and UNFCCC reporting sectors and methods defined by the IPCC, this report also characterizes gross emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. See Box 2-1 for more information on how economic sectors are defined. For more information on trends in the LULUCF sector, see Section 2.1.

Using this categorization, transportation activities accounted for the largest portion (28.4 percent) of total U.S. greenhouse gas emissions in 2022. Emissions from electric power accounted for the second largest portion (24.9 percent), while emissions from industry accounted for the third-largest portion (22.9 percent) of total U.S. greenhouse gas emissions in 2022. Emissions from industry have in general declined over the past decade due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements.

The remaining 23.8 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 10.0 percent of emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion. An increasing amount of carbon is stored in agricultural soils each year, but this carbon sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for roughly 7.3 percent and 6.2 percent of greenhouse gas emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered (in the form of carbon) by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in carbon stocks in coastal wetlands. Table 2-10 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-13 shows the trend in emissions by sector from 1990 to 2022.

Figure 2-13: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors

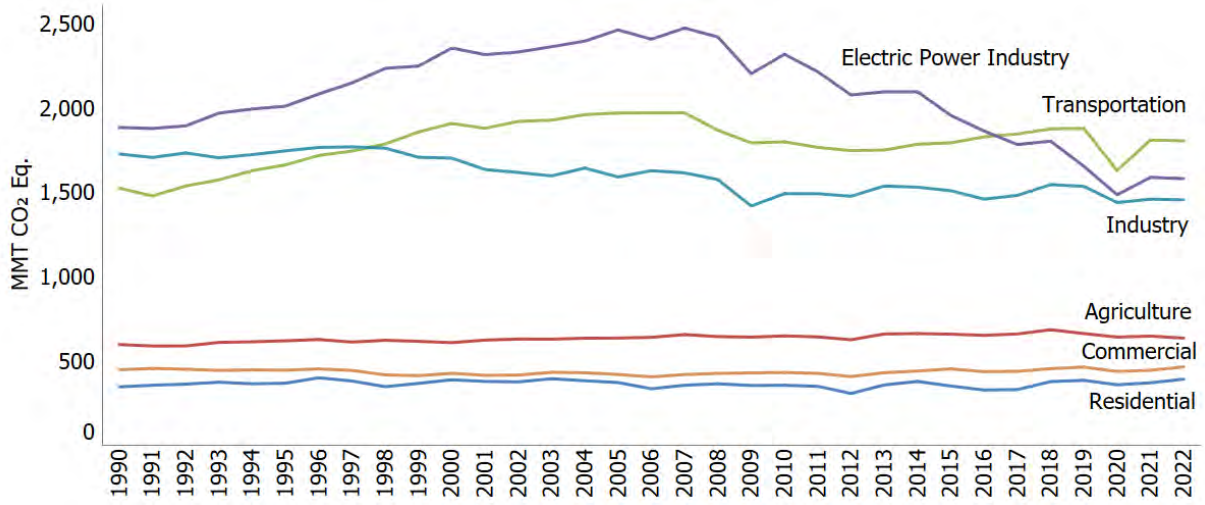

Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq. and Percent of Total in 2022)

Sector/Source	1990	2005	2018	2019	2020	2021	2022	Percent of Total Emissions[a]
Transportation	**1,521.4**	**1,965.9**	**1,871.6**	**1,874.6**	**1,625.3**	**1,805.5**	**1,801.5**	**28.4%**
CO_2 from Fossil Fuel Combustion	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3	27.6%
Substitution of Ozone Depleting Substances	+	63.1	35.5	34.0	32.5	31.2	29.6	0.5%
Mobile Combustion[b]	40.6	34.1	13.7	15.1	12.2	12.7	12.2	0.2%
Non-Energy Use of Fuels	11.8	10.2	9.2	8.8	7.8	8.0	8.4	0.1%
Electric Power Industry	**1,880.2**	**2,457.4**	**1,799.2**	**1,650.8**	**1,482.2**	**1,584.4**	**1,577.5**	**24.9%**
CO_2 from Fossil Fuel Combustion	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7	24.1%
Stationary Combustion[b]	18.7	27.7	23.1	20.2	18.9	20.4	22.9	0.4%
Incineration of Waste	13.3	13.6	13.7	13.3	13.3	12.8	12.7	0.2%
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2	0.1%
Electrical Equipment	24.7	11.9	5.0	6.1	5.9	6.0	5.1	0.1%
Industry	**1,723.3**	**1,587.3**	**1,541.9**	**1,531.8**	**1,435.9**	**1,455.8**	**1,452.5**	**22.9%**
CO_2 from Fossil Fuel Combustion	833.1	796.8	770.7	770.1	722.9	740.7	761.8	12.0%
Natural Gas Systems	251.2	236.5	223.0	227.3	217.0	210.4	209.7	3.3%
Non-Energy Use of Fuels	83.9	107.2	108.9	97.4	89.9	103.5	94.3	1.5%
Petroleum Systems	59.0	58.5	93.8	97.8	82.3	72.8	61.6	1.0%
Coal Mining	112.7	75.6	62.2	56.0	48.3	47.1	46.1	0.7%
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9	0.7%
Iron and Steel Production	104.8	70.1	42.9	43.1	37.7	41.9	40.7	0.6%
Substitution of Ozone Depleting Substances	+	8.0	31.9	33.1	33.9	32.2	33.4	0.5%

Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8	0.5%
Landfills (Industrial)	12.2	16.1	18.7	18.8	18.9	18.9	18.9	0.3%
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6	0.2%
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2	0.2%
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6	0.1%
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5	0.1%
Fluorochemical Production	70.9	30.0	8.7	9.3	6.9	7.1	7.8	+%
Wastewater Treatment	6.6	7.1	7.5	7.6	7.6	7.6	7.7	+%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1	+%
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3	+%
Mobile Combustion[b]	3.6	5.6	5.5	5.6	5.3	5.5	5.9	+%
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2	+%
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0	+%
Electronics Industry	3.3	4.5	4.8	4.5	4.5	4.8	4.7	+%
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8	+%
Stationary Combustion[b]	4.8	4.5	3.9	3.8	3.6	3.6	3.5	+%
Aluminum Production	26.1	7.2	2.9	3.3	3.2	2.5	2.2	+%
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1	+%
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0	+%
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7	+%
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5	+%
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3	+%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3	+%
Magnesium Production and Processing	5.7	3.0	1.1	1.0	0.9	1.2	1.2	+%
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9	+%
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8	+%
SF_6 and PFCs from Other Product Use	1.4	1.5	0.9	0.8	0.7	0.5	0.8	+%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4	+%
Carbide Production and Consumption	0.3	0.2	0.2	0.2	0.2	0.2	0.2	+%
Agriculture	**595.9**	**634.3**	**683.5**	**661.0**	**640.0**	**645.9**	**634.0**	**10.0%**
N_2O from Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8	4.6%
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6	3.0%
Manure Management	52.5	70.2	84.3	83.5	83.8	83.6	81.7	1.3%
CO_2 from Fossil Fuel Combustion	43.4	50.8	39.8	39.7	39.1	39.8	39.3	0.6%
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9	0.3%
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3	0.1%
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3	0.1%

Mobile Combustion[b]	1.4	1.6	1.2	1.2	1.2	1.2	1.2	+%
Field Burning of Agricultural Residues	0.7	0.8	0.8	0.9	0.8	0.8	0.8	+%
Stationary Combustion[b]	0.1	+	0.1	0.1	0.1	0.1	0.1	+%
Commercial	**447.0**	**418.9**	**453.5**	**462.6**	**436.9**	**443.7**	**463.7**	**7.3%**
CO_2 from Fossil Fuel Combustion	228.3	227.1	246.3	251.7	229.3	237.5	258.7	4.1%
Landfills (Municipal)	185.5	131.6	107.7	109.9	105.2	103.1	100.9	1.6%
Substitution of Ozone Depleting Substances	+	21.4	58.5	59.8	60.8	61.9	62.9	1.0%
Wastewater Treatment	30.9	33.6	35.0	35.1	35.6	35.1	35.0	0.6%
Composting	0.7	3.6	4.3	4.3	4.4	4.4	4.4	0.1%
Stationary Combustion[b]	1.5	1.5	1.7	1.7	1.6	1.6	1.7	0.0%
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+	+%
Residential	**345.6**	**371.2**	**376.8**	**384.2**	**358.0**	**369.6**	**391.3**	**6.2%**
CO_2 from Fossil Fuel Combustion	338.6	358.9	338.9	342.9	314.8	318.0	334.1	5.3%
Substitution of Ozone Depleting Substances	0.2	7.0	31.9	35.1	39.0	47.3	52.2	0.8%
Stationary Combustion[b]	6.8	5.3	6.0	6.2	4.2	4.2	5.0	0.1%
U.S. Territories	**23.4**	**59.7**	**26.3**	**25.1**	**23.4**	**23.9**	**22.7**	**0.4%**
CO_2 from Fossil Fuel Combustion	20.0	51.9	25.9	24.8	23.3	23.8	22.6	0.4%
Non-Energy Use of Fuels	3.4	7.6	0.2	0.2	0.1	0.1	0.1	+%
Stationary Combustion[b]	0.1	0.2	0.1	0.1	0.1	0.1	0.1	+%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**100.0%**
LULUCF Sector Net Total[c]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**	**(13.5%)**
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**86.5%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for 2022.

[b] Includes CH_4 and N_2O emissions from fuel combustion.

[c] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total gross emissions presented are without LULUCF. Total net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Box 2-1: Methodology for Aggregating Emissions by Economic Sector

In presenting the economic sectors in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, the *Inventory* expands upon the standard sectors common for reporting under the Paris Agreement and the UNFCCC. Discussing greenhouse gas emissions relevant to U.S.-specific economic sectors improves communication of the report's findings.

The electric power economic sector includes CO_2, CH_4 and N_2O emissions from the combustion of fossil fuels that are included in the EIA electric power sector. Carbon dioxide, CH_4, and N_2O emissions from waste incineration are included in the electric power economic sector, as the majority of MSW is combusted in plants that produce electricity. The electric power economic sector also includes SF_6 from electrical equipment, and a portion of CO_2 from other process uses of carbonates (from pollution control equipment installed in electric power plants).

The transportation economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA transportation fuel-consuming sector. (Additional analyses and refinement of the EIA data are further explained in the Energy chapter of this report.) Emissions of CH_4 and N_2O from mobile combustion are also

apportioned to the transportation economic sector based on the EIA transportation fuel-consuming sector. Emissions of ODS substitutes are apportioned to the transportation economic sector based on emissions from refrigerated transport and motor vehicle air-conditioning systems. Finally, CO_2 emissions from non-energy uses of fossil fuels identified as lubricants for transportation vehicles are included in the transportation economic sector.

The industry economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA industrial fuel-consuming sector, minus the agricultural use of fuel explained below. The CH_4 and N_2O emissions from stationary and mobile combustion are also apportioned to the industry economic sector based on the EIA industrial fuel-consuming sector, minus emissions apportioned to the agriculture economic sector. Emissions of ODS substitutes are apportioned based on their specific end-uses within the source category, with most emissions falling within the industry economic sector. Finally, CH_4 emissions from industrial landfills and CH_4 and N_2O from industrial wastewater treatment are included in the industry economic sector.

Additionally, all process-related emissions from sources with methods considered within the IPCC IPPU sector are apportioned to the industry economic sector. This includes the process-related emissions (i.e., emissions from the actual process to make the material, not from fuels to power the plant) from activities such as cement production, iron and steel production and metallurgical coke production, and ammonia production. Additionally, fugitive emissions from energy production sources, such as natural gas systems, coal mining, and petroleum systems are included in the industry economic sector. A portion of CO_2 from other process uses of carbonates (from pollution control equipment installed in large industrial facilities) is also included in the industry economic sector. Finally, all remaining CO_2 emissions from non-energy uses of fossil fuels are assumed to be industrial in nature (besides the lubricants for transportation vehicles specified above) and are attributed to the industry economic sector.

The agriculture economic sector includes CO_2 emissions from the combustion of fossil fuels that are based on supplementary sources of agriculture fuel use data, because EIA includes agriculture equipment in the industrial fuel-consuming sector. Agriculture fuel use estimates are obtained from U.S. Department of Agriculture survey data, in combination with EIA Fuel Oil and Kerosene Sales (FOKS) data (EIA 1991 through 2022). Agricultural operations are based on annual energy expense data from the Agricultural Resource Management Survey (ARMS) conducted by the National Agricultural Statistics Service (NASS) of the USDA. NASS collects information on farm production expenditures including expenditures on diesel fuel, gasoline, LP gas, natural gas, and electricity use on the farm with the annual ARMS. A USDA publication (USDA/NASS 2023) shows national totals, as well as selected States and ARMS production regions. These supplementary data are subtracted from the industrial fuel use reported by EIA to obtain agriculture fuel use. Carbon dioxide emissions from fossil fuel combustion, and CH_4 and N_2O emissions from stationary and mobile combustion, are then apportioned to the agriculture economic sector based on agricultural fuel use.

The other IPCC Agriculture emission source categories apportioned to the agriculture economic sector include N_2O emissions from agricultural soils, CH_4 from enteric fermentation, CH_4 and N_2O from manure management, CH_4 from rice cultivation, CO_2 emissions from liming and urea application, and CH_4 and N_2O from field burning of agricultural residues.

The residential economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA residential fuel-consuming sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel-consuming sector. Emissions of ODS substitutes are apportioned to the residential economic sector based on emissions from residential air-conditioning systems. N_2O emissions from the application of fertilizers to developed land (termed “settlements” by the IPCC) are also included in the residential economic sector.

The commercial economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA commercial fuel-consuming sector. Emissions of CH_4 and N_2O from mobile combustion are also apportioned to the commercial economic sector based on the EIA commercial fuel-consuming sector. Emissions of ODS substitutes are apportioned to the commercial economic sector based on emissions from commercial refrigeration/air-conditioning systems. Public works sources, including direct CH_4 from municipal landfills, CH_4

from anaerobic digestion at biogas facilities, CH_4 and N_2O from domestic wastewater treatment, and composting, are also included in the commercial economic sector.

Emissions with Electricity Distributed to Economic Sectors

It is also useful to view greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from the electric power sector are allocated to the economic end-use sectors in which the electricity is used). For example, greenhouse gas emissions from some economic sectors, i.e., commercial and residential and industry, increase substantially when indirect emissions from electricity end-use are included, due to the relatively large share of electricity use by buildings (75 percent of the electricity generated in the United States for heating, ventilation, and air conditioning; lighting; and appliances, etc.)[9] and use of electricity for powering industrial machinery.

The generation, transmission, and distribution of electricity directly accounted for 24.9 percent of total U.S. greenhouse gas emissions in 2022. Electric power-related emissions decreased by 16.1 percent since 1990 mainly due to fuel switching in the electric power sector. From 2021 to 2022, electric power-related emissions decreased by 0.4 percent. Between 2021 and 2022, the consumption of natural gas and petroleum for electric power generation increased by 7.6 percent and 18.9 percent, respectively, while the consumption of coal decreased by 6.4 percent. Electric power-related emissions are still lower than pre-pandemic 2019 levels. Table 2-11 provides a detailed summary of emissions from electric power-related activities.

From 2021 to 2022, electricity sales to the residential end-use sector increased by 2.6 percent. Electricity sales to the commercial end-use and industrial sectors increased by 4.7 percent and 2.0 percent, respectively. Overall, from 2021 to 2022, the amount of electricity retail sales (in kWh) increased by 3.2 percent.

Table 2-11: Electric Power-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Fuel Type or Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**1,836.4**	**2,417.5**	**1,770.7**	**1,624.2**	**1,457.0**	**1,557.7**	**1,549.2**
Fossil Fuel Combustion	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7
Coal	*1,546.5*	*1,982.8*	*1,152.9*	*973.5*	*788.2*	*910.1*	*851.5*
Natural Gas	*175.4*	*318.9*	*577.9*	*616.6*	*634.8*	*612.8*	*659.3*
Petroleum	*97.5*	*98.0*	*22.2*	*16.2*	*16.2*	*17.7*	*20.5*
Geothermal	*0.5*	*0.5*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2
CH_4	**0.5**	**1.0**	**1.4**	**1.4**	**1.4**	**1.4**	**1.3**
Stationary Sources[a]	0.5	1.0	1.4	1.4	1.4	1.4	1.3
Incineration of Waste	+	+	+	+	+	+	+
N_2O	**18.6**	**27.1**	**22.1**	**19.1**	**17.9**	**19.4**	**21.9**
Stationary Sources[a]	18.2	26.7	21.7	18.8	17.5	19.0	21.6
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
SF_6	**24.7**	**11.8**	**5.0**	**6.1**	**5.9**	**6.0**	**5.1**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
CF_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	+	+	+	+	+	+	+
Total	**1,880.2**	**2,457.4**	**1,799.2**	**1,650.8**	**1,482.2**	**1,584.4**	**1,577.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

[9] See https://www.nrel.gov/news/features/2023/nrel-researcher-reveal-how-buildings-across-the-united-states-do-and-could-use-energy.html#:~:text=Buildings%20are%20responsible%20for%2040,buildings%20stock%20is%20also%20essential.

[a] Includes only stationary combustion emissions related to the generation of electricity.
Note: Totals may not sum due to independent rounding.

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electric power sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to each economic sector's share of retail sales of electricity (EIA 2020; USDA/NASS 2023). These source categories include CO_2 from fossil fuel combustion, CH_4 and N_2O from stationary combustion, incineration of waste, other process uses of carbonates, and SF_6 from electrical equipment. Note that only 50 percent of the emissions from other process uses of carbonates were associated with electric power and distributed as described; the remaining emissions from other process uses of carbonates were attributed to the industry economic end-use sector.[10]

When emissions from electricity use are distributed among these economic end-use sectors, 2022 emissions from industrial activities account for the largest share of total U.S. greenhouse gas emissions (29.5 percent), followed closely by emissions from transportation (28.5 percent). Emissions from the commercial and residential sectors also increase substantially when emissions from electricity are included (15.8 and 15.3 percent, respectively). In all economic end-use sectors except agriculture, CO_2 accounts for more than 78 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Table 2-12 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electric power distributed to them. Figure 2-14 shows the trend in these emissions by sector from 1990 to 2022.

Figure 2-14: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors

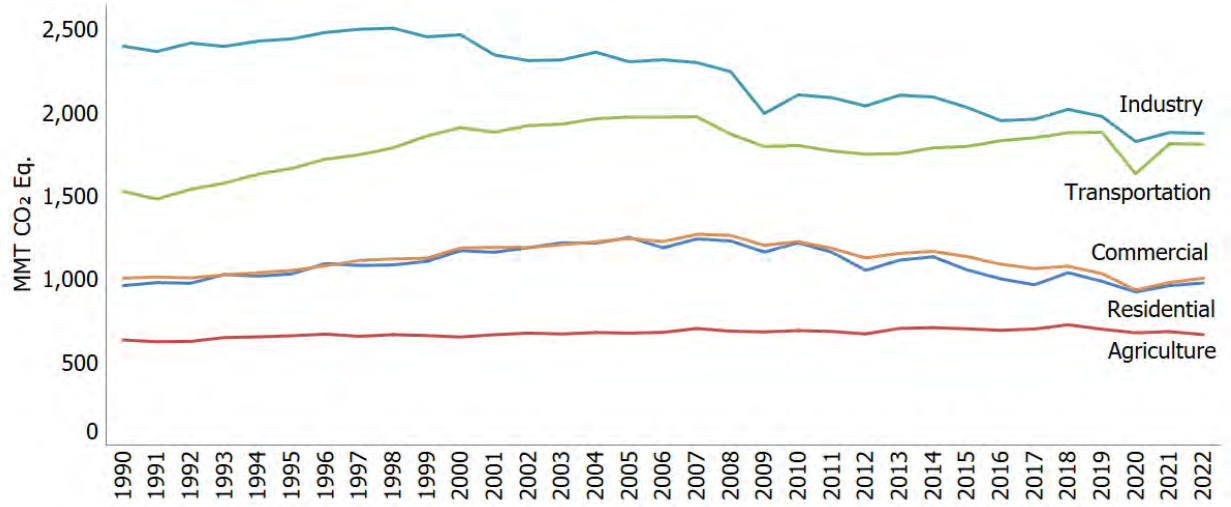

Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-12: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (MMT CO_2 Eq.) and Percent of Total in 2022

Emissions by Gas	1990	2005	2018	2019	2020	2021	2022	Percent[a]
Industry	**2,397.3**	**2,302.9**	**2,017.1**	**1,974.8**	**1,823.5**	**1,877.8**	**1,872.9**	**29.5%**
Direct Emissions	**1,723.3**	**1,587.3**	**1,541.9**	**1,531.8**	**1,435.9**	**1,455.8**	**1,452.5**	**22.9%**

[10] Emissions were not distributed to U.S. Territories, since the electric power sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

CO_2	1,173.8	1,136.4	1,110.7	1,118.3	1,036.9	1,071.1	1,080.8	17.0%
CH_4	413.3	371.2	352.2	337.7	323.3	311.3	299.8	4.7%
N_2O	35.7	29.8	30.3	26.0	27.6	26.8	23.6	0.4%
HFCs, PFCs, SF_6 and NF_3	100.6	49.8	48.6	49.8	48.1	46.5	48.3	0.8%
Electricity-Related	**674.0**	**715.6**	**475.3**	**443.0**	**387.6**	**422.0**	**420.3**	**6.6%**
CO_2	658.3	704.0	467.7	435.9	381.0	414.9	412.8	6.5%
CH_4	0.2	0.3	0.4	0.4	0.4	0.4	0.3	+%
N_2O	6.7	7.9	5.8	5.1	4.7	5.2	5.8	0.1%
SF_6	8.8	3.5	1.3	1.6	1.5	1.6	1.4	+%
Transportation	**1,524.6**	**1,970.8**	**1,876.5**	**1,879.5**	**1,629.5**	**1,810.6**	**1,807.8**	**28.5%**
Direct Emissions	**1,521.4**	**1,965.9**	**1,871.6**	**1,874.6**	**1,625.3**	**1,805.5**	**1,801.5**	**28.4%**
CO_2	1,480.8	1,868.7	1,822.3	1,825.5	1,580.6	1,761.6	1,759.7	27.7%
CH_4	6.4	3.1	1.7	1.7	1.4	1.5	1.5	+%
N_2O	34.3	31.0	12.1	13.4	10.7	11.2	10.7	0.2%
HFCs[b]	+	63.1	35.5	34.0	32.5	31.2	29.6	0.5%
Electricity-Related	**3.1**	**4.8**	**4.9**	**4.9**	**4.2**	**5.2**	**6.3**	**0.1%**
CO_2	3.1	4.8	4.8	4.9	4.1	5.1	6.2	0.1%
CH_4	+	+	+	+	+	+	+	+%
N_2O	+	0.1	0.1	0.1	0.1	0.1	0.1	+%
SF_6	+	+	+	+	+	+	+	+%
Residential	**958.0**	**1,247.7**	**1,035.9**	**984.0**	**919.5**	**958.0**	**973.5**	**15.3%**
Direct Emissions	**345.6**	**371.2**	**376.8**	**384.2**	**358.0**	**369.6**	**391.3**	**6.2%**
CO_2	338.6	358.9	338.9	342.9	314.8	318.0	334.1	5.3%
CH_4	5.9	4.5	5.1	5.3	3.6	3.6	4.3	0.1%
N_2O	0.9	0.8	0.8	0.8	0.6	0.6	0.7	+%
SF_6	0.2	7.0	31.9	35.1	39.0	47.3	52.2	0.8%
Electricity-Related	**612.4**	**876.5**	**659.1**	**599.7**	**561.5**	**588.4**	**582.2**	**9.2%**
CO_2	598.1	862.2	648.6	590.1	551.9	578.5	571.8	9.0%
CH_4	0.2	0.3	0.5	0.5	0.5	0.5	0.5	+%
N_2O	6.1	9.7	8.1	6.9	6.8	7.2	8.1	0.1%
SF_6	8.0	4.2	1.8	2.2	2.2	2.2	1.9	+%
Commercial	**1,002.5**	**1,241.1**	**1,074.3**	**1,030.5**	**931.5**	**976.8**	**1,002.6**	**15.8%**
Direct Emissions	**447.0**	**418.9**	**453.5**	**462.6**	**436.9**	**443.7**	**463.7**	**7.3%**
CO_2	228.3	227.1	246.3	251.7	229.3	237.5	258.7	4.1%
CH_4	203.6	150.9	125.9	127.8	122.9	120.5	118.5	1.9%
N_2O	15.1	19.4	22.8	23.2	23.9	23.7	23.6	0.4%
HFCs	+	21.4	58.5	59.8	60.8	61.9	62.9	1.0%
Electricity-Related	**555.5**	**822.2**	**620.8**	**567.8**	**494.6**	**533.2**	**539.0**	**8.5%**
CO_2	542.6	808.9	611.0	558.7	486.2	524.2	529.3	8.3%
CH_4	0.1	0.3	0.5	0.5	0.5	0.5	0.4	+%
N_2O	5.5	9.1	7.6	6.6	6.0	6.5	7.5	0.1%
SF_6	7.3	4.0	1.7	2.1	2.0	2.0	1.7	+%
Agriculture	**631.1**	**672.6**	**722.7**	**696.3**	**674.4**	**681.6**	**663.6**	**10.5%**
Direct Emissions	**595.9**	**634.3**	**683.5**	**661.0**	**640.0**	**645.9**	**634.0**	**10.0%**
CO_2	50.5	58.7	47.0	46.9	47.1	47.4	47.9	0.8%
CH_4	241.9	264.6	285.2	280.4	282.6	282.0	277.0	4.4%
N_2O	303.5	311.0	351.3	333.7	310.3	316.4	309.1	4.9%
Electricity-Related	**35.2**	**38.3**	**39.2**	**35.2**	**34.4**	**35.7**	**29.7**	**0.5%**
CO_2	34.3	37.7	38.6	34.7	33.8	35.1	29.2	0.5%
CH_4	+	+	+	+	+	+	+	+%
N_2O	0.3	0.4	0.5	0.4	0.4	0.4	0.4	+%
SF_6	0.5	0.2	0.1	0.1	0.1	0.1	0.1	+%
U.S. Territories	**23.4**	**59.7**	**26.3**	**25.1**	**23.4**	**23.9**	**22.7**	**0.4%**
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**100.0%**
LULUCF Sector Net Total[c]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	(13.5%)
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**86.5%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.
[a] Percent of total (gross) emissions excluding emissions from LULUCF for the year 2022.
[b] Includes primarily HFC-134a.
[c] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.
Notes: Total gross emissions are presented without LULUCF. Net emissions are presented with LULUCF. Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding.

Industry

The industry economic sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate, and with the distribution of electricity-related emissions (e.g., powering industrial machinery), accounted for 29.5 percent of U.S. greenhouse gas emissions in 2022. This end-use sector also includes emissions that are produced as a byproduct of the non-energy-related industrial process activities. The variety of activities producing these non-energy-related emissions includes CH_4 emissions from petroleum and natural gas systems, fugitive CH_4 and CO_2 emissions from coal mining, byproduct CO_2 emissions from cement production, and HFC, PFC, SF_6, and NF_3 byproduct emissions from the electronics industry, to name a few.

Since 1990, industry sector emissions have declined by 21.9 percent. The decline has occurred both in direct emissions and indirect emissions associated with electricity use. Structural changes within the U.S. economy that led to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., shifts from producing steel to computer equipment) have had a significant effect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 28.5 percent of U.S. greenhouse gas emissions in 2022. The largest sources of transportation greenhouse gas emissions in 2022 were light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (36.5 percent); medium- and heavy-duty trucks (22.9 percent); passenger cars (20.4 percent); commercial aircraft (7.2 percent); pipelines (3.8 percent); ships and boats (2.8 percent); other aircraft (2.0 percent), and rail (2.0 percent). These figures include direct CO_2, CH_4, and N_2O emissions from fossil fuel combustion used in transportation, indirect emissions from electricity use, and emissions from non-energy use (i.e., lubricants) used in transportation, as well as HFC emissions from mobile air conditioners and refrigerated transport allocated to these vehicle types.

From 1990 to 2022, total transportation emissions from fossil fuel combustion increased by 19.4 percent due, in large part, to increased demand for travel. From 2021 to 2022, emissions decreased by 0.1 percent. Vehicle miles traveled (VMT) by light-duty motor vehicles (passenger cars and light-duty trucks) increased by 46.7 percent from 1990 to 2022 as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 19.4 percent from 1990 to 2022 when including electricity. This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 29.6 MMT CO_2 Eq. in 2022, led to an increase in overall greenhouse gas emissions from transportation activities of 18.6 percent.

The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from approximately 29.6 percent of new vehicle sales in 1990 to 48.0 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly between 2005 and 2013. Light-duty VMT grew by less than one percent or declined each year between 2005 and 2013, then grew at a faster rate until 2016 (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Since 2016, the rate of light-duty VMT growth has slowed to one percent or less each year. Average new vehicle fuel economy has increased almost every year since 2005, while light-duty truck market share decreased to

33.0 percent in 2009 and has since varied from year to year between 35.6 and 63.1 percent. Light-duty truck market share was about 63.1 percent of new vehicles in model year 2022 (EPA 2023b).

Table 2-13 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals. Historically, the majority of electricity use in the transportation sector was for rail transport. However, more recently there has been increased electricity use in on-road electric and plug-in hybrid vehicles. Despite this increase, almost all of the energy used for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. Indirect emissions from electricity are less than 1 percent of direct emissions in the transportation sector. For a more detailed breakout of emissions by fuel type by vehicle see Table A-93 in Annex 3.

Figure 2-15: Trends in Transportation-Related Greenhouse Gas Emissions

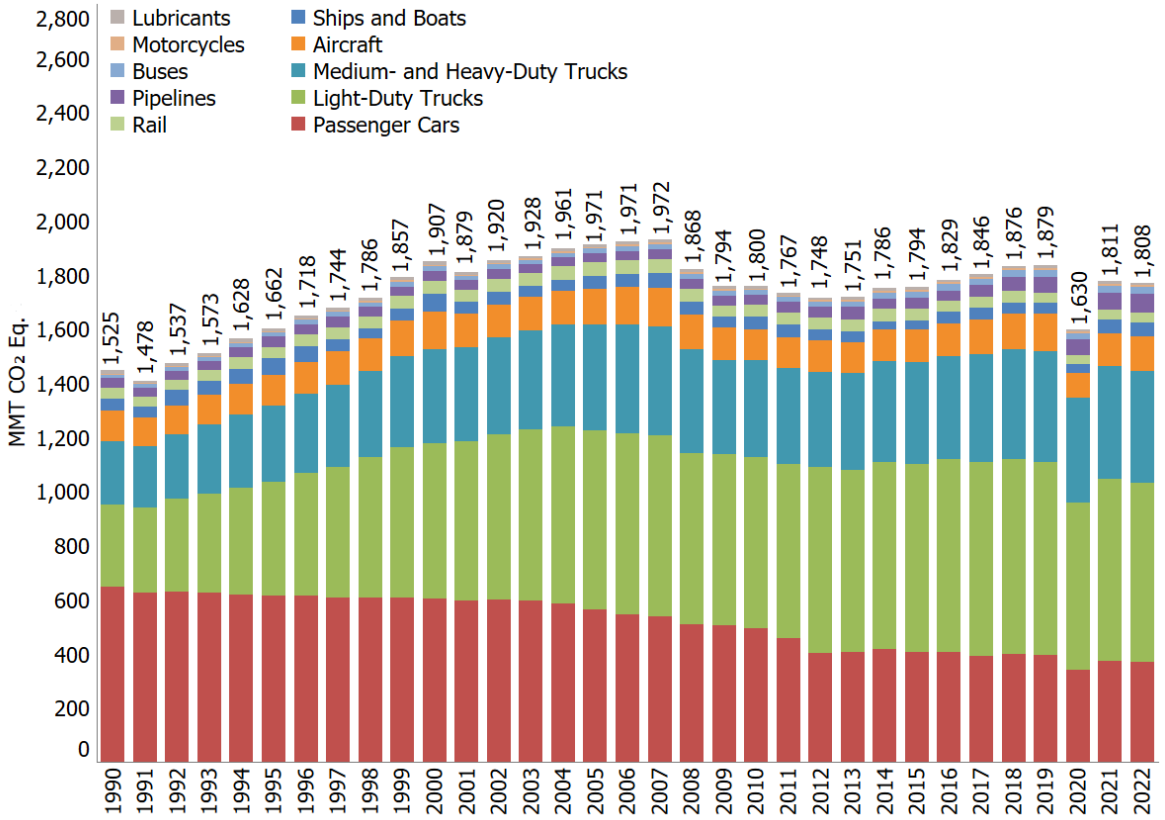

Table 2-13: Transportation-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Vehicle Type	1990	2005	2018	2019	2020	2021	2022
Passenger Cars	**648.4**	**564.4**	**398.7**	**395.5**	**341.7**	**374.2**	**369.5**
CO_2	622.2	521.1	386.5	384.2	331.9	365.0	361.0
CH_4	3.8	1.2	0.3	0.3	0.3	0.3	0.2
N_2O	22.5	13.3	2.5	2.6	2.0	1.9	1.7
HFCs	0.0	28.8	9.4	8.4	7.6	7.0	6.6
Light-Duty Trucks	**302.4**	**659.3**	**720.6**	**711.7**	**615.3**	**671.7**	**660.2**
CO_2	292.1	614.0	699.0	690.1	596.2	654.0	644.5
CH_4	1.5	1.0	0.6	0.6	0.5	0.5	0.5
N_2O	8.7	14.0	4.6	5.6	4.4	4.2	3.8
HFCs	0.0	30.2	16.4	15.4	14.2	13.0	11.4

Medium- and Heavy-Duty Trucks	**234.5**	**391.0**	**406.5**	**409.3**	**386.7**	**417.0**	**413.1**
CO_2	233.1	386.2	397.9	400.3	377.8	407.7	403.6
CH_4	0.5	0.2	0.1	0.1	0.1	0.1	0.1
N_2O	1.0	1.5	2.8	3.0	2.7	3.0	3.1
HFCs	0.0	3.2	5.6	5.8	6.1	6.3	6.3
Buses	**13.3**	**17.8**	**24.9**	**25.3**	**24.0**	**26.1**	**26.3**
CO_2	13.2	17.5	24.3	24.7	23.4	25.6	25.7
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.2	0.2	0.2	0.2	0.2
HFCs	0.0	0.2	0.4	0.4	0.4	0.4	0.4
Motorcycles	**3.4**	**5.0**	**7.4**	**7.5**	**6.7**	**7.5**	**7.6**
CO_2	3.4	4.9	7.3	7.4	6.6	7.4	7.4
CH_4	+	+	+	+	+	+	+
N_2O	+	+	0.1	0.1	0.1	0.1	0.1
Commercial Aircraft[a]	**110.8**	**133.8**	**130.7**	**137.8**	**92.0**	**120.0**	**130.8**
CO_2	109.9	132.7	129.6	136.7	91.3	119.0	129.7
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	0.9	1.1	1.1	1.1	0.7	1.0	1.1
Other Aircraft[b]	**78.0**	**59.5**	**44.6**	**45.6**	**31.0**	**35.5**	**37.0**
CO_2	77.3	59.0	44.2	45.2	30.7	35.1	36.7
CH_4	0.1	0.1	+	+	+	+	+
N_2O	0.6	0.5	0.4	0.4	0.2	0.3	0.3
Ships and Boats[c]	**47.0**	**45.5**	**41.1**	**40.0**	**32.2**	**50.7**	**49.9**
CO_2	46.3	44.3	36.9	35.5	27.5	45.4	44.4
CH_4	0.4	0.5	0.5	0.4	0.4	0.5	0.5
N_2O	0.2	0.2	0.2	0.2	0.1	0.3	0.3
HFCs	0.0	0.5	3.6	3.9	4.2	4.5	4.8
Rail	**39.0**	**51.4**	**42.5**	**39.7**	**34.2**	**35.5**	**35.6**
CO_2	38.5	50.8	41.9	39.1	33.7	34.9	35.0
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.3	0.4	0.3	0.3	0.3	0.3	0.3
HFCs	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Other Emissions from Electric Power[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pipelines[e]	**36.0**	**32.8**	**50.3**	**58.3**	**58.0**	**64.4**	**69.3**
CO_2	36.0	32.8	50.3	58.3	58.0	64.4	69.3
Lubricants	**11.8**	**10.2**	**9.2**	**8.8**	**7.8**	**8.0**	**8.4**
CO_2	11.8	10.2	9.2	8.8	7.8	8.0	8.4
Total Transportation	**1,524.6**	**1,970.8**	**1,876.5**	**1,879.5**	**1,629.5**	**1,810.6**	**1,807.8**
International Bunker Fuels[f]	*54.7*	*44.6*	*32.4*	*26.2*	*22.7*	*22.7*	*25.3*
Ethanol CO_2[g]	*4.1*	*21.6*	*78.6*	*78.7*	*68.1*	*75.4*	*75.0*
Biodiesel CO_2[g]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Consists of emissions from jet fuel consumed by domestic operations of commercial aircraft (no bunkers).

[b] Consists of emissions from jet fuel and aviation gasoline consumption by general aviation and military aircraft.

[c] Fluctuations in emission estimates are associated with fluctuations in reported fuel consumption and may reflect issues with data sources.

[d] Other emissions from electric power are a result of waste incineration (as the majority of MSW is combusted in "trash-to-steam" electric power plants), electrical equipment, and a portion of other process uses of carbonates (from pollution control equipment installed in electric power plants).

[e] CO_2 estimates reflect natural gas used to power pipelines, but not electricity. While the operation of pipelines produces CH_4 and N_2O, these emissions are not directly attributed to pipelines in the Inventory.

[f] Emissions from International Bunker Fuels include emissions from both civilian and military activities; these emissions are not included in the transportation totals.

[g] Ethanol and biodiesel CO_2 estimates are presented for informational purposes only. See Section 3.11 and the estimates in LULUCF (see Chapter 6), in line with IPCC methodological guidance and reporting obligations under the Paris Agreement and the UNFCCC, for more information on ethanol and biodiesel.

Notes: Passenger cars and light-duty trucks include vehicles typically used for personal travel and less than 8,500 lbs; medium- and heavy-duty trucks include vehicles larger than 8,500 lbs. HFC emissions primarily reflect HFC-134a. Totals may not sum due to independent rounding.

Residential

The residential end-use sector, including electricity-related emissions, accounted for 15.3 percent of U.S. greenhouse gas emissions in 2022. This sector is heavily reliant on electricity for meeting energy needs, with electricity use for building-related activities like lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Emissions from the residential sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in housing and building attributes (e.g., larger sizes and improved insulation). A shift toward energy-efficient products and more stringent energy efficiency standards for household equipment has also contributed to recent trends in energy demand in households.

Commercial

The commercial end-use sector, including electricity-related emissions, accounted for 15.8 percent of U.S. greenhouse gas emissions in 2022. Like the residential sector it is heavily reliant on electricity for meeting energy needs, with electricity use for building-related activities like lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Energy-related emissions from the commercial sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Decreases in energy-related emissions in the commercial sector in recent years can be largely attributed to an overall reduction in energy use driven by a reduction in heating degree days and increases in energy efficiency.

Municipal landfills and wastewater treatment are included in the commercial sector, with landfill emissions decreasing since 1990 and wastewater treatment emissions increasing slightly.

Agriculture

The agriculture end-use sector accounted for 10.5 percent of U.S. greenhouse gas emissions in 2022 when electricity-related emissions are distributed, and includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2022, agricultural soil management was the largest source of N_2O emissions, and enteric fermentation was the largest source of CH_4 emissions in the United States. This sector also includes small amounts of CO_2 emissions from fossil fuel combustion by motorized farm equipment such as tractors. Indirect emissions from electricity use in agricultural activities (e.g., powering buildings and equipment) are about 5 percent of direct emissions.

Box 2-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total (gross) greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) aggregate energy use, because energy-related activities are the largest sources of emissions; (2) energy use per capita as a measure of efficiency; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

Table 2-14 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.1 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use, overall gross domestic product (GDP) and national population (see Table 2-14 and Figure 2-16). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use and associated fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.9 percent since 2005. Since 2005, GDP, and national population, generally continued to increase, and energy use has decreased slightly, noting 2020 was impacted by the COVID-19 pandemic.

Table 2-14: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2018	2019	2020	2021	2022	Avg. Annual Change Since 1990[a]	Avg. Annual Change Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	103	101	92	97	97	-0.1%	-0.9%
Energy Use[c]	100	119	118	117	107	113	115	0.5%	-0.2%
GDP[d]	100	159	201	206	201	213	217	2.5%	1.9%
Population[e]	100	118	130	131	132	132	133	0.9%	0.7%

[a] Average annual growth rate.
[b] Gross total GWP-weighted values.
[c] Energy-content-weighted values (EIA 2024).
[d] GDP in chained 2017 dollars (BEA 2024).
[e] U.S. Census Bureau (2024).

Figure 2-16: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product

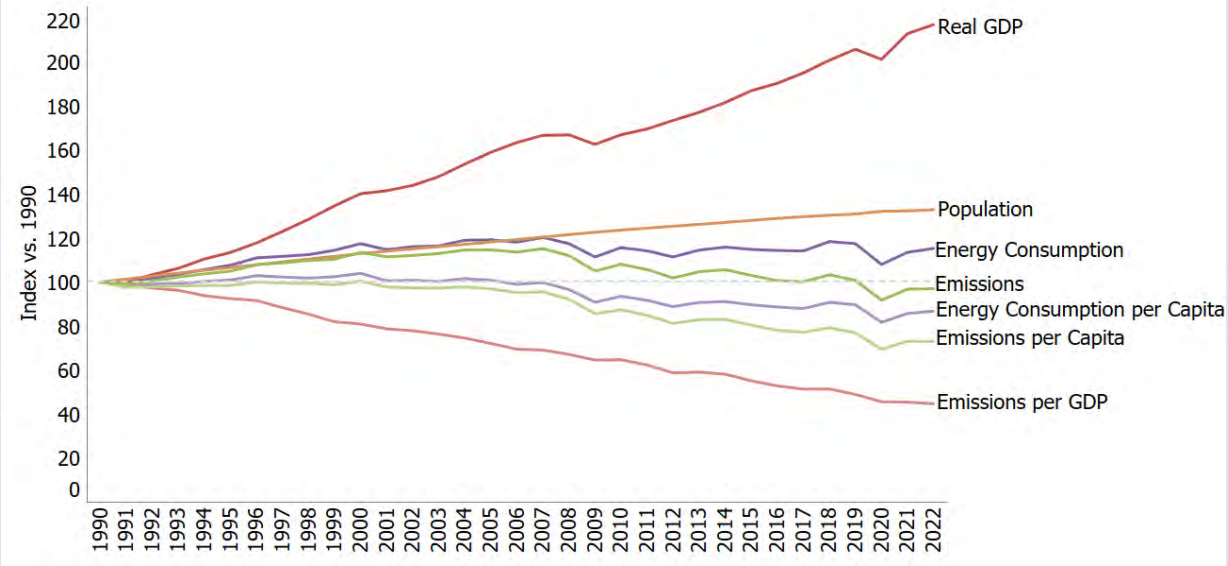

Source: BEA (2024), U.S. Census Bureau (2024), and gross emission estimates in this report.

2.3 Precursor Greenhouse Gas Emissions (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the Paris Agreement and the UNFCCC[11] request that information be provided on emissions of compounds that are precursors to greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance, by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). Carbon monoxide is produced when carbon-containing fuels are combusted incompletely in energy, transportation, and industrial processes, and is also emitted from practices such as agricultural burning and waste disposal and treatment. Anthropogenic sources of nitrogen oxides (i.e., NO and NO_2) are primarily fossil fuel combustion (for energy, transportation, industrial process) and agricultural burning. Anthropogenic sources of NMVOCs, which include hundreds of organic compounds that participate in atmospheric chemical reactions (propane, butane, xylene, toluene, ethane, and many others)—are emitted primarily from transportation, industrial processes, oil and natural gas production, waste practices, agricultural burning, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from coal combustion for electric power generation and the metals industry.

As noted above and summarized in Chapter 6 of IPCC (2021), these compounds can have important indirect effects on Earth's radiative balance. For example, reactions between NMVOCs and NO_x in the presence of sunlight lead to formation of tropospheric ozone, a greenhouse gas. Concentrations of NMVOCs, NO_x, and CO can also impact the abundance and lifetime of primary greenhouse gases. This largely occurs by altering the atmospheric concentrations of the hydroxyl radical (OH), which is the main sink for atmospheric CH_4. For example, NO_x emissions can lead to increases in O_3 concentrations and subsequent OH production, which will increase the amount of OH molecules that are available to destroy CH_4. In contrast, NMVOCs and CO can both react directly with OH, leading to lower OH concentrations, a longer atmospheric lifetime of CH_4, and a decrease in CO_2 production (i.e., CO+OH→ CO_2). Changes in atmospheric CH_4 can also feedback on background concentrations of tropospheric O_3. Other indirect impacts include the formation of sulfate and nitrate aerosol from emissions of NO_x and SO_2, both of which have a net negative impact on radiative forcing.

Since 1970, the United States has published triennial estimates of emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2023a), which are regulated under the Clean Air Act. Emissions of each of these precursor greenhouse gases has decreased significantly since 1990 as a result of implementation of Clean Air Act programs, as well as technological improvements.[12] Precursor emission estimates for this report for 1990 through 2022 were obtained from data published on EPA's National Emissions Inventory (NEI) Air Pollutants Emissions Trends Data website (EPA 2023a). For Table 2-15, NEI-reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Emissions Inventory System (EIS) source categories to those more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on the crosswalk detailed in Annex 6.3. Table 2-15 shows that fuel combustion accounts for the majority of emissions of these precursors. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs. Precursor emissions from Agriculture and LULUCF categories are estimated separately and therefore are not taken from EPA (2023a).

[11] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[12] More information is available online at: https://www.epa.gov/clean-air-act-overview/progress-cleaning-air-and-improving-peoples-health and https://gispub.epa.gov/neireport/2017/.

Table 2-15: Emissions of NO_x, CO, NMVOCs, and SO_2 (kt)

Gas/Activity	1990	2005	2018	2019	2020	2021	2022
NO_x	**22,896**	**19,754**	**8,064**	**7,639**	**6,879**	**6,996**	**6,589**
Energy	21,966	18,863	7,384	7,048	6,235	6,308	5,964
IPPU	774	672	461	440	393	403	389
Agriculture	16	18	17	18	17	18	19
LULUCF	56	149	130	61	158	190	142
Waste	84	51	73	73	76	76	75
CO	**133,549**	**76,691**	**38,656**	**36,234**	**38,911**	**41,677**	**38,853**
Energy	124,713	64,455	30,760	30,349	28,427	28,845	28,173
IPPU	4,099	1,701	1,022	1,011	855	902	897
Agriculture	407	480	433	468	446	480	501
LULUCF	3,301	8,877	5,259	3,224	7,841	10,107	7,939
Waste	1,028	1,178	1,182	1,182	1,342	1,343	1,343
NMVOCs	**20,918**	**12,708**	**8,987**	**8,804**	**9,040**	**9,454**	**9,325**
Energy	13,067	8,694	5,506	5,444	5,306	5,568	5,442
IPPU	6,982	3,668	3,119	2,996	3,366	3,508	3,505
Agriculture	+	194	206	208	196	206	206
LULUCF	NA	NA	NA	NA	NA	NA	NA
Waste	870	152	156	157	173	172	172
SO_2	**20,924**	**13,108**	**2,001**	**1,676**	**1,471**	**1,621**	**1,522**
Energy	19,400	12,312	1,643	1,344	1,173	1,315	1,229
IPPU	1,488	776	335	309	266	274	261
Agriculture	+	0	0	0	+	+	+
LULUCF	NA	NA	NA	NA	NA	NA	NA
Waste	36	20	23	23	33	32	31

+ Does not exceed 0.5 kt.

NA (Not Available)

Note: Totals by gas may not sum due to independent rounding.

Source: (EPA 2023a) except for estimates from forest fires, grassland fires, and field burning of agricultural residues. Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 82.0 percent of total gross greenhouse gas emissions on a carbon dioxide (CO_2) equivalent basis in 2022.[1] This included 96.5, 40.2, and 10.8 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively.[2] Energy-related CO_2 emissions alone constituted 76.9 percent of total gross U.S. greenhouse gas emissions from all sources on a CO_2-equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total gross national emissions (5.1 percent collectively).

Emissions from fossil fuel combustion contribute the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1 and Figure 3-2). Globally, approximately 33,500 million metric tons (MMT) of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2022, of which the United States accounted for approximately 14 percent.[3] Due to their relative importance over time (see Figure 3-2), fossil fuel combustion-related CO_2 emissions are considered in more detail than other energy-related emissions in this report (see Figure 3-3).

Fossil fuel combustion also emits CH_4 and N_2O. Stationary combustion of fossil fuels was the second largest source of N_2O emissions in the United States and mobile fossil fuel combustion was the fifth largest source. Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 emissions from natural gas systems, coal mining, and petroleum systems.

[1] Estimates are presented in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.), which weight each gas by its global warming potential, or GWP, value. See section on global warming potentials in the Executive Summary.

[2] The contribution of energy non-CO_2 emissions is based on gross totals so excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related methane (CH_4) and (N_2O) including LULUCF non-CO_2 emissions, is 37.1 percent and 9.8 percent respectively.

[3] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *Global energy-related CO_2 emissions, 2022.* Available at: https://www.iea.org/reports/co2-emissions-in-2022 (IEA 2022).

Figure 3-1: 2022 Energy Sector Greenhouse Gas Sources

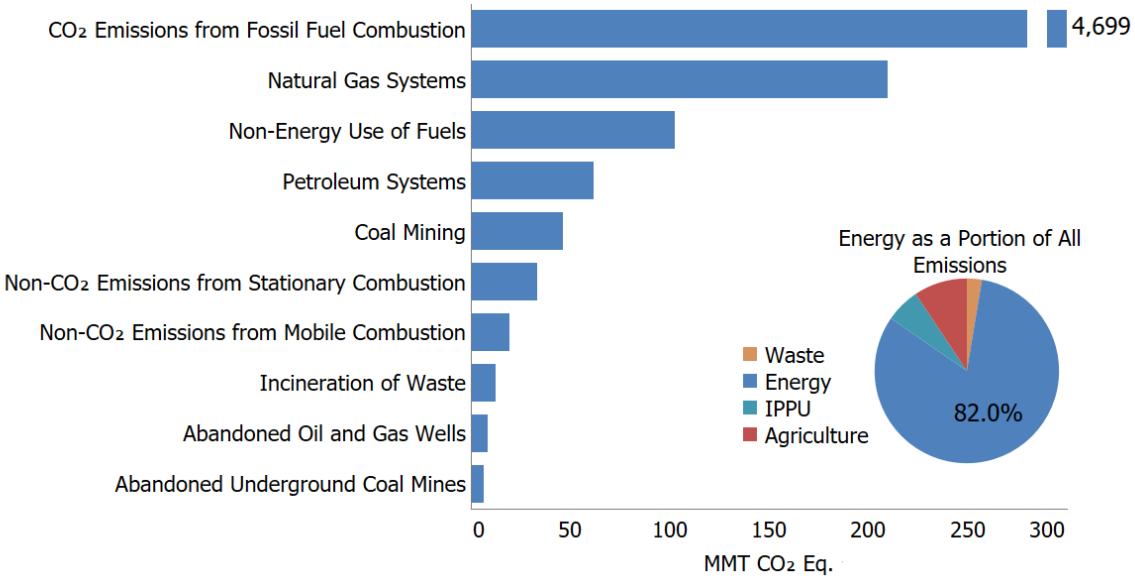

Figure 3-2: Trends in Energy Sector Greenhouse Gas Sources

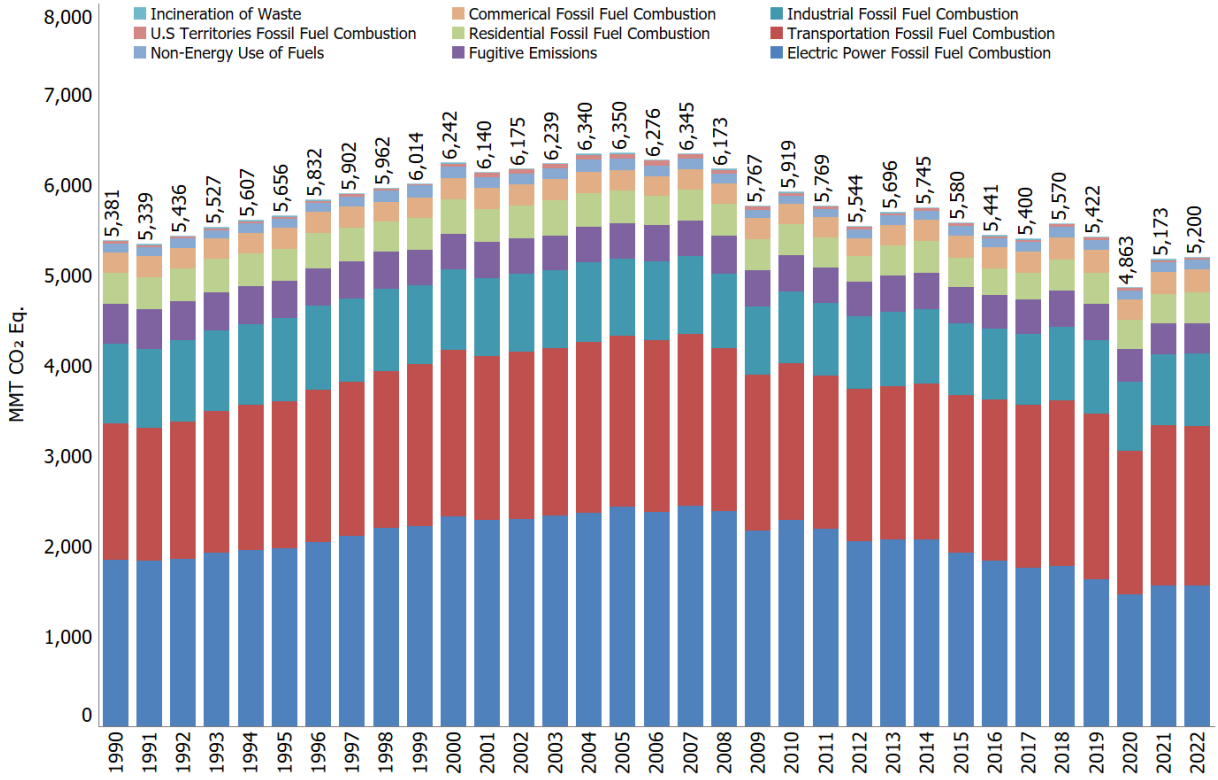

Figure 3-3: 2022 U.S. Fossil Carbon Flows (MMT CO_2 Eq.)

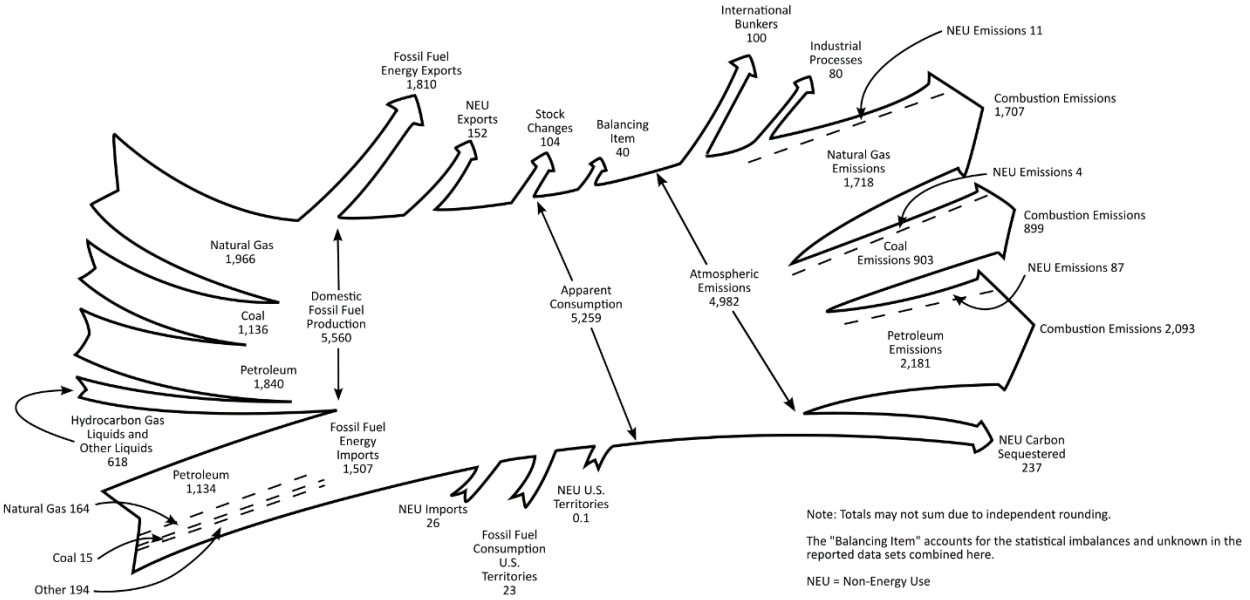

Table 3-1 summarizes emissions from the Energy sector in units of MMT CO_2 Eq., while unweighted gas emissions in kilotons (kt) are provided in Table 3-2. Overall, emissions due to energy-related activities were 5,199.8 MMT CO_2 Eq. in 2022,[4] a decrease of 3.4 percent since 1990 and an increase of 0.5 percent since 2021. The increase in emissions in 2021 and 2022 was due to continued rebounding activity levels after the coronavirus (COVID-19) pandemic reduced overall demand for fossil fuels across all sectors in 2020. Longer term trends are driven by a number of factors including a shift from coal to natural gas and renewables in the electric power sector.

Table 3-1: CO_2, CH_4, and N_2O Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**4,910.9**	**5,923.1**	**5,190.6**	**5,059.1**	**4,520.2**	**4,840.7**	**4,875.5**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*
Electricity Generation	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	*215.2*	*206.9*	*220.0*	*217.7*	*190.6*	*192.5*	*195.3*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*81.9*	*82.6*	*71.8*	*79.1*	*79.6*

[4] Following the current reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the IPCC *Fifth Assessment Report* (AR5) GWP values. See Chapter 1, Introduction for more information.

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*
Biomass-MSW[a]	*18.5*	*14.7*	*16.1*	*15.7*	*15.6*	*15.3*	*14.9*
CH_4	**409.0**	**358.5**	**336.2**	**321.7**	**305.3**	**293.3**	**282.4**
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**61.2**	**67.9**	**43.2**	**41.6**	**37.1**	**39.2**	**41.9**
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Natural Gas Systems	+	+	+	+	+	+	0.2
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*
Total	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from biomass and biofuel consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and Paris Agreement and UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

Table 3-2: CO_2, CH_4, and N_2O Emissions from Energy (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**4,910,861**	**5,923,075**	**5,190,611**	**5,059,075**	**4,520,249**	**4,840,748**	**4,875,487**
Fossil Fuel Combustion	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
Non-Energy Use of Fuels	99,104	124,988	118,382	106,474	97,757	111,624	102,808
Natural Gas Systems	32,427	26,312	32,768	38,525	36,719	35,780	36,470
Petroleum Systems	9,585	10,210	34,777	45,498	28,937	24,140	21,967
Incineration of Waste	12,900	13,254	13,339	12,948	12,921	12,476	12,357
Coal Mining	4,606	4,169	3,139	2,992	2,197	2,455	2,474
Abandoned Oil and Gas Wells	7	7	8	8	8	8	8
Biomass-Wood[a]	*215,186*	*206,901*	*220,003*	*217,690*	*190,554*	*192,509*	*195,338*
International Bunker Fuels[b]	*103,634*	*113,328*	*124,279*	*113,632*	*69,638*	*80,180*	*98,241*
Biofuels-Ethanol[a]	*4,227*	*22,943*	*81,917*	*82,578*	*71,848*	*79,064*	*79,593*
Biofuels-Biodiesel[a]	*0*	*856*	*17,936*	*17,080*	*17,678*	*16,112*	*15,622*
Biomass-MSW[a]	*18,534*	*14,722*	*16,115*	*15,709*	*15,614*	*15,329*	*14,864*
CH_4	**14,607**	**12,804**	**12,007**	**11,490**	**10,903**	**10,476**	**10,084**
Natural Gas Systems	7,813	7,505	6,795	6,741	6,439	6,235	6,183
Coal Mining	3,860	2,552	2,110	1,892	1,648	1,595	1,558
Petroleum Systems	1,765	1,723	2,108	1,865	1,904	1,737	1,415
Stationary Combustion	345	313	344	351	285	286	307
Abandoned Oil and Gas Wells	279	294	301	302	303	306	303
Abandoned Underground Coal Mines	288	264	247	237	232	224	225
Mobile Combustion	258	154	101	102	91	92	93
Incineration of Waste	+	+	+	+	+	+	+

Gas/Source	1990	2005	2018	2019	2020	2021	2022
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*3*	*3*	*3*
N_2O	**231**	**256**	**163**	**157**	**140**	**148**	**158**
Stationary Combustion	84	115	95	84	78	83	93
Mobile Combustion	145	140	67	72	61	63	63
Incineration of Waste	2	1	1	1	1	1	1
Natural Gas Systems	+	+	+	+	+	+	0.6
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*4*	*3*	*2*	*2*	*3*

+ Does not exceed 0.5 kt.

[a] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Note: Totals by gas may not sum due to independent rounding.

Emissions estimates reported in the Energy chapter from fossil fuel combustion and fugitive sources include those from all 50 states, including Hawaii and Alaska, and the District of Columbia. Emissions are also included from U.S. Territories to the extent they are known to occur (e.g., coal mining does not occur in U.S. Territories). For some sources there is a lack of detailed information on U.S. Territories including some non-CO_2 emissions from biomass combustion. As part of continuous improvement efforts, EPA reviews this on an ongoing basis to ensure emission sources are included across all geographic areas including U.S. Territories if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Each year, some emission and sink estimates in the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to ensure that the trend is accurate. Key updates in this year's *Inventory* include, updated methodologies for completion and workover emissions estimates and transmission compressor station activity from both natural gas systems and petroleum systems, a shift of all product supplied of natural gasoline and unfinished oils to crude oil transfers for the time series and changes to the non-energy use of fossil fuel methodology (e.g., updates to some of the data and updated methodology for the amount of NEU HGLs). The impact of these recalculations averaged a decrease of 0.2 MMT CO_2 Eq. (less than 0.1 percent) per year across the time series. For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Box 3-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the Energy chapter do not preclude alternative examinations (e.g., economic sectors). Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from energy-related activities.

Energy Data from EPA's Greenhouse Gas Reporting Program

EPA's Greenhouse Gas Reporting Program (GHGRP)[5] dataset and the data presented in this Inventory are complementary. The *Inventory* was used to guide the development of the GHGRP, particularly in terms of scope and coverage of both sources and gases. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of Energy sector categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines (see Box 3-3 of this chapter, and Sections 3.3 Incineration of Waste, 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.7 Natural Gas Systems).[6] Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods. Under EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. It should be noted that the definitions and provisions for reporting fuel types in EPA's GHGRP may differ from those used in the Inventory in meeting the Paris Agreement and UNFCCC reporting guidelines. In line with the Paris Agreement and UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from fuel types identified in the IPCC guidelines and provides a separate reporting of emissions from biomass.

In addition to using GHGRP data to estimate emissions (Sections 3.3 Incineration of Waste, 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.7 Natural Gas Systems), EPA also uses the GHGRP fuel consumption activity data in the Energy sector to disaggregate industrial end-use sector emissions in the category of CO_2 emissions from fossil fuel combustion, for use in reporting emissions in Common Reporting Tables (CRTs) (see Box 3-3). The industrial end-use sector activity data collected for the *Inventory* (EIA 2024) represent aggregated data for the industrial end-use sector. EPA's GHGRP collects industrial fuel consumption activity data by individual categories within the industrial end-use sector. Therefore, GHGRP data are used to provide a more detailed breakout of total emissions in the industrial end-use sector within that source category.

As indicated in the respective Planned Improvements sections for source categories in this chapter, EPA continues to examine the uses of facility-level GHGRP data to improve the national estimates presented in this *Inventory*. See Annex 9 for more information on use of EPA's GHGRP in the *Inventory*.

3.1 Fossil Fuel Combustion (CRT Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the greenhouse gases CO_2, CH_4, and N_2O. Given that CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total emissions, CO_2 emissions from fossil fuel combustion are discussed at the beginning of this section. An overview of CH_4 and N_2O emissions from the combustion of fuels in stationary sources is then presented, followed by fossil fuel

[5] On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[6] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

combustion emissions for all three gases by sector: electric power, industrial, residential, commercial, U.S. Territories, and transportation.

Methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of CH_4 and N_2O emissions from stationary combustion and mobile combustion. Thus, three separate descriptions of methodologies, uncertainties, recalculations, and planned improvements are provided at the end of this section. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion are presented in Table 3-3 and Table 3-4.

Table 3-3: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
CH_4	16.9	13.1	12.5	12.7	10.5	10.6	11.2
N_2O	60.8	67.6	42.8	41.2	36.7	38.9	41.4
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

Note: Totals may not sum due to independent rounding.

Table 3-4: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
CH_4	602	467	445	453	376	379	401
N_2O	229	255	161	156	138	147	156

CO_2 from Fossil Fuel Combustion

Carbon dioxide is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total greenhouse gas emissions. Carbon dioxide emissions from fossil fuel combustion are presented in Table 3-5. In 2022, CO_2 emissions from fossil fuel combustion increased by 1.0 percent relative to the previous year (as shown in Table 3-6). The increase in CO_2 emissions from fossil fuel combustion was a result of a 1.8 percent increase in fossil fuel energy use. This increase in fossil fuel energy use was due primarily to the continued rebound in economic activity after the COVID-19 pandemic. Carbon dioxide emissions from natural gas increased by 84.8 MMT CO_2 Eq., a 5.2 percent increase from 2021. In a shift from last year's trend, CO_2 emissions from coal consumption decreased by 58.6 MMT CO_2 Eq., a 6.1 percent decrease from 2021. Both the increase in natural gas and decrease in coal consumption and emissions in 2022 are observed across all sectors. Emissions from petroleum use also increased 19.0 MMT CO_2 Eq. (0.9 percent) from 2021 to 2022. In 2022, CO_2 emissions from fossil fuel combustion were 4,699,4 MMT CO_2 Eq., or 1.1 percent below emissions in 1990 (see Table 3-5).[7]

[7] An additional discussion of fossil fuel emission trends is presented in the Trends in U.S. Greenhouse Gas Emissions chapter.

Table 3-5: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq.)

Fuel/Sector	1990	2005	2018	2019	2020	2021	2022
Coal	**1,719.8**	**2,113.7**	**1,211.6**	**1,028.1**	**835.6**	**957.4**	**898.8**
Residential	3.0	0.8	NO	NO	NO	NO	NO
Commercial	12.0	9.3	1.8	1.6	1.4	1.4	1.4
Industrial	157.8	117.8	54.4	49.4	43.0	43.0	43.0
Transportation	NO	NO	NO	NO	NO	NO	NO
Electric Power	1,546.5	1,982.8	1,152.9	973.5	788.2	910.1	851.5
U.S. Territories	0.5	3.0	2.6	3.6	3.1	2.9	2.9
Natural Gas	**998.6**	**1,166.2**	**1,592.0**	**1,649.2**	**1,615.7**	**1,622.1**	**1,706.8**
Residential	237.8	262.2	273.8	275.5	256.4	258.6	272.0
Commercial	142.0	162.9	192.5	192.9	173.5	180.4	192.3
Industrial	407.4	387.8	493.5	501.5	489.7	501.2	510.4
Transportation	36.0	33.1	50.9	58.9	58.7	65.2	70.2
Electric Power	175.4	318.9	577.9	616.6	634.8	612.8	659.3
U.S. Territories	NO	1.3	3.3	3.8	2.6	3.9	2.7
Petroleum	**2,033.3**	**2,463.8**	**2,184.2**	**2,174.9**	**1,890.0**	**2,074.4**	**2,093.4**
Residential	97.8	95.9	65.1	67.4	58.4	59.4	62.1
Commercial	74.3	54.9	52.0	57.2	54.4	55.7	65.1
Industrial	311.2	342.0	262.6	258.9	229.3	236.3	247.6
Transportation	1,432.9	1,825.5	1,762.2	1,757.7	1,514.2	1,688.4	1,681.1
Electric Power	97.5	98.0	22.2	16.2	16.2	17.7	20.5
U.S. Territories	19.5	47.6	20.1	17.5	17.5	17.0	17.0
Geothermal[a]	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Electric Power	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Total	**4,752.2**	**5,744.1**	**4,988.2**	**4,852.6**	**4,341.7**	**4,654.3**	**4,699.4**

NO (Not Occurring)

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Note: Totals may not sum due to independent rounding.

Trends in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants. The 2021 to 2022 trends reflect ongoing impacts of the COVID-19 pandemic which generally led to a reduction in demand for fossil fuels in 2020, but an increase in demand as activities continued to rebound in 2022.

Longer-term changes in energy usage patterns, however, tend to be more a function of aggregate societal trends that affect the scale of energy use (e.g., population, number of cars, size of houses, and number of houses), the efficiency with which energy is used in equipment (e.g., cars, HVAC systems, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Carbon dioxide emissions also depend on the source of energy and its carbon intensity. The amount of carbon in fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about

55 percent.[8] Table 3-6 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

Table 3-6: Annual Change in CO_2 Emissions and Total 2022 CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMT CO_2 Eq. and Percent)

Sector	Fuel Type	2018 to 2019		2019 to 2020		2020 to 2021		2021 to 2022		Total 2022
Transportation	Petroleum	-4.5	-0.3%	-243.5	-13.9%	174.2	11.5%	-7.2	-0.4%	1,681.1
Electric Power	Coal	-179.3	-15.6%	-185.4	-19.0%	121.9	15.5%	-58.6	-6.4%	851.5
Electric Power	Natural Gas	38.7	6.7%	18.2	3.0%	-22.1	-3.5%	46.5	7.6%	659.3
Industrial	Natural Gas	8.0	1.6%	-11.8	-2.4%	11.4	2.3%	9.2	1.8%	510.4
Residential	Natural Gas	1.7	0.6%	-19.1	-6.9%	2.3	0.9%	13.3	5.2%	272.0
Commercial	Natural Gas	0.4	0.2%	-19.5	-10.1%	6.9	4.0%	11.9	6.6%	192.3
Transportation	**All Fuels[a]**	**3.5**	**0.2%**	**-243.8**	**-13.4%**	**180.7**	**11.5%**	**-2.3**	**-0.1%**	**1,751.3**
Electric Power	**All Fuels[a]**	**-146.7**	**-8.4%**	**-167.2**	**-10.4%**	**101.4**	**7.0%**	**-9.3**	**-0.6%**	**1,531.7**
Industrial	**All Fuels[a]**	**-0.7**	**-0.1%**	**-47.8**	**-5.9%**	**18.5**	**2.4%**	**20.6**	**2.6%**	**801.1**
Residential	**All Fuels[a]**	**4.0**	**1.2%**	**-28.1**	**-8.2%**	**3.2**	**1.0%**	**16.0**	**5.0%**	**334.1**
Commercial	**All Fuels[a]**	**5.5**	**2.2%**	**-22.5**	**-8.9%**	**8.3**	**3.6%**	**21.2**	**8.9%**	**258.7**
All Sectors[a,b]	**All Fuels[a]**	**-135.6**	**-2.7%**	**-510.9**	**-10.5%**	**312.6**	**7.2%**	**45.1**	**1.0%**	**4,699.4**

[a] Includes sector and fuel combinations not shown in this table.

[b] Includes U.S. Territories.

Note: Totals may not sum due to independent rounding.

As shown in Table 3-6, recent trends in CO_2 emissions from fossil fuel combustion show a 2.7 percent decrease from 2018 to 2019, a 10.5 percent decrease from 2019 to 2020, a 7.2 percent increase from 2020 to 2021, and a 1.0 percent increase from 2021 to 2022. These changes contributed to an overall 5.8 percent decrease in CO_2 emissions from fossil fuel combustion from 2018 to 2022.

The overall 2021 to 2022 trends were largely driven by the gradual recovery from the COVID-19 pandemic, which saw reduced economic activity in 2020 and caused changes in energy demand and supply patterns across different sectors. The continued recovery from the COVID-19 pandemic has generally led to increased energy use and emissions across all economic sectors except electric power and transportation from 2021 to 2022. The decrease in emissions from 2021 to 2022 from electric power was due to the reduction in coal consumption for electricity generation, in a return to a pre-pandemic trend in declining coal-fired power generation.

Recent trends in CO_2 emissions from fossil fuel combustion are largely driven by the electric power sector, which until 2017 has accounted for the largest portion of these emissions. The types of fuels consumed to produce electricity have changed in recent years. Electric power sector consumption of natural gas primarily increased due to increased production capacity as natural gas-fired plants replaced coal-fired plants and increased electricity demand related to heating and cooling needs (EIA 2018; EIA 2023a). Total net electric power generation from all fossil and non-fossil sources decreased by 1.3 percent from 2018 to 2019, decreased by 2.9 percent from 2019 to 2020, increased by 2.7 percent from 2020 to 2021, and increased by 3.0 percent from 2021 to 2022 (EIA 2024a). Carbon dioxide emissions from the electric power sector decreased from 2021 to 2022 by 0.6 percent due to increased production and use of natural gas and decreased production and use of coal for electric power generation. Carbon dioxide emissions from coal consumption for electric power generation decreased by 26.1 percent overall since 2018, including a 6.4 percent decrease from 2021 to 2022.

Petroleum use in the transportation sector is another major driver of emissions, representing the largest source of CO_2 emissions from fossil fuel combustion in 2022. Emissions from petroleum consumption for transportation have decreased by 4.6 percent since 2018 and are primarily attributed to a 1.4 percent decrease in VMT over the same

[8] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States. See Annex 2.2 for more details on fuel carbon contents.

time period. As of 2017, the transportation sector is the largest source of national CO_2 emissions–whereas in prior years, electric power was the largest source sector.

In the United States, 83.0 percent of the energy used in 2022 was produced through the combustion of fossil fuels such as petroleum, natural gas, and coal (see Figure 3-4 and Figure 3-5). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 37 percent of total U.S. energy used in 2022. Natural gas and coal followed in order of fossil fuel energy demand significance, accounting for approximately 35 percent and 10 percent of total U.S. energy used, respectively. Petroleum was consumed primarily in the transportation end-use sector and the majority of coal was used in the electric power sector. Natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-6) (EIA 2024a). The remaining portion of energy used in 2022 was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (9 percent), primarily wind energy, hydroelectric power, solar, geothermal and biomass (EIA 2024a).[9]

Figure 3-4: 2022 U.S. Energy Use by Energy Source

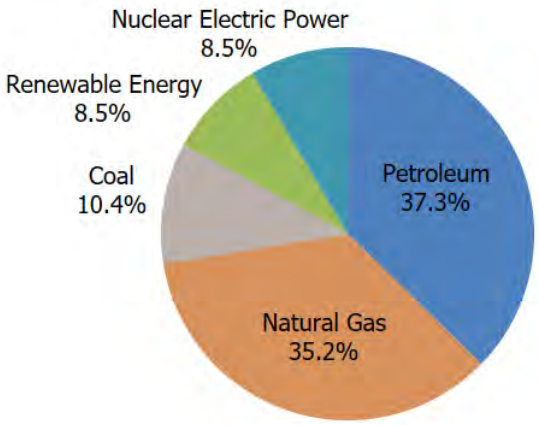

Note: Totals may not sum due to independent rounding.

Figure 3-5: Annual U.S. Energy Use

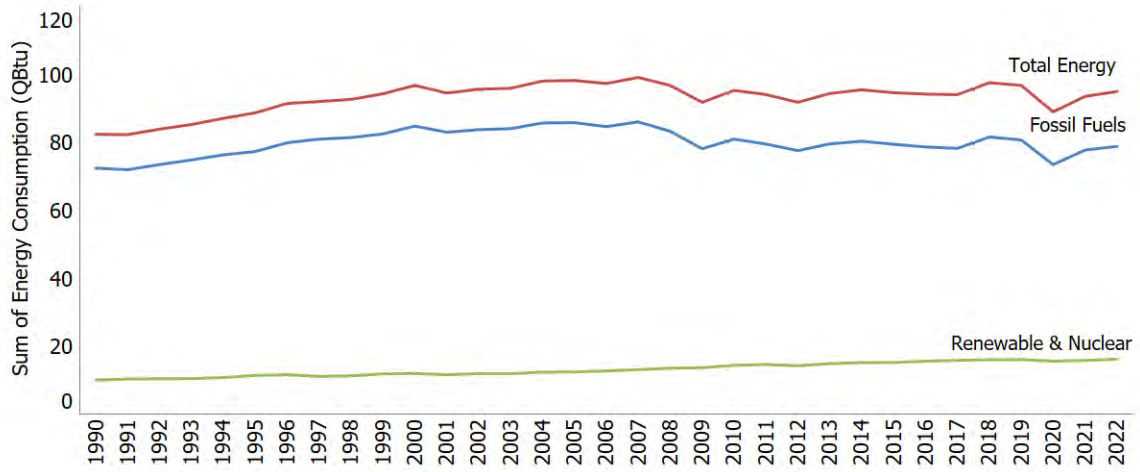

[9] Renewable energy, as defined in EIA's energy statistics, includes the following energy sources: hydroelectric power, geothermal energy, biomass, solar energy, and wind energy.

Figure 3-6: 2022 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

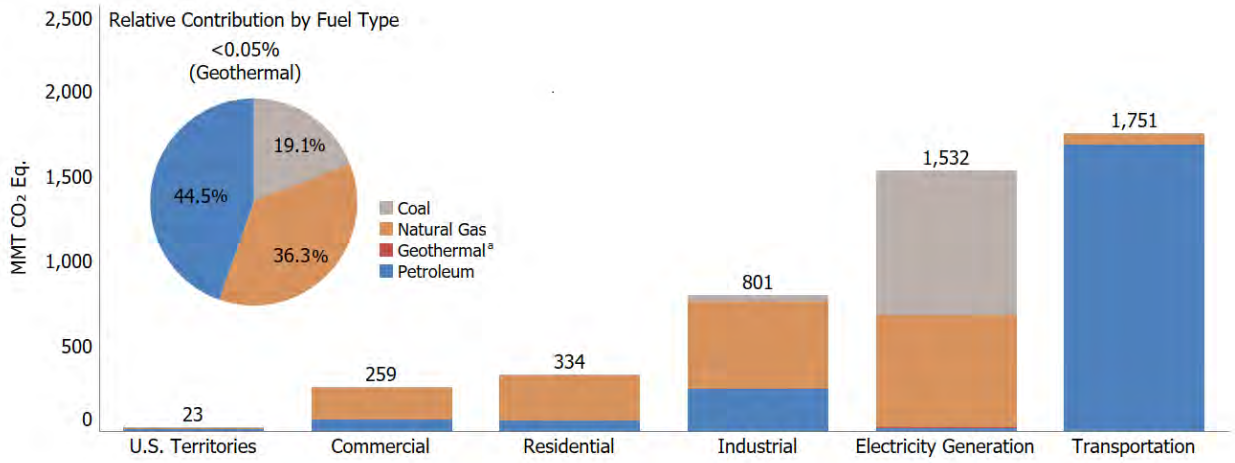

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the carbon stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[10] These other C-containing non-CO_2 gases are emitted as a byproduct of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, as per IPCC guidelines, it is assumed that all of the carbon in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

Box 3-2: Weather and Non-Fossil Energy Effects on CO_2 Emissions from Fossil Fuel Combustion Trends

The United States in 2022 experienced a colder winter overall compared to 2021, with a 7.9 percent increase in heating degree days, although 2022 heating degree days were 2.3 percent below normal (see Figure 3-7). Along with a colder winter, 2022 experienced a warmer summer, with cooling degree days 16.9 percent above normal and 4.3 percent higher compared to 2021 (see Figure 3-8) (EIA 2024a).[11] Warmer summers and colder winters can lead to increased energy use to heat and cool building spaces in the residential and commercial sectors. The combination of colder winter and warmer summer conditions in 2022 as compared to 2021 led to an overall increase in direct emissions from fossil fuel combustion in the residential and commercial sectors of 5.0 and 8.9 percent, respectively.

[10] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

[11] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65 degrees Fahrenheit, while cooling degree days are deviations of the mean daily temperature above 65 degrees Fahrenheit. Heating degree days have a considerably greater effect on energy demand and related emissions than do cooling degree days. Excludes Alaska and Hawaii. Normals are based on data from 1991 through 2020. The variation in these normals during this time period was ±16 percent and ±27 percent for heating and cooling degree days, respectively (99 percent confidence interval).

Figure 3-7: Annual Deviations from Normal Heating Degree Days for the United States (1970–2022, Index Normal = 100)

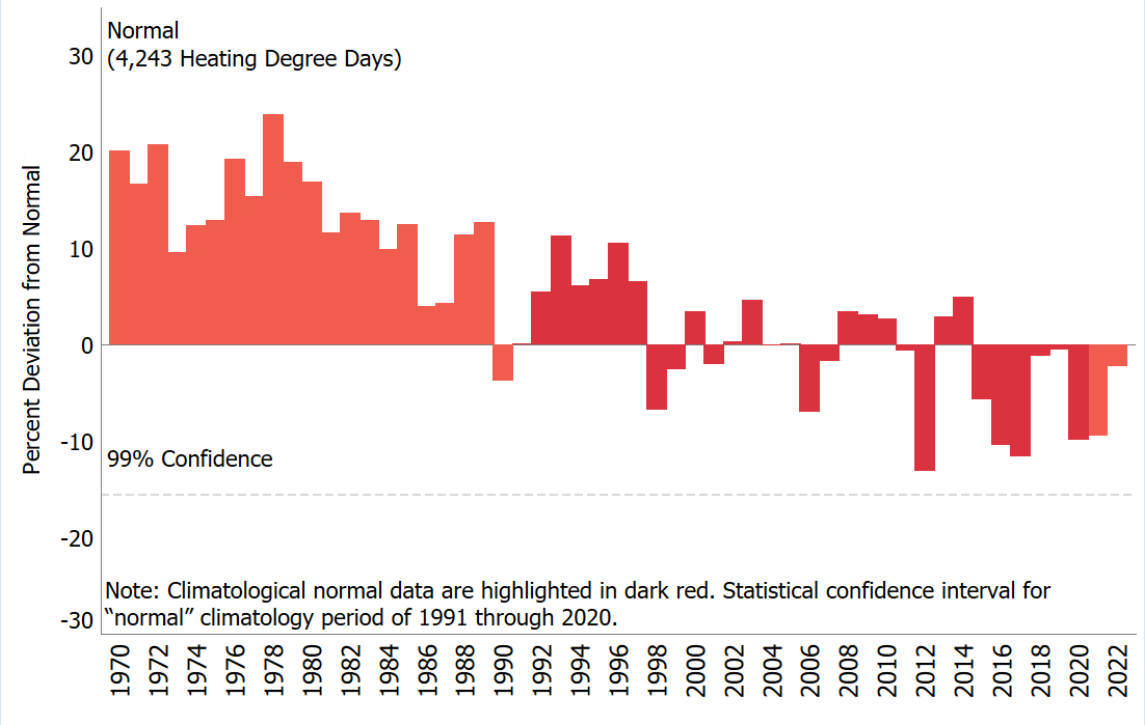

Figure 3-8: Annual Deviations from Normal Cooling Degree Days for the United States (1970–2022, Index Normal = 100)

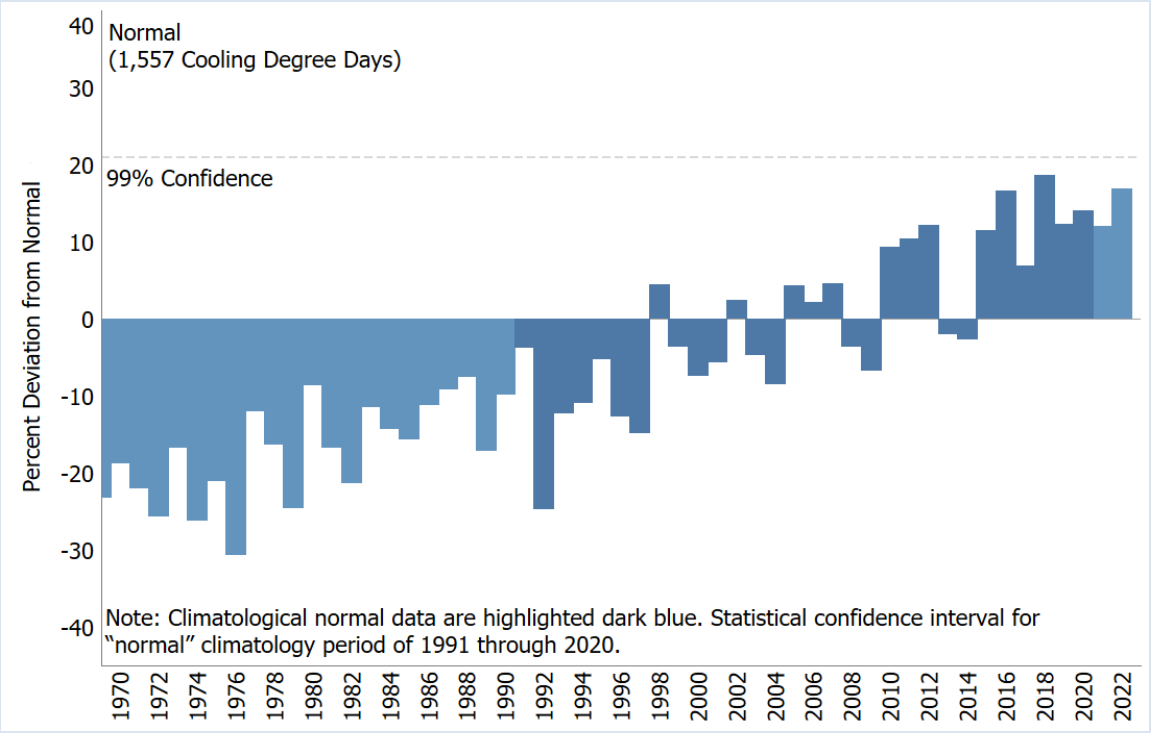

The carbon intensity of the electric power sector is impacted by the amount of non-fossil energy sources of electricity. The utilization (i.e., capacity factors)[12] of nuclear power plants in 2022 remained high at 93 percent. In 2022, nuclear power represented 19 percent of total electricity generation. Since 1990, the wind and solar power sectors have shown strong growth and have become relatively important sources of electricity. Between 1990 and 2022, renewable energy generation (in kWh) from solar and wind energy have increased from 0.1 percent in 1990 to 14 percent of total electricity generation in 2022, which helped drive the decrease in the carbon intensity of the electricity supply in the United States.

Stationary Combustion

The direct combustion of fuels by stationary sources in the electric power, industrial, commercial, and residential sectors represent the greatest share of U.S. greenhouse gas emissions. Table 3-7 presents CO_2 emissions from fossil fuel combustion by stationary sources. The CO_2 emitted is closely linked to the type of fuel being combusted in each sector (see the Methodology section of CO_2 from Fossil Fuel Combustion). In addition to CO_2 emissions, CH_4 and N_2O are emitted from fossil fuel combustion as well. Table 3-8 and Table 3-9 present CH_4 and N_2O emissions from the combustion of fuels in stationary sources. The CH_4 and N_2O emissions are linked to the type of fuel being combusted as well as the combustion technology (see the Methodology section for CH_4 and N_2O from Stationary Combustion).

Table 3-7: CO_2 Emissions from Stationary Fossil Fuel Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**1,820.0**	**2,400.1**	**1,753.4**	**1,606.7**	**1,439.6**	**1,540.9**	**1,531.7**
Coal	1,546.5	1,982.8	1,152.9	973.5	788.2	910.1	851.5
Natural Gas	175.4	318.9	577.9	616.6	634.8	612.8	659.3
Fuel Oil	97.5	98.0	22.2	16.2	16.2	17.7	20.5
Geothermal	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Industrial	**876.5**	**847.6**	**810.5**	**809.8**	**762.0**	**780.5**	**801.1**
Coal	157.8	117.8	54.4	49.4	43.0	43.0	43.0
Natural Gas	407.4	387.8	493.5	501.5	489.7	501.2	510.4
Fuel Oil	311.2	342.0	262.6	258.9	229.3	236.3	247.6
Residential	**338.6**	**358.9**	**338.9**	**342.9**	**314.8**	**318.0**	**334.1**
Coal	3.0	0.8	NO	NO	NO	NO	NO
Natural Gas	237.8	262.2	273.8	275.5	256.4	258.6	272.0
Fuel Oil	97.8	95.9	65.1	67.4	58.4	59.4	62.1
Commercial	**228.3**	**227.1**	**246.3**	**251.7**	**229.3**	**237.5**	**258.7**
Coal	12.0	9.3	1.8	1.6	1.4	1.4	1.4
Natural Gas	142.0	162.9	192.5	192.9	173.5	180.4	192.3
Fuel Oil	74.3	54.9	52.0	57.2	54.4	55.7	65.1
U.S. Territories	**20.0**	**51.9**	**25.9**	**24.8**	**23.3**	**23.8**	**22.6**
Coal	0.5	3.0	2.6	3.6	3.1	2.9	2.9
Natural Gas	NO	1.3	3.3	3.8	2.6	3.9	2.7
Fuel Oil	19.5	47.6	20.1	17.5	17.5	17.0	17.0
Total	**3,283.3**	**3,885.6**	**3,175.1**	**3,036.0**	**2,768.9**	**2,900.7**	**2,948.1**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

[12] The capacity factor equals generation divided by net summer capacity. Summer capacity is defined as "The maximum output that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30)" (EIA 2020a). Data for both the generation and net summer capacity are from EIA (2024a).

Table 3-8: CH_4 Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**0.5**	**1.0**	**1.4**	**1.4**	**1.4**	**1.4**	**1.3**
Coal	0.4	0.4	0.3	0.2	0.2	0.2	0.2
Fuel Oil	+	+	+	+	+	+	+
Natural gas	0.1	0.5	1.1	1.2	1.2	1.2	1.0
Wood	+	+	+	+	+	+	+
Industrial	**2.1**	**1.9**	**1.7**	**1.7**	**1.6**	**1.6**	**1.6**
Coal	0.5	0.3	0.2	0.1	0.1	0.1	0.1
Fuel Oil	0.2	0.2	0.2	0.2	0.1	0.1	0.2
Natural gas	0.2	0.2	0.2	0.3	0.2	0.3	0.3
Wood	1.2	1.2	1.1	1.1	1.1	1.1	1.0
Commercial	**1.2**	**1.2**	**1.4**	**1.4**	**1.3**	**1.3**	**1.4**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.2	0.2	0.2	0.2	0.3
Natural gas	0.4	0.4	0.5	0.5	0.4	0.5	0.5
Wood	0.5	0.6	0.7	0.7	0.7	0.7	0.7
Residential	**5.9**	**4.5**	**5.1**	**5.3**	**3.6**	**3.6**	**4.3**
Coal	0.3	0.1	NO	NO	NO	NO	NO
Fuel Oil	0.4	0.4	0.3	0.3	0.2	0.2	0.3
Natural Gas	0.6	0.7	0.7	0.7	0.6	0.6	0.7
Wood	4.6	3.4	4.2	4.4	2.8	2.7	3.4
U.S. Territories	**+**	**0.1**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	+	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**9.7**	**8.8**	**9.6**	**9.8**	**8.0**	**8.0**	**8.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-9: N_2O Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**18.2**	**26.7**	**21.7**	**18.8**	**17.5**	**19.0**	**21.6**
Coal	17.9	24.9	18.1	14.8	13.5	15.1	18.2
Fuel Oil	0.1	0.1	+	+	+	+	+
Natural Gas	0.3	1.7	3.6	3.9	4.0	3.9	3.4
Wood	+	+	+	+	+	+	+
Industrial	**2.8**	**2.6**	**2.2**	**2.2**	**2.0**	**2.1**	**2.0**
Coal	0.7	0.5	0.2	0.2	0.2	0.2	0.2
Fuel Oil	0.5	0.5	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.5	1.5	1.4	1.4	1.4	1.4	1.3
Commercial	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residential	**0.9**	**0.8**	**0.8**	**0.8**	**0.6**	**0.6**	**0.7**
Coal	+	+	NO	NO	NO	NO	NO
Fuel Oil	0.2	0.2	0.2	0.2	0.1	0.1	0.1

Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.6	0.4	0.5	0.5	0.3	0.3	0.4
U.S. Territories	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	+	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**22.3**	**30.5**	**25.1**	**22.2**	**20.5**	**22.0**	**24.7**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

Fossil Fuel Combustion Emissions by Sector

Table 3-10 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector, including transportation, electric power, industrial, residential, commercial, and U.S. Territories.

Table 3-10: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,514.6**	**1,899.9**	**1,833.6**	**1,838.6**	**1,591.5**	**1,772.9**	**1,770.6**
CO_2	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3
CH_4	7.2	4.3	2.8	2.9	2.5	2.6	2.6
N_2O	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Electric Power	**1,838.7**	**2,427.8**	**1,776.5**	**1,626.9**	**1,458.5**	**1,561.3**	**1,554.5**
CO_2	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7
CH_4	0.5	1.0	1.4	1.4	1.4	1.4	1.3
N_2O	18.2	26.7	21.7	18.8	17.5	19.0	21.6
Industrial	**881.3**	**852.2**	**814.4**	**813.7**	**765.6**	**784.1**	**804.7**
CO_2	876.5	847.6	810.5	809.8	762.0	780.5	801.1
CH_4	2.1	1.9	1.7	1.7	1.6	1.6	1.6
N_2O	2.8	2.6	2.2	2.2	2.0	2.1	2.0
Residential	**345.4**	**364.2**	**344.9**	**349.1**	**319.0**	**322.3**	**339.1**
CO_2	338.6	358.9	338.9	342.9	314.8	318.0	334.1
CH_4	5.9	4.5	5.1	5.3	3.6	3.6	4.3
N_2O	0.9	0.8	0.8	0.8	0.6	0.6	0.7
Commercial	**229.8**	**228.6**	**248.0**	**253.5**	**230.9**	**239.2**	**260.5**
CO_2	228.3	227.1	246.3	251.7	229.3	237.5	258.7
CH_4	1.2	1.2	1.4	1.4	1.3	1.3	1.4
N_2O	0.3	0.3	0.3	0.3	0.3	0.3	0.3
U.S. Territories[a]	**20.1**	**52.1**	**26.0**	**24.9**	**23.4**	**23.9**	**22.7**
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

[a] U.S. Territories are not apportioned by sector, and emissions shown in the table are total greenhouse gas emissions from all fuel combustion sources.
Note: Totals may not sum due to independent rounding.

Other than the greenhouse gases CO_2, CH_4, and N_2O, gases emitted from stationary combustion include the greenhouse gas precursors nitrogen oxides (NO_x), CO, NMVOCs, and sulfur dioxide (SO_2). Methane and N_2O emissions from stationary combustion sources depend upon fuel characteristics and the size and vintage of combustion device, along with combustion technology, pollution control equipment, ambient environmental conditions, and operation and maintenance practices. Nitrous oxide emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. Methane emissions from stationary combustion are primarily a function of the CH_4 content of the fuel and combustion efficiency.

Mobile combustion also produces emissions of CH_4, N_2O, and greenhouse gas precursors including NO_x, CO, and NMVOCs. As with stationary combustion, N_2O and NO_x emissions from mobile combustion are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, and the use of pollution control equipment. Nitrous oxide from mobile sources, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in vehicle idle, low speed, and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions (such as catalytic converters).

An alternative method of presenting combustion emissions is to allocate emissions associated with electric power to the sectors in which it is used. Four end-use sectors are defined: transportation, industrial, residential, and commercial. In Table 3-11 below, electric power emissions have been distributed to each end-use sector based upon the sector's share of national electricity use, with the exception of CH_4 and N_2O from transportation electricity use.[13] Emissions from U.S. Territories are also calculated separately due to a lack of end-use-specific consumption data.[14] This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity use in that sector. The results of this alternative method are presented in Table 3-11.

Table 3-11: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector with Electricity Emissions Distributed (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,517.6**	**1,904.6**	**1,838.4**	**1,843.4**	**1,595.6**	**1,778.0**	**1,776.7**
CO_2	1,472.0	1,863.3	1,817.9	1,821.4	1,576.9	1,758.6	1,757.4
CH_4	7.2	4.3	2.8	2.9	2.5	2.6	2.6
N_2O	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Industrial	**1,574.8**	**1,597.0**	**1,322.4**	**1,285.0**	**1,180.8**	**1,235.2**	**1,248.2**
CO_2	1,562.9	1,584.0	1,311.8	1,275.3	1,171.8	1,225.6	1,238.0
CH_4	2.2	2.2	2.1	2.1	2.0	2.0	1.9
N_2O	9.7	10.8	8.5	7.6	7.1	7.6	8.2
Residential	**944.2**	**1,230.1**	**995.7**	**940.2**	**871.6**	**902.1**	**912.9**
CO_2	931.3	1,214.9	981.2	926.7	860.1	890.3	899.4
CH_4	6.0	4.9	5.6	5.8	4.2	4.2	4.8
N_2O	6.9	10.3	8.8	7.7	7.3	7.7	8.7
Commercial	**773.1**	**1,040.9**	**861.0**	**813.1**	**717.6**	**764.6**	**791.6**
CO_2	766.0	1,030.1	851.3	804.4	709.6	756.1	782.0
CH_4	1.3	1.5	1.8	1.9	1.8	1.8	1.8
N_2O	5.7	9.3	7.8	6.8	6.2	6.7	7.7
U.S. Territories[a]	**20.1**	**52.1**	**26.0**	**24.9**	**23.4**	**23.9**	**22.7**
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

[a] U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.

Notes: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electric power are allocated based on aggregate national electricity use by each end-use sector.

[13] Separate calculations are performed for transportation-related CH_4 and N_2O. The methodology used to calculate these emissions is discussed in the Mobile Combustion section.

[14] U.S. Territories (including American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands) consumption data obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to territories data.

Electric Power Sector

The process of generating electricity is the largest stationary source of CO_2 emissions in the United States, representing 30.3 percent of total CO_2 emissions from all CO_2 emissions sources across the United States. Methane and N_2O accounted for a small portion of total greenhouse gas emissions from electric power, representing 0.1 percent and 1.4 percent, respectively. Electric power also accounted for 32.6 percent of CO_2 emissions from fossil fuel combustion in 2022. Methane and N_2O from electric power represented 11.4 and 52.2 percent of total CH_4 and N_2O emissions from fossil fuel combustion in 2022, respectively.

For the underlying energy data used in this chapter, the Energy Information Administration (EIA) places electric power generation into three functional categories: the electric power sector, the commercial sector, and the industrial sector. The energy use and emissions associated with the electric power sector are included here. The electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity. This includes both regulated utilities and non-utilities (e.g., independent power producers, qualifying co-generators, and other small power producers). Energy use and emissions associated with electric generation in the commercial and industrial sectors is reported in those other sectors where the producer of the power indicates that its primary business is something other than the production of electricity.[15]

Total greenhouse gas emissions from the electric power sector have decreased by 15.5 percent since 1990. From 1990 to 2007, electric power sector emissions increased by 33 percent, driven by a significant increase in electricity demand (39 percent) while the carbon intensity of electricity generated showed a modest decline (2.1 percent). From 2008 to 2022, as electricity demand increased by 5.2 percent, electric power sector emissions decreased by 35 percent, driven by a significant drop (25 percent) in the carbon intensity of electricity generated. Overall, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu, decreased by 28 percent from 1990 to 2022 with additional trends detailed in Box 3-4. This decoupling of electric power generation and the resulting CO_2 emissions is shown in Figure 3-9. This recent decarbonization of the electric power sector is a result of several key drivers.

Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54 percent of generation in 1990 to 20 percent in 2022.[16] This corresponded with an increase in natural gas generation and renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 11 percent of electric power generation in 1990 and increased over the 33-year period to represent 39 percent of electric power sector generation in 2022 (see Table 3-12). Natural gas has a much lower carbon content than coal and is generated in power plants that are generally more efficient in terms of kWh produced per Btu of fuel combusted, which has led to lower emissions as natural gas replaces coal-powered electricity generation. Natural gas and coal used in the United States in 2022 had an average carbon content of 14.43 MMT C/Qbtu and 26.13 MMT C/Qbtu respectively.

[15] Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Non-utilities typically generate electricity for sale on the wholesale electricity market (e.g., to utilities for distribution and resale to retail customers). Where electricity generation occurs outside the EIA-defined electric power sector, it is typically for the entity's own use.

[16] Values represent electricity *net* generation from the electric power sector (EIA 2024a).

Table 3-12: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990	2005	2018	2019	2020	2021	2022
Coal	54.1%	51.1%	28.4%	24.2%	19.9%	22.6%	20.3%
Natural Gas	10.7%	17.5%	34.0%	37.3%	39.5%	37.3%	38.8%
Nuclear	19.9%	20.0%	20.1%	20.4%	20.5%	19.7%	18.9%
Renewables	11.3%	8.3%	16.8%	17.6%	19.5%	19.8%	21.4%
Petroleum	4.1%	3.0%	0.6%	0.4%	0.4%	0.5%	0.5%
Other Gases[a]	+	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Net Electricity Generation (Billion kWh)[b]	2,905	3,902	4,020	3,966	3,851	3,955	4,076

+ Does not exceed 0.05 percent.

[a] Other gases include blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

[b] Represents net electricity generation from the electric power sector. Excludes net electricity generation from commercial and industrial combined-heat-and-power and electricity-only plants. Does not include electricity generation from purchased steam as the fuel used to generate the steam cannot be determined.

In 2022, CO_2 emissions from the electric power sector decreased by 0.6 percent relative to 2021. This decrease in CO_2 emissions was primarily driven by a decrease in coal consumed to produce electricity in the electric power sector. Consumption of coal for electric power decreased by 6.4 percent while consumption of natural gas increased 7.6 percent from 2021 to 2022, leading to an overall decrease in emissions. There has also been a rapid increase in renewable energy electricity generation in the electric power sector in recent years. Electricity generation from renewable sources increased by 11 percent from 2021 to 2022 (see Table 3-12). A decrease in coal-fired electricity generation and increases in natural gas and renewable energy sources for electricity generation contributed to a decoupling of emissions trends from electric power generation trends over the recent time series (see Figure 3-9).

Decreases in natural gas prices and the associated increase in natural gas generation, particularly between 2005 and 2019, was a primary driver of the fuel switching from using coal to using natural gas for electricity generation, which led to a significant decrease in CO_2 emissions from electricity generation. During this time period, the cost of natural gas (in $/MMBtu) decreased by 56 percent while the cost of coal (in $/MMBtu) increased by 74 percent (EIA 2024a). However, from 2020 to 2022, natural gas prices increased 200 percent and are now 9 percent higher than 2005 levels due to the COVID-19 pandemic and other factors disrupting the domestic and global natural gas markets. While the increase in natural gas prices led to a temporary trend reversal, with coal consumption increasing and natural gas consumption decreasing from 2020 to 2021, the broader trend of declining coal consumption for electricity generation continues. From 2021 to 2022, coal consumption decreased 6 percent while natural gas consumption increased 8 percent.

Moving forward, the shift away from coal—and increasingly towards renewable energy sources in addition to natural gas—for electricity generation will further contribute to reductions in power sector emissions. Renewable energy generation (in kWh) from wind and solar energy increased from 0.1 percent of total generation in 1990 to 5 percent in 2015 and increased at a faster pace to 14 percent of total generation in 2022. The decrease in carbon intensity occurred even as total electricity retail sales increased 45 percent, from 2,713 billion kWh in 1990 to 3,927 billion kWh in 2022.

Figure 3-9: Fuels Used in Electric Power Generation and Total Electric Power Sector CO_2 Emissions

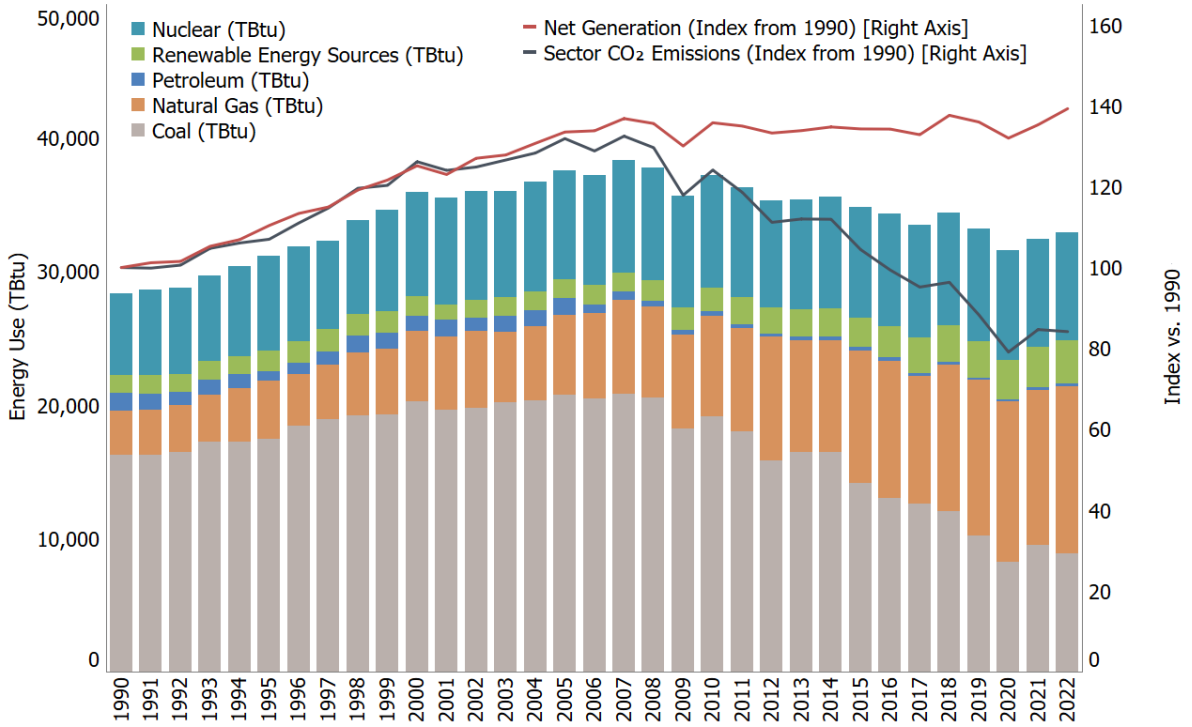

Electricity was used primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-10). Note that transportation is an end-use sector as well but is not shown in Figure 3-10 due to the sector's relatively low percentage of electricity use. The Transportation Sector and Mobile Combustion section provides a break-out of CO_2 emissions from electricity use in the transportation end-use sector.

Figure 3-10: Electric Power Retail Sales by End-Use Sector

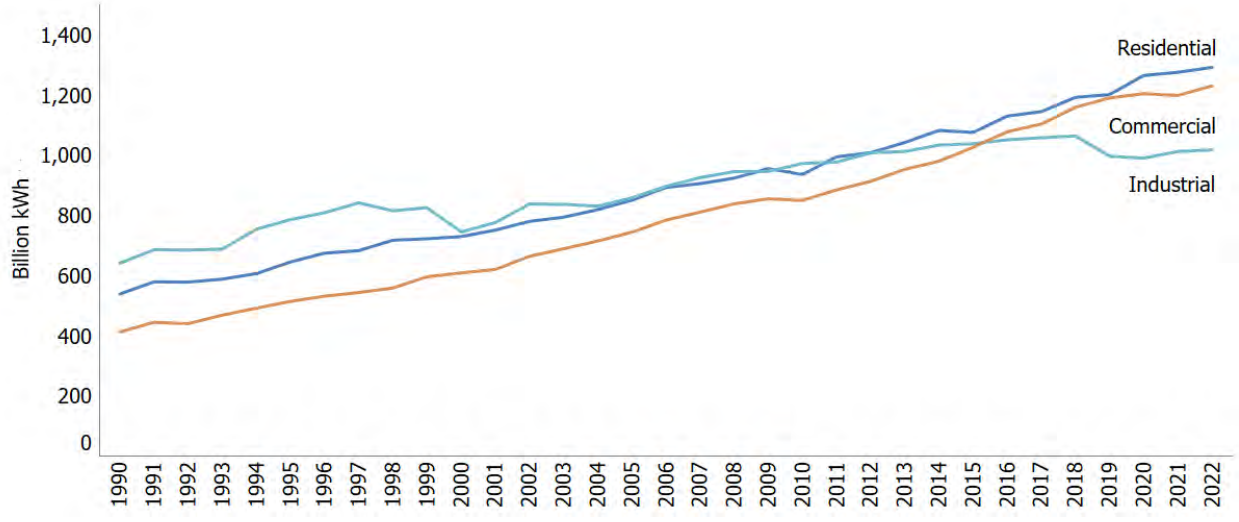

In 2022, electricity sales to the residential and commercial end-use sectors, as presented in Figure 3-10, increased by 2.6 percent and 4.7 percent relative to 2021, respectively. Electricity sales to the industrial sector in 2022

increased by approximately 2.0 percent relative to 2021. The sections below describe end-use sector energy use in more detail. Overall, in 2022, the amount of electricity retail sales (in kWh) increased by 3.2 percent relative to 2021.

Industrial Sector

Industrial sector CO_2, CH_4, and N_2O emissions accounted for 17, 14, and 5 percent of CO_2, CH_4, and N_2O emissions from fossil fuel combustion, respectively, in 2022. Carbon dioxide, CH_4, and N_2O emissions resulted from the direct consumption of fossil fuels for steam and process heat production.

The industrial end-use sector, per the underlying energy use data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy use is manufacturing, of which six industries—petroleum refineries, chemicals, paper, primary metals, food, and nonmetallic mineral products—represent the majority of the energy use (EIA 2024a; EIA 2009b).

There are many dynamics that impact emissions from the industrial sector including economic activity, changes in the make-up of the industrial sector, changes in the emissions intensity of industrial processes, and weather-related impacts on heating and cooling of industrial buildings.[17] Structural changes within the U.S. economy that lead to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

From 2021 to 2022, total industrial production and manufacturing output increased by 3.4 percent (FRB 2022). Over this period, output increased slightly across production indices for Food, Nonmetallic Mineral Products, Paper, Petroleum Refineries, and Primary Metals. Production of chemicals declined slightly between 2021 and 2022 (see Figure 3-11). From 2021 to 2022, total energy use in the industrial sector increased by 2.0 percent, driven mainly by a 2.6 percent increase in fossil fuel consumption in the industrial sector. Consumption of renewables decreased 1.6 percent from 2021 to 2022. Due to the relative increases and decreases of individual indices there was an increase in natural gas and an increase in electricity used by this sector (see Figure 3-12). In 2022, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,248.2 MMT CO_2 Eq., a 1.1 percent increase from 2021 emissions.

Through EPA's Greenhouse Gas Reporting Program (GHGRP), specific industrial sector trends can be discerned from the overall total EIA industrial fuel consumption data used for these calculations. For example, from 2021 to 2022, the underlying EIA data showed increased consumption of natural gas and petroleum and decreased consumption of coal in the industrial sector. The GHGRP data highlights that several industries contributed to these trends, including chemical manufacturing; pulp, paper and print; food processing, beverages and tobacco; minerals manufacturing; and agriculture-forest-fisheries.[18]

[17] Some commercial customers are large enough to obtain an industrial price for natural gas and/or electricity and are consequently grouped with the industrial end-use sector in U.S. energy statistics. These misclassifications of large commercial customers likely cause the industrial end-use sector to appear to be more sensitive to weather conditions.

[18] Further details on industrial sector combustion emissions are provided by EPA's GHGRP. See http://ghgdata.epa.gov/ghgp/main.do.

Figure 3-11: Industrial Production Indices (Index 2017=100)

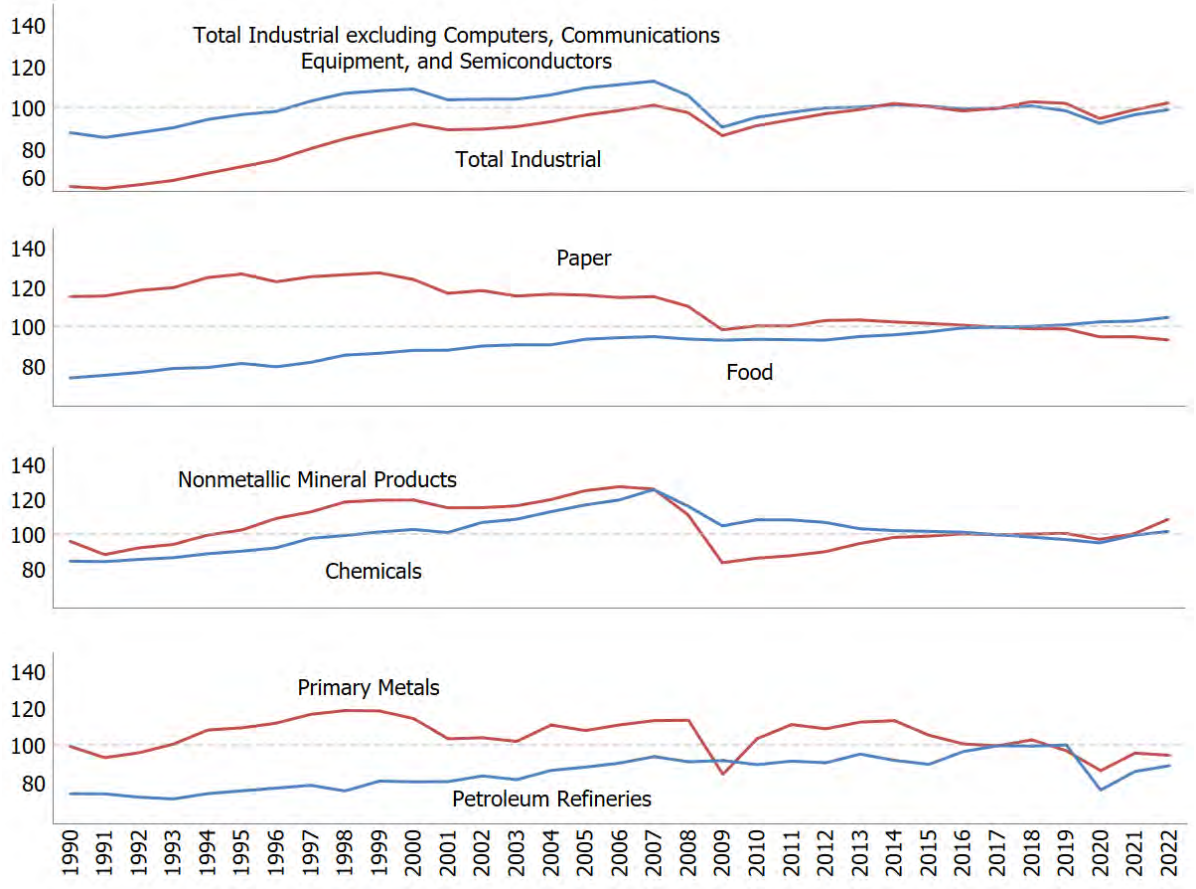

Figure 3-12: Fuels and Electricity Used in Industrial Sector, Industrial Output, and Total Sector CO_2 Emissions (Including Electricity)

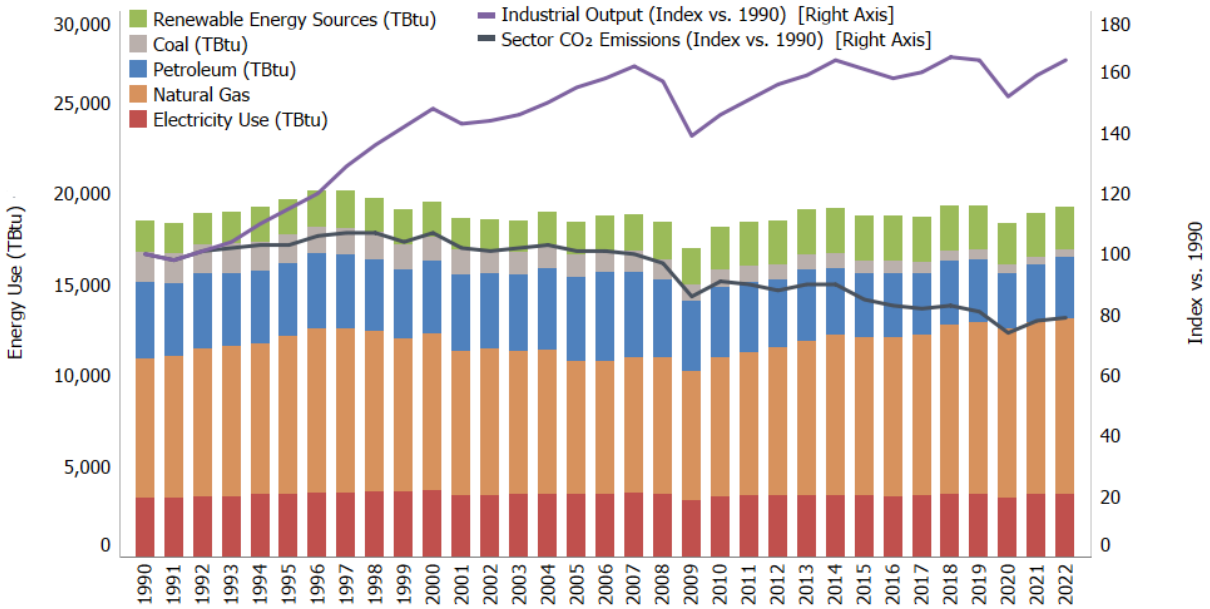

Despite the growth in industrial output (65 percent) and the overall U.S. economy (114 percent) from 1990 to 2022, direct CO_2 emissions from fossil fuel combustion in the industrial sector decreased by 8.6 percent over the same time series. A number of factors are assumed to result in decoupling of growth in industrial output from industrial greenhouse gas emissions, for example: (1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, and (2) energy-intensive industries such as steel are employing new methods, such as electric arc furnaces, that are less carbon-intensive than the older methods.

Box 3-3: Uses of Greenhouse Gas Reporting Program Data and Improvements in Reporting Emissions from Industrial Sector Fossil Fuel Combustion

As described in the calculation methodology, total fossil fuel consumption for each year is based on aggregated end-use sector consumption published by the EIA. The availability of facility-level combustion emissions through EPA's GHGRP has provided an opportunity to better characterize the industrial sector's energy consumption and emissions in the United States, through a disaggregation of EIA's industrial sector fuel consumption data from select industries.

For GHGRP 2010 through 2022 reporting years, facility-level fossil fuel combustion emissions reported through EPA's GHGRP were categorized and distributed to specific industry types by utilizing facility-reported NAICS codes (as published by the U.S. Census Bureau). As noted previously in this report, the definitions and provisions for reporting fuel types in EPA's GHGRP include some differences from the *Inventory's* use of EIA national fuel statistics to meet Paris Agreement and UNFCCC reporting guidelines. The IPCC has provided guidance on aligning facility-level reported fuels and fuel types published in national energy statistics, which guided this exercise.[19]

As with previous *Inventory* reports, the current effort represents an attempt to align, reconcile, and coordinate the facility-level reporting of fossil fuel combustion emissions under EPA's GHGRP with the national-level approach presented in this report. Consistent with recommendations for reporting the *Inventory* to the UNFCCC, progress was made on certain fuel types for specific industries and has been included in the Common Reporting Tables (CRTs) that are submitted to the UNFCCC along with this report.[20] The efforts in reconciling fuels focus on standard, common fuel types (e.g., natural gas, distillate fuel oil) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information presented in the CRTs should be viewed as an initial attempt at this exercise. Additional efforts will be made for future *Inventory* reports to improve the mapping of fuel types and examine ways to reconcile and coordinate any differences between facility-level data and national statistics. The current analysis includes the full time series presented in the CRTs. Analyses were conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data in order to disaggregate the full 1990 through 2022 time period in the CRTs. It is believed that the current analysis has led to improvements in the presentation of data in the *Inventory*, but further work will be conducted, and future improvements will be realized in subsequent *Inventory* reports. This includes incorporating the latest MECS data as it becomes available.

Residential and Commercial Sectors

Emissions from the residential and commercial sectors have generally decreased since 2005. Short-term trends are often correlated with seasonal fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Population growth and a trend towards larger houses has led to increasing energy use over

[19] See Section 4 "Use of Facility-Level Data in Good Practice National Greenhouse Gas Inventories" of the IPCC meeting report, and specifically the section on using facility-level data in conjunction with energy data, at http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[20] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

the time series, while population migration to warmer areas and improved energy efficiency and building insulation have slowed the increase in energy use in recent years. Starting in around 2014, energy use and emissions begin to decouple due to decarbonization of the electric power sector (see Figure 3-13).

Figure 3-13: Fuels and Electricity Used in Residential and Commercial Sectors, Heating and Cooling Degree Days, and Total Sector CO_2 Emissions (Including Electricity)

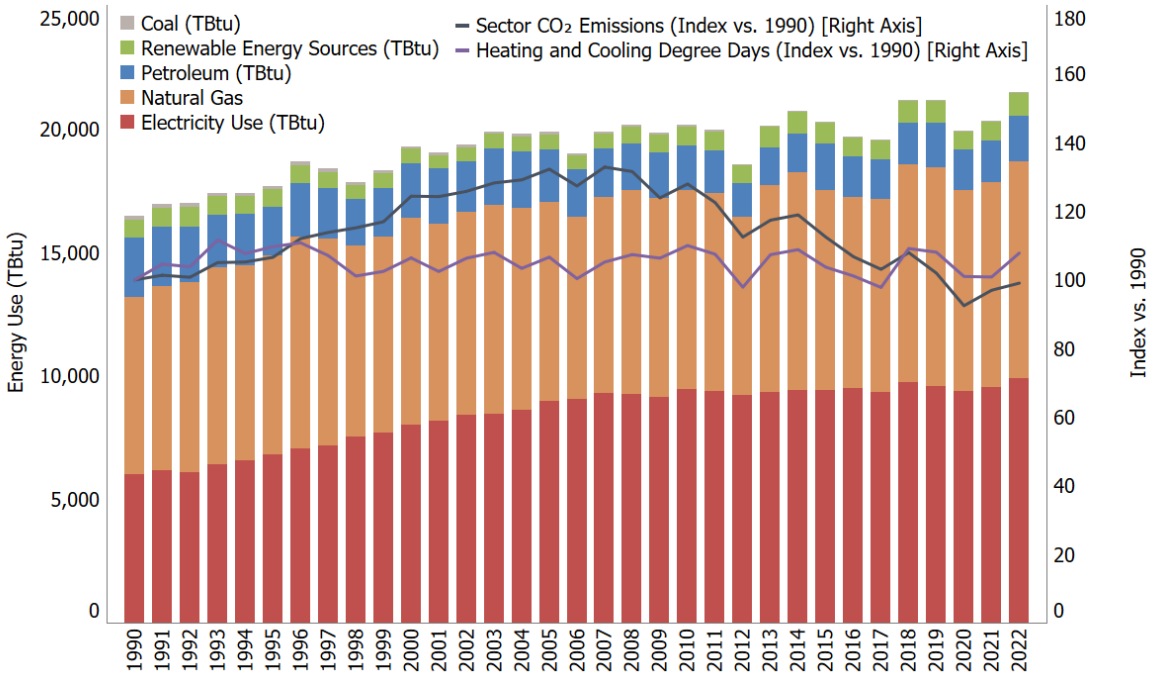

In 2022, excluding indirect emissions from electricity use, the residential and commercial sectors accounted for 7 and 6 percent of CO_2 emissions from fossil fuel combustion, respectively; 39 and 13 percent of CH_4 emissions from fossil fuel combustion, respectively; and 2 and 1 percent of N_2O emissions from fossil fuel combustion, respectively. Emissions from these sectors are primarily attributable to building -related activities such as the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Coal consumption was a minor component of energy use in the commercial sector and did not contribute to any energy use in the residential sector. Greenhouse gas emissions from commercial and residential buildings also increase substantially when emissions from electricity end-use are included, because the building sector uses 75 percent of the electricity generated in the United States (e.g., for heating, ventilation, and air conditioning; lighting; and appliances) (NREL 2023). In 2022, total emissions (CO_2, CH_4, and N_2O) from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 912.9 MMT CO_2 Eq. and 791.6 MMT CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from combined fossil fuel combustion and electricity use within the residential and commercial end-use sectors increased by 1.2 and 3.5 percent from 2021 to 2022, respectively. An increase in heating degree days (7.9 percent) and cooling degree days (4.3 percent) increased energy demand for heating and cooling in the residential and commercial sectors. This resulted in a 2.6 percent increase in residential sector electricity use. From 2021 to 2022 there was a 8.4 percent higher direct energy use in the commercial sector. In addition, a shift toward energy efficient products and more stringent energy efficiency standards for household equipment has contributed to a decrease in energy demand in households (EIA 2022), resulting in a decrease in energy-related emissions in the residential sector since 1990. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in total housing units and building attributes (e.g., larger sizes and improved insulation).

In 2022, combustion emissions from natural gas consumption represented 81 and 74 percent of the direct fossil fuel CO_2 emissions from the residential and commercial sectors, respectively. Carbon dioxide emissions from natural gas combustion in the residential and commercial sectors in 2022 increased by 5.2 percent and 6.6 percent from 2021, respectively.

U.S. Territories

Emissions from U.S. Territories are based on the fuel consumption in American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands. As described in the Methodology section of CO_2 from Fossil Fuel Combustion, this data is collected separately from the sectoral-level data available for the general calculations. As sectoral information is not available for U.S. Territories, CO_2, CH_4, and N_2O emissions are not presented for U.S. Territories in the tables above by sector, though the emissions will occur across all sectors and sources including stationary, transportation and mobile combustion sources.

Transportation Sector and Mobile Combustion

This discussion of transportation emissions follows the alternative method of presenting combustion emissions by allocating emissions associated with electricity generation to the transportation end-use sector, as presented in Table 1-9. Table 1-8 presents direct CO_2, CH_4, and N_2O emissions from all transportation sources (i.e., excluding emissions allocated to electricity consumption in the transportation end-use sector).

The transportation end-use sector and other mobile combustion accounted for 1,776.7 MMT CO_2 Eq. in 2022, which represented 37 percent of CO_2 emissions, 23 percent of CH_4 emissions, and 41 percent of N_2O emissions from fossil fuel combustion, respectively.[21] Fuel purchased in the U.S. for international aircraft and marine travel accounted for an additional 98.9 MMT CO_2 Eq. in 2022; these emissions are recorded as international bunkers and are not included in U.S. totals according to Paris Agreement and UNFCCC reporting protocols.

Transportation End-Use Sector

From 1990 to 2019, transportation emissions from fossil fuel combustion rose by 21 percent, followed by a reduction of 13 percent from 2019 to 2020, followed by an increase of 12 percent from 2020 to 2022. Overall, from 1990 to 2022, transportation emissions from fossil fuel combustion increased by 17 percent. The increase in transportation emissions from fossil fuel combustion from 1990 to 2022 was due, in large part, to increased demand for travel (see Figure 3-14). The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 47 percent from 1990 to 2022, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices over much of this period. Between 2019 and 2020, emissions from light-duty vehicles fell by 11 percent, primarily the result of the COVID-19 pandemic and associated restrictions, such as people working from home and traveling less. Light-duty vehicle VMT rebounded in 2022 but is still estimated to be 2 percent below 2019 levels.

Commercial aircraft emissions decreased by 5 percent between 2019 and 2022 but have decreased 7 percent since 2007 (FAA 2024 and DOT 1991 through 2023).[22] Decreases in jet fuel emissions (excluding bunkers) started in 2007 due in part to improved operational efficiency that results in more direct flight routing, improvements in aircraft and engine technologies to reduce fuel burn and emissions, and the accelerated retirement of older, less fuel-efficient aircraft; however, the sharp decline in commercial aircraft emissions from 2019 to 2020 and their gradual recovery since is primarily due to COVID-19 impacts on scheduled passenger air travel.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially

[21] Note that these totals include CO_2, CH_4 and N_2O emissions from some sources in the U.S. Territories (ships and boats, recreational boats, non-transportation mobile sources) and CH_4 and N_2O emissions from transportation rail electricity.

[22] Commercial aircraft consists of passenger aircraft, cargo, and other chartered flights.

diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 19 percent from 1990 to 2022. Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

Figure 3-14: Fuels Used in Transportation Sector, On-road VMT, and Total Sector CO_2 Emissions

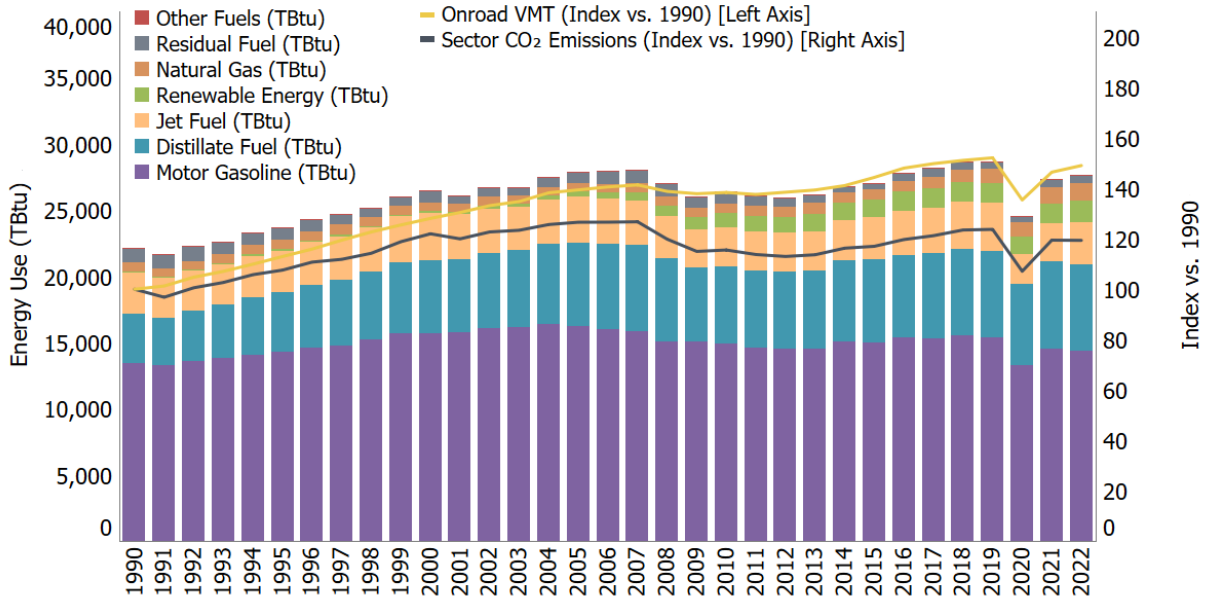

Notes: Distillate fuel, residual fuel, and jet fuel include adjustments for international bunker fuels. Distillate fuel and motor gasoline include adjustments for the sectoral allocation of these fuels. Other Fuels includes aviation gasoline and propane.

Source: Information on fuel consumption was obtained from EIA (2022).

Transportation Fossil Fuel Combustion CO_2 Emissions

Domestic transportation CO_2 emissions increased by 19 percent (285.4 MMT CO_2 Eq.) between 1990 and 2022, an annualized increase of 0.6 percent. This includes a 24 percent increase in CO_2 emissions between 1990 and 2019, followed by a 13 percent decrease in 2020. Carbon dioxide emissions then increased by 11 percent between 2020 and 2022. Among domestic transportation sources, light-duty vehicles (including passenger cars and light-duty trucks) represented 57 percent of CO_2 emissions, medium- and heavy-duty trucks and buses 24 percent, commercial aircraft 7 percent, and other sources 11 percent. See Table 3-13 for a detailed breakdown of transportation CO_2 emissions by mode and fuel type.

Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil. Carbon dioxide emissions from the combustion of ethanol and biodiesel for transportation purposes, along with the emissions associated with the agricultural and industrial processes involved in the production of biofuel, are captured in other *Inventory* sectors.[23] Ethanol consumption from the transportation sector has increased from 0.7 billion gallons in 1990 to 12.9 billion gallons in 2022, while biodiesel

[23] Biofuel estimates are presented in the Energy chapter for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). More information and additional analyses on biofuels are available at EPA's Renewable Fuels Standards website. See https://www.epa.gov/renewable-fuel-standard-program.

consumption has increased from 0.01 billion gallons in 2001 to 1.6 billion gallons in 2022." For additional information, see Section 3.10 on biofuel consumption at the end of this chapter and Table A-74 in Annex 3.2.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,005.5 MMT CO_2 in 2022, an increase of 10 percent (91.2 MMT CO_2) from 1990. The increase in CO_2 emissions from passenger cars and light-duty trucks from 1990 to 2022 was due, in large part, to increased demand for travel as fleet-wide light-duty vehicle fuel economy was relatively stable (average new vehicle fuel economy declined slowly from 1990 through 2004 and then increased more rapidly from 2005 through 2022). Carbon dioxide emissions from passenger cars and light-duty trucks peaked at 1,145.5 MMT in 2004, and since then have declined about 12 percent. The decline in new light-duty vehicle fuel economy between 1990 and 2004 (see Figure 3-15) reflects the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty vehicle VMT grew only modestly for much of the period. Light-duty vehicle VMT grew by less than one percent or declined each year between 2005 and 2013, and again between 2017 and 2019. VMT grew at faster rates of 1.6 percent from 2014 to 2015, and 1.6 percent from 2015-2016. From 2019 to 2020, light-duty vehicle VMT declined by 11.0 percent due to COVID-19 pandemic; from 2020 to 2022 light-duty vehicle VMT rebounded as a part of the ongoing recovery from the pandemic, increasing by 9.8 percent.

Average new vehicle fuel economy has improved almost every year since 2005 while the light-duty truck share of new vehicle sales decreased to about 33 percent of new vehicles in 2009 and has since varied from year to year between 36 and 63 percent. Since 2014, the light-duty truck share has steadily increased, reaching 62 percent of new vehicle sales in model year 2022. See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles (in VMT).

Medium- and heavy-duty truck CO_2 emissions increased by 73 percent from 1990 to 2022. This increase was largely due to a substantial growth in medium- and heavy-duty truck VMT, which increased by 72 percent between 1990 and 2022.

Carbon dioxide from the domestic operation of commercial aircraft increased by 18 percent (19.8 MMT CO_2) from 1990 to 2022. Across all categories of aviation, excluding international bunkers, CO_2 emissions decreased by 11 percent (20.8 MMT CO_2) between 1990 and 2022.[24] Carbon dioxide emissions from military aircraft decreased 65 percent between 1990 and 2022. Commercial aircraft CO_2 emissions increased 27 percent between 1990 and 2007, dropped 2 percent from 2007 to 2019, dropped another 33 percent from 2019 to 2020, then increased by 30 percent from 2020 to 2022. Overall, this represents a change of approximately 18 percent between 1990 and 2022. Transportation sources also produce CH_4 and N_2O; these emissions are included in Figure 3-14 and Table 3-15 and in the CH_4 and N_2O from Mobile Combustion section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

[24] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not included in national emission totals, in line with IPCC methodological guidance and UNFCCC reporting obligations.

Figure 3-15: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2022

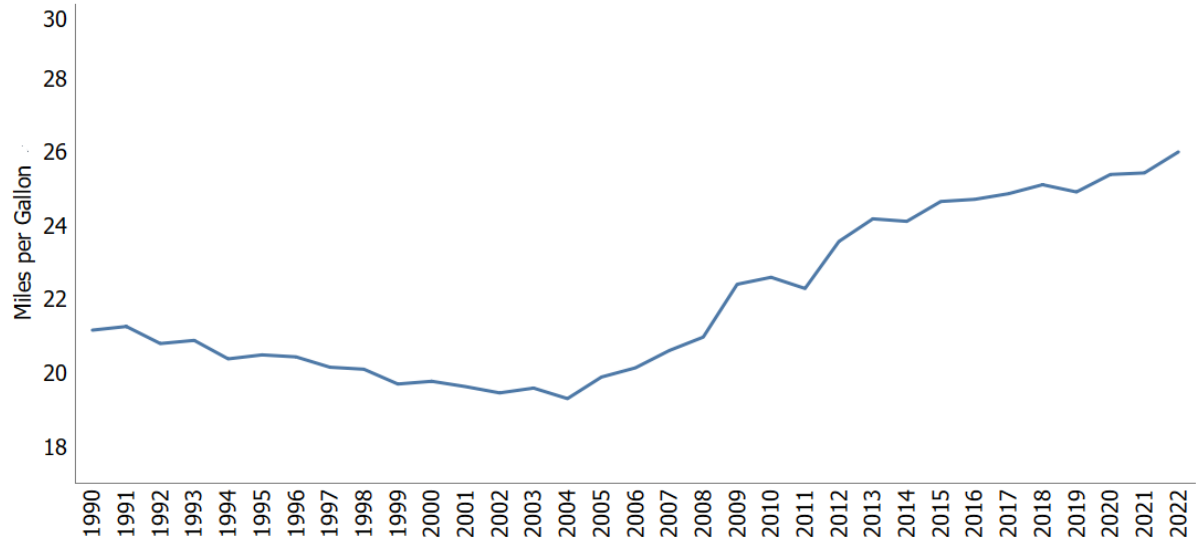

Source: EPA (2023).

Figure 3-16: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2022

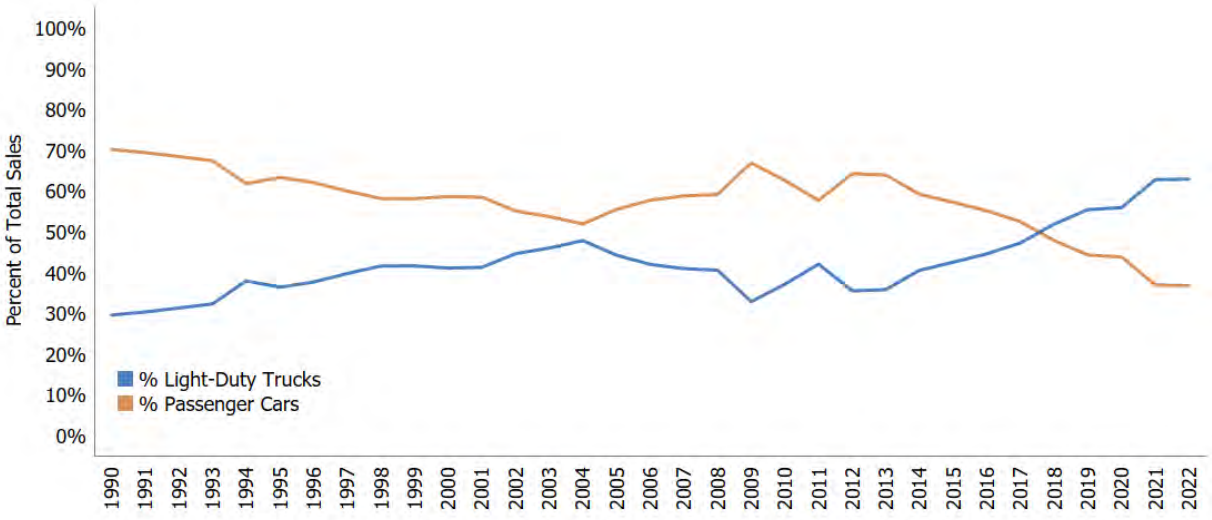

Source: EPA (2023).

Table 3-13: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO_2 Eq.)

Fuel/Vehicle Type	1990	2005	2018	2019	2020	2021	2022
Gasoline[a]	**958.9**	**1,150.1**	**1,097.0**	**1,086.5**	**936.9**	**1,028.7**	**1,014.5**
Passenger Cars	612.8	518.9	382.5	380.0	328.0	360.5	356.0
Light-Duty Trucks	283.6	583.4	667.6	658.6	565.7	619.9	609.5
Medium- and Heavy-Duty Trucks[b]	42.8	28.1	26.2	27.0	24.1	27.4	27.9
Buses	2.1	1.1	2.7	2.8	2.5	2.9	2.9
Motorcycles	3.4	4.9	7.3	7.4	6.6	7.4	7.4
Recreational Boats[c]	14.3	13.7	10.7	10.7	9.9	10.6	10.8

Distillate Fuel Oil (Diesel)[a]	**274.6**	**472.1**	**486.6**	**484.1**	**455.2**	**488.1**	**483.9**
Passenger Cars	9.4	2.2	2.8	2.7	2.5	2.7	2.7
Light-Duty Trucks	8.4	30.4	31.2	31.2	30.2	33.3	33.8
Medium- and Heavy-Duty Trucks[b]	189.0	357.2	371.5	373.0	353.5	380.1	375.6
Buses	11.1	15.5	20.4	20.7	19.8	21.4	21.4
Rail	35.5	46.1	38.5	36.0	31.2	32.5	32.5
Recreational Boats[c]	2.7	2.9	2.8	2.9	2.6	2.8	3.0
Ships and Non-Recreational Boats[d]	6.8	8.4	9.3	7.5	7.6	7.8	7.8
International Bunker Fuels[e]	*11.7*	*9.5*	*10.0*	*10.1*	*7.8*	*7.4*	*7.2*
Jet Fuel	**222.3**	**249.5**	**255.2**	**258.5**	**160.4**	**203.5**	**231.5**
Commercial Aircraft[f]	109.9	132.7	129.6	136.7	91.3	119	129.7
Military Aircraft	35.7	19.8	12.1	12.2	11.7	12.5	12.4
General Aviation Aircraft	38.5	36.8	30.6	31.4	17.6	21.1	22.7
International Bunker Fuels[e]	*38.2*	*60.2*	*83.0*	*78.3*	*39.8*	*50.8*	*66.6*
International Bunker Fuels from Commercial Aviation	*30.0*	*55.6*	*79.8*	*75.1*	*36.7*	*47.6*	*63.5*
Aviation Gasoline	**3.1**	**2.4**	**1.5**	**1.6**	**1.4**	**1.5**	**1.5**
General Aviation Aircraft	3.1	2.4	1.5	1.6	1.4	1.5	1.5
Residual Fuel Oil	**76.3**	**62.9**	**45.4**	**39.7**	**29.4**	**46.2**	**47.3**
Ships and Non-Recreational Boats[e]	22.6	19.3	14.0	14.5	7.3	24.2	22.9
International Bunker Fuels[e]	*53.7*	*43.6*	*31.4*	*25.2*	*22.1*	*21.9*	*24.4*
Natural Gas[i]	**36.0**	**33.1**	**50.9**	**58.9**	**58.7**	**65.2**	**70.2**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Buses	+	0.2	0.5	0.5	0.6	0.6	0.7
Pipeline[g]	36.0	32.8	50.3	58.3	58.0	64.4	69.3
LPG[i]	**1.4**	**1.8**	**0.8**	**0.8**	**0.5**	**0.6**	**0.6**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	0.1	0.1	+	+	+	+	+
Medium- and Heavy-Duty Trucks[b]	1.3	0.9	0.1	0.1	0.1	+	+
Buses	+	0.7	0.7	0.7	0.5	0.6	0.6
Electricity[k]	**3.0**	**4.7**	**4.8**	**4.8**	**4.1**	**5.0**	**6.1**
Passenger Cars	+	+	1.2	1.4	1.3	1.8	2.4
Light-Duty Trucks	+	+	0.2	0.2	0.3	0.7	1.1
Buses	+	+	+	+	0.1	0.1	0.1
Rail	3.0	4.7	3.4	3.1	2.4	2.5	2.5
Total [e,j]	**1,472.0**	**1,863.3**	**1,817.9**	**1,821.4**	**1,576.9**	**1758.6**	**1,757.4**
International Bunker Fuels	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
Biofuels-Ethanol[h]	*4.1*	*21.6*	*78.6*	*78.7*	*68.1*	*75.4*	*75.0*
Biofuels-Biodiesel[h]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] On-road fuel consumption data from FHWA Table MF-21 and MF-27 were used to determine total on-road use of motor gasoline and diesel fuel (FHWA 1996 through 2023). Ratios developed from MOVES3 output are used to apportion FHWA fuel consumption data to vehicle type and fuel type (see Annex 3.2 for information about the MOVES model).

[b] Includes medium- and heavy-duty trucks over 8,500 lbs.

[c] In 2014, EPA incorporated the NONROAD2008 model into the MOVES model framework. The current *Inventory* uses the Nonroad component of MOVES3 for years 1999 through 2022. See Annex 3.2 for information about the MOVES model.

[d] Note that large year over year fluctuations in emission estimates partially reflect nature of data collection for these sources.

[e] Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates of international bunker fuel-related emissions are presented for informational purposes.

[f] Commercial aircraft, as modeled in FAA's Aviation Environmental Design Tool (AEDT), consists of passenger aircraft, cargo, and other chartered flights.

[g] Pipelines reflect CO_2 emissions from natural gas-powered pipelines transporting natural gas.

[h] Ethanol and biodiesel estimates are presented for informational purposes only. See Section 3.10 of this chapter and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and Paris Agreement and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

[i] Transportation sector natural gas and LPG consumption are based on data from EIA (2023b). Prior to the 1990 to 2015 *Inventory*, data from DOE TEDB were used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 to 2016 *Inventory* and apply to the 1990 to 2022 time period.

[j] Includes emissions from rail electricity.

[k] Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales and engine efficiency data, as outlined in Browning (2018). In prior *Inventory* years, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes apply to the 2010 through 2022 time period.

Notes: This table does not include emissions from non-transportation mobile sources, such as agricultural equipment and construction/mining equipment; it also does not include emissions associated with electricity consumption by pipelines or lubricants used in transportation. In addition, this table does not include CO_2 emissions from U.S. Territories, since these are covered in a separate chapter of the *Inventory*. Totals may not sum due to independent rounding.

Mobile Fossil Fuel Combustion CH_4 and N_2O Emissions

Mobile combustion includes emissions of CH_4 and N_2O from all transportation sources identified in the U.S. *Inventory* with the exception of pipelines and electric locomotives;[25] mobile sources also include non-transportation sources such as construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources (e.g., snowmobiles, lawnmowers, etc.).[26] Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-14 and Table 3-15 provide mobile fossil fuel CH_4 and N_2O emission estimates in MMT CO_2 Eq.[27]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.4 percent) and was the fifth largest source of national N_2O emissions (4.3 percent) in 2022. From 1990 to 2022, mobile source CH_4 emissions declined by 64 percent, to 2.6 MMT CO_2 Eq. (93 kt), due largely to emissions control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH_4 emissions. Mobile source emissions of N_2O decreased by 57 percent, to 16.7 MMT CO_2 Eq. (63 kt) in 2022. Earlier generation control technologies initially resulted in elevated N_2O emissions, causing a 31 percent increase in N_2O emissions from mobile sources between 1990 and 1997. Improvements in later-generation emission control technologies have reduced N_2O output, resulting in a 67 percent decrease in mobile source N_2O emissions from 1997 to 2022 (see Figure 3-17). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars, light-duty trucks, and non-highway sources. See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles.

[25] Emissions of CH_4 from natural gas systems are reported separately. More information on the methodology used to calculate these emissions are included in this chapter and Annex 3.4.

[26] See the methodology sub-sections of the CO_2 from Fossil Fuel Combustion and CH_4 and N_2O from Mobile Combustion sections of this chapter. Note that N_2O and CH_4 emissions are reported using different categories than CO_2. CO_2 emissions are reported by end-use sector (transportation, industrial, commercial, residential, U.S. Territories), and generally adhere to a top-down approach to estimating emissions. CO_2 emissions from non-transportation mobile sources (e.g., lawn and garden equipment, farm equipment, construction equipment) are allocated to their respective end-use sector (i.e., construction equipment CO_2 emissions are included in the Industrial end-use sector instead of the transportation end-use sector). CH_4 and N_2O emissions are reported using the "mobile combustion" category, which includes non-transportation mobile sources. CH_4 and N_2O emission estimates are bottom-up estimates, based on total activity (fuel use, VMT) and emissions factors by source and technology type. These reporting schemes are in accordance with IPCC guidance. For informational purposes only, CO_2 emissions from non-transportation mobile sources are presented separately from their overall end-use sector in Annex 3.2.

[27] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2022.

Figure 3-17: Mobile Source CH_4 and N_2O Emissions

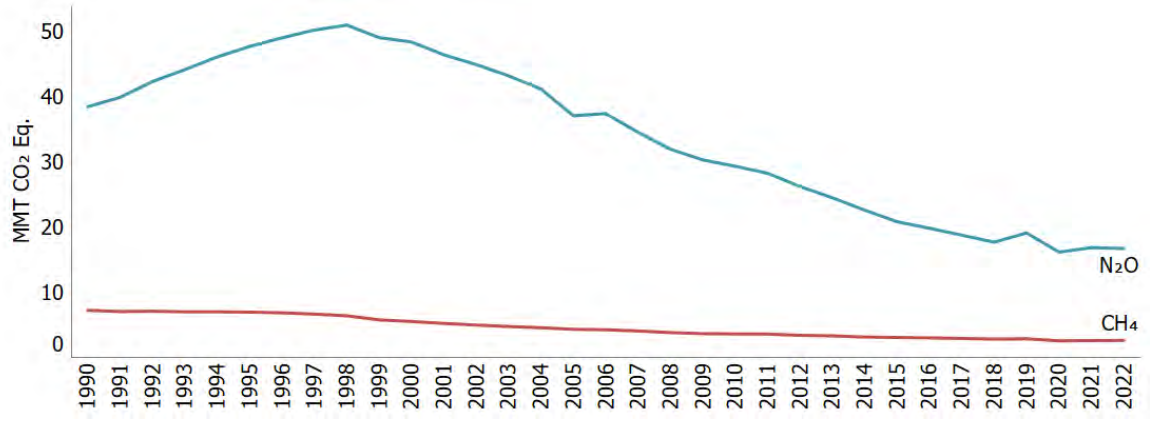

Table 3-14: CH_4 Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2018	2019	2020	2021	2022
Gasoline On-Road[b]	**5.8**	**2.4**	**0.9**	**1.0**	**0.8**	**0.8**	**0.7**
Passenger Cars	3.8	1.2	0.3	0.3	0.2	0.2	0.2
Light-Duty Trucks	1.5	1.0	0.5	0.6	0.5	0.5	0.5
Medium- and Heavy-Duty Trucks and Buses	0.5	0.1	+	+	+	+	+
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Buses	+	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**+**	**0.1**	**+**	**+**	**+**	**+**
Non-Road[c]	**1.4**	**1.8**	**1.7**	**1.7**	**1.6**	**1.6**	**1.7**
Ships and Boats	0.4	0.5	0.5	0.4	0.4	0.5	0.5
Rail[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment[e]	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment[f]	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Other[g]	0.5	0.7	0.8	0.8	0.8	0.7	0.8
Total	**7.2**	**4.3**	**2.8**	**2.9**	**2.5**	**2.6**	**2.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1. VMT estimates from FHWA are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model).

[c] Nonroad fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use (EIA 2023b).

[d] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 to 2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[e] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[f] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[g] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table 3-15: N_2O Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2018	2019	2020	2021	2022
Gasoline On-Road[b]	**32.0**	**28.5**	**7.0**	**8.1**	**6.3**	**6.0**	**5.3**
Passenger Cars	22.4	13.3	2.5	2.5	2.0	1.9	1.6
Light-Duty Trucks	8.7	14.0	4.3	5.4	4.2	3.9	3.5
Medium- and Heavy-Duty Trucks and Buses	0.8	1.2	0.2	0.2	0.1	0.1	0.1
Motorcycles	+	+	0.1	0.1	0.1	0.1	0.1
Diesel On-Road[b]	**0.2**	**0.4**	**3.0**	**3.2**	**3.0**	**3.3**	**3.5**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	0.3	0.2	0.2	0.3	0.3
Medium- and Heavy-Duty Trucks	0.2	0.3	2.4	2.7	2.5	2.7	2.9
Medium- and Heavy-Duty Buses	+	+	0.3	0.3	0.2	0.3	0.3
Alternative Fuel On-Road	**+**	**+**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Road[c]	**6.2**	**8.1**	**7.5**	**7.6**	**6.7**	**7.4**	**7.8**
Ships and Boats	0.2	0.2	0.2	0.2	0.1	0.3	0.3
Rail[d]	0.2	0.3	0.3	0.2	0.2	0.2	0.2
Aircraft	1.5	1.6	1.4	1.5	1.0	1.3	1.4
Agricultural Equipment[e]	1.2	1.4	1.1	1.1	1.1	1.1	1.1
Construction/Mining Equipment[f]	1.2	1.9	1.6	1.7	1.6	1.7	1.7
Other[g]	1.8	2.8	2.9	2.9	2.7	2.9	3.2
Total	**38.4**	**37.0**	**17.7**	**19.1**	**16.1**	**16.8**	**16.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1. VMT estimates from FHWA are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model).

[c] Nonroad fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use (EIA 2023a).

[d] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 through 2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[e] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[f] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[g] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Note: Totals may not sum due to independent rounding.

CO_2 from Fossil Fuel Combustion

Methodology and Time-Series Consistency

CO_2 emissions from fossil fuel combustion are estimated in line with a Tier 2 method described by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) Chapter 2, Figure 2.1 decision tree and

available data on energy use and country specific fuel carbon contents with some exceptions as discussed below.[28] A detailed description of the U.S. methodology is presented in Annex 2.1, and is characterized by the following steps:

1. *Determine total fuel consumption by fuel type and sector*. Total fossil fuel consumption for each year is estimated by aggregating consumption data by end-use sector (e.g., commercial, industrial), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil). Fuel consumption data for the United States were obtained directly from the EIA of the U.S. Department of Energy (DOE), primarily from the *Monthly Energy Review* (EIA 2024a). EIA data include fuel consumption statistics from the 50 U.S. states and the District of Columbia, including tribal lands. The EIA does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from EIA's International Energy Statistics (EIA 2024b).[29]

   For consistency of reporting, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA on an annual basis and used in this *Inventory* are predominantly from mid-stream or conversion energy consumers such as refiners and electric power generators. These annual surveys are supplemented with end-use energy consumption surveys, such as the Manufacturing Energy Consumption Survey, that are conducted on a periodic basis (every four years). These consumption datasets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.[30]

   Also, note that U.S. fossil fuel energy statistics are generally presented using gross calorific values (GCV) (i.e., higher heating values). Fuel consumption activity data presented here have not been adjusted to correspond to international standards, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[31]

2. *Subtract uses accounted for in the Industrial Processes and Product Use chapter*. Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—were reallocated to the Industrial Processes and Product Use chapter, as they were consumed during non-energy-related industrial activity. To make these adjustments, additional data were collected from AISI (2004 through 2021), Coffeyville (2012), U.S. Census Bureau (2001 through 2011), EIA (2024a, 2023c, 2023d), USAA (2008 through 2021), USGS (1991 through 2020), (USGS 2019), USGS (2014 through 2021a), USGS (2014 through 2021b), USGS (1995 through 2013), USGS (1995, 1998, 2000, 2001, 2002, 2007), USGS (2021a), USGS (1991 through 2015a), USGS (1991 through 2020), USGS (2014 through 2021a), USGS (1991 through 2015b), USGS (2021b), USGS (1991 through 2020).[32]

3. *Adjust for biofuels and petroleum denaturant*. Fossil fuel consumption estimates are adjusted downward to exclude fuels with biogenic origins and avoid double counting in petroleum data statistics. Carbon

[28] The IPCC Tier 3B methodology is used for estimating emissions from commercial aircraft.

[29] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed total emissions of 22.6 MMT CO_2 Eq. in 2022.

[30] See IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion in Annex 4 for a comparison of U.S. estimates using top-down and bottom-up approaches.

[31] A crude convention to convert between gross and net calorific values is to multiply the heat content of solid and liquid fossil fuels by 0.95 and gaseous fuels by 0.9 to account for the water content of the fuels. Biomass-based fuels in U.S. energy statistics, however, are generally presented using net calorific values.

[32] See sections on Iron and Steel Production and Metallurgical Coke Production, Ammonia Production and Urea Consumption, Petrochemical Production, Titanium Dioxide Production, Ferroalloy Production, Aluminum Production, and Silicon Carbide Production and Consumption in the Industrial Processes and Product Use chapter.

dioxide emissions from ethanol added to motor gasoline and biodiesel added to diesel fuel are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF, therefore, fuel consumption estimates are adjusted to remove ethanol and biodiesel.[33] For the years 1993 through 2008, petroleum denaturant is currently included in EIA statistics for both natural gasoline and finished motor gasoline. To avoid double counting, petroleum denaturant is subtracted from finished motor gasoline for these years.[34]

4. *Adjust for exports of CO_2.* Since October 2000, the Dakota Gasification Plant has been exporting CO_2 produced in the coal gasification process to Canada by pipeline. Because this CO_2 is not emitted to the atmosphere in the United States, the associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 is subtracted from EIA (2023d) coal consumption statistics that are used to calculate greenhouse gas emissions from the Energy Sector. The associated fossil fuel is the total fossil fuel burned at the plant with the CO_2 capture system multiplied by the fraction of the plant's total site-generated CO_2 that is recovered by the capture system. To make these adjustments, data for CO_2 exports were collected from Environment and Climate Change Canada (2022). A discussion of the methodology used to estimate the amount of CO_2 captured and exported by pipeline is presented in Annex 2.1.

5. *Adjust sectoral allocation of distillate fuel oil and motor gasoline.* EPA conducted a separate bottom-up analysis of transportation fuel consumption based on data from the Federal Highway Administration that indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel and motor gasoline consumption were adjusted to match the value obtained from the bottom-up analysis. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate and motor gasoline consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2008 through 2022), Benson (2002 through 2004), DOE (1993 through 2020), EIA (2007), EIA (2024a), EPA (2022), and FHWA (1996 through 2023).[35]

6. *Adjust for fuels consumed for non-energy uses*. U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. These are fossil fuels that are manufactured into plastics, asphalt, lubricants, or other products. Depending on the end-use, this can result in storage of some or all of the carbon contained in the fuel for a period of time. As the emission pathways of carbon used for non-energy purposes are vastly different than fuel combustion (since the carbon in these fuels ends up in products instead of being combusted), these emissions are estimated separately in Section3.2. Therefore, the amount of fuels used for non-energy purposes was subtracted from total fuel consumption. Data on non-fuel consumption were provided by EIA (2023c).

7. *Subtract consumption of international bunker fuels.* According to the Paris Agreement and UNFCCC reporting guidelines emissions from international transport activities, or bunker fuels, should not be included in national totals. U.S. energy consumption statistics include these bunker fuels (e.g., distillate fuel oil, residual fuel oil, and jet fuel) as part of consumption by the transportation end-use sector, however, so emissions from international transport activities were calculated separately following the same procedures used to calculate emissions from consumption of all fossil fuels (i.e., estimation of consumption, and determination of carbon content).[36] The Office of the Under Secretary of Defense (Installations and Environment) and the Defense Logistics Agency Energy (DLA Energy) of the U.S. Department of Defense (DoD) (DLA Energy 2022) supplied data on military jet fuel and marine fuel use.

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[33] Natural gas energy statistics from EIA (2023a) are already adjusted downward to account for biogas in natural gas.

[34] These adjustments are explained in greater detail in Annex 2.1.

[35] Bottom-up gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2021).

[36] See International Bunker Fuels section in this chapter for a more detailed discussion.

Commercial jet fuel use was estimated based on data from FAA (2024) and DOT (1991 through 2022); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2022) for 1990 through 2001 and 2007 through 2020, and DHS (2008) for 2003 through 2006.[37] Consumption of these fuels was subtracted from the corresponding fuels totals in the transportation end-use sector. Estimates of international bunker fuel emissions for the United States are discussed in detail in Section 3.9.

8. *Determine the total carbon content of fuels consumed.* Total carbon was estimated by multiplying the amount of fuel consumed by the amount of carbon in each fuel. This total carbon estimate defines the maximum amount of carbon that could potentially be released to the atmosphere if all of the carbon in each fuel was converted to CO_2. A discussion of the methodology and sources used to develop the carbon content coefficients are presented in Annexes 2.1 and 2.2.

9. *Estimate CO_2 Emissions.* Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 7), the carbon content of the fuels consumed, and the fraction of carbon that is oxidized. The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Annex 2.1). Carbon emissions were multiplied by the molecular-to-atomic weight ratio of CO_2 to carbon (44/12) to obtain total CO_2 emitted from fossil fuel combustion in million metric tons (MMT).

10. *Allocate transportation emissions by vehicle type.* This report provides a more detailed accounting of emissions from transportation because it is such a large consumer of fossil fuels in the United States. For fuel types other than jet fuel, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Heat contents and densities were obtained from EIA (2023c) and USAF (1998).[38]

    - For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2023); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from EPA's MOVES model and DOE (1993 through 2022).[39,40]

    - For non-road vehicles, activity data were obtained from AAR (2008 through 2022), APTA (2007 through 2022), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), BTS (2019 through 2022), DLA Energy (2022), DOC (1991 through 2022), DOE (1993 through 2022), DOT (1991 through 2022), EIA (2009a), EIA (2023a), EIA (2002), EIA (1991 through 2022), EPA (2022),[41] and Gaffney (2007).

[37] Data for 2002 were interpolated due to inconsistencies in reported fuel consumption data.

[38] For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.8, respectively.

[39] On-road fuel consumption data from FHWA Table MF-21 and MF-27 were used to determine total on-road use of motor gasoline and diesel fuel (FHWA 1996 through 2020). Data for 2021 is proxied using FHWA Traffic Volume Travel Trends. Ratios developed from MOVES3 output are used to apportion FHWA fuel consumption data to vehicle type and fuel type (see Annex 3.2 for information about the MOVES model).

[40] Transportation sector natural gas and LPG consumption are based on data from EIA (2024a). In previous Inventory years, data from DOE (1993 through 2022) TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium- and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 through 2015 Inventory and apply to the time period from 1990 to 2015.

[41] In 2014, EPA incorporated the NONROAD2008 model into the MOVES model framework (EPA 2022b). The current *Inventory* uses the Nonroad component of MOVES3 for years 1999 through 2022.

- For jet fuel used by aircraft, CO_2 emissions from commercial aircraft were developed by the U.S. Federal Aviation Administration (FAA) using a Tier 3B methodology, consistent IPCC (2006) (see Annex 3.3). Carbon dioxide emissions from other aircraft were calculated directly based on reported consumption of fuel as reported by EIA. Allocation to domestic military uses was made using DoD data (see Annex 3.8). General aviation jet fuel consumption is calculated as the remainder of total jet fuel use (as determined by EIA) nets all other jet fuel use as determined by FAA and DoD. For more information, see Annex 3.2.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. Due to data availability and sources, some adjustments outlined in the methodology above are not applied consistently across the full 1990 to 2022 time series. As described in greater detail in Annex 2.1, to align with EIA's methodology for calculating motor gasoline consumption, petroleum denaturant adjustments are applied to motor gasoline consumption only for the period 1993 through 2008. In addition to ensuring time-series consistency, to ensure consistency in reporting between the *Inventory* and the Canadian National Greenhouse Gas Inventory, the amount of associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 from the Dakota Gasification Plant is adjusted to align with the Canadian National Greenhouse Gas Inventory (Environment and Climate Change Canada 2022). This adjustment is explained in greater detail in Annex 2.1. As discussed in Annex 5, data are unavailable to include estimates of CO_2 emissions from any liquid fuel used in pipeline transport or non-hazardous industrial waste incineration, but those emissions are assumed to be insignificant.

Box 3-4: Carbon Intensity of U.S. Energy Consumption

The amount of carbon emitted from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that carbon that is oxidized. Fossil fuels vary in their average carbon content, ranging from about 53 MMT CO_2 Eq./QBtu for natural gas to upwards of 95 MMT CO_2 Eq./QBtu for coal and petroleum coke (see Tables A-42 and A-43 in Annex 2.1 for carbon contents of all fuels). In general, the carbon content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 3-16 provides a time series of the carbon intensity of direct emissions for each sector of the U.S. economy. The time series incorporates only the energy from the direct combustion of fossil fuels in each sector. For example, the carbon intensity for the residential sector does not include the energy from or emissions related to the use of electricity for lighting, as it is instead allocated to the electric power sector. For the purposes of maintaining the focus of this section, renewable energy and nuclear energy are not included in the energy totals used in Table 3-16 in order to focus attention on fossil fuel combustion as detailed in this chapter. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest carbon intensity, which is related to the large percentage of its energy derived from natural gas for heating. The carbon intensity of the commercial sector has predominantly declined since 1990 as commercial businesses shift away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher carbon intensities over this period. The carbon intensity of the transportation sector was closely related to the carbon content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 MMT CO_2 Eq./QBtu), which were the primary sources of energy. Lastly, the electric power sector had the highest carbon intensity due to its heavy reliance on coal for generating electricity.

Table 3-16: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMT CO_2 Eq./QBtu)

Sector	1990	2005	2018	2019	2020	2021	2022
Residential[a]	57.4	56.8	55.3	55.3	55.1	55.2	55.2
Commercial[a]	59.7	57.8	56.0	56.2	56.3	56.2	56.5
Industrial[a]	64.8	64.6	60.5	60.2	59.6	59.6	59.6
Transportation[a]	71.1	71.5	71.0	70.9	70.8	70.9	70.8
Electric Power[b]	87.3	85.8	75.5	72.9	70.5	72.4	70.9

U.S. Territories[c]	73.1	73.4	70.4	70.8	71.7	70.1	71.3
All Sectors[c]	**73.1**	**73.6**	**68.3**	**67.3**	**66.3**	**67.0**	**66.5**

[a] Does not include electricity or renewable energy consumption.
[b] Does not include electricity produced using nuclear or renewable energy.
[c] Does not include nuclear or renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption. Totals may not sum due to independent rounding.

For the time period of 1990 through about 2008, the carbon intensity of U.S. energy consumption was fairly constant, as the proportion of fossil fuels used by the individual sectors did not change significantly over that time. Starting in 2008 the carbon intensity of U.S. energy consumption has decreased, reflecting the shift from coal to natural gas in the electric power sector during that time period. Per capita energy consumption fluctuated little from 1990 to 2007, but then started decreasing after 2007 and, in 2022, was approximately 13.2 percent below levels in 1990 (see Figure 3-18). To differentiate these estimates from those of Table 3-16, the carbon intensity trend shown in Figure 3-18 and described below includes nuclear and renewable energy EIA data to provide a comprehensive economy-wide picture of energy consumption. Due to a general shift from a manufacturing-based economy to a service-based economy, as well as overall increases in efficiency, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2024).

Figure 3-18: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP

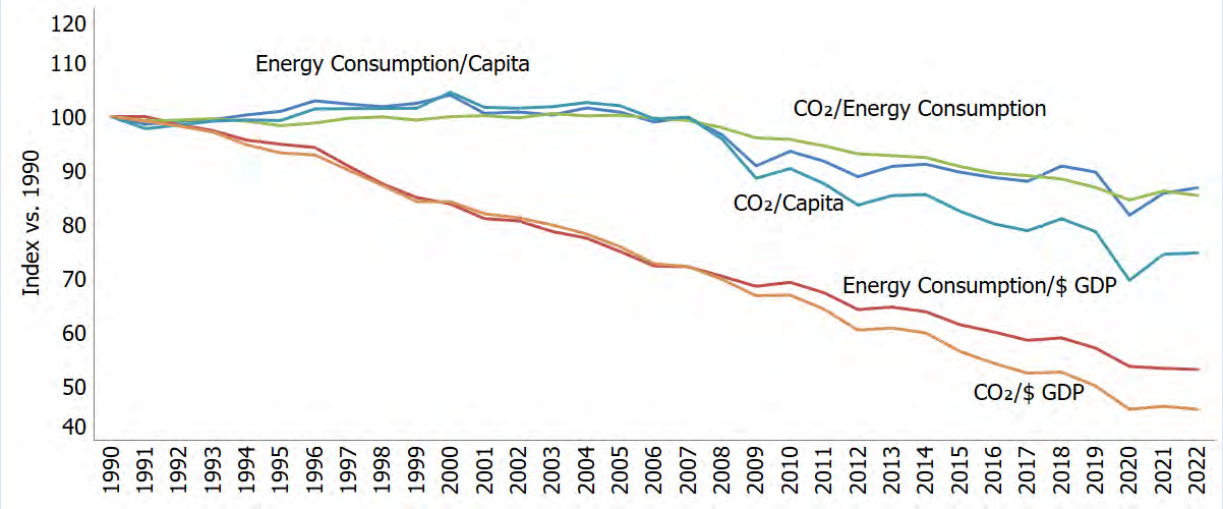

Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2023c), EPA (2010), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the

amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990). See also Annex 2.2 for a discussion of uncertainties associated with fuel carbon contents. Recent updates to carbon factors for natural gas and coal utilized the same approach as previous Inventories with updated recent data, therefore, the uncertainty estimates around carbon contents of the different fuels as outlined in Annex 2.2 were not impacted and the historic uncertainty ranges still apply.

Although national statistics of total fossil fuel and other energy consumption are relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is less certain. For example, for some fuels the sectoral allocations are based on price rates (i.e., tariffs), but a commercial establishment may be able to negotiate an industrial rate or a small industrial establishment may end up paying an industrial rate, leading to a misallocation of emissions. Also, the deregulation of the natural gas industry and the more recent deregulation of the electric power industry have likely led to some minor challenges in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

To calculate the total CO_2 emission estimate from energy-related fossil fuel combustion, the amount of fuel used in non-energy production processes were subtracted from the total fossil fuel consumption. The amount of CO_2 emissions resulting from non-energy related fossil fuel use has been calculated separately and reported in the Carbon Emitted from Non-Energy Uses of Fossil Fuels section of this report (Section 3.2). These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with carbon emitted from non-energy uses of fossil fuels can be found within that section of this chapter.

Various sources of uncertainty surround the estimation of emissions from international bunker fuels, which are subtracted from the U.S. totals (see the detailed discussions on these uncertainties provided in Section 3.9). Another source of uncertainty is fuel consumption by U.S. Territories. The United States does not collect energy statistics for its territories at the same level of detail as for the fifty states and the District of Columbia. Therefore, estimating both emissions and bunker fuel consumption by these territories is difficult.

Uncertainties in the emission estimates presented above also result from the data used to allocate CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom-up estimates of fuel consumption by vehicle type do not match aggregate fuel-type estimates from EIA. Further research is planned to improve the allocation into detailed transportation end-use sector emissions.

The uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, with @RISK software. For this uncertainty estimation, the inventory estimation model for CO_2 from fossil fuel combustion was integrated with the relevant variables from the inventory estimation model for International Bunker Fuels, to realistically characterize the interaction (or endogenous correlation) between the variables of these two models. About 170 input variables were modeled for CO_2 from energy-related fossil fuel combustion (including about 20 for non-energy fuel consumption and about 20 for International Bunker Fuels).

In developing the uncertainty estimation model, uniform distributions were assumed for all activity-related input variables and emission factors, based on the SAIC/EIA (2001) report.[42] Triangular distributions were assigned for the oxidization factors (or combustion efficiencies). The uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001) and on conversations with various agency personnel.[43]

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[42] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[43] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

The uncertainty ranges for the activity-related input variables were typically asymmetric around their inventory estimates; the uncertainty ranges for the emissions factors were symmetric. Bias (or systematic uncertainties) associated with these variables accounted for much of the uncertainties associated with these variables (SAIC/EIA 2001).[44] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte Carlo sampling.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-17. Fossil fuel combustion CO_2 emissions in 2022 were estimated to be between 4,603.1 and 4,905.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 4 percent above the 2022 emission estimate of 4,699.4 MMT CO_2 Eq.

Table 3-17: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Energy-Related Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq. and Percent)

Fuel/Sector	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal[b]	**898.8**	**868.6**	**983.9**	**-3%**	**9%**
Residential	NO	NO	NO	NO	NO
Commercial	1.4	1.3	1.6	-5%	15%
Industrial	43.0	41.0	49.9	-5%	16%
Transportation	NO	NO	NO	NO	NO
Electric Power	851.5	818.9	933.8	-4%	10%
U.S. Territories	2.9	2.5	3.4	-12%	19%
Natural Gas[b]	**1,706.8**	**1,687.3**	**1,784.4**	**-1%**	**5%**
Residential	272.0	264.4	291.1	-3%	7%
Commercial	192.3	186.9	205.8	-3%	7%
Industrial	510.4	494.9	548.0	-3%	7%
Transportation	70.2	68.2	75.1	-3%	7%
Electric Power	659.3	640.1	693.0	-3%	5%
U.S. Territories	2.7	2.4	3.2	-12%	17%
Petroleum[b]	**2,093.4**	**1,966.4**	**2,215.9**	**-6%**	**6%**
Residential	62.1	58.6	65.4	-6%	5%
Commercial	65.1	61.5	68.5	-5%	5%
Industrial	247.6	193.3	302.0	-22%	22%
Transportation	1,681.1	1,573.2	1,785.6	-6%	6%
Electric Power	20.5	19.7	22.0	-4%	7%
U.S. Territories	17.0	15.7	18.7	-7%	10%
Geothermal	**0.4**	**0.2**	**1.0**	**-48%**	**173%**
Electric Power	0.4	0.2	1.0	-48%	173%
Total (including Geothermal)[b]	**4,699.4**	**4,603.1**	**4,905.2**	**-2%**	**4%**

NO (Not Occurring)

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

[b] The low and high estimates for total emissions were calculated separately through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.

Note: Totals may not sum due to independent rounding.

[44] Although, in general, random uncertainties are the main focus of statistical uncertainty analysis, when the uncertainty estimates are elicited from experts, their estimates include both random and systematic uncertainties. Hence, both these types of uncertainties are represented in this uncertainty analysis.

QA/QC and Verification

In order to ensure the quality of the CO_2 emission estimates from fossil fuel combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating CO_2 emissions from fossil fuel combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken.

One area of QA/QC and verification is to compare the estimates and emission factors used in the *Inventory* with other sources of CO_2 emissions reporting. Two main areas and sources of data were considered. The first is a comparison with the EPA GHGRP combustion data (Subpart C) for stationary combustion sources excluding the electric power sector. This mainly focused on considering carbon factors for natural gas. The second comparison is with the EPA Air Markets Program data for electric power production. This considered carbon factors for coal and natural gas used in electric power production.

The EPA GHGRP collects greenhouse gas emissions data from large emitters including information on fuel combustion. This excludes emissions from mobile sources and smaller residential and commercial sources, those emissions are covered under supplier reporting (Subparts MM and NN) and are areas for further research. Fuel combustion CO_2 data reported in 2022 was 2,082.6 MMT CO_2. Of that, 1,577.7 MMT CO_2 was from electricity production. Therefore, the non-electric power production fuel combustion reporting was a fraction of the total covered by the *Inventory* under fossil fuel combustion. Furthermore, reporters under the GHGRP can use multiple methods of calculating emissions; one method is to use the default emission factors provided in the rule, while another is based on a tier 3 approach using their own defined emission factors. Based on data from reporters on approach used, it was determined that only about 10 percent of natural gas combustion emissions were based on a tier 3 approach. Given the small sample size compared to the overall *Inventory* calculations for natural gas combustion EPA determined it was not reasonable to consider the GHGRP tier 3 natural gas factors at this time. A more detailed analysis was done on upstream oil and gas natural gas combustion emissions using the GHGRP data as discussed in Annex 2.2.

EPA collects detailed sulfur dioxide (SO_2), nitrogen oxides (NO_X), and carbon dioxide (CO_2) emissions data and other information from power plants across the country as part of the Acid Rain Program (ARP), the Cross-State Air Pollution Rule (CSAPR), the CSAPR Update, and the Revised CSAPR Update (RCU). The CO_2 data from these Air Market Programs (AMP) can be compared to the electric power sector emissions calculated from the *Inventory* as shown in Table 3-18 for the three most recent years of data.

Table 3-18: Comparison of Electric Power Sector Emissions (MMT CO_2 Eq. and Percent)

Fuel/Sector	CO_2 Emissions (MMT CO_2 Eq.)			% Change	
	2020	2021	2022	20-21	21-22
Inventory Electric Power Sector	**1,439.6**	**1,540.9**	**1,531.7**	**7.0%**	**-0.6%**
Coal	788.2	910.1	851.5	15.5%	-6.4%
Natural Gas	634.8	612.8	659.3	-3.5%	7.6%
Petroleum	16.2	17.7	20.5	9.6%	15.9%
AMP Electric Power Sector	**1,430.8**	**1,531.7**	**1,520.1**	**7.1%**	**-0.8%**
Coal	792.7	913.4	858.5	15.2%	-6.0%
Natural Gas	629.4	609.6	652.7	-3.1%	7.1%
Petroleum	8.8	8.7	8.9	-0.8%	2.7%

Note: Totals may not sum due to independent rounding.

In general the emissions and trends from the two sources line up well. There are differences expected based on coverage and scope of each source. The *Inventory* covers all emissions from the electric power sector as defined above. The EPA AMP data covers emissions from electricity generating units of a certain size so in some respects it could cover more sources (like electric power units at industrial facilities that would be covered under the industrial sector in the *Inventory*) and not as many sources (since smaller units are excluded). The EPA AMP data also includes heat input for different fuel types. That data can be combined with emissions to calculate implied

emission factors.[45] The following Table 3-19 shows the implied emissions factors for coal and natural gas from the EPA AMP data compared to the factors used in the *Inventory* for the three most recent years of data.

Table 3-19: Comparison of Emissions Factors (MMT Carbon/QBtu)

Fuel Type	2020	2021	2022
EPA AMP			
Coal	25.67	25.66	25.53
Natural Gas	14.56	14.60	14.61
EPA Inventory			
Electric Power Coal	26.12	26.13	26.13
Natural Gas	14.43	14.43	14.43

The factors for natural gas line up reasonably well, the EPA factors are roughly 1 percent lower than those calculated from the EPA AMP data. For coal the EPA emissions factors are roughly 2 percent higher than those calculated from the EPA AMP data. One possible reason for the difference is that the EPA *Inventory* factors are based on all coal used in electric power production while the factors from the EPA AMP data are based on units where coal is the source of fuel used. There are units that use coal and other fuel sources but emissions for each fuel type could not be calculated. This is an area of further research but given current data available the approach to develop carbon factors as outlined in Annex 2 is still felt to be the most appropriate to represent total fuel combustion in the United States.

The Paris Agreement and the UNFCCC reporting guidelines also require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology. The reference approach (detailed in Annex 4) uses alternative methodologies and different data sources than those contained in this section of the report. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. In the reference approach, accounting for actual consumption of fuels at the sectoral or sub-national level is not required. One difference between the two approaches is that emissions from carbon that was not stored during non-energy use of fuels are subtracted from the sectoral approach and reported separately (see Section 3.2). These emissions, however, are not subtracted in the reference approach. As a result, the reference approach emission estimates are comparable to those of the sectoral approach, with the exception that the non-energy use (NEU) source category emissions are included in the reference approach (see Annex 4 for more details).

Recalculations Discussion

EIA (2024a) updated distillate fuel oil consumed by the transportation sector for 2010 and on. This caused transportation petroleum CO_2 emissions to increase by an average annual amount of 0.2 MMT CO_2 Eq. (less than half a percent) for the years 2010 through 2021.

EIA (2024a) updated propane consumed by the industrial sector for 2010 and on, which is used to calculate HGL (Energy Use) annually variable carbon content coefficients. In addition, EIA (2023b) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers. This change was made to reflect that natural gasoline and unfinished oils are used as feedstocks in crude oil production instead of directly consumed as an end-use fuel. EPA made the same adjustment across the timeseries. This change impacted industrial energy

[45] These emission factors can be converted from MMT Carbon/QBtu to MMT CO_2 Eq./QBtu by multiplying the emission factor by 44/12, the molecular-to-atomic weight ratio of CO_2 to C. This would assume the fraction oxidized to be 100 percent, which is the guidance in IPCC (2006) (see Annex 2.1).

consumption across the timeseries as well as non-energy use consumption, which impacts industrial energy consumption values. This change also impacted the HGL carbon content coefficient used to calculate emissions.

To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the total non-combustion consumption of HGLs as published by the EIA. Non-energy use consumption is subtracted from energy consumption, therefore this methodology change impacts industrial petroleum consumption values. Additionally, the energy HGL carbon contents are now calculated following the above methodology and have therefore increased across the timeseries, impacting U.S. Territories petroleum and industrial petroleum CO_2 emissions.

Overall, these four updates to EIA (2024a) data and methodology caused U.S. Territories petroleum CO_2 emissions to decrease by an average annual amount of less than 0.1 MMT CO_2 Eq. (less than half a percent) for the timeseries, and industrial petroleum CO_2 emissions to increase by an average annual amount of 5.0 MMT CO_2 Eq. (1.8 percent) for the timeseries.

EPA revised its calculation of change in total energy use in the industrial sector to include renewable energy and electricity. The value previously included only fossil fuel energy consumption. Additionally, EPA revised power sector carbon intensity data to correct for an error and ensure total renewable energy consumed from EIA's *Monthly Energy Review* (EIA 2024a) was being used. There were also very minor updates associated with changes in residential and commercial petroleum use due to MER updates changes in industrial coal use due to updated data on CO_2 exports.

Overall, these changes resulted in an average annual increase of 5.8 MMT CO_2 Eq. (0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2021, relative to the previous *Inventory*.

Planned Improvements

To reduce the uncertainty of CO_2 from fossil fuel combustion estimates for U.S. Territories, further expert elicitation may be conducted to better quantify the total uncertainty associated with emissions from U.S. Territories. Additionally, although not technically a fossil fuel, since geothermal energy-related CO_2 emissions are included for reporting purposes, further expert elicitation may be conducted to better quantify the total uncertainty associated with CO_2 emissions from geothermal energy use.

EPA will continue to examine the availability of facility-level combustion emissions through EPA's GHGRP to help better characterize the industrial sector's energy consumption in the United States and further classify total industrial sector fossil fuel combustion emissions by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC methodologies, although for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the *Inventory* to estimate total national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the Paris Agreement and UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions.[46] In line with the Paris Agreement and UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from fossil fuel combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this *Inventory*.

Additional analyses will be conducted to align reported facility-level fuel types and IPCC fuel types per the national energy statistics. For example, additional work will look at CO_2 emissions from biomass to ensure they are

[46] See https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.

separated in the facility-level reported data and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will continue to be relied upon.[47]

EPA is also evaluating the methods used to adjust for conversion of fuels and exports of CO_2. EPA is exploring the approach used to account for CO_2 transport, injection, and geologic storage; as part of this there may be changes made to the accounting for CO_2 exports.

Finally, another ongoing planned improvement is to evaluate data availability to update the carbon and heat content of more fuel types accounted for in this *Inventory*. This update will impact consumption and emissions across all sectors and will improve consistency with EIA data as carbon and heat contents of fuels will be accounted for as annually variable and therefore improve accuracy across the time series. Some of the fuels considered in this effort include petroleum coke, residual fuel, and woody biomass.

CH_4 and N_2O from Stationary Combustion

Methodology and Time-Series Consistency

Methane and N_2O emissions from stationary combustion were estimated by multiplying fossil fuel and wood consumption data by emission factors (by sector and fuel type for industrial, residential, commercial, and U.S. Territories; and by fuel and technology type for the electric power sector). The electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology in accordance with IPCC methodological decision tree Figure 2.1 in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and available data. The activity data and emission factors used are described in the following subsections.

More detailed information on the methodology for calculating emissions from stationary combustion, including emission factors and activity data, is provided in Annex 3.1.

Industrial, Residential, Commercial, and U.S. Territories

National coal, natural gas, fuel oil, and wood consumption data were grouped by sector: industrial, commercial, residential, and U.S. Territories. For the CH_4 and N_2O emission estimates, consumption data for each fuel were obtained from EIA's *Monthly Energy Review* (EIA 2024a). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by EIA's International Energy Statistics (EIA 2024b).[48] Fuel consumption for the industrial sector was adjusted to subtract out mobile source construction and agricultural use, which is reported under mobile sources. Construction and agricultural mobile source fuel use was obtained from EPA (2022) and FHWA (1996 through 2023). Estimates for wood biomass consumption for fuel combustion do not include municipal solid waste, tires, etc., that are reported as biomass by EIA. Non-CO_2 emissions from combustion of the biogenic portion of municipal solid waste and tires is included under waste incineration (Section 3.2). Estimates for natural gas combustion do not include biogas, and therefore non-CO_2 emissions from biogas are not included (see the Planned Improvements section, below). Tier 1 default emission factors for the industrial, commercial, and residential end-use sectors were provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). U.S. Territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

Electric Power Sector

The electric power sector uses a Tier 2 emission estimation methodology as fuel consumption for the electric

[47] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[48] U.S. Territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

power sector by control-technology type is based on EPA's Acid Rain Program Dataset (EPA 2024). Total fuel consumption in the electric power sector from EIA (2024a) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2024) data. The combustion technology and fuel use data by facility obtained from EPA (2024) were only available from 1996 to 2022 so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2024) to the total EIA (2024a) consumption for each year from 1990 to 1995.

Emissions were estimated by multiplying fossil fuel and wood consumption by technology-, fuel-, and country-specific Tier 2 emission factors. The Tier 2 emission factors used are based in part on emission factors published by EPA, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for coal wall-fired boilers, residual fuel oil, diesel oil and wood boilers, natural gas-fired turbines, and combined cycle natural gas units.[49]

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022 as discussed below. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from biomass use in Territories, but those emissions are assumed to be insignificant.

Uncertainty

Methane emission estimates from stationary sources exhibit high uncertainty, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control).

An uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, with @RISK software.

The uncertainty estimation model for this source category was developed by integrating the CH_4 and N_2O stationary source inventory estimation models with the model for CO_2 from fossil fuel combustion to realistically characterize the interaction (or endogenous correlation) between the variables of these three models. About 55 input variables were simulated for the uncertainty analysis of this source category (about 20 from the CO_2 emissions from fossil fuel combustion inventory estimation model and about 35 from the stationary source inventory models).

In developing the uncertainty estimation model, uniform distribution was assumed for all activity-related input variables and N_2O emission factors, based on the SAIC/EIA (2001) report.[50] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[51] However, the CH_4 emission factors differ from those used by EIA. These factors and uncertainty ranges are based on IPCC default uncertainty estimates (IPCC 2006).

[49] Several of the U.S. Tier 2 emission factors were used in IPCC (2006) as Tier 1 emission factors. See Table A-67 in Annex 3.1 for emission factors by technology type and fuel type for the electric power sector.

[50] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former distribution to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[51] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-20. Stationary combustion CH_4 emissions in 2022 (including biomass) were estimated to be between 5.9 and 19.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 31 percent below to 122 percent above the 2022 emission estimate of 8.6 MMT CO_2 Eq.[52] Stationary combustion N_2O emissions in 2022 (including biomass) were estimated to be between 16.5 and 33.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 33 percent below to 35 percent above the 2022 emission estimate of 24.7 MMT CO_2 Eq.

Table 3-20: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Energy-Related Stationary Combustion, Including Biomass (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stationary Combustion	CH_4	8.6	5.9	19.1	-31%	122%
Stationary Combustion	N_2O	24.7	16.5	33.4	-33%	35%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

The uncertainties associated with the emission estimates of CH_4 and N_2O are greater than those associated with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the indirect greenhouse gases, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

QA/QC and Verification

In order to ensure the quality of the non-CO_2 emission estimates from stationary combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CH_4, N_2O, and the greenhouse gas precursors from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

Recalculations Discussion

EIA (2024a) updated industrial HGL statistics, which caused CH_4 and N_2O emissions from industrial fuel oil to decrease slightly for the years 2010 through 2021.

In addition, EIA (2023b) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers. This change was made to reflect the fact that these fuels are used as feedstocks in crude oil production instead of directly consumed as end-use fuels. EPA made the change across the time series. This change impacted energy consumption across the timeseries as well as non-energy use consumption, which impacts energy consumption values.

To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the

[52] The low emission estimates reported in this section have been rounded down to the nearest integer values and the high emission estimates have been rounded up to the nearest integer values.

total non-combustion consumption of HGLs as published by the EIA. Non-energy use consumption is subtracted from energy consumption, therefore this methodology change impacts industrial fuel oil consumption values.

Other small updates included changes in residential and commercial/institutional fuel oil are use and changes in industrial coal due to updated CO_2 export data.

Overall, these updates to EIA data and methodology (2024a) caused CH_4 and N_2O emissions from industrial fuel oil to increase by an average annual amount of 0.01 MMT CO_2 Eq. and 0.01 MMT CO_2 Eq. (3 percent and 3 percent), respectively, for the time series. EIA (2024a) updated 2020 and 2021 wood energy consumed by the residential sector due to new underlying data collected by the Residential Energy Consumption Survey (RECS), which collects data about once every 5 years and uses Annual Energy Outlook growth rates to estimate data for other years. This caused CH_4 and N_2O emissions from residential wood consumption to decrease by 0.76 MMT CO_2 Eq. and 0.10 MMT CO_2 Eq. (22 percent and 13 percent) in 2020, respectively, and 0.94 MMT CO_2 Eq. and 0.12 MMT CO_2 Eq. (26 percent and 15 percent) in 2021, respectively.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary combustion and to reduce uncertainty for U.S. Territories. Efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. Territories data. Because these data are not broken out by stationary and mobile uses, further research will be aimed at trying to allocate consumption appropriately. In addition, the uncertainty of biomass emissions will be further investigated because it was expected that the exclusion of biomass from the estimates would reduce the uncertainty; and in actuality the exclusion of biomass increases the uncertainty. These improvements are not all-inclusive but are part of an ongoing analysis and efforts to continually improve these stationary combustion estimates from U.S. Territories.

Other forms of biomass-based gas consumption include biogas. As an additional planned improvement, EPA will examine EIA and GHGRP data on biogas collected and burned for energy use and determine if CH_4 and N_2O emissions from biogas can be included in future Inventories. EIA (2024a) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas.

CH_4 and N_2O from Mobile Combustion

Methodology and Time-Series Consistency

Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle miles traveled (VMT) for on-road vehicles and fuel consumption for non-road mobile sources. The activity data and emission factors used in the calculations are described in the subsections that follow. A complete discussion of the methodology used to estimate CH_4 and N_2O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

On-Road Vehicles

Estimates of CH_4 and N_2O emissions from gasoline and diesel on-road vehicles are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle type, fuel type, model year, and emission control technology. Emission estimates for alternative fuel vehicles (AFVs) are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle and fuel type.[53]

[53] Alternative fuel and advanced technology vehicles are those that can operate using a motor fuel other than gasoline or diesel. This includes electric or other bi-fuel or dual-fuel vehicles that may be partially powered by gasoline or diesel.

CH_4 and N_2O emissions factors by vehicle type and emission tier for newer (starting with model year 2004) on-road gasoline vehicles were calculated by Browning (2019) from annual vehicle certification data compiled by EPA. CH_4 and N_2O emissions factors for older (model year 2003 and earlier) on-road gasoline vehicles were developed by ICF (2004). These earlier emission factors were derived from EPA, California Air Resources Board (CARB) and Environment and Climate Change Canada (ECCC) laboratory test results of different vehicle and control technology types. The EPA, CARB and ECCC tests were designed following the Federal Test Procedure (FTP). The procedure covers three separate driving segments, since vehicles emit varying amounts of greenhouse gases depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was then analyzed to determine quantities of gases present. The emissions characteristics of driving segment 2 tests were used to define running emissions. Running emissions were subtracted from the total FTP emissions to determine start emissions. These were then recombined to approximate average driving characteristics, based upon the ratio of start to running emissions for each vehicle class from MOBILE6.2, an EPA emission factor model that predicts grams per mile emissions of CO_2, CO, HC, NO_x, and PM from vehicles under various conditions.[54]

Diesel on-road vehicle emission factors were developed by ICF (2006). CH_4 and N_2O emissions factors for newer (starting with model year 2007) on-road diesel vehicles (those using engine aftertreatment systems) were calculated from annual vehicle certification data compiled by EPA.

CH_4 and N_2O emission factors for AFVs were developed based on the 2022 Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (ANL 2022). For light-duty trucks, EPA used travel fractions for LDT1 and LDT2 (MOVES Source Type 31 for LDT1 and MOVES Source Type 32 for LDT2; see Annex 3.2 for information about the MOVES model) to determine emission factors. For medium-duty vehicles, EPA used emission factors for light heavy-duty vocational trucks. For heavy-duty vehicles, EPA used emission factors for long-haul combination trucks. For buses, EPA used emission factors for transit buses. These values represent vehicle operations only (tank-to-wheels); upstream well-to-tank emissions are calculated elsewhere in the Inventory. Biodiesel CH_4 emission factors were corrected from GREET values to be the same as CH_4 emission factors for diesel vehicles. GREET overestimated biodiesel CH_4 emission factors based upon an incorrect CH_4-to-THC ratio for diesel vehicles with aftertreatment technology.

Annual VMT data for 1990 through 2022 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2023). VMT estimates were then allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model). This corrects time series inconsistencies in FHWA definitions of vehicle types (Browning 2022a). VMT for alternative fuel vehicles (AFVs) were estimated based on Browning (2022b). The age distributions of the U.S. vehicle fleet were obtained from EPA (2004, 2022), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2022).

Control technology and standards data for on-road vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 1998, 2022b, and 2023) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1994a, 1994b, 1998, 1999) and IPCC (2006) sources.

Non-Road Mobile Sources

The nonroad mobile category for CH_4 and N_2O includes ships and boats, aircraft, locomotives, and other mobile non-road sources (e.g., construction or agricultural equipment). For locomotives, aircraft, ships, and non-recreational boats, fuel-based emission factors are applied to data on fuel consumption, following the IPCC Tier 1 approach. The Tier 2 approach for these sources would require separate fuel-based emissions factors by

[54] Additional information regarding the MOBILE model can be found at https://www.epa.gov/moves/description-and-history-mobile-highway-vehicle-emission-factor-model.

technology, for which data are not currently available. For other non-road sources, EPA uses the Nonroad component of the MOVES model to estimate fuel use. Emission factors by horsepower bin are estimated from EPA engine certification data. Because separate emission factors are applied to specific engine technologies; these non-road sources utilize a Tier 2 approach.

To estimate CH_4 and N_2O emissions from non-road mobile sources, fuel consumption data were employed as a measure of activity and multiplied by fuel-specific emission factors (in grams of N_2O and CH_4 per kilogram of fuel consumed).[55] Activity data were obtained from AAR (2008 through 2023), APTA (2007 through 2023), Rail Inc (2014 through 2022), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), Bureau of Transportation Statistics (BTS; 2023), DLA Energy (2022), DOC (1991 through 2022), DOE (1993 through 2022), DOT (1991 through 2023), EIA (2002, 2007, 2023a, 2023b), EIA (1991 through 2022), EPA (2022), Esser (2003 through 2004), FAA (2024), FHWA (1996 through 2023),[56] Gaffney (2007), FTA (2023), and Whorton (2006 through 2014). Fuel consumption data for boats and vessels in U.S. Territories data and vessel domestic vessel bunkering is proxied from 2021 proxy data. Emission factors for non-road modes were taken from IPCC (2006) and Browning (2020 and 2018).

Uncertainty

A quantitative uncertainty analysis was conducted for the mobile source sector using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, using @RISK software. The uncertainty analysis was performed on 2022 estimates of CH_4 and N_2O emissions, incorporating probability distribution functions associated with the major input variables. For the purposes of this analysis, the uncertainty was modeled for the following four major sets of input variables: (1) VMT data, by on-road vehicle and fuel type, (2) emission factor data, by on-road vehicle, fuel, and control technology type, (3) fuel consumption, data, by non-road vehicle and equipment type, and (4) emission factor data, by non-road vehicle and equipment type.

Uncertainty analyses were not conducted for NO_x, CO, or NMVOC emissions. Emission factors for these gases have been extensively researched because emissions of these gases from motor vehicles are regulated in the United States, and the uncertainty in these emission estimates is believed to be relatively low. For more information, see Section 3.11. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors due to limited emission test data, and because, unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are highly complex.

Based on the uncertainty analysis, mobile combustion CH_4 emissions from all mobile sources in 2022 were estimated to be between 2.5 and 3.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 4 percent below to 30 percent above the corresponding 2022 emission estimate of 2.6 MMT CO_2 Eq. Mobile combustion N_2O emissions from mobile sources in 2022 were estimated to be between 15.3 and 20.1MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 8 percent below to 20 percent above the corresponding 2022 emission estimate of 16.7 MMT CO_2 Eq.

[55] The consumption of international bunker fuels is not included in these activity data, but emissions related to the consumption of international bunker fuels are estimated separately under the International Bunker Fuels source category.

[56] This Inventory uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES model gasoline volumes to estimate non-road mobile source CH_4 and N_2O emissions for these categories. For agriculture, the MF-24 gasoline volume is used directly because it includes both non-road trucks and equipment. For construction and commercial/industrial category gasoline estimates, the 2014 and older MF-24 volumes represented non-road trucks only; therefore, the MOVES gasoline volumes for construction and commercial/industrial categories are added to the respective categories in the Inventory. Beginning in 2015, this addition is no longer necessary since the FHWA updated its methods for estimating on-road and non-road gasoline consumption. Among the method updates, FHWA now incorporates MOVES equipment gasoline volumes in the construction and commercial/industrial categories.

Table 3-21: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Sources (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Sources	CH_4	2.6	2.5	3.4	-4%	+30%
Mobile Sources	N_2O	16.7	15.3	20.1	-8%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

This uncertainty analysis is a continuation of a multi-year process for developing quantitative uncertainty estimates for this source category using the IPCC Approach 2 uncertainty estimation methodology. As a result, as new information becomes available, uncertainty characterization of input variables may be improved and revised. For additional information regarding uncertainty in emission estimates for CH_4 and N_2O please refer to the Uncertainty Annex. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from any liquid fuel used in pipeline transport or some biomass used in transportation sources, but those emissions are assumed to be insignificant.

QA/QC and Verification

In order to ensure the quality of the emission estimates from mobile combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. The Tier 2 procedures focused on the emission factor and activity data sources, as well as the methodology used for estimating emissions. These procedures included a qualitative assessment of the emission estimates to determine whether they appear consistent with the most recent activity data and emission factors available. A comparison of historical emissions between the current Inventory and the previous Inventory was also conducted to ensure that the changes in estimates were consistent with the changes in activity data and emission factors.

Recalculations Discussion

In previous *Inventories* (1990 through 2020 *Inventory* and before), on-highway greenhouse gas emissions were calculated using FHWA fuel consumption and vehicle miles traveled (VMT) data delineated by FHWA vehicle classes. These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from Oak Ridge National Laboratory's Transportation Energy Data Book (TEDB), to develop an estimate of fuel consumption for each vehicle type in the Inventory (i.e., passenger cars, light-duty trucks, buses, medium- and heavy-duty trucks, motorcycles). However, in 2011, FHWA changed its methods for estimating VMT and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated in the 1990 through 2008 *Inventory* and applied to the time series beginning in 2007. The FHWA methodology update resulted in large changes in VMT and fuel consumption by vehicle class, leading to a shift in emissions among vehicle classes. For example, FHWA replaced the vehicle category "Passenger Cars" with "Light-duty Vehicles-Short Wheelbase" and the "Other 2 axle-4 Tire Vehicles" category was replaced by "Light-duty Vehicles, Long Wheelbase." FHWA changed the definition of light-duty vehicles to less than 10,000 lbs. GVWR instead of 8,500 lbs. GVWR category updates pushed some single-unit heavy-duty trucks to the light-duty class. This change in vehicle classification also moved some smaller trucks and sport utility vehicles from the light truck category to the passenger cars category in this *Inventory*. These updates resulted in a disconnect in FHWA VMT and fuel consumption data in the 2006 to 2007 timeframe, generating a large drop in the light-duty truck VMT and fuel consumption trend lines between 2006 and 2007, and a corresponding increase in the passenger cars trend lines.

To address this inconsistency in the time series, EPA updated the methodology (starting with the 1990 through 2021 *Inventory*) to divide FHWA VMT data into vehicle classes and fuel type using distributions from EPA's *MOtor Vehicle Emission Simulator*, MOVES. The MOVES model is a nationally recognized model based on vehicle registration, travel activity, and emission rates that are updated with each model release. MOVES uses forecast growth factors which provide EPA's best estimate of likely future activity based on historical data (see Annex 3.2 for more information about the MOVES model). Thus, dividing FHWA total VMT data into vehicle class and fuel type using MOVES ratios provides a more consistent estimate of vehicle activity over the *Inventory* time series. MOVES ratios are also used to reallocate FHWA gasoline and diesel fuel use data (Browning 2022a). For this update, the MOVES3 model was run for calendar years 1990 and 1999 through 2022 for all vehicle types. Calendar years 1991 through 1998 were linearly interpolated from 1990 and 1999 calendar year MOVES3 outputs. Model outputs of VMT and fuel consumption were binned by calendar year, MOVES vehicle type, and fuel type; MOVES vehicle types were then mapped to the vehicle types used in the *Inventory*. Only outputs of gasoline and diesel fuel consumption from MOVES3 were used; alternative fuel VMT and fuel consumption outputs are ignored because they are calculated for the *Inventory* under a separate methodology. Total gasoline and diesel fuel consumption values from FHWA were then allocated to *Inventory* vehicle types using gasoline and diesel fuel consumption ratios by vehicle type from MOVES3. Similarly, VMT by vehicle type and fuel type was calculated by multiplying the total VMT from FHWA by VMT ratios by vehicle and fuel type generated by MOVES3. Overall, because total fuel consumption and VMT values are conserved, the changes in total emissions are small, within 0.1 percent. Observed differences in total emissions are due to changes in CH_4 and N_2O emissions, as the methodology for calculating these non-CO_2 emissions utilizes more detailed activity data and is therefore sensitive to the re-allocation of activity data. While total emissions estimates are not significantly impacted by this methodology update, there are significant changes in the allocation of emissions by vehicle type. The share of emissions allocated to passenger cars now generally decline through the time series while the share of emissions allocated to light-duty trucks increase over time.

In addition, the latest version of Argonne National Laboratory's *Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation Model (*GREET2022*)* provided updated emission factors for all alternative fuel vehicle classes (ANL 2022). Updated emission factors from GREET2022 were implemented in this *Inventory*, across the entire time series.

Additionally, new data from BTS on Amtrak fuel consumption for the time period 2019 through 2022 were included in this *Inventory* (BTS 2023).

Planned Improvements

While the data used for this report represent the most accurate information available, several areas for improvement have been identified.

- Update emission factors for ships and non-recreational boats using residual fuel and distillate fuel. Develop emission factors for locomotives using ultra-low sulfur diesel and emission factors for aircraft using jet fuel. The Inventory currently uses IPCC default values for these emission factors.
- Continue to explore potential improvements to estimates of domestic waterborne fuel consumption for future Inventories. The *Inventory* estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. Since 2015, all ships travelling within 200 nautical miles of the U.S. coastlines must use distillate fuels, thereby overestimating the residual fuel used by U.S. vessels and underestimating distillate fuel use in these ships. Additionally, the EIA has stopped publishing the Fuel Oil and Kerosene Sales report, which reported data on distillate marine fuel use in the U.S. and the territories. This affects the volume of fuel and emissions that are allocated to the domestic ships and boats source, although top-down data is still available from the Monthly Energy Review that will be used to estimate total domestic emission from diesel fuel use. New data and methods are being explored to improve the diesel ships and boats emissions estimates going forward.
- Update the analyses to use a forthcoming version of MOVES when it becomes available.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (CRT Source Category 1A)

In addition to being combusted for energy, fossil fuels are also consumed for non-energy uses (NEU) in the United States. The fuels used for these purposes are diverse, including natural gas, hydrocarbon gas liquids (HGL),[57] asphalt (a viscous liquid mixture of heavy crude oil distillates), petroleum coke (manufactured from heavy oil), and coal (metallurgical) coke (manufactured from coking coal). The non-energy applications of these fuels are equally diverse, including feedstocks for the manufacture of plastics, rubber, synthetic fibers and other materials; reducing agents for the production of various metals and inorganic products; and products such as lubricants, waxes, and asphalt (IPCC 2006). Emissions from non-energy use of lubricants, paraffin waxes, bitumen/asphalt, and solvents are reported in the Energy sector, as opposed to the Industrial Processes and Product Use (IPPU) sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology (see Box 3-5). In addition, estimates of non-energy use emissions included here do not include emissions already reflected in the IPPU sector, e.g., fuels used as reducing agents. To avoid double counting, the "raw" non-energy fuel consumption data reported by EIA are reduced to account for these emissions already included under IPPU.

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, throughout the time series and across all uses, about 64 percent of the total carbon consumed for non-energy purposes was stored in products (e.g., plastics), and not released to the atmosphere; the remaining 36 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of this *Inventory*. For example, some of the non-energy use products release CO_2 at the end of their commercial life when they are combusted after disposal; these emissions are reported separately within the Energy chapter in the Incineration of Waste source category. There are also net exports of petrochemical intermediate products that are not completely accounted for in the EIA data, and the *Inventory* calculations adjust for the effect of net exports on the mass of carbon in non-energy applications.

As shown in Table 3-22, fossil fuel emissions in 2022 from the non-energy uses of fossil fuels were 102.8 MMT CO_2 Eq., which constituted approximately 2.0 percent of overall fossil fuel emissions. In 2022, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,428.2 TBtu (see Table 3-23). A portion of the carbon in the 5,428.2 TBtu of fuels was stored (236.7 MMT CO_2 Eq.), while the remaining portion was emitted (102.8 MMT CO_2 Eq.). Non-energy use emissions decreased by 7.9 percent from 2021 to 2022, primarily due to decreases in industrial coal, natural gas, and HGL fuel consumption. See Annex 2.3 for more details.

[57] HGL (formerly referred to as liquefied petroleum gas, or LPG) are hydrocarbons that occur as gases at atmospheric pressure and as liquids under higher pressures. HGLs include paraffins, such as ethane, propane, butanes, isobutane, and natural gasoline (formerly referred to as pentanes plus), and HGLs include olefins, such as ethylene, propylene, butylene and isobutylene.

Table 3-22: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (MMT CO_2 Eq. and Percent C)

Year	1990	2005	2018	2019	2020	2021	2022
Potential Emissions	292.5	357.7	341.5	334.7	328.6	345.0	339.5
C Stored	193.4	232.7	223.2	228.2	230.8	233.4	236.7
Emissions as a % of Potential	34%	35%	35%	32%	30%	32%	30%
C Emitted	**99.1**	**125.0**	**118.4**	**106.5**	**97.8**	**111.6**	**102.8**

Note: NEU emissions presented in this table differ from the NEU emissions presented in CRT Table 1.A(a)s4 as the CRT NEU emissions do not include NEU of lubricants and other petroleum in U.S. Territories. NEU emissions from U.S. Territories are reported under U.S. Territories in the CRT Table 1.A(a)s4.

Methodology and Time-Series Consistency

As per discussion of methodology for estimating CO_2 emissions from fossil fuel combustion, NEU emissions are estimated in line with a Tier 2 method described by the *IPCC in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) Chapter 2, Figure 2.1 decision tree and available data on energy use and country specific fuel carbon contents. The first step in estimating carbon stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The carbon content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific carbon content values. Both the non-energy fuel consumption and carbon content data were supplied by the EIA (2023) (see Annex 2.1). Consumption values for industrial coking coal, petroleum coke, other oils, and natural gas in Table 3-23 and Table 3-24 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes and Product Use chapter.[58] Consumption of natural gas, HGL, naphthas, other oils, and special naphtha were adjusted to subtract out net exports of these products that are not reflected in the raw data from EIA. Consumption values were also adjusted to subtract net exports of HGL components (e.g., propylene, ethane).

For the remaining non-energy uses, the quantity of carbon stored was estimated by multiplying the potential emissions by a storage factor.

- For several fuel types—petrochemical feedstocks (including natural gas for non-fertilizer uses, HGL, naphthas, other oils, still gas, special naphtha, and industrial other coal), asphalt and road oil, lubricants, and waxes—U.S. data on carbon stocks and flows were used to develop carbon storage factors, calculated as the ratio of (a) the carbon stored by the fuel's non-energy products to (b) the total carbon content of the fuel consumed. A lifecycle approach was used in the development of these factors in order to account for losses in the production process and during use. Because losses associated with municipal solid waste management are handled separately in the Energy sector under the Incineration of Waste source category, the storage factors do not account for losses at the disposal end of the life cycle.
- For industrial coking coal and distillate fuel oil, storage factors were taken from Marland and Rotty (1984).
- For the remaining fuel types (petroleum coke, miscellaneous products and other petroleum), IPCC (2006) does not provide guidance on storage factors, and assumptions were made based on the potential fate of carbon in the respective non-energy use products. Carbon dioxide emissions from carbide production are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke.

[58] These source categories include iron and steel production, lead production, zinc production, ammonia manufacture, carbon black manufacture (included in petrochemical production), titanium dioxide production, ferroalloy production, silicon carbide production, and aluminum production.

Table 3-23: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	2005	2018	2019	2020	2021	2022
Industry	**4,110.2**	**4,961.2**	**5,261.0**	**5,143.8**	**5,096.7**	**5,343.1**	**5,301.8**
Industrial Coking Coal	NO	80.4	124.7	112.8	79.9	77.9	46.7
Industrial Other Coal	7.6	11.0	9.5	9.5	9.5	9.5	9.5
Natural Gas to Chemical Plants	280.6	260.7	675.1	663.4	660.5	663.7	654.2
Asphalt & Road Oil	1,170.2	1,323.2	792.8	843.9	832.3	898.1	916.1
HGL[a]	1,135.0	1,554.3	2,427.6	2,372.8	2,469.5	2,639.0	2,758.8
Lubricants	186.3	160.2	122.0	118.3	111.1	113.5	119.5
Natural Gasoline[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Naphtha (<401 °F)	325.4	679.2	420.6	367.7	327.8	329.3	244.2
Other Oil (>401 °F)	660.4	499.2	218.8	211.1	194.7	195.3	111.1
Still Gas	36.7	67.7	166.9	158.7	145.4	152.8	157.1
Petroleum Coke	29.1	104.2	0.0	0.0	0.0	0.0	0.0
Special Naphtha	100.6	60.9	86.9	89.1	80.4	75.7	82.4
Distillate Fuel Oil	7.0	16.0	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	31.4	12.4	10.4	9.2	11.8	13.0
Miscellaneous Products	137.8	112.8	198.0	180.2	170.7	170.8	183.4
Transportation	**176.0**	**151.3**	**137.0**	**131.3**	**115.6**	**119.0**	**125.4**
Lubricants	176.0	151.3	137.0	131.3	115.6	119.0	125.4
U.S. Territories	**50.8**	**114.9**	**3.6**	**3.6**	**1.0**	**1.0**	**1.0**
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	50.1	110.3	2.5	2.6	0.0	0.0	0.0
Total	**4,337.1**	**5,227.5**	**5,401.6**	**5,278.8**	**5,213.4**	**5,463.2**	**5,428.2**

NO (Not Occurring)

[a] Excludes natural gasoline.

[b] Formerly referred to as "pentanes plus." This source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.

Table 3-24: 2022 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (MMT C/QBtu)	Potential Carbon (MMT C)	Storage Factor (MMT C)	Carbon Stored (MMT C)	Carbon Emissions (MMT C)	Carbon Emissions (MMT CO_2 Eq.)
Industry	**5,301.8**	**NA**	**90.0**	**NA**	**64.3**	**25.7**	**94.3**
Industrial Coking Coal	46.7	25.61	1.2	0.10	0.1	1.1	3.9
Industrial Other Coal	9.5	26.10	0.2	0.67	0.2	0.1	0.3
Natural Gas to Chemical Plants	654.2	14.47	9.4	0.67	6.3	3.1	11.4
Asphalt & Road Oil	916.1	20.55	18.8	1.00	18.7	0.1	0.3
HGL[b]	2,758.8	16.82	46.4	0.67	31.1	15.3	56.2
Lubricants	119.5	20.20	2.4	0.09	0.2	2.2	8.0
Natural Gasoline[c]	0.0	18.24	0.0	0.67	0.0	0.0	0.0
Naphtha (<401° F)	244.2	18.55	4.5	0.67	3.0	1.5	5.5
Other Oil (>401° F)	111.1	20.17	2.2	0.67	1.5	0.7	2.7
Still Gas	157.1	17.51	2.8	0.67	1.8	0.9	3.3
Petroleum Coke	0.0	27.85	0.0	0.30	0.0	0.0	0.0
Special Naphtha	82.4	19.74	1.6	0.67	1.1	0.5	2.0
Distillate Fuel Oil	5.8	20.22	0.1	0.50	0.1	0.1	0.2
Waxes	13.0	19.80	0.3	0.58	0.1	0.1	0.4
Miscellaneous Products	183.4	0.00	0.0	0.00	0.0	0.0	0.0
Transportation	**125.4**	**NA**	**2.5**	**NA**	**0.2**	**2.3**	**8.4**
Lubricants	125.4	20.20	2.5	0.09	0.2	2.3	8.4
U.S. Territories	**1.0**	**NA**	**+**	**NA**	**+**	**+**	**0.1**
Lubricants	1.0	20.20	+	0.09	+	+	0.1

Other Petroleum (Misc. Prod.)	+	20.00	+	0.10	+	+	+
Total	**5,428.2**		**92.6**		**64.6**	**28.0**	**102.8**

+ Does not exceed 0.05 TBtu, MMT C, or MMT CO_2 Eq.
NA (Not Applicable)
NO (Not Occurring)
[a] To avoid double counting, net exports have been deducted.
[b] Excludes natural gasoline.
[c] Formerly referred to as "pentanes plus." this source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.
Note: Totals may not sum due to independent rounding.

Lastly, emissions were estimated by subtracting the carbon stored from the potential emissions (see Table 3-22). More detail on the methodology for calculating storage and emissions from each of these sources is provided in Annex 2.3.

Where storage factors were calculated specifically for the United States, data were obtained on (1) products such as asphalt, plastics, synthetic rubber, synthetic fibers, cleansers (soaps and detergents), pesticides, food additives, antifreeze and deicers (glycols), and silicones; and (2) industrial releases including energy recovery (waste gas from chemicals), Toxics Release Inventory (TRI) releases, hazardous waste incineration, and volatile organic compound, solvent, and non-combustion CO emissions. Data were taken from a variety of industry sources, government reports, and expert communications. Sources include EPA reports and databases such as compilations of air emission factors (EPA 2001), EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file (EPA 2023), *Toxics Release Inventory, 1998* (EPA 2000b), *Biennial Reporting System* (EPA 2000a, 2009), *Resource Conservation and Recovery Act Information System* (EPA 2013b, 2015, 2016b, 2018b, 2021), pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011, 2017), and the Chemical Data Access Tool (EPA 2014b); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010, 2013, 2017, 2021); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Census Bureau (1999, 2004, 2009, 2014, 2021); Bank of Canada (2012, 2013, 2014, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (2023); Gosselin, Smith, and Hodge (1984); EPA's *Municipal Solid Waste (MSW) Facts and Figures* (EPA 2013, 2014a, 2016a, 2018a, 2019); the U.S. Tire Manufacturers Association (USTMA 2012, 2013, 2014, 2016, 2018, 2020, 2022); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012, 2013); the Independent Chemical Information Service (ICIS 2008, 2016); the EPA Chemical Data Access Tool (CDAT) (EPA 2014b); the American Chemistry Council (ACC 2003 through 2011, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023a); the *Guide to the Business of Chemistry* (ACC 2023b); and the Chemistry Industry Association of Canada (CIAC 2023). Specific data sources are listed in full detail in Annex 2.3.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022 as discussed below.

Box 3-5: Reporting of Lubricants, Waxes, and Asphalt and Road Oil Product Use in Energy Sector

IPCC (2006) provides methodological guidance to estimate emissions from the first use of fossil fuels as a product for primary purposes other than combustion for energy purposes (including lubricants, paraffin waxes, bitumen / asphalt, and solvents) under the IPPU sector.[59] In this *Inventory*, carbon storage and carbon

[59] See for example Volume 3: Industrial Processes and Product Use, and Chapter 5: Non-Energy Products from Fuels and Solvent Use of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

emissions from product use of lubricants, waxes, and asphalt and road oil are reported under the Energy sector in the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category (CRT Source Category 1A5).[60]

The emissions are reported in the Energy sector, as opposed to the IPPU sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology. Although emissions from these non-energy uses are reported in the Energy chapter the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines*. The country-specific methodology used for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category is based on a carbon balance (i.e., carbon inputs-outputs) calculation of the aggregate amount of fossil fuels used for non-energy uses, including inputs of lubricants, waxes, asphalt and road oil (see Table 3-24).

For those inputs, U.S. country-specific data on carbon stocks and flows are used to develop carbon storage factors, which are calculated as the ratio of the carbon stored by the fossil fuel non-energy products to the total carbon content of the fuel consumed, taking into account losses in the production process and during product use.[61] The country-specific methodology to reflect national circumstances starts with the aggregate amount of fossil fuels used for non-energy uses and applies a carbon balance calculation, breaking out the carbon emissions from non-energy use of lubricants, waxes, and asphalt and road oil. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance and to avoid double counting. Due to U.S. national circumstances, reporting these carbon emissions separately under IPPU would involve making artificial adjustments to allocate both the carbon inputs and carbon outputs of the non-energy use carbon balance. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting these non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. To avoid presenting an incomplete carbon balance and a less transparent approach for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category calculation, the entire calculation of carbon storage and carbon emissions is therefore conducted in the Non-Energy Uses of Fossil Fuels category calculation methodology, and both the carbon storage and carbon emissions for lubricants, waxes, and asphalt and road oil are reported under the Energy sector.

However, emissions from non-energy uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, and zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances.

Uncertainty

An uncertainty analysis was conducted to quantify the uncertainty surrounding the estimates of emissions and storage factors from non-energy uses. This analysis, performed using @RISK software and the IPCC-recommended Approach 2 methodology (Monte Carlo stochastic simulation technique), provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the

[60] Non-methane volatile organic compound (NMVOC) emissions from solvent use are reported separately in the IPPU sector, following Chapter 5 of the *2006 IPCC Guidelines*.

[61] Data and calculations for lubricants and waxes and asphalt and road oil are in Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

inventory estimate. The results presented below provide the 95 percent confidence interval, the range of values within which emissions are likely to fall, for this source category.

As noted above, the non-energy use analysis is based on U.S.-specific storage factors for (1) feedstock materials (natural gas, HGL, natural gasoline, naphthas, other oils, still gas, special naphthas, and other industrial coal), (2) asphalt, (3) lubricants, and (4) waxes. For the remaining fuel types (the "other" category in Table 3-23 and Table 3-24) the storage factors were taken directly from IPCC (2006), where available, and otherwise assumptions were made based on the potential fate of carbon in the respective NEU products. To characterize uncertainty, five separate analyses were conducted, corresponding to each of the five categories. In all cases, statistical analyses or expert judgments of uncertainty were not available directly from the information sources for all the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-25 (emissions) and Table 3-26 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2022 was estimated to be between 71.0 and 166.6 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 31 percent below to 62 percent above the 2022 emission estimate of 102.8 MMT CO_2 Eq. The uncertainty in the emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor.

Table 3-25: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	81.4	51.7	146.6	-37%	+80%
Asphalt	CO_2	0.3	0.1	0.7	-58%	+119%
Lubricants	CO_2	16.6	13.7	19.2	-17%	+16%
Waxes	CO_2	0.4	0.3	0.7	-23%	+77%
Other	CO_2	4.2	0.8	4.9	-81%	+17%
Total	**CO_2**	**102.8**	**71.0**	**166.6**	**-31%**	**+62%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding.

Table 3-26: Approach 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2022 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	67.0%	52.3%	73.5%	-22%	+10%
Asphalt	CO_2	99.6%	99.1%	99.8%	0.5%	0.3%
Lubricants	CO_2	9.2%	3.9%	17.5%	-57%	+91%
Waxes	CO_2	57.8%	47.4%	67.5%	-18%	+17%
Other	CO_2	13.6%	8.1%	83.0%	-41%	+511%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, as a percentage of the inventory value (also expressed in percent terms).

As shown in Table 3-26, waxes and asphalt contribute least to overall storage factor uncertainty on a percentage basis. Although the feedstocks category—the largest use category in terms of total carbon flows—also appears to have relatively tight confidence limits, this is to some extent an artifact of the way the uncertainty analysis was structured. As discussed in Annex 2.3, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all of these fate processes, the current analysis addresses only the storage fates, and assumes that all carbon that is not stored is emitted. As the

production statistics that drive the storage values are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As is the case with the other uncertainty analyses discussed throughout this document, the uncertainty results above address only those factors that can be readily quantified. More details on the uncertainty analysis are provided in Annex 2.3.

QA/QC and Verification

In order to ensure the quality of the emission estimates from non-energy uses of fossil fuels, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. This effort included a general analysis, as well as portions of a category specific analysis for non-energy uses involving petrochemical feedstocks and for imports and exports. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology for estimating the fate of carbon (in terms of storage and emissions) across the various end-uses of fossil C. Emission and storage totals for the different subcategories were compared, and trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors and to improve the transparency of the calculations, facilitating future QA/QC.

For petrochemical import and export data, special attention was paid to NAICS numbers and titles to verify that none had changed or been removed. Import and export totals were compared with 2021 totals as well as their trends across the time series.

It is important to ensure no double counting of emissions between fuel combustion, non-energy use of fuels and industrial process emissions. For petrochemical feedstock production, our review of the categories suggests this is not a significant issue since the non-energy use industrial release data includes different categories of sources and sectors than those included in the Industrial Processes and Product Use (IPPU) emissions category for petrochemicals. Further data integration is not available at this time because feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. Also, GHGRP-reported data on quantities of fuel consumed as feedstocks by petrochemical producers are unable to be used due to the data failing GHGRP CBI aggregation criteria. This country-specific approach taken is better able to reflect the national situation because it is accounting for secondary product imports and exports that are not included directly in the national energy statistics. Furthermore, it is compatible with the *2006 IPCC Guidelines* as discussed in Box 3-5 above, but also as the NEU emissions are here represent different emissions from those covered in the IPPU petrochemical production category.

Recalculations Discussion

Several updates to activity data factors lead to recalculations of previous year results. The major updates are as follows:

- U.S. International Trade Commission (2023) made changes to the classification of certain cleanser types, which doubled the historic emissions data for cleanser imports while exports remained constant.
- ACC (2023b) updated polyester, polyolefin and nylon fiber, ethylene glycol, maleic anhydride, adipic acid, and acetic acid production in 2021 which resulted in a slight decrease in emissions relative to the previous *Inventory*.
- U.S. International Trade Commission (2023) updated historical import and export data from 1996 to 2021, resulting in greater net exports relative to the previous *Inventory*.
- EIA (2024) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers, reflecting that, in actuality, nearly the full volume of these fuels is used as a feedstock in crude oil production, instead of directly consumed as an end-use fuel. Under EIA's guidance, EPA shifted all product supplied of natural gasoline to crude oil transfers for the time series. Natural gasoline was entirely

recategorized, which resulted in zero emissions for the time series from 1990 to 2022. Natural gasoline previously made up 1.7 percent of total emissions on average across the time series for non-energy uses of fossil fuels.

- To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the total non-combustion consumption of HGLs as published by the EIA. A further adjustment is made to natural gas, HGL, naphtha, other oil, and special naphtha consumption to account for exports of organic chemicals, cleansers, and pesticides. Because this adjustment is apportioned based on the relative ratios of each fuel, the emissions from these fuels have also changed slightly across the time series. Additionally, to better align with EIA methodology, the non-combustion and energy HGL carbon contents are now calculated for the entire timeseries following the above methodology. Overall, this update caused emissions from the non-energy use of natural gas to decrease an average of 27 MMT CO_2 Eq. annually, or 23 percent.

Overall, these changes resulted in an average annual decrease of 10.1 MMT CO_2 Eq. (8.2 percent) in carbon emissions from non-energy uses of fossil fuels for the period 1990 through 2021, relative to the previous *Inventory*.

Planned Improvements

There are several future improvements planned:

- More accurate accounting of carbon in petrochemical feedstocks. EPA has worked with EIA to determine the cause of input/output discrepancies in the carbon mass balance contained within the NEU model. In the future, two strategies to reduce or eliminate this discrepancy will continue to be pursued as part of quality control procedures. First, accounting of carbon in imports and exports will be improved. The import/export adjustment methodology will be examined to ensure that net exports of intermediaries such as ethylene and propylene are fully accounted for. Second, the use of top-down carbon input calculation in estimating emissions will be reconsidered. Alternative approaches that rely more substantially on the bottom-up carbon output calculation will be considered instead.
- Improving the uncertainty analysis. Most of the input parameter distributions are based on professional judgment rather than rigorous statistical characterizations of uncertainty.
- Better characterizing flows of fossil carbon. Additional fates may be researched, including the fossil carbon load in organic chemical wastewaters, plasticizers, adhesives, films, paints, and coatings. There is also a need to further clarify the treatment of fuel additives and backflows (especially methyl tert-butyl ether, MTBE).
- Reviewing the trends in fossil fuel consumption for non-energy uses. Annual consumption for several fuel types is highly variable across the time series, including industrial coking coal and other petroleum. A better understanding of these trends will be pursued to identify any mischaracterized or misreported fuel consumption for non-energy uses.
- Updating the average carbon content of solvents was researched, since the entire time series depends on one year's worth of solvent composition data. The data on carbon emissions from solvents that were readily available do not provide composition data for all categories of solvent emissions and also have conflicting definitions for volatile organic compounds, the source of emissive carbon in solvents. Additional sources of solvents data will be investigated in order to update the carbon content assumptions.
- Updating the average carbon content of cleansers (soaps and detergents) was researched; although production and consumption data for cleansers are published every 5 years by the Census Bureau, the composition (C content) of cleansers has not been recently updated. Recently available composition data

sources may facilitate updating the average carbon content for this category.

- Revising the methodology for consumption, production, and carbon content of plastics was researched; because of recent changes to the type of data publicly available for plastics, the NEU model for plastics applies data obtained from personal communications. Potential revisions to the plastics methodology to account for the recent changes in published data will be investigated.
- Although U.S.-specific storage factors have been developed for feedstocks, asphalt, lubricants, and waxes, default values from IPCC are still used for two of the non-energy fuel types (industrial coking coal, distillate oil), and broad assumptions are being used for miscellaneous products and other petroleum. Over the long term, there are plans to improve these storage factors by analyzing carbon fate similar to those described in Annex 2.3 or deferring to more updated default storage factors from IPCC where available.
- Reviewing the storage of carbon black across various sectors in the *Inventory*; in particular, the carbon black abraded and stored in tires.
- Assess the current method and/or identify new data sources (e.g., EIA) for estimating emissions from ammonia/fertilizer use of natural gas.
- Investigate EIA NEU and MECS data to update, as needed, adjustments made for ammonia production and "natural gas to chemical plants, other uses" and "natural gas to other" non-energy uses, including iron and steel production, in energy uses and IPPU.

3.3 Incineration of Waste (CRT Source Category 1A)

Combustion is used to manage about 7 to 19 percent of the solid wastes generated in the United States, depending on the source of the estimate and the scope of materials included in the definition of solid waste (EPA 2000; EPA 2020; Goldstein and Madtes 2001; Kaufman et al. 2004; Simmons et al. 2006; van Haaren et al. 2010). In the context of this section, waste includes all municipal solid waste (MSW) as well as scrap tires. In the United States, combustion of MSW tends to occur at waste-to-energy facilities or industrial facilities where useful energy is recovered, and thus emissions from waste combustion are accounted for in the Energy chapter. Similarly, scrap tires are combusted for energy recovery in industrial and utility boilers, pulp and paper mills, and cement kilns. Combustion of waste results in conversion of the organic inputs to CO_2. According to the *2006 IPCC Guidelines*, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste combustion are calculated by estimating the quantity of waste combusted and the fraction of the waste that is carbon derived from fossil sources.

Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), and have their net carbon flows accounted for under the Land Use, Land-Use Change, and Forestry chapter. However, some components of MSW and scrap tires—plastics, synthetic rubber, synthetic fibers, and carbon black—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in MSW are predominantly from clothing and home furnishings. As noted above, scrap tires (which contain synthetic rubber and carbon black) are also considered a "non-hazardous" waste and are included in the waste combustion estimate, though waste disposal practices for tires differ from MSW. Estimates on emissions from hazardous waste combustion can be found in Annex 2.3 and are accounted for as part of the carbon mass balance for non-energy uses of fossil fuels.

Approximately 26.3 million metric tons of MSW were combusted in 2022 (EPA 2022). Carbon dioxide emissions from combustion of waste decreased 4.2 percent since 1990, to an estimated 12.4 MMT CO_2 (12,357 kt) in 2022. Emissions across the time series are shown in Table 3-27 and Table 3-28.

Waste combustion is also a source of CH_4 and N_2O emissions (De Soete 1993; IPCC 2006). Methane emissions from the combustion of waste were estimated to be less than 0.05 MMT CO_2 Eq. (less than 0.05 kt CH_4) in 2022 and have remained steady since 1990. Nitrous oxide emissions from the combustion of waste were estimated to be 0.3 MMT CO_2 Eq. (1.3 kt N_2O) in 2022 and have decreased by 18 percent since 1990. This decrease is driven by the decrease in total MSW combusted.

Table 3-27: CO_2, CH_4, and N_2O Emissions from the Combustion of Waste (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	12.9	13.3	13.3	12.9	12.9	12.5	12.4
CH_4	+	+	+	+	+	+	+
N_2O	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Total	**13.3**	**13.6**	**13.7**	**13.3**	**13.3**	**12.8**	**12.7**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 3-28: CO_2, CH_4, and N_2O Emissions from the Combustion of Waste (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	12,900	13,254	13,339	12,948	12,921	12,476	12,357
CH_4	+	+	+	+	+	+	+
N_2O	2	1	1	1	1	1	1

+ Does not exceed 0.05 kt.

Methodology and Time-Series Consistency

Municipal Solid Waste Combustion

To determine both CO_2 and non-CO_2 emissions from the combustion of waste, the tonnage of waste combusted and an estimated emissions factor are needed. Emission estimates from the combustion of tires are discussed separately. Data for total waste combusted was derived from *BioCycle* (van Haaren et al. 2010), EPA Facts and Figures Report, Energy Recovery Council (ERC), EPA's Greenhouse Gas Reporting Program (GHGRP), and the U.S. Energy Information Administration (EIA). Multiple sources were used to ensure a complete, quality dataset, as each source encompasses a different timeframe.

EPA determined the MSW tonnages based on data availability and accuracy throughout the time series.

- 1990-2006: MSW combustion tonnages are from Biocycle combustion data. Tire combustion data from the U.S. Tire Manufacturers Association (USTMA) are removed to arrive at MSW combusted without tires.
- 2006-2010: MSW combustion tonnages are an average of Biocycle (with USTMA tire data tonnage removed), U.S. EPA Facts and Figures, EIA, and Energy Recovery Council data (with USTMA tire data tonnage removed).
- 2011-2022: MSW combustion tonnages are from EPA's GHGRP data.

Table 3-29 provides the estimated tons of MSW combusted including and excluding tires.

Table 3-29: Municipal Solid Waste Combusted (Short Tons)

	1990	2005	2018	2019	2020	2021	2022
Waste Combusted *(excluding tires)*	33,344,839	26,486,414	29,162,364	28,174,311	27,586,271	27,867,446	26,338,130
Waste Combusted *(including tires)*	33,766,239	28,631,054	30,853,949	29,821,141	29,106,686	29,261,446	27,732,130

Sources: BioCycle, EPA Facts and Figures, ERC, GHGRP, EIA, USTMA.

CO_2 Emissions from MSW Excluding Scrap Tires

Fossil CO_2 emission factors were calculated from EPA's GHGRP data for non-biogenic sources. Using GHGRP-reported emissions for CH_4 and N_2O and assumed emission factors, the tonnage of waste combusted, excluding tires, was derived. Methane and N_2O emissions and assumed emission factors were used to estimate the amount of MSW combusted in terms of energy content. The energy content of MSW combusted was then converted into tonnage based on assumed MSW heating value. Two estimates were generated (one for CH_4 and one for N_2O) and the two were averaged together. Dividing fossil CO_2 emissions from GHGRP FLIGHT data for MSW combustors by this estimated tonnage yielded an annual CO_2 emission factor. As this data was only available following 2011, all years prior use an average of the emission factors from 2011 through 2015. See Annex 3.7 for more detail on how MSW carbon factors were calculated.

Finally, CO_2 emissions were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated fossil CO_2 emission factors are shown in Table 3-30.

Table 3-30: Calculated Fossil CO_2 Content per Ton Waste Combusted (kg CO_2/Short Ton Combusted)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Emission Factors	366	366	361	363	377	365	382

CO_2 Emissions from Scrap Tires

Scrap tires contain several types of synthetic rubber, carbon black, and synthetic fibers. Each type of synthetic rubber has a discrete carbon content, and carbon black is 100 percent C. For synthetic rubber and carbon black in scrap tires, information on average weight, disposal percentage, and total tires incinerated for energy was obtained biannually from U.S. Scrap Tire Management Summary for 2005 through 2022 data (USTMA 2022). Information about scrap tire composition was taken from the Rubber Manufacturers' Association internet site (USTMA 2012a). Emissions of CO_2 were calculated based on the amount of scrap tires used for fuel and the synthetic rubber and carbon black content of scrap tires. The mass of combusted material is multiplied by its carbon content to calculate the total amount of carbon stored. 2022 values are proxied from 2021 data. More detail on the methodology for calculating emissions from each of these waste combustion sources is provided in Annex 3.7. Table 3-31 provides CO_2 emissions from combustion of waste tires.

Table 3-31: CO_2 Emissions from Combustion of Tires (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Synthetic Rubber	0.3	1.6	1.3	1.2	1.1	1.0	1.0
C Black	0.4	2.0	1.5	1.5	1.4	1.3	1.3
Total	**0.7**	**3.6**	**2.8**	**2.7**	**2.5**	**2.3**	**2.3**

Non-CO_2 Emissions

Combustion of waste also results in emissions of CH_4 and N_2O. These emissions were calculated by multiplying the total estimated mass of waste combusted, including tires, by the respective emission factors. The emission factors for CH_4 and N_2O emissions per quantity of MSW combusted are default emission factors for the default continuously-fed stoker unit MSW combustion technology type and were taken from IPCC (2006).

Uncertainty

An Approach 2 Monte Carlo analysis was performed to determine the level of uncertainty surrounding the estimates of CO_2 emissions and N_2O emissions from the incineration of waste (given the very low emissions for CH_4, no uncertainty estimate was derived). IPCC Approach 2 analysis allows the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the *Inventory* estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for most variables; thus, uncertainty estimates for these variables were determined using assumptions based on source category knowledge and the known uncertainty estimates for the waste generation variables.

The uncertainties in the waste incineration emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include reported CO_2 emissions; N_2O and CH_4 emissions factors, and tire synthetic rubber and black carbon contents. The highest levels of uncertainty surround the reported emissions from GHGRP; the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, carbon content of carbon black).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-32. Waste incineration CO_2 emissions in 2022 were estimated to be between 10.3 and 14.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 17 percent below to 16 percent above the 2022 emission estimate of 12.4 MMT CO_2 Eq. Also at a 95 percent confidence level, waste incineration N_2O emissions in 2022 were estimated to be between 0.2 and 0.9 MMT CO_2 Eq. This indicates a range of 54 percent below to 164 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq.

Table 3-32: Approach 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from the Incineration of Waste (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Incineration of Waste	CO_2	12.4	10.3	14.4	-17%	16%
Incineration of Waste	N_2O	0.3	0.2	0.9	-54%	164%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates from waste combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and specifically focused on the emission factor and activity data sources and methodology used for estimating emissions from combustion of waste. Trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors in the use of activity data.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

Research was conducted to review the composition of carbon black abraded and stored in tires. No definitive sources were found that support updating the current factor of 28 percent carbon black for commercial and light duty tires. This factor was not updated, but additional research can be completed in future *Inventory* cycles.

3.4 Coal Mining (CRT Source Category 1B1a)

Three types of coal mining-related activities release CH_4 and CO_2 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. While surface coal mines account for the majority of U.S. coal production, underground coal mines contribute the largest share of fugitive CH_4 emissions (see Table 3-34 and Table 3-35) due to the higher CH_4 content of coal in the deeper underground coal seams. In 2022, 185 underground coal mines and 354 surface mines were operating in the United States (EIA 2023). In recent years, the total number of active coal mines in the United States has declined. In 2022, the United States was the fourth largest coal producer in the world, after China, India, and Indonesia (IEA 2022).

Table 3-33: Coal Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Underground							
Number of Mines	1,683	586	236	226	196	174	185
Production	384,244	334,399	249,804	242,557	177,380	200,122	201,525
Surface							
Number of Mines	1,656	789	430	432	350	332	354
Production	546,808	691,447	435,521	397,750	307,944	323,142	336,990
Total							
Number of Mines	**3,339**	**1,398**	**666**	**658**	**546**	**506**	**539**
Production	**931,052**	**1,025,846**	**685,325**	**640,307**	**485,324**	**523,264**	**538,515**

Fugitive CH_4 Emissions

Underground coal mines liberate CH_4 from ventilation systems and from degasification systems. Ventilation systems pump air through the mine workings to dilute noxious gases and ensure worker safety; these systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large, often highly concentrated volumes of CH_4 before, during, or after mining. Some mines recover and use CH_4 generated from ventilation and degasification systems, thereby reducing emissions to the atmosphere.

Surface coal mines liberate CH_4 as the overburden is removed and the coal is exposed to the atmosphere. Methane emissions are normally a function of coal rank (a classification related to the percentage of carbon in the coal) and depth. Surface coal mines typically produce lower-rank coals and remove less than 250 feet of overburden, so their level of emissions is much lower than from underground mines.

In addition, CH_4 is released during post-mining activities, as the coal is processed, transported, and stored for use.

Total CH_4 emissions in 2022 were estimated to be 1,558 kt (43.6 MMT CO_2 Eq.), a decline of approximately 60 percent since 1990 (see Table 3-34 and Table 3-35). In 2022, underground mines accounted for approximately 72 percent of total emissions, surface mines accounted for 14 percent, and post-mining activities accounted for 14 percent. In 2022, total CH_4 emissions from coal mining decreased by approximately 2 percent relative to the previous year. Total coal production in 2022 increased by 3 percent compared to 2021. This resulted in an increase of 4 percent in CH_4 emissions from surface mining and post-mining activities in 2022. However, surface mining and post-mining activities have a lower impact on total CH_4 compared to underground mining (72 percent of total emissions in 2022). The number of operating underground mines increased in 2022 and the amount of CH_4 recovered and used in 2022 increased by 25 percent compared to 2021. This resulted in a slight decrease in overall CH_4 emissions in 2022 (2 percent), compared to 2021.

Table 3-34: CH_4 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**83.1**	**46.7**	**43.6**	**38.5**	**35.2**	**32.9**	**31.5**
Liberated	90.6	66.9	66.7	56.6	53.7	52.3	55.7
Recovered & Used	(7.5)	(20.1)	(23.1)	(18.1)	(18.5)	(19.4)	(24.2)
Surface Mining	**12.0**	**13.3**	**7.8**	**7.2**	**5.4**	**5.7**	**6.0**
Post-Mining (UG)	**10.3**	**8.6**	**5.9**	**5.8**	**4.3**	**4.8**	**4.8**
Post-Mining (Surface)	**2.6**	**2.9**	**1.7**	**1.5**	**1.2**	**1.2**	**1.3**
Total	**108.1**	**71.5**	**59.1**	**53.0**	**46.2**	**44.7**	**43.6**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-35: CH_4 Emissions from Coal Mining (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**2,968**	**1,669**	**1,557**	**1,375**	**1,257**	**1,176**	**1,124**
Liberated	3,237	2,388	2,382	2,022	1,917	1,868	1,989
Recovered & Used	(269)	(720)	(825)	(646)	(660)	(692)	(865)
Surface Mining	**430**	**475**	**280**	**255**	**194**	**205**	**215**
Post-Mining (UG)	**368**	**306**	**212**	**206**	**155**	**170**	**173**
Post-Mining (Surface)	**93**	**103**	**61**	**55**	**42**	**44**	**47**
Total	**3,860**	**2,552**	**2,110**	**1,892**	**1,648**	**1,595**	**1,558**

Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses an IPCC Tier 3 method for estimating CH_4 emissions from underground coal mining and an IPCC Tier 2 method for estimating CH_4 emissions from surface mining and post-mining activities (for coal production from both underground mines and surface mines) in accordance with methodological decisions trees in IPCC guidelines (Volume 2, Chapter 4, Figure 4.1.1 and 4.1.2) and available data (IPCC 2006). The methodology for estimating CH_4 emissions from coal mining consists of two steps:

- Estimate CH_4 emissions from underground mines. These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total CH_4 liberated. The CH_4 recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- Estimate CH_4 emissions from surface mines and post-mining activities. Unlike the methodology for underground mines, which uses mine-specific data, the methodology for estimating emissions from surface mines and post-mining activities consists of multiplying basin-specific coal production by basin-specific gas content and an emission factor.

Step 1: Estimate CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and degasification systems. Some mines recover and

use the liberated CH_4, thereby reducing emissions to the atmosphere. Total CH_4 emitted from underground mines equals the CH_4 liberated from ventilation systems, plus the CH_4 liberated from degasification systems, minus the CH_4 recovered and used.

Step 1.1: Estimate CH_4 Liberated from Ventilation Systems

To estimate CH_4 liberated from ventilation systems, EPA uses data collected through its Greenhouse Gas Reporting Program (GHGRP)[62] (Subpart FF, "Underground Coal Mines"), data provided by the U.S. Mine Safety and Health Administration (MSHA) (MSHA 2023), and occasionally data collected from other sources on a site-specific level (e.g., state gas production databases). Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH_4 per year (about 17,525 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2023).[63] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems; they have the option of recording and reporting their own measurements, or using the measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the United States with detectable CH_4 concentrations.[64]

Since 2013, ventilation CH_4 emission estimates have been calculated based on both quarterly GHGRP data submitted by underground mines and on quarterly measurement data obtained directly from MSHA. Because not all mines report under EPA's GHGRP, the emissions of the mines that do not report must be calculated using MSHA data. The MSHA data also serves as a quality assurance tool for validating GHGRP data. For GHGRP data, reported quarterly ventilation methane emissions (metric tons) are summed for each mine to develop mine-specific annual ventilation emissions. For MSHA data, the average daily CH_4 emission rate for each mine is determined using the CH_4 total for all data measurement events conducted during the calendar year and total duration of all data measurement events (in days). The calculated average daily CH_4 emission rate is then multiplied by 365 days to estimate annual ventilation CH_4 emissions for the MSHA dataset.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Particularly gassy underground mines also use degasification systems (e.g., wells or boreholes) to remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Nineteen mines used degasification systems in 2022 and all of these mines reported the CH_4 removed through these systems to EPA's GHGRP under Subpart FF (EPA 2023). Based on the weekly measurements reported to EPA's GHGRP, degasification data summaries for each mine are added to estimate the CH_4 liberated from degasification systems. Twelve of the 19 mines with degasification systems had operational CH_4 recovery and use projects, including two mines with two recovery and use projects each (see step 1.3 below).[65]

Degasification data reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of CH_4 liberated from degasification systems. Data reported to EPA's GHGRP were used exclusively to estimate CH_4 liberated from degasification systems at 13 of the 19 mines that used degasification systems in 2022. Data from state gas well production databases were used to supplement GHGRP degasification data for the remaining six mines (DMME 2023; GSA 2023; WVGES 2023; McElroy OVS 2013).

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[62] In implementing improvements and integrating data from EPA's GHGRP, EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

[63] Underground coal mines report to EPA under Subpart FF of the GHGRP (40 CFR Part 98). In 2022, 61 underground coal mines reported to the program.

[64] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

[65] Several of the mines venting CH_4 from degasification systems use a small portion of the gas to fuel gob well blowers in remote locations where electricity is not available. However, this CH_4 use is not considered to be a formal recovery and use project.

For pre-mining wells, cumulative degasification volumes that occur prior to the well being mined through are attributed to the mine in the inventory year in which the well is mined through.[66] EPA's GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under Subpart FF.[67] Most pre-mining wells drilled from the surface are considered coalbed methane wells prior to mine-through and associated CH_4 emissions are reported under another subpart of the GHGRP (Subpart W, "Petroleum and Natural Gas Systems"). As a result, GHGRP data must be supplemented to estimate cumulative degasification volumes that occurred prior to well mine-through. There were four mines with degasification systems that include pre-mining wells that were mined through in 2022. For all of these mines, GHGRP data were supplemented with historical data from state gas well production databases (ERG 2023; GSA 2023), as well as with mine-specific information regarding the locations and dates on which the pre-mining wells were mined through (JWR 2010; El Paso 2009; ERG 2023).

Step 1.3: Estimate CH_4 Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

Twelve mines had a total of fourteen CH_4 recovery and use projects in place in 2022, including two mines that each have two recovery and use projects. Thirteen of these projects involved degasification systems with one mine having a ventilation air methane abatement project (VAM). Eleven of these mines sold the recovered CH_4 to a pipeline, including one that also used CH_4 to fuel a thermal coal dryer. One mine destroyed the recovered CH_4 (VAM) using regenerative thermal oxidation (RTO) without energy recovery and using enclosed flares.

The CH_4 recovered and used (or destroyed) at the twelve mines described above are estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the CH_4 recovered and used from six of the 12 mines that deployed degasification systems in 2022. Based on quarterly measurements, the GHGRP degasification destruction data summaries for each mine are added together to estimate the CH_4 recovered and used from degasification systems.
- State sales data were used to supplement GHGRP data to estimate CH_4 recovered and used from five mines that deployed degasification systems in 2022 (DMME 2023, ERG 2023, GSA 2023, and WVGES 2023). Four of these mines intersected pre-mining wells in 2022. Supplemental information is used for these mines because estimating CH_4 recovery and use from pre-mining wells requires additional data not reported under Subpart FF of EPA's GHGRP (see discussion in step 1.2 above) to account for the emissions avoided prior to the well being mined through. The supplemental data is obtained from state gas production databases as well as mine-specific information on the location and timing of mined-through pre-mining wells.
- For the single mine that employed VAM for CH_4 recovery and use, the estimates of CH_4 recovered and used were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2023). This mine also reported CH_4 reductions from flaring. GHGRP data were used to estimate CH_4 recovered and flared in 2022.

Step 2: Estimate CH_4 Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating CH_4 emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production obtained from the Energy Information Administration's *Annual Coal Report* (EIA 2023) is multiplied by basin-specific CH_4 contents (EPA 1996, 2005) and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions (King 1994; Saghafi

[66] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

[67] This applies for pre-drainage in years prior to the well being mined through. Beginning with the year the well is mined through, the annual volume of CH_4 liberated from a pre-drainage well is reported under Subpart FF of EPA's GHGRP.

2013). For post-mining activities, basin-specific coal production is multiplied by basin-specific CH_4 contents and a mid-range 32.5 percent emission factor for CH_4 desorption during coal transportation and storage (Creedy 1993). Basin-specific in situ gas content data were compiled from AAPG (1984) and USBM (1986).

Fugitive CO_2 Emissions

Methane and CO_2 are naturally occurring in coal seams and are collectively referred to as coal seam gas. These gases remain trapped in the coal seam until coal is mined (i.e., coal seam is exposed and fractured during mining operations). Fugitive CO_2 emissions occur during underground coal mining, surface coal mining, and post-mining activities. Methods and data to estimate fugitive CO_2 emissions from underground and surface coal mining are presented in the sections below. Fugitive CO_2 emissions from post-mining activities were not estimated due to the lack of an IPCC method and unavailability of data.

Total fugitive CO_2 emissions in 2022 were estimated to be 2,474 kt (2.5 MMT CO_2 Eq.), a decline of approximately 46 percent since 1990. In 2022, underground mines accounted for approximately 89 percent of total fugitive CO_2 emissions. In 2022, total fugitive CO_2 emissions from coal mining increased by approximately 1 percent relative to the previous year. This increase was due to an increase in annual coal production.

Table 3-36: CO_2 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**4.2**	**3.6**	**2.8**	**2.7**	**1.9**	**2.2**	**2.2**
Liberated	4.2	3.6	2.7	2.6	1.9	2.2	2.2
Recovered & Used	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Flaring	NO	NO	0.1	0.1	+	+	+
Surface Mining	**0.4**	**0.6**	**0.4**	**0.3**	**0.2**	**0.3**	**0.3**
Total	**4.6**	**4.2**	**3.1**	**3.0**	**2.2**	**2.5**	**2.5**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-37: CO_2 Emissions from Coal Mining (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**4,164**	**3,610**	**2,787**	**2,670**	**1,948**	**2,193**	**2,201**
Liberated	4,171	3,630	2,712	2,633	1,926	2,173	2,188
Recovered & Used	(8)	(21)	(23)	(18)	(19)	(19)	(24)
Flaring	NO	NO	97	55	41	40	38
Surface Mining	**443**	**560**	**353**	**322**	**249**	**262**	**273**
Total	**4,606**	**4,169**	**3,139**	**2,992**	**2,197**	**2,455**	**2,474**

NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses an IPCC Tier 1 method for estimating fugitive CO_2 emissions from underground coal mining and surface mining in accordance with methodological decisions trees in IPCC guidelines (Volume 2, Chapter 4, Figure 4.1.1a) and available data (IPCC 2019). IPCC methods and data to estimate fugitive CO_2 emissions from post-mining activities (for both underground and surface coal mining) are currently not available.

Step 1: Underground Mining

EPA used the following overarching IPCC equation to estimate fugitive CO_2 emissions from underground coal mines (IPCC 2019):

Equation 3-1: Estimating Fugitive CO_2 Emissions from Underground Mines

$$Total\ CO_2\ from\ Underground\ Mines = CO_2\ from\ underground\ mining - Amount\ of\ CO_2\ in\ gas\ recovered + CO_2\ from\ methane\ flaring$$

Step 1.1: Estimate Fugitive CO_2 Emissions from Underground Mining

EPA estimated fugitive CO_2 emissions from underground mining using the IPCC Tier 1 emission factor (5.9 m^3/metric ton) and annual coal production from underground mines (EIA 2023). The underground mining default emission factor accounts for all the fugitive CO_2 likely to be emitted from underground coal mining. Therefore, the amount of CO_2 from coal seam gas recovered and utilized for energy is subtracted from underground mining estimates in Step 2, below. Under IPCC methods, the CO_2 emissions from gas recovered and utilized for energy use (e.g., injected into a natural gas pipeline) are reported under other sectors of the *Inventory* (e.g., stationary combustion of fossil fuel or oil and natural gas systems) and not under the coal mining sector.

Step 1.2: Estimate Amount of CO_2 In Coal Seam Gas Recovered for Energy Purposes

EPA estimated fugitive CO_2 emissions from coal seam gas recovered and utilized for energy purposes by using the IPCC Tier 1 default emission factor (19.57 metric tons CO_2/million cubic meters of coal bed methane (CBM) produced) and quantity of coal seam gas recovered and utilized. Data on annual quantity of coal seam gas recovered and utilized are available from GHGRP and state sales data (GHGRP 2023; DMME 2023; ERG 2023; GSA 2023; WVGES 2023). The quantity of coal seam gas recovered and destroyed without energy recovery (e.g., VAM projects with RTO) is deducted from the total coal seam gas recovered quantity (McElroy OVS 2023).

Step 1.3: Estimate Fugitive CO_2 Emissions from Flaring

The IPCC method includes combustion CO_2 emissions from gas recovered for non-energy uses (i.e., flaring, or catalytic oxidation) under fugitive CO_2 emission estimates for underground coal mining. In effect, these emissions, though occurring through stationary combustion, are categorized as fugitive emissions in the *Inventory*. EPA estimated CO_2 emissions from methane flaring using the following equation:

Equation 3-2: Estimating CO_2 Emissions from Drained Methane Flared or Catalytically Oxidized

$$CO_2\ from\ flaring = 0.98 \times Volume\ of\ methane\ flared \times Conversion\ Factor \times Stoichiometric\ Mass\ Factor$$

Currently there are three mines that report destruction of recovered methane through flaring without energy use. Annual data for 2022 were obtained from one mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) and the GHGRP for the remaining two mines (McElroy OVS 2023; GHGRP 2023).

Step 2: Surface Mining

EPA estimated fugitive CO_2 emissions from surface mining using the IPCC Tier 1 emission factor (0.44 m^3/metric ton) and annual coal production from surface mines (EIA 2023).

Uncertainty

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. Because emission estimates of CH_4 from underground ventilation systems were based on actual measurement data from EPA's GHGRP or from MSHA, uncertainty is relatively low. A degree of imprecision was introduced because the ventilation air measurements

used were not continuous but rather quarterly instantaneous readings that were used to determine the average annual emission rates. Additionally, the measurement equipment used can be expected to have resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky & Wang 2000). Equipment measurement uncertainty is applied to GHGRP data.

Estimates of CH_4 liberated and recovered by degasification systems are relatively certain for utilized CH_4 because of the availability of EPA's GHGRP data and state gas sales information. Many of the liberation and recovery estimates use data on wells within 100 feet of a mined area. However, uncertainty exists concerning the radius of influence of each well. The number of wells counted, and thus the liberated CH_4 and avoided emissions, may vary if the drainage area is found to be larger or smaller than estimated.

EPA's GHGRP requires weekly CH_4 monitoring of mines that report degasification systems, and continuous CH_4 monitoring is required for CH_4 utilized on- or off-site. Since 2012, GHGRP data have been used to estimate CH_4 emissions from vented degasification wells, reducing the uncertainty associated with prior MSHA estimates used for this sub-source. Beginning in 2013, GHGRP data were also used for determining CH_4 recovery and use at mines without publicly available gas usage or sales records, which has reduced the uncertainty from previous estimation methods that were based on information from coal industry contacts.

Surface mining and post-mining emissions are associated with considerably more uncertainty than underground mines, because of the difficulty in developing accurate emission factors from field measurements. However, since underground coal mining, as a general matter, results in significantly larger CH_4 emissions due to production of higher-rank coal and greater depth, and estimated emissions from underground mining constitute the majority of estimated total coal mining CH_4 emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty.

The major sources of uncertainty for estimates of fugitive CO_2 emissions are the Tier 1 IPCC default emission factors used for underground mining (-50 percent to +100 percent) and surface mining (-67 percent to +200 percent) (IPCC 2019). Additional sources of uncertainty for fugitive CO_2 emission estimates include EIA's annual coal production data and data used for gas recovery projects, such as GHGRP data, state gas sales data, and VAM estimates for the single mine that operates an active VAM project. Uncertainty ranges for these additional data sources are already available, as these are the same data sources used for CH_4 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-38. Coal mining CH_4 emissions in 2022 were estimated to be between 34.8 and 47.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20.3 percent below to 9.5 percent above the 2022 emission estimate of 43.6 MMT CO_2 Eq. Coal mining fugitive CO_2 emissions in 2022 were estimated to be between 0.8 and 4.3 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 68.5 percent below to 75.4 percent above the 2022 emission estimate of 2.5 MMT CO_2 Eq.

Table 3-38: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Coal Mining (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal Mining	CH_4	43.6	34.8	47.8	-20%	+9%
Coal Mining	CO_2	2.5	0.8	4.3	-69%	+75%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for coal mining, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating fugitive emissions from

coal mining. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Emission estimates for coal mining rely in large part on data reported by coal mines to EPA's GHGRP. EPA verifies annual facility-level reports through a multi-step process to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. All reports submitted to EPA are evaluated by electronic validation and verification checks. If potential errors are identified, EPA will notify the reporter, who can resolve the issue either by providing an acceptable response describing why the flagged issue is not an error or by correcting the flagged issue and resubmitting their annual report. Additional QA/QC and verification procedures occur for each GHGRP subpart. No QA/QC issues or errors were identified in the 2022 Subpart FF data.

Recalculations Discussion

Time series recalculations were performed due to revised historical data from state natural gas sales databases for five mines, which are used to estimate avoided CH_4 emissions. Additionally, calculation errors were identified and corrected for CH_4 emissions avoided from two mines. As a result of recalculations, CH_4 emissions decreased by an average of 0.03 percent across the time series, compared to the previous *Inventory*. The biggest increase in CH_4 emissions was in 1991 where emissions increased by 0.14 percent, compared to the previous *Inventory*. The biggest decrease in CH_4 emissions was in 2006 (0.6 percent). As a result of recalculations, there was a very minor decrease in CH_4 emissions in 2021 (less than 0.005 percent), compared to the previous *Inventory*.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CH_4 and CO_2 emissions from underground and surface mining and CH_4 emissions from post-mining.

3.5 Abandoned Underground Coal Mines (CRT Source Category 1B1a)

Underground coal mines contribute the largest share of coal mine methane (CMM) emissions, with active underground mines the leading source of underground emissions. However, mines also continue to release CH_4 after closure. As mines mature and coal seams are mined through, mines are closed and abandoned. Many are sealed and some flood through intrusion of groundwater or surface water into the void. Shafts or portals are generally filled with gravel and capped with a concrete seal, while vent pipes and boreholes are plugged in a manner similar to oil and gas wells. Some abandoned mines are vented to the atmosphere to prevent the buildup of CH_4 that may find its way to surface structures through overburden fractures. As work stops within the mines, CH_4 liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH_4 at a near-steady rate over an extended period of time, or if flooded, produce gas for only a few years. The gas can migrate to the surface through the conduits described above, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when CH_4 migrates to the surface through cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned mine emissions:

- Time since abandonment;
- Gas content and adsorption characteristics of coal;
- CH_4 flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Annual gross abandoned mine CH_4 emissions ranged from 8.1 to 12.1 MMT CO_2 Eq. from 1990 to 2022, varying, in general, by less than 1 percent to approximately 19 percent from year to year. Fluctuations were due mainly to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. Gross abandoned mine emissions peaked in 1996 (12.1 MMT CO_2 Eq.) due to the large number of gassy mine[68] closures from 1994 to 1996 (72 gassy mines closed during the three-year period). In spite of this rapid rise, abandoned mine emissions have been generally on the decline since 1996. Since 2002, there have been fewer than twelve gassy mine closures each year. In 2022 there was one gassy mine closure. Gross abandoned mine emissions decreased slightly from 9.2 MMT CO_2 Eq. (330 kt CH_4) in 2021 to 9.1 (324 kt CH_4) MMT CO_2 Eq. in 2022 (see Table 3-39 and Table 3-40). Gross emissions are reduced by CH_4 recovered and used at 51 mines, resulting in net emissions in 2022 of 6.3 MMT CO_2 Eq. (225 kt CH_4).

Table 3-39: CH_4 Emissions from Abandoned Coal Mines (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Underground Mines	8.1	9.3	9.9	9.6	9.4	9.2	9.1
Recovered & Used	NO	(2.0)	(3.0)	(2.9)	(2.9)	(3.0)	(2.8)
Total	**8.1**	**7.4**	**6.9**	**6.6**	**6.5**	**6.3**	**6.3**

NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-40: CH_4 Emissions from Abandoned Coal Mines (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Underground Mines	288	334	355	341	335	330	324
Recovered & Used	NO	(70)	(107)	(104)	(103)	(106)	(100)
Total	**288**	**264**	**247**	**237**	**232**	**224**	**225**

NO (Not Occurring)
Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is primarily dependent on the mine's emissions when active and the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, the rate of coal mining, and the flow capacity of the mine in much the same way as the initial rate of a water-free conventional gas well reflects the gas content of the producing formation and the flow capacity of the well. A well or a mine that produces gas from a coal seam and the surrounding strata will produce less gas through time as the reservoir of gas is depleted. Depletion of a reservoir will follow a predictable pattern depending on the interplay of a variety of natural physical conditions imposed on the reservoir. The depletion of a reservoir is commonly modeled by mathematical equations and mapped as a type curve. Type curves, which are referred to as decline curves, have been developed for abandoned coal mines. Existing data on abandoned mine emissions through time, although sparse, appear to fit the hyperbolic type of decline curve used in forecasting production from natural gas wells.

There are sufficient mine level data available to establish decline curves for individual gassy mines abandoned since 1972. For mines abandoned prior to 1972, county level data are available. Mine status information (i.e., whether a mine is sealed, venting, or flooded) is not available for all the abandoned gassy mines. Therefore, a hybrid Tier 2/Tier 3 method was developed to model abandoned gassy mine emissions using Monte Carlo simulations. Tier 3 calculations are used for mines with known status information where decline curves can be used to directly estimate abandoned mine emissions. For mines with unknown status, a Tier 2 approach that estimates basin level emissions is used. This Tier 2 approach relies on data from other mines with known status

[68] A mine is considered a "gassy" mine if it emits more than 100 thousand cubic feet of CH_4 per day (100 Mcfd).

and located within the same basin as the unknown status mines. This approach is consistent with the IPCC 2006 Guidelines as underground mines can be considered point sources and measurement methods are available.

To estimate CH_4 emissions over time for a given abandoned mine, it is necessary to apply a decline function, initiated upon abandonment, to that mine. In the analysis, mines were grouped by coal basin with the assumption that they will generally have the same initial pressures, permeability, and isotherm. As CH_4 leaves the system, the reservoir pressure (Pr) declines as described by the isotherm's characteristics. The emission rate declines because the mine pressure (Pw) is essentially constant at atmospheric pressure for a vented mine, and the productivity index (PI), which is expressed as the flow rate per unit of pressure change, is essentially constant at the pressures of interest (atmospheric to 30 psia). The CH_4 flow rate is determined by the laws of gas flow through porous media, such as Darcy's Law. A rate-time equation can be generated that can be used to predict future emissions. This decline through time is hyperbolic in nature and can be empirically expressed as:

Equation 3-3: Decline Function to Estimate Venting Abandoned Mine Methane Emissions

$$q = q_i \left(1 + bD_i t\right)^{\left(-\frac{1}{b}\right)}$$

where,

q = Gas flow rate at time t in million cubic feet per day (mmcfd)

q_i = Initial gas flow rate at time zero (t_o), mmcfd

b = The hyperbolic exponent, dimensionless

D_i = Initial decline rate, 1/year

t = Elapsed time from t_o (years)

This equation is applied to mines of various initial emission rates that have similar initial pressures, permeability, and adsorption isotherms (EPA 2004).

The decline curves created to model the gas emission rate of coal mines must account for factors that decrease the rate of emissions after mining activities cease, such as sealing and flooding. Based on field measurement data, it was assumed that most U.S. mines prone to flooding will become completely flooded within eight years and therefore will no longer have any measurable CH_4 emissions. Based on this assumption, an average decline rate for flooded mines was established by fitting a decline curve to emissions from field measurements. An exponential equation was developed from emissions data measured at eight abandoned mines known to be filling with water located in two of the five basins. Using a least squares, curve-fitting algorithm, emissions data were matched to the exponential equation shown below. For this analysis of flooded abandoned mines, there was not enough data to establish basin-specific equations, as was done with the vented, non-flooding mines (EPA 2004). This decline through time can be empirically expressed as:

Equation 3-4: Decline Function to Estimate Flooded Abandoned Mine Methane Emissions

$$q = q_i e^{(-Dt)}$$

where,

q = Gas flow rate at time t in mmcfd

q_i = Initial gas flow rate at time zero (t_o), mmcfd

D = Decline rate, 1/year

t = Elapsed time from t_o (years)

Seals have an inhibiting effect on the rate of flow of CH_4 into the atmosphere compared to the flow rate that would exist if the mine had an open vent. The total volume emitted will be the same, but emissions will occur over a longer period of time. The methodology, therefore, treats the emissions prediction from a sealed mine similarly to the emissions prediction from a vented mine, but uses a lower initial rate depending on the degree of sealing. A

computational fluid dynamics simulator was used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The percent sealed is defined as 100 × (1 – [initial emissions from sealed mine / emission rate at abandonment prior to sealing]). Significant differences are seen between 50 percent, 80 percent, and 95 percent closure. These decline curves were therefore used as the high, middle, and low values for emissions from sealed mines (EPA 2004).

For active coal mines, those mines producing over 100 thousand cubic feet per day (Mcfd) of CH_4 account for about 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that the 531 abandoned mines closed since 1972 produced CH_4 emissions greater than 100 Mcfd when active. Further, the status of 307 of the 531 mines (or 58 percent) is known to be either: 1) vented to the atmosphere; 2) sealed to some degree (either earthen or concrete seals); or 3) flooded (enough to inhibit CH_4 flow to the atmosphere). The remaining 42 percent of the mines whose status is unknown were placed in one of these three categories by applying a probability distribution analysis based on the known status of other mines located in the same coal basin (EPA 2004). Table 3-41 presents the count of mines by post-abandonment state, based on EPA's probability distribution analysis.

Table 3-41: Number of Gassy Abandoned Mines Present in U.S. Basins in 2022, Grouped by Class According to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	43	25	50	118	144	262
Illinois	35	3	14	52	31	83
Northern Appl.	49	23	15	87	39	126
Warrior Basin	0	0	16	16	0	16
Western Basins	28	4	2	34	10	44
Total	**155**	**55**	**97**	**307**	**224**	**531**

Note: Totals may not sum due to independent rounding.

Inputs to the decline equation require the average CH_4 emission rate prior to abandonment and the date of abandonment. Generally, these data are available for mines abandoned after 1971; however, such data are largely unknown for mines closed before 1972. Information that is readily available, such as coal production by state and county, is helpful but does not provide enough data to directly employ the methodology used to calculate emissions from mines abandoned before 1972. It is assumed that pre-1972 mines are governed by the same physical, geologic, and hydrologic constraints that apply to post-1971 mines; thus, their emissions may be characterized by the same decline curves.

During the 1970s, 78 percent of CH_4 emissions from coal mining came from seventeen counties in seven states. Mine closure dates were obtained for two states, Colorado and Illinois, for the hundred-year period extending from 1900 through 1999. The data were used to establish a frequency of mine closure histogram (by decade) and applied to the other five states with gassy mine closures. As a result, basin-specific decline curve equations were applied to the 145 gassy coal mines estimated to have closed between 1920 and 1971 in the United States, representing 78 percent of the emissions. State-specific, initial emission rates were used based on average coal mine CH_4 emission rates during the 1970s (EPA 2004).

Abandoned mine emission estimates are based on all closed mines known to have active mine CH_4 ventilation emission rates greater than 100 Mcfd at the time of abandonment. For example, for 1990 the analysis included 145 mines closed before 1972 and 258 mines closed between 1972 and 1990. Initial emission rates based on MSHA reports, time of abandonment, and basin-specific decline curves influenced by a number of factors were used to calculate annual emissions for each mine in the database (MSHA 2023). Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect only ventilation emissions for pre-1990 closures. Methane degasification amounts were added to the quantity of CH_4 vented to determine the total CH_4 liberation rate for all mines that closed between 1992 and 2022. Since the sample of gassy mines described above is assumed to account for 78 percent of the pre-1972 and 98 percent of the post-1971 abandoned mine emissions, the modeled results were multiplied by 1.22 and 1.02, respectively, to account for all U.S. abandoned mine emissions.

From 1993 through 2022, emission totals were downwardly adjusted to reflect CH_4 emissions avoided from abandoned mines with CH_4 recovery and use or destruction systems. Currently, there are 51 abandoned mines with recovery projects, including 11 projects at mines abandoned before 1972 (pre-1972 mines) (EPA 2004, CMOP 2022). Because CH_4 recovered by these projects is expected to decline with the age of the mine, CH_4 recovery is assumed to be the total estimated CH_4 liberated based on the mine's decline function except for three recovery projects where additional data are available (COGIS 2018, MSHA 2023).[69]

The *Inventory* totals were not adjusted for abandoned mine CH_4 emissions avoided from 1990 through 1992 due to unavailability of data. Avoided CH_4 emissions from pre-1972 abandoned mines are estimated by multiplying the total estimated emissions from these mines in each decade by the fraction of mines with recovery projects in that decade. For recovery projects at pre-1972 abandoned mines, four projects are at mines abandoned in the 1920s, three in the 1930s, two in the 1950s, and two in the 1960s (EPA 2004).

Reviewing Coalbed Methane Outreach Program data (CMOP 2023) revealed four additional recovery projects starting in 2021. In addition to reviewing CMOP data, the recovery project list was checked against the International Coal Mine Methane Database (GMI 2021). Of the 24 operational recovery projects for U.S. abandoned coal mines currently available in the GMI dataset, 18 are already included in the AMM model. The remaining six projects in the GMI dataset are for mines that are not yet abandoned according to MSHA records (MSHA 2023). Therefore, no new recovery projects were added from the GMI database for the 1990 through 2022 *Inventory*.

Uncertainty

A quantitative uncertainty analysis was conducted for the abandoned coal mine source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. The uncertainty analysis provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the *Inventory* estimate. The results provide the range within which, with 95 percent certainty, emissions from this source category are likely to fall.

As discussed above, the parameters for which values must be estimated for each mine to predict its decline curve are: 1) the coal's adsorption isotherm; 2) CH_4 flow capacity as expressed by permeability; and 3) pressure at abandonment. Because these parameters are not available for each mine, a methodological approach to estimating emissions was used that generates a probability distribution of potential outcomes based on the most likely value and the probable range of values for each parameter. The range of values is not meant to capture the extreme values, but rather values that represent the highest and lowest quartile of the cumulative probability density function of each parameter. Once the low, mid, and high values are selected, they are applied to a probability density function.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-42. Annual abandoned coal mine CH_4 emissions in 2022 were estimated to be between 5.0 and 7.5 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 21 percent below to 20 percent above the 2022 emission estimate of 6.3 MMT CO_2 Eq. One of the reasons for the relatively narrow range is that mine-specific data is available for use in the methodology for mines closed in 1972 and later years. Emissions from mines closed prior to 1972 have the largest degree of uncertainty because no mine-specific CH_4 liberation rates at the time of abandonment exist.

[69] Data from a state oil and gas database (COGIS) is used for one project and the mine status information from MSHA for two mines (sealed and flooded) indicate zero recovery emissions for these projects.

Table 3-42: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Underground Coal Mines	CH_4	6.3	5.0	7.5	-21%	+20%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for abandoned coal mines, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating emissions from abandoned coal mines. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Recalculations Discussion

Four new abandoned mine methane recovery projects were added to the AMM model during the current *Inventory* (CMOP 2023). CMOP data indicate these recovery projects were started in 2021. Time series recalculations were performed for 2021. As a result of recalculations, CH_4 emissions decreased by 2 percent in 2021, compared to the previous *Inventory*.

3.6 Petroleum Systems (CRT Source Category 1B2a)

This category (1B2a) is defined in the IPCC methodological guidance as fugitive emissions from petroleum systems, which per IPCC guidelines include emissions from leaks, venting, and flaring. Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil exploration, production, transportation, and refining operations. During these activities, CH_4 is released to the atmosphere as emissions from leaks, venting (including emissions from operational upsets), and flaring. Carbon dioxide emissions from petroleum systems are primarily associated with onshore and offshore crude oil production and refining operations. Note, CO_2 emissions in petroleum systems exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in the fossil fuel combustion chapter (see Section 3.1). Emissions of N_2O from petroleum systems are primarily associated with flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from petroleum systems in 2022 were 61.6 MMT CO_2 Eq., an increase of 4 percent from 1990, primarily due to increases in CO_2 emissions. Total emissions decreased by 6 percent from 2010 levels and have decreased by 15 percent since 2021. Total CO_2 emissions from petroleum systems in 2022 were 21.97 MMT CO_2 (21,967 kt CO_2), 2.3 times higher than in 1990. Total CO_2 emissions in 2022 were 1.6 times higher than in 2010 and 9 percent lower than in 2021. Total CH_4 emissions from petroleum systems in 2022 were 39.6 MMT CO_2 Eq. (1,415 kt CH_4), a decrease of 20 percent from 1990. Since 2010, total CH_4 emissions decreased by 24 percent; and since 2021, CH_4 emissions decreased by 19 percent. Total N_2O emissions from petroleum systems in 2022 were 0.048 MMT CO_2 Eq. (0.179 kt N_2O), 3.8 times higher than in 1990, 2.8 times higher than in 2010, and 142 percent higher than in 2021. Since 1990, U.S. oil production has increased by 56 percent. In 2022, U.S. oil production was 163 percent higher than in 2010 and 7 percent higher than in 2021.

Each year, some estimates in the *Inventory* are recalculated with improved methods and/or data. These improvements are implemented consistently across the entire *Inventory's* time series (i.e., 1990 to 2022) to ensure that the trend is representative of changes in emissions levels. Recalculations in petroleum systems in this year's *Inventory* include:

- Updates to oil and gas production volumes, produced water production volumes, and well counts using the most recent data from Enverus.
- Updates to oil and gas production volumes using the most recent data from the United States Energy Information Administration (EIA)
- Recalculations due to Greenhouse Gas Reporting Program (GHGRP) submission revisions
- Recalculations due to methodological updates to completions and workovers.

The Recalculations Discussion section below provides more details on the updated methods.

Exploration. Exploration includes well drilling, testing, and completions. Exploration accounts for less than 0.5 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The predominant sources of CH_4 emissions from exploration are hydraulically fractured oil well completions. Other sources include well testing, well drilling, and well completions without hydraulic fracturing. Since 1990, exploration CH_4 emissions have decreased 96 percent, and while the number of hydraulically fractured wells completed increased 64 percent, there were decreases in the fraction of such completions without reduced emissions completions (RECs) or flaring. Emissions of CH_4 from exploration were highest in 2008, over 70 times higher than in 2022; and lowest in 2022. Emissions of CH_4 from exploration decreased 39 percent from 2021 to 2022, due to a decrease in emissions from hydraulically fractured oil well completions with RECs. Exploration accounts for 1 percent of total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. Emissions of CO_2 from exploration in 2022 were 25 percent lower than in 1990, and decreased by 50 percent from 2021, largely due to a decrease in emissions from hydraulically fractured oil well completions with REC and flaring (by 58 percent from 2021). Emissions of CO_2 from exploration were highest in 2014, over 13 times higher than in 2022. Exploration accounts for less than 0.5 percent of total N_2O emissions from petroleum systems in 2022. Emissions of N_2O from exploration in 2022 are 29 percent lower than in 1990, and 56 percent lower than in 2021, due to hydraulically fractured oil well completions with flaring.

Production. Production accounts for 97 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The predominant sources of emissions from production field operations are pneumatic controllers, offshore oil platforms, equipment leaks, produced water, gas engines, chemical injection pumps, and associated gas flaring. In 2022, these seven sources together accounted for 93 percent of the CH_4 emissions from production. Since 1990, CH_4 emissions from production have decreased by 15 percent primarily due to decreases in emissions from offshore production. Overall, production segment CH_4 emissions decreased by 19 percent from 2021 levels due primarily to lower pneumatic controller emissions. Production emissions account for 86 percent of the total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The principal sources of CO_2 emissions are associated gas flaring, miscellaneous production flaring, and oil tanks with flares. In 2022, these three sources together accounted for 96 percent of the CO_2 emissions from production. In 2022, CO_2 emissions from production were 3.1 times higher than in 1990, due to increases in flaring emissions from associated gas flaring, miscellaneous production flaring, and tanks. Overall, in 2022, production segment CO_2 emissions decreased by 8 percent from 2021 levels primarily due to decreases in associated gas flaring in the Williston Basin and oil tanks with flares. Production emissions accounted for 84 percent of the total N_2O emissions from petroleum systems in 2022. The principal sources of N_2O emissions are oil tanks with flares and associated gas flaring, accounting for 90% of N_2O emissions from the production segment in 2022. In 2022, N_2O emissions from production were 8.0 times higher than in 1990 and were 3.5 times higher than in 2021.

Crude Oil Transportation. Emissions from crude oil transportation account for a very small percentage of the total emissions (including leaks, vents, and flaring) from petroleum systems. Crude oil transportation activities account for 0.6 percent of total CH_4 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations accounted for 81 percent of CH_4 emissions from crude oil transportation in 2022. Since 1990,

CH_4 emissions from transportation have increased by 27 percent. In 2022, CH_4 emissions from transportation increased by 6 percent from 2021 levels. Crude oil transportation activities account for less than 0.01 percent of total CO_2 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations account for 81 percent of CO_2 emissions from crude oil transportation.

Crude Oil Refining. Crude oil refining processes and systems account for 2 percent of total fugitive (including leaks, vents, and flaring) CH_4 emissions from petroleum systems in 2022. This low share is because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is a negligible amount of CH_4 in all refined products. Within refineries, flaring accounts for 42 percent of the CH_4 emissions, while delayed cokers, uncontrolled blowdowns, and equipment leaks account for 19, 14 and 11 percent, respectively. Fugitive CH_4 emissions from refining of crude oil have decreased by 4 percent since 1990, and decreased by 3 percent from 2021; however, like the transportation subcategory, this increase has had little effect on the overall emissions of CH_4 from petroleum systems. Crude oil refining processes and systems account for 13 percent of total fugitive (including leaks, vents, and flaring) CO_2 emissions from petroleum systems. Of the total fugitive CO_2 emissions from refining, almost all (about 99 percent) of it comes from flaring.[70] Since 1990, refinery fugitive CO_2 emissions decreased by 10 percent and have decreased by 5 percent from 2021 levels, due to a decrease in flaring. Flaring occurring at crude oil refining processes and systems accounts for 16 percent of total fugitive N_2O emissions from petroleum systems. In 2022, refinery fugitive N_2O emissions increased by 4 percent since 1990 and decreased by 5 percent from 2021 levels.

Table 3-43: Total Greenhouse Gas Emissions (CO_2, CH_4, and N_2O) from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	3.4	5.7	3.2	2.5	1.1	0.8	0.4
Production	51.6	48.1	86.7	90.6	77.3	68.0	57.4
Transportation	0.2	0.1	0.2	0.3	0.2	0.2	0.2
Crude Refining	3.9	4.4	3.7	4.4	3.6	3.7	3.6
Total	**59.0**	**58.5**	**93.8**	**97.8**	**82.3**	**72.8**	**61.6**

Note: Totals may not sum due to independent rounding.

Table 3-44: CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	**3.0**	**5.3**	**0.5**	**0.5**	**0.3**	**0.2**	**0.1**
Production	**45.5**	**42.0**	**57.5**	**50.6**	**52.0**	**47.5**	**38.6**
Pneumatic Controllers	21.3	22.7	34.7	24.7	31.3	28.1	19.4
Offshore Production	9.9	7.2	5.5	5.4	5.1	5.1	5.1
Equipment Leaks	2.3	2.8	3.7	3.9	3.2	3.2	3.1
Gas Engines	2.3	2.0	2.5	2.6	2.5	2.4	2.5
Produced Water	2.6	1.8	2.7	2.8	2.5	2.6	2.7
Chemical Injection Pumps	1.3	2.2	3.0	3.4	2.7	2.4	2.2
Assoc Gas Flaring	0.6	0.4	1.9	2.5	1.3	1.0	0.8
Other Sources	5.3	2.8	3.5	5.3	3.3	2.7	2.7
Crude Oil Transportation	**0.2**	**0.1**	**0.2**	**0.3**	**0.2**	**0.2**	**0.2**
Refining	**0.7**	**0.8**	**0.8**	**0.9**	**0.7**	**0.7**	**0.7**
Total	**49.4**	**48.2**	**59.0**	**52.2**	**53.3**	**48.6**	**39.6**

Note: Totals may not sum due to independent rounding.

[70] Petroleum Systems includes fugitive emissions (leaks, venting, and flaring). In many industries, including petroleum refineries, the largest source of onsite CO_2 emissions is often fossil fuel combustion, which is covered in Section 3.1 of this chapter.

Table 3-45: CH_4 Emissions from Petroleum Systems (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	**106**	**189**	**19**	**16**	**12**	**7**	**4**
Production	**1,626**	**1,500**	**2,052**	**1,809**	**1,858**	**1,696**	**1,377**
Pneumatic Controllers	761	811	1,240	881	1,119	1,003	694
Offshore Production	353	259	197	193	183	182	182
Equipment Leaks	82	101	132	138	115	114	112
Gas Engines	81	70	91	93	89	87	88
Produced Water	92	64	95	99	90	92	95
Chemical Injection Pumps	47	80	108	123	96	85	80
Assoc Gas Flaring	20	14	66	91	47	35	30
Other Sources	189	100	124	190	119	97	98
Crude Oil Transportation	**7**	**5**	**8**	**9**	**8**	**8**	**8**
Refining	**26**	**29**	**28**	**31**	**26**	**25**	**25**
Total	**1,765**	**1,723**	**2,108**	**1,865**	**1,904**	**1,737**	**1,415**

Note: Totals may not sum due to independent rounding.

Table 3-46: CO_2 Emissions from Petroleum Systems (MMT CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	0.4	0.5	2.7	2.0	0.8	0.6	0.3
Production	6.0	6.1	29.2	39.9	25.2	20.5	18.8
Transportation	+	+	+	+	+	+	+
Crude Refining	3.2	3.6	2.9	3.6	2.9	3.0	2.9
Total	**9.6**	**10.2**	**34.8**	**45.5**	**28.9**	**24.1**	**22.0**

+ Does not exceed 0.05 MMT CO_2.

Note: Totals may not sum due to independent rounding.

Table 3-47: CO_2 Emissions from Petroleum Systems (kt CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	398	465	2,684	2,044	798	601	300
Production	6,012	6,143	29,215	39,882	25,244	20,516	18,793
Transportation	0.9	0.7	1.2	1.3	1.2	1.1	1.2
Crude Refining	3,174	3,602	2,877	3,571	2,893	3,021	2,872
Total	**9,585**	**10,210**	**34,777**	**45,498**	**28,937**	**24,140**	**21,967**

Table 3-48: N_2O Emissions from Petroleum Systems (Metric Tons CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	180	209	1,161	820	353	290	127
Production	4,996	4,588	30,822	28,047	13,614	11,414	39,859
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	7,262	8,243	7,405	9,312	7,575	7,920	7,523
Total	**12,438**	**13,040**	**39,387**	**38,180**	**21,542**	**19,624**	**47,510**

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-49: N_2O Emissions from Petroleum Systems (Metric Tons N_2O)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	0.7	0.8	4.4	3.1	1.3	1.1	0.5
Production	18.9	17.3	116.3	105.8	51.4	43.1	150.4
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	27.4	31.1	27.9	35.1	28.6	29.9	28.4
Total	**46.9**	**49.2**	**148.6**	**144.1**	**81.3**	**74.1**	**179.3**

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

See Annex 3.5 for the full time series of emissions data, activity data, emission factors, and additional information on methods and data sources.

Petroleum systems includes emission estimates for activities occurring in petroleum systems from the oil wellhead through crude oil refining, including activities for crude oil exploration, production field operations, crude oil transportation activities, and refining operations. Generally, emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by corresponding activity data (e.g., equipment count or frequency of activity). Certain sources within petroleum refineries are developed using an IPCC Tier 3 approach (i.e., all refineries in the nation report facility-level emissions data to the GHGRP, which are included directly in the national emissions estimates here). Other estimates are developed with a Tier 2 approach. Tier 1 approaches are not used.

EPA did not receive stakeholder feedback on updates in the *Inventory* through EPA's stakeholder process on oil and gas in the *Inventory*. More information on the stakeholder process can be found online.[71]

Emission Factors. Key references for emission factors include *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (GRI/EPA 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997), *Global Emissions of Methane from Petroleum Sources* (API 1992), consensus of industry peer review panels, Bureau of Ocean Energy Management (BOEM) reports, *Nonpoint Oil and Gas Emission Estimation Tool* (EPA 2017), and analysis of GHGRP data (EPA 2023).

Emission factors for hydraulically fractured (HF) oil well completions and workovers (in four control categories) were developed at the basin level using EPA's GHGRP data; year-specific data were used to calculate basin-specific emission factors from 2016-forward and the year 2016 emission factors were applied to all prior years in the time series. For basins not reporting to the GHGRP, Subpart W average emission factors were used. For more information, please see the 2023 memoranda available online.[72]

The emission factors for well testing and associated gas venting and flaring were developed using year-specific GHGRP data for years 2015 forward; earlier years in the time series use 2015 emission factors. For miscellaneous production flaring, year-specific emission factors were developed for years 2015 forward from GHGRP data, an emission factor of 0 (assumption of no flaring) was assumed for 1990 through 1992, and linear interpolation was applied to develop emission factors for 1993 through 2014. For more information, please see memoranda available online.[73] For offshore oil production, emission factors were calculated using BOEM data for offshore facilities in federal waters of the Gulf of Mexico (and these data were also applied to facilities located in state waters of the Gulf of Mexico) and GHGRP data for offshore facilities off the coasts of California and Alaska. For

[71] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[72] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[73] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

many other sources, emission factors were held constant for the period 1990 through 2022, and trends in emissions reflect changes in activity levels. Emission factors from EPA 1999 are used for all other production and transportation activities.

For associated gas venting and flaring and miscellaneous production flaring, emission factors were developed on a production basis (i.e., emissions per unit oil produced). Additionally, for these two sources, basin-specific activity and emission factors were developed for each basin that in any year from 2011 forward contributed at least 10 percent of total source emissions (on a CO_2 Eq. basis) in the GHGRP. For associated gas venting and flaring, basin-specific factors were developed for four basins: Williston, Permian, Gulf Coast, and Anadarko. For miscellaneous production flaring, basin-specific factors were developed for three basins: Williston, Permian, and Gulf Coast. For each source, data from all other basins were combined, and activity and emission factors were developed for the other basins as a single group.

For pneumatic controllers and tanks, basin-specific emission factors were calculated for all the basins reporting to the GHGRP. These emission factors were calculated for all the years with applicable GHGRP data (i.e., 2011 - 2022 or 2015 - 2022). For the remaining basins (i.e., basins not reporting to the GHGRP), Subpart W average emission factors were used. For more information, please see memoranda available online.[3]

For the exploration and production segments, in general, CO_2 emissions for each source were estimated with GHGRP data or by multiplying CO_2 content factors by the corresponding CH_4 data, as the CO_2 content of gas relates to its CH_4 content. Sources with CO_2 emission estimates calculated using GHGRP data include HF completions and workovers, associated gas venting and flaring, tanks, well testing, pneumatic controllers, chemical injection pumps, miscellaneous production flaring, and certain offshore production facilities (those located off the coasts of California and Alaska). For these sources, CO_2 was calculated using the same methods as used for CH_4. Carbon dioxide emission factors for offshore oil production in the Gulf of Mexico were derived using data from BOEM, following the same methods as used for CH_4 estimates. For other sources, the production field operations emission factors for CO_2 are generally estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in produced associated gas.

For the exploration and production segments, N_2O emissions were estimated for flaring sources using GHGRP or BOEM OGOR-B data and the same method used for CO_2. Sources with N_2O emissions in the exploration segment include well testing and HF completions with flaring. Sources with N_2O emissions in the production segment include associated gas flaring, tank flaring, miscellaneous production flaring, HF workovers with flaring, and flaring from offshore production sources.

For crude oil transportation, emission factors for CH_4 were largely developed using data from EPA (1997), API (1992), and EPA (1999). Emission factors for CO_2 were estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in whole crude post-separator.

For petroleum refining activities, year-specific emissions from 2010 forward were directly obtained from EPA's GHGRP. All U.S. refineries have been required to report CH_4, CO_2, and N_2O emissions for all major activities starting with emissions that occurred in 2010. The reported total CH_4, CO_2, and N_2O emissions for each activity was used for the emissions in each year from 2010 forward. To estimate emissions for 1990 to 2009, the 2010 to 2013 emissions data from GHGRP along with the refinery feed data for 2010 to 2013 were used to derive CH_4 and CO_2 emission factors (i.e., sum of activity emissions/sum of refinery feed) and 2010 to 2017 data were used to derive N_2O emission factors; these emission factors were then applied to the annual refinery feed in years 1990 to 2009. GHGRP delayed coker CH_4 emissions for 2010 through 2017 were increased using the ratio of certain reported emissions for 2018 to 2017, to account for a more accurate GHGRP calculation methodology that was implemented starting in reporting year 2018.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5.

Activity Data. References for activity data include Enverus data (Enverus 2023), Energy Information Administration (EIA) reports, *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (EPA/GRI 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), consensus of industry peer review panels, BOEM reports, the Oil & Gas Journal, the Interstate Oil and Gas Compact Commission, the United States Army Corps of Engineers, and analysis of GHGRP data (EPA 2023).

For HF oil well completions and workovers, pneumatic controllers, equipment leaks, chemical injection pumps, and tanks, basin-specific activity factors were calculated for all the basins reporting to the GHGRP. These factors were calculated for all the years with applicable GHGRP data (i.e., 2011 through 2022, 2016 through 2022, or 2015 through 2022). For the remaining basins (i.e., basins not reporting to the GHGRP), GHGRP average activity factors were used. For more information, please see memoranda available online.[74]

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed to estimate values, consistent with IPCC good practice. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA/GRI (1996) and/or GHGRP data. In some cases, activity data are developed by interpolating between recent data points (such as from GHGRP) and earlier data points, such as from EPA/GRI (1996). Lastly, in limited instances the previous year's data were used if current year data were not yet available.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5. The United States reports data to the UNFCCC using this *Inventory* report along with Common Reporting Tables (CRTs). This note is provided for those reviewing the CRTs: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRT 1.B.2. Disaggregating flaring and venting estimates across the Inventory would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

As noted above, EPA's GHGRP data, available starting in 2010 for refineries and in 2011 for other sources, have improved estimates of emissions from petroleum systems. Many of the previously available datasets were collected in the 1990s. To develop a consistent time series for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2009 or 2014 by interpolating activity data or emission factors or both between 1992 (when GRI/EPA data are available) and 2010 or 2015 data points. Information on time-series consistency for sources updated in this year's *Inventory* can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For information on other sources, please see the Methodology and Time-Series Consistency discussion above and Annex 3.5.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize uncertainty for petroleum systems. For more information on the approach, please see the memoranda *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* (*2018 uncertainty memo)* and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates (2021 uncertainty memo)*.[75]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from petroleum systems for the current *Inventory*. For the CH_4 uncertainty analysis, EPA focused on the eight highest methane-emitting sources for the year 2022, which together emitted 75 percent of methane from petroleum systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. For the CO_2 uncertainty analysis, EPA focused on the five highest-emitting sources for the year 2022 which together emitted 81 percent of CO_2 from petroleum systems in 2022, and extrapolated the estimated uncertainty for the remaining

[74] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[75] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

sources. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. For emission factors that are derived from methane emissions measurement studies, the PDFs are commonly determined to be lognormally distributed (GRI/EPA 1996; EPA 1999). For activity data that are derived from national datasets, the PDFs are set to a uniform distribution (see 2018 and 2021 uncertainty memos). Many emission factors and activity factors are calculated using subpart W data, and for these, the @RISK add-in determines the best fitting PDF (e.g., lognormal, gaussian), based on bootstrapping of the underlying data (see 2018 and 2021 uncertainty memos). The IPCC guidance notes that in using this Approach 2 method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. To estimate uncertainty for N_2O, EPA applied the uncertainty bounds calculated for CO_2. EPA will seek to refine this estimate in future *Inventories*.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2022, using the recommended IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-50. Petroleum systems CH_4 emissions in 2022 were estimated to be between 32.7 and 48.6 MMT CO_2 Eq., while CO_2 emissions were estimated to be between 17.9 and 27.4 MMT CO_2 Eq. at a 95 percent confidence level. Petroleum systems N_2O emissions in 2022 were estimated to be between 0.039 and 0.059 MMT CO_2 Eq. at a 95 percent confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, associated gas venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., reduced emissions completions were not used early in the time series).

Table 3-50: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petroleum Systems	CH_4	39.6	32.7	48.6	-18%	+23%
Petroleum Systems	CO_2	22.0	17.9	27.4	-19%	+25%
Petroleum Systems	N_2O	0.048	0.039	0.059	-19%	+25%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2022 CH_4 and CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

QA/QC and Verification Discussion

In order to ensure the quality of the emission estimates for petroleum systems, general (IPCC Tier 1) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8.

The petroleum systems emission estimates in the *Inventory* are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the emission calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the *Inventory* are consistent with current industry practices. EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[76]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review of the current *Inventory*. EPA held a stakeholder webinar on greenhouse gas data for oil and gas in October of 2023. EPA released memos detailing updates under consideration and requesting stakeholder feedback. EPA did not receive stakeholder feedback for the updates under consideration for the current *Inventory*.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the *Inventory*. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes, and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of *Inventory* estimates. In the past few years, EPA has reviewed, and in many cases, incorporated data from these data sources. The second type of study can provide general indications on potential over- and under-estimates.

A key challenge in using these types of studies to assess *Inventory* results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the *Inventory* and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level *Inventory* with measurement results that may be at other spatial and temporal scales, EPA has developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[77] The most recent version of the gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* estimates for the years 2012 through 2018. The gridded inventory improves efforts to compare results of this *Inventory* with atmospheric studies.

As discussed above, refinery emissions are quantified by using the total emissions reported to GHGRP for the refinery emission categories included in petroleum systems. Subpart Y has provisions that refineries are not required to report under Subpart Y if their emissions fall below certain thresholds. Each year, a review is conducted to determine whether an adjustment is needed to the Inventory emissions to include emissions from refineries that stopped reporting to the GHGRP. Based on the review of the most recent GHGRP data, EPA did not identify any additional refineries that would require gap filling. There are a total of 7 refineries that EPA previously identified (i.e., during the 1990 through 2021 *Inventory* and prior versions) as not reporting to the GHGRP and continued to gap fill annual emissions for these refineries. EPA used the last reported emissions (by source) for these refineries as proxy to gap fill annual emissions.

[76] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[77] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting and presented information to stakeholders regarding the updates under consideration. In November 2023, EPA released draft memoranda that discussed changes under consideration and requested stakeholder feedback on those changes. EPA then released final memoranda documenting the methodology implemented in the current Inventory.[78] The memorandum cited in the Recalculations Discussion below is: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Completion and Workover Emissions (*Completions and Workovers* memo).

EPA evaluated relevant information available and made an updates to the *Inventory* for hydraulically fractured (HF) oil well completions and workovers. General information for these source specific recalculations are presented below and details are available in the *Completions and Workovers* memo.

In addition to the updates to the sources mentioned above, for certain sources, CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. The emissions changes were mostly due to GHGRP data submission revisions. These sources are discussed below and include associated gas flaring, miscellaneous production flaring, pneumatic controllers, oil tanks, chemical injection pumps, produced water, offshore production (in Gulf of Mexico federal waters), gas engines, and refinery flaring.

The combined impact of revisions to 2021 petroleum systems CH_4 emission estimates on a CO_2-equivalent basis, compared to the previous *Inventory*, is a decrease from 50.2 to 48.6 MMT CO_2 Eq. (1.5 MMT CO_2 Eq., or 3 percent). The recalculations resulted in lower CH_4 emission estimates on average across the 1990 through 2021 time series, compared to the previous *Inventory*, by 2.5 MMT CO_2 Eq., or 5 percent.

The combined impact of revisions to 2021 petroleum systems CO_2 emission estimates, compared to the previous *Inventory*, is a decrease from 24.7 to 24.1 MMT CO_2 (0.5 MMT CO_2, or 2 percent). The recalculations resulted in lower emission estimates on average across the 1990 through 2021 time series, compared to the previous *Inventory*, by 0.1 MMT CO_2 Eq., or 0.2 percent.

The combined impact of revisions to 2021 petroleum systems N_2O emission estimates on a CO_2-equivalent basis, compared to the previous *Inventory*, is a decrease of 0.002 MMT CO_2, Eq. or 10.2 percent. The recalculations resulted in an average decrease in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 0.001 MMT CO_2 Eq., or 7.4 percent.

In Table 3-51 and Table 3-52 below are categories in petroleum systems with updated methodologies or with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. For more information, please see the discussion below.

Table 3-51: Recalculations of CO_2 in Petroleum Systems (MMT CO_2)

Segment/Source	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.5***	**0.6**	**0.3**
HF Completions	*0.5*	0.6	0.3
Production	***20.0***	**20.5**	**18.8**
Tanks	*5.4*	5.6	4.5
HF Workovers	*0.2*	+	+
Pneumatic Controllers	*0.1*	0.1	0.1
Equipment Leaks	*+*	+	+
Chemical Injection Pumps	*+*	+	+

[78] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2022) *Inventory* are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Miscellaneous Production Flaring	*4.2*	4.6	5.0
Transportation	***+***	**+**	**+**
Refining	***4.2***	**3.0**	**2.9**
Flares	*4.2*	3.0	2.8
Petroleum Systems Total	***24.7***	**24.1**	**22.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-52: Recalculations of CH_4 in Petroleum Systems (MMT CO_2 Eq.)

Segment/Source	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.2***	**0.2**	**0.1**
HF Completions	*0.1*	0.2	0.1
Production	***48.9***	**47.5**	**38.6**
Pneumatic Controllers	*28.4*	28.1	19.4
Chemical Injection Pumps	*3.2*	2.4	2.2
Produced Water	*2.5*	2.6	2.7
Offshore Production from GOM Federal Waters (vented and leaks)	*4.7*	4.4	4.3
HF Workovers	*0.1*	+	+
Gas Engines	*2.5*	2.4	2.5
Associated Gas Flaring	*0.8*	1.0	0.8
Transportation	***0.2***	**0.2**	**0.2**
Refining	***0.8***	**0.7**	**0.7**
Petroleum Systems Total	***50.2***	**48.6**	**39.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Exploration

HF Completions (Methodological Update)

EPA updated the calculation methodology for HF completions to use basin-level HF completion counts from Enverus and basin-specific activity factors and emission factors calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national annual average activity and emission factors calculated using Subpart W data were applied to national activity data counts to estimate HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 (first year of GHGRP data for this source) through RY2022. For basin-level HF completion event counts, EPA used Enverus data for 1990 to 2010 and Subpart W for 2011 forward. For the fraction of completions in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well completions were non-REC for 1990 to 2000. The previous *Inventory* also assumed that 10 percent of HF completions were non-REC with flaring from 1990 to 2010 (based on national Subpart W data for RY2011 and RY2012); EPA updated this value using basin-specific Subpart W data for RY2011 and RY2012. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data and used linear interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

Comparing the final completion emissions and those presented at the October 2023 webinar and in the November 2023 *Completions and Workovers* memo, the final estimates are higher for certain completion categories. These emissions increases are due not to the basin-level methodology changes discussed here but rather to changes in the Enverus dataset. EPA applied the same data processing steps to Enverus data in the fall of 2023 as it did for the previous Enverus data analysis (conducted in 2021) and data changes led to many more completions being classified as HF completions.

As a result of this methodological update, CH_4 emissions estimates are on average 10 percent lower across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 41 percent higher than in the previous *Inventory*. The largest increase in the CH_4 emissions estimates compared to the previous *Inventory* is 42 percent in 2016, and the largest decrease is 35 percent in 1999. The decrease in CH_4 emissions is predominantly due to HF completions that were non-REC with venting. Basins such as the Permian basin (basin 430), Williston basin (basin 395), and Denver basin (basin 540) had a high number of HF oil well completion events over the time series. However, they had low EFs for non-REC with venting, decreasing the overall CH_4 emissions. The update resulted in CO_2 emissions estimates that are on average 33 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 29 percent higher than in the previous *Inventory*. The largest increase in CO_2 emissions estimates compared to the previous *Inventory* is 80 percent in 2000, and the largest decrease is 17 percent in 2018. The increase in CO_2 emissions is due to HF completions that were non-REC with flaring and REC with flaring. The Permian basin (basin 430) had the highest emissions across the time series for completions that were non-REC with flaring and REC with flaring. The Permian basin had the highest number of HF oil well completions and high EFs for both control categories.

Table 3-53: HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	95,717	179,290	380	1,126	845	244	509
HF Completions – Non-REC with Flaring	898	1,190	2,797	2,801	1,989	1,272	1,269
HF Completions - REC with Venting	NO	NO	5,478	5,466	6,212	1,114	912
HF Completions - REC with Flaring	NO	NO	9,637	6,188	1,945	3,620	685
Total Emissions	**96,615**	**180,480**	**18,292**	**15,581**	**10,992**	**6,250**	**3,375**
Previous Estimate	*143,304*	*202,773*	*18,090*	*14,864*	*10,568*	*4,430*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-54: HF Completions National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	3	4	+	+	+	+	+
HF Completions – Non-REC with Flaring	155	240	485	762	355	262	131
HF Completions - REC with Venting	NO	NO	+	+	+	+	+
HF Completions - REC with Flaring	NO	NO	2,165	1,278	441	338	141
Total Emissions	**157**	**244**	**2,651**	**2,041**	**797**	**601**	**272**
Previous Estimate	*119*	*168*	*3,174*	*2,431*	*836*	*466*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Production

HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national HF workover counts calculated using analyses for NSPS OOOO (i.e., 1 percent of HF oil wells were worked over annually) and national annual average emission factors calculated using Subpart W data were applied to estimate HF oil well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors (AFs) and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, instead of applying a 1 percent workover rate to HF oil wells, EPA developed year- and basin-specific Subpart W AFs for 2016 (the first year of GHGRP data for this source) forward that represent the number of HF workovers per oil well. Year 2016 Subpart W AFs were applied to all prior years for each basin. For the fraction of workovers in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF oil well workovers were non-REC for 1990 to 2007 and 10 percent flaring from 1990 to 2007. For 2016 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data at the basin level and used linear interpolation between 2008 and 2015 to determine the percent of oil wells with RECs and the percent flaring. EPA developed year- and basin-specific Subpart W EFs for 2016 forward. Year 2016 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates are on average 62 percent lower across the time series than in the previous *Inventory*. The largest decrease in CH_4 emissions estimates compared to the previous *Inventory* is 97 percent in 2021 and the smallest decrease is 39 percent in 2018. The 2021 CH_4 emissions estimate is 97 percent lower than in the previous *Inventory*. The update resulted in CO_2 emissions estimates that are on average 51 percent lower than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 97 percent lower than in the previous *Inventory*. The largest decrease in CO_2 emissions estimates compared to the previous *Inventory* is 97 percent in 2021 and the smallest decrease is 26 percent in 1990. The decrease in emissions for both CH_4 and CO_2 was primarily due to the change in calculation method for workover counts. HF oil well workover counts decreased by an average of 52 percent across the 1990 to 2021 time series compared to the previous *Inventory*.

Table 3-55: HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	17,639	16,244	87	1,339	5	16	35
HF Workovers – Non-REC with Flaring	104	96	11	7	11	20	NO
HF Workovers - REC with Venting	NO	NO	1,304	331	130	5	63
HF Workovers - REC with Flaring	NO	NO	222	75	14	19	33
Total Emissions	**17,744**	**16,340**	**1,623**	**1,753**	**160**	**60**	**130**
Previous Estimate	*37,696*	*41,993*	*2,670*	*3,679*	*3,873*	*2,151*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-56: HF Workovers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	431	408	5	63	+	1	6
HF Workovers – Non-REC with Flaring	22,654	21,076	2,544	2,093	1,947	2,532	NO

HF Workovers - REC with Venting	NO	NO	17	14	4	+	3
HF Workovers - REC with Flaring	NO	NO	51,135	18,285	5,987	2,768	6,095
Total Emissions	**23,085**	**21,484**	**53,701**	**20,456**	**7,939**	**5,301**	**6,105**
Previous Estimate	*31,219*	*34,778*	*89,049*	*97,515*	*97,766*	*205,160*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Pneumatic Controllers (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for pneumatic controllers to use basin-specific activity factors and emission factors by bleed type (i.e., low, high, intermittent bleed) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated pneumatic controller CO_2 emissions using basin-specific emissions data such that the CO_2 emissions reflect the unique CO_2 composition of the gas in a basin.

The update for pneumatic controller CO_2 emission estimates resulted in an average increase of 61 percent across the time series and an increase of 57 percent in 2021, compared to the previous *Inventory*.

In addition, methane emissions for pneumatic controllers were impacted due to recalculations with updated data. Methane emissions from onshore production pneumatic controllers are an average of 2 percent lower across the time series and 1 percent lower in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-57: Pneumatic Controllers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
High Bleed Controllers	94,495	39,873	5,056	5,369	5,778	4,260	2,403
Low Bleed Controllers	7,109	4,132	3,740	4,819	3,704	4,561	3,992
Intermittent Bleed Controllers	NO	26,370	75,579	80,855	82,493	80,063	70,328
Total Emissions	**101,604**	**70,374**	**84,374**	**91,044**	**91,975**	**88,884**	**76,723**
Previous Estimate	*42,406*	*46,477*	*70,322*	*49,460*	*63,104*	*56,641*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-58: Pneumatic Controllers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
High Bleed Controllers	709,796	481,760	71,824	72,432	86,363	44,611	23,712
Low Bleed Controllers	51,129	62,162	32,106	50,770	36,740	46,060	35,439
Intermittent Bleed Controllers	NO	267,220	1,135,995	758,001	996,250	912,391	634,400
Total Emissions	**760,925**	**811,142**	**1,239,924**	**881,203**	**1,119,352**	**1,003,063**	**693,551**
Previous Estimate	*759,970*	*832,929*	*1,260,259*	*886,382*	*1,130,899*	*1,015,080*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Equipment Leaks (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for onshore production equipment leaks to use basin-specific equipment-level activity factors (e.g., separators per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated

equipment leak CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emissions factors for onshore production segment equipment leaks. Note, this methodological update applies only for activity factors. The previous *Inventory's* CO_2 emission factors for onshore production segment equipment leaks (by equipment type) were retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates resulted in an average increase of 7 percent across the time series and an increase of 18 percent in 2021, compared to the previous *Inventory*. Years 2015 to 2021 were impacted more by the update, with an average increase of 28 percent compared to the previous *Inventory*.

Table 3-59: Equipment Leaks National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Oil Wellheads (heavy crude)	2	2	2	1	1	1	1
Oil Wellheads (light crude)	3,159	2,857	3,330	3,416	3,280	3,272	3,195
Separators (heavy crude)	1	1	1	1	+	+	+
Separators (light crude)	613	868	2,280	2,114	1,601	1,443	1,411
Heater/Treaters (light crude)	508	474	786	1,028	846	951	905
Headers (heavy crude)	+	+	+	+	+	+	+
Headers (light crude)	185	458	712	843	432	430	485
Total Emissions	**4,468**	**4,660**	**7,111**	**7,403**	**6,161**	**6,098**	**5,997**
Previous Estimate	*4,453*	*4,681*	*5,396*	*5,351*	*5,159*	*5,159*	*NA*

+ Does not exceed 0.05 MT CO_2.
NA (Not Applicable)

Chemical Injection Pumps (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for chemical injection pumps to use basin-specific equipment-level activity factors (e.g., pumps per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated chemical injection pump CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emission factor. Note, this methodological update applies only for activity factors. The previous *Inventory's* chemical injection pumps CO_2 emission factor was retained and used to develop CO_2 estimates. The update for CO_2 emission estimates resulted in an average decrease of 29 percent across the time series and a decrease of 35 percent in 2021, compared to the previous *Inventory*.

Table 3-60: Chemical Injection Pump National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	2,646	4,464	5,955	6,784	5,338	4,749	4,449
Previous Estimate	*4,506*	*6,522*	*7,689*	*7,625*	*7,351*	*7,351*	*NA*

NA (Not Applicable)

Storage Tanks (Recalculation with Updated Data)

Carbon dioxide emissions from production storage tanks are on average 0.9 percent higher across the time series compared to the previous *Inventory*. Emissions estimates for 2021 are 4 percent higher than in the previous *Inventory*, which is primarily due to large tanks with flares. The emission changes were due to GHGRP data submission revisions.

Table 3-61: Storage Tanks National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	NO	716	5,336	6,251	5,829	5,594	4,513
Large Tanks w/VRU	NO	3	3	9	2	1	1
Large Tanks w/o Control	24	8	4	9	5	4	2
Small Tanks w/Flares	NO	3	7	9	11	10	11
Small Tanks w/o Flares	12	5	5	4	4	5	5
Malfunctioning Separator Dump Valves	12	13	30	26	21	34	8
Total Emissions	**48**	**748**	**5,386**	**6,309**	**5,871**	**5,649**	**4,539**
Previous Estimate	*47*	*748*	*5,398*	*6,024*	*5,255*	*5439*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Chemical injection Pumps (Recalculation with Updated Data)

Chemical injection pump CH_4 estimates decreased by an average of 19 percent across the time series and decreased by 26 percent in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-62: Chemical Injection Pumps National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	47,425	79,968	108,147	122,967	96,186	85,494	79,712
Previous Estimate	*47,401*	*105,458*	*138,866*	*387,416*	*116,080*	*115,678*	*NA*

NA (Not Applicable)

Produced Water (Recalculation with Updated Data)

Methane estimates from produced water increased by an average of 2 percent across the time series and increased by 4 percent in 2021, compared to the previous *Inventory*. The emission changes were due to Enverus data updates.

Table 3-63: Produced Water National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Produced Water - Regular Pressure Wells	71,854	49,840	73,727	77,370	70,374	71,749	73,665
Produced Water - Low Pressure Wells	20,482	14,207	21,016	22,055	20,061	20,452	20,998
Total Emissions	**92,336**	**64,047**	**94,743**	**99,425**	**90,435**	**92,201**	**94,663**
Previous Estimate	*91,391*	*62,458*	*92,863*	*97,735*	*88,622*	*88,622*	*NA*

NA (Not Applicable)

Associated Gas Flaring (Recalculation with Updated Data)

Associated gas flaring CH_4 emission estimates increased by an average of 2 percent across the time series and increased by 23 percent in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-64: Associated Gas Flaring National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
220 - Gulf Coast Basin (LA, TX)	901	480	2,379	2,907	3,643	2,136	1,900
360 - Anadarko Basin	452	274	350	90	21	35	30
395 - Williston Basin	2,666	3,405	36,108	58,138	28,176	21,676	18,341

430 - Permian Basin	11,662	7,992	25,286	26,063	12,695	8,178	7,546
"Other" Basins	4,314	2,335	2,089	3,760	2,353	2,790	2,072
Total Emissions	**19,995**	**14,486**	**66,211**	**90,958**	**46,888**	**34,814**	**29,889**
220 - Gulf Coast Basin (LA, TX)	*886*	*490*	*2,440*	*2,991*	*3,692*	*1,864*	*NA*
360 - Anadarko Basin	*447*	*274*	*348*	*88*	*21*	*41*	*NA*
395 - Williston Basin	*2,665*	*3,419*	*36,120*	*48,019*	*23,556*	*18,734*	*NA*
430 - Permian Basin	*11,263*	*7,805*	*25,198*	*27,484*	*13,086*	*5,852*	*NA*
"Other" Basins	*4,369*	*2,347*	*1,992*	*3,563*	*2,295*	*1,802*	*NA*
Previous Estimate	*19,630*	*14,335*	*66,096*	*82,146*	*42,649*	*28,293*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Methane estimates from gas engines decreased by an average of 2 percent across the time series and decreased by 2 percent in 2021, compared to the previous *Inventory*. The emission changes were due to Enverus data updates.

Table 3-65: Gas Engines National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Gas Engines	81,271	69,973	90,773	92,909	88,619	87,040	87,546
Previous Estimate	*81,916*	*71,348*	*91,719*	*93,608*	*89,497*	*89,233*	*NA*

NA (Not Applicable)

Miscellaneous Production Flaring (Recalculation with Updated Data)

Miscellaneous production flaring CO_2 emission estimates are on average 1 percent higher across the time series compared to the previous *Inventory*. Carbon dioxide emissions estimates for 2021 increased by 12 percent compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-66: Miscellaneous Production Flaring National CO_2 Emissions (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
220 - Gulf Coast Basin (LA, TX)	0	103	567	609	654	802	649
395 - Williston Basin	0	71	1,701	3,049	1,307	1,312	1,241
430 - Permian Basin	0	214	1,463	4,312	2,723	2,156	2,709
"Other" Basins	0	398	639	707	427	368	429
Total Emissions	**0**	**786**	**4,370**	**8,678**	**5,110**	**4,638**	**5,028**
Previous Estimate	*0*	*3,008*	*4,307*	*8,225*	*4,679*	*4,154*	*NA*

NA (Not Applicable)

Offshore Production – GOM Federal Waters (Recalculation with Updated Data)

Vented and leak CH_4 emission estimates from offshore production in GOM federal waters decreased by an average of 0.4 percent across the time series and decreased by 8 percent in 2021, compared to the previous *Inventory*. The emission changes were due to updated offshore complex counts from BOEM.

Table 3-67: Offshore Production National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
GOM Federal Waters – Vented	196,769	101,585	112,786	110,263	103,116	102,365	101,546
GOM Federal Waters - Leaks	96,575	103,712	58,938	57,577	53,860	53,395	52,961
Total Emissions	**293,344**	**205,298**	**171,724**	**167,840**	**156,976**	**155,760**	**154,507**
Previous Estimate	*293,204*	*205,207*	*171,910*	*170,190*	*162,543*	*168,798*	*NA*

NA (Not Applicable)

Transportation

Recalculations for the transportation segment have resulted in calculated CH_4 and CO_2 emissions over the time series from this segment that are lower (by less than 0.05 percent) than in the previous *Inventory*.

Refining

Recalculations due to resubmitted GHGRP data in the refining segment have resulted in a decrease in calculated CH_4 emissions by an average of 4.5 percent across the time series and a decrease of 14 percent in 2021, compared to the previous *Inventory*.

Refining CO_2 emission estimates decreased by an average of 8 percent across the time series and decreased by 28 percent in 2021, compared to the previous *Inventory*. This change in emissions is due to GHGRP resubmissions and was largely due to a change in reported flaring CO_2 emissions.

Table 3-68: Refining National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Refining	25,742	29,218	27,804	30,814	25,861	25,366	24,685
Previous Estimate	*26,398*	*29,963*	*30,313*	*35,516*	*31,023*	*29,551*	*NA*

NA (Not Applicable)

Table 3-69: Refining National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	3,023	3,431	2,814	3,523	2,859	2,989	2,836
Total Refining	**3,174**	**3,602**	**2,877**	**3,571**	**2,893**	**3,021**	**2,872**
Previous Estimate	*3,284*	*3,728*	*3,706*	*5,009*	*4,242*	*4,216*	*NA*

NA (Not Applicable)

Planned Improvements

Planned Improvements for 2025 *Inventory*

EPA updated the Enverus data and there were notable increases in the number of wells and completions identified as being hydraulically fractured compared with previous versions of the database. EPA will assess the underlying Enverus data to determine the cause of these changes.

Upcoming Data, and Additional Data that Could Inform the *Inventory*

EPA will assess new data received by the Greenhouse Gas Reporting Program, the Methane Challenge Program, and other relevant programs on an ongoing basis, which may be used to confirm or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the *Inventory*. EPA will also continue to assess studies that include and compare both top-down and bottom-up estimates, and which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in previous stakeholder comments.

Box 3-6: Carbon Dioxide Transport, Injection, and Geological Storage

Carbon dioxide is produced, captured, transported, and used for Enhanced Oil Recovery (EOR) as well as commercial and non-EOR industrial applications, or is stored geologically. This CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the *Inventory*, emissions of CO_2 from naturally-occurring CO_2 reservoirs are estimated based

on the specific application.

In the *Inventory*, CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption section, 4.15.

For EOR CO_2, as noted in the *2006 IPCC Guidelines*, "At the Tier 1 or 2 methodology levels [EOR CO_2 is] indistinguishable from fugitive greenhouse gas emissions by the associated oil and gas activities." In the U.S. estimates for oil and gas fugitive emissions, the Tier 2 emission factors for CO_2 include CO_2 that was originally injected and is emitted along with other gas from leak, venting, and flaring pathways, as measurement data used to develop those factors would not be able to distinguish between CO_2 from EOR and CO_2 occurring in the produced natural gas. Therefore, EOR CO_2 emitted through those pathways is included in CO_2 estimates in 1B2.

IPCC includes methodological guidance to estimate emissions from the capture, transport, injection, and geological storage of CO_2. The methodology is based on the principle that the carbon capture and storage system should be handled in a complete and consistent manner across the entire Energy sector. The approach accounts for CO_2 captured at natural and industrial sites as well as emissions from capture, transport, and use. For storage specifically, a Tier 3 methodology is outlined for estimating and reporting emissions based on site-specific evaluations. However, IPCC (IPCC 2006) notes that if a national regulatory process exists, emissions information available through that process may support development of CO_2 emission estimates for geologic storage.

In the United States, facilities that produce CO_2 for various end-use applications (including capture facilities such as acid gas removal plants and ammonia plants), importers of CO_2, exporters of CO_2, facilities that conduct geologic sequestration of CO_2, and facilities that inject CO_2 underground, are required to report greenhouse gas data annually to EPA through its GHGRP. Facilities reporting geologic sequestration of CO_2 to the GHGRP develop and implement an EPA-approved site-specific monitoring, reporting and verification plan, and report the amount of CO_2 sequestered using a mass balance approach.

GHGRP data relevant for this *Inventory* estimate consists of national-level annual quantities of CO_2 captured and extracted for EOR applications for 2010 to 2022 and data reported for geologic sequestration from 2016 to 2022.

The amount of CO_2 captured and extracted from natural and industrial sites for EOR applications in 2022 is 36,680 kt (36.7 MMT CO_2 Eq.) 6. The quantity of CO_2 captured and extracted is noted here for information purposes only; CO_2 captured and extracted from industrial and commercial processes is generally assumed to be emitted and included in emissions totals from those processes.

Table 3-70: Quantity of CO_2 Captured and Extracted for EOR Operations (kt CO_2)

Stage	2018	2019	2020	2021	2022
Quantity of CO_2 Captured and Extracted for EOR Operations	48,400	52,100	35,210	35,090	36,680

Several facilities are reporting under GHGRP Subpart RR (Geologic Sequestration of Carbon Dioxide). See Table 3-71 for the number of facilities reporting under Subpart RR, the reported CO_2 sequestered in subsurface geologic formations in each year, and of the quantity of CO_2 emitted from equipment leaks in each year. The quantity of CO_2 sequestered and emitted is noted here for information purposes only; EPA is considering updates to its approach for this source and is seeking feedback as part of this public review draft on potential updates that could be incorporated in future *Inventories*.

Table 3-71: Geologic Sequestration Information Reported Under GHGRP Subpart RR

Stage	2018	2019	2020	2021	2022
Number of Reporting Facilities	5	5	6	9	13
Reported Annual CO_2 Sequestered (kt)	7,662	8,332	6,802	6,947	7,953

Reported Annual CO_2 Emissions from Equipment Leaks (kt)	11	16	13	37	27

3.7 Natural Gas Systems (CRT Source Category 1B2b)

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. This category (1B2b) as defined in the IPCC methodological guidance is for fugitive emissions from natural gas systems, which per IPCC guidelines include emissions from leaks, venting, and flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from natural gas systems in 2022 were 209.7 MMT CO_2 Eq., a decrease of 17 percent from 1990 and a decrease of 0.3 percent from 2021, both primarily due to decreases in CH_4 emissions. From 2011, emissions decreased by 5 percent, primarily due to decreases in CH_4 emissions. National total dry gas production in the United States increased by 104 percent from 1990 to 2022, increased by 5 percent from 2021 to 2022, and increased by 59 percent from 2011 to 2022. Of the overall greenhouse gas emissions (209.7 MMT CO_2 Eq.), 83 percent are CH_4 emissions (173.1 MMT CO_2 Eq.), 17 percent are CO_2 emissions (36.5 MMT), and less than 0.1 percent are N_2O emissions (0.15 MMT CO_2 Eq.).

Overall, natural gas systems emitted 173.1 MMT CO_2 Eq. (6,183 kt CH_4) of CH_4 in 2022, a 21 percent decrease compared to 1990 emissions, and 1 percent decrease compared to 2021 emissions (see Table 3-72 and Table 3-73). For non-combustion CO_2, a total of 36.5 MMT CO_2 Eq. (36,470 kt) was emitted in 2022, a 12 percent increase compared to 1990 emissions, and a 2 percent increase compared to 2021 levels. The 2022 N_2O emissions were estimated to be 0.15 MMT CO_2 Eq. (0.57 kt N_2O), a 3205 percent increase compared to 1990 emissions, and a 1104 percent increase compared to 2021 levels.

The 1990 to 2022 emissions trend is not consistent across segments or gases. Overall, the 1990 to 2022 decrease in CH_4 emissions is due primarily to the decrease in emissions from the following segments: distribution (70 percent decrease), transmission and storage (38 percent decrease), processing (37 percent decrease), and exploration (97 percent decrease). Over the same time period, the production segment saw increased CH_4 emissions of 38 percent (with onshore production emissions increasing 16 percent, offshore production emissions decreasing 86 percent, and gathering and boosting [G&B] emissions increasing 108 percent), and post-meter emissions increasing by 65 percent. The 1990 to 2022 increase in CO_2 emissions is primarily due to an increase in CO_2 emissions in the production segment, where emissions from flaring have increased over time.

Methane and CO_2 emissions from natural gas systems include those resulting from normal operations, routine maintenance, and system upsets. Emissions from normal operations include natural gas engine and turbine uncombusted exhaust, flaring, and leak emissions from system components. Routine maintenance emissions originate from pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions. Emissions of N_2O from flaring activities are included in the *Inventory*, with most of the emissions occurring in the processing and production segments. Note, CO_2 emissions exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in Section 3.1.

Each year, some estimates in the *Inventory* are recalculated with improved methods and/or data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2022) to ensure that the trend is representative of changes in emissions. Recalculations in natural gas systems in this year's *Inventory* include:

- Methodological updates to transmission compressor station activity data, completions and workovers, and underground natural gas storage well events.
- Recalculations due to Greenhouse Gas Reporting Program (GHGRP) submission revisions.
- Recalculations due to updated well counts and production data from Enverus.

The Recalculations Discussion section below provides more details on the updated methods.

Below is a characterization of the six emission subcategories of natural gas systems: exploration, production (including gathering and boosting), processing, transmission and storage, distribution, and post-meter. Each of the segments is described and the different factors affecting CH_4, CO_2, and N_2O emissions are discussed.

Exploration. Exploration includes well drilling, testing, and completion. Emissions from exploration accounted for 0.1 percent of CH_4 emissions and 0.1% of CO_2 emissions from natural gas systems in 2022. Well completions accounted for approximately 90 percent of CH_4 emissions from the exploration segment in 2022, with the rest resulting from well testing and drilling. Well completion flaring emissions account for most of the CO_2 emissions. Methane emissions from exploration decreased by 97 percent from 1990 to 2022, with the largest decreases coming from hydraulically fractured gas well completions without reduced emissions completions (RECs). Methane emissions from exploration increased 58 percent from 2021 to 2022 due to increases in emissions from hydraulically fractured well completions (both non-REC with flaring and REC with venting). Methane emissions from exploration were highest from 2006 to 2008. Carbon dioxide emissions from exploration decreased by 94 percent from 1990 to 2022 primarily due to decreases in hydraulically fractured gas well completions. Carbon dioxide emissions from exploration increased by 14 percent from 2020 to 2021 due to increases in emissions from hydraulically fractured gas well completions (REC with flaring). Carbon dioxide emissions from exploration were highest from 2006 to 2008. Nitrous oxide emissions from exploration decreased 95 percent from 1990 to 2022 and increased 74 percent from 2021 to 2022.

Production (including gathering and boosting). In the production segment, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, and from well-site equipment and activities such as pneumatic controllers, tanks and separators, and liquids unloading. Gathering and boosting emission sources are included within the production sector. The gathering and boosting sources include gathering and boosting stations (with multiple emission sources on site) and gathering pipelines. The gathering and boosting stations receive natural gas from production sites and transfer it, via gathering pipelines, to transmission pipelines or processing facilities (custody transfer points are typically used to segregate sources between each segment). Boosting processes include compression, dehydration, and transport of gas to a processing facility or pipeline. Emissions from production (including gathering and boosting) accounted for 52 percent of CH_4 emissions and 23 percent of CO_2 emissions from natural gas systems in 2022. Emissions from gathering and boosting and pneumatic controllers in onshore production accounted for most of the production segment CH_4 emissions in 2022. Within gathering and boosting, the largest sources of CH_4 are compressor exhaust slip, compressor venting and leaks, and tanks. Flaring emissions account for most of the CO_2 emissions from production, with the highest emissions coming from flare stacks at gathering stations, miscellaneous onshore production flaring, and tank flaring. Methane emissions from production increased by 38 percent from 1990 to 2022, due primarily to increases in emissions from pneumatic controllers (due to an increase in the number of controllers, particularly in the number of intermittent bleed controllers) and increases in emissions from compressor exhaust slip in gathering and boosting. Methane emissions from production decreased 3 percent from 2021 to 2022 due to decreases in emissions from pneumatic controllers and liquids unloading. Carbon dioxide emissions from production increased by approximately a factor of 2.6 from 1990 to 2022 due to increases in emissions at flare stacks in gathering and boosting and miscellaneous onshore production flaring and decreased 8 percent from 2021 to 2022 due primarily to decreases in emissions at flare stacks in miscellaneous onshore production flaring and tank venting. Nitrous oxide emissions from production were 36.9 times higher in 2022 than in 1990 and 17.5 times higher in 2022 than in 2021. The increase in N_2O emissions from 1990 to 2022 and from 2021 to 2022 is primarily due to increases in emissions from condensate tank flaring.

Processing. In the processing segment, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Methane emissions from compressors, including compressor seals, are the primary emission source from this stage. Most of the CO_2 emissions come from acid gas removal (AGR) units, which are designed to remove CO_2 from natural gas. Processing plants accounted for 9 percent of CH_4 emissions and 73 percent of CO_2 emissions from natural gas systems. Methane emissions from processing decreased by 37 percent from 1990 to 2022 as emissions from compressors (leaks and venting) and equipment leaks decreased; and increased 7 percent from 2021 to 2022 due to increased emissions from gas engines. Carbon dioxide emissions from processing decreased by 6 percent from 1990 to 2022,

due to a decrease in AGR, and increased 4 percent from 2021 to 2022 due to increased emissions from flaring emissions at processing plants. Nitrous oxide emissions increased 116 percent from 2021 to 2022.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities are used to move the gas throughout the U.S. transmission system. Leak CH_4 emissions from these compressor stations and venting from pneumatic controllers account for most of the emissions from this stage. Uncombusted compressor engine exhaust and pipeline venting are also sources of CH_4 emissions from transmission. Natural gas is also injected and stored in underground formations, or liquefied and stored in above ground tanks, during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Leak and venting emissions from compressors are the primary contributors to CH_4 emissions from storage. Emissions from liquefied natural gas (LNG) stations and terminals are also calculated under the transmission and storage segment. Methane emissions from the transmission and storage segment accounted for approximately 23 percent of methane emissions from natural gas systems, while CO_2 emissions from transmission and storage accounted for 3 percent of the CO_2 emissions from natural gas systems. CH_4 emissions from this source decreased by 38 percent from 1990 to 2022 due to reduced pneumatic device and compressor station emissions (including emissions from compressors and leaks) and decreased 1 percent from 2021 to 2022 due to decreased emissions from pipeline venting transmission compressors. CO_2 emissions from transmission and storage were 6.6 times higher in 2022 than in 1990, due to increased emissions from LNG export terminals, and increased by 36 percent from 2021 to 2022, also due to LNG export terminals and flaring (both transmission and storage). The quantity of LNG exported from the United States increased by a factor of 74 from 1990 to 2022, and by 9 percent from 2021 to 2022. LNG emissions are about 1 percent of CH_4 and 86 percent of CO_2 emissions from transmission and storage in year 2022. Nitrous oxide emissions from transmission and storage increased by 405 percent from 1990 to 2022 and increased by 177 percent from 2021 to 2022.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through primarily underground mains and service lines to individual end users. There were 1,352,384 miles of distribution mains in 2022, an increase of 408,227 miles since 1990 (PHMSA 2022). Distribution system emissions, which accounted for 9 percent of CH_4 emissions from natural gas systems and less than 0.1 percent of CO_2 emissions from natural gas systems, result mainly from leak emissions from pipelines and stations. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced both CH_4 and CO_2 emissions from this stage, as have station upgrades at metering and regulating (M&R) stations. Distribution system CH_4 emissions in 2022 were 70 percent lower than 1990 levels and 1 percent lower than 2021 emissions. Distribution system CO_2 emissions in 2022 were 70 percent lower than 1990 levels and 1 percent lower than 2021 emissions. Annual CO_2 emissions from this segment are less than 0.1 MMT CO_2 Eq. across the time series.

Post-Meter. Post-meter includes leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles. Leak emissions from residential appliances and industrial facilities and power plants account for the majority of post-meter CH_4 emissions. Methane emissions from the post-meter segment accounted for approximately 8 percent of emissions from natural gas systems in 2022. Post-meter CH_4 emissions increased by 65 percent from 1990 to 2022 and increased by 3 percent from 2021 to 2022, due to increases in the number of residential houses using natural gas and increased natural gas consumption at industrial facilities and power plants. CO_2 emissions from post-meter account for less than 0.01 percent of total CO_2 emissions from natural gas systems.

Total greenhouse gas emissions from the six subcategories within natural gas systems are shown in MMT CO_2 Eq. in Table 3-72. Total CH_4 emissions for these same segments of natural gas systems are shown in MMT CO_2 Eq. (Table 3-73) and kt (Table 3-74). Most emission estimates are calculated using a net emission approach. However, a few sources are still calculated with a potential emission approach. Reductions data are applied to those sources. In 2022, 2.6 MMT CO_2 Eq. CH_4 is subtracted from production segment emissions, 4.3 MMT CO_2 Eq. CH_4 is subtracted from the transmission and storage segment, and 0.1 MMT CO_2 Eq. CH_4 is subtracted from the distribution segment to calculate net emissions. More disaggregated information on potential emissions, net

emissions, and reductions data is available in Annex 3.6, Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems.

Table 3-72: Total Greenhouse Gas Emissions (CH_4, CO_2, and N_2O) from Natural Gas Systems (MMT CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	7.3	22.3	2.9	2.3	0.3	0.1	0.2
Production	68.4	97.9	114.1	114.5	105.8	101.5	98.3
Processing	52.2	31.8	36.3	40.4	39.3	39.7	41.8
Transmission and Storage	64.2	46.2	41.7	41.8	43.1	40.7	40.7
Distribution	51.0	28.5	15.6	15.5	15.5	15.3	15.3
Post-Meter	8.1	9.6	12.5	12.8	13.0	13.0	13.4
Total	**251.2**	**236.5**	**223.0**	**227.3**	**217.0**	**210.4**	**209.7**

Note: Totals may not sum due to independent rounding.

Table 3-73: CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	6.7	19.6	2.6	2.1	0.2	0.1	0.2
Production	65.2	93.4	104.9	103.6	96.7	92.2	89.7
Onshore Production	*39.9*	*64.4*	*60.5*	*58.0*	*53.1*	*48.3*	*46.2*
Gathering and Boosting	*20.5*	*27.0*	*43.6*	*44.8*	*42.7*	*43.3*	*42.8*
Offshore Production	*4.8*	*2.0*	*0.9*	*0.8*	*0.9*	*0.6*	*0.6*
Processing	23.9	13.0	13.5	14.2	13.8	14.2	15.1
Transmission and Storage	64.0	46.0	41.2	40.5	41.1	39.8	39.6
Distribution	50.9	28.5	15.6	15.5	15.5	15.3	15.2
Post-Meter	8.1	9.6	12.5	12.8	13.0	13.0	13.4
Total	**218.8**	**210.1**	**190.3**	**188.7**	**180.3**	**174.6**	**173.1**

Note: Totals may not sum due to independent rounding.

Table 3-74: CH_4 Emissions from Natural Gas Systems (kt)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	238	700	93	75	7	4	6
Production	2,328	3,335	3,748	3,701	3,453	3,293	3,202
Onshore Production	*1,424*	*2,299*	*2,162*	*2,073*	*1,895*	*1,726*	*1,650*
Gathering and Boosting	*733*	*963*	*1,556*	*1,601*	*1,527*	*1,545*	*1,528*
Offshore Production	*170*	*73*	*31*	*28*	*32*	*22*	*23*
Processing	853	463	483	507	495	507	541
Transmission and Storage	2,285	1,645	1,470	1,448	1,468	1,421	1,413
Distribution	1,819	1,018	556	554	553	547	544
Post-Meter	290	344	445	457	463	464	477
Total	**7,813**	**7,505**	**6,795**	**6,741**	**6,439**	**6,235**	**6,183**

Note: Totals may not sum due to independent rounding.

Table 3-75: CO_2 Emissions from Natural Gas Systems (MMT)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	0.6	2.7	0.3	0.2	0.1	+	+
Production	3.2	4.6	9.1	10.8	9.1	9.3	8.6
Processing	28.3	18.8	22.8	26.2	25.5	25.5	26.7
Transmission and Storage	0.2	0.2	0.5	1.2	2.0	0.9	1.2
Distribution	0.1	+	+	+	+	+	+
Post-Meter	+	+	+	+	+	+	+
Total	**32.4**	**26.3**	**32.8**	**38.5**	**36.7**	**35.8**	**36.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-76: CO_2 Emissions from Natural Gas Systems (kt)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	619	2,710	325	249	97	32	37
Production	3,236	4,554	9,118	10,844	9,102	9,331	8,558
Processing	28,338	18,836	22,769	26,189	25,471	25,525	26,672
Transmission and Storage	179	181	537	1,224	2,030	874	1,185
Distribution	54	30	17	16	16	16	16
Post-Meter	1	1	2	2	2	2	2
Total	**32,427**	**26,312**	**32,768**	**38,525**	**36,719**	**35,780**	**36,470**

Note: Totals may not sum due to independent rounding.

Table 3-77: N_2O Emissions from Natural Gas Systems (Metric Tons CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	518	1,708	148	114	46	15	27
Production	3,853	5,467	5,768	6,157	3,687	8,115	142,002
Processing	NO	2,977	3,002	5,082	4,353	4,083	8,808
Transmission and Storage	228	276	205	553	943	415	1,149
Distribution	NO	NO	NO	NO	NO	NO	NO
Post-Meter	NO	NO	NO	NO	NO	NO	NO
Total	**4,599**	**10,428**	**9,123**	**11,906**	**9,029**	**12,628**	**151,986**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Table 3-78: N_2O Emissions from Natural Gas Systems (Metric Tons N_2O)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	2.0	6.4	0.6	0.4	0.2	0.1	0.1
Production	14.5	20.6	21.8	23.2	13.9	30.6	535.9
Processing	NO	11.2	11.3	19.2	16.4	15.4	33.2
Transmission and Storage	0.9	1.0	0.8	2.1	3.6	1.6	4.3
Distribution	NO	NO	NO	NO	NO	NO	NO
Post-Meter	NO	NO	NO	NO	NO	NO	NO
Total	**17.4**	**39.3**	**34.4**	**44.9**	**34.1**	**47.7**	**573.5**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

See Annex 3.6 for the full time series of emissions data, activity data, and emission factors, and additional information on methods and data sources—for example, the specific years of reporting data from EPA's GHGRP that are used to develop certain factors.

This section provides a general overview of the methodology for natural gas system emission estimates in the *Inventory*, which involves the calculation of CH_4, CO_2, and N_2O emissions for over 100 emissions sources (i.e., equipment types or processes), and then the summation of emissions for each natural gas segment.

The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For most sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered "potential methane factors" and emission reduction data to calculate net emissions. The estimates are developed with an IPCC Tier 2 approach. Tier 1 approaches are not used.

Emission Factors. Key references for emission factors for CH_4 and CO_2 emissions from the U.S. natural gas industry include a 1996 study published by the Gas Research Institute (GRI) and EPA (GRI/EPA 1996), EPA's GHGRP (EPA 2023b), and others.

The 1996 GRI/EPA study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating segments of the U.S. natural gas system. The GRI/EPA study was based on a combination of process engineering studies, collection of activity data, and measurements at representative natural gas facilities conducted in the early 1990s. Year-specific natural gas CH_4 compositions are calculated using U.S. Department of Energy's Energy Information Administration (EIA) annual gross production data for National Energy Modeling System (NEMS) oil and gas supply module regions in conjunction with data from the Gas Technology Institute (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001). These year-specific CH_4 compositions are applied to emission factors, which therefore may vary from year to year due to slight changes in the CH_4 composition of natural gas for each NEMS region.

GHGRP Subpart W data were used to develop CH_4, CO_2, and N_2O emission factors for many sources in the *Inventory*. In the exploration and production segments, GHGRP data were used to develop emission factors used for all years of the time series for well testing, gas well completions and workovers with and without hydraulic fracturing, pneumatic controllers and chemical injection pumps, condensate tanks, liquids unloading, miscellaneous flaring, gathering and boosting pipelines, and certain sources at gathering and boosting stations. In the processing segment, for recent years of the time series, GHGRP data were used to develop emission factors for leaks, compressors, flares, dehydrators, and blowdowns/venting. In the transmission and storage segment, GHGRP data were used to develop factors for all years of the time series for LNG stations and terminals and transmission pipeline blowdowns, and for pneumatic controllers for recent years of the time series.

Other data sources used for CH_4 emission factors include Zimmerle et al. (2015) for transmission and storage station leaks and compressors, GTI (2009 and 2019) for commercial and industrial meters, Lamb et al. (2015) for recent years for distribution pipelines and meter/regulator stations, Zimmerle et al. (2019) for gathering and boosting stations, Bureau of Ocean Energy Management (BOEM) reports, and Fischer et al. (2019) and IPCC (2019) for post-meter emissions.

For CO_2 emissions from sources in the exploration, production, and processing segments that use emission factors not directly calculated from GHGRP data, data from the 1996 GRI/EPA study and a 2001 GTI publication were used to adapt the CH_4 emission factors into related CO_2 emission factors. For sources in the transmission and storage segment that use emission factors not directly calculated from GHGRP data, and for sources in the distribution segment, data from the 1996 GRI/EPA study and a 1993 GTI publication were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. CO_2 emissions from post-meter sources (commercial, industrial and vehicles) were estimated using default emission factors from IPCC (2019). Carbon dioxide emissions from post-meter residential sources are included in fossil fuel combustion data.

Flaring N_2O emissions were estimated for flaring sources using GHGRP data.

See Annex 3.6 for more detailed information on the methodology and data used to calculate CH_4, CO_2, and N_2O emissions from natural gas systems.

Activity Data. Activity data were taken from various published data sets, as detailed in Annex 3.6. Key activity data sources include data sets developed and maintained by EPA's GHGRP (EPA 2023b); Enverus (Enverus 2023); BOEM; Federal Energy Regulatory Commission (FERC); EIA; the Natural Gas STAR and Methane Challenge Programs annual data; Oil and Gas Journal; and PHMSA.

For a few sources, recent direct activity data are not available. For these sources, either 2021 data were used as a proxy for 2022 data, or a set of industry activity data drivers was developed and used to calculate activity data over the time series. Drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations. More information on activity data and drivers is available in Annex 3.6.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.6.

Calculating Net Emissions. For most sources, net emissions are calculated directly by applying emission factors to activity data. Emission factors used in net emission approaches reflect technology-specific information and take into account regulatory and voluntary reductions. However, for production, transmission and storage, and distribution, some sources are calculated using potential emission factors, and CH_4 that is not emitted is deducted from the total CH_4 potential estimates. To account for use of such technologies and practices that result in lower emissions but are not reflected in "potential" emission factors, data are collected on both regulatory and voluntary reductions. Regulatory actions addressed using this method include EPA National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents. Voluntary reductions included in the *Inventory* are those reported to Natural Gas STAR and Methane Challenge for certain sources.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. GHGRP data available (starting in 2011) and other recent data sources have improved estimates of emissions from natural gas systems. To develop a consistent time series, for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2010 by interpolating activity data or emission factors or both between 1992 and 2011 data points. Information on time-series consistency for sources updated in this year's *Inventory* can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For detailed documentation of methodologies, please see Annex 3.5.

The United States reports data to the UNFCCC using this *Inventory* report along with Common Reporting Tables (CRTs). This note is provided for those reviewing the CRTs: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRT 1.B.2. Disaggregating flaring and venting estimates across the *Inventory* would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

Uncertainty

EPA has conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize the uncertainty for natural gas systems. For more information on the approach, please see the memoranda *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* (*2018 uncertainty memo*) and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates* (*2021*

uncertainty memo).[79]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from natural gas systems for the current *Inventory*. For the CH_4 uncertainty analysis, EPA focused on the 17 highest-emitting sources for the year 2022, which together emitted 75 percent of methane from natural gas systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. For the CO_2 uncertainty analysis, EPA focused on the three highest-emitting sources for the year 2022, which together emitted 81 percent of CO_2 from natural gas systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. To estimate uncertainty for N_2O, EPA applied the uncertainty bounds calculated for CO_2. EPA will seek to refine this estimate in future Inventories. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. For emission factors that are derived from methane emissions measurement studies, the PDFs are commonly determined to be lognormally distributed (GRI/EPA 1996; GTI 2001; GTI 2009; Lamb et al. 2015; Zimmerle et al. 2015; Fischer et al. 2018; GTI 2019). For activity data that are derived from national datasets, the PDFs are set to a uniform distribution (see 2018 and 2021 uncertainty memos). Many emission factors and activity factors are calculated using Subpart W data, and for these, the @RISK add-in determines the best fitting PDF (e.g., lognormal, gaussian), based on bootstrapping of the underlying data (see 2018 and 2021 uncertainty memos). The IPCC guidance notes that in using this Approach 2 method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. The understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2022, using the IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-79. Natural gas systems CH_4 emissions in 2022 were estimated to be between 141.2 and 203.0 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems CO_2 emissions in 2022 were estimated to be between 31.9 and 42.1 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems N_2O emissions in 2022 were estimated to be between 0.13 and 0.18 MMT CO_2 Eq. at a 95 percent confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., liquids unloading with plunger lifts and reduced emissions completions were not used early in the time series and cast iron distribution mains were more prevalent than plastic mains in early years). Transmission and gas processing compressor leak and vent emissions were also higher in the early years of the time series.

Table 3-79: Approach 2 Quantitative Uncertainty Estimates for CH_4 and Non-combustion CO_2 Emissions from Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound[b]	Upper Bound[b]
Natural Gas Systems	CH_4	173.1	141.2	203.0	-18%	+17%

[79] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Natural Gas Systems	CO_2	36.5	31.9	42.1	-12%	+15%
Natural Gas Systems	N_2O	0.15	0.13	0.18	-12%	+15%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo simulation analysis conducted for the year 2022 CH_4 and CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in Table 3-73 and Table 3-74.

QA/QC and Verification Discussion

In order to ensure the quality of the emission estimates for natural gas systems, general (IPCC Tier 1) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8.

The natural gas systems emission estimates in the *Inventory* are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the *Inventory* are consistent with current industry practices. The EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.[80]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review of the current *Inventory*. EPA held a stakeholder webinar in October of 2023. EPA released memos detailing updates under consideration and requesting stakeholder feedback.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the *Inventory*. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of *Inventory* estimates. In the past few years, EPA has reviewed and, in many cases, incorporated data from these data sources. The second type of study can provide general indications of potential over- and under-estimates. In addition, in recent years information from top-down studies has been directly incorporated to quantify emissions from well blowouts.

A key challenge in using these types of studies to assess *Inventory* results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the *Inventory* and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level *Inventory* with measurement results that may be at other spatial and temporal scales, EPA has developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[81] The most recent version of the gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* estimates for the years 2012 to 2018. The gridded inventory improves efforts to compare results of this *Inventory* with atmospheric studies.

[80] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[81] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting and presented information to stakeholders regarding the updates under consideration. In November 2023, EPA released draft memoranda that discussed changes under consideration and requested stakeholder feedback on those changes. EPA then released final memoranda documenting the methodology implemented in the current Inventory.[82] Memoranda cited in the Recalculations Discussion below are: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Transmission Compressor Station Activity (*Transmission Station Activity* memo), Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Completion and Workover Emissions (*Completions and Workovers* memo), and Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Underground Natural Gas Storage Well Emission Events (*Storage Well Events* memo).

EPA evaluated relevant information available and made several updates to the *Inventory*, including for transmission compressor stations, completions and workovers, and underground natural gas storage wells. General information for these source specific recalculations are presented below and details are available in the *Transmission Station Activity*, *Completions and Workovers*, and *Storage Well Events* memos, including additional considerations for the updates.

In addition to the updates to the sources mentioned above, for certain sources, CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. The emissions changes were mostly due to GHGRP data submission revisions. These sources are discussed below and include pneumatic controllers, well pad equipment leaks, condensate tanks, liquids unloading, gas engines (in production segment), miscellaneous production flaring, gathering and boosting (G&B) station blowdowns, G&B pneumatic controllers, G&B yard piping, G&B acid gas removal units (AGRU), natural gas processing flares, and transmission pipeline venting.

The combined impact of revisions to 2021 natural gas systems CH_4 emissions, compared to the previous *Inventory*, is a decrease from 181.4 to 174.6 MMT CO_2 Eq. (6.8 MMT CO_2 Eq., or 4 percent). The recalculations resulted in an average increase in the annual CH_4 emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 1.9 MMT CO_2 Eq., or 0.8 percent.

The combined impact of revisions to 2021 natural gas systems CO_2 emissions, compared to the previous *Inventory*, is a decrease from 36.2 MMT to 35.8 MMT, or 1.1 percent. The recalculations resulted in an average increase in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 0.4 MMT CO_2 Eq., or 1.5 percent.

The combined impact of revisions to 2021 natural gas systems N_2O emissions, compared to the previous *Inventory*, is an increase from 7.6 kt CO_2 Eq. to 12.6 kt CO_2 Eq., or 65 percent. The recalculations resulted in an average increase in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 10.4 percent.

In Table 3-80 and Table 3-81 below are categories in natural gas systems with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. No changes made to N_2O estimates resulted in a change greater than 0.05 MMT CO_2 Eq. For more information, please see the Recalculations Discussion below.

[82] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2022) *Inventory* are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Table 3-80: Recalculations of CO_2 in Natural Gas Systems (MMT CO_2)

Segment and Emission Sources with Changes of Greater than 0.05 MMT CO_2 due to Recalculations	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***+***	**+**	**+**
Gas Well Completions	*+*	+	+
Production	***9.1***	**9.3**	**8.6**
Gas Well Workovers	*+*	+	+
Pneumatic Controllers	*0.1*	+	+
Well Pad Equipment Leaks	*+*	0.1	0.1
Chemical Injection Pumps	*+*	+	+
Misc. Onshore Production Flaring	*1.0*	1.1	0.7
Condensate Tanks	*0.9*	1.1	0.6
G&B Station - AGRU	*2.3*	2.2	2.0
Processing	***26.1***	**25.5**	**26.7**
Flares	*7.4*	6.9	8.5
Transmission and Storage	***0.9***	**0.9**	**1.2**
Transmission Compressor Station Leaks and Venting	*0.1*	0.1	0.1
Storage Wells	*+*	+	+
Distribution	***+***	**+**	**+**
Post-Meter	***+***	**+**	**+**
Total	**36.2**	**35.8**	**36.5**

+ Does not exceed 0.05 MMT CO_2.

Note: Totals may not sum due to independent rounding.

Table 3-81: Recalculations of CH_4 in Natural Gas Systems (MMT CO_2 Eq.)

Segment and Emission Sources with Changes of Greater than 0.05 MMT CO_2 due to Recalculations	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.2***	**0.1**	**0.2**
Gas Well Completions	*0.2*	0.1	0.2
Production	***94.1***	**92.2**	**89.7**
Gas Well Workovers	*0.2*	0.04	0.05
Well Pad Equipment Leaks	*9.6*	9.4	10.8
Pneumatic Controllers	*21.3*	20.9	18.0
Condensate Tanks	*1.2*	1.2	1.1
Liquids Unloading	*3.4*	2.8	2.4
Gas Engines	*5.5*	5.3	5.3
G&B Stations – Station Blowdowns	*1.2*	1.0	0.9
G&B Stations – Pneumatic Controllers	*0.7*	0.6	0.5
G&B Station – Yard Piping	*2.6*	2.7	2.8
Processing	***14.3***	**14.2**	**15.1**
Flares	*0.8*	0.8	0.9
Transmission and Storage	***44.5***	**39.8**	**39.6**
Transmission Compressor Station Leaks and Venting	*25.9*	21.3	21.5
Storage Wells	*0.3*	0.3	0.3
Pipeline Venting	*4.8*	4.6	3.7
Distribution	***15.3***	**15.3**	**15.2**
Post-Meter	***13.0***	**13.0**	**13.4**
Total	***181.4***	**174.6**	**173.1**

Note: Totals may not sum due to independent rounding.

Exploration

HF Completions (Methodological Update)

EPA updated the calculation methodology for HF completions to use basin-level HF completion counts from Enverus and basin-specific activity factors and emission factors calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national annual average activity and emission factors calculated using Subpart W data were applied to national completion counts to estimate HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 through RY2022. For basin-level HF completion event counts, EPA used Enverus data for 1990 to 2010 and Subpart W for 2011 forward. For the fraction of completions in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well completions were non-REC for 1990 to 2000. The previous *Inventory* also assumed that 10 percent of HF completions were non-REC with flaring from 1990 to 2010 (based on national Subpart W data for RY2011 and RY2012); EPA updated this value using basin-specific Subpart W data for RY2011 and RY2012. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data and used linear interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

Comparing the final completion emissions and those presented at the October 2023 webinar and in the November 2023 *Completions and Workovers* memo, the final estimates are higher for certain completion categories. These emissions increases are due not to the basin-level methodology changes discussed here but rather to changes in the Enverus dataset. EPA applied the same data processing steps to Enverus data in the fall of 2023 as it did for the previous Enverus data analysis (conducted in 2021) and data changes led to many more completions being classified as HF completions.

As a result of this methodological update, CH_4 emissions estimates for HF completions are on average 55 percent higher across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 54 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 134 percent in 1998 with an average increase of 92 percent over the 1990 through 2010 time period. CH_4 emissions decreased or were similar for 2011 forward and the largest decrease between the updates and the previous *Inventory* is 54 percent in 2021. CH_4 emissions increased on average across the time series, but particularly in earlier years due to gas well HF completions that were non-REC with venting, particularly in the Appalachian basin (Eastern Overthrust) [basin 160a]. The Appalachian basin (Eastern Overthrust) had a large number of gas well HF completion events that were non-REC with venting and the highest EF of any basin. The update resulted in CO_2 emissions estimates that are on average 54 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 3 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 141 percent in 1996, and the largest decrease between the updates and the previous *Inventory* is 44 percent in 2013. CO_2 emissions increased predominantly due to non-REC with flaring events in the Appalachian basin (basin 160A) and the East Texas basin (basin 260); these two basins had the highest EFs of any basin.

Table 3-82: HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	187,841	590,423	1,210	678	75	166	83
HF Completions – Non-REC with Flaring	3,112	11,791	652	399	154	31	1,605
HF Completions - REC with Venting	NO	6,710	28,946	18,150	4,594	2,487	3,376

HF Completions - REC with Flaring	NO	2,238	1,345	1,148	634	127	190
Total Emissions	**190,954**	**611,162**	**32,154**	**20,375**	**5,458**	**2,811**	**5,253**
Previous Estimate	*111,265*	*345,098*	*32,147*	*20,002*	*5,220*	*6,111*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-83: HF Completions National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	15	50	+	+	+	+	+
HF Completions – Non-REC with Flaring	472	2,023	57	43	10	2	5
HF Completions - REC with Venting	NO	4	3	+	+	+	+
HF Completions - REC with Flaring	NO	496	233	199	87	13	31
Total Emissions	**487**	**2,573**	**293**	**243**	**97**	**15**	**36**
Previous Estimate	*289*	*1,418*	*290*	*214*	*96*	*15*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Non-HF Completions (Methodological Update)

EPA updated the activity data sources and calculation methodology for non-HF completions to use basin-level non-HF completion counts from Enverus and basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., vented, flared). Previously, national non-HF completion counts and national annual average activity and emission factors calculated using historical data analyses, and Subpart W data were applied to estimate non-HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 through RY2022. For basin-level non-HF gas well completion event counts, EPA used Enverus data across the time series. For the fraction of completions in each control category, EPA implemented at the basin level the previous *Inventory's* approach and the percent of non-HF gas well completions that are vented in 2011 is applied to all prior years. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data for each basin. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for non-HF completions are on average 419 percent higher across the time series than in the previous *Inventory*. The 2021 CH_4 estimate is 43 percent higher than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 1,533 percent in 1991, and the largest decrease between the updates and the previous *Inventory* is 63 percent in 2018. Methane emissions increased primarily due to gas well non-HF completions that were vented. The Appalachian basin (Eastern Overthrust) [basin 160a] and the Appalachian basin (basin 160) had many non-HF completion events that were vented and average EFs more than 2 times higher than the national average across the 1990-2022 time series. The update resulted in CO_2 emissions estimates that are on average 1,312 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 7,331 percent higher than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 7,331 percent in 2021, and the largest decrease between the updates and the previous *Inventory* is 47 percent in 2018. The increase in CO_2 emissions is due to non-HF completions that were flared, primarily in the Gulf Coast basin (basin 220). The Gulf Coast basin had the highest fraction of non-HF completions that were flared of any basin.

Table 3-84: Non-HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Completions - vented	44,362	84,955	79	319	1,548	284	159
Non-HF Completions - flared	547	545	113	+	NO	98	NO
Total Emissions	**44,909**	**85,500**	**192**	**320**	**1,548**	**381**	**159**
Previous Estimate	*5,736*	*10,363*	*513*	*796*	*2,659*	*267*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)

Table 3-85: Non-HF Completions National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Completions - vented	1,398	3,531	1	8	197	8	549
Non-HF Completions - flared	127,316	126,743	15,699	42	NO	16,449	NO
Total Emissions	**128,714**	**130,274**	**15,700**	**50**	**197**	**16,457**	**549**
Previous Estimate	*4,862*	*8,784*	*29,834*	*81*	*364*	*221*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Production

HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national HF workover counts calculated using analyses for NSPS OOOO (i.e., 1 percent of HF gas wells were worked over annually) and national annual average emission factors calculated using Subpart W data were applied to estimate HF gas well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, instead of applying a 1 percent workover rate to HF gas wells, EPA developed year- and basin-specific Subpart W AFs for 2015 forward that represent the number of HF workovers per gas well. Year 2015 Subpart W AFs were applied to all prior years for each basin. For the fraction of workovers in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well workovers were non-REC for 1990 to 2000. The previous Inventory also assumed that 10 percent of HF workovers were non-REC with flaring from 1990 to 2010; EPA updated this value using basin-specific data from Subpart W. For 2011 forward, EPA determined the percent contribution of each control category directly from Subpart W data at the basin-level. EPA used linear interpolation for interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year-and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for HF workovers are on average 43 percent lower across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 94 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 5 percent in 1990, and the largest decrease between the updates and the previous *Inventory* is 99 percent in 2019. The update resulted in CO_2 emissions estimates that are on average 60 percent lower than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 67 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 53 percent in 2013, and the

largest decrease between the updates and the previous *Inventory* is 99 percent in 2019. The decrease in emissions for both CH_4 and CO_2 was primarily due to the change in calculation method for workover counts. HF gas well workover counts decreased by an average of 73 percent across the 1990 through 2021 time series compared to the previous *Inventory*.

Table 3-86: HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	22,198	37,917	114	96	4	17	35
HF Workovers – Non-REC with Flaring	242	483	29	2	1	+	19
HF Workovers - REC with Venting	NO	231	1,667	73	229	457	113
HF Workovers - REC with Flaring	NO	+	6	4	1	2	17
Total Emissions	**22,440**	**38,632**	**1,816**	**174**	**234**	**476**	**185**
Previous Estimate	*21,427*	*57,972*	*19,594*	*13,612*	*6,771*	*8,144*	*NA*

+ Does not exceed 0.5 mt.
NO (Not Occurring)
NA (Not Applicable)

Table 3-87: HF Workovers National CO_2Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	1	2	+	+	+	+	+
HF Workovers – Non-REC with Flaring	32	67	2	+	+	+	+
HF Workovers - REC with Venting	NO	+	+	+	+	+	+
HF Workovers - REC with Flaring	NO	+	1	+	+	+	3
Total Emissions	**33**	**69**	**4**	**1**	**+**	**+**	**3**
Previous Estimate	*56*	*165*	*99*	*86*	*8*	*1*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Non-HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for non-HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., vented, flared). Previously, national annual average activity and emission factors calculated using historical data analyses and Subpart W data were applied along with national gas well counts to estimate non-HF gas well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, EPA developed year-specific Subpart W AFs for 2015 forward. Year 2015 Subpart W data was applied to prior years for each basin. For the fraction of workovers in each control subcategory, EPA applied year- and basin-specific AFs for 2011 forward, retained the previous *Inventory's* assumption that all non-HF workovers were vented in 1990 to 1992, and used linear interpolation between the 1992 and 2011 activity factors at the basin-level. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for non-HF workovers are on average 277 percent higher than in the previous *Inventory*. The 2021 estimate is 180 percent higher than in the previous *Inventory*. The largest increase between the estimates and the previous *Inventory* for CH_4 emissions is 698 percent

in 2017, and the smallest increase is 78 percent in 2018. The increase in CH_4 emissions is due to non-HF workovers that were vented. In the Chautauqua Platform basin (basin 355), all non-HF workovers were vented, and it had the highest CH_4 EF in 2017. The update resulted in CO_2 emissions estimates for non-HF workovers that are higher across the entire time series than the previous *Inventory* (on average 3,067 percent higher). The 2021 CO_2 emissions estimate is 116 percent higher than in the previous *Inventory*. The largest increase between estimates and the previous *Inventory* for CO_2 emissions is 7,432 percent in 1994, and the smallest increase is 78 percent in 2018. The increase in CO_2 emissions is due to non-HF workovers that were flared, particularly in the Bend Arch basin (basin 425). The Bend Arch basin has a high non-HF completion per total gas well AF and a high fraction of non-HF workovers that were flared compared to other basins over the time series.

Table 3-88: Non-HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Workovers - vented	1,415	2,083	1,139	866	959	1,068	1,594
Non-HF Workovers - flared	NO	1,077	1	5	+	43	3
Total Emissions	**1,415**	**3,159**	**1,140**	**870**	**959**	**1,111**	**1,597**
Previous Estimate	*532*	*752*	*415*	*436*	*259*	*396*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)

Table 3-89: Non-HF Workovers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Workovers - vented	87	180	61	51	2,163	199	460
Non-HF Workovers - flared	NO	174,881	269	665	34	9,591	424
Total Emissions	**87**	**175,062**	**329**	**716**	**2,197**	**9,790**	**885**
Previous Estimate	*32*	*3,701*	*185*	*294*	*476*	*4,539*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Equipment Leaks (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for onshore production equipment leaks to use basin-specific equipment-level activity factors (e.g., separators per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated equipment leak CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emissions factors for onshore production segment equipment leaks. Note, this methodological update applies only for activity factors. The previous *Inventory's* CO_2 emission factors for onshore production segment equipment leaks (by equipment type) were retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates for equipment leaks resulted in an average increase of 12 percent across the time series compared to the previous *Inventory*. Years 1990 through 2002 were minimally impacted by the updates, with an increase of 2 percent for CO_2 emissions. Years 2020 and 2021 showed larger increases of 69 and 48 percent for 2020 and 2021, respectively, which is mostly due to much higher emissions from meters and piping in the Powder River Basin.

Methane emissions for equipment leaks were impacted due to recalculations with updated data. CH_4 emission estimates were an average of 5 percent lower across the time series compared to the previous *Inventory*. The 2021 CH_4 estimate is 2 percent lower in 2021 compared to the previous *Inventory*. These CH_4 emissions changes were due to GHGRP submission revisions.

Table 3-90: Production Equipment Leaks National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Heaters	1,639	3,642	10,485	3,412	4,261	4,014	4,359
Separators	5,372	14,404	19,114	19,689	21,306	17,239	15,518
Dehydrators	1,261	1,690	794	677	589	893	683
Meters/Piping	5,400	10,527	11,199	11,775	30,564	24,424	11,022
Compressors	2,673	7,178	7,818	7,236	6,966	9,079	20,310
Total Emissions	**16,344**	**37,441**	**49,410**	**42,789**	**63,686**	**55,649**	**51,893**
Previous Estimate	*18,497*	*33,300*	*38,458*	*37,974*	*37,608*	*37,608*	*NA*

NA (Not Applicable)

Table 3-91: Production Equipment Leaks National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Heaters	12,305	18,436	79,890	16,158	18,568	17,581	18,476
Separators	41,579	80,745	121,349	126,037	129,133	109,610	94,591
Dehydrators	12,904	11,381	5,449	3,656	3,070	4,078	3,105
Meters/Piping	43,055	63,764	79,864	84,730	153,917	130,390	75,719
Compressors	30,307	61,753	71,705	64,771	60,637	73,636	193,389
Total Emissions	**140,150**	**236,079**	**358,256**	**295,352**	**365,325**	**335,295**	**385,280**
Previous Estimate	*137,647*	*262,188*	*363,367*	*298,930*	*369,466*	*343,686*	*NA*

NA (Not Applicable)

Chemical Injection Pumps (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for chemical injection pumps to use basin-specific equipment-level activity factors (e.g., pumps per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For the current *Inventory*, EPA calculated chemical injection pump CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emission factor. Note, this methodological update applies only for activity factors. The previous *Inventory's* chemical injection pumps CO_2 emission factor was retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates resulted in an average decrease of 9 percent across the time series compared to the previous *Inventory*. There were larger decreases of 31 and 39 percent for 2020 and 2021, respectively. The recent years of the time series used basin-specific activity factors and certain basins had lower activity factors compared to the national average factors (e.g., Permian Basin, Denver Basin, San Juan, Paradox, AK Cook Inlet).

Table 3-92: Chemical Injection Pumps National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	2,153	6,749	10,254	9,392	7,339	6,469	6,428
Previous Estimate	*2,275*	*7,760*	*11,053*	*10,899*	*10,635*	*10,635*	*NA*

NA (Not Applicable)

Pneumatic Controllers (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for pneumatic controllers to use basin-specific activity factors and emission factors by bleed type (i.e., low, high, intermittent bleed) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous

Inventory still relied on a national-level methodology to estimate CO_2 emissions. For the current *Inventory*, EPA calculated pneumatic controller CO_2 emissions using basin-specific emissions data such that the CO_2 emissions reflect the unique CO_2 composition of the gas in a basin.

The update for pneumatic controller CO_2 emission estimates resulted in an average decrease of 44 percent across the time series compared to the previous *Inventory*. This average decrease is generally consistent for all years.

Methane emissions for pneumatic controllers were impacted due to recalculations with updated data. Methane emissions estimates are on average 0.3 percent lower across the time-series than in the previous *Inventory*. The estimate for 2021 is 2 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-93: Pneumatic Controllers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Low Bleed Controllers	NO	1,318	2,325	2,283	2,047	1,773	2,180
High Bleed Controllers	23,058	32,794	4,378	2,898	2,373	2,418	1,726
Intermittent Bleed Controllers	15,076	41,267	56,974	57,147	48,052	44,964	37,897
Total Emissions	**38,135**	**75,378**	**63,677**	**62,328**	**52,472**	**49,155**	**41,803**
Previous Estimate	*70,028*	*129,648*	*115,235*	*115,591*	*98,144*	*91,662*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-94: Pneumatic Controllers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Low Bleed Controllers	NO	22,656	33,220	31,099	27,238	25,247	29,877
High Bleed Controllers	355,671	480,272	86,764	52,676	42,269	41,435	30,700
Intermittent Bleed Controllers	233,661	565,070	830,140	875,168	748,219	680,708	583,144
Total Emissions	**589,332**	**1,067,997**	**950,124**	**958,943**	**817,727**	**747,391**	**643,721**
Previous Estimate	*581,039*	*1,075,712*	*956,125*	*959,080*	*814,318*	*760,534*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Storage Tanks (Recalculation with Updated Data)

Methane emissions for production condensate storage tanks are on average lower than the previous *Inventory* by less than 0.1 percent across the 1990 to 2021 time series. The 2021 estimate is 6 percent lower than in the previous *Inventory*. The production storage tanks CO_2 emissions estimates are on average 3 percent higher across the 1990 to 2021 time series than in the previous Inventory. The 2021 estimate is 25 percent higher than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-95: Storage Tanks National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	520	337	1,284	819	765	715	467
Large Tanks w/VRU	NO	27	141	464	743	597	94
Large Tanks w/o Control	16,743	6,828	15,179	3,149	5,323	4,205	3,319
Small Tanks w/Flares	NO	51	235	207	200	161	166
Small Tanks w/o Flares	92,334	31,003	43,050	61,331	47,423	35,460	33,455
Malfunctioning Separator Dump Valves	7	4	40	79	255	212	67
Total Emissions	109,605	38,250	59,929	66,049	54,708	41,351	37,567
Previous Estimate	*106,429*	*38,461*	*60,556*	*67,595*	*53,613*	*44,217*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-96: Storage Tanks National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	587	421	1,476	974	1,108	1,049	575
Large Tanks w/VRU	NO	2	+	+	1	1	+
Large Tanks w/o Control	2	1	36	1	1	1	+
Small Tanks w/Flares	NO	13	86	82	41	27	20
Small Tanks w/o Flares	48	17	26	32	23	17	18
Malfunctioning Separator Dump Valves	+	+	+	+	1	+	+
Total Emissions	**637**	**455**	**1,625**	**1,089**	**1,175**	**1,094**	**613**
Previous Estimate	*628*	*456*	*1,507*	*956*	*862*	*873*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Liquids Unloading (Recalculation with Updated Data)

Liquids unloading CH_4 emissions estimates decreased by an average of 9 percent across the 1990 to 2021 time series compared with the previous *Inventory*. The 2021 estimate decreased by 17 percent compared with the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-97: Liquids Unloading National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Liquids Unloading With Plunger Lifts	0	128,295	82,501	75,081	51,457	33,916	30,384
Liquids Unloading Without Plunger Lifts	77,767	198,728	132,866	104,484	84,251	65,655	54,227
Total Emissions	**77,767**	**327,023**	**215,367**	**179,565**	**135,707**	**99,572**	**84,611**
Previous Estimate	*76,815*	*358,925*	*265,173*	*209,964*	*158,968*	*120,145*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Gas engines CH_4 emissions estimates are on average 2 percent lower across the 1990 to 2021 time series compared with the previous *Inventory*. The 2021 estimate is 4 percent lower than in the previous *Inventory*. These changes were due to revisions to Enverus data.

Table 3-98: Production Gas Engines National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Gas Engines	116,587	194,140	201,660	196,996	192,854	188,374	188,611
Previous Estimate	*115,689*	*198,005*	*207,052*	*202,060*	*197,027*	*197,027*	*NA*

NA (Not Applicable)

Miscellaneous Production Flaring (Recalculation with Updated Data)

Miscellaneous production flaring CO_2 emissions estimates are on average 1 percent higher across the 1993 to 2021 time series compared with the previous *Inventory*, and the 2021 estimate is 12 percent higher compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-99: Miscellaneous Production Flaring National Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Miscellaneous Flaring-Gulf Coast Basin	NO	164	135	395	251	316	206
Miscellaneous Flaring-Williston Basin	NO	+	6	3	4	7	+
Miscellaneous Flaring-Permian Basin	NO	263	690	926	808	578	231

Miscellaneous Flaring-Other Basins	NO	117	476	334	237	211	238
Total Emissions	**NO**	**544**	**1,308**	**1,659**	**1,301**	**1,112**	**676**
Previous Estimate	*NO*	*543*	*1,326*	*1,595*	*1,298*	*991*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Gathering and Boosting – Station Blowdowns (Recalculation with Updated Data)

Methane emissions estimates for gathering and boosting station blowdowns are on average 0.7 percent lower across the 1990 to 2021 time series than in the previous *Inventory*. The 2021 estimate is 17 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-100: Station Blowdowns National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Station Blowdowns	20,218	26,155	79,313	39,059	40,519	35,161	32,036
Previous Estimate	*20,517*	*26,113*	*78,548*	*38,412*	*40,468*	*42,231*	*NA*

NA (Not Applicable)

Gathering and Boosting – Pneumatic Controllers (Recalculation with Updated Data)

Gathering and boosting pneumatic controllers CH_4 emissions estimates are on average 0.1 percent higher across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 is 2 percent lower than in the previous *Inventory*, largely because of a decrease in emissions from high-bleed pneumatic devices. These changes were due to GHGRP submission revisions.

Table 3-101: Pneumatic Controllers National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
High-Bleed Pneumatic Devices	17,092	22,111	25,030	24,187	22,981	20,709	18,854
Intermittent Bleed Pneumatic Devices	78,424	101,451	173,929	184,542	171,679	156,842	145,574
Low-Bleed Pneumatic Devices	2,713	3,509	5,799	6,996	6,965	6,564	6,572
Total Emissions	**98,229**	**127,072**	**204,758**	**215,725**	**201,625**	**184,116**	**171,000**
Previous Estimate	*99,843*	*127,073*	*204,748*	*215,339*	*201,415*	*187,290*	*NA*

NA (Not Applicable)

Gathering and Boosting – Acid Gas Removal Units (Recalculation with Updated Data)

Carbon dioxide emissions estimates for acid gas removal units (AGRU) are on average 0.3 percent lower across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 decreased by 4 percent compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-102: Acid Gas Removal Units National Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
AGRU	241	311	707	1,191	1,629	2,222	2,044
Previous Estimate	*245*	*311*	*707*	*1,288*	*1,655*	*2,304*	*NA*

NA (Not Applicable)

Gathering and Boosting – Yard Piping (Recalculation with Updated Data)

Methane emissions estimates for yard piping are on average 0.6 percent higher across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 is 4 percent higher than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-103: Yard Piping National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Yard Piping	36,319	46,984	86,270	94,306	94,463	96,785	101,777
Previous Estimate	*36,773*	*46,802*	*85,996*	*94,191*	*93,253*	*93,253*	*NA*

NA (Not Applicable)

Processing

Flares (Recalculation with Updated Data)

Processing segment flare CH_4 emission estimates are on average 0.5 percent lower across the 1993 to 2021 time series than in the previous *Inventory*. The CH_4 estimate for 2021 is 7 percent lower than in the previous Inventory. The processing segment flare CO_2 emission estimates decreased by an average of 0.4 percent over the 1993 to 2021 time series, while the CO_2 estimate for 2021 decreased by 6 percent compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-104: Processing Segment Flares National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	NO	NA	24,173	43,887	36,985	26,807	33,586
Previous Estimate	*NO*	*NA*	*24,148*	*43,613*	*36,928*	*28,784*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Table 3-105: Processing Segment Flares National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	NO	3,517	5,948	9,776	8,121	6,941	8,533
Previous Estimate	*NO*	*3,517*	*5,945*	*9,859*	*8,120*	*7,381*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Transmission and Storage

Transmission Compressor Station Leaks and Venting (Methodological Update)

EPA updated the methodology to estimate national level activity data for transmission compressor stations (i.e., station and compressor counts). EPA used annual data for 1996 to 2022 from FERC and PHMSA to estimate national transmission station counts and total transmission compressor counts. FERC requires major interstate transmission compression facilities to report annual data on station counts, total compressor counts, and total transmission pipeline miles. EPA compiled annual FERC data and scaled it up to the national level using PHMSA national transmission pipeline miles for 1996 to 2022. EPA retained existing *Inventory* activity data for 1990 to 1992 and used linear interpolation to estimate national station and total compressor counts for 1993 to 1995.

Total compressor counts were apportioned to reciprocating and centrifugal compressor types using data from GHGRP's Subpart W. EPA retained existing *Inventory* activity data for 1990 to 1992 and used linear interpolation

for intermediate time series years. For more details on this update, refer to the *Transmission Station Activity* memo.

This update impacts CH_4 and CO_2 emissions from leaks (including compressor leaks), dehydrator vents, pneumatic devices, flaring, and venting at transmission compression stations. As a result of this update, CH_4 emissions estimates increased by an average of 2.6 percent across the time series and decreased by 18 percent in 2021, compared to the previous *Inventory*. Emissions estimates of CO_2 increased by an average of 2.5 percent across the time series and decreased by 16 percent in 2021, compared to the previous *Inventory*.

Table 3-106: Transmission Compressor Station National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Station Total Emissions	1,096,527	704,651	581,117	585,617	580,273	585,666	588,497
Station + Compressor Fugitive Emissions	NE	NE	118,592	120,704	120,256	125,440	128,128
Reciprocating Compressor	NE	NE	347,685	342,485	333,385	325,130	322,725
Centrifugal Compressor (wet seals)	NE	NE	50,116	51,544	52,360	53,652	50,524
Centrifugal Compressor (dry seals)	NE	NE	64,724	70,884	74,272	81,444	87,120
Dehydrator vents	1,991	1,931	2,132	2,170	2,162	2,255	2,304
Flaring	305	296	606	432	522	364	492
Pneumatic Devices	213,081	87,701	31,749	31,640	30,120	30,585	31,170
High Bleed	NE	NE	9,781	9,797	9,119	8,951	8,350
Intermittent Bleed	NE	NE	21,132	21,074	20,222	20,882	22,157
Low Bleed	NE	NE	836	769	779	753	663
Station Venting	145,241	138,843	127,165	136,920	136,332	143,132	146,659
Total Emissions	**1,457,144**	**933,422**	**742,770**	**756,779**	**749,409**	**762,002**	**769,121**
Previous Estimate	*1,459,223*	*871,649*	*809,418*	*891,620*	*911,471*	*923,868*	*NA*

NE (Not Estimated at individual source level due to lack of data)
NA (Not Applicable)

Table 3-107: Transmission Compressor Station National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Station Total Emissions	32,285	20,747	17,110	17,242	17,085	17,244	17,327
Station + Compressor Fugitive Emissions	NE	NE	3,492	3,554	3,541	3,693	3,773
Reciprocating Compressor	NE	NE	10,237	10,084	9,816	9,573	9,502
Centrifugal Compressor (wet seals)	NE	NE	1,476	1,518	1,542	1,580	1,488
Centrifugal Compressor (dry seals)	NE	NE	1,906	2,087	2,187	2,398	2,565
Dehydrator vents	59	57	63	64	64	66	68
Flaring	78,386	76,030	70,366	78,424	93,510	62,974	82,004
Pneumatic Devices Transmission	6,274	4,526	945	915	863	841	876
High Bleed	NE	NE	290	280	256	226	221
Intermittent Bleed	NE	NE	631	614	587	598	639
Low Bleed	NE	NE	23	21	20	17	16
Station Venting	4,276	4,148	4,580	4,662	4,645	4,845	4,949
Total Emissions	**121,281**	**105,508**	**93,065**	**101,307**	**116,166**	**85,970**	**105,224**
Previous Estimate	*121,473*	*98,281*	*101,654*	*118,915*	*140,933*	*102,280*	*NA*

NE (Not Estimated at individual source level due to lack of data)
NA (Not Applicable)

Underground Natural Gas Storage Well Events (Methodological Update)

EPA updated the *Inventory* with CO_2 and CH_4 estimates resulting from underground natural gas storage well events that occurred in several years across the inventory time series. Previously, EPA included emissions only from the Aliso Canyon event (occurring 2015 to 2016). This update incorporates emissions from 9 events identified as occurring at storage wells. For the update, emissions from individual events were added to the year in which they occurred.

EPA calculated CH_4 emissions using the reported leak size and applying inventory assumptions for CH_4 content. The CH_4 emissions estimates were then adjusted using a 60 percent combustion efficiency if there was evidence of combustion or ignition during the event. EPA calculated CO_2 emissions only for the events where combustion or ignition occurred, using the 60 percent combustion efficiency. The *Storage Well Events* memo presents additional information and considerations for this update.

One commenter provided feedback and it focused on the 60 percent combustion efficiency. The commenter suggested using 30 percent as the combustion efficiency instead of 60 percent based on research from Gvakharia et al., 2017, which lists 30 percent as the lowest flare efficiency.[83] The commenter noted the study used to justify the 60 percent combustion efficiency evaluated engineered flares which may not be representative of combustion during emergency events.

The newly incorporated events occurred in years 1992, 1998, 2001, 2002, 2003, 2004, 2006, 2010, and 2011. They emitted on average 7,085 metric tons of CH_4 and 27,056 metric tons CO_2.

Methane emissions estimates for underground natural gas storage wells increased 15 percent across the time series compared to previous estimates. The largest increase between the updates and the previous estimates occurs in 2004, which incorporates CH_4 emissions from the Moss Bluff event.

Updates to CO_2 emissions resulted in an increase of 1,693 percent across the time series compared to previous estimates. This increase is mostly due to additions for 2001 and 2004 estimates, resulting from Yaggy and Moss Bluff events, respectively. Combustion occurred at both of these events, resulting in the application of the 60 percent combustion efficiency.

Pipeline Venting (Recalculation with Updated Data)

Transmission pipeline venting CH_4 emission estimates are on average 0.1 percent lower across the 1990 to 2021 time series than in the previous *Inventory*. The CH_4 emissions estimate for 2021 is 4 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-108: Pipeline Venting National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Pipeline Venting	177,951	183,159	208,438	187,266	220,544	165,703	133,761
Previous Estimate	*177,951*	*183,159*	*208,438*	*187,266*	*220,560*	*172,287*	*NA*

NA (Not Applicable)

Distribution

There were no methodological updates to the distribution segment and recalculations resulted in an average decrease in CH_4 emissions across the 1990 to 2021 time series of less than 0.1 percent and an average decrease in calculated CO_2 emissions across the 1990 to 2021 time series of less than 0.1 percent, compared to the previous *Inventory*.

[83] Gvakharia et al, 2017. Methane, Black Carbon, and Ethane Emissions from Natural Gas Flares in the Bakken Shale, North Dakota. *Environmental Science & Technology.* 51: 5317-5325. https://doi.org/10.1021/acs.est.6b05183.

Post-Meter

There were no methodological updates to estimate post-meter emissions and recalculations resulted in an average decrease in CH_4 emissions across the 1990 to 2021 time series of less than 0.1 percent and an average decrease in calculated CO_2 emissions across the 1990 to 2021 time series of less than 0.1 percent, compared to the previous *Inventory*.

Planned Improvements

Planned Improvements for 2025 *Inventory*

EPA updated the Enverus data and there were notable increases in the number of wells and completions identified as being hydraulically fractured compared with previous versions of the database. EPA will assess the underlying Enverus data to determine the cause of these changes.

Upcoming Data, and Additional Data that Could Inform the *Inventory*

EPA will assess new data received by EPA's Greenhouse Gas Reporting Program and Methane Challenge Program on an ongoing basis, which may be used to validate or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the *Inventory*. EPA will also continue to assess studies that include and compare both top-down and bottom-up emission estimates, which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in previous stakeholder comments.

3.8 Abandoned Oil and Gas Wells (CRT Source Categories 1B2a and 1B2b)

The term "abandoned wells", as used in the *Inventory*, encompasses various types of oil and gas wells, including orphaned wells and other non-producing wells:

- Wells with no recent production, and not plugged. Common terms (such as those used in state databases) might include: inactive, temporarily abandoned, shut-in, dormant, and idle.
- Wells with no recent production and no responsible operator. Common terms might include: orphaned, deserted, long-term idle, and abandoned.
- Wells that have been plugged to prevent migration of gas or fluids.

The U.S. population of abandoned oil and gas wells (including orphaned wells and other non-producing wells) is around 3.9 million (with around 3.0 million abandoned oil wells and 0.9 million abandoned gas wells). The methods to calculate emissions from abandoned wells involve calculating the total populations of plugged and unplugged abandoned oil and gas wells in the United States and the application of emission factors. An estimate of the number of orphaned wells within this population is not developed as part of the methodology. Wells that are plugged have much lower average emissions than wells that are unplugged (less than 1 kg CH_4 per well per year, versus over 100 kg CH_4 per well per year). Around 43 percent of the abandoned well population in the United States is plugged. This fraction has increased over the *Inventory* time series (from around 22 percent in 1990) as more wells fall under regulations and programs requiring or promoting plugging of abandoned wells.

Abandoned oil wells. Abandoned oil wells emitted 235 kt CH_4 and 5 kt CO_2 in 2022. Emissions of both gases increased by 3 percent from 1990, while the total population of abandoned oil wells increased 40 percent.

Abandoned gas wells. Abandoned gas wells emitted 68 kt CH_4 and 3 kt CO_2 in 2022. Emissions of both gases increased by 33 percent from 1990, while the total population of abandoned gas wells increased 83 percent.

Table 3-109: CH_4 Emissions from Abandoned Oil and Gas Wells (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	6.4	6.6	6.6	6.6	6.6	6.6	6.6
Abandoned Gas Wells	1.4	1.6	1.8	1.8	1.9	1.9	1.9
Total	**7.8**	**8.2**	**8.4**	**8.5**	**8.5**	**8.6**	**8.5**

Note: Totals may not sum due to independent rounding.

Table 3-110: CH_4 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	228	236	237	237	237	237	235
Abandoned Gas Wells	51	58	64	65	66	69	68
Total	**279**	**294**	**301**	**302**	**303**	**306**	**303**

Note: Totals may not sum due to independent rounding.

Table 3-111: CO_2 Emissions from Abandoned Oil and Gas Wells (MMT CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	+	+	+	+	+	+	+
Abandoned Gas Wells	+	+	+	+	+	+	+
Total	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-112: CO_2 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	5	5	5	5	5	5	5
Abandoned Gas Wells	2	3	3	3	3	3	3
Total	**7**	**7**	**8**	**8**	**8**	**8**	**8**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses a Tier 2 method from IPCC (2019) to quantify emissions from abandoned oil and gas wells. EPA's approach is based on the number of plugged and unplugged abandoned wells in the Appalachian region and in the rest of the U.S., and emission factors for plugged and unplugged abandoned wells in Appalachia and the rest of the U.S. Methods for abandoned wells are unavailable in IPCC (2006). The details of this approach and of the data sources used are described in the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo).*

EPA developed abandoned well CH_4 emission factors using data from Kang et al. (2016) and Townsend-Small et al. (2016). Plugged and unplugged abandoned well CH_4 emission factors were developed at the national-level (using emission data from Townsend-Small et al.) and for the Appalachia region (using emission data from measurements in Pennsylvania and Ohio conducted by Kang et al. and Townsend-Small et al., respectively). The Appalachia region emissions factors were applied to abandoned wells in states in the Appalachian basin region, and the national-level emission factors were applied to abandoned wells in all other states. EPA developed abandoned well CO_2 emission factors using the CH_4 emission factors and an assumed ratio of CO_2-to-CH_4 gas content, similar to the approach used to calculate CO_2 emissions for many sources in Petroleum Systems and Natural Gas Systems. For abandoned

oil wells, EPA used the Petroleum Systems default production segment associated gas ratio of 0.020 MT CO_2/MT CH_4, which was derived through API TankCalc modeling runs. For abandoned gas wells, EPA used the Natural Gas Systems default production segment CH_4 and CO_2 gas content values (GRI/EPA 1996, GTI 2001) to develop a ratio of 0.044 MT CO_2/MT CH_4. The same respective emission factors are applied for each year of the time series.

EPA developed state-level annual counts of abandoned wells for 1990 through 2022 by summing together an annual estimate of abandoned wells in the Enverus data set (Enverus 2023), and an estimate of total abandoned wells not included the Enverus dataset (see 2018 Abandoned Wells Memo for additional information on how the value was calculated) for each state. References reviewed to develop the number of abandoned wells not included in the Enverus dataset include historical records collected by state agencies and by USGS.

The state-level abandoned well population was then split into plugged and unplugged wells by applying an assumption that all abandoned wells were unplugged in 1950 and using Enverus data to calculate the fraction of plugged abandoned wells in 2022. Linear interpolation was applied between the 1950 value and 2022 value to calculate the plugged fraction for intermediate years. See the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo)* for details.[84]

Abandoned Oil Wells

Table 3-113: Abandoned Oil Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source	1990	2005	2018	2019	2020	2021	2022
Plugged abandoned oil wells	475,939	810,564	1,156,633	1,192,282	1,227,566	1,263,583	1,281,380
Unplugged abandoned oil wells	1,697,730	1,787,095	1,781,964	1,783,807	1,784,834	1,785,340	1,767,543
Total Abandoned Oil Wells	2,173,669	2,597,659	2,938,597	2,976,089	3,012,400	3,048,923	3,048,923
Abandoned oil wells in Appalachia	22%	20%	19%	19%	18%	18%	18%
Abandoned oil wells outside of Appalachia	78%	80%	81%	81%	82%	82%	82%
CH_4 from plugged abandoned oil wells (kt)	0.17	0.25	0.34	0.35	0.36	0.36	0.37
CH_4 from unplugged abandoned oil wells(kt)	227.6	236.1	236.5	236.9	237.0	236.8	235.0
Total CH_4 from abandoned oil wells (kt)	**227.7**	**236.4**	**236.8**	**237.2**	**237.3**	**237.2**	**235.4**
Total CO_2 from abandoned oil wells (kt)	**4.6**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**

Abandoned Gas Wells

Table 3-114: Abandoned Gas Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source	1990	2005	2018	2019	2020	2021	2022
Plugged abandoned gas wells	110,089	210,902	348,625	359,018	372,605	389,745	395,236
Unplugged abandoned gas wells	355,620	404,960	447,374	448,504	453,988	463,119	457,628
Total Abandoned Gas Wells	465,709	615,862	795,999	807,522	826,593	852,864	852,864
Abandoned gas wells in Appalachia	28%	25%	24%	24%	24%	26%	26%

[84] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Abandoned gas wells outside of Appalachia	72%	75%	76%	76%	76%	74%	74%
CH_4 from plugged abandoned gas wells (kt)	0.06	0.11	0.17	0.17	0.19	0.21	0.21
CH_4 from unplugged abandoned gas wells (kt)	51.1	57.5	64.1	64.5	65.9	68.5	67.8
Total CH_4 from abandoned gas wells (kt)	**51.1**	**57.6**	**64.3**	**64.7**	**66.1**	**68.7**	**68.0**
Total CO_2 from abandoned gas wells (kt)	**2.2**	**2.5**	**2.8**	**2.8**	**2.9**	**3.0**	**3.0**

Uncertainty

To characterize uncertainty surrounding estimates of abandoned well emissions, EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo simulation technique). See the 2018 Abandoned Wells Memo for details of the uncertainty analysis methods. EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around total methane emissions from abandoned oil and gas wells in year 2022, then applied the calculated bounds to both CH_4 and CO_2 emissions estimates for each population. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. EPA used measurement data from the Kang et al. (2016) and Townsend-Small et al. (2016) studies to characterize the CH_4 emission factor PDFs. For activity data inputs (e.g., total count of abandoned wells, split between plugged and unplugged), EPA assigned default uncertainty bounds of ± 10 percent based on expert judgment.

The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

The results presented below in Table 3-115 provide the 95 percent confidence bound within which actual emissions from abandoned oil and gas wells are likely to fall for the year 2022, using the recommended IPCC methodology. Abandoned oil well CH_4 emissions in 2022 were estimated to be between 1.1 and 19.7 MMT CO_2 Eq., while abandoned gas well CH_4 emissions were estimated to be between 0.3 and 5.4 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series.

Table 3-115: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum and Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Oil Wells	CH_4	6.6	1.1	19.7	-83%	+204%
Abandoned Gas Wells	CH_4	1.9	0.3	5.4	-83%	+204%
Abandoned Oil Wells	CO_2	0.005	0.001	0.014	-83%	+204%
Abandoned Gas Wells	CO_2	0.003	0.0005	0.008	-83%	+204%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo simulation analysis conducted for total abandoned oil and gas well CH_4 emissions in year 2022.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in the table.

QA/QC and Verification Discussion

The emission estimates in the *Inventory* are continually reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. In order to ensure the quality of emission estimates for abandoned wells, general (IPCC Tier 1) quality assurance/quality control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Additionally, EPA reviewed the current Enverus dataset and compared it with results from the previous dataset to identify outliers and instances of significant changes to abandoned oil and gas well counts.

EPA performs a thorough review of information associated with new studies to assess whether the assumptions in the *Inventory* are consistent with industry practices and whether new data is available that could be considered for updates to the estimates. As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held a stakeholder webinar on greenhouse gas data for oil and gas in October of 2023.

Recalculations Discussion

EPA updated the *Inventory* with revised abandoned oil and gas well counts developed from Enverus data (Enverus 2023). Compared to the previous *Inventory*, annual abandoned oil well counts increased by an average of 2 percent across the time series and increased by 4 percent in 2021. Annual abandoned gas well counts increased by 2 percent across the time series and 7 percent in 2021. Similarly, both plugged wells and unplugged wells increased by 2 percent across the time series. As a result of this update, calculated abandoned oil well CH_4 and CO_2 emissions increased by an average of 2 percent each year across the time series and increased by 3 percent in 2021, compared to the previous *Inventory*. Abandoned gas well CH_4 and CO_2 emissions increased by an average of 1 percent across the time series and increased by 8 percent in 2021, compared to the previous *Inventory*.

Planned Improvements

EPA will continue to assess new data and stakeholder feedback on considerations (such as potential use of emission factor data from regions not included in the measurement studies on which current emission factors are based) to improve the abandoned well count estimates and emission factors. In future Inventories, EPA will assess data that become available from Department of Interior and Department of Energy orphan well plugging programs.

3.9 International Bunker Fuels (CRT Source Category 1: Memo Items)

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the Paris Agreement and the UNFCCC, are not included in national emission totals, but are reported separately based upon location of fuel sales. The decision to report emissions from international bunker fuels separately, instead of allocating them to a particular country, was made by the Intergovernmental

Negotiating Committee in establishing the Framework Convention on Climate Change.[85] These decisions are reflected in the IPCC methodological guidance, including IPCC (2006), in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC 2006).[86]

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[87] Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4 and N_2O for marine transport modes, and CO_2 and N_2O for aviation transport modes. Emissions from ground transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

The *2006 IPCC Guidelines* distinguish between three different modes of air traffic: civil aviation, military aviation, and general aviation. Civil aviation comprises aircraft used for the commercial transport of passengers and freight, military aviation comprises aircraft under the control of national armed forces, and general aviation applies to recreational and small corporate aircraft. The *2006 IPCC Guidelines* further define international bunker fuel use from civil aviation as the fuel combusted for civil (e.g., commercial) aviation purposes by aircraft arriving or departing on international flight segments. However, as mentioned above, and in keeping with the *2006 IPCC Guidelines*, only the fuel purchased in the United States and used by aircraft taking-off (i.e., departing) from the United States are reported here. The standard fuel used for civil and military aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[88]

Emissions of CO_2 from aircraft are essentially a function of fuel consumption. Nitrous oxide emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Recent data suggest that little or no CH_4 is emitted by modern engines (Anderson et al. 2011), and as a result, CH_4 emissions from this category are reported as zero. In jet engines, N_2O is primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase.

International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger carrying, military (i.e., U.S. Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going vessels: distillate diesel fuel and residual fuel oil. Carbon dioxide is the primary greenhouse gas emitted from marine shipping.

Overall, aggregate greenhouse gas emissions in 2022 from the combustion of international bunker fuels from both aviation and marine activities were 99.1 MMT CO_2 Eq., or 5.2 percent below emissions in 1990 (see Table 3-116 and Table 3-117). Emissions from international flights and international shipping voyages departing from the United States have increased by 74.4 percent and decreased by 51.7 percent, respectively, since 1990. The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 (from marine transport modes) and N_2O were also emitted.

[85] See report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the work of its ninth session, held at Geneva from 7 to 18 February 1994 (A/AC.237/55, annex I, para. 1c).

[86] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[87] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

[88] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

Table 3-116: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (MMT CO_2 Eq.)

Gas/Mode	1990	2005	2018	2019	2020	2021	2022
CO_2	**103.6**	**113.3**	**124.3**	**113.6**	**69.6**	**80.2**	**98.2**
Aviation	38.2	60.2	83.0	78.3	39.8	50.8	66.6
Commercial	*30.0*	*55.6*	*79.8*	*75.1*	*36.7*	*47.6*	*63.5*
Military	*8.2*	*4.6*	*3.2*	*3.2*	*3.1*	*3.2*	*3.1*
Marine	65.4	53.1	41.3	35.4	29.9	29.4	31.6
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	NO	NO	NO	NO	NO	NO	NO
Marine	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**0.8**	**0.9**	**1.0**	**0.9**	**0.5**	**0.6**	**0.8**
Aviation	0.3	0.5	0.7	0.7	0.3	0.4	0.6
Marine	0.4	0.4	0.3	0.2	0.2	0.2	0.2
Total	**104.6**	**114.3**	**125.3**	**114.6**	**70.3**	**80.9**	**99.1**

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-117: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (kt)

Gas/Mode	1990	2005	2018	2019	2020	2021	2022
CO_2	**103,634**	**113,328**	**124,279**	**113,632**	**69,638**	**80,180**	**98,241**
Aviation	38,205	60,221	82,953	78,280	39,781	50,812	66,646
Marine	65,429	53,107	41,325	35,351	29,857	29,369	31,595
CH_4	**7**	**5**	**4**	**4**	**3**	**3**	**3**
Aviation	NO	NO	NO	NO	NO	NO	NO
Marine	7	5	4	4	3	3	3
N_2O	**3**	**3**	**4**	**3**	**2**	**2**	**3**
Aviation	1	2	3	2	1	2	2
Marine	2	1	1	1	1	1	1

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Methodology and Time-Series Consistency

Emissions of CO_2 were for the most part estimated by applying carbon content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under Section 3.1. Carbon content and fraction oxidized factors for jet fuel (except for commercial aviation as per below), distillate fuel oil, and residual fuel oil are the same as used for CO_2 from Fossil Fuel Combustion and are presented in Annex 2.1, Annex 2.2, and Annex 3.8 of this *Inventory*. Density conversions were taken from ASTM (1989) and USAF (1998). Heat content for distillate fuel oil and residual fuel oil were taken from EIA (2024) and USAF (1998), and heat content for jet fuel was taken from EIA (2024). See below for details on how emission estimates for commercial aviation were determined.

A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.8 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), which is also referenced in the *2006 IPCC Guidelines* (IPCC 2006). For aircraft emissions, the following value, in units of grams of pollutant per kilogram of fuel consumed (g/kg), was employed: 0.1 for N_2O (IPCC 2006). For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.315 for CH_4 and 0.08 for N_2O. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Activity data on domestic and international aircraft fuel consumption were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 1990 and 2000 through 2022 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines* (IPCC 2006).

International aviation CO_2 estimates for 1990 and 2000 through 2022 were obtained directly from FAA's AEDT model (FAA 2024). The radar-informed method that was used to estimate CO_2 emissions for commercial aircraft for 1990 and 2000 through 2022 was not possible for 1991 through 1999 because the radar dataset was not available for years prior to 2000. FAA developed Official Airline Guide (OAG) schedule-informed inventories modeled with AEDT and great circle trajectories for 1990, 2000, and 2010. Because fuel consumption and CO_2 emission estimates for years 1991 through 1999 are unavailable, consumption estimates for these years were calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on 2000 through 2005 data. See Annex 3.3 for more information on the methodology for estimating emissions from commercial aircraft jet fuel consumption.

Data on U.S. Department of Defense (DoD) aviation bunker fuels and total jet fuel consumed by the U.S. military was supplied by the Office of the Under Secretary of Defense (Installations and Environment), DoD. Estimates of the percentage of each Service's total operations that were international operations were developed by DoD. Military aviation bunkers included international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Military aviation bunker fuel emissions were estimated using military fuel and operations data synthesized from unpublished data from DoD's Defense Logistics Agency Energy (DLA Energy 2023). Together, the data allow the quantity of fuel used in military international operations to be estimated. Densities for each jet fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 3-118. See Annex 3.8 for additional discussion of military data.

Table 3-118: Aviation Jet Fuel Consumption for International Transport (TBtu)

Nationality	1990	2005	2018	2019	2020	2021	2022
U.S. and Foreign Carriers	426	791	1,104	1,068	521	677	902
U.S. Military	116	64	44	44	43	44	44
Total	**542**	**854**	**1,148**	**1,112**	**564**	**721**	**946**

Note: Totals may not sum due to independent rounding.

In order to quantify the civilian international component of marine bunker fuels, activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were collected for individual shipping agents on a monthly basis by the U.S. Customs and Border Protection. This information was then reported in unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 1991 through 2022) for 1990 through 2001, 2007 through 2022, and the Department of Homeland Security's Bunker Report for 2003 through 2006 (DHS 2008). Fuel consumption data for 2002 was interpolated due to inconsistencies in reported fuel consumption data. Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DLA Energy (2023). The total amount of fuel provided to naval vessels was reduced by 21 percent to account for fuel used while the vessels were not underway (i.e., in port). Data on the percentage of steaming hours underway versus not underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 3-119.

Table 3-119: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	2005	2018	2019	2020	2021	2022
Residual Fuel Oil	4,781	3,881	2,790	2,246	1,964	1,953	2,172
Distillate Diesel Fuel & Other	617	444	684	702	461	437	435
U.S. Military Naval Fuels	522	471	285	281	296	285	263
Total	**5,920**	**4,796**	**3,759**	**3,229**	**2,721**	**2,674**	**2,870**

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[89] For example, smaller aircraft on shorter routes often carry sufficient fuel to complete several flight segments without refueling in order to minimize time spent at the airport gate or take advantage of lower fuel prices at particular airports. This practice, called tankering, when done on international flights, complicates the use of fuel sales data for estimating bunker fuel emissions. Tankering is less common with the type of large, long-range aircraft that make many international flights from the United States, however. Similar practices occur in the marine shipping industry where fuel costs represent a significant portion of overall operating costs and fuel prices vary from port to port, leading to some tankering from ports with low fuel costs.

Uncertainties exist with regard to the total fuel used by military aircraft and ships. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the DoD Components (e.g., Army, Department of Navy and Air Force) from the Defense Logistics Agency Energy. These data may not include fuel used in aircraft and ships as a result of a Service procuring fuel from, selling fuel to, trading fuel with, or giving fuel to other ships, aircraft, governments, or other entities.

Additionally, there are uncertainties in historical aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities reported as bunker fuel emissions had to be estimated based on a combination of available data and expert judgment. Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data, which reports fuel used while underway and fuel used while not underway. This approach does not capture some voyages that would be classified as domestic for a commercial vessel. Conversely, emissions from fuel used while not underway preceding an international voyage are reported as domestic rather than international as would be done for a commercial vessel. There is uncertainty associated with ground fuel estimates for 1997 through 2022, including estimates for the quantity of jet fuel allocated to ground transportation. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type.

There are also uncertainties in fuel end-uses by fuel type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995. The data were adjusted for trends in fuel use based on a closely correlating, but not matching, data set. All assumptions used to develop the estimate were based on process knowledge, DoD data, and expert judgments. The magnitude of the potential errors related to the various uncertainties has not been calculated but is believed to be small. The uncertainties associated with future military bunker fuel emission estimates could be reduced through revalidation of assumptions based on data regarding current equipment and operational tempo, however, it is doubtful data with more fidelity exist at this time.

[89] See uncertainty discussions under section 3.1 CO_2 from Fossil Fuel Combustion.

Although aggregate fuel consumption data have been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO_2 in the *2006 IPCC Guidelines* (IPCC 2006) is to use data by specific aircraft type, number of individual flights and, ideally, movement data to better differentiate between domestic and international aviation and to facilitate estimating the effects of changes in technologies. The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[90]

There is also concern regarding the reliability of the existing DOC (1991 through 2022) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

QA/QC and Verification

In order to ensure the quality of the emission estimates from international bunker fuels, General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8 The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO_2, CH_4, and N_2O emissions from international bunker fuels in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated. No corrective actions were necessary.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

EPA will evaluate data availability to update the sources for densities, energy contents, and emission factors applied to estimate emissions from aviation and marine fuels. Many are from sources from the late 1990s, such as IPCC/UNEP/OECD/IEA (1997). Potential sources with more recent data include the International Maritime Organization (IMO) greenhouse gas emission inventory, International Air Transport Association (IATA)/ICAO greenhouse gas reporting system (CORSIA), and the EPA Greenhouse Gas Reporting Program (GHGRP) Technical Support Document for Petroleum Products. Specifically, EPA will evaluate data availability to support updating the heat contents and carbon contents of jet fuel with input from EIA.

A longer-term effort is underway to consider the feasibility of including data from a broader range of domestic and international sources for bunker fuels. Potential sources include the IMO greenhouse gas emission inventory, data from the U.S. Coast Guard on vehicle operation currently used in criteria pollutant modeling, data from the International Energy Agency (IEA), relevant updated FAA models to improve aviation bunker fuel estimates, and researching newly available marine bunker data.

[90] U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends website, and reported under the Mobile Combustion section. It should be noted that these estimates are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates reported under the Mobile Combustion section overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights, but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes.

3.10 Biomass and Biofuels Consumption (CRT Source Category 1A)

The combustion of biomass—such as wood, charcoal, the biogenic portions of MSW, and wood waste and biofuels such as ethanol, biogas, and biodiesel—generates CO_2 in addition to CH_4 and N_2O already covered in this chapter. In line with the reporting requirements for inventories submitted under the Paris Agreement and the UNFCCC, CO_2 emissions from biomass and biofuel combustion have been estimated separately from fossil fuel CO_2 emissions and are not directly included in the energy sector contributions to U.S. totals. In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands. For a more complete description of this methodological approach, see the Land Use, Land-Use Change, and Forestry chapter (Chapter 6), which accounts for the contribution of any resulting CO_2 emissions to U.S. totals within the Land Use, Land-Use Change, and Forestry sector's approach.

Therefore, CO_2 emissions from biomass and biofuel consumption are not included specifically in summing energy sector totals. However, they are presented here for informational purposes and to provide detail on biomass and biofuels consumption.

In 2022, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electric power sectors were approximately 195.3 MMT CO_2 Eq. (195,338 kt) (see Table 3-120 and Table 3-121). As the largest consumer of woody biomass, the industrial sector was responsible for 62.9 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 22.3 percent of the total, while the electric power and commercial sectors accounted for the remainder.

Table 3-120: CO_2 Emissions from Wood Consumption by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	135.3	136.3	134.4	132.1	127.3	128.2	122.8
Residential	59.8	44.3	54.1	56.3	35.6	35.5	43.6
Commercial	6.8	7.2	8.7	8.7	8.6	8.5	8.6
Electric Power	13.3	19.1	22.8	20.7	19.1	20.3	20.4
Total	**215.2**	**206.9**	**220.0**	**217.7**	**190.6**	**192.5**	**195.3**

Note: Totals may not sum due to independent rounding.

Table 3-121: CO_2 Emissions from Wood Consumption by End-Use Sector (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	135,348	136,269	134,417	132,069	127,301	128,209	122,824
Residential	59,808	44,340	54,122	56,251	35,585	35,484	43,565
Commercial	6,779	7,218	8,669	8,693	8,554	8,528	8,563
Electric Power	13,252	19,074	22,795	20,677	19,115	20,288	20,385
Total	**215,186**	**206,901**	**220,003**	**217,690**	**190,554**	**192,509**	**195,338**

Note: Totals may not sum due to independent rounding.

Carbon dioxide emissions from combustion of the biogenic components of MSW by the electric power sector were an estimated 14.9 MMT CO_2 (14,864 kt) in 2022. Emissions across the time series are shown in Table 3-122 and Table 3-123. As discussed in Section 3.3, MSW is combusted to produce electricity and the CO_2 emissions from the fossil portion of the MSW (e.g., plastics, textiles, etc.) are included in the energy sector FFC estimates. The MSW also includes biogenic components (e.g., food waste, yard trimmings, natural fibers) and the CO_2 emissions associated with that biogenic portion is included here.

Table 3-122: CO_2 Emissions from Biogenic Components of MSW (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Electric Power	18.5	14.7	16.1	15.7	15.6	15.3	14.9

Table 3-123: CO_2 Emissions from Biogenic Components of MSW (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Electric Power	18,534	14,722	16,115	15,709	15,614	15,329	14,864

The transportation sector is responsible for most of the fuel ethanol consumption in the United States. Ethanol used for fuel is currently produced primarily from corn grown in the Midwest, but it can be produced from a variety of biomass feedstocks. Most ethanol for transportation use is blended with gasoline to create a 90 percent gasoline, 10 percent by volume ethanol blend known as E-10 or gasohol.

In 2022, the United States transportation sector consumed an estimated 1,094.9 trillion Btu of ethanol (94 percent of total), and as a result, produced approximately 75.0 MMT CO_2 Eq. (74,953 kt) (see Table 3-124 and Table 3-125) of CO_2 emissions. Smaller quantities of ethanol were also used in the industrial and commercial sectors. Ethanol fuel production and consumption has grown significantly since 1990 due to the favorable economics of blending ethanol into gasoline and federal policies that have encouraged use of renewable fuels.

Table 3-124: CO_2 Emissions from Ethanol Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	4.1	21.6	78.6	78.7	68.1	75.4	75.0
Industrial	0.1	1.2	1.4	1.6	1.6	1.5	1.9
Commercial	0.1	0.2	1.9	2.2	2.2	2.1	2.7
Total	**4.2**	**22.9**	**81.9**	**82.6**	**71.8**	**79.1**	**79.6**

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.
Note: Totals may not sum due to independent rounding.

Table 3-125: CO_2 Emissions from Ethanol Consumption (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	4,059	21,616	78,603	78,739	68,085	75,417	74,953
Industrial	105	1,176	1,404	1,610	1,582	1,509	1,919
Commercial	63	151	1,910	2,229	2,182	2,139	2,721
Total	**4,227**	**22,943**	**81,917**	**82,578**	**71,848**	**79,064**	**79,593**

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.
Note: Totals may not sum due to independent rounding.

The transportation sector is assumed to be responsible for all of the biodiesel consumption in the United States (EIA 2024a). Biodiesel is currently produced primarily from soybean oil, but it can be produced from a variety of biomass feedstocks including waste oils, fats, and greases. Biodiesel for transportation use appears in low-level blends (less than 5 percent) with diesel fuel, high-level blends (between 6 and 20 percent) with diesel fuel, and 100 percent biodiesel (EIA 2024b).

In 2022, the United States consumed an estimated 211.6 trillion Btu of biodiesel, and as a result, produced approximately 15.6 MMT CO_2 Eq. (15,622 kt) (see Table 3-126 and Table 3-127) of CO_2 emissions. Biodiesel production and consumption has grown significantly since 2001 due to the favorable economics of blending biodiesel into diesel and federal policies that have encouraged use of renewable fuels (EIA 2024b). There was no measured biodiesel consumption prior to 2001 EIA (2024a).

Table 3-126: CO_2 Emissions from Biodiesel Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	NO	0.9	17.9	17.1	17.7	16.1	15.6

NO (Not Occurring)

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.

Table 3-127: CO_2 Emissions from Biodiesel Consumption (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	NO	856	17,936	17,080	17,678	16,112	15,622

NO (Not Occurring)

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.

Methodology and Time-Series Consistency

Woody biomass emissions were estimated by applying two gross heat contents from EIA (Lindstrom 2006) to U.S. consumption data (EIA 2024a) (see Table 3-129), provided in energy units for the industrial, residential, commercial, and electric power sectors. One heat content (16.95 MMBtu/MT wood and wood waste) was applied to the industrial sector's consumption, while the other heat content (15.43 MMBtu/MT wood and wood waste) was applied to the consumption data for the other sectors. An EIA emission factor of 0.434 MT C/MT wood (Lindstrom 2006) was then applied to the resulting quantities of woody biomass to obtain CO_2 emission estimates. The woody biomass is assumed to contain black liquor and other wood wastes, have a moisture content of 12 percent, and undergo complete combustion to be converted into CO_2.

Data for total waste incinerated, excluding tires, from 1990 to 2022 was derived following the methodology described in Section 3.3. Biogenic CO_2 emissions associated with MSW combustion were obtained from EPA's GHGRP FLIGHT data for MSW combustion sources (EPA 2023). Dividing biogenic CO_2 emissions from GHGRP FLIGHT data for MSW combustors by estimated MSW tonnage combusted yielded an annual biogenic CO_2 emission factor. This approach follows the same approach used to develop the fossil CO_2 emissions from MSW combustion as discussed in Section 3.3. As this data was only available following 2011, all years prior use an average of the emission factors from 2011 through 2015.

Biogenic CO_2 emissions from MSW combustion were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated biogenic CO_2 emission factors are shown in Table 3-128.

Table 3-128: Calculated Biogenic CO_2 Content per Ton Waste (kg CO_2/Short Ton Combusted)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
CO_2 Emission Factors	556	556	553	558	566	550	564

The amount of ethanol allocated across the transportation, industrial, and commercial sectors was based on the sector allocations of ethanol-blended motor gasoline. The sector allocations of ethanol-blended motor gasoline were determined using a bottom-up analysis conducted by EPA, as described in the Methodology section of Fossil Fuel Combustion. Total U.S. ethanol consumption from EIA (2024a) was allocated to individual sectors using the same sector allocations as ethanol-blended motor gasoline. The emissions from ethanol consumption were calculated by applying an emission factor of 18.67 MMT C/Qbtu (EPA 2010) to adjusted ethanol consumption estimates (see Table 3-130). The emissions from biodiesel consumption were calculated by applying an emission

factor of 20.1 MMT C/Qbtu (EPA 2010) to U.S. biodiesel consumption estimates that were provided in energy units (EIA 2024a) (see Table 3-131).[91]

Table 3-129: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	1,441.9	1,451.7	1,432.0	1,407.0	1,356.2	1,365.9	1,308.5
Residential	580.0	430.0	524.9	545.5	345.1	344.1	422.5
Commercial	65.7	70.0	84.1	84.3	83.0	82.7	83.0
Electric Power	128.5	185.0	221.1	200.5	185.4	196.7	197.7
Total	**2,216.2**	**2,136.7**	**2,262.0**	**2,237.3**	**1,969.6**	**1,989.4**	**2,011.7**

Note: Totals may not sum due to independent rounding.

Table 3-130: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	59.3	315.8	1,148.2	1,150.2	994.6	1,101.7	1,094.9
Industrial	1.5	17.2	20.5	23.5	23.1	22.0	28.0
Commercial	0.9	2.2	27.9	32.6	31.9	31.2	39.7
Total	**61.7**	**335.1**	**1,196.6**	**1,206.3**	**1,049.5**	**1,155.0**	**1,162.7**

Note: Totals may not sum due to independent rounding.

Table 3-131: Biodiesel Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	NO	11.6	242.9	231.3	239.4	218.2	211.6

NO (Not Occurring)

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

It is assumed that the combustion efficiency for biomass is 100 percent, which is believed to be an overestimate of the efficiency of biomass combustion processes in the United States. Decreasing the combustion efficiency would decrease emission estimates for CO_2. Additionally, the heat content applied to the consumption of woody biomass in the residential, commercial, and electric power sectors is unlikely to be a completely accurate representation of the heat content for all the different types of woody biomass consumed within these sectors. Emission estimates from ethanol and biodiesel production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Recalculations Discussion

EIA (2024a) updated 2020 and 2021 wood energy consumed by the residential sector due to new underlying data collected by the Residential Energy Consumption Survey (RECS), which collects data about once every 5 years and uses Annual Energy Outlook growth rates to estimate data for other years. This caused CO_2 emissions from residential wood consumption to decrease by 9.9 MMT CO_2 Eq. (4.9 percent) in 2020 and 12.3 MMT CO_2 Eq. (6.0 percent) in 2021 compared to estimates in the previous *Inventory* for these years.

[91] CO_2 emissions from biodiesel do not include emissions associated with the carbon in the fuel that is from the methanol used in the process. Emissions from methanol use and combustion are assumed to be accounted for under Non-Energy Use of Fuels. See Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Planned Improvements

Future research will investigate the availability of data on woody biomass heat contents and carbon emission factors to see if there are newer, improved data sources available for these factors.

Currently, emission estimates from biomass and biomass-based fuels included in this *Inventory* are limited to woody biomass, biogenic components of MSW, ethanol, and biodiesel. Additional forms of biomass-based fuel consumption include biogas, and other renewable diesel fuels. EPA will investigate additional forms of biomass-based fuel consumption, research the availability of relevant emissions factors, and integrate these into the *Inventory* as feasible. EPA will examine EIA data on biogas and other renewable diesel fuels to see if these fuel types can be included in future Inventories. EIA (2024a) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas. Distillate fuel statistics are adjusted in this *Inventory* to remove other renewable diesel fuels as well as biodiesel. Additionally, options for including "Other Renewable Fuels," as defined by EIA, will be evaluated.

The availability of facility-level combustion emissions through EPA's GHGRP will be examined to help better characterize the industrial sector's energy consumption in the United States and further classify woody biomass consumption by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, although for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the *Inventory* to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under Paris Agreement and UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under EPA's GHGRP may also include industrial process emissions.[92]

In line with the Paris Agreement and UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from biomass combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this *Inventory*. Additionally, analyses will focus on aligning reported facility-level fuel types and IPCC fuel types per the national energy statistics, ensuring CO_2 emissions from biomass are separated in the facility-level reported data, and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[93]

3.11 Energy Sources of Precursor Greenhouse Gases

In addition to the main greenhouse gases addressed above, energy-related activities are also sources of greenhouse gas precursors. The reporting requirements of the Paris Agreement and the UNFCCC[94] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse

[92] See https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.

[93] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[94] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from energy-related activities from 1990 to 2022 are reported in Table 3-132.

Table 3-132: NO_x, CO, NMVOC, and SO_2 Emissions from Energy-Related Activities (kt)

Gas/Activity	1990	2005	2018	2019	2020	2021	2022
NO_x	**21,804**	**18,196**	**6,812**	**6,503**	**5,630**	**5,570**	**5,225**
Fossil Fuel Combustion	21,678	18,188	6,804	6,496	5,624	5,563	5,218
Transportation[a]	*12,132*	*12,628*	*4,486*	*4,322*	*3,618*	*3,546*	*3,228*
Industrial	*2,475*	*1,486*	*820*	*800*	*751*	*721*	*721*
Electric Power Sector	*6,045*	*3,440*	*1,025*	*898*	*762*	*807*	*781*
Commercial	*451*	*288*	*186*	*187*	*193*	*189*	*188*
Residential	*575*	*346*	*288*	*290*	*300*	*300*	*300*
Petroleum and Natural Gas Systems	127	8	7	7	7	6	6
International Bunker Fuels	1,953	1,699	1,456	1,280	977	1,008	1,132
CO	**124,584**	**63,891**	**30,237**	**29,854**	**27,897**	**28,283**	**27,607**
Fossil Fuel Combustion	124,353	63,686	30,050	29,660	27,703	28,098	27,426
Transportation[a]	*119,478*	*59,540*	*26,024*	*25,621*	*23,546*	*23,912*	*23,235*
Residential	*3,620*	*2,393*	*2,751*	*2,860*	*2,968*	*2,950*	*2,950*
Industrial	*705*	*976*	*620*	*600*	*670*	*658*	*655*
Electric Power Sector	*329*	*582*	*505*	*428*	*362*	*423*	*428*
Commercial	*220*	*195*	*151*	*151*	*157*	*154*	*158*
Petroleum and Natural Gas Systems	232	205	186	194	194	185	181
International Bunker Fuels	102	131	158	150	83	101	128
NMVOCs	**12,269**	**8,081**	**5,050**	**4,987**	**4,822**	**5,167**	**5,045**
Fossil Fuel Combustion	11,793	6,079	2,632	2,593	2,391	2,454	2,329
Transportation[a]	*10,932*	*5,608*	*2,127*	*2,072*	*1,846*	*1,912*	*1,786*
Residential	*693*	*322*	*382*	*397*	*431*	*429*	*429*
Commercial	*9*	*18*	*14*	*14*	*14*	*14*	*14*
Industrial	*117*	*87*	*80*	*81*	*74*	*73*	*74*
Electric Power Sector	*43*	*44*	*30*	*29*	*26*	*27*	*27*
Petroleum and Natural Gas Systems	476	2,002	2,418	2,394	2,431	2,713	2,716
International Bunker Fuels	57	54	50	45	32	34	40
SO_2	**22,638**	**13,331**	**1,827**	**1,509**	**1,288**	**1,423**	**1,327**
Fossil Fuel Combustion	21,482	13,235	1,770	1,447	1,138	1,272	1,176
Electric Power Sector	*14,432*	*9,436*	*1,189*	*921*	*758*	*898*	*819*
Industrial	*2,886*	*1,378*	*259*	*234*	*172*	*168*	*159*
Transportation[a]	*793*	*724*	*45*	*40*	*23*	*24*	*25*
Commercial	*485*	*318*	*18*	*19*	*13*	*14*	*13*
Residential	*2,886*	*1,378*	*259*	*234*	*172*	*168*	*159*
Petroleum and Natural Gas Systems	156	96	56	61	150	151	151
International Bunker Fuels	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)

[a] The scope of the NEI for aircraft related precursor emissions included under the transportation is different from the Paris Agreement and UNFCCC reporting scope. The NEI precursor estimate methodology does not exclude emissions that could be considered international bunkers given local impacts from these emissions. The precursor estimates are based on modeled using FAA- and state-supplied landing and take-off data for all aircraft types (including ground support equipment and auxiliary engines) used for public, private, and military purposes.

Note: Totals may not sum due to independent rounding.

Source: (EPA 2023a). Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2022 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 3-132, NEI reported emissions of CO, NO_x, NMVOCs, and SO_2 were recategorized from NEI Emissions Inventory System (EIS) sectors to source categories more

closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on discussions between the EPA *Inventory* and NEI staff (see crosswalk documented in Annex 6.3).[95] EIS sectors mapped to the energy sector categories in this report include: fuel combustion for electric utilities, industrial, and other; petroleum and related industries; highway vehicles; off-highway; and other mobile sources (e.g., commercial marine vessels and rail). As described in the NEI Technical Support Documentation (TSD) (EPA 2023b), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends website (EPA 2023a; EPA 2023b). No quantitative estimates of uncertainty were calculated for this source category.

[95] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRTs), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

4. Industrial Processes and Product Use

Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. The industrial processes and product use categories included in this chapter are presented in Figure 4-1 and Figure 4-2. Greenhouse gas emissions from industrial processes can occur in two different ways. First, they may be generated and emitted as the byproducts of various non-energy-related industrial activities. Second, they may be emitted due to their use in manufacturing processes or by end-consumers. Combustion-related energy use emissions from industry are reported in Chapter 3, Energy.

In the case of byproduct emissions, the emissions are generated by an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically or physically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated greenhouse gases (e.g., HFC-23). The greenhouse gas byproduct generating processes included in this chapter include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, ceramics production, non-metallurgical magnesia production, and soda ash consumption not associated with glass manufacturing), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, other fluorochemical production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption.

Greenhouse gases that are used in manufacturing processes or by end-consumers include man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). The present contribution of HFCs, PFCs, SF_6, and NF_3 gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, many of them will continue to persist in the atmosphere long after they were first released. In addition, many of these gases have high global warming potentials; SF_6 is the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. Use of HFCs continues since they are the primary substitutes for ozone depleting substances (ODS), which are being phased-out under the Montreal Protocol on Substances that Deplete the Ozone Layer; however, production and consumption of HFCs are being phased down under the Kigali Amendment to the Montreal Protocol and in the United States under the American Innovation and Manufacturing Act. Hydrofluorocarbons, PFCs, SF_6, and NF_3 are employed and emitted by a number of other industrial sources in the United States, such as the electronics industry, electric power transmission and distribution, PFCs and SF_6 for other product use, and magnesium metal production and processing. Carbon dioxide is also consumed and emitted through various end-use applications. In addition, nitrous oxide is used in and emitted by the electronics industry and anesthetic and aerosol applications.

In 2022, IPPU generated emissions of 383.2 million metric tons of CO_2 equivalent (MMT CO_2 Eq.), or 6.0 percent of total U.S. greenhouse gas emissions.[1] Carbon dioxide emissions from all industrial processes were 168.9 MMT CO_2 Eq. (168,937 kt CO_2) in 2022, or 3.3 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.04 MMT CO_2 Eq. (1 kt CH_4) in 2022, which was 0.01 percent of U.S. CH_4 emissions. Nitrous oxide emissions from IPPU were 16.1 MMT CO_2 Eq. (61 kt N_2O) in 2022, or 4.1 percent of total U.S. N_2O emissions. In 2022 combined emissions of HFCs, PFCs, SF_6, and NF_3 totaled 198.1 MMT CO_2 Eq. Total emissions from IPPU in 2022 were 3.9 percent more than 1990 emissions. Total emissions from IPPU remained relatively constant between 2021 and 2022, increasing by 0.4 percent due to offsetting trends within the sector. More information on emissions of greenhouse gas precursors emissions that also result from IPPU are presented in Section 4.27 of this chapter.

The largest source of IPPU-related emissions is the substitution of ozone depleting substances, which accounted for 46.5 percent of sector emissions in 2022. These emissions have increased by 79.1 percent since 2005, and 3.2 percent between 2021 and 2022. Cement production was the second largest source of IPPU emissions in 2022, accounting for 10.9 percent of IPPU emissions in 2022. Iron and steel production and metallurgical coke production was the third largest source of IPPU emissions, accounting for 10.6 percent of the sector total in 2022.

Figure 4-1: Industrial Processes and Product Use Sector Greenhouse Gas Sources

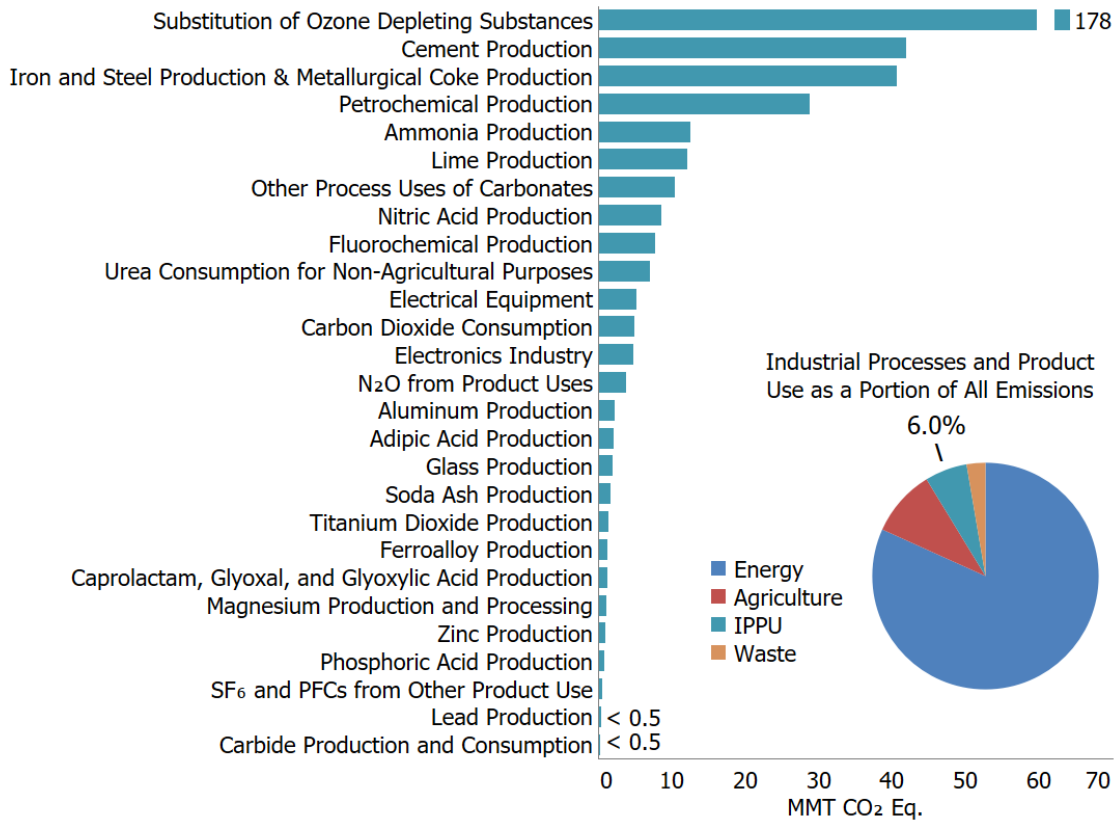

The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources, as shown in Figure 4-2. Emissions resulting from most types of metal production have declined significantly since 1990, largely due to production shifting to other countries, but also due to transitions to less-emissive methods of

[1] Emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories.

production (in the case of iron and steel) and to improved practices (in the case of PFC emissions from aluminum production). Carbon dioxide and CH_4 emissions from some chemical production sources (e.g., petrochemical production, urea consumption for non-agricultural purposes) have increased since 1990, while emissions from other chemical production sources (e.g., ammonia production, phosphoric acid production) have decreased. Emissions from mineral sources have either increased (e.g., cement production) or not changed significantly (e.g., lime production) since 1990 and largely follow economic cycles. Hydrofluorocarbon emissions from the substitution of ODS have increased drastically since 1990 and are the largest source of IPPU emissions (46.5 percent in 2022), while the emissions of HFCs, PFCs, SF_6, and NF_3 from other sources have generally declined. Nitrous oxide emissions from the production of nitric acid have decreased. Some emission sources (e.g., adipic acid) exhibit varied interannual trends. Trends are explained further within each emission source category throughout the chapter.

Figure 4-2: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

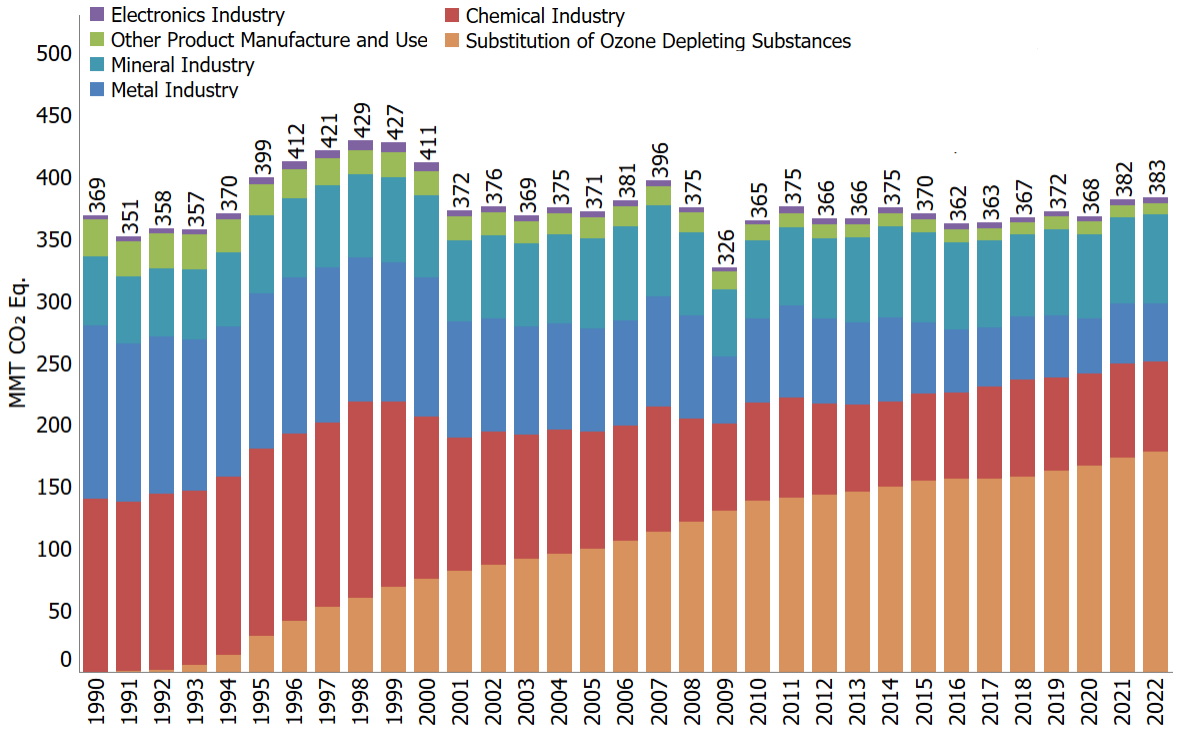

Table 4-1 summarizes emissions for the IPPU chapter in MMT CO_2 Eq. using IPCC *Fifth Assessment Report* (AR5) GWP values, following the requirements of the current United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories (IPCC 2007).[2] Unweighted gas emissions in kt are also provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the Common Reporting Tables (CRTs), corresponding generally to: mineral industry, chemical industry, metal industry, and emissions from the uses of HFCs, PFCs, SF_6, and NF_3.

Each year, some emission and sink estimates in the IPPU sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to

[2] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

ensure that the trend is accurate. Key updates to this year's *Inventory* include the addition of new categories previously not estimated: CO_2 emissions from ceramics production and non-metallurgical magnesia within other process use of carbonates category; fluorinated gases from production of fluorochemicals other than HCFC-22 within the fluorochemical production category; and SF_6 and PFCs from additional product uses within the other product manufacture and use category. In addition, there were changes to the petrochemical production methodology to calculate emissions from methanol production; updates to emission estimates from urea consumption for non-agricultural purposes driven by revisions to quantities of urea applied, urea imports, and urea exports; and revisions to the method for estimating SF_6 emissions from electrical equipment for estimating using CARB data from electrical equipment in California. Together, these methodological and data updates increased IPPU sector greenhouse gas emissions by an average 20.4 MMT CO_2 Eq. (7.2 percent) across the time series. For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**213.7**	**195.9**	**164.4**	**168.2**	**160.7**	**168.8**	**168.9**
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7
Iron and Steel Production	*99.1*	*66.2*	*41.6*	*40.1*	*35.4*	*38.6*	*37.7*
Metallurgical Coke Production	*5.6*	*3.9*	*1.3*	*3.0*	*2.3*	*3.2*	*3.0*
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Magnesium Production and Processing	0.1	+	+	+	+	+	+
CH_4	**0.1**	**+**	**+**	**+**	**+**	**+**	**+**
Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
N_2O	**29.6**	**22.2**	**23.1**	**18.7**	**20.8**	**19.7**	**16.1**
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
N_2O from Product Uses	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**
Substitution of Ozone Depleting Substances[a]	0.3	99.5	157.9	162.1	166.2	172.6	178.1
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	+	+
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+
Electrical Equipment	+	+	0.0	+	+	+	+
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8
SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6
Fluorochemical Production	5.8	3.3	+	+	+	+	+
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Total[b]	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

[b] Total does not include other fluorinated gases, such as HFEs and PFPEs, which are reported separately in Section 4.24.

Note: Totals may not sum due to independent rounding. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in *Inventory* totals and are included for informational purposes only in Section 4.24. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**213,682**	**195,933**	**164,404**	**168,175**	**160,701**	**168,838**	**168,937**
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884
Iron and Steel Production & Metallurgical Coke Production	104,740	70,082	42,863	43,095	37,724	41,873	40,672
Iron and Steel Production	*99,132*	*66,161*	*41,581*	*40,089*	*35,398*	*38,648*	*37,718*
Metallurgical Coke Production	*5,608*	*3,921*	*1,282*	*3,006*	*2,325*	*3,224*	*2,954*
Petrochemical Production	20,075	26,882	27,200	28,483	27,926	30,656	28,788
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610
Lime Production	11,700	14,552	13,106	12,112	11,299	11,870	12,208
Other Process Uses of Carbonates	7,103	8,472	7,938	8,973	9,012	8,583	10,384

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	6,113	6,150	5,805	6,600	7,053
Carbon Dioxide Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704
Titanium Dioxide Production	1,195	1,755	1,541	1,340	1,340	1,474	1,474
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446
Ferroalloy Production	2,152	1,392	2,063	1,598	1,377	1,567	1,327
Zinc Production	632	1,030	999	1,026	977	1,007	947
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840
Lead Production	516	553	527	531	450	439	428
Carbide Production and Consumption	243	213	184	175	154	172	210
Substitution of Ozone Depleting Substances[a]	+	1	3	3	4	4	4
Magnesium Production and Processing	129	4	2	2	3	3	3
CH_4	**3**	**2**	**2**	**1**	**1**	**1**	**1**
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
N_2O	**112**	**84**	**87**	**71**	**79**	**74**	**61**
Nitric Acid Production	41	38	32	34	31	30	33
N_2O from Product Uses	*14*	*14*	*14*	*14*	*14*	*14*	*14*
Adipic Acid Production	51	24	35	18	28	25	8
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	5	5	4	5	5
Electronics Industry	+	+	1	1	1	1	1
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	+	+	+	+	+	+	+
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**101**	**83**	**179**	**173**	**167**	**139**	**172**
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	+	+	+	+	+	+	+
Aluminum Production	M	M	M	M	M	M	M
SF_6 and PFCs from Other Product Use	101	83	178	173	167	138	172
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+
Electrical Equipment	+	+	0	+	+	+	+
SF_6	**2**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	1	1	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+

Gas/Source	1990	2005	2018	2019	2020	2021	2022
SF_6 and PFCs from Other Product Use	0	0	+	+	+	+	+
Fluorochemical Production	0	0	+	+	+	+	+
NF_3	**+**	**0**	**+**	**0**	**0**	**0**	**0**
Electronics Industry	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M (Mixture of gases)

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

Note: Totals by gas may not sum due to independent rounding.

This chapter presents emission estimates calculated in accordance with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its refinements. For additional detail on IPPU sources that are not included in this *Inventory* report, please review Annex 5, Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included. These sources are not included due to various national circumstances, such as emissions from a source may not currently occur in the United States, data are not currently available for those emission sources (e.g., glyoxal and glyoxylic acid production, CH_4 from direct reduced iron production), emissions are included elsewhere within the *Inventory* report, or data suggest that emissions are not significant (e.g., other various fluorinated gas emissions from other product uses). In terms of geographic scope, emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from District of Columbia and U.S. Territories to the extent to which industries are occurring. While most IPPU sources do not occur in U.S. Territories (e.g., electronics manufacturing does not occur in U.S. Territories), they are estimated and accounted for where they are known to occur (e.g., cement production, lime production, electrical equipment). EPA will review this on an ongoing basis to ensure emission sources are included across all geographic areas if they occur. Information on planned improvements for specific IPPU source categories can be found in the Planned Improvements section of the individual source category.

In addition, as mentioned in the Energy chapter of this report (Box 3-5), fossil fuels consumed for non-energy uses for primary purposes other than combustion for energy (including lubricants, paraffin waxes, bitumen asphalt, and solvents) are reported in the Energy chapter. According to the *2006 IPCC Guidelines*, these non-energy uses of fossil fuels are to be reported under the IPPU, rather than the Energy sector; however, due to national circumstances regarding the allocation of energy statistics and carbon balance data, the United States reports these non-energy uses in the Energy chapter of this *Inventory*. Although emissions from these non-energy uses are reported in the Energy chapter, the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines* and are well documented and scientifically based. The methodologies used are described in Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance, and avoid double counting. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, and emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. For more information, see the Methodology discussion in Section 3.1, CO_2 from Fossil Fuel Combustion, Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Finally, as stated in the Energy chapter, portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—are

reallocated to the IPPU chapter, as they are consumed during non-energy related industrial process activity. Emissions from uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances. This approach is compatible with the *2006 IPCC Guidelines* and is well documented and scientifically based. The emissions from these feedstocks and reducing agents are reported under the IPPU chapter to improve transparency and to avoid double counting of emissions under both the Energy and IPPU sectors. More information on the methodology to adjust for these emissions within the Energy chapter is described in the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRT Source Category 1A]) and Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. Additional information is listed within each IPPU emission source in which this approach applies.

Box 4-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the IPPU chapter do not preclude alternative examinations. Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from industrial processes and from the use of greenhouse gases in products.

QA/QC and Verification Procedures

The quality of IPPU source categories is assured through application of the U.S. Inventory QA/QC plan outlined in Annex 8. Two types of checks were performed using this plan: (1) general (Tier 1) procedures consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* that focus on annual procedures and checks to be used when gathering, maintaining, handling, documenting, checking, and archiving the data, supporting documents, and files; and (2) source category-specific (Tier 2) procedures that focus on checks and comparisons of the emission factors, activity data, and methodologies used for estimating emissions from the relevant industrial process and product use sources. Examples of these procedures include: checks to ensure that activity data and emission estimates are consistent with historical trends; that consistent, complete and data sources are used and documented; that interpolation or extrapolation techniques are consistent across sources; and that common units, and conversion factors are used where applicable. Consistent with the *2006 IPCC Guidelines*, additional category-specific QC procedures were performed for more significant emission categories or sources where significant methodological and data updates have taken place. Any significant findings and errors identified are documented and corrected. Application of these procedures, specifically category-specific QC procedures and updates/improvements as a result of QA processes (expert, public, and UNFCCC technical expert reviews), are described further within respective source categories, in the Recalculations Discussion and Planned Improvement sections.

For sources that use data from EPA's Greenhouse Gas Reporting Program (GHGRP), EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic

checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[3] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with the general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. See Box 4-2 below for more information on use of GHGRP data in this chapter.

For most IPPU categories, activity data are obtained via aggregation of facility-level data from EPA's GHGRP (see Box 4-2 below and Annex 9), national commodity surveys conducted by U.S. Geological Survey (USGS) National Minerals Information Center, U.S. Department of Energy (DOE), U.S. Census Bureau, and industry associations such as Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American Chemistry Council (ACC), and American Iron and Steel Institute (AISI) (specified within each source category). The emission factors used include those derived from the EPA's GHGRP and application of IPCC default factors.

Box 4-2: Industrial Process and Product Use Data from EPA's Greenhouse Gas Reporting Program

EPA collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases.

In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year, but reporting is required for all facilities in some industries. Calendar year 2010 was the first year for which data were collected for facilities subject to 40 CFR Part 98, though some source categories first collected data for calendar year 2011. For more information, see Annex 9, Use of EPA Greenhouse Gas Reporting Program in Inventory.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this *Inventory*, consistent with IPCC guidelines (e.g., minerals, chemicals, product uses). Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods; however, it should be noted that the coverage and definitions for source categories (e.g., allocation of energy and IPPU emissions) in EPA's GHGRP may differ from those used in this *Inventory* in meeting the Paris Agreement and UNFCCC reporting guidelines (IPCC 2011) and is an important consideration when incorporating GHGRP data in the *Inventory*. In line with the Paris Agreement and UNFCCC reporting guidelines, the *Inventory* is a comprehensive accounting of all emissions from source categories identified in the *2006 IPCC Guidelines*. EPA has paid particular attention to ensuring both completeness and time-series consistency for major recalculations that have occurred from the incorporation of GHGRP data into these categories, consistent with *2006 IPCC Guidelines* and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories.*[4]

For certain source categories in this *Inventory* (e.g., nitric acid production, lime production, cement production, petrochemical production, carbon dioxide consumption, ammonia production, and urea consumption for non-agricultural purposes), EPA has integrated data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is

[3] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[4] See https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

only publishing data values that meet these aggregation criteria.[5] Specific uses of aggregated facility-level data are described in the respective methodological sections (e.g., including other sources using GHGRP data that is not aggregated CBI, such as aluminum, electronics industry, electrical equipment, HCFC-22 production, and magnesium production and processing). For other source categories in this chapter, as indicated in the respective planned improvements sections,[6] EPA is continuing to analyze how facility-level GHGRP data may be used to improve the national estimates presented in this *Inventory*, giving particular consideration to ensuring time-series consistency and completeness.

Additionally, EPA's GHGRP has and will continue to enhance QA/QC procedures and assessment of uncertainties within the IPPU categories (see those categories for specific QA/QC details regarding the use of GHGRP data).

4.1 Cement Production (CRT Source Category 2A1)

Cement production is an energy- and raw material-intensive process that results in the generation of carbon dioxide (CO_2) both from the energy consumed in making the clinker precursor to cement and from the chemical process to make the clinker. This reporting category (2A1) includes emissions from production of clinker and use of cement kiln dust. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of cement are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

During the clinker production process, the key reaction occurs when calcium carbonate ($CaCO_3$), in the form of limestone or similar rocks or in the form of cement kiln dust (CKD), is heated in a cement kiln at a temperature range of about 700 to 1,000 degrees Celsius (1,300 to 1,800 degrees Fahrenheit) to form lime (i.e., calcium oxide, or CaO) and CO_2 in a process known as calcination or calcining. The quantity of CO_2 emitted during clinker production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ heated in the clinker kiln forms one mole of CaO and one mole of CO_2. The CO_2 is vented to the atmosphere as part of the kiln exhaust:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Next, over a temperature range of 1000 to 1450 degrees Celsius, the CaO combines with alumina, iron oxide and silica that are also present in the clinker raw material mix to form hydraulically reactive compounds within white-hot semifused (sintered) nodules of clinker. These "sintering" reactions are highly exothermic and produce few CO_2 process emissions. The clinker is then rapidly cooled to maintain quality and then very finely ground with a small amount of gypsum and potentially other materials (e.g., ground granulated blast furnace slag, etc.) to make portland and similar cements.

Masonry cement consists of plasticizers (e.g., ground limestone, lime, etc.) and portland cement, and the amount of portland cement used accounts for approximately 3 percent of total clinker production (USGS 2023b; 2023c). No

[5] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

[6] Ammonia production, glass production, lead production, and other fluorinated gas production.

additional emissions are associated with the production of masonry cement. Carbon dioxide emissions that result from the production of lime used to produce portland and masonry cement are included in Section 4.2.

Carbon dioxide emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States. Cement is produced in 34 states and Puerto Rico. Texas, Missouri, California, and Florida were the leading cement-producing states in 2022 and accounted for approximately 43 percent of total U.S. production (USGS 2023b). In 2022, shipments of cement were estimated to have increased by about 3 percent from 2021, and net imports increased by about 17 percent compared to 2021 (USGS 2023b).

In 2022, U.S. clinker production totaled 80,500 kilotons, which was an increase of 1 percent compared to 2021 and an increase of 25 percent compared to 1990 (EPA 2023). The resulting CO_2 emissions were estimated to be 41.9 MMT CO_2 Eq. (41,884 kt) (see Table 4-3 and Table 4-4). The total construction value and cement shipments increased by 11 percent and 4 percent, respectively, during the first nine months of 2022 compared to the same time period in 2021. This increase was attributed to continued economic recovery from the COVID-19 pandemic and the November 2021 passage of the Bipartisan Infrastructure Law. Despite the increases, growth was constrained by increased costs, labor and production shortages, and ongoing supply chain disruptions (USGS 2023b).

Table 4-3: CO_2 Emissions from Cement Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9

Table 4-4: CO_2 Emissions from Cement Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884

Greenhouse gas emissions from cement production, which are primarily driven by production levels, increased every year from 1991 through 2006 but decreased in the following years until 2009. Emissions from cement production were at their highest levels in 2006 and at their lowest levels in 2009. Emissions in 2009 were approximately 28 percent lower than 2008 emissions and 12 percent lower than 1990 due to the economic recession and the associated decrease in demand for construction materials. Since 2009, emissions have increased by 41 percent due to increasing demand for cement. Cement continues to be a critical component of the construction industry; therefore, the availability of public and private construction funding, as well as overall economic conditions, have considerable impact on the level of cement production.

Methodology and Time-Series Consistency

Carbon dioxide emissions from cement production are estimated using the Tier 2 method from the *2006 IPCC Guidelines* as this is a key category, in accordance with the IPCC methodological decision tree and available data. The Tier 2 methodology was used because detailed and complete data (including weights and composition) for carbonate(s) consumed in clinker production are not available,[7] and thus a rigorous Tier 3 approach is impractical. Tier 2 specifies the use of aggregated plant or national clinker production data and an emission factor, which is the product of the average lime mass fraction for clinker of 65 percent and a constant reflecting the mass of CO_2 released per unit of lime. The U.S. Geological Survey (USGS) mineral commodity expert for cement has confirmed that this is a reasonable assumption for the United States (Van Oss 2013a). This calculation yields an emission factor of 0.510 tons of CO_2 per ton of clinker produced, which was determined as follows:

[7] As discussed further under "Planned Improvements," most cement-producing facilities that report their emissions to the GHGRP use CEMS to monitor combined process and fuel combustion emissions for kilns, making it difficult to quantify the process emissions on a facility-specific basis. By the end of 2022, the percentage of facilities not using CEMS was 1 percent.

Equation 4-1: *2006 IPCC Guidelines* Tier 1 Emission Factor for Clinker (precursor to Equation 2.4)

$$EF_{clinker} = 0.650\ CaO \times \left[\left(44.01 \frac{g}{mole} CO_2\right) \div \left(56.08 \frac{g}{mole} CaO\right)\right] = 0.510 \frac{\text{tons } CO_2}{\text{ton clinker}}$$

During clinker production, some of the raw materials, partially reacted raw materials, and clinker enters the kiln line's exhaust system as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). To the degree that the CKD contains carbonate raw materials which are then calcined, there are associated CO_2 emissions. At some plants, essentially all CKD is directly returned to the kiln, becoming part of the raw material feed, or is likewise returned to the kiln after first being removed from the exhaust. In either case, the returned CKD becomes a raw material, thus forming clinker, and the associated CO_2 emissions are a component of those calculated for the clinker overall. At some plants, however, the CKD cannot be returned to the kiln because it is chemically unsuitable as a raw material or chemical issues limit the amount of CKD that can be so reused. Any clinker that cannot be returned to the kiln is either used for other (non-clinker) purposes or is landfilled. The CO_2 emissions attributable to the non-returned calcinated portion of the CKD are not accounted for by the clinker emission factor and thus a CKD correction factor should be applied to account for those emissions. The USGS reports the amount of CKD used to produce clinker, but no information is currently available on the total amount of CKD produced annually.[8] Because data are not currently available to derive a country-specific CKD correction factor, a default correction factor of 1.02 (2 percent) was used to account for CKD CO_2 emissions, as recommended by the IPCC (IPCC 2006).[9] Total cement production emissions were calculated by adding the emissions from clinker production and the emissions assigned to CKD.

Small amounts of impurities (i.e., not calcium carbonate) may exist in the raw limestone used to produce clinker. The proportion of these impurities is generally minimal, although a small amount (1 to 2 percent) of magnesium oxide (MgO) may be desirable as a flux. Per the IPCC Tier 2 methodology, a correction for MgO is not used, since the amount of MgO from carbonate is likely very small and the assumption of a 100 percent carbonate source of CaO already yields an overestimation of emissions (IPCC 2006).

The 1990 through 2012 activity data for clinker production were obtained from USGS (Van Oss 2013a; Van Oss 2013b). Clinker production data for 2013 were also obtained from USGS (USGS 2014). USGS compiled the data (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including facilities in Puerto Rico. Clinker production values in the current *Inventory* report utilize GHGRP data for the years 2014 through 2022 (EPA 2023). Clinker production data are summarized in Table 4-5. Details on how this GHGRP data compares to USGS reported data can be found in the section on QA/QC and Verification.

Table 4-5: Clinker Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Clinker Production	64,355	88,783	74,900	78,600	78,200	79,400	80,500

Note: Clinker production from 1990 through 2022 includes Puerto Rico (relevant U.S. Territories).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022. The methodology for cement production spliced activity data from two different sources: USGS for

[8] The USGS *Minerals Yearbook: Cement* notes that CKD values used for clinker production are likely underreported.

[9] As stated on p. 2.12 of the *2006 IPCC Guidelines*, Vol. 3, Chapter 2: "…As data on the amount of CKD produced may be scarce (except possibly for plant-level reporting), estimating emissions from lost CKD based on a default value can be considered good practice. The amount of CO_2 from lost CKD can vary but range typically from about 1.5 percent (additional CO_2 relative to that calculated for clinker) for a modern plant to about 20 percent for a plant losing a lot of highly calcinated CKD (van Oss 2005). In the absence of data, the default CKD correction factor (CF_{ckd}) is 1.02 (i.e., add 2 percent to the CO_2 calculated for clinker). If no calcined CKD is believed to be lost to the system, the CKD correction factor will be 1.00 (van Oss 2005)…"

1990 through 2013 and GHGRP starting in 2014. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw materials are $CaCO_3$, when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent; 65 percent is used as a representative value (Van Oss 2013a). This contributes to the uncertainty surrounding the emission factor for clinker which has an uncertainty range of ±3 percent with uniform densities (Van Oss 2013b). The amount of CO_2 from CKD loss can range from 1.5 to 8 percent depending upon plant specifications, and uncertainty was estimated at ±5 percent with uniform densities (Van Oss 2013b). Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of the total thickness. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated. EPA assigned uncertainty bounds of ±3 percent and a normal probability density function for clinker production and uncertainty bounds of ±5 percent and a uniform probability density function for the emission factor, based on expert judgment (Van Oss 2013b).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-6. Based on the uncertainties associated with total U.S. clinker production, the CO_2 emission factor for clinker production, and the emission factor for additional CO_2 emissions from CKD, 2022 CO_2 emissions from cement production were estimated to be between 40.1 and 43.8 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 4 percent below and 5 percent above the emission estimate of 41.9 MMT CO_2 Eq.

Table 4-6: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate [a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	41.9	40.1	43.8	-4%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

EPA relied upon the latest guidance from the IPCC on the use of facility-level data in national inventories and applied a category-specific QC process to compare activity data from EPA's GHGRP with existing data from USGS surveys. This was to ensure time-series consistency of the emission estimates presented in the *Inventory*. Total U.S. clinker production is assumed to have low uncertainty because facilities routinely measure this for economic reasons and because both USGS and GHGRP take multiple steps to ensure that reported totals are accurate. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the reporting industry (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year

comparison checks, along with manual reviews involving outside data checks) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[10] Facilities are also required to monitor and maintain records of monthly clinker production per section 98.84 of the GHGRP regulation (40 CFR 98.84).

EPA's GHGRP requires all facilities producing portland cement to report greenhouse gas emissions, including CO_2 process emissions from each kiln, CO_2 combustion emissions from each kiln, CH_4 and N_2O combustion emissions from each kiln, and CO_2, CH_4, and N_2O emissions from each stationary combustion unit other than kilns (40 CFR Part 98 Subpart H). Source-specific quality control measures for the cement production category are included in section 98.84, Monitoring and QA/QC Requirements.

As mentioned above, EPA compares GHGRP clinker production data (EPA 2023) to the USGS clinker production data (USGS 2023a; USGS 2023c). For the year 2014, 2020, and 2022, USGS and GHGRP clinker production data showed a difference of approximately 1 percent. In 2018, the difference between USGS and GHGRP clinker production data was approximately 3 percent, which resulted in a difference in emissions of about 1.2 MMT CO_2 Eq. In 2015, 2016, 2017, 2019, and 2021, that difference was less than 0.5 percent (less than 0.2 MMT CO_2 Eq.) between the two sets of activity data. The information collected by the USGS National Minerals Information Center surveys continue to be an important data source.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Cement Production source category. Most cement production facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor and report CO_2 emissions, thus reporting combined process and combustion emissions from kilns. In implementing further improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon, in addition to category-specific QC methods recommended by the *2006 IPCC Guidelines*.[11] EPA's long-term improvement plan includes continued assessment of the feasibility of using additional GHGRP information beyond aggregation of reported facility-level clinker data, in particular disaggregating the combined process and combustion emissions reported using CEMS, to separately present national process and combustion emissions streams consistent with IPCC and UNFCCC guidelines. This long-term planned analysis is still in development and has not been applied for this current *Inventory*.

EPA continues to review methods and data used to estimate CO_2 emissions from cement production in order to account for organic material in the raw material and to discuss the carbonation that occurs across the duration of the cement product. Work includes identifying data and studies on the average carbon content for organic materials in kiln feed in the United States and on CO_2 reabsorption rates via carbonation for various cement products. This information is not reported by facilities subject to GHGRP reporting. This is a long-term improvement.

[10] See GHGRP Verification Fact Sheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[11] See IPCC Technical Bulletin on Use of Facility-Specific Data in National Greenhouse Gas Inventories http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.2 Lime Production (CRT Source Category 2A2)

Lime is a manufactured product with many industrial, chemical, and environmental applications. This reporting category (2A2) includes process emissions from the production of lime. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of lime are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide (CO_2) is generated during the calcination stage, when limestone—consisting of calcium carbonate ($CaCO_3$) and/or magnesium carbonate ($MgCO_3$)—is roasted at high temperatures in a kiln to produce calcium oxide (CaO) and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere.

$$CaCO_3 \rightarrow CaO + CO_2$$

Some facilities, however, recover CO_2 generated during the production process for use in sugar refining and precipitated calcium carbonate (PCC) production.[12] PCC is used as a filler or coating in the paper, food, and plastic industries and is derived from reacting hydrated high-calcium quicklime with CO_2, a production process that does not result in net emissions of CO_2 to the atmosphere.

For U.S. operations, the term "lime" refers to a variety of chemical compounds. These include CaO, or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

The current lime market is approximately distributed across six end-use categories, as follows: metallurgical uses, 35 percent; environmental uses, 29 percent; chemical and industrial uses, 21 percent; construction uses, 10 percent; miscellaneous uses, 3 percent; and refractory dolomite, 1 percent (USGS 2021). The major uses are in steel making, chemical and industrial applications (such as the manufacture of fertilizer, glass, paper and pulp, and precipitated calcium carbonate, and in sugar refining), flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction, and water treatment, as well as uses in mining, pulp and paper and precipitated calcium carbonate manufacturing (USGS 2023a). Lime is also used as a CO_2 scrubber, and there has been experimentation on the use of lime to capture CO_2 from electric power plants. Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from limestone consumption for FGD systems are reported under Section 4.4 Other Process Uses of Carbonate Production (CRT Source Category 2A4).

Emissions from lime production have fluctuated over the time series depending on lime end-use markets – primarily the steel making industry and FGD systems for utility and industrial plants – and also energy costs. One significant change to lime end-use since 1990 has been the increase in demand for lime for FGD at coal-fired electric power plants, which can be attributed to compliance with sulfur dioxide (SO_2) emission regulations of the Clean Air Act Amendments of 1990. Phase I went into effect on January 1, 1995, followed by Phase II on January 1, 2000. To supply lime for the FGD market, the lime industry installed more than 1.8 million tons per year of new capacity by the end of 1995 (USGS 2023a). The need for air pollution controls continued to drive the FGD lime market, which had doubled between 1990 and 2019 (2021, 2023a, 2023b).

The U.S. lime industry temporarily shut down some individual gas-fired kilns and, in some case, entire lime plants during 2000 and 2001, due to significant increases in the price of natural gas. Lime production continued to

[12] The amount of CO_2 captured from lime production for sugar refining and PCC production is reported under CRT Source Category 2H3 "Other", but within this report, they are included in this chapter.

decrease in 2001 and 2002, a result of lower demand from the steel making industry, lime's largest end-use market, when domestic steel producers were affected by low priced imports and slowing demand (USGS 2023a).

Emissions from lime production peaked in 2006 at approximately 30.3 percent above 1990 levels, due to strong demand from the steel and construction markets (road and highway construction projects), before dropping to its second lowest level in 2009 at approximately 2.5 percent below 1990 emissions, driven by the economic recession and downturn in major markets including construction, mining, and steel (USGS 2023a). In 2010, the lime industry began to recover as the steel, FGD, and construction markets also recovered (USGS 2023a). Fluctuation in lime production since 2015 has been driven largely by demand from the steel making industry (USGS 2021). In 2020, a significant decline in lime production occurred due to plants temporarily closing as a result of the global COVID-19 pandemic (USGS 2023a). This resulted in the lowest level of emissions in 2020 at approximately 3.4 percent below 1990 emissions. Emissions increased annually since then, with 2022 levels similar to emissions in 2019.

Lime production in the United States—including Puerto Rico—was reported to be 16,994 kilotons in 2022, an increase of about 1.3 percent compared to 2021 levels (USGS 2023a). Compared to 1990, lime production increased by about 7.3 percent. At year-end 2022, 73 primary lime plants were operating in the United States, including Puerto Rico (USGS 2023a).[13] Principal lime producing states were, in alphabetical order, Kentucky, Missouri, Ohio, and Texas (USGS 2023a).

U.S. lime production resulted in estimated net CO_2 emissions of 12.2 MMT CO_2 Eq. (12,208 kt) (see Table 4-7 and Table 4-8). Carbon dioxide emissions from lime production increased by about 2.8 percent compared to 2021 levels. Compared to 1990, CO_2 emissions have increased by about 4.3 percent. The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described above.

Table 4-7: CO_2 Emissions from Lime Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2

Table 4-8: Gross, Recovered, and Net CO_2 Emissions from Lime Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Gross	11,959	15,074	13,609	12,676	11,875	12,586	12,750
Recovered[a]	259	522	503	564	576	716	542
Net Emissions	**11,700**	**14,552**	**13,106**	**12,112**	**11,299**	**11,870**	**12,208**

Note: Totals may not sum due to independent rounding.

[a] For sugar refining and PCC production.

Methodology and Time-Series Consistency

To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors, consistent with Tier 2 methodology from the *2006 IPCC Guidelines* and in accordance with the IPCC methodological decision tree and available data. The emission factor is the product of the stoichiometric ratio between CO_2 and CaO, and the average CaO and MgO content for lime. The CaO and MgO content for lime is assumed to be 95 percent for both high-calcium and dolomitic lime (IPCC 2006). The emission factors were calculated as follows:

[13] In 2022, 68 operating primary lime facilities in the United States reported to the EPA Greenhouse Gas Reporting Program.

Equation 4-2: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, High-Calcium Lime (Equation 2.9)

$$EF_{\text{High-Calcium Lime}} = \left[\left(44.01\frac{\text{g}}{\text{mole}}CO_2\right) \div \left(56.08\frac{\text{g}}{\text{mole}}CaO\right)\right] \times \left(0.9500\frac{CaO}{\text{lime}}\right) = 0.7455\ \frac{\text{g } CO_2}{\text{g lime}}$$

Equation 4-3: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, Dolomitic Lime (Equation 2.9)

$$EF_{\text{Dolomitic Lime}} = \left[\left(88.02\frac{\text{g}}{\text{mole}}CO_2\right) \div \left(96.39\frac{\text{g}}{\text{mole}}CaO \bullet MgO\right)\right] \times \left(0.9500\ \frac{CaO \bullet MgO}{\text{lime}}\right) = 0.8675\ \frac{\text{g } CO_2}{\text{g lime}}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H_2O to ($Ca(OH)_2$ and $[Ca(OH)_2 \bullet Mg(OH)_2]$) (IPCC 2006). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 30 percent for dolomitic hydrated lime.

The *2006 IPCC Guidelines* (Tier 2 method) also recommends accounting for emissions from lime kiln dust (LKD) through application of a correction factor. LKD is a byproduct of the lime manufacturing process typically not recycled back to kilns. LKD is a very fine-grained material and is especially useful for applications requiring very small particle size. Most common LKD applications include soil reclamation and agriculture. Emissions from the application of lime for agricultural purposes are reported in the Agriculture chapter under 5.5 Liming (CRT Source Category 3G). Currently, data on annual LKD production is not readily available to develop a country-specific correction factor. Lime emission estimates were multiplied by a factor of 1.02 to account for emissions from LKD (IPCC 2006). See the Planned Improvements section associated with efforts to improve uncertainty analysis and emission estimates associated with LKD.

Lime emission estimates were further adjusted to account for the amount of CO_2 captured for use in on-site processes. All the domestic lime facilities are required to report these data to EPA under its GHGRP. The total national-level annual amount of CO_2 captured for on-site process use was obtained from EPA's GHGRP (EPA 2023) based on reported facility-level data for years 2010 through 2022. The amount of CO_2 captured/recovered for non-marketed on-site process use is deducted from the total gross emissions (i.e., from lime production and LKD). The net lime emissions are presented in Table 4-7 and Table 4-8. GHGRP data on CO_2 removals (i.e., CO_2 captured/recovered) was available only for 2010 through 2022. Since GHGRP data are not available for 1990 through 2009, IPCC "splicing" techniques were used as per the *2006 IPCC Guidelines* on time-series consistency (IPCC 2006, Volume 1, Chapter 5).

Lime production data (i.e., lime sold and non-marketed lime used by the producer) by type (i.e., high-calcium and dolomitic quicklime, high-calcium and dolomitic hydrated lime, and dead-burned dolomite) for 1990 through 2022 (see Table 4-9) were obtained from U.S. Geological Survey (USGS) *Minerals Yearbook* (USGS 2023a) and are compiled by USGS to the nearest ton. Dead-burned dolomite data are additionally rounded by USGS to no more than one significant digit to avoid disclosing company proprietary data. Production data for the individual quicklime (i.e., high-calcium and dolomitic) and hydrated lime (i.e., high-calcium and dolomitic) types were not provided prior to 1997. These were calculated based on total quicklime and hydrated lime production data from 1990 through 1996 and the three-year average ratio of the individual lime types from 1997 to 1999. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2023a). Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent based on recommendations from the IPCC and using the water content values for high-calcium hydrated lime and dolomitic hydrated lime mentioned above, and is presented in Table 4-10 (IPCC 2006). The CaO and CaO•MgO contents of lime, both 95 percent, were obtained from the IPCC (IPCC 2006).

Table 4-9: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
High-Calcium Quicklime	11,166	14,100	12,400	11,300	10,700	11,200	11,500
Dolomitic Quicklime	2,234	2,990	2,810	2,700	2,390	2,700	2,640
High-Calcium Hydrated	1,781	2,220	2,430	2,430	2,320	2,430	2,410
Dolomitic Hydrated	319	474	265	267	252	244	244
Dead-Burned Dolomite	342	200	200	200	200	200	200

Table 4-10: Adjusted Lime Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
High-Calcium	12,466	15,721	14,174	13,074	12,394	12,974	13,259
Dolomitic	2,800	3,522	3,196	3,087	2,766	3,071	3,011

Note: Minus water content of hydrated lime.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of lime products and CO_2 recovery rates for on-site process use over the time series. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants produce lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed, especially at captive lime production facilities. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2, whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. Quantifying the amount of CO_2 that is reabsorbed would require a detailed accounting of lime use in the United States and additional information about the associated processes where both the lime and byproduct CO_2 are "reused." Research conducted thus far has not yielded the necessary information to quantify CO_2 reabsorption rates.[14] Some additional information on the amount of CO_2 consumed on site at lime facilities, however, has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[15] The lime generated by these processes is included in the USGS data for commercial lime consumption. In the pulping industry, mostly using the Kraft (sulfate) pulping process, lime is consumed in order to causticize a process liquor (green liquor) composed of sodium carbonate and sodium sulfide. The green liquor results from the dilution of the smelt created by combustion of the black liquor where biogenic carbon (C) is present from the wood. Kraft

[14] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[15] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + \text{heat} \rightarrow CaO + H_2O$], and no CO_2 is released.

mills recover the calcium carbonate "mud" after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin and therefore is not included in the industrial processes totals (Miner and Upton 2002). In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands (see the Land Use, Land-Use Change, and Forestry chapter).

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Another uncertainty is the assumption that calcination emissions for LKD are around 2 percent. EPA assigned uncertainty ranges of ±2 percent and a triangular probability density function for the LKD correction factor based on expert judgment (RTI 2023). The National Lime Association (NLA) has commented that the estimates of emissions from LKD in the United States could be closer to 6 percent. They also note that additional emissions (approximately 2 percent) may also be generated through production of other byproducts/wastes (off-spec lime that is not recycled, scrubber sludge) at lime plants (Seeger 2013). Publicly available data on LKD generation rates, total quantities not used in cement production, and types of other byproducts/wastes produced at lime facilities are limited. NLA compiled and shared historical emissions information and quantities for some waste products reported by member facilities associated with generation of total calcined byproducts and LKD, as well as methodology and calculation worksheets that member facilities complete when reporting. There is uncertainty regarding the availability of data across the time series needed to generate a representative country-specific LKD factor. Uncertainty of the activity data is also a function of the reliability and completeness of voluntarily reported plant-level production data. EPA assigned uncertainty ranges of ±1 percent for lime production and a normal probability density function, based on expert judgment (USGS 2012). Further research, including discussion with NLA, and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on the *2006 IPCC Guidelines*. More information can be found in the Planned Improvements section below.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-11. Lime CO_2 emissions for 2022 were estimated to be between 12.1 and 12.3 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 1 percent below and 1 percent above the emission estimate of 12.2 MMT CO_2 Eq.

Table 4-11: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	12.2	12.1	12.3	-1%	+1%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as noted in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods associated with reporting on CO_2 captured for onsite use applicable to lime manufacturing facilities can be found under Subpart S (lime

manufacturing) of the GHGRP regulation (40 CFR Part 98).[16]EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2023).[17] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA plans to review GHGRP emissions and activity data reported to EPA under Subpart S of the GHGRP regulation (40 CFR Part 98), and aggregated activity data on lime production by type in particular. In addition, initial review of data has identified that several facilities use CEMS to report emissions. Under Subpart S, if a facility is using a CEMS, they are required to report combined combustion emissions and process emissions. EPA continues to review how best to incorporate GHGRP and notes that particular attention will be made to also ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required because the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[18]

Future improvements involve improving and/or confirming the representativeness of current assumptions associated with emissions from production of LKD and other byproducts/wastes as discussed in the Uncertainty section, per comments from the NLA provided during a prior Public Review comment period for a previous (1990 through 2018) *Inventory.* EPA met with NLA in summer of 2020 for clarification on data needs and available data and to discuss planned research into GHGRP data. Previously, EPA met with NLA in spring of 2015 to outline specific information required to apply IPCC methods to develop a country-specific correction factor to more accurately estimate emissions from production of LKD. In 2016, NLA compiled and shared historical emissions information reported by member facilities on an annual basis under voluntary reporting initiatives from 2002 through 2011 associated with generation of total calcined byproducts and LKD. Reporting of LKD was only differentiated for the years 2010 and 2011. This emissions information was reported on a voluntary basis consistent with NLA's facility-level reporting protocol, which was also provided to EPA. To reflect information provided by NLA, EPA updated the qualitative description of uncertainty. At the time of this *Inventory*, this planned improvement is in process and has not been incorporated into this current *Inventory* report.

[16] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[17] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[18] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.3 Glass Production (CRT Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of carbon dioxide (CO_2) from both the energy consumed in making glass and the glass production process itself. This reporting category (2A3) includes emissions from the production of glass. Emissions from fuels consumed for energy purposes during the production of glass are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Glass production employs a variety of raw materials in a glass-batch. These include formers, fluxes, stabilizers, and sometimes colorants. The major raw materials (i.e., fluxes and stabilizers) that emit process-related CO_2 emissions during the glass melting process are limestone, dolomite, and soda ash. The main former in all types of glass is silica (SiO_2). Other major formers in glass include feldspar and boric acid (i.e., borax). Fluxes are added to lower the temperature at which the batch melts. Most commonly used flux materials are soda ash (sodium carbonate, Na_2CO_3) and potash (potassium carbonate, K_2O). Stabilizers make glass more chemically stable and keep the finished glass from dissolving and/or falling apart. Commonly used stabilizing agents in glass production are limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$), alumina (Al_2O_3), magnesia (MgO), barium carbonate ($BaCO_3$), strontium carbonate ($SrCO_3$), lithium carbonate (Li_2CO_3), and zirconia (ZrO_2) (DOE 2002). Glass makers also use a certain amount of recycled scrap glass (cullet), which comes from in-house return of glassware broken in the production process or other glass spillage or retention, such as recycling or from cullet broker services.

The raw materials (primarily soda ash, limestone, and dolomite) release CO_2 emissions in a complex high-temperature chemical reaction during the glass melting process. This process is not directly comparable to the calcination process used in lime manufacturing, cement manufacturing, and process uses of carbonates (i.e., limestone/dolomite use) but has the same net effect in terms of generating process CO_2 emissions (IPCC 2006).

The U.S. glass industry can be divided into four main categories: containers, flat (window) glass, fiber glass, and specialty glass. The majority of commercial glass produced is container and flat glass (EPA 2009). The United States is one of the major global exporters of glass. Domestically, demand comes mainly from the construction, auto, bottling, and container industries. There are more than 1,700 facilities that manufacture glass in the United States, with the largest companies being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.[19]

The glass container sector is one of the leading soda ash consuming sectors in the United States. In 2022, glass production accounted for 49 percent of total domestic soda ash consumption (USGS 2023). Emissions from soda ash production are reported in Section 4.12.

In 2022, 2,250 kilotons of soda ash, 1,370 kilotons of limestone, 925 kilotons of dolomite, and 1.9 kilotons of other carbonates were consumed for glass production (USGS 2023; EPA 2023). Use of soda ash, limestone, dolomite, and other carbonates in glass production resulted in aggregate CO_2 emissions of 2.0 MMT CO_2 Eq. (1,956 kt), which are summarized in Table 4-12 and Table 4-13. Overall, emissions have decreased by 14 percent compared to 1990. Emissions decreased by 1 percent compared to 2021 levels.

Emissions from glass production have remained relatively consistent over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. Specifically, the extended downturn in residential and commercial construction and automotive industries between 2008 and 2010 resulted in reduced consumption of glass products, causing a drop in global demand for limestone, dolomite, and soda ash and resulting in lower emissions. Some commercial food and beverage package

[19] Excerpt from Glass & Glass Product Manufacturing Industry Profile, First Research. Available online at: http://www.firstresearch.com/Industry-Research/Glass-and-Glass-Product-Manufacturing.html.

manufacturers are shifting from glass containers towards lighter and more cost-effective polyethylene terephthalate (PET) based containers, putting downward pressure on domestic consumption of soda ash (USGS 1995 through 2015b). Glass production in 2022 was steady, changing by no more than 2 percent over the course of the year (Federal Reserve 2023).

Table 4-12: CO_2 Emissions from Glass Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0

Table 4-13: CO_2 Emissions from Glass Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956

Methodology and Time-Series Consistency

Carbon dioxide emissions were calculated based on Tier 3 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of input carbonates (i.e., limestone, dolomite, soda ash, and other carbonates) by the carbonate-based emission factor (in metric tons CO_2/metric ton carbonate) and the average carbonate-based mineral mass fraction.

2010 through 2022

The methodology for estimating CO_2 emissions from glass production for years 2010 through 2022 used the quantities of limestone, dolomite, and a group of other carbonates (i.e., barium carbonate, potassium carbonate, lithium carbonate, and strontium carbonate) used for glass production, obtained from GHGRP (EPA 2023). USGS data on the quantity of soda ash used for glass production was used because it was obtained directly from the soda ash producers and includes use by smaller artisanal glass operations, which are excluded in the GHGRP data.

GHGRP collects data from glass production facilities with greenhouse gas emissions greater than 25,000 metric tons CO_2 Eq. The reporting threshold is used to exclude artisanal glass operations that are expected to have much lower greenhouse gas emissions than the threshold. These smaller facilities have not been accounted for yet for this portion of the time series for limestone, dolomite, or other carbonates due to limited data. Facilities report the total quantity of each type of carbonate used in glass production each year to GHGRP, with data collection starting in 2010 (EPA 2023).

Using the total quantities of each carbonate, EPA calculated the metric tons of emissions resulting from glass production by multiplying the quantity of input carbonates (i.e., limestone, dolomite, soda ash, and other carbonates) by carbonate-based emission factors in metric tons CO_2/metric ton carbonate (limestone, 0.43971; dolomite, 0.47732; soda ash, 0.41492; and other carbonates, 0.262), and by the average carbonate-based mineral mass fraction for each year. IPCC default emission factors were used for limestone, dolomite, and soda ash, and the emission factor for other carbonates is based on expert judgment (RTI 2022).

1990 through 2009

Data from GHGRP on the quantity of limestone, dolomite, and other carbonates used in glass production are not available for 1990 through 2009. Additionally, USGS does not collect data on the quantity of other carbonates used for glass production.

To address time-series consistency, total emissions from 1990 to 2009 were calculated using the Federal Reserve Industrial Production Index for glass production in the United States as a surrogate for the total quantity of carbonates used in glass production. The production index measures real output expressed as a percentage of real output in a base year, which is currently 2017 (Federal Reserve 2023). Since January 1971, the Federal Reserve has released the monthly glass production index for NAICS code 3272 (Glass and Glass Product Manufacturing) as part

of release G.17, "Industrial Production and Capacity Utilization" (Federal Reserve 2023). The monthly index values for each year were averaged to calculate an average annual glass production index value. Total annual process emissions were calculated by taking a ratio of the average annual glass production index for each year to the average annual glass production index for base year 2017, and multiplying by the calculated 2017 emissions (process-related) based on GHGRP data.

Emissions from limestone, dolomite, and other carbonate consumption were disaggregated from total annual emissions, using the average percent contribution of each to annual emissions from these three carbonates for 2010 through 2014 based on GHGRP data: 64.5 percent limestone, 35.5 percent dolomite, and 0.1 percent other carbonates.

The methodology for estimating CO_2 emissions from the use of soda ash for glass production and data sources for the amount of soda ash used in glass production are consistent with the methodology used for 2010 through 2022. The average mineral mass fractions for soda ash are only available starting in 2010. The average carbonate-based mineral mass fractions from the GHGRP, averaged across 2010 through 2014, indicate that soda ash contained 98.7 percent sodium carbonate (Na_2CO_3). This averaged value is used to estimate emissions for 1990 through 2009. The years 2010 to 2014 were used to determine the average carbonate-based mineral mass fractions because those years were deemed to better represent historic glass production from 1990 to 2009.

Data on soda ash used for glass production for 1990 through 2022 were obtained from the U.S. Bureau of Mines (1991 and 1993a), the USGS *Minerals Yearbook: Soda Ash* (USGS 1995 through 2015b), and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2017 through 2023). Data on limestone, dolomite, and other carbonates used for glass production and on average carbonate-based mineral mass fraction for 2010 through 2022 were obtained from GHGRP (EPA 2023). The quantities of limestone, dolomite, and other carbonates were calculated for 1990 through 2009 using the Federal Reserve Industrial Production Index (Federal Reserve 2023).

The amount of limestone, dolomite, soda ash, and other carbonates used in glass production each year and the annual average Federal Reserve production indices for glass production are shown in Table 4-14.

Table 4-14: Limestone, Dolomite, Soda Ash, and Other Carbonates Used in Glass Production (kt) and Average Annual Production Index for Glass and Glass Product Manufacturing

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	1,409	1,690	1,442	1,370	1,334	1,397	1,370
Dolomite	714	857	871	883	824	893	925
Soda Ash	3,177	3,050	2,280	2,220	2,130	2,280	2,250
Other Carbonates	2	3	2	2	2	2	1.9
Total	**5,302**	**5,599**	**4,596**	**4,475**	**4,289**	**4,572**	**4,547**
Production Index[a]	94.3	113.1	102.5	99.8	92.4	88.3	86.8

[a] Average Annual Production Index uses 2017 as the base year.

Note: Totals may not sum due to independent rounding.

As discussed above, methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare USGS and GHGRP data sets for 2010 through 2022. To address the inconsistencies, adjustments were made as described above.

Uncertainty

The methodology in this *Inventory* report uses GHGRP data for the average mass fraction of each mineral used in glass production. These minerals are limestone, dolomite, soda ash, and other carbonates (barium carbonate ($BaCO_3$), potassium carbonate (K_2CO_3), lithium carbonate (Li_2CO_3), and strontium carbonate ($SrCO_3$)). The mass fractions are reported directly by the glass manufacturers, for each year from 2010 to 2022.

The methodology uses the quantities of limestone, dolomite, and other carbonates used in glass manufacturing which is reported directly by the glass manufacturers for years 2010 through 2022 and the amount of soda ash used in glass manufacturing which is reported by soda ash producers for the full time series. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for all carbonate quantities and the Federal Reserve Industrial Production Index for glass production, and using this suggested uncertainty provided in Section 2.4.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of ±2 percent for the carbonate emission factors, ±2 percent for the mineral mass fractions, and ±1 percent for the calcination fraction, and using this suggested uncertainty provided in Section 2.4.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors, mineral mass fractions, and calcination fraction.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-15. In 2022, glass production CO_2 emissions were estimated to be between 1.9 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below and 2 percent above the emission estimate of 2.0 MMT CO_2 Eq.

Table 4-15: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Glass Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Glass Production	CO_2	2.0	1.9	2.0	-2%	+2%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[20] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

During annual QC, a transcription error for the 1990 value of CO_2 emissions from glass production was identified and corrected in Table 4-12 and Table 4-13. No recalculations were needed or performed due to this transcription error, and no other recalculations were performed for the 1990 through 2021 portion of the time series.

[20] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

EPA plans to evaluate updates to uncertainty levels for the activity data and mineral mass fraction values from EPA's GHGRP. This is a near-term planned improvement that is anticipated for inclusion in 2025 report.

Some glass producing facilities in the United States do not report to EPA's GHGRP because they fall below the reporting threshold for this industry. EPA will continue ongoing research on the availability of data to better assess the completeness of emission estimates from glass production and how to refine the methodology to ensure complete national coverage of this category. When reporting began in 2010, EPA received data from more facilities that were above the reporting threshold than expected, and total emissions for these reporting facilities were higher than expected for all glass production facilities in the United States (EPA 2009). Research will include reassessing previous assessments of GHGRP industry coverage using the reporting threshold of 25,000 metric tons CO_2 Eq. This is a medium-term planned improvement.

4.4 Other Process Uses of Carbonates (CRT Source Category 2A4)

Limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$),[21] and other carbonates such as soda ash, magnesite, and siderite are basic materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy (i.e., iron and steel production, ferroalloy production, and magnesium production), glass production, environmental pollution control, ceramics production, and non-metallurgical magnesia production. This reporting category (2A4) includes emissions from other uses of limestone, dolomite, and other carbonates not included in other categories; the production of ceramics; other uses of soda ash not included elsewhere; and the production of non-metallurgical magnesia. This section addresses mineral industry use of these carbonates: limestone, dolomite, soda ash, and magnesite. Emissions from the use of these carbonates are organized into four subcategories: other process uses of carbonates (i.e., limestone and dolomite consumption), ceramics production, other uses of soda ash, and non-metallurgical magnesia production.

For industrial applications, carbonates are heated sufficiently enough to calcine the material and generate CO_2 as a byproduct.

$$CaCO_3 \rightarrow CaO + CO_2$$

$$MgCO_3 \rightarrow MgO + CO_2$$

Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, and as a raw material for the production of glass, lime, and cement.

Emissions from limestone and dolomite used in the production of cement, lime, glass, and iron and steel are excluded from the other process uses of carbonates category and reported under their respective source categories (e.g., Section 4.3, Glass Production). Emissions from soda ash production are reported under Section 4.12, Soda Ash Production (CRT Source Category 2B7). Emissions from soda ash consumption associated with glass manufacturing are reported under Section 4.3, Glass Production (CRT Source Category 2A3). Emissions from the use of limestone and dolomite in liming of agricultural soils are included in the Agriculture chapter under Section 5.5, Liming (CRT Source Category 3G). Emissions from limestone and dolomite used in the production of iron and steel and magnesium production are reported under Section 4.18, Iron and Steel Production (CRT Source Category 2C1).

[21] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Emissions from dolomite used in the production of magnesium are reported under Section 4.21, Magnesium Production and Processing (CRT Source Category 2C4). As noted in Section 4.19, Ferroalloy Production (CRT Source Category 2C2), emissions from the production of ferromanganese are not included in this *Inventory* because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Emissions from fuels consumed for energy purposes during these processes are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter in Section 3.1, Fossil Fuel Combustion (CRT Source Category 1A). Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from lime consumption for FGD systems and from sugar refining are reported under Section 4.3, Lime Production (CRT Source Category 2A2). Emissions from the use of dolomite in primary magnesium metal production are reported under Section 4.21, Magnesium Production and Processing (CRT Source Category 2C4).

Limestone and dolomite are widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. In 2018, the leading limestone producing states were Texas, Florida, Ohio, Missouri, and Pennsylvania, which contributed 46 percent of the total U.S. output (USGS 2022a). Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Pennsylvania, New York, and Utah which currently contribute more than a third of the total U.S. output (USGS 2022a).

Ceramics include the production of bricks and roof tiles, vitrified clay pipes, refractory products, expanded clay products, wall and floor tiles, table and ornamental ware (i.e., household ceramics), sanitary ware, technical ceramics (e.g., aerospace, automotive, electronic, or biomedical applications), and inorganic bonded abrasives. Most ceramic products are made from one or more different types of clay (e.g., shales, fire clay, and ball clay) with varying carbonate contents. The process of manufacturing ceramic products, regardless of the product type or scale, is essentially the same. This process consists of raw material processing (grinding, calcining, and drying), forming (wet or dry process), firing (single or multiple stage firing process), and final processing. Process CO_2 emissions are produced during the calcination process in the kiln or dryer, where carbonates are heated to high temperatures which results in metal oxides and CO_2. In 2018, the leading clay producing states were Georgia, Wyoming, Texas, Alabama, and North Carolina, which contributed 60 percent of the total U.S. output (USGS 2022f).

Other uses of soda ash include the consumption of soda ash for non-glass purposes. Excluding glass production, soda ash consumption by end use in 2022 included chemicals, 54 percent, soap and detergent manufacturing, 9 percent; distributers, 10 percent; flue gas desulfurization, 7 percent; other uses, 17 percent; pulp and paper production, 1 percent; and water treatment, 2 percent (USGS 2023a). Chemicals produced using soda ash include sodium-based inorganic chemicals such as sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates. (USGS 2022g). Internationally, two types of soda ash are produced: natural and synthetic. In 2019, 93 percent of the global soda ash production came from China, the United States, Russia, Germany, India, Turkey, Poland, and France. The United States only produces natural soda ash and only in two states: Wyoming and California (USGS 2021a).

Non-metallurgical magnesia production comprises of three categories of magnesia products: calcined magnesia, deadburned magnesia, and fused magnesia. Magnesia is produced by calcining magnesite ($MgCO_3$) which results in the release of CO_2. Non-metallurgical magnesia is used in agricultural, industrial, refractory, and electrical insulating applications. Specific applications include fertilizers, construction materials, plastics, and flue gas desulphurization. China, Russia, and Turkey account for 83 percent of global production capacity of magnesia from magnesite (USGS 2022e). In the United States, only one facility located in Nevada produces non-metallurgical magnesia using magnesite as the raw material.

In 2022, 18,671 kilotons (kt) of limestone, 2,052 kt of dolomite, 2,391 kt of soda ash, and 388 kt of magnesite were consumed for these emissive applications, which excludes consumption for the production of cement, lime, glass, and iron and steel (Willett 2023; USGS 2022b). Usage of limestone, dolomite, soda ash, and magnesite resulted in aggregate CO_2 emissions of 10.4 MMT CO_2 Eq. (10,384 kt) (see Table 4-16 and Table 4-17). The 2022 emissions increased 21 percent compared to 2021, primarily as a result of increased limestone consumption attributed to

sulfur oxide removal. Growth in the public and private construction markets contributed to an increase in consumption of crushed stone in 2022. Overall emissions have increased 46 percent from 1990 through 2022.

Table 4-16: CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Other Uses of Carbonates	4.8	6.2	6.3	7.4	7.4	7.0	8.8
Ceramics Production	0.8	0.8	0.4	0.4	0.4	0.4	0.4
Other Uses of Soda Ash[a]	1.4	1.3	1.1	1.0	1.0	1.0	1.0
Non-Metallurgical Magnesia Production	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Total	**7.1**	**8.5**	**7.9**	**9.0**	**9.0**	**8.6**	**10.4**

[a] Soda ash consumption not associated with glass manufacturing.
Note: Totals may not sum due to independent rounding.

Table 4-17: CO_2 Emissions from Other Process Uses of Carbonates (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Other Uses of Carbonates	4,843	6,155	6,283	7,386	7,441	6,972	8,781
Ceramics Production	757	822	418	399	397	400	407
Other Uses of Soda Ash[a]	1,390	1,305	1,069	1,036	958	979	992
Non-Metallurgical Magnesia Production	113	191	169	152	216	231	204
Total	**7,103**	**8,472**	**7,938**	**8,973**	**9,012**	**8,583**	**10,384**

[a] Soda ash consumption not associated with glass manufacturing.
Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Other Uses of Carbonates (Limestone and Dolomite Consumption)

Carbon dioxide emissions from other uses of carbonates, specifically limestone and dolomite consumption, were calculated using a Tier 2 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of limestone or dolomite consumed by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton carbonate for limestone and 0.47732 metric ton CO_2/metric ton carbonate for dolomite.[22] This methodology was used for limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization. Flux stone used during the production of iron and steel was deducted from the other uses of carbonates source category estimate and attributed to the iron and steel production source category estimate. Similarly, limestone and dolomite consumption for glass manufacturing, cement, and lime manufacturing are excluded from this category and attributed to their respective categories.

Consumption data for 1990 through 2022 of limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization (see Table 4-18) were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995a through 2023b), preliminary data for 2022 from USGS Crushed Stone Commodity Expert (Willett 2023), American Iron and Steel Institute limestone and dolomite consumption data (AISI 2018 through 2021), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. In addition, the estimated values for limestone and dolomite consumption for flux stone used during the production of iron and steel were adjusted using emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) Subpart Q for the iron and steel sector to account for the impacts of the COVID-19 pandemic in 2020 and 2021. Iron and steel GHGRP process emissions data

[22] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

decreased by approximately 8 percent from 2021 to 2022 (EPA 2023). This adjustment method is consistent with the method used in Section 4.18, Iron and Steel Production (CRT Source Category 2C1).

During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use; therefore, data on consumption by end use for 1990 was estimated by applying the 1991 ratios of total limestone and dolomite consumption by end use to total 1990 limestone and dolomite consumption values. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 ratios of total limestone and dolomite use by end uses to the 1992 total values.

In 1991, the U.S. Bureau of Mines, now known as the USGS, began compiling production and end use information through surveys of crushed stone manufacturers. Manufacturers provided different levels of detail in survey responses, so information was divided into three categories: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified-reported" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "unspecified-estimated" production). Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

A large quantity of crushed stone was reported to the USGS under the category "unspecified uses." A portion of this consumption is believed to be limestone or dolomite used for emissive end uses. The quantity listed for "unspecified uses" was, therefore, allocated to all other reported end-uses according to each end-use's fraction of total consumption in that year.[23]

Table 4-18: Limestone and Dolomite Consumption from Other Uses of Carbonates (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	10,016	10,465	12,816	15,146	13,707	12,788	17,891
Dolomite	919	3,254	1,356	1,520	2,962	2,826	1,915
Total	**10,935**	**13,719**	**14,172**	**16,667**	**16,669**	**15,614**	**19,806**

Note: Totals may not sum due to independent rounding.

Ceramics Production

Carbon dioxide emissions from ceramics production were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of clay consumed for emissive purposes by a carbonate content value of clay of 10 percent, limestone fraction of 85 percent and dolomite fraction of 15 percent, respectively, and by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton of limestone and 0.47732 metric ton CO_2/metric ton of dolomite.[24] To estimate annual process CO_2 emissions, EPA evaluated the end-uses of each type of clay published by USGS to identify the emissive end-uses that fall into the ceramics production subcategory. The emissive end-uses were organized into three groups: ceramics, glass, and floor & tile; refractories; and heavy clay products. The total limestone and dolomite consumption from the three emissive groupings for ceramics production for 1990 through 2022 (see Table 4-19) were obtained from USGS (Simmons 2024).

[23] This approach was recommended by USGS, the data collection agency.

[24] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

Table 4-19: Limestone and Dolomite Consumption from Ceramics Production (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	1,444	1,569	797	762	758	764	776
Dolomite	255	277	141	135	134	135	137
Total	**1,699**	**1,846**	**938**	**897**	**892**	**899**	**913**

Note: Totals may not sum due to independent rounding.

Other Uses of Soda Ash

Carbon dioxide emissions from soda ash consumption were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Excluding glass manufacturing which is reported under Section 4.3 Glass Production (CRT Source Category 2A3), most soda ash is consumed in chemical production, with smaller amounts used in soap production, pulp and paper, flue gas desulfurization, and water treatment. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed. The activity data for soda ash consumption for 1990 to 2022 (see Table 4-20) were obtained from the *U.S. Geological Survey (USGS) Minerals Yearbook for Soda Ash* (1994 through 2015b) and *USGS Mineral Industry Surveys for Soda Ash* (USGS 2017a, 2018, 2019, 2020b, 2021b, 2022a, 2023a). Soda ash consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-20: Other Uses of Soda Ash Consumption Not Associated with Glass Manufacturing (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Soda Ash[a]	3,351	3,144	2,576	2,497	2,310	2,360	2,391

[a] Soda ash consumption is sales reported by producers which exclude imports. Historically, imported soda ash is less than 1 percent of the total U.S. consumption (Kostick 2012).

Non-Metallurgical Magnesia Production

Carbon dioxide emissions from non-metallurgical magnesia production were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of magnesium ore extracted from the mine and processed at the facility by the carbonate content for magnesite or limestone, respectively, and by the emission factor for magnesite or limestone calcination, respectively: 0.52197 metric ton CO_2/metric ton carbonate for magnesite and 0.43971 metric ton CO_2/metric ton carbonate for limestone.[25] A USGS report on magnesite deposits at Gabbs, Nevada lists the carbonate content of magnesite as 98 percent magnesite and 1 percent limestone (USGS 1948). In the absence of other data, all magnesium ore extracted from the mine is assumed to be used for non-metallurgical magnesium production. Magnesium ore extracted from the mine and processed at the facility for non-metallurgical magnesia production for 2002 through 2022 (see Table 4-21) was obtained from the Nevada Department of Environmental Quality (McNeece 2023). This data was not available for 1990 through 2001. To address this gap in data availability and time-series consistency, carbonate consumption for 1990 through 2001 were estimated by multiplying the average ratio of magnesium ore consumption to production capacity for 2002 to 2004 by the production capacity of the facility in Nevada. Production capacity for 1990 through 2001 was obtained from the *USGS Minerals Yearbook for Magnesium Compounds* (USGS 1990 through 2002).

[25] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

Table 4-21: Magnesite and Limestone Consumption from Non-Metallurgical Magnesia Production (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Magnesite	214	363	321	289	410	439	388
Limestone	2	4	3	3	4	4	4
Total	**216**	**367**	**325**	**292**	**414**	**443**	**392**

Note: Totals may not sum due to independent rounding.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied for non-metallurgical magnesia production to compare the magnesium ore consumption data to production capacity data for years where there was overlap. To address inconsistencies, adjustments were made, as described above.

Uncertainty

The uncertainty levels presented in this section account for uncertainty associated with activity data. Data on limestone and dolomite consumption are collected by USGS through voluntary national surveys. USGS contacts the mines (i.e., producers of various types of crushed stone) for annual sales data. Data on other carbonate consumption are not readily available. The producers report the annual quantity sold to various end-users and industry types. USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, and the rest is estimated by USGS. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the producer/mines and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. EPA contacted the USGS National Minerals Information Center Crushed Stone commodity expert to assess the current uncertainty ranges associated with the limestone and dolomite consumption data compiled and published by USGS. During this discussion, the expert confirmed that EPA's range of uncertainty was still reasonable (Willett 2017). EPA assigned an uncertainty range of ±10 percent for limestone and dolomite consumption, based on expert judgement (Willett 2017). EPA assigned an uncertainty range of ±5 percent for soda ash consumption, and using this suggested uncertainty provided in Volume 3, Chapter 2, Section 2.4.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

Uncertainty in the estimates also arises in part due to variations in the chemical composition of limestone. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed. EPA assigned an uncertainty range of ±3 percent for the CO_2 emission factors for limestone and dolomite consumption, and using this suggested uncertainty provided in Volume 3, Chapter 2, Section 2.5.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

For emissions from ceramics production, data on clay consumption are collected by USGS through voluntary national surveys. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The accuracy of distribution by end use is also uncertain because this value is reported by the producer and not the end user. Uncertainty in the estimates also arises in part due to the variations in the carbonate content of the various clays used for the various types of ceramics. As discussed above, as no information is available on the carbonate content for each clay, fractions of limestone and dolomite consumed and a carbonate content for clay from the *2006 IPCC Guidelines* are used. EPA assigned an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for other process uses of carbonates, respectively.

For emissions from soda ash consumption, the primary source of uncertainty results from the fact that these emissions are dependent upon the type of processing employed by each end-use. Specific emission factors for each end-use are not available, so a Tier 1 default emission factor is used for all end-uses. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash. Additional uncertainty comes from the reported consumption and allocation of consumption within sectors that is collected on a quarterly basis by the USGS. Efforts have been made to categorize company sales within the correct end-use sector. EPA assigned an uncertainty range of ±2 percent for the CO_2 emission factor for soda ash consumption. The uncertainty range is derived from the default ranges for soda ash consumption for glass production in Volume 3, Chapter 2, Section 2.4.2.1 of the *2006 IPCC Guidelines* which is representative of soda ash consumption not associated with glass production, based on expert judgment (RTI 2023).

For non-metallurgical magnesia production, uncertainties arise due to variations in the chemical composition of the carbonates used in production of caustic-calcined magnesia production. As noted, minor quantities of other carbonates beyond limestone and magnesite are also used but unknown. These other carbonates are likely small and have a minimal impact on the derived emission factor. EPA assigned an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for other process uses of carbonates, respectively. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-22.

A normal probability density function was assigned for all activity data, and a triangular probability density function was assigned for all emission factors (RTI 2023). Carbon dioxide emissions from other process uses of carbonates in 2022 were estimated to be between 9.2 and 12.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 15 percent above the emission estimate of 10.4 MMT CO_2 Eq.

Table 4-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Other Process Uses of Carbonates	CO_2	10.4	9.2	12.0	-12%	+15%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

For the current *Inventory*, emission estimates for new subcategories ceramics production and non-metallurgical magnesia production were incorporated across the entire time series. No other recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA plans to review the uncertainty ranges assigned to activity data. This planned improvement is currently planned as a medium-term improvement.

4.5 Ammonia Production (CRT Source Category 2B1)

Emissions of carbon dioxide (CO_2) occur during the production of synthetic ammonia (NH_3), primarily through the use of natural gas, petroleum coke, or naphtha as a feedstock. The natural gas-, naphtha-, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions. This reporting category (2B1) includes emissions from the production of ammonia. Due to national circumstances, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. More information on this approach can be found in the Methodology section below.

Ammonia production requires a source of nitrogen (N) and hydrogen (H). Nitrogen is obtained from air through liquid air distillation or an oxidative process where air is burnt and the residual nitrogen is recovered. In the United States, the majority of ammonia is produced using a natural gas feedstock as the hydrogen source. One synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some U.S. plants, some of the CO_2 produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. In 2022, 16 companies operated 35 ammonia producing facilities in 16 states. Approximately 60 percent of domestic ammonia production capacity is concentrated in Louisiana, Oklahoma, and Texas (USGS 2023).

Synthetic ammonia production from natural gas feedstock consists of five principal process steps. The primary reforming step converts methane (CH_4) to CO_2, carbon monoxide (CO), and hydrogen (H_2) in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2 in this step of the process. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. In the shift conversion step, the CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air. Carbon dioxide is removed from the process gas by the shift conversion process, and the H_2 is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released from the solution.

The conversion process for conventional steam reforming of CH_4, including the primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88CH_4 + 1.26Air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$

To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced during the production of ammonia is emitted directly to the atmosphere. Some of the ammonia and some of the CO_2 produced by the synthetic ammonia process are used as raw materials in the production of urea [$CO(NH_2)_2$], which has a variety of agricultural and industrial applications.

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Only the CO_2 emitted directly to the atmosphere from the synthetic ammonia production process is accounted for in determining emissions from ammonia production. The CO_2 that is captured during the ammonia production process and used to produce urea does not contribute to the CO_2 emission estimates for ammonia production

presented in this section. Instead, CO_2 emissions resulting from the consumption of urea are attributed to the urea consumption or urea application source category (under the assumption that the carbon stored in the urea during its manufacture is released into the environment during its consumption or application). Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6. Emissions of CO_2 resulting from non-agricultural applications of urea (e.g., use as a feedstock in chemical production processes) are accounted for in Section 4.6.

Emissions from fuel used for energy at ammonia plants are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. The consumption of natural gas and petroleum coke as fossil fuel feedstocks for NH_3 production are adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. More information on this methodology is described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Total emissions of CO_2 from ammonia production in 2022 were 12.6 MMT CO_2 Eq. (12,610 kt) and are summarized in Table 4-23 and Table 4-24. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia. Since 1990, emissions from ammonia production have decreased by 12 percent. Emissions in 2022 increased by about 3 percent from the 2021 levels. One facility in Kansas produces ammonia from petroleum coke and began operations in 2000. All other facilities use natural gas as feedstock.

Emissions from ammonia production increased steadily from 2015 to 2018, due to the addition of new ammonia production facilities and new production units at existing facilities in 2016, 2017, and 2018. Agriculture continues to drive demand for nitrogen fertilizers, accounting for approximately 88 percent of domestic ammonia consumption (USGS 2023).

Table 4-23: CO_2 Emissions from Ammonia Production (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6

Table 4-24: CO_2 Emissions from Ammonia Production (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610

Methodology and Time-Series Consistency

Estimates of CO_2 emissions from the production of synthetic ammonia for 2010 through 2022 are estimated using a country-specific approach consistent with Tier 3 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data (IPCC 2006). The methodology for 2010 to 2022 directly uses the process CO_2 emissions reported to subpart G of the U.S. EPA Greenhouse Gas Reporting Program (GHGRP) (EPA 2018, EPA 2023). Estimates for 1990 to 2009 emissions are based on reported and calculated data on natural gas and petroleum coke feedstock used for ammonia production, consistent with IPCC Tier 2 methods and in accordance with the IPCC methodological decision tree and available data.

Emissions from fuel used for energy at ammonia plants are accounted for in the Energy chapter. This approach differs slightly from the *2006 IPCC Guidelines* which indicates that "in the case of ammonia production no distinction is made between fuel and feedstock emissions with all emissions accounted for in the IPPU Sector." Disaggregated data on fuel used for ammonia feedstock and fuel used for energy for ammonia production are not available in the United States. The Energy Information Administration (EIA), where energy use data are obtained for the *Inventory* (see the Energy chapter), does not provide data broken out by industrial category. EIA data are only available at the broad industry sector level. Furthermore, the GHGRP data used to estimate emissions are based on feedstock use and not fuel use. The method uses the same science informing the 2006 IPCC guidelines

and is consistent with avoiding double counting in the reporting of fuel use emissions under Energy and IPPU reporting. See more information in introduction to this Chapter.

Petroleum Coke Feedstock

Since 2000, one facility in the United States has produced ammonia using petroleum coke as a feedstock. For 2010 to 2022, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated using CO_2 emissions reported by the facility to GHGRP (EPA 2018; EPA 2023).

For 2006 to 2009, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated by multiplying the following: quantity of petroleum coke feedstock reported by the facility (CVR 2008 through 2022); the *Inventory* heating content value for petroleum coke (consistent with values used in the Energy chapter); the petroleum coke carbon content; and a stoichiometric CO_2/C factor of 44/12.

For 2000 to 2005, the quantity of petroleum coke feedstock was not available and was estimated by multiplying the average ratio of petroleum coke feedstock quantity to ammonia production quantity produced from petroleum coke from 2006 through 2010 by total ammonia production for 2000 to 2005 (ACC 2023). The years 2006 to 2010 were used to determine the average ratio of petroleum coke feedstock quantity to the ammonia quantity produced from petroleum coke because that period was deemed to better represent historic ammonia production from petroleum coke for the period from 2000 to 2005.

For 2000 to 2005, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated by multiplying the following: the average ratio of petroleum coke feedstock quantity to ammonia production quantity; total ammonia production quantity (ACC 2023); the *Inventory* heating content value for petroleum coke (consistent with values used in the Energy chapter); the petroleum coke carbon content; and the stoichiometric ratio of CO_2 to C (44/12).

Natural Gas Feedstock

For 2017 through 2022, facilities directly reported to GHGRP the quantity of natural gas feedstock used for ammonia production along with the carbon content of the natural gas feedstock (EPA 2018; EPA 2023).

For 2010 through 2016, the quantity of natural gas feedstock was calculated using GHGRP process CO_2 emissions for 2010 through 2016, average molecular weight of the feedstock from 2017 through 2021, and average carbon content from 2017 through 2021. Data from years 2017 to 2021 were used to determine the average molecular weight and the average carbon content because that period better represents historic ammonia production from 2010 to 2016. Using all available data from 2017 to 2021 allowed for the maximum number of data points available at the time of adopting this methodology to ensure that the average was representative. The averages were not updated using later data to exclude any new facilities that might not be representative of facilities that were operating during the earlier years of the GHGRP.

For 2010 to 2022, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock were estimated using the CO_2 emissions reported to the GHGRP (EPA 2018; EPA 2023) and subtracting the CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock as determined in the Petroleum Coke Feedstock section above.

For 1990 to 2009, the quantity of natural gas feedstock was not available and was estimated by multiplying the average ratio of natural gas feedstock quantity to ammonia production quantity from 2010 through 2014 by total ammonia production for each year for 1990 to 2009 (ACC 2023). The years 2010 to 2014 were used to determine the average ratio of natural gas feedstock quantity to ammonia production because that period better represents

historic ammonia production from 1990 to 2009.[26] For 1990 to 2009, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock were estimated using the natural gas feedstock quantity as determined above and the *Inventory* CO_2 emissions factor and heating content value for natural gas (consistent with values used in the Energy chapter).

Urea Production Adjustments

Emissions of CO_2 from ammonia production from both feedstocks and for all years from 1990 to 2022 were adjusted to account for the use of some CO_2 emissions resulting from ammonia production as a raw material in the production of urea. The CO_2 emissions reported for ammonia production are reduced by a factor of 0.733, which corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of ammonia (NH_3) and CO_2 to urea (IPCC 2006; EFMA 2000), and multiplied by total annual domestic urea production.

All synthetic ammonia production and subsequent urea production are assumed to be from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of ammonia production from petroleum coke feedstock at the one facility located in Kansas.

Table 4-25: Total Ammonia Production, Total Urea Production, and Recovered CO_2 Consumed for Urea Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Total Ammonia Production	15,425	10,143	16,010	16,410	17,020	15,420	16,800
Total Urea Production	7,450	5,270	10,700	11,400	11,500	10,521	11,272
Recovered CO_2 Consumed for Urea Production	5,463	3,865	7,847	8,360	8,433	7,715	8,266

Total ammonia production, total urea production, and recovered CO_2 consumed for urea production are shown in Table 4-25. Total ammonia production data for 2011 through 2022 were obtained from American Chemistry Council (ACC 2023). For years 1990 through 2011, ammonia production data were obtained from the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2011) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Data on facility-level process emissions for 2010 through 2022 and data on natural gas feedstock used and carbon content of the natural gas feedstock starting in 2017 were obtained from GHGRP (EPA 2018; EPA 2023). Natural gas and petroleum coke heating values come from national-level data (EIA 2023), and natural gas and petroleum coke carbon contents are the same as used in the Energy chapter calculations.

Data on urea production for 2010 through 2022 were obtained from GHGRP (EPA 2018, EPA 2023). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2010 and 2011). Urea production data for 1990 through 2008 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 1994-2009). The U.S. Census Bureau ceased collection of urea production statistics in 2011.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for ammonia production spliced activity data from different sources: U. S. Census Bureau data for 1990 through 2010, ACC data beginning in 2011, and GHGRP data beginning in 2010 and 2017. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

[26] The number of facilities reporting to GHGRP has increased since 2010: 22 facilities reported from 2010 to 2012; 23 from 2013 to 2015; 26 in 2016; 28 in 2017 and 29 from 2018 to 2022. Using data from 2010 to 2014 excludes the newer facilities that might not be representative of facilities in earlier years.

Uncertainty

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. Uncertainty in the back calculation of natural gas feedstock used for 1990 through 2009 also exists. Using the average ratio of natural gas feedstock quantity to ammonia production, determined using GHGRP data from 2010 to 2014, does not account for efficiency gains in ammonia production since 1990 (e.g., potential decreases in gas usage per ton of ammonia, manufacturing shift from steam-driven turbines to electrical-drive turbines). Uncertainties are also associated with ammonia production estimates and the assumption that all ammonia production and subsequent urea production was from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock. Uncertainty is also associated with the representativeness of the emission factor used for the petroleum coke-based ammonia process. It is also assumed that ammonia and urea are produced at co-located plants from the same natural gas raw material. The uncertainty of the total urea production activity data, based on USGS *Minerals Yearbook: Nitrogen* data, is a function of the reliability of reported production data and is influenced by the completeness of the survey responses. EPA assigned an uncertainty range of ±5 percent for ammonia production and a range of ±2 percent for urea production, natural gas feedstock quantity, petroleum coke feedstock quantity, and carbon content of natural gas feedstock, and using the suggested uncertainty provided in Section 3.2.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgement, a normal probability density function was assigned for all variables.

Recovery of CO_2 from ammonia production plants for purposes other than urea production (e.g., commercial sale, etc.) has not been considered in estimating the CO_2 emissions from ammonia production, as data concerning the disposition of recovered CO_2 are not available. Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere; however, for reporting purposes, CO_2 consumption for urea production is provided in this chapter.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-26. Carbon dioxide emissions from ammonia production in 2022 were estimated to be between 12.2 and 13.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 12.6 MMT CO_2 Eq.

Table 4-26: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production	CO_2	12.6	12.2	13.1	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied to ammonia production emission estimates consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to ammonia facilities can be found

under Subpart G (Ammonia Production) of the regulation (40 CFR Part 98).[27] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[28] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

More details on the greenhouse gas calculation, monitoring, and QA/QC methods applicable to reporting of urea produced at ammonia production facilities can be found under Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Recalculations

For 2021, the urea consumption value was changed from a rounded value to a more precise unrounded value. As a result, recalculations were performed for emissions from ammonia for 2021. Compared to the previous *Inventory*, total CO_2 emissions from the production of ammonia production (from natural gas and petroleum coke feedstocks) decreased by less than 1 percent (15 kt) in 2021.

Planned Improvements

Currently the *Inventory* does not separately track fuel energy use for ammonia production. To be more consistent with *2006 IPCC Guidelines*, EPA is considering whether to include natural gas fuel use as part of ammonia production emissions as a future improvement. The data are still being evaluated as part of EPA's efforts to disaggregate other industrial sector categories' energy use in the Energy chapter of the *Inventory*. If possible, this will be incorporated in future *Inventory* reports. If incorporated, the fuel energy use and emissions will be removed from current reporting under Energy to avoid double counting.

4.6 Urea Consumption for Non-Agricultural Purposes (CRT Source Category 2B10)

Urea is produced using ammonia (NH_3) and carbon dioxide (CO_2) as raw materials. All urea produced in the United States is assumed to be produced at ammonia production facilities where both ammonia and CO_2 are generated. There were 35 plants producing ammonia in the United States in 2022, with two additional plants sitting idle for the entire year (USGS 2023b).

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

This section accounts for CO_2 emissions associated with urea consumed exclusively for non-agricultural purposes. This reporting category (2B10) includes emissions from IPCC assessment reports that do not fall within any other CRT source category, which includes emissions from urea consumption for non-agricultural purposes. Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6 of the Agriculture chapter.

[27] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[28] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

The industrial applications of urea include its use in adhesives, binders, sealants, resins, fillers, analytical reagents, catalysts, intermediates, solvents, dyestuffs, fragrances, deodorizers, flavoring agents, humectants and dehydrating agents, formulation components, monomers, paint and coating additives, photosensitive agents, and surface treatments agents. In addition, urea is used for abating nitrogen oxide (NO_x) emissions from coal-fired power plants and diesel transportation motors.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2022 were estimated to be 7.1 MMT CO_2 Eq. (7,053 kt) and are summarized in Table 4-27 and Table 4-28. Net CO_2 emissions from urea consumption for non-agricultural purposes have increased by approximately 86 percent from 1990 to 2022 and increased by approximately 7 percent from 2021 to 2022.

Table 4-27: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption	3.8	3.7	6.1	6.2	5.8	6.6	7.1

Table 4-28: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption	3,784	3,653	6,113	6,150	5,805	6,600	7,053

Methodology and Time-Series Consistency

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated using a country-specific method consistent with the Tier 1 method used to estimate emissions from ammonia production in the *2006 IPCC Guidelines* which states that the "CO_2 recovered [from ammonia production] for downstream use can be estimated from the quantity of urea produced where CO_2 is estimated by multiplying urea production by 44/60, the stoichiometric ratio of CO_2 to urea" (IPCC 2006). The amount of urea consumed in the United States for non-agricultural purposes is multiplied by a factor representing the amount of CO_2 used as a raw material to produce the urea. This method is based on the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The amount of urea consumed for non-agricultural purposes in the United States is estimated by deducting the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Agriculture chapter (see Table 5-25), from the total domestic supply of urea as reported in Table 4-29. The domestic supply of urea is estimated based on the amount of urea produced plus urea imports and minus urea exports. A factor of 0.733 tons of CO_2 per ton of urea consumed is then applied to the resulting supply of urea for non-agricultural purposes to estimate CO_2 emissions from the amount of urea consumed for non-agricultural purposes. The 0.733 tons of CO_2 per ton of urea emission factor is based on the stoichiometry of carbon in urea. This corresponds to a stoichiometric ratio of CO_2 to urea of 44/60, assuming complete conversion of carbon in urea to CO_2 (IPCC 2006; EFMA 2000).

Urea production data for 1990 through 2008 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009a). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011. Urea production data for 2011 through 2022 were obtained from GHGRP (EPA 2018; EPA 2023a; EPA 2023b).

Urea import data for 2022 were not available at the time of publication and were estimated using 2021 values. Urea import data for 2013 to 2021 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2023a). Urea import data for 2011 and 2012 were taken from U.S. Fertilizer Import/Exports from the United States Department of Agriculture (USDA) Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012. Urea import data for the previous years were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for

1997 through 2010 (U.S. Census Bureau 2001 through 2011), The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992 (see Table 4-29).

Urea export data for 2022 were not available at the time of publication and were estimated using 2021 values. Urea export data for 2013 to 2021 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2023a). Urea export data for 1990 through 2012 were taken from U.S. Fertilizer Import/Exports from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012.

Table 4-29: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Urea Production	7,450	5,270	10,700	11,400	11,500	10,521	11,272
Urea Applied as Fertilizer	3,296	4,779	6,732	6,865	6,998	7,131	7,265
Urea Imports	1,860	5,026	5,110	4,410	4,190	5,880	5,880
Urea Exports	854	536	743	559	777	270	270
Urea Consumed for Non-Agricultural Purposes	5,160	4,981	8,335	8,386	7,915	9,000	9,617

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for urea consumption for non-agricultural purposes spliced activity data from different sources: USGS data for 1990 through 2008, U. S. Census Bureau data for 2009 and 2010, and GHGRP data beginning in 2011. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

There is limited publicly available data on the quantities of urea produced and consumed for non-agricultural purposes. Therefore, the amount of urea used for non-agricultural purposes is estimated based on a balance that relies on estimates of urea production, urea imports, urea exports, and the amount of urea used as fertilizer. EPA uses an uncertainty range of ±10 percent for urea production and ±5 percent for urea imports and urea exports, consistent with the ranges for activity data that are not obtained directly from plants, and using this suggested uncertainty provided in Section 3.2.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for all activity data. The primary uncertainties associated with this source category are associated with the accuracy of these estimates as well as the fact that each estimate is obtained from a different data source. Because urea production estimates are no longer available from the USGS, there is additional uncertainty associated with urea produced beginning in 2011. There is also uncertainty associated with the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-30. Carbon dioxide emissions associated with urea consumption for non-agricultural purposes during 2022 were estimated to be between 6.8 and 7.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 7.1 MMT CO_2 Eq.

Table 4-30: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Consumption for Non-Agricultural Purposes	CO_2	7.1	6.8	7.3	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to reporting of urea production occurring at ammonia facilities can be found under Subpart G (Ammonia Manufacturing) of the regulation (40 CFR Part 98).[29] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[30] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported urea production data against external datasets including the USGS *Minerals Yearbook* data. The comparison shows consistent trends in urea production over time.

Recalculations Discussion

Based on updated quantities of urea applied for agricultural uses for 2017 through 2021, updated urea imports from USGS for 2021, and updated urea exports from USGS for 2021, recalculations were performed for 2017 through 2021. Compared to the previous *Inventory*, CO_2 emissions from urea consumption for non-agricultural purposes increased by less than 1 percent for 2017 (46 kt CO_2) and 2018 (2 kt CO_2), decreased by less than 1 percent for 2019 (4 kt CO_2) and 2020 (10 kt CO_2) and increased by 32 percent for 2021 (1,611 kt CO_2).

Planned Improvements

At this time, there are no specific planned improvements for estimating CO_2 emissions from urea consumption for non-agricultural purposes.

[29] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[30] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

4.7 Nitric Acid Production (CRT Source Category 2B2)

Nitrous oxide (N_2O) is emitted during the production of nitric acid (HNO_3), an inorganic compound used primarily to make synthetic commercial fertilizers. Nitric acid is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. This reporting category (2B2) includes emissions from production of nitric acid. Emissions from fuels consumed for energy purposes during the production of nitric acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

There are two types of nitric acid: weak nitric acid and high-strength nitric acid. The weak nitric acid production method utilizes oxidation, condensation, and absorption to produce nitric acid at concentrations between 30 and 70 percent nitric acid. High-strength nitric acid (90 percent or greater nitric acid) can be produced by two methods: (1) through the dehydration, bleaching, condensing, and absorption of the weak nitric acid or (2) through the oxidation of ammonia into nitric oxide, which is oxidized and cooled into dinitrogen tetroxide and then pressurized and oxidized into high-strength nitric acid. Most U.S. plants were built between 1960 and 2000. As of 2022, there were 31 active nitric acid production plants that produce weak nitric acid in the United States (EPA 2023). One plant produces both weak and high-strength nitric acid (EPA 2010).

The basic process technology for producing nitric acid has not changed significantly over time. During this process, N_2O is formed as a byproduct and released from reactor vents into the atmosphere.

Nitric acid is made from the reaction of ammonia (NH_3) with oxygen (O_2) in two stages. The overall reaction is:

$$4NH_3 + 8O_2 \rightarrow 4HNO_3 + 4H_2$$

Currently, the nitric acid industry in the United States controls emissions of NO and NO_2 (i.e., NO_x), using a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very effective at destroying N_2O. Five nitric acid plants had NSCR systems installed between 1964 and 1977, over half due to the finalization of the Nitric Acid Plant New Source Performance Standards (NSPS) which went into effect in 1971. Four additional nitric acid plants had NSCR systems installed between 2016 and 2018, as a result of EPA Consent Decrees to control NO_X emissions more effectively. NSCR systems are used in approximately one-third of the weak acid production plants. For N_2O abatement, U.S. facilities are using both tertiary (i.e., NSCR and SCR) and secondary controls (i.e., catalysts added to the ammonia reactor to lessen potential N_2O production).

Emissions from the production of nitric acid are generally directly proportional to the annual amount of nitric acid produced because emissions are calculated as the product of the total annual production and plant-specific emission factors. There are a few instances, however, where that relationship has not been directly proportional. For example, in 2015 and 2019, nitric acid production decreased and emissions increased compared to the respective preceding years; in 2016, nitric acid production increased and emissions decreased compared to 2015. N_2O emissions for those years are calculated based on data from the GHGRP as discussed in the Methodology section below. According to data from plants reporting to GHGRP, plant-specific operations can affect the emission factor used, including: (1) site-specific fluctuations in ambient temperature and humidity, (2) catalyst age and condition, (3) process changes, such as fluctuations in process pressure or temperature and replacing the ammonia catalyst, (4) the addition, removal, maintenance, and utilization of abatement technologies, and (5) the number of nitric acid trains, which are reaction vessels where ammonia is oxidized to form nitric acid. Changes in those operating conditions for the years in question (2015, 2016, and 2019) caused changes in emission factors, which resulted in emissions changing disproportionally to production in those years.

Nitrous oxide emissions from this source were estimated to be 8.6 MMT CO_2 Eq. (33 kt of N_2O) in 2022 and are summarized in Table 4-31 and Table 4-32. Emissions from nitric acid production have decreased by 20 percent since 1990, while production has increased by 9 percent over the same time period (see Table 4-31 and Table

4-32). Emissions have decreased by 33 percent since 1997, the highest year of production in the time series. From 2021 to 2022, nitric acid production increased by 1 percent, while overall emissions from nitric acid production increased by 9.4 percent from 2021 to 2022.

Table 4-31: N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6

Table 4-32: N_2O Emissions from Nitric Acid Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Nitric Acid Production	41	38	32	34	31	30	33

Methodology and Time-Series Consistency

Emissions of N_2O from nitric acid production are estimated using methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. For 2010 through 2022, a Tier 3 method was used to estimate emissions based on GHGRP data. For 1990 through 2009, a Tier 2 method was used to estimate emissions from nitric acid production based on U.S. Census Bureau data.

2010 through 2022

Process N_2O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2022 by aggregating reported facility-level data (EPA 2018; EPA 2023).[31]

Since 2010, in the United States, all nitric acid facilities that produce weak nitric acid (30 to 70 percent) have been required to report annual greenhouse gas emissions data to EPA as per the requirements of the GHGRP (Subpart V). Beginning with 2018, the rule was changed to include facilities that produce nitric acid of any strength. The only facility that produces high-strength nitric acid also produces weak nitric acid. All N_2O emissions from nitric acid production originate from the production of weak nitric acid.

Process emissions and nitric acid production reported to the GHGRP provide complete estimates of greenhouse gas emissions for the United States because there are no reporting thresholds. While facilities are allowed to stop reporting to the GHGRP if the total reported emissions from nitric acid production are less than 25,000 metric tons CO_2 Eq. per year for five consecutive years or less than 15,000 metric tons CO_2 Eq. per year for three consecutive years, no facilities have stopped reporting as a result of these provisions.[32] All nitric acid facilities are required to either calculate process N_2O emissions using a site-specific emission factor that is the average of the emission factor determined through annual performance tests for each nitric acid train under typical operating conditions or directly measure process N_2O emissions using monitoring equipment.[33]

Emissions from facilities vary from year to year, depending on the amount of nitric acid produced with and without abatement technologies and other conditions affecting the site-specific emission factor. To maintain consistency

[31] National N_2O process emissions, national production, and national share of nitric acid production with abatement and without abatement technology were aggregated from the GHGRP facility-level data for 2010 to 2022 (i.e., percent production with and without abatement).

[32] See 40 CFR 98.2(i)(1) and 40 CFR 98.2(i)(2) for more information about these provisions.

[33] Facilities must use standard methods - either EPA Method 320 or ASTM D6348-03 for annual performance tests—and must follow associated QA/QC procedures consistent with category-specific QC of direct emission measurements during these performance tests.

across the time series and with the rounding approaches taken by other data sets, GHGRP nitric acid data are rounded and are shown in Table 4-33.

1990 through 2009

Using GHGRP data for 2010, country-specific N_2O emission factors were calculated for nitric acid production with abatement and without abatement (i.e., controlled and uncontrolled emission factors). The following 2010 emission factors were derived for production with abatement and without abatement: 3.3 kg N_2O/metric ton HNO_3 produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.99 kg N_2O/metric ton HNO_3 produced at plants not equipped with abatement technology. Country-specific weighted emission factors were derived by weighting these emission factors by percent production with abatement and without abatement over time periods 1990 through 2008 and 2009. These weighted emission factors were used to estimate N_2O emissions from nitric acid production for years prior to the availability of GHGRP data (i.e., 1990 through 2008 and 2009). A separate weighted emission factor is included for 2009 due to data availability for that year.

EPA verified the installation dates of N_2O abatement technologies for all facilities based on GHGRP facility-level information and confirmed that all abatement technologies were accounted for in the derived emission factors (Icenhour 2020). Due to the lack of information on abatement equipment utilization, it is assumed that once abatement technology was installed in facilities, the equipment was consistently operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific weighted N_2O emission factors were used in conjunction with annual production to estimate N_2O emissions for 1990 through 2009, using the following equations:

Equation 4-4: *2006 IPCC Guidelines* Tier 3: N_2O Emissions From Nitric Acid Production (Equation 3.6)

$$E_i = P_i \times EF_{weighted,i}$$

$$EF_{weighted,i} = \left[\left(\%P_{c,i} \times EF_c\right) + \left(\%P_{unc,i} \times EF_{unc}\right)\right]$$

where,

E_i	=	Annual N_2O Emissions for year i (kg/yr)
P_i	=	Annual nitric acid production for year i (metric tons HNO_3)
$EF_{weighted,i}$	=	Weighted N_2O emission factor for year i (kg N_2O/metric ton HNO_3)
$\%P_{c,i}$	=	Percent national production of HNO_3 with N_2O abatement technology (%)
EF_c	=	N_2O emission factor, with abatement technology (kg N_2O/metric ton HNO_3)
$\%P_{unc,i}$	=	Percent national production of HNO_3 without N_2O abatement technology (%)
EF_{unc}	=	N_2O emission factor, without abatement technology (kg N_2O/metric ton HNO_3)
i	=	year from 1990 through 2009

- For 2009: Weighted N_2O emission factor = 5.46 kg N_2O/metric ton HNO_3.
- For 1990 through 2008: Weighted N_2O emission factor = 5.66 kg N_2O/metric ton HNO_3.

Nitric acid production data for the United States for 1990 through 2009 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2008, 2009, 2010a, 2010b) (see Table 4-33). EPA used GHGRP facility-level information to verify that all reported N_2O abatement equipment were incorporated into the estimation of N_2O emissions from nitric acid production over the full time series (EPA 2021).

Table 4-33: Nitric Acid Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	7,200	6,710	8,210	8,080	7,970	7,800	7,860

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for nitric acid production spliced activity data from two different sources: U.S. Census Bureau production data for 1990 through 2009 and GHGRP production data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with the parameters used to estimate N_2O emissions includes the share of U.S. nitric acid production attributable to each emission abatement technology (i.e., utilization) over the time series (especially prior to 2010), and the associated emission factors applied to each abatement technology type. While some information has been obtained through outreach with industry associations, limited information is available over the time series (especially prior to 2010) for a variety of facility level variables, including plant-specific production levels, plant production technology (e.g., low or high pressure, etc.), and abatement technology destruction and removal efficiency rates. Production data prior to 2010 were obtained from National Census Bureau, which does not provide uncertainty estimates with their data. Facilities reporting to EPA's GHGRP must measure production using equipment and practices used for accounting purposes. While emissions are often directly proportional to production, the emission factor for individual facilities can vary significantly from year to year due to site-specific fluctuations in ambient temperature and humidity, catalyst age and condition, nitric acid production process changes, the addition or removal of abatement technologies, and the number of nitric acid trains at the facility. At this time, EPA does not estimate uncertainty of the aggregated facility-level information. As noted in the QA/QC and verification section below, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. The annual production reported by each nitric acid facility under EPA's GHGRP and then aggregated to estimate national N_2O emissions is assumed to have low uncertainty. EPA assigned an uncertainty range of ±5 percent for facility-reported N_2O emissions, and using this suggested uncertainty provided in section 3.4.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of ±2 percent for nitric acid production, and using this suggested uncertainty provided in section 3.3.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for facility-reported N_2O emissions and nitric acid production.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-34. Nitrous oxide emissions from nitric acid production were estimated to be between 8.2 and 9.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2022 emissions estimate of 8.6 MMT CO_2 Eq.

Table 4-34: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N_2O	8.6	8.2	9.0	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to nitric acid facilities can be found under Subpart V: Nitric Acid Production of the GHGRP regulation (40 CFR Part 98). [34]

The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the Subpart (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred (EPA 2015). [35] EPA's review of observed trends noted that while emissions have generally mirrored production, in 2015 and 2019 nitric acid production decreased compared to the previous year and emissions increased. While review is ongoing, based on feedback from the verification process to date, these changes are due to facility-specific changes (e.g., in the nitric production process and management of abatement equipment).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

Pending resources, EPA is considering a near-term improvement to both review and refine quantitative uncertainty estimates and the associated qualitative discussion.

4.8 Adipic Acid Production (CRT Source Category 2B3)

Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. This reporting category (2B3) includes emissions from the production of adipic acid. Emissions from fuels consumed for energy purposes during the production of adipic acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Adipic acid is produced through a two-stage process during which nitrous oxide (N_2O) is generated in the second stage. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce

[34] See Subpart V monitoring and reporting regulation http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[35] See GHGRP Verification Factsheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

adipic acid. Nitrous oxide is generated as a byproduct of the nitric acid oxidation stage and is emitted in the waste gas stream (Thiemens and Trogler 1991). The second stage is represented by the following chemical reaction:

$$(CH_2)_5CO(cyclohexanone) + (CH_2)_5CHOH(cyclohexanol) + wHNO_3 \rightarrow HOOC(CH_2)_4COOH(adipic\ acid) + xN_2O + yH_2O$$

Process emissions from the production of adipic acid vary with the types of technologies and level of emission controls employed by a facility. In 1990, two major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, three major adipic acid production facilities had control systems in place (Reimer et al. 1999). In 2022, thermal reduction was applied as an N_2O abatement measure at one adipic acid facility (EPA 2023).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers, with the United States accounting for the largest share of global adipic acid production capacity in recent years. In 2022, the United States had two companies with a total of two adipic acid production facilities (one in Texas and one in Florida), following the ceased operations of a third major production facility at the end of 2015 (EPA 2023).

Commercially, adipic acid is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6; 9 percent is used in the production of polyester polyols; 4 percent is used in the production of plasticizers; and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food grade adipic acid is used to provide some foods with a "tangy" flavor (Thiemens and Trogler 1991).

Compared to 1990, national adipic acid production in 2022 has increased by 3 percent to approximately 780,000 metric tons (ACC 2023). Nitrous oxide emissions from adipic acid production were estimated to be 2.1 MMT CO_2 Eq. (8 kt N_2O) in 2022 and are summarized in Table 4-35 and Table 4-36. Over the period 1990 through 2022, facilities have reduced emissions by 84.5 percent due to the widespread installation of pollution control measures in the late 1990s. The main reason for the 68 percent decrease in N_2O emissions from adipic acid production between 2021 and 2022 is increased utilization of N_2O abatement equipment at one adipic acid production facility.

EPA reviewed GHGRP facility reported information on the date of abatement technology installation in order to better reflect trends and changes in emissions abatement within the industry across the time series. The facility using the facility-specific emission factor developed through annual performance testing has reported no installation and no utilization of N_2O abatement technology. The facility using direct measurement of N_2O emissions has reported the use of thermal reduction as an N_2O abatement technology; the first unit began operation in 1980, and the second unit began operation in 2023 (Ard 2024; Ascend 2023).

Significant changes in the amount of time that the N_2O abatement device at one facility was in operation has been the main cause of fluctuating emissions in recent years. These fluctuations are most evident for years where trends in emissions and adipic acid production were not directly proportional: (1) between 2016 and 2017, (2) between 2017 and 2018, (3) between 2019 and 2020, (4) between 2020 and 2021, and (5) between 2021 and 2022. As noted above, changes in control measures and abatement technologies at adipic acid production facilities, including maintenance of equipment, can result in annual emission fluctuations. Little additional information is available on drivers of trends, and the amount of adipic acid produced is not reported under EPA's GHGRP.

Table 4-35: N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1

Table 4-36: N_2O Emissions from Adipic Acid Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	51	24	35	18	28	25	8

Methodology and Time-Series Consistency

Emissions of N_2O from adipic acid production are estimated using methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. For 2010 through 2022, a Tier 3 method was used to estimate emissions. For 1990 through 2009, emissions are estimated using both Tier 2 and Tier 3 methods. Due to confidential business information (CBI), plant names are not provided in this section; therefore, the four adipic acid-producing facilities that have operated over the time series will be referred to as Plants 1 through 4. As noted above, one currently operating facility uses thermal reduction as an N_2O abatement technology.

2010 through 2022

All emission estimates for 2010 through 2022 were obtained through analysis of GHGRP data (EPA 2010 through 2023). Facility-level greenhouse gas emissions data were obtained from EPA's GHGRP for the years 2010 through 2022 (EPA 2010 through 2023) and aggregated to national N_2O emissions. Consistent with IPCC Tier 3 methods, all adipic acid production facilities are required to either calculate N_2O emissions using a facility-specific emission factor developed through annual performance testing under typical operating conditions or directly measure N_2O emissions using monitoring equipment.[36]

1990 through 2009

For years 1990 through 2009, which were prior to EPA's GHGRP reporting, for both Plants 1 and 2, emission estimates were obtained directly from the plant engineers and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered CBI and hence are not published (Desai 2010, 2011). These estimates were based on continuous process monitoring equipment installed at the two facilities.

For Plant 4, 1990 through 2009 N_2O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines*:

Equation 4-5: *2006 IPCC Guidelines* Tier 2: N_2O Emissions From Adipic Acid Production (Equation 3.8)

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

where,

E_{aa}	=	N_2O emissions from adipic acid production, metric tons
Q_{aa}	=	Quantity of adipic acid produced, metric tons
EF_{aa}	=	Emission factor, metric ton N_2O/metric ton adipic acid produced
DF	=	N_2O destruction factor
UF	=	Abatement system utility factor

The adipic acid production is multiplied by an emission factor (i.e., N_2O emitted per unit of adipic acid produced), which has been estimated to be approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). The "N_2O destruction factor" in the equation represents the percentage of N_2O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the

[36] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 for annual performance testing, and must follow associated QA/QC procedures during these performance tests consistent with category-specific QC of direct emission measurements.

abatement equipment operates during the annual production period. Plant-specific production data for Plant 4 were obtained across the time series through personal communications (Desai 2010, 2011). The plant-specific production data were then used for calculating emissions as described above.

For Plant 3, 2005 through 2009 emissions were obtained directly from the plant (Desai 2010, 2011). For 1990 through 2004, emissions were estimated using plant-specific production data and the IPCC factors as described above for Plant 4. Plant-level adipic acid production for 1990 through 2003 was estimated by allocating national adipic acid production data to the plant level using the ratio of known plant capacity to total national capacity for all U.S. plants (ACC 2023; CMR 2001, 1998; CW 1999; C&EN 1992 through 1995). For 2004, actual plant production data were obtained and used for emission calculations (CW 2005).

Plant capacities for 1990 through 1994 were obtained from *Chemical & Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for the year 2000 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). For 2001 through 2003, the plant capacities for three plants were held constant at year 2000 capacities. Plant capacity for 1999 to 2003 for the one remaining plant was kept the same as 1998.

National adipic acid production data (see Table 4-37) from 1990 through 2022 were obtained from the American Chemistry Council (ACC 2023).

Table 4-37: Adipic Acid Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	755	865	825	810	710	760	780

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for adipic acid production spliced activity data from multiple sources: plant-specific emissions data and publicly available plant capacity data for 1990 through 2009 and GHGRP emission data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with N_2O emission estimates includes the methods used by companies to monitor and estimate emissions. While some information has been obtained through outreach with facilities, limited information is available over the time series on these methods, abatement technology destruction and removal efficiency rates, and plant-specific production levels. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for facility-reported N_2O emissions, and using this suggested uncertainty provided in section 3.4.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-38. Nitrous oxide emissions from adipic acid production for 2022 were estimated to be between 2.0 and 2.2 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 4 percent below to 4 percent above the 2022 emission estimate of 2.1 MMT CO_2 Eq.

Table 4-38: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	2.1	2.0	2.2	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to adipic acid facilities can be found under Subpart E (Adipic Acid Production) of the GHGRP regulation (40 CFR Part 98).[37] The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[38] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year comparisons of reported data.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA has no specific planned improvements related to adipic acid.

4.9 Caprolactam, Glyoxal and Glyoxylic Acid Production (CRT Source Category 2B4)

This reporting category (2B4) includes emissions from the production of caprolactam, glyoxal (ethanedial), and glyoxylic acid. Emissions from fuels consumed for energy purposes during the production of caprolactam, glyoxal,

[37] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[38] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

and glyoxylic acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Caprolactam

Caprolactam ($C_6H_{11}NO$) is a colorless monomer produced for nylon-6 fibers and plastics. A substantial proportion of the fiber is used in carpet manufacturing. Most commercial processes used for the manufacture of caprolactam begin with benzene, but toluene can also be used. The production of caprolactam can give rise to emissions of nitrous oxide (N_2O).

During the production of caprolactam, emissions of N_2O can occur from the ammonia oxidation step, emissions of carbon dioxide (CO_2) from the ammonium carbonate step, emissions of sulfur dioxide (SO_2) from the ammonium bisulfite step, and emissions of non-methane volatile organic compounds (NMVOCs). Emissions of CO_2, SO_2 and NMVOCs from the conventional process are unlikely to be significant in well-managed plants. Modified caprolactam production processes are primarily concerned with elimination of the high volumes of ammonium sulfate that are produced as a byproduct of the conventional process (IPCC 2006).

In the most commonly used process where caprolactam is produced from benzene, benzene is hydrogenated to cyclohexane which is then oxidized to produce cyclohexanone ($C_6H_{10}O$). The classical route (Raschig process) and basic reaction equations for production of caprolactam from cyclohexanone are (IPCC 2006):

$$Oxidation\ of\ NH_3\ to \frac{NO}{NO_2}$$

$$\downarrow$$

$$NH_3\ reacted\ with \frac{CO_2}{H_2O} to\ yield\ ammonium\ carbonate\ (NH_4)_2CO_3$$

$$\downarrow$$

$$(NH_4)_2CO_3\ reacted\ with \frac{NO}{NO_2} (from\ NH_3\ oxidation) to\ yield\ ammonium\ nitrite\ (NH_4NO_2)$$

$$\downarrow$$

$$NH_3\ reacted\ with \frac{SO_2}{H_2O} to\ yield\ ammonium\ bisulphite\ (NH_4HSO_3)$$

$$\downarrow$$

$$NH_4NO_2\ and\ (NH_4HSO_3) reacted\ to\ yield\ hydroxylamine\ disulphonate\ (NOH(SO_3NH_4)_2)$$

$$\downarrow$$

$$(NOH(SO_3NH_4)_2)\ hydrolised\ to\ yield\ hydroxylamine\ sulphate\ ((NH_2OH)_2.H_2SO_4)\ and$$

$$ammonium\ sulphate\ ((NH_4)_2SO_4)$$

$$\downarrow$$

$$Cylohexanone\ reaction:$$

$$C_6H_{10}O\ + \frac{1}{2}(NH_2OH)_2.H_2SO_4(+NH_3\ and\ H_2SO_4) \rightarrow C_6H_{10}NOH\ + (NH_4)_2SO_4\ + H_2O$$

$$\downarrow$$

$$Beckmann\ rearrangement:$$

$$C_6H_{10}NOH\ \ (+H_2SO_4\ and\ SO_2) \rightarrow C_6H_{11}NO.H_2SO_4\ (+4NH_3\ and\ H_2O) \rightarrow C_6H_{11}NO\ + 2(NH4)_2SO_4$$

In 2004, three facilities produced caprolactam in the United States (ICIS 2004). Another facility, Evergreen Recycling, was in operation from 2000 to 2001 (ICIS 2004; Textile World 2000) and from 2007 through 2015 (Shaw

2015). Caprolactam production at Fibrant LLC (formerly DSM Chemicals) in Georgia ceased in 2018 (Cline 2019). As of 2022, two companies in the United States produced caprolactam at two facilities: AdvanSix (formerly Honeywell) in Virginia (AdvanSix 2023) and BASF in Texas (BASF 2023).

Nitrous oxide emissions from caprolactam production in the United States were estimated to be 1.3 MMT CO_2 Eq. (5 kt N_2O) in 2022 and are summarized in Table 4-39 and Table 4-40. National emissions from caprolactam production decreased by approximately 10.5 percent over the period of 1990 through 2022. Emissions in 2022 increased by approximately 9.8 percent from the 2021 levels. This annual increase returned caprolactam production to levels consistent with 2017 before the COVID-19 pandemic.

Table 4-39: N_2O Emissions from Caprolactam Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Caprolactam Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3

Table 4-40: N_2O Emissions from Caprolactam Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Caprolactam Production	6	7	5	5	4	5	5

Glyoxal

Glyoxal is mainly used as a crosslinking agent for vinyl acetate/acrylic resins, disinfectant, gelatin hardening agent, textile finishing agent (permanent-press cotton, rayon fabrics), and wet-resistance additive (paper coatings) (IPCC 2006). It is also used for enhanced oil-recovery. It is produced from oxidation of acetaldehyde with concentrated nitric acid, or from the catalytic oxidation of ethylene glycol, and N_2O is emitted in the process of oxidation of acetaldehyde.

Glyoxal (ethanedial) ($C_2H_2O_2$) is produced from oxidation of acetaldehyde (ethanal) (C_2H_4O) with concentrated nitric acid (HNO_3). Glyoxal can also be produced from catalytic oxidation of ethylene glycol (ethanediol) (CH_2OHCH_2OH).

Glyoxylic Acid

Glyoxylic acid is produced by nitric acid oxidation of glyoxal. Glyoxylic acid is used for the production of synthetic aromas, agrochemicals, and pharmaceutical intermediates (IPCC 2006).

Preliminary data suggests that glyoxal and glyoxylic acid may be produced in small quantities domestically but are largely imported to the United States. EPA does not currently estimate the emissions associated with the production of glyoxal and glyoxylic acid because activity data are not available. See Annex 5 for more information.

Methodology and Time-Series Consistency

Emissions of N_2O from the production of caprolactam are calculated using the Tier 1 methodology from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. The Tier 1 equation is as follows:

Equation 4-6: *2006 IPCC Guidelines* Tier 1: N_2O Emissions From Caprolactam Production (Equation 3.9)

$$E_{N_2O} = EF \times CP$$

where,

E_{N_2O} = Annual N_2O Emissions (kg)

EF = N_2O emission factor (default) (kg N_2O/metric ton caprolactam produced)

CP = Caprolactam production (metric tons)

During the caprolactam production process, N_2O is generated as a byproduct of the high temperature catalytic oxidation of ammonia (NH_3), which is the first reaction in the series of reactions to produce caprolactam. The amount of N_2O emissions can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 111.1 metric tons of caprolactam are required to generate one metric ton of N_2O, resulting in an emission factor of 9.0 kg N_2O per metric ton of caprolactam (IPCC 2006). When applying the Tier 1 method, the *2006 IPCC Guidelines* state that it is good practice to assume that there is no abatement of N_2O emissions and to use the highest default emission factor available in the guidelines. In addition, EPA did not find support for the use of secondary catalysts to reduce N_2O emissions, such as those employed at nitric acid plants.

The activity data for caprolactam production (see Table 4-41) from 1990 to 2022 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2023). EPA will continue to analyze and assess alternative sources of production data as a quality control measure.

Table 4-41: Caprolactam Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	626	795	530	515	480	510	560

Carbon dioxide and methane (CH_4) emissions may also occur from the production of caprolactam, but currently the IPCC does not have methodologies for calculating these emissions associated with caprolactam production.

Methodological approaches, consistent with the *2006 IPCC Guidelines*, have been applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Estimation of emissions of N_2O from caprolactam production can be treated as analogous to estimation of emissions of N_2O from nitric acid production. Both production processes involve an initial step of NH_3 oxidation, which is the source of N_2O formation and emissions (IPCC 2006). Therefore, uncertainties for the default emission factor values in the *2006 IPCC Guidelines* are an estimate based on default values for nitric acid plants. In general, default emission factors for gaseous substances have higher uncertainties because mass values for gaseous substances are influenced by temperature and pressure variations and gases are more easily lost through process leaks. The default values for caprolactam production have a relatively high level of uncertainty due to the limited information available (IPCC 2006). EPA assigned uncertainty bounds of ±5 percent for caprolactam production, based on expert judgment. EPA assigned an uncertainty range of ±40 percent for the N_2O emission factor, and using this suggested uncertainty provided in Section 3.5.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for activity data, and a triangular probably density function was assigned for the emission factor.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Nitrous oxide emissions from caprolactam, glyoxal and glyoxylic acid production for 2022 were estimated to be between 0.9 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 31 percent below to 31 percent above the 2022 emission estimate of 1.3 MMT CO_2 Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Caprolactam Production	N_2O	1.3	0.9	1.8	-31%	+31%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for 2020 and 2021 to reflect updated caprolactam production data from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2023). Compared to the previous *Inventory*, annual N_2O emissions decreased by 2 percent in 2020 and 2021, with a decrease of 0.02 MMT CO_2 Eq. in 2020 and 2021.

Planned Improvements

Pending resources, EPA will research other available datasets for caprolactam production and industry trends, including facility-level data. EPA continues to research available activity data and emissions associated with the production of glyoxal and glyoxylic acid. Preliminary data suggests that glyoxal and glyoxylic acid may be produced in small quantities domestically but are largely imported to the United States. See Annex 5 for more information. This planned improvement is subject to data availability and will be implemented in the medium- to long-term.

4.10 Carbide Production and Consumption (CRT Source Category 2B5 & 2B10)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of silicon carbide (SiC), a material used for industrial abrasive, metallurgical, and other non-abrasive applications in the United States, and CO_2 is emitted from the consumption of SiC. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of silicon carbide are accounted for in the industrial end-use sector reported under the Energy chapter. Additionally, some metallurgical and non-abrasive applications of SiC are emissive at high temperatures due to the SiC oxidation temperature (Biscay 2021). While emissions should be accounted for where they occur based on *2006 IPCC Guidelines*, emissions from SiC consumption are accounted for here until additional data on SiC consumption by end-use are available. The reporting category (2B5) includes emissions from the production of SiC, and the reporting category (2B10) includes emissions from the consumption of SiC.

To produce SiC, silica sand or quartz (SiO_2) is reacted with carbon (C) in the form of petroleum coke. A portion (about 35 percent) of the carbon contained in the petroleum coke is retained in the SiC. The remaining carbon is

emitted as CO_2, CH_4, or carbon monoxide (CO). The overall reaction is shown below, but in practice, it does not proceed according to stoichiometry:

$$SiO_2 + 3C \rightarrow SiC + 2CO \ (+ O_2 \rightarrow 2CO_2)$$

Carbon dioxide and CH_4 are also emitted during the production of calcium carbide, a chemical used to produce acetylene. Carbon dioxide is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter.

Markets for manufactured abrasives, including SiC, are heavily influenced by activity in the U.S. manufacturing sector, especially in the aerospace, automotive, furniture, housing, and steel manufacturing sectors. Specific applications of abrasive-grade SiC in 2018 included antislip abrasives, blasting abrasives, bonded abrasives, coated abrasives, polishing and buffing compounds, tumbling media, and wire-sawing abrasives (USGS 2021). Approximately 50 percent of SiC is used in metallurgical applications, which include primarily iron and steel production, and other non-abrasive applications, which include use in advanced or technical ceramics and refractories (USGS 2023a; Washington Mills 2023).

As a result of the economic downturn in 2008 and 2009, demand for SiC decreased in those years. Low-cost imports, particularly from China, combined with high relative operating costs for domestic producers, continue to put downward pressure on the production of SiC in the United States. Consumption of SiC in the United States has recovered somewhat from its low in 2009 to 2020; 2021 consumption data was withheld to avoid disclosing company proprietary data (USGS 1991b through 2021), and 2022 USGS data has not yet been released.

Silicon carbide was manufactured by two facilities in the United States, one of which produced primarily non-abrasive SiC (USGS 2021). USGS production values for the United States consists of SiC used for abrasives and for metallurgical and other non-abrasive applications (USGS 2021). During the COVID-19 pandemic in 2020, the U.S. Department of Homeland Security considered abrasives manufacturing part of the critical manufacturing sector, and as a result, pandemic "stay-at-home" orders issued in March 2020 did not affect the abrasives manufacturing industry. These plants remained at full operation (USGS 2021a). In 2022, imports and exports continued to recover from the negative effects of the COVID-19 pandemic (USGS 2023b). Consumption of SiC increased by approximately 27 percent from 2021 to 2022, rising above pre-pandemic levels (U.S. Census Bureau 2005 through 2022).

Carbon dioxide emissions from SiC production and consumption in 2022 were 0.2 MMT CO_2 Eq. (210 kt CO_2), which are about 14 percent lower than emissions in 1990 (see Table 4-43 and Table 4-44). Approximately 50 percent of these emissions resulted from SiC production, while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2022 were 0.01 MMT CO_2 Eq. (0.5 kt CH_4) (see Table 4-43 and Table 4-44). These tables indicate minor changes in emissions in recent years.

Table 4-43: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production							
CO_2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	+	+	+	+	+	+	+
SiC Consumption							
CO_2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-44: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production							
CO_2	170	92	92	92	92	92	105
CH_4	1	+	+	+	+	+	+
SiC Consumption							
CO_2	73	121	93	84	62	80	105

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from the production of SiC are calculated using the Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Emissions of CO_2 from the consumption of SiC are a country-specific source calculated using a country-specific methodology based on available data. The *2006 IPCC Guidelines* do not provide guidance for estimating emissions from use of SiC or SiC consumption, but the country-specific methodology used is based on the stoichiometry of SiC consumption and is compatible with the *2006 IPCC Guidelines* and consistent with a Tier 1 approach.

Annual estimates of SiC production were multiplied by the default emission factors, as shown below:

Equation 4-78: *2006 IPCC Guidelines* Tier 1: Emissions from Carbide Production (Equation 3.11)

$$E_{sc,CO2} = EF_{sc,CO2} \times Q_{sc}$$

$$E_{sc,CH4} = EF_{sc,CH4} \times Q_{sc} \times \left(\frac{1\ metric\ ton}{1000\ kg}\right)$$

where,

$E_{sc,CO2}$ = CO_2 emissions from production of SiC, metric tons

$EF_{sc,CO2}$ = Emission factor for production of SiC, metric ton CO_2/metric ton SiC

Q_{sc} = Quantity of SiC produced, metric tons

$E_{sc,CH4}$ = CH_4 emissions from production of SiC, metric tons

$EF_{sc,CH4}$ = Emission factor for production of SiC, kilogram CH_4/metric ton SiC

Emission factors were taken from the *2006 IPCC Guidelines*:

- 2.62 metric tons CO_2/metric ton SiC
- 11.6 kg CH_4/metric ton SiC

Production data includes silicon carbide manufactured for abrasive applications as well as for metallurgical and other non-abrasive applications (USGS 2021).

Silicon carbide industrial abrasives production data for 1990 through 2022 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2021; USGS 2023a). Silicon carbide production data published by USGS have been rounded to the nearest 5,000 metric tons to avoid disclosing company proprietary data. For the period 1990 through 2001, reported USGS production data include production from two facilities located in Canada that ceased operations in 1995 and 2001. Using SiC production data from Canada (ECCC 2022), U.S. SiC production for 1990 through 2001 was adjusted to reflect only U.S. production.

Emissions from SiC consumption are calculated by multiplying the annual SiC consumption for metallurgical and other non-abrasive uses by the carbon content of SiC (about 30.0 percent), which is based on the molecular weight

of SiC, and converted to CO_2. This conversion calculation equates to 1.10 and is consistent with the IPCC default emission factor to calculate CO_2 emissions from the consumption of acetylene, a calcium carbide product, and demonstrates a methodology consistent with the *2006 IPCC Guidelines*. The amount of SiC used by other non-abrasive applications is determined by multiplying the annual SiC consumption by 50 percent (the percentage that the USGS allocates as usage by metallurgical and other non-abrasive applications) and then subtracting the amount of SiC used for metallurgical applications (USGS 1991a through 2021; USGS 2023a).

Emissions from SiC consumption are estimated for the entire time series using USGS consumption data (USGS 1991b through 2021) and data from the U.S. International Trade Commission (USITC) database on net imports and exports of SiC (U.S. Census Bureau 2005 through 2022) (Table 4-45). Total annual SiC consumption (utilization) was estimated by subtracting annual exports of SiC from the total of annual national SiC production and annual imports. Data on the annual consumption of SiC for metallurgical uses were obtained from USGS *Minerals Yearbook: Silicon* (USGS 1991b-2021; USGS 2023c). USGS withheld consumption data for metallurgical uses from publication for 2017, 2018, and 2021, and 2022 due to concerns of disclosing company-specific sensitive information, SiC consumption for 2017 and 2018 were estimated using 2016 values, and SiC consumption for 2021 and 2022 were estimated using the 2020 value (USGS 2023c). Additionally, as the USGS has not yet released the 2022 data, SiC consumption for 2022 was estimated using the 2020 value.

The petroleum coke portion of the total CO_2 process emissions from silicon carbide production is adjusted for within the Energy chapter, as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Table 4-45: Production and Consumption of Silicon Carbide (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production	65,000	35,000	35,000	35,000	35,000	35,000	40,000
SiC Consumption	132,465	220,149	168,526	152,412	113,756	146,312	191,133

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Silicon carbide production data published by the USGS is rounded to the nearest 5,000 tons and has been consistently reported at 35,000 tons since 2003 to avoid disclosure of company proprietary data. This translates to an uncertainty range of ±7 percent and a normal probability density function for SiC production (USGS 2021). There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. An alternative is to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced; however, these data were not available. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). EPA assigned an uncertainty of ±10 percent for the Tier 1 CO_2 and CH_4 emission factors for the SiC production processes, and using this suggested uncertainty provided in Section 3.6.3.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors. There is also uncertainty associated with the use or destruction of CH_4 generated from the process, in addition to uncertainty associated with levels of production, net imports, consumption levels, and the percent of total consumption that is attributed to metallurgical and other non-abrasive uses. EPA assigned an uncertainty range of ±5 percent for the primary data inputs for consumption (i.e., crude imports, ground and refined imports, crude exports, ground and refined exports, utilization [metallurgical applications]) to calculate overall uncertainty from SiC production, and using this suggested uncertainty provided in Section 3.6.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-46. Silicon carbide production and consumption CO_2 emissions from 2022 were estimated to be between 10 percent below and 10 percent above the emission estimate of 0.2 MMT CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 10 percent below and 11 percent above the emission estimate of 0.01 MMT CO_2 Eq. at the 95 percent confidence level.

Table 4-46: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.2	0.2	0.2	-10%	+10%
Silicon Carbide Production	CH_4	+	+	+	-10%	+11%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is initiating research for data on SiC consumption by end-use for consideration in updating emissions estimates from SiC consumption and to account for emissions where they occur. This planned improvement is subject to data availability and will be implemented in the medium- to long-term given significance of emissions.

EPA has not integrated aggregated facility-level GHGRP information to inform estimates of CO_2 and CH_4 from SiC production and consumption. The aggregated information (e.g., activity data and emissions) associated with silicon carbide did not meet criteria to shield underlying confidential business information (CBI) from public disclosure. EPA plans to examine the use of GHGRP silicon carbide emissions data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories. This planned improvement is ongoing and has not been incorporated into this *Inventory* report. This is a long-term planned improvement.

4.11 Titanium Dioxide Production (CRT Source Category 2B6)

Titanium dioxide (TiO_2) is manufactured using one of two processes: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related carbon dioxide

(CO_2). The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2. The reporting category (2B6) includes emissions from production of TiO_2. In accordance with the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of titanium dioxide are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. The chloride process is based on the following chemical reactions and does emit CO_2:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$

The carbon in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (rutile ore) to form CO_2. Since 2004, all TiO_2 produced in the United States has been produced using the chloride process, and a special grade of "calcined" petroleum coke is manufactured specifically for this purpose.

The principal use of TiO_2 is as a white pigment in paint, lacquers, and varnishes. It is also used as a pigment in the manufacture of plastics, paper, and other products. In 2022, U.S. TiO_2 production totaled 1,100,000 metric tons (USGS 2023b). Five plants produced TiO_2 in the United States in 2022.

Emissions of CO_2 from titanium dioxide production in 2022 were estimated to be 1.5 MMT CO_2 Eq. (1,474 kt CO_2), which represents an increase of 23 percent since 1990 (see Table 4-47 and Table 4-48). Compared to 2021, emissions from titanium dioxide production remained the same because production was consistent from 2021 to 2022. Annual production dipped in 2019 and 2020 and increased in 2021 and 2022.

Table 4-47: CO_2 Emissions from Titanium Dioxide (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Titanium Dioxide	1.2	1.8	1.5	1.3	1.3	1.5	1.5

Table 4-48: CO_2 Emissions from Titanium Dioxide (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Titanium Dioxide	1,195	1,755	1,541	1,340	1,340	1,474	1,474

Methodology and Time-Series Consistency

Emissions of CO_2 from TiO_2 production are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Annual national TiO_2 production is multiplied by chloride process-specific emission factors provided by IPCC (IPCC 2006). The Tier 1 equation is as follows:

Equation 4-9: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Titanium Production (Equation 3.12)

$$E_{td} = EF_{td} \times Q_{td}$$

where,

E_{td} = CO_2 emissions from TiO_2 production, metric tons

EF_{td} = Emission factor (chloride process), metric ton CO_2/metric ton TiO_2

Q_{td} = Quantity of TiO_2 produced, metric tons

The petroleum coke portion of the total CO_2 process emissions from TiO_2 production is adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology

section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Data were obtained for the total amount of TiO_2 produced each year. For years prior to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. As of 2004, the last remaining sulfate process plant in the United States closed; therefore, 100 percent of production since 2004 used the chloride process (USGS 2005). An emission factor of 1.34 metric tons CO_2/metric ton TiO_2 was applied to the estimated chloride-process production (IPCC 2006). It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other carbon inputs.

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines*. Titanium dioxide production data and the percentage of total TiO_2 production capacity that used the chloride process for 1990 through 2018 (see Table 4-49) were obtained through the U.S. Geological Survey (USGS) *Minerals Yearbook: Titanium* (USGS 1991 through 2022). Production data for 2019 and 2020 were obtained from the USGS Minerals Yearbook: Titanium, advanced data release of the 2020 tables (USGS 2023a). Production data for 2020 and 2021 were obtained from the *Minerals Commodity Summaries: Titanium and Titanium Dioxide* (USGS 2023b).[39] Data on the percentage of total TiO_2 production capacity that used the chloride process were not available for 1990 through 1993, so data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate process plant closed in September 2001, the chloride process percentage for 2001 was estimated (Gambogi 2002). By 2002, only one sulfate process plant remained online in the United States, and this plant closed in 2004 (USGS 2005).

Table 4-49: Titanium Dioxide Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production	979	1,310	1,150	1,000	1,000	1,100	1,100

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Each year, the USGS collects titanium industry data for titanium mineral and pigment production operations. If TiO_2 pigment plants do not respond, production from the operations is estimated based on prior year production levels and industry trends. Variability in response rates fluctuates from 67 to 100 percent of TiO_2 pigment plants over the time series. EPA currently uses an uncertainty range of ±5 percent and a normal probability density function for the primary data inputs (i.e., TiO_2 production and chloride process capacity values) to calculate overall uncertainty from TiO_2 production, and using this suggested uncertainty provided in Section 3.7.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Additionally, the EPA uses an uncertainty range of ±15 percent and a triangular probability density function for the CO_2 chloride process carbon consumption rate, and using this uncertainty provided in Section 3.7.2.2 of the *2006 IPCC Guidelines* is representative of operations in the United States. based on expert judgment (RTI 2023).

Although some TiO_2 may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated using petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing

[39] EPA has not integrated aggregated facility-level GHGRP information for titanium dioxide production facilities (40 CFR Part 98 Subpart EE). The relevant aggregated information (activity data, emission factor) from these facilities did not meet criteria to shield underlying CBI from public disclosure.

agent used in each process rather than on the amount of TiO_2 produced, sufficient data were not available to do so.

As of 2004, the last remaining sulfate-process plant in the United States closed. Since annual TiO_2 production was not reported by USGS by the type of production process used (chloride or sulfate) prior to 2004 and only the percentage of total production capacity by process was reported, the percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride process. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available. EPA assigned an uncertainty range of ±15 percent and a triangular probability density function for the Tier 1 CO_2 emission factor for the titanium dioxide (chloride route) production process, and using this uncertainty provided in Table 3.9 of the *2006 IPCC Guidelines* is representative of operations in the United States based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-49. Titanium dioxide consumption CO_2 emissions from 2022 were estimated to be between 1.3 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.5 MMT CO_2 Eq.

Table 4-50: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.5	1.3	1.7	-12%	+13%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Updated USGS data on TiO_2 production was available for 2019 and 2020, resulting in updated emissions estimates for those years. Compared to the previous *Inventory*, emissions for 2019 decreased by 9 percent (134 kt CO_2), and emissions for 2020 increased by 12 percent (147 kt CO_2).

Planned Improvements

EPA plans to examine the use of GHGRP titanium dioxide emissions and other data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[40] This planned improvement is ongoing and has not been

[40] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

incorporated into this *Inventory* report. This is a long-term planned improvement given the significance of these emissions.

4.12 Soda Ash Production (CRT Source Category 2B7)

Carbon dioxide (CO_2) is generated as a byproduct of calcining trona ore to produce soda ash (sodium carbonate, Na_2CO_3) and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed. This reporting category (2B7) includes emissions from the production of soda ash by any of four processes, of which calcining trona ore is the only emissive process used in the United States. Emissions from soda ash consumption associated with glass production are reported under Section 4.3, glass production. Emissions from soda ash consumption not associated with glass production are reported under Section 4.4, other process uses of carbonates. Emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Calcining involves placing crushed trona ore into a kiln to convert sodium bicarbonate into crude sodium carbonate that will later be filtered into pure soda ash. The emission of CO_2 during trona-based production is based on the following reaction:

$$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O(Trona) \rightarrow 3Na_2CO_3(Soda\ Ash) + 5H_2O + CO_2$$

Soda ash is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. The largest use of soda ash is for glass manufacturing. Emissions from soda ash used in glass production are reported under Section 4.3. In addition, soda ash is used primarily to manufacture many sodium-based inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2018b). Internationally, two types of soda ash are produced: natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash production. Trona is the principal ore from which natural soda ash is made.

The United States represents about one-fifth of total world soda ash output (USGS 2023a). Only two states produce natural soda ash: Wyoming and California. Of these two states, net emissions of CO_2 from soda ash production were only calculated for Wyoming where trona ore is used.[41] Soda ash end uses in 2022 (excluding glass production) consisted of chemical production, 54 percent; other uses, 17 percent; wholesale distributors (e.g., for use in agriculture, water treatment, and grocery wholesale), 10 percent; soap and detergent manufacturing, 9 percent; flue gas desulfurization, 7 percent; water treatment, 2 percent; and pulp and paper production, 1 percent (USGS 2023b).[42]

[41] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a byproduct, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted. A facility in a third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona ore in the state. For a brief time, sodium bicarbonate was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Prior to 2004, because the trona ore was mined in Wyoming, the production numbers given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

[42] Percentages may not add up to 100 percent due to independent rounding.

U.S. natural soda ash is competitive in world markets because it is generally considered a better-quality raw material than synthetically produced soda ash, and most of the world's soda ash is synthetic. Although the United States continues to be a major supplier of soda ash, China surpassed the United States in soda ash production in 2003, becoming the world's leading producer.

In 2022, CO_2 emissions from the production of soda ash from trona ore were 1.7 MMT CO_2 Eq. (1,704 kt CO_2) (see Table 4-51 and Table 4-52). Total emissions from soda ash production in 2022 decreased by approximately 1 percent compared to emissions in 2021, as soda ash production returned to 2018 levels observed before the COVID-19 pandemic. Emissions have increased by approximately 19 percent from 1990 levels.

Trends in emissions have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. The U.S. soda ash industry saw a decline in domestic and export sales caused by adverse global economic conditions in 2009, followed by a steady increase in production through 2019 before a significant decrease in 2020 due to the COVID-19 pandemic.

Table 4-51: CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7

Table 4-52: CO_2 Emissions from Soda Ash Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704

Methodology and Time-Series Consistency

Carbon dioxide emissions from soda ash production are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. During the soda ash production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as byproducts of the calcination process. Carbon dioxide emissions from the calcination of trona ore can be estimated based on the chemical reaction shown above. Based on this formula and the IPCC default emission factor of 0.0974 metric tons CO_2 per metric ton of trona ore, both of which are consistent with an IPCC Tier 1 approach, one metric ton of CO_2 is emitted when approximately 10.27 metric tons of trona ore are processed (IPCC 2006).

Data is not currently available for the quantity of trona used in soda ash production. Because trona ore is used primarily for soda ash production, EPA assumes that all trona ore production was used in soda ash production. The activity data for trona ore production (see Table 4-53) for 1990 through 2022 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2016 through 2017, 2018a, 2019, 2020, 2021, 2022b, 2023b). Soda ash production[43] data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. EPA will continue to analyze and assess opportunities to use facility-level data from EPA's GHGRP to improve the emission estimates for the soda ash production source category consistent with IPCC[44] and UNFCCC guidelines.

[43] EPA has assessed the feasibility of using emissions information (including activity data) from EPA's GHGRP program. At this time, the aggregated information associated with production of soda ash did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

[44] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

Table 4-53: Trona Ore Used in Soda Ash Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Trona Ore Use[a]	14,700	17,000	17,600	18,400	15,000	17,600	17,500

[a] Trona ore use is assumed to be equal to trona ore production.

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022.

Uncertainty

Emission estimates from soda ash production have relatively low associated uncertainty levels because reliable and accurate data sources are available for the emission factor and activity data for trona-based soda ash production. One source of uncertainty is the purity of the trona ore used for manufacturing soda ash. The emission factor used for this estimate assumes the ore is 100 percent pure and likely overestimates the emissions from soda ash manufacture. The average water-soluble sodium carbonate-bicarbonate content for ore mined in Wyoming ranges from 85.5 to 93.8 percent (USGS 1995c).

EPA is aware of one facility producing soda ash from a liquid alkaline feedstock process, based on EPA's GHGRP. Soda ash production data was collected by the USGS from voluntary surveys. A survey request was sent to each of the five soda ash producers, all of which responded, representing 100 percent of the total production data (USGS 2023b). EPA assigned an uncertainty range of ±5 percent for trona production, and using the suggested uncertainty provided in Section 3.8.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of -15 percent to 0 percent range for the trona emission factor, based on expert judgment on the purity of mined trona (USGS 1995c). Per this expert judgment, a normal probability density function was assigned for activity data, and a triangular probability density function was assigned for the emission factor.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-54. Soda ash production CO_2 emissions for 2022 were estimated to be between 1.5 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below and 8 percent above the emission estimate of 1.7 MMT CO_2 Eq.

Table 4-54: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production	CO_2	1.7	1.5	1.7	-9%	+8%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CO_2 emissions from soda ash production.

4.13 Petrochemical Production (CRT Source Category 2B8)

The production of some petrochemicals results in carbon dioxide (CO_2) and methane (CH_4) emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. This reporting category (2B8) includes CO_2 emissions from the production of acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, and methanol, and CH_4 emissions from the production of acrylonitrile. The petrochemical industry uses primary fossil fuels (i.e., natural gas, coal, petroleum, etc.) for non-fuel purposes in the production of carbon black and other petrochemicals. Per the IPCC methodological guidance, emissions from fuels and feedstocks transferred out of the system for use in energy purposes (e.g., indirect or direct process heat or steam production) are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Worldwide, more than 90 percent of acrylonitrile (vinyl cyanide, C_3H_3N) is made by way of direct ammoxidation of propylene with ammonia (NH_3) and oxygen over a catalyst. This process is referred to as the SOHIO process, named after the Standard Oil Company of Ohio (SOHIO) (IPCC 2006). The primary use of acrylonitrile is as the raw material for the manufacture of acrylic and modacrylic fibers. Other major uses include the production of plastics (acrylonitrile-butadiene-styrene [ABS] and styrene-acrylonitrile [SAN]), nitrile rubbers, nitrile barrier resins, adiponitrile, and acrylamide. All U.S. acrylonitrile facilities use the SOHIO process (AN 2014). The SOHIO process involves a fluidized bed reaction of chemical-grade propylene, ammonia, and oxygen over a catalyst. The process produces acrylonitrile as its primary product, and the process yield depends on the type of catalyst used and the process configuration. The ammoxidation process produces byproduct CO_2, carbon monoxide (CO), and water from the direct oxidation of the propylene feedstock and produces other hydrocarbons from side reactions.

Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum- or coal-based feedstock at a high temperature. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. The other major use of carbon black is as a pigment. The predominant process used in the United States to produce carbon black is the furnace black (or oil furnace) process. In the furnace black process, carbon black oil (a heavy aromatic liquid) is continuously injected into the combustion zone of a natural gas-fired furnace. Furnace heat is provided by the natural gas and a portion of the carbon black feedstock; the remaining portion of the carbon black feedstock is pyrolyzed to carbon black. The resultant CO_2 and uncombusted CH_4 are released from thermal incinerators used as control devices, process dryers, and equipment leaks. Three facilities in the United States use other types of carbon black processes. Specifically, one facility produces carbon black by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), a second facility produces carbon black by the thermal cracking of other hydrocarbons (i.e., thermal black process), and a third facility produces carbon black by the open burning of carbon black feedstock (i.e., lamp black process) (EPA 2000).

Ethylene (C_2H_4) is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE); polyvinyl chloride (PVC); ethylene dichloride; ethylene oxide; and ethylbenzene. Virtually all ethylene is produced from steam cracking of ethane, propane, butane, naphtha, gas oil, and other feedstocks. The representative chemical equation for steam cracking of ethane to ethylene is shown below:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

Small amounts of CH_4 are also generated from the steam cracking process. In addition, CO_2 and CH_4 emissions result from combustion units.

Ethylene dichloride ($C_2H_4Cl_2$) is used to produce vinyl chloride monomer, which is the precursor to polyvinyl chloride (PVC). Ethylene dichloride was also used as a fuel additive until 1996 when leaded gasoline was phased out. Ethylene dichloride is produced from ethylene by either direct chlorination, oxychlorination, or a combination of the two processes (i.e., the "balanced process"); most U.S. facilities use the balanced process. The direct chlorination and oxychlorination reactions are shown below:

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \text{ (direct chlorination)}$$

$$C_2H_4 + \tfrac{1}{2}O_2 + 2HCl \rightarrow C_2H_4Cl_2 + 2H_2O \text{ (oxychlorination)}$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \text{ (direct oxidation of ethylene during oxychlorination)}$$

In addition to the byproduct CO_2 produced from the direct oxidation of the ethylene feedstock, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene oxide (C_2H_4O) is used in the manufacture of glycols, glycol ethers, alcohols, and amines. Approximately 70 percent of ethylene oxide produced worldwide is used in the manufacture of glycols, including monoethylene glycol. Ethylene oxide is produced by reacting ethylene with oxygen over a catalyst. The oxygen may be supplied to the process through either an air (air process) or a pure oxygen stream (oxygen process). The byproduct CO_2 from the direct oxidation of the ethylene feedstock is removed from the process vent stream using a recycled carbonate solution, and the recovered CO_2 may be vented to the atmosphere or recovered for further utilization in other sectors, such as food production (IPCC 2006). The combined ethylene oxide reaction and byproduct CO_2 reaction is exothermic and generates heat, which is recovered to produce steam for the process. The ethylene oxide process also produces other liquid and off-gas byproducts (e.g., ethane that may be burned for energy recovery within the process. Almost all facilities, except one in Texas, use the oxygen process to manufacture ethylene oxide (EPA 2008).

Methanol (CH_3OH) is a chemical feedstock most often converted into formaldehyde, acetic acid and olefins. It is also an alternative transportation fuel, as well as an additive used by municipal wastewater treatment facilities in the denitrification of wastewater. Methanol is most commonly synthesized from a synthesis gas (i.e., "syngas" – a mixture containing H_2, CO, and CO_2) using a heterogeneous catalyst. There are a number of process techniques that can be used to produce syngas. Worldwide, steam reforming of natural gas is the most common method; most methanol producers in the United States also use steam reforming of natural gas to produce syngas. Other syngas production processes in the United States include partial oxidation of natural gas and coal gasification.

Emissions of CO_2 and CH_4 from petrochemical production in 2022 were 28.8 MMT CO_2 Eq. (28,788 kt CO_2) and 0.005 MMT CO_2 Eq. (0.17 kt CH_4), respectively (see Table 4-55 and Table 4-56). Carbon dioxide emissions from petrochemical production are driven primarily from ethylene production, while CH_4 emissions are only from acrylonitrile production. Since 1990, total CO_2 emissions from petrochemical production increased by 43 percent, and CH_4 emissions declined by 22 percent. Emissions of CO_2 were 6 percent lower in 2022 than in 2021, and emissions of CH_4 were 12 percent higher in 2022 than in 2021. The increase in CO_2 emissions since 1990 is due primarily to increased ethylene and methanol production, which have been driven by the increased natural gas production in the United States. The reduction in CO_2 emissions since 2021 is due to a reduction in emissions from ethylene production, despite an increase in ethylene production. Since CH_4 emissions from acrylonitrile are calculated using a Tier 1 approach based on production as the activity data, the decrease in CH_4 emissions since 1990 and the increase since 2021 correspond with changes in the production levels for acrylonitrile.

Table 4-55: CO_2 and CH_4 Emissions from Petrochemical Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2	**20.1**	**26.9**	**27.2**	**28.5**	**27.9**	**30.7**	**28.8**
Carbon Black	3.4	4.3	3.4	3.3	2.6	3.0	3.1
Ethylene	13.1	19.0	19.4	20.7	20.7	22.8	20.7

Ethylene Dichloride	0.3	0.5	0.4	0.5	0.5	0.4	0.4
Ethylene Oxide	1.1	1.5	1.3	1.4	1.7	1.9	1.7
Methanol	1.0	0.3	1.4	1.6	1.6	1.7	2.0
Acrylonitrile	1.2	1.3	1.3	1.0	0.9	0.9	1.0
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Acrylonitrile	+	+	+	+	+	+	+
Total	**20.1**	**26.9**	**27.2**	**28.5**	**27.9**	**30.7**	**28.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-56: CO_2 and CH_4 Emissions from Petrochemical Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2	**20,075**	**26,882**	**27,200**	**28,483**	**27,926**	**30,656**	**28,788**
Carbon Black	3,381	4,269	3,440	3,300	2,610	3,000	3,060
Ethylene	13,126	19,024	19,400	20,700	20,700	22,800	20,700
Ethylene Dichloride	254	455	440	503	456	376	428
Ethylene Oxide	1,123	1,489	1,300	1,370	1,680	1,930	1,650
Methanol	977	319	1,370	1,620	1,630	1,700	2,000
Acrylonitrile	1,214	1,325	1,250	990	850	850	950
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Acrylonitrile	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt CH_4.

Note: Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 were calculated using the estimation methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, and country-specific methods from EPA's GHGRP. The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO_2 and CH_4 emissions from production of acrylonitrile,[45] and a country-specific approach similar to the IPCC Tier 2 method was used to estimate CO_2 emissions from production of carbon black, ethylene oxide, ethylene, ethylene dichloride, and methanol, as CO_2 emissions from petrochemical production is a key category. The Tier 2 method for petrochemicals is a total feedstock carbon mass balance method used to estimate total CO_2 emissions, but it is not applicable for estimating CH_4 emissions.

As noted in the *2006 IPCC Guidelines*, the Tier 2 total feedstock carbon mass balance method is based on the assumption that all of the carbon input to the process is converted either into primary and secondary products or into CO_2. Further, the guideline states that while the total carbon mass balance method estimates total carbon emissions from the process, it does not directly provide an estimate of the amount of the total carbon emissions emitted as CO_2, CH_4, or non-CH_4 volatile organic compounds (NMVOCs). This method accounts for all the carbon as CO_2, including CH_4.

A methodology refinement for emissions from methanol production was implemented in this *Inventory* to transition from a Tier 1 method to a country-specific approach similar to a Tier 2 method, using the process CO_2 emissions reported to Subpart X of the GHGRP. As part of this refinement, CH_4 emissions from methanol production for every year in the time series are now included in the CO_2 emissions estimates to avoid double counting because the GHGRP reporting method is a mass balance method under which all carbon input to the process is assumed to be converted either into primary and secondary products or into CO_2.

[45] EPA has not integrated aggregated facility-level GHGRP information for acrylonitrile production. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Note, a subset of facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor CO_2 emissions from process vents and/or stacks from stationary combustion units or use the optional combustion methodology for ethylene production facilities. These facilities are required to also report CO_2, CH_4 and N_2O emissions from combustion of process off-gas in flares. The CO_2 emissions from flares are included in aggregated CO_2 results. Analysis of aggregated annual reports from those facilities shows that flared CH_4 and N_2O emissions are less than 300 kt CO_2 Eq./year. Since data is only available from a subset of facilities and not consistently reported over time and since CH_4 and N_2O emissions are shown to be insignificant, they are excluded from this analysis. See the planned improvements section below and Annex 5.

Carbon Black, Ethylene, Ethylene Dichloride, and Ethylene Oxide

2010 through 2022

Carbon dioxide emissions and national production for carbon black, ethylene, ethylene dichloride, and ethylene oxide were aggregated directly from EPA's GHGRP dataset for 2010 through 2022 (EPA 2023).

These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of carbon black, ethylene, ethylene dichloride, ethylene oxide. In 2022, data reported to the GHGRP included 3,060,000 metric tons of CO_2 emissions from carbon black production; 20,700,000 metric tons of CO_2 from ethylene production; 428,000 metric tons of CO_2 from ethylene dichloride production; and 1,650,000 metric tons of CO_2 from ethylene oxide production.

Since 2010, EPA's GHGRP requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) under Subpart X to facilitate verification of reported emissions. Most petrochemical production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each petrochemical process unit to estimate facility-level process CO_2 emissions; ethylene production facilities also have a third option. The mass balance method is used by most facilities[46] and assumes that all the carbon input is converted into primary and secondary products or is emitted to the atmosphere as CO_2. To apply the mass balance, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. To apply the optional combustion methodology, ethylene production facilities must measure the quantity, carbon content, and molecular weight of the fuel to a stationary combustion unit when that fuel includes any ethylene process off-gas. These data are used to calculate the total CO_2 emissions from the combustion unit. The facility must also estimate the fraction of the emissions that is attributable to burning the ethylene process off-gas portion of the fuel. This fraction is multiplied by the total emissions to estimate the emissions from ethylene production. The QA/QC and Verification section below has a discussion of non-CO_2 emissions from ethylene production facilities.

All non-energy uses of residual fuel and some non-energy uses of "other oil" are assumed to be used in the production of carbon black; therefore, consumption of these fuels is adjusted for within the Energy chapter to avoid double-counting of emissions from fuel used in the carbon black production presented here within IPPU sector. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Section 3.1 and Annex 2.1.

1990 through 2009

Prior to 2010, for carbon black, ethylene, ethylene dichloride, and ethylene oxide processes, an average national CO_2 emission factor was calculated based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2009) to estimate CO_2 emissions. For these 4 types of petrochemical processes, CO_2 emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for petrochemical type "i"

[46] A few facilities producing ethylene dichloride, ethylene, and methanol used CO_2 CEMS; those CO_2 emissions have been included in the aggregated GHGRP emissions presented here.

with annual production for petrochemical type "i" and then averaging the derived emission factors obtained for each calendar year 2010 through 2013 (EPA 2023). The years 2010 through 2013 were used in the development of carbon dioxide emission factors as these years are more representative of operations in 1990 through 2009 for these facilities. The average emission factors for each petrochemical type were applied across all prior years because petrochemical production processes in the United States have not changed significantly since 1990, though some operational efficiencies have been implemented at facilities over the time series.

The average country-specific CO_2 emission factors that were calculated from the GHGRP data are as follows:

- 2.59 metric tons CO_2/metric ton carbon black produced
- 0.79 metric tons CO_2/metric ton ethylene produced
- 0.040 metric tons CO_2/metric ton ethylene dichloride produced
- 0.46 metric tons CO_2/metric ton ethylene oxide produced

Annual production data for carbon black for 1990 through 2009 were obtained from the International Carbon Black Association (Johnson 2003 and 2005 through 2010). Annual production data for ethylene, ethylene dichloride, and ethylene oxide for 1990 through 2009 were obtained from the American Chemistry Council's (ACC) *Business of Chemistry* (ACC 2023).

Methanol

2015 through 2022

Carbon dioxide emissions and national production for methanol were aggregated directly from EPA's GHGRP data for 2015 through 2022 (EPA 2023). These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of methanol. In 2022, data reported to the GHGRP included 2,000,000 metric tons of CO_2 emissions from methanol production.

As noted above, since 2010, EPA's GHGRP requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) under Subpart X to facilitate verification of reported emissions. Methanol production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each methanol process unit to estimate facility-level process CO_2 emissions. Most methanol production facilities use the mass balance method. As noted above, when using the mass balance method, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. For 2010 to 2014, the methanol data reported to GHGRP is considered CBI; therefore, the direct use of the GHGRP data starts with the 2015 reported information.

1990 through 2014

In this *Inventory*, similar to the methodology for other petrochemicals that utilize GHGRP data, an average national CO_2 emission factor for years prior to 2015 was calculated for methanol production based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2014) to estimate CO_2 emissions. Methanol CO_2 emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for methanol with annual production for methanol and then averaging the derived emission factors obtained for each year 2015 through 2022. The average country-specific CO_2 emission factor from the GHGRP data for these years was determined to be 0.26 metric tons CO_2/metric ton methanol produced. Annual methanol production data for 1990 through 2014 were obtained from the ACC's *Business of Chemistry* (ACC 2023). The average country-specific CO_2 emission factor from the GHGRP data is lower than the IPCC Tier 1 emission factor of 0.67 metric tons CO_2/metric ton methanol produced value that was used in previous versions of the *Inventory*. The main difference between the IPCC Tier 1 emission factor and the GHGRP emission factor is that the IPCC emission factor includes emissions from combustion of natural gas fuel in the reformer as well as vented CO_2 from the process; therefore, the use of the IPCC Tier 1 emission factor would double count emissions from natural gas combustion in the IPPU

chapter and the Energy chapter. EPA already accounts for emissions from combustion of natural gas fuel in the reformer as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Acrylonitrile

Carbon dioxide and methane emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Acrylonitrile emissions represent about 3 percent of total petrochemical emissions in 2022 so a Tier 1 approach is deemed acceptable, and higher Tier methods could not be used due to data sensitivities which are described below. Annual acrylonitrile production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2022. Emission factors used to estimate acrylonitrile production emissions are as follows:

- 0.18 kg CH_4/metric ton acrylonitrile produced
- 1.00 metric tons CO_2/metric ton acrylonitrile produced

Annual acrylonitrile production data for 1990 through 2022 were obtained from ACC's *Business of Chemistry* (ACC 2023). EPA is unable to apply the aggregated facility-level GHGRP information for acrylonitrile production needed for a Tier 2 approach due to sensitive nature of reported data. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Production of each type of petrochemical are shown in Table 4-57.

Table 4-57: Production of Selected Petrochemicals (kt)

Chemical	1990	2005	2018	2019	2020	2021	2022
Carbon Black	1,307	1,651	1,280	1,210	990	1,140	1,170
Ethylene	16,542	23,975	30,500	32,400	33,500	34,700	35,400
Ethylene Dichloride	6,283	11,260	12,500	12,600	11,900	11,500	12,100
Ethylene Oxide	2,429	3,220	3,310	3,800	4,680	4,860	5,310
Methanol	3,750	1,225	5,830	6,460	6,580	7,110	8,030
Acrylonitrile	1,214	1,325	1,250	990	850	850	950

As noted earlier in the introduction section of the Petrochemical Production section, the allocation and reporting of emissions from both fuels and feedstocks transferred out of the system for use in energy purposes to the Energy chapter differs slightly from the *2006 IPCC Guidelines*. According to the *2006 IPCC Guidelines*, emissions from fuel combustion from petrochemical production should be allocated to this source category within the IPPU chapter. Due to national circumstances, EIA data on primary fuel for feedstock use within the energy balance are presented by commodity only, with no resolution on data by industry sector (i.e., petrochemical production). In addition, under EPA's GHGRP, reporting facilities began reporting in 2014 on annual feedstock quantities for mass balance and CEMS methodologies (79 FR 63794), as well as the annual average carbon content of each feedstock (and molecular weight for gaseous feedstocks) for the mass balance methodology beginning in reporting year 2017 (81 FR 89260).[47] The United States is currently unable to report non-energy fuel use from petrochemical production under the IPPU chapter due to CBI issues. Therefore, consistent with *2006 IPCC Guidelines*, fuel consumption data reported by EIA are adjusted to account for these overlaps to avoid double-counting. More information on the non-energy use of fossil fuel feedstocks for petrochemical production can be found in Annex 2.3.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for ethylene production, ethylene dichloride production, and ethylene oxide production spliced activity data from two different sources: ACC for 1990 through 2009 and GHGRP for 2010 through 2022. The methodology for methanol production spliced activity data from two different sources: ACC for 1990 through 2014 and GHGRP for 2015 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap

[47] See https://www.epa.gov/ghgreporting/historical-rulemakings.

technique was applied to compare the two data sets for years where there was overlap. For ethylene production, the data sets were determined to be consistent, and adjustments were not needed. For ethylene dichloride production, ethylene oxide production, and methanol production, the data sets were determined to be inconsistent. The GHGRP data includes production of ethylene dichloride and ethylene oxide as intermediates, while it is unclear if the ACC data does. Methanol production data from GHGRP are significantly higher than the ACC data for every year since 2015; the reason for the difference is not clear. Therefore, no adjustments were made to the ethylene dichloride, ethylene oxide, and methanol activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent. The methodology for carbon black production also spliced activity data from two different sources: ICBA for 1990 through 2009 and GHGRP for 2010 through 2022. The overlap technique was applied to these data for 2010 and 2011. The data sets were determined to be consistent, and adjustments were not needed.

Uncertainty

The CO_2 and CH_4 emission factors used for acrylonitrile production are based on a limited number of studies. Using plant-specific factors instead of default or average factors could increase the accuracy of the emission estimates; however, such data were not available for the current *Inventory* report. For acrylonitrile, EPA assigned an uncertainty range of ±60 percent for the CO_2 emission factor, ±10 percent for the CH_4 emission factor, and a normal probability density function for both, and using the suggested uncertainty provided in Table 3.27 of the *2006 IPCC Guidelines* is appropriate based on expert judgment, (RTI 2023). The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production, ethylene, ethylene dichloride, ethylene oxide, and methanol are based on reported GHGRP data. Refer to the Methodology section for more details on how these emissions were calculated and reported to EPA's GHGRP. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide production, and using the suggested uncertainty provided in Table 3.27 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). There is some uncertainty in the applicability of the average emission factors for each petrochemical type across all prior years. While petrochemical production processes in the United States have not changed significantly since 1990, some operational efficiencies have been implemented at facilities over the time series.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-58. Petrochemical production CO_2 emissions from 2022 were estimated to be between 27.6 and 30.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below to 4 percent above the emission estimate of 28.8 MMT CO_2 Eq. Petrochemical production CH_4 emissions from 2022 were estimated to be between 0.0 and 0.01 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 14 percent below to 14 percent above the emission estimate of 0.005 MMT CO_2 Eq.

Table 4-58: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Petrochemical Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO_2	28.8	27.6	30.0	-4%	+4%
Petrochemical Production	CH_4	+	0.0	0.01	-14%	+14%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For petrochemical production, QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan, as described in the QA/QC and Verification Procedures section of the IPPU chapter and Annex 8. Source-specific quality control measures for this category included the QA/QC requirements and verification procedures of EPA's GHGRP. More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part 98).[48] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[49] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported production data by petrochemical type against external datasets.

For ethylene, ethylene dichloride and ethylene oxide, it is possible to compare CO_2 emissions calculated using the GHGRP data to the CO_2 emissions that would have been calculated using the Tier 1 approach if GHGRP data were not available. For ethylene, the GHGRP emissions were within ±8 percent of the emissions calculated using the Tier 1 approach prior to 2018; for 2018 through 2022, the GHGRP emissions were between 76 percent and 87 percent of what would be calculated using the Tier 1 approach. For ethylene dichloride, the GHGRP emissions are typically higher than the Tier 1 emissions by up to 25 percent, but in 2010 and 2021, GHGRP emissions were slightly lower than the Tier 1 emissions. For ethylene oxide, GHGRP emissions typically vary from the Tier 1 emissions by up to ±20 percent, but in 2021 and 2022, the GHGRP emissions were significantly higher than the Tier 1 emissions. This was likely due to GHGRP data capturing the production of ethylene oxide as an intermediate in the onsite production of ethylene glycol.

For methanol, GHGRP production data was consistently higher than ACC production data in all years between 2015 and 2022. Even though the GHGRP production was higher than the ACC production, the GHGRP CO_2 emissions estimated using the methodology refinement in this *Inventory* are significantly lower than the emissions calculated using the Tier 1 approach in all years between 2015 and 2022. Additionally, there is a trend towards increasing differences over these years starting with an 873 kt CO_2 difference in 2015 and increasing to a 3,000 kt CO_2 difference in 2022. GHGRP emissions were between 43 percent and 61 percent of the Tier 1 emissions in 2015 and 2018, respectively. As discussed in the Methodology and Time-Series Consistency section above, EPA has determined that using the IPCC Tier 1 emissions factor to calculate methanol emissions results in double counting of natural gas combustion emissions in both this chapter and in the Energy chapter; therefore, use of the GHGRP derived emissions is deemed appropriate. For the years 1990 through 2014, the use of the GHGRP derived emission factor also results in lower emissions than those calculated using the IPCC Tier 1 emission factor. While this avoids the double counting of emissions with the Energy chapter, as described below in the Planned Improvements section, EPA intends to examine the emissions from methanol facilities that report to the GHGRP and may have been operating prior to 2010 to assess whether a more specific process-only emission factor can be developed from the GHGRP data for use in estimating CO_2 emissions from methanol production in 1990 through 2014.

EPA's GHGRP mandates that all petrochemical production facilities report their annual emissions of CO_2, CH_4, and N_2O from each of their petrochemical production processes. Source-specific quality control measures for the Petrochemical Production category included the QA/QC requirements and verification procedures of EPA's GHGRP. The QA/QC requirements differ depending on the calculation methodology used.

[48] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[49] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

As part of a planned improvement effort, EPA has assessed the potential of using GHGRP data to estimate CH_4 emissions from ethylene production. As discussed in the Methodology section above, CO_2 emissions from ethylene production in this chapter are based on data reported under the GHGRP, and these emissions are calculated using a Tier 2 approach that assumes all of the carbon in the fuel (i.e., ethylene process off-gas) is converted to CO_2. Ethylene production facilities also calculate and report CH_4 emissions under the GHGRP when they use the optional combustion methodology. The facilities calculate CH_4 emissions from each combustion unit that burns off-gas from an ethylene production process unit using a Tier 1 approach based on the total quantity of fuel burned, a default or measured higher heating value, and a default emission factor. Because multiple other types of fuel in addition to the ethylene process unit off-gas may be burned in these combustion units, the facilities also report an estimate of the fraction of emissions that is due to burning the ethylene process off-gas component of the total fuel. Multiplying the total emissions by the estimated fraction provides an estimate of the CH_4 emissions from the ethylene production process unit. These ethylene production facilities also calculate CH_4 emissions from flares that burn process vent emissions from ethylene processes. The CO_2 emissions are calculated using either a Tier 2 approach based on measured gas volumes and measured carbon content or higher heating value, or a Tier 1 approach based on the measured gas flow and a default emission factor; the CH_4 emissions are calculated based on a Tier 1 approach using the CO_2 emissions and default emission factors. Nearly all ethylene production facilities use the optional combustion methodology under the GHGRP. The CH_4 emissions from ethylene production under the GHGRP have not been included in this chapter because this approach double counts carbon (i.e., all of the carbon in the CH_4 emissions is also included in the CO_2 emissions from the ethylene process units). EPA continues to assess the GHGRP data for ways to better disaggregate the data and incorporate it into the *Inventory*.

These facilities are also required to report emissions of N_2O from combustion of ethylene process off-gas in both stationary combustion units and flares. Facilities using CEMS (consistent with a Tier 3 approach) are also required to report emissions of CH_4 and N_2O from combustion of petrochemical process-off gases in flares. Preliminary analysis of the aggregated reported CH_4 and N_2O emissions from facilities using CEMS and N_2O emissions from facilities using the optional combustion methodology suggests that these annual emissions are less than 0.4 percent of total petrochemical emissions, which is not significant enough to prioritize for inclusion in the report at this time. Pending resources and significance, EPA may include these N_2O emissions in future reports to enhance completeness. Future QC efforts to validate the use of Tier 1 default emission factors and report on the comparison of Tier 1 emission estimates and GHGRP data are described below in the Planned Improvements section.

Recalculations Discussion

A methodology refinement for calculating emissions from methanol production was implemented in this *Inventory*. As discussed in the Methodology and Time-Series Consistency section, the previously used Tier 1 approach was replaced with a country-specific approach similar to a Tier 2 method based on emissions aggregated directly from EPA's GHGRP data for 2015 through 2022 (EPA 2023) and an average country-specific CO_2 emission factor from the GHGRP data applied to production data from ACC's *Business of Chemistry* for 1990 through 2014 (ACC 2023). For 2015 through 2021, these changes resulted in a reduction in the reported CO_2 emissions between 43 percent (873 kt) in 2015 to 61 percent (2,110 kt) in 2018. For 1990 through 2014, the refinement resulted in a reduction of 61 percent each year (287 kt in 2011 to 2,449 kt in 1997).

Additionally, CH_4 emissions previously reported from methanol production were reduced to zero for all years of the time series because, as noted above in the Methodology and Time Series Consistency section, the methodology refinement is based on the assumption that all carbon input to the process is converted either to primary and secondary products or to CO_2.

Planned Improvements

Improvements include completing category-specific QC of activity data and emission factors, along with further assessment of CH_4 and N_2O emissions to enhance completeness in reporting of emissions from U.S. petrochemical

production, pending resources, significance and time-series consistency considerations. For example, EPA is planning additional assessment of fuel combustion emissions data reported by methanol production facilities for ways to estimate process-based emissions in the *Inventory* separately from combustion emissions for 1990 through 2014. If the GHGRP data can be categorized by type of methanol process design, it may be possible to use GHGRP data for single reformer process units to develop a ratio of process-to-total emissions to adjust the IPCC emission factor. Potential difficulties with this analysis are that some of the methanol producing facilities also produce other chemicals and the combustion unit names may not clearly identify the process unit to which they apply, and some combustion unit data may be aggregated for multiple combustion units. The EPA is also planning additional assessment of ways to use CH_4 data from the GHGRP in the *Inventory*. One possible approach EPA is assessing would be to adjust the CO_2 emissions from the GHGRP downward by subtracting the carbon that is also included in the reported CH_4 emissions, per the discussion in the Petrochemical Production QA/QC and Verification section, above. As of this current report, timing and resources have not allowed EPA to complete these analyses of activity data, emissions, and emission factors but they remain priority improvements within the IPPU chapter.

Pending resources, a secondary potential improvement for this source category would focus on continuing to analyze the fuel and feedstock data from EPA's GHGRP to better disaggregate energy-related emissions and allocate them more accurately between the Energy and IPPU sectors of the *Inventory*. EPA will continue to look for ways to incorporate this data into future Inventories that will allow for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter. This planned improvement is still under development and has not been completed to report on progress in this current *Inventory*.

4.14 HCFC-22 Production (CRT Source Category 2B9a)

This reporting category (2B9a) includes by-product emissions of HCFC-23 (trifluoromethane or CHF_3) from production of HCFC-22 (chlorodifluoromethane). HFC-23 is generated as a byproduct during the manufacture of HCFC-22, which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Between 2000 and 2007, U.S. production fluctuated but generally remained above 1990 levels. In 2008 and 2009, U.S. production declined markedly and has remained near 2009 levels since. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses was phased out in 2020 under the U.S. Clean Air Act.[50] Feedstock production, however, is permitted to continue indefinitely. Per the IPCC methodological guidance, emissions from energy use are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where x + y = 5), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful

[50] As construed, interpreted, and applied in the terms and conditions of the *Montreal Protocol on Substances that Deplete the Ozone Layer* [42 U.S.C. §7671m(b), CAA §614].

byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 may be released to the atmosphere, recaptured for use in a limited number of applications, or destroyed.

Two facilities produced HCFC-22 in the United States in 2022. Emissions of HFC-23 from this activity in 2022 were estimated to be 1.8 MMT CO_2 Eq. (0.1 kt) (see Table 4-59 and Table 4-60). This quantity represents an 18 percent increase from 2021 emissions and a 95 percent decrease from 1990 emissions. The decrease from 1990 emissions was caused primarily by changes in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The decrease from 2021 emissions was caused by both a decrease in the HFC-23 emission rate at one plant and a decrease in the total quantity of HCFC-22 produced. The long-term decrease in the emission rate is primarily attributable to six factors: (a) five plants that did not capture and destroy the HFC-23 generated have ceased production of HCFC-22 since 1990; (b) one plant that captures and destroys the HFC-23 generated began to produce HCFC-22; (c) one plant implemented and documented a process change that reduced the amount of HFC-23 generated; (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale; (e) another plant began destroying HFC-23; and (f) the same plant, whose emission rate was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

Emissions from HCFC-22 production are reported under fluorochemical production (CRT category 2B9) in this *Inventory*, which also includes the production of fluorochemicals other than HCFC-22 described further in section 4.15 of this chapter.

Table 4-59: HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HCFC-22 Production	38.6	16.8	2.7	3.1	1.8	2.2	1.8

Table 4-60: HFC-23 Emissions from HCFC-22 Production (kt HFC-23)

Year	1990	2005	2018	2019	2020	2021	2022
HCFC-22 Production	3	1	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

To estimate HFC-23 emissions for five of the eight HCFC-22 plants that have operated in the United States since 1990, methods comparable to the Tier 3 methods in the *2006 IPCC Guidelines* (IPCC 2006) were used throughout the time series. Emissions for 2010 through 2022 were obtained through reports submitted by U.S. HCFC-22 production facilities to EPA's Greenhouse Gas Reporting Program (GHGRP). EPA's GHGRP mandates that all HCFC-22 production facilities report their annual emissions of HFC-23 from HCFC-22 production processes and HFC-23 destruction processes. Previously, data were obtained by EPA through collaboration with an industry association that received voluntarily reported HCFC-22 production and HFC-23 emissions annually from all U.S. HCFC-22 producers from 1990 through 2009. These emissions were aggregated and reported to EPA on an annual basis.

For the other three plants, the last of which closed in 1993, methods comparable to the Tier 1 method in the *2006 IPCC Guidelines* were used. Emissions from these three plants have been calculated using the recommended emission factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced).

The five plants that have operated since 1994 measure (or, for the plants that have since closed, measured) concentrations of HFC-23 as well as mass flow rates of process streams to estimate their generation of HFC-23. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. One plant that releases a small fraction of its byproduct HFC-23 periodically measures HFC-23 concentrations at process vents using gas chromatography. This information is combined with information on quantities of products (e.g., HCFC-22) to estimate HFC-23 emissions.

To estimate 1990 through 2009 emissions, reports from an industry association were used that aggregated HCFC-22 production and HFC-23 emissions from all U.S. HCFC-22 producers and reported them to EPA (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, and 2010). To estimate 2010 through 2022 emissions, facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through EPA's GHGRP were analyzed. In 1997 and 2008, comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production were performed (RTI 1997; RTI 2008). The 1997 and 2008 reviews enabled U.S. totals to be reviewed, updated, and where necessary, corrected. The reviews also allowed plant-level uncertainty analyses (Monte-Carlo simulations) to be performed for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-61.

Table 4-61: HCFC-22 Production (kt)

Year	1990	2005	2012	2018	2019	2020	2021	2022
Production	139	156	96	C	C	C	C	C

C (CBI)

Note: HCFC-22 production in 2013 through 2022 is considered confidential business information (CBI) as there were only two producers of HCFC-22 in those years.

Uncertainty

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo stochastic simulation for 2006. The Monte Carlo analysis used estimates of the uncertainties in the individual variables in each plant's estimating procedure. This analysis was based on the generation of 10,000 random samples of model inputs from the probability density functions for each input. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates. The simulation for 2006 yielded a 95-percent confidence interval for U.S. emissions of 6.8 percent below to 9.6 percent above the reported total.

The relative errors yielded by the Monte Carlo stochastic simulation for 2006 were applied to the U.S. emission estimate for 2022. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the two remaining plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants has changed between 2006 and 2022 (because one plant has closed), the plant that currently accounts for most emissions had a relative uncertainty in its 2006 (as well as 2005) emissions estimate that was similar to the relative uncertainty for total U.S. emissions. Thus, the closure of one plant is not likely to have a large impact on the uncertainty of the national emission estimate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-62. HFC-23 emissions from HCFC-22 production were estimated to be between 1.7 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 1.8 MMT CO_2 Eq.

Table 4-62: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	1.8	1.7	2.0	-7%	+10%

[a] Range of emissions reflects a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[51] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the HCFC-22 Production category. Under EPA's GHGRP, HCFC-22 producers are required to (1) measure concentrations of HFC-23 and HCFC-22 in the product stream at least weekly using equipment and methods (e.g., gas chromatography) with an accuracy and precision of 5 percent or better at the concentrations of the process samples, (2) measure mass flows of HFC-23 and HCFC-22 at least weekly using measurement devices (e.g., flowmeters) with an accuracy and precision of 1 percent of full scale or better, (3) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable standards and suitable methods published by a consensus standards organization, (4) calibrate gas chromatographs at least monthly through analysis of certified standards, and (5) document these calibrations.

Recalculations Discussion

The 2019 emissions estimate increased by 0.05 kg of HFC-23 to reflect newly reported emissions from a facility that destroys HFC-23. This increased the 2019 emissions estimate by two ten thousandths of a percent.

Planned Improvements

At this time, there are no specific planned improvements for estimating HFC-23 emissions from HCFC-22 production.

4.15 Production of Fluorochemicals Other Than HCFC-22 (CRT Source Category 2B9b)

This reporting category, fluorochemical production (2B9b), facilities in the United States produced or transformed approximately 200 fluorinated gases other than HCFC-22 in 2022, including saturated and unsaturated hydrofluorocarbons (HFCs), saturated and unsaturated perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluoroethers (HFEs), perfluoroalkylamines, and dozens of others. Emissions from fluorochemical production may include emissions of the intentionally manufactured chemical as well as reactant and by-product emissions. The compounds emitted depend upon the production or transformation process, but may include, e.g., HFCs, PFCs, SF_6, nitrous oxide (N_2O), NF_3, and many others. Potential sources of fluorinated GHG emissions at fluorochemical production facilities include process vents, equipment leaks, and evacuating returned

[51] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

containers[52] Production-related emissions of fluorinated GHGs occur from both process vents and equipment leaks. Process vent emissions occur from manufacturing equipment such as reactors, distillation columns, and packaging equipment. Equipment leak emissions, or fugitive emissions, occur from valves, flanges, pump seals, compressor seals, pressure relief valves, connectors, open-ended lines, and sampling connections. In addition, users of fluorinated GHGs may return empty containers (e.g., cylinders) to the production facility for reuse; prior to reuse, the residual fluorinated GHGs (often termed "heels") may be evacuated from the container and are a potential emission source. In many cases, these "heels" are recovered or exhausted to a treatment device for destruction. In other cases, however, they are released into the atmosphere.[53]

Emissions of all HFCs, PFCs, NF_3, and SF_6 from production of fluorochemicals other than hydrochlorofluorocarbon (HCFC)-22 are presented in Table 4-63 below for the years 1990, 2005, and the period 2018 to 2022. Per the IPCC methodological guidance, emissions from energy use are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

The fluorinated GHG emissions reported under the Greenhouse Gas Reporting Program (GHGRP) include emissions of HFCs, PFCs, SF_6, NF_3, and numerous "other" fluorinated GHGs, such as octafluorotetrahydrofuran (C_4F_8O), trifluoromethyl sulfur pentafluoride (SF_5CF_3), and hexafluoropropylene oxide. Because they are not included among the seven UNFCCC-reportable gases or gas groups, the "other" fluorinated GHGs are not included in *Inventory* totals. However, their emissions are presented below because they often have high GWPs and large GWP-weighted emissions.

Total emissions of HFCs, PFCs, SF_6, and NF_3 from fluorochemical production are estimated to have increased from 32 MMT CO_2 Eq. (3,400 MT) in 1990 to a peak of 45 MMT CO_2 Eq. (5,700 MT) in 1999, declining to 3.9 MMT CO_2 Eq. (860 MT) in 2016[54] and rising again to 6.0 MMT CO_2 Eq. (1,200 MT) in 2022. These trends reflect estimated changes in fluorinated gas production and increasing use of control devices. Prior to 2000, only 2 facilities are known to have operated control devices to destroy fluorinated GHG emissions. After 2000, additional production facilities began to install and use control devices to destroy fluorinated GHG emissions,[55] and fluorinated GHG emissions declined sharply from 45 MMT CO_2 Eq. (5,700 MT) in 1999 to 13 MMT CO_2 Eq. (2,300 MT) in 2005. Emissions continued to fall more slowly through 2016, reflecting the installation of controls at an additional 4 facilities in 2011, 2012, 2015, and 2016. Total fluorinated GHG emissions rose from 2017 to 2022 as production increased at some facilities.

Emissions from the production of fluorochemicals other than HCFC-22 are reported under fluorochemical production (CRT category 2B9) in conjunction with emissions from HCFC-22 production described in Section 4.14 of this chapter.

HFC Emissions

Estimated emissions of HFCs increased from 8.7 MMT CO_2 Eq. in 1990 to a peak of 14 MMT CO_2 Eq. in 1999 (1,200 to 2,600 MT), declining with some fluctuation to 2.5 MMT CO_2 Eq. in 2022. Emissions in 1990 were primarily from facilities producing compounds other than saturated HFCs. The subsequent trends in emissions were driven by the growth in production of saturated HFCs and the imposition of controls. Production of saturated HFCs is estimated to have increased from around 0.3 MMT CO_2 Eq. (2,000 MT) in 1990 to over 300 MMT CO_2 Eq. (100,000 MT) by

[52] The totals presented below also include emissions from destruction of previously produced fluorinated GHGs that are shipped to production facilities for destruction, e.g., because they are found to be irretrievably contaminated.

[53] IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

[54] Emissions in MMT CO_2 Eq. were similar in 2017, but the 2017 emissions in MT were considerably higher (4,500 MT) due to anomalously high emissions of one low-GWP, unsaturated HFC at one facility.

[55] One facility is assumed to have installed controls in 2000, another installed controls in 2003, and three facilities are assumed to have installed controls in 2005.

2010 as HFCs replaced ozone-depleting substances, which were being phased out under the Montreal Protocol and Clean Air Act (EPA 2023a; EPA 2023b). This increase in HFC production drove HFC emissions to their 1999 peak. However, estimated emissions declined significantly from 1999 to 2005 due to the assumed addition of controls in 2000 and subsequent years. Estimated emissions of HFCs resumed their increase from 2005 to 2010, reaching 7.2 MMT CO_2 Eq. (2,300 MT), but again declined sharply in 2011 to 4.6 MMT CO_2 Eq. (1,200 MT) based on addition of controls. Since 2012, HFC emissions have continued to trend downward with some fluctuations, hitting a minimum of 1.7 MMT CO_2 Eq. in 2021. With the phase-out of production of saturated HFCs (Kigali Amendment, and U.S. AIM program), the downward trend of HFC emissions is expected to continue, but the share of HFC emissions that are not associated with saturated HFC production (approximately 0.7 MMT CO_2 Eq. in 2022) is likely to persist in the absence of additional controls.

PFC Emissions

Emissions of PFCs increased gradually from 18 MMT CO_2 Eq. (2,000 MT) in 1990 to 24 MMT CO_2 Eq. (2,800 MT) in 1999 but dropped to 4.0 MMT CO_2 Eq. (490 MT) by 2005, reflecting the addition of controls at high-emitting facilities and apparent changes to the mix of products produced at another facility.[56] Overall PFC emissions from 2005 to 2022 have remained relatively steady, oscillating around 2.5 MMT CO_2 Eq. The upward trend between 1990 and 1999 was largely driven by the three facilities that reported their historical emissions to the EPA. In the absence of historical emissions data for other facilities, the quantities of fluorinated GHGs produced or transformed at other facilities emitting PFCs are estimated to have remained generally steady between 1990 and 2009 and therefore do not contribute to the emissions trend before 2010. For most of the fluorinated GHGs produced at these facilities, there was no available industry information to inform activity estimates or trends for 1990 to 2009. Therefore, as discussed in the Methodology section below, 2010 production values from EPA's GHGRP were assumed to have held constant for these compounds from 1990 to 2010.

SF_6 Emissions

Emissions of SF_6 are estimated to have risen gradually from 5.8 MMT CO_2 Eq. (250 MT) in 1990 to a peak of 7.5 MMT CO_2 Eq. (320 MT) in 1995, to have declined slowly to 7.0 MMT CO_2 Eq. in 2000, and then to have declined more rapidly to a minimum of 0.0004 MMT CO_2 Eq. (0.01 MT) in 2017, after which emissions rose and fluctuated between 0.056 MMT CO_2 Eq. (in 2020) and 0.0024 MMT CO_2 Eq. (in 2022). The rapid emissions decline after 2000 was driven first by the imposition of controls at one facility and then by the cessation of production in 2010 at a major U.S. SF_6-producing facility.

NF_3 Emissions

Since 1990, estimated emissions of NF_3 have fluctuated between 0.11 MMT CO_2 Eq. and 0.72 MMT CO_2 Eq., with peaks occurring in 2000 (0.71 MMT CO_2 Eq.), 2010 (0.70 MMT CO_2 Eq.), and 2020 (0.72 MMT CO_2 Eq.), and lows occurring in 1990 (0.29 MMT CO_2 Eq.), 2003 (0.33 MMT CO_2 Eq.), and 2018 (0.11 MMT CO_2 Eq.). NF_3 may be emitted both from the production of NF_3 and from the production of other fluorochemicals. The dominant source since 2010 has been production of NF_3. Trends after 2010 were driven by changes both in NF_3 production and in

[56] In a summary of 1990 through 2010 emissions submitted to EPA (described more below), 3M, which owns several facilities that historically emitted PFCs, noted that the mix of products produced at its various facilities had changed over time, leading to changes in the magnitude and contents of emissions. This change in magnitude and contents was particularly pronounced at 3M's Decatur facility (referred to elsewhere in this document as "3M Company"), where emissions declined from 15.8 MMT CO_2 Eq. in 2000 to 0.53 MMT CO_2 Eq. in 2002, and where the contents of emissions changed from HFCs, PFCs, SF_6 and other fluorinated GHGs in 2000 to PFCs and other fluorinated GHGs in 2003. (Emissions in 2002 were not differentiated by group). Emissions were also reduced after the installation of a control device at the Cordova facility. 3M noted that Initial start-up of the thermal oxidizer occurred in 2003, but that it took time to optimize the operation of the thermal oxidizer and treatment of the various gas streams, leading to a decrease in emissions over several years.

the emission rate (kg NF_3 emitted/kg NF_3 produced) for NF_3 production, with both contributing to increased emissions since 2018. For 1990 through 2009, the NF_3 that is emitted from the production of NF_3 is assumed to be influenced by the trajectory of NF_3 production, which is generally assumed to follow production trends in the semiconductor industry except where NF_3 facility capacity limits production further. Semiconductor production increased steadily from 1995 to 2007 but is estimated to have declined from 2007 through 2010. As described in the Methodology section under "Estimated Emissions for 3M facilities," the NF_3 that is emitted from production of other fluorochemicals is assumed to have been emitted as a constant fraction of the "other" fluorinated GHGs whose 1990 through 2010 emissions were reported by 3M facilities. This fraction was estimated based on the fraction of "other" fluorinated GHG emissions accounted for by NF_3 between 2011 and 2015 and is highly uncertain. Nevertheless, because the highest-emitting 3M facilities reported decreasing emissions of all other fluorinated GHG groups between 2000 and 2005 (due to the installation of a control device at one facility and apparent production changes at another), NF_3 emissions also appear likely to have decreased during this period.

Other Fluorinated GHG Emissions

Other fluorinated GHGs, i.e., those not included in the UNFCCC-reportable gases or gas groups, are also emitted in significant quantities from fluorinated gas production and transformation processes. Estimated emissions of these other fluorinated GHGs are provided in Table 4-64 for the years 1990, 2005, and the period 2018 to 2022. The other fluorinated GHGs with the highest estimated emissions in 2022 are presented separately, and the remaining other fluorinated GHGs are aggregated.

Total emissions of other fluorinated GHGs increased from 4.7 MMT CO_2 Eq. (450 MT) in 1990 to a peak of 10.1 MMT CO_2 (870 MT) in 2000, declining rapidly to 0.90 MMT CO_2 Eq. in 2009 and then declining more slowly to 0.13 MMT CO_2 Eq. (40 MT) in 2021 and 2022. Between 1990 and 2009, estimated emissions of other fluorinated GHGs were primarily driven by the emissions reported by 3M facilities, which showed significant declines between 2000 and 2005, reflecting apparent production changes at one facility and the installation of a control device at another. The decline in emissions from 2019 to 2020 was due to a decrease in the emission rate at one facility.

Table 4-63: Emissions of HFCs, PFCs, SF_6, and NF_3 from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	6.7	1.7	1.3	1.1	0.9	0.7	1.0
HFC-125	0.1	1.9	0.4	0.4	0.4	0.4	0.3
HFC-143a	0.1	0.8	0.7	0.6	0.3	0.2	0.3
HFC-134a	+	0.4	0.3	0.3	0.2	0.2	0.3
1H,4H-Perfluorobutane	0.0	0.0	0.0	+	+	+	0.2
1H,6H-Perfluorohexane	0.0	0.0	0.0	+	+	+	0.2
Other HFCs	1.6	0.5	0.2	0.2	0.2	0.2	0.3
Perfluorocyclobutane	11.2	0.7	1.3	1.4	1.1	1.3	1.3
PFC-14 (Perfluoromethane)	2.4	1.4	1.0	0.9	0.9	0.9	1.0
Other PFCs	3.9	1.9	0.7	0.7	0.4	0.4	0.6
Nitrogen trifluoride	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Sulfur hexafluoride	5.8	3.3	+	+	+	+	+
Total	**32.3**	**13.2**	**5.9**	**6.2**	**5.2**	**4.9**	**5.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Table does not sum due to independent rounding.

Table 4-64: Emissions of HFCs, PFCs, SF_6, and NF_3 from Production of Fluorochemicals Other Than HCFC-22 (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	540	140	100	89	71	56	77
HFC-125	43	600	130	130	120	110	105
HFC-143a	30	160	160	120	63	49	57
HFC-134a	37	340	200	220	180	180	190
1H,4H-Perfluorobutane	0	0	0	1.2	0.60	1.2	53
1H,6H-Perfluorohexane	0	0	0	0.92	0.47	0.90	41
Other HFCs	500	400	270	260	230	250	270
Perfluorocyclobutane	1,200	70	130	150	120	130	140
PFC-14 (Perfluoromethane)	360	210	150	130	140	140	160
Other PFCs	420	210	71	77	41	49	59
Nitrogen trifluoride	18	37	6.7	35	45	31	31
Sulfur hexafluoride	250	140	0.15	0.17	0.24	0.21	0.10
Total HFCs, PFCs, SF_6, and NF_3	**3,400**	**2,300**	**1,200**	**1,200**	**1,000**	**1,000**	**1,200**

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-65: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
Octafluorotetrahydrofuran	2.4	1.9	+	0.1	+	+	+
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	+	+	+	+	+	+	+
Trifluoromethyl sulphur pentafluoride	1.2	0.9	+	0.1	+	+	+
Hexafluoropropylene oxide	0.3	0.3	0.3	0.3	+	+	+
FC-3283/FC-8270 (Perfluorotripropylamine)	+	+	+	+	+	+	+
Others	0.8	0.5	0.1	0.1	0.1	+	+
Total Other Fluorinated GHGs	**4.7**	**3.7**	**0.6**	**0.6**	**0.1**	**0.1**	**0.1**

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-66: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
Octafluorotetrahydrofuran	170	140	4	4	2	1	2
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	6	4	5	6	3	6	3
Trifluoromethyl sulphur pentafluoride	66	53	3	4	1	1	1
Hexafluoropropylene oxide	34	34	32	32	2	2	2

FC-3283/FC-8270 (Perfluorotripropylamine)	+	+	+	+	1	1	1
Others	170	120	76	84	35	33	35
Total Other Fluorinated GHGs	450	350	120	130	43	43	45

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-67: Production and Transformation of Fluorinated GHGs (kt)[a]

Set of Facilities	1990	2005	2018	2019	2020	2021	2022
Facilities reporting their F-GHG emissions, production, and transformation to GHGRP after 2010[b]	86	271	376	371	352	348	370
Facilities reporting only their F-GHG production and transformation to GHGRP after 2010	3.3	3.3	11.2	9.7	8.2	7.5	11.2
Total Production and Transformation	89	274	387	381	360	356	381

[a] Totals are presented across species to protect confidential business information.

[b] Includes 1 facility that reported production, but not emissions, of SF_6 through 2010.

Note: Tables may not sum due to independent rounding.

Methodology

The *2006 IPCC Guidelines* as elaborated by the 2019 Refinement include Tier 1, Tier 2, and Tier 3 methods for estimating fluorinated GHG emissions from production of fluorinated compounds. The Tier 1 method calculates emissions by multiplying a default emission factor by total production. Specific default emission factors exist for production of SF_6 and NF_3; a more general default emission factor covers production of all other fluorinated GHGs. (The more general default emission factor was developed based on data from U.S. facilities collected under the GHGRP between 2011 and 2016.) The Tier 2 method calculates emissions using a mass-balance approach. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of fluorinated GHGs emitted from process vents, leaks, container venting, and other sources, considering any abatement technology. The Tier 3 method is often implemented by developing and applying facility-specific emission factors indexed to production.

Based on available data on emissions and activity, EPA used a form of the IPCC Tier 3 method to estimate fluorinated GHG emissions from most U.S. production of fluorinated compounds. Emissions from U.S. production for which there are fewer data are based on the Tier 1 method.

Overview of GHGRP Data for this Source Category

As discussed further below, much of the data used to develop the estimates presented here come from the GHGRP. The data were collected under two sections of the GHGRP regulation—Subpart L, Fluorinated Gas Production; and Subpart OO, Suppliers of Industrial Greenhouse Gases. Under Subpart L, certain fluorinated gas production facilities must report their emissions from a range of processes and sources, detailed further below. Data collected under Subpart L include emissions data for calendar years 2011 through 2022. Under Subpart OO, fluorinated GHG suppliers (including fluorinated GHG producers) must report the quantities of each fluorinated GHG that they produce, transform, destroy, import, or export. Data collected under Subpart OO include production and transformation data for calendar years 2010 through 2022. Facilities' production and transformation data are not shown here because they are considered confidential business information under the GHGRP.

Emissions Reported Under Subpart L of the GHGRP

Under Subpart L, facilities that produce a fluorinated gas must report their greenhouse gas emissions if the facility emits 25,000 MT CO_2 Eq. or more per year in combined emissions from fluorinated gas production, stationary fuel combustion units, miscellaneous uses of carbonate, and all other applicable source categories listed in the rule. (For purposes of calculating emissions from fluorinated gas production for inclusion in the total that is compared to the threshold, emissions are assumed to be uncontrolled.) Facilities must report their fluorinated GHG emissions from the production and transformation of fluorinated gases, from venting of residual fluorinated GHGs from containers, and from destruction of previously produced fluorinated GHGs. The emissions reported from production and transformation include both emissions from process vents and emissions from equipment leaks.

Under the GHGRP, "fluorinated GHGs," whose emissions must be reported, include SF_6, NF_3, and any fluorocarbon except for substances with vapor pressures below 1 Torr at 25 degrees C and substances that are regulated as "controlled substances" under EPA's ozone-protection regulations at 40 CFR Part 82, Subpart A (e.g., chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and halons). In addition to SF_6 and NF_3, this definition includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrofluoroethers (HFEs), fully fluorinated tertiary amines, perfluoropolyethers (including PFPMIE), and hydrofluoropolyethers, and others. "Fluorinated gases," from whose production or transformation emissions must be reported, include the fluorinated GHGs detailed above as well as CFCs and HCFCs.[57]

Facilities calculate emissions from process vents using one of two methods. For vents that emit 10,000 MT CO_2 Eq. or more (considering controls) of fluorinated GHGs from continuous processes, facilities must use emissions testing to establish an emission factor at least every ten years, or sooner if the process changes in a way that will significantly affect emissions from the vent. For other process vents, facilities may use measurements, engineering calculations, or engineering assessments to establish the emission factor. Facilities then calculate their annual emissions based on the measured or calculated emission factor and related activity data, considering the extent to which the process is controlled and any destruction device or process malfunctions.

To calculate emissions from equipment leaks, facilities that report under Subpart L are required to collect information on the number and type of pieces of equipment; service of each piece of equipment; concentration of each fluorinated GHG in the stream; and the time period each piece of equipment was in service. Facilities use one or more of the following methods to calculate emissions from equipment leaks (EPA 1995):

- Average Emission Factor Approach in EPA Protocol for Equipment Leak Estimates.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with EPA Method 21.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with site-specific leak detection methods.
- Site-specific leak detection methods.

Most emissions are reported by chemical; the exceptions are (1) fluorinated GHGs that are emitted in quantities of 1,000 MT CO_2 Eq. or less across all production and transformation processes at a facility and (2) fluorinated GHGs that are emitted from facilities that produce only one fluorinated GHG, where the emitted fluorinated GHG is not the fluorinated gas produced. In these cases, the emissions are reported in CO_2 Eq. by fluorinated GHG group. There are 12 fluorinated GHG groups, each of which encompasses a set of GHGs with roughly similar atmospheric behavior, including similar GWPs and atmospheric lifetimes. These include, e.g., fully fluorinated GHGs such as PFCs and SF_6, saturated HFCs with two or fewer hydrogen-carbon bonds, saturated HFCs with more than two carbon-hydrogen bonds, unsaturated HFCs and PFCs, and others (see Table 4-68 for a full list).

[57] HCFC-22 is considered a fluorinated gas under the GHGRP, but emissions from HCFC-22 production are reported separately from emissions from production of other fluorinated gases.

Table 4-68: Fluorinated GHG Groups Under Which Certain Emissions Are Reported Under Subpart L of the GHGRP and Associated GWPs

Fluorinated GHG Group	GHGRP Default Global Warming Potential (100-yr.)
Fully fluorinated GHGs	10,000
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	3,700
Saturated HFCs with 3 or more carbon-hydrogen bonds	930
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	5,700
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	2,600
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	270
Fluorinated formates	350
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	30
Unsaturated PFCs, unsaturated HFCs, unsaturated HCFCs, unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	1
Fluorotelomer alcohols	1
Fluorinated GHGs with carbon-iodine bond(s)	1
Other fluorinated GHGs	2,000

Two other datasets reported under Subpart L are relevant to estimating uncontrolled emission factors. (As discussed further below, such uncontrolled emission factors are applied to years before Subpart L reporting began (for CY 2011) and before emission controls were put into place.) First, in addition to reporting emissions by chemical at the facility level, facilities report emissions from each production and transformation process at the facility in tons of CO_2 Eq. by fluorinated GHG group. To calculate CO_2 Eq. emissions, facilities use a chemical-specific 100-year GWP where one is available for the compound of interest. If no chemical-specific 100-year GWP is available for the compound of interest, facilities use the GHGRP default GWP for the fluorinated GHG group of which the compound is a member. These default GWPs are shown in Table 4-63.

Second, for each process, facilities also report the extent to which emissions are abated (the effective destruction efficiency or EDE) as a range. The EDE is calculated as follows:

$$EDE = 1 - \frac{CE_{PV}}{UE_{PV}}$$

where:

EDE = Effective destruction efficiency of the process

CE_{PV} = Actual GWP-weighted controlled emissions from all vents for the process, MT CO_2 Eq.

UE_{PV} = Hypothetical GWP-weighted uncontrolled emissions from all vents for the process, MT CO_2 Eq. (CE_{PV} will equal UE_{PV} if the process is not controlled, resulting in a calculated EDE of 0).

Note that the EDE is based on the extent to which emissions from process vents are controlled. Emissions from equipment leaks are not included in the EDE calculation. Table 4-69 provides the EDE ranges available for facilities to report and the arithmetic means of each range. The use of these datasets to calculate uncontrolled emission factors is discussed in more detail in the "1990-2010 Emissions Estimates" section below.

Verification of GHGRP Reports

Data reported under the GHGRP, including emissions and production, are electronically verified using range checks, internal consistency checks, and time-series consistency checks. Where the data fail a preliminary check, EPA contacts the facility to see whether there is an explanation for the issue or whether the data are indeed erroneous. In the latter case, facilities are required to correct the data. Where one or more of the anomalous data elements is not explained or corrected, the report for that facility for that year is considered unverified.

1990-2010 Emissions Estimates

For 14 of the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions are estimated using (1) facility- and chemical-specific emission factors based on the emissions data discussed under "2011-2022 Emissions" below, (2) reported or estimated production and transformation of fluorinated GHGs at each facility in each year, i.e., activity data, and (3) reported and estimated levels of emissions control at each facility in each year. (For the other 3 fluorinated ga production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions were estimated using data submitted by the company, as explained further below.)

Facility- and Chemical-Specific Emission Factors Reflecting Emissions Controls

Facility- and chemical-specific emission factors were developed based on the 2011 to 2015 emissions reported under the GHGRP (discussed above) and the 2011 to 2015 production and transformation of fluorinated GHGs reported under the GHGRP. (Production and transformation of CFCs and HCFCs are not reported under the GHGRP.) For each emitted fluorinated GHG at each facility, emissions of the fluorinated GHG were summed over the five-year period. This sum was then divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility over the five-year period.[58] As discussed further below in the Uncertainty section, emissions of any particular fluorinated GHG are likely to occur only from a subset of the production or transformation processes at each facility, but in the absence of information on chemical-specific emissions at the process level, it was assumed that all fluorinated GHG production and transformation processes at the facility emit all fluorinated GHGs at the facility. This yielded the emission factors for each fluorinated GHG at each facility. Both emissions and activity (production + transformation) totals were summed over the five-year period to account for the intermittent and variable nature of some emissions and production/transformation processes. Compounds that were not emitted or produced/transformed between 2011 and 2015 but that were emitted or produced/transformed later were assumed not to have been emitted or produced/transformed (as applicable) before 2011.

Facility- and Chemical-Specific Emission Factors Reflecting No Emissions Controls

The 2011 to 2015 emissions reported under the GHGRP reflect emissions controls to the extent those are implemented at each facility. Because facilities have not always controlled their fluorinated GHG emissions since 1990, uncontrolled emission factors were developed for each facility to apply to years when the facility's emissions were not believed to be controlled. To estimate uncontrolled emissions, GHGRP data were first used to assess the 2011 to 2015 levels of control for each production or transformation process at each facility.

To calculate uncontrolled emissions from each process and fluorinated GHG group, a point estimate of the effective destruction efficiency (EDE, described above) was required and was estimated using the arithmetic mean

[58] Permit data for two facilities indicated that they began controlling emissions at some point between 2011 and 2015. However, the actual emissions reported by these facilities did not change substantially after the date when the permit indicated that controls were imposed. For this reason, the reported 2011 to 2015 emissions and emission factors are believed to be representative of emissions for these facilities before 2011.

of the lower and upper bounds of the EDE range reported for the process.[59] This was consistent with the approach taken in the *2019 Refinement* to develop the Tier 1 factor for fluorinated gas production facilities. The reported vented emissions for each process and fluorinated GHG group were divided by (1 - arithmetic mean EDE) to obtain the estimated uncontrolled emissions from process vents for that process and fluorinated GHG group. For each fluorinated GHG group, the controlled emissions across processes (including emissions from both vents and leaks) and the uncontrolled emissions across processes (including emissions from both vents and leaks) were then summed, and the first was divided by the second. This yielded an average level of control for each fluorinated GHG group at each facility. All fluorinated GHGs within each fluorinated GHG group at each facility were assumed to be controlled to the same level. To estimate the uncontrolled emissions of each fluorinated GHG within each group at each facility, the emissions of each fluorinated GHG were divided by the level of control estimated for its fluorinated GHG group at the facility. The same procedure was used to estimate uncontrolled emission factors as had been used to estimate controlled emission factors: the estimated uncontrolled 2011 to 2015 emissions of each fluorinated GHG were summed, and this sum was divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility from 2011 to 2015.

Table 4-69: Destruction Efficiency Range Values Used to Estimate Pre-Abatement Emissions for Production and Transformation Processes

DE ranges	Lower Bound	Upper Bound	Arithmetic Mean of Bounds
>=0% to <75%	0.0	0.75	0.375
>=75% to <95%	0.75	0.95	0.85
>=95% to <99%	0.95	0.99	0.97
>=99%	0.99	0.9999	0.995

Estimated Levels of Emissions Controls

As discussed above, both uncontrolled emission factors and controlled emission factors were developed for each facility and fluorinated GHG; these emission factors were developed for estimating emissions from production and transformation processes for years 1990 to 2010. The following information and assumptions were used to determine whether and when emissions from facilities were likely to have been controlled from 1990 to 2010. For the estimated status of emissions controls at each facility reporting under Subpart L, and, where relevant, the starting year for those controls, see Table 4-70.

- Facilities with publicly available information on the presence and use of control devices were assumed to control their emissions starting in the year specified in the publicly available information. Publicly available information included operating permits, news articles on facility modifications, company press releases, etc. Where the publicly available information documents that a control device was in place beginning in a certain year, the facility was assumed to control process emissions beginning in that year, and the controlled emission factor was used in estimating emissions for that year and the following years. The uncontrolled emission factor was used to estimate emissions in earlier years.
- In the absence of other control information, facilities that never reported DRE ranges other than ">=0% to <75%" for their production and transformation processes during reporting years 2011 and 2012 were assumed to have no control devices in place during the time period 1990 to 2012.
- Facilities that reported DRE ranges other than ">=0% to <75%" for at least one production or transformation process for 2011 or 2012 but for which other control information was not available were assumed to have begun controlling their emissions in 2005.

[59] Note that facilities would report a range of 0% to 75% even if they do not abate emissions at all; thus, the assumption that emissions are 37.5 percent controlled may overestimate the hypothetical uncontrolled emissions of some facilities, e.g., those that do not abate any emissions.

Table 4-70: Estimated Starting Years for Emission Controls at Each Fluorinated Gas Production Facility Reporting under Subpart L of the GHGRP

Facility Name	Estimated Start Year	Basis of Estimation
3M COMPANY	No controls	Never reported a DRE range other than ">=0% to <75%"
3M CORDOVA	2003	Climate News Article[60]
3M Cottage Grove Center - Site	2016	Reported a DRE range other than ">=0% to <75%" for the first time in 2016
Airgas Therapeutics LLC - Scott Medical Products	No controls	Never reported a DRE range other than ">=0% to <75%"
ANDERSON DEVELOPMENT COMPANY	No controls	Never reported a DRE range other than ">=0% to <75%"
ARKEMA, INC.	2005	Reported a DRE range other than ">=0% to <75%" in 2011
Chemours - Corpus Christi Plant	No controls	Never reported a DRE range other than ">=0% to <75%"
CHEMOURS CHAMBERS WORKS	2005	Reported a DRE range other than ">=0% to <75%" in 2011
CHEMOURS COMPANY - FAYETTEVILLE WORKS	2015	Reported a DRE range other than ">=0% to <75%" for the first time in 2015
CHEMOURS EL DORADO	2005	Reported a DRE range other than ">=0% to <75%" in 2011
CHEMOURS LOUISVILLE WORKS	No controls	Never reported a DRE range other than ">=0% to <75%"
CHEMOURS WASHINGTON WORKS	2005	Reported a DRE range other than ">=0% to <75%" in 2011
DAIKIN AMERICA INC.	1993	Title V operating permit[61]
HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	2012	Title V operating permit[62]
HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	2011	Title V operating permit[63]
Honeywell Metropolis	No controls	Never reported a DRE range other than ">=0% to <75%" (did not report under Subpart L)
MEXICHEM FLUOR INC.	1993	Title V operating permit[64]
Versum Materials US, LLC	No controls	Never reported a DRE range other than ">=0% to <75%"

Activity Data

The activity data for production and transformation of fluorinated compounds for 1990 to 2010 are based on production and transformation data reported to EPA by certain facilities for certain years, on production capacity data, and on fluorinated GHG production and consumption trends estimated for the various fluorinated GHG-consuming industries.

Production and Production Capacity Data

Production data are available from reporting to the U.S. GHGRP under Subpart OO, Suppliers of Industrial Greenhouse Gases, and from an industry survey conducted by U.S. EPA in 2008 and 2009. Production and transformation data were reported under Subpart OO for 2010 and later years. The responses to the industry survey included production data for certain fluorinated gases at certain facilities for the years 2004, 2005, and

[60] See https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/.

[61] Daikin (2013) http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0.

[62] Honeywell (2011) https://edms.deq.louisiana.gov/app/doc/view?doc=8579001.

[63] Honeywell (2012) https://edms.deq.louisiana.gov/app/doc/view?doc=7812895.

[64] See https://edms.deq.louisiana.gov/app/doc/view?doc=1309650.

2006. 2004 to 2006 production data are available for 15 fluorinated compounds. Year 2006 production at an SF_6-producing facility was estimated based on production capacity data as described below (Rand 2007). Production of certain compounds at one other facility was estimated based on 2003 production capacity estimates from SRI 2004.

Estimated Production

Estimated production for facilities and fluorinated GHGs for which production or production capacity data were available for some years before 2010.

For facilities and fluorinated GHGs for which production or production capacity data were available for 2006 or 2003, production between 2006 or 2003 (as applicable) and 2010 (or 2011) was estimated by interpolating between the 2006 production or 2003 production capacity value and the 2010 (or 2011) production value reported under Subpart OO.

For the years before the earliest year with production or production capacity data (e.g., years 1990 to 2002 or 2003), production was estimated based on growth or consumption trends for the major industries using each fluorinated GHG.

- For fluorinated compounds that are commonly emitted in the semiconductor industry, estimates of U.S. layer-weighted semiconductor production (Total Manufactured Layer Area, or TMLA) were used to inform the fluorinated compound production estimates (EPA 2023c). Fluorinated compound production values were assumed to vary with TMLA from 1990 to 2002 or 2003. For example, 1998 production of PFC-14 at a particular facility was estimated by multiplying the 2003 production of PFC-14 at that facility by the ratio between the TMLA estimated for 1998 and the TMLA estimated for 2003. Fluorinated compounds for which TMLA was used to estimate production include PFC-14, PFC-116, PFC-218, perfluorocyclobutane (c-C_4F_8), and NF_3. (Note that the TMLA data were also extrapolated from year 1995 to 1990 based on the average change per year from 1995 to 2009.)

- SF_6 is commonly used in electric power systems, magnesium production, and electronics manufacturing. SF_6 consumption estimates across these three industries for 1990 to 2003 were used to inform the SF_6 production data (EPA 2023d); SF_6 production was assumed to vary with consumption totals from 1990 to 2003.

- For HFCs commonly used as replacements for ozone-depleting substances (ODS), such as HFCs used as substitutes for CFCs and HCFCs in air-conditioning and refrigeration equipment, HFC production data for certain fluorinated compounds from the Vintaging Model (VM) were used to inform the HFC production estimates (EPA 2023b). HFC production values were assumed to vary with the VM estimates of production. The industry trend data were applied to the list of HFCs in Table 4-71.

Table 4-71: List of Saturated HFCs, Unsaturated HFCs (Hydrofluoroolefins or HFOs), and Unsaturated HCFCs (Hydrochlorofluoroolefins or HCFOs) whose 1990-2009 Production Was Estimated Using Vintaging Model, Virgin Manufacturing by Chemical

Fluorinated Gas
HFC-23
HFC-32
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-236fa
HFC-245fa
HFC-365mfc
HCFO-1233zd(E)
HFO-1234yf
HFO-1234ze
HFO-1336mzz(Z)
HFC-4310mee

Estimated production for facilities and fluorinated GHGs for which production data before 2010 were not available.

In the absence of production data for the period 1990 to 2009, the production data reported to the GHGRP under Subpart OO were extrapolated backward based on the industry trends discussed above. For compounds for which industry trend data were unavailable, production was assumed to have remained constant over the time series.

In both cases, 2009 production was estimated by conducting a trend analysis on the Subpart OO production data for years 2010 to 2015. In instances where there did not appear to be a trend, the average of the production values for years 2010 to 2015 was used as the estimated production for year 2009. In instances where there was a trend, the year 2010 (or 2011) production value was used as the estimated production for year 2009.

If the industry trend information discussed above was applicable to a fluorinated compound, it was assumed that production varied with the industry trend from 1990 to 2009. If no industry trend information was available, it was assumed that production from 1990 to 2008 remained constant at the 2009 value.

For facilities and fluorinated compounds where information was available on annual production capacity, the estimated activity data was reviewed and compared to the known production capacity. For instances where the estimated activity data exceeded known production capacity for a certain year, the production estimate was set equal to the capacity value. In addition, where information was available on the starting year for production of a fluorinated GHG at a facility, production was only estimated beginning in the process startup year through 2009.

Estimated Emissions for 3M Facilities

3M provided 1990, 1995, 2000, and 2002 through 2010 emissions data for three facilities: 3M Cordova, 3M Company, and 3M Cottage Grove Center - Site.[65] Therefore, speciated 1990-2010 emissions at these facilities were estimated using a different methodology than that described above.[66]

[65] For 1990, 1995, and 2000, 3M provided emissions data for a Pilot Development Center in addition to the other three facilities. Emissions by group from the Pilot Development Center were added to and are represented by the emissions by group for 3M Cottage Grove Center – Site.

[66] 3M's methods for estimating its emissions are described in detail in "3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions," February 2024 (3M, 2024). In brief, 3M estimated emissions from its processes using

3M emissions data were provided by facility and by fluorinated GHG group in metric tons of CO_2 Eq., weighted by 100-year GWPs from various IPCC Assessment Reports. The fluorinated GHG groups included HFCs, PFCs, SF_6, HFEs, and other fluorinated GHGs. (3M noted that the "other fluorinated GHG" category included NF_3.) GWPs from the IPCC *Third Assessment Report* (TAR) were used to report totals for 1990, 1995, 2000, and 2003 to 2006. GWPs from the IPCC *Fifth Assessment Report* (AR5) was used to report totals for 2002, and GWPs from the IPCC *Fourth Assessment Report* (AR4) were used to report totals for 2007 to 2010. The emissions were also categorized as emissions from electrochemical fluorination (ECF) processes and downstream (DS) emissions. The DS emissions for 1990, 1995, and 2000 were reported as a total for each facility rather than by fluorinated GHG group.

To present emissions estimates by compound, EPA needed to disaggregate the data provided by 3M. The first step was to disaggregate the 1990, 1995, and 2000 DS emissions into fluorinated GHG groups. Since the 2003 to 2006 data were calculated using the same set of GWPs as the 1990, 1995, and 2000 data, the DS emissions of each group at each facility for 2003 to 2006 were divided by the total DS 2003 to 2006 emissions at that facility to obtain a set of fractions. These fractions were then multiplied by the 1990, 1995, and 2000 DS totals to sort those emissions into groups.

For 2002, ECF and DS emissions were only reported under the PFC group. (3M noted that chemical classifications were not preserved when 2002 emissions were recalculated using GWP values from AR5.) Since data for every other year showed emissions reported from multiple fluorinated GHG groups, and since 2004 was the closest year with emissions well sorted into fluorinated GHG groups, the ECF and DS emissions for 2002 were separated into multiple fluorinated GHG groups using the 2004 ECF and DS groups shares for each facility.

The next step was to disaggregate the emissions of each fluorinated GHG group into emissions of the relevant compounds in that group. To accomplish this, EPA assumed that emissions of each fluorinated GHG group before 2011 consisted of the same fluorinated GHGs, in the same proportions, as from 2011 through 2015. However, each compound's share of the GWP-weighted emissions of the group in a given year depends on the GWPs used for that compound and for the other compounds in the group in that year. To account for this, EPA multiplied the reported 2011 to 2015 emissions of each compound in metric tons by the corresponding GWPs for that compound from the TAR, AR4, and AR5 to generate three sets of emissions by compound in metric tons of CO_2 Eq. For each set, the sum of emissions across 2011 to 2015 for each compound were divided by the total emissions for the corresponding fluorinated GHG group for those five years to calculate shares for each group.

The 3M emissions data by group for 1990, 1995, 2000, and 2002 to 2010 were then speciated by compound using the appropriate set of share values for each year. Since 3M Company only reported emissions of one compound in 2011 to 2015 but had emissions from multiple fluorinated GHG groups in 1990, 1995, 2000, and 2002 to 2010, the share values for 3M Cordova were used to speciate the 1990, 1995, 2000, and 2002-2010 emissions by group for 3M COMPANY. The speciated emissions in metric tons of CO_2 Eq. by compound for each facility were then divided by the appropriate TAR, AR4, or AR5 GWP for each compound to obtain the estimated emissions in metric tons of each compound for 1990, 1995, 2000, and 2002 to 2010.

Linear interpolation was then used to estimate emissions for 1991 to 1994, 1996 to 1999, and 2001 for each compound for these three facilities.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

There is a subset of facilities that report production and transformation of fluorinated gases under Subpart OO and that also have emission levels less than the threshold value for reporting under Subpart L (i.e., uncontrolled emissions below the 25,000-MT CO_2 Eq. threshold). For these facilities, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the

emission factors that were developed using methods similar to those used for developing emission factors under the GHGRP. As under the GHGRP, emission factors were multiplied by different types of activity data (e.g., production) to estimate emissions for each facility and year. In 2003 and later years, 3M also accounted for emission reductions attributable to operation of the thermal oxidizer at the Cordova plant.

specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table. Emissions are assumed to have been flat at the 2010 value in the years before 2010.

Estimated Emissions for SF_6 Production Facility

For an SF_6 production facility that ceased production in 2010, the year before emissions from fluorinated gas production were required to be reported under the GHGRP, SF_6 emissions were estimated using historical production capacity, the global growth rate of SF_6 sales reported in RAND 2007, and the Tier 1 default emission factor for production of SF_6 in the 2019 Refinement. For this plant, a 1982 SF_6 production capacity of 1,200 short tons (Perkins 1982) was multiplied by the ratio between the RAND survey SF_6 sales totals for 2006 and 1982, 1.52 (RAND 2007), resulting in estimated production of 1,652 metric tons in 2006. This production was assumed to have declined linearly to zero in 2011.

2011-2022 Emissions Estimates

For the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 2011 to 2022 emissions are estimated using the fluorinated GHG emissions reported under Subpart L of the GHGRP.

As discussed above, most emissions reported under Subpart L are reported by chemical, but some emissions are reported only by fluorinated GHG group in MT CO_2 Eq. Between 2011 and 2022, the share of total CO_2 Eq. emissions reported only by fluorinated GHG group has ranged between 1 and 2 percent. In this analysis, to ensure that all emissions are reported by species, emissions that are reported only by fluorinated GHG group are assumed to consist of the fluorinated GHGs in that group that are reported by chemical at the facility. As discussed further in the Uncertainty section, this is likely to result in incorrect speciation of some emissions, but the impact of this incorrect speciation is expected to be small.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

As discussed above, for facilities that produce fluorinated GHGs but that do not report their emissions under subpart L, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table.

Uncertainty

The estimates in this memo are subject to a number of uncertainties. These uncertainties are generally greater for years before 2011, when reporting of fluorinated GHG emissions from fluorinated gas production began under the GHGRP, than for 2011 and following years. However, the emissions estimated from 2011 to 2022 are also subject to various uncertainties. The uncertainties for both the 1990 to 2010 and 2011 to 2022 periods are discussed in more detail below.

1990-2010 Uncertainty

The uncertainty of emissions estimated for 1990 through 2010 is considerably greater than that for emissions for 2011 through 2022 because emissions were not reported under the GHGRP. EPA has estimated emissions using estimated emission rates, fluorochemical production and transformation activity, and levels of control, and each set of estimates is subject to uncertainty.

Uncertainty regarding activity data

Identity of emitting processes

In reality, emissions of particular fluorinated GHGs are linked to production and/or transformation of particular fluorinated gases at facilities. However, GHGRP information/data does not link emissions of specific fluorinated GHGs to production or transformation of specific fluorinated gases. For the estimates presented here, therefore, all emissions are indexed to total production across all fluorinated gases. This may not capture trends in emissions that are driven by trends in production or transformation of subsets of the fluorinated gases produced at a facility.

Produced and emitted gases change over time

The set of gases produced at a facility, and therefore the set of fluorinated GHGs that are emitted by that facility, may change over time. It is likely that certain production and transformation processes that existed from 2011 to 2015 (the basis of the emission factors used to back-cast emissions in this analysis) did not exist throughout the entire previous time series (1990 to 2010). In such cases, emissions of the fluorinated GHGs emitted from the new processes will be overestimated by this analysis for certain years before 2011. On the other hand, it is also likely that some production and transformation processes, and their associated fluorinated GHG emissions, occurred only during the 1990 to 2010 period and not later, meaning that their emissions are not represented in the emission factors developed based on the 2011 to 2015 emissions and production data collected under the GHGRP. Such emissions will therefore not be captured by this analysis. The most prominent example of the second situation is probably production of CFCs and HCFCs other than HCFC-22 between 1990 and 2009, which has declined steadily since 1990 as the production of CFCs and HCFCs for emissive uses has been phased out under the Montreal Protocol and Clean Air Act. Production of CFCs and HCFCs can sometimes result in emissions of HFCs or PFCs.

Quantity of produced gases

Where production or production capacity data were available for certain fluorinated gases, facilities, and years before 2010, those data were incorporated into this analysis. However, even for facilities and compounds for which data were available in certain years, there were several years for which data were not available. For multiple produced compounds, data were available only in 2010. To estimate trends in production of compounds for years before production or production capacity data were available, production of certain compounds was indexed to known national production or consumption trends for those compounds. This is the case for most HFCs, several PFCs, SF_6, and NF_3. National production estimates are available for HFCs, increasing confidence in country-level production estimates, but the distribution of production among the various HFC-producing facilities is uncertain. Where estimated production was indexed to consumption (for several PFCs, SF_6, and NF_3), the uncertainty is larger than for HFCs because changes in net imports/exports (which are not known) may also affect the production trend.

For certain fluorinated gases, trend information was not available; therefore, production was back-cast by assuming that it had remained constant at the 2010 level from 1990 through 2009. This is a highly uncertain assumption.

Some production and transformation activity is not reported under Subpart OO or modeled in back-casting

Under Subpart OO, quantities of fluorinated GHGs that are produced and transformed at the same facility are not reported to us, although any emissions from such processes are reported under Subpart L. Such unreported production and transformation are therefore not captured in the 1990 to 2010 activity estimates used to estimate 1990 through 2010 emissions. To the extent that such unreported production and transformation drive emissions and change over time, the trends will not be captured by this analysis.

Facilities that no longer produce fluorinated gases or that started producing them after 1990

Some facilities may have produced fluorinated gases at some point between 1990 and 2010 that no longer produced those compounds after 2010. One SF_6 producer is known to fall into this category and its 1990 to 2010 emissions were estimated, but there may be other facilities that are not included in this analysis. On the other hand, some facilities for which 1990 to 2010 emissions were estimated may not have produced them over the

entire time series, in which case emissions of the compounds those facilities are assumed to have emitted could be overestimated.

Uncertainty regarding emission factors

Emission rates change over time

The emission factors used to estimate 1990 to 2010 emissions are based on the emissions and production reported from 2011 to 2015, reflecting emission rates during that period. For processes that have been used throughout the timeseries, emission rates may have changed over time as the process was optimized to increase efficiency, decreasing by-product emissions, or alternatively, as the process was optimized to maximize production, which sometimes increases by-product emissions. Emission rates also depend on the extent to which emissions are controlled at the facility, the uncertainties for which are discussed further below.

Emissions from container venting and destruction may not scale with production

In this analysis, emissions from container venting and destruction of previously produced fluorinated GHGs were included in the emission factors used to estimate 1990 to 2010 emissions. This implicitly assumes that such emissions scale with production and transformation. While this seems likely to be broadly true, there may be exceptions. However, since emissions from container venting and destruction are generally a small share of facility emissions (2 percent, on average), the impact of such exceptions is expected to be small.

Uncertainty regarding levels of control

In this analysis, the arithmetic mean of the DRE range reported by each facility for each process was used to estimate the DRE for that process and the uncontrolled emissions for that process. Since the emissions implied by the bounds of each DRE range span at least a factor of four,[67] this is an uncertain assumption. The uncertainty is mitigated somewhat by the fact that there are generally several processes at each facility, meaning that departures from the assumed mean average out to some extent. There is also uncertainty in the assumptions that (1) all fluorinated GHGS within a particular fluorinated GHG group are abated to the same extent and (2) facilities for which control device start dates are unavailable began to control emissions in 2005.

Quantitative uncertainty estimate for uncontrolled emission factors from *2019 Refinement*

As noted above, 2011 to 2016 data from the GHGRP was used to develop the Tier 1 default uncontrolled emission factor for the *2019 Refinement*, using methods similar to those described here. A Monte Carlo analysis performed to assess the uncertainty of the Tier 1 default factor indicated that the uncertainty for each facility's uncontrolled emission factor was less than 50 percent. This uncertainty estimate considered the uncertainty regarding the levels of control, but not the uncertainty of applying factors from one time period at the facility to much earlier time period (although the variability of each facility's emission factor over the 6-year span of the *2019 Refinement* analysis was found to be relatively low).

Uncertainty regarding the identity of 3M emitted compounds

For the three 3M facilities that submitted their 1990 through 2010 emissions by fluorinated GHG group, it is assumed that the emissions of each group consist of the compounds in that group that were reported by species by the facility from 2011 through 2014. However, 3M indicated that the mix of products made at its facilities had changed over time, which would have affected the identities of the fluorinated GHGs emitted. For example, at one facility, only one compound was reported to be emitted for 2011-2015 but 3M's historical emissions data showed multiple fluorinated GHG groups for that facility for 1990 to 2010. For that facility, it is assumed that emissions consisted of the compounds in each gas type that were reported by species by the 3M facility that was determined to be the most similar. Additionally, there were a few years of data for these three facilities where some emissions were reported as a total rather than separated by group. For these years, the group shares were assumed to be

[67] For example, the DRE range 0 to 75% implies emissions of (1-0) x uncontrolled emissions to (1-75%) x uncontrolled emissions, or, rearranging and calculating, 0.25 x uncontrolled emissions to 1 x uncontrolled emissions, a factor of four.

the same as in nearby years. There is uncertainty involved with each of the assumptions made while speciating emissions for these three facilities, though the uncertainty is minimal regarding total emissions in metric tons of CO_2 Eq. In at least one case, the speciation method appears to have resulted in an overestimate for an individual compound. In this analysis, 3M's emissions of C_4F_8O are estimated to have peaked at around 410 MT in 2000, but at least one study has inferred considerably lower global emissions (around 120 MT) for that year based on atmospheric measurements of C_4F_8O (Vollmer et al. 2019).

2011-2022 Uncertainty

Emissions from 2011 to 2022 reflect reporting by fluorinated gas production facilities under the GHGRP. As discussed above, emissions reported under the GHGRP are based on facility- and process-specific measurements or calculations and are therefore expected to be reasonably accurate for the reporting facilities. (Emissions from the largest sources, process vents emitting 10,000 MT CO_2 Eq. or more annually, are estimated using Tier 3 methods.)

Unverified reports

Ninety-five percent (171/180) of the Subpart L reports submitted by fluorinated gas production facilities from 2011 to 2022 are considered to be fully verified; five percent (9/180) of the reports include one or more data elements that are not verified. One facility accounts for two thirds (6/9) of the unverified reports. Many of the issues in the unverified reports for this facility relate to time-series inconsistencies that have arisen as the facility updates reports for recent years, but not previous years, to reflect refinements to estimated emission rates. This facility has accounted for between 6 percent (in 2011) and 29 percent (in 2022) of the GWP-weighted emissions reported for this source category. The uncertainties for this facility therefore have an appreciable impact on the uncertainty of the estimates for the source category as a whole, particularly in years before 2022.

Facilities that do not produce fluorinated gases but may emit fluorinated GHGs from other fluorochemical production processes

Under the GHGRP, EPA collects information from facilities that produce fluorinated gases. While this likely includes most, and possibly all, U.S. facilities that produce fluorochemicals of any kind, it is possible that some fluorochemical producers do not report either their production of fluorochemicals or their emissions of fluorinated GHGs to EPA under the GHGRP. In this case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

At fluorinated gas production facilities that currently report their emissions under the GHGRP, it is possible that some processes that emit fluorinated GHGs neither produce nor transform a fluorinated gas, in which case their emissions would not be reported under the GHGRP. In that case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

Exclusion of nitrous oxide

The GHGRP does not currently require facilities to report emissions of nitrous oxide (N_2O) from fluorinated gas production or transformation, but the IPCC *2019 Refinement* includes a default emission factor for N_2O from production of NF_3, implying such emissions may occur. The GHGRP data (and this analysis) may therefore underestimate emissions of N_2O from fluorinated gas production. Because the GWP of N_2O is considerably lower than that of saturated HFCs, PFCs, and other fluorinated GHGs, any underestimate is expected to be relatively small.

Identity of emitted compounds

In this analysis, it is assumed that emissions that are reported only in MT CO_2 Eq. by fluorinated GHG group consist of the compounds in that group that are reported by species by the facility. However, if that were actually the case, emissions of those compounds would have been included in the speciated emissions rather than reported separately in MT CO_2 Eq. This analysis therefore incorrectly speciates some emissions. As noted in the Methodology section, the share of total CO_2 Eq. emissions reported only by fluorinated GHG group is small, ranging

between 1 and 2 percent. Moreover, while the emissions are not assigned to the exact species emitted, they are assigned to a species that is closely related and likely to have similar atmospheric impacts (e.g., another saturated HFC with two or fewer carbon-hydrogen bonds). The impact of this uncertainty is therefore limited.

Quantities of Reactants Consumed or Fluorinated Gases Produced

The emissions reported under Subpart L are required to be calculated using process activity data, such as the quantity of reactants consumed or the quantity of the fluorinated gas product produced. In general, the uncertainties in process activity levels are expected to be small. The *2019 Refinement* places such uncertainties "in the region of 1 percent."

Because the uncertainties enumerated above are either small or difficult to quantify, EPA did not attempt to include them in the 2022 quantitative uncertainty estimate for this source category. The 2022 quantitative uncertainty estimate includes the following uncertainties:

Process Vent Emission Factors

Process vent emission factors that were developed based on stack testing (for continuous process vents emitting 10,000 MT CO_2 Eq. or more) were estimated to have an uncertainty (95-percent confidence interval) of ±35 percent based on Subpart L requirements.[68] Process vent emission factors that were developed based on calculations (for batch process vents and for continuous process vents emitting less than 10,000 MT CO_2 Eq.) were estimated to have a larger uncertainty of ±50 percent. Continuous processes were assumed to have two vents per process; batch processes were assumed to have five vents per process.[69]

Equipment Leak Estimates

The estimated equipment leaks reported by each facility for each process were estimated to have an uncertainty of ± 90 percent. The uncertainty of leak estimates depends on the method used to estimate leaks; there are multiple methods. For simplicity, this analysis uses a conservatively high uncertainty estimate that is appropriate for the Average EF Approach.

Venting of Residual Gas in Containers

The reported emissions of fluorinated GHGs from venting of residual gas in returned containers were estimated to have an uncertainty of ± 30 percent for each facility. This estimate is based on the Subpart L requirement to either measure the contents of each container or to measure the contents of at least 30 representative containers for each compound and container size and type.

Facilities that produce fluorinated gases but do not report their emissions to the GHGRP

EPA estimated emissions for fluorinated gas production facilities that do not report their emissions under Subpart L of the GHGRP. The estimates presented here for 2011 to 2022 are based on aggregated production estimates, the Tier 1 default emission factor in the *2019 Refinement*, and the default fluorinated GHG speciation from Table 3.28b (chapter 3.10.2 of *2019 Refinement*). There is considerable uncertainty in both the magnitude of the emissions and the identity of the emitted compounds. The *2019 Refinement* estimates the uncertainty of the Tier 1 emission factor as -98 percent to +470 percent. (In the quantitative uncertainty estimate below, which is based on error propagation, values of ±98 percent were used because error propagation requires the assumption of symmetric uncertainty bounds.) In 2022, estimated emissions from the six non-reporting facilities accounted for 44 percent of total estimated U.S. emissions from fluorinated gas production and transformation. In contrast,

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[68] *Technical Support Document for Emissions from Production of Fluorinated Gases*, Office of Air and Radiation, U.S. Environmental Protection Agency, November 5, 2010. Available online at: https://www.epa.gov/sites/default/files/2015-02/documents/subpart-l_techsuppdoc.pdf.

[69] *Economic Impact Analysis for the Mandatory Reporting of Greenhouse Gas Emissions F-Gases: Subparts I, L, DD, QQ, SS*, U.S. Environmental Protection Agency, November 2010. Available online at: https://www.regulations.gov/document/EPA-HQ-OAR-2009-0927-0179.

production and transformation by these facilities accounted for just three percent of total fluorinated GHG production and transformation across all facilities. Because the emissions estimated for several of the six facilities exceeded the 25,000 MT CO_2 Eq. reporting threshold under Subpart L, but these facilities have not reported their emissions under Subpart L, it appears likely that emissions from at least some facilities are overestimated.

The four uncertainties listed immediately above were convolved using error propagation to arrive at an overall uncertainty estimate for 2022. The results of the Approach 1 quantitative uncertainty analysis are summarized in Table 4-72. Emissions of HFCs, PFCs, SF_6, and NF_3 from production of fluorochemicals other than HCFC-22 were estimated to fall between 4.83 and 7.08 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 19 percent above the emission estimate of 5.95 MMT CO_2 Eq.

Table 4-72: Approach 1 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, and NF_3 from Production of Fluorochemicals other than HCFC-22 (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound[a]	Upper Bound[a]	Lower Bound	Upper Bound
Production of Fluorochemicals other than HCFC-22	HFCs, PFCs, SF_6, and NF_3	5.95	4.83	7.08	-19%	+19%

[a] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[70] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the Fluorinated Gas Production category. Under the GHGRP, fluorinated gas producers are required to (1) develop and periodically update process vent-specific emission factors using either measurements or engineering calculations, depending on the nature of the process (continuous vs. batch) and the magnitude of emissions from the vent, (2) take more measurements of vent emissions where variability is high, (3) use methods for sampling, measuring volumetric flow rates, non-fluorinated-GHG gas analysis, and measuring stack gas moisture that have been validated using a scientifically sound validation protocol, (4) use a quality-assured analytical measurement technology capable of detecting the analyte of interest at the concentration of interest and use a sampling and analytical procedure validated with the analyte of interest at the concentration of interest, (5) periodically test the performance of destruction devices used to control emissions, (6) account for any malfunctions in the process or destruction device, (6) account for emissions from equipment leaks, (7) measure the quantities of residual gas that are vented from returned containers (or develop an emission factor based on at least 30 measurements per gas and container size and type), (8) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable

[70] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

standards and suitable methods published by a consensus standards organization, (9) calibrate analytical equipment used to determine the concentration of fluorinated GHGs, and (10) document all measurements and calibrations.

The 1990, 1995, 2000, and 2002 through 2010 emissions data reported by 3M for three facilities was compared to the 1990 through 2010 emissions previously calculated for those facilities using the same calculation method used for other facilities that have reported their emissions under the GHGRP since 2011. The overall trajectory of the 3M-reported emissions, as well as the minima and maxima of those emissions, were similar to those previously calculated, but the increases and decreases in the 3M-reported emissions were more gradual. 3M explained that the gradual changes were due to changes in the compounds and quantities produced and to the gradual deployment and optimization of the destruction device at the 3M Cordova facility.

Recalculations

This is a new category included for the current (i.e., 1990 to 2022) *Inventory*, thus, no recalculations were performed.

Planned Improvements

EPA is planning to refine its estimates of emissions from non-reporting facilities after confirming with the facilities that their actual per-facility uncontrolled emissions fall below 25,000 MT CO_2 Eq.. EPA is also planning to refine its estimates of emissions for other facilities between 1990 and 2009, e.g., by comparing these against emissions inferred from atmospheric measurements. Moreover, EPA is continuing to seek datasets that can be used to improve and/or QA/QC emissions estimates, particularly for the years 1990 to 2009. These datasets may include, for example, real-time facility-specific estimates or additional global "top-down," atmosphere-based emissions estimates that could be used to establish an upper limit on emissions of certain compounds.

4.16 Carbon Dioxide Consumption (CRT Source Category 2B10)

Carbon dioxide (CO_2) is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). CO_2 used for EOR is injected underground to enable additional petroleum to be produced. For the purposes of this analysis, CO_2 used in food and beverage applications is assumed to be emitted to the atmosphere. This reporting category (2B10) includes emissions from IPCC assessment reports that do not fall within any other CRT source category, which includes emissions from CO_2 consumption. A further discussion of CO_2 used in EOR is described in the Energy chapter in Box 3-6 titled "Carbon Dioxide Transport, Injection, and Geological Storage" and is not included in this section.

Carbon dioxide is produced from naturally-occurring CO_2 reservoirs, as a byproduct from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a byproduct from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component.

In 2022, the amount of CO_2 produced and captured for commercial applications and subsequently emitted to the atmosphere was 5.0 MMT CO_2 Eq. (5,000 kt) (see Table 4-73 and Table 4-74). This is less than a 1 percent increase (10 kt) from 2021 levels and is an increase of approximately 240 percent (3,528 kt) since 1990.

Table 4-73: CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0

Table 4-74: CO_2 Emissions from CO_2 Consumption (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000

Methodology and Time-Series Consistency

Carbon dioxide emission estimates for 1990 through 2022 utilize a country-specific method and were based on the quantity of CO_2 extracted and transferred for industrial applications (i.e., non-EOR end-uses). Some of the CO_2 produced by these facilities is used for EOR, and some is used in other commercial applications (e.g., chemical manufacturing, food and beverage). The IPCC does not have specific methodological guidelines for CO_2 consumption, but the country-specific methodology used is consistent with a Tier 3 approach since it relies on facility-specific information.

2010 through 2022

For 2010 through 2022, data from EPA's GHGRP (Subpart PP) were aggregated from facility-level reports to develop a national-level estimate for use in the *Inventory* (EPA 2023). Facilities report CO_2 extracted or produced from natural reservoirs and industrial sites, and CO_2 captured from energy and industrial processes and transferred to various end-use applications to EPA's GHGRP. This analysis includes only reported CO_2 transferred to food and beverage end-uses. EPA is continuing to analyze and assess integration of CO_2 transferred to other end-uses to enhance the completeness of estimates under this source category. Other end-uses include industrial applications, such as metal fabrication. EPA is analyzing the information reported to ensure that other end-use data excludes non-emissive applications and publication will not reveal CBI. Additionally, a small amount of CO_2 is used as a refrigerant; use and emissions from this application are reported under Section 4.25 Substitution of Ozone Depleting Substances (CRT Source Category 2F). Reporters subject to EPA's GHGRP Subpart PP are also required to report the quantity of CO_2 that is imported and/or exported. Currently, these data are not publicly available through the GHGRP due to data confidentiality reasons and hence are excluded from this analysis.

Facilities subject to Subpart PP of EPA's GHGRP are required to measure CO_2 extracted or produced. More details on the calculation and monitoring methods applicable to extraction and production facilities can be found under Subpart PP: Suppliers of Carbon Dioxide of the regulation, Part 98[71] The number of facilities that reported data to EPA's GHGRP Subpart PP (Suppliers of Carbon Dioxide) for 2010 through 2022 is much higher (ranging from 44 to 53) than the number of facilities included in the *Inventory* for the 1990 to 2009 time period prior to the availability of GHGRP data (4 facilities). The difference is largely due to the fact the 1990 to 2009 data includes only CO_2 transferred to end-use applications from naturally occurring CO_2 reservoirs and excludes industrial sites.

1990 through 2009

For 1990 through 2009, data from EPA's GHGRP are not available. For this time period, CO_2 production data from four naturally-occurring CO_2 reservoirs were used to estimate annual CO_2 emissions. These facilities were Jackson Dome in Mississippi, Bravo and West Bravo Domes in New Mexico, and McCallum Dome in Colorado. The facilities in Mississippi and New Mexico produced CO_2 for use in both EOR and in other commercial applications (e.g.,

[71] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

chemical manufacturing, food production). The fourth facility in Colorado (McCallum Dome) produced CO_2 for commercial applications only (New Mexico Bureau of Geology and Mineral Resources 2006).

Carbon dioxide production data and the percentage of production that was used for non-EOR applications for the Jackson Dome, Mississippi facility were obtained from Advanced Resources International (ARI 2006, 2007) for 1990 to 2000, and from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2010) for 2001 to 2009 (see Table 4-75). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2009 and reported the percentage of the total average annual production that was used for EOR. Production from 1990 to 1999 was set equal to 2000 production, due to lack of publicly available production data for 1990 through 1999. Carbon dioxide production data for the Bravo Dome and West Bravo Dome were obtained from ARI for 1990 through 2009 (ARI 1990 to 2010). Data for the West Bravo Dome facility were only available for 2009. The percentage of total production that was used for non-EOR applications for the Bravo Dome and West Bravo Dome facilities for 1990 through 2009 were obtained from New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003; New Mexico Bureau of Geology and Mineral Resources 2006). Production data for the McCallum Dome (Jackson County), Colorado facility were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) for 1999 through 2009 (COGCC 2014). Production data for 1990 to 1998 and percentage of production used for EOR were assumed to be the same as for 1999, due to lack of publicly available data.

Table 4-75: CO_2 Production (kt CO_2) and the Percent Used for Non-EOR Applications

Year	Jackson Dome, MS CO_2 Production (kt) (% Non-EOR)	Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	West Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	McCallum Dome, CO CO_2 Production (kt) (% Non-EOR)	Total CO_2 Production from Extraction and Capture Facilities (kt)	% Non-EOR[a]
1990	1,344 (100%)	63 (1%)	+	65 (100%)	NE	NE
2005	1,254 (27%)	58 (1%)	+	63 (100%)	NE	NE
2018	IE	IE	IE	IE	58,400[b]	7%
2019	IE	IE	IE	IE	61,300[b]	8%
2020	IE	IE	IE	IE	44,700[b]	11%
2021	IE	IE	IE	IE	43,980[b]	11%
2022	IE	IE	IE	IE	46,800[b]	11%

+ Does not exceed 0.5 percent.
NE (Not Estimated)
IE (Included Elsewhere)
[a] Includes only food and beverage applications.
[b] For 2010 through 2022, the publicly available GHGRP data were aggregated at the national level based on GHGRP CBI criteria. The Dome-specific CO_2 production values are accounted for (i.e., included elsewhere) in the Total CO_2 Production from Extraction and Capture Facilities values starting in 2010 and are not able to be disaggregated.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for CO_2 consumption spliced activity data from two different sources: Industry data for 1990 through 2009 and GHGRP data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap (IPCC 2006). The data sets were determined to be inconsistent; the GHGRP data include CO_2 from industrial sources while the industry data do not. No adjustments were made to the activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent.

Uncertainty

There is uncertainty associated with the data reported through EPA's GHGRP. Specifically, there is uncertainty associated with the amount of CO_2 consumed for food and beverage applications, given the GHGRP does have provisions that Subpart PP reporters are not required to report to the GHGRP if their emissions fall below certain

thresholds, in addition to the exclusion of the amount of CO_2 transferred to all other end-use categories. This latter category might include CO_2 quantities that are being used for non-EOR industrial applications such as firefighting. Second, uncertainty is associated with the exclusion of imports/exports data for CO_2 suppliers. Currently these data are not publicly available through EPA's GHGRP and hence are excluded from this analysis. EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[72] Given the lack of specific uncertainty ranges available on the data used, EPA assigned an uncertainty range of ±5 percent and a normal probability density function for CO_2 consumed for food and beverage applications. The uncertainty range is derived from the default range for solvent use in Section 5.5 of Chapter 3 of the *2006 IPCC Guidelines*. These values are representative of CO_2 used in food and beverage based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-76. Carbon dioxide consumption CO_2 emissions for 2022 were estimated to be between 4.8 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 5.0 MMT CO_2 Eq.

Table 4-76: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO_2 Consumption	CO_2	5.0	4.8	5.2	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to CO_2 Consumption can be found under Subpart PP (Suppliers of Carbon Dioxide) of the regulation (40 CFR Part 98).[73] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[74] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

[72] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[73] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[74] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

EPA will continue to evaluate the potential to include additional GHGRP data on other emissive end-uses to improve the accuracy and completeness of estimates for this source category. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[75]

These improvements are still in process and will be incorporated into future *Inventory* reports. These are near-to medium-term improvements.

4.17 Phosphoric Acid Production (CRT Source Category 2B10)

Phosphoric acid (H_3PO_4) is a basic raw material used in the production of phosphate-based fertilizers. Phosphoric acid production from natural phosphate rock is a source of carbon dioxide (CO_2) emissions, due to the chemical reaction of the inorganic carbon (calcium carbonate) component of the phosphate rock. This reporting category (2B10) includes emissions that do not fall within any other CRT source category, which includes production of phosphoric acid. Emissions from fuels consumed for energy purposes during the production of phosphoric acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Phosphate rock is mined in Florida and North Carolina, which account for more than 75 percent of total domestic output, and in Idaho and Utah (USGS 2023). It is used primarily as a raw material for wet-process phosphoric acid production. The composition of natural phosphate rock varies, depending on the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic carbon in the form of calcium carbonate (limestone) and may also contain organic carbon.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). Phosphate rock also contains naturally occurring limestone ($CaCO_3$), ranging from 0.2 to 4.5 percent (as CO_2), with domestic phosphate rock from Florida containing 3.1 percent limestone (as CO_2) (EFMA 2000). The generation of CO_2 from limestone in the phosphate rock is from the associated limestone-sulfuric acid reaction, as shown below:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

Total U.S. phosphate rock production in 2022 was an estimated 21 million metric tons (USGS 2023). Between 1990 and 2022, domestic phosphate rock production decreased by approximately 58 percent. Total imports of phosphate rock to the United States in 2022 were 2.4 million metric tons (USGS 2023). Between 2018 and 2021, most of the imported phosphate rock (95 percent) came from Peru, with 5 percent from Morocco (USGS 2023). All phosphate rock mining companies in the United States are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines.

Total CO_2 emissions from phosphoric acid production were 0.8 MMT CO_2 Eq. (840 kt CO_2) in 2022 (see Table 4-77 and Table 4-78). Domestic consumption of phosphate rock in 2022 was estimated to have decreased 3.9 percent

[75] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

relative to 2021 levels. The COVID-19 pandemic did not impact the domestic phosphate rock market as both the fertilizer industry and related agricultural businesses were considered essential industries and were unaffected by pandemic "stay-at-home" orders issued in March 2020 (USGS 2021a).

Table 4-77: CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8

Table 4-78: CO_2 Emissions from Phosphoric Acid Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840

Methodology and Time-Series Consistency

The United States uses a country-specific methodology consistent with and comparable to an IPCC Tier 1 approach to calculate emissions from production of phosphoric acid from phosphate rock based on the stoichiometry of the process reaction shown above. The *2006 IPCC Guidelines* do not provide a method for estimating process emissions (CO_2) from phosphoric acid production. Carbon dioxide emissions from production of phosphoric acid from phosphate rock are estimated by multiplying the average amount of inorganic carbon (expressed as CO_2) contained in the natural phosphate rock as calcium carbonate by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption. The estimation methodology is as follows:

Equation 4-10: CO_2 Emissions from Phosphoric Acid Production

$$E_{pa} = C_{pr} \times Q_{pr}$$

where,

E_{pa} = CO_2 emissions from phosphoric acid production, metric tons

C_{pr} = Average amount of carbon (expressed as CO_2) in natural phosphate rock, metric ton CO_2/ metric ton phosphate rock

Q_{pr} = Quantity of phosphate rock used to produce phosphoric acid

The CO_2 emissions calculation methodology assumes that all of the inorganic carbon (calcium carbonate) content of the phosphate rock reacts to produce CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic carbon content of the phosphate rock is converted to CO_2 and that all of the organic carbon content remains in the phosphoric acid product.

From 1993 to 2004, the U.S. Geological Survey (USGS) *Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-79). For the years 1990 through 1992, and 2005 through 2022, only nationally aggregated mining data was reported by USGS. For the years 1990, 1991, and 1992, the breakdown of phosphate rock mined in Florida and North Carolina and the amount mined in Idaho and Utah are approximated using data reported by USGS for the average share of U.S. production in those states from 1993 to 2004. For the years 2005 through 2022, the same approximation method is used, but the share of U.S. production was assumed to be consistent with the ratio of production capacity in those states, which were obtained from the USGS commodity specialist for phosphate rock (USGS 2012; USGS 2021b). For 1990 through 2022, data on U.S. domestic consumption of phosphate rock, consisting of domestic reported sales and use of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption, were obtained from USGS *Minerals Yearbook: Phosphate Rock*

(USGS 1994 through 2015b) and from USGS *Minerals Commodity Summaries: Phosphate Rock* (USGS 2016 through 2021a, 2022). From 2004 through 2022, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2022).

The carbonate content of phosphate rock varies depending upon where the material is mined. Composition data for domestically mined and imported phosphate rock were provided by the Florida Institute of Phosphate Research, now known as the Florida Industrial and Phosphate Research Institute (FIPR 2003a). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-79). Similar to the phosphate rock mined in Morocco, phosphate rock mined in Peru contains approximately 5 percent CO_2 (Golder Associates and M3 Engineering 2016).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (more than 75 percent of domestic production), and carbonate content data for phosphate rock mined in Morocco and Peru are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation assumes that all of the domestic production of phosphate rock is used in uncalcined form. As of 2006, the USGS noted that one phosphate rock producer in Idaho produces calcined phosphate rock; however, no production data were available for this single producer (USGS 2006). The USGS confirmed that no significant quantity of domestic production of phosphate rock is in the calcined form (USGS 2012).

Table 4-79: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	1990	2005	2018	2019	2020	2021	2022
U.S. Domestic Consumption[a]	49,800	35,200	23,300	23,400	22,600	21,900	21,000
FL and NC	*42,494*	*28,160*	*18,170*	*18,250*	*17,630*	*17,080*	*16,380*
ID and UT	*7,306*	*7,040*	*5,130*	*5,150*	*4,970*	*4,820*	*4,620*
Exports—FL and NC	6,240	0	0	0	0	0	0
Imports	451	2,630	2,770	2,140	2,520	2,460	2,400
Total U.S. Consumption	**44,011**	**37,830**	**26,070**	**25,540**	**25,120**	**24,360**	**23,400**

[a] U.S. domestic consumption values are based on reported phosphate rock sold or used by producers.
Note: Totals may not sum due to independent rounding.

Table 4-80: Chemical Composition of Phosphate Rock (Percent by Weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco	Peru
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56	NA
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46	NA
Organic Carbon (as C)	0.60	0.83	0.35	0.00	0.10	NA
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00	5.00

NA (Not Available)
Sources: FIPR (2003a), Golder Associates and M3 Engineering (2016)

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022.

Uncertainty

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2021. Prior to 2006, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was

reported. Regional production for 2021 was estimated based on regional production data from 2017 to 2020 and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2021 regional production data represents actual production in those regions. Total U.S. phosphate rock production data are not considered to be a significant source of uncertainty because all the domestic phosphate rock producers report their annual production to the USGS. Data for exports of phosphate rock used in the emission calculations are reported to the USGS by phosphate rock producers and are not considered to be a significant source of uncertainty. Data for imports for consumption are based on international trade data collected by the U.S. Census Bureau. These U.S. government economic data are not considered to be a significant source of uncertainty. Based on expert judgement of the USGS, EPA assigned an uncertainty range of ±5 percent to the percentage of phosphate rock produced from Florida and North Carolina, and ±5 percent to phosphoric acid production and imports (USGS 2012). Per this expert judgment, a normal probability density function was assigned for all activity data.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock, as the composition of phosphate rock varies depending upon where the material is mined and may also vary over time. The *Inventory* relies on one study (FIPR 2003a) of chemical composition of the phosphate rock; limited data are available beyond this study. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of FIPR indicated that in the phosphoric acid production process, the organic carbon content of the mined phosphate rock generally remains in the phosphoric acid product, which is what produces the color of the phosphoric acid product (FIPR 2003b). Organic carbon is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic carbon in the phosphate rock into CO_2; however, according to air permit information available to the public, at least one facility has calcining units permitted for operation (NCDENR 2013).

Finally, USGS indicated that in 2021 less than 5 percent of domestically-produced phosphate rock was used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2022). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions assumes that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic carbon content in phosphate rock, but none from the organic carbon content.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-81. 2022 phosphoric acid production CO_2 emissions were estimated to be between 0.7 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.8 MMT CO_2 Eq.

Table 4-81: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	0.8	0.7	1.1	-18%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for 2021 to reflect updated USGS data on the total U.S. production of phosphate rock. This update resulted in a decrease of 35 kt CO_2 in 2021.

Planned Improvements

EPA continues to evaluate potential improvements to the *Inventory* estimates for this source category, which include direct integration of EPA's GHGRP data for 2010 through 2022 along with assessing applicability of reported GHGRP data to update the inorganic carbon content of phosphate rock for prior years to ensure time-series consistency. Specifically, EPA would need to assess that averaged inorganic carbon content data (by region or other approaches) meets GHGRP confidential business information (CBI) screening criteria. EPA would then need to assess the applicability of GHGRP data for the averaged inorganic carbon content (by region or other approaches) from 2010 through 2022, along with other information to inform estimates in prior years in the time series (1990 through 2009) based on the sources of phosphate rock used in production of phosphoric acid over time. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely upon the latest guidance from the IPCC on the use of facility-level data in national inventories.[76] These long-term planned improvements are still in development by EPA and have not been implemented into the current *Inventory* report.

4.18 Iron and Steel Production (CRT Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of carbon dioxide (CO_2) and methane (CH_4) as raw materials are refined into iron and then transformed into crude steel. This reporting category (2C1) includes emissions from the production of iron and steel. Per the IPCC methodological guidance, emissions from conventional fuels (e.g., natural gas, fuel oil) consumed for energy purposes during the production of iron and steel are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Iron and steel production includes seven distinct production processes: metallurgical coke production, sinter production, direct reduced iron (DRI) production, pellet production, pig iron.[77] production, electric arc furnace

[76] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

[77] Pig iron is the common industry term to describe what should technically be called crude iron. Pig iron is a subset of crude iron that has lost popularity over time as industry trends have shifted. Throughout this report, pig iron will be used

(EAF) steel production, and basic oxygen furnace (BOF) steel production. The number of production processes at a particular plant is dependent upon the specific plant configuration. Most process CO_2 generated from the iron and steel industry is a result of the production of crude iron.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold off-site for use as synthetic natural gas are also accounted for in these calculations. In general, CO_2 emissions are generated in these production processes through the reduction and consumption of various carbon-containing inputs (e.g., ore, scrap, flux, coke byproducts). Fugitive CH_4 emissions can also be generated from these processes, as well as from sinter, direct iron, and pellet production.

In 2022, approximately eleven integrated iron and steel steelmaking facilities utilized BOFs to refine and produce steel from iron, and raw steel was produced at 101 facilities across the United States. As of 2020, approximately 29 percent of steel production was attributed to BOFs and 71 percent to EAFs (AISI 2020). The trend in the United States for integrated facilities has been a shift towards fewer BOFs and more EAFs. EAFs use scrap steel as their main input and use significantly less energy than BOFs. There are also 14 cokemaking facilities, of which 3 facilities are co-located with integrated iron and steel facilities (ACCCI 2021). In the United States, seven states account for roughly 61 percent of total raw steel production: Indiana, Alabama, Tennessee, Kentucky, Mississippi, Arkansas, and Ohio (AISI 2023).

Total annual production of crude steel in the United States was fairly constant between 2000 and 2008 and ranged from a low of 99,320,000 tons to a high of 109,880,000 tons (2001 and 2004, respectively). Due to the decrease in demand caused by the global economic downturn (particularly from the automotive industry), crude steel production in the United States sharply decreased to 65,459,000 tons in 2009. Crude steel production was fairly constant from 2011 through 2014, and after a dip in production from 2014 to 2015, crude steel production steadily increased. Crude steel production dipped again in 2020 due to the COVID-19 pandemic and returned to pre-pandemic levels in 2021. Production declined by approximately 6 percent in 2022 (AISI 2023). This decline may be attributable to projections for decreased global end-use consumption due to multiple factors including the conflict in Ukraine, continuing coronavirus disease 2019 (COVID-19) mitigation measures in China, rising energy costs and interest rates, and global inflation (USGS 2023a). The United States was the fourth largest producer of raw steel in the world, behind China, India, and Japan, accounting for approximately 4.3 percent of world production in 2022 (AISI 2004 through 2023).

The majority of CO_2 emissions from the iron and steel production process come from the use of metallurgical coke in the production of pig iron and from the consumption of other process byproducts, with lesser amounts emitted from the use of carbon-containing flux and from the removal of carbon from pig iron used to produce steel.

According to the *2006 IPCC Guidelines*, the production of metallurgical coke from coking coal is considered to be an energy use of fossil fuel, and the use of coke in iron and steel production is considered to be an industrial process source. The *2006 IPCC Guidelines* suggest that emissions from the production of metallurgical coke should be reported separately in the Energy sector, while emissions from coke consumption in iron and steel production should be reported in the Industrial Processes and Product Use sector. The approaches and emission estimates for both metallurgical coke production and iron and steel production, however, are presented here because much of the relevant activity data is used to estimate emissions from both metallurgical coke production and iron and steel production. For example, some byproducts (e.g., coke oven gas) of the metallurgical coke production process are consumed during iron and steel production, and some byproducts of the iron and steel production process (e.g., blast furnace gas) are consumed during metallurgical coke production. Emissions associated with the consumption of these byproducts are attributed at the point of consumption. Emissions associated with the use of conventional

interchangeably with crude iron, but it should be noted that in other data sets or reports pig iron and crude iron may not be used interchangeably and may provide different values.

fuels (e.g., natural gas, fuel oil) for electricity generation, heating and annealing, or other miscellaneous purposes downstream of the iron and steelmaking furnaces are reported in the Energy chapter.

Metallurgical Coke Production

Emissions of CO_2 from metallurgical coke production in 2022 were 3.0 MMT CO_2 Eq. (2,954 kt CO_2) (see Table 4-82 and Table 4-83). Emissions decreased by 8 percent from 2021 to 2022 and have decreased by 47 percent since 1990. Coke production in 2022 was about 9 percent lower than in 2021 and 59 percent below 1990 (EIA 2023, AISI 2023).

Significant activity data for 2020 through 2022 were not available in time for publication of this report due to industry consolidation that impacts the publication of data without revealing confidential business information. Activity data for these years were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

Table 4-82: CO_2 Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	5.6	3.9	1.3	3.0	2.3	3.2	3.0

Table 4-83: CO_2 Emissions from Metallurgical Coke Production (kt CO_2)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	5,608	3,921	1,282	3,006	2,325	3,224	2,954

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2022 were 37.7 MMT CO_2 Eq. (37,718 kt) and 0.0077 MMT CO_2 Eq. (0.3 kt CH_4), respectively (see Table 4-84 through Table 4-87). Emissions from iron and steel production decreased by 2 percent from 2021 to 2022 and have decreased by 62 percent since 1990, due to restructuring of the industry, technological improvements, and increased scrap steel utilization. Carbon dioxide emission estimates include emissions from the consumption of carbonaceous materials in the blast furnace, EAF, and BOF, as well as blast furnace gas and coke oven gas consumption for other activities at the steel mill.

Significant activity data for 2020 through 2022 were not available in time for publication of this report due to industry consolidation that impacts the publication of data without revealing confidential business information. Activity data for these years were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

In 2022, domestic production of pig iron decreased by 11 percent from 2021 levels. Overall, domestic pig iron production has declined since the 1990s; pig iron production in 2022 was 59 percent lower than in 2000 and 60 percent below 1990. Carbon dioxide emissions from iron production have decreased by 81 percent (37.0 MMT CO_2 Eq.) since 1990. Carbon dioxide emissions from steel production have decreased by 16 percent (1.3 MMT CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 62 percent (61.4 MMT CO_2 Eq.) from 1990 to 2022.

Table 4-84: CO_2 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	2.4	1.7	0.9	0.9	0.7	0.8	0.8
Iron Production	45.7	17.7	9.6	9.4	8.4	9.0	8.7
Pellet Production	1.8	1.5	0.9	0.9	0.8	0.8	0.8
Steel Production	8.0	9.4	6.0	5.8	5.7	5.8	6.7
Other Activities[a]	41.2	35.9	24.1	23.2	19.8	22.1	20.8
Total	**99.1**	**66.2**	**41.6**	**40.1**	**35.4**	**38.6**	**37.7**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.
Note: Totals may not sum due to independent rounding.

Table 4-85: CO_2 Emissions from Iron and Steel Production (kt CO_2)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	2,448	1,663	937	876	749	836	787
Iron Production	45,709	17,666	9,589	9,365	8,420	9,038	8,673
Pellet Production	1,817	1,503	924	878	751	838	789
Steel Production	7,964	9,395	5,982	5,812	5,657	5,816	6,655
Other Activities [a]	41,194	35,934	24,149	23,158	19,820	22,119	20,814
Total	**99,132**	**66,161**	**41,581**	**40,089**	**35,398**	**38,648**	**37,718**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.
Note: Totals may not sum due to independent rounding.

Table 4-86: CH_4 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	+	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-87: CH_4 Emissions from Iron and Steel Production (kt CH_4)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	0.9	0.6	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

Emission estimates for metallurgical coke, EAF steel production, and BOF steel production presented in this chapter utilize a country-specific approach based on Tier 2 methodologies provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. These Tier 2 methodologies call for a mass balance accounting of the carbonaceous inputs and outputs during the iron and steel production process and the metallurgical coke production process. Estimates for pig iron production apply Tier 2 methods consistent with the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production, pellet production and DRI production) for which available data are insufficient to apply a Tier 2 method (e.g., country-specific carbon contents of inputs and outputs are not known). The majority of emissions are captured with higher tier methods, as sinter production, pellet production, and DRI production only account for roughly 8 percent of total iron and steel production emissions.

The Tier 2 methodology equation is as follows:

Equation 4-11: CO_2 Emissions from Coke, Pig Iron, EAF Steel, and BOF Steel Production, based on *2006 IPCC Guidelines* Tier 2 Methodologies

$$E_{CO_2} = \left[\sum_a (Q_a \times C_a) - \sum_b (Q_b \times C_b)\right] \times \frac{44}{12}$$

where,

E_{CO2} = Emissions from coke, pig iron, EAF steel, or BOF steel production, metric tons

a = Input material *a*

b = Output material *b*

Q_a = Quantity of input material *a*, metric tons

C_a = Carbon content of input material *a*, metric tons C/metric ton material

Q_b = Quantity of output material *b*, metric tons

C_b = Carbon content of output material *b*, metric tons C/metric ton material

44/12 = Stoichiometric ratio of CO_2 to C

The Tier 1 methodology equations are as follows:

Equation 4-12: *2006 IPCC Guidelines* Tier 1: Emissions from Sinter, Direct Reduced Iron, and Pellet Production (Equations 4.6, 4.7, and 4.8)

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,CO2} = Q_d \times EF_{d,CO2}$$

$$E_{p,CO2} = Q_p \times EF_{p,CO2}$$

where,

$E_{s,p}$ = Emissions from sinter production process for pollutant *p* (CO_2 or CH_4), metric ton

Q_s = Quantity of sinter produced, metric tons

$EF_{s,p}$ = Emission factor for pollutant *p* (CO_2 or CH_4), metric ton *p*/metric ton sinter

$E_{d,CO2}$ = Emissions from DRI production process for CO_2, metric ton

Q_d = Quantity of DRI produced, metric tons

$EF_{d,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton DRI

$E_{p,CO2}$ = Emissions from pellet production process for CO_2, metric ton

Q_p = Quantity of pellets produced, metric tons

$EF_{p,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton pellets produced

A significant number of activity data that serve as inputs to emissions calculations were unavailable for 2020 through 2022 at the time of publication and were estimated using 2019 values. To estimate annual emissions for these years, the EPA used process emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) subpart Q for the iron and steel sector to adjust the estimated values for 2020 through 2022. GHGRP process emissions data decreased by approximately 14 percent from 2019 to 2020, increased by approximately 12 percent from 2020 to 2021, and decreased by approximately 6 percent from 2021 to 2022 (EPA 2023). These percentage changes were applied to 2019 activity data values to produce estimates for 2020 through 2022.

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical coke which is used primarily as a reducing agent in the production of iron and steel but is also used in the production of other metals including zinc and lead (see Zinc Production and Lead Production sections of this chapter). Emissions associated with producing metallurgical coke from coking coal are estimated and reported separately from emissions that result from the iron and steel production process. To estimate emissions from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines* was

utilized. The amount of carbon contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze and coke oven gas) is deducted from the amount of carbon contained in materials consumed during the metallurgical coke production process (i.e., natural gas, blast furnace gas, and coking coal). For calculations, activity data for these inputs, including natural gas, blast furnace gas, and coking coke consumed for metallurgical coke production, are in units consistent with the carbon content values. Light oil, which is produced during the metallurgical coke production process, is excluded from the deductions due to data limitations. The amount of carbon contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-88). The amount of coal tar produced was approximated using a production factor of 0.03 tons of coal tar per ton of coking coal consumed. The amount of coke breeze produced was approximated using a production factor of 0.075 tons of coke breeze per ton of coking coal consumed (Steiner 2008; DOE 2000). Data on the consumption of carbonaceous materials (other than coking coal) as well as coke oven gas production were available for integrated steel mills only (i.e., steel mills with co-located coke plants); therefore, carbonaceous material (other than coking coal) consumption and coke oven gas production were excluded from emission estimates for merchant coke plants. Carbon contained in coke oven gas used for coke-oven underfiring was not included in the deductions to avoid double-counting.

Table 4-88: Material Carbon Contents for Metallurgical Coke Production

Material	kg C/kg
Coal Tar[a]	0.62
Coke[a]	0.83
Coke Breeze[a]	0.83
Coking Coal[b]	0.75
Material	**kg C/GJ**
Coke Oven Gas[c]	12.1
Blast Furnace Gas[c]	70.8

[a] Source: IPCC (2006), Vol. 3 Chapter 4, Table 4.3
[b] Source: EIA (2017b)
[c] Source: IPCC (2006), Vol. 2 Chapter 1, Table 1.3

Although the *2006 IPCC Guidelines* provide a Tier 1 CH_4 emission factor for metallurgical coke production (i.e., 0.1 g CH_4 per metric ton of coke production), it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the metallurgical coke production process either exits the process as part of a carbon-containing output or as CO_2 emissions. This is consistent with a preliminary assessment of aggregated facility-level greenhouse gas CH_4 emissions reported by coke production facilities under EPA's GHGRP. The assessment indicates that CH_4 emissions from coke production are insignificant and below 500 kt or 0.05 percent of total national emissions. Pending resources and significance, EPA continues to assess the possibility of including these emissions in future Inventories to enhance completeness but has not incorporated these emissions into this report.

Data relating to the mass of coking coal consumed at metallurgical coke plants and the mass of metallurgical coke produced at coke plants were taken from the Energy Information Administration (EIA) *Quarterly Coal Report: October through December* (EIA 1998 through 2019) and EIA *Quarterly Coal Report: January through March* (EIA 2021 through 2023) (see Table 4-89). Data on the volume of natural gas consumption, blast furnace gas consumption, and coke oven gas production for metallurgical coke production at integrated steel mills were obtained from the American Iron and Steel Institute (AISI) *Annual Statistical* Report (AISI 2004 through 2023) and through personal communications with AISI (Steiner 2008) (see Table 4-90). These data from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (Steiner 2008). The factor for the quantity of coke breeze produced per ton of coking coal consumed was obtained through Table 2-1 of the report *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000). Data on

natural gas consumption and coke oven gas production at merchant coke plants were not available and were excluded from the emission estimate. Carbon contents for metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the *2006 IPCC Guidelines*. The carbon content for coke breeze was assumed to equal the carbon content of coke. Carbon contents for coking coal was from EIA.

Table 4-89: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	16,635	16,261	13,076	15,957	14,523
Coke Production at Coke Plants	25,054	15,167	12,525	11,676	9,392	11,381	10,337
Coke Breeze Production	2,645	1,594	1,248	1,220	981	1,197	1,089
Coal Tar Production	1,058	638	499	488	392	479	436

Table 4-90: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Million ft^3)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	80,750	77,692	66,492	74,206	69,829
Natural Gas Consumption	599	2,996	2,275	2,189	1,873	2,091	1,967
Blast Furnace Gas Consumption	24,602	4,460	4,022	3,914	3,350	3,738	3,518

Iron and Steel Production

To estimate emissions from pig iron production in the blast furnace, the amount of carbon contained in the produced pig iron and blast furnace gas were deducted from the amount of carbon contained in inputs (i.e., metallurgical coke, sinter, natural ore, pellets, natural gas, fuel oil, coke oven gas, carbonate fluxes or slagging materials, and direct coal injection). For calculations, activity data for these inputs, including coke consumed for pig iron production, are in units consistent with the carbon content values. The carbon contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific carbon content by each material type (see Table 4-91). In the absence of a default carbon content value from the *2006 IPCC Guidelines* for pellet, sinter, or natural ore consumed for pig iron production, a country-specific approach based on Tier 2 methodology is used. Pellet, sinter, and natural ore used as an input for pig iron production is assumed to have the same carbon content as direct reduced iron (2 percent), based on expert judgment (RTI 2024). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process. Carbon contained in blast furnace gas used as a blast furnace input was not included in the deductions to avoid double-counting.

Emissions from steel production in EAFs were estimated by deducting the carbon contained in the steel produced from the carbon contained in the EAF anode, charge carbon, and scrap steel added to the EAF. Small amounts of carbon from DRI and pig iron to the EAFs were also included in the EAF calculation. For BOFs, estimates of carbon contained in BOF steel were deducted from carbon contained in inputs such as natural gas, coke oven gas, fluxes (i.e., limestone and dolomite), and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-91). For EAFs, the amount of EAF anode consumed was approximated by multiplying total EAF steel production by the amount of EAF anode consumed per metric ton of steel produced (0.002 metric tons EAF anode per metric ton steel produced [Steiner 2008]). The amount of carbon-containing flux (i.e., limestone and dolomite) used in EAF and BOF steel production was deducted from the "Other Process Uses of Carbonates" source category (CRT Source Category 2A4) to avoid double-counting.

Carbon dioxide emissions from the consumption of blast furnace gas and coke oven gas for other activities occurring at the steel mill were estimated by multiplying the amount of these materials consumed for these purposes by the material-specific carbon content (see Table 4-91).

Table 4-91: Material Carbon Contents for Iron and Steel Production

Material	kg C/kg
Coke	0.83
Direct Reduced Iron	0.02
Dolomite	0.13
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83
Limestone	0.12
Pig Iron	0.04
Steel	0.01
Material	**kg C/GJ**
Coke Oven Gas	12.1
Blast Furnace Gas	70.8

Source: IPCC (2006), Table 4.3. Coke Oven Gas and Blast Furnace Gas, Table 1.3.

Carbon dioxide emissions associated with sinter production, direct reduced iron production, pellet production, pig iron production, steel production, and other steel mill activities were summed to calculate the total CO_2 emissions from iron and steel production (see Table 4-84 and Table 4-85).

The sinter production process results in fugitive emissions of CH_4, which are emitted via leaks in the production equipment, rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying Tier 1 emission factors taken from the *2006 IPCC Guidelines* for sinter production (see Table 4-92). Although the *2006 IPCC Guidelines* also provide a Tier 1 methodology for CH_4 emissions from pig iron production, it is not appropriate to use because CO_2 emissions for pig iron production are estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the pig iron production process either exits the process as part of a carbon-containing output or as CO_2 emissions; the estimation of CH_4 emissions is precluded. Annual analysis of facility-level emissions reported during iron production further supports this assumption and indicates that CH_4 emissions are below 500 kt CO_2 Eq. and well below 0.05 percent of total national emissions. The production of direct reduced iron could also result in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas, etc.); however, these emission estimates are excluded due to data limitations. Pending further analysis and resources, EPA may include these emissions in future reports to enhance completeness. EPA is still assessing the possibility of including these emissions in future reports and have not included this data in the current report.

Table 4-92: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Sinter	0.07	kg CH_4/metric ton

Source: IPCC (2006), Table 4.2.

Emissions of CO_2 from sinter production, direct reduced iron production, and pellet production were estimated by multiplying total national sinter production, total national direct reduced iron production, and total national pellet production by Tier 1 CO_2 emission factors (see Table 4-93). Because estimates of sinter production, direct reduced iron production, and pellet production were not available, production was assumed to equal consumption.

Table 4-93: CO_2 Emission Factors for Sinter Production, Direct Reduced Iron Production, and Pellet Production

Material Produced	Metric Ton CO_2/Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7
Pellet Production	0.03

Source: IPCC (2006), Table 4.1.

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted for within the Energy chapter to avoid double-counting of emissions reported within the IPPU chapter as these fuels were consumed during non-energy related activities. More information on this methodology and examples of adjustments made between the IPPU and Energy chapters are described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Sinter consumption and pellet consumption data for 1990 through 2020 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2022) and through personal communications with AISI (Steiner 2008) (see Table 4-94). These data from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

In general, direct reduced iron (DRI) consumption data were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2022; USGS 2023b) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2023a). Data for DRI consumed in EAFs were not available for the years 1990 and 1991. EAF DRI consumption in 1990 and 1991 was calculated by multiplying the total DRI consumption for all furnaces by the EAF share of total DRI consumption in 1992. Data for DRI consumed in BOFs were not available for the years 1990 through 1993. BOF DRI consumption in 1990 through 1993 was calculated by multiplying the total DRI consumption for all furnaces (excluding EAFs and cupola) by the BOF share of total DRI consumption (excluding EAFs and cupola) in 1994.

The Tier 1 CO_2 emission factors for sinter production, direct reduced iron production and pellet production were obtained through the *2006 IPCC Guidelines* (IPCC 2006). Time-series data for pig iron production, coke, natural gas, fuel oil, sinter, and pellets consumed in the blast furnace; pig iron production; and blast furnace gas produced at the iron and steel mill and used in the metallurgical coke ovens and other steel mill activities were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008) (see Table 4-94 and Table 4-95). Data including blast furnace gas, coke oven gas, natural gas, limestone, sinter, and natural ore consumption for blast furnaces, coke production, and steelmaking furnaces (EAFs and BOFs) from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section. Similarly, the percent of total steel production for EAF and BOF steelmaking processes were withheld for 2021 and 2022, so the 2020 values were used as estimated data for the missing 2021 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data for EAF steel production, carbon-containing flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2022) and through personal communications with AISI (AISI 2006 through 2016, Steiner 2008). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (Steiner 2008). Data for BOF steel production, carbon-containing flux, natural gas, natural ore, pellet, sinter consumption as well as BOF steel production were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2023) and through personal communications with AISI (Steiner 2008). Data for EAF consumption of natural gas and BOF consumption of coke oven gas, limestone, and natural ore from the AISI *Annual Statistical Report* were not available for 2021 and 2022, so 2020 values were used as estimated data for the missing 2021 and 2022 values and adjusted using GHGRP emissions data, as described earlier in this

Methodology and Time-Series Consistency section. Data for EAF and BOF scrap steel, pig iron, and DRI consumption were obtained from the USGS *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2022; USGS 2023b) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2023a). Data on coke oven gas and blast furnace gas consumed at the iron and steel mill (other than in the EAF, BOF, or blast furnace) were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008). These data were not available for 2021 and 2022, so 2020 values were used as estimated data for the missing 2021 and 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section. Some data from the *AISI Annual Statistical Report* on natural gas consumption were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's *Natural Gas Annual 2019* (EIA 2020). Carbon contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the *2006 IPCC Guidelines*. The carbon contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (EIA 2017b) and EPA (EPA 2010). Heat contents for fuel oil and direct injection coal were obtained from EIA (EIA 1992, 2011); natural gas heat content was obtained from Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021). Heat contents for coke oven gas and blast furnace gas were provided in Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021) and confirmed by AISI staff (Carroll 2016).

Table 4-94: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	12,239	8,315	4,687	4,378	3,747	4,182	3,935
Direct Reduced Iron Production	517	1,303	C	C	C	C	C
Pellet Production	60,563	50,096	30,793	29,262	25,044	27,949	26,300
Pig Iron Production							
Coke Consumption	24,946	13,832	7,618	7,291	6,240	6,964	6,553
Pig Iron Production	49,669	37,222	24,058	22,302	18,320	22,246	19,791
Direct Injection Coal Consumption	1,485	2,573	2,569	2,465	2,110	2,354	2,216
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,133	1,137	1,118	1,129	1,123
Scrap Steel Consumption	42,691	46,600	C	C	C	C	C
Flux Consumption	319	695	998	998	998	998	998
EAF Steel Production	33,511	52,194	58,904	61,172	51,349	57,307	53,926
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	C	C	C	C	C
Scrap Steel Consumption	14,713	11,400	C	C	C	C	C
Flux Consumption	576	582	408	363	311	347	326
BOF Steel Production	43,973	42,705	27,704	26,591	21,384	23,865	22,457

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Table 4-95: Production and Consumption Data for the Calculation of CO_2 Emissions from Iron and Steel Production (Million ft^3 unless otherwise specified)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	40,204	37,934	32,465	36,232	34,095
Fuel Oil Consumption (thousand gallons)	163,397	16,170	3,365	2,321	1,986	2,217	2,086

Coke Oven Gas Consumption	22,033	16,557	13,337	12,926	11,063	12,346	11,618
Blast Furnace Gas Production	1,439,380	1,299,980	871,860	836,033	715,509	798,522	751,418
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	8,556	9,115	7,801	8,706	8,192
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	405	389	333	372	350
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	67,008	64,377	55,096	61,489	57,861
Blast Furnace Gas Consumption	1,414,778	1,295,520	867,838	832,119	712,159	794,783	747,900

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The estimates of CO_2 emissions from metallurgical coke production are based on assessing uncertainties in material production and consumption data and average carbon contents. Uncertainty is associated with the total U.S. coking coal consumption, total U.S. coke production, and materials consumed during this process. Data for coking coal consumption and metallurgical coke production are from different data sources (EIA) than data for other carbonaceous materials consumed at coke plants (AISI), which does not include data for merchant coke plants. There is uncertainty associated with the fact that coal tar and coke breeze production were estimated based on coke production because coal tar and coke breeze production data were not available. Since merchant coke plant data is not included in the estimate of other carbonaceous materials consumed at coke plants, the mass balance equation for CO_2 from metallurgical coke production cannot be reasonably completed; therefore, for the purpose of this analysis, uncertainty parameters are applied to primary data inputs to the calculation (i.e., coking coal consumption and metallurgical coke production) only.

The estimates of CO_2 emissions from iron and steel production are based on material production and consumption data and average carbon contents. There is uncertainty associated with the assumption that pellet production, direct reduced iron and sinter consumption are equal to production. There is uncertainty with the representativeness of the associated IPCC default emission factors. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal. There is also uncertainty associated with the carbon contents for pellets, sinter, and natural ore, which are assumed to equal the carbon contents of direct reduced iron, when consumed in the blast furnace. There is uncertainty associated with the consumption of natural ore under current industry practices. For EAF steel production, there is uncertainty associated with the amount of EAF anode and charge carbon consumed due to inconsistent data throughout the time series. Also for EAF steel production, there is uncertainty associated with the assumption that 100 percent of the natural gas attributed to "steelmaking furnaces" by AISI is process-related and nothing is combusted for energy purposes. Uncertainty is also associated with the use of process gases such as blast furnace gas and coke oven gas. Data are not available to differentiate between the use of these gases for processes at the steel mill versus for energy generation (i.e., electricity and steam generation); therefore, all consumption is attributed to iron and steel production. These data and carbon contents produce a relatively accurate estimate of CO_2 emissions; however, there are uncertainties associated with each.

For calculating the emissions estimates from iron and steel and metallurgical coke production, EPA utilizes a number of data points taken from the AISI *Annual Statistical Report* (ASR). This report serves as a benchmark for information on steel companies in United States, regardless if they are a member of AISI, which represents integrated producers (i.e., blast furnace and EAF). During the compilation of the 1990 through 2016 *Inventory* report EPA initiated conversation with AISI to better understand and update the qualitative and quantitative uncertainty metrics associated with AISI data elements. AISI estimates their data collection response rate to range from 75 to 90 percent, with certain sectors of the iron and steel industry not being covered by the ASR; therefore, there is some inherent uncertainty in the values provided in the AISI ASR, including material production and consumption data. There is also some uncertainty to which materials produced are exported to Canada. As

indicated in the introduction to this section, the trend for integrated facilities has moved to more use of EAFs and fewer BOFs. This trend may not be completely captured in the current data which also increases uncertainty. EPA assigned an uncertainty range of ±10 percent for the primary data inputs (i.e., consumption and production values for each production process, heat and carbon content values), a normal probability density function for consumption and production values for each production process, and a triangular probability density function for heat and carbon content values to calculate overall uncertainty from iron and steel production, and using this suggested uncertainty provided in Table 4.4 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). During EPA's discussion with AISI, AISI noted that an uncertainty range of ±5 percent would be a more appropriate approximation to reflect their coverage of integrated steel producers in the United States. EPA will continue to assess the best range of uncertainty for these values. EPA assigned an uncertainty range of ±25 percent and a triangular probability density function for the Tier 1 CO_2 emission factors for the sinter, direct reduced iron, and pellet production processes, and using this suggested uncertainty provided in Table 4.4 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-96 for metallurgical coke production and iron and steel production. Total CO_2 emissions from metallurgical coke production and iron and steel production for 2022 were estimated to be between 34.3 and 47.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 16 percent above the emission estimate of 40.7 MMT CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production for 2022 were estimated to be between 0.007 and 0.008 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 0.0077 MMT CO_2 Eq.

Table 4-96: Approach 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production and Metallurgical Coke Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Metallurgical Coke & Iron and Steel Production	CO_2	40.7	34.3	47.1	-16%	+16%
Metallurgical Coke & Iron and Steel Production	CH_4	+	+	+	-7%	+7%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). As part of a multiyear improvement effort, EPA is reviewing the iron and steel methodology and available data, conducting additional category specific QC checks and will report on findings when that review is complete (i.e., projected to be complete at earliest for the 2025 report). More information is provided under Planned Improvements below.

Recalculations Discussion

Recalculations were performed for the year 2021 with updated USGS values for DRI, pig iron, and scrap steel consumption for both BOF and EAF steel production. Additionally, revisions to GHGRP data for 2020 and 2021 resulted in minor changes to activity data that were adjusted using GHGRP data, as described in the Methodology and Time-Series Consistency section. Compared to the previous *Inventory*, CO_2 emissions from steel production increased by less than 1 percent (7 kt CO_2) in 2020 and by less than 1 percent (211 kt CO_2) in 2021.

Planned Improvements

Significant activity data for 2020 through 2022 were not available for this report and were estimated using 2019 values and adjusted using GHGRP emissions data. EPA will continue to explore sources of 2020 through 2022 data and other estimation approaches. EPA will evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for Iron and Steel Production process categories. Particular attention will be made to ensure time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[78] This is a near to medium-term improvement, and per preliminary work, EPA estimates that the earliest this improvement could be incorporated is the next (i.e., 2025) *Inventory* submission.

Additional improvements include accounting for emission estimates for the production of metallurgical coke in the Energy chapter as well as identifying the amount of carbonaceous materials, other than coking coal, consumed at merchant coke plants. Other potential improvements include identifying the amount of coal used for direct injection and the amount of coke breeze, coal tar, and light oil produced during coke production. Efforts will also be made to identify information to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters. Additional efforts will be made to improve the reporting and transparency in accounting for fuels between the IPPU and Energy chapters, particularly the inclusion of a quantitative summary of the carbon balance in the United States. This planned improvement is a long-term improvement and is still in development. It is not included in this current *Inventory* report. EPA estimates that the earliest this improvement could be incorporated is the next (i.e., 2025) *Inventory* submission.

4.19 Ferroalloy Production (CRT Source Category 2C2)

Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). This reporting category (2C2) includes emissions of carbon dioxide (CO_2) and methane (CH_4) from the production of several ferroalloys. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of ferroalloys are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. Emissions from the production of two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (96 to 99 percent silicon), and miscellaneous alloys (32 to 65 percent silicon) have been calculated.

Emissions from the production of ferrochromium and ferromanganese are not included because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Additionally, production of ferrochromium in the United States ceased in 2009 (USGS 2013a).

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing

[78] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

environment, CO is initially produced and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon (FeSi) is given below:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

While most of the carbon contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

Ferroalloys are used to alter the material properties of the steel. Ferroalloys are produced in conjunction with the iron and steel industry, often at co-located facilities, and production trends closely follow that of the iron and steel industry. As of 2020, 11 facilities in the United States produce ferroalloys (USGS 2022b).

Emissions of CO_2 from ferroalloy production in 2022 were 1.3 MMT CO_2 Eq. (1,327 kt CO_2) (see Table 4-97 and Table 4-98), which is a 15 percent reduction since 2021 and a 38 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2022 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4), which is a 15 percent decrease since 2021 and a 45 percent decrease since 1990. Variability in emissions over the past five years is attributable to facility shutdowns in 2018 and 2020 (USGUS 2020; USGS 2021). The latter facility reopened its ferrosilicon production facility in 2021, owing to increased demand for ferrosilicon products and improved domestic pricing (USGS 2022c).

Table 4-97: CO_2 and CH_4 Emissions from Ferroalloy Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	2.2	1.4	2.1	1.6	1.4	1.6	1.3
CH_4	+	+	+	+	+	+	+
Total	**2.2**	**1.4**	**2.1**	**1.6**	**1.4**	**1.6**	**1.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-98: CO_2 and CH_4 Emissions from Ferroalloy Production (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	2,152	1,392	2,063	1,598	1,377	1,567	1,327
CH_4	1	+	1	+	+	+	+

+ Does not exceed 0.5 kt

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from ferroalloy production are calculated[79] using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Annual ferroalloy production is multiplied by material-specific emission factors provided by IPCC (IPCC 2006). The Tier 1 equations for CO_2 and CH_4 emissions are as follows:

Equation 4-13: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions for Ferroalloy Production (Equation 4.15)

$$E_{CO_2} = \sum_i (MP_i \times EF_i)$$

[79] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with production of ferroalloys did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

where,

E_{CO2} = CO_2 emissions, metric tons

MP_i = Production of ferroalloy type *i*, metric tons

EF_i = Generic emission factor for ferroalloy type *i*, metric tons CO_2/metric ton specific ferroalloy product

Equation 4-14: *2006 IPCC Guidelines* Tier 1: CH_4 Emissions for Ferroalloy Production (Equation 4.18)

$$E_{CH_4} = \sum_i (MP_i \times EF_i)$$

where,

E_{CH4} = CH_4 emissions, kg

MP_i = Production of ferroalloy type *i*, metric tons

EF_i = Generic emission factor for ferroalloy type *i*, kg CH_4/metric ton specific ferroalloy product

Default emission factors were used because country-specific emission factors are not currently available. The following emission factors were used to develop annual CO_2 and CH_4 estimates:

- Ferrosilicon, 25 to 55 percent Si and Miscellaneous Alloys, 32 to 65 percent Si: 2.5 metric tons CO_2/metric ton of alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Ferrosilicon, 56 to 95 percent Si: 4.0 metric tons CO_2/metric ton alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Silicon Metal: 5.0 metric tons CO_2/metric ton metal produced, 1.2 kg CH_4/metric ton metal produced.

It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke in an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon (C) and 10 percent inert material (Onder and Bagdoyan 1993).

The use of petroleum coke for ferroalloy production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRT Source Category 1A]) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Ferroalloy production data for 1990 through 2022 (see Table 4-99) were obtained from the U.S. Geological Survey (USGS) through the *Minerals Yearbook: Silicon* (USGS 1996 through 2022) and the *Minerals Industry Survey: Silicon* (USGS 2023a). The following data were available from the USGS publications for the time series:

- Ferrosilicon, 25 to 55 percent Si: Annual production data were available from 1990 through 2010.
- Ferrosilicon, 56 to 95 percent Si: Annual production data were available from 1990 through 2010.
- Silicon Metal: Annual production data were available from 1990 through 2005. Production data for 2005 were used as estimates for 2006 through 2010 because data for these years were not available due to government information disclosure rules.
- Miscellaneous Alloys, 32 to 65 percent Si: Annual production data were available from 1990 through 1998. Starting 1999, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS ceased publication of production quantity by ferroalloy product and began reporting all the ferroalloy production data as a single category (i.e., Total Silicon Materials Production). This is due to the small number of ferroalloy manufacturers in the United States and government information disclosure rules. Ferroalloy product shares developed from the 2010 production data (i.e., ferroalloy product production divided by total ferroalloy production) were used with the total silicon materials production quantity to estimate the production quantity by ferroalloy product type for 2011 through 2022 (USGS 2017 through 2022).

Table 4-99: Production of Ferroalloys (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Ferrosilicon 25%-55%	321,385	123,000	189,846	147,034	126,681	144,227	122,119
Ferrosilicon 56%-95%	109,566	86,100	167,511	129,736	111,778	127,259	107,752
Silicon Metal	145,744	148,000	183,642	142,229	122,541	139,514	118,128
Misc. Alloys 32-65%	72,442	NA	NA	NA	NA	NA	NA

NA (Not Available) for product type, aggregated with ferrosilicon (25-55% Si)

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Annual ferroalloy production was reported by the USGS in three broad categories until the 2010 publication: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal (through 2005 only, 2005 value used as an estimate for 2006 through 2010). Starting with the *2011 Minerals Yearbook: Silicon*, USGS started reporting all the ferroalloy production under a single category: total silicon materials production. The total silicon materials quantity was allocated across the three categories, based on the 2010 production shares for the three categories. Refer to the Methodology section for further details. Additionally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing proprietary company data. Emissions from this production category, therefore, were not estimated.

Some ferroalloys may be produced using wood or other biomass as a primary or secondary carbon source (carbonaceous reductants); however, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not be counted under this source because wood-based carbon is of biogenic origin.[80] Even though emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available, and are also often considered confidential business information.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging would reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

EPA assigned a uncertainty range of ±25 percent for the primary emission factors (i.e., ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, and silicon metal), and an uncertainty range of ±5 percent for the 2010 production values for ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, and silicon metal production and the 2021 total silicon materials production value used to calculate emissions from overall ferroalloy production. Using these suggested uncertainties provided in in Table 4.9 of Section 4.3.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert

[80] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

judgment (RTI 2023). Per this expert judgment, a normal probability density function was assumed for all activity data, and a triangular probability density function was assumed for emission factors.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-100. Ferroalloy production CO_2 emissions from 2022 were estimated to be between 1.2 and 1.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 13 percent above the emission estimate of 1.3 MMT CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 13 percent above the emission estimate of 0.01 MMT CO_2 Eq.

Table 4-100: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.3	1.2	1.5	-13%	+13%
Ferroalloy Production	CH_4	+	+	+	-12%	+13%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 to 2021 portion of the time series.

Planned Improvements

Pending available resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC procedures for the Ferroalloy Production source category. Given the small number of facilities and reporting thresholds, particular attention will be made to ensure completeness and time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[81] This is a long-term planned improvement, and EPA is still assessing the possibility of incorporating this improvement into the *Inventory*. This improvement has not been included in the current *Inventory* report.

[81] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.20 Aluminum Production (CRT Source Category 2C3)

Aluminum is a lightweight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. As of recent reporting, the United States was the ninth[82] largest producer of primary aluminum with an estimated aluminum production of 860 thousand metric tons, with approximately 1.2 percent of the world total production (USGS 2022). The United States was also a major importer of primary aluminum. This reporting category (2C3) includes emissions from the production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Héroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon (C) lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, most of this carbon is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 1.4 MMT CO_2 Eq. (1,446 kt) in 2022 (see Table 4-101 and Table 4-102). The carbon anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke and is accounted for here and not under the CO_2 from fossil fuel combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here.

Table 4-101: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4

Table 4-102: CO_2 Emissions from Aluminum Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed High Voltage Anode Effects (HVAEs). HVAEs cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given smelter and level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase. Another type of anode effect, Low Voltage Anode Effects (LVAEs), became a concern in the early 2010s as the aluminum industry increasingly began to use cell technologies with higher amperage and additional anodes (IPCC 2019). LVAEs emit CF_4 and are included in PFC emission totals from 2006 forward.

Since 1990, emissions of CF_4 and C_2F_6 have both declined by 96 and 97 percent respectively, to 0.62 MMT CO_2 Eq.

[82] Based on the U.S. USGS (2022) Aluminum factsheet, assuming all countries grouped under the "other countries" categories all have lower production than the U.S. Available at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-aluminum.pdf.

of CF_4 (0.1 kt) and 0.08 MMT CO_2 Eq. of C_2F_6 (0.01 kt) in 2022, respectively, as shown in Table 4-103 and Table 4-104. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. These actions include technology and operational changes such as employee training, use of computer monitoring, and changes in alumina feeding techniques. Since 1990, aluminum production has declined by 78 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 78 percent. PFC emissions decreased by approximately 18 percent between 2021 and 2022. Aluminum production also decreased in 2022, down 3 percent from 2021.

Table 4-103: PFC Emissions from Aluminum Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CF_4	16.1	2.6	1.0	1.1	1.2	0.8	0.7
C_2F_6	3.2	0.5	0.4	0.3	0.2	0.1	0.1
Total	**19.3**	**3.1**	**1.4**	**1.4**	**1.4**	**0.9**	**0.8**

Note: Totals may not sum due to independent rounding.

Table 4-104: PFC Emissions from Aluminum Production (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CF_4	2.4	0.4	0.2	0.2	0.2	0.1	0.1
C_2F_6	0.29	0.05	0.03	0.03	0.02	0.01	0.01

In 2022, U.S. primary aluminum production totaled approximately 0.86 million metric tons, a 3 percent decrease from 2021 production levels (USGS 2023). In 2022, three companies managed production at six operational primary aluminum smelters in five states. Two smelters operated at full capacity during 2022.The other four smelters operated at reduced capacity and one of these four smelters began a temporary shutdown in June (USGS 2023). Domestic smelters were operating at about 52 percent of capacity of 1.64 million tons per year at year end 2022 (USGS 2023).

Methodology and Time-Series Consistency

Process CO_2 and PFC (i.e., CF_4 and C_2F_6) emission estimates from primary aluminum production for 2010 through 2022 are available from EPA's GHGRP Subpart F (Aluminum Production) (EPA 2023). Under EPA's GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2022) are available to be incorporated into the *Inventory*. EPA's GHGRP mandates that all facilities that contain an aluminum production process must report: CF_4 and C_2F_6 emissions from anode effects in all prebake and Søderberg electrolysis cells, CO_2 emissions from anode consumption during electrolysis in all prebake and Søderberg cells, and all CO_2 emissions from onsite anode baking. To estimate the process emissions, EPA's GHGRP uses the process-specific equations detailed in Subpart F (aluminum production).[83] These equations are based on the Tier 2/Tier 3 IPCC (2006) methods for primary aluminum production, and Tier 1 methods when estimating missing data elements. It should be noted that the same methods (i.e., *2006 IPCC Guidelines*) were used for estimating the emissions prior to the availability of the reported GHGRP data in the *Inventory*. Prior to 2010, aluminum production data were provided through EPA's Voluntary Aluminum Industrial Partnership (VAIP).

As previously noted, the use of petroleum coke for aluminum production is adjusted for within the Energy chapter to avoid double counting emissions as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the

[83] Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. See https://www.ecfr.gov/cgi-bin/text-idx?SID=24a41781dfe4218b339e914de03e8727&mc=true&node=pt40.23.98&rgn=div5#sp40.23.98.f.

Methodology section of CO_2 from Fossil Fuel Combustion (3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels [CRT Source Category 1A]) and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Process CO_2 Emissions from Anode Consumption and Anode Baking

Carbon dioxide emission estimates for the years prior to the introduction of EPA's GHGRP in 2010 were estimated using *2006 IPCC Guidelines* methods, but individual facility reported data were combined with process-specific emissions modeling. These estimates were based on information previously gathered from EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, U.S. Geological Survey (USGS) Mineral Commodity reviews, and The Aluminum Association (USAA) statistics, among other sources. Since pre- and post-GHGRP estimates use the same methodology, emission estimates are comparable across the time series.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the carbon anode, as described by the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption, (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and/or following years, or (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all carbon in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a carbon consumption figure. This approach corresponds to either the IPCC Tier 2 or Tier 3 method, depending on whether smelter-specific data on anode impurities are used. The second approach interpolates smelter-specific anode consumption rates to estimate emissions during years for which anode consumption data are not available. This approach avoids substantial errors and discontinuities that could be introduced by reverting to Tier 1 methods for those years. The last approach corresponds to the IPCC Tier 1 method (IPCC 2006) and is used in the absence of present or historic anode consumption data.

The equations used to estimate CO_2 emissions in the Tier 2 and 3 methods vary depending on smelter type (IPCC 2006). For Prebake cells, the process formula accounts for various parameters, including net anode consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, the formula accounts for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. For Søderberg cells, the process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, anode consumption (and some anode impurity) data have been reported for 1990, 2000, 2003, 2004, 2005, 2006, 2007, 2008, and 2009. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, 13 out of 14 operating smelters in 2006, 5 out of 14 operating smelters in 2007 and 2008, and 3 out of 13 operating smelters in 2009. For years where CO_2 emissions data or CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming representative (e.g., previously reported or industry default) values.

In the absence of any previous historical smelter-specific process data (i.e., 1 out of 13 smelters in 2009; 1 out of 14 smelters in 2006, 2007, and 2008; 1 out of 15 smelters in 2005; and 5 out of 23 smelters between 1990 and

2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Process PFC Emissions from Anode Effects

High Voltage Anode Effects

Smelter-specific PFC emissions from aluminum production for 2010 through 2022 were reported to EPA under its GHGRP. To estimate their PFC emissions from HVAEs and report them under EPA's GHGRP, smelters use an approach identical to the Tier 3 approach in the *2006 IPCC Guidelines* (IPCC 2006). Specifically, they use a smelter-specific slope coefficient as well as smelter-specific operating data to estimate an emission factor using the following equation:

$$PFC = S \times AE$$

$$AE = F \times D$$

where,

PFC = CF_4 or C_2F_6, kg/MT aluminum

S = Slope coefficient, PFC/AE

AE = Anode effect, minutes/cell-day

F = Anode effect frequency per cell-day

D = Anode effect duration, minutes

They then multiply this emission factor by aluminum production to estimate PFC emissions from HVAEs. All U.S. aluminum smelters are required to report their emissions under EPA's GHGRP.

Perfluorocarbon emissions for the years prior to 2010 were estimated using the same equation, but the slope-factor used for some smelters was technology-specific rather than smelter-specific, making the method a Tier 2 rather than a Tier 3 approach for those smelters. Emissions and background data were reported to EPA under the VAIP. For 1990 through 2009, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 94 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC technology-specific slope coefficients were applied (IPCC 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP to estimate emission factors over time. For 1990 through 2009, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, representative values (e.g., previously reported or industry averages) were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2009, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS, and then allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions (see Table 1-5).

Table 4-105: Summary of HVAE Emissions (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HVAE Emissions	19.3	3.1	1.4	1.4	1.4	0.9	0.7

Low Voltage Anode Effects

LVAE emissions of CF_4 were estimated for 2006 through 2022 (see Table 1-6) based on the Tier 1 (technology-specific, production-based) method in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019). Prior to 2006, LVAE emissions are believed to have been negligible.[84] The Tier 1 method is used in the LVAE emissions calculations from aluminum production in the absence of smelter-specific data available to quantify the LVAE-specific process emissions. National aluminum production estimates (allocated to smelters as described below) and the technology used in individual smelters were the best available data to perform the emissions calculations, as smelter-specific production data is not publicly available.

The following equation was used to estimate LVAE PFC emissions:

Equation 4-15: CF_4 Emissions Resulting from Low Voltage Anode Effects

$$LVAE\ E_{CF4} = LVAE\ EF_{CF4} \times MP$$

where,

LVAE E_{CF4} = LVAE emissions of CF_4 from aluminum production, kg CF_4

LVAE EF_{CF4} = LVAE emission factor for CF_4 (default by cell technology type)

MP = Metal production by cell technology type, tons Al.

In the LVAE emissions calculations, the Metal Production (MP) factor is calculated differently for the years 2006 through 2009 than for 2010 and beyond. For years prior to GHGRP reporting (2006 through 2009), the MP factor is calculated by dividing the annual production reported by USGS with the total U.S. capacity reported for this specific year, based on the USGS yearbook and applying this national utilization factor to each facility's production capacity to obtain an estimated facility production value. For GHGRP reporting years (2010+), the methodology to calculate the MP value was changed to allocate the total annual production reported by USAA, based on the distribution of CO_2 emissions amongst the operating smelters in a specific year. The latter improves the accuracy of the LVAE emissions estimates over assuming capacity utilization is the same at all smelters. The main drawback of using this methodology to calculate the MP factor is that, in some instances, it led to production estimates that are slightly larger (less than six percent) than the production capacity reported that year. In practice, this is most likely explained by the differences in process efficiencies at each facility and to a lesser extent, differences in measurements and methods used by each facility to obtain their CO_2 estimates and the degree of uncertainty in the USGS annual production reporting.

Once LVAE emissions were estimated, they were then combined with HVAE emissions estimates to calculate total PFC emissions from aluminum production.

Table 4-106: Summary of LVAE Emissions (MMT CO_2 Eq.)

Year	2006	2018	2019	2020	2021	2022
LVAE Emissions	0.13	0.05	0.07	0.06	0.05	0.05

Production Data

Between 1990 and 2009, production data were provided under the VAIP by 21 of the 23 U.S. smelters that operated during at least part of that period. For the non-reporting smelters, production was estimated based on

[84] The *2019 Refinement* states, "Since 2006, the global aluminum industry has undergone changes in technology and operating conditions that make LVAE emissions much more prevalent[12]; these changes have occurred not only through uptake of newer technologies (e.g., $PFPB_L$ to $PFPB_M$) but also during upgrades within the same technology in order to maximize productivity and reduce energy use" (IPCC 2019). Footnote #12 uses the example of $PFPB_L$, which is prevalent in the United States, as an older technology that has been upgraded.

the difference between reporting smelters and national aluminum production levels as reported to USGS, with allocation to specific smelters based on reported production capacities (USGS 1990 through 2009).

National primary aluminum production data for 2010 through 2022 were compiled using USGS Mineral Industry Surveys, and the USGS Mineral Commodity Summaries (see Table 1-7).

Table 4-107: Production of Primary Aluminum (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	4,048	2,481	891	1,093	1,012	889	860

Methodological approaches were applied to the entire time-series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty was estimated for the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP, taking into consideration the uncertainties associated with aluminum production, anode effect minutes, and slope factors. The uncertainty bounds used for these parameters were established based on information collected under the VAIP and held constant through 2022. Uncertainty surrounding the reported CO_2, CF_4, and C_2F_6 emission values were determined to have a normal distribution with uncertainty ranges of approximately 6 percent below to 6 percent above, 16 percent below to 16 percent above, and 20 percent below to 20 percent above their 2022 emission estimates, respectively.

For LVAE, since emission values were not reported through EPA's GHGRP but estimated instead through a Tier 1 methodology, the uncertainty analysis examined uncertainty associated with primary capacity data as well as technology-specific emission factors. Uncertainty for each facility's primary capacity, reported in the USGS Yearbook, was estimated to have a Pert Beta distribution with an uncertainty range of 7 percent below to 7 percent above the capacity estimates based on the uncertainty of reported capacity data, the number of years since the facility reported new capacity data, and uncertainty in capacity utilization. Uncertainty was applied to LVAE emission factors according to technology using the uncertainty ranges provided in the *2019 Refinement to the 2006 IPCC Guidelines*. An uncertainty range for Horizontal Stud Søderberg (HSS) technology was not provided in the *2019 Refinement to the 2006 IPCC Guidelines* due to insufficient data, so a normal distribution and uncertainty range of ±99 percent was applied for that technology based on expert judgment. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2, CF_4, and C_2F_6 emission estimates for the U.S. aluminum industry as a whole, and the results are provided below.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-108. Aluminum production-related CO_2 emissions were estimated to be between 1.41 and 1.48 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 3 percent below to 3 percent above the emission estimate of 1.446 MMT CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 0.62 and 0.73 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 8 percent above the emission estimate of 0.676 MMT CO_2 Eq. Aluminum production-related C_2F_6 emissions were estimated to be between 0.075 and 0.09 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the emission estimate of 0.083 MMT CO_2 Eq. Finally, Aluminum production-related aggregated PFCs emissions were estimated to be between 0.71 and 0.82 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below to 7 percent above the emission estimate of 0.759 MMT CO_2 Eq.

Table 4-108: Approach 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	1.446	1.41	1.48	-3%	+3%
Aluminum Production	CF_4	0.676	0.62	0.73	-8%	+8%
Aluminum Production	C_2F_6	0.083	0.075	0.09	-9%	+9%
Aluminum Production	PFCs	0.759	0.71	0.82	-7%	+7%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[85] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CO_2 and PFC emissions from aluminum production.

4.21 Magnesium Production and Processing (CRT Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. This reporting category (2C4) includes emissions from magnesium metal production and processing. Sulfur hexafluoride has been used in this application around the world for more than 30 years. A dilute gaseous mixture of SF_6 with dry air and/or carbon dioxide (CO_2) is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride.

[85] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

The amount of SF_6 reacting in magnesium production and processing is considered to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Alternative cover gases, such as AM-cover™ (containing HFC-134a), Novec™ 612 (FK-5-1-12) and dilute sulfur dioxide (SO_2) systems can and are being used by some facilities in the United States. However, many facilities in the United States are still using traditional SF_6 cover gas systems. Carbon dioxide is also released during primary magnesium production if carbonate based raw materials, such as dolomite, are used. During the processing of these raw materials to produce magnesium, calcination occurs which results in a release of CO_2 emissions.

The magnesium industry emitted 1.1 MMT CO_2 Eq. (0.05 kt) of SF_6, 0.03 MMT CO_2 Eq. (0.02 kt) of HFC-134a, and 0.003 MMT CO_2 Eq. (2.9 kt) of CO_2 in 2022. This represents a decrease of approximately 4 percent from total 2021 emissions (see Table 4-109 and Table 4-110) and a decrease in SF_6 emissions by 3 percent. In 2022, total HFC-134a emissions decreased from 0.040 MMT CO_2 Eq. to 0.029 MMT CO_2 Eq., or a 28 percent decrease as compared to 2021 emissions. FK 5-1-12 emissions in 2022 were consistent with 2021. The emissions of the carrier gas, CO_2, increased from 2.91 kt in 2021 to 2.94 kt in 2022, or 1 percent.

Table 4-109: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	5.6	3.0	1.1	0.9	0.9	1.2	1.1
HFC-134a	0.0	0.0	0.1	0.1	0.1	+	+
CO_2	0.1	+	+	+	+	+	+
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*
Total	**5.7**	**3.0**	**1.1**	**1.0**	**0.9**	**1.2**	**1.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions of FK 5-1-12 are not included in totals.

Note: Totals may not sum due to independent rounding.

Table 4-110: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (kt)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	0.2	0.1	+	+	+	+	+
HFC-134a	0.0	0.0	0.1	+	+	+	+
CO_2	129.0	3.6	1.6	2.4	3.0	2.9	2.9
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*

+ Does not exceed 0.5 kt

[a] Emissions of FK 5-1-12 are not included in totals.

Methodology and Time-Series Consistency

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry as well as emissions data reported through Subpart T (Magnesium Production and Processing) of EPA's GHGRP. The Partnership started in 1999 and, in 2010, participating companies represented 100 percent of U.S. primary and secondary production and 16 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). SF_6 emissions for 1999 through 2010 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. Partners reported their SF_6 consumption, which is assumed to be equivalent to emissions. Along with SF_6, some Partners reported their HFC-134a and FK 5-1-12 consumed, which is also assumed to be equal to emissions. The last reporting year under the Partnership was 2010. Emissions data for 2011 through 2020 are obtained through EPA's GHGRP. Under the program, owners or operators of facilities that have a magnesium production or casting process must report emissions from use of cover or carrier gases, which include SF_6, HFC-134a, FK 5-1-12 and CO_2. Consequently, cover and carrier gas emissions from magnesium

production and processing were estimated for three time periods, depending on the source of the emissions data: 1990 through 1998 (pre-EPA Partnership), 1999 through 2010 (EPA Partnership), and 2011 through 2022 (EPA GHGRP). The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS) as available.

1990 through 1998

To estimate emissions for 1990 through 1998, industry SF_6 emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. For this period, it was assumed that there was no use of HFC-134a or FK 5-1-12 cover gases, and hence emissions were not estimated for these alternatives.

Sulfur hexafluoride emission factors from 1990 through 1998 were based on a number of sources and assumptions. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995. The primary production emission factors were 1.2 kg SF_6 per metric ton for 1990 through 1993, and 1.1 kg SF_6 per metric ton for 1994 through 1997. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average Partner value. An emission factor for die casting of 4.1 kg SF_6 per metric ton, which was available for the mid-1990s from an international survey (Gjestland and Magers 1996), was used for years 1990 through 1996. For 1996 through 1998, the emission factor for die casting was assumed to decline linearly to the level estimated based on Partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that was reported in the RAND survey of major SF_6 manufacturers, which showed a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 1990 through 2001 were assumed to be the same as the 2002 emission factor for all but one facility, which used an emission factor derived from 2011 GHGRP data and held constant to back cast emissions for 1990-1998. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-110. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

The quantities of CO_2 carrier gas used for each production type have been estimated using the 1999 estimated CO_2 emissions data and the annual calculated rate of change of SF_6 use in the 1990 through 1999 time period. For each year and production type, the rate of change of SF_6 use between the current year and the subsequent year was first estimated. This rate of change was then applied to the CO_2 emissions of the subsequent year to determine the CO_2 emission of the current year.

Carbon dioxide emissions from the calcination of dolomite in the primary production of magnesium were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the estimated primary production of magnesium by an emissions factor of 3.62 kilogram of CO_2 per kilogram of magnesium produced.[86] For 1990 through 1998, production was estimated to be equal to the production capacity of the facility.

1999 through 2010

The 1999 through 2010 emissions from primary and secondary production were based on information provided by EPA's industry Partners. In some instances, there were years of missing Partner data, including SF_6 consumption and metal processed. For these situations, emissions were estimated through interpolation where possible, or by holding company-reported emissions (as well as production) constant from the previous year. For alternative cover gases, including HFC-134a and FK 5-1-12, mainly reported data was relied upon. That is, unless a Partner reported using an alternative cover gas, it was not assumed it was used. Emissions of alternate gases were also estimated through linear interpolation where possible.

[86] See https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_4_Ch4_Metal_Industry.pdf.

The die casting emission estimates for 1999 through 2010 were also based on information supplied by industry Partners. When a Partner was determined to be no longer in production, its metal production and usage rates were set to zero. Missing data on emissions or metal input was either interpolated or held constant at the last available reported value. In 1999 through 2010, Partners were assumed to account for all die casting tracked by USGS. For 1999, die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. This emission factor was developed using magnesium production and SF_6 usage data for the year 1999. In 2008, the derived emission factor for die casting began to increase after many years of largely decreasing emission factors. As determined through an analysis of activity data reported from the USGS, this increase is due to a temporary decrease in production at many facilities between 2008 and 2010, which reflects the change in production that occurred during the recession.

The emissions from other casting operations were estimated by multiplying emission factors (kg SF_6 per metric ton of metal produced or processed) by the amount of metal produced or consumed from USGS, with the exception of some years for which Partner sand casting emissions data are available. The emission factors for sand casting activities were acquired through the data reported by the Partnership for 2002 to 2006. For 1999 through 2001, the sandcasting emission factor was held constant at the 2002 Partner-reported level. For 2007 through 2010, the sandcasting Partner did not report and the reported emission factor from 2005 was applied to the Partner and to a non GHGRP sand casters. Activity data for 2005 was obtained from USGS (USGS 2005b). One non partner sand casting facility reported to GHGRP in 2011 and had an emission factor derived for 2011, this factor was used to back cast emissions for this facility from 1999 to 2010.

The emission factors for primary production, secondary production and sand casting for the 1999 to 2010 are not published to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 Partner value of 1.1 kg SF_6 per metric ton. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives. The emission factors for casting activities are provided below in Table 4-111.

The emissions of HFC-134a and FK-5-1-12 were included in the estimates for only instances where Partners reported that information to the Partnership. Emissions of these alternative cover gases were not estimated for instances where emissions were not reported.

Carbon dioxide carrier gas emissions were estimated using the emission factors developed based on GHGRP-reported carrier gas and cover gas data, by production type. It was assumed that the use of carrier gas, by production type, is proportional to the use of cover gases. Therefore, an emission factor, in kg CO_2 per kg cover gas and weighted by the cover gases used, was developed for each of the production types. GHGRP data, on which these emissions factors are based, was available for primary, secondary, die casting and sand casting. The emission factors were applied to the quantity of all cover gases used (SF_6, HFC-134a, and FK-5-1-12) by production type in this time period for producers that reported CO_2 emissions from 2011-2022 through the GHGP. Carrier gas emissions for the 1999 through 2010 time period were only estimated for those Partner companies that reported using CO_2 as a carrier gas through the GHGRP. Using this approach helped ensure time-series consistency. Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using the ratio of total CO_2 emissions to total cover gas emissions for primary, secondary, die and sand in a given year and the total SF_6 emissions from each permanent mold, wrought, and anodes processes respectively in that same year. CO_2 emissions from the calcination of dolomite were estimated using the same approach as described above. At the end of 2001, the sole magnesium production plant operating in the United States that produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions ceased its operations (USGS 1995b through 2023).

Table 4-111: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Die Casting[a]	Permanent Mold	Wrought	Anodes
1999	1.75[b]	2	1	1
2000	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.79	2	1	1
2005	0.77	2	1	1
2006	0.88	2	1	1
2007	0.64	2	1	1
2008	0.97	2	1	1
2009	1.41	2	1	1
2010	1.43	2	1	1

[a] Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000 through 2010), Partners made up 100 percent of die casters in the United States.

[b] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

2011 through 2022

For 2011 through 2022, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For sand and die casting, some emissions data was obtained through EPA's GHGRP. Additionally, in 2018 a new GHGRP reporter began reporting permanent mold emissions. The balance of the emissions for this industry segment was estimated based on previous Partner reporting (i.e., for Partners that did not report emissions through EPA's GHGRP) or were estimated by multiplying emission factors by the amount of metal produced or consumed. Partners who did not report through EPA's GHGRP were assumed to have continued to emit SF_6 at the last reported level, which was from 2010 in most cases, unless publicly available sources indicated that these facilities have closed or otherwise eliminated SF_6 emissions from magnesium production (ARB 2015). Many Partners that did report through the GHGRP showed increases in SF_6 emissions driven by increased production related to a continued economic recovery after the 2008 recession. One Partner in particular reported an anonymously large increase in SF_6 emissions from 2010 to 2011, further driving increases in emissions between the two time periods of inventory estimates. All Partners were assumed to have continued to consume magnesium at the last reported level. Where the total metal consumption estimated for the Partners fell below the U.S. total reported by USGS, the difference was multiplied by the emission factors discussed in the section above, i.e., non-partner emission factors. For the other types of production and processing (i.e., permanent mold, wrought, and anode casting), emissions were estimated by multiplying the industry emission factors with the metal production or consumption statistics obtained from USGS (USGS 1995b-2023). USGS data for 2022 were not yet available at the time of the analysis, so the 2021 values were held constant through 2022 as an estimate.

Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using an approach consistent with the 1999 through 2010 time series.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022. 2006 IPCC Guidance methodologies were used throughout the time series, mainly either a Tier 2 or Tier 3 approach depending on available data.

Uncertainty

Uncertainty surrounding the total estimated emissions in 2022 is attributed to the uncertainties around SF_6, HFC-134a, and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2022 SF_6 emissions from

magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2022 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2022 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. An uncertainty of 5 percent was assigned to the emissions (usage) data reported by each GHGRP reporter for all the cover and carrier gases (per the *2006 IPCC Guidelines*). If facilities did not report emissions data during the current reporting year through EPA's GHGRP, SF_6 emissions data were held constant at the most recent available value reported through the Partnership. The uncertainty associated with these values was estimated to be 30 percent for each year of extrapolation (per the *2006 IPCC Guidelines*). The uncertainty of the total inventory estimate remained relatively constant between 2021 and 2022.

Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-111). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with die casting and sand casting activities utilized emission factors based on Partner reported data with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Previous measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-112. Total emissions associated with magnesium production and processing were estimated to be between 1.06 and 1.24 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7.9 percent below to 7.7 percent above the 2022 emission estimate of 1.15 MMT CO_2 Eq. The uncertainty estimates for 2022 are slightly higher to the uncertainty reported for 2021 in the previous *Inventory*. This increase in uncertainty is attributed to the increased number of facilities with interpolated emissions and the increasing number of years for facilities with emissions held constant.

Table 4-112: Approach 2 Quantitative Uncertainty Estimates for SF_6, HFC-134a and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6, HFC-134a, CO_2	1.2	1.1	1.2	-7.9%	+7.7%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the

introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[87] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

One die casting facility which had previously had emissions back cast at a constant level had its back casting methodology updated using linear growth from 0 to reported emissions levels between 2001 and 2014, resulting in decreases in SF_6 emissions across 2001 to 2013.

Sand Casting Emissions for 2021 were updated based on 2021 specific data available in the 2021 data tables release from USGS's Mineral Yearbook. 2021 data was previously held constant at 2020 levels due to USGS Mineral Yearbook data only going through 2020. The updated production of sand cast magnesium was larger than what was estimated for 2021 in the previous *Inventory* cycle leading to an increase in SF_6 emissions in 2021.

One sand casting facility, which had previously only been estimated from 2011 onward, was confirmed to have emissions across the time series, an updated emission factor for 2011 was calculated and used to back cast emissions from 1990 to 2010.

Review of facility responses indicate that changes over time in the emission factors for this industry have occurred as facilities switch to using systems with cover gases other than SF_6 (e.g. SO_2) and also during time-periods where back-up SF_6-based systems are used due to the failure of the primary (non-SF_6) system have occurred, leading to the periodic spike in SF_6 usage rates.

Planned Improvements

Cover gas research conducted over the last decade has found that SF_6 used for magnesium melt protection can have degradation rates on the order of 20 percent in die casting applications (Bartos et al. 2007). Current emission estimates assume (per the *2006 IPCC Guidelines*) that all SF_6 utilized is emitted to the atmosphere. Additional research may lead to a revision of the *2006 IPCC Guidelines* to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the *Inventory* methodology.

Additional emissions are generated as byproducts from the use of alternate cover gases, which are not currently accounted for. Research on this topic is developing, and as reliable emission factors become available, these emissions will be incorporated into the *Inventory.*

4.22 Lead Production (CRT Source Category 2C5)

In 2022, lead was produced in the United States using only secondary production processes. Until 2014, lead production in the United States involved both primary and secondary processes—both of which emit carbon

[87] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

dioxide (CO_2) (Sjardin 2003). This reporting category (2C5) includes emissions from the production of lead. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of lead are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). Primary lead production, in the form of direct smelting, previously occurred at a single smelter in Missouri. This primary lead smelter was closed at the end of 2013, and a small amount of residual lead was processed during demolition of the facility in 2014 (USGS 2015). Beginning in 2015, primary lead production no longer occurred in the United States.

Similar to primary lead production, CO_2 emissions from secondary lead production result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process. Carbon dioxide emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin 2003). Secondary production primarily involves the recycling of lead acid batteries and post-consumer scrap at secondary smelters. Secondary lead production in the United States has fluctuated over the past 20 years, reaching a high of 1,180,000 metric tons in 2007 and again in 2019. In 2022, secondary lead production accounted for 100 percent of total U.S. lead production. The lead-acid battery industry accounted for about 92 percent of the reported U.S. lead consumption in 2022 (USGS 2023a).

In 2022, secondary lead production in the United States decreased by approximately 3 percent compared to 2021 (USGS 2023a). Secondary lead production in 2022 is 3 percent higher than in 1990 (USGS 1994 and 2023a). The United States has become more reliant on imported refined lead, owing to the closure of the last primary lead smelter in 2013. Exports of spent starting-lighting-ignition (SLI) batteries decreased between 2014 and 2017, and subsequently recovered beginning in 2018. Exports were 10 percent higher in the first 9 months of 2021 compared to the same time period in 2014 (USGS 2015 through 2023b). In the first 9 months of 2022, 24.6 million spent SLI lead-acid batteries were exported, 4 percent less than that in the same time period in 2021 (USGS 2023b).

Emissions of CO_2 from lead production in 2022 were 0.4 MMT CO_2 Eq. (428 kt), which is a 3 percent decrease compared to 2021 and a 17 percent decrease compared to 1990 (see Table 4-113 and Table 4-114) (USGS 1994; USGS 2023a; USGS 2023b).

The United States was the third largest mine producer of lead in the world, behind China and Australia, and accounted for approximately 6 percent of world production in 2022 (USGS 2023a).

Table 4-113: CO_2 Emissions from Lead Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4

Table 4-114: CO_2 Emissions from Lead Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Lead Production	516	553	527	531	450	439	428

Methodology and Time-Series Consistency

Carbon dioxide emissions from lead production[88] are calculated based on Sjardin's work (Sjardin 2003) for lead production emissions and use Tier 1 methods from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. The Tier 1 equation is as follows:

Equation 4-16: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions From Lead Production (Equation 4.32)

$$CO_2\ Emissions = (DS\ \times EF_{DS})\ + (S\ \times EF_S)$$

where,

DS	=	Lead produced by direct smelting, metric ton
S	=	Lead produced from secondary materials
EF_{DS}	=	Emission factor for direct smelting, metric tons CO_2/metric ton lead product
EF_S	=	Emission factor for secondary materials, metric tons CO_2/metric ton lead product

For primary lead production using direct smelting, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO_2/metric ton lead produced for the treatment of secondary raw materials (i.e., pretreatment of lead acid batteries). Since the secondary production of lead involves both the use of the direct smelting process and the treatment of secondary raw materials, Sjardin recommends an additive emission factor to be used in conjunction with the secondary lead production quantity. The direct smelting factor (0.25) and the sum of the direct smelting and pretreatment emission factors (0.45) are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The production and use of coking coal for lead production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion (CRT Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

The 1990 through 2022 activity data for primary and secondary lead production (see Table 4-115) were obtained from the U.S. Geological Survey (USGS 1994 through 2023a).

Table 4-115: Lead Production (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Primary	404,000	143,000	0	0	0	0	0
Secondary	922,000	1,150,000	1,170,000	1,180,000	1,000,000	975,000	950,000

Methodological approaches discussed below were applied to applicable years to ensure time-series consistency in emissions from 1990 through 2022.

[88] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Lead Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

Uncertainty

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averaged the values provided by three other studies (Dutrizac et al. 2000; Morris et al. 1983; Ullman 1997). For secondary production, Sjardin (2003) added a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. EPA assigned an uncertainty range of ±20 percent for these emission factors, and using this suggested uncertainty provided in Table 4.23 of the *2006 IPCC Guidelines* for a Tier 1 emission factor by process type is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assumed for emission factors.

There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS which is collected via voluntary surveys; the uncertainty of the activity data is a function of the reliability of reported plant-level production data and the completeness of the survey response. EPA currently uses an uncertainty range of ±10 percent for primary and secondary lead production, and using this suggested uncertainty provided in Table 4.23 of the *2006 IPCC Guidelines* for Tier 1 national production data is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assumed for all activity data.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-116. Lead production CO_2 emissions in 2022 were estimated to be between 0.4 and 0.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below and 16 percent above the emission estimate of 0.4 MMT CO_2 Eq.

Table 4-116: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO_2	0.4	0.4	0.5	-15%	+16%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Initial review of activity data show that EPA's GHGRP Subpart R lead production data and resulting emissions are fairly consistent with those reported by USGS. EPA is still reviewing available GHGRP data, reviewing QC analysis to understand differences in data reporting (i.e., threshold implications), and assessing the possibility of including this planned improvement in future *Inventory* reports (see Planned Improvements section below). Currently, GHGRP data are used for QA purposes only.

Recalculations Discussion

Recalculations were implemented for 2020 and 2021 based on revised USGS data for secondary lead production. Compared to the previous *Inventory*, emissions decreased by 3 percent (14 kt CO_2) for 2020 and by 2 percent (7 kt CO_2) for 2021 (USGS 2023b).

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Lead Production source category, in particular considering completeness of reported lead production given the reporting threshold. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[89]

4.23 Zinc Production (CRT Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes currently used in the United States, only the electrothermic and Waelz kiln secondary processes result in non-energy carbon dioxide (CO_2) emissions (Viklund-White 2000). This reporting category (2C6) includes emissions from the production of zinc. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of zinc are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

The majority of zinc produced in the United States is used for galvanizing. Galvanizing is a process where zinc coating is applied to steel in order to prevent corrosion. Zinc is used extensively for galvanizing operations in the automotive and construction industry. Zinc is also used in the production of zinc alloys and brass and bronze alloys (e.g., brass mills, copper foundries, and copper ingot manufacturing). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

Production of zinc can be conducted with a range of pyrometallurgical (e.g., electrothermic furnace, Waelz kiln, flame reactor, batch retorts, Pinto process, and PIZO process) and hydrometallurgical (e.g., hydrometallurgical recovery, solvent recovery, solvent extraction-electrowinning, and electrolytic) processes. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003). Primary production in the United States is conducted through the non-emissive electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other processes. Worldwide primary zinc production also employs a pyrometallurgical process using an Imperial Smelting Furnace; however, this process is not used in the United States (Sjardin 2003).

In the electrothermic process, roasted zinc concentrate and secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke is added to the electric retort furnace as a carbon-containing reductant. This concentration step, using metallurgical coke and high temperatures, reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process also generates non-energy CO_2 emissions.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

[89] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \quad \text{(Reaction 2)}$$

In the Waelz kiln process, electric arc furnace (EAF) dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent (typically carbon-containing metallurgical coke). When kiln temperatures reach approximately 1,100 to 1,200 degrees Celsius, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. The use of carbon-containing metallurgical coke in a high-temperature fuming process results in non-energy CO_2 emissions. Through this process, approximately 0.33 metric tons of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

In the flame reactor process, a waste feed stream, which can include EAF dust, is processed in a high-temperature environment (greater than 2,000 °C) created by the combustion of natural gas or coal and oxygen-enriched air. Volatile metals, including zinc, are forced into the gas phase and drawn into a combustion chamber, where air is introduced and oxidation occurs. The metal oxide product is then collected in a dust collection system (EPA 1992).

In 2022, the only companies in the United States that used emissive technology to produce secondary zinc products were Befesa Holding US Inc (Befesa) and Steel Dust Recycling (SDR). The secondary zinc facilities operated by Befesa were acquired from American Zinc Recycling (AZR) (formerly "Horsehead Corporation") in 2021. PIZO Operating Company, LLC (PIZO) operated a secondary zinc production facility that processed EAF dust in Blytheville, AR from 2009 to 2012.

For Befesa, EAF dust is recycled in Waelz kilns at their Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. The former AZR facility in Beaumont, TX processed EAF dust via flame reactor from 1993 through 2009 (AZR 2021, Horsehead 2014). These Waelz kiln and flame reactor facilities produce intermediate zinc products (crude zinc oxide or calcine). Prior to 2014, most of output from these facilities were transported to their Monaca, PA facility where the products were smelted into refined zinc using electrothermic technology. In April 2014, the Monaca smelter was permanently closed and replaced by a new facility in Mooresboro, NC in 2014.

The Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products, which is assumed to be non-emissive as described above. Production at the Mooresboro facility was idled in April 2016 and re-started in March 2020 (Recycling Today 2020). Direct consumption of coal, coke, and natural gas were replaced with electricity consumption (Horsehead 2012b). The Mooresboro facility uses leaching and solvent extraction (SX) technology combined with electrowinning, melting, and casting technology. In this process, Waelz Oxide (WOX) is first washed in water to remove soluble elements such as chlorine, potassium, and sodium, and then is leached in a sulfuric acid solution to dissolve the contained zinc creating a pregnant liquor solution (PLS). The PLS is then processed in a solvent extraction step in which zinc is selectively extracted from the PLS using an organic solvent creating a purified zinc-loaded electrolyte solution. The loaded electrolyte solution is then fed into the electrowinning process in which electrical energy is applied across a series of anodes and cathodes submerged in the electrolyte solution causing the zinc to deposit on the surfaces of the cathodes. As the zinc metal builds up on these surfaces, the cathodes are periodically harvested in order to strip the zinc from their surfaces (Horsehead 2015).

SDR recycles EAF dust into intermediate zinc products using Waelz kilns and sells the intermediate products to companies who smelt it into refined products.

Emissions of CO_2 from zinc production in 2022 were estimated to be 0.9 MMT CO_2 Eq. (947 kt CO_2) (see Table 4-117). All 2022 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the United States have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2022, emissions were estimated to be 50 percent higher than they were in 1990. Emissions decreased 6 percent from 2021 levels.

Table 4-117: CO_2 Emissions from Zinc Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9

Table 4-118: CO_2 Emissions from Zinc Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Zinc Production	632	1,030	999	1,026	977	1,007	947

U.S. zinc mine production increased by 9 percent in 2022 compared to 2021, due in part to higher mill throughput and zinc ore grades at the Red Dog Mine in Alaska, the largest zinc mine in the United States. In 2022, United States primary and secondary refined zinc production were estimated to total 220,000 metric tons (USGS 2023) (see Table 4-119), remaining at approximately the same production level as in 2021. Secondary zinc production fell to its lowest point in the time series in 2019, following the closure of the Monaca, PA smelter in 2014 and issues with the AZR secondary zinc refinery in Mooresboro, NC. Secondary zinc production has increased significantly since the reopening of the idled Mooresboro facility in March 2020 (USGS 2021; AZP 2021).

Table 4-119: Zinc Production (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Primary	262,704	191,120	101,000	101,000	101,000	101,000	101,000
Secondary	95,708	156,000	15,000	14,000	79,000	119,000	119,000
Total	**358,412**	**347,120**	**116,000**	**115,000**	**180,000**	**220,000**	**220,000**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 emissions from zinc production[90] using the electrothermic primary production and Waelz kiln secondary production processes are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data (IPCC 2006). The Tier 1 equation used to estimate emissions from zinc production is as follows:

Equation 4-17: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Zinc Production (Equation 4.33)

$$E_{CO2} = Zn \times EF_{default}$$

where,

E_{CO_2} = CO_2 emissions from zinc production, metric tons

Zn = Quantity of zinc produced, metric tons

$EF_{default}$ = Default emission factor, metric tons CO_2/metric ton zinc produced

The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from metallurgical coke consumption factors and other data presented in Vikland-White (2000). These coke consumption factors as well as other inputs used to develop the Waelz kiln emission factors are shown below. IPCC does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were also applied to zinc produced from electrothermic processes. Starting in 2014, refined zinc produced in the United States used hydrometallurgical processes and is assumed to be non-emissive.

[90] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Zinc Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

For Waelz kiln-based production, IPCC recommends the use of emission factors based on EAF dust consumption, if possible, rather than the amount of zinc produced since the amount of reduction materials used is more directly dependent on the amount of EAF dust consumed. Since only a portion of emissive zinc production facilities consume EAF dust, the emission factor based on zinc production is applied to the non-EAF dust consuming facilities, while the emission factor based on EAF dust consumption is applied to EAF dust consuming facilities.

The Waelz kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced (i.e., 1.19 metric tons coke/metric ton zinc produced) (Viklund-White 2000), and the following equation:

Equation 4-18: Waelz Kiln CO_2 Emission Factor for Zinc Produced

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

Refined zinc production levels for AZR's Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). The Monaca facility was permanently shut down in April 2014 and replaced by AZR's new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

Metallurgical coke consumption for non-EAF dust consuming facilities for 1990 through 2004 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States, as provided by the U.S. Geological Survey (USGS) *Minerals Yearbook: Zinc* (USGS 1994 through 2006). Metallurgical coke consumption for 2005 through 2013 were based on the secondary zinc production values obtained from the Horsehead Corporation Annual Report Form 10-K: 2005 through 2008 from the 2008 10-K (Horsehead Corp 2009); 2009 and 2010 from the 2010 10-K (Horsehead Corp. 2011); and 2011 through 2013 from the associated 10-K (Horsehead Corp. 2012a, 2013, 2014). Metallurgical coke consumption levels for 2014 and later were zero due to the closure of the AZR (formerly "Horsehead Corporation") electrothermic furnace facility in Monaca, PA. The secondary zinc produced values for each year were then multiplied by the 3.70 metric tons CO_2/metric ton zinc produced emission factor to develop CO_2 emission estimates for the AZR electrothermic furnace facility.

The Waelz kiln emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed (i.e., 0.4 metric tons coke/metric ton EAF dust consumed) (Viklund-White 2000), and the following equation:

Equation 4-19: Waelz Kiln CO_2 Emission Factor for EAF Dust Consumed

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

Metallurgical coke consumption for EAF dust consuming facilities for 1990 through 2022 were calculated based on the values of EAF dust consumed. The total amount of EAF dust consumed by the Waelz kilns currently operated by Befesa was available from AZR (formerly "Horsehead Corporation") in financial reports for years 2006 through 2015 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, 2015, and 2016), from correspondence with AZR for 2016 through 2019 (AZR 2020), and from correspondence with Befesa for 2020 through 2022 (Befesa 2022, 2023). The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor to develop CO_2 emission estimates for Befesa's Waelz kiln facilities.

The amount of EAF dust consumed by SDR and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2022 (SDR 2012, 2014, 2015, 2017, 2018, 2021, 2022, 2023). The SDR facility has been operational since 2008, underwent expansion in 2011 to include a second unit (operational since early- to mid-2012), and expanded its capacity again in 2017 (SDR 2018). Annual consumption data for SDR was not publicly

available for the years 2008, 2009, and 2010. These data were estimated using data for AZR's Waelz kilns for 2008 through 2010 (Horsehead 2007, 2008, 2010a, 2010b, 2011). Annual capacity utilization ratios were calculated using AZR's annual consumption and total capacity for the years 2008 through 2010. AZR's annual capacity utilization ratios were multiplied with SDR's total capacity to estimate SDR's consumption for each of the years, 2008 through 2010 (SDR 2013). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to SDR's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

PIZO's facility in Arkansas was operational from 2009 to 2012 (PIZO 2021). The amount of EAF dust consumed by PIZO's facility for 2009 through 2012 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of AZR's Waelz kilns and multiplying this utilization ratio by PIZO's total capacity (PIZO 2012). EAF dust consumption for PIZO's facility for 2011 through 2012 were estimated by applying the average annual capacity utilization rates for AZR and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012; SDR 2012; PIZO 2012). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

The production and use of coking coal for zinc production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRT Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Beginning with the 2017 USGS *Minerals Commodity Summary: Zinc*, United States primary and secondary refined zinc production were reported as one value, total refined zinc production. Prior to this publication, primary and secondary refined zinc production statistics were reported separately. For years 2016 through 2022, only one facility produced primary zinc. Primary zinc produced from this facility was subtracted from the USGS 2016 to 2022 total zinc production statistic to estimate secondary zinc production for these years.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

There is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns. The estimate for the total amount of EAF dust consumed in Waelz kilns is based on combining the totals for (1) the EAF dust consumption value obtained for the kilns currently operated by Befesa (and formerly operated by AZR or Horsehead Corporation) and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated by SDR. For the 1990 through 2015 estimates, EAF dust consumption values for the kilns currently operated by Befesa were obtained from annual financial reports to the Securities and Exchange Commission (SEC) by AZR. In 2016, AZR reorganized as a private company and ceased providing annual reports to the SEC (Recycling Today 2017). EAF dust consumption values for subsequent years from the Befesa kilns and SDR have been obtained from personal communication with facility representatives. Since actual EAF dust consumption information is not available for PIZO's facility (2009 through 2010) and SDR's facility (2008 through 2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's website) by the capacity utilization factor for AZR (which was available from Horsehead Corporation financial reports).The EAF dust consumption for PIZO's facility for 2011 through 2012 was estimated by multiplying the average capacity utilization factor developed from AZR and SDR's annual capacity utilization rates by PIZO's EAF dust recycling capacity. Therefore, there is uncertainty associated with the assumption used to estimate PIZO's annual EAF dust consumption values for 2009 through 2012 and SDR's annual EAF dust consumption values for 2008 through 2010. EPA uses an uncertainty range of ±5 percent for these EAF dust consumption data inputs, based upon expert elicitation from the USGS commodity specialist. Per this expert judgment, a normal probability density function was assigned for EAF dust consumption data inputs.

There is also uncertainty associated with the emission factors used to estimate CO_2 emissions from secondary zinc production processes. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depends upon the accuracy of these materials balances. Data limitations prevented the development of emission factors for the electrothermic process. Therefore, emission factors for the Waelz kiln process were applied to both electrothermic and Waelz kiln production processes. Consistent with the ranges in Table 4.25 of the *2006 IPCC Guidelines*, EPA assigned an uncertainty range of ±20 percent for the Tier 1 Waelz kiln emission factors, which are provided by Viklund-White in the form of metric tons of coke per metric ton of EAF dust consumed and metric tons of coke per metric ton of zinc produced. In order to convert coke consumption rates to CO_2 emission rates, values for the heat and carbon content of coke were obtained from Table 4.2 – Tier 2 of the *2006 IPCC Guidelines*. An uncertainty range of ±10 percent was assigned to these coke data elements, and using the suggested uncertainty provided in Table 4.25, Tier 2 – National Reducing Agent & Process Materials Data of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors and the heat and carbon content of coke.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-120. Zinc production CO_2 emissions from 2022 were estimated to be between 0.8 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.9 MMT CO_2 Eq.

Table 4-120: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	0.9	0.8	1.1	-18%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for the year 2021 based on updated EAF dust consumption data. Compared to the previous *Inventory*, 2021 emissions from zinc production increased by 4 percent (38 kt CO_2).

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for zinc production, in particular considering completeness of reported zinc production given the reporting threshold. Given the small number of facilities in the United States, particular attention will be made to risks for disclosing CBI and ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing

improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[91] This is a long-term planned improvement, and EPA is still assessing the possibility of including this improvement in future *Inventory* reports.

4.24 Electronics Industry (CRT Source Category 2E)

The electronics industry uses multiple greenhouse gases in its manufacturing processes. In semiconductor manufacturing, these include long-lived fluorinated greenhouse gases used for plasma etching and chamber cleaning (CRT Source Category 2E1), fluorinated heat transfer fluids used for temperature control and other applications (CRT Source Category 2E4), and nitrous oxide (N_2O) used to produce thin films through chemical vapor deposition and in other applications (reported under CRT Source Category 2H3). Similar to semiconductor manufacturing, the manufacturing of micro-electro-mechanical systems (MEMS) devices (reported under CRT Source Category 2E5 Other) and photovoltaic (PV) cells (CRT Source Category 2E3) requires the use of multiple long-lived fluorinated greenhouse gases for various processes.

The gases most commonly employed in the electronics industry are trifluoromethane (hydrofluorocarbon (HFC)-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other fluorinated compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

In addition to emission estimates for these seven commonly used fluorinated gases, this *Inventory* contains emissions estimates for N_2O and other HFCs and unsaturated, low-GWP PFCs including C_5F_8, C_4F_6, HFC-32, HFC-41, and HFC-134a. These additional HFCs and PFCs are emitted from etching and chamber cleaning processes in much smaller amounts, accounting for 0.02 percent of emissions (in CO_2 Eq.) from these processes.

For semiconductors, a single 300 mm silicon wafer that yields between 400 to 600 semiconductor products (devices or chips) may require more than 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere. Plasma enhanced chemical vapor deposition (PECVD) chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is typically generated and emitted as a process byproduct. In some cases, emissions of the byproduct gas can rival or even exceed emissions of the input gas, as is the case for NF_3 used in remote plasma chamber cleaning, which often generates CF_4 as a byproduct.

[91] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

Nitrous oxide is used in manufacturing semiconductor devices to produce thin films by CVD and nitridation processes as well as for N-doping of compound semiconductors and reaction chamber conditioning (Doering 2000).

Liquid perfluorinated compounds are also used as heat transfer fluids (F-HTFs) for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated gas emissions (EPA 2006). Unweighted F-HTF emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers (specifically, PFPMIEs), and perfluoroalkylmorpholines. Three percent or less consist of HFCs, PFCs, and SF_6 (where PFCs are defined as compounds including only carbon and fluorine). With the exceptions of the hydrofluoroethers and most of the HFCs, all of these compounds are very long-lived in the atmosphere and have global warming potentials (GWPs) near 10,000.[92]

MEMS and photovoltaic cell manufacturing require thin film deposition and etching of material with a thickness of one micron or more, so the process is less intricate and complex than semiconductor manufacturing. The manufacturing process is different than semiconductors, but generally employs similar techniques. Like semiconductors, MEMS and photovoltaic cell manufacturers use fluorinated compounds for etching, cleaning reactor chambers, and temperature control. CF_4, SF_6, and the Bosch process (which consists of alternating steps of SF_6 and C_4F_8) are used to manufacture MEMS (EPA 2010). Photovoltaic cell manufacturing predominately uses CF_4, to etch crystalline silicon wafers, and C_2F_6 or NF_3 during chamber cleaning after deposition of SiN_x films (IPCC 2006), although other F-GHGs may be used. Similar to semiconductor manufacturing, both MEMS and photovoltaic cell manufacturing use N_2O in depositing films and other manufacturing processes. MEMS and photovoltaic manufacturing may also employ HTFs for cooling process equipment (EPA 2010).

Emissions from all fluorinated greenhouse gases (including F-HTFs) and N_2O for semiconductors, MEMS and photovoltaic cells manufacturing are presented in Table 4-121 below for the years 1990, 2005, and the period 2018 to 2022. The rapid growth of the electronics industry and the increasing complexity (growing number of layers and functions)[93] of electronic products led to an increase in emissions of 152 percent between 1990 and 1999, when emissions peaked at 8.4 MMT CO_2 Eq. Emissions began to decline after 1999, reaching a low point in 2009 before rebounding to 2006 emission levels and more or less plateauing at the current level, which represents a 43 percent decline from 1999 to 2022. Together, industrial growth, adoption of emissions reduction technologies (including but not limited to abatement technologies) and shifts in gas usages resulted in a net increase in emissions of approximately 43 percent between 1990 and 2022. Total emissions from semiconductor manufacture in 2022 were lower than 2021 emissions, decreasing by 2.2 percent, largely due to a large decrease in SF_6 emissions. The decrease in SF_6 are seen in facilities that manufacture 200 mm wafer size that do not have abatement systems installed as well as 300 mm wafer size that have abatement systems installed.

For U.S. semiconductor manufacturing in 2022, total CO_2-equivalent emissions of all fluorinated greenhouse gases and N_2O from deposition, etching, and chamber cleaning processes were estimated to be 4.7 MMT CO_2 Eq. This is a

[92] The GWP of PFPMIE, a perfluoropolyether used as an F-HTF, is included in the IPCC *Fourth Assessment Report* with a value of 10,300. The GWPs of the perfluorinated amines and perfluoroalkylmorpholines that are used as F-HTFs have not been evaluated in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (78 FR 20632), which is expected given that these compounds are both saturated and fully fluorinated. EPA assigns a default GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[93] Complexity is a term denoting the circuit required to connect the active circuit elements (transistors) on a chip. Increasing miniaturization, for the same chip size, leads to increasing transistor density, which, in turn, requires more complex interconnections between those transistors. This increasing complexity is manifested by increasing the levels (i.e., layers) of wiring, with each wiring layer requiring fluorinated gas usage for its manufacture.

decrease in emissions from 1999 of 44 percent, and an increase in emissions from 1990 of 42 percent. These trends are driven by the above stated reasons.

Photovoltaic cell and MEMS manufacturing emissions of all fluorinated greenhouse gases are in Table 4-121. While EPA has developed a simple methodology to estimate emissions from non-reporters and to back-cast emissions from these sources for the entire time series, there is very high uncertainty associated with these emission estimates.

The emissions reported by facilities manufacturing MEMS included emissions of C_2F_6, C_3F_8, c-C_4F_8, CF_4, HFC-23, NF_3, N_2O and SF_6,[94] and were equivalent to only 0.110 percent to 0.260 percent of the total reported emissions from electronics manufacturing in 2011 to 2022. F-GHG emissions, the primary type of emissions for MEMS, ranged from 0.0003 to 0.012 MMT CO_2 Eq. from 1991 to 2022. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing (GHGRP reporters must choose a single classification per fab). Emissions from non-reporters have not been estimated.

Total CO_2-equivalent emissions from manufacturing of photovoltaic cells were estimated to range from 0.0003 MMT CO_2 Eq. to 0.0320 MMT CO_2 Eq. from 1998 to 2022 and were equivalent to between 0.003 percent to 0.77 percent of the total reported emissions from electronics manufacturing. F-GHG emissions, the primary type of emissions for photovoltaic cells, ranged from 0.0003 to 0.032 MMT CO_2 Eq. from 1998 to 2022. Emissions from manufacturing of photovoltaic cells were estimated using an emission factor developed from reported data from a single manufacturer between 2015 and 2016. This emission factor was then applied to production capacity estimates from non-reporting facilities. Reported emissions from photovoltaic cell manufacturing consisted of CF_4, C_2F_6, c-C_4F_8, CHF_3, NF_3, and N_2O.[95]

Emissions of F-HTFs, grouped by HFCs, PFCs or SF_6 are presented in Table 4-121. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only.

Since reporting of F-HTF emissions began under EPA's GHGRP in 2011, total F-HTF emissions (reported and estimated non-reported) have fluctuated between 0.4 MMT CO_2 Eq. and 0.9 MMT CO_2 Eq., with an overall declining trend between 2011 to 2022. An analysis of the data reported to EPA's GHGRP indicates that F-HTF emissions account for anywhere between 9 percent and 17 percent of total annual emissions (F-GHG, N_2O and F-HTFs) from semiconductor manufacturing.[96] Table 4-123 shows F-HTF emissions in tons by compound group based on reporting to EPA's GHGRP and the interpolated share of F-HTF emissions to F-GHG emissions for select years prior to reporting. [97]

[94] Gases not reported by MEMS manufacturers to the GHGRP are currently listed as "NE" in the CRTs. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[95] Gases not reported by PV manufacturers to the GHGRP are currently listed as "NE" in the CRTs. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[96] Emissions data for HTFs (in tons of gas) from the semiconductor industry from 2011 through 2022 were obtained from the EPA GHGRP annual facility emissions reports.

[97] Many fluorinated heat transfer fluids consist of perfluoropolymethylisopropyl ethers (PFPMIEs) of different molecular weights and boiling points that are distilled from a mixture. "BP 200 °C" (and similar terms below) indicate the boiling point of the fluid in degrees Celsius. For more information, see https://www.regulations.gov/document?D=EPA-HQ-OAR-2009-0927-0276.

Table 4-121: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Electronics Industry (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CF_4	0.8	1.0	1.6	1.5	1.5	1.6	1.6
C_2F_6	1.8	1.8	1.1	0.9	0.8	0.9	0.9
C_3F_8	+	0.1	0.1	0.1	0.1	0.1	0.1
C_4F_8	0.0	0.1	0.1	0.1	0.1	0.1	0.1
HFC-23	0.2	0.2	0.3	0.3	0.3	0.4	0.3
SF_6	0.5	0.8	0.8	0.8	0.8	0.9	0.7
NF_3	+	0.4	0.5	0.5	0.6	0.6	0.6
C_4F_6	+	+	+	+	+	+	+
C_5F_8	+	+	+	+	+	+	+
CH_2F_2	+	+	+	+	+	+	+
CH_3F	+	+	+	+	+	+	+
CH_2FCF_3	+	+	+	+	+	+	0.0
Total Semiconductors	**3.3**	**4.3**	**4.5**	**4.2**	**4.2**	**4.5**	**4.4**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_3F_8	0.0	+	0.0	0.0	0.0	0.0	0.0
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	+	+	+	+	+	+
NF_3	0.0	0.0	+	+	+	+	+
Total MEMS	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NF_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total PV	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (Semiconductors)	+	0.1	0.2	0.2	0.3	0.3	0.3
N_2O (MEMS)	0.0	+	+	+	+	+	+
N_2O (PV)	0.0	+	+	+	+	+	+
Total N_2O	**+**	**0.1**	**0.2**	**0.2**	**0.3**	**0.3**	**0.3**
HFC, PFC and SF_6 F-HTFs	0.0	+	+	+	+	+	+
Total Electronics Industry	**3.3**	**4.5**	**4.8**	**4.5**	**4.5**	**4.8**	**4.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-122: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
CF_4	114.8	145.3	236.7	223.9	227.6	238.2	247.2
C_2F_6	160.0	163.4	99.1	85.0	75.9	78.7	81.6
C_3F_8	0.4	7.3	12.2	10.7	9.6	11.2	13.6
C_4F_8	0.0	10.9	6.0	5.7	5.8	6.3	6.1
HFC-23	14.6	14.1	26.5	25.7	26.6	30.4	25.2
SF_6	21.7	33.4	33.4	33.3	32.3	38.4	31.4
NF_3	2.8	26.2	34.1	33.5	36.2	39.2	39.4
C_4F_6	0.7	0.9	0.8	0.9	0.8	1.0	0.9
C_5F_8	0.5	0.6	0.5	0.4	0.4	0.4	0.4
CH_2F_2	0.6	0.8	0.9	1.0	1.0	1.0	1.0
CH_3F	1.4	1.8	2.4	2.5	2.8	2.9	2.4
CH_2FCF_3	+	+	+	+	+	+	0.0
N_2O	135.9	463.3	883.4	816.0	1,020.8	1,083.0	1,113.2

+ Does not exceed 0.05 MT.

Table 4-123: F-HTF Emissions from Electronics Manufacture by Compound Group (kt CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HFCs	0.0	0.9	2.7	1.1	0.9	1.1	1.5
PFCs	0.0	3.8	10.0	8.5	7.8	5.5	7.4
SF_6	0.0	5.6	13.2	6.1	12.9	9.0	4.2
HFEs	0.0	39.4	4.6	1.3	5.4	3.8	14.4
PFPMIEs	0.0	110.5	182.8	174.8	151.0	149.4	165.3
Perfluoalkylromorpholines	0.0	66.4	58.4	57.1	61.3	53.7	19.7
Perfluorotrialkylamines	0.0	209.9	413.7	367.5	382.0	367.5	237.1
Total F-HTFs	**0.0**	**436.5**	**685.4**	**616.5**	**621.2**	**590.1**	**449.6**

Note: Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Methodology and Time-Series Consistency

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, semiconductor manufacturing Partner-reported emissions data received through EPA's PFC[98] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions from etching and chamber cleaning processes in the absence of emission control strategies (Burton and Beizaie 2001)[99]—and estimates of industry activity (i.e., total manufactured layer area and manufacturing capacity). The availability and applicability of reported emissions data from the EPA Partnership and EPA's GHGRP and activity data differ across the 1990 through 2022 time series. Consequently, fluorinated greenhouse gas (F-GHG) emissions from etching and chamber cleaning processes for semiconductors were estimated using seven distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2022. Nitrous oxide emissions were estimated using five distinct methods, one each for the period 1990 through 1994, 1995 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2022. The methodology discussion below for these time periods focuses on semiconductor emissions from etching, chamber cleaning, and uses of N_2O. Other emissions for MEMS, photovoltaic cells, and HTFs were estimated using the approaches described immediately below.

MEMS

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of MEMS are available for the years 2011 to 2022. Emissions from manufacturing of MEMS for years prior to 2011 were calculated by linearly interpolating emissions between 1990 (at zero MMT CO_2 Eq.) and 2011, the first year where emissions from manufacturing of MEMS was reported to the GHGRP. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing; however, emissions from MEMS manufacturing are likely being included in semiconductor totals. Emissions were not estimated for non-reporters.

[98] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[99] A Partner refers to a participant in the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily reported their PFC emissions to the EPA by way of a third party, which aggregated the emissions through 2010.

Photovoltaic Cells

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of photovoltaic cells are available for 2011, 2012, 2015, and 2016 from two manufacturers. EPA estimates the emissions from manufacturing of PVs from non-reporting facilities by multiplying the estimated capacity of non-reporters by a calculated F-GHG emission factor and N_2O emission factor based on GHGRP reported emissions from the manufacturer (in MMT CO_2 Eq. per megawatt) that reported emissions in 2015 and 2016. This manufacture's emissions are expected to be more representative of emissions from the sector, as their emissions were consistent with consuming only CF_4 for etching processes and are a large-scale manufacturer, representing 28 percent of the U.S. production capacity in 2016. The second photovoltaic manufacturer only produced a small fraction of U.S. production (<4 percent). They also reported the use of NF_3 in remote plasma cleaning processes, which does not have an emission factor in Part 98 for PV manufacturing, requiring them to report emissions equal to consumption. The total F-GHG emissions from non-reporters are then disaggregated into individual gases using the gas distribution from the 2015 to 2016 manufacturer. Manufacturing capacities in megawatts were drawn from DisplaySearch, a 2015 Congressional Research Service Report on U.S. Solar Photovoltaic Manufacturing, and self-reported capacity by GHGRP reporters. EPA estimated that during the 2015 to 2016 period, 28 percent of manufacturing capacity in the United States was represented through reported GHGRP emissions. Capacities are estimated for the full time series by linearly scaling the total U.S. capacity between zero in 1997 to the total capacity reported of crystalline silicon (c-Si) PV manufacturing in 2000 in DisplaySearch and then linearly scaling between the total capacity of c-Si PV manufacturing in DisplaySearch in 2009 to the total capacity of c-Si PV manufacturing reported in the Congressional Research Service report in 2012. Capacities were held constant for non-reporters for 2012 to 2019. In 2020, non-reporter capacity declined due to the closure of several PV manufacturing plants. This capacity was held constant for 2021 and 2022. Average emissions per MW from the GHGRP reporter in 2015 and 2016 were then applied to the total capacity prior to 2015. Emissions for 2014 from the GHGRP reporter that reported in 2015 and 2016 were scaled to the number of months open in 2014. For 1998 through 2022, emissions per MW (capacity) from the GHGRP reporter were applied to the non-reporters. For 2017 through 2022, there are no reported PV emissions. Therefore, emissions were estimated using the EPA-derived emission factor and estimated manufacturing capacity from non-reporters only.

HTFs

Facility emissions of F-HTFs from semiconductor manufacturing are reported to EPA under its GHGRP and are available for the years 2011 through 2022. EPA estimates the emissions of F-HTFs from non-reporting semiconductor facilities by calculating the ratio of GHGRP-reported fluorinated HTF emissions to GHGRP reported F-GHG emissions from etching and chamber cleaning processes, and then multiplying this ratio by the F-GHG emissions from etching and chamber cleaning processes estimated for non-reporting facilities. Fluorinated HTF use in semiconductor manufacturing is assumed to have begun in the early 2000s and to have gradually displaced other HTFs (e.g., de-ionized water and glycol) in semiconductor manufacturing (EPA 2006). For time-series consistency, EPA interpolated the share of F-HTF emissions to F-GHG emissions between 2000 (at 0 percent) and 2011 (at 17 percent) and applied these shares to the unadjusted F-GHG emissions during those years to estimate the emissions.

Semiconductors

1990 through 1994

From 1990 through 1994, Partnership data were unavailable, and emissions were modeled using PEVM (Burton

and Beizaie 2001).[100] The 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet to be developed.

PEVM is based on the recognition that fluorinated greenhouse gas emissions from semiconductor manufacturing vary with: (1) the number of layers that comprise different kinds of semiconductor devices, including both silicon wafer and metal interconnect layers, and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of manufactured layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[101] and (2) product type (discrete, memory or logic).[102] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per Integrated Circuit (IC) specific to product type (Burton and Beizaie 2001; ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, Inc. 2012).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled emissions and hence may be use here to estimate 1990 through 1994 emissions. The emission factor is used to estimate U.S. uncontrolled emissions using publicly available data on world (including U.S.) silicon consumption.

As it was assumed for this time period that there was no consequential adoption of fluorinated-gas-reducing measures, a fixed distribution of fluorinated-gas use was assumed to apply to the entire U.S. industry to estimate gas-specific emissions. This distribution was based upon the average fluorinated-gas purchases made by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001).

PEVM only addressed the seven main F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, HFC-23, SF_6, and NF_3) used in semiconductor manufacturing. Through reporting under Subpart I of EPA's GHGRP, data on other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) used in semiconductor manufacturing became available and EPA was therefore able to extrapolate this data across the entire 1990 to 2022 timeseries. To estimate emissions for these "other F-GHGs", emissions data from Subpart I between 2014 to 2016 were used to estimate the average share or percentage contribution of these gases as compared to total F-GHG emissions. Subpart I emission factors were updated for 2014 by EPA as a

[100] Various versions of the PEVM exist to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years.

[101] By decreasing features of Integrated Circuit components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with 65 nm feature sizes might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality, while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS 2007).

[102] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

result of a larger set of emission factor data becoming available, so reported data from 2011 through 2013 was not utilized for the average. To estimate non-reporter emissions from 2011-2022, the average emissions data from Subpart I of 2011 to 2022 was used.

To estimate N_2O emissions, it was assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through 1994.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more representative (e.g., in terms of capacity utilization in a given year) than PEVM-estimated emissions and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total capacity of the plants operated by the Partners and the total capacity of all of the semiconductor plants in the United States; this ratio represents the share of capacity attributable to the Partnership. This method assumes that Partners and non-Partners have identical capacity utilizations and distributions of manufacturing technologies. Plant capacity data is contained in the World Fab Forecast (WFF) database and its predecessors, which is updated quarterly. Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

For this time period, the N_2O emissions were estimated using an emission factor that was applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N_2O emissions were regressed against the corresponding TMLA of facilities that reported no use of abatement systems. Details on EPA's GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2012 section. The total U.S. TMLA for 1995 through 1999 was estimated using PEVM.

2000 through 2006

Emissions for the years 2000 through 2006—the period during which Partners began the consequential application of fluorinated greenhouse gas-reduction measures—were estimated using a combination of Partner-reported emissions and adjusted PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions, those from non-Partners, were estimated using PEVM, with one change. To ensure time-series consistency and to reflect the increasing use of remote clean technology (which increases the efficiency of the production process while lowering emissions of fluorinated greenhouse gases), the average non-Partner emission factor (PEVM emission factor) was assumed to begin declining gradually during this period. Specifically, the non-Partner emission factor for each year was determined by linear interpolation, using the end points of 1999 (the original PEVM emission factor) and 2011 (a new emission factor determined for the non-Partner population based on GHGRP-reported data, described below).

The portion of the U.S. total emissions attributed to non-Partners is obtained by multiplying PEVM's total U.S. emissions figure by the non-Partner share of U.S. total silicon capacity for each year as described above.[103] Gas-specific emissions from non-Partners were estimated using linear interpolation between the gas-specific emissions distributions of 1999 (assumed to be the same as that of the total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partners that reported through the GHGRP as a result of emitting more than 25,000 MT CO_2 Eq. per year). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC

[103] This approach assumes that the distribution of linewidth technologies is the same between Partners and non-Partners. As discussed in the description of the method used to estimate 2007 emissions, this is not always the case.

fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor Equipment and Materials Industry 2011).[104, 105, 106] For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2007 through 2010

For the years 2007 through 2010, emissions were also estimated using a combination of Partner reported emissions and adjusted PEVM modeled emissions to provide estimates for non-Partners; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2010 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[107] Second, the scope of the 2007 through 2010 estimates was expanded relative to the estimates for the years 2000 through 2006 to include emissions from research and development (R&D) fabs. This additional enhancement was feasible through the use of more detailed data published in the WFF. PEVM databases were updated annually as described above. The published world average capacity utilization for 2007 through 2010 was used for production fabs, while for R&D fabs a 20 percent figure was assumed (SIA 2009).

In addition, publicly available utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. The Semiconductor Capacity Utilization (SICAS) Reports from SIA provides the global semiconductor industry capacity and utilization, differentiated by discrete and IC products (SIA 2009 through 2011). PEVM estimates were adjusted using technology-weighted capacity shares that reflect the relative influence of different utilization. Gas-specific emissions for non-Partners were estimated using the same method as for 2000 through 2006.

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[104] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2 to 3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFF were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percent. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers, and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities were estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV) to determine the average design capacity over the 2006 period.

[105] In 2006, the industry trend in co-ownership of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases are not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[106] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time, discrete devices did not use PFCs during manufacturing and therefore only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards, discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

[107] EPA considered applying this change to years before 2007 but found that it would be difficult due to the large amount of data (i.e., technology-specific global and non-Partner TMLA) that would have to be examined and manipulated for each year. This effort did not appear to be justified given the relatively small impact of the improvement on the total estimate for 2007 and the fact that the impact of the improvement would likely be lower for earlier years because the estimated share of emissions accounted for by non-Partners is growing as Partners continue to implement emission-reduction efforts.

For this time period emissions of other F-GHGs (C_5F_8, CH_2F_2, CH_3F, CH_2FCF_3, $C_2H_2F_4$) were estimated using the method described above for 1990 to 1994. Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2011 through 2012

The fifth method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2012. This methodology differs from previous years because the EPA's Partnership with the semiconductor industry ended (in 2010) and reporting under EPA's GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 MT CO_2 Eq. per year (based on default F-GHG-specific emission factors and total capacity in terms of substrate area) are required to report their emissions to EPA. This population of reporters to EPA's GHGRP included both historical Partners of EPA's PFC Reduction/Climate Partnership as well as non-Partners some of which use gallium arsenide (GaAs) technology in addition to Si technology.[108] Emissions from the population of manufacturers that were below the reporting threshold were also estimated for this time period using EPA-developed emission factors and estimates of facility-specific production obtained from WFF. Inventory totals reflect the emissions from both reporting and non-reporting populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of F-GHGs (for all types of F-GHGs) used in etch and clean processes as well as emissions of fluorinated heat transfer fluids. (Fluorinated heat transfer fluids are used to control process temperatures, thermally test devices, and clean substrate surfaces, among other applications.) They also report N_2O emissions from CVD and other processes. The F-GHGs and N_2O were aggregated, by gas, across all semiconductor manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. At this time, emissions that result from heat transfer fluid use that are HFC, PFC and SF_6 are included in the total emission estimates from semiconductor manufacturing, and these GHGRP-reported emissions have been compiled and presented in Table 4-121. F-HTF emissions resulting from other types of gases (e.g., HFEs) are not presented in semiconductor manufacturing totals in Table 4-121 and Table 4-122 but are shown in Table 4-123 for informational purposes.

Changes to the default emission factors and default destruction or removal efficiencies (DREs) used for GHGRP reporting affected the emissions trend between 2013 and 2014. These changes did not reflect actual emission rate changes but data improvements. Therefore, for the current *Inventory*, EPA adjusted the time series of GHGRP-reported data for 2011 through 2013 to ensure time-series consistency using a series of calculations that took into account the characteristics of a facility (e.g., wafer size and abatement use). To adjust emissions for facilities that did not report abatement in 2011 through 2013, EPA simply applied the revised emission factors to each facility's estimated gas consumption by gas, process type and wafer size. In 2014, EPA also started collecting information on fab-wide DREs and the gases abated by process type, which were used in calculations for adjusting emissions from facilities that abated F-GHGs in 2011 through 2013.

- To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first calculated the quantity of gas abated in 2014 using reported F-GHG emissions, the revised default DREs (or the estimated site-specific DRE,[109] if a site-specific DRE was indicated), and the fab-wide DREs reported in 2014.[110] To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first estimated

[108] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

[109] EPA generally assumed site-specific DREs were as follows: CF_4, Etch (90 percent); all other gases, Etch (98 percent); NF_3, Clean (95 percent); CF_4, Clean (80 percent), and all other gases, Clean (80 percent). There were a few exceptions where a higher DRE was assumed to ensure the calculations operated correctly when there was 100 percent abatement.

[110] If abatement information was not available for 2014 or the reported incorrectly in 2014, data from 2015 or 2016 was substituted.

the percentage of gas passing through abatement systems for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 and NF_3.

- EPA then estimated the quantity of NF_3 abated for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 (which is not abated) and NF_3. This abated quantity was then subtracted from the total abated quantity calculated as described in the bullet above.
- To account for the resulting remaining abated quantity, EPA assumed that the percentage of gas passing through abatement systems was the same across all remaining gas and process type combinations where abatement was reported for 2014.
- The percentage of gas abated was then assumed to be the same in 2011 through 2013 (if the facility claimed abatement that year) as in 2014 for each gas abated in 2014.

The revised emission factors and DREs were then applied to the estimated gas consumption for each facility by gas, process type and wafer size.[111]

For the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP, emission estimates are based on EPA-developed emission factors for the F-GHGs and N_2O and estimates of manufacturing activity. The new emission factors (in units of mass of CO_2 Eq./TMLA [million square inches (MSI)]) are based on the emissions reported under EPA's GHGRP by facilities without abatement and on the TMLA estimates for these facilities based on the WFF (SEMI 2012, 2013).[112] In a refinement of the method used to estimate emissions for the non-Partner population for prior years, different emission factors were developed for different subpopulations of fabs, disaggregated by wafer size (200 mm and 300 mm). For each of these groups, a subpopulation-specific emission factor was obtained using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of seven F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, SF_6 and NF_3)[113] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA), and facility-reported N_2O emissions were regressed against the corresponding TMLA to estimate a N_2O emissions factor (CO_2 Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. Information on the use of point-of-use abatement by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement.

For 2011 and 2012, estimates of TMLA relied on the capacity utilization of the fabs published by the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012). Similar to the assumption for 2007 through 2010, facilities with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. All other facilities in the United States are assumed to utilize the average percent of the manufacturing capacity without distinguishing whether fabs produce discrete products or logic products.

Non-reporting fabs were then broken out into subpopulations by wafer size (200 mm and 300 mm). using information available through the WFF. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the CO_2-equivalent emissions of that subpopulation.

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[111] Since facilities did not report by fab before 2014, fab-wide DREs were averaged if a facility had more than one fab. For facilities that reported more than one wafer size per facility, the percentages of a facility's emissions per wafer size were estimated in 2014 and applied to earlier years, if possible. If the percentage of emissions per wafer size were unknown, a 50/50 split was used.

[112] EPA does not have information on fab-wide DREs for this time period, so it is not possible to estimate uncontrolled emissions from fabs that reported point-of-use abatement. These fabs were therefore excluded from the regression analysis. (They are still included in the national totals.)

[113] Only seven gases were aggregated because inclusion of F-GHGs that are not reported in the *Inventory* results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

Gas-specific, CO_2-equivalent emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, CO_2-equivalent emissions from which the aggregate emission factors, based on GHGRP-reported data, were developed. Estimated in this manner, the non-reporting population accounted for 4.9 and 5.0 percent of U.S. emissions in 2011 and 2012, respectively. The GHGRP-reported emissions and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

2013 and 2014

For 2013 and 2014, as for 2011 and 2012, F-GHG and N_2O emissions data received through EPA's GHGRP were aggregated, by gas, across all semiconductor-manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. However, for these years WFF data was not available. Therefore, an updated methodology that does not depend on the WFF derived activity data was used to estimate emissions for the segment of the industry that are not covered by EPA's GHGRP. For the facilities that did not report to the GHGRP (i.e., which are below EPA's GHGRP reporting threshold or are R&D facilities), emissions were estimated based on the proportion of total U.S. emissions attributed to non-reporters for 2011 and 2012. EPA used a simple averaging method by first estimating this proportion for both F-GHGs and N_2O for 2011, 2012, and 2015 and 2016, resulting in one set of proportions for F-GHGs and one set for N_2O, and then applied the average of each set to the 2013 and 2014 GHGRP reported emissions to estimate the non-reporters' emissions. Fluorinated gas-specific, CO_2-equivalent emissions for non-reporters were estimated using the corresponding reported distribution of gas-specific, CO_2-equivalent emissions reported through EPA's GHGRP for 2013 and 2014.

GHGRP-reported emissions in 2013 were adjusted to capture changes to the default emission factors and default destruction or removal efficiencies used for GHGRP reporting, affecting the emissions trend between 2013 and 2014. EPA used the same method to make these adjustments as described above for 2011 and 2012 GHGRP data.

2015 through 2022

Similar to the methods described above for 2011 and 2012, and 2013 and 2014, EPA relied upon emissions data reported directly through the GHGRP. For 2015 through 2022, EPA took an approach similar to the one used for 2011 and 2012 to estimate emissions for the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP. However, in a change from previous years, EPA was able to develop new annual emission factors for 2015 through 2022 using TMLA from WFF and a more comprehensive set of emissions, i.e., fabs with as well as without abatement control, as new information about the use of abatement in GHGRP fabs and fab-wide were available. Fab-wide DREs represent total fab CO_2 Eq.-weighted controlled F-GHG and N_2O emissions (emissions after the use of abatement) divided by total fab CO_2 Eq.-weighted uncontrolled F-GHG and N_2O emissions (emission prior to the use of abatement).

Using information about reported emissions and the use of abatement and fab-wide DREs, EPA was able to calculate uncontrolled emissions (each total F-GHG and N_2O) for every GHGRP reporting fab. Using this, coupled with TMLA estimated using methods described above (see 2011 through 2012), EPA derived emission factors by year, gas type (F-GHG or N_2O), and wafer size (200 mm and less or 300 mm) by dividing the total annual emissions reported by GHGRP reporters by the total TMLA estimated for those reporters. These emission factors were multiplied by estimates of non-reporter TMLA to arrive at estimates of total F-GHG and N_2O emissions for non-reporters for each year. For each wafer size, the total F-GHG emissions were disaggregated into individual gases using the shares of total emissions represented by those gases in the emissions reported to the GHGRP by unabated fabs producing that wafer size.

Data Sources

GHGRP reporters, which consist of former EPA Partners and non-Partners, estimated their emissions using a default emission factor method established by EPA. Like the Tier 2c Method in the *2019 Refinement to the 2006 IPCC Guidelines*, this method uses different emission and byproduct generation factors for different F-GHGs and process types and uses factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes

(in situ thermal, in situ plasma, and remote plasma). Starting with 2014 reported emissions, EPA's GHGRP required semiconductor manufacturers to apply updated emission factors to estimate their F-GHG emissions. For the years 2011 through 2013 reported emissions, semiconductor manufacturers used older emission factors to estimate their F-GHG emissions (Federal Register / Vol. 75, No. 230 /December 1, 2010, 74829). Subpart I emission factors were updated for 2014 by EPA as a result of a larger set of emission factor data becoming available as part of the Subpart I petition process, which took place from 2011 through 2013. In addition to semiconductor manufacturing, GHGRP also includes reported emissions from MEMS and PV producers.

Historically, semiconductor industry partners estimated and reported their emissions using a range of methods and uneven documentation. It is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *2006 IPCC Guidelines*. Partners are estimated to have accounted for between 56 and 79 percent of F-GHG emissions from U.S. semiconductor manufacturing between 1995 and 2010, with the percentage declining in recent years as Partners increasingly implemented abatement measures.

Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) WFF (formerly World Fab Watch) database (1996 through 2012, 2013, 2016, 2018, 2021, and 2023) (e.g., Semiconductor Materials and Equipment Industry 2021). Actual worldwide capacity utilizations for 2008 through 2010 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA 2009 through 2011). Estimates of the number of layers for each linewidth was obtained from International Technology Roadmap for Semiconductors: 2013 Edition (Burton and Beizaie 2001; ITRS 2007; ITRS 2008; ITRS 2011; ITRS 2013). PEVM utilized the WFF, SICAS, and ITRS, as well as historical silicon consumption estimates published by VLSI. Actual quarterly U.S. capacity utilizations for 2011, 2012, 2014 to 2022 were obtained from the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022).

Estimates of PV manufacturing capacity, which are used to calculate emissions from non-reporting facilities, are based on data from two sources. A historical market analysis from DisplaySearch provided estimates of U.S. manufacturing capacity from 2000 to 2009 (DisplaySearch 2010). Domestic PV cell production for 2012 was obtained from a Congressional Research Service report titled *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support* (Platzer 2015).

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The Monte Carlo stochastic simulation was performed on the total emissions estimate from the electronics industry, represented in equation form as:

Equation 4-20: Total Emissions from Electronics Industry

$$\begin{aligned}\text{Total Emissions } (\mathrm{E}_T) &= \text{Semiconductors F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{Semi}) \\ &+ \text{MEMS F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{MEMS}) + \text{PV F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{PV}) \\ &+ \text{HFC, PFC and } \mathrm{SF_6} \text{ F-HTFs Emissions } (\mathrm{E}_{HTF})\end{aligned}$$

The uncertainty in the total emissions for the electronics industry, presented in Table 4-124 below, results from the convolution of four distributions of emissions, namely from semiconductors manufacturing, MEMS manufacturing, PV manufacturing and emissions of heat transfer fluids. The approaches for estimating uncertainty in each of the sources are described below:

Semiconductors Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from semiconductor manufacturing, represented in equation form as:

Equation 4-21: Total Emissions from Semiconductor Manufacturing

$$\begin{aligned}\text{Semiconductors F-GHG and } N_2O \text{ Emissions } (E_{Semi}) \\ = \text{ GHGRP Reported F-GHG Emissions } (ER,\text{F-GHG, Semi}) \\ + \text{ Non-Reporters' Estimated F-GHG Emissions } \left(E_{NR,\text{F-GHG},Semi}\right) \\ + \text{ GHGRP Reported } N_2O \text{ Emissions } \left(E_{R,N_2O,Semi}\right) \\ + \text{ Non-Reporters' Estimated } N_2O \text{ Emissions } \left(E_{NR,N_2O,Semi}\right)\end{aligned}$$

The uncertainty in E_{Semi} results from the convolution of four distributions of emissions, $E_{R,F\text{-}GHG,Semi}$ $E_{R,N2O,Semi}$ $E_{NR,F\text{-}GHG,Semi}$ and $E_{NR,N2O,Semi}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for E_{Semi} are described in the remainder of this section.

The uncertainty estimate of $E_{R,\ F\text{-}GHG,Semi}$, or GHGRP-reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm or less wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment are based on an uncertainty analysis conducted during the assessment of emission estimation methods for the Subpart I rulemaking in 2012 (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028).[114] This assessment relied on facility-specific gas information by gas and wafer size, and incorporated uncertainty associated with both emission factors and gas consumption quantities. The 2012 analysis did not consider the use of abatement.

For the industry segment that manufactured 200 mm wafers, estimates of uncertainty at a 95 percent CI ranged from ±29 percent for C_3F_8 to ±10 percent for CF_4. For the corresponding 300 mm industry segment, estimates of uncertainty at the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. For gases for which uncertainty was not analyzed in the 2012 assessment (e.g., CH_2F_2), EPA applied the 95 percent CI range equivalent to the range for the gas and industry segment with the highest uncertainty from the 2012 assessment. These gas and wafer-specific uncertainty estimates were developed to represent uncertainty at a facility-level, but they are applied to the total emissions across all the facilities that did not abate emissions as reported under EPA's GHGRP at a national-level. Hence, it is noted that the uncertainty estimates used may be overestimating the uncertainties at a national-level.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full abatement (abatement of all gases from all cleaning and etching equipment) and partial abatement. These assumptions used to develop uncertainties for the partial and full abatement facilities are identical for 200 mm and 300 mm wafer processing facilities. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. The triangular distributions range from an asymmetric and highly uncertain distribution of zero percent minimum to 90 percent maximum with 70 percent most likely value for CF_4 to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C_4F_8, NF_3, and SF_6. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. It is assumed that no more than 50 percent

[114] On November 13, 2013, EPA published a final rule revising Subpart I (Electronics Manufacturing) of the GHGRP (78 FR 68162). The revised rule includes updated default emission factors and updated default destruction and removal efficiencies that are slightly different from those that semiconductor manufacturers were required to use to report their 2012 emissions. The uncertainty analyses that were performed during the development of the revised rule focused on these updated defaults but are expected to be reasonably representative of the uncertainties associated with the older defaults, particularly for estimates at the country level. (They may somewhat underestimate the uncertainties associated with the older defaults at the facility level.) For simplicity, the 2012 estimates are assumed to be unbiased although in some cases, the updated (and therefore more representative) defaults are higher or lower than the older defaults. Multiple models and sensitivity scenarios were run for the Subpart I analysis. The uncertainty analysis presented here made use of the Input gas and wafer size model (Model 1) under the following conditions: Year = 2010, f = 20, n = SIA3.

of the gases are abated (i.e., the maximum value) and that 50 percent is the most likely value, and the minimum is zero percent. Consideration of abatement then resulted in four additional industry segments, two 200-mm wafer-processing segments (one fully and one partially abating each gas) and two 300-mm wafer-processing segment (one fully and the other partially abating each gas). Gas-specific emission uncertainties were estimated by convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Monte Carlo simulation.

The uncertainty in $E_{R,F\text{-}GHG,Semi}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments, and then running a Monte Carlo simulation which results in the 95 percent CI for emissions from GHGRP-reporting facilities ($E_{R,F\text{-}GHG,Semi}$).

The uncertainty in $E_{R,N2O,Semi}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). Similar to analyses completed for Subpart I (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028), the uncertainty of N_2O consumed was assumed to be 20 percent. Consumption of N_2O for GHGRP reporting facilities was estimated by back-calculating from emissions reported and assuming no abatement. The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of zero percent, mode of 20 percent and maximum value of 84 percent. The minimum was selected based on physical limitations, the mode was set equivalent to the Subpart I default N_2O utilization rate for chemical vapor deposition, and the maximum was set equal to the maximum utilization rate found in ISMI Analysis of Nitrous Oxide Survey Data (ISMI 2009). The inputs were used to simulate emissions for each of the GHGRP reporting, N_2O-emitting facilities. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each facilities' reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR,\ F\text{-}GHG,Semi}$ and $E_{NR,\ N2O,Semi}$ entailed developing estimates of uncertainties for the emissions factors and the corresponding estimates of TMLA.

The uncertainty in TMLA depends on the uncertainty of two variables—an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. The most probable utilization is assumed to be 82 percent, with the highest and lowest utilization assumed to be 89 percent, and 70 percent, respectively. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS; the smallest number varied by technology generation between one and two layers less than given in the ITRS and largest number of layers corresponded to the figure given in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population.

The uncertainty around the emission factors for non-reporting facilities is the total combined uncertainties of individual gases and the TMLA of each reporting facility in that category. The combined uncertainty of emissions of individual gases from non-reporters is equal to the uncertainty of total emissions for non-reporting facilities.

The uncertainty around the emission factors for non-reporting facilities is the total combined uncertainties of individual gases (MT units) and the TMLA of each reporting facility in that category. The combined uncertainty of emissions of individual gases from non-reporters is equal to the uncertainty of total emissions for non-reporting facilities. For each wafer size for reporting facilities, emissions of individual gases were regressed on TMLA (with an intercept forced to zero) for 10,000 emission and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5^{th} and the 97.5^{th} percentile of these emission factors are determined, and the bounds are assigned as the percent difference from the estimated emission factor.

The next step in estimating the uncertainty in emissions of reporting and non-reporting facilities in semiconductor

manufacture is convolving the distribution of reported emissions, emission factors, and TMLA using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported F-GHG gas- and wafer size-specific emissions are assumed to be normally distributed, and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The were some instances, though, where departures from normality were observed for variables, including for the distributions of the gas- and wafer size-specific N_2O emissions, TMLA, and non-reporter emission factors, both for F-GHGs and N_2O. As a result, the distributions for these parameters were assumed to follow a PERT beta distribution.

MEMS Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from MEMS manufacturing, represented in equation form as:

Equation 4-22: Total Emissions from MEMS Manufacturing

$$\text{MEMS F-GHG and } N_2O \text{ Emissions } (E_{MEMS}) = \text{GHGRP Reported F-GHG Emissions } (E_{R,F\text{-}GHG,MEMS}) + \text{GHGRP Reported } N_2O \text{ Emissions } (E_{R,N2O,\,MEMS})$$

$$\begin{aligned}&\text{MEMS F-GHG and } N_2O \text{ Emissions } (E_{MEMS})\\ &= \text{GHGRP Reported F-GHG Emissions } \left(E_{R,\,F\text{-}GHG,MEMS}\right)\\ &+ \text{GHGRP Reported } N_2O \text{ Emissions } \left(E_{R,N_2O,MEMS}\right)\end{aligned}$$

Emissions from MEMS manufacturing are only quantified for GHGRP reporters. MEMS manufacturers that report to the GHGRP all report the use of 200 mm wafers. Some MEMS manufacturers report using abatement equipment. Therefore, the estimates of uncertainty at the 95 percent CI for each gas emitted by MEMS manufacturers are set equal to the gas-specific uncertainties for manufacture of 200mm semiconductor wafers with partial abatement. The same assumption is applied for uncertainty levels for GHGRP reported MEMS N_2O emissions ($E_{R,N2O,MEMS}$).

PV Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from PV manufacturing, represented in equation form as:

Equation 4-23: Total Emissions from PV Manufacturing

$$\text{PV F-GHG and } N_2O \text{ Emissions } (E_{PV}) = \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,F\text{-}GHG,PV}) + \text{Non-Reporters' Estimated } N_2O \text{ Emissions } (E_{NR,N2O,PV})$$

$$\begin{aligned}&\text{PV F-GHG and } N_2O \text{ Emissions } (E_{PV})\\ &= \text{Non-Reporters' Estimated F-GHG Emissions } \left(E_{NR,F\text{-}GHG,PV}\right)\\ &+ \text{Non-Reporters' Estimated N2O Emissions } \left(E_{NR,N_2O,PV}\right)\end{aligned}$$

Emissions from PV manufacturing are only estimated for non-GHGRP reporters in 2022. There were no reported emissions from PV manufacturing in GHGRP in 2022. The "Non-Reporters' Estimated F-GHG Emissions" term in Equation 4-23 was estimated using an emission factor developed using emissions from reported data in 2015 and 2016 and total non-reporters' capacity. Due to a lack of information and data and because they represent similar physical and chemical processes, the uncertainty at the 95 percent CI level for non-reporter PV capacity is assumed to be the same as the uncertainty in non-reporter TMLA for semiconductor manufacturing. Similarly, the uncertainty for the PV manufacture emission factors are assumed to be the same as the uncertainties in emission factors used for non-reporters in semiconductor manufacture.

Heat Transfer Fluids Emission Uncertainty

There is a lack of data related to the uncertainty of emission estimates of heat transfer fluids used for electronics manufacture. Therefore, per the *2006 IPCC Guidelines* (IPCC 2006, Volume 3, Chapter 6), uncertainty bounds of 20

percent were applied to estimate uncertainty associated with the various types of heat transfer fluids, including PFCs, HFC, and SF_6, at the national level.

The results of the Approach 2 quantitative uncertainty analysis for electronics manufacturing are summarized in Table 4-124. These results were obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility that manufactures semiconductors, MEMS, or PVs and use heat transfer fluids. The emissions estimate for total U.S. F-GHG, N_2O, and HTF emissions from electronics manufacturing were estimated to be between 4.44 and 5.02 MMT CO_2 Eq. at a 95 percent CI level. This range represents 6 percent below to 6 percent above the 2022 emission estimate of 4.73 MMT CO_2 Eq. for all emissions from electronics manufacture. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-124: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, NF_3 and N_2O Emissions from Electronics Manufacture (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Electronics Industry	HFC, PFC, SF_6, NF_3, and N_2O	4.7	4.4	5.0	-6%	+6%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For its GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[115] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

Any resubmitted emissions data reported to EPA's GHGRP from all prior years were updated in this *Inventory*. Additionally, EPA made the following changes:

- To estimate non-reporter F-GHG and N_2O emissions, EPA relies on data reported through Subpart I and the World Fab Forecast. This process requires EPA to map facilities that report through Subpart I and which are also represented in the World Fab Forecast. For this *Inventory* update, EPA identified and made

[115] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

corrections to a few instances of this mapping based on new information and additional reviews of the data. This had minimal effects on emission estimates.

- EPA re-ran regression analyses for years 2010 to 2021 to reflect updates to Subpart I and the World Fab Forecast. These changes had minor effects on the emission factors, standard error, and R^2 values for all years. This resulted in the recalculation of non-reporter's F-GHG and N_2O estimates for all years.
- EPA recalculated HTF emissions for years 1990 to 2021 using IPCC *Fifth Assessment Report* (AR5) GWP values (IPCC 2013). Emission estimates were incorrectly calculated using the IPCC *Fourth Assessment Report* (AR4) GWP values (IPCC 2007) in the previous *Inventory* (EPA 2023). Overall, the impact of these recalculations led to an average decrease of 0.009 MMT CO_2 Eq. (0.19 percent) across the time series (1990 through 2021).
- EPA recalculated fluorinated GHG consumption for 2014 to 2021 using the following methodology. Fluorinated GHG consumption estimates for unabated fabs were calculated using reported GHGRP emissions data and default emission factors for Subpart I. Because certain fluorinated GHGs are generated as by-products as well as used as input gases, both input gas emission factors and by-product gas emission factors were factored into this calculation. For abated fabs, a "consumption factor" was developed by dividing the reported emissions of each fluorinated GHG from unabated fabs by the estimated consumption of each fluorinated GHG for each wafer size. Fluorinated GHG consumption for 2021 was estimated based on GDP growth of the 2020 consumption estimate. The consumption estimate will be updated with reported 2021 GHGRP emissions data.
- EPA refined the non-reporting population for 2015 to 2022 by conducting an analysis into the criteria being used to determine which fabs should be included and excluded from this population. Overall, the impact of this refinement led to an average increase in semiconductor emissions by 0.02 MMT CO_2 Eq. (0.45 percent) for the time series 2015 to 2022.
- EPA recalculated non-reporter emissions for 2015 to 2022 by developing emission factors for individual gases and calculated on an MT basis. Overall, the impact of this refinement led to an average increase in semiconductor emissions by 0.04 MMT CO_2 Eq. (0.84 percent) for the time series 2014 to 2022.

Planned Improvements

The *Inventory* methodology uses data reported through the EPA Partnership (for earlier years) and EPA's GHGRP (for later years) to extrapolate the emissions of the non-reporting population. While these techniques are well developed, the accuracy of the emissions estimates for the non-reporting population could be further increased through EPA's further investigation of and improvement upon the accuracy of estimated activity in the form of TMLA.

The *Inventory* uses utilization from two different sources for various time periods–SEMI to develop PEVM and to estimate non-Partner emissions for the period 1995 to 2010 and U.S. Census Bureau for 2011 through 2022. SEMI reported global capacity utilization for manufacturers through 2011. U.S. Census Bureau capacity utilization include U.S. semiconductor manufacturers as well as assemblers. Further analysis on the impacts of using a new and different source of utilization data could prove to be useful in better understanding of industry trends and impacts of utilization data sources on historical emission estimates.

Estimates of semiconductor non-reporter and non-Partner emissions are based on EPA-developed emission factors for the time periods pre-2010, 2011 through 2012, and 2015 through 2022. Based on the data available for these time periods, the methods used to develop emission factors for non-reporters and non-Partners are slightly inconsistent for semiconductors (e.g., how data representing emissions and TMLA from the manufacture of various wafer sizes are aggregated or disaggregated for purposes of calculating emission factors). Further analyses to support potentially adjusting the methods for developing these emission factors could be done to better ensure consistency across the time series.

The methodology for estimating semiconductor emissions from non-reporters uses data from the International Technology Roadmap for Semiconductors (ITRS) on the number of layers associated with various technology node sizes. The ITRS has now been replaced by the International Roadmap for Devices and Systems (IRDS), which has published updated data on the number of layers used in each device type and node size (in nanometers). Incorporating this updated dataset will improve the accuracy of emissions estimates from non-reporting semiconductor fabs.

4.25 Substitution of Ozone Depleting Substances (CRT Source Category 2F)

This reporting category (2F) includes emissions from the substitution of ozone-depleting substance (ODS). Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and carbon dioxide (CO_2) are used as alternatives to several classes of ODS that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[116] Ozone-depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and directs EPA to address HFCs by phasing down production and consumption (i.e., production plus import minus export), maximizing reclamation and minimizing releases from equipment, and facilitating the transition to next-generation technologies through sector-based restrictions. Emission estimates for HFCs, PFCs, and CO_2 used as substitutes for ODSs are provided in Table 4-125 and Table 4-126.[117]

Table 4-125: Emissions of HFCs, PFCs, and CO_2 from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	6.1	6.9	7.8	9.4	10.5
HFC-125	+	8.2	48.8	53.1	57.8	66.3	72.0
HFC-134a	+	72.8	56.4	55.3	54.1	50.0	48.3
HFC-143a	+	10.0	29.7	29.9	29.9	30.0	29.8
HFC-236fa	0.0	1.0	0.8	0.7	0.7	0.6	0.6
CF_4	0.0	+	+	+	+	+	0.1
CO_2	+	+	+	+	+	+	+
Other Saturated HFCs[a]	0.3	6.9	15.9	16.0	15.9	16.3	16.8
Other PFCs and HFOs[b]	+	0.1	+	+	+	+	+
Total	**0.3**	**99.5**	**157.9**	**162.1**	**166.2**	**172.7**	**178.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Other Saturated HFCs represents an unspecified mix of saturated HFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-43-10mee.

[b] Other PFCs and HFOs represents an unspecified mix of PFCs and HFOs, which includes HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse

[116] [42 U.S.C § 7671, CAA Title VI].

[117] Emissions of ODS are not included here consistent with UNFCCC reporting guidelines for national inventories noted in Box 4-1. See Annex 6.2 for more details on emissions of ODS. Emissions from CO_2 used in the food and beverage industry are separately reported in Chapter 4.16 Carbon Dioxide Consumption but does not include CO_2 in ODS substitute use sectors as a refrigerant, foam blowing agent, or fire extinguishing agent.

collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon n-C_6F_{14}.
Note: Totals may not sum due to independent rounding.

Table 4-126: Emissions of HFCs, PFCs, and CO_2 from ODS Substitution (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	0	1	2	2	2	2	3
HFC-32	0	397	9,008	10,156	11,461	13,958	15,582
HFC-125	+	2,580	15,406	16,761	18,240	20,909	22,704
HFC-134a	+	56,029	43,419	42,558	41,590	38,447	37,167
HFC-143a	+	2,093	6,188	6,230	6,234	6,240	6,203
HFC-236fa	0	127	99	91	84	78	72
CF_4	0	3	5	5	4	4	4
CO_2	14	1,325	3,093	3,303	3,516	3,734	3,969
Other Saturated HFCs[a]	M	M	M	M	M	M	M
Other PFCs and HFOs[b]	M	M	M	M	M	M	M

+ Does not exceed 0.5 MT.
M (Mixture of Gases).
[a] Other Saturated HFCs represents an unspecified mix of saturated HFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-43-10mee.
[b] Other PFCs and HFOs represents an unspecified mix of PFCs and HFOs, which includes HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon n-C_6F_{14}.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[118] In 1993, the use of HFCs in foam production began, and in 1994 ODS substitutes for halons entered widespread use in the United States as halon production was phased out. In 1995, these compounds also found applications as solvents. Non-fluorinated ODS substitutes, such as CO_2, have been used in place of ODS in certain foam production and fire extinguishing uses since the 1990s.

The use and subsequent emissions of HFCs, PFCs, and CO_2 as ODS substitutes has been increasing from small amounts in 1990 to 178.1 MMT CO_2 Eq. emitted in 2022. This increase was in large part the result of efforts to phase out CFCs, HCFCs, and other ODSs in the United States. Use and emissions of HFCs are expected to start decreasing in the next few years and continue downward as production and consumption of HFCs are phased down to 15 percent of their baseline levels by 2036 through an allowance allocation and trading program established by EPA. Improvements in recovery practices and the use of alternative gases and technologies, through voluntary actions and in response to existing and potential future regulations under the AIM Act, will also contribute to a reduction in HFC use and emissions.

Table 4-127 presents emissions of HFCs, PFCs, and CO_2 as ODS substitutes by end-use sector for 1990 through 2022. The refrigeration and air-conditioning sector is further broken down by sub-sector. The end-use sectors that contributed the most toward emissions of HFCs, PFCs, and CO_2 as ODS substitutes in 2022 include refrigeration and air-conditioning (144.6 MMT CO_2 Eq., or approximately 81 percent), aerosols (17.0 MMT CO_2 Eq., or approximately 10 percent), and foams (11.7 MMT CO_2 Eq., or approximately 7 percent). Within the refrigeration and air-conditioning end-use sector residential unitary AC, part of the Residential Stationary Air-conditioning subsector

[118] R-404A contains HFC-125, HFC-143a, and HFC-134a.

shown below, was the highest emitting end-use (40.8 MMT CO_2 Eq.), followed by large retail food, which is part of the Commercial Refrigeration subsector. Each of the end-use sectors is described in more detail below.

Table 4-127: Emissions of HFCs, PFCs, and CO_2 from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990	2005	2018	2019	2020	2021	2022
Refrigeration/Air Conditioning	**+**	**83.0**	**122.7**	**126.5**	**130.6**	**139.5**	**144.6**
Commercial Refrigeration	+	14.9	39.6	40.2	40.6	41.0	41.4
Domestic Refrigeration	+	0.2	1.2	1.2	1.2	1.1	1.0
Industrial Process Refrigeration	+	1.8	13.8	15.0	16.2	17.4	18.6
Transport Refrigeration	+	1.6	6.9	7.4	7.9	8.4	8.8
Mobile Air Conditioning	+	61.5	28.7	26.6	24.6	22.9	20.8
Residential Stationary Air Conditioning	+	1.2	26.2	29.4	33.2	41.5	46.4
Commercial Stationary Air Conditioning	+	1.7	6.2	6.6	6.9	7.3	7.6
Aerosols	**0.2**	**10.2**	**16.7**	**17.0**	**17.3**	**17.7**	**17.0**
Foams	**+**	**3.5**	**14.2**	**14.1**	**13.7**	**10.8**	**11.7**
Solvents	**+**	**1.6**	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**
Fire Protection	**+**	**1.2**	**2.4**	**2.5**	**2.5**	**2.6**	**2.6**
Total	**0.3**	**99.5**	**157.9**	**162.1**	**166.2**	**172.7**	**178.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End-uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning and heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, metallurgical, and other industries). As the ODS phaseout has taken effect, most equipment has been retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[119] R-404A, and R-507A.[120] Lower-GWP options such as hydrofluoroolefin (HFO)-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) and HFC/HFO blends in retail food refrigeration, are also being used. Manufacturers of residential and commercial air conditioning have announced their plans to use HFC-32 and R-454B[121] in the future, and at least one manufacturer has announced the availability of chillers operating on HFC-32 as of 2023 (Carrier, 2023). These refrigerants are emitted to the atmosphere during equipment operation (as a result of component failure, leaks, and purges), as well as at manufacturing (if charged at the factory), installation, servicing, and disposal events.

[119] R-410A contains HFC-32 and HFC-125.

[120] R-507A, also called R-507, contains HFC-125 and HFC-143a.

[121] R-454B contains HFC-32 and HFO-1234yf.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have replaced the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but the industry is using HFC-227ea as well. Conversely, since the use of CFC propellants in other types of aerosols was banned in the Unites States in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid or roll-on deodorants and finger-pump sprays. The transition away from ODSs in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. Other low-GWP options such as HFO-1234ze(E) are being used as well. These propellants are released into the atmosphere as the aerosol products are used.

Foams

Chlorofluorocarbons and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds into alternatives such as CO_2 and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce PU appliance, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a, HFC-134a, and CO_2 are used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Low-GWP fluorinated foam blowing agents in use include HFO-1234ze(E) and HCFO-1233zd(E). Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

Chlorofluorocarbons, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of these solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and import of virgin halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236fa is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23 and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. Fluoroketone FK-5-1-12 is also used as

a low-GWP option and 2-BTP is being use in niche applications. As fire protection equipment is tested or deployed, emissions of these fire protection agents occur.

Methodology and Time-Series Consistency

Using a Tier 2 method in accordance with the IPCC methodological decision tree, a detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs, PFCs, and CO_2. The name of the model refers to the fact that it tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. The Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for 80 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.9.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The uncertainty analysis quantifies the level of uncertainty associated with the aggregate emissions across the 80 end-uses in the Vintaging Model. In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock (e.g., number of air conditioning units in operation) for the current year or ODS consumption before transition to alternatives began (e.g., in 1985 for most end-uses). Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed.

Inputs to the ODS substitutes uncertainty model generally take on a normal distribution with a 90 to 95 percent confidence interval but do utilize other probability density functions such as a uniform or PERT BETA distribution. The uncertainty inputs are based on conversations with industry experts and how certain assumptions are developed in the Vintaging Model. For example, if the Vintaging Model estimates are specifically aligned with actual reported data, then the uncertainty is decreased. This can be seen with the unitary AC end-use where annual stock data is aligned with sales data published by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). The stock is assumed to be fairly accurate and therefore, uncertainty range for the stock of unitary AC is set to an upper and lower bound of only 2.5 percent. The most significant sources of uncertainty for the substitution of ODS source category include the total stock of refrigerant installed in industrial process refrigeration and cold storage equipment, as well as the charge size for technical aerosols using HFC-134a. For technical aerosols, a triangular distribution is utilized to apply an asymmetrical range to the inventory value. This is to account for the

uncertainty that technical aerosols using HFC-134a might have higher market penetration than what the Vintaging Model currently estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-128. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 170.8 and 205.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4.1 percent below to 15.1 percent above the emission estimate of 178.1 MMT CO_2 Eq.

Table 4-128: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	178.1	170.8	205.1	-4.1%	+15.1%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter. Category specific QA/QC findings are described below.

The QA and verification process for individual gases and sources in the Vintaging Model includes review against up-to-date market information, including equipment stock estimates, leak rates, and sector transitions to new chemicals and technologies. In addition, comparisons against published emission and consumption sources by gas and by source are performed when available as described further below. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates. For the purposes of reporting emissions to protect Confidential Business Information (CBI), some HFCs and PFCs are grouped into two unspecified mixes of saturated HFCs and other PFCs and HFOs. The HFCs and PFCs within the unspecified mix of HFCs and PFCs are modelled and verified individually in the same process as all other gases and sources in the Vintaging Model.

Data from EPA's Greenhouse Gas Reporting Program (GHGRP)[122] and emissions of some fluorinated greenhouse gases estimated for the contiguous United States by scientists at the National Oceanic and Atmospheric Administration (NOAA) were used to perform additional quality control as specified in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019)*. These comparisons are detailed further in Annex 3.9.

Recalculations Discussion

For the current *Inventory*, updates to the Vintaging Model included updating 2022 growth rates for residential and commercial unitary air-conditioning to align with annual sales estimates published by AHRI. Projected growth rates

[122] For the GHGRP data, EPA verifies annual facility-level and company-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data.

were updated for residential unitary air-conditioning to align with projected residential housing available from the Energy Information Administration (EIA) and commercial unitary air-conditioning growth rates were updated based on new commercial floorspace growth projections from EIA (EPA 2023a). Growth rates for window units were updated to align with sales data for Energy Star- and non-Energy Star-certified units (EPA 2023b).

The Vintaging Model was also updated to include the addition of two end-uses representing multi-split air-conditioning units: small ductless mini-split and multi-split air-conditioning and large ductless mini-split and multi-split air-conditioning. These end-uses were split from the existing residential unitary air-conditioning end-use. Stock for ductless mini-split and multi-split air-conditioning systems were estimated based on the EIA Residential Energy and Consumption Survey (RECS) and growth projected based on annual sales of split systems under 33,000 BTU/h (small mini/multi-splits) and split systems between 33,000 BTU/h and 65,000 BTU/h (large mini/multi-splits) published by AHRI (EPA 2023c).

In addition, the market size and growth rates of the streaming agents end-use in the Fire Suppression sector was updated, improving alignment of halon 1211 consumption with the 2022 Fire Suppression Technical Options Committee (FSTOC) estimates, the lifetime was adjusted to reflect internal inspection timelines, rather than physical extinguisher lifetimes, and refilling of leaks throughout the lifetime of extinguishers was modeled (EPA 2023d).

Together, these updates increased ODS substitute emissions on average by 0.06 MMT CO_2 Eq. (0.6 percent) between 1990 and 2021, compared to the previous (i.e., 2023) *Inventory* submission.

Planned Improvements

Future improvements to the Vintaging Model are planned for the Refrigeration and Air-conditioning, Fire Suppression, and Aerosols sectors. Specifically, refrigerated storage space estimates published biannually from the United States Department of Agriculture (USDA) are being compared to cold storage warehouse space currently estimated in the Vintaging Model. Flooding agent fire suppression market transitions are under review to align more closely with real world activities. In addition, further refinement of HFC consumption in MDIs is expected from review of data collected on HFC use for MDI production, imports, and exports in response to requests pursuant to AIM Act regulations for application-specific allowances for MDIs. EPA expects these revisions to be prepared for the 2025 *Inventory* submission.

As discussed above, future reporting under the AIM Act may provide useful information for verification purposes and possible improvements to the Vintaging Model, such as information on HFC stockpiling behaviors. EPA expects this reporting by late 2023 and incorporation into the 2025 or 2026 report. Should the data suggest structural changes to the model, such as the handling of stockpiles before use, EPA expects to introduce the revised model for the 2025 or 2026 *Inventory* submission.

Several potential improvements to the *Inventory* were identified in the 2022 *Inventory* submission based on the comparisons mentioned above and discussed in Annex 3.9—net supply values from the GHGRP and emission estimates derived from atmospheric measurements—and remain valid. To estimate HFC emissions for just the contiguous United States, matching the coverage by the atmospheric measurements, EPA will investigate the availability of data from Alaska, Hawaii, and U.S. territories. This is planned by the next (i.e., 2025) *Inventory* submission. To improve estimates of HFC-125 and HFC-143a, further research into the refrigeration market can be made. Research in this industry on the shift away from blends such as R-404A or success in lowering emission rates could be used to improve the *Inventory* estimate. This is planned for the 2025 *Inventory*. That said, for the years where both the atmospheric measurements and the model display a roughly constant emission of HFC-143a at similar levels, the new results suggest robust estimates for the refrigeration market. Uncertainty estimates by species would aid in comparisons to atmospheric data. EPA continues to explore the possibility of revising the Monte Carlo analysis to differentiate between species, starting with the higher-emitted HFCs identified above, in a future (i.e., 2025) *Inventory* submission. Reclamation reports and, when available, information gathered under the AIM Act, could be used to improve the understanding of how chemical moves through the economy and could resolve some of the temporal effects discussed in Annex 3.9. This would likely require revisions to the basic model

structure and could be introduced for the 2026 or 2027 *Inventory* submission. The additional data from the atmospheric measurements suggests additional items to investigate. The faster uptick in HFC-32 and HFC-125 emissions suggests additional emissions of R-410A compared to the model's estimation. Further investigation into the average emission rate, the variability over time of the emission rate, stocks, lifetimes, and other factors will be investigated for the next (i.e., 2025) *Inventory* submission.

4.26 Electrical Equipment (CRT Source Category 2G1)

The largest use of sulfur hexafluoride (SF_6), both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas. Another greenhouse gas emitted in much smaller amounts by the electric power industry is tetrafluoromethane (CF_4), which is mixed with SF_6 to avoid liquefaction at low temperatures (Middleton 2000). While mixed gas circuit breakers are more common in extremely cold climates in geographies outside of the United States, some U.S. manufacturers of electrical equipment are emitting CF_4 during the manufacturing of equipment designed to hold the SF_6/CF_4 gas mixture. However, no electrical equipment facilities in the United States have reported emissions of or equipment using CF_4. SF_6 emissions exceed PFC emissions from electric power systems on both a GWP-unweighted and GWP-weighted basis. This reporting category (2G1) includes emissions from electrical equipment.

Fugitive emissions of SF_6 and CF_4 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 and CF_4 from equipment manufacturing and from electrical equipment systems were estimated to be 5.1 MMT CO_2 Eq. (0.3 kt) in 2022. This quantity represents a 79 percent decrease from the estimate for 1990 (see Table 4-129 and Table 4-130). There are a few potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's voluntary SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership) and EPA's GHGRP, regulatory drivers at the state and local levels, and research and development of alternative gases to SF_6 that can be used in gas-insulated substations. Utilities participating in the Partnership have lowered their emission factor from 13 percent in 1999 (kg SF_6 emitted per kg of nameplate capacity) to 0.9 percent in 2022. SF_6 emissions reported by electric power systems to EPA's GHGRP have decreased by 56 percent from 2011 to 2022,[123] with much of the reduction seen from utilities that are not participants in the Partnership. These utilities may be making relatively large reductions in emissions as they take advantage of relatively large and/or inexpensive emission reduction opportunities (i.e., "low hanging fruit," such as replacing major leaking circuit breakers) that Partners have already taken advantage of under the voluntary program

[123] Analysis of emission trends from facilities reporting to EPA's GHGRP is imperfect due to an inconsistent group of reporters year to year. A facility that has reported total non-biogenic greenhouse gas emissions below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years to EPA's GHGRP can discontinue reporting for all direct emitter subparts. For this sector, most of the variability in the group of reporters is due to facilities exiting the GHGRP due to being below one of these thresholds; however, facilities must re-enter the program if their emissions at a later date are above 25,000 MT CO_2 Eq., which may occur for a variety of reasons, including changes in facility size and changes in emission rates.

(Ottinger et al. 2014). Total emissions from electrical equipment in 2022 were lower than 2021 emissions, decreasing by 15.3 percent.

Table 4-129: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Electric Power Systems	24.3	11.2	4.7	5.7	5.3	5.6	4.8
Electrical Equipment Manufacturers	0.3	0.7	0.3	0.4	0.5	0.4	0.3
Total	24.7	11.9	5.0	6.1	5.9	6.0	5.1

Note: Totals may not sum due to independent rounding.

Table 4-130: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

	1990	2005	2018	2019	2020	2021	2022
SF_6 Emissions	1.0	0.5	0.2	0.3	0.3	0.3	0.2
CF_4 Emissions	+	+	NO	+	+	+	+

+ Does not exceed 0.5 kt.
NO (Not Occurring)

Methodology and Time-Series Consistency

The estimates of emissions from electrical equipment are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1990 through 1998 Emissions from Electric Power Systems

Emissions from electric power systems from 1990 through 1998 were estimated based on (1) the emissions estimated for this source category in 1999, which, as discussed in the next section, were based on the emissions reported during the first year of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership), and (2) the RAND survey of global SF_6 emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 through 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales was used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the *2006 IPCC Guidelines*.[124] (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the discussion of substitutes for ozone-depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

[124] Ideally, sales to utilities in the United States between 1990 and 1999 would be used as a model. However, this information was not available. There were only two U.S. manufacturers of SF_6 during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

Equation 4-24: Estimation for SF_6 Emissions from Electric Power Systems

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms) [125]

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be MMT CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1999 through 2022 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2022 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); (3) SF_6 emissions from California estimated by the California Air Resources Board (CARB) and (4) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, 2013, and 2016 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013, and 2017), and 2019, 2020, and 2021 Homeland Infrastructure Foundation-Level Data (HIFLD) (HIFLD 2019, 2020, and 2021), which was applied to the electric power systems that do not report to EPA (Non-Reporters). Total U.S. transmission mileage was interpolated between 2016 and 2019 to estimate transmission mileage of electric power systems in 2017 and 2018. (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

[125] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

Partners

Over the period from 1999 to 2022, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership,[126] represented 49 percent, on average, of total U.S. transmission miles. Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a Partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2012, many Partners began reporting their emissions (for 2011 and later years) through EPA's GHGRP (discussed further below) rather than through the Partnership. In 2022, less than 1 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 99.6 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP.[127] Overall, the emission rates reported by Partners have decreased significantly throughout the time series.

Non-Partners

Non-Partners consist of two groups: Utilities that have reported to the GHGRP beginning in 2012 (reporting 2011 emissions) or later years (GHGRP-only Reporters) and utilities that have never reported to the GHGRP (Non-Reporters). EPA's GHGRP requires users of SF_6 in electric power systems to report emissions if the facility has a total SF_6 nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF_6 emissions equal to 25,000 metric tons of CO_2 equivalent at the historical emission rate reported under the Partnership). As under the Partnership, electric power systems that report their SF_6 emissions under EPA's GHGRP are required to use the Tier 3 utility-level mass-balance approach. GHGRP-Only Reporters accounted for 16 percent of U.S. transmission miles and 14 percent of estimated U.S. emissions from electric power system in 2022.[128]

From 1999 through 2018, emissions from both GHGRP-only Reporters and Non-Reporters were estimated in the same way. From 1999 through 2008, emissions were estimated using the results of a regression analysis that correlated the 1999 emissions from Partner utilities with their 1999 transmission miles.[129] The 1999 regression coefficient (emission factor) was held constant through 2008 and multiplied by the transmission miles estimated for the non-Partners for each year.

The 1999 regression equation for Non-Partners was developed based on the emissions reported by a subset of Partner utilities who reported non-zero emissions and non-zero transmission miles (representing approximately 50 percent of total U.S. transmission miles). The regression equation for 1999 is displayed in the equation below.

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[126] Starting in the 1990 to 2015 *Inventory*, partners who had reported three years or less of data prior to 2006 were removed. Most of these Partners had been removed from the list of current Partners but remained in the Inventory due to the extrapolation methodology for non-reporting partners.

[127] Only data reported as of August 21, 2023 are used in the emission estimates for the prior year of reporting. Emissions for Partners that did not report to the Partnership or GHGRP are extrapolated for three years using a utility-specific transmission mile growth rate. After four consecutive years of non-reporting they are included in the 'non-reporting Partners' category. It should be noted that data reported through EPA's GHGRP must go through a verification process. For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted.

[128] GHGRP-reported and Partner transmission miles from a number of facilities were equal to zero with non-zero emissions. These facilities emissions were added to the emissions totals for their respective parent companies when identifiable and not included in the regression equation when not identifiable or applicable. Other facilities reported non-zero transmission miles with zero emissions, or zero transmission miles and zero emissions. These facilities were not included in the development of the regression equations (discussed further below). These emissions are already implicitly accounted for in the relationship between transmission miles and emissions.

[129] In the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV.

Equation 4-25: Regression Equation for Estimating SF_6 Emissions of Non-Reporting Facilities in 1999

$$\text{Emissions (kg)} = 0.771 \times \text{Transmission Miles}$$

The 1999 emission factor (0.77 SF_6 emissions/Transmission Miles) for the non-Partners was held constant to estimate non-Partner emissions from 2000-2008. Non-partner emissions were assumed to decrease beginning in 2009, trending toward the regression coefficient (emission factor) calculated for the GHGRP-only reporters based on their reported 2011 emissions and transmission miles. Emission factors for 2009 and 2010 were linearly interpolated between the 1999 and 2011 emission factors. For 2009, the emissions of non-Partners were estimated by multiplying their transmission miles by the interpolated 2009 emission factor (0.65 kg/transmission mile).

The 2011 regression equation was developed based on the emissions reported by GHGRP-Only Reporters who reported non-zero emissions and non-zero transmission miles (representing approximately 23 percent of total U.S. transmission miles). The regression equation for 2011 is displayed below.

Equation 4-26: Regression Equation for Estimating SF_6 Emissions of GHGRP-Only Reporters in 2011

$$\text{Emissions (kg)} = 0.397 \times \text{Transmission Miles}$$

For 2011 and later years, the emissions of GHGRP-only reporters were generally equated to their reported emissions, unless they did not report. The emissions of GHGRP-only reporters that have years of non-reporting between reporting years are gap filled by interpolating between reported values.

For 2010 and later years, the emissions of non-Reporters were estimated by multiplying their transmission miles by the estimated 2010 emission factor (0.52 kg/transmission mile), which was held constant from 2010 through 2022.

Off-ramping GHGRP Facilities

The GHGRP program has an "off-ramp" provision (40 CFR Part 98.2(i)) that exempts facilities from reporting under certain conditions. If reported total greenhouse gas emissions are below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years, the facility may elect to discontinue reporting. Emissions of GHGRP reporters that have off-ramped are extrapolated for three years of non-reporting using a utility-specific transmission mile growth rate, unless the utility has transmission mileage in California. After three consecutive years of non-reporting, emissions for facilities (except those in California) that off-ramped from GHGRP were estimated using an emissions rate derived from the reported emissions and transmission miles of GHGRP-only reporters in the respective year. For facilities in California, a California-specific emissions rate is used as described in the following section.

Table 4-131: GHGRP-only Average Emission Rate (kg per mile)

Year	2011	2018	2019	2020	2021	2022
Average emission rate	0.43	0.22	0.29	0.27	0.25	0.22

Table 4-132: Categorization of Utilities and Timeseries for Application of Corresponding Emission Estimation Methodologies

Categorization of Utilities	Timeseries
Partners	1999 - 2021
Non-Partners (GHGRP-Only)	2011 – 2021
Non-Partners (Remaining Non-Reporting Utilities)	1999 – 2021
Off-ramping GHGRP Facilities	2017 – 2021

California

CARB reports the total SF_6 emissions from electrical equipment within the state of California (CARB 2023). Because California utilities are required to report their SF_6 emissions to CARB even when they are not required to report to the GHGRP, CARB's estimates of California SF_6 emissions are expected to be more accurate for the California utilities that do not report to GHGRP than the methodology described above. As a result, the CARB SF_6 emissions estimates are used as California's contribution to the national total for 2011-2022, except in years where CARB's estimate is smaller than the California estimates reported to EPA or years for which CARB has not published estimates. Since CARB's emissions estimates include emissions from facilities that do not report to GHGRP, emissions for California GHGRP reporters that have off-ramped are not extrapolated. Specifically, CARB estimates are used for 2011, 2012, 2013, 2014, 2017, 2018, 2019, 2020, and 2021.

For each utility with transmission mileage in California, the GHGRP or voluntarily reported emissions attributed to California for that utility were determined using the percentage of that utility's transmission mileage within California based on data from HIFLD. These emissions across all California utilities were summed to find the California emissions that were reported through GHGRP or voluntarily to the EPA. Then, if CARB's emissions estimates for the reporting year were larger than the those from GHGRP and voluntary reporting, CARB's emissions replaced the California emissions from GHGRP and voluntary reporting.

If CARB's emissions estimates were lower than the California emissions from GHGRP and voluntary reporting, it is assumed there is likely an error, as this would imply negative emissions by GHGRP non-reporters. This was the case in 2015 and 2016. For these years, the GHGRP and voluntarily reported emissions from California are retained, and emissions from non-reporting utilities are estimated using a California-specific SF_6 emissions rate, which is based on CARB emission data. The California SF_6 emissions rate of 0.41 lbs SF_6 per transmission mile is found by taking the average of CARB emissions divided by the total California transmission mileage in years where CARB estimates are larger. Emissions from California non-reporting utilities are then found by multiplying the California SF_6 emissions rate by the California transmission mileage from non-reporting utilities. This methodology is also used if CARB has not published emissions estimates for a particular year. CARB has not yet published estimates for 2022.

Table 4-133: California GHGRP and Voluntarily Reported SF_6 Emissions Compared to CARB's SF_6 Emissions (MMT CO_2 Eq.)

	2011	2015	2016	2017	2018	2019	2020	2021	2022
CA GHGRP and Voluntary	0.19	0.16	0.24	0.12	0.11	0.14	0.20	0.14	0.15
CARB (CARB 2023)	0.24	0.14	0.10	0.18	0.14	0.17	0.24	0.24	NE
Final CA	0.24	0.21	0.29	0.18	0.14	0.17	0.24	0.24	0.20

NE (Not Estimated)

Total Industry Emissions

Total electric power system emissions from 1999 through 2022 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), the GHGRP-only reported emissions, off-ramping GHGRP Facilities (non-reporters), non-reporters who eventually report to GHGRP, and the non-reporting utilities' emissions (except California). Then, the California GHGRP and voluntarily reported emissions are subtracted from the total and replaced with CARB's emissions (or GHGRP and voluntarily reported emissions plus California non-reporting utilities' emissions).

Non-Partner Transmission Miles

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, 2012, and 2016 were obtained from the 2001, 2004, 2007, 2010, 2013, and 2017 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013, and 2017). For 2019 to 2022 non-reporter transmission mileage was derived by subtracting reported transmission mileage data from the total U.S.

transmission mileage from 2019 to 2022 HIFLD Data (HIFLD 2019, 2020, 2021, and 2022). The following trends in transmission miles have been observed over the time series:

- The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 yet declined by almost 4,000 miles between 2003 and 2006. Given these fluctuations, periodic increases are assumed to occur gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and decrease by 0.20 percent between 2003 and 2006.
- The U.S. transmission system's annual growth rate grew to 1.7 percent from 2006 to 2009 as transmission miles increased by more than 33,000 miles.
- The annual growth rate for 2009 through 2012 was calculated to be 1.4 percent as transmission miles grew yet again by over 29,000 miles during this time period.
- The annual transmission mile growth rate for 2012 through 2016 was calculated to be 0.2 percent, as transmission miles increased by approximately 5,500 miles.
- The annual transmission mile growth rate for 2016 through 2020 was calculated to be 0.9 percent, as transmission miles increased by approximately 26,000 miles.
- The annual transmission mile growth rate for 2020 through 2021 was calculated to be 2.2 percent, as transmission miles increased by approximately 16,000 miles.
- The annual transmission mile growth rate for 2021 through 2022 was calculated to be 0.7 percent, as transmission miles increased by approximately 5,500 miles.

Transmission miles for each year for non-reporters were calculated by interpolating between UDI reported values obtained from the 2001, 2004, 2007, 2010, 2013 and 2017 UDI directories and HIFLD data for 2019 and subsequent years. In cases where a non-reporter previously reported the GHGRP or the Partnership, transmission miles were interpolated between the most recently reported value and the next available UDI value.

1990 through 2022 Emissions from Manufacture of Electrical Equipment

Three different methods were used to estimate 1990 to 2022 emissions from original electrical equipment manufacturers (OEMs).

- OEM SF_6 emissions from 1990 through 2000 were derived by assuming that manufacturing emissions equaled 10 percent of the quantity of SF_6 provided with new equipment. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002). The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000.
- OEM SF_6 emissions from 2000 through 2010 were estimated by (1) interpolating between the emission rate estimated for 2000 (10 percent) and an emission rate estimated for 2011 based on reporting by OEMs through the GHGRP (5.7 percent), and (2) estimating the quantities of SF_6 provided with new equipment for 2001 to 2010. The quantities of SF_6 provided with new equipment were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (156.5 MMT CO_2 Eq. in 2010). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2010 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF_6 provided with new equipment for the entire industry. Additionally, to obtain the 2011 emission rate (necessary for estimating 2001 through 2010 emissions), the estimated 2011 emissions (estimated using the third methodology listed below) were divided by the estimated total quantity of SF_6

provided with new equipment in 2011. The 2011 quantity of SF_6 provided with new equipment was estimated in the same way as the 2001 through 2010 quantities.

- OEM CF_4 emissions from 1991 through 2010 were estimated by using an average ratio of reported SF_6 and CF_4 emissions from 2011 through 2013. This ratio was applied to the estimated SF_6 emissions for 1991 through 2010 to arrive at CF_4 emissions. CF_4 emissions are estimated starting in 1991 and assumed zero prior to 1991 based on the entry of the CF_4/SF_6 gas mixture into the market (Middleton 2000).
- OEM emissions from 2011 through 2022 were estimated using the SF_6 and CF_4 emissions from OEMs reporting to the GHGRP, and an assumption that these reported emissions account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs (those that report and those that do not).
- OEM SF_6 emissions from facilities off-ramping from the GHGRP were determined by extrapolation. First, emission growth rates were calculated for each reporting year for each OEM reporting facility as well as an average emissions growth rate (2011 through 2022). Averages of reported emissions from last three consecutive reporting years were multiplied by the average growth rate for each off-ramping OEM to estimate emissions for the non-reporting year(s).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

To estimate the uncertainty associated with emissions of SF_6 and CF_4 from electrical equipment, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting (through the Partnership or EPA's GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF_6 data was assumed to have an uncertainty of +/- 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all Partner-reported data was estimated to be 4.5 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 7.4 percent.

As discussed below, EPA has substantially revised its method for estimating emissions from non-Reporters, assuming that the average emission rate of non-Reporters has declined much more slowly than the average emission rate of reporting facilities rather than declining at the same rate. This assumption brings the U.S. SF_6 emissions estimated in this *Inventory* into better agreement with the U.S. SF_6 emissions inferred from atmospheric observations. However, it must be emphasized that the actual emission rates of non-Reporters remain unknown. It is possible that they are lower or even higher than estimated here. One possibility is that SF_6 sources other than electric power systems are contributing to the emissions inferred from atmospheric observations, implying that the emissions from non-Reporters are lower than estimated here. Another is that the emissions inferred from atmospheric measurements are over- (or under-) estimated, implying that emissions from non-Reporters could be either lower or higher than estimated here. These uncertainties are difficult to quantify and are not reflected in the estimated uncertainty below. The estimated uncertainty below accounts only for the two sources of uncertainty associated with the regression equations used to estimate emissions in 2019 from Non-Reporters: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for Non-Reporters. Uncertainties were also estimated regarding (1) estimates of SF_6 and CF_4 emissions from OEMs reporting to EPA's GHGRP, and (2) the assumption on the percent share of OEM emissions from OEMs reporting to EPA's GHGRP.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 1-57. electrical equipment emissions were estimated to be between 3.8 and 6.4 MMT CO_2 Eq. at the 95 percent confidence level, a range of approximately 25 percent below and 25 percent above the emission estimate of 5.1 MMT CO_2 Eq. CF_4 emissions were estimated to be between 0.000006 and 0.000009 MMT CO_2 Eq. at the 95 percent confidence level, a range of approximately 20 percent below and 20 percent above the emission estimate of 0.0000074 MMT CO_2 Eq.

Table 4-134: Approach 2 Quantitative Uncertainty Estimates for SF_6 and CF_4 Emissions from Electrical Equipment (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to 2022 Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Equipment	SF_6	5.1	3.8	6.4	-25%	+25%
Electrical Equipment	CF_4	0.0000074	0.000006	0.000009	-20%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

In addition to the uncertainty quantified above for the 2022 estimate, there is uncertainty associated with the emission rates of GHGRP-only facilities before 2011 and of non-Reporters throughout the time series. As noted above in the discussion of the uncertainty of non-Reporters for 2022, these uncertainties are difficult to quantify.

There is also uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998 (RAND 2004), and emissions based on atmospheric measurements declined by 17 percent over the same period (Levin et al. 2010).

Several pieces of evidence indicate that U.S. SF_6 emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF_6 that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from DILO, a major manufacturer of SF_6 recycling equipment, stated that most U.S. utilities began recycling rather than venting SF_6 within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported its emissions for all the years from 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details. Category specific QC findings are described below.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[130] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

[130] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Additionally, EPA provides additional quality control for the SF_6 emissions estimates using atmospheric derived estimates for comparison. The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1: General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. Further, it identifies fluorinated gases as particularly suited for such comparisons. The *2019 Refinement* makes this conclusion for fluorinated gases based on their lack of significant natural sources,[131] their generally long atmospheric lifetimes, their well-known loss mechanisms, and the potential uncertainties in bottom-up inventory methods for some of their sources. Unlike non-fluorinated greenhouse gases (CO_2, CH_4, and N_2O), SF_6 has no significant natural sources; therefore, the SF_6 estimates derived from atmospheric measurements are driven overwhelmingly by anthropogenic emissions. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC (2019) Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC (2019) Volume 1, Chapter 6). Emission estimates derived from atmospheric measurements of SF_6 made at NOAA and described in Hu et al. (2022) were used to perform a comparison to the inventory estimates. This comparison resulted in changes to historical emission estimates, as more thoroughly described in the previous *Inventory* cycle (EPA 2022). No further changes were made to the electrical equipment estimates for the current (i.e., 1990 through 2022) *Inventory* based on this comparison.

Recalculations Discussion

Several updates to activity data led to recalculations of previous *Inventory* results. The major updates are as follows:

- As discussed in the methodology above, CARB estimates of SF_6 emissions from electrical equipment in California were used as California's contribution to the national total starting in 2011, except in cases where CARB emissions were lower than GHGRP and voluntarily reported emissions from California, or in years where CARB has not published SF_6 emissions estimates.
- Updates were made to reporter emissions where facilities had resubmitted data.
- A correction was made to estimate 2021 nameplate capacities for two off-ramping utilities, which off-ramped in 2021; these estimations were inadvertently omitted in the previous *Inventory*.
- SF_6 emissions from electrical equipment manufacturing was corrected due to an erroneous data pull in the previous *Inventory*. This caused emissions to increase in years 2011 through 2019.
- Partner transmission mileage used for calculating average share of Partner utilities across the time series and for estimating nameplate capacity for non-reporting utilities was corrected. The calculation was previously referencing partner transmission mileage for the prior year for 2013 through 2021.

Planned Improvements

EPA plans to revisit the methodology for determining emissions from the manufacture of electrical equipment, in particular, the assumption that emissions reported by OEMs account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs. Additional market research will be required to confirm or modify the assumptions regarding the portion of industry not reporting to the GHGRP program.

[131] See Harnisch and Eisenhauer (1998).

4.27 SF_6 and PFCs from Other Product Use (CRT Source Category 2G.2)

There are a variety of other products and processes that use fluorinated greenhouse gases. This section estimates emissions of sulphur hexafluoride (SF_6) and perfluorocarbons (PFCs) from other product use (CRT Source Category 2G.2), including military and scientific applications. Many of these applications utilize SF_6 or PFCs to exploit their unique chemical properties, such as the high dielectric strength of SF_6 and the stability of PFCs. Emission profiles from these processes may vary greatly, ranging from immediate and unavoidable release of all of the chemical to largely avoidable, delayed release from leak-tight products after decades of use.

Military applications employ SF_6 and PFCs in many processes, such as the use of SF_6 in the radar systems of military reconnaissance planes of the Boeing E-3A type, commonly known as Airborne Warning and Control Systems (AWACS). These systems use SF_6 to prevent electric flashovers in the hollow conductors of the antenna, where voltages can reach up to 135 kilovolts (kV). During ascent of the planes, SF_6 is automatically released from the AWACS to maintain appropriate pressure difference between the system and the outside air. During descent, the system is automatically charged with SF_6 from an SF_6 container on board. Most emissions occur during ascent but may also occur from system leakage during other phases of flight or during time on the ground. Emissions from AWACS are largely dependent on the number of active planes and sorties (take-offs) per year.

Other uses of SF_6 in military applications include the oxidation of lithium in navel torpedoes and infrared decoys. SF_6 has also been documented for use in the quieting of torpedo propellers, as well as a by-product of the processing of nuclear material for the production of fuel and nuclear warheads.

Military electronics are believed to be a key application for PFC heat transfer fluids, particularly in areas such as ground and airborne radar avionics, missile guidance systems, and sonar. PFCs may also be used to cool electric motors, especially for equipment where noise reduction is a priority (e.g., submarines). The specific PFCs used in military applications are similar to heat transfer fluids identified in the electronics industry (see Section 4.24). PFCs are typically contained in a closed system, so the emissions are most likely to occur during the manufacture, maintenance, and disposal of equipment.

SF_6 and PFCs are also employed in several scientific applications, such as for use in particle accelerators. Particle accelerators can be found in university and research settings, as well as in industrial and medical applications. SF_6 is typically used as an insulating gas and is operated in a vessel exceeding atmospheric pressure. The amount of SF_6 used in particle accelerators is largely dependent on the terminal voltage of the unit. Emissions of SF_6 typically occur when SF_6 is transferred to storage tanks while maintenance is occurring, when pressure relief valves are actuated, and through slow leaks. The emission and charge assumptions for industrial and medical particle accelerators differ from those of university and research accelerators, as discussed in the methodology below. PFCs (particularly PFC-14) may also be used in particle accelerators as particle detectors or counters (Workman 2022).

SF_6 may also be employed in other high-voltage scientific equipment, including lasers, x-rays, and electron microscopes. SF_6 emission estimates for this equipment were not disaggregated from particle accelerators for this *Inventory*.

There is a range of unidentified processes that also use SF_6 and PFCs, such as R&D activities. PFCs are likely used primarily as heat transfer fluids (HTFs). Emissions reported for these unknown activities group under “Other Scientific Applications”.

Emissions of SF_6 and PFCs from the applications outlined above are presented in Table 4-135.

Table 4-135: SF_6 and PFC Emissions from Other Product Use (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	0.6	0.6	0.4	0.4	0.3	+	0.3
Total AWACs	**0.6**	**0.6**	**0.4**	**0.4**	**0.3**	**+**	**0.3**
SF_6	0.3	0.3	0.0	0.0	0.0	0.0	0.0
PFCs	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Total Other Military Applications	**0.4**	**0.4**	**0.2**	**0.2**	**0.2**	**0.1**	**0.2**
SF_6	0.4	0.5	0.4	0.2	0.1	0.2	0.2
PFC-14	+	+	+	+	+	+	+
Total Particle Accelerators	**0.4**	**0.5**	**0.4**	**0.2**	**0.1**	**0.2**	**0.2**
SF_6	+	+	+	+	0.1	0.2	0.1
PFCs	+	+	+	+	+	+	+
Total Other Scientific Applications	**+**	**+**	**+**	**+**	**0.1**	**0.2**	**0.1**
Total Other Product Use	**1.4**	**1.5**	**0.9**	**0.8**	**0.7**	**0.5**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: PFC subtotals include estimates for HFEs. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions are based primarily on data reported through the Federal Energy Management Program (FEMP). However, the availability of data from FEMP differs across the 1990 through 2022 time series. Consequently, additional emission estimates were made through utilizing methodologies from the IPCC. Emissions from military applications and scientific applications were estimated separately, and the approaches are described immediately below.

Military Applications

1990 through 2007

FEMP data was not readily available for the 1990 to 2007 period as the first reporting year was in 2008. Thus for this period, estimated SF_6 emissions from AWACS were calculated based using the IPCC Tier 1 methodology (IPCC 2006). IPCC provided a default emissions factor of 740kg of SF_6 per plane per year. It was assumed that the U.S. AWAC fleet between 1990 through 2022 remained constant at 33 planes. The IPCC methodology was utilized for all years from 1990 to 2007.

Emissions for other military applications were estimated by taking the average of the emissions estimated for other applications as described in the next section for first five FEMP reporting years (i.e., 2008 through 2012) and held constant between 1990 through 2007. Emissions from AWACS were not specifically reported by FEMP; the estimates developed for AWACS using the IPCC methodology above were employed to determine emissions from remaining unidentified military applications.

2008 through 2021

For the period 2008 through 2021, the Department of Defense (DOD) reported emission data through FEMP which were used to develop estimates for SF_6 and PFCs from other military applications. SF_6 emission estimates developed for AWACS using the IPPC Tier 1 methodology (see 1990 through 2007) were compared against SF_6 emissions reported by DOD between 2008 and 2021. In years where SF_6 emissions reported by DOD was smaller than those estimated using the IPCC Tier 1 methodology, DOD-reported emissions were assumed to account for total AWAC emissions; in years where DOD emissions were greater than the calculated AWAC emissions, the remainder is assumed to be from other SF_6 applications.

Emissions from PFCs, HFEs, and other perfluoro compounds are directly reported by DOD. In years where there are data gaps from FEMP between two reporting years, expected emissions were interpolated.

2022

Estimates for emissions from AWACS and other military uses for 2022 were determined by taking an average of the previous five reporting years (i.e., 2017 through 2021).

Scientific Applications

1990 through 2007

For the period 1990 through 2007, where no reported data is available from the Department of Energy (DOE), estimates for emissions of SF_6 and PFCs from other product use at Department of Energy Laboratories were determined by taking an average of the first five reporting years (i.e., 2008 through 2012) and held constant from 1990 to 2007.

SF_6 emissions from other (non-DOE) research and industrial particle accelerators in the United States was calculated based on the IPCC Tier 1 methodology for estimating emissions from industrial and university/research particle accelerators. Default emission factors, charge sizes, and usage rates are provided by size and type of accelerator in the IPCC methodology. These default assumptions were multiplied against the number of particle accelerators estimated to be active in the United States by year. This methodology remained the same from 1990 to 2007.

2008 through 2021

For the period 2008 through 2021, SF_6 and PFC emissions from government particle accelerators and other scientific equipment were developed using DOE-reported emissions. SF_6 and PFC emissions from particle accelerators were directly reported by DOE. Other fugitive emissions reported by DOE for SF_6 were assumed to represent emissions from particle accelerators and other scientific equipment, as well as two DOE-managed power facilities (WAPA and BPA).[132] Emissions from these two facilities were subtracted out to present only SF_6 emissions from scientific equipment. Reported fugitive emissions for PFC-14 were assumed to wholly represent particle accelerator applications. SF_6 emissions from non-government particle accelerators were estimated using the IPPC Tier 1 methodology used for 1990 through 2007.

Process emissions from other applications for SF_6 and PFCs were reported by DOE for activities such as R&D, and these emissions were summed by gas. However, the estimates presented here do not include emissions reported for semiconductor research and manufacture, or from refrigeration and air conditioning. Emissions from additional PFCs, HFEs, and other perfluoro compounds are directly reported by DOE and are reported as "Other Applications." Emissions reported to FEMP were generally calculated based on consumption data. In a number of years, negative values for emissions were reported due to more gas being returned to supply than purchased in a given year. When negative values were reported, EPA took the average of that year and the proceeding and following year and applied that value to all three years. This 3-year average was assumed to be more representative of actual emissions.

In years where there are data gaps between two reporting years, emissions were interpolated.

2022

For emission estimates developed using DOE-reported emissions, estimates for 2022 were determined by taking an average of the previous five reporting years (i.e., 2017 through 2021). SF_6 emissions from non-government

[132] DOE-reported fugitive emissions for SF_6 and PFCs includes emissions from high-voltage scientific equipment such as lasers, x-rays, and electron microscopes. Emissions from this equipment is included in the particle accelerators total.

particle accelerators were estimated using the same IPPC Tier 1 methodology used for 2008 through 2021.

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The Monte Carlo stochastic simulation was performed on the total emissions estimate from other product use, represented in equation form as:

Equation 4-27: Total Emissions from Other Product Use

$$\begin{aligned}&\text{Total Emissions } (E_T)\\ &\quad = \text{ Military Applications } SF_6 \text{ and PFC Emissions } \left(E_{Military}\right)\\ &\quad + \text{ Scientific Applications of } SF_6 \text{ and PFC Emissions } \left(E_{Scientific}\right)\end{aligned}$$

The uncertainty in the total emissions for other product use, presented in Table 4-124 below, results from the convolution of two distributions of emissions, namely from military applications and scientific applications. The approaches for estimating uncertainty in each of the sources are described below:

Military Applications Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from military applications, represented in equation form as:

Equation 4-28: Total Emissions from Military Applications

$$\begin{aligned}&\text{Military Applications } SF_6 \text{ and PFC Emissions } \left(E_{Military}\right)\\ &\quad = \text{ Military AWACS } SF_6 \text{ Emissions } \left(E_{AWACS,SF_6,Military}\right)\\ &\quad + \text{ Other Military Applications } SF_6 \text{ Emissions } \left(E_{Other,SF_6,Military}\right)\\ &\quad + \text{ Other Military Applications PFC Emissions } \left(E_{Other,PFC,Military}\right)\end{aligned}$$

The uncertainty in $E_{Military}$ results from the convolution of three distributions of emissions, $E_{AWACS,SF6,Military}$, $E_{Other,SF6,Military}$, and $E_{Other,PFC,Military}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for $E_{Military}$ are described in the remainder of this section.

The uncertainty estimate of $E_{AWACS,SF6,Military}$, or SF_6 emissions from AWACS, is developed based on the number of AWACS in commission in the United States and the per-plane emission factor. The estimated number of active planes installed with AWACS is 33, although estimates range between 31 and 35. The IPCC provides a per-plane emission factor of 740 kg of SF_6 per plane annually and estimates the uncertainty to have bounds of ±14 percent.

The uncertainty in $E_{Other,SF6,Military}$ and $E_{Other,PFC,Military}$, or SF_6 and PFC emissions from other military applications, was obtained by determining the accuracy of government-reported emissions data and reviewing the methodology the Department of Defense uses for developing inventory estimates.

The next step in estimating the uncertainty in emissions from military AWACS and other military applications is convolving the distribution of reported emissions, emission factors, and number of AWACS using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported emissions and emission factors are assumed to be normally distributed, and the number of AWACS is assumed to have a uniform distribution since this is a discrete number of planes. The uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean.

Scientific Applications Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from scientific applications,

represented in equation form as:

Equation 4-29: Total Emissions from Scientific Applications

$$\begin{aligned}&\text{Scientific Applications } SF_6 \text{ and PFC Emissions } \left(E_{Scientific}\right)\\&= \text{ Particle Accelerators } SF_6 \text{ Emissions } \left(E_{Accelerators,SF_6,Scientific}\right)\\&+ \text{ Particle Accelerators PFC Emissions } \left(E_{Accelerators,PFC,Military}\right)\\&+ \text{ Other Scientific Applications } SF_6 \text{ Emissions } \left(E_{Other,SF_6,Scientific}\right)\\&+ \text{Other Scientific Applications PFC Emissions } \left(E_{Other,PFC,Scientific}\right)\end{aligned}$$

The uncertainty in $E_{Scientific}$ results from the convolution of four distributions of emissions, $E_{Accelerators,SF6,Scientific}$, $E_{Accelerators,PFC,Military}$, $E_{Other,SF6,Scientific}$, and $E_{Other,PFC,Scientific}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for $E_{Scientific}$ are described in the remainder of this section.

The uncertainty estimate of $E_{Accelerators,SF6,Scientific}$ and $E_{Accelerators,PFC,Scientific}$, or SF_6 and PFC emissions from particle accelerators, is developed based on fugitive and process emissions reported by the Department of Energy and emission estimates from the number active university and industrial particle accelerators in the United States. The number of active particle accelerators in the United States for the time series 1990 through 2022 was determined using expert judgment; default emission factors and charge sizes for particle accelerators of various sizes were provided by IPCC guidelines. Emissions of SF_6 from electrical transmission and distribution equipment were removed from total emissions estimates for this source category, as they are reported elsewhere in the *Inventory.*

The uncertainty in $E_{Other,SF6,Scientific}$ and $E_{Other,PFC,Scientific}$, or SF_6 and PFC emissions from other scientific applications, was obtained by determining the accuracy of government-reported emissions data and reviewing the methodology the Department of Energy uses for developing inventory estimates.

The next step in estimating the uncertainty in emissions from particle accelerators and other scientific applications is convolving the distribution of calculated emissions, emission factors, number of accelerators using Monte Carlo simulation. Similarly, the distributions of the reported emissions and emission factors for this Monte Carlo simulation are assumed to be normally distributed, and the number of particle accelerators and other scientific applications is assumed to have a uniform distribution since this is a discrete number of accelerators. The uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean.

The emissions estimate for total U.S. SF_6 and PFC emissions from other product use were estimated to be between 0.5 and 1.1 MMT CO_2 Eq. at a 95 percent CI level. This range represents 36 percent below and 38 percent above the 2022 emission estimate of 0.8 MMT CO_2 Eq. for all emissions from others product use. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-136: Approach 2 Quantitative Uncertainty Estimates for SF_6 and PFC Emissions from Other Product Use (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Other Product Use	SF_6 and PFC	0.8	0.5	1.1	-36%	+38%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

This is a new category included for the current (i.e., 1990 to 2022) *Inventory*, thus, no recalculations were performed.

4.28 Nitrous Oxide from Product Uses (CRT Source Category 2G3)

Nitrous oxide (N_2O) is a clear, colorless, oxidizing liquefied gas with a slightly sweet odor which is used in a wide variety of specialized product uses and applications. This reporting category (2G3) includes exhalation emissions of N_2O that arise from medical applications and evaporative emissions of N_2O from use as a propellant in aerosol products primarily in food industry. The amount of N_2O that is actually emitted depends upon the specific product use or application.

There are a total of three N_2O production facilities currently operating in the United States (Ottinger 2021). Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as an anesthetic in various dental and veterinary applications. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2022 was approximately 15 kt (see Table 4-137).

Table 4-137: N_2O Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	16	15	15	15	15	15	15

Nitrous oxide emissions were 3.8 MMT CO_2 Eq. (14 kt N_2O) in 2022 (see Table 4-138). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 4-138: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
N_2O Product Usage	3.8	3.8	3.8	3.8	3.8	3.8	3.8

Table 4-139: N_2O Emissions from N_2O Product Usage (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
N_2O Product Usage	14	14	14	14	14	14	14

Methodology and Time-Series Consistency

Emissions from N_2O product uses are calculated using a country-specific methodology that is consistent with *2006 IPCC Guidelines* and based on available data. The *2006 IPCC Guidelines* do not define tier methodologies for this source category. Emissions of N_2O are estimated using the national N_2O production by subcategory use or application, the share of the subcategory, and the appropriate emission rate for each category. The following equation is adapted from Equation 8.24 of the *2006 IPCC Guidelines*:

Equation 4-30: N_2O Emissions from Product Use

$$E_{pu} = \sum_{a} (P \times S_a \times ER_a)$$

where,

E_{pu} = N_2O emissions from product uses, metric tons

P = Total U.S. production of N_2O, metric tons

a = specific application

S_a = Share of N_2O usage by application *a*

ER_a = Emission rate for application *a*, percent

The share of total quantity of N_2O usage by end-use represents the share of national N_2O produced that is used by the specific subcategory (e.g., anesthesia, food processing). In 2020, the medical/dental industry used an estimated 89.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other subcategories, including semiconductor manufacturing, atomic absorption spectrometry, sodium azide production, auto racing, and blowtorches, used the remainder of the N_2O produced. This subcategory breakdown changed slightly in the mid-1990s. For instance, the small share of N_2O usage in the production of sodium azide declined significantly during the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). For 1990 through 1996, N_2O usage was allocated across the following subcategories: medical applications, food processing propellant, and sodium azide production. A usage emissions rate was then applied for each subcategory to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were assumed to release emissions into the atmosphere that are not captured under another source category, and therefore these subcategories were the only usage subcategories with emission rates. Emissions of N_2O from semiconductor manufacturing are described in Section 4.24 and reported under CRT Source Category 2H3. For the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed or reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). Nitrous oxide production data for 1993 through 1995 were not available. Production data for

1996 was specified as a range in two data sources (Heydorn 1997; Tupman 2002). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2002) provided a narrower range (15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2002) data are considered more industry-specific and current; therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2002). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to the lack of publicly available data, production estimates for years 2004 through 2022 were held constant at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to the lack of publicly available data, the share of total quantity of N_2O usage data for years 2004 through 2021 was assumed to equal the 2003 value. The emission factor for the food processing propellant industry was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997) and confirmed by a N_2O industry expert (Tupman 2002). The emission factor for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emission factor for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The overall uncertainty associated with the 2022 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively. The uncertainty associated with N_2O production data is ±25 percent, and a uniform probability density function is assigned, based on expert judgment (RTI 2023). The uncertainty associated with the market share for the medical/dental subcategory is ±0.56 percent, and uncertainty for the market share of food propellant subcategory is ±25 percent, both based on expert judgment (RTI 2023). Uncertainty for emission factors was assumed to be zero, and using this suggested uncertainty provided in the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-140. Nitrous oxide emissions from N_2O product usage were estimated to be between 2.9 and 4.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 24 percent below to 24 percent above the emission estimate of 3.8 MMT CO_2 Eq.

Table 4-140: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O from Product Uses	N_2O	3.8	2.9	4.6	-24%	+24%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 to 2021 portion of the time series.

Planned Improvements

EPA recently initiated an evaluation of alternative production statistics for cross-verification and updating time-series activity data, emission factors, assumptions, etc., and a reassessment of N_2O product use subcategories that accurately represent trends. This evaluation includes conducting a literature review of publications and research that may provide additional details on the industry. This work remains ongoing, and thus far no additional sources of data have been found to update this category.

Pending additional resources and planned improvement prioritization, EPA may also evaluate production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses.

Finally, for future Inventories, EPA will examine data from EPA's GHGRP to improve the emission estimates for the N_2O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing CBI and time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as required in this *Inventory*. This is a lower priority improvement, and EPA is still assessing the possibility of incorporating aggregated GHGRP CBI data to estimate emissions; therefore, this planned improvement is still in development and not incorporated in the current *Inventory* report.

4.29 Industrial Processes and Product Use Sources of Precursor Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various greenhouse gas precursors. The reporting requirements of the Paris Agreement and the UNFCCC[133] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse gases (e.g., ozone) and atmospheric aerosol (e.g., particulate sulfate). Combustion byproducts such as CO and NO_x are emitted from industrial applications that employ thermal incineration as a control technology. NMVOCs, commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum-based products, and can also result from the product storage and handling.

[133] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

Accidental releases of precursors associated with product use and handling can constitute major emissions in this category. In the United States, emissions from product use are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The major categories of product uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (e.g., electronics), dry cleaning, and non-industrial uses (e.g., uses of paint thinner). Product usage in the United States also results in the emission of hydrofluorocarbons (HFCs) and small amounts of hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances and the Electronics Industry in this chapter.

Total emissions of NO_x, CO, NMVOCs, and SO_2 from non-energy industrial processes and product use from 1990 to 2022 are reported in Table 4-141.

Table 4-141: NO_x, CO, NMVOC, and SO_2 Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
NO_x	**774**	**672**	**461**	**440**	**393**	**403**	**389**
Mineral Industry	160	200	118	114	101	99	95
Other Industrial Processes[a]	326	355	218	206	187	189	184
Metal Industry	96	58	63	60	52	60	56
Chemical Industry	192	80	61	59	54	55	53
CO	**4,099**	**1,701**	**1,022**	**1,011**	**855**	**902**	**897**
Metal Industry	2,261	707	447	448	340	355	335
Other Industrial Processes[a]	564	662	332	331	294	309	329
Mineral Industry	182	120	111	106	96	95	95
Chemical Industry	1,093	211	132	126	125	142	138
NMVOCs	**6,982**	**3,668**	**3,119**	**2,996**	**3,366**	**3,508**	**3,505**
Other Industrial Processes[a]	6,270	3,396	3,003	2,883	3,261	3,398	3,401
Chemical Industry	601	221	88	86	81	84	79
Mineral Industry	9	10	7	7	6	6	6
Metal Industry	102	40	21	20	17	19	19
SO_2	**1,488**	**776**	**335**	**309**	**266**	**274**	**261**
Other Industrial Processes[a]	474	256	145	134	120	126	119
Chemical Industry	283	242	106	97	83	83	75
Mineral Industry	166	138	25	25	26	28	28
Metal Industry	566	140	58	53	37	38	39

[a] Other Industrial Processes includes storage and transport, other industrial processes (manufacturing of agriculture, food, and kindred products; wood, pulp, paper, and publishing products; rubber and miscellaneous plastic products; machinery products; construction; transportation equipment; and textiles, leather, and apparel products), and miscellaneous sources (catastrophic/accidental release, other combustion (structural fires), health services, repair shops, and fugitive dust). It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.

Note: Totals by gas may not sum due to independent rounding.

Source: (EPA 2023a). Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2020 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 4-141, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs were recategorized from NEI Emissions Inventory System (EIS) sectors to source categories more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC based on

discussions between the EPA GHG Inventory and NEI staff (see crosswalk documented in Annex 6.3).[134] EIS sectors mapped to the IPPU sector categories in this report include: chemical and allied product manufacturing, metals processing, storage and transport, solvent utilization, other industrial processes, and miscellaneous sources. As described in the NEI Technical Support Documentation (TSD) (EPA 2023c), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2021, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends web site (EPA 2023a; EPA 2023c). A quantitative uncertainty analysis was not performed.

[134] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRTs), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of methane (CH_4) from enteric fermentation, livestock manure management, rice cultivation and field burning of agricultural residues; nitrous oxide (N_2O) emissions from agricultural soil management, livestock manure management, and field burning of agricultural residues; as well as carbon dioxide (CO_2) emissions from liming and urea fertilization (see Figure 5-1). Additional CO_2, CH_4 and N_2O fluxes from agriculture-related land-use and land-use conversion activities, such as cultivation of cropland, management on grasslands, grassland fires, aquaculture, and conversion of forest land to cropland, are presented in the Land Use, Land-Use Change, and Forestry (LULUCF) chapter. Carbon dioxide emissions from stationary and mobile on-farm energy use and CH_4 and N_2O emissions from stationary on-farm energy use are reported in the Energy chapter under the Industrial sector emissions. Methane and N_2O emissions from mobile on-farm energy use are reported in the Energy chapter under mobile fossil fuel combustion emissions.

Figure 5-1: 2022 Agriculture Sector Greenhouse Gas Emission Sources

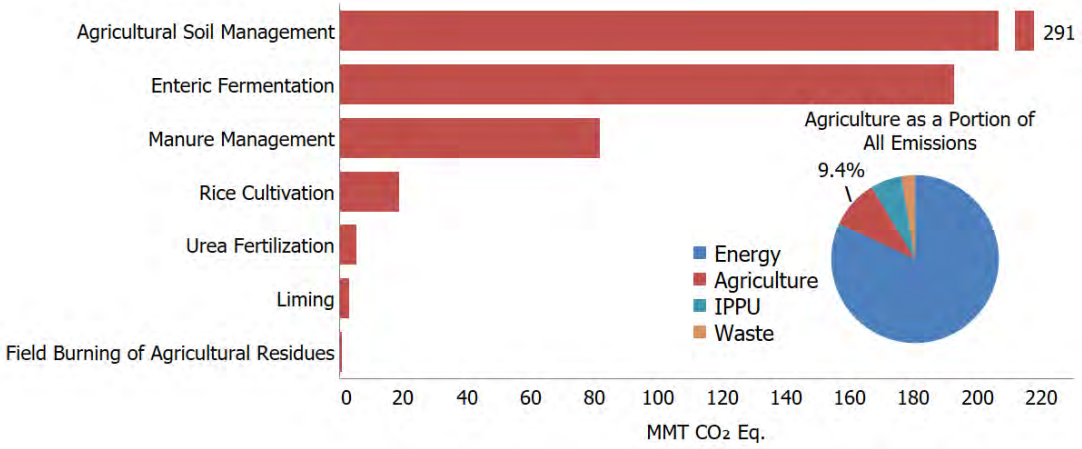

In 2022, the Agriculture sector was responsible for emissions of 593.4 MMT CO_2 Eq.,[1] or 9.4 percent of total U.S. greenhouse gas emissions. Emissions of N_2O by agricultural soil management through activities such as fertilizer

[1] Following the current reporting requirements under the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC), this Inventory report presents CO_2 equivalent values based on the IPCC *Fifth Assessment Report* (AR5) GWP values. See the Introduction chapter as well as Chapter 9 for more information.

application and other agricultural practices that increased nitrogen availability in the soil was the largest source of U.S. N_2O emissions, accounting for 74.6 percent, and the largest source of emissions from the Agriculture sector, accounting for 49.0 percent of total sector emissions. Methane emissions from enteric fermentation and manure management represented 27.4 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively, and 32.5 and 10.9 percent of Agriculture sector emissions, respectively. Of all domestic animal types, beef and dairy cattle were the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Manure management and field burning of agricultural residues were also small sources of N_2O emissions. Urea fertilization and liming each accounted for 0.1 percent of total CO_2 emissions from anthropogenic activities.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2022, CO_2 and CH_4 emissions from agricultural activities increased by 21 percent and 14.5 percent, respectively, while N_2O emissions from agricultural activities fluctuated from year to year but increased by 1.9 percent overall. Trends in sources of agricultural emissions over the 1990 to 2022 time series are shown in Figure 5-2.

Figure 5-2: Trends in Agriculture Sector Greenhouse Gas Emission Sources

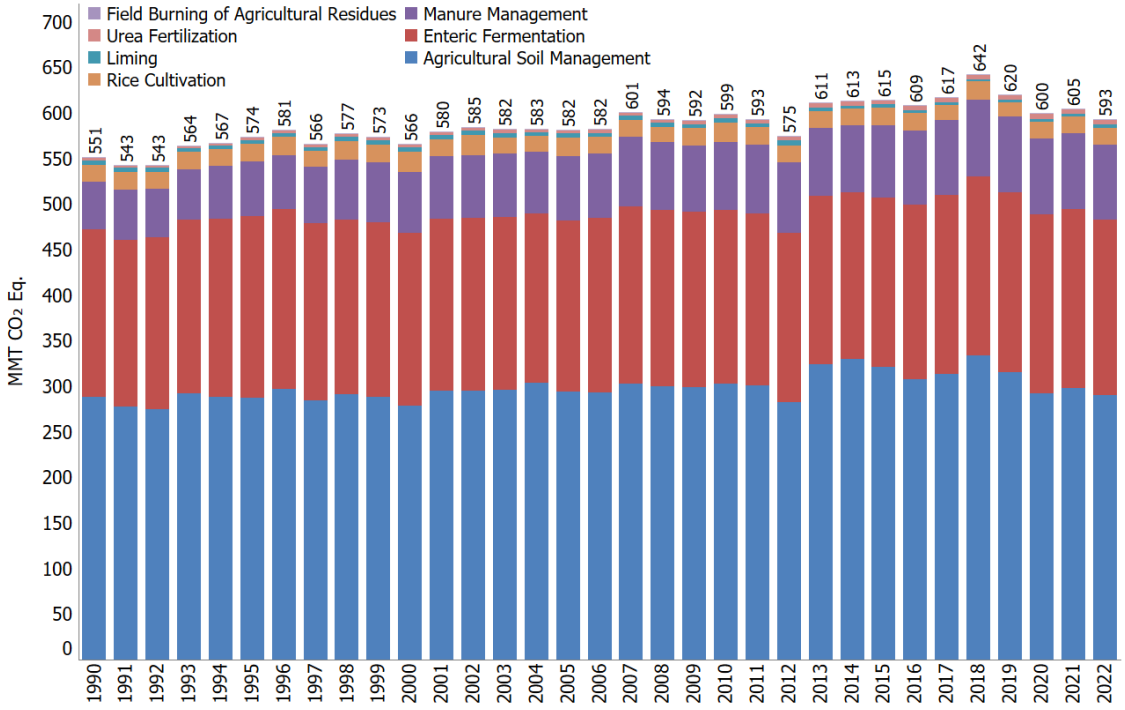

Each year, some emission estimates in the Agriculture sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 through 2021) to ensure that the trend is accurate. This year's key improvements include: manure management: updates to beef feedlot and poultry waste management system (WMS) data; field burning of agricultural residues: addition of residue burning from sugarcane. For more information on specific methodological updates, please see the Recalculations Discussions within the respective source category sections of this chapter. In total, the methodological and historic data improvements made to the Agriculture sector in this *Inventory* increased greenhouse gas emission estimates by an average of 5.3 MMT CO_2 Eq. (0.9 percent) across the time series.

Emissions reported in the Agriculture chapter include those from all states; however, for Hawaii and Alaska some agricultural practices that can increase nitrogen availability in the soil, and thus cause N_2O emissions, are not

included (see chapter sections on Uncertainty and Time-Series Consistency and Planned Improvements for more details). Emissions from the Agriculture sector occurring in U.S. Territories and the District of Columbia are not estimated due to incomplete data, with the exception of urea fertilization in Puerto Rico. EPA continues to identify and review available data on an ongoing basis to include agriculture emissions from U.S. Territories, to the extent they are occurring, in future *Inventories*. Other minor outlying U.S. Territories in the Pacific Islands have no permanent populations (e.g., Baker Island) and therefore EPA assumes no agricultural activities are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Table 5-1: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**7.1**	**7.9**	**7.2**	**7.2**	**8.0**	**7.6**	**8.6**
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
CH_4	**241.7**	**264.4**	**285.0**	**280.2**	**282.4**	**281.8**	**276.8**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6
N_2O	**302.3**	**309.5**	**350.2**	**332.6**	**309.2**	**315.3**	**308.0**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**7,106**	**7,856**	**7,176**	**7,237**	**8,019**	**7,616**	**8,595**
Urea Fertilization	2,417	3,504	4,936	5,034	5,132	5,229	5,327
Liming	4,690	4,351	2,240	2,203	2,887	2,387	3,268
CH_4	**8,633**	**9,444**	**10,179**	**10,008**	**10,087**	**10,066**	**9,885**
Enteric Fermentation	6,539	6,722	7,028	7,045	7,010	7,017	6,878
Manure Management	1,398	1,964	2,418	2,382	2,390	2,373	2,312
Rice Cultivation	677	735	711	558	664	653	674
Field Burning of Agricultural Residues	19	23	22	23	22	22	22
N_2O	**1,141**	**1,168**	**1,322**	**1,255**	**1,167**	**1,190**	**1,162**
Agricultural Soil Management	1,090	1,110	1,258	1,191	1,102	1,124	1,097
Manure Management	50	57	63	63	64	65	64
Field Burning of Agricultural Residues	1	1	1	1	1	1	1

Note: Totals by gas may not sum due to independent rounding.

Box 5-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*). Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The

presentation of emissions provided in the Agriculture chapter does not preclude alternative examinations (e.g., economic sectors). Rather, this chapter presents emissions in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follow this common format and provide an explanation of the application of methods used to calculate emissions from agricultural activities.

5.1 Enteric Fermentation (CRT Source Category 3A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.[2]

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, level of activity and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2022 were 192.6 MMT CO_2 Eq. (6,878 kt). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2022. Emissions from dairy cattle in 2022 accounted for 25 percent, and the remaining methane emissions were from swine, horses, sheep, goats, American bison, mules and asses.[3]

[2] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

[3] Enteric fermentation emissions from poultry are not estimated because no IPCC method has been developed for determining enteric fermentation CH_4 emissions from poultry; at this time, developing a country-specific method would require a disproportionate amount of resources given the small magnitude of this source category. Enteric fermentation emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	2005	2018	2019	2020	2021	2022
Beef Cattle	132.8	139.6	141.2	141.7	140.5	140.3	137.0
Dairy Cattle	43.3	41.3	48.6	48.5	48.8	49.4	48.9
Swine	2.3	2.6	3.1	3.2	3.2	3.1	3.1
Horses	1.1	2.0	1.4	1.3	1.2	1.1	1.0
Sheep	2.9	1.5	1.3	1.3	1.3	1.3	1.3
Goats	0.6	0.7	0.7	0.7	0.7	0.7	0.7
American Bison	0.1	0.5	0.4	0.4	0.5	0.5	0.5
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**183.1**	**188.2**	**196.8**	**197.3**	**196.3**	**196.5**	**192.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-4: CH_4 Emissions from Enteric Fermentation (kt CH_4)

Livestock Type	1990	2005	2018	2019	2020	2021	2022
Beef Cattle	4,742	4,986	5,042	5,062	5,018	5,010	4,891
Dairy Cattle	1,547	1,473	1,737	1,732	1,743	1,764	1,748
Swine	81	92	110	115	115	111	110
Horses	40	70	48	46	43	40	37
Sheep	102	55	47	47	47	47	46
Goats	23	26	24	25	25	25	25
American Bison	4	17	15	16	16	17	17
Mules and Asses	1	2	3	3	3	3	3
Total	**6,539**	**6,722**	**7,028**	**7,045**	**7,010**	**7,017**	**6,878**

Note: Totals may not sum due to independent rounding.

From 1990 to 2022, emissions from enteric fermentation have increased by 5.2 percent. From 2021 to 2022, emissions decreased by 2 percent, largely driven by a decrease in beef cattle populations. While emissions generally follow trends in cattle populations, there are exceptions across the time series. For example, while dairy cattle emissions increased 13 percent over the entire time series, the population has declined by 4.5 percent, and milk production increased 45.9 percent (USDA 2021; USDA 2022). These trends indicate that while emissions per head are increasing, emissions per unit of product (i.e., meat, milk) are decreasing.

Generally, from 1990 to 1995 emissions from beef cattle increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Beef cattle emissions generally increased from 2004 to 2007, as beef cattle populations increased, and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2007 to 2014, as populations again decreased, but increased from 2015 to 2018, consistent with another increase in population over those same years. Emissions and populations generally declined from 2018 to 2022, with a slight post-pandemic rebound in 2021.

Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy cattle population decline during the same period. Similar to beef cattle, dairy cattle emissions rose from 2004 to 2007 due to population increases and a decrease in feed digestibility (based on an analysis of more than 350 dairy cow diets used by producers across the United States). Dairy cattle emissions continued to trend upward from 2007 to 2018, generally in line with dairy cattle population changes.

plans to include this emissions category in the *Inventory*. See Annex 5 for more information on significance of estimated camel emissions.

Regarding trends in other animals, populations of sheep have steadily declined, with an overall decrease of 55 percent since 1990. Horse populations peaked in 2007 and have been declining by an average of 4 percent annually since 2007, with their current population 6 percent lower than it was in 1990. Goat populations increased by about 20 percent through 2007 followed by a steady decrease through 2012. Since 2012, goat populations continue to increase by 1 percent annually. Swine populations have trended upward through most of the time series, increasing 43 percent from 1990 to 2020. However, swine populations decreased by around 5 percent from 2020 to 2022. The population of American bison more than quadrupled over the 1990 to 2022 time period, while the population of mules and asses increased by a factor of five.

Methodology and Time-Series Consistency

Livestock enteric fermentation emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of enteric fermentation CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle. Emission estimates for other domesticated animals (horses, sheep, swine, goats, American bison, and mules and asses) were estimated using the IPCC Tier 1 approach, as suggested by the *2006 IPCC Guidelines* (see the Planned Improvements section).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach. The Cattle Enteric Fermentation Model (CEFM), developed by EPA and used to estimate cattle CH_4 emissions from enteric fermentation using IPCC's Tier 2 method, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022. See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation. In addition, variables and the resulting emissions are also available at the state level in Annex 3.10.

Inventory Methodology for Cattle

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle
  - Calves
  - Heifer Replacements
  - Cows
- Beef Cattle
  - Calves
  - Heifer Replacements
  - Heifer and Steer Stockers
  - Animals in Feedlots (Heifers and Steer)
  - Cows
  - Bulls

Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.10. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) *QuickStats* database (USDA 2023).

Diet characteristics were estimated by region for dairy, grazing beef, and feedlot beef cattle. These diet characteristics were used to calculate digestible energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each regional population category. The IPCC recommends Y_m ranges of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies and scientific literature, expert opinion, and modeling of animal physiology.

The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009. Estimates of DE were national averages based on the feed components of the diets observed in the literature for the following year groupings: 1990 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 2006, 2007, and 2008 onward.[4] Base year Y_m values by region were estimated using Donovan (1999). As described in ERG (2016), a ruminant digestion model (COWPOLL, as selected in Kebreab et al. 2008) was used to evaluate Y_m for each diet evaluated from the literature, and a function was developed to adjust regional values over time based on the national trend. Dairy replacement heifer diet assumptions were based on the observed relationship in the literature between dairy cow and dairy heifer diet characteristics.

For feedlot animals, the DE and Y_m values used for 1990 were recommended by Johnson (1999). Values for DE and Y_m for 1991 through 1999 were linearly extrapolated based on the 1990 and 2000 data. DE and Y_m values for 2000 onwards were based on survey data in Galyean and Gleghorn (2001) and Vasconcelos and Galyean (2007).

For grazing beef cattle, Y_m values were based on Johnson (2002), DE values for 1990 through 2006 were based on specific diet components estimated from Donovan (1999), and DE values from 2007 onwards were developed from an analysis by Archibeque (2011), based on diet information in Preston (2010) and USDA-APHIS:VS (2010). Weight and weight gains for cattle were estimated from Holstein (2010), Doren et al. (1989), Enns (2008), Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.10 for more details on the method used to characterize cattle diets and weights in the United States.

Calves younger than 4 months are not included in emission estimates because calves consume mainly milk and the IPCC recommends the use of a Y_m of zero for all juveniles consuming only milk. Diets for calves aged 4 to 6 months are assumed to go through a gradual weaning from milk decreasing to 75 percent at 4 months, 50 percent at age 5 months, and 25 percent at age 6 months. The portion of the diet made up with milk still results in zero emissions. For the remainder of the diet, beef calf DE and Y_m are set equivalent to those of beef replacement heifers, while dairy calf DE is set equal to that of dairy replacement heifers and dairy calf Y_m is provided at 4 and 7 months of age by Soliva (2006). Estimates of Y_m for 5- and 6-month-old dairy calves are linearly interpolated from the values provided for 4 and 7 months.

To estimate CH_4 emissions, the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, heifers and steers in feedlots, bulls, beef calves 4 to 6 months, and dairy calves 4 to 6 months), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis in order to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, bulls, and calves. To estimate emissions from cattle, monthly population data from the transition matrix were multiplied by the calculated emission factor for each cattle type in each state. More details are provided in Annex 3.10.

[4] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003 as well.

Non-Cattle Livestock

Emission estimates for other animal types were based on average emission factors (Tier 1 default IPCC emission factors) representative of entire populations of each animal type. The methodology is in accordance with the methodological decision tree for methane emissions from enteric fermentation (IPCC 2019). Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2022. Additionally, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle.

Annual livestock population data for 1990 to 2022 for sheep, swine, goats, horses, mules and asses, and American bison were obtained for available years from USDA-NASS (USDA 2023; USDA 2019). Horse, goat, and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019); the remaining years between 1990 and 2022 were interpolated and extrapolated from the available estimates (with the exception of goat populations being held constant between 1990 and 1992). American bison population estimates were available from USDA for 2002, 2007, 2012, and 2017 (USDA 2019) and from the National Bison Association (1999) for 1990 through 1999. Additional years were based on observed trends from the National Bison Association (1999), interpolation between known data points, and extrapolation beyond 2012, as described in more detail in Annex 3.10.

Methane emissions from sheep, goats, swine, horses, American bison, and mules and asses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006; IPCC 2019). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For American bison, the emission factor for buffalo was used and adjusted based on the ratio of live weights to the 0.75 power. The methodology is the same as that recommended by IPCC (2006).

Uncertainty

A quantitative uncertainty analysis for this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology based on a Monte Carlo stochastic simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 *Inventory* (i.e., 2003 submission to the UNFCCC). While there are plans to update the uncertainty to reflect recent methodological updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2022 emission estimates in this *Inventory*.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run) to ensure only positive values would be simulated. For some key input variables, the uncertainty ranges around their estimates (used for *Inventory* estimation) were collected from published documents and other public sources; others were based on expert opinion and best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions, as well as the largest degree of uncertainty in the emission estimates—due mainly to the difficulty in estimating the diet characteristics for grazing members of this animal group. Among non-cattle, horses represent the largest percent of uncertainty in the uncertainty analysis last conducted in 2001 because the Food and Agricultural Organization (FAO) of the United Nations population estimates used for horses at that time had a higher degree of uncertainty than for the USDA population estimates used for swine, goats, and sheep. The horse populations are

drawn from the same USDA source as the other animal types[5], and therefore the uncertainty range around horses is likely overestimated. Cattle calves, American bison, mules and asses were excluded from the initial uncertainty estimate because they were not included in emission estimates at that time.

The uncertainty ranges associated with the activity data-related input variables were ±10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis are summarized in Table 5-5. Based on this analysis, enteric fermentation CH_4 emissions in 2022 were estimated to be between 171.4 and 227.2 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2022 emission estimate of 192.6 MMT CO_2 Eq.

As a comparison to the Approach 2, a quantitative uncertainty analysis for this source category was performed using the IPCC (2006) recommended Approach 1 based on simple error propagation. Enteric fermentation CH_4 emissions in 2022 were estimated to be between 132.6 and 252.6 MMT CO_2 Eq., which indicates a range of ±31 percent above and below the 2022 emission estimate of 192.6 MMT CO_2 Eq. A ±10 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±40 percent default uncertainty factor is applied to the emission factors (IPCC 2019).

Table 5-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b, c] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	192.6	171.4	227.2	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2022 estimates.
[c] The overall uncertainty calculated in 2003, and applied to the 2022 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology. Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the *U.S. Inventory QA/QC Plan* outlined in Annex 8. Category-specific or Tier 2 QA procedures included independent review of emission estimate methodologies from previous *Inventories*.

As part of the quality assurance process, average implied emissions factors for U.S. dairy and beef cattle were developed based on CEFM output and compared to emission factors for other countries provided by IPCC (2006). This comparison is discussed in further detail in Annex 3.10.

Over the past few years, particular importance has been placed on harmonizing the data exchange between the enteric fermentation and manure management source categories. The current *Inventory* utilizes the same transition matrix from the CEFM for estimating cattle populations and weights for both source categories, and the CEFM is used to output volatile solids and nitrogen excretion estimates using the diet assumptions in the model in

[5] The change from using FAO data to USDA data for horse populations took place during the development of the 1990 through 2011 *Inventory*, published in 2013.

conjunction with the energy balance equations from the IPCC (2006). This approach facilitates the QA/QC process for both of these source categories.

Recalculations Discussion

In the previous *Inventory*, 1990 to 2020 estimates were retained from the 1990 through 2020 *Inventory*, and 2021 estimates were based on a simplified approach that used emission factors and extrapolated population estimates for all animals. For the current *Inventory*, the CEFM was used for cattle for all years, resulting in different estimates for 2021 than the prior *Inventory*.

For cattle, there were also changes to emissions resulting from activity data changes, including:

- The USDA published minor data revisions that EPA incorporated into the CEFM:
  - Calf birth data were revised for 2020;
  - Dairy cow milk production values were updated for several states for 2020;
  - Slaughter data were revised for 2020.
- EPA revised annual milk fat values in the CEFM from 2000 through 2021 with updated annual values from USDA's Economic Research Services (ERS) dairy data (USDA 2022). In the previous *Inventory*, EPA derived annual averages from monthly ERS milk fat values, which is no longer available beyond 2010 (USDA 2021).
- EPA discovered and corrected an error within the CEFM related to the urinary energy input used for feedlot cattle, which affected VS results for this animal group. The urinary energy default was updated from 0.04 to 0.02 for feedlot cattle. These updates will affect values in Section 5.2 Manure Management.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. In addition to the documented approaches currently used to address data availability, EPA conducts the following annual assessments to identify and determine the applicability of newer data when updating the estimates to extend time series each year:

- Further research to improve the estimation of dry matter intake (as gross energy intake) using data from appropriate production systems;
- Updating input variables that are from older data sources, such as beef births by month, beef and dairy annual calving rates, and beef cow lactation rates;
- Investigating the availability of data for dairy births by month, to replace the current assumption that births are evenly distributed throughout the year;
- Investigating the availability of annual data for the DE, Y_m, and crude protein values of specific diet and feed components for grazing and feedlot animals (including investigating the availability of existing models to estimate diet characteristics, as well as the use and impact of feed additives on emissions);
- Further investigation on additional sources or methodologies for estimating DE for dairy cattle, given the many challenges in characterizing dairy cattle diets;
- Further evaluation of the assumptions about weights and weight gains for beef cows, such that trends beyond 2007 are updated, rather than held constant; and
- Further evaluation of the estimated weight for dairy cows (i.e., 1,500 lbs) that is based solely on Holstein cows as mature dairy cow weight is likely slightly overestimated, based on knowledge of the breeds of dairy cows in the United States.

Depending upon the outcome of ongoing investigations, future improvement efforts for enteric fermentation could include some of the following options which are additional to the regular updates, and may or may not have implications for regular updates once addressed:

- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses). Efforts to move to Tier 2 will consider the emissions significance of livestock types;
- Investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry;
- Comparison of the current CEFM with other models that estimate enteric fermentation emissions for quality assurance and verification;
- Investigation of recent research implications suggesting that certain parameters in enteric models may be simplified without significantly diminishing model accuracy; and
- Recent changes that have been implemented to the CEFM warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated. EPA plans to perform this uncertainty analysis following the completed updates to the CEFM.

EPA is continuously investigating these recommendations and potential improvements and working with USDA and other experts to utilize the best available data and methods for estimating emissions. Many of these improvements are major updates and may take multiple years to implement in full.

5.2 Manure Management (CRT Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions.[6] Methane is produced by the anaerobic decomposition of manure and nitrous oxide is produced from direct and indirect pathways through the processes of nitrification and denitrification; in addition, there are many underlying factors that can affect these resulting emissions from manure management, as described below.

When livestock manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO_2 and little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and animal type (particularly the different animal digestive systems), also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

As previously stated, N_2O emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the nitrogen (N) cycle through the nitrification and denitrification of the N in livestock dung

[6] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

and urine.[7] There are two pathways for indirect N_2O emissions. The first is the result of the volatilization of N in manure (as NH_3 and NO_x) and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure into the groundwater below, into riparian zones receiving drain or runoff water, or into the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure (manure includes both feces and urine), the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N_2O emissions to occur, the manure must first be handled aerobically where organic N is mineralized or decomposed to NH_4 which is then nitrified to NO_3 (producing some N_2O as a byproduct) (nitrification). Next, the manure must be handled anaerobically where the nitrate is then denitrified to N_2O and N_2 (denitrification). NO_x can also be produced during denitrification (Groffman et al. 2000; Robertson and Groffman 2015). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system (WMS).

Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation due to differences in manure characteristics. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. However, storage systems are often designed to minimize leaching (e.g., clay soil or synthetic liners in lagoons). Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate provided in this chapter does not account for any leaching losses.

Estimates of CH_4 emissions from manure management in 2022 were 64.7 MMT CO_2 Eq. (2,312 kt); in 1990, emissions were 39.1 MMT CO_2 Eq. (1,398 kt). This represents a 65 percent increase in emissions from 1990. Emissions increased on average by 0.8 MMT CO_2 Eq. (2 percent) annually over this period. The majority of this increase is due to dairy cattle and beef cattle manure, where emissions increased 109 and 146 percent, respectively. From 2021 to 2022, there was a 3 percent decrease in total CH_4 emissions from manure management, mainly due to a decrease in swine, dairy, and beef cattle populations.

Although a large quantity of managed manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy cattle and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations controlling the application of manure nutrients to land have shifted manure management practices at smaller dairies from daily spread systems to storage and management of the manure on site. In many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems. Nitrous oxide emissions from manure management vary significantly between the types of management system used and can also result in indirect emissions due to other forms of nitrogen loss from the system (IPCC 2006).

While national dairy animal populations have decreased since 1990, some states have seen increases in their dairy cattle populations as the industry becomes more concentrated in certain areas of the country and the number of animals contained on each facility increases. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus, the shift

[7] Direct and indirect N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (i.e., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the agricultural soil management source category within the Agriculture sector.

toward larger dairy cattle and swine facilities since 1990 has translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This significant shift in both the dairy cattle and swine industries was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, 2002, 2007, 2012, and 2017 farm-size distribution data reported in the U.S. Department of Agriculture (USDA) *Census of Agriculture* (USDA 2019d).

In 2022, total N_2O emissions from manure management were estimated to be 17.0 MMT CO_2 Eq. (64 kt); in 1990, emissions were 13.4 MMT CO_2 Eq. (50 kt). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have increased since 1990. Multiple drivers increase N_2O emissions, such as increasing nitrogen excretion rates for some animal types (see Annex, Table A-163) and increasing numbers of animals on feedlots versus other dry systems (e.g., pasture). Across the entire time series, the overall net effect is that N_2O emissions showed a 27 percent increase from 1990 to 2022, but recent declines in a few animal populations (e.g., swine and dairy cattle) resulted in a 0.9 percent decrease from 2021 to 2022.

Table 5-6 and Table 5-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.[8]

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMT CO_2 Eq.)

Gas/Animal Type	1990	2005	2018	2019	2020	2021	2022
CH_4[a]	**39.1**	**55.0**	**67.7**	**66.7**	**66.9**	**66.4**	**64.7**
Dairy Cattle	16.0	26.4	35.7	34.4	34.7	34.3	33.4
Swine	17.4	22.7	24.7	24.9	24.9	24.6	23.8
Poultry	3.8	3.4	3.0	3.1	3.0	3.0	3.0
Beef Cattle	1.8	2.2	4.2	4.1	4.2	4.4	4.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**13.4**	**15.2**	**16.6**	**16.8**	**16.9**	**17.1**	**17.0**
Beef Cattle	5.2	6.0	5.9	6.0	6.1	6.4	6.4
Dairy Cattle	5.5	5.5	6.2	6.2	6.2	6.3	6.2
Swine	1.1	1.5	1.8	1.8	1.9	1.8	1.8
Poultry	1.3	1.8	2.3	2.3	2.3	2.3	2.3
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA
Total	**52.5**	**70.2**	**84.3**	**83.5**	**83.8**	**83.6**	**81.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

[8] Manure management emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement plans to include this emissions category in the Inventory. See Annex 5 for more information on significance of estimated camel emissions.

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the agricultural soils management category. Totals may not sum due to independent rounding.

Table 5-7: CH_4 and N_2O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2018	2019	2020	2021	2022
CH_4[a]	**1,398**	**1,964**	**2,418**	**2,382**	**2,390**	**2,373**	**2,312**
Dairy Cattle	572	943	1,274	1,227	1,238	1,226	1,193
Swine	621	812	882	890	888	877	851
Poultry	135	123	108	111	109	108	108
Beef Cattle	63	78	149	148	150	157	154
Horses	4	5	3	3	3	3	2
Sheep	3	2	2	2	2	2	2
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**50**	**57**	**63**	**63**	**64**	**65**	**64**
Beef Cattle	20	23	22	23	23	24	24
Dairy Cattle	21	21	23	23	24	24	23
Swine	4	6	7	7	7	7	7
Poultry	5	7	9	9	9	9	9
Sheep	+	1	1	1	1	1	1
Horses	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA

+ Does not exceed 0.5 kt.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the agricultural soils management category. Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type, including Tier 1, Tier 2, and use of the CEFM previously described for enteric fermentation. These methodologies use:

- IPCC (2019) Tier 1 default N_2O emission factors and MCFs for dry systems
- U.S. specific MCFs for liquid systems (ERG 2001)
- U.S. specific values for volatile solids (VS) production rate and nitrogen excretion rate for some animal types, including cattle values from the CEFM

This combination of Tier 1 and Tier 2 methods was applied to all livestock animal types and follows guidance for methodological choice presented in decision trees from the IPCC (2006). This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management.

See Annex 3.11 for more detailed information on the methodologies (including detailed formulas and emission factors), data used to calculate CH_4 and N_2O emissions, and emission results (including input variables and results at the state-level) from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of manure management CH_4 emissions for 1990 through 2022:

- Animal population data (by animal type and state);
- Typical animal mass (TAM) data (by animal type);
- Portion of manure managed in each WMS, by state and animal type;
- VS production rate (by animal type and state or United States);
- Methane producing potential (B0) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection efforts).

Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources are described below:

- Annual animal population data for 1990 through 2022 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from the USDA-NASS. For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the Cattle Enteric Fermentation Model (CEFM) that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Section 5.1 and in more detail in Annex 3.10. Goat population data for 1992, 1997, 2002, 2007, 2012, and 2017; horse and mule and ass population data for 1987, 1992, 1997, 2002, 2007, 2012, and 2017; and American bison population for 2002, 2007, 2012, and 2017 were obtained from the *Census of Agriculture* (USDA 2019d). American bison population data for 1990 through 1999 were obtained from the National Bison Association (1999).
- The TAM is an annual average weight that was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and others (Meagher 1986; EPA 1992; Safley 2000; ERG 2003b; IPCC 2006; ERG 2010a). For a description of the TAM data used for cattle, see Annex 3.10.
- WMS usage was estimated for swine and dairy cattle for different farm size categories using state and regional data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2016c) and EPA (ERG 2000a; EPA 2002a and 2002b; ERG 2018, ERG 2019). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a; USDA APHIS 2000; UEP 1999, ERG 2023). For other animal types, manure management system usage was based on previous estimates (EPA 1992). American bison WMS usage was assumed to be the same as not on feed (NOF) cattle, while mules and asses were assumed to be the same as horses.
- VS production rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. VS production rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data that was not available in the most recent *Handbook* were obtained from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines* (IPCC 2006). American bison VS production was assumed to be the same as NOF bulls.
- B_0 was determined for each animal type based on literature values (Morris 1976; Bryant et al. 1976; Hashimoto 1981; Hashimoto 1984; EPA 1992; Hill 1982; Hill 1984).
- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2019). The IPCC 2019 factors are more representative of U.S. systems and reflect the latest science. MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.

- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information available in the AgSTAR project database (EPA 2023). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).
- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) was multiplied by the B_0 (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4). The CH_4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH_4 emissions. See details in Step 5 of Annex 3.11.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect manure management N_2O emissions for 1990 through 2022:

- Animal population data (by animal type and state);
- TAM data (by animal type);
- Portion of manure managed in each WMS (by state and animal type);
- Total Kjeldahl N excretion rate (Nex);
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volatilization ($EF_{volatilization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volatilization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

Nitrous oxide emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources (except for population, TAM, and WMS, which were described above) are described below:

- Nex for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex were assumed to be the same as NOF bulls.[9]
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006).
- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture*

[9] Nex of American bison on grazing lands are accounted for and discussed in the agricultural soil management source category and included under pasture, range and paddock (PRP) emissions. Because American bison are maintained entirely on unmanaged WMS and N_2O emissions from unmanaged WMS are not included in the manure management source category, there are no N_2O emissions from American bison included in the manure management source category.

Operations (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.11).

To estimate N_2O emissions for cattle (except for calves), the estimated amount of N excreted (kg per animal-year) that is managed in each WMS for each animal type, state, and year were taken from the CEFM. For calves and other animals, the amount of N excreted (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EF_{WMS}, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to N_2O. These emissions were summed over state, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year). See details in Step 6 of Annex 3.11.

Indirect N_2O emissions from volatilization (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{gas}$) divided by 100, the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Indirect N_2O emissions from runoff and leaching (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions. See details in Step 6 of Annex 3.11.

Following these steps, direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year) for the years 1990 to 2022.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022. In some cases, the activity data source changed over the time series. For example, updated WMS distribution data were applied to 2016 for dairy cows and 2009 for swine. While previous WMS distribution data were from another data source, EPA integrated the more recent data source to reflect the best available current WMS distribution data for these animals. EPA assumed a linear interpolation distribution for years between the two data sources. Refer to Annex 3.11 for more details on data sources and methodology.

Uncertainty

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 *Inventory* (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. A normal probability distribution was assumed for all variables in the estimation equations. While there are plans to update the uncertainty to reflect recent manure management updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2022 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-8. Manure management CH_4 emissions in 2022 were estimated to be between 53.1 and 77.7 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2022 emission estimate of 64.7 MMT CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 14.3 and 21.1 MMT CO_2

Eq. (or approximately 16 percent below and 24 percent above the actual 2022 emission estimate of 17.0 MMT CO_2 Eq.).

A quantitative uncertainty analysis for this source category was also performed using the IPCC (2006) recommended Approach 1 based on simple error propagation as well. Based on this analysis, manure management:

- CH_4 emissions in 2022 were estimated to be between 50.4 and 79.0 MMT CO_2 Eq., which indicates a range of ±21 percent above and below the 2022 emission estimate of 64.7 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±30 percent default uncertainty factor for Tier 1 and ±20 percent default uncertainty factor for Tier 2 is applied to the emission factors (IPCC 2006).
- N_2O emissions in 2022 were estimated to be between 11.8 and 22.2 MMT CO_2 Eq., which indicates a range of ±31 percent above and below the 2022 emission estimate of 17.0 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±50 percent default uncertainty factor is applied to the emission factors (IPCC 2006).
- CH_4 and N_2O emissions in 2022 were estimated to be between 66.5 and 96.9 MMT CO_2 Eq., which indicates a range of ±19 percent above and below the 2022 emission estimate of 81.7 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±20-50 percent default uncertainty factor is applied to the emission factors (IPCC 2006).

Table 5-8: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	64.7	53.1	77.7	-18%	+20%
Manure Management	N_2O	17.0	14.3	21.1	-16%	+24%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Tier 2 activities focused on comparing estimates for the previous and current Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. In addition, manure N data were checked by comparing state-level data with bottom-up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and WMS type for the full time series, between national level estimates for N excreted, both for pasture and managed systems, and the sum of county estimates for the full time series. This was done to ensure consistency between excreted N within the manure management sector and those data provided to the managed soils sector. All errors identified were corrected.

Time-series data, including population, are validated by experts to ensure they are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_0, and MCF were also compared to the IPCC default values and validated by experts. Although significant differences exist in some instances, these differences are due to the use of U.S.-specific data and the differences in U.S. agriculture as compared to other countries. The

U.S. manure management emission estimates use the most reliable country-specific data, which are more representative of U.S. animals and systems than the IPCC (2006) default values.

For additional verification of the 1990 to 2022 estimates, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default IPCC (2006) values. Table 5-9 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC (2006) default emission factors. The U.S. implied emission factors fall within the range of the IPCC (2006) default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are less than the IPCC (2006) default value for those animals due to the use of U.S.-specific data for typical animal mass and VS excretion. There is an increase in implied emission factors for dairy cattle and swine across the time series. This increase reflects the dairy cattle and swine industry trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH_4 emissions. See the Recalculations for explanations for changes that affect emissions which impact these implied emission factors.

Table 5-9: IPCC (2006) Implied Emission Factor Default Values Compared with Calculated Values for CH_4 from Manure Management (kg/head/year)

Animal Type	IPCC Default CH_4 Emission Factors (kg/head/year)[a]	1990	2005	2018	2019	2020	2021	2022
Dairy Cattle	48-112	29.3	53.0	67.0	65.0	65.9	65.0	64.1
Beef Cattle	1-2	0.8	0.9	1.8	1.8	1.8	1.9	1.9
Swine	10-45	11.5	13.3	12.0	11.6	11.5	11.8	11.6
Sheep	0.19-0.37	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Goats	0.13-0.26	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	0.02-1.4	0.1	0.1	0.05	0.05	0.05	0.05	0.05
Horses	1.56-3.13	1.9	1.4	1.2	1.2	1.2	1.2	1.2
American Bison	NA	0.8	0.9	0.9	0.9	0.9	0.9	0.9
Mules and Asses	0.76-1.14	0.4	0.4	0.4	0.4	0.4	0.4	0.4

NA (Not Applicable)

[a] Ranges reflect *2006 IPCC Guidelines* (Volume 4, Table 10.14) default emission factors for North America across different climate zones.

In addition, default IPCC (2006) emission factors for N_2O were compared to the U.S. *Inventory* implied N_2O emission factors. Default N_2O emission factors from the *2006 IPCC Guidelines* were used to estimate N_2O emission from each WMS in conjunction with U.S.-specific Nex values. The implied emission factors differed from the U.S. *Inventory* values due to the use of U.S.-specific Nex values and differences in populations present in each WMS throughout the time series.

Recalculations Discussion

In the previous *Inventory*, 1990 to 2020 estimates were retained from the 1990 through 2020 *Inventory*, and 2021 estimates were based on a simplified approach that used emission factors and extrapolated population estimates for all animals. For the current *Inventory*, the calculations were rerun for all years, resulting in different estimates for 2021 than the prior *Inventory*.

There were also changes to emissions resulting from activity data changes, including:

- EPA updated the WMS distributions for broilers, layers, and beef feedlot animal types. For broilers, this affected 1993 through 2021, for layers 2000 through 2021, and for beef feedlots all years of the time series (ERG 2023).

- EPA updated the calf TAM values to coincide with values used within the CEFM. This affected all years of the time series.
- EPA updated the solid storage direct N_2O emission factor to the updated guidance provided in IPCC (2019).
- EPA updated how poultry digesters were applied, splitting other poultry and caged layers (previously done for broilers) as well as the year for which select swine anaerobic digesters were shutdown per notes provided in AgSTAR.
- EPA discovered and corrected an error within the CEFM (see NIR section 5.1 and annex 3.10) related to the urinary energy input used for feedlot cattle, which affected VS results for this animal group. The urinary energy default was updated from 0.04 to 0.02 for feedlot cattle.

The cumulative effect of all these recalculations had a minor impact on the overall manure management emissions estimates:

- CH_4 emissions increased an average 0.6 percent over the time series, with the largest decrease of 0.2 percent (0.1 MMT CO_2 Eq) in 2002 to the largest increase of 1.8 percent (1.2 MMT CO_2 Eq.) in 2017.
- N_2O emissions increased an average 3.4 percent over the time series, with the largest decrease of 3.6 percent (0.6 MMT CO_2 Eq.) in 2020 and the largest increase of 7.8 percent (1.0 MMT CO_2 Eq.) in 1990.
- Over the time series the average total emissions increased by 1.2 percent from the previous *Inventory*. The changes ranged from the largest decrease 0.5 percent (0.4 MMT CO_2 Eq.) in 2020, to the largest increase 2.1 percent (1.1 MMT CO_2 Eq.) in 1990.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. In addition to the documented approaches currently used to address data availability, EPA conducts data assessments to pursue a number of potential improvements.

Potential improvements (long-term improvements) for future *Inventory* years include:

- Providing supplemental details on CH_4 emissions reductions due to the use of anaerobic digesters (the *Inventory* currently estimates only emissions from anaerobic digestion systems).
- Investigating the updated IPCC *2019 Refinement* default N_2O emissions factor for anaerobic digesters. Historically, EPA has not estimated N_2O emissions from digesters as the default guidance was no emissions. Incorporating AgSTAR data for N_2O emissions, like CH_4 emissions, is a longer-term goal for EPA.
- Investigating updates to the current anaerobic digester MCFs based on IPCC (2019).

EPA is aware of the following potential updates or improvements but notes that implementation will be based on available resources and data availability:

- Updating the B_0 data used in the *Inventory*, as data become available. EPA is conducting outreach with counterparts from USDA as to available data and research on B_0.
- Comparing CH_4 and N_2O emission estimates with estimates from other models and more recent studies and compare the results to the *Inventory*.
- Comparing manure management emission estimates with on-farm measurement data to identify opportunities for improved estimates.
- Comparing VS and Nex data to literature data to identify opportunities for improved estimates.

- Determining if there are revisions to the U.S.-specific method for calculating liquid systems for MCFs based on updated guidance from the IPCC *2019 Refinement*. EPA previously began this investigation to determine the potential differences between the methods.
- Investigating improved emissions estimate methodologies for swine pit systems with less than one month of storage (the updated swine WMS data included this WMS category).
- Improving the linkages with the Enteric Fermentation source category estimates. For future Inventories, it may be beneficial to have the CEFM and Manure Management calculations in the same model, as they rely on much of the same activity data and on each other's outputs to properly calculate emissions. EPA has begun this investigation and plans to develop a model to calculate emissions for these two categories.
- Continuing to investigate new sources of WMS data. EPA is collaborating with the USDA to collect or use existing survey data for potential improvements to the *Inventory*.
- Revising the uncertainty analysis to address changes that have been implemented to the CH_4 and N_2O estimates. The plan is to align the timing of the updated Manure Management uncertainty analysis with the uncertainty analysis for Enteric Fermentation.

5.3 Rice Cultivation (CRT Source Category 3C)

Most of the world's rice is grown on flooded fields (Baicich 2013) that create anaerobic conditions leading to CH_4 production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH_4 produced by methanogenic bacteria in flooded rice fields is oxidized in the soil and converted to CO_2 by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH_4 into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH_4 also escapes via ebullition (i.e., bubbling through the water) and to a much lesser extent by diffusion through the water (van Bodegom et al. 2001).

Water management is arguably the most important factor affecting CH_4 emissions in rice cultivation, and improved water management has the largest potential to mitigate emissions (Yan et al. 2009). Upland rice fields are not flooded, and therefore do not produce CH_4, but large amounts of CH_4 can be emitted in continuously irrigated fields, which is the most common practice in the United States (USDA 2012). Single or multiple aeration events with drainage of a field during the growing season can significantly reduce these emissions (Wassmann et al. 2000a), but drainage may also increase N_2O emissions. Deepwater rice fields (i.e., fields with flooding depths greater than one meter, such as natural wetlands) tend to have fewer living stems reaching the soil, thus reducing the amount of CH_4 transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH_4 emissions from flooded rice fields including rice residue straw management and application of organic amendments, in addition to cultivar selection due to differences in the amount of root exudates[10] among rice varieties (Neue et al. 1997). These practices influence the amount of organic matter available for methanogenesis, and some practices, such as mulching rice straw or composting organic amendments, can reduce the amount of labile carbon and limit CH_4 emissions (Wassmann et al. 2000b).

[10] The roots of rice plants add organic material to the soil through a process called "root exudation." Root exudation is thought to enhance decomposition of the soil organic matter and release nutrients that the plant can absorb for production. The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

Fertilization practices also influence CH_4 emissions, particularly the use of fertilizers with sulfate, which can reduce CH_4 emissions (Wassmann et al. 2000b; Linquist et al. 2012). Other environmental variables also impact the methanogenesis process such as soil temperature and soil type. Soil temperature regulates the activity of methanogenic bacteria, which in turn affects the rate of CH_4 production. Soil texture influences decomposition of soil organic matter but is also thought to have an impact on oxidation of CH_4 in the soil (Sass et al. 1994).

Rice is currently cultivated in 12 states, including Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, Tennessee, and Texas. Soil types, rice varieties, and cultivation practices vary across the United States, but most farmers apply fertilizers and do not harvest crop residues. In addition, a second, ratoon rice crop is sometimes grown in the Southeastern region of the country. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Methane emissions from ratoon crops are higher than those from the primary crops due to the increased amount of labile organic matter available for anaerobic decomposition in the form of relatively fresh crop residue straw. Emissions tend to be higher in rice fields if the residues have been in the field for less than 30 days before planting the next rice crop (Lindau and Bollich 1993; IPCC 2006; Wang et al. 2013).

A combination of Tier 1 and 3 methods are used to estimate CH_4 emissions from rice cultivation across most of the time series, while a surrogate data method has been applied to estimate national emissions for 2021 to 2022 in this *Inventory* due to lack of data in these years of the time series. National emission estimates based on surrogate data will be recalculated in a future *Inventory* with the Tier 1 and 3 methods as data becomes available.

Overall, rice cultivation is a minor source of CH_4 emissions in the United States relative to other source categories (see Table 5-10, Table 5-11, and Figure 5-3). Most emissions occur in Arkansas, California, Louisiana, Mississippi, Missouri, and Texas. In 2022, CH_4 emissions from rice cultivation were 18.9 MMT CO_2 Eq. (674 kt CH_4). Annual emissions fluctuated between 1990 and 2022, which is largely due to differences in the amount of rice harvested areas over time. There has been a marginal decrease in emissions since 1990. Interestingly, the estimated emissions in 2022 are roughly the same as emissions in 1990.

Table 5-10: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

State	1990	2005	2018	2019	2020	2021	2022
Arkansas	6.3	8.8	8.0	5.6	6.8	NE	NE
California	3.2	3.4	3.7	3.5	3.6	NE	NE
Florida	+	+	+	+	+	NE	NE
Illinois	+	+	+	+	+	NE	NE
Kentucky	+	+	+	+	+	NE	NE
Louisiana	3.5	3.8	3.7	3.2	3.7	NE	NE
Minnesota	+	+	+	+	+	NE	NE
Mississippi	1.1	1.3	0.7	0.6	0.6	NE	NE
Missouri	0.5	1.2	1.2	0.9	1.0	NE	NE
New York	+	+	+	+	+	NE	NE
Tennessee	+	+	+	+	+	NE	NE
Texas	4.3	1.9	2.6	1.9	2.9	NE	NE
Total	**18.9**	**20.6**	**19.9**	**15.6**	**18.6**	**18.3**	**18.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

NE (Not Estimated). State-level emissions are not estimated for 2021 through 2022 in this *Inventory*. A surrogate method is used to estimate emissions for these years only at the national scale.

Note: Totals may not sum due to independent rounding.

Table 5-11: CH_4 Emissions from Rice Cultivation (kt CH_4)

State	1990	2005	2018	2019	2020	2021	2022
Arkansas	224.2	315.5	287.1	200.5	243.4	NE	NE
California	114.5	122.8	131.5	123.9	129.1	NE	NE
Florida	+	1.2	+	+	+	NE	NE
Illinois	+	0.4	0.1	+	0.1	NE	NE
Kentucky	+	+	+	+	+	NE	NE
Louisiana	124.9	135.0	131.4	113.7	130.4	NE	NE
Minnesota	1.0	1.7	+	0.8	+	NE	NE
Mississippi	39.0	46.5	24.3	20.3	21.5	NE	NE
Missouri	19.5	42.7	43.0	31.8	34.4	NE	NE
New York	0.2	+	+	+	+	NE	NE
Tennessee	+	0.1	+	+	+	NE	NE
Texas	153.5	69.5	93.6	67.0	104.7	NE	NE
Total	**677**	**735**	**711**	**558**	**664**	**653**	**674**

+ Does not exceed 0.5 kt.

NE (Not Estimated). State-level emissions are not estimated for 2021 through 2022 in this *Inventory*. A surrogate method is used to estimate emissions for these years only at the national scale.

Note: Totals may not sum due to independent rounding.

Figure 5-3: Annual CH_4 Emissions from Rice Cultivation, 2020, Using the Tier 3 DayCent Model

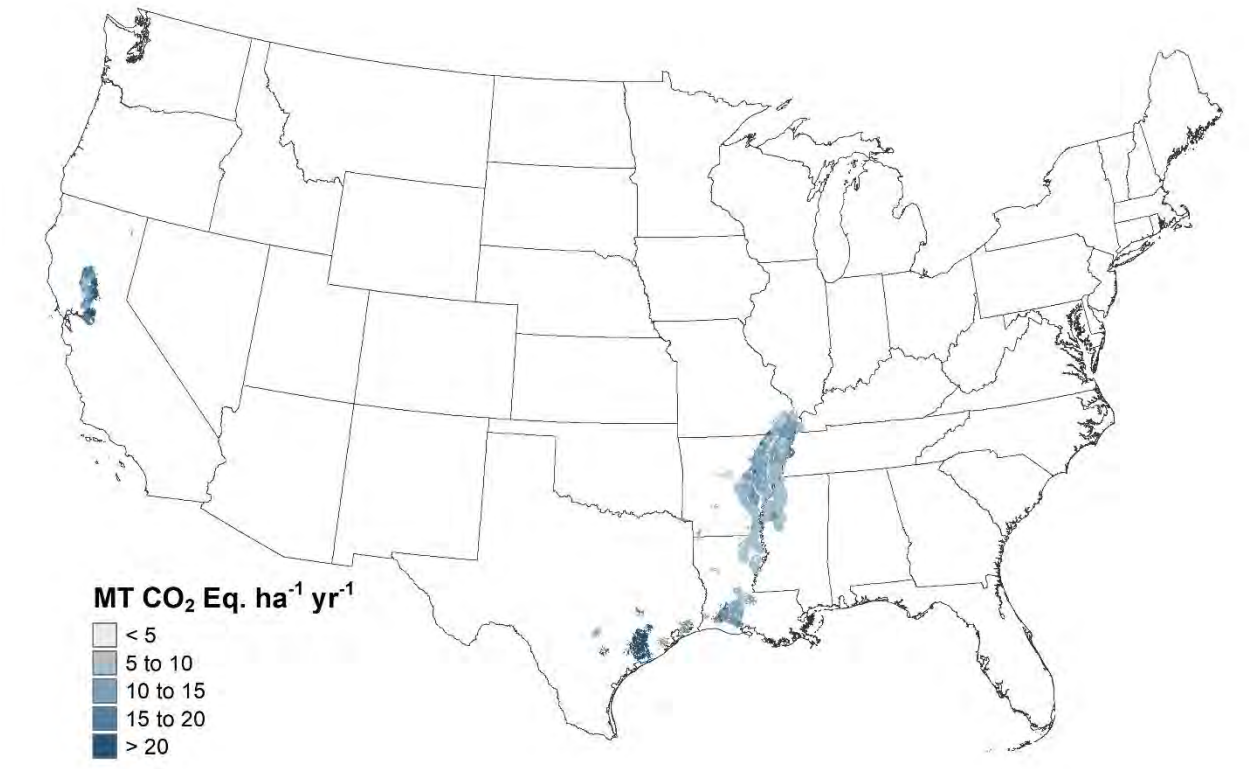

Note: Only national-scale emissions are estimated for 2021 and 2022 in this *Inventory* using a surrogate data method described in the Methodology section; therefore, the fine-scale emission patterns in this map are based on the estimates for 2020.

Methodology and Time-Series Consistency

The methodology used to estimate CH_4 emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The Tier 3 method utilizes the DayCent process-based model to estimate CH_4 emissions from rice cultivation (Cheng et al. 2013) and has been tested in the United States (see Annex 3.12) and Asia (Cheng et al. 2013, 2014). The model simulates hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH_4, as well as CH_4 transport through the plant and via ebullition (Cheng et al. 2013). The method captures the influence of organic amendments and rice straw management on methanogenesis in the flooded soils, and ratooning of rice crops with a second harvest during the growing season. In addition to CH_4 emissions, DayCent simulates soil carbon stock changes and N_2O emissions (Parton et al. 1987 and 1998; Del Grosso et al. 2010) and allows for a seamless set of simulations for crop rotations that include both rice and non-rice crops.

The Tier 1 method is applied to estimate CH_4 emissions from rice when grown in rotation with crops that are not simulated by DayCent, such as vegetable crops. The Tier 1 method is also used for areas converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland, and settlements. In addition, the Tier 1 method is used to estimate CH_4 emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). The Tier 3 method using DayCent has not been fully tested for estimating emissions associated with these conditions.

The Tier 1 method for estimating CH_4 emissions from rice production utilizes a default base emission rate and scaling factors (IPCC 2006). The base emission rate represents emissions for continuously flooded fields with no organic amendments. Scaling factors are used to adjust the base emission rate for water management and organic amendments that differ from continuous flooding with no organic amendments. The method accounts for pre-season and growing season flooding; types and amounts of organic amendments; and the number of rice production seasons within a single year (i.e., single cropping and double-cropping with ratooning). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[11]

Rice cultivation areas are based on crop and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021, Johnson and Mueller 2010). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (See Section 6.1, Representation of the U.S. Land Base for more information).

The NRI is a statistically based sample of all non-federal land and includes approximately 604,000 survey locations in agricultural cropland and grassland for the conterminous United States and Hawaii of which 7,888 include one or more years of rice cultivation. The Tier 3 method is used to estimate CH_4 emissions from 5,998 of the NRI survey locations, and the remaining 1,890 survey locations are estimated with the Tier 1 method. Each NRI survey location is associated with a survey weight that allows scaling of CH_4 emission to the entire land base with rice cultivation (i.e., each weight approximates the amount of area with the same land-use/management history as the survey location). Land-use and some management information in the NRI (e.g., crop type, soil attributes, and irrigation) were collected on a 5-year cycle beginning in 1982, along with cropping rotation data in four out of five years for each five-year time period (i.e., 1979 to 1982, 1984 to 1987, 1989 to 1992, and 1994 to 1997). The NRI program began collecting annual data in 1998, with data through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021). CDL data have a 30 to 58 m spatial resolution, depending on the year. NRI survey locations are overlaid on the CDL in a geographic information

[11] See http://www.nrel.colostate.edu/projects/ALUsoftware/.

system, and the crop types are extracted to extend the cropping histories. The harvested rice areas in each state are presented in Table 5-12.

Table 5-12: Rice Area Harvested (1,000 Hectares)

State/Crop	1990	2005	2018	2019	2020	2021	2022
Arkansas	611	782	659	512	663	NE	NE
California	251	237	226	218	224	NE	NE
Florida	0	3	0	0	0	NE	NE
Illinois	0	1	0	0	1	NE	NE
Kentucky	0	0	0	0	0	NE	NE
Louisiana	399	400	356	313	383	NE	NE
Minnesota	3	6	0	3	0	NE	NE
Mississippi	177	191	98	96	109	NE	NE
Missouri	48	96	99	74	85	NE	NE
New York	1	0	0	0	0	NE	NE
Tennessee	0	1	0	0	0	NE	NE
Texas	294	104	164	119	167	NE	NE
Total	**1,784**	**1,823**	**1,603**	**1,335**	**1,633**	**NE**	**NE**

NE (Not Estimated). Area data will be updated in the next *Inventory*.
Note: Totals may not sum due to independent rounding.

The Southeastern states have sufficient growing periods for a ratoon crop in some years (Table 5-13). For example, the growing season length is occasionally sufficient for ratoon crops to be grown on about two percent of the rice fields in Arkansas. No data are available about ratoon crops in Missouri or Mississippi, so the average amount of ratooning in Arkansas was assigned to these states. Ratoon cropping occurs much more frequently in Louisiana (LSU 2015 for years 2000 through 2013, 2015) and Texas (TAMU 2015 for years 1993 through 2015), averaging 32 percent and 45 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (49 percent). Ratoon rice crops are not grown in California. Ratooning practices are assigned to individual NRI locations using a hot-deck imputation method with six complete imputations for each NRI location to address uncertainty. The method is based on random assignment of ratooning to approximate the percentages of fields managed with ratooning provided in Table 5-14.

Table 5-13: Average Ratooned Area as Percent of Primary Growth Area (Percent)

State	1990-2015
Arkansas[a]	1.9%
California	0%
Florida[b]	45.2%
Louisiana[c]	39.5%
Mississippi[a]	37.8%
Missouri[a]	2.4%
Texas[d]	49.5%

[a] Arkansas: *1990–2000* (Slaton 1999 through 2001); *2001–2011* (Wilson 2002 through 2007, 2009 through 2012); *2012–2013* (Hardke 2013, 2014). Estimates of ratooning for Missouri and Mississippi are based on the data from Arkansas.
[b] Florida - Ratoon: *1990–2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002–2003* (Kirstein 2003 through 2004, 2006); *2004* (Cantens 2004 through 2005); *2005–2013* (Gonzalez 2007 through 2014).
[c] Louisiana: *1990–2013* (Linscombe 1999, 2001 through 2014).
[d] Texas: *1990–2002* (Klosterboer 1997, 1999 through 2003); *2003–2004* (Stansel 2004 through 2005); *2005* (Texas Agricultural Experiment Station 2006); *2006–2013* (Texas Agricultural Experiment Station 2007 through 2014).

While rice crop production in the United States includes a minor amount of land with mid-season drainage or alternate wet-dry periods, the majority of rice growers use continuously flooded water management systems (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). Therefore, continuous flooding was assumed in the DayCent simulations and the Tier 1 analysis. Variation in flooding can be incorporated in future inventories if updated water management data are available.

Winter flooding is another key practice associated with water management in rice fields, and the impact of winter flooding on CH_4 emissions is addressed in the Tier 3 and Tier 1 analyses. Flooding is used to prepare fields for the next growing season, and to create waterfowl habitat (Young 2013; Miller et al. 2010; Fleskes et al. 2005). Fitzgerald et al. (2000) suggests that as much as 50 percent of the annual emissions may occur during winter flooding. Winter flooding is a common practice with an average of 34 percent of fields managed with winter flooding in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields managed with winter flooding in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of flooding is assumed to be relatively constant over the *Inventory* time series. Similar to ratooning practices, winter flooding is assigned to individual NRI locations using a hot-deck imputation method with six complete imputations for each NRI location to address uncertainty. The method is based on random assignment of winter flooding to approximate the percentages of fields managed with winter flooding as discussed above.

A data splicing method is used to estimate emissions from 2021 to 2022 associated with the rice CH_4 emissions for Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving average (ARMA) errors was used to estimate the relationship between the surrogate data and emissions data from 1990 through 2020, which were derived using the Tier 3 methods (Brockwell and Davis 2016). Surrogate data are based on rice commodity statistics from USDA-NASS.[12] See Box 5-2 for more information about the surrogate data method. For the Tier 1 method, a linear-time series model is used to estimate emissions for 2021 to 2022 without surrogate data.

Box 5-2: Surrogate Data Method

An approach to extend the time series is needed to estimate emissions from rice cultivation because there are gaps in activity data at the end of the time series. This is mainly because the National Resources Inventory (NRI) does not release data every year, and the NRI is a key data source for estimating greenhouse gas emissions.

A surrogate data method has been selected to impute missing emissions at the end of the time series. A linear regression model with autoregressive moving average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the observed 1990 to 2020 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., CH_4 emissions), $X\beta$ is the surrogate data that is used to predict the missing emissions data, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the observed data for 1990 to 2020 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2021 to 2022.

A critical issue in using splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions with related information without compiling the full inventory. For example, predicting CH_4 emissions will increase the total variation in the emission estimates for these specific years, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2020).

[12] See https://quickstats.nass.usda.gov/.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and data splicing methods are used to approximate emissions for the remainder of the 2021 to 2022 time series based on the emissions data from 1990 to 2020. The surrogate data method and linear time series approach, used for the Tier 3 and 1 methods, respectively, are consistent with data splicing methods in IPCC (2006).

Uncertainty

Sources of uncertainty in the Tier 3 method include management practices, uncertainties in model structure (i.e., algorithms and parameterization), and variance associated with the NRI sample. Sources of uncertainty in the IPCC (2006) Tier 1 method include the emission factors, management practices, and variance associated with the NRI sample. The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For the first variance component, a Monte Carlo analysis was used to propagate uncertainties in the Tier 1 and 3 methods for the management data, as well as emission factors and model structure/parameterization, respectively. The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire area of rice cultivation, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method (See Box 5-2 for information about propagating uncertainty with the surrogate data method). The uncertainties from the Tier 1 and 3 approaches are combined to produce the final CH_4 emissions estimate using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12.

Rice cultivation CH_4 emissions in 2022 were estimated to be between 5.1 and 32.6 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 73 percent below to 73 percent above the 2022 emission estimate of 18.9 MMT CO_2 Eq. (see Table 5-14).

Table 5-14: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Inventory Method	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	Tier 3	CH_4	15.9	2.2	29.6	-86%	+86%
Rice Cultivation	Tier 1	CH_4	3.0	2.0	4.0	-34%	+34%
Rice Cultivation	**Total**	**CH_4**	**18.9**	**5.1**	**32.6**	**-73%**	**+73%**

[a] Range of emission estimates is the 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Quality control measures include checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Model results are compared to field measurements to verify that results adequately represent CH_4 emissions. The comparisons included over 17 long-term experiments, representing about 238 combinations of management treatments across all the sites. A statistical relationship was developed to assess uncertainties in the model structure and parameterization, adjusting the estimates for model bias and assessing precision in the resulting estimates (methods are described in Ogle et al. 2007). See Annex 3.12 for more information.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations, including a) updated time series of land representation data that identifies which points and years were sown with rice (Nelson et al 2020), b) extending the time-series of crop history with CDL data, c) imputing ratooning and winter flooding onto individual NRI survey points, d) updated fertilizer and organic amendment additions, and e) revisions to the approach for assigning organic matter amendments and crop residue inputs. As a result of these changes, CO_2-equivalent emissions changed annually with an average annual increase of 0.97 MMT CO_2 Eq., or 5.5 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key planned improvement for rice cultivation is to refine the model algorithms and re-calibration of the Tier 3 DayCent model using the latest observational data from experiments. Another improvement is collection of more information about water management and refinement of the application to incorporate mid-season drainage and alternate wetting and drying systems. Improvements are expected to be completed for the next *Inventory* (i.e., 2025 submission to the UNFCCC, 1990 through 2023 *Inventory*), pending prioritization of resources.

5.4 Agricultural Soil Management (CRT Source Category 3D)

Nitrous oxide is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral nitrogen (N) (Firestone and Davidson 1989).[13] Mineral nitrogen is made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of nitrogen from the atmosphere.[14] Several agricultural activities increase mineral nitrogen availability in soils that lead to direct N_2O emissions at the site of a management activity (see Figure 5-4) (Mosier et al. 1998). These activities include synthetic nitrogen fertilization; application of managed livestock manure; application of other organic materials such as biosolids (i.e., treated sewage sludge); deposition of manure on soils by domesticated animals in pastures, range, and paddocks (PRP) (i.e., unmanaged manure); retention of crop residues (nitrogen-fixing legumes and non-legume crops and forages); and drainage of organic soils[15] (i.e., Histosols) (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, cover crops, and fallowing of land, can influence nitrogen mineralization from soil organic matter and levels of asymbiotic nitrogen fixation. Indirect emissions of N_2O occur when nitrogen is transported from a site and is subsequently converted to N_2O; there are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized nitrogen, and (2) surface runoff and leaching of applied/mineralized nitrogen

[13] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of nitrification and denitrification.

[14] Asymbiotic nitrogen fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[15] Drainage of organic soils in former wetlands enhances mineralization of nitrogen-rich organic matter, thereby increasing N_2O emissions from these soils.

into groundwater and surface water.[16] Direct and indirect emissions from agricultural lands are included in this section (i.e., cropland and grassland as defined in Section 6.1). Nitrous oxide emissions from forest land and settlements soils are found in Sections 6.2 and 6.10, respectively.

Figure 5-4: Sources and Pathways of Nitrogen that Result in N_2O Emissions from Agricultural Soil Management

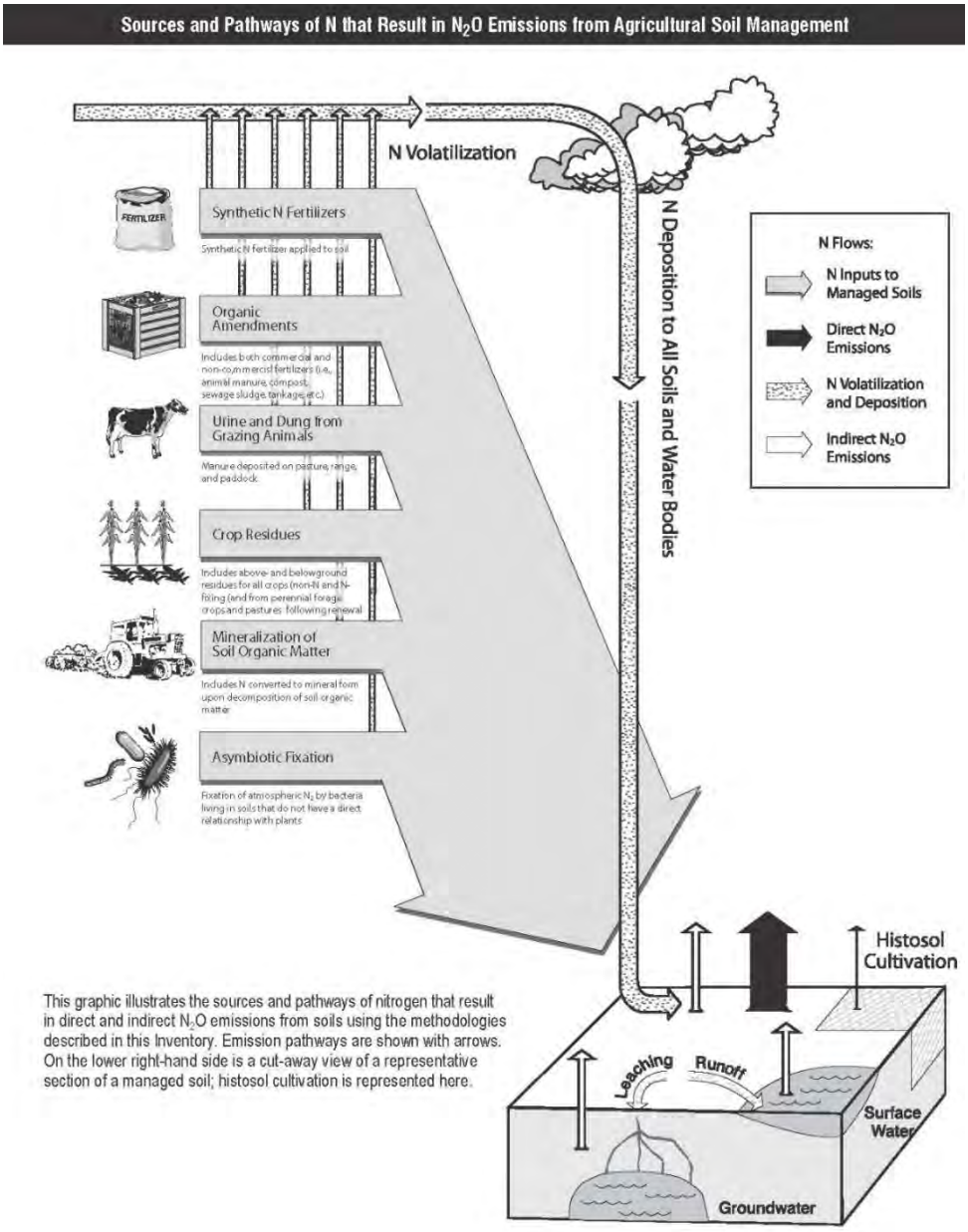

[16] These processes entail volatilization of applied or mineralized nitrogen as NH_3 and NO_x, transformation of these gases in the atmosphere (or upon deposition), and deposition of the nitrogen primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x. In addition, hydrological processes lead to leaching and runoff of NO_3^- that is converted to N_2O in aquatic systems, e.g., wetlands, rivers, streams and lakes. Note: N_2O emissions are not estimated for aquatic systems associated with nitrogen inputs from terrestrial systems in order to avoid double-counting.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions in 2022 are 290.8 MMT CO_2 Eq. (1,097 kt) (see Table 5-15 and Table 5-16). Annual N_2O emissions from agricultural soils are 3.2 percent greater in 2022 compared to 1990, but emissions fluctuated between 1990 and 2022 due to inter-annual variability largely associated with weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2022, cropland accounted for 68 percent of total direct emissions on average from agricultural soil management, while grassland accounted for 32 percent. On average, 79 percent of indirect emissions are from croplands and 21 percent from grasslands. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 5-17 and Table 5-18.

Table 5-15: N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Direct	**258.8**	**265.6**	**298.3**	**280.9**	**262.8**	**267.7**	**262.5**
Cropland	174.9	180.6	208.9	193.4	182.4	184.3	180.3
Grassland	83.9	85.1	89.4	87.5	80.3	83.4	82.1
Indirect	**29.9**	**28.4**	**35.1**	**34.7**	**29.4**	**30.3**	**28.3**
Cropland	23.6	22.3	28.1	28.0	23.3	24.1	22.2
Grassland	6.4	6.1	7.0	6.8	6.1	6.2	6.1
Total	**288.8**	**294.1**	**333.4**	**315.6**	**292.1**	**298.0**	**290.8**

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-16: N_2O Emissions from Agricultural Soils (kt N_2O)

Activity	1990	2005	2018	2019	2020	2021	2022
Direct	**977**	**1,002**	**1,126**	**1,060**	**992**	**1,010**	**990**
Cropland	660.0	681.4	788.3	729.9	688.5	695.4	680.6
Grassland	316.7	321.1	337.4	330.0	303.1	314.6	309.9
Indirect	**113**	**107**	**133**	**131**	**111**	**114**	**107**
Cropland	89.0	84.2	106.2	105.6	88.0	91.1	83.9
Grassland	24.0	23.1	26.4	25.5	22.9	23.3	22.9
Total	**1,090**	**1,110**	**1,258**	**1,191**	**1,102**	**1,124**	**1,097**

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-17: Direct N_2O Emissions from Agricultural Soils by Land Use Type and Nitrogen Input Type (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Cropland	**174.9**	**180.6**	**208.9**	**193.4**	**182.4**	**184.3**	**180.3**
Mineral Soils	**171.5**	**177.3**	**205.9**	**190.5**	**179.5**	**181.4**	**177.4**
Synthetic Fertilizer	61.0	64.3	70.3	65.7	63.2	63.4	62.0
Organic Amendment[a]	11.5	12.7	14.7	14.6	14.4	14.7	14.6
Residue N[b]	34.1	35.0	39.6	34.5	37.6	33.2	32.4
Mineralization and Asymbiotic Fixation	64.8	65.3	81.3	75.7	64.3	70.1	68.4
Drained Organic Soils	3.4	3.2	3.0	2.9	2.9	2.9	2.9
Grassland	**83.9**	**85.1**	**89.4**	**87.5**	**80.3**	**83.4**	**82.1**
Mineral Soils	**81.6**	**82.8**	**87.2**	**85.2**	**78.1**	**81.1**	**79.8**
Synthetic Fertilizer	+	+	+	+	+	+	+
PRP Manure	15.4	14.2	14.0	13.6	13.3	13.9	13.8
Managed Manure[c]	+	+	+	+	+	+	+

Biosolids (i.e., treated Sewage Sludge)	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Residue N[d]	27.1	28.4	28.0	28.3	28.2	26.3	25.9
Mineralization and Asymbiotic Fixation	38.9	39.8	44.8	42.9	36.2	40.5	39.8
Drained Organic Soils	2.3	2.2	2.2	2.2	2.2	2.3	2.3
Total	**258.8**	**265.6**	**298.3**	**280.9**	**262.8**	**267.7**	**262.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Organic amendment inputs include managed manure, daily spread manure, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).

[b] Cropland residue nitrogen inputs include nitrogen in unharvested cover crops as well as harvested crops.

[c] Managed manure inputs include managed manure and daily spread manure amendments that are applied to grassland soils.

[d] Grassland residue nitrogen inputs include residual biomass, both legumes and grasses, that is ungrazed and becomes dead organic matter.

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-18: Indirect N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Cropland	**23.6**	**22.3**	**28.1**	**28.0**	**23.3**	**24.1**	**22.2**
Volatilization & Atm. Deposition	6.6	7.0	7.9	7.1	7.5	7.4	7.3
Surface Leaching & Run-Off	17.0	15.3	20.3	20.9	15.8	16.7	14.9
Grassland	**6.4**	**6.1**	**7.0**	**6.8**	**6.1**	**6.2**	**6.1**
Volatilization & Atm. Deposition	3.4	3.4	3.3	3.2	3.0	3.1	3.2
Surface Leaching & Run-Off	2.9	2.7	3.7	3.6	3.1	3.0	2.9
Total	**29.9**	**28.4**	**35.1**	**34.7**	**29.4**	**30.3**	**28.3**

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Figure 5-5 and Figure 5-6 show regional patterns for direct N_2O emissions. Figure 5-7 and Figure 5-8 show indirect N_2O emissions from volatilization, and Figure 5-9 and Figure 5-10 show the indirect N_2O emissions from leaching and runoff in croplands and grasslands, respectively.

Direct N_2O emissions from croplands occur throughout all of the cropland regions but tend to be high in the Midwestern Corn Belt Region (particularly, Illinois, Iowa, Kansas, Minnesota, Nebraska), where a large portion of the land is used for growing highly fertilized corn and nitrogen-fixing soybean crops (see Figure 5-5). There are high emissions from the Southeastern region, and portions of the Great Plains. Emissions are also high in the Lower Mississippi River Basin from Missouri to Louisiana, and highly productive irrigated areas, such as Platte River, which flows from Colorado and Wyoming through Nebraska, Snake River Valley in Idaho, and the Central Valley in California. Direct emissions from croplands are low in mountainous regions of the Eastern United States because only a small portion of land is cultivated, and in much of the Western United States where rainfall and access to irrigation water are limited, in addition to mountainous, which are generally not suitable for crop production.

Direct N_2O emissions from grasslands are more evenly distributed throughout the United States compared to emissions from cropland due to suitable areas for grazing in most regions (see Figure 5-6). Total emissions tend be highest in the Great Plains and western United States where a large proportion of the land is dominated by grasslands with cattle and sheep grazing (particularly Kansas, Montana, Nebraska, New Mexico, Oklahoma, South Dakota, Texas).

Figure 5-5: Croplands, 2020 Annual Direct N_2O Emissions Estimated Using the Tier 3 DayCent Model

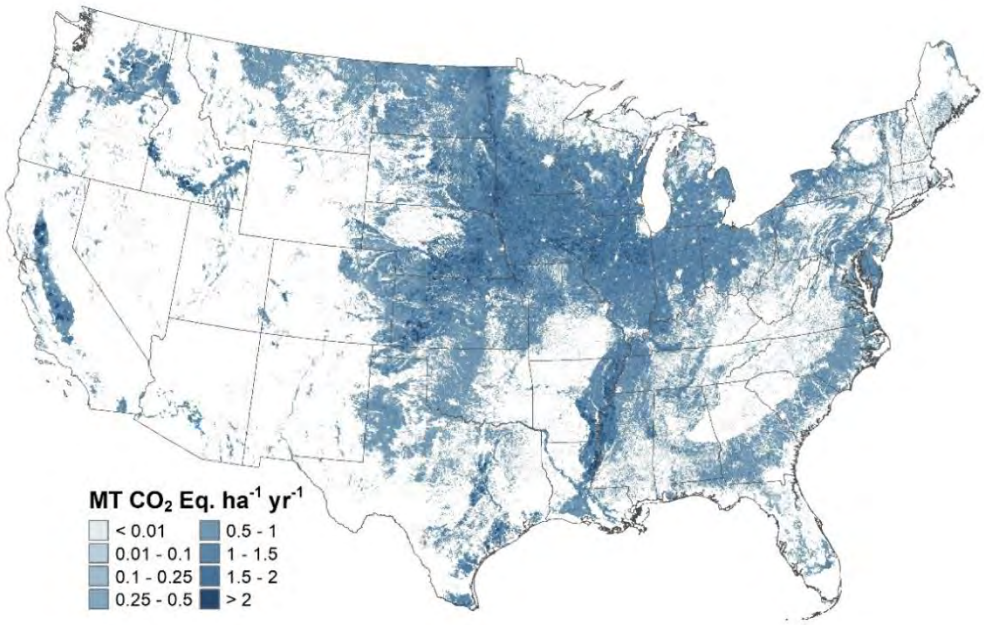

Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-6: Grasslands, 2020 Annual Direct N_2O Emissions Estimated Using the Tier 3 DayCent Model

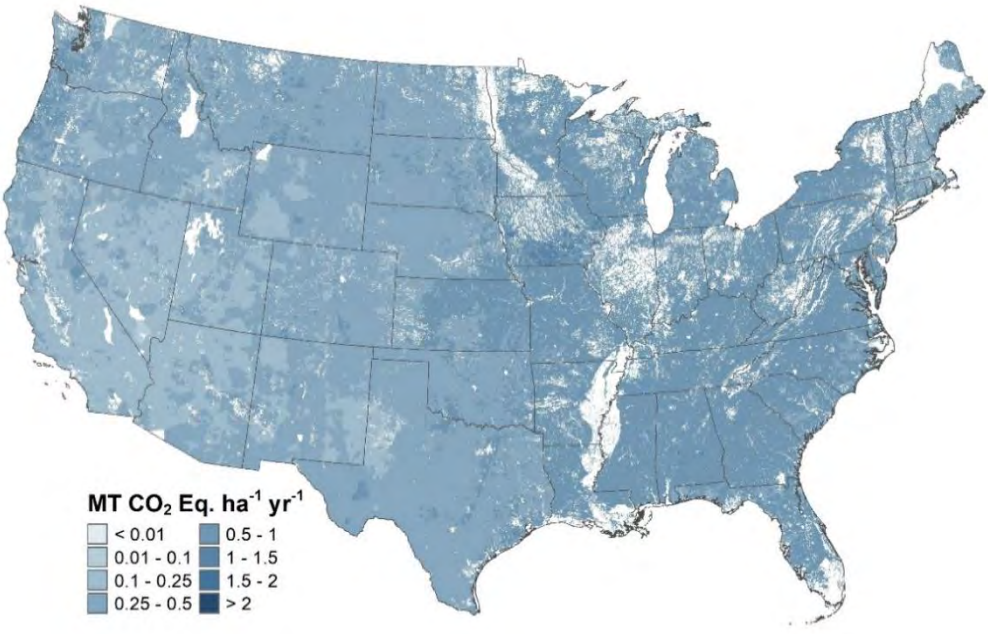

Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Indirect N_2O emissions from volatilization in croplands have a similar pattern as the direct N_2O emissions with higher emissions in the Midwestern Corn Belt, Lower Mississippi River Basin, Southeastern region, and parts of the Great Plains and irrigated areas of the Western United States. Indirect N_2O emissions from volatilization in grasslands are higher in the Eastern and Central United States, along with relatively small areas scattered around the Western United States. The higher emissions are partly due to large additions of PRP manure nitrogen, which in turn, stimulates NH_3 volatilization.

Indirect N_2O emissions from surface runoff and leaching of applied/mineralized nitrogen in croplands is highest in the Midwestern Corn Belt. There are also relatively high emissions associated with nitrogen management in the Lower Mississippi River Basin, Piedmont region of the Southeastern United States and the Mid-Atlantic states. In addition, areas of high emissions occur in portions of the Great Plains that have irrigated croplands with high leaching rates of applied/mineralized nitrogen. Indirect N_2O emissions from surface runoff and leaching of applied/mineralized nitrogen in grasslands are higher in the eastern United States and coastal Northwest region. These regions have greater precipitation and higher levels of leaching and runoff compared to arid to semi-arid regions in the Western United States.

Figure 5-7: Croplands, 2020 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DayCent Model

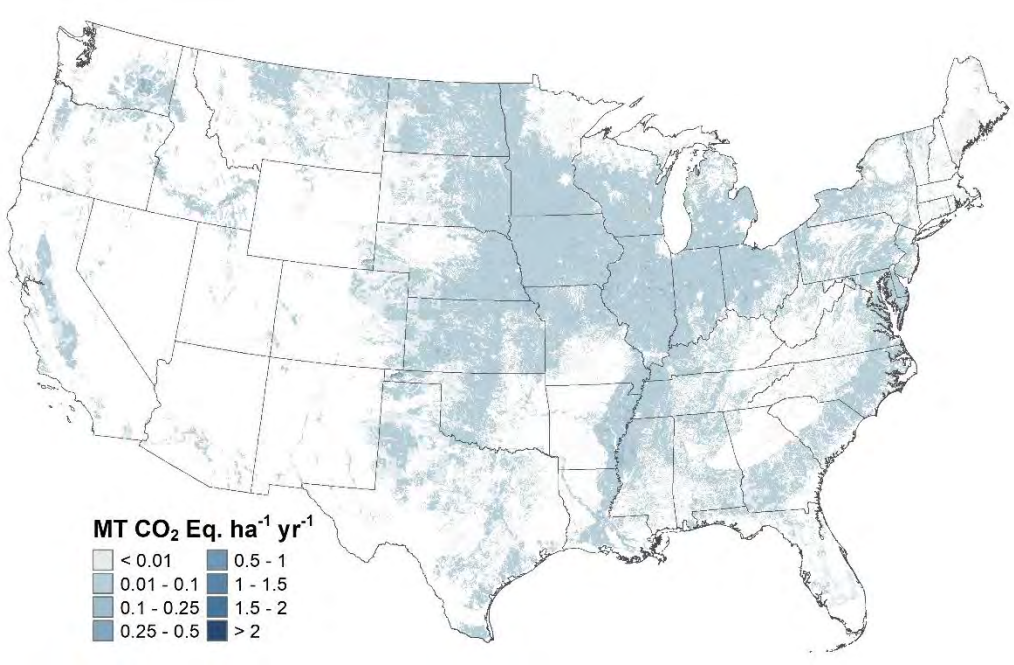

Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-8: Grasslands, 2020 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DayCent Model

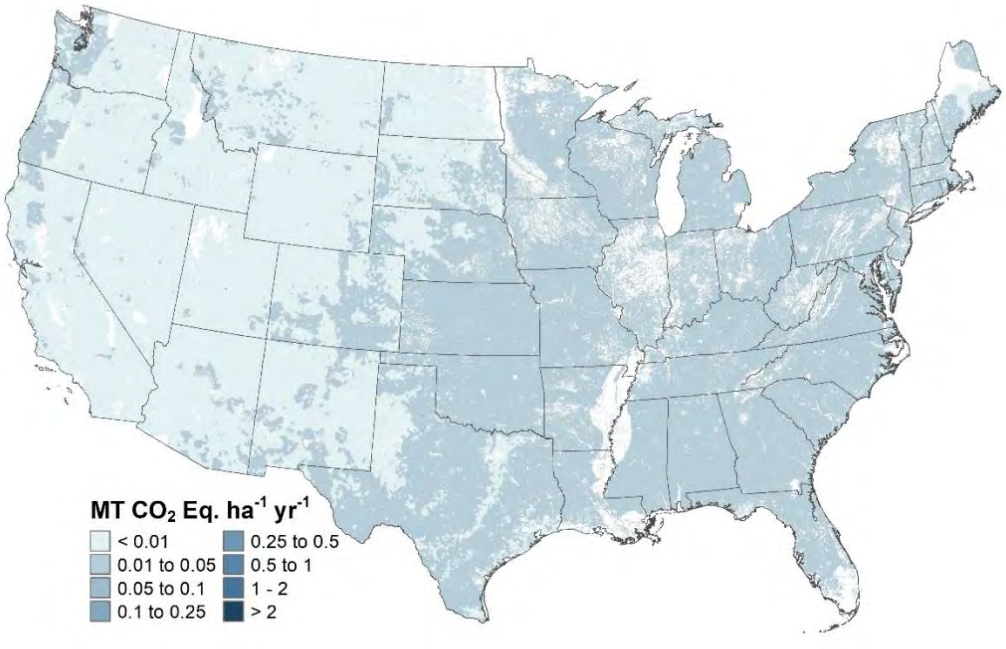

Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-9: Croplands, 2020 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model

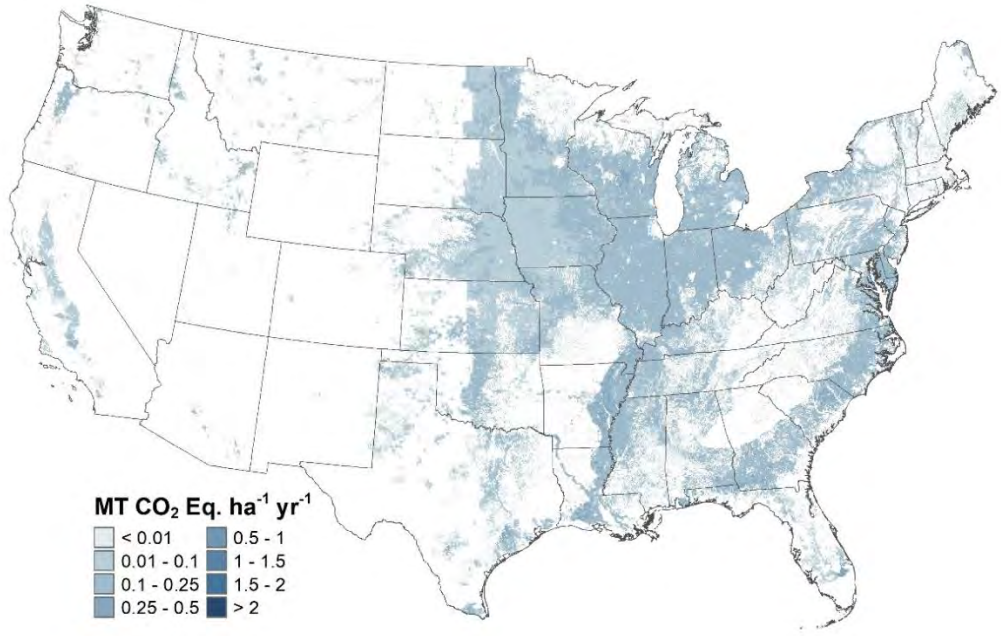

Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-10: Grasslands, 2020 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model

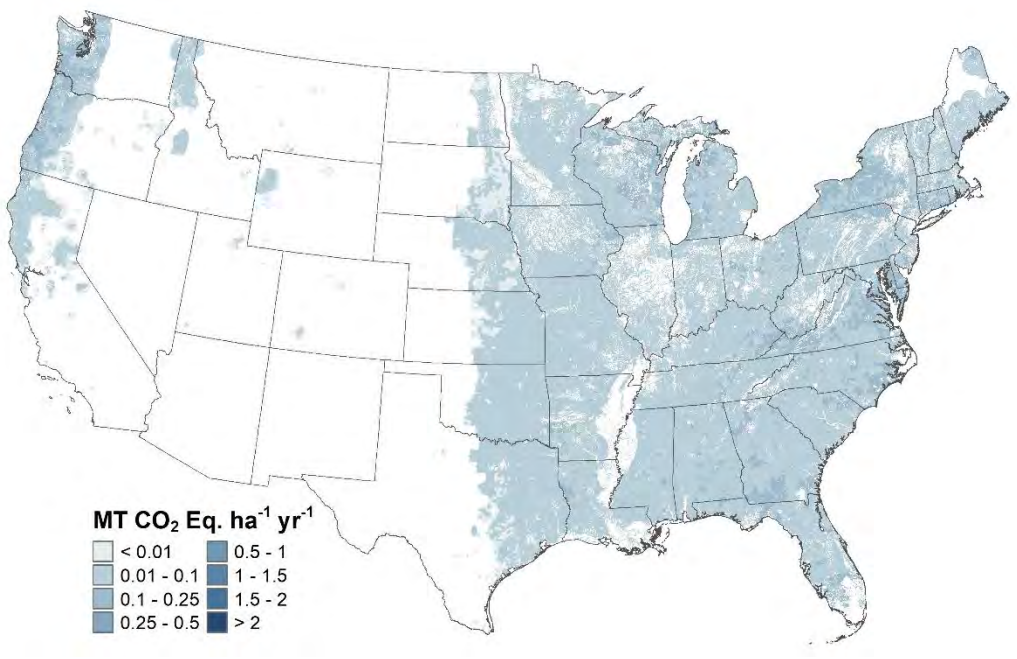

Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Methodology and Time-Series Consistency

The *2006 IPCC Guidelines* (IPCC 2006) divide emissions from the agricultural soil management source category into five components, including (1) direct emissions from nitrogen additions to cropland and grassland mineral soils from synthetic fertilizers, biosolids (i.e., treated sewage sludge), crop residues (legume nitrogen-fixing and non-legume crops), and organic amendments; (2) direct emissions from soil organic matter mineralization due to land use and management change; (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to manure deposited by livestock on PRP grasslands; and (5) indirect emissions from soils and water from nitrogen additions and manure deposition to soils that lead to volatilization, leaching, or runoff of nitrogen and subsequent conversion to N_2O.

In this source category, the United States reports on all croplands, as well as all managed grasslands, whereby anthropogenic greenhouse gas emissions are estimated in a manner consistent with the managed land concept (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation[17] and mineralization of nitrogen associated with decomposition of soil organic matter and residues. One recommendation from IPCC (2006) that has not been completely adopted is the estimation of emissions from grassland pasture renewal, which involves occasional plowing to improve forage production in pastures. Currently no data are available to address pasture renewal.

In addition, estimates of N_2O emissions from managed croplands and grasslands are not available for Alaska and Hawaii except for managed manure and PRP nitrogen, and biosolid additions for Alaska, and managed manure and

[17] Nitrogen inputs from asymbiotic nitrogen fixation are not directly addressed in *2006 IPCC Guidelines* but are a component of the nitrogen inputs and total emissions from managed lands and are included in the Tier 3 approach developed for this source.

PRP nitrogen, biosolids additions, and crop residue for Hawaii. There is a planned improvement to include the additional sources of emissions in a future *Inventory*.

Direct N_2O Emissions

The methodology used to estimate direct N_2O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches, along with application of a splicing method for latter years in the *Inventory* time series (IPCC 2006; Del Grosso et al. 2010). A Tier 3 process-based model (DayCent) is used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, as well as the direct emissions from non-federal grasslands except for applications of biosolids (i.e., treated sewage sludge) (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 5-3 for further elaboration). Moreover, the Tier 3 approach addresses direct N_2O emissions and soil carbon stock changes from mineral cropland soils in a single analysis. Carbon and nitrogen dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil carbon and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are considered between carbon and nitrogen cycling in soils.

Crop and land use histories are based on the USDA National Resources Inventory (NRI) (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021; Johnson and Mueller 2010). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1).

The NRI is a statistically-based sample and includes 364,333 survey locations on agricultural land for the conterminous United States that are included in the Tier 3 method. The Tier 1 approach is used to estimate the emissions from an annual average of 239,757 locations in the NRI survey across the time series, which are designated as cropland or grassland (discussed later in this section). The Tier 1 method is used to estimate emissions for components that are not simulated by DayCent. DayCent has not been parametrized to simulate some crop types and soil types, as described below. Each survey location is associated with a survey weight that allows scaling of N_2O emissions from NRI survey locations to the entire country (i.e., each survey weight is an approximation of the amount of area with the same land-use/management history as the survey location). Each NRI survey location was sampled on a 5-year cycle from 1982 until 1997. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, which are currently available through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021). CDL data have a 30 to 58 m spatial resolution, depending on the year. Specifically, NRI survey locations are overlaid on the CDL in a geographic information system, and the crop types are extracted to extend the cropping histories for the inventory analysis.

Box 5-3: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different nitrogen inputs (i.e., synthetic fertilizer, manure, nitrogen fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total nitrogen applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this *Inventory* is based on application of a process-based model (i.e., DayCent) that represents the interaction of nitrogen inputs, land use and management, as well as environmental conditions at specific locations, such as freeze-thaw effects that generate pulses of N_2O emissions (Wagner-Riddle et al. 2017; Del Grosso et al. 2022). Consequently, the Tier 3 approach accounts for land-use and management impacts and their interaction with environmental factors,

such as weather patterns and soil characteristics, in a more comprehensive manner, which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific nitrogen fertilization rates), additional data inputs (e.g., daily weather, soil types), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate that the method is an improvement over lower tier methods for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding nitrogen cycling. Tier 1 assumes that nitrogen added to a system is subject to N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that may create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model in the Tier 3 approach includes the legacy effect of nitrogen added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

DayCent is used to estimate N_2O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, sweet potatoes, tobacco, tomatoes, and wheat, but is not applied to estimate N_2O emissions from other crops or rotations with other crops,[18] such as sugarcane, some vegetables, and perennial/horticultural crops. Areas that are converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland and settlements, are not simulated with DayCent. DayCent is also not used to estimate emissions from land areas with very gravelly, cobbly, or shaley soils in the topsoil (greater than 35 percent by volume in the top 30 cm of the soil profile), or to estimate emissions from drained organic soils (*Histosols*). The Tier 3 method has not been fully tested for estimating N_2O emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils. In addition, federal grassland areas are not simulated with DayCent due to limited activity data on land use histories. For areas that are not included in the DayCent simulations, Tier 1 methods are used to estimate emissions, including (1) direct emissions from nitrogen inputs for crops on mineral soils that are not simulated by DayCent; (2) direct emissions from PRP nitrogen additions on federal grasslands; (3) direct emissions for land application of biosolids (i.e., treated sewage sludge) to soils; and (4) direct emissions from drained organic soils in croplands and grasslands.

A splicing method is used to estimate soil N_2O emissions for 2021 to 2022 at the national scale because new activity data have not been incorporated into the analysis for those years. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions that are derived using the Tier 3 method. Surrogate data for these regression models includes corn and soybean yields from USDA-NASS statistics,[19] and weather data from the PRISM Climate Group (PRISM 2022). For the Tier 1 method, a linear-time series model is used to estimate emissions for 2021-2022 without surrogate data. In addition, the linear time series model is used to estimate emissions data for 2018 to 2022 for other organic nitrogen amendments (i.e., commercial organic fertilizer) due to a gap in the activity data during the latter part of the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). See Box 5-4 for more information about the splicing method. Emission estimates for years with imputed data will be recalculated in future *Inventory* reports when new NRI data and other organic amendment nitrogen data are available.

[18] A small proportion of the major commodity crop production, such as corn and wheat, is included in the Tier 1 analysis because these crops are rotated with other crops or land uses (e.g., forest lands) that are not simulated by DayCent.

[19] See https://quickstats.nass.usda.gov/.

Box 5-4: Data Splicing Method

An approach to extend the time series is needed for agricultural soil management because there are typically activity data gaps at the end of the time series. This is mainly because the NRI survey program, which provides critical information for estimating greenhouse gas emissions and removals, does not release data every year.

Splicing methods have been used to impute missing data at the end of the emission time series for both the Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate emissions based on the emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by the equation:

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil nitrous oxide), Xβ for the Tier 3 method contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. The term Xβ for the Tier 1 method only contains year as a predictor of emission patterns over the time series (change in emissions per year), and therefore, is a linear time series model with no surrogate data. Parameters are estimated using standard statistical techniques, and used in the model described above to predict the missing emissions data.

A critical issue with splicing methods is to account for the additional uncertainty introduced by predicting emissions without compiling the full inventory. Specifically, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This additional uncertainty is quantified within the model framework using a Monte Carlo approach. Consequently, the uncertainty from the original inventory data is combined with the uncertainty in the data splicing model. The approach requires estimating parameters in the data splicing models in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the draws of parameters values that are selected in each Monte Carlo iteration, and used to produce estimates with inventory data). Therefore, the data splicing method generates emissions estimates from each surrogate data model in the Monte Carlo analysis, which are used to derive confidence intervals in the estimates for the missing emissions data. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach for Mineral Cropland Soils

The DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001 and 2011) is used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops (see list in previous section) based on the crop histories in the 2017 NRI (USDA-NRCS 2020) and extended through 2020 using CDL (USDA-NASS 2021). Crops simulated by DayCent are grown on approximately 85 percent of total cropland area in the United States. The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1[20] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2022), and soil attributes from the Soil Survey Geographic

[20] Net Primary Production is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2020. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature, and moisture stress on crop production (see Metherell et al. 1993) but does not incorporate the additional information about crop condition provided with remote sensing data.

Database (SSURGO) (Soil Survey Staff 2020). DayCent is used to estimate direct N_2O emissions due to mineral nitrogen available from the following sources: (1) application of synthetic fertilizers; (2) application of livestock manure; (3) retention of crop residues in the field for nitrogen-fixing legumes and non-legume crops and subsequent mineralization of nitrogen during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); (4) mineralization of nitrogen from decomposition of soil organic matter; and (5) asymbiotic fixation.

Management activity data from several sources supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2022; USDA-NRCS 2018; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006 and 2013 to 2016. These data are combined with other datasets in an imputation analysis. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use Gradient Boosting (Friedman 2001) to determine the likely management practice at a given NRI survey location; and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method for certain variables that are adapted to reflect the trending information (Little 1988, van Buuren 2012). Gradient boosting is a machine learning technique used in regression and classification tasks, among others. It combines predictions from multiple weak prediction models and outperforms many complicated machine learning algorithms. It makes the best predictions at specific NRI survey locations or at state or region level models. The predictive mean matching method identifies the most similar management activity recorded in the CEAP surveys that match the prediction from the gradient boosting algorithm. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the gradient boosting. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2020). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). To determine the trends in tillage management, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and OpTIS Data Product[21] for 2008 to 2020 (Hagen et al. 2020). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). For cover crops, CEAP data are combined with information from USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OpTIS[22] data (Hagen et al. 2020). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

The IPCC method considers crop residue nitrogen inputs and nitrogen mineralized from soil organic matter as activity data. However, they are not treated as activity data in DayCent simulations because residue production, symbiotic nitrogen fixation (e.g., legumes), mineralization of nitrogen from soil organic matter, and asymbiotic nitrogen fixation are internally generated by the model as part of the simulation. In other words, DayCent accounts for the influence of symbiotic nitrogen fixation, mineralization of nitrogen from soil organic matter and crop residue retained in the field, and asymbiotic nitrogen fixation on N_2O emissions, but these are not model inputs.

The N_2O emissions from crop residues are reduced by approximately 3 percent (the assumed average burned portion for crop residues in the United States) to avoid double counting associated with non-CO_2 greenhouse gas

[21] OpTIS data on tillage practices provided by Regrow Agriculture, Inc.

[22] OpTIS data on cover crop management provided by Regrow Agriculture, Inc.

emissions from agricultural residue burning. Estimated levels of residue burning are based on state inventory data (ILENR 1993; Oregon Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996).

Uncertainty in the emission estimates from DayCent is associated with input uncertainty due to missing management data in the NRI survey that is imputed from other sources; model uncertainty due to incomplete specification of carbon and nitrogen dynamics in the DayCent model parameters and algorithms; and sampling uncertainty associated with the statistical design of the NRI survey. Uncertainty is estimated with two variance components (Ogle et al. 2010). The first variance component quantifies the uncertainty in management activity data, model structure and parameterization. To assess this uncertainty, carbon and nitrogen dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007; Del Grosso et al. 2010). The data is combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2020. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), and random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base. The second variance component is computed using the replicate weights provided with the NRI survey data, and a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are summed to quantify the total uncertainty and produce confidence intervals associated with the estimated emissions.

In order to ensure time-series consistency, the DayCent model is applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for 2021 to 2022 based on the pattern in emissions data from 1990 to 2020 (see Box 5-4). The pattern is determined using a linear regression model with moving-average (ARMA) errors. Linear extrapolation is a standard data splicing method for approximating missing values at the end of an inventory time series (IPCC 2006). The time series will be updated with the Tier 3 method in the future as new activity data are incorporated into the analysis.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., nitrogen fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with nitrogen dynamics in the soil profile, including immobilization of nitrogen by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of synthetic nitrogen fertilizer added to the soil, or mineral nitrogen made available through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of nitrogen from the atmosphere, is determined for each nitrogen source and then divided by the total amount of mineral nitrogen in the soil according to the DayCent model simulation. For 2021 to 2022, the contribution of each nitrogen source is based on the average of values that are estimated for 2018 to 2020. The percentages are then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to nitrogen management practices. This approach is only an approximation because it assumes that all nitrogen made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case (Delgado et al. 2009). However, this approach allows for further disaggregation of emissions by source of nitrogen, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of nitrogen.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DayCent (e.g., DayCent has not been parametrized to simulate all crop types and some soil types such

as *Histosols*). For the Tier 1 method, estimates of direct N_2O emissions from nitrogen applications are based on mineral soil N that is made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) decomposition and mineralization of nitrogen from above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure commercial organic amendments are only included in the Tier 1 analysis because these data are not available at the county-level, which is necessary for the DayCent simulations. Consequently, all commercial organic fertilizer, as well as manure that is not added to crops in the DayCent simulations, are included in the Tier 1 analysis. The following sources are used to derive activity data:

- A process-of-elimination approach is used to estimate synthetic nitrogen fertilizer additions for crop areas that are not simulated by DayCent. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS using sales records from 1990 to 2012 (Brakebill and Gronberg 2017). For 2013 through 2017, fertilizer sales data from AAPFCO (AAPFCO 2013 through 2022) [23] after adjusting for the proportion of on-farm application to determine the amount applied to crops. The amount of fertilizer applied after 2017 is estimated using the data splicing method described in Box 5-4 for the linear time series model. Then the portion of fertilizer applied to crops and grasslands simulated by DayCent is subtracted from the on-farm sales data (see Tier 3 Approach for mineral cropland soils and direct N_2O emissions from grassland soils sections for information on data sources), and the remainder of the total fertilizer used on farms is assumed to be applied to crops that are not simulated by DayCent. At a minimum, 3 percent of state-level on-farm fertilizer sales are assumed to be applied to cropland in the Tier 1 method.
- Similarly, a process-of-elimination approach is used to estimate manure nitrogen additions for crops that are not simulated by DayCent. The total amount of manure available for land application to soils has been estimated with methods described in the manure management section (Section 5.2) and annex (Annex 3.11). The amount of manure nitrogen applied in the Tier 3 approach to crops and grasslands is subtracted from total annual manure nitrogen available for land application (see Tier 3 Approach for mineral cropland soils and direct N_2O emissions from grassland soils sections for information on data sources). This difference is assumed to be applied to crops that are not simulated by DayCent.
- Commercial organic fertilizer additions are based on organic fertilizer consumption statistics through 2017,[24] which are converted from mass of fertilizer to units of nitrogen using average organic fertilizer nitrogen content, ranging between 2.3 to 4.2 percent across the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). Commercial fertilizers include dried manure and biosolids (i.e., treated sewage sludge), but the amounts are removed from the commercial fertilizer data to avoid double counting[25] with the manure nitrogen dataset described above and the biosolids (i.e., treated sewage sludge) amendment data discussed later in this section.
- Crop residue nitrogen is derived by combining amounts of above- and below-ground biomass, which are determined based on NRI crop area data (USDA-NRCS 2020), as extended using the CDL data (USDA-NASS 2021), crop production yield statistics (USDA-NASS 2023), dry matter fractions (IPCC 2006), linear equations to

[23] The fertilizer consumption data in AAPFCO are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b).

[24] Soil N_2O emissions are imputed using data splicing methods for commercial fertilizers, i.e., other organic fertilizers, after 2017 because the activity data are not available.

[25] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and biosolids (i.e., treated sewage sludge) are also included in other datasets in this Inventory. Consequently, the proportions of dried manure and biosolids, which are provided in the reports (TVA 1991 through 1994; AAPFCO 1995 through 2022), are used to estimate the nitrogen amounts in dried manure and biosolids. To avoid double counting, the resulting nitrogen amounts for dried manure and biosolids are subtracted from the total nitrogen in commercial organic fertilizers before estimating emissions using the Tier 1 method.

estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and nitrogen contents of the residues (IPCC 2006). Nitrogen inputs from residue were reduced by 3 percent to account for average residue burning portions in the United States.

The total amounts of soil mineral nitrogen from applied synthetic and organic fertilizers, manure nitrogen additions and crop residues are multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 method. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 1 methods are applied from 1990 to 2020, and a linear extrapolation method[26] is used to approximate emissions for 2021 to 2022 based on the emission patterns between 1990 and 2020 (see Box 5-4). The exceptions include crop residue nitrogen which is estimating using the Tier 1 method for 1990 to 2022 with no linear extrapolation, and for other organic nitrogen fertilizers (i.e., commercial fertilizers), which are estimated with linear time series model for 2018 to 2022 due to a gap in the activity data during the latter part of the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). For the extrapolation, the emission pattern is determined using a linear regression model with moving-average (ARMA) errors. Linear extrapolation is a standard data splicing method for approximating missing values at the end of an inventory time series (IPCC 2006). As with the Tier 3 method, the time series that is based on the splicing methods will be recalculated in a future *Inventory* report with updated activity data.

Tier 1 and 3 Approaches from Mineral Grassland Soils

As with N_2O emissions from croplands, the Tier 3 process-based approach with application of the DayCent model and Tier 1 method described in IPCC (2006) are combined to estimate emissions from non-federal grasslands and PRP manure nitrogen additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass or mixed grass/legume forage primarily for livestock grazing. Rangelands are extensive areas of native grassland that are not intensively managed, while pastures are seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation, fertilization, or inter-seeding legumes. DayCent is used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2020) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), nitrogen fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as daily spread or manure collected from other animal waste management systems such as lagoons and digesters), and synthetic fertilizer application. Other nitrogen inputs are simulated within the DayCent framework, including nitrogen input from mineralization due to decomposition of soil organic matter and nitrogen inputs from senesced grass litter, as well as asymbiotic fixation of nitrogen from the atmosphere. The simulations used the same weather, soil, and synthetic nitrogen fertilizer data as discussed under the Tier 3 Approach in the mineral cropland soils section. Synthetic nitrogen fertilization rates are based on data from the Carbon Sequestration Rural Appraisals (CSRA) conducted by the USDA-NRCS (USDA-NRCS, unpublished data). The CSRA was a solicitation of expert knowledge from USDA-NRCS staff throughout the United States to support the *Inventory*. Biological nitrogen fixation is simulated within DayCent, and therefore is not an input to the model.

Manure nitrogen deposition from grazing animals in PRP systems (i.e., PRP manure nitrogen) is a key input of nitrogen to grasslands. The amounts of PRP manure nitrogen applied on non-federal grasslands for each NRI survey location are based on the amount of nitrogen excreted by livestock in PRP systems that is estimated in the manure management section (see Section 5.2 and Annex 3.11). The total amount of nitrogen excreted in each county is divided by the grassland area to estimate the nitrogen input rate associated with PRP manure. The resulting rates are a direct input into the DayCent simulations. The nitrogen input is subdivided between urine and dung based on a 50:50 split. DayCent simulations of non-federal grasslands accounted for approximately 71

percent of total PRP manure nitrogen in aggregate across the country.[27] The remainder of the PRP manure nitrogen in each state is assumed to be excreted on federal grasslands, and the N_2O emissions are estimated using the IPCC (2006) Tier 1 method.

Biosolids (i.e., treated sewage sludge) are assumed to be applied on grasslands.[28] Application of biosolids is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007) (see Section 7.2 for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Biosolids data are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at NRI survey locations. Therefore, DayCent could not be used to simulate the influence of biosolids on N_2O emissions from grassland soils, and consequently, emissions from biosolids are estimated using the IPCC (2006) Tier 1 method.

Soil N_2O emission estimates from DayCent are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). There is also sampling uncertainty for the NRI survey that is quantified with replicate sampling weights associated with the survey, as discussed for Tier 3 method associated with mineral cropland soils. N_2O emissions for the PRP manure nitrogen deposited on federal grasslands and applied biosolids nitrogen are estimated using the Tier 1 method by multiplying the nitrogen input by the default emission factor. Emissions from manure nitrogen are estimated at the state level and aggregated to the entire country, but emissions from biosolids nitrogen are calculated exclusively at the national scale. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2020 based on the Tier 1 and 3 methods, except for biosolids (discussed below). In order to ensure time-series consistency, emissions from 2021 to 2022 are estimated using a splicing method as described in Box 5-4, with a linear extrapolation based on the emission patterns in the 1990 to 2020 data. Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). As with croplands, estimates for 2021 to 2022 will be recalculated in a future *Inventory* when the activity data are updated. Biosolids application data are compiled through 2022 in this *Inventory*, and therefore soil N_2O emissions and confidence intervals are estimated using the Tier 1 method for all years without application of the splicing method.

Tier 1 Approach for Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 method is used to estimate direct N_2O emissions due to drainage of organic soils in croplands and grasslands at a state scale. State-scale estimates of the total area of drained organic soils are obtained from the 2017 NRI (USDA-NRCS 2020), and extended through 2022 using CDL (USDA-NASS 2021) and the Forest Inventory and Analysis (FIA) survey data, which is harmonized with the NRI data (Nelson et al. 2020). Organic soils are identified using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The IPCC climate region map is used to subdivide areas into temperate and tropical climates according to the climate classification from IPCC (2006). To estimate annual emissions, the total temperate area is multiplied by the IPCC default emission factor for temperate regions, and the total tropical area is multiplied by the IPCC default emission factor for tropical regions (IPCC 2006). In order to ensure time-series consistency, the Tier 1 methods are applied from 1990 to 2022.

[27] A small amount of PRP nitrogen (less than 1 percent) is deposited in grazed pasture that is in rotation with annual crops and is reported in the grassland N_2O emissions.

[28] A portion of biosolids may be applied to croplands, but there is no national dataset to disaggregate the amounts between cropland and grassland.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for mineral and drained organic soils occurring in both croplands and grasslands are summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-15 and Table 5-16). Further elaboration on the methodology and data used to estimate soil N_2O emissions are described in Annex 3.12.

Indirect N_2O Emissions Associated with Nitrogen Management in Cropland and Grasslands

Indirect N_2O emissions occur when synthetic nitrogen applied or made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of nitrogen as NO_x (nitrogen oxides) and NH_3 (ammonia) following application of synthetic fertilizer, organic amendments (e.g., manure, biosolids), and deposition of PRP manure. Nitrogen made available from mineralization of soil organic matter and residue, including nitrogen incorporated into crops and forage from symbiotic nitrogen fixation, and input of nitrogen from asymbiotic fixation also contributes to volatilized nitrogen emissions. Volatilized nitrogen can be returned to soils through atmospheric deposition, and a portion of the deposited nitrogen is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil nitrogen (primarily in the form of NO_3^-, i.e., nitrate) that is made available through anthropogenic activity on managed lands, including organic and synthetic fertilization, organic amendments, mineralization of soil organic matter and residue, and inputs of nitrogen into the soil from asymbiotic fixation. Nitrate is subject to denitrification in water bodies, which leads to N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the nitrogen for reporting purposes, which here includes croplands and grasslands.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Atmospheric Deposition of Volatilized Nitrogen

The Tier 3 DayCent model and IPCC (2006) Tier 1 methods are combined to estimate the amount of nitrogen that is volatilized and eventually emitted as N_2O. DayCent is used to estimate nitrogen volatilization for land areas whose direct emissions are simulated with DayCent (i.e., most commodity and some specialty crops and most grasslands). The nitrogen inputs included are the same as described for direct N_2O emissions in the Tier 3 approach for mineral cropland and grassland soils sections. Nitrogen volatilization from all other areas is estimated using the Tier 1 method with default IPCC fractions for nitrogen subject to volatilization (i.e., synthetic and manure nitrogen on croplands not simulated by DayCent, other organic nitrogen inputs (i.e., commercial fertilizers), PRP manure nitrogen excreted on federal grasslands, and biosolids [i.e., treated sewage sludge] application on grasslands).

The IPCC (2006) default emission factor is multiplied by the amount of volatilized nitrogen generated from both DayCent and Tier 1 methods to estimate indirect N_2O emissions occurring with re-deposition of the volatilized nitrogen from 1990-2020 (see Table 5-18). A linear extrapolation data splicing method, described in Box 5-4, is applied to estimate emissions from 2021 to 2022 based on the emission patterns from 1990 to 2020. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized nitrogen, the Tier 3 DayCent model and IPCC (2006) Tier 1 method are combined to estimate the amount of nitrogen that is subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DayCent is used to simulate the amount of nitrogen transported from lands in the Tier 3 Approach. Nitrogen transport from all other areas is estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of nitrogen subject to leaching and runoff associated with

nitrogen applications on croplands that are not simulated by DayCent, applications of biosolids on grasslands, other organic N fertilizer applications, crop residue nitrogen inputs, and PRP manure nitrogen excreted on federal grasslands.

For both the DayCent Tier 3 and IPCC (2006) Tier 1 methods, NO_3^- leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions, as discussed in IPCC (2006). In the United States, the threshold for significant NO_3^- leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation does not exceed 80 percent of PET (Note: All irrigated systems are assumed to have significant amounts of leaching of nitrogen even in drier climates).

For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions that occur in groundwater and waterways (see Table 5-18). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

In order to ensure time-series consistency, indirect soil N_2O emissions are estimated using the Tier 1 and 3 approaches from 1990 to 2020 and then a linear extrapolation data splicing method, described in Box 5-4, is applied to estimate emissions from 2021 to 2022 based on the emission patterns from 1990 to 2020. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the direct N_2O emissions, the time series will be recalculated in a future *Inventory* when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DayCent; (2) the components of indirect emissions (nitrogen volatilized and leached or runoff) simulated by DayCent; (3) direct emissions estimated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (nitrogen volatilized and leached or runoff) estimated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions as well as the components of indirect emissions that are estimated from DayCent are derived from two variance components (Ogle et al. 2010). For the first component, a Monte Carlo Analysis (consistent with IPCC Approach 2) is used to address uncertainties in management activity data as well as model parameterization and structure (Del Grosso et al. 2010). The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire land base, and computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For 2021 to 2022 (and 2018 to 2022 for other organic nitrogen fertilizers) there is additional uncertainty propagated through the Monte Carlo Analysis associated with the splicing method (See Box 5-4) except for the Tier 1 method for biosolids and crop residue nitrogen inputs, which do not use the data splicing method for 2021 to 2022.

Simple error propagation methods (IPCC 2006) are used to derive confidence intervals for direct emissions estimated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions. Uncertainty in the splicing method is also included in the error propagation for 2021-2022 (see Box 5-4). Additional details on the uncertainty methods are provided in Annex 3.12. Table 5-19 shows the combined uncertainty for soil N_2O emissions. The estimated direct soil N_2O emissions range from 28 percent below to 28 percent above the 2022 emission estimate of 262.5 MMT CO_2 Eq. The combined uncertainty for indirect soil N_2O emissions ranges from 51 percent below to 123 percent above the 2022 estimate of 28.3 MMT CO_2 Eq.

Table 5-19: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2022 (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	262.5	189.6	335.3	-28%	+28%
Indirect Soil N_2O Emissions	N_2O	28.3	13.7	63.3	-51%	+123%

Note: Due to lack of data, uncertainties in PRP manure nitrogen production, other organic fertilizer amendments, and biosolids (i.e., treated sewage sludge) amendments to soils are currently treated as certain. These sources of uncertainty will be included in a future *Inventory* (IPCC 2006).

Additional uncertainty is associated with an incomplete estimation of N_2O emissions from managed croplands and grasslands in Hawaii and Alaska. The *Inventory* currently includes the N_2O emissions from managed manure and PRP nitrogen, and biosolid additions for Alaska and managed manure and PRP nitrogen, biosolid additions, and crop residue for Hawaii. Land areas used for agriculture in Alaska and Hawaii are small relative to major crop commodity states in the conterminous United States, so the emissions are likely to be minor for the other sources of nitrogen (e.g., synthetic fertilizer and crop residue inputs). Regardless, there is a planned improvement to include the additional sources of emissions in a future *Inventory*.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. DayCent results for N_2O emissions and NO_3^- leaching are compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005; Del Grosso et al. 2008), and further evaluated by comparing the model results to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data for cropland are available for 64 sites with 769 observations of management practice effects, and measurement data for grassland are available for 12 sites with 88 observations of management practice effects. Nitrate leaching data are available for 14 sites, representing 432 observations of management practice effects. In general, DayCent predicted N_2O emission and nitrate leaching for these sites reasonably well. See Annex 3.12 for more detailed information about the comparisons.

Databases containing input data and probability distribution functions required for DayCent simulations of croplands and grasslands and unit conversion factors have been checked. In addition, program scripts that are used to run the Monte Carlo uncertainty analysis have been checked. Errors were found in the synthetic nitrogen application rates for the Tier 3 method for a subset of years in some states, with overapplication based on comparisons to the synthetic fertilizer sales data. An error in the uncertainty calculation was found due to improper formulation of land area variances. A minor error was also identified in manure deposited in pasture, range, and paddock. Databases containing input data, emission factors, and calculations required for the Tier 1 method have been checked and updated as needed. Quality control identified a problem with error propagation in the Tier 1 uncertainty analysis associated with the emission factors. There was also an error identified in the leaching calculation based on irrigation status. All of these errors were corrected. Links between spreadsheets have also been checked, updated, and corrected as needed.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations, including a) updated time series of land representation data (Nelson et al. 2020), b) re-calibration of the soil carbon module in the DayCent model (See Annex 3.12); c) a more accurate output variable to estimate asymbiotic nitrogen fixation in

the Tier 3 method, and d) corrections associated with manure deposited on pasture, range and paddock in addition to estimation of leaching based on irrigation status. The combined impact from these changes resulted in an average annual increase in emissions of 3.3 MMT CO_2 Eq., or 1.1 percent, from 1990 to 2021 relative to the previous *Inventory*.

Planned Improvements

Several planned improvements are underway associated with improving the DayCent biogeochemical model. These improvements include a better representation of plant phenology, particularly senescence events following grain filling in crops. In addition, crop parameters associated with temperature and water stress effects on plant production will be further improved in DayCent with additional model calibration. In addition, there is an improvement underway to calibrate the nitrogen submodule in order to more accurately predict nitrogen-gas losses and nitrate leaching rates. Experimental study sites will continue to be added for quantifying model structural uncertainty with priority given to studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013). In addition, improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (see Section 5.7).

For Tier 1, there is a planned improvement to include all sources of nitrogen for Alaska and Hawaii in the *Inventory* for agricultural soil management, which currently only addresses managed manure nitrogen and PRP nitrogen, and biosolids additions for grasslands in both states, in addition to crop residue nitrogen inputs for Hawaii. There is also an improvement to incorporate the Tier 1 emission factor for N_2O emissions from drained organic soils by using the revised factors in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). There is a planned improvement for the Tier 1 method associated with estimating soil N_2O emissions from nitrogen mineralization due to soil organic matter decomposition that is accelerated with land use conversions to cropland and grassland. Lastly, a review of available data on biosolids (i.e., treated sewage sludge) application will also be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Improvements are expected to be completed for the next *Inventory* (i.e., 2025 submission to the UNFCCC, 1990 through 2023 *Inventory*), pending prioritization of resources.

5.5 Liming (CRT Source Category 3G)

Crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are added to soils by land managers to increase soil pH (i.e., to reduce acidification). Carbon dioxide emissions occur as these compounds react with hydrogen ions in soils. The rate of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and whether limestone or dolomite is applied. Emissions from limestone and dolomite that are used in industrial processes (e.g., cement production, glass production, etc.) are reported in the IPPU chapter. Emissions from liming of soils have fluctuated between 1990 and 2022 in the United States, ranging from 2.2 MMT CO_2 Eq. to 6.0 MMT CO_2 Eq. across the entire time series. In 2022, liming of soils in the United States resulted in emissions of 3.3 MMT CO_2 Eq. (0.9 MMT C), representing a 30 percent decrease in emissions since 1990 (see Table 5-20 and Table 5-21). The trend is driven by variation in the amount of limestone and dolomite applied to soils over the time period.

Table 5-20: Emissions from Liming (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Limestone	4.1	3.9	2.0	1.9	2.5	2.0	2.9
Dolomite	0.6	0.4	0.2	0.3	0.4	0.4	0.3
Total	**4.7**	**4.4**	**2.2**	**2.2**	**2.9**	**2.4**	**3.3**

Note: Totals may not sum due to independent rounding.

Table 5-21: Emissions from Liming (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Limestone	1.1	1.1	0.6	0.5	0.7	0.5	0.8
Dolomite	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Total	**1.3**	**1.2**	**0.6**	**0.6**	**0.8**	**0.7**	**0.9**

+ Does not exceed 0.05 MMT C.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Carbon dioxide emissions from application of limestone and dolomite to soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite, which are applied to soils (see Table 5-22), were multiplied by CO_2 emission factors from West and McBride (2005). These country-specific emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of carbonates that are transported from soils through hydrological processes and eventually deposited in ocean basins (West and McBride 2005). This analysis of lime dissolution is based on studies in the Mississippi River basin, where the vast majority of lime application occurs in the United States (West 2008). Moreover, much of the remaining lime application is occurring under similar precipitation regimes, and so the emission factors are considered a reasonable approximation for all lime application in the United States (West 2008) (see Box 5-5).

The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the U.S. Geological Survey (USGS) *Minerals Yearbook* (Tepordei 1994 through 2015; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a, 2014, 2015, 2016, 2017, 2020a, 2022a, 2022b, 2022c, 2023a), as well as preliminary data that will eventually be published in the *Minerals Yearbook* for the latter part of the time series (Willett 2023b). Data for the final year of the inventory is based on the *Mineral Industry Surveys*, as discussed below (USGS 2023). The U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) compiled production and use information through surveys of crushed stone manufacturers. However, manufacturers provided different levels of detail in survey responses so the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production).

Box 5-5: Comparison of the Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from liming of soils were estimated using a Tier 2 methodology based on emission factors specific to the United States that are lower than the IPCC (2006) default emission factors. Most lime application in the United States occurs in the Mississippi River basin, or in areas that have similar soil and rainfall regimes as the Mississippi River basin. Under these conditions, a significant portion of dissolved agricultural lime leaches through the soil into groundwater. Groundwater moves into channels and is transported to larger rivers and eventually the ocean where $CaCO_3$ precipitates to the ocean floor (West and McBride 2005). The U.S.-specific emission factors (0.059 metric ton C/metric ton limestone and 0.064 metric ton C/metric ton dolomite) are about half of the IPCC (2006) emission factors (0.12 metric ton C/metric ton limestone and 0.13 metric ton

C/metric ton dolomite). For comparison, the 2022 U.S. emission estimate from liming of soils is 3.3 MMT CO_2 Eq. using the country-specific factors. In contrast, emissions would be estimated at 6.6 MMT CO_2 Eq. using the IPCC (2006) default emission factors.

Data on "specified" limestone and dolomite amounts were used directly in the emission calculation because the end use is provided by the manufacturers and can be used to directly determine the amount applied to soils. However, it is not possible to determine directly how much of the limestone and dolomite is applied to soils for manufacturer surveys in the "unspecified" and "estimated" categories. For these categories, the amounts of crushed limestone and dolomite applied to soils were determined by multiplying the percentage of total "specified" limestone and dolomite production that is applied to soils, by the total amounts of "unspecified" and "estimated" limestone and dolomite production. In other words, the proportion of total "unspecified" and "estimated" crushed limestone and dolomite that was applied to soils is proportional to the amount of total "specified" crushed limestone and dolomite that was applied to soils.

In addition, data were not available for 1990, 1992, and 2022 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2022 data, 2021 fractions were applied to the 2022 estimates of total crushed stone. The basis for these estimates is from the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2023* (USGS 2023).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1996 and by the USGS from 1997 to the present. In 1994, the "Crushed Stone" chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Table 5-22: Applied Minerals (MMT)

Mineral	1990	2005	2018	2019	2020	2021	2022
Limestone	19.0	18.1	9.4	8.9	11.6	9.3	13.5
Dolomite	2.4	1.9	0.9	1.2	1.6	1.6	1.5

The same methods are applied throughout the time series. The activity data are extended in the last two years of the time series based on proportions of specified, unspecified and estimated agricultural limestone and dolomite so that estimates are consistent with the previous year's data. These years will be recalculated when additional data are available on the amounts of limestone and dolomite that are used for agricultural purposes.

Uncertainty

Uncertainty regarding the amount of limestone and dolomite applied to soils was estimated at ±15 percent with normal densities (Tepordei 2003; Willett 2013b). Analysis of the uncertainty associated with the emission factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not addressed in this analysis, but is assumed to be a relatively small contributor to the overall uncertainty (West 2005). The probability distribution functions for the fraction of lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were represented as triangular distributions between ranges of zero and 100 percent of the estimates. The uncertainty surrounding these two components largely drives the overall uncertainty. The emission factor distributions were truncated at 0 so that emissions were not less than 0.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO_2 emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-23. Carbon dioxide emissions from carbonate lime application to soils in 2022 were estimated to be between 0.50 and 6.18 MMT CO_2 Eq. at the 95 percent confidence level. This confidence interval represents a range of 85 percent below to 89 percent above the 2022 emission estimate of 3.3 MMT CO_2 Eq. Some carbon in the carbonate lime applied to agricultural soils is not emitted to the atmosphere due to the dominance of the carbonate lime dissolving in carbonic acid rather than nitric acid (West and McBride 2005).

Table 5-23: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming	CO_2	3.3	0.50	6.18	-85%	+89%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific QA/QC plan for liming has been developed and implemented, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The quality control effort focused on the Tier 1 procedures for this *Inventory*, and no errors were identified in this *Inventory*.

Recalculations Discussion

Limestone and dolomite application data for 2020 and 2021 were updated with the recent published data from Willett, J.C. (2023a). With these revisions, the emissions decreased by 1 and 22 percent for 2020 and 2021 (respectively) relative to the previous *Inventory*.

Planned Improvements

At this time there are no specific planned improvements for estimating emissions from liming.

5.6 Urea Fertilization (CRT Source Category 3H)

The use of urea ($CO(NH_2)_2$) as a fertilizer leads to greenhouse gas emissions through the release of CO_2 that was fixed during the production of urea. In the presence of water and urease enzymes, urea that is applied to soils as fertilizer is converted into ammonium (NH_4^+), hydroxyl ion (OH), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States were 5.3 MMT CO_2 Eq. (1.5 MMT C) in 2022 (Table 5-24 and Table 5-25). Carbon dioxide emissions have increased by 120 percent between 1990 and 2022 due to an increasing amount of urea that is applied to soils. The variation in emissions across the time series is driven by differences in the amounts of fertilizer applied to soils each year. Carbon dioxide emissions associated with urea used for non-agricultural purposes are reported in the IPPU chapter (Section 4.6).

Table 5-24: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3

Table 5-25: CO_2 Emissions from Urea Fertilization (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Fertilization	0.7	1.0	1.3	1.4	1.4	1.4	1.5

Methodology and Time-Series Consistency

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology following the *2006 IPCC Guidelines* Figure 11.5 decision tree for CO_2 emissions from urea fertilization.[29] The method assumes that carbon in the urea is released after application to soils and converted to CO_2. The annual amounts of urea applied to croplands (see Table 5-26) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizer* reports (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2022).[30] These amounts were multiplied by the default IPCC (2006) emission factor (0.20 metric tons of carbon per metric ton of urea), which is equal to the carbon content of urea on an atomic weight basis. National estimates from urea fertilization also include emissions from Puerto Rico.

Fertilizer sales data are reported in fertilizer years (July previous year through June current year), so a calculation was performed to convert the data to calendar years (January through December). According to monthly fertilizer use data (TVA 1992b), 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year, and 65 percent is applied between January and June of the current calendar year.

Fertilizer sales data for the 2018 through 2022 fertilizer years were not available for this *Inventory*. Therefore, urea application in the 2018 through 2022 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2013 through 2017) at the state scale. A trend of five years was chosen as opposed to a longer trend as it best captures the current inter-annual variability in consumption. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States. The fertilizer year data is then converted into calendar year (Table 5-26) data using the method described above.

Table 5-26: Applied Urea (MMT)

	1990	2005	2018	2019	2020	2021	2022
Urea Fertilizer[a]	3.3	4.8	6.7	6.9	7.0	7.1	7.3

[a] These numbers represent amounts applied to all agricultural land, including cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, settlements remaining settlements, land converted to settlements, forest land remaining forest land and land converted to forest land, as it is not currently possible to apportion the data by land-use/conversion category.

The same methods were applied to the entire time series to ensure time-series consistency from 1990 through 2022. In addition, activity data are extended using a data splicing method with a linear extrapolation based on the last five years of urea fertilization data to ensure consistency in the time series. These years will be recalculated when additional data are available on urea fertilization.

[29] *2006 IPCC Guidelines* Volume 4, Chapter 11, Figure 11.5 (page 11.33)

[30] The amount of urea consumed for non-agricultural purposes in the United States is reported in the Industrial Processes and Product Use chapter, Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Uncertainty

An Approach 2 Monte Carlo analysis is conducted as described by the IPCC (2006). The largest source of uncertainty is the default emission factor, which assumes that 100 percent of the carbon in $CO(NH_2)_2$ applied to soils is emitted as CO_2. The uncertainty surrounding this factor incorporates the possibility that some of the carbon may not be emitted to the atmosphere, and therefore the uncertainty range is set from 50 percent emissions to the maximum emission value of 100 percent using a triangular distribution. In addition, urea consumption data have uncertainty that is represented as a normal density. Due to the highly skewed distribution of the resulting emissions from the Monte Carlo uncertainty analysis, the estimated emissions are based on the analytical solution to the equation, and the confidence interval is approximated based on the values at 2.5 and 97.5 percentiles.

Carbon dioxide emissions from urea fertilization of agricultural soils in 2022 are estimated to be between 3.05 and 5.49 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 3 percent above the 2022 emission estimate of 5.33 MMT CO_2 Eq. (Table 5-27).

Table 5-27: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	5.33	3.05	5.49	-43%	+3%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

There are additional uncertainties that are not quantified in this analysis. There is uncertainty surrounding the assumptions underlying conversion of fertilizer years to calendar years. These uncertainties are negligible over multiple years because an over- or under-estimated value in one calendar year is addressed with a corresponding increase or decrease in the value for the subsequent year. In addition, there is uncertainty regarding the fate of carbon in urea that is incorporated into solutions of urea ammonium nitrate (UAN) fertilizer. Emissions of CO_2 from UAN applications to soils are not estimated in the current *Inventory* (see Planned Improvements).

QA/QC and Verification

A source-specific QA/QC plan for Urea Fertilization has been developed and implemented, consistent with the U.S. Inventory QA/QC plan. No quality control problems were discovered in this process except a correction to the emissions factor value in documentation tables.

Recalculations Discussion

Fertilizer consumption data was updated with the latest published estimate. In turn, the fertilizer values were recalculated using the data splicing method for 2018 to 2021 based on the revised fertilizer amount for 2017. This update led to an average decrease in emissions for the years 2017 through 2021 of 0.01 MMT CO_2 Eq., or 0.1 percent. The remainder of the time series was not affected.

Planned Improvements

A key planned improvement is to incorporate Urea Ammonium Nitrate (UAN) in the estimation of Urea CO_2 emissions. Activity data for UAN have been identified, but additional information is needed to fully incorporate this type of fertilizer into the analysis, which will be completed in a future *Inventory*.

5.7 Field Burning of Agricultural Residues (CRT Source Category 3F)

Crop production creates large quantities of agricultural crop residues, which farmers manage in a variety of ways. For example, crop residues can be left in the field and possibly incorporated into the soil with tillage; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and applied to soils; transported to landfills; or burned in the field. The *2006 IPCC Guidelines* does not consider field burning of crop residues to be a net source of CO_2 emissions because it is assumed the carbon released to the atmosphere as CO_2 during burning is reabsorbed during the next growing season by the crop (IPCC 2006). However, crop residue burning is a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

In the United States, field burning of agricultural residues occurs in southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane and wheat (McCarty 2009). In 2022, CH_4 and N_2O emissions from field burning of agricultural residues were 0.6 MMT CO_2 Eq. (22 kt) and 0.2 MMT CO_2 Eq. (1 kt), respectively (Table 5-28 and Table 5-29). Annual emissions of CH_4 and N_2O have increased from 1990 to 2022 by 14 percent and 16 percent, respectively. The increase in emissions over time is partly due to higher yielding crop varieties with larger amounts of residue production and fuel loads, but also linked with an increase in the area burned for some crop types.

Table 5-28: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990	2005	2018	2019	2020	2021	2022
CH_4	**0.5**	**0.6**	**0.6**	**0.7**	**0.6**	**0.6**	**0.6**
Sugarcane	0.1	0.2	0.1	0.2	0.1	0.1	0.1
Wheat	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Maize	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	0.0	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Lentils	0.0	+	+	+	+	+	+
Chickpeas	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Wheat	0.1	0.1	+	+	+	+	+
Maize	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+

Peanuts	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Vegetables	0.0	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	0.0	+	+	+	+	+	+
Chickpeas	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**0.7**	**0.8**	**0.8**	**0.9**	**0.8**	**0.8**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-29: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2018	2019	2020	2021	2022
CH_4	**19**	**23**	**22**	**23**	**22**	**22**	**22**
Sugarcane	4	6	5	6	5	5	5
Wheat	6	6	5	5	5	5	5
Maize	2	4	5	5	5	5	5
Rice	3	3	2	3	2	3	3
Soybeans	1	2	2	2	2	2	2
Cotton	1	2	1	1	1	1	1
Sorghum	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	0	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Lentils	0	+	+	+	+	+	+
Chickpeas	0	0	0	0	0	0	0
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Wheat	+	+	+	+	+	+	+
Maize	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+

Grass Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Vegetables	0	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	0	+	+	+	+	+	+
Chickpeas	0	0	0	0	0	0	0
CO	**407**	**480**	**433**	**468**	**446**	**480**	**501**
NOx	**16**	**18**	**17**	**18**	**17**	**18**	**19**

+ Does not exceed 0.5 kt CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

A country-specific Tier 2 method is used to estimate greenhouse gas emissions from field burning of agricultural residues from 1990 to 2014 (for more details comparing the country-specific approach to the IPCC (2006) default approach, see Box 5-6), and a data splicing method with a linear extrapolation is applied to complete the emissions time series from 2015 to 2022. The exception is sugarcane for which emissions have been estimated from 1990 to 2020, with 2021 to 2022 estimated with the data splicing method. The following equation is used to estimate the amounts of carbon and nitrogen released (R_i, where *i* is *C* or *N*) from burning.

Equation 5-1: Elemental C or N Released through Oxidation of Crop Residues

$$R_i = CP \times RCR \times DMF \times F_i \times FB \times CE$$

$$FB = \frac{AB}{CAH}$$

where,

Crop Production (CP)	=	Annual production of crop, by state, kt crop production
Residue: Crop Ratio (RCR)	=	Amount of residue produced per unit of crop production, kt residue/kt crop production
Dry Matter Fraction (DMF)	=	Amount of dry matter per unit of residue biomass for a crop, kt residue dry matter/ kt residue biomass
Fraction C or N (F_i)	=	Fraction of C or N per unit of dry matter for a crop, kt C or N /kt residue dry matter
Fraction Burned (FB)	=	Proportion of residue biomass consumed, unitless
Combustion Efficiency (CE)	=	Proportion of residue actually burned, unitless
Area Burned (AB)	=	Total area of crop burned, by state, ha
Crop Area Harvested (CAH)	=	Total area of crop harvested, by state, ha

Crop production data are available by state and year from USDA-NASS (2019) for 22 crops that are burned in the conterminous United States, including maize, rice, wheat, barley, oats, other small grains, sorghum, cotton, grass hay, legume hay, peas, sunflower, tobacco, vegetables, chickpeas, dry beans, lentils, peanuts, soybeans, potatoes,

sugarbeets, and sugarcane.[31] Crop area data are based on the 2015 and 2017 National Resources Inventories (NRI) (USDA-NRCS 2018; USDA-NRCS 2020). To estimate total crop production, the crop yield data from USDA Quick Stats (USDA-NASS 2019) are multiplied by the area data for these crops from the NRI survey. The production data for the crop types are presented in Table 5-30. Alaska and Hawaii are not included in the current analysis, but there is a planned improvement to estimate residue burning emissions for these two states in a future *Inventory*.

The amount of elemental carbon or nitrogen released through oxidation of the crop residues is used in the following equation to estimate the amount of CH_4, CO, N_2O, and NO_x emissions (E_g, where g is the specific gas, i.e., CH_4, CO, N_2O, and NO_x) from the field burning of agricultural residues:

Equation 5-2: Emissions from Crop Residue Burning

$$E_g = R_i \times EF_g \times CF$$

where,

Emission ratio (EF_g) = emission ratio by gas, g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released

Conversion Factor (CF) = conversion by molecular weight ratio of CH_4-C to C (16/12), CO-C to C (28/12), N_2O-N to N (44/28), or NO_x-N to N (30/14)

Box 5-6: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Field Burning of Agricultural Residues are calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997). The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; (3) the IPCC (2006) method provides emission factors based on the dry matter content rather than emission rates related to the amount of carbon and nitrogen in the residues; and (4) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this *Inventory* includes emissions from twenty-one crops.

A comparison of the methods in the current Inventory and the default IPCC (2006) approach was undertaken for 2014 to determine the difference in estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used with default factors and country-specific values for mass of fuel.

Equation 5-3: Estimation of Greenhouse Gas Emissions from Fire

$$Emissions\ (kt) = AB \times M_B \times C_f \times G_{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)

[31] Kentucky bluegrass (produced on farms for turf grass installations) may have small areas of burning that are not captured in the sample of locations that were used in the remote sensing analysis (see Planned Improvements).

Mass of Fuel (M_B) = U.S.- Specific Values using NASS Statistics[32] (metric tons dry matter)

Combustion Factor (C_f) = IPCC (2006) default combustion factor with fuel biomass consumption (metric tons dry matter ha^{-1})

Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) Tier 1 method approach resulted in 21 percent lower emissions of CH_4 and 40 percent lower emissions of N_2O compared to this *Inventory*. In summary, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data. Emissions are estimated based on specific carbon and nitrogen content of the fuel, which is converted into CH_4, CO, N_2O and NO_x, compared to IPCC (2006) approach that is based on dry matter rather than elemental composition.

Emissions from field burning of agricultural residues are calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997). The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; (3) the IPCC (2006) method provides emission factors based on the dry matter content rather than emission rates related to the amount of carbon and nitrogen in the residues; and (4) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this *Inventory* includes emissions from 21 crops.

A comparison of the methods in the current *Inventory* and the default IPCC (2006) approach was undertaken for 2014 to determine the difference in estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used with default factors and country-specific values for mass of fuel.

Equation 5-4: Estimation of Greenhouse Gas Emissions from Fire

$$Emissions\ (kt) = AB \times M_B \times C_f \times G_{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)

Mass of Fuel (M_B) = U.S.- Specific Values using NASS Statistics[33] (metric tons dry matter)

Combustion Factor (C_f) = IPCC (2006) default combustion factor with fuel biomass consumption (metric tons dry matter ha^{-1})

Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) Tier 1 method approach resulted in 21 percent lower emissions of CH_4 and 40 percent lower emissions of N_2O compared to this *Inventory*. In summary, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data. Emissions are estimated based on specific carbon and nitrogen content of the fuel, which is converted into

[32] NASS yields are used to derive mass of fuel values because IPCC (2006) only provides default values for 4 of the 21 crops included in the *Inventory*.

[33] NASS yields are used to derive mass of fuel values because IPCC (2006) only provides default values for 4 of the 21 crops included in the *Inventory*.

CH_4, CO, N_2O and NO_x, compared to IPCC (2006) approach that is based on dry matter rather than elemental composition.

Table 5-30: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2010	2018	2019	2020
Maize	296,065	371,256	398,618	NE	NE	NE
Rice	9,543	11,751	11,976	NE	NE	NE
Wheat	79,805	68,077	68,530	NE	NE	NE
Barley	9,281	5,161	3,942	NE	NE	NE
Oats	5,969	2,646	2,364	NE	NE	NE
Other Small Grains	2,651	2,051	1,803	NE	NE	NE
Sorghum	23,687	14,382	14,052	NE	NE	NE
Cotton	4,605	6,106	4,638	NE	NE	NE
Grass Hay	44,150	49,880	46,761	NE	NE	NE
Legume Hay	90,360	91,819	85,813	NE	NE	NE
Peas	51	660	839	NE	NE	NE
Sunflower	1,015	1,448	1,212	NE	NE	NE
Tobacco	1,154	337	470	NE	NE	NE
Vegetables	+	1,187	1,469	NE	NE	NE
Chickpeas	+	5	+	NE	NE	NE
Dry Beans	467	1,143	1,461	NE	NE	NE
Lentils	+	101	254	NE	NE	NE
Peanuts	1,856	2,176	1,925	NE	NE	NE
Soybeans	56,612	86,980	95,198	NE	NE	NE
Potatoes	18,924	20,026	19,279	NE	NE	NE
Sugarbeets	24,951	25,635	33,336	NE	NE	NE
Sugarcane	26,047	38,928	34,252	36,680	37,361	42,400

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
NE (Not Estimated)
Note: The amount of crop production has not been compiled for 2015 to 2021 so a data splicing method is used to estimate emissions for this portion of the time series.

The area burned is determined based on an analysis of remote sensing products (McCarty et al. 2009, 2010, 2011). The presence of fires has been analyzed at 3,600 survey locations in the NRI from 1990 to 2002 with LANDFIRE data products developed from 30 m Landsat imagery (LANDFIRE 2008), and from 2003 through 2014 using 1 km Moderate Resolution Imaging Spectroradiometer imagery (MODIS) Global Fire Location Product (MCD14ML), combining observations from Terra and Aqua satellites (Giglio et al. 2006). A sample of states are included in the analysis with high, medium and low burning rates for agricultural residues, including Arkansas, California, Florida, Indiana, Iowa and Washington. The area burned is determined directly from the analysis for these states for all crops, with the exception of sugarcane as discussed later in this section.

For other states within the conterminous United States, the area burned for the 1990 through 2014 portion of the time series is estimated from a logistical regression model that has been developed from the data collected from the remote sensing products for the six states. The logistical regression model is used to predict occurrence of fire events. Several variables are tested in the logistical regression including a) the historical level of burning in each state (high, medium or low levels of burning) based on an analysis by McCarty et al. (2011), b) year that state laws limit burning of fields, in addition to c) mean annual precipitation and mean annual temperature from a 4-kilometer gridded product from the PRISM Climate Group (2015). A K-fold model fitting procedure is used due to low frequency of burning and likelihood that outliers could influence the model fit. Specifically, the model is trained with a random selection of sample locations and evaluated with the remaining sample. This process is repeated ten times to select a model that is most common among the set of ten, and avoid models that appear to be influenced by outliers due to the random draw of survey locations for training the model. In order to address

uncertainty, a Monte Carlo analysis is used to sample the parameter estimates for the logistical regression model and produce one thousand estimates of burning for each crop in the remaining forty-two states included in this *Inventory*. State-level area burned data are divided by state-level crop area data to estimate the percent of crop area burned by crop type for each state. Table 5-31 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

Table 5-31: U.S. Average Percent Crop Area Burned by Crop (Percent)

Crop	1990	2005	2010	2018	2019	2020
Maize	+	+	+	NE	NE	NE
Rice	12%	11%	12%	NE	NE	NE
Wheat	3%	3%	2%	NE	NE	NE
Barley	1%	1%	1%	NE	NE	NE
Oats	1%	1%	1%	NE	NE	NE
Other Small Grains	5%	4%	4%	NE	NE	NE
Sorghum	1%	1%	1%	NE	NE	NE
Cotton	7%	10%	9%	NE	NE	NE
Grass Hay	+	+	+	NE	NE	NE
Legume Hay	+	+	+	NE	NE	NE
Peas	1%	1%	1%	NE	NE	NE
Sunflower	+	+	+	NE	NE	NE
Tobacco	1%	1%	1%	NE	NE	NE
Vegetables	+	+	+	NE	NE	NE
Chickpeas	+	+	+	NE	NE	NE
Dry Beans	+	+	+	NE	NE	NE
Lentils	+	1%	1%	NE	NE	NE
Peanuts	5%	5%	5%	NE	NE	NE
Soybeans	1%	1%	1%	NE	NE	NE
Potatoes	+	+	+	NE	NE	NE
Sugarbeets	+	+	+	NE	NE	NE
Sugarcane	6%	5%	6%	4%	6%	4%

+ Does not exceed 0.5 percent.
NE (Not Estimated)

The method for estimating burned area of sugarcane is similar to the approach for other crops. Areas with sugarcane production are identified in the 2017 USDA NRI survey (USDA-NRCS 2020) based on Cropland Data Layer (USDA-NASS 2021).[34] We use the MODIS burned area product from 2002 to 2020 to identify NRI survey locations with sugarcane production that have residue burning, similar to the process for other crops described above (Giglio et al. 2015). However, area of residue burning for sugarcane was estimated for 1990 to 2001 using a linear extrapolation of the area burned from 2002 to 2020, instead of analyzing the remote sensing data for this portion of the time series. This approach is a common data splicing method for filling data gaps in time series (IPCC 2006).

Additional parameters are needed to estimate emissions from the area that has residue burning, including residue: crop ratios, dry matter fractions, carbon fractions, nitrogen fractions and combustion efficiency. Residue: crop product mass ratios, residue dry matter fractions, and the residue N contents are obtained from several sources (IPCC 2006 and sources at bottom of Table 5-32). The residue carbon contents for all crops are based on IPCC (2006) default value for herbaceous biomass. The combustion efficiency is assumed to be 90 percent for all crop types (IPCC/UNEP/OECD/IEA 1997). See Table 5-32 for a summary of the crop-specific conversion factors. Emission ratios and mole ratio conversion factors for all gases are based on the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 5-33).

[34] USDA-NRI program aggregates sugarcane with other crops, but areas planted with sugarcane are identified in the USDA-NASS Crop Data Layer.

Table 5-32: Parameters for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction	Combustion Efficiency (Fraction)
Maize	0.707	0.56	0.47	0.01	0.90
Rice	1.340	0.89	0.47	0.01	0.90
Wheat	1.725	0.89	0.47	0.01	0.90
Barley	1.181	0.89	0.47	0.01	0.90
Oats	1.374	0.89	0.47	0.01	0.90
Other Small Grains	1.777	0.88	0.47	0.01	0.90
Sorghum	0.780	0.60	0.47	0.01	0.90
Cotton	7.443	0.93	0.47	0.01	0.90
Grass Hay	0.208	0.90	0.47	0.02	0.90
Legume Hay	0.290	0.67	0.47	0.01	0.90
Peas	1.677	0.91	0.47	0.01	0.90
Sunflower	1.765	0.88	0.47	0.01	0.90
Tobacco	0.300	0.87	0.47	0.01	0.90
Vegetables	0.708	0.08	0.47	0.01	0.90
Chickpeas	1.588	0.91	0.47	0.01	0.90
Dry Beans	0.771	0.90	0.47	0.01	0.90
Lentils	1.837	0.91	0.47	0.02	0.90
Peanuts	1.600	0.94	0.47	0.02	0.90
Soybeans	1.500	0.91	0.47	0.01	0.90
Potatoes	0.379	0.25	0.47	0.02	0.90
Sugarbeets	0.196	0.22	0.47	0.02	0.90
Sugarcane	0.410	0.25	0.47	0.02	0.90

NE (Not Estimated)

Notes: Chickpeas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Cotton: Combined sources (Heitholt et al. 1992; Halevy 1976; Wells and Meredith 1984; Sadras and Wilson 1997; Pettigrew and Meredith 1997; Torbert and Reeves 1994; Gerik et al. 1996; Brouder and Cassmen 1990; Fritschi et al. 2003; Pettigrew et al. 2005; Bouquet and Breitenbeck 2000; Mahroni and Aharonov 1964; Bange and Milroy 2004; Hollifield et al. 2000; Mondino et al. 2004; Wallach et al. 1978).

Lentils: IPCC (2006), Table 11.2; Beans & pulses.

Peas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Peanuts: IPCC (2006); Table 11.2; Root ratio and belowground N content values are for Root crops, other.

Sugarbeets: IPCC (2006); Table 11.2; values are for Tubers.

Sunflower: IPCC (2006), Table 11.2; values are for Grains.

Sugarcane: combined sources (Wiedenfels 2000, Dua and Sharma 1976; Singels & Bezuidenhout 2002; Stirling et al. 1999; Sitompul et al. 2000).

Tobacco: combined sources (Beyaert 1996; Moustakas and Ntzanis 2005; Crafts-Brandner et al. 1994; Hopkinson 1967; Crafts-Brandner et al. 1987).

Vegetables (Combination of carrots, lettuce/cabbage, melons, onions, peppers and tomatoes):

Carrots: McPharlin et al. (1992); Gibberd et al. (2003); Reid and English (2000); Peach et al. (2000); see IPCC Tubers for R:S and N fraction.

Lettuce, cabbage: combined sources (Huett and Dettman 1991; De Pinheiro Henriques & Marcelis 2000; Huett and Dettman 1989; Peach et al. 2000; Kage et al. 2003; Tan et al. 1999; Kumar et al. 1994; MacLeod et al. 1971; Jacobs et al. 2004; Jacobs et al. 2001; Jacobs et al. 2002); values from IPCC Grains used for N fraction.

Melons: Valantin et al. (1999); squash for R:S; IPCC Grains for N fraction.

Onion: Peach et al. (2000), Halvorson et al. (2002); IPCC (2006) Tubers for N fraction.

Peppers: combined sources (Costa and Gianquinto 2002; Marcussi et al. 2004; Tadesse et al. 1999; Diaz-Perez et al. 2008); IPCC Grains for N fraction.

Tomatoes: Scholberg et al. (2000a,b); Akintoye et al. (2005); values for AGR-N and BGR-N are from Grains.

Table 5-33: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH_4:C	0.005[a]	16/12
CO:C	0.060[a]	28/12
N_2O:N	0.007[b]	44/28
NO_x:N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).
[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

To ensure time-series consistency, the same method is applied from 1990 to 2014 for all crops except sugarcane in which the method was applied for 1990 to 2020. For this *Inventory*, new activity data on the burned areas have not been analyzed for 2015 to 2022 for individual crops. The exception is sugarcane in which burned areas have not been analyzed for 2021 to 2022. To complete the emissions time series, a linear extrapolation of the trend is applied to estimate the emissions for the latter part of the time series. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors is used to estimate the trend in emissions over time from 1990 through 2014, and the trend is used to approximate the CH_4, N_2O, CO and NO_x from 2015 to 2022 for all crops except for sugarcane, which was estimated using this method for 2021 to 2022 (Brockwell and Davis 2016). This extrapolation method is consistent with data splicing methods in IPCC (2006). The Tier 2 method described previously will be applied to recalculate the emissions for the latter part of the time series in a future *Inventory*.

Uncertainty

Emissions are estimated using a linear regression model with autoregressive moving-average (ARMA) errors for 2022. The linear regression ARMA model produced estimates of the upper and lower bounds to quantify uncertainty, and the results are summarized in Table 5-34. Methane emissions from field burning of agricultural residues in 2022 are between 0.55 and 0.70 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 11 percent below and 11 percent above the 2022 emission estimate of 0.6 MMT CO_2 Eq. Nitrous oxide emissions are between 0.18 and 0.23 MMT CO_2 Eq., or approximately 13 percent below and 13 percent above the 2022 emission estimate of 0.2 MMT CO_2 Eq.

Table 5-34: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.6	0.55	0.70	-11%	+11%
Field Burning of Agricultural Residues	N_2O	0.2	0.18	0.23	-13%	+13%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Due to data limitations, there are additional uncertainties in agricultural residue burning, particularly the potential omission of burning associated with Kentucky bluegrass (produced on farms for turf grass installation).

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues is implemented with Tier 1 analyses, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process.

Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. An error was identified in the calculation of the emissions using the IPCC (2006) equation after the initial compilation, which was corrected in Box 5.6. An error was also found with the estimation of non-CO_2 emissions from burning of sugarcane residue related to the GWP factors. This error was corrected.

Recalculations Discussion

Recalculations have been conducted for this *Inventory* associated with the addition of residue burning from sugarcane, which was not included in the previous *Inventory*. As a result of this change, CH_4 emissions increased by an annual average of 0.14 MMT CO_2 Eq., or 32 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*. In addition, N_2O emissions increased by an annual average of 0.03 MMT CO_2 Eq., or 21 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key planned improvement is to estimate the emissions associated with field burning of agricultural residues in the states of Alaska and Hawaii. In addition, a method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in several other source categories, including agricultural soil management, cropland remaining cropland, and land converted to cropland chapters of the *Inventory*. The method is based on simulating burning events directly within the DayCent process-based model framework using information derived from remote sensing fire products as described in the Methodology section. This improvement will lead to greater consistency in the methods across sources, ensuring mass balance of carbon and nitrogen in the *Inventory* analysis.

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the greenhouse gas fluxes resulting from land use and land-use change in the United States.[1] The Intergovernmental Panel on Climate Change's *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between all land use types including: forest land, cropland, grassland, wetlands, and settlements (as well as other land).

The greenhouse gas flux from forest land remaining forest land is reported for all forest ecosystem carbon (C) pools (i.e., aboveground biomass, belowground biomass, dead wood, litter, and mineral and organic soils), harvested wood pools, and non-carbon dioxide (non-CO_2) emissions from forest fires, the application of synthetic nitrogen fertilizers to forest soils, and the draining of organic soils. Fluxes from land converted to forest land are included for aboveground biomass, belowground biomass, dead wood, litter, and carbon stock changes from mineral soils, while carbon stock changes from drained organic soils and all non-CO_2 emissions from land converted to forest land are included in the fluxes from forest land remaining forest land as it is not currently possible to separate these fluxes by conversion category (e.g., grassland converted to forestland).

Fluxes are reported for four agricultural land use/land-use change categories: cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland. The reported greenhouse gas fluxes from these agricultural lands include changes in soil organic carbon stocks in mineral and organic soils due to land use and management, and for the subcategories of forest land converted to cropland and forest land converted to grassland, the changes in aboveground biomass, belowground biomass, dead wood, and litter carbon stocks are also reported. The greenhouse gas flux from grassland remaining grassland also includes estimates of non-CO_2 emissions from grassland fires occurring on both grassland remaining grassland and land converted to grassland.

Fluxes from wetlands remaining wetlands include changes in carbon stocks and methane (CH_4) and nitrous oxide (N_2O) emissions from managed peatlands, aboveground and belowground biomass, dead organic matter, soil carbon stock changes and CH_4 emissions from coastal wetlands, as well as N_2O emissions from aquaculture. In addition, CH_4 emissions from reservoirs and other constructed waterbodies are included for the subcategory flooded land remaining flooded land. Estimates for land converted to wetlands include aboveground and belowground biomass, dead organic matter and soil carbon stock changes, and CH_4 emissions from land converted to vegetated coastal wetlands. CO_2 and CH_4 emissions are included for reservoirs and other constructed waterbodies under the subcategory land converted to flooded land. See Section 6.1 for additional information on wetlands included in this *Inventory*.

[1] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux of CO_2 being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Fluxes from settlements remaining settlements include changes in carbon stocks from organic soils, N_2O emissions from nitrogen fertilizer additions to soils, and CO_2 fluxes from settlement trees and landfilled yard trimmings and food scraps. The reported greenhouse gas flux from land converted to settlements includes changes in carbon stocks in mineral and organic soils due to land use and management for all land use conversions to settlements, and the carbon stock changes in aboveground biomass, belowground biomass, dead wood, and litter are also included for the subcategory forest land converted to settlements.

In 2022, the Land Use, Land-Use Change, and Forestry (LULUCF) sector resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 MMT CO_2 Eq.[2] This represents an offset of approximately 14.5 percent of total (i.e., gross) greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 were 58.4 and 9.1 MMT CO_2 Eq., respectively, and combined represent 1.1 percent of total greenhouse gas emissions.[3] In 2022, the overall net flux from LULUCF resulted in a removal of 854.2 MMT CO_2 Eq. Emissions, removals and net greenhouse gas flux from LULUCF are summarized in Figure 6-1 and Table 6-1 by land use and category, and Table 6-2 and Table 6-3 by gas in MMT CO_2 Eq. and kt, respectively. Trends in LULUCF sources and sinks over the 1990 to 2022 time series are shown in Figure 6-2.

Flooded land remaining flooded land was the largest source of non-CO_2 emissions from LULUCF in 2022, accounting for 65.5 percent of the LULUCF sector non-CO_2 emissions. Non-CO_2 emissions from forest fires are the second largest source of LULUCF sector emissions; these emissions have increased 155.2 percent since 1990 and accounted for 21.9 percent of LULUCF non-CO_2 emissions in 2022. Coastal wetlands remaining coastal wetlands and settlements remaining settlements soils accounted for 6.6 and 3.8 percent of non-CO_2 emissions from LULUCF in 2022, respectively, and the remaining sources account for less than one percent each.

[2] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[3] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

Figure 6-1: 2022 LULUCF Chapter Greenhouse Gas Sources and Sinks

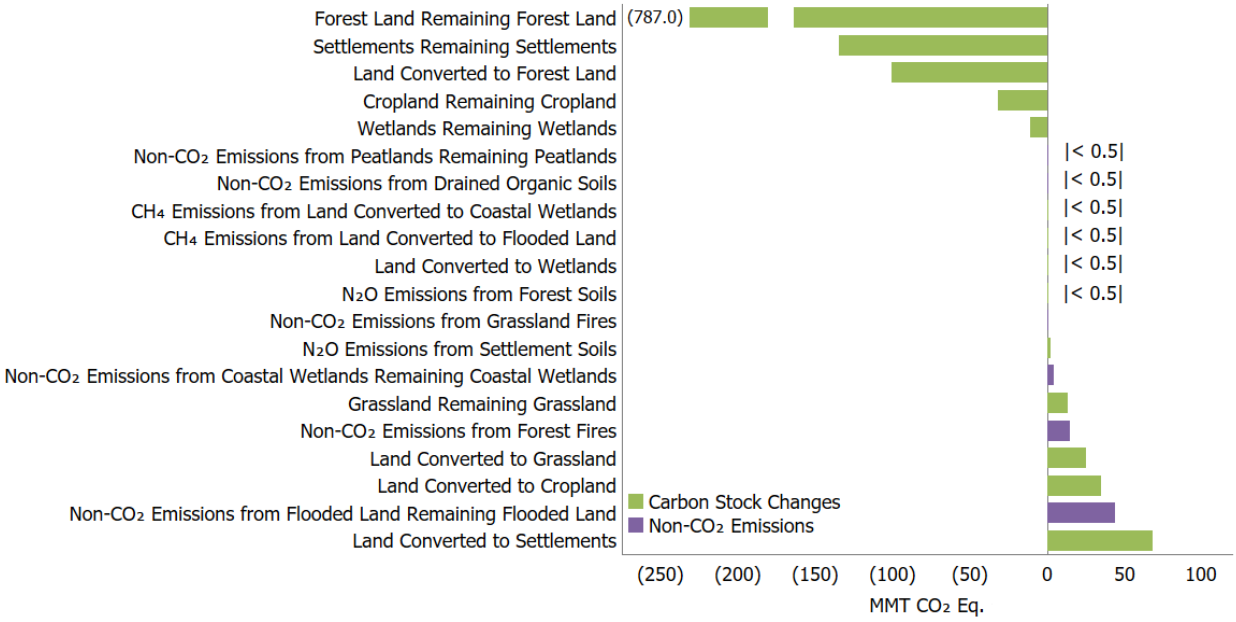

Note: Parentheses in horizontal axis indicate net sequestration.

Figure 6-2: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

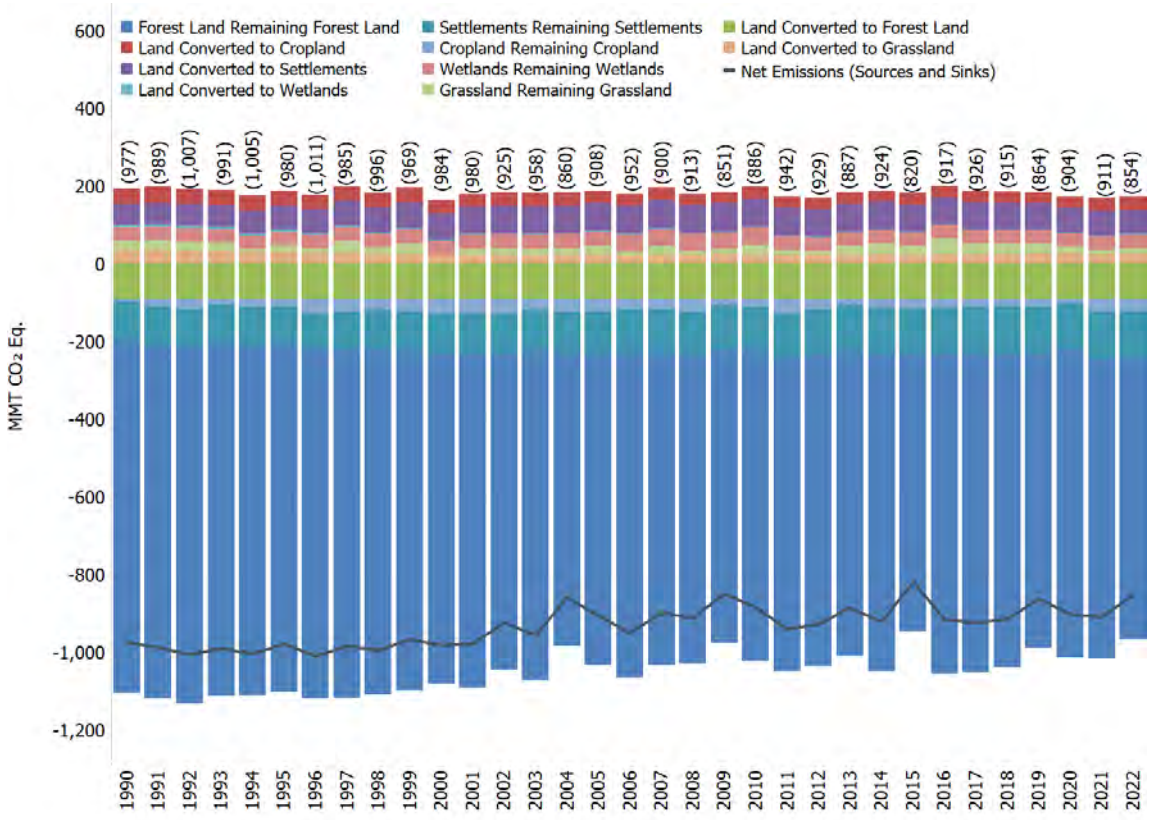

Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Forest Land Remaining Forest Land	**(968.8)**	**(860.0)**	**(863.4)**	**(807.0)**	**(846.3)**	**(823.8)**	**(771.7)**
Changes in Forest Carbon Stocks[a]	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)
Non-CO_2 Emissions from Forest Fires[b]	5.8	15.5	9.7	5.7	15.3	19.9	14.8
N_2O Emissions from Forest Soils[c]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**
Changes in Forest Carbon Stocks[e]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**
Changes in Mineral and Organic Soil Carbon Stocks	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**
Changes in all Ecosystem Carbon Stocks[f]	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland	**24.6**	**24.9**	**29.7**	**28.9**	**17.1**	**11.5**	**14.0**
Changes in Mineral and Organic Soil Carbon Stocks	24.4	24.1	28.6	28.5	16.1	10.6	13.4
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.8	1.1	0.3	1.1	0.9	0.6
Land Converted to Grassland	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**
Changes in all Ecosystem Carbon Stocks[f]	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands	**36.8**	**39.4**	**38.2**	**38.1**	**38.1**	**38.1**	**38.1**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.6	0.6	0.5	0.6
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(10.8)	(10.1)	(11.1)	(11.1)	(11.1)	(11.1)	(11.1)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
CH_4 Emissions from Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2
Land Converted to Wetlands	**7.2**	**1.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Changes in Land Converted to Flooded Land	3.6	0.6	0.3	0.3	0.3	0.3	0.3
CH_4 Emissions from Land Converted to Flooded Land	2.9	0.4	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(109.1)**	**(115.2)**	**(131.0)**	**(131.5)**	**(131.8)**	**(132.3)**	**(132.3)**
Changes in Organic Soil Carbon Stocks	9.9	10.1	14.4	14.6	15.1	15.4	15.4
Changes in Settlement Tree Carbon Stocks	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)
N_2O Emissions from Settlement Soils[h]	2.1	3.1	2.4	2.5	2.5	2.5	2.5
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(13.4)	(13.1)	(12.8)	(12.5)	(11.8)
Land Converted to Settlements	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**
Changes in all Ecosystem Carbon Stocks[f]	57.2	77.1	71.4	70.2	68.8	68.2	68.2
LULUCF Emissions[i]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1

LULUCF Carbon Stock Change[j]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Sector Net Total[k]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include N_2O emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land-use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[h] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.

[i] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[j] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land-use conversion categories.

[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The carbon stock changes and emissions of CH_4 and N_2O from LULUCF are summarized in Table 6-2 (MMT CO_2 Eq.) and Table 6-3 (kt). Total net carbon sequestration in the LULUCF sector decreased by approximately 10.9 percent between 1990 and 2022. This decrease was primarily due to a decline in the rate of net carbon accumulation in forest land, as well as an increase in emissions from land converted to settlements.[4] Specifically, there was a net carbon accumulation in settlements remaining settlements, which increased from 1990 to 2022, while the net carbon accumulation in forest land remaining forest land and land converted to wetlands slowed over this period. Net carbon accumulation remained steady from 1990 to 2022 in land converted to forest land, cropland remaining cropland, land converted to cropland, and wetlands remaining wetlands, while net carbon accumulation fluctuated in grassland remaining grassland.

Flooded land remaining flooded land was the largest source of CH_4 emissions from LULUCF in 2022, totaling 44.2 MMT CO_2 Eq. (1,579 kt of CH_4). Forest fires resulted in CH_4 emissions of 9.1 MMT CO_2 Eq. (325 kt of CH_4).

For N_2O emissions, forest fires were the largest source from LULUCF in 2022, totaling 5.7 MMT CO_2 Eq. (22 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2022 totaled to 2.5 MMT CO_2 Eq. (10 kt of N_2O). This represents an increase of 22.8 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2022 resulted in N_2O emissions of 0.4 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455.1 percent since 1990, but still account for a relatively small portion of overall emissions.

[4] Carbon sequestration estimates are net figures. The carbon stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the carbon stock decreases, and the pool acts as a source. When gains exceed losses, the carbon stock increases, and the pool acts as a sink; also referred to as net carbon sequestration or removal.

Table 6-2: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Carbon Stock Change (CO_2)[a]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
Forest Land Remaining Forest Land	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)
Land Converted to Forest Land	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland	24.4	24.1	28.6	28.5	16.1	10.6	13.4
Land Converted to Grassland	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands	(9.8)	(9.0)	(10.5)	(10.5)	(10.5)	(10.6)	(10.6)
Land Converted to Wetlands	4.1	1.1	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	(111.2)	(118.3)	(133.5)	(134.0)	(134.3)	(134.8)	(134.8)
Land Converted to Settlements	57.2	77.1	71.4	70.2	68.8	68.2	68.2
CH_4	**53.1**	**58.6**	**55.6**	**52.5**	**59.3**	**62.2**	**58.4**
Forest Land Remaining Forest Land: Forest Fires[b]	3.4	9.2	6.0	3.4	9.8	12.7	9.1
Forest Land Remaining Forest Land: Drained Organic Soils[c]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[d]	0.1	0.4	0.6	0.2	0.6	0.5	0.3
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	2.9	0.4	0.2	0.2	0.2	0.2	0.2
Land Converted to Wetlands: Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
N_2O	**4.8**	**10.4**	**7.2**	**5.5**	**9.1**	**10.8**	**9.1**
Forest Land Remaining Forest Land: Forest Fires[b]	2.4	6.3	3.7	2.3	5.5	7.2	5.7
Forest Land Remaining Forest Land: Forest Soils[e]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Forest Land Remaining Forest Land: Drained Organic Soils[c]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Remaining Grassland: Grassland Fires[d]	0.1	0.4	0.5	0.1	0.5	0.4	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[f]	2.1	3.1	2.4	2.5	2.5	2.5	2.5
LULUCF Carbon Stock Change[a]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Emissions[g]	**57.9**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.5**
LULUCF Sector Net Total[h]	**(976.7)**	**(907.6)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.5)**	**(854.3)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining

settlements, and land converted to settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[e] Estimates include N_2O emissions from nitrogen fertilizer additions on both forest land remaining forest land and land converted to forest land.

[f] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements.

[g] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[h] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-3: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (kt)

Gas/Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Carbon Stock Change (CO_2)[a]	**(1,034,678)**	**(976,578)**	**(978,287)**	**(921,607)**	**(972,765)**	**(983,418)**	**(921,792)**
Forest Land Remaining Forest Land	(974,778)	(876,001)	(873,508)	(813,183)	(862,033)	(844,194)	(787,006)
Land Converted to Forest Land	(100,216)	(100,151)	(100,409)	(100,284)	(100,297)	(100,305)	(100,294)
Cropland Remaining Cropland	(5,042)	(31,622)	(17,786)	(19,418)	(8,819)	(31,970)	(31,710)
Land Converted to Cropland	45,403	34,501	31,936	31,376	29,297	34,893	35,110
Grassland Remaining Grassland	24,366	24,071	28,557	28,536	16,086	10,566	13,352
Land Converted to Grassland	35,255	21,792	25,178	25,404	28,696	24,542	25,621
Wetlands Remaining Wetlands	(9,770)	(8,984)	(10,469)	(10,509)	(10,535)	(10,582)	(10,559)
Land Converted to Wetlands	4063	1069	304	309	305	309	313
Settlements Remaining Settlements	(111,203)	(118,335)	(133,464)	(134,000)	(134,301)	(134,842)	(134,812)
Land Converted to Settlements	57,242	77,081	71,373	70,161	68,836	68,165	68,195
CH_4	**1,898**	**2,091**	**1,983**	**1,875**	**2,118**	**2,218**	**2,087**
Forest Land Remaining Forest Land: Forest Fires[b]	122	328	213	120	349	452	327
Forest Land Remaining Forest Land: Drained Organic Soils[c]	1	1	1	1	1	1	1
Grassland Remaining Grassland: Grassland Fires[d]	4	15	22	6	20	18	12
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	1,509	1,569	1,578	1,579	1,579	1,579	1,579
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	149	151	153	153	154	154	154
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	102	16	8	8	8	8	8
Land Converted to Wetlands: Land Converted to Coastal Wetlands	10	10	7	7	7	6	6
N_2O	**18**	**39**	**27**	**21**	**34**	**41**	**34**
Forest Land Remaining Forest Land: Forest Fires[b]	9	24	14	9	21	27	21
Forest Land Remaining Forest Land: Forest Soils[e]	+	2	2	2	2	2	2

Forest Land Remaining Forest Land: Drained Organic Soils[c]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[d]	+	1	2	1	2	2	1
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	+	1	1	1	1	1	1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[f]	8	12	9	9	9	10	10

+ Absolute value does not exceed 0.5 kt.

[a] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[e] Estimates include N_2O emissions from nitrogen fertilizer additions on both forest land remaining forest land and land converted to forest land.

[f] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Each year, some emission and sink estimates in the LULUCF sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emissions and removals estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to ensure that the trend is accurate. Of the updates implemented for this *Inventory*, the most significant include (1) managed forest land in Hawaii and several U.S. Territories[5] were included for the first time in the current *Inventory* which resulted in an increase in managed forest land area of approximate 1.3 M ha and associated increases in carbon stocks of 286 MMT C for the year 2023 in this *Inventory;* (2) updated methodological framework and accounting of carbon in structural components of trees across the United States for total tree cubic-foot volume, biomass, and carbon which led to an increase in estimated forest carbon stocks; and (3) incorporating new U.S. Department of Agriculture (USDA) National Resources Inventory (NRI) data through 2017, incorporating USDA-Natural Resources Conservation Service (NRCS) Conservation Effects Assessment Program (CEAP) survey data for 2013 to 2016, incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020, in addition to other methodological updates for the estimation of croplands and grasslands described further in those respective category sections. Together, these and other updates increased total carbon sequestration estimates by an average of 133.6 MMT CO_2 Eq. (15.5 percent) and decreased total non-CO_2 emissions by 2.2 MMT CO_2 Eq. (2.6 percent) across the time series, compared to the previous *Inventory* (i.e., 1990 to 2021). For more information on specific methodological updates, please see the Recalculations Discussion within the respective category section of this chapter.

Emissions and removals reported in the LULUCF chapter include those from all states; however, for Hawaii and Alaska some emissions and removals from land use and land-use change are not included in most cases (see chapter sections on Uncertainty and Planned Improvements for more details). In addition, U.S. Territories are not included for most categories. EPA continues to review available data on an ongoing basis to include emissions and

[5] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

removals from U.S. Territories in future *Inventories* to the extent they are occurring (e.g., see Box 6-2). See Annex 5 for more information on EPA's assessment of the emissions and removals not included in this *Inventory*.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the gross emissions total presented in this report for the United States excludes emissions and removals from LULUCF. The LULUCF Sector Net Total presented in this report for the United States includes emissions and removals from LULUCF. All emissions and removals estimates are calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines), 2013 Supplement to the 2006 IPCC Guidelines for National GHG Inventories: Wetlands,* and the *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC.[6] The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the Land Use Land-Use Change and Forestry chapter does not preclude alternative examinations. Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follow this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

6.1 Representation of the U.S. Land Base

A national land use representation system that is consistent and complete, both temporally and spatially, is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the *Inventory* time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should: (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (Table 6-4), (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing) (Table 6-5), and (3) account for greenhouse gas fluxes on all managed lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic greenhouse gas emissions and removals associated with land use and management to occur on managed land, and all emissions and removals on managed land should be reported based on this guidance (see IPCC (2010), Ogle et al. (2018) for further discussion). Consequently, managed land serves as a proxy for anthropogenic emissions and removals. This proxy is intended to provide a practical framework for conducting an inventory, even though some of the greenhouse gas emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. This section of the *Inventory* has been developed in order to comply with this guidance. While the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) provide guidance for factoring out natural emissions and removals, the United States does not apply this guidance and estimates all emissions/removals on managed land regardless of whether the driver was natural.

[6] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Three databases are used to track land management in the United States and are used as the basis to classify United States land area into the thirty-six IPCC land use and land-use change categories (Table 6-5) (IPCC 2006). The three primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI),[7] the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[8] Database, and the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD).[9] See Table 6-6 for an overview of the land area databases used to characterize land use in federal and non-federal lands in the conterminous United States, Alaska, and Hawaii.

The total land area included in the United States *Inventory* is 936 million hectares across the 50 states.[10] Approximately 886 million hectares of this land base is considered *managed* and 50 million hectares is *unmanaged*, a distribution that has remained stable over the time series of the *Inventory* (Table 6-5). In 2022, the United States had a total of 281 million hectares of managed forest land (0.47 percent decrease compared to 1990). There are 160 million hectares of cropland (8.3 percent decrease compared to 1990), 339 million hectares of managed grassland (0.35 percent increase compared to 1990), 39 million hectares of managed wetlands (3 percent increase compared to 1990), 47 million hectares of settlements (41 percent increase compared to 1990), and 21 million hectares of managed other land (1.2 percent decrease compared to 1990) (Table 6-5).

Wetlands are not differentiated between managed and unmanaged with the exception of remote areas in Alaska, and so are classified and reported mostly as managed land within the coterminous United States.[11] In addition, carbon stock changes are not currently estimated for the entire managed land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the *Inventory* (e.g., grassland remaining grassland within interior Alaska).[12,13] Planned improvements are under development to estimate carbon stock changes and greenhouse gas emissions on all managed land and to ensure consistency between the total area of managed land in the land-representation description and the remainder of the *Inventory*.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement and economic patterns (Figure 6-3). Forest land tends to be more common in the eastern United States, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and grassland is more common in the western United States and Alaska. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper

[7] NRI data are available at https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[8] FIA data are available at https://www.fia.fs.usda.gov/tools-data/index.php.

[9] NLCD data are available at http://www.mrlc.gov/ and MRLC is a consortium of several U.S. government agencies.

[10] The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future *Inventories*. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2.

[11] According to the IPCC (2006), wetlands are considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Alaska is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. As a result, all wetlands in the conterminous United States and Hawaii are reported as managed in the land representation, but emission/removal estimates only developed for those wetlands that are included under the flooded lands, coastal wetlands or peat extraction categories. Efforts are underway to better reflect wetland estimates in the future *Inventories*. See the Planned Improvements section of the *Inventory* for future refinements to the wetland area estimates.

[12] Other discrepancies occur because the coastal wetlands analysis is based on another land use product (NOAA C-CAP) that is not currently incorporated into the land representation analysis for this section, which relies on the NRI and NLCD for wetland areas. EPA anticipates addressing these discrepancies in future *Inventories*.

[13] These "managed area" discrepancies also occur in the Common Reporting Tables (CRTs) submitted to the UNFCCC.

Midwest and eastern portions of the country, as well as coastal regions. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-4: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land Use Categories	1990	2005	2018	2019	2020	2021	2022
Managed Lands	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**
Forest	282,375	281,806	280,971	280,440	281,067	281,071	281,041
Croplands	174,498	165,632	161,394	160,693	160,112	160,079	160,033
Grasslands	337,867	340,022	338,927	339,801	339,562	339,260	339,048
Settlements	33,427	40,172	45,971	46,312	46,641	46,960	47,185
Wetlands	37,456	38,310	38,495	38,551	38,430	38,478	38,566
Other	20,911	20,588	20,773	20,734	20,718	20,682	20,657
Unmanaged Lands	**49,708**	**49,711**	**49,710**	**49,710**	**49,710**	**49,710**	**49,710**
Forest	9,766	9,782	9,814	9,815	9,817	9,818	9,819
Croplands	0	0	0	0	0	0	0
Grasslands	25,090	25,154	25,268	25,266	25,265	25,264	25,262
Settlements	0	0	0	0	0	0	0
Wetlands	4,118	4,057	3,936	3,935	3,935	3,935	3,936
Other	10,734	10,718	10,693	10,693	10,693	10,693	10,693
Total Land Areas	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**
Forest	292,140	291,588	290,784	290,255	290,883	290,889	290,861
Croplands	174,498	165,632	161,394	160,693	160,112	160,079	160,033
Grasslands	362,957	365,176	364,195	365,068	364,827	364,524	364,310
Settlements	33,427	40,172	45,971	46,312	46,641	46,960	47,185
Wetlands	41,574	42,366	42,430	42,486	42,365	42,413	42,502
Other	31,645	31,306	31,466	31,428	31,411	31,375	31,350

Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

Land Use & Land-Use Change Categories[a]	1990	2005	2018	2019	2020	2021	2022
Total Forest Land	**282,375**	**281,806**	**280,971**	**280,440**	**281,067**	**281,071**	**281,041**
FF	281,290	280,587	279,683	279,167	279,818	279,829	279,802
CF	208	137	101	88	77	77	76
GF	775	968	1,038	1,048	1,036	1,037	1,040
WF	15	23	21	18	16	15	15
SF	11	18	20	21	20	19	20
OF	77	73	108	98	99	94	89
Total Cropland	**174,498**	**165,632**	**161,394**	**160,693**	**160,112**	**160,079**	**160,033**
CC	162,273	150,417	149,721	149,503	149,823	150,591	151,276
FC	173	77	63	64	60	63	65
GC	11,673	14,623	11,231	10,758	9,914	9,132	8,418
WC	119	178	99	98	86	81	75
SC	75	102	107	105	101	97	94
OC	186	235	173	166	129	115	107
Total Grassland	**337,867**	**340,022**	**338,927**	**339,801**	**339,562**	**339,260**	**339,048**
GG	328,566	315,931	318,960	320,255	320,856	321,910	322,779
FG	572	1,663	4,184	4,202	4,177	4,162	3,894
CG	8,177	17,746	13,594	13,491	13,205	12,200	11,444
WG	168	466	181	172	159	143	134
SG	43	525	230	190	139	100	93
OG	341	3,692	1,778	1,491	1,026	746	705
Total Wetlands	**37,456**	**38,310**	**38,495**	**38,551**	**38,430**	**38,478**	**38,566**

WW	36,900	36,288	37,236	37,425	37,448	37,626	37,783
FW	37	71	96	85	83	78	76
CW	145	637	362	310	261	221	187
GW	326	1,169	564	501	415	342	314
SW	0	38	17	14	10	2	2
OW	47	107	220	216	212	210	204
Total Settlements	**33,427**	**40,172**	**45,971**	**46,312**	**46,641**	**46,960**	**47,185**
SS	30,562	31,445	40,769	41,615	42,466	43,189	43,748
FS	301	466	468	455	448	446	440
CS	1,231	3,604	1,917	1,726	1,528	1,366	1,228
GS	1,276	4,371	2,630	2,349	2,062	1,830	1,648
WS	4	59	30	25	18	14	14
OS	54	229	157	141	120	115	108
Total Other Land	**20,911**	**20,588**	**20,773**	**20,734**	**20,718**	**20,682**	**20,657**
OO	20,177	17,022	18,050	18,293	18,553	18,805	18,874
FO	51	77	98	101	101	108	111
CO	287	603	629	582	540	489	444
GO	371	2,764	1,772	1,541	1,309	1,068	1,018
WO	22	100	206	206	205	204	200
SO	2	21	17	11	10	10	10
Grand Total	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**

[a] The abbreviations are "F" for forest land, "C" for cropland, "G" for grassland, "W" for wetlands, "S" for settlements, and "O" for other lands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., "FF" is forest land remaining forest land), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., "CF" is Cropland Converted to Forest Land).

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for wetlands, which based on the definitions for the current U.S. Land Representation assessment includes both managed and unmanaged lands. U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See the Planned Improvements section for discussion on plans to include U.S. Territories in future *Inventories*. In addition, carbon stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the *Inventory* (see land use chapters e.g., Forest Land Remaining Forest Land for more information). Totals may not sum due to independent rounding.

Figure 6-3: Percent of Total Land Area for Each State in the General Land Use Categories for 2022

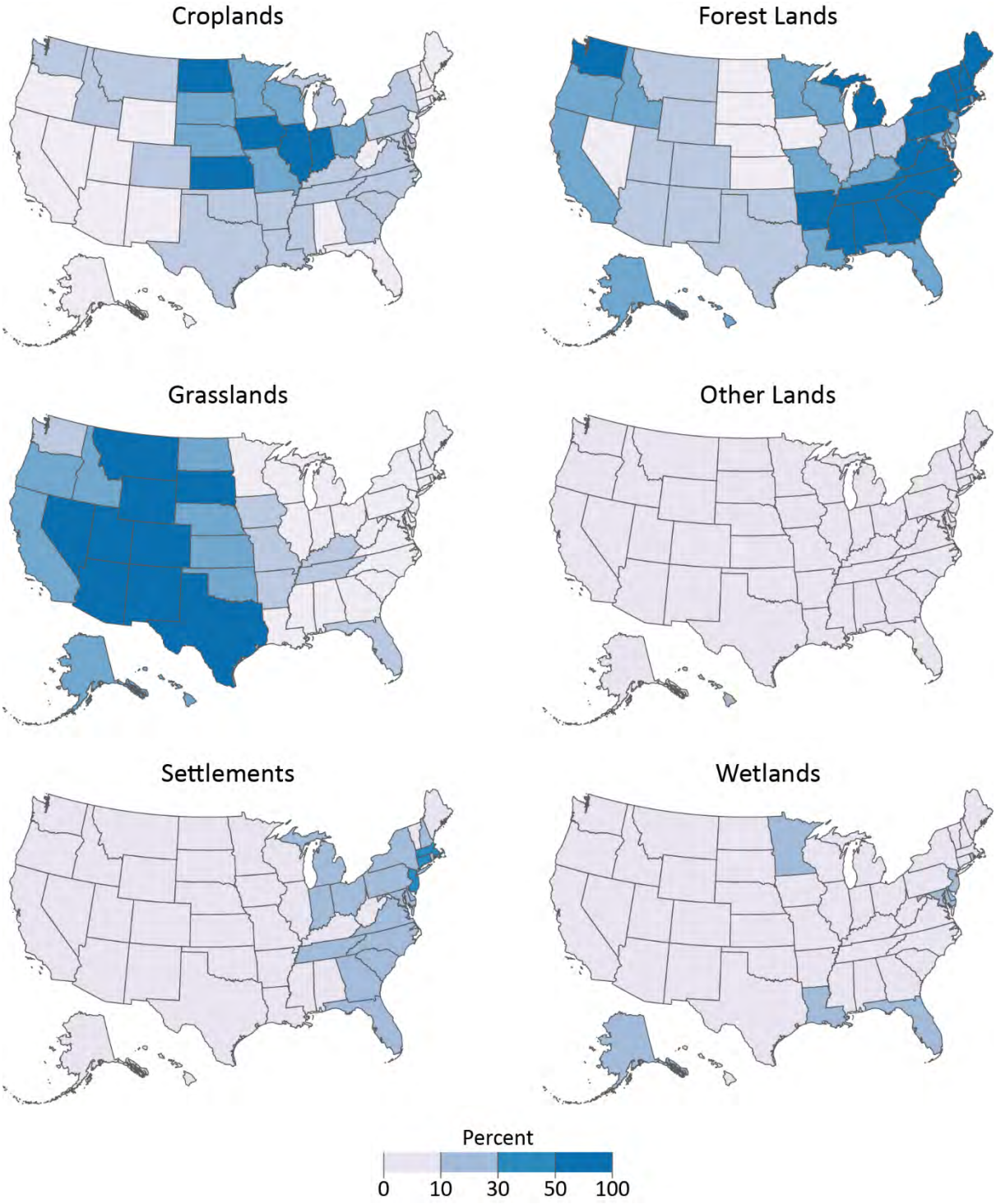

Methodology and Time-Series Consistency

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land use category, but does not provide detailed information on transfer of land area between categories following land-use change and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes (i.e., additions and/or losses) between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., forest land converted to cropland, cropland converted to forest land, and grassland converted to cropland), using survey samples or other forms of data, but does not provide spatially-explicit location data. Approach 3 extends Approach 2 by providing spatially-explicit location data, such as surveys with spatially identified sample locations and maps obtained from remote sensing products. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. NRI, FIA and NLCD are Approach 3 data sources that provide spatially-explicit representations of land use and land-use conversions. Lands are treated as remaining in the same category (e.g., cropland remaining cropland) if a land-use change has not occurred in the last 20 years, consistent with the IPCC guidelines (2006). Otherwise, the land is classified in a land-use change category based on the current use and most recent use before conversion to the current use (e.g., cropland converted to forest land).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The United States definition of managed land is similar to the general definition of managed land provided by the IPCC (2006), but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community, or societal objectives where these areas are readily accessible to society.[14]
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced

[14] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management or origin (i.e., constructed rather than natural origin). Therefore, unless wetlands are converted into cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, most wetlands are reported as managed with the exception of wetlands in remote areas of Alaska, but emissions from managed wetlands are only reported for coastal regions, flooded lands (e.g., reservoirs) and peatlands where peat extraction occurs due to insufficient activity data to estimate emissions and limited resources to improve the *Inventory*. See the Planned Improvements section of the *Inventory* for future refinements to the wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO_2 fertilization, they are not influenced by a direct human intervention.[15]

In addition, land that is previously managed remains in the managed land base for 20 years before re-classifying the land as unmanaged in order to account for legacy effects of management on carbon stocks.[16] Unmanaged land is also re-classified as managed over time if anthropogenic activity is introduced into the area based on the definition of managed land.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: forest land, cropland, grassland, wetlands, settlements and other land. In order to reflect national circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of forest land is based on the FIA definition of forest,[17] while definitions of cropland, grassland, and settlements are based on the NRI.[18] The definitions for other land and wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 120 feet (36.6 meters) wide and at least one acre (0.4 hectare) in size with at least ten percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 m) at maturity in situ. Forest land includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and non-forest lands, that have at least ten percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 m) wide or an acre (0.4 ha) in size. However, land is not classified as forest land if completely surrounded by urban or developed lands, even if the criteria are consistent with the tree area and cover requirements for forest land. These areas are classified as settlements. In addition, forest land does not include land that is predominantly under an agricultural land use (Nelson et al. 2020).
- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with agroforestry, such as alley cropping and windbreaks,[19] if the dominant use is crop production, assuming the stand or woodlot does not meet the criteria for forest land. Lands in temporary fallow or

[15] There are some areas, such as forest land and grassland in Alaska that are classified as unmanaged land due to the remoteness of their location.

[16] There are examples of managed land transitioning to unmanaged land in the United States. For example, in 2018, 100 hectares of managed grassland converted to unmanaged because data indicated that no further grazing occurred. Livestock data are collected annually by the Department of Agriculture, and no livestock had occurred in the area since the mid-1970s, and therefore there was no longer active management through livestock grazing. The area is also remote, at least 10 miles from roads and settlements, and therefore the land was no longer managed based on the implementation criteria.

17 See https://www.fia.fs.usda.gov/library/field-guides-methods-proc/docs/2022/core_ver9-2_9_2022_SW_HW%20table.pdf, page 23.

[18] See https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[19] Currently, there is no data source to account for biomass carbon stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the cropland land base.

enrolled in conservation reserve programs (i.e., set-asides[20]) are also classified as cropland, as long as these areas do not meet the forest land criteria. Roads through cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from cropland area estimates and are, instead, classified as settlements.

- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Land is also categorized as grassland if there have been three or fewer years of continuous hay production.[21] Savannas, deserts, and tundra are considered grassland. Drained wetlands are considered grassland if the dominant vegetation meets the plant cover criteria for grassland. Woody plant communities of low forbs, shrubs and woodlands, such as sagebrush, mesquite, chaparral, mountain shrubland, and pinyon-juniper, are also classified as grassland if they do not meet the criteria for forest land. Grassland includes land managed with agroforestry practices, such as silvopasture and windbreaks, if the land is principally grass, grass-like plants, forbs, and shrubs suitable for grazing and browsing, and assuming the stand or woodlot does not meet the criteria for forest land. Roads through grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from grassland and are, instead, classified as settlements.
- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year, in addition to lakes, reservoirs, and rivers. In addition, all coastal wetlands are considered managed regardless of whether the water level is changed or if they were created by human activity. Certain areas that fall under the managed wetlands definition are included in other land uses based on the IPCC guidance and national circumstances, including lands that are flooded for most or just part of the year in croplands (e.g., rice cultivation and cranberry production), grasslands (e.g., wet meadows dominated by grass cover) and forest lands (e.g., riparian forests near waterways). See Section 6.8 for more information.
- *Settlements*: A land-use category representing developed areas consisting of units equal to or greater than 0.25 acres (0.1 ha) that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are all tracts that may meet the definition of forest land, and tracts of less than ten acres (4.05 ha) that may meet the definitions for cropland, grassland, or other land but are completely surrounded by urban or built-up land, and so are included in the settlements category. Rural transportation corridors located within other land uses (e.g., forest land, cropland, and grassland) are also included in settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories. Following the guidance provided by the IPCC (2006), carbon stock changes and non-CO_2 emissions are not estimated for other lands because these areas are largely devoid of biomass, litter and soil carbon pools. However, carbon stock changes and non-CO_2 emissions should be estimated for land converted to other land during the first 20 years following conversion to account for legacy effects.

[20] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees, but is still classified as cropland based on national circumstances.

[21] Areas with four or more years of continuous hay production are cropland because the land is typically more intensively managed with cultivation, greater amounts of inputs, and other practices. Occasional harvest of hay from grasslands typically does not involve cultivation or other intensive management practices.

Land Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land Use Data Sources

The three main sources for land use data in the United States are the NRI, FIA, and the NLCD (Table 6-6). These data sources are combined to account for land use in all 50 states. FIA and NRI data are used when available for an area because these surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that are needed to estimate carbon stock changes, N_2O, and CH_4 emissions on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use. Sources of land use data included in the land representation in this *Inventory* are consistent with those included in the previous *Inventory.*

Table 6-6: Data Sources Used to Determine Land Use and Land Area for the Conterminous United States, Hawaii, and Alaska

	NRI	FIA	NLCD
Forest Land			
Conterminous United States			
Non-Federal		•	
Federal		•	
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal		•	
Federal		•	
Croplands, Grasslands, Other Lands, Settlements, and Wetlands			
Conterminous United States			
Non-Federal	•		
Federal			•
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal			•
Federal			•

National Resources Inventory

For the *Inventory*, the NRI is the official source of data for land use and land-use change on non-federal lands in the conterminous United States and Hawaii, and is also used to determine the total land base for the conterminous United States and Hawaii. The NRI is a statistically-based survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the United States Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160 acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land use information (Nusser and Goebel 1997). The NRI survey utilizes data obtained from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for croplands and grasslands (i.e., agricultural lands), and is used as the

basis to account for carbon stock changes in agricultural lands (except federal grasslands). The NRI survey was conducted every five years between 1982 and 1997, but shifted to annualized data collection in 1998. The land use between five-year periods from 1982 and 1997 are assumed to be the same for a five-year time period if the land use is the same at the beginning and end of the five-year period (note: most of the data have the same land use at the beginning and end of the five-year periods). If the land use had changed during a five-year period, then the change is assigned at random to one of the five years. For crop histories, years with missing data are estimated based on the sequence of crops grown during years preceding and succeeding a missing year in the NRI history. This gap-filling approach allows for development of a full time series of land use data for non-federal lands in the conterminous United States and Hawaii. This *Inventory* incorporates data through 2017 from the NRI. The land use patterns are assumed to remain the same from 2018 through 2022 for this *Inventory*, but the time series will be updated when new data are integrated into the land representation analysis.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is the official source of data on forest land area and management data for the *Inventory* and is another statistically-based survey for the United States. The Forest Inventory and Analysis engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for each consecutive phase are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate carbon stock changes for forest land. Historically, FIA inventory surveys have been conducted periodically, with all plots in a state being measured at a frequency of every five to ten years. A new national plot design and annual sampling design was introduced by the FIA program in 1998 and is now used in all states. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every five to seven years in the eastern United States and once every ten years in the western United States. See Annex 3.13 for the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2019 through 2022; see Table A-202 in Annex 3.13).

National Land Cover Dataset

As noted above, while the NRI survey sample covers the conterminous United States and Hawaii, land use data are only collected on non-federal lands. Gaps exist in the land representation when the NRI and FIA datasets are combined, such as federal grasslands operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[22] The NLCD is used to account for land use on federal lands in the conterminous United States and Hawaii, in addition to federal and non-federal lands in Alaska with the exception of forest lands in Alaska.

NLCD products provide land-cover for 1992, 2001, 2004, 2006, 2008, 2011, 2013, 2016, 2019, and 2021 in the conterminous United States (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015, Dewitz, 2023), and also for Alaska in 2001, 2011, and 2016 and Hawaii in 2001. Note that the 2021 NLCD product was not available at the time the land representation was begun for this *Inventory* so it was not included. A NLCD change product is not available for Hawaii because data are only available for one year, i.e., 2001. The NLCD products are based primarily on Landsat Thematic Mapper imagery at a 30-meter resolution, and the land-cover categories have been aggregated into the 36 IPCC land-use categories for the conterminous United States and Alaska, and into the six IPCC land-use categories for Hawaii. The land-use patterns are assumed to remain the same after the last year of

[22] The NRI survey program does not include U.S. Territories with the exception of non-federal lands in Puerto Rico. The FIA program recently began implementing surveys of forest land in U.S. Territories and those data will be used in the years ahead. Furthermore, NLCD does not include coverage for all U.S. Territories.

data in the time series, which is 2001 for Hawaii, 2019 for the conterminous United States and 2016 for Alaska, but the time series will be updated when new data are released.

For the conterminous United States, the aggregated maps of IPCC land-use categories obtained from the NLCD products were used in combination with the NRI database to represent land use and land-use change for federal lands, with the exception of forest lands, which are based on FIA. Specifically, NRI survey locations designated as federal lands were assigned a land use/land-use change category based on the NLCD maps that had been aggregated into the IPCC categories. This analysis addressed shifts in land ownership across years between federal or non-federal classes as represented in the NRI survey (i.e., the ownership is classified for each survey location in the NRI). The sources of these additional data are discussed in subsequent sections of the report.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. The following criteria are used in order to apply the definition in an analysis of managed land:

- All croplands and settlements are designated as managed so only grassland, forest land, wetlands or other lands may be designated as unmanaged land;[23]
- All forest lands with active fire protection are considered managed;
- All forest lands designated for timber harvests are considered managed;
- All grasslands are considered managed at a county scale if there are grazing livestock in the county;
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure;
- Protected lands maintained for recreational and conservation purposes are considered managed (i.e., managed by public and/or private organizations);
- Lands with active and/or past resource extraction are considered managed; and
- Lands that were previously managed but subsequently classified as unmanaged remain in the managed land base for 20 years following the conversion to account for legacy effects of management on carbon stocks.

The analysis of managed lands, based on the criteria listed above, is conducted using a geographic information system (Ogle et al. 2018). Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Forest lands with active fire management are determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all forest lands in the conterminous United States have active fire protection, and are therefore designated as managed regardless of accessibility or other criteria. In addition, forest lands with timber harvests are designated as managed based on county-level estimates of timber products in the U.S. Forest Service Timber Products Output Reports (U.S. Department of Agriculture 2012). Timber harvest data lead to additional designation of managed forest land in Alaska. The designation of grasslands as managed is based on grazing livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2015). Accessibility is evaluated based on a 10-km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10-km buffer surrounding settlements using NLCD.

Lands maintained for recreational purposes are determined from analysis of the Protected Areas Database (U.S. Geological Survey 2012). The Protected Areas Database includes lands protected from conversion of natural habitats to anthropogenic uses and describes the protection status of these lands. Lands are considered managed

[23] All wetlands are considered managed in this *Inventory* with the exception of remote areas in Alaska. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Hawaii is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. Regardless, a planned improvement is underway to subdivide managed and unmanaged wetlands.

that are protected from development if the regulations allow for extractive or recreational uses or suppression of natural disturbance (e.g., forest lands with active fire protection). Lands that are protected from development and not accessible to human intervention, including no suppression of disturbances or extraction of resources, are not included in the managed land base.

Multiple data sources are used to determine lands with active resource extraction: Alaska Oil and Gas Information System (Alaska Oil and Gas Conservation Commission 2009), Alaska Resource Data File (U.S. Geological Survey 2012), Active Mines and Mineral Processing Plants (U.S. Geological Survey 2005), and *Coal Production and Preparation Report* (U.S. Energy Information Administration 2011). A buffer of 3,300 and 4,000 meters is established around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. The buffer size is based on visual analysis of disturbance to the landscape for approximately 130 petroleum extraction sites and 223 mines. After applying the criteria identified above, the resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands in Alaska. The remaining land represents the unmanaged land base. The resulting spatial product is also used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii.[24]

Approach for Combining Data Sources

The managed land base in the United States has been classified into the 36 IPCC land use/land-use conversion categories (Table 6-5) using definitions developed to meet national circumstances, while adhering to IPCC guidelines (2006).[25] In practice, the land was initially classified into land-use subcategories within the NRI, FIA, and NLCD datasets, and then aggregated into the 36 broad land use and land-use change categories identified in IPCC (2006).

All three datasets provide information on forest land areas in the conterminous United States, but the area data from FIA serve as the official dataset for forest land. Therefore, another step in the analysis is to address the inconsistencies in the representation of the forest land among the three databases. NRI and FIA have different criteria for classifying forest land in addition to different sampling designs, leading to discrepancies in the resulting estimates of forest land area on non-federal land in the conterminous United States. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying forest land on federal lands. Any change in forest land area in the NRI and NLCD also requires a corresponding change in other land use areas because of the dependence between the forest land area and the amount of land designated as other land uses, such as the amount of grassland, cropland, and wetlands (i.e., areas for the individual land uses must sum to the total managed land area of the country).

FIA is the main database for forest statistics, and consequently, the NRI and NLCD are adjusted to achieve consistency with FIA estimates of forest land in the conterminous United States. Adjustments are made in the forest land remaining forest land, land converted to forest land, and forest land converted to other uses (i.e., grassland, cropland, settlements, other lands, and wetlands). All adjustments are made at the state scale to address the discrepancies in areas associated with forest land and conversions to and from forest land. There are three steps in this process. The first step involves adjustments to land converted to forest land (grassland, cropland, settlements, other lands, and wetlands), followed by a second step in which there are adjustments in forest land converted to another land use (i.e., grassland, cropland, settlements, other lands, and wetlands), and the last step is to adjust forest land remaining forest land.

In the first step, land converted to forest land in the NRI and NLCD are adjusted to match the state-level estimates in the FIA data for non-federal and federal land converted to forest land, respectively. FIA data have not provided

[24] The exception is cropland and settlement areas in the NRI, which are classified as managed, regardless of the managed land base obtained from the spatial analysis described in this section.

[25] Definitions are provided in the previous section.

specific land-use categories that are converted to forest land in the past, but rather a sum of all land converted to forest land.[26] The NRI and NLCD provide information on specific land-use conversions, such as grassland converted to forest land. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of specific land-use conversions into forest land for the state, prior to any further adjustments. For example, if 50 percent of the land-use change to forest land is associated with grassland converted to forest land in a state according to NRI or NLCD, then half of the discrepancy with FIA data in the area of land converted to forest land is addressed by increasing or decreasing the area in grassland converted to forest land. Moreover, any increase or decrease in grassland converted to forest land in NRI or NLCD is addressed by a corresponding change in the area of grassland remaining grassland, so that the total amount of managed area is not changed within an individual state. Since the sum of all land converted to forest land is used to adjust specific land-use conversions into forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where specific land-use conversions into forest land do not exist in the FIA data.

In the second step, state-level areas are adjusted in the NRI and NLCD to address discrepancies with FIA data for forest land converted to other uses. Similar to land converted to forest land, FIA have not provided information on the specific land-use changes in the past,[27] so areas associated with forest land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount of area in each conversion class in these datasets. Since the sum of all forest land converted to other uses is used to adjust specific land-used conversions out of forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where a specific land-use conversion out of forest land does not exist in the FIA data.

In the final step, the area of forest land remaining forest land in each state according to the NRI and NLCD is adjusted to match the FIA estimates for non-federal and federal land, respectively. It is assumed that the majority of the discrepancy in forest land remaining forest land is associated with less-precise estimates of grassland remaining grassland and wetlands remaining wetlands in the NRI and NLCD. This step also assumes that there are no changes in the land-use conversion categories. Therefore, corresponding adjustments are made in the area estimates of grassland remaining grassland and wetlands remaining wetlands from the NRI and NLCD. This adjustment balances the change in forest land remaining forest land area, which ensures no change in the overall amount of managed land within an individual state. The adjustments are based on the proportion of land within each of these land-use categories at the state level according to NRI and NLCD (i.e., a higher proportion of grassland led to a larger adjustment in grassland area).

The modified NRI data are then aggregated to provide the land use and land-use change data for non-federal lands in the conterminous United States, and the modified NLCD data are aggregated to provide the land use and land-use change data for federal lands. Data for all land uses in Hawaii are based on NRI for non-federal lands and on NLCD for federal lands. Land use data in Alaska are based on the NLCD data after adjusting this dataset to be consistent with forest land areas in the FIA (Table 6-6). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Land representation for both non-federal and federal forest lands in the conterminous United States and Alaska are based on the FIA. The FIA is used as the basis for both forest land area data as well as to estimate carbon stocks and fluxes on forest land in the conterminous United States and Alaska. The FIA does have survey plots in Alaska that are used to determine the carbon stock changes, and the associated area data for this region are harmonized with NLCD using the methods described above. NRI is used in the current report to provide forest land areas on non-federal lands in Hawaii, and NLCD is

[26] The FIA program has started to collect data on the specific land uses that are converted to forest land, which will be further investigated and incorporated into a future *Inventory*.

[27] The FIA program has started to collect data on the specific land uses following conversion from forest land, which will be further investigated and incorporated into a future *Inventory*.

used for federal lands. In Hawaii and the U.S. Territories, FIA data are being collected; these data were used to compile area estimates and emissions and removals for forest land in this *Inventory*.

- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. The NRI is used as the basis for both cropland area data as well as to estimate soil carbon stocks and fluxes on cropland. The NLCD is used to determine cropland area and soil carbon stock changes on federal lands in the conterminous United States and Hawaii. The NLCD is also used to determine croplands in Alaska, but carbon stock changes are not estimated for this region in the current *Inventory*.
- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. The NRI is used as the basis for both grassland area data as well as to estimate soil carbon stocks and non-CO_2 greenhouse emissions on grassland. Grassland area and soil carbon stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. The NLCD is also used to estimate the areas of federal and non-federal grasslands in Alaska, and the federal grasslands in Hawaii, but the current *Inventory* does not include carbon stock changes in these areas.
- *Wetlands*: The NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while the land representation data for federal wetlands and wetlands in Alaska are based on the NLCD.[28]
- *Settlements*: The NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of forest land or grassland under ten acres (4.05 ha) are contained within settlements or urban areas, they are classified as settlements (urban) in the NRI database. If these parcels exceed the ten-acre (4.05 ha) threshold and are grassland, they are classified as grassland by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Land representation for settlements on federal lands and Alaska is based on the NLCD.
- *Other Land*: Any land that is not classified into one of the previous five land-use categories is categorized as other land using the NRI for non-federal areas in the conterminous United States and Hawaii and using the NLCD for the federal lands in all regions of the United States and for non-federal lands in Alaska.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is from highest to lowest priority based on the following order:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure, and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as grassland, forest land, wetlands, and cropland, respectively, but when located in close proximity to settlement areas, they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage, or fiber. The consequence of this ranking is that crops in rotation with pasture are classified as cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as cropland, even though these areas may also meet the definitions of grassland or forest land, respectively. Similarly, wetlands are considered croplands if they are used for crop production, such as rice or cranberries. Forest land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards)

[28] This analysis does not distinguish between managed and unmanaged wetlands except for remote areas in Alaska, but there is a planned improvement to subdivide managed and unmanaged wetlands for the entire land base.

or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while wetlands and then other land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a discrete land-use category. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a wetland is classified as forest land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, wetlands are classified as cropland if they are used for crop production, such as rice, or as grassland if they are composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing. Regardless of the classification, emissions and removals from these areas should be included in the *Inventory* if the land is considered managed, and therefore impacted by anthropogenic activity in accordance with the guidance provided by the IPCC (2006).

QA/QC and Verification

The land base obtained from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) Survey (U.S. Census Bureau 2010). The United States Census Bureau gathers data on the population and economy and has a database of land areas for the country. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are obtained from remote sensing data instead of the land survey approach used by the United States Census Survey. The Census does not provide a time series of land-use change data or land management information, which is needed for estimating greenhouse gas emissions from land use and land-use change. Regardless, the Census does provide sufficient information to provide a quality assurance check on the *Inventory* data. There are 46 million more hectares of land in the United States according to the Census, compared to the total area estimate of 936 million hectares obtained from the combined NRI, FIA, and NLCD data, a 4.8 percent difference. Much of this difference is associated with open water in coastal regions and the Great Lakes, which is included in the TIGER Survey of the Census, but not included in the land representation using the NRI, FIA and NLCD. There is only a 0.4 percent difference when open water in coastal regions is removed from the TIGER data. General QC procedures for data gathering and data documentation also were applied consistent with the QA/QC and Verification Procedures described in Annex 8.

Recalculations Discussion

The land representation estimates were recalculated from the previous *Inventory* with the following datasets: a) updated FIA data from 1990 to 2022 for the conterminous United States and Alaska, b) NRI data from 1990 to 2017 for the conterminous United States and Hawaii, and c) NLCD data for the conterminous United States from 2001 through 2019 and Alaska from 2001 through 2016. There were several changes in methods that resulted in small changes between this *Inventory* and the previous *Inventory*. First, pasture land was previously classified as cropland in the compilation of forest land conversion estimates using FIA data and is now classified as grassland to align with methods and definitions used to classify grasslands using NRI data. This led to a decrease in total managed cropland area and an increase in grassland area. Second, FIA data are now used to classify forest land and conversions to and from forest land in coastal southeast and southcentral Alaska which resulted in minor changes, primarily between forest land, wetlands, and grasslands, between this *Inventory* and the previous *Inventory*. Lastly, methods for classifying wetlands using FIA data were refined so that all water bodies are now classified as wetlands (previously some water bodies were classified as other lands) aligning with methods and definitions in the NRI. Collectively, these refinements in FIA methods to better align with methods for the other data sources (i.e., NRI and NLCD) resulted in changes throughout the entire representation of land (see "Approach for Combining Data Sources"). Specifically, managed wetland area decreased, on average over the time series, by 1.2 percent. Grassland and forest land increased by 0.1 percent and 0.04 percent, respectively. Settlement area decreased by 0.05 percent and cropland and managed other lands were essentially unchanged in the latest *Inventory*.

Planned Improvements

Research is underway to harmonize NRI and FIA sampling frames to improve consistency and facilitate estimation using multi-frame sampling. This includes development of a common land use classification schema between the two land inventories that can be used in the harmonization process. These steps will allow for population estimation exclusive of auxiliary information (e.g., NLCD). The multi-frame sample will also serve as reference data for the development of spatially explicit and spatially continuous map products for each year in the *Inventory* time series. Another key planned improvement for the *Inventory* is to fully incorporate area data by land-use type for U.S. Territories. Although most of the managed land in the United States is included in the current land use data for the conterminous United States, Alaska, and Hawaii, a complete reporting of all lands in the United States, including U.S. Territories, is a key goal for the near future. An initial assessment of data sources for land use area data for U.S. Territories by land-use category are provided in Box 6-2. In addition, this *Inventory* includes forest land areas estimated for American Samoa, Guam, Hawaii, Northern Marianas Islands, U.S. Virgin Islands, and Puerto Rico using periodic inventories from the FIA program. These estimates are included in the forest land category, and the methods for compiling these area estimates and the associated carbon stocks and fluxes and integration of these estimates into the land representation will be refined to compensate for data limitations in the time series while also taking advantage of new data and data products. See Box 6-2.

Box 6-2: Preliminary Estimates of Land Use in U.S. Territories

Several programs have developed land-cover maps for U.S. Territories using remote sensing imagery, including the Gap Analysis Program, Caribbean Land Cover project, National Land Cover Dataset (NLCD), USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). Land-cover data can be used to inform a land use classification if there is a time series to evaluate the dominant practices. For example, land that is principally used for timber production with tree cover over most of the time series is classified as forest land even if there are a few years of grass dominance following timber harvest. These products were reviewed and evaluated for use in the national *Inventory* as a step towards implementing a planned improvement to include U.S. Territories in the land representation for the *Inventory*. Recommendations are to use the NOAA C-CAP Regional Land Cover Database for the smaller island Territories (U.S. Virgin Islands, Guam, Northern Marianas Islands, and American Samoa) because this program is ongoing and therefore will be continually updated. The C-CAP product does not cover the entire territory of Puerto Rico, so the NLCD was used for this area. Results are presented below (in hectares). The total land area of all U.S. Territories is 1.05 million hectares, representing 0.1 percent of the total land base for the United States (see Table 6-7).

Table 6-7: Total Land Area (Hectares) by Land Use Category for U.S. Territories

	Puerto Rico	U.S. Virgin Islands	Guam	Northern Marianas Islands	American Samoa	Total
Cropland	19,712	138	236	289	389	20,764
Forest Land	404,004	13,107	24,650	25,761	15,440	482,962
Grasslands	299,714	12,148	15,449	13,636	1,830	342,777
Other Land	5,502	1,006	1,141	5,186	298	13,133
Settlements	130,330	7,650	11,146	3,637	1,734	154,496
Wetlands	24,525	4,748	1,633	260	87	31,252
Total	**883,788**	**38,796**	**54,255**	**48,769**	**19,777**	**1,045,385**

Note: Totals may not sum due to independent rounding.

Methods in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) have been applied to estimate emissions and removals from coastal wetlands. Specifically, greenhouse gas emissions from coastal wetlands have been developed for the *Inventory* using the NOAA C-CAP land-cover product. The NOAA C-CAP product is not used directly in the land representation analysis, however, so a planned improvement for future Inventories is to reconcile the coastal wetlands data from the C-CAP product with the wetlands area data provided in the NRI, FIA and NLCD. Estimates from flooded lands are also included in this *Inventory*, but data are not directly used in the land representation analysis at this time; this is a planned improvement to include for future inventories. In addition, the current *Inventory* does not include a classification of managed and unmanaged wetlands, except for remote areas in Alaska. Consequently, there is a planned improvement to classify managed and unmanaged wetlands for the conterminous United States and Hawaii, and more detailed wetlands datasets will be evaluated and integrated into the analysis to meet this objective.

6.2 Forest Land Remaining Forest Land (CRT Category 4A1)

Changes in Forest Carbon Stocks (CRT Category 4A1)

Delineation of Carbon Pools

For estimating carbon stocks or stock change (flux), carbon in forest ecosystems can be divided into the following five storage pools (IPCC 2006):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 millimeters (mm) diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes all duff, humus, and fine woody debris above the mineral soil as well as woody fragments with diameters of up to 7.5 cm.
- Soil organic carbon (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools. Organic (e.g., peat and muck) soils have a minimum of 12 to 20 percent organic matter by mass and develop under poorly drained conditions of wetlands. All other soils are classified as mineral soil types and typically have relatively low amounts of organic matter.

In addition, there are two harvested wood pools included when estimating carbon flux:

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

Forest Carbon Cycle

Carbon is continuously cycled among the previously defined carbon storage pools and the atmosphere as a result of biogeochemical processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and grow, carbon is removed from the atmosphere and stored in living tree biomass. As trees die

and otherwise deposit litter and debris on the forest floor, carbon is released to the atmosphere and is also transferred to the litter, dead wood, and soil pools by organisms that facilitate decomposition.

The net change in forest carbon is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of all harvested biomass carbon to the atmosphere. Instead, harvesting transfers a portion of the carbon stored in wood to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 in the case of decomposition and as CO_2, CH_4, N_2O, CO, and NO_x when the wood product combusts. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases carbon immediately, and these emissions are reported for information purposes in the Energy sector while the harvest (i.e., the associated reduction in forest carbon stocks) and subsequent combustion are implicitly estimated in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the portion of harvested timber combusted to produce energy does not enter the HWP pools). Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and carbon is released to the atmosphere. If wood products are disposed of in SWDS, the carbon contained in the wood may be released many years or decades later or may be stored almost permanently in the SWDS. These latter fluxes, with the exception of CH_4 from wood in SWDS, which is included in the Waste sector, are also estimated in the LULUCF sector.

Net Change in Carbon Stocks within Forest Land of the United States

This section describes the general method for quantifying the net changes in carbon stocks in the five carbon storage pools and two harvested wood pools (a more detailed description of the methods and data is provided in Annex 3.13). The underlying methodology for determining carbon stock and stock change relies on data from the national forest inventory (NFI) conducted by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service. The annual NFI is implemented across all U.S. forest lands within the conterminous 48 states, Alaska, Puerto Rico, and the U.S. Virgin Islands, and periodic inventories are available for Hawaii and some of the other U.S. Territories. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the carbon estimates (Domke et al. 2022; Westfall et al. 2023). First, in the conterminous 48 states and coastal southeast and southcentral Alaska, the total carbon stocks are estimated for each carbon storage pool at the individual NFI plot, next the annual net changes in carbon stocks for each pool at the population level are estimated, and then the changes in stocks are summed for all pools to estimate total net flux at the population level (e.g., U.S. state). Changes in carbon stocks from disturbances, such natural disturbances (e.g., wildfires, insects/disease, wind) or harvesting, are included in the net changes (see Box 6-3 for more information). For instance, an inventory conducted after a fire implicitly includes only the carbon stocks remaining on the NFI plot. The IPCC (2006) recommends estimating changes in carbon stocks from forest lands according to several land-use types and conversions, specifically forest land remaining forest land and land converted to forest land, with the former being lands that have been forest lands for 20 years or longer and the latter being lands (i.e., croplands, grassland, wetlands, settlements and other lands) that have been converted to forest lands for less than 20 years.

The methods and data used to delineate forest carbon stock changes by these two categories continue to improve and in order to facilitate this delineation, a combination of estimation approaches was used to compile estimates in this *Inventory*. Methods for compiling carbon stocks and stock changes on forest land in interior Alaska are different from those used for estimation in the conterminous U.S. and coastal Alaska due to the recency of the operational FIA inventory in that region and differences in sampling protocols (see Annex 3.13 for more details). Finally, estimates of carbon stocks and stock changes on forest land in Hawaii and the U.S. Territories of American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands (hereafter referred to as the U.S. Territories) are included for the first time in this *Inventory*. The FIA program has conducted annual inventories in parts of Puerto Rico (Mainland, Vieques, Culebra) and the U.S. Virgin Islands and periodic inventories in Hawaii, American Samoa, Guam, Northern Mariana Islands, and Puerto Rico (Mona Island). These inventories in combination with published estimates of carbon stocks, stock changes, and IPCC (2019) default estimates were used to compile estimates of carbon stocks and stock changes on forest land for these regions (see Annex 3.13 for more details).

Forest Area in the United States

Approximately 32 percent of the managed U.S. land area is estimated to be forested based on the U.S. definition of forest land as provided in Section 6.1. All annual and periodic NFI plots included in the public FIA database as of September 2023 (which includes data collected through 2022 – note that the COVID 19 pandemic resulted in delays in data collection in many states) were used in this *Inventory*. The NFIs from the conterminous United States (USDA Forest Service 2023a, 2023b), Alaska, Hawaii, and the U.S. Territories comprise an estimated 282 million hectares of forest land that are considered managed and are included in the current *Inventory*. Some differences also exist in forest land area estimates from the latest update to the Resources Planning Act (RPA) Assessment (Oswalt et al. 2019) and the forest land area estimates included in this report, which are based on the annual and periodic NFI data through 2022 for all states (USDA Forest Service 2023b; Nelson et al. 2020). The methods for compiling area estimates for Hawaii and the U.S. Territories in this section are different from those in Section 6.1 because they do not rely on FIA data. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation (see Annex 3.13). This prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. Agroforestry systems that meet the definition of forest land are also not currently included in the current *Inventory* since they are not explicitly inventoried (i.e., classified as an agroforestry system) by either the FIA program or the Natural Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 67 percent (208 million hectares) of U.S. forests in Alaska, Hawaii and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Approximately ten percent of Alaska forest land and 73 percent of forest land in the conterminous United States are classified as timberland. Of the remaining non-timberland in the conterminous United States, Alaska, and Hawaii, nearly 33 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 102 million hectares are lower productivity forest lands (Oswalt et al. 2019). Historically, the timberlands in the conterminous United States have been more frequently or intensively surveyed than the forest lands removed from production because they do not meet the minimum level of productivity.

Since the late 1980s, gross forest land area in Alaska, Hawaii, and the conterminous United States has increased by about 13 million hectares (Oswalt et al. 2019). The southern region of the United States contains the most forest land (Figure 6-4). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Estimated forest land area in the conterminous United States and Alaska represented in this *Inventory* is stable, but there are substantial conversions as described in 6.1 and each of the land conversion sections for each land-use category (e.g., land converted to cropland, land converted to grassland). The major influences on the net carbon flux from forest land across the 1990 to 2022 time series are management activities, natural disturbance, particularly wildfire, and the ongoing impacts of current and previous land-use conversions. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems and also the area converted to forest land. For example, intensified management of forests that leads to an increased rate of growth of aboveground biomass (and possible changes to the other carbon storage pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of carbon in the aboveground biomass pool.[29] Though harvesting forests removes much of the carbon in aboveground biomass (and possibly changes carbon density in other pools), on average, the estimated volume of annual net growth in aboveground tree biomass in the conterminous United States is essentially twice the volume of annual removals on timberlands (Oswalt et al. 2019). The net effects of forest management and changes in forest land remaining forest land are captured in the estimates of carbon stocks and fluxes presented in this section.

[29] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Species-specific carbon fractions are used to convert dry biomass to carbon (Westfall et al. 2023).

Figure 6-4: Changes in Forest Area by Region for Forest Land Remaining Forest Land in the conterminous United States and Alaska (1990-2022)

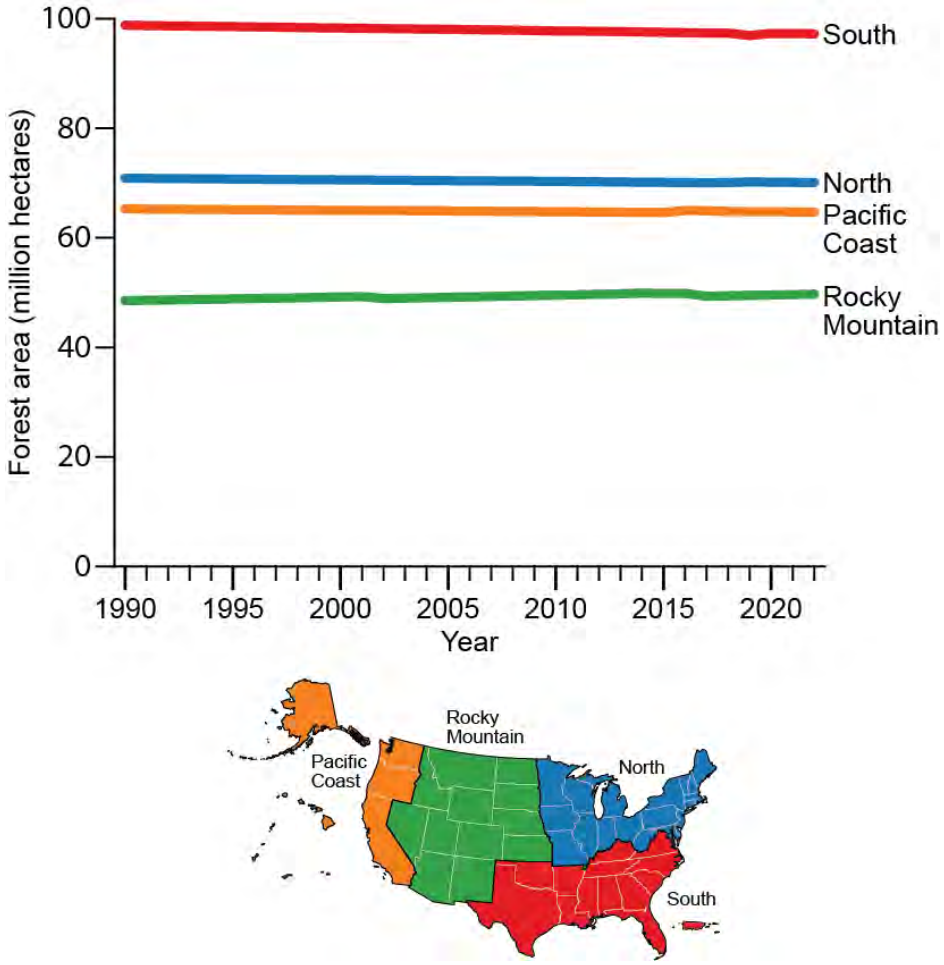

Forest Carbon Stocks and Stock Change

In the forest land remaining forest land category, forest management practices, the regeneration of forest areas cleared more than 20 years prior to the reporting year, and timber harvesting have resulted in net removal (i.e., net sequestration or accumulation) of carbon each year from 1990 through 2022. The rate of forest clearing in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century, many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence carbon fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests and natural disturbance have also affected net carbon fluxes. Because most of the timber harvested from U.S. forest land is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, substantial quantities of carbon in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). By maintaining current harvesting practices and regeneration activities on forest lands, along with continued input of harvested wood into the HWP pool, carbon stocks in the forest land remaining forest land category are likely to continue to increase in the near term, though

possibly at a slower rate. Changes in carbon stocks in the forest ecosystem and harvested wood pools associated with forest land remaining forest land were estimated to result in net removal of 787.0 MMT CO_2 Eq. (214.6 MMT carbon) in 2022 (Table 6-8, Table 6-9, Table A-203, Table A-204 and state-level estimates in Table A-207). The estimated net uptake of carbon in the Forest Ecosystem was 694.3 MMT CO_2 Eq. (189.3 MMT carbon) in 2022 (Table 6-8 and Table 6-9). The majority of this uptake in 2022, 491.7 MMT CO_2 Eq. (134.1 MMT carbon), was from aboveground biomass. Overall, estimates of average carbon density in forest ecosystems (including all pools) increased consistently over the time series with an average of approximately 208 MT carbon ha^{-1} from 1990 to 2022. This was calculated by dividing the forest ecosystem carbon stock estimates by the forest land area estimates for every year (see Table 6-10 and Table A-206) and then calculating the mean across the entire time series, i.e., 1990 through 2022. The increasing forest ecosystem carbon density, when combined with relatively stable forest area, results in net carbon accumulation over time. However, due to an aging forest land base, increases in the frequency and severity of disturbances in forests in some regions, among other drivers of change, forest carbon density is increasing at a slower rate resulting in an overall decline in the sink strength of forest land remaining forest land in the United States. Aboveground live biomass is responsible for the majority of net carbon uptake among all forest ecosystem pools (Figure 6-5). These increases may be influenced in some regions by reductions in carbon density or forest land area due to natural disturbances (e.g., wildfire, weather, insects/disease), particularly in Alaska. The inclusion of all managed forest land in Alaska has increased the interannual variability in carbon stock change estimates over the time series, and much of this variability can be attributed to severe fire years (e.g., 2022). The distribution of carbon in forest ecosystems in Alaska is substantially different from forests in the conterminous United States. In Alaska, more than nine percent of forest ecosystem carbon is stored in the litter carbon pool whereas in the conterminous United States, less than seven percent of the total ecosystem carbon stocks are in the litter pool. Much of the litter material in forest ecosystems is combusted during fire (IPCC 2006) leading to substantial carbon losses in this pool during severe fire years (Figure 6-5, Table A-206).

The estimated net accumulation of carbon in the HWP pool, i.e., the balance of additions from the transfer of harvested wood from the forest ecosystem and losses from the current decay of wood harvested in the past, was 92.8 MMT CO_2 Eq. (25.3 MMT carbon) in 2022 (Table 6-8, Table 6-9, Table A-203, and Table A-204). The majority of this uptake, 63.9 MMT CO_2 Eq. (17.4 MMT carbon), was from solid wood and paper in SWDS. Products in use accounted for an estimated 28.8 MMT CO_2 Eq. (7.9 MMT carbon) in 2022.

Table 6-8: Net CO_2 Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Forest Ecosystem	**(851.0)**	**(770.0)**	**(779.6)**	**(726.2)**	**(765.2)**	**(749.5)**	**(694.3)**
Aboveground Biomass	(600.9)	(550.8)	(536.7)	(516.3)	(522.8)	(513.0)	(491.7)
Belowground Biomass	(116.8)	(107.5)	(105.4)	(102.3)	(102.2)	(100.9)	(96.9)
Dead Wood	(132.0)	(131.2)	(138.0)	(133.4)	(136.2)	(135.3)	(131.4)
Litter	(2.4)	20.5	(1.5)	26.5	(3.4)	(0.1)	26.4
Soil (Mineral)	2.0	(0.8)	1.3	(1.3)	(1.3)	(0.9)	(1.2)
Soil (Organic)	(1.6)	(1.0)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(106.0)**	**(93.9)**	**(86.9)**	**(96.8)**	**(94.7)**	**(92.8)**
Products in Use	(54.8)	(42.6)	(28.8)	(22.6)	(32.3)	(30.4)	(28.8)
SWDS	(69.0)	(63.4)	(65.1)	(64.3)	(64.5)	(64.3)	(63.9)
Total Net Flux	**(974.8)**	**(876.0)**	**(873.5)**	**(813.2)**	**(862.0)**	**(844.2)**	**(787.0)**

[a] These estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land. See the section below on CO_2, CH_4, and N_2O emissions from drained organic soils for the methodology used to estimate the CO_2 emissions from drained organic soils. Also, Table 6-28 and Table 6-29 for non-CO_2 emissions from drainage of organic soils from both forest land remaining forest land and land converted to forest land.

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1. This results in small differences (less than 0.5 million hectares) in the forest land area estimates in this section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-206 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in interior Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Harvested wood estimates are based on results from annual surveys (see Annex 3.13, Table A-199) and models. Totals may not sum due to independent rounding.

Table 6-9: Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Forest Ecosystem	**(232.1)**	**(210.0)**	**(212.6)**	**(198.1)**	**(208.7)**	**(204.4)**	**(189.3)**
Aboveground Biomass	(163.9)	(150.2)	(146.4)	(140.8)	(142.6)	(139.9)	(134.1)
Belowground Biomass	(31.9)	(29.3)	(28.8)	(27.9)	(27.9)	(27.5)	(26.4)
Dead Wood	(36.0)	(35.8)	(37.6)	(36.4)	(37.1)	(36.9)	(35.8)
Litter	(0.7)	5.6	(0.4)	7.2	(0.9)	(0.0)	7.2
Soil (Mineral)	0.5	(0.2)	0.4	(0.4)	(0.3)	(0.2)	(0.3)
Soil (Organic)	(0.4)	(0.3)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(28.9)**	**(25.6)**	**(23.7)**	**(26.4)**	**(25.8)**	**(25.3)**
Products in Use	(14.9)	(11.6)	(7.8)	(6.2)	(8.8)	(8.3)	(7.9)
SWDS	(18.8)	(17.3)	(17.8)	(17.5)	(17.6)	(17.5)	(17.4)
Total Net Flux	**(265.8)**	**(238.9)**	**(238.2)**	**(221.8)**	**(235.1)**	**(230.2)**	**(214.6)**

[a] These estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the carbon flux from drained organic soils. Also, see Table 6-28 and Table 6-29 for greenhouse gas emissions from non-CO_2 gases changes from drainage of organic soils from forest land remaining forest land and land converted to forest land.

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1 so there are small differences in the forest land area estimates in this Section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1). See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest ecosystem and harvested wood carbon storage pools are presented in Table 6-10. Together, the estimated aboveground biomass and soil carbon pools account for a large proportion of total forest ecosystem carbon stocks. Forest land area estimates are also provided in Table 6-10, but these do not precisely match those in Section 6.1 for forest land remaining forest land. This is because the forest land area estimates in Table 6-10 include estimates of managed forest land in Hawaii and the U.S. Territories compiled using FIA estimates in this section while the area estimates for managed forest land in Hawaii and the U.S. Territories in Section 6.1 were compiled using different methods. Differences also exist because forest land area estimates are based on the latest NFI data through 2022, and woodland areas previously included as forest land have been separated and included in the grassland categories in this *Inventory*.[30]

Table 6-10: Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	1990	2005	2019	2020	2021	2022	2023
Forest Area (1,000 ha)	***283,500***	***282,521***	***281,137***	***281,779***	***281,780***	***281,752***	***281,725***
Carbon Pools (MMT C)							
Forest Ecosystem	**55,142**	**58,536**	**61,519**	**61,717**	**61,926**	**62,130**	**62,320**
Aboveground Biomass	12,739	15,122	17,199	17,340	17,483	17,622	17,757
Belowground Biomass	2,255	2,718	3,124	3,151	3,179	3,207	3,233
Dead Wood	1,977	2,521	3,038	3,074	3,111	3,148	3,184
Litter	3,789	3,794	3,775	3,767	3,768	3,768	3,761
Soil (Mineral)	28,407	28,401	28,400	28,400	28,401	28,401	28,401
Soil (Organic)	5,976	5,981	5,983	5,983	5,983	5,983	5,983
Harvested Wood	**1,895**	**2,353**	**2,671**	**2,694**	**2,721**	**2,747**	**2,772**
Products in Use	1,249	1,447	1,523	1,530	1,538	1,547	1,555
SWDS	646	906	1,147	1,165	1,182	1,200	1,217
Total C Stock	**57,037**	**60,890**	**64,189**	**64,411**	**64,647**	**64,877**	**65,092**

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1 so there are small differences in the forest land area estimates in this section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base (CRT Category 4.1). See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stocks do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Harvested wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Population estimates compiled using FIA data are assumed to represent stocks as of January 1 of the inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2022 requires estimates of carbon stocks for 2022 and 2023.

[30] See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

Figure 6-5: Estimated Net Annual Changes in Carbon Stocks for All Carbon Pools in Forest Land Remaining Forest Land in the Conterminous United States and Alaska (1990-2022)

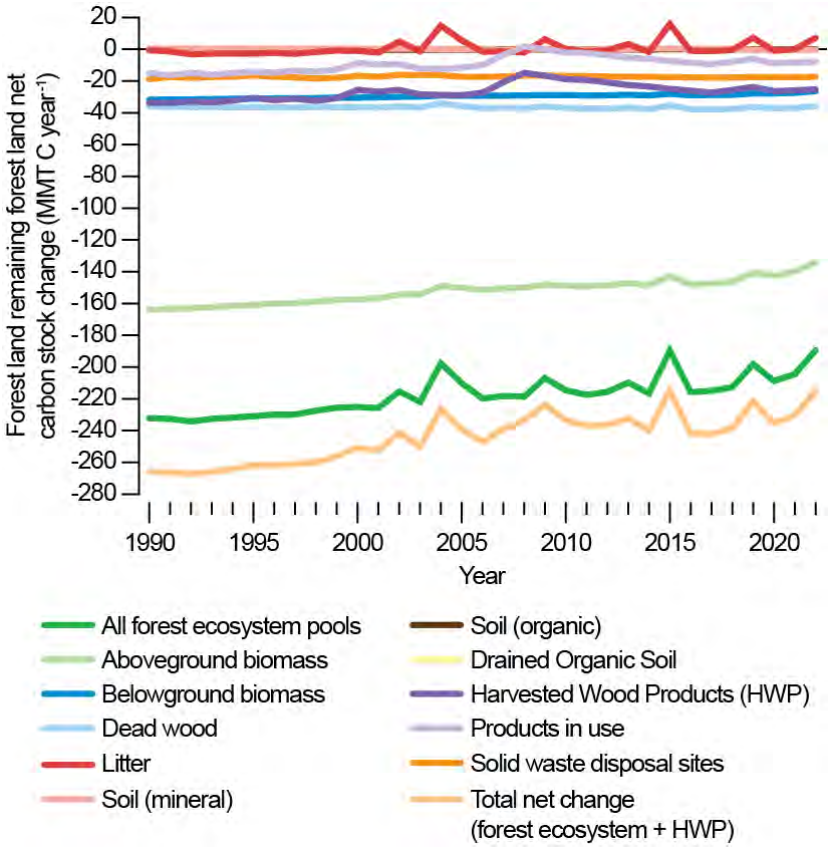

Box 6-3: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly includes all carbon losses due to disturbances such as forest fires, because only carbon remaining in the forest is estimated. Net carbon stock change is estimated by subtracting consecutive carbon stock estimates. A forest fire disturbance removes carbon from the forest. The inventory data from the NFI on which net carbon stock estimates are based already reflect this carbon loss. Therefore, estimates of net annual changes in carbon stocks for U.S. forest land already includes CO_2 emissions from forest fires occurring in the conterminous states (48 states), Hawaii, Puerto Rico, and Guam as well as the portion of managed forest lands in Alaska. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these separate estimates are highlighted here. Note that these CO_2 estimates are based on the same methodology as applied for the non-CO_2 greenhouse gas emissions from forest fires that are also quantified in a separate section below as required by IPCC Guidance and the UNFCCC.

Emissions estimates are developed using IPCC (2019) methodology and based on U.S.-specific data and models to quantify the primary fire-specific components: area burned; availability and combustibility of fuel; fire severity (or consumption); and CO_2 and non-CO_2 emissions. Estimated CO_2 emissions for fires on forest lands in the United States for 2022 are 129.2 MMT CO_2 per year (Table 6-11). This estimate is an embedded component of the net annual forest carbon stock change estimates provided previously (i.e., Table 6-9), but this separate approach to estimating CO_2 emissions is necessary in order to associate these emissions with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that in Alaska, a portion of the forest lands are considered unmanaged, therefore the estimates for Alaska provided in Table 6-11 include only managed forest land within the state, which is consistent with carbon stock change estimates provided above.

Table 6-11: Estimates of CO_2 (MMT per Year) Emissions[a] from Forest Fires in the Conterminous 48 States, Hawaii, Puerto Rico, Guam, and Alaska

	1990	2005	2018	2019	2020	2021	2022
CO_2 emitted from fires on forest land in the Conterminous 48 States, Hawaii, Puerto Rico, and Guam (MMT yr^{-1})	11.9	28.6	77.5	19.1	124.0	156.7	71.8
CO_2 emitted from fires on managed forest land in Alaska (MM Tyr^{-1})	43.2	113.5	7.1	34	0.4	6.8	57.4
Total CO_2 emitted (MMTyr^{-1})	**55.1**	**142.2**	**84.6**	**53**	**124.4**	**163.5**	**129.2**

[a] These emissions have already been included in the estimates of net annual changes in carbon stocks, which include the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodology described herein is consistent with the *2006 IPCC Guidelines for National Inventories*. Forest ecosystem carbon stocks and net annual carbon stock change were determined according to the stock-difference method for the conterminous United States and coastal southeast and southcentral Alaska, which involved applying carbon estimation factors to annual forest inventories across time to obtain carbon stocks and then subtracting between the years to obtain the stock change. The gain-loss method was used to estimate carbon stocks and net annual carbon stock changes in interior Alaska, Hawaii, and the U.S. Territories. The approaches for estimating carbon stocks and stock changes on forest land remaining forest land are described in Annex 3.13. All annual and periodic NFI plots available in the public FIA database (USDA Forest Service 2023b) were used in the current *Inventory*. Additionally, NFI plots established and measured in 2014 as part of a pilot inventory in interior Alaska were also included in this *Inventory* as were plots established and measured since 2015 as part of the operational NFI in interior Alaska. Some of the data from the pilot and operational NFI in interior Alaska are not yet available in the public FIA database. Only plots which meet the definition of forest land (see Section 6.1) are measured in the NFI; as part of the pre-field process in the FIA program, all plots or portions of plots (i.e., conditions) are classified into a land-use category. This land use information on each forest and non-forest plot was used to estimate forest land area and land converted to and from forest land over the time series. The estimates in this section of the report are based on land use information from the NFI and they may differ from the other land-use categories where area estimates reported in the Land Representation were not updated (see Section 6.1). Further, managed forest land area estimates for Hawaii and the U.S. Territories were compiled using FIA data in this section which is different from how estimates for these lands were compiled in Section 6.1 (see Annex 3.13 for details on differences).

To implement the stock-difference approach, forest land conditions in the conterminous United States and coastal Alaska were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 to t_1 was then projected to 2022. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class to obtain population estimates for the nation. In cases where there are t_1 estimates in the last year (e.g., 2022) of the NFI no projections are necessary for those plots.

To implement the gain-loss approach in interior Alaska, forest land conditions in Alaska were observed on NFI plots from 2014 to 2022. Plot-level data from the NFI were harmonized with auxiliary data describing climate, forest structure, disturbance, and other site-specific conditions to develop non-parametric models to predict carbon stocks by forest ecosystem carbon pool as well as fluxes over the entire inventory period, 1990 to 2022. First, carbon stocks for each forest ecosystem carbon pool were predicted for the year 2016 for all NFI plot locations

(each plot representing 12,015 ha). Next, the chronosequence of sampled NFI plots and auxiliary information (e.g., climate, forest structure, disturbance, and other site-specific data) were used to predict annual gains and losses for each forest ecosystem carbon pool. The annual gains and losses were then combined with the stock estimates and disturbance information to compile plot- and population-level carbon stocks and fluxes for each year from 1990 to 2022.

To implement the gain-loss approach in Hawaii and the U.S. Territories, a combination of Tier 1 and Tier 2 methods were applied. All forest land conditions were observed on annual and periodic NFI plots from 2001 to 2019 (see Annex 3.13 for specific inventories included for each Island). Plot-level data from the NFI were harmonized with data describing ecological zone (FAO 2010), soil attributes (Johnson and Kern 2003; Deenik and McClellan, 2007, IPCC 2019), and dead wood and litter carbon stocks (Oswalt et al. 2008; IPCC 2019). Only estimates of carbon stocks in live trees were consistently available in the NFI for Hawaii and the U.S. Territories for each inventory. These estimates were used to obtain average annual carbon stock change estimates for above and belowground live trees which were applied to each forest plot to capture growth, harvest removals, and mortality. The carbon stocks and annual stock change estimates were compared with country-specific estimates (Oswalt et al. 2008; Selmants et al. 2017), and IPCC (2019) default estimates to ensure they were consistent with other sources. There were limited data available on disturbances and management activities on NFI plots over the times series so Tier 1 methods were applied for dead wood and litter. It was assumed that the average transfer rate into dead wood and litter pools is equivalent to the average transfer rate out of the dead organic matter pool so there are no net carbon stock changes included for these pools in the time series (IPCC 2006). Similarly, given data limitations on forest soils and changes on NFI plots over the time series, a Tier 1 approach was also used for soil carbon with country-specific estimates (Johnson and Kern 2003) and IPCC (2019) defaults used to estimate soil carbon stocks with no net carbon stock change reported.

To estimate carbon stock changes in harvested wood, estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the carbon in forest ecosystems within the conterminous United States and Alaska and harvested wood products for all of the United States is provided below. See Annex 3.13 for details and additional information related to the methods and data.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

Forest Ecosystem Carbon from Forest Inventory

The United States applied the compilation approach described in Woodall et al. (2015a) for the current *Inventory* which removes the older periodic inventory data, which may be inconsistent with annual inventory data, from the estimation procedures. This approach enables the attribution of forest carbon accumulation by forest growth, land-use change, and natural disturbances such as fire. Development will continue on a system that attributes changes in forest carbon to disturbances and delineates land converted to forest land from forest land remaining forest land. As part of this development, carbon pool science will continue and will be expanded to improve the estimates of carbon stock transfers from forest land to other land uses and include techniques to better identify land-use change (see the Planned Improvements section below).

Unfortunately, the annual FIA inventory system does not extend into the 1970s, necessitating the adoption of a system to estimate carbon stocks prior to the establishment of the annual forest inventory. The estimation of carbon stocks prior to the annual national forest inventory consisted of a modeling framework comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest uptake, forest aging, and disturbance effects (e.g., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses carbon stock transfers associated with afforestation and deforestation (Woodall et al. 2015b). Both modules are developed from land use area statistics and carbon stock change or carbon stock transfer by age class. The

required inputs are estimated from more than 625,000 forest and non-forest observations recorded in the FIA national database (U.S. Forest Service 2023a, b, c). Model predictions prior to the annual inventory period are constructed from the estimation system using the annual estimates. The estimation system is driven by the annual forest inventory system conducted by the FIA program (Frayer and Furnival 1999; Bechtold and Patterson 2005; Westfall et al. 2022; USDA Forest Service 2023d, 2023a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m^2 ground plot per 2,403 ha of land and water area. A five or seven-panel design, with 20 percent or 14.3 percent of the field plots typically measured each year within a state, is used in the eastern United States and a ten-panel design, with typically ten percent of the field plots measured each year within a state, is used in the western United States. The interpenetrating hexagonal design across the U.S. landscape enables the sampling of plots at various intensities in a spatially and temporally unbiased manner. Typically, tree and site attributes are measured with higher sample intensity while other ecosystem attributes such as downed dead wood are sampled during summer months at lower intensities. The first step in incorporating FIA data into the estimation system is to identify annual and periodic inventory datasets by state and U.S. Territory. Inventories include data collected on permanent inventory plots on forest lands and were organized as separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Many of the annual inventories reported for states are represented as "moving window" averages, which mean that a portion—but not all—of the previous year's inventory is updated each year (USDA Forest Service 2023d). Forest carbon estimates are organized according to these state surveys, and the frequency of surveys varies by state.

Using this FIA data, separate estimates were prepared for the five carbon storage pools identified by IPCC (2006) as described above. All estimates for the conterminous United States and Alaska were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2023b, 2023c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. Only live (and in some cases) standing dead wood estimates are available in the annual and periodic FIA inventories in Hawaii and the U.S. Territories. For this reason, a combination of approaches was used to obtain estimates for all carbon pools for the time series in these locations.

Carbon in Biomass

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the litter. Separate estimates were made for above- and belowground biomass components. Over the last decade, the USDA Forest Service's FIA program and collaborators from universities and industry have been developing a new national methodology for the prediction of individual-tree volume, biomass, and carbon content. The resulting methodology is referred to as the National-Scale Volume and Biomass (NSVB) framework. The previous methodology used was the Component Ratio Method (CRM) framework (Woodall et al. 2010). While CRM was nationally consistent, tree biomass was still based on the volume predicted by regional models and tree carbon was assumed to be 50-percent of biomass, regardless of species. Hence, the need for NSVB, a nationally consistent methodology for compatible predictions of tree volume, biomass, and carbon content (Westfall et al. In press).

The NSVB covers timber tree species in the conterminous United States and coastal Alaska. All other trees (i.e., trees that are woodland species and trees within Pacific and Caribbean Islands) use regional models for volume and biomass, with updated carbon fractions (when available). While NSVB did not directly update models for trees that are considered woodland species or trees within the Pacific (USDA Forest Service 2022a, b) and Caribbean Islands (collectively referred to hereafter as "non-NSVB trees"), volume, biomass, and carbon estimates for these trees have also changed. For non-NSVB trees, the standardization of tree defects and how variables are reported (i.e., whether models for total-stem or merchantable-bole volumes are available) may be reflected as differences in volume estimates. Additionally, biomass estimates for non-NSVB trees are based on regional biomass models and no longer are adjusted as they were under the CRM. Finally, updates to carbon fractions (when available) and calculation of aboveground biomass are reflected in aboveground and belowground biomass carbon estimates (see Recalculations section and Annex 3.13 for more details).

Understory vegetation is a minor component of biomass, which is defined in the FIA program as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that ten percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density were based on information in Birdsey (1996) and tree biomass estimates from the FIADB. Understory biomass represented over one percent of carbon in biomass, but its contribution rarely exceeded two percent of the total carbon stocks or stock changes across all forest ecosystem carbon pools each year.

Carbon in Dead Organic Matter

Dead organic matter is calculated as three separate pools—standing dead trees, downed dead wood, and litter—with carbon stocks estimated from sample data or from models as described below. The standing dead tree carbon pool includes aboveground and belowground (coarse root) biomass for trees of at least 2.54 cm dbh. Calculations followed the basic methods applied to live trees (Westfall et al. 2023) with additional modifications to account for decay and structural loss (Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. A modeling approach, using litter carbon measurements from FIA plots (Domke et al. 2016), was used to estimate litter carbon for every FIA plot used in the estimation framework. These estimates are now available in the FIADB (USDA Forest Service 2023b).

Carbon in Forest Soil

Soil carbon is the largest terrestrial carbon sink with much of that carbon in forest ecosystems. The FIA program has been consistently measuring soil attributes as part of the annual inventory since 2001 and has amassed an extensive inventory of soil measurement data on forest land in the conterminous United States and coastal Alaska (O'Neill et al. 2005). Observations of mineral and organic soil carbon on forest land from the FIA program and the International Soil Carbon Monitoring Network were used to develop and implement a model framework that enabled the prediction of mineral and organic (i.e., undrained organic soils) soil carbon to a depth of 100 cm from empirical measurements collected on sample plots at a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of soil carbon stocks specific to forest land in the United States (Domke et al. 2017). These estimates are now available in the FIADB (USDA Forest Service 2023b). This approach allowed for separation of mineral and organic soils, the latter also referred to as Histosols, in the forest land remaining forest land category. Note that mineral and organic (i.e., undrained organic soils) soil carbon stock changes are reported to a depth of 100 cm for forest land remaining forest land to remain consistent with past reporting in this category, however for consistency across land-use categories, mineral (e.g., cropland, grassland, settlements) soil carbon is reported to a depth of 30 cm in Section 6.3 Land Converted to Forest Land. Estimates of carbon stock changes from organic soils shown in Table 6-8 and Table 6-9 include the emissions from drained organic forest soils, and the methods used to develop these estimates can be found in the Drained Organic Soils section below.

Harvested Wood Carbon

Estimates of the HWP contribution to forest carbon sinks and emissions (hereafter called "HWP contribution") were based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating the HWP contribution. IPCC (2006) provides methods that allow for reporting of the HWP contribution using one of several different methodological approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP carbon stocks (see Annex 3.13 for more details about each approach). The United States uses the production approach to report HWP

contribution. Under the production approach, carbon in exported wood was estimated as if it remains in the United States, and carbon in imported wood was not included in the estimates. Though reported, U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.13). Annual estimates of change were calculated by tracking the annual estimated additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in SWDS. The carbon loss from harvest is reported in the forest ecosystem component of the forest land remaining forest land and land converted to forest land sections and for informational purposes in the Energy sector, but the non-CO_2 emissions associated with biomass energy are included in the Energy sector emissions (see Chapter 3). EPA includes HWP within the forest chapter because forests are the source of wood that goes into the HWP estimates.

Solidwood products include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools were tracked beginning in 1900, with the exception of additions of softwood lumber to housing, which began in 1800. Solidwood and paper product production and trade data were taken from USDA Forest Service and USDC Bureau of the Census, among other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; AF&PA 2023; FAO 2023). Estimates for disposal of products reflects the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP contribution using any one of the three main approaches listed above. These are:

(1A) annual change of carbon in wood and paper products in use in the United States,

(1B) annual change of carbon in wood and paper products in SWDS in the United States,

(2A) annual change of carbon in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of carbon in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) Carbon in imports of wood, pulp, and paper to the United States,

(4) Carbon in exports of wood, pulp and paper from the United States, and

(5) Carbon in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP contribution under the production estimation approach. A key assumption for estimating these variables that adds uncertainty in the estimates was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for forest ecosystems through a combination of sample-based and model-based approaches to uncertainty estimation for forest ecosystem CO_2 flux using IPCC Approach 1 (Table 6-12 and Table A-214 for state-level uncertainties). A Monte Carlo stochastic simulation of the methods described above, and probabilistic sampling of carbon conversion factors, were used to determine the HWP uncertainty using IPCC Approach 2. See Annex 3.13 for additional information. The 2022 net annual change for forest carbon stocks was estimated to be between –866.5 and –708.3 MMT CO_2 Eq. around a central estimate of –787.0 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of –769.6 to –618.9 MMT CO_2 Eq. around a central estimate of –694.3 MMT CO_2 Eq. for forest ecosystems and –118.0 to -70.0 MMT

CO_2 Eq. around a central estimate of -92.8 MMT CO_2 Eq. for HWP.

Table 6-12: Quantitative Uncertainty Estimates for Net CO_2 Flux from Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem C Pools[a]	CO_2	(694.3)	(769.6)	(618.9)	-10.9%	+10.9%
Harvested Wood Products[b]	CO_2	(92.8)	(118.0)	(70.0)	-27.2%	+24.6%
Total Forest	**CO_2**	**(787.0)**	**(866.5)**	**(708.3)**	**-10.1%**	**+10.0%**

[a] Range of flux estimates predicted through a combination of sample-based and model-based uncertainty for a 95 percent confidence interval, IPCC Approach 1.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, IPCC Approach 2.

Notes: Parentheses indicate negative values or net uptake. Totals may not sum due to independent rounding.

QA/QC and Verification

The FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous U.S., dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for carbon stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available (USDA Forest Service 2023d).

General quality control procedures were used in performing calculations to estimate carbon stocks based on survey data. For example, the carbon datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Oswalt et al. (2019) or selected population estimates generated from the FIA database, which are available at an FIA internet site (USDA Forest Service 2023b). Agreement between the carbon datasets and the original inventories is important to verify accuracy of the data used.

Additional verification analyses are currently underway to compare forest carbon stock change estimates developed using the NSVB model to estimates stemming from other forest biomass models as well as remote sensing imagery.

Estimates of the HWP variables and the HWP contribution under the production estimation approach use data from USDC Bureau of the Census and USDA Forest Service surveys of production and trade, among other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; AF&PA 2023; FAO 2023). Factors to convert wood and paper to units of carbon are based on estimates by industry and U.S. Forest Service published sources (see Annex 3.13). The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual carbon change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of carbon in houses standing in 2001 needs to match an independent estimate of carbon in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards used in the Waste sector each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in carbon in products in use in the United States and, to a lesser degree,

reduce uncertainty in estimates of annual change in carbon in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH_4 emissions from landfills based on EPA (2006) data are reasonable in comparison to CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

There were several methodological improvements implemented in the current *Inventory* which have resulted in substantial changes when compared to the previous (1990 through 2021) *Inventory*.

First, there were new FIA data included for several states, in some cases, multiple years of new data in this *Inventory* resulting from delays that occurred due to the global pandemic. Delays still exist in some states so it is possible that multiple years of data may be available in the years ahead leading to small changes in forest ecosystem carbon stocks and stock changes throughout the time series. These changes are most notable in the conterminous United States (Table 6-14) and coastal southeast and southcentral Alaska (Table 6-15). In coastal Alaska, remeasurement data from the FIA program facilitated the use of the compilation system used in most of the conterminous United States, improving consistency and facilitating the disaggregation of forest land conversions in this region for the first time. This transition in compilation methodology resulted in a 10.6 percent increase in forest land area (449,287 ha) in coastal Alaska which contributed, in part, to increases in forest ecosystem carbon stocks across all pools (Table 6-15).

This *Inventory* also implemented new methods for estimating standing live and dead aboveground biomass carbon in the FIA program (Westfall et al. 2023). These new methods, leveraging the newly developed national-scale volume and biomass framework (NSVB), represent nearly a decade of research and development in the FIA program. The new methods: 1) greatly simplify predictions of aboveground biomass because only five model specifications are used nationally instead of dozens of species- and species-group specific models used in each region and/or state, 2) eliminate administrative boundaries (e.g., regions or states) in favor of ecologically-based regions (i.e., ecodivisons) to capture variation in tree size and volume (or biomass) within species or species groups, 3) models are based on tree measurements from in-situ data which also facilitates more accurate quantification of model uncertainty, 4) result in consistent model behavior for all tree species and sizes, and 5) use species-specific carbon fractions for biomass to carbon conversions compared to the previous method which assumed a default 50 percent biomass to carbon fraction.

The implementation of the NSVB models resulted in an increase in estimates of aboveground biomass carbon stocks on forest land in the United States of approximately 11 percent (1,761.9 MMT C) in the current *Inventory* for the year 2022 relative to the previous *Inventory* estimate for the year 2022 (Table 6-13) and accounted for 34 percent of the total increase in estimates of forest carbon stocks in this *Inventory* relative to the previous *Inventory* for the same year (Table 6-13). These increases can largely be attributed to more accurate characterization of top and limb biomass in the new models (Westfall et al. 2023). This also led to small increases in estimates of belowground biomass carbon stocks since that model is based on a ratio of aboveground biomass. There were also increases of more than 11 percent (321 MMT C) in estimates of dead wood carbon stocks due to the implementation of the new NSVB models in the FIA program for standing dead trees (Table 6-13), which accounted for 6.2 percent of the increases in estimates of forest ecosystem carbon stocks in this *Inventory* relative to the previous *Inventory* for the same year.

The litter and soil model framework used in this *Inventory* and implemented across the entire time series was formally adopted in the FIA program this year and predictions compiled using this framework are now available in the public FIA database (USDA Forest Service 2023b). As part of the formal adoption of these methods in the FIA program, all variables and associated datasets used in the models were evaluated. New climate normals for the time period 1991 to 2020 were included in both the litter and soil models using PRISM data for the conterminous United States and climate normals for 1981 to 2010 (the only period available) were included for the first time in coastal Alaska. Collectively, these updates and improvements resulted in carbon stock estimates that were 10.1 percent larger (3,150.7 MMT C) in this *Inventory* relative to the previous *Inventory* for mineral and organic soil in the United States and overall accounted for approximately 48 percent of the total increases in forest carbon stock

in the current *Inventory* for the year 2022 when compared to the previous *Inventory* for the same year (Table 6-13, Table 6-14). In coastal Alaska, there were comparable increases in predictions in the *Inventory* relative to previous *Inventories*. These increases can be attributed to increases in estimates of forest land area in coastal Alaska as well as the incorporation of climate data in the litter and soil models. Estimates of litter carbon stocks also decreased slightly on forest land remaining forest land relative to the previous Inventory (Table 6-13) due to the implementation of the NSVB models where the litter model relies on estimates of aboveground biomass as a model parameter. Finally, new data on wildfire in Interior Alaska in the latest *Inventory* also contributed to updated estimates in the time series for this area of forest land where there were decreases in the estimates of all but the organic soil carbon pools (Table 6-16). Collectively these updates and improvements resulted in a 2.3 percent decrease (119.1 MMT C) in estimates of litter carbon stocks on forest land in the United States

Managed forest land in Hawaii and several U.S. Territories[31] were included for the first time in the current *Inventory* which resulted in an increase in managed forest land area of approximate 1.3 M ha and associated increases in carbon stocks of 286 MMT C for the year 2023 in this *Inventory*. While the inclusion of these forest land areas represents a relatively small increase in forest area and forest ecosystem carbon stocks overall, their inclusion represents an important improvement toward completeness in this *Inventory*.

Table 6-13: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***279,800***	***281,752***	***281,725***
Carbon Pools (MMT C)			
Forest	**56,951**	**62,130**	**62,320**
Aboveground Biomass	15,861	17,622	17,757
Belowground Biomass	3,143	3,207	3,233
Dead Wood	2,827	3,148	3,184
Litter	3,888	3,768	3,761
Soil (Mineral)	25,916	28,401	28,401
Soil (Organic)	5,317	5,983	5,983
Harvested Wood	**2,749**	**2,747**	**2,772**
Products in Use	1,549	1,547	1,555
SWDS	1,200	1,200	1,217
Total Stock	**59,701**	**64,877**	**65,092**

Note: Totals may not sum due to independent rounding.

Table 6-14: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in the Conterminous United States

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***249,821***	***250,036***	***249,999***
Carbon Pools (MMT C)			
Forest	**46,575**	**51,195**	**51,391**
Aboveground Biomass	14,947	16,641	16,773
Belowground Biomass	2,959	3,006	3,032
Dead Wood	2,558	2,883	2,920
Litter	2,474	2,383	2,384
Soil (Mineral)	23,086	25,467	25,467
Soil (Organic)	550	815	815

[31] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

Note: Totals may not sum due to independent rounding.

Table 6-15: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Coastal Southeast and Southcentral Alaska

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***4,222***	***4,671***	***4,681***
Carbon Pools (MMT C)			
Forest	**1,235**	**1,458**	**1,460**
Aboveground Biomass	362	421	423
Belowground Biomass	76	85	85
Dead Wood	94	107	107
Litter	129	130	130
Soil (Mineral)	411	470	470
Soil (Organic)	163	245	245

Note: Totals may not sum due to independent rounding.

Table 6-16: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Interior Alaska

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***25,758***	***25,758***	***25,758***
Carbon Pools (MMT C)			
Forest	**9,142**	**9,192**	**9,183**
Aboveground Biomass	551	485	484
Belowground Biomass	107	92	92
Dead Wood	176	154	153
Litter	1,285	1,248	1,240
Soil (Mineral)	2,419	2,308	2,308
Soil (Organic)	4,604	4,905	4,905

Note: Totals may not sum due to independent rounding.

Table 6-17: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Hawaii and United States Territories

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***NE***	***1,287***	***1,287***
Carbon Pools (MMT C)			
Forest	**NE**	**285**	**286**
Aboveground Biomass	NE	76	77
Belowground Biomass	NE	23	24
Dead Wood	NE	4	4
Litter	NE	7	7
Soil (Mineral)	NE	156	156
Soil (Organic)	NE	19	19

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

The new FIA data and methodological improvements described throughout this text and specifically in this section on recalculations of estimates of forest ecosystem carbon stocks extend to forest ecosystem carbon stock changes in the current *Inventory*. In total, estimates for the forest land remaining forest land sink increased 21.4 percent (sink estimates increased by 40.8 MMT C). On average across the time-series, these recalculations resulted in a

21.7 percent increase in estimates of the forest sink across the time series (sink estimates increased on average, 43.4 MMT C over the time series) relative to the previous *Inventory* (Table 6-18).

Changes in estimates of forest ecosystem carbon stock changes accounted for most of the increases between this *Inventory* and the previous *Inventory* (Table 6-18) and of those, new data and improvements in methods in the conterminous United States accounted for 97 percent (-41.8 MMT C) increases in estimates of forest ecosystem carbon stock changes in the current Inventory relative to the same year in the previous Inventory (Table 6-19). Estimates of carbon stock changes in the aboveground biomass pool increased by 25.2 percent in the current Inventory relative to the same year in the previous Inventory and accounted for 65.2 percent (-27.2 MMT C) of the increase in estimates from this *Inventory* (Table 6-19). These changes can be directly attributed to the implementation of the NSVB models in the FIA program. These increases extend to the belowground biomass pool where the increases in estimates of aboveground biomass resulted in increases in the estimates of belowground biomass by 23.8 percent (-5.1 MMT C). These increases accounted for 12.2 percent of the total increase in carbon stock changes in the forest ecosystem pools in this *Inventory*. There were also substantial increases in dead wood carbon stock changes which can also be attributed to the implementation of the NSVB models for standing dead trees (Westfall et al. In press). There was a 34.4 percent increase (-9.5 MMT C) in estimates of dead wood carbon stock changes between this Inventory and the same year in the previous Inventory. This increase in the estimates of dead wood accounts for 22.8 percent of the total increases in estimates of forest ecosystem carbon stock changes in this Inventory relative to the same year in the previous *Inventory* (Table 6-19).

There were also small differences in the estimates of carbon stock changes for the litter and the soil carbon pools in the conterminous United States, coastal and Interior Alaska (Table 6-19, Table 6-20, Table 6-21). These changes were all relatively small when compared to changes in live and standing dead biomass.

The inclusion of forest land in Hawaii and several U.S. Territories[32] also contributed to increases in the estimates of carbon stock changes in the current Inventory. Collectively, these areas contributed -1.3 MMT C to the forest land remaining forest land carbon sink in the year 2022 in the current *Inventory* (Table 6-22).

Finally, new data included in the HWP time series resulted in a minor decrease (< 1 percent) in carbon stocks in the HWP pools (Table 6-13) and an associated decrease of 7.9 percent (2.2 MMT C) in estimates of carbon stock changes (Table 6-18). These decreases are the result of decreases in estimates of carbon stock changes for products in use (19.4 percent) in the current *Inventory* relative to the same year in the previous *Inventory* (Table 6-18). With the easing of the global pandemic and the return of consumers to the marketplace, there was a rebound in the purchase and accumulation of solid wood products. Alternatively, paper products in use have been declining in recent years, which could be the result of greater digitization across society. These trends are expected to continue in 2023.

Table 6-18: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(161.6)**	**(204.4)**	**(189.3)**
Aboveground Biomass	(111.6)	(139.9)	(134.1)
Belowground Biomass	(22.1)	(27.5)	(26.4)
Dead Wood	(27.6)	(36.9)	(35.8)
Litter	0.5	(0.0)	7.2
Soil (Mineral)	(1.1)	(0.2)	(0.3)
Soil (Organic)	0.0	(0.0)	(0.0)
Drained organic soil	0.2	0.2	0.2
Harvested Wood	**(28.0)**	**(25.8)**	**(25.3)**
Products in Use	(10.3)	(8.3)	(7.9)

[32] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

SWDS	(17.7)	(17.5)	(17.4)
Total Net Flux	**(189.6)**	**(230.2)**	**(214.6)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-19: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in the Conterminous United States

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(158.5)**	**(200.3)**	**(195.9)**
Aboveground Biomass	(108.1)	(135.3)	(132.1)
Belowground Biomass	(21.3)	(26.4)	(25.8)
Dead Wood	(27.7)	(37.2)	(36.8)
Litter	(0.5)	(1.0)	(0.8)
Soil (Mineral)	(1.1)	(0.2)	(0.3)
Soil (Organic)	0.0	(0.1)	(0.1)

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-20: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Coastal Alaska

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(2.0)**	**(1.9)**	**(1.9)**
Aboveground Biomass	(1.3)	(1.4)	(1.4)
Belowground Biomass	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.1)	(0.1)
Litter	0.0	(0.1)	(0.1)
Soil (Mineral)	0.0	0.0	0.0
Soil (Organic)	0.0	0.0	0.0

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-21: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Interior Alaska

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(1.2)**	**(1.1)**	**9.6**
Aboveground Biomass	(2.1)	(2.1)	0.4
Belowground Biomass	(0.5)	(0.5)	0.0
Dead Wood	0.4	0.4	1.1
Litter	1.0	1.0	8.0
Soil (Mineral)	0.0	0.0	0.0
Soil (Organic)	0.0	0.0	0.0

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-22: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Hawaii and United States Territories

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**NE**	**(1.4)**	**(1.3)**
Aboveground Biomass	NE	(1.0)	(1.0)
Belowground Biomass	NE	(0.3)	(0.3)
Dead Wood	NE	(0.0)	0.0

Litter	NE	0.0	(0.0)
Soil (Mineral)	NE	(0.0)	0.0
Soil (Organic)	NE	0.0	0.0

NE (Not Estimated)

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

Reliable estimates of forest carbon stocks and changes across the diverse ecosystems of the United States require a high level of investment in both annual monitoring and associated analytical techniques. Development of improved monitoring/reporting techniques is a continuous process that occurs simultaneously with annual *Inventory* submissions. Planned improvements can be broadly assigned to the following categories: development of a robust estimation and reporting system, individual carbon pool estimation, coordination with other land-use categories, and periodic and annual inventory data incorporation.

While this *Inventory* submission includes carbon change by forest land remaining forest land and land converted to forest land and carbon stock changes for all IPCC pools in these two categories, there are many improvements that are still necessary. The estimation approach used for the conterminous United States in the current *Inventory* for the forest land category operates at the state scale, whereas previously the western United States and southeast and southcentral coastal Alaska operated at a regional scale. While this is an improvement over previous Inventories and led to improved estimation and separation of land-use categories in the current *Inventory*, including coastal Alaska, research is underway to leverage all FIA data (periodic and annual inventories) and auxiliary information (i.e., remotely sensed information) to operate at finer spatial and temporal scales. As in past submissions, emissions and removals associated with natural (e.g., wildfire, insects, and disease) and human (e.g., harvesting) disturbances are implicitly included in the report given the design of the annual NFI, but not explicitly estimated. In addition to integrating auxiliary information into the estimation framework and leveraging all NFI plot measurements, alternative estimators are also being evaluated which will eliminate latency in population estimates from the NFI, improve annual estimation and characterization of interannual variability, facilitate attribution of fluxes to particular activities, and allow for streamlined harmonization of NFI data with auxiliary data products. This will also facilitate separation of prescribed and wildfire emissions in future reports. The transparency and repeatability of estimation and reporting systems will be improved through the dissemination of open-source code (e.g., R programming language) in concert with the public availability of the periodic and annual NFI (USDA Forest Service 2023b). Also, several FIA database processes are being institutionalized to increase efficiency and QA/QC in reporting and further improve transparency, completeness, consistency, accuracy, and availability of data used in reporting. Finally, a combination of approaches was used to estimate uncertainty associated with carbon stock changes in the forest land remaining forest land category in this report. There is research underway investigating more robust approaches to estimate total uncertainty (Clough et al. 2016), which will be considered in future *Inventory* reports.

The modeling framework used to estimate downed dead wood within the dead wood carbon pool (Smith et al. 2022) will be updated similar to the litter (Domke et al. 2016) and soil carbon pools (Domke et al. 2017). With the implementation of the new models for volume, biomass, and carbon estimation for live and standing dead trees, the methods for litter and soil carbon estimation used in this *Inventory* and recent *Inventories* have been adopted in the FIA program so there is now alignment and consistency between litter and soil carbon estimates in this *Inventory* and the FIA database. Finally, components of other pools, such as carbon in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014; Johnson et al. 2017), are being explored but may require additional investment in field inventories before improvements can be realized in the *Inventory* report.

The foundation of forest carbon estimation and reporting is the annual NFI. The ongoing annual surveys by the FIA program are expected to improve the accuracy and precision of forest carbon estimates as new state surveys become available (USDA Forest Service 2023b). With the exception of Wyoming (which will have sufficient remeasurements in the years ahead), all other states in the conterminous United States and coastal Alaska now

have sufficient annual NFI data to consistently estimate carbon stocks and stock changes for the future using the state-level compilation system. The FIA program continues to install permanent plots in interior Alaska as part of the operational NFI, and as more plots are added to the NFI, they will be used to improve estimates for all managed forest land in Alaska. Estimates of carbon stocks and stock changes for Hawaii and the U.S. Territories were included in this *Inventory* using Tier 1 and Tier 2 methods. The methods used to include all managed forest land in the conterminous United States will be used in future Inventories for Hawaii and U.S. Territories as additional forest carbon data become available (only a small number of plots from Hawaii are currently available from the annualized sampling design). To that end, research is underway to incorporate all NFI information (both annual and periodic data) and the dense time series of remotely sensed data in multiple inferential frameworks for estimating greenhouse gas emissions and removals as well as change (i.e., disturbance or land-use changes) detection and attribution across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid the efforts to improve estimates for interior Alaska, Hawaii, and the U.S. Territories, as well as the entire inventory system. In addition to fully inventorying all managed forest land in the United States, the more intensive sampling (i.e., more samples) of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve spatial and temporal resolution of carbon pools (Westfall et al. 2013) as this information becomes available. Increased sample intensity of some carbon pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The NFI sampling frame extends beyond the forest land-use category (e.g., woodlands, which fall into the grasslands land-use category, and urban areas, which fall into the settlements land-use category) with inventory-relevant information for trees outside of forest land. These data will be utilized as they become available in the NFI.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using U.S.-specific data and models for annual area of forest burned, fuel, consumption, and emission consistent with IPCC (2019). In 2022, emissions from this source were estimated to be 9.1 MMT CO_2 Eq. of CH_4 and 5.7 MMT CO_2 Eq. of N_2O (Table 6-23; kt units provided in Table 6-24). The estimates of non-CO_2 emissions from forest fires include the conterminous 48 states, Hawaii, Puerto Rico, Guam and managed forest land in Alaska (Ogle et al. 2018) because the fire data in use with the current methods identifies fires on these areas within the interval 1990 through 2022.

Table 6-23: Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.)[a]

Gas	1990	2005	2018	2019	2020	2021	2022
CH_4	3.4	9.2	6.0	3.4	9.8	12.7	9.1
N_2O	2.4	6.3	3.7	2.3	5.5	7.2	5.7
Total	**5.8**	**15.4**	**9.7**	**5.7**	**15.3**	**19.9**	**14.8**

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

Note: Totals may not sum due to independent rounding.

Table 6-24: Non-CO_2 Emissions from Forest Fires (kt)[a]

Gas	1990	2005	2018	2019	2020	2021	2022
CH_4	122	328	213	120	349	452	327
N_2O	9	24	14	9	21	27	21
CO	3179	8447	4648	3054	7266	9598	7593
NO_x	49	124	93	51	123	160	121

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

Methodology and Time-Series Consistency

Non-CO_2 emissions from forest fires—primarily CH_4 and N_2O emissions—were calculated consistent with IPCC (2019) methodology, which represent updates of the IPCC (2006) guidance on reporting fire emissions. For the conterminous states and Alaska, estimates were developed with U.S.-specific data and models on area burned, fuel, consumption, and emissions as provided through the Wildland Fire Emissions Inventory System calculator (WFEIS, French et al. 2011, 2014). However, these fire emissions models did not extend to include Hawaii, Puerto Rico, or Guam, so forest fire estimates for these areas relied on Tier 1 emissions factors (IPCC 2019). Spatial definitions of wildland burned areas were the starting point for all estimates, from WFEIS or Tier 1. The three burned area datasets in use are the Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007), MODIS burned area mapping (MODIS MCD64A1 V6.1, Giglio et al. 2018), and Wildland Fire Interagency Geospatial Service (WFIGS) fire perimeters (WFIGS 2023). The MTBS data available for this report (MTBS 2023) included fires from 1990 through 2021 for all states and Puerto Rico (the exception was Alaska 2021 where emissions calculations were not available). The MODIS-based records include 2001 through 2022 for the 48 conterminous states plus Alaska. The WFIGS-based records for 2020 through 2022 included all states plus Puerto Rico and Guam. Note that N_2O emissions are not included in WFEIS calculations; the emissions provided here are based on the average N_2O to CO_2 ratio of 0.000166 (Larkin et al. 2014; IPCC 2019). See the emissions from forest fires section in Annex 3.13 for further details on all fire-related emissions calculations for forests. Consistent use of available data sources, data processing, and calculation methods were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty estimates for non-CO_2 emissions from forest fires are based on a Monte Carlo (IPCC Approach 2) approach to propagate variability among the alternate WFEIS annual estimates per state. Uncertainty in parts of the WFEIS system are not currently quantified. Among potential sources for future analysis are burned areas from MTBS, WFIGS, or MODIS, the fuels models or the Consume model (Prichard et al. 2014). See Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-25.

Table 6-25: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq. and Percent)[a]

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	9.1	6.2	12.1	-32%	+32%
Non-CO_2 Emissions from Forest Fires	N_2O	5.7	3.6	7.8	-36%	+37%

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for estimating non-CO_2 emissions from forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process and results were consistent with values expected from those calculations. The QA/QC procedures did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The methods used in the current (1990 through 2022) *Inventory* to compile estimates of non-CO_2 emissions from forest fires represent a slight change relative to the previous (1990 through 2021) *Inventory*. The basic components of calculating forest fire emissions (IPCC 2019) remain unchanged, but the WFEIS-based estimates now include MTBS, WFIGS, and MODIS based burns (depending on year). The MTBS and WFIGS based estimates are now calculated per burn event (i.e., separately for each forest fire), which improves precision for scaling or allocating emissions such as to managed versus unmanaged lands in Alaska.

An additional source of change leading to recalculations are recent and ongoing updates to the MTBS fire records (i.e., including both most-recent as well as possible updates to past years' fires). The WFEIS calculations now use version 6.1 of the MODIS burned area model and updated versions of the Fuel Characteristic Classification System (FCCS) fuel layer and the Consume model (see WFEIS 2023) for additional details on updates. The addition of forest fire emissions for Hawaii, Puerto Rico, and Guam had little effect on the magnitude of overall emissions.

Estimates of non-CO_2 emissions from forest fires (e.g., Table 6-24) are lower for most years over the time series 1990-2021 in comparison with the previous Inventory (EPA 2023), with an average decrease of 12 percent across all years. For, 2021 the estimate decreased from 24.4 to 19.9 MMT CO_2 Eq. (an 18.7 percent decrease). Changes over the time series are expected because the entire interval is recalculated each year in response to modifications in the fire datasets that can affect all years. For example, MTBS updates burn perimeters for all years as data resolution changes. This year, the WFEIS calculator updated a fuel dataset as well as the Consume model (noted above). The addition of estimates for Hawaii, Puerto Rico, and Guam had negligible effect on the estimates.

Planned Improvements

Continuing improvements are planned for developing better fire and site-specific estimates for forest fires, for example, improving on the Tier-1 factors currently employed for Hawaii, Puerto Rico, and Guam. Additional focus will be on addressing three aspects of reporting: best use of WFEIS, better resolution of uncertainty as discussed above, and identification of burned areas that are not currently captured by the burn records in use.

N_2O Emissions from N Additions to Forest Soils

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropland soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once midway through their life cycle). While the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the annual application rate is quite low over the entire area of forest land.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer N that is transformed and transported to another location through volatilization in the form of ammonia (NH_3) and nitrogen oxide (NO_x), in addition to leaching and runoff of nitrates (NO_3), and later converted into N_2O at off-site locations. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct soil N_2O emissions from forest land remaining forest land and land converted to forest land[33] in 2022 were 0.3 MMT CO_2 Eq. (1.2 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2022 were 0.4 MMT CO_2 Eq. (1.5 kt) and have increased by 455 percent from 1990 to 2022. Total forest soil N_2O emissions are summarized in Table 6-26.

[33] The N_2O emissions from land converted to forest land are included with forest land remaining forest land because it is not currently possible to separate the activity data by land use conversion category.

Table 6-26: N_2O Fluxes from Soils in Forest Land Remaining Forest Land and Land Converted to Forest Land (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2018	2019	2020	2021	2022
Direct N_2O Fluxes from Soils							
MMT CO_2 Eq.	0.1	0.3	0.3	0.3	0.3	0.3	0.3
kt N_2O	0.2	1.2	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Fluxes from Soils							
MMT CO_2 Eq.	+	0.1	0.1	0.1	0.1	0.1	0.1
kt N_2O	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Total (MMT CO_2 Eq.)	**0.1**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total (kt N_2O)	**0.3**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 kt.

Note: Totals may not sum due to independent rounding. The N_2O emissions from land converted to forest land are included with forest land remaining forest land because it is not currently possible to separate the activity data by land use conversion category.

Methodology and Time-Series Consistency

The IPCC Tier 1 approach is used to estimate N_2O from soils within forest land remaining forest land and land converted to forest land. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted are for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also incorporated N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N_2O emissions from fertilizer applications to forests are based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Fertilizer application is rare for hardwoods and therefore not included in the inventory (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer is multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast are not available for 2005 through 2022, so data from 2004 are used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir is addressed in the inventory because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir stands (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area are multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2022, so data from 2004 are used for these years. The annual area estimates are multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests is multiplied by the IPCC (2006) default emission factor of one percent to estimate direct N_2O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land are calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site. The amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions.

The same method is applied in all years of this *Inventory* to ensure time-series consistency from 1990 through 2022.

Uncertainty

The amount of N_2O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic carbon availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default

methodology, except variation in estimated fertilizer application rates and estimated areas of forested land receiving nitrogen fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only applications of synthetic nitrogen fertilizers to forest are captured in this *Inventory*, so applications of organic nitrogen fertilizers are not estimated. However, the total quantity of organic nitrogen inputs to soils in the United States is included in the *Inventory* within the agricultural soil management source category (Section 5.4) and settlements remaining settlements (Section 6.10).

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level[34] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

Uncertainty is quantified using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-27. Direct N_2O fluxes from soils in 2022 are estimated to be between 0.1 and 1.0 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the emission estimate of 0.3 MMT CO_2 Eq. for 2022. Indirect N_2O emissions in 2022 are 0.1 MMT CO_2 Eq. and have a range are between 0.01 and 0.3 MMT CO_2 Eq., which is 86 percent below to 238 percent above the emission estimate for 2022.

Table 6-27: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in Forest Land Remaining Forest Land and Land Converted to Forest Land (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
Forest Land Remaining Forest Land			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	0.3	0.1	1.0	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	+	0.3	-86%	+238%

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

The spreadsheet containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges are checked and verified based on the sources of these data consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

CO_2, CH_4, and N_2O Emissions from Drained Organic Soils[35]

Drained organic soils on forest land are identified separately from other forest soils largely because mineralization of the exposed or partially dried organic material results in continuous CO_2 and N_2O emissions (IPCC 2006). In addition, the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*

[34] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent is used in the analysis.

[35] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both Forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

(IPCC 2014) calls for estimating CH_4 emissions from these drained organic soils and the ditch networks used to drain them.

Organic soils are identified on the basis of thickness of organic horizon and percent organic matter content. All organic soils are assumed to have originally been wet, and drained organic soils are further characterized by drainage or the process of artificially lowering the soil water table, which exposes the organic material to drying and the associated emissions described in this section. The land base considered here is drained inland organic soils that are coincident with forest area as identified by the NFI of the USDA Forest Service (USDA Forest Service 2022b).

The estimated area of drained organic soils on forest land is 70,849 ha and did not change over the time series based on the data used to compile the estimates in the current *Inventory*. These estimates are based on permanent plot locations of the NFI (USDA Forest Service 2022b) coincident with mapped organic soil locations (STATSGO2 2016), which identifies forest land on organic soils. Forest sites that are drained are not explicitly identified in the data, but for this estimate, planted forest stands on sites identified as mesic or xeric (which are identified in USDA Forest Service 2022c, d) are labeled "drained organic soil" sites.

Land use, region, and climate are broad determinants of emissions as are more site-specific factors such as nutrient status, drainage level, exposure, or disturbance. Current data are limited in spatial precision and thus lack site specific details. At the same time, corresponding emissions factor data specific to U.S. forests are similarly lacking. Tier 1 estimates are provided here following IPCC (2014). Total annual non-CO_2 emissions on forest land with drained organic soils in 2022 are estimated as 0.1 MMT CO_2 Eq. per year (Table 6-28; kt units provided in Table 6-29).

The Tier 1 methodology provides methods to estimate emissions of CO_2 from three pathways: direct emissions primarily from mineralization; indirect, or off-site, emissions associated with dissolved organic carbon releasing CO_2 from drainage waters; and emissions from (peat) fires on organic soils. Data about forest fires specifically located on drained organic soils are not currently available; as a result, no corresponding estimate is provided here. Non-CO_2 emissions provided here include CH_4 and N_2O. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. Emission of N_2O can be significant from these drained organic soils in contrast to the very low emissions from wet organic soils.

Table 6-28: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.1	0.1	0. 1	0.1	0.1
Total	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] This table includes estimates from forest land remaining forest land and land converted to forest land.

[b] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

Note: Totals may not sum due to independent rounding.

Table 6-29: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (kt)

Source	1990	2005	2018	2019	2020	2021	2022
CH_4	1	1	1	1	1	1	1
N_2O	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

[a] This table includes estimates from forest land remaining forest land and land converted to forest land.

[b] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

Methodology and Time-Series Consistency

The Tier 1 methods for estimating CO_2, CH_4 and N_2O emissions from drained inland organic soils on forest lands follow IPCC (2006), with extensive updates and additional material presented in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). With the exception of quantifying area of forest on drained organic soils, which is user-supplied, all quantities necessary for Tier 1 estimates are provided in Chapter 2, Drained Inland Organic Soils of IPCC (2014).

Estimated area of drained organic soils on forest land is 70,849 ha based on analysis of the permanent NFI of the USDA Forest Service and did not change over the time series. The most recent plot data per state within the inventories were used in a spatial overlay with the STATSGO2 (2016) soils data, and forest plots coincident with the soil order histosol were selected as having organic soils. Information specific to identifying "drained organic" are not in the inventory data so an indirect approach was employed here. Specifically, artificially regenerated forest stands (inventory field STDORGCD=1) on mesic or xeric sites (inventory field 11≤PHYSCLCD≤29) are labeled "drained organic soil" sites. From this selection, forest area and sampling error for forest on drained organic sites are based on the population estimates developed within the inventory data for each state (USDA Forest Service 2022d). Eight states, all temperate forests (including pine forest in northern Florida, which largely display characteristics of temperate forests), were identified as having drained organic soils (Table 6-30).

Table 6-30: States identified as having Drained Organic Soils, Area of Forest on Drained Organic Soils, and Sampling Error

State	Forest on Drained Organic Soil (1,000 ha)	Sampling Error (68.3% as ± Percentage of Estimate)
Florida	2.4	79
Georgia	3.7	71
Michigan	18.7	34
Minnesota	30.2	19
North Carolina	1.3	99
Virginia	2.3	102
Washington	2.1	101
Wisconsin	10.1	30
Total	**70.8**	**14**

Note: Totals may not sum due to independent rounding.

The Tier 1 methodology provides methods to estimate emissions for three pathways of carbon emission as CO_2. Note that subsequent mention of equations and tables in the remainder of this section refer to Chapter 2 of IPCC (2014). The first pathway–direct CO_2 emissions–is calculated according to Equation 2.3 and Table 2.1 as the product of forest area and emission factor for temperate drained forest land. The second pathway—indirect, or off-site, emissions—is associated with dissolved organic carbon (DOC) releasing CO_2 from drainage waters according to Equation 2.4 and Table 2.2, which represent a default composite of the three pathways for this flux: (1) the flux of DOC from natural (undrained) organic soil; (2) the proportional increase in DOC flux from drained organic soils relative to undrained sites; and (3) the conversion factor for the part of DOC converted to CO_2 after export from a site. The third pathway—emissions from (peat) fires on organic soils—assumes that the drained organic soils burn in a fire, but not any wet organic soils. However, this *Inventory* currently does not include emissions for this pathway because data on the combined fire and drained organic soils information are not available at this time; this may become available in the future with additional analysis.

Non-CO_2 emissions, according to the Tier 1 method, include methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO). Emissions associated with peat fires include factors for CH_4 and CO in addition to CO_2, but fire estimates are assumed to be zero for the current *Inventory*, as discussed above. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. From this, two separate emission factors are used, one for emissions from the area of drained soils and a second for emissions from drainage ditch waterways. Calculations are conducted according to Equation 2.6 and Tables 2.3 and 2.4, which includes the default fraction of the total area of drained organic soil which is occupied by ditches. Emissions of N_2O can be significant from these drained soils in contrast to the very low emissions from wet organic soils. Calculations are conducted according to Equation 2.7 and Table 2.5, which provide the estimate as kg N per year.

Methodological calculations were applied to the entire set of estimates for 1990 through 2022. Year-specific data are not available. Estimates are based on a single year and applied as the annual estimates over the interval.

Uncertainty

Uncertainties are based on the sampling error associated with forest area of drained organic soils and the uncertainties provided in the Chapter 2 (IPCC 2014) emissions factors (Table 6-31). The estimates and resulting quantities representing uncertainty are based on the IPCC Approach 1–error propagation. However, probabilistic sampling of the distributions defined for each emission factor produced a histogram result that contained a mean and 95 percent confidence interval. The primary reason for this approach was to develop a numerical representation of uncertainty with the potential for combining with other forest components. The methods and parameters applied here are identical to previous inventories, but input values were resampled for this *Inventory*, which results in minor changes in the number of significant digits in the resulting estimates, relative to past values. The total non-CO_2 emissions in 2022 from drained organic soils on forest land remaining forest land and land converted to forest land were estimated to be between zero and 0.150 MMT CO_2 Eq. around a central estimate of 0.068 MMT CO_2 Eq. at a 95 percent confidence level.

Table 6-31: Quantitative Uncertainty Estimates for Non-CO_2 Emissions on Drained Organic Forest Soils (MMT CO_2 Eq. and Percent)[a]

Source	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
CH_4	+	+	+	-69%	+82%
N_2O	0.1	+	0.1	-118%	+132%
Total	**0.1**	**+**	**0.2**	**-107%**	**+121%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of flux estimates predicted through a combination of sample-based and IPCC defaults for a 95 percent confidence interval, IPCC Approach 1.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

IPCC (2014) guidance cautions of a possibility of double counting some of these emissions. Specifically, the off-site emissions of dissolved organic carbon from drainage waters may be double counted if soil carbon stock and change is based on sampling and this carbon is captured in that sampling. Double counting in this case is unlikely since plots identified as drained were treated separately in this chapter. Additionally, some of the non-CO_2 emissions may be included in either the wetlands or sections on N_2O emissions from managed soils. These paths to double counting emissions are unlikely here because these issues are taken into consideration when developing the estimates and this chapter is the only section directly including such emissions on forest land.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

Additional data will be compiled to update estimates of forest areas on drained organic soils as new reports and geospatial products become available. For example, current and recent past estimates are based on drained organic soils identified in a limited number of the conterminous states; if forests on drained organic soils are identified in additional areas including Alaska, Hawaii, Puerto Rico, or Guam, they will be included in future *Inventories*.

6.3 Land Converted to Forest Land (CRT Category 4A2)

The carbon stock change estimates for land converted to forest land that are provided in this Inventory include all forest land in an inventory year that had been in another land use(s) during the previous 20 years.[36] For example, cropland or grassland converted to forest land during the past 20 years would be reported in this category. Converted lands are in this category for 20 years as recommended in the *2006 IPCC Guidelines* (IPCC 2006), after which they are classified as forest land remaining forest land. Estimates of carbon stock changes from all pools (i.e., aboveground and belowground biomass, dead wood, litter and soils), as recommended by IPCC (2006), are included in the land converted to forest land category of this *Inventory*.

Area of Land Converted to Forest in the United States[37]

Land conversion to and from forests has occurred regularly throughout United States history. The 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. Recent analyses suggest that net accumulation of forest area continues in areas of the United States, in particular the northeastern United States (Woodall et al. 2015b). Specifically, the annual conversion of land from other land-use categories (i.e., cropland, grassland, wetlands, settlements, and other lands) to forest land resulted in a fairly continuous net annual accretion of forest land area from over the time series at an average rate of 1.0 million ha year-1.

Over the 20-year conversion period used in the land converted to forest land category, the conversion of grassland to forest land resulted in the largest source of carbon transfer and uptake, accounting for approximately 38

[36] The annual NFI data used to compile estimates of carbon transfer and uptake in this section are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series.

[37] The estimates reported in this section only include the 48 conterminous states in the United States. Land use conversions to forest land in Alaska are currently included in the Forest Land Remaining Forest Land section because currently there is insufficient data to separate the changes and estimates for Hawaii were not included because there is insufficient NFI data to support inclusion at this time. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 and Section 6.3.

percent of the uptake annually. Estimated carbon uptake has remained relatively stable over the time series across all conversion categories (see Table 6-24). The net flux of carbon from all forest pool stock changes in 2022 was -100.3 MMT CO_2 Eq. (-27.4 MMT C) (see Table 6-24 and Table 6-25).

Mineral soil carbon stocks increased slightly over the time series for land converted to forest land. The small gains are associated with cropland converted to forest land, settlements converted to forest land, and other land converted to forest land. Much of this conversion is from soils that are more intensively used under annual crop production or settlement management, or are conversions from other land, which has little to no soil carbon. In contrast, grassland converted to forest land leads to a loss of soil carbon across the time series, which negates some of the gain in soil carbon with the other land-use conversions. Managed pasture to forest land is the most common conversion. This conversion leads to a loss of soil carbon because pastures are mostly improved in the United States with fertilization and/or irrigation, which enhances carbon input to soils relative to typical forest management activities.

Table 6-32: Net CO_2 Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Forest Land	**(17.6)**	**(17.5)**	**(17.3)**	**(17.3)**	**(17.2)**	**(17.2)**	**(17.2)**
Aboveground Biomass	(10.2)	(10.1)	(10.0)	(10.0)	(10.0)	(10.0)	(10.0)
Belowground Biomass	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
Dead Wood	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)
Litter	(3.3)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)
Mineral Soil	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(36.7)**	**(36.9)**	**(37.2)**	**(37.2)**	**(37.2)**	**(37.2)**	**(37.2)**
Aboveground Biomass	(22.5)	(22.7)	(22.8)	(22.8)	(22.8)	(22.8)	(22.8)
Belowground Biomass	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Dead Wood	(4.0)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)
Litter	(7.6)	(7.7)	(7.7)	(7.7)	(7.7)	(7.7)	(7.7)
Mineral Soil	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Other Land Converted to Forest Land	**(5.2)**	**(5.3)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**
Aboveground Biomass	(2.2)	(2.2)	(2.3)	(2.3)	(2.3)	(2.3)	(2.3)
Belowground Biomass	(0.3)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Dead Wood	(0.7)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Litter	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Mineral Soil	(0.7)	(0.8)	(1.0)	(0.9)	(0.9)	(0.9)	(0.9)
Settlements Converted to Forest Land	**(31.9)**	**(31.6)**	**(31.4)**	**(31.4)**	**(31.4)**	**(31.4)**	**(31.4)**
Aboveground Biomass	(19.8)	(19.6)	(19.5)	(19.4)	(19.4)	(19.4)	(19.4)
Belowground Biomass	(3.4)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)
Dead Wood	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)
Litter	(4.9)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)
Mineral Soil	(0.0)	(0.03)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Wetlands Converted to Forest Land	**(8.8)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**
Aboveground Biomass	(4.9)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)
Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Litter	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(59.7)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**
Total Belowground Biomass Flux	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**
Total Dead Wood Flux	**(12.0)**	**(12.0)**	**(12.1)**	**(12.1)**	**(12.1)**	**(12.1)**	**(12.1)**
Total Litter Flux	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**
Total Mineral Soil Flux	**(0.8)**	**(0.8)**	**(1.0)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**

Total Flux	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. Territories are currently included in the forest land remaining forest land section because there is insufficient data to separate the changes at this time. It is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 and Section 6.3. The forest ecosystem carbon stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see 6.10 for estimates of carbon stock change from settlement trees). It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for all organic soils are included in Table 6-8 of the Forest Land Remaining Forest Land section of the *Inventory*.

Table 6-33: Net Carbon Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Forest Land	**(4.8)**	**(4.8)**	**(4.7)**	**(4.7)**	**(4.7)**	**(4.7)**	**(4.7)**
Aboveground Biomass	(2.8)	(2.8)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Belowground Biomass	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Dead Wood	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Litter	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Mineral Soil	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Grassland Converted to Forest Land	**(10.0)**	**(10.1)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.1)**
Aboveground Biomass	(6.1)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)
Belowground Biomass	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)
Mineral Soil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Land Converted to Forest Land	**(1.4)**	**(1.4)**	**(1.5)**	**(1.5)**	**(1.5)**	**(1.5)**	**(1.5)**
Aboveground Biomass	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Litter	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Mineral Soil	(0.2)	(0.2)	(0.3)	(0.2)	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(8.7)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**
Aboveground Biomass	(5.4)	(5.4)	(5.3)	(5.3)	(5.3)	(5.3)	(5.3)
Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Litter	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Mineral Soil	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**
Aboveground Biomass	(1.3)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Belowground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Total Belowground Biomass Flux	**(2.5)**	**(2.5)**	**(2.5)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**
Total Dead Wood Flux	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**
Total Litter Flux	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**
Total Mineral Soil Flux	**(0.2)**	**(0.2)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.3)**	**(0.2)**
Total Flux	**(27.3)**	**(27.3)**	**(27.4)**	**(27.4)**	**(27.4)**	**(27.4)**	**(27.4)**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. Territories are currently included in the forest land remaining forest land section because there is not sufficient data to separate the changes at this time. It is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 and Section 6.3. The forest ecosystem carbon stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for organic soils are included in Table 6-9 and Table 6-10 of the Forest Land Remaining Forest Land section of the *Inventory*.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate stock changes in all forest carbon pools for land converted to forest land. National Forest Inventory data and IPCC (2006) defaults for reference carbon stocks were used to compile separate estimates for the five carbon storage pools. Estimates for aboveground and belowground biomass, dead wood and litter were based on data collected from the extensive array of permanent, annual NFI plots and associated models (e.g., live tree belowground biomass estimates) in the United States (USDA Forest Service 2023b, 2023c). Carbon conversion factors were applied at the individual plot and then appropriately expanded to state population estimates, which are summed to provide the national estimate. To ensure consistency in the land converted to forest land category where carbon stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

The methods used for estimating carbon stocks and stock changes in the land converted to forest land are consistent with those used for forest land remaining forest land. For land-use conversion, IPCC (2006) default biomass carbon stock values were applied in the year of conversion on individual plots to estimate the C stocks removed due to land-use conversion from croplands and grasslands. There is no biomass loss data or IPCC (2006) defaults to include transfers, losses, or gains of carbon in the year of the conversion for other land use (i.e., other lands, settlements, wetlands) conversions to forest land so these were incorporated for these conversion categories. All annual NFI plots included in the public FIA database as of September 2023 were used in this Inventory. Forest land conditions were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2022. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class to obtain population estimates for the nation.

Carbon in Biomass

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above and belowground biomass components. If inventory plots included data on individual trees, aboveground tree carbon was based on Westfall et al. (2023). The component ratio method (CRM) which is a function of volume, species, and diameter was used to compile estimates for woodland species where diameter measurements are taken at root collar and to compile belowground biomass carbon for all tree species (Woodall et al. (2011a). An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each woodland tree following the same CRM method.

Understory vegetation is a minor component of biomass and is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For the current *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density were

based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of carbon in biomass, but its contribution rarely exceeded 2 percent of the total.

Biomass losses associated with conversion from grassland and cropland to forest land were assumed to occur in the year of conversion. To account for these losses, IPCC (2006) defaults for aboveground and belowground biomass on grasslands and aboveground biomass on croplands were subtracted from sequestration in the year of the conversion. As previously discussed, for all other land use (i.e., other lands, settlements, wetlands) conversions to forest land no biomass loss data were available, and no IPCC (2006) defaults currently exist to include transfers, losses, or gains of carbon in the year of the conversion, so none were incorporated for these conversion categories. As defaults or country-specific data become available for these conversion categories, they will be incorporated.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with carbon stocks estimated from sample data or from models. The standing dead tree carbon pool includes aboveground and belowground (coarse root) biomass for trees of at least 2.54 cm dbh. Calculations followed the basic method applied to live trees (Westfall et al. 2023, Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. A modeling approach, using litter carbon measurements from FIA plots (Domke et al. 2016) was used to estimate litter carbon for every FIA plot used in the estimation framework. Dead organic matter carbon stock estimates are included for all land-use conversions to forest land.

Mineral Soil Carbon Stock Changes

A Tier 2 method is applied to estimate mineral soil C stock changes for land converted to forest land (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land use, and land management activity, and then assigned reference carbon levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003, 2006). Land use and land-use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA) and the 2017 National Resources Inventory (NRI) (USDA-NRCS 2020). The areas have been modified in the NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land-use categories (see Section 6.1 for more information). Note that soil C in this Inventory is reported to a depth of 100 cm in the forest land remaining forest land category (Domke et al. 2017) while other land-use categories report soil C to a depth of 30 cm. However, to ensure consistency in the land converted to forest land category where C stock transfers occur between land-use categories, soil C estimates were based on a 30 cm depth using methods from Ogle et al. (2003, 2006) and IPCC (2006). See Annex 3.12 for more information about this method.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Mineral soil organic C stock changes from 2021 to 2022 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. The extrapolation is based on a linear regression model with moving-average

(ARMA) errors using the 1990 to 2020 emissions data and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for land converted to forest land through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 Eq. flux (IPCC Approach 1). Uncertainty estimates for forest pool carbon stock changes were developed using the same methodologies as described in the forest land remaining forest land section for aboveground and belowground biomass, dead wood, and litter. The exception was when IPCC default estimates were used for reference carbon stocks in certain conversion categories (i.e., cropland converted to forest land and grassland converted to forest land). In those cases, the uncertainties associated with the IPCC (2006) defaults were included in the uncertainty calculations. IPCC Approach 2 was used to propagate errors with estimation of mineral soils carbon stock changes for land-use conversions, and is described in the cropland remaining cropland section.

Uncertainty estimates are presented in Table 6-34 for each land conversion category and carbon pool. Uncertainty estimates were obtained using a combination of sample-based and model-based approaches for all non-soil carbon pools (IPCC Approach 1) and a Monte Carlo approach (IPCC Approach 2) was used for mineral soil. Uncertainty estimates were combined using the error propagation model (IPCC Approach 1). The combined uncertainty for all carbon stocks in land converted to forest land ranged from 11 percent below to 11 percent above the 2022 carbon stock change estimate of –100.3 MMT CO_2 Eq.

Table 6-34: Quantitative Uncertainty Estimates for Forest Carbon Pool Stock Changes (MMT CO_2 Eq. per Year) in 2022 from Land Converted to Forest Land by Land Use Change

Land Use/Carbon Pool	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Range[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Forest Land	(17.2)	(25.8)	(8.7)	-50%	50%
Aboveground Biomass	(10.0)	(18.4)	(1.7)	-83%	83%
Belowground Biomass	(1.7)	(2.7)	(0.7)	-61%	61%
Dead Wood	(2.2)	(3.4)	(1.0)	-56%	56%
Litter	(3.2)	(4.3)	(2.1)	-34%	34%
Non-federal Mineral Soils	(0.1)	(0.3)	0.0	-142%	142%
Federal Mineral Soils	(0.0)	(0.1)	0.1	-8,796%	8,796%
Grassland Converted to Forest Land	(37.2)	(39.6)	(34.8)	-6%	6%
Aboveground Biomass	(22.8)	(24.2)	(21.5)	-6%	6%
Belowground Biomass	(2.7)	(3.0)	(2.5)	-10%	10%
Dead Wood	(4.1)	(4.3)	(4.0)	-3%	3%
Litter	(7.7)	(8.3)	(7.2)	-7%	7%
Non-federal Mineral Soils	0.2	(0.1)	0.5	-142%	142%
Federal Mineral Soils	0.0	(0.1)	0.1	-1,310%	1,310%
Other Lands Converted to Forest Land	(5.5)	(7.8)	(3.2)	-42%	42%
Aboveground Biomass	(2.3)	(4.4)	(0.2)	-92%	92%
Belowground Biomass	(0.4)	(0.8)	0.1	-121%	121%
Dead Wood	(0.8)	(1.3)	(0.2)	-74%	74%
Litter	(1.2)	(1.8)	(0.6)	-53%	53%
Non-federal Mineral Soils	(0.9)	(1.4)	(0.5)	-49%	49%
Federal Mineral Soils	(0.0)	(0.2)	0.1	-666%	666%
Settlements Converted to Forest Land	(31.4)	(37.9)	(24.9)	-21%	21%
Aboveground Biomass	(19.4)	(25.6)	(13.3)	-32%	32%
Belowground Biomass	(3.3)	(4.6)	(2.0)	-40%	40%

Dead Wood	(3.8)	(4.9)	(2.6)	-31%	31%
Litter	(4.8)	(5.7)	(3.9)	-19%	19%
Non-federal Mineral Soils	(0.1)	(0.1)	(0.0)	-32%	32%
Federal Mineral Soils	(0.0)	(0.0)	0.0	-193%	193%
Wetlands Converted to Forest Land	(8.9)	(9.1)	(8.8)	-2%	2%
Aboveground Biomass	(5.0)	(5.2)	(4.9)	-3%	3%
Belowground Biomass	(0.9)	(0.9)	(0.9)	-3%	3%
Dead Wood	(1.2)	(1.3)	(1.2)	-4%	4%
Litter	(1.8)	(1.9)	(1.7)	-3%	3%
Non-federal Mineral Soils	0.0	0.0	0.0	0%	0%
Federal Mineral Soils	0.0	0.0	0.0	0%	0%
Total: Aboveground Biomass	(59.6)	(70.3)	(48.9)	-18%	18%
Total: Belowground Biomass	(9.0)	(10.7)	(7.2)	-19%	19%
Total: Dead Wood	(12.1)	(13.8)	(10.3)	-15%	15%
Total: Litter	(18.8)	(20.4)	(17.2)	-9%	8%
Total: Mineral Soils	(0.9)	(1.3)	(0.5)	-42%	42%
Total: Lands Converted to Forest Lands	**(100.3)**	**(111.4)**	**(89.2)**	**-11%**	**11%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NA (Not Applicable)

[a] Range of flux estimate for 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for organic soils are included in Table 6-8 and Table 6-9 of the Forest Land Remaining Forest Land section of the *Inventory*.

QA/QC and Verification

See QA/QC and Verification sections under Forest Land Remaining Forest Land and for mineral soil estimates, Cropland Remaining Cropland.

Recalculations Discussion

The approach for estimating carbon stock changes in land converted to forest land is consistent with the methods used for forest land remaining forest Land and is described in Annex 3.13. The land converted to forest land estimates in this Inventory are based on the land-use change information in the annual NFI. All conversions are based on empirical estimates compiled using plot remeasurements from the NFI, IPCC (2006) default biomass carbon stocks removed from croplands and grasslands in the year of conversion on individual plots and the Tier 2 method for estimating mineral soil carbon stock changes (Ogle et al. 2003, 2006; IPCC 2006). All annual NFI plots included in the public FIA database as of September 2023 were used in this *Inventory*. This is the fourth year that remeasurement data from the annual NFI were available throughout the conterminous United States (with the exception of Wyoming) and coastal southeast and southcentral Alaska to estimate land-use conversion. The availability of remeasurement data from the annual NFI allowed for consistent plot-level estimation of carbon stocks and stock changes for forest land remaining forest land and the land converted to forest land categories. Estimates in the previous *Inventory* were based on state-level carbon density estimates and a combination of NRI data and NFI data in the eastern United States. The refined analysis in this *Inventory* resulted in changes in the land converted to forest land categories. Overall, the land converted to forest land carbon stock changes increased by approximately 2 percent in 2022 between the previous *Inventory* (1990 through 2021) and the current *Inventory* (Table 6-35). While the overall change is relatively small, changes by conversion categories were substantial between this *Inventory* and the previous *Inventory*. These changes can be attributed to six methodological improvements implemented this year. First, managed pastureland was previously classified as cropland and is now classified as grassland to align with NRI definitions and classifications. This resulted in a substantial structural decrease in the cropland converted to forest land category area and associated carbon stock changes and a substantial structural increase in the grassland converted to forest land area and associated carbon stock changes.

Second, in this *Inventory* all NFI plots with evidence of water are classified as wetlands to align with definitions and classifications in the NRI. In the previous *Inventory*, some NFI plots with evidence of water were classified as other land. This methodological improvement resulted in increases in the wetlands converted to forest land category and decreases in the other land converted to forest land category. Third, estimates of carbon stocks and stock changes on managed forest land in coastal Alaska are now compiled in the same ways as the conterminous United States allowing for estimates of land conversions. This led to small increases in the area and associated carbon stock change estimates in the land converted to forest land category. Fourth, the implementation of new methods for estimating aboveground biomass carbon in live and standing dead trees resulted in changes across all land use conversion categories in the aboveground and belowground biomass, dead wood, and litter pools. Fifth, new climate normals (1990 through 2020) were incorporated in the litter model resulting in additional changes in that pool. Finally, there were new NFI data incorporated into the latest *Inventory* which contributed to changes when compared with the previous *Inventory*.

Table 6-35: Recalculations of the Net Carbon Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Conversion category and Carbon pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Cropland Converted to Forest Land	**(10.3)**	**(4.7)**	**(4.7)**
Aboveground Biomass	(6.0)	(2.7)	(2.7)
Belowground Biomass	(1.2)	(0.5)	(0.5)
Dead Wood	(1.3)	(0.6)	(0.6)
Litter	(1.8)	(0.9)	(0.9)
Mineral Soil	(0.1)	(0.0)	(0.0)
Grassland Converted to Forest Land	**(3.4)**	**(10.2)**	**(10.1)**
Aboveground Biomass	(1.7)	(6.2)	(6.2)
Belowground Biomass	(0.3)	(0.7)	(0.7)
Dead Wood	(0.3)	(1.1)	(1.1)
Litter	(1.1)	(2.1)	(2.1)
Mineral Soil	0.1	0.1	0.1
Other Land Converted to Forest Land	**(2.9)**	**(1.5)**	**(1.5)**
Aboveground Biomass	(1.3)	(0.6)	(0.6)
Belowground Biomass	(0.2)	(0.1)	(0.1)
Dead Wood	(0.4)	(0.2)	(0.2)
Litter	(0.7)	(0.3)	(0.3)
Mineral Soil	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.3)**	**(8.6)**	**(8.6)**
Aboveground Biomass	(5.7)	(5.3)	(5.3)
Belowground Biomass	(1.1)	(0.9)	(0.9)
Dead Wood	(1.1)	(1.0)	(1.0)
Litter	(1.5)	(1.3)	(1.3)
Mineral soil	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(0.9)**	**(2.4)**	**(2.4)**
Aboveground Biomass	(0.4)	(1.4)	(1.4)
Belowground Biomass	(0.1)	(0.2)	(0.2)
Dead Wood	(0.1)	(0.3)	(0.3)
Litter	(0.4)	(0.5)	(0.5)
Mineral Soil	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(15.0)**	**(16.3)**	**(16.3)**
Total Belowground Biomass Flux	**(2.8)**	**(2.4)**	**(2.4)**
Total Dead Wood Flux	**(3.2)**	**(3.3)**	**(3.3)**
Total Litter Flux	**(5.5)**	**(5.1)**	**(5.1)**
Total SOC (Mineral) Flux	**(0.3)**	**(0.3)**	**(0.2)**
Total Flux	**(26.8)**	**(27.4)**	**(27.4)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

There are many improvements necessary to improve the estimation of carbon stock changes associated with land-use conversion to forest land over the entire time series. First, soil carbon has historically been reported to a depth of 100 cm in the forest land remaining forest land category (Domke et al. 2017) while other land-use categories (e.g., grasslands and croplands) report soil carbon to a depth of 30 cm. To ensure greater consistency in the land converted to forest land category where carbon stock transfers occur between land-use categories, all mineral soil estimates in the land converted to forest land category in this Inventory are based on methods from Ogle et al. (2003, 2006) and IPCC (2006). Methods have recently been developed (Domke et al. 2017) to estimate soil carbon to depths of 20, 30, and 100 cm in the forest land category using in situ measurements from the FIA program within the USDA Forest Service and the International Soil Carbon Network. In subsequent Inventories, a common reporting depth will be defined for all land-use conversion categories and Domke et al. (2017) will be used in the forest land remaining forest land and land converted to forest land categories to ensure consistent reporting across all forest land. Second, due to the 5 to 10-year remeasurement periods within the FIA program and limited land-use change information available over the entire time series, estimates presented in this section may not reflect the entire 20-year conversion history. Third, since the sum of all land converted to forest land is used to adjust specific land-use conversions into forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where specific land-use conversions into forest land do not exist in the FIA data. These difference in area estimates may result in differences between the summed estimates for mineral soil carbon stock changes across all states and the estimates reported in Table 6-31 through Table 6-34. Work is underway to integrate the dense time series of remotely sensed data into a new estimation system, which will facilitate land conversion estimation over the entire time series.

6.4 Cropland Remaining Cropland (CRT Category 4B1)

Carbon in cropland ecosystems occurs in biomass, dead organic matter, and soils. However, carbon storage in cropland biomass and dead organic matter is relatively ephemeral and does not need to be reported according to the IPCC (2006), with the exception of carbon stored in perennial woody crop biomass, such as citrus groves and apple orchards, in addition to the biomass, downed wood and dead organic matter in agroforestry systems. Within soils, carbon is found in organic and inorganic forms of carbon, but soil organic carbon is the main source and sink for atmospheric CO_2. IPCC (2006) recommends reporting changes in soil organic carbon stocks due to agricultural land use and management activities for mineral and organic soils.[38]

Well-drained mineral soils typically contain from 1 to 6 percent organic carbon by weight, whereas mineral soils with high water tables for substantial periods of a year may contain significantly more carbon (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the soil organic carbon to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of carbon loss depends on subsequent management practices, climate and soil type (Ogle et al. 2005). Agricultural practices, such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, application of biosolids (i.e., treated sewage sludge) and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net carbon stock change (Paustian et al. 1997a; Lal 1998; Conant et al. 2001; Ogle et al. 2005; Griscom et al. 2017; Ogle et al. 2019). Eventually, the soil can reach a new equilibrium that reflects a balance

[38] Carbon dioxide emissions associated with liming and urea application are also estimated but are included in the Liming and Urea Fertilization sections of the Agriculture chapter of the *Inventory*.

between carbon inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and carbon loss through microbial decomposition of organic matter (Paustian et al. 1997b).

Organic soils, also referred to as histosols, include all soils with more than 12 to 20 percent organic carbon by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil that accelerates both the decomposition rate and CO_2 emissions.[39] Due to the depth and richness of the organic layers, carbon loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). Due to deeper drainage and more intensive management practices, the use of organic soils for annual crop production leads to higher carbon loss rates than drainage of organic soils in grassland or forests (IPCC 2006).

Cropland remaining cropland includes all cropland in an inventory year that has been cropland for a continuous time period of at least 20 years. This determination is based on the United States Department of Agriculture (USDA) National Resources Inventory (NRI) for non-federal lands (USDA-NRCS 2020) and the National Land Cover Dataset for federal lands (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). Cropland includes all land that is used to produce food and fiber, forage that is harvested and used as feed (e.g., hay and silage), in addition to cropland that has been enrolled in the Conservation Reserve Program (CRP)[40] (i.e., considered set-aside cropland).

There are two discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for cropland remaining cropland. First, croplands in Alaska are not included in the *Inventory*, and second, some miscellaneous croplands that occur throughout the United States are also not included in the *Inventory* due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). These differences lead to discrepancies between the managed area in cropland remaining cropland and the cropland area included in the *Inventory* analysis (Table 6-39). Improvements are underway to incorporate croplands in Alaska and miscellaneous croplands as part of future *Inventories* (see Planned Improvements section).

Land use and land management of mineral soils are the largest contributor to total net carbon stock change, especially in the early part of the time series (see Table 6-36 and Table 6-37). In 2022, mineral soils are estimated to sequester 62.0 MMT CO_2 Eq. (16.9 MMT C). This level of carbon storage in mineral soils represents a more than 58 percent increase since the initial reporting year of 1990. Carbon dioxide emissions from organic soils are 30.3 MMT CO_2 Eq. (8.3 MMT C) in 2022, which is an 11 percent decrease in losses of soil carbon compared to 1990. In total, United States agricultural soils in cropland remaining cropland sequestered approximately 31.7 MMT CO_2 Eq. (8.6 MMT C) in 2022.

Table 6-36: Net CO_2 Flux from Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT CO_2 Eq.)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Mineral Soils	(39.2)	(61.8)	(47.1)	(48.5)	(38.2)	(62.2)	(62.0)
Organic Soils	34.2	30.2	29.3	29.1	29.4	30.2	30.3

[39] N_2O emissions from drained organic soils are included in the Agricultural Soil Management section of the Agriculture chapter of the *Inventory*.

[40] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10 to 15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

Total Net Flux	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-37: Net CO_2 Flux from Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT C)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Mineral Soils	(10.7)	(16.9)	(12.9)	(13.2)	(10.4)	(17.0)	(16.9)
Organic Soils	9.3	8.2	8.0	7.9	8.0	8.2	8.3
Total Net Flux	**(1.4)**	**(8.6)**	**(4.9)**	**(5.3)**	**(2.4)**	**(8.7)**	**(8.6)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Soil organic carbon stocks increase in cropland remaining cropland largely due to conservation tillage (i.e., reduced- and no-till practices), land set-aside from production in the Conservation Reserve Program, annual crop production with hay or pasture in rotations, and manure amendments (Ogle et al. 2023). The mineral soil carbon stock changes between 1990 and 2022 range from 38.2 to 69.6 MMT CO_2 Eq. per year, with a mean of 55.9 MMT CO_2 Eq. Soil organic carbon losses from drainage of organic soils are relatively stable across the time series with a mean emission of 30.2 MMT CO_2 Eq. per year.

The spatial variability in the 2020 annual soil organic carbon stock changes[41] are displayed in Figure 6-6 and Figure 6-7 for mineral and organic soils, respectively. Isolated areas with high rates of carbon accumulation occur throughout the agricultural land base in the United States, but there are more concentrated areas, such as the Maryland, Delaware, and Virginia where there have been relatively high adoption rates of cover crop management. The regions with the highest rates of emissions from drainage of organic soils occur in the Southeastern Coastal Region (particularly Florida and Louisiana), Northeast and upper Midwest surrounding the Great Lakes, and isolated areas along the Pacific Coast (particularly California), which coincides with the largest concentrations of organic soils in the United States that are used for agricultural production.

[41] Only national-scale emissions are estimated for 2021 to 2022 in this *Inventory* using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 6-6: Total Net Annual Soil Carbon Stock Changes for Mineral Soils under Agricultural Management within States, 2020, Cropland Remaining Cropland

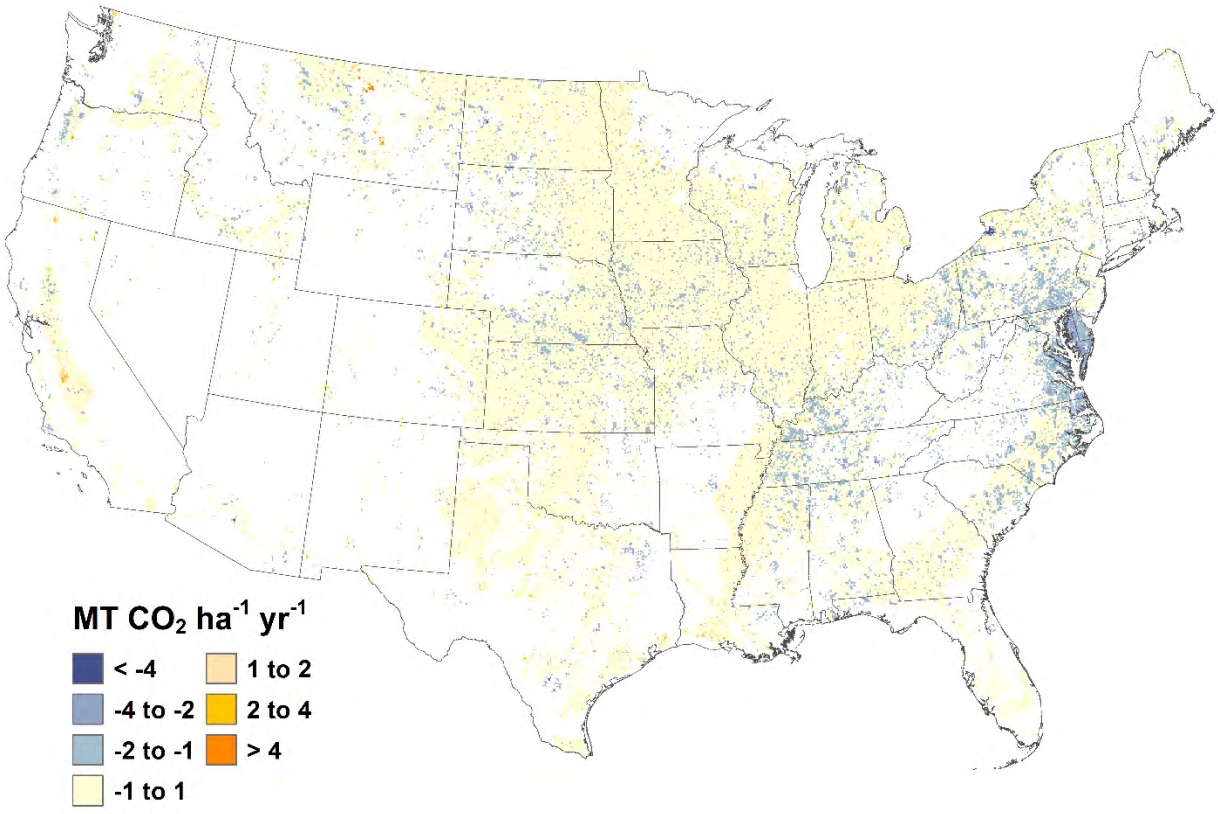

Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020. Negative values represent a net increase in soil organic carbon stocks, and positive values represent a net decrease in soil organic carbon stocks.

Figure 6-7: Total Net Annual Soil Carbon Stock Changes for Organic Soils under Agricultural Management within States, 2020, Cropland Remaining Cropland

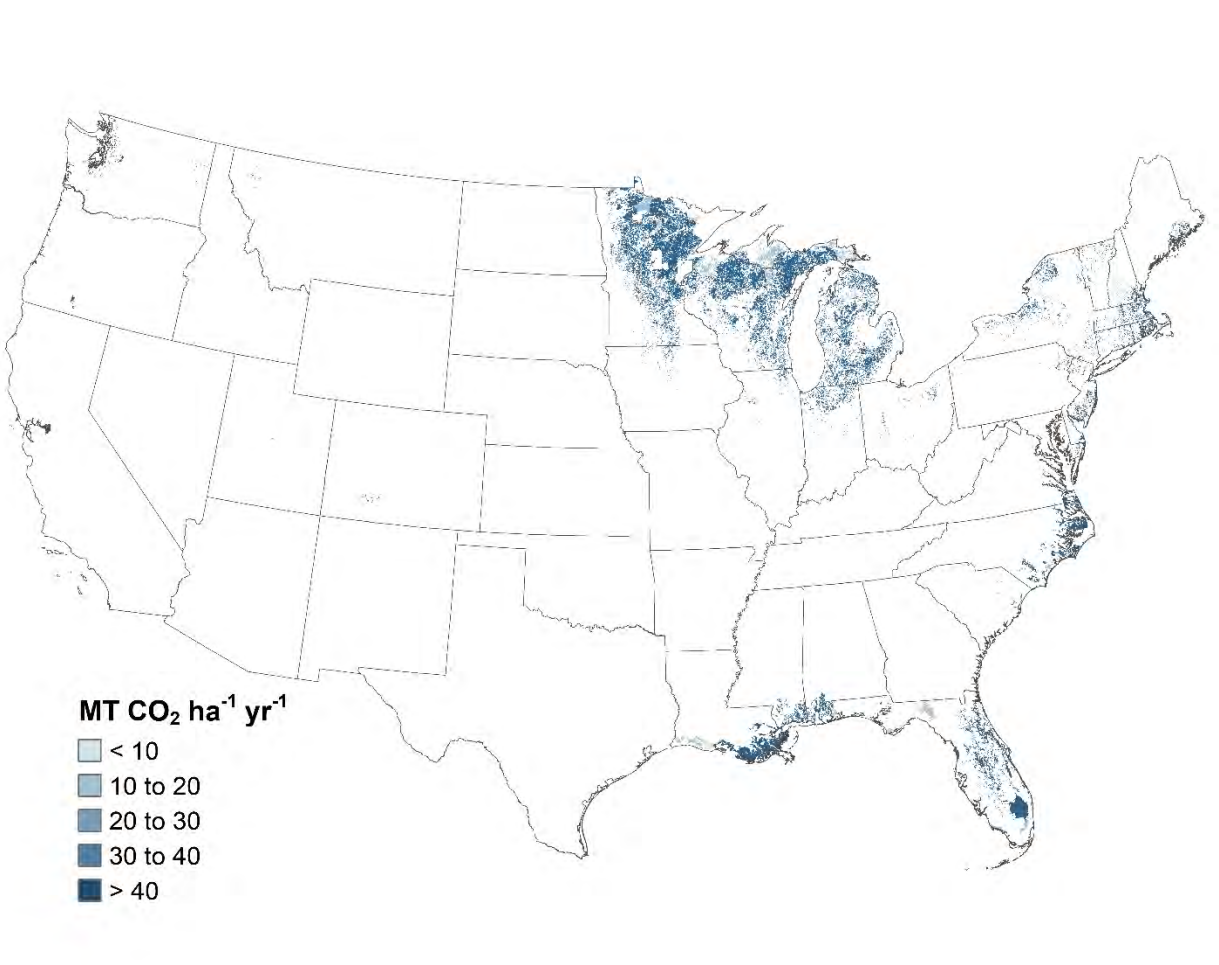

Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in soil organic carbon stocks for cropland remaining cropland, including (1) agricultural land use and management activities on mineral soils; and (2) agricultural land use and management activities on organic soils. Carbon dioxide emissions and removals[42] due to changes in mineral soil organic carbon stocks are estimated using a Tier 3 method for the majority of annual crops (Ogle et al. 2010, 2023). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (see list of crops in the Mineral Soil Carbon Stock Changes section below) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale, regardless of crop). Emissions from organic soils are estimated using a Tier 2 IPCC method. While a combination of Tier 2 and 3 methods are used to estimate carbon stock changes across most of the time series, a surrogate data method has been applied to

[42] Removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil carbon pools.

estimate stock changes in the last two years of the *Inventory*. Stock change estimates based on surrogate data will be recalculated in a future *Inventory* report using the Tier 2 and 3 methods when data become available.

Soil organic carbon stock changes on non-federal lands are estimated for cropland remaining cropland (as well as agricultural land falling into the IPCC categories land converted to cropland, grassland remaining grassland, and land converted to grassland) according to land-use histories recorded in the USDA NRI survey through 2017 (USDA-NRCS 2020), and the cropping histories were extended through 2020 using the USDA-NASS Crop Data Layer Product (CDL) (USDA-NASS 2021). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land-use areas are consistent across all land- use categories (see Section 6.1 for more information).

The NRI is a statistically-based sample and includes approximately 604,000 survey locations in agricultural land for the conterminous United States and Hawaii. There are 364,333 survey locations that are included in the Tier 3 method, and another 239,757 locations included in the Tier 2 method. Each survey location is associated with a weight that allows scaling of carbon stock changes from NRI survey locations to the entire country (i.e., each weight represents the amount of area that is expected to have the same land use/management history as the sample point).

Land use and some management information (e.g., crop type, soil attributes, and irrigation) are collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data has been collected for 4 out of 5 years during each survey cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018 to 2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021), by overlaying NRI survey locations on the CDL in a geographic information system and extracting the crop types to extend the cropping histories. NRI survey locations are classified as cropland remaining cropland in a given year between 1990 and 2020 if the land use has been cropland for a continuous time period of at least 20 years. The NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of cropland remaining cropland in the early part of the time series to the extent that some areas are converted to cropland between 1971 and 1978.

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate organic carbon stock changes for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat, but is not applied to estimate organic carbon stock changes from other crops or rotations with other crops. The model-based approach uses the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil organic carbon stock changes, soil nitrous oxide (N_2O) emissions from agricultural soil management, and methane (CH_4) emissions from rice cultivation. Carbon and nitrogen dynamics are linked in plant-soil systems through the biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil carbon and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between carbon and nitrogen cycling in soils.

The remaining crops on mineral soils are estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method is also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), and soil organic carbon stock changes on federal croplands. Mineral soil organic carbon stocks are estimated using a Tier 2 method for these areas because the DayCent model, which is used for the Tier 3 method, has not been fully tested for estimating carbon stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. In addition, there is insufficient information to simulate croplands on federal lands using DayCent.

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 stock change data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[43] and weather data from the PRISM Climate Group (PRISM 2022). See Box 6-4 for more information about the surrogate data method. Stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data.

Box 6-4: Surrogate Data Method

Time series extension is needed because there are typically gaps at the end of the time series. This is mainly because the NRI, which provides critical data for estimating greenhouse gas emissions and removals, does not release new activity data every year.

A surrogate data method has been used to impute missing emissions at the end of the time series for soil organic carbon stock changes in cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland. A linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the modeled 1990 to 2020 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), Xβ contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the emissions data for 1990 to 2020 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2021 to 2022.

A critical issue with the application of splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions rather than compiling the full inventory. Consequently, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each iteration of the Monte Carlo analysis for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2020), estimating emissions from each model and deriving confidence intervals combining uncertainty across all iterations. This approach propagates uncertainties through the calculations from the original inventory and the surrogate data method. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes are estimated to a 30 cm depth using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of carbon, nitrogen, and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g.,

[43] See https://quickstats.nass.usda.gov/.

planting, harvesting, fertilization, manure amendments, tillage, irrigation, cover crops, and grazing; more information is provided below). The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, for most croplands[44] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2022), and soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC (2006) because the simulation model treats changes as continuous over time as opposed to the simplified discrete changes represented in the default method (see Box 6-5 for additional information).

Box 6-5: Tier 3 Approach for Soil Carbon Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil organic carbon stock changes for the majority of agricultural land with mineral soils. This approach results in a more complete and accurate estimation of soil organic carbon stock changes and entails several fundamental differences from the IPCC Tier 1 or 2 methods, as described below.

1) The IPCC Tier 1 and 2 methods are simplified approaches for estimating soil organic carbon stock changes and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven management systems) in the United States. In contrast, the Tier 3 model incorporates the same variables (i.e., climate, soils, and management systems) with considerably more detail both temporally and spatially, and captures multi-dimensional interactions through the more complex model structure.

2) The IPCC Tier 1 and 2 methods have a coarser spatial resolution in which data are aggregated to soil types in climate regions, of which there about 30 combinations in the United States. In contrast, the Tier 3 model simulates soil carbon dynamics at about 364,000 individual NRI survey locations in crop fields and grazing lands.

The IPCC Tier 1 and 2 methods use a simplified approach for estimating changes in carbon stocks that assumes a step-change from one equilibrium level of the carbon stock to another equilibrium level. In contrast, the Tier 3 approach simulates a continuum of carbon stock changes that may reach a new equilibrium over an extended period of time depending on the environmental conditions (i.e., a new equilibrium often requires hundreds to thousands of years to reach). More specifically, the DayCent model, which is used in the United States Inventory, simulates soil carbon dynamics (and CO_2 emissions and uptake) on a daily time step based on carbon emissions and removals from plant production and decomposition processes. These changes in soil organic carbon stocks are influenced by multiple factors that affect primary production and decomposition, including changes in land use and management, weather variability and secondary feedbacks between management activities, climate, and soils.

Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2020). Additional sources of activity data are used to supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2022; USDA-

[44] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2020. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

NRCS 2018; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006 and 2013 to 2016. These data are combined with other datasets in an imputation analysis. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use Gradient Boosting (Friedman 2001) to determine the likely management practice at a given NRI survey location; and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method for certain variables that are adapted to reflect the trending information (Little 1988; van Buuren 2012). Gradient boosting is a machine learning technique used in regression and classification tasks, among others. It combines predictions from multiple weak prediction models and outperforms many complicated machine learning algorithms. It makes the best predictions at specific NRI survey locations or at state or region level models. The predictive mean matching method identifies the most similar management activity recorded in the CEAP surveys that match the prediction from the gradient boosting algorithm. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the gradient boosting. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2020). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). To determine the trends in tillage management, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and OpTIS Data Product[45] for 2008 to 2020 (Hagen et al. 2020). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). For cover crops, CEAP data are combined with information from USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OpTIS data (Hagen et al. 2020). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

Uncertainty in the carbon stock estimates from DayCent associated with management activity includes input uncertainty due to missing management data in the NRI survey, which is imputed from other sources as discussed above; model uncertainty due to incomplete specification of carbon and nitrogen dynamics in the DayCent model algorithms and associated parameterization; and sampling uncertainty associated with the statistical design of the NRI survey. Uncertainty is estimated with two variance components (Ogle et al. 2010). The first variance component quantifies the uncertainty in management activity data, model structure and parameterization. To assess this uncertainty, carbon and nitrogen dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007, 2010, 2023). The data are combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2020. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), and random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020 using the DayCent model. Further elaboration on the methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

[45] OpTIS data on tillage and cover crop practices provided by Regrow Agriculture, Inc.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). The time series of activity data will be updated in a future inventory, and emissions from 2021 to 2022 will be recalculated.

Tier 2 Approach. In the IPCC Tier 2 method, data on climate, soil types, land use, and land management activity are used to classify land area and apply appropriate factors to estimate soil organic carbon stock changes to a 30 cm depth (Ogle et al. 2003, 2006). The primary source of activity data for land use, crop and irrigation histories is the 2017 NRI survey (USDA-NRCS 2020). Each NRI survey location is classified by soil type, climate region, and management condition using data from other sources. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled for these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Therefore, land-use patterns for the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015).

Additional management activities needed for the Tier 2 method are based on the imputation product described for the Tier 3 approach, including tillage practices, mineral fertilization, and manure amendments that are assigned to NRI survey locations. Activity data used exclusively in the Tier 2 method are wetland restoration for Conservation Reserve Program land from Euliss and Gleason (2002). Climate zones in the United States are determined from the IPCC climate map (IPCC 2006), and then assigned to NRI survey locations.

Reference carbon stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provides a more robust sample for estimating the reference condition. Country-specific carbon stock change factors are derived from published literature to determine the impact of management practices on soil organic carbon storage (Ogle et al. 2003, 2006). The factors represent changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. However, country-specific factors associated with organic matter amendments are not estimated due to an insufficient number of studies in the United States to analyze the impacts of this practice. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Uncertainty in soil carbon stock changes is estimated with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data and carbon stock change factors. To assess this uncertainty, changes in soil organic carbon stocks for mineral soils are estimated 1,000 times for 1990 through 2020 using a Monte Carlo stochastic simulation approach and probability distribution functions for the country-specific stock change factors, reference carbon stocks, and land use activity data (Ogle et al. 2003; Ogle et al. 2006). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC

2006). As with the Tier 3 method, time series of activity data will be updated in a future inventory, and emissions from 2021 to 2022 will be recalculated (see Planned Improvements section).

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in cropland remaining cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) rather than default IPCC rates. As with mineral soils, uncertainty is estimated with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data and emission factors. A Monte Carlo stochastic simulation with 1,000 iterations is used to quantify this uncertainty with probability distribution functions for the country-specific organic soil emission factors and land use activity data. The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Further elaboration on the methodology and data used to estimate stock changes from organic soils are described in Annex 3.12.

In order to ensure time-series consistency, the same Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in a future inventory when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is quantified for changes in soil organic carbon stocks associated with cropland remaining cropland (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-38 for each subsource (mineral and organic soil carbon stocks) and the methods that are used in the *Inventory* analyses (i.e., Tier 2 and Tier 3). Uncertainty for the Tier 2 and 3 approaches is derived from two variance components (Ogle et al. 2010). For the first component, a Monte Carlo approach is used to address uncertainties in management activity data as well as model parameterization and structure or emissions factors for the Tier 3 and Tier 2 methods, respectively (Ogle et al. 2010, 2023). The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire land base, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities (see Annex 3.12 for further discussion). For 2021 to 2022, additional uncertainty is propagated through a Monte Carlo analysis that is associated with the surrogate data method (see Box 6-3). Soil organic carbon stock changes from the Tier 2 and 3 approaches are combined using the simple error propagation method provided by the IPCC (2006). The combined uncertainty is calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic carbon stocks in cropland remaining cropland ranges from 212 percent below to 212 percent above the 2022 stock change estimate of -31.7 MMT CO_2 Eq. The large relative uncertainty around the 2022 stock change estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error.

Table 6-38: Approach 2 Quantitative Uncertainty Estimates for Soil Carbon Stock Changes occurring within Cropland Remaining Cropland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(58.8)	(123.6)	5.9	-110%	+110%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.2)	(8.4)	2.0	-162%	+162%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	30.3	12.7	47.9	-58%	+58%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(31.7)**	**(99.0)**	**35.6**	**-212%**	**+212%**

[a] Range of C stock change estimates is a 95 percent confidence interval.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Uncertainty is also associated with lack of reporting of agricultural woody biomass and dead organic matter carbon stock changes. However, woody biomass carbon stock changes are likely minor in perennial crops, with relatively small amounts of woody crops such as orchards and nut plantations. There will be removal and replanting of tree crops each year, but the net effect on biomass carbon stock changes is probably minor because the overall area and tree density is relatively constant across time series. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have more significant changes over the *Inventory* time series, compared to perennial woody crops, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter carbon stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. This trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. In addition, results from the DayCent model are compared to field measurements and soil monitoring sites associated with the NRI (Spencer et al. 2011), and a statistical relationship has been developed to assess uncertainties in the predictive capability of the model (Ogle et al. 2007). The comparisons include 69 long-term experiment sites and 145 NRI soil monitoring network sites, with 1406 observations across all of the sites (see Annex 3.12 for more information). Quality control uncovered several errors in the Tier 2 method following the initial analysis, such as no estimation for some NRI survey locations (i.e., federal lands and Hawaii), double counting some NRI survey locations with aggregation to the national scale, and errors in the estimation of the two variance components associated with the uncertainty analysis. The errors have been corrected following the diagnosis of the quality control issues.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to the need for recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) extending the time series for crop histories through 2020 using USDA-NASS CDL data; c) incorporating USDA-NRCS CEAP survey data for 2013 to 2016; d) incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020; e) modifying the statistical imputation method for the management activity data associated with about tillage practices, mineral fertilization, manure amendments, cover crop management, and

planting and harvest dates using gradient boosting instead of an artificial neural network; f) updating time series of synthetic nitrogen fertilizer sales data, PRP nitrogen and manure nitrogen available for application to soils; g) constraining synthetic nitrogen fertilization and manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; h) re-calibrating the soil carbon module in the DayCent model using Bayesian methods; and i) expanding the crops in the Tier 3 method to include dry beans, lentils, onions, peas and tomatoes, which shifted some NRI survey locations from the Tier 2 to the Tier 3 method. The combined impact from these improvements resulted in an average annual increase in soil C stocks of 4.2 MMT CO_2 Eq., or 26 percent, from 1990 to 2021 relative to the previous *Inventory*.

Planned Improvements

A key improvement is conducting an analysis of carbon stock changes in Alaska for cropland. The improvement will be conducted using the Tier 2 method for mineral and organic soils that is described earlier in this section. The analysis will initially focus on land-use change, which typically has a larger impact on soil organic carbon stock changes than management practices, but will be further refined over time to incorporate management data. The improvement will resolve most of the differences between the managed land base for cropland remaining cropland and amount of area currently included in cropland remaining cropland (see Table 6-39).

Table 6-39: Comparison of Managed Land Area in Cropland Remaining Cropland and Area in the Current Cropland Remaining Cropland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	*Inventory*	Difference
1990	162,273	162,247	26
1991	161,840	161,814	26
1992	161,343	161,317	26
1993	159,577	159,551	26
1994	157,890	157,864	26
1995	157,277	157,251	26
1996	156,639	156,613	26
1997	156,018	155,992	26
1998	152,335	152,309	26
1999	151,432	151,406	26
2000	151,257	151,231	26
2001	150,734	150,708	26
2002	150,426	150,400	26
2003	151,055	151,029	26
2004	150,787	150,761	26
2005	150,417	150,391	26
2006	149,908	149,882	26
2007	150,117	150,091	26
2008	149,718	149,692	26
2009	149,660	149,634	26
2010	149,222	149,196	26
2011	148,626	148,600	26
2012	148,297	148,271	26
2013	148,660	148,633	26
2014	149,141	149,115	26
2015	148,525	148,499	26
2016	148,436	148,410	26

2017	148,331	148,305	26
2018	149,720	149,694	26
2019	149,503	149,477	26
2020	149,822	149,796	26
2021	150,591	*	*
2022	151,276	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

There are several other planned improvements underway related to the plant production module in DayCent. Crop parameters associated with temperature effects on plant production will be further improved in DayCent with additional model calibration. Senescence events following grain filling in crops, such as wheat, are being modified based on recent model algorithm development, and will be incorporated. There will also be further testing and parameterization of the DayCent model to reduce uncertainty, particularly the submodules that are used to approximate the cycling of nitrogen through the plant-soil system, which will also have impacts on carbon cycling in the model simulations.

Improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that are used in the field burning of agricultural residues source category (see Section 5.7). This improvement will more accurately represent the carbon inputs to the soil that are associated with residue burning. In addition, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Another improvement is to estimate biomass carbon stock changes in agroforestry systems and perennial tree crops. Methods combining survey data and remote sensing imagery are under development to determine the extent of land with agroforestry and perennial tree crops. In addition, a meta-analysis is being conducted to derive country-specific factors for biomass C stock changes in agroforestry systems. Although the influence of perennial tree crop biomass is expected to be minor, carbon stock changes may be significantly impacted by the effect of agroforestry practices.

Many of these improvements are expected to be completed for the next (1990 through 2023) *Inventory* (i.e., 2025 submission), pending prioritization of resources.

6.5 Land Converted to Cropland (CRT Category 4B2)

Land converted to cropland includes all current cropland in an inventory year that had been in another land use(s) during the previous 20 years (IPCC 2006), and used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage). For example, grassland or forest land converted to cropland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006).

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983; Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining (Tubiello et al. 2015).

The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic carbon stocks with land use change. All soil organic carbon stock changes are estimated and reported for land converted to cropland, but reporting of carbon stock changes for aboveground and belowground biomass, dead wood, and litter pools is limited to forest land converted to cropland and grassland converted to cropland for woodland conversions (i.e., woodland conversion to cropland).[46]

Grassland converted to cropland is the largest source of emissions from 1990 to 2000, while forest land converted to cropland is the largest source of emissions from 2001 to 2022. This shift is largely due to reduced losses of carbon from mineral soils after 2001. The high losses of carbon from forest land converted to cropland is due to reductions in biomass and dead organic matter carbon following conversion from forests (Table 6-40 and Table 6-41). The net change in total carbon stocks for 2022 led to CO_2 emissions to the atmosphere of 35.1 MMT CO_2 Eq. (9.6 MMT C), including 12.1 MMT CO_2 Eq. (3.3 MMT C) from aboveground biomass carbon losses, 2.0 MMT CO_2 Eq. (0.6 MMT C) from belowground biomass carbon losses, 2.3 MMT CO_2 Eq. (0.6 MMT C) from dead wood carbon losses, 3.4 MMT CO_2 Eq. (0.9 MMT C) from litter carbon losses, 12.6 MMT CO_2 Eq. (3.4 MMT C) from mineral soils and 2.7 MMT CO_2 Eq. (0.7 MMT C) from drainage and cultivation of organic soils. The overall net loss of carbon has declined by 23 percent from 1990 to 2022.

Table 6-40: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Land Converted to Cropland by Land-Use Change Category (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Grassland Converted to Cropland	**27.3**	**17.2**	**13.7**	**13.0**	**10.6**	**16.1**	**16.3**
Aboveground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	24.6	13.7	10.7	10.1	8.0	13.5	13.6
Organic Soils	2.4	3.3	2.7	2.7	2.4	2.4	2.4
Forest Land Converted to Cropland	**19.2**	**19.2**	**19.7**	**19.7**	**19.7**	**19.6**	**19.6**
Aboveground Live Biomass	11.4	11.6	11.9	11.9	11.9	11.9	11.9
Belowground Live Biomass	1.9	2.0	2.0	2.0	2.0	2.0	2.0
Dead Wood	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Litter	3.2	3.3	3.3	3.4	3.4	3.4	3.4
Mineral Soils	0.4	0.2	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.1	+	+	+	+	+	+
Other Lands Converted to Cropland	**(1.8)**	**(2.5)**	**(1.6)**	**(1.6)**	**(1.2)**	**(1.1)**	**(1.1)**
Mineral Soils	(1.9)	(2.6)	(1.7)	(1.6)	(1.2)	(1.1)	(1.1)
Organic Soils	0.1	0.1	+	+	+	+	+
Settlements Converted to Cropland	**(0.0)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Mineral Soils	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.7**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Mineral Soils	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Organic Soils	0.5	0.5	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**11.6**	**11.7**	**12.0**	**12.0**	**12.1**	**12.1**	**12.1**
Belowground Live Biomass	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Dead Wood	**2.2**	**2.2**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**

[46] Changes in biomass carbon stocks are estimated for forest land converted to cropland and grassland converted to cropland for woodland conversions. There is a planned improvement to include the effect of other land use conversions, in addition to herbaceous grassland conversions to cropland in a future *Inventory*. Note: changes in dead organic matter are assumed negligible for other land use conversions to cropland, except forest land and woodland conversions.

Litter	**3.3**	**3.3**	**3.4**	**3.4**	**3.4**	**3.4**	**3.4**
Total Mineral Soil Flux	**23.2**	**11.3**	**9.2**	**8.6**	**6.9**	**12.5**	**12.6**
Total Organic Soil Flux	**3.2**	**3.9**	**3.0**	**3.0**	**2.6**	**2.6**	**2.7**
Total Net Flux	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-41: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Land Converted to Cropland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Grassland Converted to Cropland	**7.4**	**4.7**	**3.7**	**3.6**	**2.9**	**4.4**	**4.4**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	6.7	3.7	2.9	2.8	2.2	3.7	3.7
Organic Soils	0.7	0.9	0.7	0.7	0.6	0.6	0.7
Forest Land Converted to Cropland	**5.2**	**5.2**	**5.4**	**5.4**	**5.4**	**5.4**	**5.4**
Aboveground Live Biomass	3.1	3.2	3.2	3.3	3.3	3.3	3.3
Belowground Live Biomass	0.5	0.5	0.5	0.6	0.6	0.6	0.6
Dead Wood	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Litter	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Mineral Soils	0.1	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Cropland	**(0.5)**	**(0.7)**	**(0.4)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**
Mineral Soils	(0.5)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.3)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Cropland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	0.1	0.1	+	+	+	+	+
Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**3.2**	**3.2**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**
Belowground Live Biomass	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Dead Wood	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Litter	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Total Mineral Soil Flux	**6.3**	**3.1**	**2.5**	**2.4**	**1.9**	**3.4**	**3.4**
Total Organic Soil Flux	**0.9**	**1.1**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**
Total Net Flux	**12.4**	**9.4**	**8.7**	**8.6**	**8.0**	**9.5**	**9.6**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to cropland, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with conversion of forest lands to croplands, as well as (2) the impact from all land use conversions to cropland on mineral and soil organic carbon stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter carbon stock changes for forest land converted to cropland. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023). However, there is no country-specific data for cropland biomass, so only a default biomass estimate (IPCC 2006) for croplands was used to estimate carbon stock changes (litter and dead wood carbon stocks were assumed to be zero since no reference carbon density estimates exist for croplands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. Details for each of the carbon attributes described below are available in Domke et al. (2022) and Westfall et al. (2023). If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

For dead organic matter, if FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011; Westfall et al. 2023) with additional modifications for woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016). See Annex 3.13 for more information about reference carbon density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic stock changes are estimated for land converted to cropland according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020). Land use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a five-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, which are currently available through 2017 (USDA-NRCS 2020), and the time series for cropping histories was extended through 2020 using the USDA-NASS Crop Data Layer Product (CDL) (USDA-NASS 2021) and National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as land converted to cropland in a given year between 1990 and 2020 if the land use is cropland but had been another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998, which may have led to an underestimation of land converted to cropland in the early part of the time series to the extent that some areas are converted to cropland from 1971 to 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach using the DayCent ecosystem model (Ogle et al. 2010, 2023) is applied to estimate carbon stock changes from 1990 to 2020 for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat. Soil organic carbon stock changes on the remaining mineral soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003, 2006), including land used to produce some vegetables and perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[47]

For the years 2021 to 2022, a surrogate data method is used to estimate soil organic carbon stock changes at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 stock change data from the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[48] and weather data from the PRISM Climate Group (PRISM 2022). See Box 6-4 in the Methodology section of Cropland Remaining Cropland for more information about the surrogate data method. Stock change estimates for 2021 to 2022 will be recalculated in future *Inventories* when the time series of activity data are updated.

Tier 3 Approach. For the Tier 3 method, mineral soil organic carbon stocks and stock changes are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. National estimates are obtained by using the model to simulate historical land use change patterns as recorded in the USDA NRI survey (USDA-NRCS 2020). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020. See the cropland remaining cropland section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (described in Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Time series of activity data will be updated in a future *Inventory*, and emissions from 2020 to 2022 will be recalculated.

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic carbon stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in cropland remaining cropland. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the 2021 to 2022 time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future *Inventory*, and emissions from 2021 to 2022 will be recalculated.

[47] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2018).

[48] See https://quickstats.nass.usda.gov/.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) as described in the cropland remaining cropland section for organic soils. Further elaboration on the methodology is also provided in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series (i.e., 2021 to 2022) are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in a future *Inventory* when new activity data are incorporated into the analysis.

Uncertainty

The uncertainty analyses for biomass, dead wood and litter carbon losses with forest land converted to cropland and grassland converted to cropland for woodland conversions are conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux associated with forest land remaining forest land. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in cropland remaining cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method, which is also described in cropland remaining cropland.

Uncertainty estimates are presented in Table 6-42 for each sub-source (i.e., biomass carbon stocks, dead wood carbon stocks, litter carbon stocks, soil organic carbon stocks for mineral and organic soils) and the method applied in the *Inventory* analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates for the total carbon stock changes for biomass, dead organic matter and soils are combined using the simple error propagation methods provided by the IPCC (2006). The combined uncertainty for total carbon stock changes in land converted to cropland ranged from 93 percent below to 93 percent above the 2022 stock change estimate of 35.1 MMT CO_2 Eq. The large relative uncertainty in the 2022 estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-42: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Cropland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Converted to Cropland	**16.3**	**(12.1)**	**44.7**	**-174%**	**174%**
Aboveground Live Biomass	0.1	+	0.3	-128%	124%
Belowground Live Biomass	+	+	+	-100%	56%
Dead Wood	+	+	0.1	-100%	173%
Litter	+	+	0.1	-100%	147%
Mineral Soil C Stocks: Tier 3	11.0	(17.2)	39.3	-256%	256%
Mineral Soil C Stocks: Tier 2	2.6	0.6	4.5	-77%	77%

Organic Soil C Stocks: Tier 2	2.4	0.5	4.4	-79%	79%
Forest Land Converted to Cropland	**19.6**	**3.4**	**35.8**	**-82%**	**82%**
Aboveground Live Biomass	11.9	(3.2)	27.1	-127%	127%
Belowground Live Biomass	2.0	(0.6)	4.6	-127%	127%
Dead Wood	2.2	(0.6)	5.1	-128%	127%
Litter	3.4	(0.9)	7.6	-127%	128%
Mineral Soil C Stocks: Tier 2	0.1	+	0.2	-107%	107%
Organic Soil C Stocks: Tier 2	+	+	0.1	-429%	429%
Other Lands Converted to Cropland	**(1.1)**	**(2.1)**	+	**-99%**	**99%**
Mineral Soil C Stocks: Tier 2	(1.1)	(2.1)	+	-99%	99%
Organic Soil C Stocks: Tier 2	+	+	+	0%	0%
Settlements Converted to Cropland	**(0.1)**	**(0.3)**	+	**-97%**	**97%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	(0.1)	-71%	71%
Organic Soil C Stocks: Tier 2	+	+	0.1	-103%	103%
Wetlands Converted to Croplands	**0.4**	**(0.1)**	**0.8**	**-115%**	**115%**
Mineral Soil C Stocks: Tier 2	0.2	+	0.3	-124%	124%
Organic Soil C Stocks: Tier 2	0.2	(0.2)	0.6	-173%	173%
Total: Land Converted to Cropland	**35.1**	**2.4**	**67.8**	**-93%**	**93%**
Aboveground Live Biomass	**12.1**	**(3.1)**	**27.2**	**-126%**	**126%**
Belowground Live Biomass	**2.0**	**(0.5)**	**4.6**	**-126%**	**126%**
Dead Wood	**2.3**	**(0.6)**	**5.1**	**-126%**	**125%**
Litter	**3.4**	**(0.9)**	**7.7**	**-126%**	**126%**
Mineral Soil C Stocks: Tier 3	**11.0**	**(17.2)**	**39.3**	**-256%**	**256%**
Mineral Soil C Stocks: Tier 2	**1.6**	**(0.7)**	**3.8**	**-144%**	**144%**
Organic Soil C Stocks: Tier 2	**2.7**	**0.7**	**4.7**	**-73%**	**73%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with lack of reporting of agricultural biomass and dead organic matter carbon stock changes. Biomass carbon stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land that is used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have led to larger changes in biomass carbon stocks at least in some regions of the United States. However, there are currently no datasets to evaluate the trends. Changes in dead organic matter carbon stocks are assumed to be negligible with conversion of land to croplands with the exception of forest lands, which are included in this analysis. This assumption will be further explored in a future *Inventory*.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland for information on QA/QC steps.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to the need for recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) extending the time series for crop histories through 2020 using USDA-NASS CDL data; c) incorporating USDA-NRCS CEAP survey data for 2013 to 2016; d) incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020; e) modifying the statistical imputation method for the management activity data associated with about tillage practices, mineral fertilization, manure amendments, cover crop management, planting and harvest dates using gradient boosting instead of an artificial neural network; f) updating time series of synthetic nitrogen fertilizer sales data, PRP nitrogen and manure nitrogen available for application to soils; g)

constraining synthetic nitrogen fertilization and manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; h) re-calibrating the soil carbon module in the DayCent model using Bayesian methods; i) expanding the crops in the Tier 3 method to include dry beans, lentils, onions, peas and tomatoes, which shifted some NRI survey locations from the Tier 2 to the Tier 3 method, and j) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks associated with forest land converted to cropland. Finally, see further updates in Section 6.2, describing updates to the estimates for aboveground volume and biomass which impacted lands converted to cropland estimates. As a result, land converted to cropland has an estimated smaller carbon loss of 20.7 MMT CO_2 Eq. on average over the time series. This represents a 37 percent average decrease in carbon stock change losses for land converted to cropland compared to the previous *Inventory*, and is mainly due to less loss of carbon associated with forest land converted to cropland.

Planned Improvements

A key improvement is to estimate the biomass carbon stock changes for other land use changes beyond only forest land converted to cropland and grassland converted to cropland for woodland conversion, which is included in the current *Inventory*. Additional planned improvements are discussed in the Planned Improvements section of Cropland Remaining Cropland.

6.6 Grassland Remaining Grassland (CRT Category 4C1)

Carbon in grassland ecosystems occurs in biomass, dead organic matter, and soils. Soils are the largest pool of carbon in grasslands, and have the greatest potential for longer-term storage or release of carbon. Biomass and dead organic matter carbon pools are relatively ephemeral compared to the soil carbon pool, with the exception of carbon stored in tree and shrub biomass that occurs in grasslands. The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic carbon stocks with land use and management. Carbon stock changes for aboveground and belowground biomass, dead wood and litter pools are reported for woodlands (i.e., a subcategory of grasslands[49]), and may be extended to include agroforestry management associated with grasslands in the future. For soil organic carbon, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting changes due to (1) agricultural land use and management activities on mineral soils, and (2) agricultural land use and management activities on organic soils.[50]

Grassland remaining grassland includes all grassland in an inventory year that had been grassland for a continuous time period of at least 20 years (USDA-NRCS 2018). Grassland includes pasture and rangeland that are primarily, but not exclusively used for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or inter-seeding of legumes. Woodlands are also considered grassland and are areas of continuous tree cover that do not meet the definition of forest land (see Section 6.1 for more information about the criteria for forest land).

There is a discrepancy between the current land representation (see Section 6.1) and the area data that have been used in the inventory for grassland remaining grassland. Specifically, grasslands in Alaska are not included in the *Inventory*, and this land base is approximately 50 million hectares. This difference leads to a discrepancy between

[49] Woodlands are considered grasslands in the U.S. land representation because they do not meet the definition of forest land.

[50] CO_2 emissions associated with liming and urea fertilization are also estimated but included in the Agriculture chapter of the report.

the managed area in grassland remaining grassland in the land representation and the grassland area included in the emissions and removals estimation for the grassland remaining grassland land-use category (Table 6-46). Improvements are underway to incorporate grasslands in Alaska as part of future *Inventories* (see Planned Improvements section).

For grassland remaining grassland, there has been considerable variation in carbon stocks between 1990 and 2022. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes are small on a per hectare rate basis across the time series even in the years with a larger total change in stocks. The net change in total carbon stocks for 2022 led to net CO_2 emissions to the atmosphere of 13.4 MMT CO_2 Eq. (3.6 MMT C), including -1.3 MMT CO_2 Eq. (-0.4 MMT C) from net gains of aboveground biomass C, -0.2 MMT CO_2 Eq. (-0.1 MMT C) from net gains in belowground biomass carbon, 2.8 MMT CO_2 Eq. (0.8 MMT C) from net losses in dead wood carbon, less than 0.05 MMT CO_2 Eq. (less than 0.05 MMT C) from net gains in litter C, 6.5 MMT CO_2 Eq. (1.8 MMT C) from net losses in mineral soil organic carbon, and 5.5 MMT CO_2 Eq. (1.5 MMT C) from losses of carbon due to drainage and cultivation of organic soils (Table 6-43 and Table 6-44). Losses of carbon are 45.2 percent lower in 2022 compared to 1990, but as noted previously, stock changes are highly variable from 1990 to 2022, with an average annual change of 19.9 MMT CO_2 Eq. (5.4 MMT C).

Table 6-43: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Aboveground Live Biomass	(2.7)	(2.1)	(1.4)	(1.4)	(1.4)	(1.4)	(1.3)
Belowground Live Biomass	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	3.2	3.1	2.9	2.9	2.9	2.9	2.8
Litter	(0.4)	(0.2)	+	+	+	+	+
Mineral Soils	18.6	18.6	22.0	22.0	9.3	3.8	6.5
Organic Soils	6.1	5.1	5.3	5.3	5.5	5.5	5.5
Total Net Flux	**24.4**	**24.1**	**28.6**	**28.5**	**16.1**	**10.6**	**13.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Aboveground Live Biomass	(0.7)	(0.6)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Belowground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	0.9	0.8	0.8	0.8	0.8	0.8	0.8
Litter	(0.1)	(0.1)	+	+	+	+	+
Mineral Soils	5.1	5.1	6.0	6.0	2.5	1.0	1.8
Organic Soils	1.7	1.4	1.4	1.4	1.5	1.5	1.5
Total Net Flux	**6.6**	**6.6**	**7.8**	**7.8**	**4.4**	**2.9**	**3.6**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

The spatial variability in soil organic carbon stock changes for 2020[51] is displayed in Figure 6-8 for mineral soils and in Figure 6-9 for organic soils. Although relatively small on a per-hectare basis, grassland soils gained carbon in

[51] Only national-scale emissions are estimated for 2021 to 2022 in the current *Inventory* using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on land use data from 2020.

isolated areas that mostly occurred in pastures of the upper Midwest and eastern United States; losses occurred primarily in the northwestern region. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils that occur in managed grassland, including the Southeastern Coastal Region (particularly Florida), areas surrounding the Great Lakes in the upper Midwest and Northeast, and a few isolated areas along the Pacific Coast.

Figure 6-8: Total Net Annual Soil Carbon Stock Changes for Mineral Soils under Agricultural Management within States, 2020, Grassland Remaining Grassland

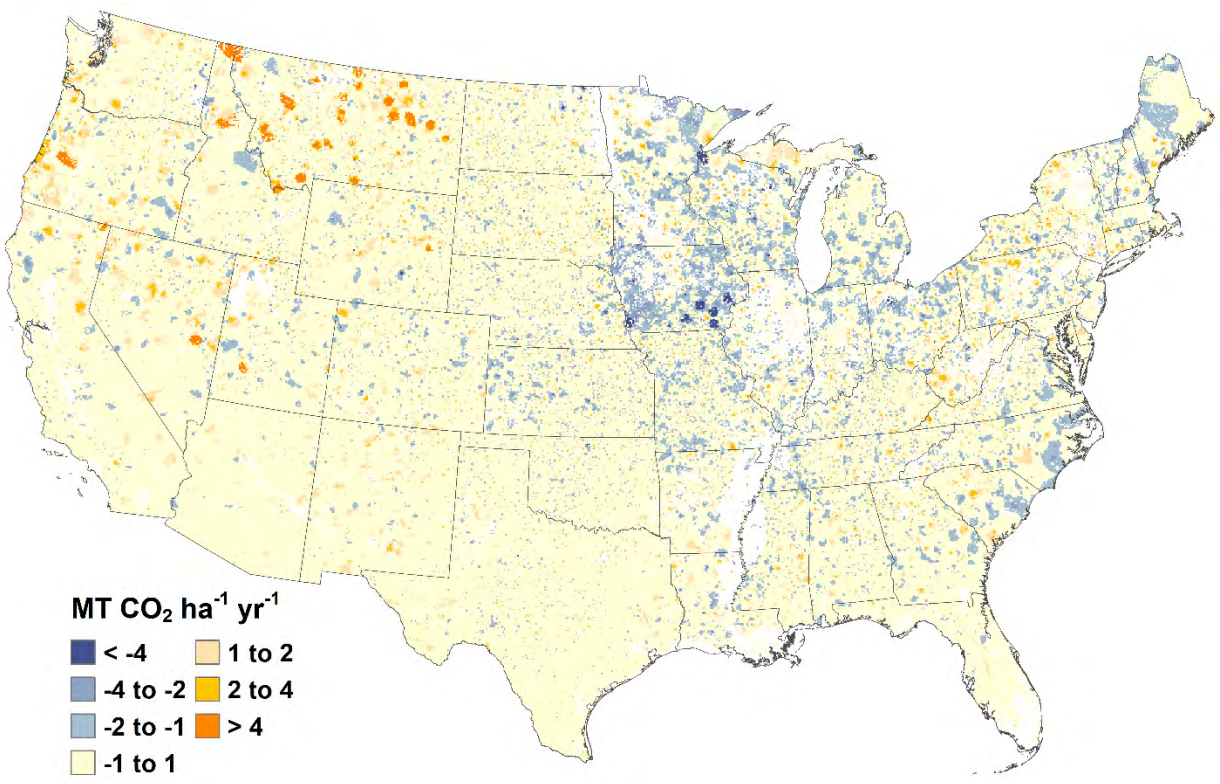

Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2020. Negative values represent a net increase in soil organic carbon stocks, and positive values represent a net decrease in soil organic carbon stocks.

Figure 6-9: Total Net Annual Soil Carbon Stock Changes for Organic Soils under Agricultural Management within States, 2020, Grassland Remaining Grassland

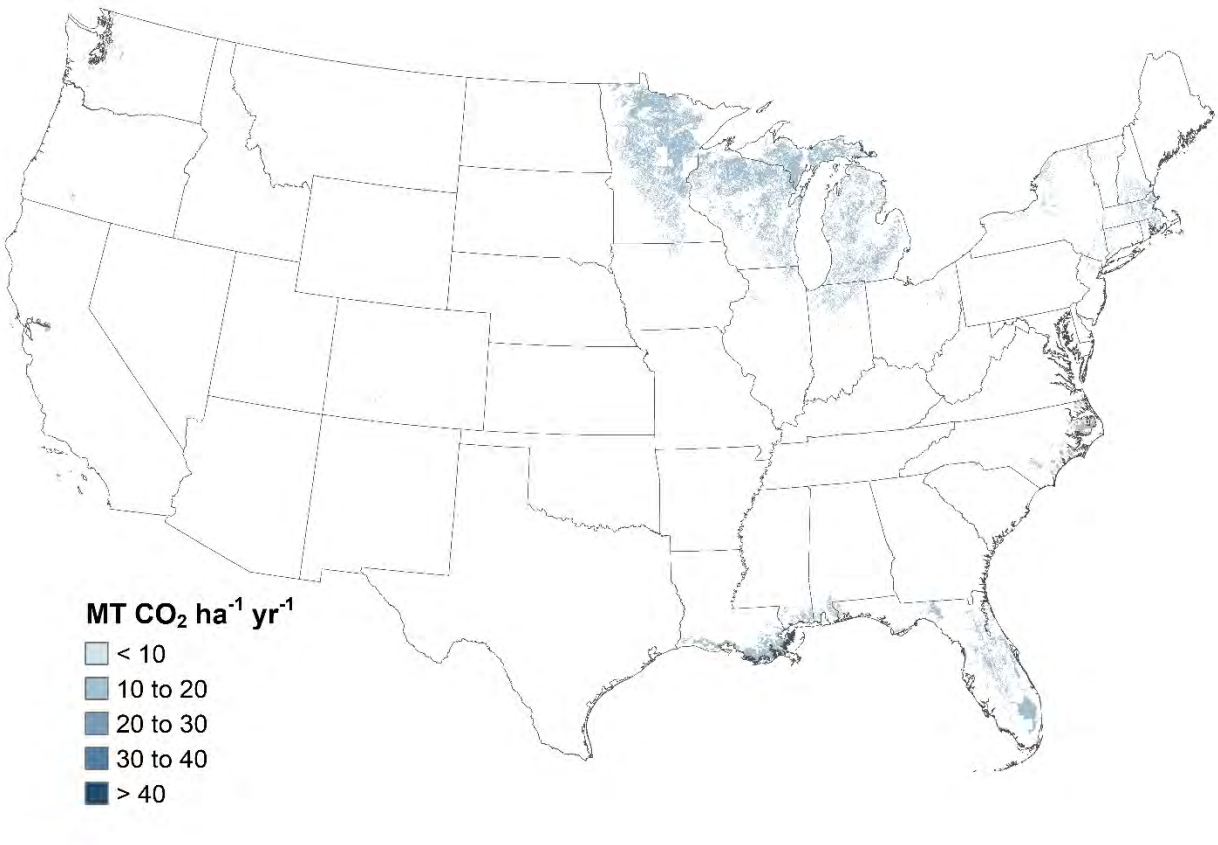

Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2020.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for grassland remaining grassland, including (1) aboveground and belowground biomass, dead wood and litter carbon for woodlands, as well as (2) soil organic carbon stocks for mineral and organic soils.

Biomass, Dead Wood and Litter Carbon Stock Changes

Woodlands are lands that do not meet the definition of forest land or agroforestry (see Section 6.1), but include woody vegetation with carbon storage in aboveground and belowground biomass, dead wood and litter carbon (IPCC 2006) as described in the Forest Land Remaining Forest Land section. Carbon stocks and net annual carbon stock change were determined according to the stock-difference method for the conterminous United States, which involved applying carbon estimation factors to annual forest inventories across time to obtain carbon stocks and then subtracting the values between years to estimate the stock changes. The methods for estimating carbon stocks and stock changes for woodlands in grassland remaining grassland are consistent with those in the forest

land remaining forest land section and are described in Annex 3.13. All annual National Forest Inventory (NFI) plots available in the public FIA database (USDA Forest Service 2023) were used in the current *Inventory*. While the NFI is an all-lands inventory, only those plots that meet the definition of forest land are typically measured. However, in some cases, particularly in the Central Plains and Southwest United States, woodlands have been measured as part of the survey. This analysis is limited to those plots and is not considered a comprehensive assessment of trees outside of forest land that meet the definition of grassland. The same methods are applied from 1990 to 2022 in order to ensure time-series consistency. This methodology is consistent with IPCC guidance (2006).

Soil Carbon Stock Changes

The following section includes a brief description of the methodology used to estimate changes in soil organic carbon stocks for grassland remaining grassland, including: (1) agricultural land use and management activities on mineral soils; and (2) agricultural land use and management activities on organic soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils is provided in the Cropland Remaining Cropland section and Annex 3.12.

Soil organic carbon stock changes are estimated for grassland remaining grassland on non-federal lands according to land use histories recorded in the USDA National Resources Inventory (NRI) (USDA-NRCS 2020). Land use and some management information (e.g., grass type, soil attributes, and irrigation) were originally collected for each NRI survey location on a five-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the data provided in the National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the NLCD are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as grassland remaining grassland in a given year between 1990 and 2020 if the land use had been grassland for 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of grassland remaining grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate carbon stock changes from 1990 to 2020 for most mineral soils in grassland remaining grassland. The carbon stock changes for the remaining soils are estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume), as well as additional stock changes associated with biosolids (i.e., treated sewage sludge) amendments and federal land.[52]

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions data from the Tier 2 and 3 methods. Surrogate data for these regression models are based on weather data from the PRISM Climate Group (PRISM Climate Group 2022). See Box 6-4 in the Methodology section of Cropland Remaining Cropland for more information about the surrogate data method.

[52] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2020).

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes for grassland remaining grassland are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in Cropland Remaining Cropland. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2020). The amount of manure produced by each livestock type is calculated for managed and unmanaged waste management systems based on methods described in Section 5.2 and Annex 3.11. Manure nitrogen deposition from grazing animals (i.e., pasture/range/paddock (PRP) manure) is an input to the DayCent model to estimate the influence of PRP manure on carbon stock changes for lands included in the Tier 3 method. Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020 using the NRI survey data. Further elaboration on the Tier 3 methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Stock change estimates for 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data (see the Planned Improvements section in Cropland Remaining Cropland).

Tier 2 Approach. The Tier 2 approach is based on the same methods described in the Tier 2 portion of the Cropland Remaining Cropland section for mineral soils, with the exception of the manure nitrogen deposition from grazing animals (i.e., PRP manure), and the land use and management data that are used in the *Inventory* for federal grasslands. First, the PRP nitrogen manure is included in the Tier 2 method that is not deposited on lands included in the Tier 3 method. Second, the NRI (USDA-NRCS 2020) provides land use and management histories for all non-federal lands, and is the basis for the Tier 2 analysis for these areas. However, NRI does not provide land use information on federal lands. The land use data for federal lands is based on the NLCD (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). In addition, the Bureau of Land Management (BLM) manages some of the federal grasslands, and compiles information on grassland condition through the BLM Rangeland Inventory (BLM 2014). To estimate soil organic carbon stock changes from federal grasslands, rangeland conditions in the BLM data are aligned with IPCC grassland management categories of nominal, moderately degraded, and severely degraded in order to apply the appropriate emission factors. Further elaboration on the Tier 2 methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future *Inventory*, and emissions from 2021 to 2022 will be recalculated.

Additional Mineral Carbon Stock Change Calculations

A Tier 2 method is used to adjust annual carbon stock change estimates for mineral soils between 1990 and 2022 to account for additional carbon stock changes associated with biosolids (i.e., treated sewage sludge) amendments. Estimates of the amounts of biosolids nitrogen applied to agricultural land are derived from national data on biosolids generation, disposition, and nitrogen content (see Section 7.2 for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Although biosolids can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in grassland remaining grassland. Total biosolids generation data for 1988, 1996, and 1998, in dry mass units, are

obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. Nitrogen application rates from Kellogg et al. (2000) are used to determine the amount of area receiving biosolids amendments. The soil organic carbon storage rate is estimated at 0.38 metric tons carbon per hectare per year for biosolids amendments to grassland as described above. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in grassland remaining grassland are estimated using the Tier 2 method in IPCC (2006), which utilizes country-specific carbon loss rates (Ogle et al. 2003) rather than default IPCC rates. For more information, see the cropland remaining cropland section for organic soils and Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series (i.e., 2021 to 2022) are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter carbon losses with woodlands is conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux associated with forest land remaining forest land. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Uncertainty analysis for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in Cropland Remaining Cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method.

Uncertainty estimates are presented in Table 6-45 for each subcategory (i.e., soil organic carbon stocks for mineral and organic soils) and the method applied in the *Inventory* analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for total carbon stock changes in grassland remaining grassland ranges from more than 926 percent below and above the 2022 stock change estimate of 13.4 MMT CO_2 Eq. The large relative uncertainty in the 2022 estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error with this data splicing method.

Table 6-45: Approach 2 Quantitative Uncertainty Estimates for Carbon Stock Changes Occurring Within Grassland Remaining Grassland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Woodland Biomass:					
Aboveground live biomass	(1.3)	(1.5)	(1.2)	-10%	12%
Belowground live biomass	(0.2)	(0.3)	(0.2)	-8%	8%
Dead wood	2.8	2.5	3.2	-13%	14%
Litter	+	+	0.1	-22%	22%
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	7.4	(116.1)	131.0	-1,663%	1,663%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	0.1	(0.4)	0.6	-448%	448%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Biosolids [i.e., Treated Sewage Sludge] Amendments)	(1.0)	(1.5)	(0.5)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	5.5	1.2	9.9	-79%	79%
Combined Uncertainty for Flux Associated with Carbon Stock Changes Occurring in Grassland Remaining Grassland	**13.4**	**(110.3)**	**137.0**	**-926%**	**926%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter carbon stock changes for agroforestry systems. Changes in biomass and dead organic matter carbon stocks are assumed to be negligible in other grasslands, largely comprised of herbaceous biomass, although there are significant changes at sub-annual time scales across seasons.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks in woodlands for grassland remaining grassland; c) constraining manure N applications in the Tier 3 method at the state scale rather than the national scale; and d) re-calibrating the soil carbon module in the DayCent model using Bayesian methods. See the Recalculations Discussion in the cropland remaining cropland section for other improvements. As a result of these improvements, grassland remaining grassland has a larger average loss of 10.7 MMT CO_2 Eq. across the time series compared to the previous *Inventory*, which is an 1,850 percent change on average over the time series. The large average value for the percentage change is due to an increase from near zero to 7.0 MMT CO_2 Eq. for the estimated carbon stock change in 1994.

Planned Improvements

A key improvement planned for the *Inventory* includes conducting an analysis of carbon stock changes for grasslands in Alaska. This improvement will be a significant development that will resolve the majority of the discrepancy between the managed land base for grassland remaining grassland and amount of area currently included in grassland remaining grassland emissions and removals calculations (see Table 6-46).

Table 6-46: Comparison of Managed Land Area in Grassland Remaining Grassland and the Area in the current Grassland Remaining Grassland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	*Inventory*	Difference
1990	328,565	279,705	48,861
1991	328,058	279,205	48,853
1992	327,601	278,755	48,846
1993	325,869	277,030	48,839
1994	324,249	275,418	48,831
1995	323,373	274,549	48,824
1996	322,517	273,701	48,816
1997	321,752	272,944	48,808
1998	319,811	271,010	48,801
1999	318,903	270,110	48,793
2000	317,917	269,131	48,785
2001	317,060	268,282	48,778
2002	316,443	267,883	48,560
2003	316,545	268,206	48,340
2004	316,350	268,232	48,118
2005	315,930	268,034	47,897
2006	315,422	267,748	47,675
2007	315,164	267,712	47,452
2008	315,090	267,861	47,228
2009	315,163	268,159	47,005
2010	314,765	267,984	46,781
2011	314,270	267,712	46,557
2012	313,977	267,586	46,391
2013	314,640	268,416	46,224
2014	315,329	269,271	46,058
2015	315,427	269,535	45,891
2016	315,327	269,602	45,725
2017	316,056	270,339	45,717
2018	318,959	273,168	45,791
2019	320,255	274,471	45,784
2020	320,855	275,079	45,777
2021	321,909	*	*
2022	322,779	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

Additionally, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements. For information about

other improvements, see the Planned Improvements section in Cropland Remaining Cropland.

Non-CO_2 Emissions from Grassland Fires (CRT Source Category 4C1)

Fires are common in grasslands and are thought to have been a key feature shaping the evolution of the grassland vegetation in North America (Daubenmire 1968; Anderson 2004). Fires can occur naturally through lightning strikes but are also an important management practice to remove standing dead vegetation and improve forage for grazing livestock. Woody and herbaceous biomass will be oxidized in a fire, although in this section the current focus is primarily on herbaceous biomass.[53] Biomass burning emits a variety of trace gases including non-CO_2 greenhouse gases such as CH_4 and N_2O, as well as CO and NO_x that can become greenhouse gases when they react with other gases in the atmosphere (Andreae and Merlet 2001). IPCC (2006) recommends reporting non-CO_2 greenhouse gas emissions from all wildfires and prescribed burning occurring in managed grasslands.

Biomass burning in grasslands of the United States (including burning emissions in grassland remaining grassland and land converted to grassland) is a relatively small source of emissions, but it has increased by 184 percent since 1990. In 2022, CH_4 and N_2O emissions from biomass burning in grasslands were 0.3 MMT CO_2 Eq. (12 kt) and 0.3 MMT CO_2 Eq. (1 kt), respectively. Annual emissions from 1990 to 2022 have averaged approximately 0.4 MMT CO_2 Eq. (14 kt) of CH_4 and 0.3 MMT CO_2 Eq. (1 kt) of N_2O (see Table 6-47 and Table 6-48).

Table 6-47: CH_4 and N_2O Emissions from Biomass Burning in Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
CH_4	0.1	0.4	0.6	0.2	0.6	0.5	0.3
N_2O	0.1	0.4	0.5	0.2	0.5	0.4	0.3
Total Net Flux	**0.2**	**0.8**	**1.1**	**0.3**	**1.1**	**0.9**	**0.6**

Note: Totals may not sum due to independent rounding.

Table 6-48: CH_4, N_2O, CO, and NO_x Emissions from Biomass Burning in Grassland (kt)

	1990	2005	2018	2019	2020	2021	2022
CH_4	4	15	22	6	20	18	12
N_2O	+	1	2	1	2	2	1
CO	122	430	610	170	575	509	346
NO_x	7	26	37	10	35	31	21

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland, including (1) determination of the land base that is classified as managed grassland; (2) assessment of managed grassland area that is burned each year, and (3) estimation of emissions resulting from the fires. For this *Inventory*, the IPCC Tier 1 method is applied to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland from 1990 to 2020 (IPCC 2006). A data splicing method is used to estimate the emissions from 2021 to 2022, which is discussed later in this section.

The land area designated as managed grassland is based primarily on the USDA National Resources Inventory (NRI) (Nusser and Goebel 1997; USDA-NRCS 2020). NRI has survey locations across the entire United States, but does not

[53] A planned improvement is underway to incorporate woodland tree biomass into the *Inventory* for non-CO_2 emissions from grassland fires.

classify land use on federally-owned areas, and so survey locations on federal lands are designated as grassland using land cover data from the National Land Cover Dataset (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015) (see Section 6.1).

The area of biomass burning in grasslands (grassland remaining grassland and land converted to grassland) is determined using 30-m burned area data from the Monitoring Trends in Burn Severity (MTBS) program for 1990 through 2020 (MTBS 2023; Picotte, et al. 2020).[54] NRI survey locations on grasslands are designated as burned in a year if there is a fire within 500 m of the survey point according to the MTBS fire data. The area of biomass burning is estimated from the NRI spatial weights and aggregated to the country (Table 6-49).

Table 6-49: Thousands of Grassland Hectares Burned Annually

Year	1990	2005	2018	2019	2020	2021	2022
Thousand Hectares	457	1,612	2,290	637	2156	NE	NE

NE (Not Estimated)

Notes: Burned area was not estimated (NE) for 2021 to 2022, but will be updated in a future *Inventory*.

For 1990 to 2020, the total area of grassland burned is multiplied by the IPCC default factor for grassland biomass (4.1 tonnes dry matter per ha) (IPCC 2006) to estimate the amount of combusted biomass. A combustion factor of 1 is assumed in this *Inventory*, and the resulting biomass estimate is multiplied by the IPCC default grassland emission factors for CH_4 (2.3 g CH_4 per kg dry matter), N_2O (0.21 g N_2O per kg dry matter), CO (65 g CO per kg dry matter) and NO_x (3.9 g NO_x per kg dry matter) (IPCC 2006).

A linear extrapolation of the trend in the time series is applied to estimate emissions for 2021 to 2022. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to derive the trend in emissions over time from 1990 to 2020, and the trend is used to approximate the 2021 to 2022 emissions. The Tier 1 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

The same methods are applied from 1990 to 2020, and a data splicing method is used to extend the time series from 2021 to 2022 ensuring a consistent time series of emissions data. The trend extrapolation is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006).

Uncertainty

Emissions are estimated using a linear regression model with ARMA errors for 2021 to 2022. The model produces estimates for the upper and lower bounds of the emission estimate and the results are summarized in Table 6-50. Methane emissions from biomass burning in grassland for 2022 are estimated to be between approximately 0.0 and 0.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 100 percent below and 137 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions are estimated to be between approximately 0.0 and 0.7 MMT CO_2 Eq., or 100 percent below and 137 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq.

[54] See http://www.mtbs.gov.

Table 6-50: Uncertainty Estimates for Non-CO_2 Greenhouse Gas Emissions from Biomass Burning in Grassland (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Burning	CH_4	0.3	+	0.8	-100%	+137%
Grassland Burning	N_2O	0.3	+	0.7	-100%	+137%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by linear regression time-series model for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of emissions from biomass burning in grasslands of Alaska. Grassland burning emissions could be relatively large in this region of the United States, and therefore extending this analysis to include Alaska is a planned improvement for the *Inventory*. There is also uncertainty due to lack of reporting on the combustion of woody biomass, and this is another planned improvement.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Recalculations Discussion

While the methods for calculating non-CO_2 emissions from grassland burning remained the same, the two primary data sources have been updated from the previous *Inventory*. We used the current NRI 2017 dataset (USDA-NRCS 2020) and the current release of MTBS burn perimeter data (MTBS 2023). In the original estimation of non-CO_2 emissions, the same set of NRI survey locations was used for the entire time series, but the locations identified with burning were allowed to vary inter-annually with this revision. These changes resulted in a net increase in CO_2-equivalent emissions by an annual average of 0.1 MMT CO_2 Eq., or 19 percent from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

Two key planned improvements have been identified for this source category, including 1) incorporation of country-specific grassland biomass factors, and 2) extending the analysis to include Alaska. In the current *Inventory*, biomass factors are based on a global default for grasslands that is provided by the IPCC (2006). There is considerable variation in grassland biomass, however, which would affect the amount of fuel available for combustion in a fire. Alaska has an extensive area of grassland and includes tundra vegetation, although some of the areas are not managed. There has been an increase in fire frequency in boreal forest of the region (Chapin et al. 2008), and this may have led to an increase in burning of neighboring grassland areas. There is also an effort under development to incorporate grassland fires into DayCent model simulations. Lastly, a future *Inventory* will incorporate non-CO_2 greenhouse emissions from burning woodland tree biomass in grasslands. These improvements are expected to reduce uncertainty and produce more accurate estimates of non-CO_2 greenhouse gas emissions from grassland burning.

6.7 Land Converted to Grassland (CRT Category 4C2)

Land converted to grassland includes all current grassland in an inventory year that had been in another land use(s) during the previous 20 years (IPCC 2006).[55] For example, cropland or forest land converted to grassland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). Grassland includes pasture and rangeland that are used primarily but not exclusively for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes.

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983, Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic carbon stocks due to land use change. All soil organic carbon stock changes are estimated and reported for land converted to grassland, but there is limited reporting of other pools in this *Inventory*. Losses of aboveground and belowground biomass, dead wood and litter carbon from forest land converted to grassland are reported, as well as gains and losses associated with conversions to woodlands[56] from other land uses, including croplands converted to grasslands, settlements converted to grasslands and other lands converted to grasslands. However, the current *Inventory* does not include the gains and losses in aboveground and belowground biomass, dead wood and litter carbon for other land use conversions to grassland that are not woodlands.[57]

There is a discrepancy between the current land representation (see Section 6.1) and the area data that have been used in the inventory for land converted to grassland. Specifically, grassland in Alaska is not included in the *Inventory*, and this leads to a difference between the managed area in land converted to grassland in the land representation and the grassland area included in the emissions and removal calculations for land converted to grassland (Table 6-54). Improvements are underway to incorporate grassland area in Alaska as part of future *Inventories* (see Planned Improvements section).

The largest carbon losses with land converted to grassland are associated with aboveground biomass, belowground biomass, and litter carbon losses from forest land converted to grassland (see Table 6-51 and Table 6-52). These three pools led to net emissions in 2022 of 31.3, 4.3, and 8.0 MMT CO_2 Eq. (8.5, 1.2, and 2.2 MMT C), respectively. The losses associated with forest land converted to grassland are partially offset by gains associated with other land converted to grassland and due to cropland converted to grassland, which leads to less intensive management of the soil. Drainage of organic soils for grassland management led to CO_2 emissions to the atmosphere of 1.4 MMT CO_2 Eq. (0.4 MMT C). The total net carbon stock change in 2022 for land converted to

[55] USDA NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of land converted to grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978.

[56] Woodlands are considered grasslands in the U.S. land representation because they do not meet the definition of forest land.

[57] Changes in biomass carbon stocks are not currently reported for other conversions to grassland (other than forest land conversion to grassland and other land-use conversions to woodlands), but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed negligible for other land use conversions (i.e., other than forest land) to grassland based on the Tier 1 method in IPCC (2006).

grassland is estimated as a loss of 25.6 MMT CO_2 Eq. (7.0 MMT C) or a net source of emissions, which represents a decrease in carbon stock loss by 27 percent compared to the initial reporting year of 1990.

Table 6-51: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Grassland	**(10.2)**	**(16.9)**	**(10.8)**	**(10.3)**	**(9.3)**	**(13.6)**	**(12.5)**
Aboveground Live Biomass	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	+	+	+	+	+
Litter	(0.1)	(0.1)	+	+	+	+	+
Mineral Soils	(10.4)	(18.1)	(11.7)	(11.1)	(10.1)	(14.4)	(13.3)
Organic Soils	0.6	1.4	1.1	1.1	1.0	1.0	1.0
Forest Land Converted to Grassland	**50.2**	**49.0**	**46.9**	**46.9**	**46.8**	**46.8**	**46.8**
Aboveground Live Biomass	34.5	33.4	31.8	31.8	31.8	31.8	31.8
Belowground Live Biomass	4.8	4.6	4.4	4.4	4.4	4.4	4.4
Dead Wood	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Litter	8.6	8.5	8.2	8.2	8.2	8.2	8.2
Mineral Soils	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Grassland	**(4.0)**	**(9.6)**	**(10.2)**	**(10.5)**	**(8.2)**	**(8.0)**	**(8.0)**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(3.8)	(9.4)	(10.1)	(10.4)	(8.1)	(7.9)	(7.9)
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland	**(0.6)**	**(0.7)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**
Aboveground Live Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(0.1)	(0.3)	(0.5)	(0.5)	(0.4)	(0.4)	(0.4)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**(0.1)**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**33.9**	**32.9**	**31.4**	**31.4**	**31.3**	**31.3**	**31.3**
Belowground Live Biomass	**4.7**	**4.5**	**4.4**	**4.3**	**4.3**	**4.3**	**4.3**
Dead Wood	**2.2**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**
Litter	**8.4**	**8.2**	**8.0**	**8.0**	**8.0**	**8.0**	**8.0**
Total Mineral Soil Flux	**(14.6)**	**(27.9)**	**(22.4)**	**(22.1)**	**(18.7)**	**(22.8)**	**(21.7)**
Total Organic Soil Flux	**0.7**	**1.8**	**1.5**	**1.5**	**1.4**	**1.4**	**1.4**
Total Net Flux	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-52: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Grassland	**(2.8)**	**(4.6)**	**(3.0)**	**(2.8)**	**(2.5)**	**(3.7)**	**(3.4)**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	(2.8)	(4.9)	(3.2)	(3.0)	(2.8)	(3.9)	(3.6)
Organic Soils	0.2	0.4	0.3	0.3	0.3	0.3	0.3
Forest Land Converted to Grassland	**13.7**	**13.3**	**12.8**	**12.8**	**12.8**	**12.8**	**12.8**
Aboveground Live Biomass	9.4	9.1	8.7	8.7	8.7	8.7	8.7
Belowground Live Biomass	1.3	1.3	1.2	1.2	1.2	1.2	1.2
Dead Wood	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Litter	2.4	2.3	2.2	2.2	2.2	2.2	2.2
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Grassland	**(1.1)**	**(2.6)**	**(2.8)**	**(2.9)**	**(2.2)**	**(2.2)**	**(2.2)**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	(1.0)	(2.6)	(2.8)	(2.8)	(2.2)	(2.2)	(2.2)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Grassland	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**9.2**	**9.0**	**8.6**	**8.6**	**8.5**	**8.5**	**8.5**
Belowground Live Biomass	**1.3**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
Dead Wood	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Litter	**2.3**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Total Mineral Soil Flux	**(4.0)**	**(7.6)**	**(6.1)**	**(6.0)**	**(5.1)**	**(6.2)**	**(5.9)**
Total Organic Soil Flux	**0.2**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total Net Flux	**9.6**	**5.9**	**6.9**	**6.9**	**7.8**	**6.7**	**7.0**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to grassland, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with forest land converted to grassland and other land use conversions to woodlands, as well as (2) the impact from all land use conversions to grassland on mineral and organic soil organic carbon stocks.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 3 method is applied to estimate biomass, dead wood and litter carbon stock changes for forest land converted to grassland. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023) and in the Eastern US, IPCC (2006) defaults for biomass in grasslands. There is limited data on grassland carbon stocks so only default biomass estimates (IPCC 2006) for grasslands were used to estimate carbon stock changes (litter and dead wood carbon stocks were assumed to be zero since no reference carbon density estimates exist for croplands) in the eastern United States. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion.

The amount of biomass carbon that is lost abruptly with forest land converted to grasslands is estimated based on the amount of carbon before conversion and the amount of carbon following conversion according to remeasurements in the FIA program. This approach is consistent with IPCC (2006) that assumes there is an abrupt change during the first year, but does not necessarily capture the slower change over the years following conversion until a new steady state is reached. It was determined that using an IPCC Tier 1 approach that assumes all carbon is lost in the year of conversion for forest land converted to grasslands in the West and Great Plains states does not accurately characterize the transfer of carbon in woody biomass during abrupt or gradual land use change. To estimate this transfer of carbon in woody biomass, state-specific carbon densities for woody biomass remaining on these former forest lands following conversion to grasslands were developed and included in the estimation of carbon stock changes from forest land converted to grasslands in the West and Great Plains states. A review of the literature in grassland and rangeland ecosystems (Asner et al. 2003; Huang et al. 2009; Tarhouni et al. 2016), as well as an analysis of FIA data, suggests that a conservative estimate of 50 percent of the woody biomass carbon density was lost during conversion from forest land to grasslands. This estimate was used to develop state-specific carbon density estimates for biomass, dead wood, and litter for grasslands in the West and Great Plains states, and these state-specific carbon densities were applied in the compilation system to estimate the carbon losses associated with conversion from forest land to grassland in the West and Great Plains states. Further, losses from forest land to what are often characterized as woodlands are included in this category using FIA plot remeasurements and the methods and models briefly described below and in detail in Domke et al. (2022) and Westfall et al. (2023).

If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). If FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011, Westfall et al. 2023) with additional modifications to woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011).

If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016). See Annex 3.13 for more information about reference carbon density estimates for forest land.

Soil Carbon Stock Changes

Soil organic carbon stock changes are estimated for land converted to grassland according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey location on a five-year cycle beginning in 1982. In 1998, the NRI Program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018 through 2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021), while survey locations identified as grasslands are assumed to not change over this time period. However, the areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as land converted to grassland in a given year between 1990 and 2020 if the land use is grassland but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of land converted to grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate carbon stock changes in mineral soils for most of the area in land converted to grassland. Carbon stock changes on the remaining area are estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, and perennial/horticultural crops; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models includes weather data from the PRISM Climate Group (PRISM Climate Group 2022). See Box 6-4 in the Methodology section of cropland remaining cropland for more information about the surrogate data method.

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020. See the cropland remaining cropland section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in cropland remaining cropland. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data (see the Planned Improvements section in cropland remaining cropland).

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic carbon stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in grassland remaining grassland and Annex 3.12. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to grassland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) as described in the cropland remaining cropland section. Further elaboration on the methodology is also provided in Annex 3.12 for organic soils.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Annual carbon emissions from drained organic soils from 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data.

Uncertainty

The uncertainty analyses for biomass, dead wood and litter carbon losses with forest land converted to grassland and other land use conversions to woodlands are conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux in the forest land remaining forest land category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in cropland remaining cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with a surrogate data method, which is also described in the Cropland Remaining Cropland section.

Uncertainty estimates are presented in Table 6-53 for each subsource (i.e., biomass carbon stocks, mineral and organic carbon stocks in soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total carbon stocks in land converted to grassland ranges from 156 percent below to 156 percent above the 2022 stock change estimate of 25.6 MMT CO_2 Eq. The large relative uncertainty around the 2022 stock change estimate is partly due to large uncertainties in biomass and dead organic matter carbon losses with forest land conversion to grassland, in addition to variation in soil organic carbon stock changes that is not explained by the surrogate data method.

Table 6-53: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Grassland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Grassland	**(12.5)**	**(32.1)**	**7.0**	**-156%**	**156%**
Aboveground Live Biomass	(0.1)	(0.3)	+	-136%	134%
Belowground Live Biomass	+	+	+	-78%	100%
Dead Wood	+	(0.1)	+	-128%	100%
Litter	+	(0.1)	+	-170%	100%
Mineral Soil C Stocks: Tier 3	(11.6)	(31.0)	7.8	-167%	167%
Mineral Soil C Stocks: Tier 2	(1.7)	(3.7)	0.2	-114%	114%
Organic Soil C Stocks: Tier 2	1.0	+	2.0	-96%	96%
Forest Land Converted to Grassland	**46.8**	**12.2**	**81.4**	**-74%**	**74%**
Aboveground Live Biomass	31.8	(1.4)	64.9	-104%	104%
Belowground Live Biomass	4.4	(0.2)	9.0	-104%	105%
Dead Wood	2.4	(0.1)	5.0	-105%	104%
Litter	8.2	(0.4)	16.8	-104%	104%
Mineral Soil C Stocks: Tier 2	(0.1)	(0.2)	+	-140%	140%
Organic Soil C Stocks: Tier 2	0.1	(0.0)	0.2	-130%	130%
Other Lands Converted to Grassland	**(8.0)**	**(12.9)**	**(3.1)**	**-61%**	**61%**
Aboveground Live Biomass	(0.1)	(0.1)	+	-69%	44%
Belowground Live Biomass	+	+	+	-100%	100%
Dead Wood	+	(0.1)	+	-85%	100%
Litter	(0.1)	(0.1)	+	-60%	47%
Mineral Soil C Stocks: Tier 2	(7.9)	(12.8)	(3.0)	-62%	62%
Organic Soil C Stocks: Tier 2	0.1	+	0.1	-111%	111%
Settlements Converted to Grassland	**(0.8)**	**(1.0)**	**(0.5)**	**-35%**	**35%**
Aboveground Live Biomass	(0.2)	(0.3)	(0.1)	-56%	61%
Belowground Live Biomass	+	+	+	-42%	100%
Dead Wood	+	(0.1)	+	-67%	100%
Litter	(0.1)	(0.1)	+	-66%	59%
Mineral Soil C Stocks: Tier 2	(0.4)	(0.6)	(0.2)	-56%	56%
Organic Soil C Stocks: Tier 2	+	+	+	-432%	432%
Wetlands Converted to Grasslands	**0.1**	**(0.2)**	**0.3**	**-289%**	**283%**
Aboveground Live Biomass	(0.1)	(0.1)	+	-85%	38%
Belowground Live Biomass	+	+	+	-100%	100%
Dead Wood	+	+	+	-95%	100%
Litter	+	+	+	-112%	100%
Mineral Soil C Stocks: Tier 2	+	+	+	-173%	173%
Organic Soil C Stocks: Tier 2	0.2	+	0.4	-112%	112%
Total: Land Converted to Grassland	**25.6**	**(14.4)**	**65.7**	**-156%**	**156%**
Aboveground Live Biomass	**31.3**	**(1.8)**	**64.5**	**-106%**	**106%**
Belowground Live Biomass	**4.3**	**(0.2)**	**9.0**	**-106%**	**106%**
Dead Wood	**2.3**	**(0.3)**	**4.8**	**-111%**	**111%**
Litter	**8.0**	**(0.6)**	**16.6**	**-107%**	**107%**
Mineral Soil C Stocks: Tier 3	**(11.6)**	**(31.0)**	**7.8**	**-167%**	**167%**
Mineral Soil C Stocks: Tier 2	**(10.1)**	**(15.4)**	**(4.9)**	**-52%**	**52%**

Organic Soil C Stocks: Tier 2	**1.4**	**0.4**	**2.4**	**-74%**	**74%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter carbon stock changes for conversions to agroforestry systems and herbaceous grasslands. The influence of agroforestry is difficult to address because there are currently no datasets to evaluate the trends in the area and associated carbon stocks in agroforestry systems. The influence of land use change to herbaceous grasslands and agroforestry will be further explored in a future *Inventory*.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland for information on QA/QC steps.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks associated with forest land converted to grassland (see Recalculations Discussion of Chapter 6.2 Forest Land Remaining Forest Land for more details); c) constraining manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; and d) re-calibrating the soil carbon module in the DayCent model using Bayesian methods. See the Recalculations Discussion in the cropland remaining cropland section for other improvements. Finally, see further updates in Section 6.2, describing updates to the estimates for aboveground volume and biomass which impacted lands converted to grassland estimates. As a result, land converted to grassland has an estimated increase in losses of carbon stock changes, leading to a net change of 53 MMT CO_2 Eq. on average over the time series, representing a 237 percent change on average compared to the previous *Inventory*. Land converted to grassland is a net source of emissions across the time series based on the recalculations in this *Inventory*. This change from a net sink to a net source is mostly due to larger estimated losses of biomass and dead organic matter with forest land converted to grassland, and smaller estimated gains in mineral soil carbon stocks for cropland and other lands converted to grasslands.

Planned Improvements

The key improvement planned for the inventory is conducting an analysis of carbon stock changes for grassland in Alaska. This will resolve the majority of the discrepancy between the managed land base for land converted to grassland and amount of area currently included in land converted to grassland emissions and removals calculations (see Table 6-54).

Table 6-54: Comparison of Managed Land Area in Land Converted to Grassland and Area in the current Land Converted to Grassland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	**Managed Land**	***Inventory***	**Difference**
1990	9,301	9,297	4
1991	9,492	9,488	4
1992	9,710	9,706	4
1993	11,619	11,615	4
1994	13,372	13,368	4
1995	14,039	14,035	4
1996	14,727	14,723	4

1997	15,411	15,408	4
1998	19,289	19,285	4
1999	20,143	20,139	4
2000	21,257	21,253	4
2001	22,349	22,345	4
2002	23,087	22,817	270
2003	22,986	22,445	541
2004	23,920	23,108	811
2005	24,091	23,009	1,082
2006	24,693	23,341	1,352
2007	24,694	23,072	1,622
2008	25,266	23,373	1,893
2009	25,424	23,260	2,163
2010	25,769	23,336	2,434
2011	26,176	23,471	2,704
2012	26,164	23,292	2,871
2013	25,154	22,116	3,038
2014	23,981	20,776	3,205
2015	24,101	20,730	3,372
2016	23,531	19,993	3,538
2017	22,808	19,270	3,538
2018	19,968	16,429	3,538
2019	19,546	16,008	3,538
2020	18,706	15,168	3,538
2021	17,351	*	*
2022	16,269	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

In addition, the amount of biomass carbon that is lost abruptly or the slower changes that continue to occur over a decade or longer with forest land converted to grasslands will be further refined in a future *Inventory*. The current values are estimated based on the amount of carbon before conversion and an estimated level of carbon left after conversion based on limited plot data from the FIA and published literature for the Western United States and Great Plains Regions. The amount of carbon left after conversion will be further investigated with additional data collection, particularly in the Western United States and Great Plains, including tree biomass, understory biomass, dead wood and litter carbon pools. In addition, biomass carbon stock changes will be estimated for conversions from other land uses to herbaceous grasslands. For information about other improvements, see the Planned Improvements section in Cropland Remaining Cropland.

6.8 Wetlands Remaining Wetlands (CRT Category 4D1)

Wetlands remaining wetlands includes all wetlands in an inventory year that have been classified as a wetland for the previous 20 years, and in this *Inventory*, the flux estimates include peatlands, coastal wetlands, and flooded land.

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands that have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction (which results in the emissions reported under peatlands remaining peatlands), and abandonment, restoration, rewetting, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely eliminated when peatlands are drained in preparation for peat extraction (Strack et al. 2004 as cited in the *2006 IPCC Guidelines*). Drained land surface and ditch networks contribute to the CH_4 flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under the IPCC Tier 1 methodology (IPCC 2006), but are included in the emissions estimates for peatlands remaining peatlands consistent with the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Nitrous oxide emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions. Although methodologies are provided to estimate emissions and removals from rewetted organic soils (which includes rewetted/restored peatlands) in IPCC (2013) guidelines, information on the areal extent of rewetted/restored peatlands in the United States is currently unavailable. The current *Inventory* estimates CO_2, CH_4 and N_2O emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO_2, N_2O, and CH_4 Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO_2, N_2O, and CH_4 emissions from lands undergoing active peat extraction (i.e., peatlands remaining peatlands) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: *Sphagnum* bogs in northern states (e.g., Minnesota) and wetlands in states further south (e.g., Florida). The peat from *Sphagnum* bogs in northern states, which is nutrient-poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient-rich.

IPCC (2006 and 2013) recommend considering both on-site and off-site emissions when estimating CO_2 emissions from peatlands remaining peatlands using the Tier 1 approach. Current IPCC methodologies estimate only on-site N_2O and CH_4 emissions. This is because off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat where subsequent runoff or leaching into waterbodies can result in indirect N_2O emissions that are already included within the agricultural soil management category.

On-site emissions from managed peatlands occur as the land is drained and cleared of vegetation, and the underlying peat is exposed to sun, weather and oxygen. As this occurs, some of the peat deposit is lost and CO_2 is emitted from the oxidation of the peat. Since N_2O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N_2O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands occurring on highly fertile/nutrient-rich soils, mostly located in the southern peatlands in Florida, contain significant amounts of organic nitrogen in inert/microbially inaccessible forms. Draining land in preparation for peat extraction allows bacteria to convert the organic nitrogen

into nitrates through nitrogen mineralization which leach to the surface where they are reduced to N_2O during nitrification. Nitrate availability also contributes to the activity of methanogens and methanotrophs that result in CH_4 emissions (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Drainage ditches, which are constructed to drain the land in preparation for peat extraction, also contribute to the flux of CH_4 through *in situ* production and lateral transfer of CH_4 from the organic soil matrix (IPCC 2013).

Off-site CO_2 emissions from managed peatlands occur from waterborne dissolved organic carbon losses and the horticultural and landscaping use of peat. Dissolved organic carbon from water drained off peatlands reacts within aquatic ecosystems and is converted to CO_2, which is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). During the horticultural and landscaping use of peat, nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most (nearly 94 percent) of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for the aforementioned horticultural and landscaping purposes.

Total emissions from peatlands remaining peatlands are estimated to be 0.6 MMT CO_2 Eq. in 2022 (see Table 6-55 and Table 6-56) comprising 0.6 MMT CO_2 Eq. (572 kt) of CO_2, 0.004 MMT CO_2 Eq. (0.13 kt) of CH_4 and 0.0004 MMT CO_2 Eq. (0.002 kt) of N_2O. Total emissions in 2022 are 4.7 percent greater than total emissions in 2021.

Total emissions from peatlands remaining peatlands have fluctuated between 0.6 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993, followed by an increasing trend until reaching peak emissions in 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009. The trend reversed in 2009 and total emissions have generally decreased between 2009 and 2021, however, total emissions from peatlands increased slightly in 2022 compared to 2021. Carbon dioxide emissions from peatlands remaining peatlands have fluctuated between 0.6 and 1.3 MMT CO_2 across the time series, and these emissions drive the trends in total emissions. Methane and N_2O emissions remained close to zero across the time series.

Table 6-55: Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	**1.1**	**1.1**	**0.7**	**0.6**	**0.6**	**0.5**	**0.6**
Off-site	1.0	1.0	0.6	0.6	0.5	0.5	0.5
On-site	0.1	0.1	+	+	+	+	+
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Total	**1.1**	**1.1**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-56: Emissions from Peatlands Remaining Peatlands (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	**1,055**	**1,101**	**650**	**613**	**590**	**547**	**572**
Off-site	985	1,030	608	572	550	509	533
On-site	70	71	42	41	41	38	39
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Off-Site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from peatlands remaining peatlands were calculated by apportioning the annual weight of peat produced in the United States (Table 6-57) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the conterminous 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS; USGS 1995 through 2018; USGS 2023a; USGS 2023b; USGS 2023c). Hawaii is assumed to have no peat production due to its absence from these sources. To develop these data, the USGS (U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey; USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The estimates for Alaska rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1993 through 2015). Similar to the U.S. Geological Survey, the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys (DGGS) solicits voluntary reporting of peat production from producers for the *Alaska's Mineral Industry* report. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the conterminous United States and Alaska, large variations in peat production can also result from variation in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates emissions from Alaska separately from the conterminous United States because Alaska previously conducted its own mineral surveys and reported peat production by volume, rather than by weight (Table 6-58). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).[58] Peat production was not reported for 2015 in *Alaska's Mineral Industry 2014* report (DGGS 2015), and reliable data are not available beyond 2012, so Alaska's peat production in 2013 through 2021 (reported in cubic yards) was assumed to be equal to the 2012 value.

Consistent with IPCC (2013) guidelines, off-site CO_2 emissions from dissolved organic carbon were estimated based on the total area of peatlands managed for peat extraction, which is calculated from production data using the methodology described in the On-Site CO_2 Emissions section below. Carbon dioxide emissions from dissolved organic carbon were estimated by multiplying the area of managed peatlands by the default emission factor for dissolved organic C provided in IPCC (2013).

The United States has largely imported peat from Canada for horticultural purposes; in 2022, imports of *Sphagnum* moss (nutrient-poor) peat from Canada represented 96 percent of total U.S. peat imports and 80 percent of U.S. domestic consumption (USGS 2023c). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). To be consistent with the Tier 1 method, only domestic peat production is accounted for when estimating off-site emissions. Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

[58] Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, "where deposits of high-quality [but nutrient poor] *Sphagnum* moss are extensive" (USGS 2008).

Table 6-57: Peat Production of Conterminous 48 States (kt)

Type of Deposit	1990	2005	2018	2019	2020	2021	2022
Nutrient-Rich	595.1	657.6	338.4	329.4	343.4	291.6	306.0
Nutrient-Poor	55.4	27.4	50.6	36.6	10.6	32.4	34.0
Total Production	**692.0**	**685.0**	**389.0**	**366.0**	**354.0**	**324.0**	**340.0**

Note: Totals may not sum due to independent rounding.

Sources: United States Geological Survey (USGS) (1991–2017) *Minerals Yearbook: Peat (1994–2016);* United States Geological Survey (USGS) (2018) *Minerals Yearbook: Peat – Tables-only release (2018);* United States Geological Survey (USGS) (2023) *Mineral Commodity Summaries: Peat (2023).*

Table 6-58: Peat Production of Alaska (Thousand Cubic Meters)

	1990	2005	2018	2019	2020	2021	2022
Total Production	49.7	47.8	93.1	93.1	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014)*.

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emission estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of land managed for peat extraction is currently not available for the United States, but consistent with IPCC (2006), an average production rate for the industry was applied to derive a land area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).[59] The area of land managed for peat extraction in the conterminous United States was estimated using both nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year, see Table 6-59. The annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO_2 emission estimates.

Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from peatlands remaining peatlands in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the assumption that a single hectare yields 100 metric tons, see Table 6-60. The IPCC (2006) on-site emissions equation also includes a term that accounts for emissions resulting from the change in carbon stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in carbon stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

Table 6-59: Peat Production Area of Conterminous 48 States (Hectares)

	1990[a]	2005	2018	2019	2020	2021	2022
Nutrient-Rich	5,951	6,576	3,384	3,294	3,434	2,916	3,060
Nutrient-Poor	554	274	506	366	106	324	340
Total Production	**6,920**	**6,850**	**3,890**	**3,660**	**3,540**	**3,240**	**3,400**

[59] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

[a] A portion of the production in 1990 is of unknown nutrient type, resulting in a total production value greater than the sum of nutrient-rich and nutrient-poor.
Note: Totals may not sum due to independent rounding.

Table 6-60: Peat Production Area of Alaska (Hectares)

	1990	2005	2018	2019	2020	2021	2022
Nutrient-Rich	0	0	0	0	0	0	0
Nutrient-Poor	286	104	212	329	428	428	428
Total Production	**286**	**104**	**212**	**329**	**428**	**428**	**428**

Note: Totals may not sum due to independent rounding.

On-site N_2O Emissions

IPCC (2006) indicates the calculation of on-site N_2O emission estimates using Tier 1 methodology only considers nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO_2 emissions methodology above details the calculation of nutrient-rich area data from production data. In order to estimate N_2O emissions, the land area estimate of nutrient-rich peatlands remaining peatlands was multiplied by the appropriate default emission factor taken from IPCC (2013). See the Planned Improvements section for additional information on identified research activities to improve peatland land area estimates.

On-site CH_4 Emissions

IPCC (2013) also suggests basing the calculation of on-site CH_4 emission estimates on the total area of peatlands managed for peat extraction. Area data is derived using the calculation from production data described in the On-site CO_2 Emissions section above. In order to estimate CH_4 emissions from drained land surface, the land area estimate of peatlands remaining peatlands was multiplied by the emission factor for direct CH_4 emissions taken from IPCC (2013). In order to estimate CH_4 emissions from drainage ditches, the total area of peatland was multiplied by the default fraction of peatland area that contains drainage ditches, and the appropriate emission factor taken from IPCC (2013). See Table 6-61 for the calculated area of ditches and drained land.

Table 6-61: Peat Production (Hectares)

	1990	2005	2018	2019	2020	2021	2022
Conterminous 48 States							
Area of Drained Land	6,574	6,508	3,696	3,477	3,363	3,078	3,230
Area of Ditches	346	343	195	183	177	162	170
Total Production	**6,920**	**6,850**	**3,890**	**3,660**	**3,540**	**3,240**	**3,400**
Alaska							
Area of Drained Land	272	99	202	312	407	407	407
Area of Ditches	14	5	11	16	21	21	21
Total Production	**286**	**104**	**212**	**329**	**428**	**428**	**428**

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. The same data sources were used throughout the time series, when available. When data were unavailable or the available data were outliers, missing values were estimated based on the past available data.

Uncertainty

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO_2, CH_4, and N_2O emissions from peatlands remaining peatlands for 2022, using the following assumptions:

- The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed.
- The uncertainty associated with peat production data stems from the fact that the USGS receives data from smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution).
- The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the conterminous United States, or ± 25 percent with a normal distribution. It should be noted that the DGGS estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008).
- The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008).
- IPCC (2006 and 2013) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed.
- The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed.
- The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-62. Carbon dioxide emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.5 and 0.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 16 percent below to 16 percent above the 2022 emission estimate of 0.6 MMT CO_2 Eq. Methane emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.001 and 0.006 MMT CO_2 Eq. This indicates a range of 59 percent below to 79 percent above the 2022 emission estimate of 0.004 MMT CO_2 Eq. Nitrous oxide emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.0002 and 0.0006 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 52 percent below to 53 percent above the 2022 emission estimate of 0.0004 MMT CO_2 Eq.

Table 6-62: Approach 2 Quantitative Uncertainty Estimates for CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.6	0.5	0.7	-16%	+16%
Peatlands Remaining Peatlands	CH_4	+	+	+	-59%	+79%
Peatlands Remaining Peatlands	N_2O	+	+	+	-52%	+53%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

A QA/QC analysis was performed to review input data and calculations, and no issues were identified. In addition, the emission trends were analyzed to ensure they reflected activity data trends.

Recalculations Discussion

The conterminous United States peat production estimates for peatlands remaining peatlands were updated using the Peat section of the *Mineral Commodity Summaries 2023*. The 2023 edition updated 2018, 2019, 2020, and 2021 peat production data and provided peat type production estimates for 2022. Updated data decreased previously estimated emissions for 2018 by 18 percent, 2019 by 19 percent, 2020 by 19 percent, and 2021 by 22 percent versus estimated emissions for 2018, 2019, 2020, and 2021 in the previous (i.e., 1990 through 2021) *Inventory* for peatlands remaining peatlands. According to USGS, peat production estimations for 2018 through 2022 were revised in the *Mineral Commodity Summaries 2023* due to a company having shut down sometime in 2017 (USGS 2023d). Previously, USGS was estimating production for this company due to lack of peat production survey responses.

Although Alaska peat production data for 2015 through 2022 were unavailable, 2014 data are available in the *Alaska's Mineral Industry 2014* report. However, the reported values represented an apparent 98 percent decrease in production since 2012. Due to the uncertainty of the most recent data, 2013 through 2022 value were assumed to be equal to the 2012 value, seen in the *Alaska's Mineral Industry 2013* report. If updated Alaska data are available for the next *Inventory* cycle, this will result in a recalculation in the next (i.e., 1990 through 2023) *Inventory* report.

Planned Improvements

Edits to the trends and methodology sections are planned based on expert review comments.

EPA notes the following improvements may be implemented or investigated within the next two or three *Inventory* cycles pending time and resource:

- The implied emission factors will be calculated and included in this chapter for future *Inventories*. Currently, the N_2O emissions calculation uses different land areas than the CO_2 and CH_4 emission calculations (see Methodology and Time Series Consistency in this chapter), so estimating the implied emission factor per total land area is not appropriate. The inclusion of implied emission factors in this chapter will provide another method of QA/QC and verification for *Inventory* data.

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement until data are available or identified:

- In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from peatlands remaining peatlands, future efforts will investigate if improved data sources exist for determining the quantity of peat harvested per hectare and the total area of land undergoing peat extraction.
- EPA plans to identify a new source for Alaska peat production. The current source has not been reliably updated since 2012 and Alaska Department of Natural Resources indicated future publication of data has been discontinued.

Coastal Wetlands Remaining Coastal Wetlands

Consistent with ecological definitions of wetlands,[60] the United States has historically included under the category of wetlands those coastal shallow water areas of estuaries and bays that lie within the extent of the Land Representation. Guidance on quantifying greenhouse gas emissions and removals on coastal wetlands is provided in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (*Wetlands Supplement*), which recognizes the particular importance of vascular plants in sequestering CO_2 from the atmosphere within biomass, dead organic material (DOM; including litter and dead wood stocks) and soils. Thus, the *Wetlands Supplement* provides specific guidance on quantifying emissions and removals on organic and

[60] See https://water.usgs.gov/nwsum/WSP2425/definitions.html; accessed August 2023.

mineral soils that are covered or saturated for part of the year by tidal fresh, brackish or saline water and are vegetated by vascular plants and may extend seaward to the maximum depth of vascular plant vegetation. The United States calculates emissions and removals based upon the stock change method for soil carbon (C) and the gain-loss method for biomass and DOM. Presently, this *Inventory* does not calculate the lateral flux of carbon to or from any land use. Lateral transfer of organic carbon to coastal wetlands and to marine sediments within U.S. waters is the subject of ongoing scientific investigation; there is currently no IPCC methodological guidance for lateral fluxes of carbon.

The United States recognizes both vegetated wetlands and unvegetated open water as coastal wetlands. Per guidance provided by the *Wetlands Supplement*, sequestration of carbon into biomass, DOM and soil carbon pools is recognized only in vegetated coastal wetlands and does not occur in unvegetated open water coastal wetlands. The United States takes the additional step of recognizing that carbon stock losses occur when vegetated coastal wetlands are converted to Unvegetated open water coastal wetlands.

This *Inventory* includes all privately- and publicly-owned coastal wetlands (i.e., mangroves and tidal marsh) along the oceanic shores of the conterminous United States, including the District of Columbia., but does not include coastal wetlands remaining coastal wetlands in Alaska, Hawaii, or any of the United States Territories. Seagrasses are not currently included within the *Inventory* due to insufficient data on distribution, change through time and carbon stocks or carbon stock changes as a result of anthropogenic influence (see Planned Improvements).

Under the coastal wetlands remaining coastal wetlands category, the following emissions and removals are quantified in this chapter:

1) Carbon stock changes and CH_4 emissions on vegetated coastal wetlands remaining vegetated coastal wetlands,

2) Carbon stock changes on vegetated coastal wetlands converted to unvegetated open water coastal wetlands,

3) Carbon stock changes on unvegetated open water coastal wetlands converted to vegetated coastal wetlands, and

4) Nitrous oxide emissions from aquaculture in coastal wetlands.

Vegetated coastal wetlands hold carbon in all five carbon pools (i.e., aboveground biomass, belowground biomass, dead organic matter [DOM; dead wood and litter], and soil), though typically soil carbon and, to a lesser extent, aboveground and belowground biomass are the dominant pools, depending on wetland type (i.e., forested vs. marsh). vegetated coastal wetlands are net accumulators of carbon over centuries to millennia as soils accumulate carbon under anaerobic soil conditions and carbon accumulates in plant biomass. Large emissions from soil carbon and biomass stocks occur when vegetated coastal wetlands are converted to unvegetated open water coastal wetlands (e.g., when vegetated coastal wetlands are lost due to subsidence, channel cutting through vegetated coastal wetlands), but are still recognized as coastal wetlands in this *Inventory*. These carbon stock losses resulting from conversion to unvegetated open water coastal wetlands can cause the release of decades to centuries of accumulated soil carbon, as well as the standing stock of biomass carbon. Conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands, either through restoration efforts or naturally, initiates the building of carbon stocks within soils and biomass. In applying the *Wetlands Supplement* methodologies for estimating CH_4 emissions, coastal wetlands in salinity conditions greater than 18 parts per thousand have little to no CH_4 emissions compared to those experiencing lower salinity brackish and freshwater conditions. Therefore, conversion of vegetated coastal wetlands to or from unvegetated open water coastal wetlands are conservatively assumed to not result in a change in salinity condition and are assumed to have no impact on CH_4 emissions. The *Wetlands Supplement* provides methodologies to estimate N_2O emissions from coastal wetlands that occur due to aquaculture. The N_2O emissions from aquaculture result from the nitrogen derived from consumption of the applied food stock that is then excreted as nitrogen load available for conversion to N_2O. While N_2O emissions can also occur due to anthropogenic nitrogen loading from the watershed and atmospheric deposition, these

emissions are not reported here to avoid double-counting of indirect N_2O emissions with the agricultural soils management, forest land and settlements categories.

The *Wetlands Supplement* provides methodologies for estimating carbon stock changes and CH_4 emissions from mangroves, tidal marshes and seagrasses. Depending upon their height and area, carbon stock changes from mangroves may be reported under the forest land category or under coastal wetlands. If mangrove stature is 5 m or greater or if there is evidence that trees can obtain that height, mangroves are reported under the forest land category because they meet the definition of forest land. Mangrove forests that are less than 5 m are reported under coastal wetlands because they meet the definition of wetlands. All other non-drained, intact coastal marshes are reported under coastal wetlands.

Because of human activities and level of regulatory oversight, all coastal wetlands within the conterminous United States are included within the managed land area described in Section 6.1, and as such, estimates of carbon stock changes, emissions of CH_4, and emissions of N_2O from aquaculture from all coastal wetlands are included in this *Inventory.* At the present stage of inventory development, coastal wetlands are not explicitly shown in the land representation analysis while work continues to harmonize data from NOAA's Coastal Change Analysis Program (C-CAP)[61] with NRI, FIA and NLDC data used to compile the land representation (see Section 6.1). However, a check was undertaken to confirm that coastal wetlands recognized by C-CAP represented a subset of wetlands recognized by the NRI for marine coastal states.

The greenhouse gas fluxes for all four wetland categories described above are summarized in Table 6-63. Coastal wetlands remaining coastal wetlands are generally a net carbon sink, with the fluxes ranging from -5.6 to -6.7 MMT CO_2 Eq. across the majority of the time series; however, between 2006 and 2010, they were a net source of emissions (ranging from 3.2 to 53.5 MMT CO_2 Eq.), resulting from a large loss of vegetated coastal wetlands to open water due to hurricanes (Table 6-63). Recognizing removals of CO_2 to soil of 12.5 MMT CO_2 Eq. and CH_4 emissions of 4.3 MMT CO_2 Eq. in 2022, vegetated coastal wetlands remaining vegetated coastal wetlands are a net sink of 8.2MMT CO_2 Eq. Loss of coastal wetlands, primarily in the Mississippi Delta as a result of hurricane impacts and sediment diversion and other human impacts, recognized as vegetated coastal wetlands converted to unvegetated coastal wetlands, drive an emission of 1.5 MMT CO_2 Eq. since 2011, primarily from soils. Building of new wetlands from open water, recognized as unvegetated coastal wetlands converted to vegetated coastal, results each year in removal of 0.1 MMT CO_2 Eq. Aquaculture is a minor industry in the United States, resulting in an emission of N_2O across the time series of between 0.1 to 0.2 MMT CO_2 Eq. In total, coastal wetlands are a net sink of 6.7 MMT CO_2 Eq. in 2022.

Table 6-63: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	**(8.4)**	**(8.4)**	**(8.3)**	**(8.3)**	**(8.3)**	**(8.2)**	**(8.2)**
Biomass C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Flux	(12.5)	(12.6)	(12.5)	(12.5)	(12.5)	(12.5)	(12.5)
Net CH_4 Flux	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Biomass C Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter C Flux	+	+	+	+	+	+	+
Soil C Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Unvegetated Open Water Coastal Wetlands Converted to Vegetated	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

[61] See https://coast.noaa.gov/digitalcoast/tools/lca.html; accessed September 2023.

Coastal Wetlands							
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	+	+	+	+	+
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Net N_2O Flux from Aquaculture in Coastal Wetlands	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Biomass C Flux	**+**	**+**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Total Dead Organic Matter C Flux	**(+)**	**(+)**	**+**	**+**	**+**	**+**	**+**
Total Soil C Flux	**(10.8)**	**(10.1)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.1)**
Total CH_4 Flux	**4.2**	**4.2**	**4.3**	**4.3**	**4.3**	**4.3**	**4.3**
Total N_2O Flux	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Flux	**(6.5)**	**(5.7)**	**(6.7)**	**(6.7)**	**(6.7)**	**(6.7)**	**(6.7)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Emissions and Removals from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands

The conterminous United States currently has 2.98 million hectares of intertidal vegetated coastal wetlands remaining vegetated coastal wetlands comprised of tidally influenced palustrine emergent marsh (663,014 ha), palustrine scrub shrub (133,582 ha) and estuarine emergent marsh (1,892,507 ha), estuarine scrub shrub (95,225 ha) and estuarine forested wetlands (195,199 ha). Mangroves fall under both estuarine forest and estuarine scrub shrub categories depending upon height. Dwarf mangroves, found in subtropical states along the Gulf of Mexico, do not attain the height status to be recognized as forest land, and are therefore always classified within vegetated coastal wetlands. vegetated coastal wetlands remaining vegetated coastal wetlands are found in cold temperate (53,968 ha), warm temperate (896,583 ha), subtropical (1,966,101 ha) and Mediterranean (62,874 ha) climate zones.

Soils are the largest carbon pool in vegetated coastal wetlands remaining vegetated coastal wetlands, reflecting long-term removal of atmospheric CO_2 by vegetation and transfer into the soil pool in the form of both autochthonous and allochthonous decaying organic matter. Soil carbon emissions are not assumed to occur in coastal wetlands that remain vegetated. This *Inventory* includes changes in carbon stocks in both biomass and soils. Changes in DOM carbon stocks are not included. Methane emissions from decomposition of organic matter in anaerobic conditions are present at salinity less than half that of sea water. Mineral and organic soils are not differentiated in terms of carbon stock changes or CH_4 emissions.

Table 6-64 through Table 6-66 summarize nationally aggregated biomass and soil carbon stock changes and CH_4 emissions on vegetated coastal wetlands remaining vegetated coastal wetlands. Intact vegetated coastal wetlands remaining vegetated coastal wetlands hold a total biomass carbon stock of 35.96 MMT C. Removals from biomass carbon stocks in 2022 were 0.05 MMT CO_2 Eq. (0.01 MMT C), which has increased over the time series (Table 6-64 and Table 6-65). Carbon dioxide emissions from biomass in vegetated coastal wetlands remaining vegetated coastal wetlands between 2002 and 2011, with very low sequestration between 2002 and 2006 and emissions of 0.21 MMT CO_2 Eq. between 2007 and 2011, are not inherently typical and are a result of coastal wetland loss over time. Most of the coastal wetland loss has occurred in palustrine and estuarine emergent wetlands. Vegetated coastal wetlands maintain a large carbon stock within the top 1 meter of soil (estimated to be 804 MMT C) to which carbon accumulated at a rate of 12.5 MMT CO_2 Eq. (3.4 MMT C) in 2022, a value that has remained relatively constant across the reporting period. For vegetated coastal wetlands remaining vegetated coastal wetlands, methane emissions of 4.3 of MMT CO_2 Eq. (154 kt CH_4) in 2022 (Table 6-66) offset carbon removals resulting in a net removal of 8.2 MMT CO_2 Eq. in 2022; this rate has been relatively consistent across the reporting period. Dead organic matter stock changes are not calculated in vegetated coastal wetlands remaining vegetated coastal wetlands since this stock is considered to be in a steady state when using Tier 1 methods (IPCC 2014). Due to federal regulatory protection, loss of vegetated coastal wetlands through human activities slowed considerably

in the 1970s and the current annual rates of carbon stock change and CH_4 emissions are relatively constant over time.

Table 6-64: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil Flux	(12.5)	(12.6)	(12.5)	(12.5)	(12.5)	(12.5)	(12.5)
Total C Stock Change	**(12.6)**	**(12.6)**	**(12.5)**	**(12.5)**	**(12.5)**	**(12.5)**	**(12.5)**

+ Absolute value does not exceed 0.05 MMT $C0_2$ Eq.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-65: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	(+)	+	(+)	(+)	(+)	(+)	(+)
Soil Flux	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)
Total C Stock Change	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**

+ Absolute value does not exceed 0.05 MMT C.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-66: CH_4 Emissions from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT CO_2 Eq. and kt CH_4)

Year	1990	2005	2018	2019	2020	2021	2022
Methane Emissions (MMT CO_2 Eq.)	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Methane Emissions (kt CH_4)	149	151	153	153	154	154	154

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in biomass carbon stocks, soil carbon stocks and emissions of CH_4 for vegetated coastal wetlands remaining vegetated coastal wetlands. Dead organic matter is not calculated for vegetated coastal wetlands remaining vegetated coastal wetlands since it is assumed to be in steady state (IPCC 2014).

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Above- and belowground biomass carbon stocks for palustrine (freshwater) and estuarine (saline) marshes are estimated for vegetated coastal wetlands remaining vegetated coastal wetlands on land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Federal and non-federal lands are represented. Trends in land cover change are extrapolated to 1990 and 2022 from these datasets. Based upon NOAA C-CAP, coastal wetlands are subdivided into palustrine and estuarine classes and further subdivided into emergent marsh, scrub shrub and forest classes (Table 6-67). Biomass is not sensitive to soil organic matter content but is differentiated based on climate zone. Aboveground biomass carbon stocks for non-forested wetlands data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground

biomass carbon stock for subtropical estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017). Root to shoot ratios from the *Wetlands Supplement* (Table 6-69; IPCC 2014) were used to account for belowground biomass, which were multiplied by the aboveground carbon stock. Above- and belowground values were summed to obtain total biomass carbon stocks. Biomass carbon stock changes per year for wetlands remaining wetlands were determined by calculating the difference in area between that year and the previous year to calculate gain/loss of area for each climate type, which was multiplied by the mean biomass for that climate type.

Table 6-67: Area of Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands, Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands, and Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (ha)

Year	1990	2005	2018	2019	2020	2021	2022
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	2,975,477	2,985,783	2,974,523	2,975,789	2,977,055	2,978,322	2,979 588
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	1,720	2,515	1,488	1,488	1,488	1,488	1,488
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	952	1,769	2,406	2,406	2,406	2,406	2,406

Table 6-68: Aboveground Biomass Carbon Stocks for Vegetated Coastal Wetlands (t C ha^{-1})

	Climate Zone			
Wetland Type	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	3.25	3.17	2.24	4.69
Palustrine Emergent Wetland	3.25	3.17	2.24	4.69
Estuarine Forested Wetland	N/A	N/A	17.83	N/A
Estuarine Scrub/Shrub Wetland	3.05	3.05	2.43	3.44
Estuarine Emergent Wetland	3.05	3.10	2.43	3.44

Source: All data from Byrd et al. (2017, 2018 and 2020) except for subtropical estuarine forested wetlands, which is from Lu and Megonigal (2017); N/A means there are currently no estuarine forested wetlands that are less than 5 meters tall; these forested wetlands meet the definition of forest land and are included in the Forest Land section.

Table 6-69: Root to Shoot Ratios for Vegetated Coastal Wetlands

	Climate Zone			
Wetland Type	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.15	1.15	3.65	3.63
Palustrine Emergent Wetland	1.15	1.15	3.65	3.63
Estuarine Forested Wetland	N/A	N/A	0.96	N/A
Estuarine Scrub/Shrub Wetland	2.11	2.11	3.65	3.63
Estuarine Emergent Wetland	2.11	2.11	3.65	3.63

Source: All values from IPCC (2014); N/A means there are currently no estuarine forested wetlands that are less than 5 meters tall; these forested wetlands meet the definition of forest land and are included in the Forest Land section.

Soil Carbon Stock Changes

Soil carbon stock changes are estimated for vegetated coastal wetlands remaining vegetated coastal wetlands for both mineral and organic soils. Soil carbon stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Table 6-70; Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al.

2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012a&b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Breithaupt et al. 2014; Crooks et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022).

Tier 2 estimates of soil carbon removals associated with annual soil carbon accumulation on managed vegetated coastal wetlands remaining vegetated coastal wetlands were developed with country-specific soil carbon removal factors multiplied by activity data of land area for vegetated coastal wetlands remaining vegetated coastal wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of vegetated coastal wetlands remaining vegetated coastal wetlands on an annual basis. To estimate soil carbon stock changes, no differentiation is made between organic and mineral soils since currently, no statistical evidence supports disaggregation (Holmquist et al. 2018).

Table 6-70: Annual Soil Carbon Accumulation Rates for Vegetated Coastal Wetlands (t C ha^{-1} yr^{-1})

Climate Zone	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.010	1.544	0.45	0.845
Palustrine Emergent Wetland	1.010	1.544	0.454	0.845
Estuarine Forested Wetland	N/A	N/A	0.821	N/A
Estuarine Scrub/Shrub Wetland	1.254	1.039	0.821	0.845
Estuarine Emergent Wetland	1.254	1.039	1.587	0.845

Source: All data from CCRCN (2023)[62]; N/A means there are no estuarine forested wetlands outside of subtropical regions.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for vegetated coastal wetlands remaining vegetated coastal wetlands are derived from the same wetland map used in the analysis of wetland soil C fluxes, produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *Wetlands Supplement.* The methodology follows Equation 4.9, Chapter 4 of the *Wetlands Supplement*; Tier 1 emissions factors are multiplied by the area of freshwater (palustrine) coastal wetlands. The CH_4 fluxes applied are determined based on salinity; only palustrine wetlands are assumed to emit CH_4. Estuarine coastal wetlands in the C-CAP classification include wetlands with salinity less than 18 ppt, a threshold at which methanogenesis begins to occur (Poffenbarger et al. 2011), but the dataset currently does not differentiate estuarine wetlands based on their salinities and, as a result, CH_4 emissions from estuarine wetlands are not included at this time.

Uncertainty

Underlying uncertainties in the estimates of soil and biomass carbon stock changes and CH_4 emissions include uncertainties associated with Tier 2 literature values of soil carbon stocks, biomass carbon stocks and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to vegetated coastal wetlands remaining vegetated coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil carbon stock and CH_4 flux applied. Uncertainties for soil and biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Because mean soil and biomass carbon stocks for each available community

[62] Coastal Carbon Network (2023). Database: Coastal Carbon Library (Version 1.0.0). Smithsonian Environmental Research Center. Dataset. https://doi.org/10.25573/serc.21565671. Accessed September 2023.

class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *2013 Wetlands Supplement*. Uncertainties for CH_4 flux are the Tier 1 default values reported in the *2013 IPCC Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to apply CH_4 flux emission factors (delineation of an 18 ppt boundary) that will need significant improvement to reduce uncertainties. Details on the emission/removal trends and methodologies through time are described in more detail in the introduction and the Methodology section. The combined uncertainty was calculated using the IPCC Approach 1 method of summing the squared uncertainty for each individual source (C-CAP, soil, biomass and CH_4) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-71 for each subcategory (i.e., soil carbon, biomass carbon and CH_4 emissions). The combined uncertainty across all subcategory is 37.0 percent below and above the estimate of -6.4 MMT CO_2 Eq, which is primarily driven by the uncertainty in the CH_4 estimates because there is high variability in CH_4 emissions when the salinity is less than 18 ppt. In 2021, the total flux was -8.2 MMT CO_2 Eq., with lower and upper estimates of -11.3 and -5.2 MMT CO_2 Eq.

Table 6-71: IPCC Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes and CH_4 Emissions occurring within Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands in 2021 (MMT CO_2 Eq. and Percent)

Source/Sink	Gas	2022 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Change	CO_2	(0.05)	(0.06)	(0.03)	-24.1%	+24.1%
Soil C Stock Change	CO_2	(12.5)	(14.7)	(10.3)	-17.7	+17.7%
CH_4 emissions	CH_4	4.3	3.0	5.6	-29.9%	+29.9%
Total Flux		**(8.2)**	**(11.3)**	**(5.2)**	**-36.5%**	**+36.5%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided the National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal QA/QC assessment consistent with the general QC checks outlined in the Inventory QA/QC Plan. Acceptance of final datasets into archive and dissemination are contingent upon the product compilation being compliant with mandatory QA/QC requirements (McCombs et al. 2016). QA/QC and verification of soil carbon stock datasets have been provided by the Smithsonian Environmental Research Center and coastal wetland inventory team leads who reviewed summary tables against reviewed sources. Biomass carbon stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads before inclusion in this *Inventory*. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil and biomass carbon stock change data are based upon peer-reviewed literature and CH_4 emission factors derived from the *Wetlands Supplement*.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since 2016 and other relevant data that were not previously included. Table 6-70 shows the new values. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub

wetlands, which resulted in an annual average increase of removals of 2.3 MMT CO_2 Eq. for the entire time series. For vegetated coastal wetlands remaining vegetated coastal wetlands in 2022, inclusion of the updated values resulted in an increase of the sink from -5.9 MMT CO_2 Eq. to -8.2 MMT CO_2 Eq.

Planned Improvements

Harmonization across all spatial datasets used to calculate activity data is underway. Once completed, a better representation of forested tidal wetlands, palustrine tidal wetlands, and forest land near the tidal boundary will be obtained.

Work is currently underway to examine the feasibility of incorporating seagrass soil and biomass carbon stocks into the vegetated coastal wetlands remaining vegetated coastal wetlands estimates. Additionally, investigation into quantifying the distribution, area, and emissions resulting from impounded waters (i.e., coastal wetlands where tidal connection to the ocean has been restricted or eliminated completely) is underway.

Box 6-6: State-Level Case Studies for the Estimation of GHG Removals in Seagrasses

North Carolina and Maryland are the first states to include seagrasses within their state-level inventory. North Carolina has the largest extent of seagrass coverage along the U.S. Atlantic coast, measuring approximately 86,412 acres in 2021. Seagrass mapping efforts occurred in 2007, 2013, and 2020 using a field-validated aerial image classification. The Tier 1 soil carbon accumulation rate was used and currently, biomass is not included due to lack of local data. The analysis shows that these high salinity seagrass habitats provided a net carbon sink to the state, although greenhouse gas removals decreased over time due to loss in seagrass coverage. Overall, seagrass beds in 2021 sequestered approximately 0.055 MMT CO_2 Eq. (55.14 kt CO_2 Eq.) in the soils alone.

In Maryland, the state greenhouse gas inventory comprises blue carbon stocks and fluxes from estuarine wetlands and seagrasses. Maryland currently has long-term monitoring of submerged aquatic vegetation (SAV) extent and density through annual surveying, and the rate of carbon sequestration and methane emission was a regional average for coastal wetlands. This study at state-level calculation offers an opportunity to maintain consistency in reporting across spatial scales and allows positioning SAV in its role as a carbon sink, in addition to its benefits in water quality and habitat conservation, perpetuating Maryland's role as a leader in blue carbon accounting.

These two case studies demonstrate the importance of refining emission factor data and harmonizing the inclusion of this ecosystem in the land representation analysis (reconciling the National Ocean and Atmospheric Administration [NOAA] Coastal Change Analysis Program [C-CAP] data with the National Resource Inventory, Forest Inventory Analysis, and the National Land Cover Database).

Emissions from Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands

Vegetated coastal wetlands converted to unvegetated open water coastal wetlands is a source of emissions from soil, biomass, and DOM carbon stocks. An estimated 1,488 ha of vegetated coastal wetlands were converted to unvegetated open water coastal wetlands in 2022, which largely occurred within estuarine and palustrine emergent wetlands. Prior to 2006, annual conversion to unvegetated open water coastal wetlands was higher than current rates: 1,720 between 1990 and 2000 and 2,515 ha between 2001 and 2005. The Mississippi Delta represents more than 40 percent of the total coastal wetland of the United States, and over 90 percent of the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands. The drivers of coastal wetlands loss include legacy human impacts on sediment supply through rerouting river flow, direct impacts of channel cutting on hydrology, salinity and sediment delivery, and accelerated subsidence from aquifer extraction.

Each of these drivers directly contributes to wetland erosion and subsidence, while also reducing the resilience of the wetland to build with sea-level rise or recover from hurricane disturbance. Over recent decades, the rate of Mississippi Delta wetland loss has slowed, though episodic mobilization of sediment occurs during hurricane events (Couvillion et al. 2011; Couvillion et al. 2016). The land cover analysis between the 2006 and 2011 C-CAP surveys coincides with two such events, hurricanes Katrina and Rita (both making landfall in the late summer of 2005), that occurred between these C-CAP survey dates. The subsequent 2016 C-CAP survey determined that erosion rates had slowed.

Shallow nearshore open water within the U.S. land representation is recognized as falling under the coastal wetlands category within this *Inventory*. While high resolution mapping of coastal wetlands provides data to support IPCC Approach 2 methods for tracking land cover change, the depth in the soil profile to which sediment is lost is less clear. This *Inventory* adopts the Tier 1 methodological guidance from the *Wetlands Supplement* for estimating emissions following the methodology for excavation (see Methodology section, below) when vegetated coastal wetlands are converted to unvegetated open water coastal wetlands, assuming a 1 m depth of disturbed soil. This 1 m depth of disturbance is consistent with estimates of wetland carbon loss provided in the literature and the *Wetlands Supplement* (Crooks et al. 2009; Couvillion et al. 2011; Delaune and White 2012; IPCC 2014). The same assumption on depth of soils impacted by erosion has been applied here. It is a reasonable Tier 1 assumption, based on experience, but estimates of emissions are sensitive to the depth to which the assumed disturbances have occurred (Holmquist et al. 2018). A Tier 1 assumption is also adopted in that all mobilized carbon is immediately returned to the atmosphere (as assumed for terrestrial land-use categories), rather than redeposited in long-term carbon storage. The science is currently under evaluation to adopt more refined emissions factors for mobilized coastal wetland carbon based upon the geomorphic setting of the depositional environment.

In 2022, there were 1,488 ha of vegetated coastal wetlands converted to unvegetated open water coastal wetlands (Table 6-67) across all wetland types and climates, which resulted in 1.5 MMT CO_2 Eq. (0.4 MMT C) and 0.06 MMT CO_2 Eq. (0.02 MMT C) lost through soil and biomass, respectively, with minimal DOM C stock loss (Table 6-72, and Table 6-73). Across the reporting period, the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands was greatest between the 2006 to 2011 C-CAP reporting period (11,373 ha) and has decreased since then to current levels (Table 6-67).

Table 6-72: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Total C Stock Change	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-73: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	+	+	+	+	+	+	+
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	0.5	0.7	0.4	0.4	0.4	0.4	0.4
Total C Stock Change	**0.5**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**

+ Absolute value does not exceed 0.05 MMT C.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM carbon stocks for vegetated coastal wetlands converted to unvegetated open water coastal wetlands.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Biomass carbon stock changes for palustrine and estuarine marshes are estimated for vegetated coastal wetlands converted to unvegetated open water coastal wetlands on lands below the elevation of high tides (taken to be mean high water spring tide elevation) within the U.S. land representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Publicly-owned and privately-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2021 from these datasets. The C-CAP database provides peer reviewed country-specific mapping to support IPCC Approach 3 quantification of coastal wetland distribution, including conversion to and from open water. Biomass carbon stocks are not sensitive to soil organic content but are differentiated based on climate zone. Non-forested aboveground biomass carbon stock data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[63]; Table 6-68). Aboveground biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-69; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks. Conversion to open water results in emissions of all biomass carbon stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year in each climate zone by its mean biomass.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks for subtropical estuarine forested wetlands, are an emission from vegetated coastal wetlands converted to unvegetated open water coastal wetlands across all years in the time series. Data on DOM carbon stocks are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2021 time series. Conversion to open water results in emissions of all DOM carbon stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year by its Tier 1 DOM carbon stock.

Soil Carbon Stock Changes

Soil carbon stock changes are estimated for vegetated coastal wetlands converted to unvegetated open water coastal wetlands. Country-specific soil carbon stocks were updated in 2018 based upon analysis of an assembled dataset of 1,959 cores from across the conterminous United States (Holmquist et al. 2018). This analysis

[63] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed September 2023.

demonstrated that it was not justified to stratify carbon stocks based upon mineral or organic soil classification, climate zone, or wetland classes; therefore, a single soil carbon stock of 270 t C ha^{-1} was applied to all classes. Following the Tier 1 approach for estimating CO_2 emissions with extraction provided within the *Wetlands Supplement*, soil carbon loss with conversion of vegetated coastal wetlands to unvegetated open water coastal wetlands is assumed to affect soil carbon stock to one-meter depth (Holmquist et al. 2018) with all emissions occurring in the year of wetland conversion, and multiplied by activity data of vegetated coastal wetland area converted to unvegetated open water wetlands. The methodology follows Eq. 4.6 in the *Wetlands Supplement*.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of vegetated coastal wetlands to unvegetated open water coastal wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass carbon stock changes are associated with country-specific (Tier 2) literature values of these stocks, while the uncertainties with the Tier 1 estimates are associated with subtropical estuarine forested wetland DOM stocks. Assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data are also included in this uncertainty assessment. The IPCC default assumption of 1 m of soil erosion with anthropogenic activities was adopted to provide standardization in U.S. tidal carbon accounting (Holmquist et al. 2018). This depth of potentially erodible tidal wetland soil has not been comprehensively addressed since most soil cores analyzed were shallow (e.g., less than 50 cm) and do not necessarily reflect the depth to non-wetland soil or bedrock (Holmquist et al. 2018). Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil carbon stock applied. Because mean soil and biomass carbon stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). For aboveground biomass carbon stocks, the mean standard error was very low and largely influenced by the uncertainty associated with the estimated map area (Byrd et al. 2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks was derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (+/-10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-74 for each subcategory (i.e., soil carbon, biomass carbon, and DOM emissions). The combined uncertainty across all subcategory is 32.0 percent above and below the estimate of 1.5 MMT CO_2 Eq, which is driven by the uncertainty in the soil carbon estimates. In 2022, the total carbon flux was 1.5 MMT CO_2 Eq., with lower and upper estimates of 1.0 and 2.0 MMT CO_2 Eq.

Table 6-74: Approach 1 Quantitative Uncertainty Estimates for CO_2 Flux Occurring within Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock	0.06	0.05	0.08	-24.1%	+24.1%
Dead Organic Matter C Stock	0.0005	0.000	0.001	-25.8%	+25.8%
Soil C Stock	1.5	1.3	1.7	-15.0%	+15.0%
Total Flux	**1.5**	**1.0**	**2.0**	**-32.0%**	**+32.0%**

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

Data provided by NOAA (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping) undergo internal agency QA/QC procedures. Acceptance of final datasets into archive and dissemination are contingent upon assurance that the data product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of the soil carbon stock dataset have been provided by the Smithsonian Environmental Research Center and by the Coastal Wetlands project team leads who reviewed the estimates against primary scientific literature. Biomass carbon stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads before inclusion in the *Inventory*. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and were verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

The depth of soil carbon affected by conversion of vegetated coastal wetlands converted to unvegetated coastal wetlands will be updated from the IPCC default assumption of 1 m of soil erosion when mapping and modeling advancements can quantitatively improve accuracy and precision. Improvements are underway to address this, first conducting a review of literature publications. Until the time where these more detailed and spatially distributed data are available, the IPCC default assumption that the top 1 m of soil is disturbed by anthropogenic activity will be applied. This is a longer-term improvement.

More detailed research is in development that provides a longer-term assessment and more highly refined rates of wetlands loss across the Mississippi Delta (e.g., Couvillion et al. 2016). The Mississippi Delta is the largest extent of coastal wetlands in the United States. Higher resolution imagery analysis would improve quantification of conversation to open water, which occurs not only at the edge of the marsh but also within the interior. Improved mapping could provide a more refined regional Approach 2-3 land representation to support the national-scale assessment provided by C-CAP.

An approach for calculating the fraction of remobilized coastal wetland soil carbon returned to the atmosphere as CO_2 is currently under review and may be included in future reports.

Research by USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands is also underway. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the *Inventory*.

Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands

Open water within the U.S. land base, as described in Section 6.1, is recognized as coastal wetlands within this *Inventory*. The appearance of vegetated tidal wetlands on lands previously recognized as open water reflects either the building of new vegetated marsh through sediment accumulation or the transition from other lands uses through an intermediary open water stage as flooding intolerant plants are displaced and then replaced by wetland plants. Biomass, DOM and soil carbon accumulation on unvegetated open water coastal wetlands converted to vegetated coastal wetlands begins with vegetation establishment.

Within the United States, conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands is predominantly due to engineered activities, which include active restoration of wetlands (e.g., wetlands restoration in San Francisco Bay), dam removals or other means to reconnect sediment supply to the nearshore (e.g., Atchafalaya Delta, Louisiana, Couvillion et al. 2011). Wetland restoration projects have been ongoing in the United States since the 1970s. Early projects were small, a few hectares in size. By the 1990s, restoration projects, each hundreds of hectares in size, were becoming common in major estuaries. In several coastal areas e.g., San Francisco Bay, Puget Sound, Mississippi Delta and south Florida, restoration activities are in planning and implementation phases, each with the goal of recovering tens of thousands of hectares of wetlands.

In 2022, 2,406 ha of unvegetated open water coastal wetlands were converted to vegetated coastal wetlands across all wetland types and climates, which has steadily increased over the reporting period (Table 6-66). This resulted in 0.007 MMT CO_2 Eq. (0.002 MMT C) and 0.1 MMT CO_2 Eq. (0.03 MMT C) sequestered in soil and biomass, respectively (Table 6-75 and Table 6-76). The soil carbon stock has increased during the *Inventory* reporting period, likely due to increasing vegetated coastal wetland restoration over time. While DOM carbon stock increases are present, they are minimal in the early part of the time series and zero in the later because there are no conversions from unvegetated open water coastal wetlands to subtropical estuarine forested wetlands between 2011 and 2016 (and by proxy through 2022), and that is the only coastal wetland type where DOM data is currently available.

Throughout the reporting period, the amount of open water coastal wetlands converted to vegetated coastal wetlands has increased over time, reflecting the increase in engineered restoration activities mentioned above.

Table 6-75: CO_2 Flux from Carbon Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-76: CO_2 Flux from Carbon Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass C Flux	(0.01)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(0.01)**	**(0.02)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**

+ Absolute value does not exceed 0.005 MMT C.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM carbon stocks, and CH_4 emissions for unvegetated open water coastal wetlands converted to vegetated coastal wetlands.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Quantification of regional coastal wetland biomass carbon stock changes for palustrine and estuarine marsh vegetation are presented for unvegetated open water coastal wetlands converted to vegetated coastal wetlands on lands below the elevation of high tides (taken to be mean high water spring tide elevation) according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Privately-owned and publicly-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2022 from these datasets (Table 6-65). C-CAP provides peer reviewed high resolution level mapping of coastal wetland distribution, including conversion to and from open water. Biomass carbon stock is not sensitive to soil organic content but differentiated based on climate zone. Data for non-forested wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Table 6-68; Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for subtropical estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[64]). Aboveground biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-69; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks.

Conversion of open water to vegetated coastal wetlands results in the establishment of a standing biomass carbon stock; therefore, stock changes that occur are calculated by multiplying the C-CAP derived area gained that year in each climate zone by its mean biomass. While the process of revegetation of unvegetated open water wetlands can take many years to occur, it is assumed in the calculations that the total biomass is reached in the year of conversion.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are included for subtropical estuarine forested wetlands for vegetated coastal wetlands converted to unvegetated open water coastal wetlands across all years. Tier 1 default or country-specific data on DOM are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. Tier 1 estimates of subtropical estuarine forested wetland DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2021 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by its Tier 1 DOM C stock. Similar to biomass carbon stock gains, gains in DOM can take many years to occur, but for this analysis, the total DOM stock is assumed to accumulate during the first year of conversion.

Soil Carbon Stock Change

Soil carbon stock changes are estimated for unvegetated open water coastal wetlands converted to vegetated coastal wetlands. Country-specific soil carbon removal factors associated with soil carbon accretion, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature and updated this year based upon refined review of the dataset (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al. 2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012 a & b; Bianchi et al.

[64] See https://doi.org/10.25573/serc.21565671; accessed September 2023.

2013; Drexler et al. 2013; Watson and Byrne 2013; Crooks et al. 2014; Breithaupt et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022). Soil carbon stock changes are stratified based upon wetland class (Estuarine, Palustrine) and subclass (Emergent Marsh, Scrub Shrub). For soil carbon stock change, no differentiation is made for soil type (i.e., mineral, organic). Soil carbon removal factors were developed from literature references that provided soil carbon removal factors disaggregated by climate region and vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above (see Table 6-70 for values).

Tier 2 level estimates of carbon stock changes associated with annual soil carbon accumulation in vegetated coastal wetlands were developed using country-specific soil carbon removal factors multiplied by activity data on unvegetated coastal wetlands converted to vegetated coastal wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of unvegetated coastal wetlands converted to vegetated coastal wetlands on an annual basis.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of vegetated open water coastal wetlands to vegetated coastal wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass carbon stock changes include uncertainties associated with country-specific (Tier 2) literature values of these carbon stocks, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes that determines the soil carbon stock applied. Because mean soil and biomass carbon stocks for each available community class are in a fairly narrow range, the same overall uncertainty was applied to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). For aboveground biomass carbon stocks, the mean standard error was very low and largely influenced by error in estimated map area (Byrd et al. 2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass (Table 6-69), are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks were derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-77 for each subcategory (i.e., soil carbon, biomass carbon and DOM emissions). The combined uncertainty across all subsources is 33.43 percent above and below the estimate of -0.1 MMT CO_2 Eq. In 2022, the total carbon flux was -0.1 MMT CO_2 Eq., with lower and upper estimates of -0.1 and -0.08 MMT CO_2 Eq.

Table 6-77: Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes Occurring within Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range (MMT CO_2 Eq.)		Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	(0.1)	(0.12)	(0.08)	-20.0%	+20.0%
Dead Organic Matter C Stock Flux	0	0	0	-25.8%	+25.8%
Soil C Stock Flux	(0.008)	(0.009)	(0.006)	-17.7%	+17.7%
Total Flux	**(0.1)**	**(0.14)**	**(0.01)**	**-33.3%**	**+33.3%**

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided data (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping), which undergo internal agency QA/QC assessment procedures. Acceptance of final datasets into the archive for dissemination are contingent upon assurance that the product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of soil carbon stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetlands project team leads who reviewed the summary tables against primary scientific literature. Aboveground biomass carbon reference stocks are derived from an analysis by the Blue Carbon Monitoring project and reviewed by U.S. Geological Survey prior to publishing, the peer-review process during publishing, and the coastal wetland inventory team leads before inclusion in the *Inventory*. Root to shoot ratios and DOM data are derived from peer-reviewed literature and undergo review as per IPCC methodology. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed and verified by a second QA team. A team of two evaluated and verified there were no computational errors within calculation worksheets. Two biogeochemists at the USGS, also members of the NASA Carbon Monitoring System Science Team, corroborated the simplifying assumption that where salinities are unchanged CH_4 emissions are constant with conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since 2016 and other relevant data that were not previously included. Table 6-70 shows the new values. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in a minimal annual average increases in removals of 0.001 MMT CO_2 Eq. for the entire time series.

Planned Improvements

The USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the *Inventory*.

N_2O Emissions from Aquaculture in Coastal Wetlands

Shrimp and fish cultivation in coastal areas increases nitrogen loads resulting in direct emissions of N_2O. Nitrous oxide is generated and emitted as a byproduct of the conversion of ammonia (contained in fish urea) to nitrate

through nitrification and nitrate to N_2 gas through denitrification (Hu et al. 2012). Nitrous oxide emissions can be readily estimated from data on fish production (IPCC 2014).

Aquaculture production in the United States has fluctuated slightly from year to year, with resulting N_2O emissions between 0.1 and 0.2 MMT CO_2 Eq. between 1990 and 2022 (Table 6-78). Aquaculture production data were updated through 2019; data through 2022 are not yet available and in this analysis are held constant with 2019 emissions of 0.2 MMT CO_2 Eq. (0.5 Kt N_2O).

Table 6-78: N_2O Emissions from Aquaculture in Coastal Wetlands (MMT CO_2 Eq. and kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Emissions (MMT CO_2 Eq.)	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Emissions (kt N_2O)	0.4	0.6	0.5	0.5	0.5	0.5	0.5

Methodology and Time-Series Consistency

The methodology to estimate N_2O emissions from aquaculture in coastal wetlands follows the Tier 1 guidance in the *Wetlands Supplement* by applying country-specific fisheries production data and the IPCC Tier 1 default emission factor.

Each year NOAA Fisheries document the status of U.S. marine fisheries in the annual report of *Fisheries of the United States* (National Marine Fisheries Service 2022), from which activity data for this analysis is derived.[65] The fisheries report has been produced in various forms for more than 100 years, primarily at the national level, on U.S. recreational catch and commercial fisheries landings and values. In addition, data are reported on U.S. aquaculture production, the U.S. seafood processing industry, imports and exports of fish-related products, and domestic supply and per capita consumption of fisheries products. Within the aquaculture chapter, the mass of production for catfish, striped bass, tilapia, trout, crawfish, salmon and shrimp are reported. While some of these fisheries are produced on land and some in open water cages within coastal wetlands, all have data on the quantity of food stock produced, which is the activity data that is applied to the IPCC Tier 1 default emissions factor to estimate emissions of N_2O from aquaculture. It is not apparent from the data as to the amount of aquaculture occurring above the extent of high tides on river floodplains. While some aquaculture occurs on coastal lowland floodplains, this is likely a minor component of tidal aquaculture production because of the need for a regular source of water for pond flushing. The estimation of N_2O emissions from aquaculture is not sensitive to salinity using IPCC approaches, and as such, the location of aquaculture ponds within the boundaries of coastal wetlands does not influence the calculations.

Other open water shellfisheries for which no food stock is provided, and thus no additional N inputs, are not applicable for estimating N_2O emissions (e.g., clams, mussels, and oysters) and have not been included in the analysis. The IPCC Tier 1 default emissions factor of 0.00169 kg N_2O-N per kg of fish/shellfish produced is applied to the activity data to calculate total N_2O emissions.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty estimates are based upon the Tier 1 default 95 percent confidence interval provided in Table 4.15, chapter 4 of the *Wetlands Supplement* for N_2O emissions and on expert judgment of the NOAA *Fisheries of the United States* fisheries production data. Given the overestimate of fisheries production from coastal wetland areas

[65] See https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2020; accessed September August 2023.

due to the inclusion of fish production in non-coastal wetland areas, this is a reasonable initial first approximation for an uncertainty range.

Uncertainty estimates for N_2O emissions from aquaculture production are presented in Table 6-79 for N_2O emissions. The combined uncertainty is 116 percent above and below the estimate of 0.13 MMT CO_2 Eq. In 2022, the total flux was 0.13 MMT CO_2 Eq., with lower and upper estimates of 0.00 and 0.29 MMT CO_2 Eq.

Table 6-79: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions from Aquaculture Production in Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Emissions Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.13	0.00	0.29	-116%	+116%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

NOAA provided internal QA/QC review of reported fisheries data. The coastal wetlands inventory team consulted with the coordinating lead authors of the coastal wetlands chapter of the *Wetlands Supplement* to assess which fisheries production data to include in estimating emissions from aquaculture. It was concluded that N_2O emissions estimates should be applied to any fish production to which food supplement is supplied be they pond or coastal open water and that salinity conditions were not a determining factor in production of N_2O emissions.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Flooded Land Remaining Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural emission of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation, but these waterbodies would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as "reservoirs" or "other constructed waterbodies" (IPCC 2019). Other constructed waterbodies include canals/ditches and ponds (flooded land <8 ha surface area). Reservoirs are defined as flooded land greater than 8 ha. IPCC guidance (IPCC 2019) provides default emission factors for reservoirs, ponds, and canals/ditches.

Land that has been flooded for greater than 20 years is defined as flooded land remaining flooded land and land flooded for 20 years or less is defined as land converted to flooded land. The distinction is based on literature reports that CH_4 and CO_2 emissions are high immediately following flooding, but decline to a steady background level approximately 20 years after flooding (Abril et al. 2005; Barros et al. 2011; Teodoru et al. 2012). Emissions of CH_4 are estimated for flooded land remaining flooded land, but CO_2 emissions are not included as they are

primarily the result of decomposition of organic matter entering the waterbody from the catchment or contained in inundated soils and are captured in Chapter 6, Land Use, Land-Use Change, and Forestry.

Nitrous oxide emissions from flooded lands are largely related to input of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting of N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Section 5.4, Agricultural Soil Management) and wastewater management (Section 7.2, Wastewater Treatment and Discharge).

Emissions from Flooded Land Remaining Flooded Land–Reservoirs

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. In 2022, the United States and Puerto Rico hosted 10.2 million ha of reservoir surface area in the flooded land remaining flooded land category (see Methodology and Time-Series Consistency below for calculation details). These reservoirs are distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-10) (IPCC 2019).

Figure 6-10: U.S. Reservoirs (black polygons) in the Flooded Land Remaining Flooded Land Category in 2022

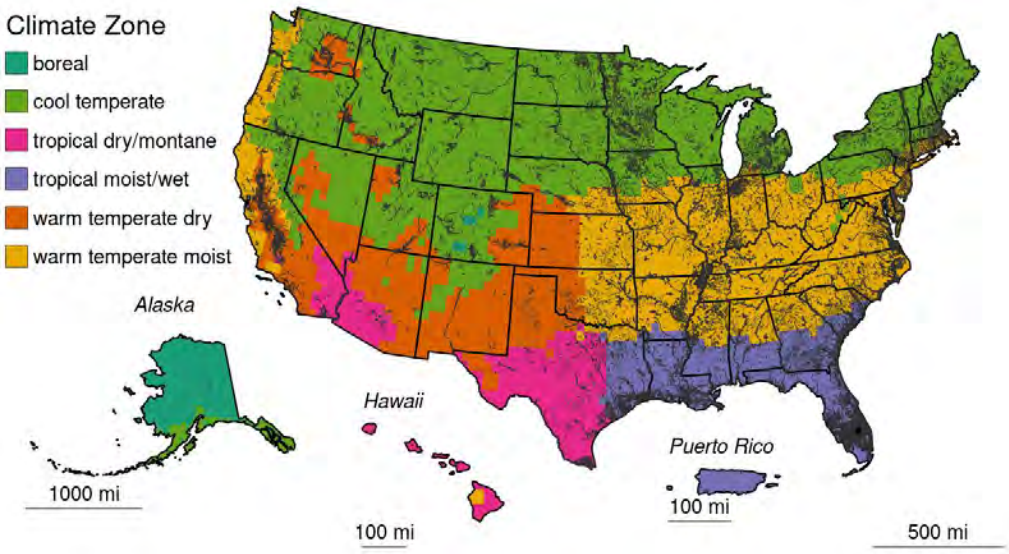

Note: Colors represent climate zone used to derive IPCC default emission factors.

Methane is produced in reservoirs through the microbial breakdown of organic matter. Per unit area, CH_4 emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae), but negatively with system size (i.e., depth, surface area). Methane produced in reservoirs can be emitted from the reservoir surface or exported from the reservoir when CH_4-rich water passes through the dam. This exported CH_4 can be released to the atmosphere as the water passes through hydropower turbines or the downstream river channel. Methane emitted to the atmosphere via this pathway is referred to as "downstream emissions."

Table 6-80 and Table 6-81 below summarize nationally aggregated CH_4 emissions from reservoirs. The increase in CH_4 emissions through the time series is attributable to reservoirs matriculating from the land converted to flooded land category into the flooded land remaining flooded land category.

Table 6-80: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emission	26.2	27.7	27.9	27.9	27.9	27.9	27.9
Downstream Emission	2.4	2.5	2.5	2.5	2.5	2.5	2.5
Total	**28.6**	**30.2**	**30.4**	**30.4**	**30.4**	**30.4**	**30.4**

Note: Totals may not sum to due independent rounding.

Table 6-81: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emission	937	989	997	997	997	997	997
Downstream Emission	84	89	90	90	90	90	90
Total	**1,022**	**1,078**	**1,086**	**1,086**	**1,087**	**1,087**	**1,087**

Note: Totals may not sum to due independent rounding.

Methane emissions from reservoirs in Texas, Florida, and Louisiana (Figure 6-11, Table 6-82) compose 34 percent of national CH_4 emissions from reservoirs in 2022. Emissions from these states are particularly high due to 1) the large expanse of reservoirs in these states (Table 6-85) and 2) the high CH_4 emission factor for the tropical dry/montane and topical moist climate zones which encompass a majority of the flooded land area in these states (Figure 6-10, Table 6-83).

Methane emissions from reservoirs in flooded land remaining flooded land increased 6.4 percent from 1990 to 2022 due to the matriculation of reservoirs in land converted to flooded land to flooded land remaining flooded land.

Figure 6-11: Total CH_4 Emissions (Downstream + Surface) from Reservoirs in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

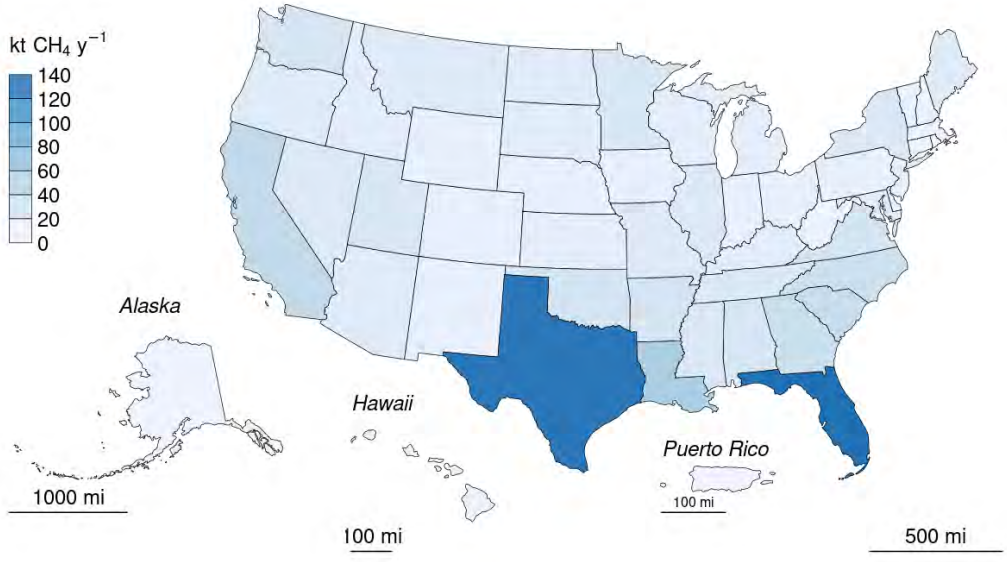

Table 6-82: Surface and Downstream CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

State	Surface	Downstream	Total
Alabama	22	2	24
Alaska	1	+	1
Arizona	14	1	16
Arkansas	25	2	27
California	42	4	46
Colorado	7	1	7
Connecticut	3	+	3
Delaware	3	+	3
District of Columbia	+	+	+
Florida	143	13	155
Georgia	35	3	38
Hawaii	1	+	1
Idaho	12	1	13
Illinois	17	2	19
Indiana	7	1	7
Iowa	7	1	7
Kansas	10	1	11
Kentucky	13	1	14
Louisiana	58	5	64
Maine	14	1	15
Maryland	13	1	14
Massachusetts	5	+	5
Michigan	9	1	10
Minnesota	21	2	23
Mississippi	20	2	21
Missouri	17	1	18
Montana	16	1	17
Nebraska	7	1	7
Nevada	17	2	19
New Hampshire	3	+	4
New Jersey	9	1	9
New Mexico	7	1	7
New York	18	2	20
North Carolina	33	3	36
North Dakota	14	1	15
Ohio	7	1	7
Oklahoma	26	2	28
Oregon	14	1	16
Pennsylvania	7	1	8
Puerto Rico	+	+	+
Rhode Island	1	+	1
South Carolina	38	3	41
South Dakota	12	1	14
Tennessee	20	2	21
Texas	138	12	150
Utah	21	2	23
Vermont	5	+	5
Virginia	25	2	27
Washington	23	2	25
West Virginia	3	+	3
Wisconsin	10	1	11
Wyoming	7	1	8

+ Indicates values less than 0.5 kt.

Methodology and Time-Series Consistency

Estimates of CH_4 emission for reservoirs in flooded land remaining flooded land follow the Tier 1 methodology in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate-specific emission factor (Table 6-83). Downstream emissions are calculated as nine percent of the surface emission (Tier 1 default). Total CH_4 emissions from reservoirs are calculated as the sum of surface and downstream emissions. National emissions are calculated as the sum of state emissions.

The IPCC default surface emission factors used in the Tier 1 methodology are derived from model-predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, Table 7A.2) which were collapsed into six climate zones using a regression tree approach. All six aggregated climate zones are present in the United States.

Table 6-83: IPCC (2019) Default CH_4 Emission Factors for Surface Emission from Reservoirs in Flooded Land Remaining Flooded Land

Climate	Surface emission factor (MT CH_4 ha^{-1} y^{-1})
Boreal	0.0136
Cool Temperate	0.054
Warm Temperate Dry	0.1509
Warm Temperate Moist	0.0803
Tropical Dry/Montane	0.2837
Tropical Moist/Wet	0.1411

Note: downstream CH_4 emissions are calculated as 9 percent of surface emissions. Downstream emissions are not calculated for CO_2.

Area estimates

U.S. reservoirs were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[66] the National Inventory of Dams (NID),[67] the National Wetlands Inventory (NWI),[68] the Navigable Waterways (NW) network,[69] and the EPA's Safe Drinking Water Information System (SDWIS).[70] The NHD only covers the conterminous U.S., whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico.

Waterbodies in the NHDWaterbody layer that were greater than or equal to 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered reservoirs: 1) the waterbody was classified as "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to a nearby NID feature (between 100 m to 1000 m), 5) the waterbody intersected a public drinking water intake.

[66] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[67] See https://nid.sec.usace.army.mil.

[68] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[69] See https://hifld-geoplatform.opendata.arcgis.com/maps/aaa3767c7d2b41f69e7528f99cf2fb76_0/about.

[70] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

EPA assumes that all features included in the NW network are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. Navigable Waterway features greater than 8 ha in surface area are defined as reservoirs.

NWI features were considered "managed" if they had a Special Modifier value indicating the presence of management activities (Figure 6-12). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see "Water Regime" in Figure 6-12). NWI features that met these criteria, were greater than 8 ha in surface area, and were not a canal/ditch (see emissions from land converted to flooded land – other constructed waterbodies) were defined as reservoirs.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for identified flooded lands were taken from the NHD, NWI or NW. If features from the NHD, NWI, or NW datasets overlapped, duplicated areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

Reservoir age was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series.

Figure 6-12: Selected Features from NWI that Meet Flooded Lands Criteria

MODIFIERS

In order to more adequately describe the wetland and deepwater habitats, one each of the water regime, water chemistry, soil, or special modifiers may be applied at the class or lower level in the hierarchy

Water Regime			Special Modifiers	Water Chemistry		Soil
Nontidal	**Saltwater Tidal**	**Freshwater Tidal**		**Halinity/Salinity**	**pH Modifiers for Fresh Water**	
A Temporarily Flooded	L Subtidal	Q Regularly Flooded-Fresh Tidal	b Beaver	1 Hyperhaline / Hypersaline	a Acid	g Organic
B Seasonally Saturated	M Irregularly Exposed	R Seasonally Flooded-Fresh Tidal	d Partly Drained/Ditched	2 Euhaline / Eusaline	t Circumneutral	n Mineral
C Seasonally Flooded	N Regularly Flooded	S Temporarily Flooded- Fresh Tidal	f Farmed	3 Mixohaline / M ixosaline (Brackish)	i Alkaline	
D Continuously Saturated	P Irregularly Flooded	T Semipermanently Flooded-Fresh Tidal	m Managed	4 Polyhaline		
E Seasonally Flooded / Saturated		V Permanently Flooded-Fresh Tidal	h Diked/Impounded	5 Mesohaline		
F Semipermanently Flooded			r Artificial Substrate	6 Oligohaline		
G Intermittently Exposed			s Spoil	0 Fresh		
H Permanently Flooded			x Excavated			
J Intermittently Flooded						
K Artificially Flooded						

Must also meet one selected special modifier (red box) to be included in the flooded lands inventory

Included in the flooded lands inventory if it meets water regime qualifier (gold box)

Source (modified): https://www.fws.gov/sites/default/files/documents/wetlands-and-deepwater-map-code-diagram.pdf

IPCC (2019) allows for the exclusion of managed waterbodies from the inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the inventory based on expert judgment that neither the surface area nor water residence time was substantially altered by their associated dams.

Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[71]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the inventory.

[71] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

The surface area of reservoirs in flooded land remaining flooded land increased by approximately 6 percent from 1990 to 2022 (Table 6-84) due to reservoirs matriculating into flooded land remaining flooded land when they reached 20 years of age.

Table 6-84: National Totals of Reservoir Surface Area in Flooded Land Remaining Flooded Land (millions of ha)

Surface Area (millions of ha)	1990	2005	2018	2019	2020	2021	2022
Reservoir	9.6	10.1	10.2	10.2	10.2	10.2	10.2

Table 6-85: State Breakdown of Reservoir Surface Area in Flooded Land Remaining Flooded Land (millions of ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	0.22	0.23	0.23	0.23	0.23	0.23	0.23
Alaska	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Arizona	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Arkansas	0.28	0.29	0.29	0.29	0.29	0.29	0.29
California	0.37	0.39	0.39	0.39	0.39	0.39	0.39
Colorado	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Connecticut	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Delaware	0.03	0.03	0.03	0.03	0.03	0.03	0.03
District of Columbia	+	+	+	+	+	+	+
Florida	0.98	1.01	1.01	1.01	1.01	1.01	1.01
Georgia	0.27	0.29	0.29	0.29	0.29	0.29	0.29
Hawaii	+	+	+	+	+	+	+
Idaho	0.17	0.19	0.19	0.19	0.19	0.19	0.19
Illinois	0.17	0.18	0.22	0.22	0.22	0.22	0.22
Indiana	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Iowa	0.08	0.09	0.10	0.10	0.10	0.10	0.10
Kansas	0.09	0.11	0.11	0.11	0.11	0.11	0.11
Kentucky	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Louisiana	0.40	0.41	0.41	0.41	0.41	0.41	0.41
Maine	0.25	0.26	0.26	0.26	0.26	0.26	0.26
Maryland	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Massachusetts	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Michigan	0.16	0.17	0.17	0.17	0.17	0.17	0.17
Minnesota	0.38	0.38	0.39	0.39	0.39	0.39	0.39
Mississippi	0.18	0.19	0.19	0.19	0.19	0.19	0.19
Missouri	0.19	0.21	0.21	0.21	0.21	0.21	0.21
Montana	0.27	0.29	0.29	0.29	0.29	0.29	0.29
Nebraska	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Nevada	0.09	0.09	0.09	0.09	0.09	0.09	0.09
New Hampshire	0.06	0.06	0.06	0.06	0.06	0.06	0.06
New Jersey	0.11	0.11	0.11	0.11	0.11	0.11	0.11
New Mexico	0.05	0.05	0.05	0.05	0.05	0.05	0.05
New York	0.31	0.32	0.32	0.32	0.32	0.32	0.32
North Carolina	0.39	0.41	0.41	0.41	0.41	0.41	0.41
North Dakota	0.10	0.25	0.26	0.26	0.26	0.26	0.26
Ohio	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Oklahoma	0.24	0.27	0.27	0.27	0.27	0.27	0.27
Oregon	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Pennsylvania	0.09	0.11	0.11	0.11	0.11	0.11	0.11
Puerto Rico	+	+	+	+	+	+	+
Rhode Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02
South Carolina	0.31	0.32	0.33	0.33	0.33	0.33	0.33

South Dakota	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Tennessee	0.18	0.24	0.24	0.24	0.24	0.24	0.24
Texas	0.63	0.70	0.71	0.71	0.71	0.71	0.71
Utah	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Vermont	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Virginia	0.30	0.31	0.31	0.31	0.31	0.31	0.31
Washington	0.24	0.24	0.24	0.24	0.24	0.24	0.24
West Virginia	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Wisconsin	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Wyoming	0.12	0.13	0.14	0.14	0.14	0.14	0.14
Total	**9.47**	**10.10**	**10.20**	**10.20**	**10.20**	**10.20**	**10.20**

+ Indicates values less than 0.005 million ha.

Note: Totals may not sum due to independent rounding.

Uncertainty

Uncertainty in estimates of CH_4 emissions from reservoirs in flooded land remaining flooded land (Table 6-86) are developed using Monte Carlo simulations (IPCC Approach 2) and include uncertainty in the default emission factors and land areas. Each iteration of the simulation draws surface and downstream emission factors from a statistical distribution based on the mean and variance in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). The CH_4 emission factors for surface and downstream emissions are modeled using normal and lognormal distributions, respectively. The 2019 IPCC Refinement does not contain sufficient information to define a normal distribution for the CO_2 emission factor and a uniform distribution bounded by the 95% confidence internal of the mean is assumed. Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 - 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the reservoir area estimates is assumed and is based on expert judgment. Each iteration of the simulation draws a surface area for each waterbody from a uniform distribution bounded by ± 15 percent of the estimated surface area.

Table 6-86: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Reservoir						
Surface	CH_4	27.9	27.4	28.4	-1.7%	+1.7%
Downstream	CH_4	2.5	2.4	3.1	-5.6%	+22.4%
Total	**CH_4**	**30.4**	**29.9**	**31.3**	**-1.6%**	**+2.9%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration with many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of

the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity - by flow and/or volume control. This data source added 418 reservoirs totaling 736,344 ha.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual increase in CH_4 emission estimates from reservoirs of 1.23 MMT CO_2 Eq., or 4 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

The EPA recently completed a survey of greenhouse gas emissions from 108 reservoirs in the conterminous United States.[72] The data will be used to develop country-specific emission factors for U.S. reservoirs to be used in the 1990 through 2024 *Inventory* submission.

Emissions from Flooded Land Remaining Flooded Land–Other Constructed Waterbodies

The IPCC (IPCC 2019) provides emission factors for several types of "other constructed waterbodies" including freshwater ponds and canals/ditches. IPCC (2019) describes ponds as waterbodies that are "…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture." Furthermore, the IPCC "Decision tree for types of Flooded Land" (IPCC 2019, Fig. 7.2) defines a size threshold of 8 ha to distinguish reservoirs from "other constructed waterbodies." For this *Inventory*, ponds are defined as managed flooded land that are 1) less than 8 ha in surface area, and 2) not categorized as canals/ditches. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emissions than the latter. Activity data on pond salinity are not uniformly available for the conterminous United States and all ponds in the inventory are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are often sites of substantial CH_4 emissions from anaerobic sediments.

Canals and ditches (terms are used interchangeably) are linear water features constructed to transport water (i.e., stormwater drainage, aqueduct), to irrigate or drain land, to connect two or more bodies of water, or to serve as a

[72] See https://www.epa.gov/air-research/research-emissions-us-reservoirs.

waterway for watercraft. The geometry and construction of canals and ditches varies widely and includes narrow earthen channels (<1 m wide) and concrete lined aqueducts in excess of 50 m wide. Canals and ditches can be extensive in many agricultural, forest and settlement areas, and may also be significant sources of emissions in some circumstances.

Methane emissions from freshwater ponds in flooded land remaining flooded land increased by approximately 1 percent from 1990 to 2022. Methane emissions from canals and ditches have remained constant throughout the time series because age data are not available for canals and ditches, thus they are assumed to be greater than 20-years old in 1990 and are included in flooded land remaining flooded land throughout the time series. Overall, CH_4 emissions from other constructed waterbodies have remained fairly constant since 1990 (Table 6-87 and Table 6-88).

Table 6-87: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Other Constructed Waterbodies							
Canals and Ditches	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Freshwater Ponds	11.4	11.5	11.5	11.5	11.5	11.5	11.5
Total	**13.7**	**13.8**	**13.8**	**13.8**	**13.8**	**13.8**	**13.8**

Note: Totals may not sum due to independent rounding.

Table 6-88: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Other Constructed Waterbodies							
Canals and Ditches	80.9	80.9	80.9	80.9	80.9	80.9	80.9
Freshwater Ponds	406.6	411.0	411.7	411.8	411.8	411.8	411.9
Total	**487.5**	**491.9**	**492.6**	**492.6**	**492.7**	**492.7**	**492.7**

Note: Totals may not sum due to independent rounding.

Florida and Louisiana have the greatest methane emissions from canals and ditches in the United States (Figure 6-13, Table 6-89). Presumably, most of these canals serve to drain the extensive wetland complexes in these states (Davis, 1973). California has the third greatest methane emissions from canals and ditches. Canals and ditches in California primarily serve to convey water from the mountains to urban and agricultural areas. Michigan and Minnesota have the fourth and fifth largest methane emissions from canals and ditches. These systems serve to drain historic wetlands to facilitate row-crop agriculture. Texas, Florida, and Georgia have the greatest methane emissions from freshwater ponds, although states throughout the eastern United States make significant contributions to the national total. These patterns of emissions are in accordance with the distribution of other constructed waterbodies in the United States.

Table 6-89: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

State	Canals and Ditches	Freshwater Ponds	Total
Alabama	+	10.5	10.6
Alaska	+	+	+
Arizona	1.5	1.0	2.4
Arkansas	3.1	9.4	12.4
California	7.0	9.2	16.2
Colorado	2.9	4.8	7.7
Connecticut	+	1.8	1.8
Delaware	+	0.9	0.9
District of Columbia	+	+	+

Florida	15.6	30.7	46.2
Georgia	+	21.0	21.2
Hawaii	+	+	0.5
Idaho	1.7	2.4	4.1
Illinois	1.0	11.7	12.8
Indiana	1.7	10.6	12.3
Iowa	+	11.2	11.6
Kansas	+	15.4	15.5
Kentucky	+	7.7	7.9
Louisiana	9.4	5.9	15.3
Maine	+	3.5	3.5
Maryland	+	2.3	2.7
Massachusetts	+	2.3	2.3
Michigan	5.4	10.0	15.4
Minnesota	4.7	12.7	17.3
Mississippi	1.6	13.4	15.1
Missouri	2.4	20.7	23.1
Montana	2.0	10.5	12.5
Nebraska	2.0	9.1	11.1
Nevada	0.7	0.8	1.5
New Hampshire	+	1.0	1.1
New Jersey	+	3.0	3.4
New Mexico	0.8	2.1	2.9
New York	+	8.3	8.7
North Carolina	2.6	12.2	14.8
North Dakota	0.8	20.6	21.3
Ohio	0.8	8.9	9.7
Oklahoma	+	19.3	19.4
Oregon	1.0	3.6	4.6
Pennsylvania	+	4.1	4.1
Puerto Rico	+	+	+
Rhode Island	+	+	+
South Carolina	1.3	10.4	11.7
South Dakota	+	16.6	16.9
Tennessee	+	6.7	6.8
Texas	4.6	32.1	36.8
Utah	0.8	2.0	2.8
Vermont	+	0.8	0.8
Virginia	0.5	7.3	7.9
Washington	+	2.0	2.5
West Virginia	+	1.5	1.5
Wisconsin	+	3.8	4.2
Wyoming	0.9	4.8	5.7
Total	**80.9**	**411.9**	**492.7**

+ Indicates values less than 0.5 kt.

Note: Totals may not sum due to independent rounding.

Figure 6-13: 2022 CH_4 Emissions from A) Ditches and Canals and B) Freshwater Ponds in Flooded Land Remaining Flooded Land (kt CH_4)

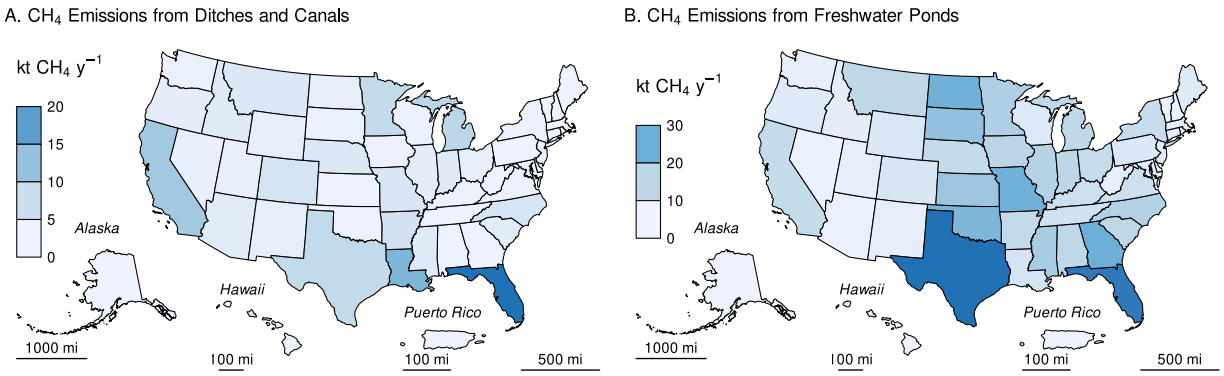

Methodology and Time-Series Consistency

Estimates of CH_4 emissions for other constructed waterbodies in flooded land remaining flooded Land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Based on IPCC guidance, methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-90). Although literature data on greenhouse gas emissions from canals and ditches is relatively sparse, they have the highest default emission factor of all flooded land types (Table 6-90). Default emission factors for freshwater ponds are on the higher end of those for reservoirs. There are insufficient data to support climate-specific emission factors for ponds or canals and ditches. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-90: IPCC (2019) Default CH_4 Emission Factors for Surface Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Other Constructed Waterbody	Surface emission factor (MT CH_4 ha^{-1} y^{-1})
Freshwater ponds	0.183
Canals and ditches	0.416

Area estimates

Other constructed waterbodies were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[73] the National Inventory of Dams (NID),[74] the National Wetlands Inventory (NWI),[75] the Navigable Waterways (NW) network,[76] and the EPA's Safe Drinking Water Information System (SDWIS).[77] The NHD

[73] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[74] See https://nid.sec.usace.army.mil.

[75] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[76] See https://hifld-geoplatform.opendata.arcgis.com/maps/aaa3767c7d2b41f69e7528f99cf2fb76_0/about.

[77] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, District of Columbia, and Puerto Rico. The following paragraphs present the criteria used to identify other constructed waterbodies in the NHD, NW, and NWI.

Waterbodies in the NHDWaterbody layer that were greater than 20-years old, less than 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered freshwater ponds in flooded land remaining flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m), the waterbody intersected a drinking water intake.

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features that were less than 8 ha in surface area and not identified as canals/ditch (see below) were considered freshwater ponds. Only 2.1 percent of NW features met these criteria, and they were primarily associated with larger navigable waterways, such as lock chambers on impounded rivers.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-12). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see "Water Regime" in Figure 6-12). NWI features that met these criteria, were less than 8 ha in surface area, and were not a canal/ditch (see below) were defined as freshwater ponds.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Canals and ditches, a subset of other constructed waterbodies, were identified in the NWI by their morphology. Unlike a natural water body, canals and ditches are typically narrow, linear features with abrupt angular turns. Figure 6-14 contrasts the unique shape of ditches/canals vs more natural water features.

Figure 6-14: Left: NWI Features Identified as Canals/Ditches (pink) by Unique Narrow, Linear/Angular Morphology. Right: Non-Canal/Ditches with More Natural Morphology (blue)

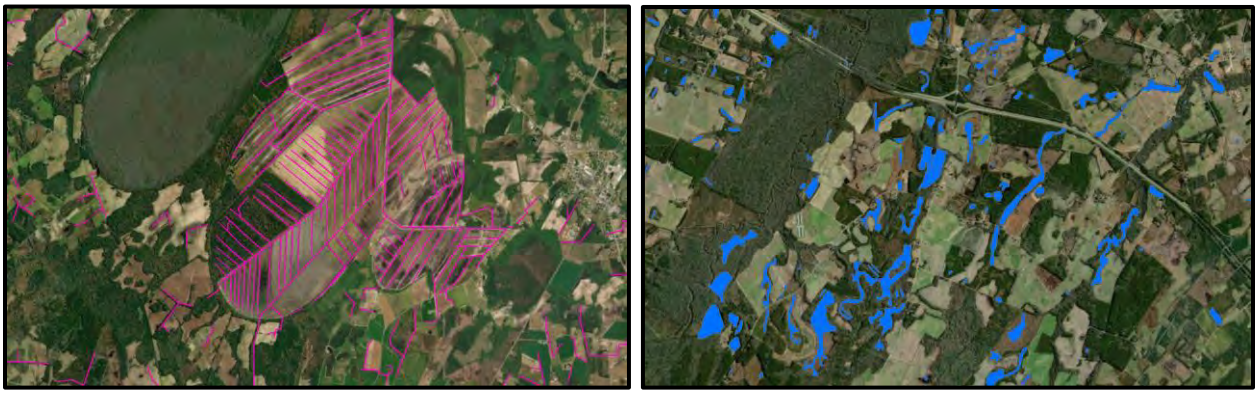

This morphology was identified systematically using shape attributes in a decision tree model. A training set of 752 features were identified as either "ditch" or "not ditch" using expert judgment. The training set was used to train a decision tree which was used to categorize millions of NWI features based on three shape attribute ratios (Figure 6-12).

Table 6-91: Predictors used in Decision Tree to Identify Canal/Ditches

Shape Length : # of Shape Vertices
Shape Area : Shape Length
Shape Area : # of Shape Vertices

The decision tree built a model using 80 percent of the 752 training features and used the 20 percent to validate the model. The model was 93.1 percent accurate. Below are the validation results (Table 6-92).

Table 6-92: Validation Results for Ditch/Canal Classification Decision Tree

	Truth	
Prediction	Ditch/Canal	Not Ditch/Canal
Ditch/Canal	49	5
Not Ditch/Canal	8	27

The decision tree model was then applied to the entire NWI dataset using the following shape attribute ratios (Figure 6-15).

Figure 6-15: Structure of Decision Tree Used to Identify Canals/Ditches

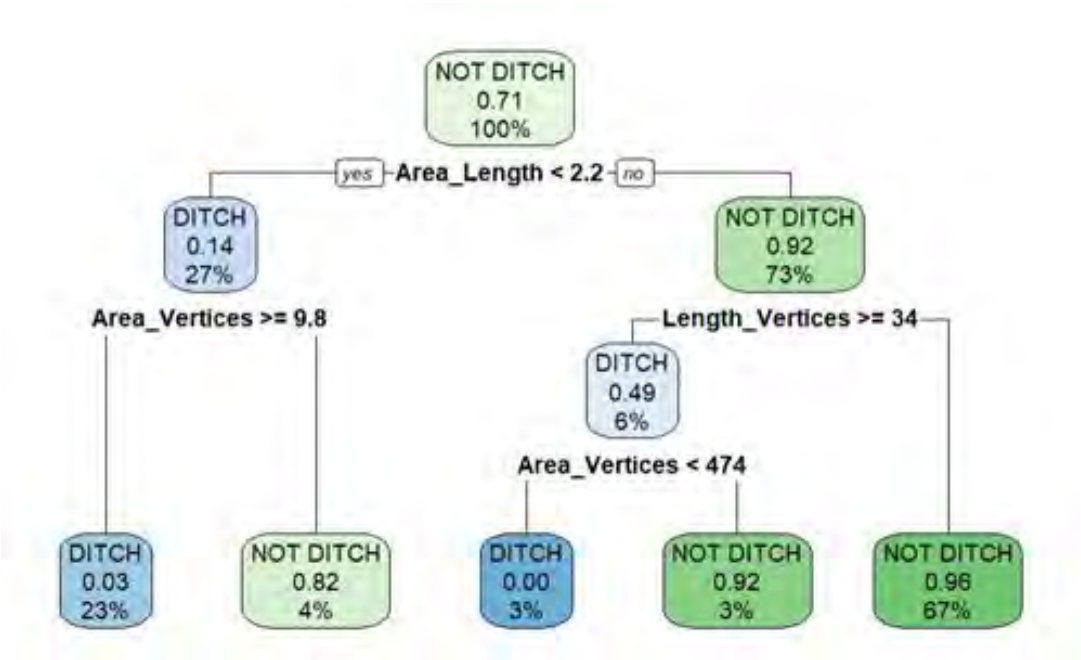

Surface areas for other constructed waterbodies were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, these areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

The age of other constructed waterbody features was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series. No canal/ditch features were associated with a nearby dam, therefore all canal/ditch features were assumed to be greater than 20-years old through the time series.

For the year 2022, this *Inventory* contains 2,250,662 ha of freshwater ponds and 194,412 ha of canals and ditches in flooded land remaining flooded land (Table 6-93). The surface area of freshwater ponds increased by 28,632 ha (1.3 percent) from 1990 to 2022 due to flooded lands matriculating from land converted to flooded land to flooded land remaining flooded land. All canals and ditches were assumed to be greater than 20-years old throughout the time series, thus the surface area of these flooded lands is constant throughout the time series.

Table 6-93: National Surface Area Totals in Flooded Land Remaining Flooded Land - Other Constructed Waterbodies (ha)

	1990	2005	2018	2019	2020	2021	2022
Canals and ditches	194,412	194,412	194,412	194,412	194,412	194,412	194,412
Freshwater ponds	2,222,030	2,245,881	2,249,672	2,250,007	2,250,337	2,250,540	2,250,662
Total	**2,416,442**	**2,440,292**	**2,444,084**	**2,444,418**	**2,444,749**	**2,444,951**	**2,445,074**

Note: Totals may not sum due to independent rounding.

Canals and ditches in the conterminous United States are most abundant in the Gulf Coast states and California (Figure 6-16A, Table). Florida contains 19 percent of all U.S. canal and ditch surface area, most of which were constructed in the early 1900s for drainage, flood protection, and water storage purposes. Freshwater ponds are more widely distributed across the United States (Figure 6-16B, Table 6-95). Texas has the greatest surface area of freshwater ponds, equivalent to 8 percent of all freshwater pond surface area in the United States, closely followed by Florida.

Figure 6-16: 2022 Surface Area of A) Ditches and Canals and B) Freshwater Ponds in Flooded Land Remaining Flooded Land (ha)

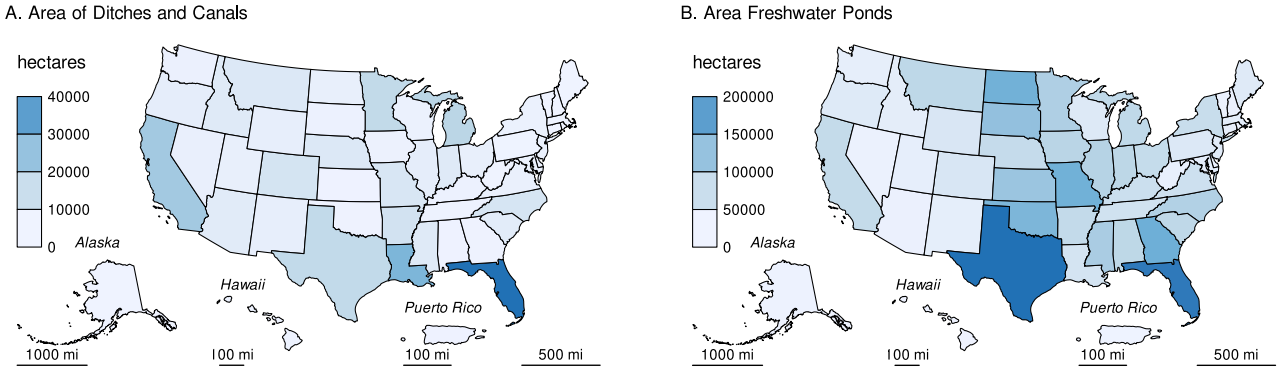

Table 6-94: State Totals of Surface Area in Flooded Land Remaining Flooded Land— Canals and Ditches (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	228	228	228	228	228	228	228
Alaska	115	115	115	115	115	115	115
Arizona	3,536	3,536	3,536	3,536	3,536	3,536	3,536
Arkansas	7,349	7,349	7,349	7,349	7,349	7,349	7,349
California	16,725	16,725	16,725	16,725	16,725	16,725	16,725
Colorado	6,874	6,874	6,874	6,874	6,874	6,874	6,874
Connecticut	28	28	28	28	28	28	28
Delaware	130	130	130	130	130	130	130
District of Columbia	1	1	1	1	1	1	1
Florida	37,482	37,482	37,482	37,482	37,482	37,482	37,482
Georgia	352	352	352	352	352	352	352

Hawaii	538	538	538	538	538	538	538
Idaho	4,027	4,027	4,027	4,027	4,027	4,027	4,027
Illinois	2,489	2,489	2,489	2,489	2,489	2,489	2,489
Indiana	4,064	4,064	4,064	4,064	4,064	4,064	4,064
Iowa	867	867	867	867	867	867	867
Kansas	258	258	258	258	258	258	258
Kentucky	672	672	672	672	672	672	672
Louisiana	22,565	22,565	22,565	22,565	22,565	22,565	22,565
Maine	56	56	56	56	56	56	56
Maryland	967	967	967	967	967	967	967
Massachusetts	132	132	132	132	132	132	132
Michigan	12,897	12,897	12,897	12,897	12,897	12,897	12,897
Minnesota	11,235	11,235	11,235	11,235	11,235	11,235	11,235
Mississippi	3,936	3,936	3,936	3,936	3,936	3,936	3,936
Missouri	5,670	5,670	5,670	5,670	5,670	5,670	5,670
Montana	4,740	4,740	4,740	4,740	4,740	4,740	4,740
Nebraska	4,864	4,864	4,864	4,864	4,864	4,864	4,864
Nevada	1,587	1,587	1,587	1,587	1,587	1,587	1,587
New Hampshire	103	103	103	103	103	103	103
New Jersey	944	944	944	944	944	944	944
New Mexico	2,002	2,002	2,002	2,002	2,002	2,002	2,002
New York	925	925	925	925	925	925	925
North Carolina	6,321	6,321	6,321	6,321	6,321	6,321	6,321
North Dakota	1,819	1,819	1,819	1,819	1,819	1,819	1,819
Ohio	1,819	1,819	1,819	1,819	1,819	1,819	1,819
Oklahoma	278	278	278	278	278	278	278
Oregon	2,498	2,498	2,498	2,498	2,498	2,498	2,498
Pennsylvania	143	143	143	143	143	143	143
Puerto Rico	249	249	249	249	249	249	249
Rhode Island	1	1	1	1	1	1	1
South Carolina	3,226	3,226	3,226	3,226	3,226	3,226	3,226
South Dakota	703	703	703	703	703	703	703
Tennessee	442	442	442	442	442	442	442
Texas	11,152	11,152	11,152	11,152	11,152	11,152	11,152
Utah	1,875	1,875	1,875	1,875	1,875	1,875	1,875
Vermont	95	95	95	95	95	95	95
Virginia	1,306	1,306	1,306	1,306	1,306	1,306	1,306
Washington	1,125	1,125	1,125	1,125	1,125	1,125	1,125
West Virginia	28	28	28	28	28	28	28
Wisconsin	887	887	887	887	887	887	887
Wyoming	2,086	2,086	2,086	2,086	2,086	2,086	2,086
Total	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**

Table 6-95: State Totals of Surface Area in Flooded Land Remaining Flooded Land—Freshwater Ponds (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	57,034	57,342	57,355	57,355	57,355	57,355	57,355
Alaska	2,367	2,370	2,370	2,370	2,370	2,370	2,370
Arizona	5,199	5,236	5,249	5,249	5,253	5,253	5,253
Arkansas	50,880	51,211	51,211	51,211	51,211	51,211	51,211
California	50,219	50,426	50,499	50,504	50,511	50,513	50,519
Colorado	26,174	26,448	26,478	26,479	26,480	26,480	26,494
Connecticut	9,630	9,697	9,699	9,699	9,699	9,699	9,699
Delaware	4,717	4,721	4,721	4,721	4,721	4,721	4,721
District of Columbia	16	16	16	16	16	16	16
Florida	167,317	167,453	167,496	167,502	167,502	167,508	167,508

Georgia	113,254	114,898	114,969	114,972	114,972	114,972	114,972
Hawaii	1,580	1,592	1,595	1,595	1,595	1,595	1,595
Idaho	13,220	13,352	13,359	13,359	13,359	13,360	13,360
Illinois	63,516	64,044	64,144	64,149	64,159	64,160	64,169
Indiana	57,593	58,065	58,170	58,175	58,175	58,175	58,185
Iowa	57,450	59,612	60,745	60,929	61,051	61,147	61,168
Kansas	81,828	83,900	83,976	83,985	83,985	84,002	84,004
Kentucky	41,427	41,808	41,837	41,837	41,837	41,837	41,837
Louisiana	32,085	32,210	32,221	32,221	32,226	32,226	32,226
Maine	19,102	19,149	19,159	19,159	19,159	19,159	19,159
Maryland	12,569	12,739	12,810	12,810	12,812	12,815	12,818
Massachusetts	12,359	12,413	12,457	12,464	12,470	12,472	12,476
Michigan	54,525	54,672	54,701	54,701	54,709	54,709	54,709
Minnesota	68,801	69,082	69,173	69,176	69,202	69,210	69,220
Mississippi	72,832	73,209	73,336	73,343	73,363	73,375	73,383
Missouri	109,573	112,993	113,068	113,071	113,073	113,077	113,079
Montana	56,860	57,246	57,263	57,268	57,269	57,269	57,269
Nebraska	48,051	49,380	49,649	49,667	49,697	49,706	49,709
Nevada	4,452	4,455	4,508	4,509	4,512	4,512	4,515
New Hampshire	5,427	5,526	5,585	5,585	5,586	5,587	5,587
New Jersey	16,192	16,232	16,253	16,253	16,253	16,253	16,253
New Mexico	11,379	11,394	11,398	11,401	11,401	11,401	11,406
New York	45,224	45,485	45,590	45,592	45,592	45,598	45,598
North Carolina	66,205	66,661	66,744	66,744	66,747	66,750	66,751
North Dakota	112,310	112,384	112,469	112,475	112,485	112,489	112,492
Ohio	48,028	48,393	48,591	48,605	48,637	48,651	48,656
Oklahoma	103,243	105,224	105,288	105,304	105,318	105,324	105,333
Oregon	19,304	19,487	19,532	19,534	19,539	19,539	19,539
Pennsylvania	22,018	22,256	22,289	22,289	22,289	22,289	22,289
Puerto Rico	708	708	708	708	708	708	708
Rhode Island	2,204	2,213	2,220	2,220	2,220	2,220	2,220
South Carolina	55,794	56,456	56,673	56,682	56,686	56,686	56,686
South Dakota	90,237	90,447	90,504	90,515	90,516	90,521	90,521
Tennessee	35,927	36,307	36,332	36,337	36,343	36,344	36,344
Texas	172,580	175,497	175,569	175,574	175,575	175,575	175,575
Utah	10,703	10,764	10,772	10,772	10,773	10,773	10,773
Vermont	4,316	4,381	4,392	4,392	4,392	4,392	4,392
Virginia	39,938	39,996	40,000	40,000	40,000	40,000	40,000
Washington	10,943	11,081	11,119	11,119	11,122	11,123	11,123
West Virginia	8,027	8,156	8,166	8,166	8,166	8,166	8,166
Wisconsin	20,845	20,989	21,003	21,003	21,003	21,003	21,003
Wyoming	25,851	26,106	26,243	26,243	26,244	26,246	26,250
Total	**2,222,030**	**2,245,881**	**2,249,672**	**2,250,007**	**2,250,337**	**2,250,540**	**2,250,662**

Uncertainty

Uncertainty in estimates of CH_4 emissions from other constructed waterbodies (ponds, canals/ditches) in flooded land remaining flooded land (Table 6-96) are estimated using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in default emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the flooded land area estimates is assumed and is based on expert judgment.

Table 6-96: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Canals and ditches	CH_4	2.3	2.1	2.4	-5.1%	+7.0%
Freshwater pond	CH_4	11.5	11.5	11.5	-0.04%	+0.04%
Total	**CH_4**	**13.8**	**13.7**	**13.9**	**-0.8%**	**+1.0%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID.[78] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity—by flow and/or volume control. This data source added 54 features totaling 173 ha of other constructed waterbodies.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current (1990 through 2022) *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual decrease in CH_4 emission estimates from other constructed waterbodies of 2.7 MMT CO_2 Eq., or 17 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

[78] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

Planned Improvements

Default emission factors for canals/ditches were derived from a global dataset that include few measurements from U.S. systems. The EPA plans to conduct a literature survey to determine if sufficient data are available to derive a country-specific emission factor for the 1990 through 2024 *Inventory* submission.

Canal and ditch surface area included here may overlap with ditches and canals included in CH_4 emission estimates for ditches draining inland organic soils (IPCC 2013, section 2.2.2.1). EPA plans to reconcile ditch/canal surface areas between the two managed land types (flooded land vs drained inland organic soils) in the next (i.e., 1990 through 2023) *Inventory*.

Features less than 8 ha in the NW that were not identified as Canal/Ditch were defined as freshwater ponds. Many of these features are lock chambers connected to an upstream reservoir. These systems likely have emission rates more similar to a reservoir than freshwater pond. In the next (1990 through 2023) *Inventory* these systems will be classified as reservoirs.

6.9 Land Converted to Wetlands (CRT Source Category 4D2)

Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Land converted to vegetated coastal wetlands occurs as a result of inundation of unprotected low-lying coastal areas with gradual sea-level rise, flooding of previously drained land behind hydrological barriers, and through active restoration and creation of coastal wetlands through removal of hydrological barriers. Based upon NOAA C-CAP, wetlands are subdivided into freshwater (Palustrine) and saline (Estuarine) classes and further subdivided into emergent marsh, scrub shrub and forest classes All other land categories (i.e., forest land, cropland, grassland, settlements and other lands) are identified as having some area converting to vegetated coastal wetlands. This *Inventory* does not include land converted to unvegetated open water coastal wetlands (see Planned Improvements section below). Between 1990 and 2022 the rate of annual transition for land converted to vegetated coastal wetlands ranged from 0 to 2,650 ha per year, depending on the type of land converted.[79] Conversion rates from forest land were relatively consistent between 1990 and 2010 (ranging between 2,409 and 2,650 ha) and decreased to 625 ha starting in 2011; the majority of these conversions resulted in increases in the area of palustrine wetlands, which also initiates CH_4 emissions when lands are inundated with fresh water.[80] Little to no conversion of cropland, grassland, settlement, or other lands to vegetated coastal wetlands occurred during the reporting period, with converted areas ranging from 0 to 25 ha per year.[81]

[79] Data from C-CAP; see https://coast.noaa.gov/digitalcoast/tools/. Accessed October 2023.

[80] Currently, the C-CAP dataset categorizes coastal wetlands as either palustrine (fresh water) or estuarine (presence of saline water). This classification does not differentiate between estuarine wetlands with salinity ≤ 18 ppt (when methanogenesis begins to occur) and those that are >18 ppt (where negligible to no CH_4 is produced); therefore, it is not possible at this time to account for CH_4 emissions from estuarine wetlands in the *Inventory*.

[81] At the present stage of *Inventory* development, coastal wetlands are not explicitly shown in the land representation analysis (Section 6.1) while work continues harmonizing data from NOAA's Coastal Change Analysis Program (C-CAP) with NRI, FIA and NLDC data used to compile the land representation (NOAA OCM 2020).

Conversion to coastal wetlands resulted in a biomass carbon stock loss of 0.2 MMT CO_2 Eq. (0.03 MMT C) in 2022 (Table 6-97 and Table 6-98). Loss of forest biomass through conversion of forest lands to vegetated coastal wetlands is the primary driver behind biomass carbon stock change being a source rather than a sink across the time series. Conversion of cropland, grassland, settlement and other lands result in a net increase in biomass stocks. Conversion of lands to vegetated coastal wetlands resulted in a DOM loss of 0.03 MMT CO_2 Eq. (0.008 MMT C) in 2022 (Table 6-97 and Table 6-98), which is driven by the loss of DOM when forest land is converted to vegetated coastal wetlands. This is likely an overestimate of loss because wetlands inherently preserve dead organic material. Conversion of cropland, grassland, settlement and other land results in a net increase in DOM Across all time periods, soil carbon accumulation resulting from lands converted to vegetated coastal wetlands is a carbon sink and has ranged between -0.14 and -0.3 MMT CO_2 Eq. (-0.04 and -0.07 MMT C; Table 6-97 and Table 6-98). Conversion of lands to coastal wetlands resulted in CH_4 emissions of 0.17 MMT CO_2 Eq. (6.1 kt CH_4) in 2022 (Table 6-99). Methane emissions due to the conversion of lands to vegetated coastal wetlands are largely the result of forest land converting to palustrine emergent and scrub shrub coastal wetlands in warm temperate climates. Emissions were the highest between 1990 and 2002 (0.28 MMT CO_2 Eq., 10.0 kt CH_4) and have continually decreased to current levels. This decrease was driven by a reduction in the rate of conversion of forest land to palustrine scrub-shrubs and emergent wetlands.

Table 6-97: Net CO_2 Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.49**	**0.50**	**(+)**	**0.01**	**0.02**	**0.03**	**0.04**
Biomass C Stock	0.62	0.62	0.13	0.13	0.13	0.13	0.13
Dead Organic Matter C Flux	0.11	0.12	0.03	0.03	0.03	0.03	0.03
Soil C Stock	(0.24)	(0.24)	(0.16)	(0.15)	(0.14)	(0.13)	(0.12)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.03)**	**(0.03)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**
Biomass C Stock	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Soil C Stock	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.60**	**0.60**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**
Total Dead Organic Matter Flux	**0.11**	**0.12**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Soil C Flux	**(0.25)**	**(0.25)**	**(0.18)**	**(0.17)**	**(0.16)**	**(0.15)**	**(0.14)**
Total Flux	**0.46**	**0.47**	**(0.02)**	**(0.02)**	**(0.01)**	**0.00**	**0.01**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-98: Net CO_2 Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT C)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**

Wetlands							
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.13**	**0.14**	**+**	**+**	**0.006**	**0.008**	**0.01**
Biomass C Stock	0.17	0.17	0.04	0.04	0.04	0.04	0.04
Dead Organic Matter C Flux	0.03	0.03	0.01	0.01	0.01	0.01	0.01
Soil C Stock	(0.06)	(0.06)	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**()**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**
Biomass C Stock	(+)	(0.01)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(0.01)	(+)	(+)	(+)	(+)	(+)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.16**	**0.16**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Dead Organic Matter Flux	**0.03**	**0.03**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Total Soil C Flux	**(0.07)**	**(0.07)**	**(0.05)**	**(0.05)**	**(0.04)**	**(0.04)**	**(0.04)**
Total Flux	**0.13**	**0.13**	**(0.01)**	**(+)**	**(+)**	**+**	**+**

+ Absolute value does not exceed 0.005 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-99: CH_4 Emissions from Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq. and kt CH_4)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	+	0.01	0.04	0.04	0.05	0.05	0.05
Forest Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	0.28	0.27	0.19	0.18	0.17	0.16	0.15
CH_4 Emissions (kt CH_4)	9.88	9.74	6.85	6.48	6.10	5.76	5.41
Grassland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	0.01	0.07	0.07	0.08	0.08	0.09
Other Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	0.01	0.01	0.01	0.01	0.02
CH_4 Emissions (kt CH_4)	0.08	0.14	0.43	0.47	0.50	0.52	0.54
Settlements Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	+	+	+	+	+	+
Total CH_4 Emissions (MMT CO_2 Eq.)	**0.28**	**0.28**	**0.21**	**0.20**	**0.19**	**0.18**	**0.17**
Total CH_4 Emissions (kt CH_4)	**9.98**	**9.91**	**7.39**	**7.06**	**6.73**	**6.41**	**6.09**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq. or 0.005 kt CH_4.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section provides a description of the methodology used to estimate changes in biomass, dead organic matter and soil carbon stocks and CH_4 emissions for land converted to vegetated coastal wetlands. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Biomass carbon stocks for land converted to vegetated coastal wetlands are estimated for palustrine and estuarine marshes for land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants within the U.S. land representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). Both federal and non-federal lands are represented. Delineating vegetated coastal wetlands from ephemerally flooded upland grasslands represents a particular challenge in remote sensing. Moreover, at the boundary between wetlands and uplands, which may be gradual on low lying coastlines, the presence of wetlands may be ephemeral depending upon weather and climate cycles and as such, impacts on the emissions and removals will vary over these time frames. Trends in land cover change are extrapolated to 1990 and 2021 from these datasets using the C-CAP change data closest in date to a given year. Biomass is not sensitive to soil organic content. Aboveground biomass carbon stocks for non-forested coastal wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). Aboveground biomass carbon removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class. The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[82]). Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (IPCC 2014) and summed with aboveground biomass to obtain total biomass carbon stocks. Aboveground biomass carbon stocks for forest land, cropland, and grassland that are lost with the conversion to vegetated coastal wetlands were derived from Tier 1 default values (IPCC 2006; IPCC 2019). Biomass carbon stock changes are calculated by subtracting the biomass carbon stock values of each land use category (i.e., forest land, cropland, and grassland) from those of vegetated coastal wetlands in each climate zone and multiplying that value by the corresponding C-CAP derived area gained that year in each climate zone. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The total coastal wetland biomass carbon stock change is accounted for during the year of conversion; therefore, no interannual changes are calculated during the remaining years it is in the category.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are accounted for in subtropical estuarine forested wetlands for lands converted to vegetated coastal wetlands across all years. Tier 1 estimates of mangrove DOM carbon stocks were used for subtropical estuarine forested wetlands (IPCC 2014). Neither Tier 1 or 2 data on DOM are currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone or estuarine forested wetlands in climates other than subtropical climates. Tier 1 DOM C stocks for forest land converted to vegetated coastal wetlands were derived from IPCC (2019) to account for the loss of DOM that occurs with conversion. Changes in DOM are assumed to be negligible for other land use conversions (i.e., other than forest land) to coastal wetlands based on the Tier 1 method in IPCC (2006). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2022 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by the

[82] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed October 2023.

difference between Tier 1 DOM carbon stocks for vegetated coastal wetlands and forest land. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The coastal wetland DOM stock is assumed to be in steady state once established in the year of conversion; therefore, no interannual changes are calculated.

Soil Carbon Stock Changes

Soil carbon removals are estimated for land converted to vegetated coastal wetlands across all years. Soil carbon stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature[83] (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al. 2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012 a & b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Breithaupt et al. 2014; Crooks et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022). To estimate soil carbon stock changes, no differentiation is made for soil type (i.e., mineral, organic). Soil C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class.

As per IPCC (2014) guidance, land converted to vegetated coastal wetlands is assumed to remain in this category for up to 20 years before transitioning to vegetated coastal wetlands remaining vegetated coastal wetlands. Tier 2 level estimates of soil carbon stock changes associated with annual soil carbon accumulation from land converted to vegetated coastal wetlands were developed using country-specific soil carbon removal factors multiplied by activity data of land area for land converted to vegetated coastal wetlands for a given year in addition to the previous 19-year cumulative area. Guidance from the *Wetlands Supplement* allows for the rate of soil carbon accumulation to be instantaneously equivalent to that in natural settings and that soil carbon accumulation is initiated when natural vegetation becomes established; this is assumed to occur in the first year of conversion. No loss of soil carbon as a result of land conversion to coastal wetlands is assumed to occur. Since the C-CAP coastal wetland area dataset begins in 1996, the area converted prior to 1996 is assumed to be the same as in 1996. Similarly, the coastal wetland area data for 2017 through 2022 is assumed to be the same as in 2016. The methodology follows Eq. 4.7, Chapter 4 of the *IPCC Wetlands Supplement* (IPCC 2014) and is applied to the area of land converted to vegetated coastal wetlands on an annual basis.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for land converted to vegetated coastal wetlands are derived from the same wetland map used in the analysis of wetland soil carbon fluxes for palustrine wetlands, and are produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *IPCC Wetlands Supplement.* The methodology follows Eq. 4.9, Chapter 4 of the *IPCC Wetlands Supplement* and a global warming potential of 28 is used (IPCC 2013). Because land converted to vegetated coastal wetlands is held in this category for up to 20 years before transitioning to vegetated coastal wetlands remaining to vegetated coastal wetlands, CH_4 emissions in a given year represent the cumulative area held in this category for that year and the prior 19 years.

Uncertainty

Underlying uncertainties in estimates of soil carbon removal factors, biomass change, DOM, and CH_4 emissions

[83] Coastal Carbon Network (2023). Database: Coastal Carbon Library (Version 1.0.0). Smithsonian Environmental Research Center. Dataset. https://doi.org/10.25573/serc.21565671. Accessed October 2023

include error in uncertainties associated with Tier 2 literature values of soil carbon removal estimates, biomass stocks, DOM, and IPCC default CH_4 emission factors, uncertainties linked to interpretation of remote sensing data, as well as assumptions that underlie the methodological approaches applied.

Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines what flux is applied. Because mean soil and biomass carbon removal for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to estimate the CH_4 flux (e.g., delineation of an 18 ppt boundary), which will need significant improvement to reduce uncertainties. The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-100 for each carbon pool and the CH_4 emissions. The combined uncertainty is 42.6 percent above and below the estimate of 0.17 MMT CO_2 Eq. In 2022, the total flux was 0.17 MMT CO_2 Eq., with lower and upper estimates of 0.10 and 0.24 MMT CO_2 Eq.

Table 6-100: Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes occurring within Land Converted to Vegetated Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	0.12	0.1	0.15	-20.0%	20.0%
Dead Organic Matter Flux	0.03	0.02	0.03	-25.8%	25.8%
Soil C Stock Flux	(0.14)	(0.2)	(0.1)	-17.7%	17.7%
Methane Emissions	0.17	0.12	0.22	-29.9%	29.9%
Total Uncertainty	**0.18**	**0.11**	**0.26**	**-42.2%**	**42.2%**

[a] Range of flux estimates based on error propagation at 95 percent confidence interval.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal mandatory QA/QC assessment (McCombs et al. 2016). QA/QC and verification of soil carbon stock dataset has been provided by the Smithsonian Environmental Research Center and coastal wetland inventory team leads. Biomass carbon stocks are derived from peer-review literature, reviewed by U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads prior to inclusion in the *Inventory* and from IPCC reports. As a QC step, a check was undertaken confirming that coastal wetlands recognized by C-CAP represent a subset of wetlands recognized by the NRI for marine coastal states. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil carbon stock, emissions/removals data are based upon peer-reviewed literature and CH_4 emission factors are derived from the *Wetlands Supplement*.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since

2016 and other relevant data that were not previously included. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in a minimal annual average increase (0.001 MMT CO_2 Eq.) for the entire time series.

Planned Improvements

Currently, the only coastal wetland conversion that is reported in the *Inventory* is lands converted to vegetated coastal wetlands. The next (1990 through 2023) *Inventory* submission is expected to include carbon stock change data for lands converted to unvegetated open water coastal wetlands.

Land Converted to Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural production of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation but would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as "reservoirs" or "other constructed waterbodies" (IPCC 2019). Reservoirs are defined as flooded land greater than 8 ha and includes the seasonally flooded land on the perimeter of permanently flooded land (i.e., inundation areas). IPCC guidance (IPCC 2019) provides default emission factors for reservoirs and several types of "other constructed waterbodies" including freshwater ponds and canals/ditches.

Land that has been flooded for 20 years or greater is defined as flooded land remaining flooded land and land flooded for less than 20 years is defined as land converted to flooded land. The distinction is based on literature reports that CO_2 and CH_4 emissions are high immediately following flooding as labile organic matter is rapidly degraded but decline to a steady background level approximately 20 years after flooding (Abril et al. 2005, Barros et al. 2011, Teodoru et al. 2012). Both CO_2 and CH_4 emissions are estimated for land converted to flooded land.

Nitrous oxide emissions from flooded lands are largely related to inputs of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Section 5.4, Agricultural Soil Management) and wastewater management (Section 7.2, Wastewater Treatment and Discharge).

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. The permanently wetted portion of reservoirs are typically surrounded by periodically inundated land referred to as a "drawdown zone" or "inundation area." Greenhouse gas emissions from inundation areas are considered significant and similar per unit area to the emissions from the water surface and are therefore included in the total reservoir surface area when estimating greenhouse gas emissions from flooded land. Lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed flooded land (see Area Estimates below) (IPCC 2019).

In 2022, the United States and Puerto Rico contained 72,461 ha of reservoir surface area in land converted to flooded land (see Methodology and Time-Series Consistency below for calculation details) distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-17) (IPCC 2019).

Emissions from Land Converted to Flooded Land–Reservoirs

Figure 6-17: U.S. Reservoirs (black polygons) in the Land Converted to Flooded Land Category in 2022

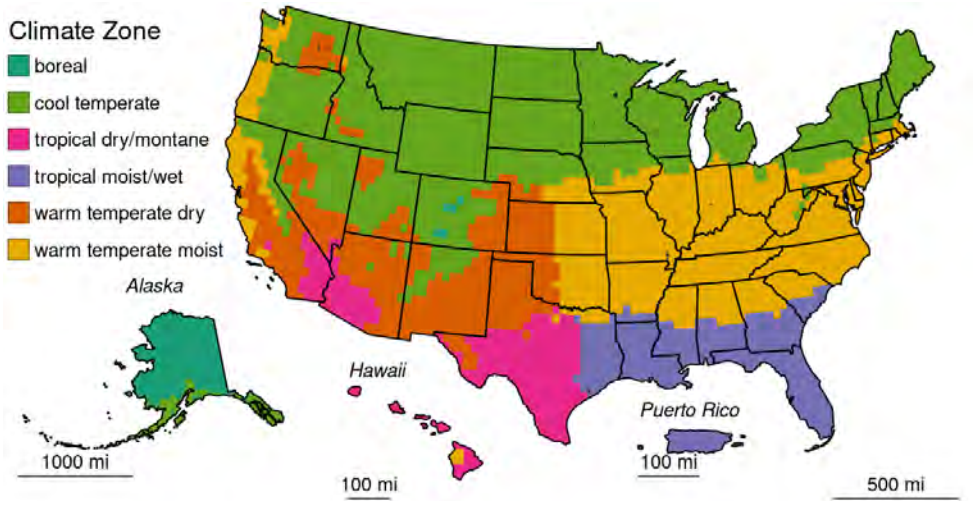

Note: Colors represent climate zone used to derive IPCC default emission factors. Reservoirs (indicated by black polygons) are sparsely distributed across United States, but can be seen in MN, IL, and IN in this image.

Methane and CO_2 are produced in reservoirs through the natural breakdown of organic matter. Per unit area emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae). Greenhouse gases produced in reservoirs can be emitted directly from the water surface and inundation areas or as greenhouse gas-enriched water passes through the dam and the downstream river. Sufficient information exists to estimate downstream CH_4 emissions using Tier 1 IPCC guidance (IPCC 2019), but no guidance is provided for downstream CO_2 emissions. Table 6-101 and Table 6-102 below summarize nationally aggregated CH_4 and CO_2 emissions from reservoirs in land converted to flooded land. The decrease in CO_2 and CH_4 emissions through the time series is attributable to reservoirs matriculating from the land converted to flooded land category into the flooded land remaining flooded land category. Emissions have been stable since 2005, reflecting the low rate of new flooded land creation over the past 17 years.

Table 6-101: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emissions	2.5	0.4	0.2	0.2	0.2	0.2	0.2
Downstream Emissions	0.2	+	+	+	+	+	+
Total	**2.7**	**0.4**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+Indicates values less than 0.05 MMT CO_2

Note: Totals may not sum due to independent rounding.

Table 6-102: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emissions	90	14	7	7	7	7	7
Downstream Emissions	8	1	1	1	1	1	1
Total	**98**	**15**	**8**	**8**	**8**	**7**	**7**

Note: Totals may not sum due to independent rounding.

Table 6-103: CO_2 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoir	3.5	0.6	0.3	0.3	0.3	0.3	0.3

Table 6-104: CO_2 Emissions from Land Converted to Flooded Land—Reservoirs (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoir	0.9	0.2	0.1	0.1	0.1	0.1	0.1

Methane and CO_2 emissions from reservoirs in Minnesota were 8-fold greater than from any other state (Figure 6-18 and Table 6-105). This is attributed to nineteen reservoirs created in Minnesota after 2001 which impound 54,064 ha of water, 96 percent of which is located in Mille Lacs Lake.

North Dakota is the second largest source of CO_2 and CH_4 from reservoirs in land converted to flooded land. Over ninety-nine percent of land converted to flooded land reservoir surface area in North Dakota is attributed to Devils Lake. Both Mille Lacs and Devils Lakes are natural waterbodies provisioned with dams for water level management.

Figure 6-18: 2022 A) CH_4 and B) CO_2 Emissions from U.S. Reservoirs in Land Converted to Flooded Land

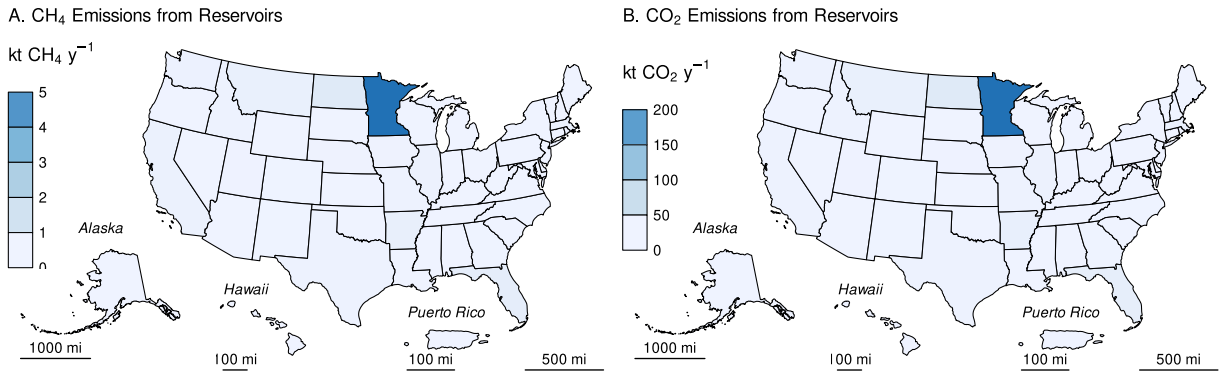

Table 6-105: Methane and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land in 2022 (kt CH_4; kt CO_2)

	CH_4			CO_2[a]
State	Surface	Downstream	Total	Surface
Alabama	0	0	0	0
Alaska	0	0	0	0
Arizona	0	0	0	0
Arkansas	+	+	+	9
California	+	+	+	3
Colorado	+	+	+	1
Connecticut	+	+	+	+
Delaware	0	0	0	0
District of Columbia	0	0	0	0
Florida	+	+	+	13
Georgia	+	+	+	1
Hawaii	0	0	0	0
Idaho	+	+	+	2

Illinois	+	+	+	4
Indiana	+	+	+	+
Iowa	+	+	+	2
Kansas	+	+	+	+
Kentucky	0	0	0	0
Louisiana	+	+	+	+
Maine	+	+	+	+
Maryland	+	+	+	+
Massachusetts	+	+	+	5
Michigan	+	+	+	+
Minnesota	5	+	5	202
Mississippi	+	+	+	+
Missouri	+	+	+	2
Montana	+	+	+	8
Nebraska	+	+	+	1
Nevada	+	+	+	+
New Hampshire	+	+	+	1
New Jersey	0	0	0	0
New Mexico	+	+	+	1
New York	+	+	+	+
North Carolina	+	+	+	1
North Dakota	+	+	1	22
Ohio	+	+	+	1
Oklahoma	0	0	0	0
Oregon	+	+	+	1
Pennsylvania	+	+	+	1
Puerto Rico	0	0	0	0
Rhode Island	0	0	0	0
South Carolina	0	0	0	0
South Dakota	+	+	+	+
Tennessee	+	+	+	1
Texas	+	+	+	3
Utah	+	+	+	1
Vermont	0	0	0	0
Virginia	0	0	0	0
Washington	+	+	+	3
West Virginia	+	+	+	+
Wisconsin	+	+	+	1
Wyoming	+	+	+	1

+ Indicates values greater than zero and less than 0.5 kt.

[a] CO_2: Only surface CO_2 emissions are included in the *Inventory*.

Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for reservoirs in land converted to flooded land follow the Tier 1 methodology in the IPCC guidance (IPCC 2019). All calculations are performed at the state level and summed to obtain national estimates. Emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate-specific emission factor (Table 6-106). Downstream CH_4 emissions are calculated as 9 percent of the surface CH_4 emission (Tier 1 default). The IPCC guidance (IPCC 2019) does not address downstream CO_2 emissions, presumably because there are insufficient data in the literature to estimate this emission pathway.

The IPCC default surface emission factors are derived from model-predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, Table 7A.2) which were collapsed into six climate zones using a regression tree approach. All six aggregated climate zones are present in the United States.

Table 6-106: IPCC (2019) Default CH_4 and CO_2 Emission Factors for Surface Emissions from Reservoirs in Land Converted to Flooded Land

	Surface emission factor	
Climate	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Boreal	0.0277	3.45
Cool Temperate	0.0847	3.74
Warm Temperate Dry	0.1956	6.23
Warm Temperate Moist	0.1275	5.35
Tropical Dry/Montane	0.3923	10.82
Tropical Moist/Wet	0.2516	10.16

Note: Downstream CH_4 emissions are calculated as 9 percent of surface emissions. Downstream emissions are not calculated for CO_2.

Area estimates

U.S. reservoirs were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[84] the National Inventory of Dams (NID),[85] the National Wetlands Inventory (NWI),[86] and the Navigable Waterways (NW) network,[87] and the EPA's Safe Drinking Water Information System (SDWIS).[88] The NHD only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico. The following paragraphs present the criteria used to identify other constructed waterbodies in the NHD, NW, and NWI.

Waterbodies in the NHDWaterbody layer that were less than or equal to 20-years old, greater than or equal to 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered reservoirs in land converted to flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m).

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features greater than 8 ha in surface area are defined as reservoirs.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-19). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see 'Water Regime' in Figure 6-19). NWI features that met these criteria, were greater than 8 ha in surface area, and were not a canal/ditch (see emissions from land converted to flooded land–other constructed waterbodies) were defined as reservoirs.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for identified flooded lands were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, duplicate areas were erased. The first step was to take the final NWI flooded lands

[84] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[85] See https://nid.sec.usace.army.mil.

[86] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[87] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[88] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

Reservoir age was determined by assuming they were created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the feature was greater than 20-years old throughout the time series. Only reservoirs less than or equal to 20-years old are included in land converted to flooded land.

Figure 6-19: Selected Features from NWI that meet Flooded Lands Criteria

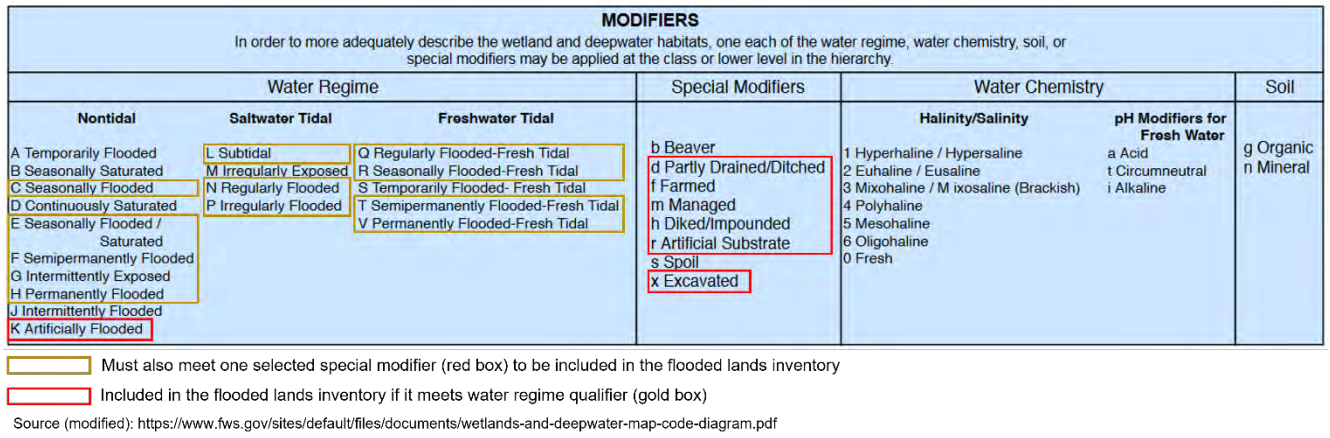

IPCC (2019) allows for the exclusion of managed waterbodies from the inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the inventory based on expert judgment that neither the surface area nor water residence time was substantially altered by their associated dams.

Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[89]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the *Inventory*.

The surface area of reservoirs in land converted to flooded land decreased by nearly 90 percent from 1990 to 2022 (Table 6-107). This is due to reservoirs that were less than 20-years old at the beginning of time series entering the flooded land remaining flooded land category when they exceeded 20 years of age. The rate at which flooded land has aged out of the land converted to flooded land category has outpaced the rate of new dam construction. New dam construction has slowed considerably during the time series with only nine new dams constructed in 2022,[90] versus 552 in 1990 (Figure 6-20).

Table 6-107: National Totals of Reservoir Surface Area in Land Converted to Flooded Land (thousands of ha)

Surface Area (thousands of ha)	1990	2005	2018	2019	2020	2021	2022
Reservoir	566	115	78	77	75	74	73

[89] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[90] See https://nid.sec.usace.army.mil.

Figure 6-20: Number of Dams Built per Year from 1990 through 2022

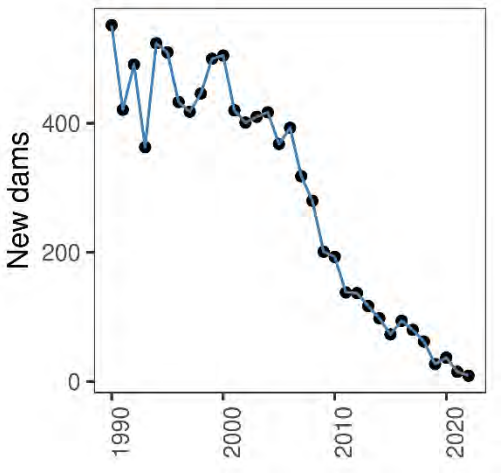

Table 6-108: State Breakdown of Reservoir Surface Area in Land Converted to Flooded Land (thousands of ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	7.5	0.0	0.0	0.0	0.0	0.0	0.0
Alaska	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Arizona	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Arkansas	10.1	2.9	1.8	1.8	1.8	1.8	1.8
California	19.6	2.1	0.5	0.5	0.5	0.5	0.5
Colorado	5.9	1.3	0.3	0.3	0.3	0.3	0.3
Connecticut	2.3	2.2	0.0	0.0	0.0	0.0	0.0
Delaware	0.0	0.0	0.0	0.0	0.0	0.0	0.0
District of Columbia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Florida	25.7	3.8	1.5	1.5	1.4	1.2	1.2
Georgia	20.6	4.9	0.1	0.1	0.1	0.1	0.1
Hawaii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Idaho	17.7	1.2	0.5	0.5	0.5	0.5	0.5
Illinois	49.2	39.4	1.4	1.3	1.3	0.8	0.8
Indiana	10.6	0.3	0.1	0.1	0.1	0.1	0.1
Iowa	12.3	3.1	1.0	1.0	0.7	0.7	0.5
Kansas	19.6	0.4	0.2	0.2	0.1	0.1	0.0
Kentucky	1.3	0.1	0.0	0.0	0.0	0.0	0.0
Louisiana	9.4	0.2	0.0	0.0	0.0	0.0	0.0
Maine	10.9	4.4	0.0	0.0	0.0	0.0	0.0
Maryland	0.8	0.1	0.1	0.1	0.1	0.1	0.1
Massachusetts	1.6	0.5	1.5	1.5	1.4	1.4	1.2
Michigan	11.6	0.9	0.1	0.1	0.1	0.1	0.1
Minnesota	9.9	6.4	54.6	54.6	54.3	54.2	54.1
Mississippi	6.2	0.6	0.1	0.1	0.1	0.1	0.1
Missouri	16.4	0.5	0.4	0.4	0.4	0.4	0.4
Montana	14.4	3.9	2.1	2.1	2.1	2.1	2.1
Nebraska	5.8	1.7	0.6	0.6	0.3	0.3	0.3
Nevada	1.6	1.1	0.1	0.1	0.1	0.1	0.1
New Hampshire	0.4	0.2	0.1	0.1	0.1	0.1	0.1
New Jersey	0.7	0.6	0.0	0.0	0.0	0.0	0.0
New Mexico	1.3	0.1	0.1	0.1	0.1	0.1	0.1
New York	4.2	2.6	0.1	0.1	0.1	0.1	0.1

North Carolina	19.7	0.7	0.3	0.2	0.2	0.2	0.2
North Dakota	7.5	3.5	6.3	6.3	6.3	6.2	5.9
Ohio	7.2	1.3	0.3	0.3	0.2	0.2	0.1
Oklahoma	28.7	0.2	0.0	0.0	0.0	0.0	0.0
Oregon	6.2	0.4	0.2	0.2	0.2	0.1	0.1
Pennsylvania	12.6	1.3	0.1	0.1	0.1	0.1	0.1
Puerto Rico	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rhode Island	0.1	0.0	0.0	0.0	0.0	0.0	0.0
South Carolina	18.5	5.8	0.0	0.0	0.0	0.0	0.0
South Dakota	0.5	3.9	0.8	0.8	0.0	0.0	0.0
Tennessee	58.7	0.0	0.1	0.1	0.1	0.1	0.1
Texas	74.8	0.9	0.3	0.3	0.2	0.2	0.2
Utah	1.9	0.1	0.3	0.3	0.3	0.3	0.3
Vermont	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Virginia	5.8	0.4	0.0	0.0	0.0	0.0	0.0
Washington	5.3	1.6	0.9	0.9	0.5	0.5	0.5
West Virginia	3.1	1.6	0.1	0.0	0.0	0.0	0.0
Wisconsin	1.9	0.4	0.2	0.2	0.2	0.2	0.2
Wyoming	15.1	6.5	0.4	0.2	0.2	0.2	0.2
Total	**565.8**	**114.6**	**77.6**	**77.1**	**74.7**	**73.7**	**72.5**

Uncertainty

Uncertainty in estimates of CH_4 and CO_2 emissions from reservoirs on land converted to flooded land were developed using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory (Table 1-105). Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the flooded land area estimates is assumed and is based on expert judgment.

Table 6-109: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Reservoir						
Surface	CH_4	0.19	0.17	0.21	-11.5%	+11.9%
Surface	CO_2	0.2	0.26	0.33	-11.7%	+12.4%
Downstream	CH_4	+	+	0.08	-54.1%	+397.0%
Total		**0.5**	**0.44**	**0.59**	**-12.2%**	**+18.8%**

+ Indicates values less than 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation

Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity—by flow and/or volume control. This data source added 418 reservoirs totaling 736,344 ha.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current 1990 through 2022 *Inventory* has major updates for MS, ND, NM, and MT.

Overall, the recalculations resulted in substantial increases in methane and carbon dioxide emissions in the first few years of the time series (e.g., increase of 3.8 MMT CO_2 Eq. in 1990), but the differences were minor by 2008 through 2021 (<0.1 MMT CO_2 Eq.).

Planned Improvements

The EPA recently completed a survey of greenhouse gas emissions from 108 reservoirs in the conterminous United States.[91] The data will be used to develop country-specific emission factors for U.S. reservoirs to be used in the 1990 through 2024 *Inventory* submission.

Emissions from Land Converted to Flooded Land–Other Constructed Waterbodies

Freshwater ponds are the only type of flooded lands within the "other constructed waterbodies" subcategory of land converted to flooded land that are included in this *Inventory* (see Methodology for details) because age data are not available for canals and ditches. All canals and ditches are assumed to be greater than 20-years old throughout the time series and are included in flooded land remaining flooded land.

IPCC (2019) describes ponds as waterbodies that are "…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture." The IPCC "Decision tree for types of Flooded Land" (IPCC 2019, Fig. 7.2) elaborates on this description by defining waterbodies less than 8 ha as a subset of "other constructed waterbodies." For this *Inventory*, ponds are defined as managed flooded land not identified as "canal/ditch" (see Methods below) with

[91] See https://www.epa.gov/air-research/research-emissions-us-reservoirs.

surface area less than 8 ha. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emission rates than the latter. Activity data on pond salinity is not uniformly available for the United States and all ponds in land converted to flooded land are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are sites of substantial CH_4 and CO_2 emissions from anaerobic sediments.

Methane and CO_2 emissions from freshwater ponds decreased 95 percent from 1990 to 2022 due to flooded land matriculating from land converted to flooded land to flooded land remaining flooded land. In 2022, states in the Great Plains region generally had the greatest CO_2 and CH_4 emissions from freshwater ponds in land converted to flooded land (Table 6-110 through Table 6-114, Figure 6-21). Mississippi had the second greatest emissions of all states, partly due to the relatively high CO_2 emission factor for the tropical moist/wet climate zone (Figure 6-17, Table 6-115).

Table 6-110: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT CO_2 Eq.

Table 6-111: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	5	1	+	+	+	+	+

+ Indicates values less than 0.5 kt.

Table 6-112: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	+	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT C.

Table 6-113: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	0.04	0.01	+	+	+	+	+

+ Indicates values less than 0.005 MMT C.

Table 6-114: CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land in 2022 (MT CO_2 Eq.)

	Freshwater Ponds		
State	CH_4	CO_2	Total
Alabama	0	0	0
Alaska	0	0	0
Arizona	0	0	0
Arkansas	1	1	3
California	126	146	272
Colorado	382	290	672
Connecticut	0	0	0
Delaware	0	0	1
District of Columbia	0	0	0
Florida	18	37	55
Georgia	164	293	457

Hawaii	0	0	0
Idaho	0	0	0
Illinois	83	74	157
Indiana	66	69	135
Iowa	282	254	535
Kansas	435	456	891
Kentucky	3	3	5
Louisiana	3	6	10
Maine	1	1	2
Maryland	58	60	118
Massachusetts	381	358	738
Michigan	41	30	71
Minnesota	317	232	549
Mississippi	400	612	1,012
Missouri	133	139	271
Montana	509	371	880
Nebraska	620	567	1,186
Nevada	103	80	183
New Hampshire	80	59	139
New Jersey	0	0	0
New Mexico	57	46	103
New York	120	96	215
North Carolina	107	112	219
North Dakota	229	167	396
Ohio	289	285	574
Oklahoma	339	378	717
Oregon	89	71	161
Pennsylvania	29	25	54
Puerto Rico	0	0	0
Rhode Island	0	0	0
South Carolina	47	49	95
South Dakota	455	332	788
Tennessee	11	11	22
Texas	83	138	222
Utah	207	151	359
Vermont	15	11	26
Virginia	10	11	21
Washington	140	132	272
West Virginia	19	19	38
Wisconsin	93	68	162
Wyoming	369	269	639
Total	**6,917**	**6,510**	**13,427**

Figure 6-21: 2022 A) CH_4 and B) CO_2 Emissions from Other Constructed Waterbodies (Freshwater Ponds) in Land Converted to Flooded Land (MT CO_2 Eq.)

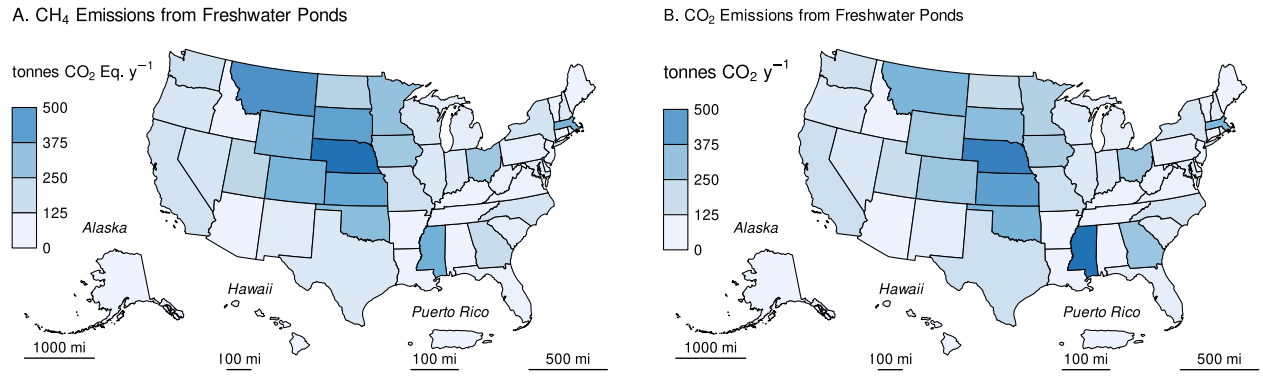

Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for other constructed waterbodies in land converted to flooded land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Greenhouse gas emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-115). Due to a lack of empirical data on CO_2 emissions from recently created ponds, IPCC (2019) states "For all types of ponds created by damming, the methodology described above to estimate CO_2 emissions from land converted to reservoirs may be used." This *Inventory* uses IPCC default CO_2 emission factors for land converted to reservoirs when estimating CO_2 emissions from land converted to freshwater ponds. IPCC guidance also states that "there is insufficient information available to derive separate CH_4 emission factors for recently constructed ponds…" and allows for the use of IPCC default CH_4 emission factors for land remaining flooded land. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-115: IPCC Default Methane and CO_2 Emission Factors for Other Constructed Waterbodies in Land Converted to Flooded Land

		Emission Factor	
Other Constructed Waterbody	**Climate Zone**	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Freshwater ponds	Boreal	0.183	3.45
Freshwater ponds	Cool Temperate	0.183	3.74
Freshwater ponds	Warm Temperate Dry	0.183	6.23
Freshwater ponds	Warm Temperate Moist	0.183	5.35
Freshwater ponds	Tropical Dry/Montane	0.183	10.82
Freshwater ponds	Tropical Moist/Wet	0.183	10.16

Area Estimates

Other constructed waterbodies were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[92] the National Inventory of Dams (NID),[93] the National Wetlands Inventory (NWI),[94] and the Navigable Waterways (NW) network[95], and the EPA's Safe Drinking Water Information System (SDWIS)[96]. The NHD only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico.

Waterbodies in the NHDWaterbody layer that were less than or equal to 20-years old, less than 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered freshwater ponds in land converted to flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m).

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features that were less than 8 ha in surface area and not identified as canals/ditch (see below) were considered freshwater ponds. Only 2.1 percent of NW features met these criteria, and they were primarily associated with larger navigable waterways, such as lock chambers on impounded rivers.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-19). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see 'Water Regime' in Figure 6-19). NWI features that met these criteria, were less than 8 ha in surface area, and were not a canal/ditch were defined as freshwater ponds.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed". The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for other constructed waterbodies were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, duplicate areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

The age of other constructed waterbody features was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series. No canal/ditch features were associated with a nearby dam, therefore all canal/ditch features were assumed to be greater than 20-years old through the time series.

For the year 2022, this *Inventory* contains 1,350 ha of freshwater ponds in land converted to flooded land. The surface area of freshwater ponds decreased by 95 percent from 1990 to 2022 due to flooded lands aging out of land converted to flooded land more quickly than new flooded lands entered the category. The greatest reduction in freshwater pond surface area occurred in Iowa, Kansas, and Georgia (Table 6-117). Freshwater ponds in the 2021 inventory are most abundant in Nebraska, Montana, and Kansas (Figure 6-22).

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[92] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[93] See https://nid.sec.usace.army.mil.

[94] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[95] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[96] Not publicly available due to security concerns.

Table 6-116: National Surface Area Totals of Other Constructed Waterbodies in Land Converted to Flooded Land (ha)

Other Constructed Waterbodies	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	25,492	5,357	2,604	2,317	1,983	1,673	1,472

Figure 6-22: Surface Area of Other Constructed Waterbodies in Land Converted to Flooded Land (ha) in 2022

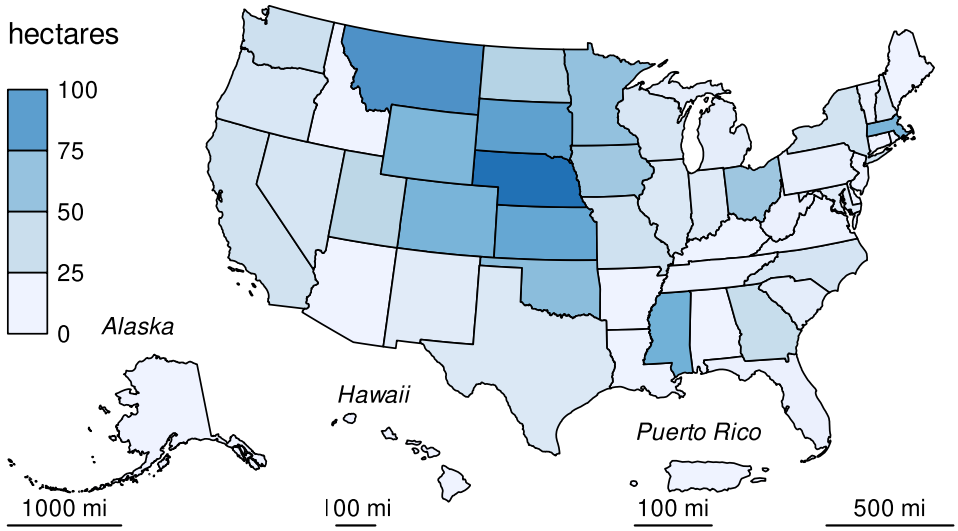

Table 6-117: State Surface Area Totals of Other Constructed Waterbodies in Land Converted to Flooded Land (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	317	13	0	0	0	0	0
Alaska	3	0	0	0	0	0	0
Arizona	39	16	4	4	0	0	0
Arkansas	331	0	0	0	0	0	0
California	263	103	45	40	33	31	25
Colorado	279	71	79	78	89	89	75
Connecticut	67	2	0	0	0	0	0
Delaware	4	0	0	0	0	0	0
District of Columbia	0	0	0	0	0	0	0
Florida	154	58	15	10	10	4	4
Georgia	1,686	83	35	32	32	32	32
Hawaii	11	4	0	0	0	0	0
Idaho	133	8	1	1	1	0	0
Illinois	557	133	42	37	27	26	16
Indiana	494	133	28	23	23	23	13
Iowa	2,592	1,580	474	290	172	76	55
Kansas	2,099	147	113	104	103	87	85
Kentucky	394	30	1	1	1	1	1
Louisiana	130	17	7	7	1	1	1
Maine	51	10	0	0	0	0	0
Maryland	226	81	20	20	18	15	11

Massachusetts	68	79	93	86	80	78	74
Michigan	162	37	16	16	8	8	8
Minnesota	344	142	103	101	79	71	62
Mississippi	414	200	124	117	98	85	78
Missouri	3,451	104	38	34	32	29	26
Montana	400	109	105	100	99	99	99
Nebraska	1,427	374	182	164	133	125	121
Nevada	21	64	26	26	22	22	20
New Hampshire	154	61	17	17	16	16	16
New Jersey	50	21	0	0	0	0	0
New Mexico	14	14	19	17	17	17	11
New York	312	124	31	29	29	24	23
North Carolina	498	92	28	28	25	22	21
North Dakota	90	135	67	61	51	48	45
Ohio	431	293	121	107	75	60	56
Oklahoma	2,008	147	111	95	81	75	66
Oregon	220	69	25	22	18	17	17
Pennsylvania	255	33	6	6	6	6	6
Puerto Rico	0	0	0	0	0	0	0
Rhode Island	9	7	0	0	0	0	0
South Carolina	826	230	22	13	9	9	9
South Dakota	227	98	105	94	93	89	89
Tennessee	389	37	14	9	2	2	2
Texas	2,950	89	21	16	17	16	16
Utah	68	19	42	42	40	40	40
Vermont	70	11	3	3	3	3	3
Virginia	58	4	2	2	2	2	2
Washington	153	57	31	31	28	27	27
West Virginia	130	10	4	4	4	4	4
Wisconsin	146	21	18	18	18	18	18
Wyoming	316	190	79	79	78	75	72
Total	**25,492**	**5,357**	**2,317**	**1,983**	**1,673**	**1,472**	**1,350**

Uncertainty

Uncertainty in estimates of CO_2 and CH_4 emissions from land converted to flooded land–other constructed water bodies include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in the NHD, NWI, NID, and NW are unknown, but uncertainty for remote sensing products is ±10 to 15 percent (IPCC 2003). EPA assumes an uncertainty of ± 15 percent for the flooded land area inventory based on expert judgment. These uncertainties do not include the underestimate of pond surface area discussed above.

Table 6-118: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land

Source	Gas	2022 Emission Estimate (kt CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (kt CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Freshwater ponds	CH_4	6.90	6.80	7.10	-2.3%	+2.7%
Freshwater ponds	CO_2	6.51	6.38	6.62	-2.0%	+1.8%
Total		**13.42**	**13.18**	**13.70**	**-1.8%**	**+2.1%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Totals may not sum due to independent rounding.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS with collaboration from many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory. Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory.* The assumption is that any waterbody used as a public drinking water source is managed in some capacity - by flow and/or volume control. This data source added 54 features totaling 173 ha of other constructed waterbodies.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for “year of dam completion” for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual increase in CH_4 and CO_2 emissions from other constructed waterbodies of 0.03 MMT CO_2 Eq., or 51 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

Features < 8 ha in the NW that were not identified as canal/ditch were defined as freshwater ponds. Many of these features are lock chambers connected to an upstream reservoir. These systems likely have emission rates more similar to a reservoir than freshwater pond. In the next (i.e., 1990 through 2023) *Inventory* these systems will be classified as reservoirs.

6.10 Settlements Remaining Settlements (CRT Category 4E1)

Soil Carbon Stock Changes (CRT Category 4E1)

Soil organic C stock changes for settlements remaining settlements occur in both mineral and organic soils. However, the United States does not estimate changes in soil organic C stocks for mineral soils in settlements remaining settlements. This approach is consistent with the assumption of the Tier 1 method in the 2006 *IPCC Guidelines* (IPCC 2006) that inputs equal outputs, and therefore the soil organic C stocks do not change in this land use category. This assumption may be re-evaluated in the future if funding and resources are available to conduct an analysis of soil organic C stock changes for mineral soils in settlements remaining settlements.

Drainage of organic soils is common when wetland areas have been developed for settlements. Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic carbon by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. Drainage of organic soils leads to aeration of the soil that accelerates decomposition rate and CO_2 emissions.[97] Due to the depth and richness of the organic layers, carbon loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986).

Settlements remaining settlements includes all areas that have been settlements for a continuous time period of at least 20 years according to the 2017 United States Department of Agriculture (USDA) National Resources Inventory (NRI) (USDA-NRCS 2020)[98] or according to the National Land Cover Dataset (NLCD) for federal lands (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). There are discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for settlements remaining settlements. Specifically, Alaska and the small amount of settlements on federal lands are not included in this *Inventory* even though these areas are part of the U.S. managed land base. There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future *Inventory* (see Planned Improvements section).

CO_2 emissions from drained organic soils in settlements are 15.4 MMT CO_2 Eq. (4.2 MMT C) in 2022 (see Table 6-119 and Table 6-120). Although the flux is relatively small, the amount has increased by 56 percent since 1990 due to an increase in area of drained organic soils in settlements.

Table 6-119: Net CO_2 Flux from Soil C Stock Changes in Settlements Remaining Settlements (MMT CO_2 Eq.)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Organic Soils	9.9	10.1	14.4	14.6	15.1	15.4	15.4

[97] N_2O emissions from drained organic soils are included in the N_2O Emissions from Settlement Soils section.

[98] NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of Settlements Remaining Settlements in the early part of the time series to the extent that some areas are converted to settlements between 1971 and 1978.

Table 6-120: Net CO_2 Flux from Soil C Stock Changes in Settlements Remaining Settlements (MMT C)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Organic Soils	2.7	2.7	3.9	4.0	4.1	4.2	4.2

Methodology and Time-Series Consistency

An IPCC Tier 2 method is used to estimate soil organic C stock changes for organic soils in settlements remaining settlements (IPCC 2006). Organic soils in settlements remaining settlements are assumed to be losing C at a rate similar to croplands due to deep drainage, and therefore emission rates are based on country-specific values for cropland (Ogle et al. 2003).

The land area designated as settlements is based primarily on the 2017 NRI (USDA-NRCS 2020) with additional information from the NLCD to the extend the time series through 2020 (Yang et al. 2018). Soils are classified as organic using data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). All settlements occurring on organic soil are assumed to be drained for the purposes of approximating greenhouse gas emissions. The area of drained organic soils is estimated from the NRI spatial weights and aggregated to the country (Table 6-121). The area of land on organic soils in settlements remaining settlements has increased from 216 thousand hectares in 1990 to over 327 thousand hectares in 2020.

Table 6-121: Thousands of Hectares of Drained Organic Soils in Settlements Remaining Settlements

	1990	2005	2014	2015	2016	2017	2018	2019	2020	2021	2022
Area (Thousand Hectares)	216	219	276	283	291	302	311	317	327	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

To estimate CO_2 emissions from drained organic soils across the time series from 1990 to 2020, the area of organic soils by climate (i.e., cool temperate, warm temperate, subtropical) in settlements remaining settlements is multiplied by the appropriate country-specific emission factors for cropland remaining cropland under the assumption that there is deep drainage of the soils. The emission factors are 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions, and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2020 time series (see Box 6-4 in cropland remaining cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, and is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The Tier 2 method described previously will be applied in future inventories to recalculate the estimates beyond 2020 as new activity data are integrated into the analysis.

Uncertainty

The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The first variance component is associated with uncertainty in the emission factor, and the second variance component is associated with scaling of the data from the NRI survey to the entire area of drained organic soils in settlements remaining settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). There is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods that was

incorporated into the analysis for the latter part of the time series. Soil carbon losses from drained organic soils in settlements remaining settlements for 2022 are estimated to be between 7.7 and 23.2 MMT CO_2 Eq. at a 95 percent confidence level (Table 6-115). This indicates a range of 50 percent below and 50 percent above the 2022 emission estimate of 15.4 MMT CO_2 Eq.

Table 6-122: Uncertainty Estimates for CO_2 Emissions from Drained Organic Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
		(MMT CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soils	CO_2	15.4	7.7	23.2	-50%	+50%

[a] Range of emission estimates is a 95 percent confidence interval.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this *Inventory*.

Recalculations Discussion

Recalculations are associated with updated land areas for drainage of organic soils in settlements remaining settlements, and update that was made by incorporating new USDA-NRCS NRI data through 2017 and extending the time series using NLCD. As a result of this change, CO_2-equivalent emissions changed annually with an average annual decrease of 1.8 MMT CO_2 Eq., or 14 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key improvement is to estimate CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands. This improvement will resolve most of the differences between the managed land base for settlements remaining settlements and amount of area currently included in this *Inventory* as settlements remaining settlements (see Table 6-123). This improvement will be made pending prioritization of resources to expand the inventory for this source category.

Table 6-123: Area of Managed Land in Settlements Remaining Settlements that is not included in the current *Inventory* (Thousand Hectares)

Year	Area (Thousand Hectares)		
	SRS Managed Land Area (Section 6.1)	SRS Area Included in Inventory	Difference
1990	30,548	30,366	182
1991	30,545	30,364	182
1992	30,543	30,361	182
1993	30,470	30,288	182
1994	30,385	30,203	182
1995	30,322	30,141	182
1996	30,263	30,081	182
1997	30,193	30,011	182
1998	30,127	29,945	182
1999	30,073	29,891	182
2000	30,015	29,834	182
2001	29,963	29,781	182
2002	29,956	29,774	182
2003	30,479	30,298	182
2004	30,973	30,791	182
2005	31,432	31,250	182
2006	31,940	31,758	182
2007	32,397	32,215	182
2008	33,015	32,833	182
2009	33,591	33,410	182
2010	34,166	33,984	182
2011	34,731	34,549	182
2012	35,302	35,120	182
2013	36,224	36,042	182
2014	37,159	36,977	182
2015	38,026	37,844	182
2016	38,938	38,756	182
2017	39,861	39,679	182
2018	40,756	40,574	182
2019	41,602	41,420	182
2020	42,452	42,270	182
2021	43,175	*	*
2022	43,734	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

Changes in Carbon Stocks in Settlement Trees (CRT Category 4E1)

Settlements are land uses where human populations and activities are concentrated. In these areas, the anthropogenic impacts on tree growth, stocking and mortality are particularly pronounced (Nowak 2012) in comparison to forest lands where non-anthropogenic forces can have more significant impacts. Estimates included in this section include net CO_2 and carbon flux from trees on settlements remaining settlements and land converted to settlements as it is not possible to report on these separately at this time.

Trees in settlement areas of the United States are estimated to account for an average annual net sequestration of 118.2 MMT CO_2 Eq. (32.2 MMT C) over the period from 1990 through 2022. Net carbon sequestration from settlement trees in 2022 is estimated to be 138.5 MMT CO_2 Eq. (37.8 MMT C) (Table 6-124). Dominant factors affecting carbon flux trends for settlement trees are changes in the amount of settlement area (increasing

sequestration due to more land and trees) and net changes in tree cover (e.g., tree losses versus tree gains through planting and natural regeneration), with percent tree cover trending downward recently. In addition, changes in species composition, tree sizes and tree densities affect base carbon flux estimates. Annual sequestration increased by 43 percent between 1990 and 2022 due to increases in settlement area and changes in total tree cover.

Trees in settlements often grow faster than forest trees because of their relatively open structure (Nowak and Crane 2002). Because tree density in settlements is typically much lower than in forested areas, the carbon storage per hectare of land is in fact smaller for settlement areas than for forest areas. Also, percent tree cover in settlement areas is less than in forests and this urban tree cover varies significantly across the United States (e.g., Nowak and Greenfield 2018a). To quantify the carbon stored in settlement trees, the methodology used here requires analysis per unit area of tree cover, rather than per unit of total land area (as is done for forest lands).

Table 6-124: Net Flux from Trees in Settlements Remaining Settlements (MMT CO_2 Eq. and MMT C)[a]

Year	1990	2005	2018	2019	2020	2021	2022
MMT CO_2 Eq.	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)
MMT C	(26.3)	(31.9)	(36.7)	(37.0)	(37.3)	(37.6)	(37.8)

[a] These estimates include net CO_2 and C flux from trees on settlements remaining settlements and land converted to settlements as it is not possible to report on these separately at this time.

Note: Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

To estimate net carbon sequestration in settlement areas, three types of data are required for each state:

1. Settlement area
2. Percent tree cover in settlement areas
3. Carbon sequestration density per unit of tree cover

Settlement Area

Settlement area is defined in Section 6.1 as a land-use category representing developed areas. The data used to estimate settlement area within Section 6.1 comes from the latest NRI as updated through 2017, with the extension of the time series through 2022 based on assuming the settlement area is the same as 2017. The NRI data is also harmonized with the FIA dataset, which is available through 2022, and the 2019 NLCD dataset. This process of combining the datasets extends the time series to ensure that there is a complete and consistent representation of land use data for all source categories in the LULUCF sector. Annual estimates of the net CO_2 flux (Table 6-124) were developed based on estimates of annual settlement area and tree cover derived from NLCD developed lands. Developed land, which was used to estimate tree cover in settlement areas, is about six percent higher than the area categorized as settlements in the representation of the U.S. land base developed for this report.

Percent Tree Cover in Settlement Areas

Percent tree cover in settlement area by state is needed to convert settlement land area to settlement tree cover area. Converting to tree cover area is essential as tree cover, and thus carbon estimates, can vary widely among states in settlement areas due to variations in the amount of tree cover (e.g., Nowak and Greenfield 2018a). However, since the specific geography of settlement area is unknown because they are based on NRI sampling methods, NLCD developed land was used to estimate the percent tree cover to be used in settlement areas. The NLCD developed land cover classes 21-24 (developed, open space (21), low intensity (22), medium intensity (23), and high intensity (24)) were used to estimate percent tree cover in settlement area by state (U.S. Department of Interior 2018; MRLC 2013).

a) "Developed, Open Space – areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes." Plots designated as either park, recreation, cemetery, open space, institutional or vacant land were classified as "Developed, Open Space".

b) "Developed, Low Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 to 49 percent of total cover. These areas most commonly include single-family housing units." Plots designated as single family or low-density residential land were classified as "Developed, Low Intensity".

c) "Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 to 79 percent of the total cover. These areas most commonly include single-family housing units." Plots designated as medium density residential, other urban or mixed urban were classified as "Developed, Medium Intensity".

d) "Developed High Intensity – highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover." Plots designated as either commercial, industrial, high density residential, downtown, multi-family residential, shopping, transportation or utility were classified as "Developed, High Intensity".

As NLCD is known to underestimate tree cover (Nowak and Greenfield 2010), photo-interpretation of tree cover within NLCD developed lands was conducted for the years of c. 2016 and 2020 using 1,000 random points to determine an average adjustment factor for NLCD tree cover estimates in developed land and determine recent tree cover changes. This photo-interpretation of change followed methods detailed in Nowak and Greenfield (2018b). Percent tree cover (%TC) in settlement areas by state was estimated as:

%TC in state = state NLCD %TC x national photo-interpreted %TC / national NLCD %TC

Percent tree cover in settlement areas by year was set as follows:

- 1990 to 2011: used 2011 NLCD tree cover adjusted with 2011 photo-interpreted values
- 2012 to 2015: used 2011 NLCD tree cover adjusted with photo-interpreted values, which were interpolated from values between 2011 and 2016
- 2016 to 2020: used 2016 NLCD tree cover adjusted with 2020 photo-interpreted values

Carbon Sequestration Density per Unit of Tree Cover

Methods for quantifying settlement tree biomass, carbon sequestration, and carbon emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, net carbon sequestration estimates followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and urban areas within entire states were used to estimate carbon in tree biomass from field data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, crown competition, and growing season to generate estimates of gross carbon sequestration in settlement trees for all 50 states and the District of Columbia. Third, estimates of carbon emissions due to mortality and decomposition were subtracted from gross carbon sequestration estimates to obtain estimates of net carbon sequestration. Carbon storage, gross and net sequestration estimates were standardized per unit tree cover based on tree cover in the study area.

Settlement tree carbon estimates are based on published literature (Nowak et al. 2013; Nowak and Crane 2002; Nowak 1994) as well as newer data from the i-Tree database[99] and U.S. Forest Service urban forest inventory data (e.g., Nowak et al. 2016, 2017) (Table 6-125). These data are based on collected field measurements in several U.S. cities between 1989 and 2017. Carbon storage and sequestration in these cities were estimated using the U.S. Forest Service's i-Tree Eco model (Nowak et al. 2008). This computer model uses standardized field data from randomly located plots, along with local hourly air pollution and meteorological data, to quantify urban forest structure, monetary values of the urban forest, and environmental effects, including total carbon stored and annual carbon sequestration (Nowak et al. 2013).

In each city, a random sample of plots were measured to assess tree stem diameter, tree height, crown height and crown width, tree location, species, and canopy condition. The data for each tree were used to estimate total dry-weight biomass using allometric models, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, and wood moisture content. Total dry weight biomass was converted to carbon by dividing by two (50 percent carbon content). An adjustment factor of 0.8 was used for open grown trees to account for settlement trees having less aboveground biomass for a given stem diameter than predicted by allometric models based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only carbon stored in wood. Estimated carbon storage was divided by tree cover in the area to estimate carbon storage per square meter of tree cover.

Table 6-125: Carbon Storage (kg C/m² tree cover), Gross and Net Sequestration (kg C/m² tree cover/year) and Tree Cover (percent) among Sampled U.S. Cities (see Nowak et al. 2013)

			Sequestration						
City	Storage	SE	Gross	SE	Net	SE	Ratio[a]	Tree Cover	SE
Adrian, MI	12.17	1.88	0.34	0.04	0.13	0.07	0.36	22.1	2.3
Albuquerque, NM	5.61	0.97	0.24	0.03	0.20	0.03	0.82	13.3	1.5
Arlington, TX	6.37	0.73	0.29	0.03	0.26	0.03	0.91	22.5	0.3
Atlanta, GA	6.63	0.54	0.23	0.02	0.18	0.03	0.76	53.9	1.6
Austin, TX	3.57	0.25	0.17	0.01	0.13	0.01	0.73	30.8	1.1
Baltimore, MD	10.30	1.24	0.33	0.04	0.20	0.04	0.59	28.5	1.0
Boise, ID	7.33	2.16	0.26	0.04	0.16	0.06	0.64	7.8	0.2
Boston, MA	7.02	0.96	0.23	0.03	0.17	0.02	0.73	28.9	1.5
Camden, NJ	11.04	6.78	0.32	0.20	0.03	0.10	0.11	16.3	9.9
Casper, WY	6.97	1.50	0.22	0.04	0.12	0.04	0.54	8.9	1.0
Chester, PA	8.83	1.20	0.39	0.04	0.25	0.05	0.64	20.5	1.7
Chicago (region), IL	9.38	0.59	0.38	0.02	0.26	0.02	0.70	15.5	0.3
Chicago, IL	6.03	0.64	0.21	0.02	0.15	0.02	0.70	18.0	1.2
Corvallis, OR	10.68	1.80	0.22	0.03	0.20	0.03	0.91	32.6	4.1
El Paso, TX	3.93	0.86	0.32	0.05	0.23	0.05	0.72	5.9	1.0
Freehold, NJ	11.50	1.78	0.31	0.05	0.20	0.05	0.64	31.2	3.3
Gainesville, FL	6.33	0.99	0.22	0.03	0.16	0.03	0.73	50.6	3.1
Golden, CO	5.88	1.33	0.23	0.05	0.18	0.04	0.79	11.4	1.5
Grand Rapids, MI	9.36	1.36	0.30	0.04	0.20	0.05	0.65	23.8	2.0
Hartford, CT	10.89	1.62	0.33	0.05	0.19	0.05	0.57	26.2	2.0
Houston, TX	4.55	0.48	0.31	0.03	0.25	0.03	0.83	18.4	1.0
Indiana[b]	8.80	2.68	0.29	0.08	0.27	0.07	0.92	20.1	3.2
Jersey City, NJ	4.37	0.88	0.18	0.03	0.13	0.04	0.72	11.5	1.7
Kansas[b]	7.42	1.30	0.28	0.05	0.22	0.04	0.78	14.0	1.6
Kansas City (region), MO/KS	7.79	0.85	0.39	0.04	0.26	0.04	0.67	20.2	1.7

[99] See http://www.itreetools.org.

Lake Forest Park, WA	12.76	2.63	0.49	0.07	0.42	0.07	0.87	42.4	0.8
Las Cruces, NM	3.01	0.95	0.31	0.14	0.26	0.14	0.86	2.9	1.0
Lincoln, NE	10.64	1.74	0.41	0.06	0.35	0.06	0.86	14.4	1.6
Los Angeles, CA	4.59	0.51	0.18	0.02	0.11	0.02	0.61	20.6	1.3
Milwaukee, WI	7.26	1.18	0.26	0.03	0.18	0.03	0.68	21.6	1.6
Minneapolis, MN	4.41	0.74	0.16	0.02	0.08	0.05	0.52	34.1	1.6
Moorestown, NJ	9.95	0.93	0.32	0.03	0.24	0.03	0.75	28.0	1.6
Morgantown, WV	9.52	1.16	0.30	0.04	0.23	0.03	0.78	39.6	2.2
Nebraska[b]	6.67	1.86	0.27	0.07	0.23	0.06	0.84	15.0	3.6
New York, NY	6.32	0.75	0.33	0.03	0.25	0.03	0.76	20.9	1.3
North Dakota[b]	7.78	2.47	0.28	0.08	0.13	0.08	0.48	2.7	0.6
Oakland, CA	5.24	0.19	NA	NA	NA	NA	NA	21.0	0.2
Oconomowoc, WI	10.34	4.53	0.25	0.10	0.16	0.06	0.65	25.0	7.9
Omaha, NE	14.14	2.29	0.51	0.08	0.40	0.07	0.78	14.8	1.6
Philadelphia, PA	8.65	1.46	0.33	0.05	0.29	0.05	0.86	20.8	1.8
Phoenix, AZ	3.42	0.50	0.38	0.04	0.35	0.04	0.94	9.9	1.2
Roanoke, VA	9.20	1.33	0.40	0.06	0.27	0.05	0.67	31.7	3.3
Sacramento, CA	7.82	1.57	0.38	0.06	0.33	0.06	0.87	13.2	1.7
San Francisco, CA	9.18	2.25	0.24	0.05	0.22	0.05	0.92	16.0	2.6
Scranton, PA	9.24	1.28	0.40	0.05	0.30	0.04	0.74	22.0	1.9
Seattle, WA	9.59	0.98	0.67	0.06	0.55	0.05	0.82	27.1	0.4
South Dakota[b]	3.14	0.66	0.13	0.03	0.11	0.02	0.87	16.5	2.2
Syracuse, NY	9.48	1.08	0.30	0.03	0.22	0.04	0.72	26.9	1.3
Tennessee[b]	6.47	0.50	0.34	0.02	0.30	0.02	0.89	37.7	0.8
Washington, DC	8.52	1.04	0.26	0.03	0.21	0.03	0.79	35.0	2.0
Woodbridge, NJ	8.19	0.82	0.29	0.03	0.21	0.03	0.73	29.5	1.7

SE (Standard Error)
NA (Not Available)
[a] Ratio of net to gross sequestration
[b] Statewide assessment of urban areas

To determine gross sequestration rates, tree growth rates need to be estimated. Base growth rates were standardized for open-grown trees in areas with 153 days of frost-free length based on measured data on tree growth (Nowak et al. 2013). These growth rates were adjusted to local tree conditions based on length of frost-free season, crown competition (as crown competition increased, growth rates decreased), and tree condition (as tree condition decreased, growth rates decreased). Annual growth rates were applied to each sampled tree to estimate gross annual sequestration–that is, the difference in carbon storage estimates between year 1 and year (x + 1) represents the gross amount of carbon sequestered. These annual gross carbon sequestration rates for each tree were then scaled up to city estimates using tree population information. Total carbon sequestration was divided by total tree cover to estimate a gross carbon sequestration density (kg C/m^2 of tree cover/year). The area of assessment for each city or state was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates.

Where gross carbon sequestration accounts for all carbon sequestered, net carbon sequestration for settlement trees considers carbon emissions associated with tree death and removals. The third step in the methodology estimates net carbon emissions from settlement trees based on estimates of annual mortality, tree condition, and assumptions about whether dead trees were removed from the site. Estimates of annual mortality rates by diameter class and condition class were obtained from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass (Nowak et al. 2002). The estimated annual gross carbon emission rates for each plot were then scaled up to city estimates using tree population information.

The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric models applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric model could be found

for the particular species, the average result for the genus or botanical relative was used. The adjustment (0.8) to account for less live tree biomass in open-grown urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost-free days divided by 153. Growth rates were then adjusted for CLE. The CLE-adjusted growth rate was then adjusted based on tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013).

Estimates of gross and net sequestration rates for each of the 50 states and the District of Columbia (Table 6-126) were compiled in units of carbon sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state settlement area and developed land percent tree cover data to calculate each state's annual net carbon sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified here to incorporate developed land percent tree cover data.

Net annual carbon sequestration estimates were obtained for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.73, the average ratio for net/gross sequestration (Table 6-126). However, state specific ratios were used where available.

State Carbon Sequestration Estimates

The gross and net annual carbon sequestration values for each state were multiplied by each state's settlement area of tree cover, which was the product of the state's settlement area and the state's tree cover percentage based on NLCD developed land. The model used to calculate the total carbon sequestration amounts for each state, can be written as follows:

Equation 6-1: Net State Annual Carbon Sequestration

$$\text{Net state annual C sequestration (t C/yr)} = \text{Gross state sequestration rate (t C/ha/yr)} \times \text{Net to Gross state sequestration ratio} \times \text{state settlement Area (ha)} \times \%\ \text{state tree cover in settlement area}$$

The results for all 50 states and the District of Columbia are given in Table 6-126. This approach is consistent with the default IPCC Gain-Loss methodology in IPCC (2006), although sufficient field data are not yet available to separately determine interannual gains and losses in carbon stocks in the living biomass of settlement trees. Instead, the methodology applied here uses estimates of net carbon sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

Table 6-126: Estimated Annual Carbon Sequestration, Tree Cover, and Annual Carbon Sequestration per Area of Tree Cover for settlement areas in the United States by State and the District of Columbia (2022)

State	Gross Annual Sequestration (Metric Tons C/Year)	Net Annual Sequestration (Metric Tons C/Year)	Tree Cover (Percent)	Gross Annual Sequestration per Area of Tree Cover (kg C/m²/Year)	Net Annual Sequestration per Area of Tree Cover (kg C/m²/Year)	Net: Gross Annual Sequestration Ratio
Alabama	2,268,736	1,653,170	53.1	0.376	0.274	0.73
Alaska	150,345	109,553	47.0	0.169	0.123	0.73

Arizona	165,494	120,591	4.5	0.388	0.283	0.73
Arkansas	1,316,764	959,492	48.5	0.362	0.264	0.73
California	2,015,461	1,468,615	16.8	0.426	0.311	0.73
Colorado	142,538	103,864	7.9	0.216	0.157	0.73
Connecticut	649,817	473,505	58.2	0.262	0.191	0.73
Delaware	101,819	74,193	24.2	0.366	0.267	0.73
DC	12,919	9,414	24.9	0.366	0.267	0.73
Florida	4,632,104	3,375,296	39.9	0.520	0.379	0.73
Georgia	3,886,939	2,832,313	55.9	0.387	0.282	0.73
Hawaii	302,023	220,076	41.4	0.637	0.464	0.73
Idaho	59,771	43,553	7.3	0.201	0.146	0.73
Illinois	669,891	488,132	15.4	0.310	0.226	0.73
Indiana	479,505	443,378	17.0	0.274	0.254	0.92
Iowa	177,874	129,612	8.5	0.263	0.191	0.73
Kansas	288,317	224,359	10.7	0.310	0.241	0.78
Kentucky	984,663	717,499	36.5	0.313	0.228	0.73
Louisiana	1,585,823	1,155,549	46.6	0.435	0.317	0.73
Maine	445,519	324,639	55.1	0.242	0.176	0.73
Maryland	857,152	624,585	39.8	0.353	0.257	0.73
Massachusetts	1,093,110	796,521	56.8	0.278	0.203	0.73
Michigan	1,410,284	1,027,638	34.4	0.241	0.175	0.73
Minnesota	325,047	236,853	13.0	0.251	0.183	0.73
Mississippi	1,630,583	1,188,165	56.9	0.377	0.275	0.73
Missouri	878,510	640,148	23.0	0.313	0.228	0.73
Montana	45,414	33,092	4.8	0.201	0.147	0.73
Nebraska	97,770	82,504	7.3	0.261	0.220	0.84
Nevada	35,783	26,074	4.8	0.226	0.165	0.73
New Hampshire	392,480	285,990	58.8	0.238	0.174	0.73
New Jersey	961,860	700,883	40.4	0.321	0.234	0.73
New Mexico	188,804	137,577	10.1	0.288	0.210	0.73
New York	1,606,981	1,170,966	39.6	0.263	0.192	0.73
North Carolina	3,457,794	2,519,606	53.7	0.341	0.249	0.73
North Dakota	18,730	8,900	1.7	0.244	0.116	0.48
Ohio	1,276,930	930,467	28.0	0.271	0.198	0.73
Oklahoma	718,922	523,860	21.9	0.364	0.265	0.73
Oregon	674,472	491,470	39.6	0.265	0.193	0.73
Pennsylvania	1,900,962	1,385,183	39.9	0.267	0.195	0.73
Rhode Island	127,720	93,066	49.6	0.283	0.206	0.73
South Carolina	2,052,656	1,495,718	53.3	0.370	0.269	0.73
South Dakota	29,351	25,453	2.8	0.258	0.224	0.87
Tennessee	1,678,890	1,501,125	40.8	0.332	0.297	0.89
Texas	4,416,309	3,218,052	28.2	0.403	0.294	0.73
Utah	119,794	87,291	11.6	0.235	0.172	0.73
Vermont	188,016	137,002	50.2	0.234	0.170	0.73
Virginia	2,111,293	1,538,445	52.5	0.321	0.234	0.73
Washington	1,139,218	830,119	37.3	0.282	0.206	0.73
West Virginia	774,594	564,427	63.6	0.264	0.192	0.73
Wisconsin	711,938	518,771	25.7	0.246	0.180	0.73
Wyoming	29,558	21,538	4.7	0.199	0.145	0.73
Total	**51,287,245**	**37,768,294**				

Uncertainty

Uncertainty associated with changes in carbon stocks in settlement trees includes the uncertainty associated with settlement area, percent tree cover in developed land and how well it represents percent tree cover in settlement areas, and estimates of gross and net carbon sequestration for each of the 50 states and the District of Columbia. A

ten percent uncertainty was associated with settlement area estimates based on expert judgment. Uncertainty associated with estimates of percent settlement tree coverage for each of the 50 states was based on standard error associated with the photo-interpretation of national tree cover in developed lands. Uncertainty associated with estimates of gross and net carbon sequestration for each of the 50 states and the District of Columbia was based on standard error estimates for each of the state-level sequestration estimates (Table 6-127). These estimates are based on field data collected in each of the 50 states and the District of Columbia, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass models, conversion factors, and decomposition assumptions used to calculate carbon sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil carbon stocks, and there is likely some overlap between the settlement tree carbon estimates and the forest tree carbon estimates (e.g., Nowak et al. 2013). Due to data limitations, settlement soil flux is not quantified as part of this analysis, while reconciliation of settlement tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate in 2022. The results of this quantitative uncertainty analysis are summarized in Table 6-127. The change in carbon stocks in settlement trees in 2022 was estimated to be between -208.5 and -66.6 MMT CO_2 Eq. at a 95 percent confidence level. This analysis indicates a range of 51 percent more sequestration to 52 percent less sequestration than the 2022 flux estimate of -138.5 MMT CO_2 Eq.

Table 6-127: Approach 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Changes in Carbon Stocks in Settlement Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Flux Estimate	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
		(MMT CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Settlement Trees	CO_2	(138.5)	(208.5)	(66.6)	-51%	+52%

[a] Range of C stock change estimates predicted by Monte Carlo stochastic simulation with a 95 percent confidence interval.

Note: Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for settlement trees included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

The compilation methods remained the same in the latest *Inventory* relative to the previous *Inventory*. New data from the NRI and NLCD resulted in a small decrease in the settlement area for 2021, leading to no substantial change in the net carbon sequestration (Table 6-128).

Table 6-128: Recalculations of the Settlement Tree Categories

Category	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Settlement Area (km^2)	469,705	469,600	471,851
Settlement Tree Coverage (km^2)	151,694	151,664	152,442
Net C Flux (MMT C)	(37.6)	(37.6)	(37.8)

Net CO_2 Flux MMT CO_2 Eq.	(137.8)	(137.8)	(138.5)

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in Section 6.1, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between settlement trees and the forest land categories. Estimates for settlement trees are based on tree cover in settlement areas. Work is needed to clarify how much of this settlement area tree cover may also be accounted for in "forest" area assessments as some of these forests may be adjacent to settlement areas. For example, "forest" as defined by the USDA Forest Service Forest Inventory and Analysis (FIA) program fall within urban areas. Nowak et al. (2013) estimates that 1.5 percent of forest plots measured by the FIA program fall within land designated as Census urban, suggesting that approximately 1.5 percent of the carbon reported in the forest source category might also be counted in the urban areas. The potential overlap with settlement areas is unknown at this time but research is underway to develop spatially explicit and spatially continuous land representation products which will eliminate the potential for double counting. Future research may also enable more complete coverage of changes in the carbon stock of trees for all settlements land.

N_2O Emissions from Settlement Soils (CRT Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 1 to 2 percent are currently applied to lawns, golf courses, and other landscaping within settlement areas, and contributes to soil N_2O emissions. The area of settlements is considerably smaller than other land uses that are managed with fertilizer, particularly cropland soils, and therefore, settlements account for a smaller proportion of total synthetic fertilizer application in the United States. In addition to synthetic N fertilizers, a portion of surface applied biosolids (i.e., treated sewage sludge) is used as an organic fertilizer in settlement areas, and drained organic soils (i.e., soils with high organic matter content, known as *histosols*) also contribute to emissions of soil N_2O.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions in the form of synthetic fertilizers and biosolids as well as enhanced mineralization of N in drained organic soils. Indirect emissions result from fertilizer and biosolids N that is transformed and transported to another location in a form other than N_2O (i.e., volatilization of ammonia [NH_3] and nitrogen oxide [NO_x], and leaching/runoff of nitrate [NO_3^-]), and later converted into N_2O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N_2O emissions from soils in settlements remaining settlements[100] are 2.5 MMT CO_2 Eq. (10 kt of N_2O) in 2022. There is an overall increase of 23 percent from 1990 to 2022 due to an expanding settlement area leading to more synthetic N fertilizer applications that peaked in the mid-2000s. Inter-annual variability in these emissions is directly attributable to variability in total synthetic fertilizer consumption, area of drained organic soils, and biosolids applications in the United States. Emissions from this source are summarized in Table 6-129.

Table 6-129: N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2018	2019	2020	2021	2022
MMT CO_2 Eq.							
Direct N_2O Emissions from Soils	**1.7**	**2.6**	**2.1**	**2.1**	**2.2**	**2.2**	**2.2**
Synthetic Fertilizers	0.8	1.5	0.8	0.8	0.8	0.8	0.8

[100] Estimates of Soil N_2O for settlements remaining settlements include emissions from land converted to settlements because it was not possible to separate the activity data.

Biosolids	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.8	1.0	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Emissions from Soils	**0.3**	**0.5**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total	**2.1**	**3.1**	**2.4**	**2.5**	**2.5**	**2.5**	**2.5**
kt N_2O							
Direct N_2O Emissions from Soils	**7**	**10**	**8**	**8**	**8**	**8**	**8**
Synthetic Fertilizers	3	5	3	3	3	3	3
Biosolids	1	1	1	1	1	1	1
Drained Organic Soils	3	4	4	4	4	4	4
Indirect N_2O Emissions from Soils	**1**	**2**	**1**	**1**	**1**	**1**	**1**
Total	**8**	**12**	**9**	**9**	**9**	**10**	**10**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

For settlement soils, the IPCC Tier 1 approach is used to estimate soil N_2O emissions from synthetic N fertilizer, biosolids additions, and drained organic soils. Estimates of direct N_2O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, the amount of N in biosolids applied to non-agricultural land and surface disposal (see Section 7.2 for a detailed discussion of the methodology for estimating biosolids available for non-agricultural land application), and the area of drained organic soils within settlements.

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Brakebill and Gronberg 2017). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1987 through 2012 (Brakebill and Gronberg 2017). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2013 through 2017 are based on 2012 values adjusted for total annual total N fertilizer sales in the United States (AAPFCO 2016 through 2022) because there are no activity data on non-farm application after 2012. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. Since the total N fertilizer sales is only available through 2017 (AAPFCO 2022), the amount of synthetic fertilization from 2018 to 2022 is determined using a linear extrapolation method (see Box 6-4 in cropland remaining cropland). This method is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2017 fertilization data. To estimate direct N_2O for the time series, the total amount of fertilizer N applied to settlements is multiplied by the IPCC default emission factor (1 percent) (IPCC 2006) for 1990 to 2022.

Biosolids applications are derived from national data on biosolids generation, disposition, and N content (see Section 7.2 for further detail). The total amount of N resulting from these sources is multiplied by the IPCC default emission factor for applied N (one percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2022.

The IPCC (2006) Tier 1 method is also used to estimate direct N_2O emissions due to drainage of organic soils in settlements at the national scale. Estimates of the total area of drained organic soils are obtained from the 2017 National Resources Inventory (NRI) (USDA-NRCS 2020) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The NRI time series has been extended through 2020 using the National Land Cover Dataset (Yang et al. 2018). The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). All settlements occurring on organic soil are assumed to be drained for the purposes of approximating greenhouse gas emissions. To estimate annual emissions from 1990 to 2020, the total area is multiplied by the IPCC default emission factor for temperate regions (IPCC 2006). The annual emissions for 2021 to 2022 are estimated using a linear extrapolation method (see Box 6-4 in Cropland Remaining Cropland). This *Inventory* does not include soil N_2O emissions from drainage of organic soils in Alaska and federal lands, although this is a planned improvement for a future *Inventory*.

For indirect emissions, the total N applied from fertilizer and biosolids is multiplied by the IPCC default factors of 10 percent for volatilization and 30 percent for leaching/runoff to calculate the amount of N volatilized and the

amount of N leached/runoff. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions from 1990 to 2022 for biosolids and synthetic fertilization.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2022 for biosolids. For synthetic fertilizer, a linear extrapolation method is used to approximate fertilizer application for the remainder of the 2018 to 2022 time series and then used to estimate emissions. For drainage of organic soils, the methods described above are applied for 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2022 time series (see Box 6-4 in cropland remaining cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, which is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The time series will be recalculated in a future *Inventory* with the methods described previously for drainage of organic soils.

Uncertainty

The amount of N_2O emitted from settlement soils depends not only on N inputs and area of drained organic soils, but also on a large number of variables that can influence rates of nitrification and denitrification, including organic C availability; rate, application method, and timing of N input; oxygen gas partial pressure; soil moisture content; pH; temperature; and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O emissions is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate these variables, except variation in the total amount of fertilizer N and biosolids application, which leads to uncertainty in the results.

Uncertainties exist in both the fertilizer N and biosolids application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ±50 percent.[101] For emissions from drained organic soils, the total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The first variance component is associated with uncertainty in the emission factor, and the second variance component is associated with scaling of the data from the NRI survey to the entire area of drained organic soils in settlements remaining settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). There is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods that was incorporated into the analysis for the latter part of the time series.

Uncertainty is propagated through the calculations of N_2O emissions from fertilizer N and drainage of organic soils based on a Monte Carlo analysis. The results are combined with the uncertainty in N_2O emissions from the biosolids application using simple error propagation methods (IPCC 2006). The results are summarized in Table 6-130. Direct N_2O emissions from soils in settlements remaining settlements in 2022 are estimated to be between 1.2 and 3.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 54 percent above the 2022 emission estimate of 2.2 MMT CO_2 Eq. Indirect N_2O emissions in 2022 are between 0.1 and 1.1 MMT CO_2 Eq., ranging from 76 percent below to 218 percent above the estimate of 0.3 MMT CO_2 Eq.

[101] No uncertainty is provided with the USGS fertilizer consumption data (Brakebill and Gronberg 2017) so a conservative ±50 percent is used in the analysis. Biosolids data are also assumed to have an uncertainty of ±50 percent.

Table 6-130: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements						
Direct N_2O Emissions from Soils	N_2O	2.2	1.2	3.4	-47%	+54%
Indirect N_2O Emissions from Soils	N_2O	0.3	0.1	1.1	-76%	+218%

[a] Range of emission estimates is a 95 percent confidence interval.

Note: These estimates include direct and indirect N_2O emissions from settlements remaining settlements and land converted to settlements because it was not possible to separate the activity data.

QA/QC and Verification

The spreadsheet containing fertilizer, drainage of organic soils, and biosolids applied to settlements and calculations for N_2O and uncertainty ranges have been checked consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). An error was found in the initial calculations for emissions from drained organic soils, which was corrected.

Recalculations Discussion

Recalculations are associated with updated land areas for drainage of organic soils in settlements remaining settlements, by incorporating new USDA-NRCS NRI data through 2017 and extending the time series using CDL and NLCD for grassland converted to settlements, cropland converted to settlements, other land converted to settlements and wetlands converted to settlements. In addition, recalculations are associated with revised fertilizer application data from the AAPFCO report. As a result of these changes, CO_2-equivalent emissions changed annually with an average annual increase of 0.36 MMT CO_2 Eq., or 17 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

This source will be extended to include soil N_2O emissions from drainage of organic soils in Alaska and federal lands in order to provide a complete inventory of emissions for this category. Data on fertilizer amounts from 2018 to 2022 will be updated after data are released for the latter part of the time series. These improvements will be incorporated into a future I*nventory*, pending prioritization of resources.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (CRT Category 4E1)

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are put in landfills. A portion of the carbon contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates within the *Inventory* are associated with particular land uses. For example, harvested wood products are reported under forest land remaining forest land because these wood products originated from the forest ecosystem. Similarly, carbon stock changes in yard trimmings and food scraps are reported under settlements remaining settlements because the bulk of the carbon, which comes from yard trimmings, originates from settlement areas. While the majority of food scraps originate from cropland and grassland, in this *Inventory*

they are reported with the yard trimmings in the settlements remaining settlements section. Additionally, landfills are considered part of the managed land base under settlements (see Section 6.1), and reporting these carbon stock changes that occur entirely within landfills fits most appropriately within the settlements remaining settlements section. The CH_4 emissions resulting from anaerobic decomposition of yard trimmings and food scraps in landfills are reported in the Waste chapter, see Section 7.1.

The estimated amount of yard trimmings collected annually has stagnated since 1990 and the fraction that is landfilled has been declining since 1990. From 1970 to 1990, yard trimmings collected for disposal increased by about 51 percent. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps are estimated to have been generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2020). Since then, programs banning or discouraging yard trimmings disposal in landfills have led to an increase in backyard composting and the use of mulching mowers, and consequently a slowing of year-over-year increases in the tonnage of yard trimmings generated. From 1990 to 2022, yard trimmings collected for disposal are estimated to have increased 1.1. percent. At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills per year—from 72 percent in 1990 to 30 percent in 2022. The net effect of the slight increase in generation and the increase in composting is a 58 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990. Composting trends and emissions estimations are presented in the Waste chapter, Section 7.3 composting.

Food scrap generation has grown by an estimated 165 percent since 1990. Though the proportion of total food scraps generated that are eventually discarded in landfills has decreased from an estimated 82 percent in 1990 to 55 percent in 2020, the tonnage disposed of in landfills has increased considerably (by an estimated 78 percent) due to the increase in food scrap generation. Although the total tonnage of food scraps disposed of in landfills has increased from 1990 to 2022, the difference in the amount of food scraps added from one year to the next generally decreased, and consequently the annual *net changes* in carbon stock from food scraps have generally decreased as well (as shown in Table 6-131 and Table 6-132). Landfilled food scraps decompose over time, producing CH_4 and CO_2. Decomposition happens at a higher rate initially, then decreases. As decomposition decreases, the carbon stock becomes more stable. Because the cumulative carbon stock left in the landfill from previous years is (1) not decomposing as much as the carbon introduced from food scraps in a single more recent year; and (2) is much larger than the carbon introduced from food scraps in a single more recent year, the total carbon stock in the landfill is primarily driven by the more stable "older" carbon stock, thus resulting in decreasing annual changes in later years.

Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in the annual net change in landfill carbon storage from 24.5 MMT CO_2 Eq. (6.7 MMT C) in 1990 to 11.8 MMT CO_2 Eq. (3.2 MMT C) in 2022 (Table 6-131 and Table 6-132), a decrease of 48 percent over the time series.

Table 6-131: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Yard Trimmings	**(20.1)**	**(7.5)**	**(8.3)**	**(8.2)**	**(8.2)**	**(8.2)**	**(8.1)**
Grass	(1.7)	(0.6)	(0.8)	(0.8)	(0.8)	(0.8)	(0.7)
Leaves	(8.7)	(3.4)	(3.8)	(3.8)	(3.8)	(3.8)	(3.7)
Branches	(9.8)	(3.4)	(3.7)	(3.7)	(3.7)	(3.7)	(3.6)
Food Scraps	**(4.4)**	**(3.9)**	**(5.2)**	**(4.8)**	**(4.5)**	**(4.3)**	**(3.7)**
Total Net Flux	**(24.5)**	**(11.4)**	**(13.4)**	**(13.1)**	**(12.8)**	**(12.5)**	**(11.8)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-132: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Yard Trimmings	**(5.5)**	**(2.0)**	**(2.3)**	**(2.2)**	**(2.2)**	**(2.2)**	**(2.2)**
Grass	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.4)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Branches	(2.7)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Food Scraps	**(1.2)**	**(1.1)**	**(1.4)**	**(1.3)**	**(1.2)**	**(1.2)**	**(1.0)**
Total Net Flux	**(6.7)**	**(3.1)**	**(3.7)**	**(3.6)**	**(3.5)**	**(3.4)**	**(3.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the carbon that remains is effectively removed from the carbon cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of carbon in landfills can increase, with the net effect being removal of carbon from the atmosphere. Estimates of the net carbon flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled carbon stocks between inventory years and uses a country-specific methodology based on the methodology for estimating the amount of harvested wood products stored in solid waste disposal systems that is provided in the Land Use, Land-Use Change, and Forestry sector in IPCC (2003) and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Carbon stock estimates were calculated by determining the mass of landfilled carbon resulting from yard trimmings and food scraps discarded in a given year; adding the accumulated landfilled carbon from previous years; and subtracting the mass of carbon that was landfilled in previous years and has since decomposed and been emitted as CO_2 and CH_4.

To determine the total landfilled carbon stocks for a given year, the following data and factors were assembled:

(1) The composition of the yard trimmings (i.e., the proportion of grass, leaves and branches);

(2) The mass of yard trimmings and food scraps discarded in landfills;

(3) The carbon storage factor of the landfilled yard trimmings and food scraps; and

(4) The rate of decomposition of the degradable carbon.

The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted carbon storage factor (i.e., based on differences in moisture content and carbon content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2010, 2015, 2017 and 2018. To provide data for some of the missing years, detailed backup data were obtained from the 2012, 2013, and 2014, 2015, and 2017 versions of the *Advancing Sustainable Materials Management: Facts and Figures* reports (EPA 2019), as well as historical data tables that EPA developed for 1960 through 2012 (EPA 2016). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Since the *Advancing Sustainable Materials Management: Facts and Figures* reports for 2019 through 2022 were unavailable, landfilled material generation, recovery, and disposal data for 2019 through 2022 were proxied equal to 2018 values.

The amount of carbon disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying

by the initial (i.e., pre-decomposition) carbon content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial carbon contents and the carbon storage factors were determined by Barlaz (1998, 2005, 2008).

The amount of carbon remaining in the landfill for each subsequent year was tracked based on a simple model of carbon fate based on a laboratory experiment simulating decomposition of landfilled biogenic materials by methanogenic microbes (Barlaz 1998, 2005, 2008). Carbon remaining in landfilled materials is expressed as a proportion of initial carbon content, shown in the row labeled "C Storage Factor, Proportion of Initial C Stored (%)" in Table 6-133.

The modeling approach applied to simulate U.S. landfill carbon flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of carbon stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH_4 and CO_2.[102] The degradable portion of the carbon is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-133.

The first-order decay rates, *k*, for each waste component are derived from De la Cruz and Barlaz (2010):

- De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, *f*, is calculated so that the weighted average decay rate for all components is equal to the EPA AP-42 default decay rate (0.04) for mixed municipal solid waste (MSW) for regions that receive more than 25 inches of rain annually (EPA 1995). Because AP-42 values were developed using landfill data from approximately 1990, De la Cruz and Barlaz used 1990 waste composition for the United States from EPA's *Characterization of Municipal Solid Waste in the United States: 1990 Update* (EPA 1991) to calculate *f*. De la Cruz and Barlaz multiplied this correction factor by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.
- De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

Similar to the methodology in the Landfills section of the *Inventory* (Section 7.1), which estimates CH_4 emissions, the overall MSW decay rate is estimated by partitioning the U.S. landfill population into three categories based on annual precipitation ranges of: (1) Less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 $year^{-1}$, respectively. De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 $year^{-1}$), but not for the other two overall MSW decay rates.

To maintain consistency between landfill-related methodologies across the *Inventory*, EPA developed correction factors (*f*) for decay rates of 0.038 and 0.057 $year^{-1}$ through linear interpolation. A weighted national average component-specific decay rate is calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The percent of census population is calculated for each of the three categories of annual precipitation (noted in the previous paragraph); the population data are used as a surrogate for the number of landfills in each annual precipitation category. Precipitation range percentages weighted by population are updated over time as new Census data are available, to remain consistent with percentages used in the Waste chapter, Section 7.1 landfills. The component-specific decay rates are shown in Table 6-133.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including

[102] The CH_4 emissions resulting from anaerobic decomposition of yard trimmings and food scraps in landfills are reported in the Waste chapter, Section 7.1—Landfills.

dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

For each of the four materials (grass, leaves, branches, food scraps), the stock of carbon in landfills for any given year is calculated according to Equation 6-2:

Equation 6-2: Total Carbon Stock for Yard Trimmings and Food Scraps in Landfills

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \left\{[CS_i \times ICC_i] + \left[\left(1 - (CS_i \times ICC_i)\right) \times e^{-k(t-n)}\right]\right\}$$

where,

t	=	Year for which carbon stocks are being estimated (year),
i	=	Waste type for which carbon stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$	=	Stock of carbon in landfills in year *t*, for waste *i* (metric tons),
$W_{i,n}$	=	Mass of waste *i* disposed of in landfills in year *n* (metric tons, wet weight),
n	=	Year in which the waste was disposed of (year, where 1960 < *n* < *t*),
MC_i	=	Moisture content of waste *i* (percent of water),
CS_i	=	Proportion of initial carbon that is stored for waste *i* (percent),
ICC_i	=	Initial carbon content of waste *i* (percent),
e	=	Natural logarithm, and
k	=	First-order decay rate for waste *i*, (year^{-1}).

For a given year *t*, the total stock of carbon in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of carbon in landfills (F_t) for year *t* is calculated in as the change in carbon stock compared to the preceding year according to Equation 6-3:

Equation 6-3: Carbon Stock Annual Flux for Yard Trimmings and Food Scraps in Landfills

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 6-2, the carbon placed in a landfill in year *n* is tracked for each year *t* through the end of the inventory period. For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of carbon in landfills. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (507,000 metric tons) decomposes, leaving a total of 628,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2022, the total food scraps carbon originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable carbon had decomposed). By summing the carbon remaining from 1960 with the carbon remaining from food scraps disposed of in subsequent years (1961 through 2021), the total landfill carbon from food scraps in 2022 was 53.0 million metric tons. This value is then added to the carbon stock from grass, leaves, and branches to calculate the total landfill carbon stock in 2022, yielding a value of 292.6 million metric tons (as shown in Table 6-134). In the same way total net flux is calculated for forest carbon and harvested wood products, the total net flux of landfill carbon for yard trimmings and food scraps for a given year (Table 6-132) is the difference in the landfill carbon stock for the following year and the stock in the current year. For example, the net change in 2022 shown in Table 6-132 (3.2 MMT C with rounding) is equal to the stock in 2023 (295.9 MMT C) minus the stock in 2022 (292.6 MMT C). The carbon stocks calculated through this procedure are shown in Table 6-134.

To develop the 2023 carbon stock estimate, estimates of yard trimming and food scrap carbon stocks were forecasted for 2023, based on data from 1990 through 2022. These forecasted values were used to calculate net changes in carbon stocks for 2022. Excel's FORECAST.ETS function was used to predict a 2023 value using historical data via an algorithm called "Exponential Triple Smoothing." This method determined the overall trend and provided appropriate carbon stock estimates for 2023.

Table 6-133: Moisture Contents, Carbon Storage Factors (Proportions of Initial Carbon Sequestered), Initial C Contents, and Decay Rates for Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
C Storage Factor, Proportion of Initial C Stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate ($year^{-1}$)	0.313	0.179	0.015	0.151

Note: The decay rates are presented as weighted averages based on annual precipitation categories and population residing in each precipitation category.

Table 6-134: Carbon Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022	2023
Yard Trimmings	**156.0**	**203.1**	**231.6**	**233.9**	**236.1**	**238.4**	**240.6**	**242.8**
Branches	14.6	18.1	20.7	20.9	21.1	21.3	21.6	21.8
Leaves	66.7	87.4	100.4	101.5	102.5	103.6	104.6	105.6
Grass	74.7	97.7	110.5	111.5	112.5	113.5	114.5	115.4
Food Scraps	**17.9**	**33.2**	**46.9**	**48.3**	**49.6**	**50.9**	**52.0**	**53.0**
Total Carbon Stocks	**173.9**	**236.3**	**278.5**	**282.2**	**285.7**	**289.2**	**292.6**	**295.9**

[a] 2023 C stock estimate was forecasted using 1990 to 2022 data.

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. When available, the same data source was used across the entire time series for the analysis. When data were unavailable, missing values were estimated using linear interpolation or forecasting, as noted above.

Uncertainty

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of carbon), initial carbon content, moisture content, decay rate, and proportion of carbon stored. The carbon storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate for 2022. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-135. Total yard trimmings and food scraps CO_2 flux in 2022 was estimated to be between -17.3 and -4.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 58 percent above the 2022 flux estimate of -11.8 MMT CO_2 Eq.

Table 6-135: Approach 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2021 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(11.8)	(17.3)	(4.9)	-47%	+58%

[a] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Parentheses indicate negative values or net carbon sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan. Source-specific quality control measures for landfilled yard trimmings and food scraps included checking that input data were properly transposed within the spreadsheet, checking calculations were correct, and confirming that all activity data and calculations documentation was complete and updated to ensure data were properly handled through the inventory process.

Order of magnitude checks and checks of time-series consistency were performed to ensure data were updated correctly and any changes in emissions estimates were reasonable and reflected changes in activity data. An annual change trend analysis was also conducted to ensure the validity of the emissions estimates. Errors that were found during this process were corrected as necessary.

To ensure consistency across the LULUCF and Waste sectors, and the accuracy of emissions, EPA plans to perform a comparison of the activity data used and carbon inputs between the landfilled yard trimmings and food scraps, and the Waste chapter, Section 7.1—Landfills categories.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

EPA notes the following improvements may be implemented or investigated within the next two or three *Inventory* cycles pending time and resource constraints:

- MSW data more recent than 2018 have not been released through the *Advancing Sustainable Materials Management* reports. EPA will monitor the release schedule for these data and evaluate data for integration into the *Inventory* when released. Six new food waste management pathways were introduced in the 2018 *Advancing Sustainable Materials Management* report. Time series data for all of these pathways are not provided prior to 2018 but EPA plans to investigate potential data sources and/or methods to address time-series consistency and apply these data to the time series.
- EPA has been made aware of inconsistencies in landfilled food scraps data reported to the EPA Greenhouse Gas Reporting Program (GHGRP) and will evaluate changes to how landfilled and energy recovery values for yard trimmings and food scraps are calculated.

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement these improvements until data are available or identified:

- EPA also plans to continue to investigate updates to the decay rate estimates for food scraps, leaves, grass, and branches, as well as evaluate using decay rates that vary over time based on Census population

and climate data changes over time. Currently the inventory calculations use 2010 U.S. Census data, but 2020 U.S. Census data may be available.

- Other improvements include investigation into yard waste composition to determine if changes need to be made based on changes in residential practices. A review of available literature will be conducted to determine if there are changes in the allocation of yard trimmings. For example, leaving grass clippings in place is becoming a more common practice, thus reducing the percentage of grass clippings in yard trimmings disposed in landfills. In addition, agronomists may be consulted for determining the mass of grass per acre on residential lawns to provide an estimate of total grass generation for comparison with *Inventory* estimates.
- EPA will continue to evaluate data from recent peer-reviewed literature that may modify the default carbon storage factors, initial carbon contents, and decay rates for yard trimmings and food scraps in landfills – particularly updates to population precipitation ranges used to calculate k values. Based upon this evaluation, changes may be made to the default values.
- Finally, EPA plans to review available data to ensure all types of landfilled yard trimmings and food scraps are being included in the *Inventory* estimates, such as debris from road construction and commercial food waste not included in other *Inventory* estimates.

6.11 Land Converted to Settlements (CRT Category 4E2)

Land converted to settlements includes all settlements in an inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015).[103] For example, cropland, grassland or forest land converted to settlements during the past 20 years would be reported in this category. Converted lands are retained in this category for 20 years as recommended by IPCC (2006).

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining globally (Tubiello et al. 2015). IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic carbon stocks due to land-use change. All soil organic carbon stock changes are estimated and reported for land converted to settlements, but there is limited reporting of other pools in this *Inventory.* Loss of aboveground and belowground biomass, dead wood and litter carbon are reported for forest land converted to settlements and woodlands associated with grasslands converted to settlements, but not for other land-use conversions to settlements.

There are discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for land converted to settlements. Specifically, this *Inventory* includes all settlements in the conterminous United States and Hawaii, but does not include settlements in Alaska. Areas of drained organic soils in settlements on federal lands are also not included in this *Inventory.* These differences lead to discrepancies between the managed area in land converted to settlements and the settlement area included in the inventory analysis (Table 6-129). There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future *Inventory* (see Planned Improvements section).

[103] NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of land converted to settlements in the early part of the time series to the extent that some areas are converted to settlements from 1971 to 1978.

Forest land converted to settlements is the largest source of emissions from 1990 to 2022, accounting for approximately 76 percent of the average total loss of carbon among all of the land-use conversions in Land Converted to Settlements. Total losses of aboveground and belowground biomass, dead wood and litter carbon losses in 2022 for all conversions are 35.6, 6.2, 6.7, and 9.2 MMT CO_2 Eq., respectively (9.7, 1.7, 1.8, and 2.5 MMT C). Mineral and organic soils also lost 9.2 and 1.3 MMT CO_2 Eq. in 2022 (2.5 and 0.3 MMT C). The total net flux is 68.2 MMT CO_2 Eq. in 2022 (18.6 MMT C), which is a 19 percent increase in CO_2 emissions compared to the emissions in the initial reporting year of 1990 (Table 6-136 and Table 6-137). The main driver of net emissions for this source category is the conversion of forest land to settlements, with large losses of biomass, deadwood and litter carbon.

Table 6-136: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Settlements	**2.6**	**8.2**	**3.9**	**3.5**	**3.1**	**2.9**	**2.9**
Mineral Soils	2.1	6.9	3.4	2.9	2.6	2.5	2.5
Organic Soils	0.5	1.2	0.6	0.5	0.4	0.4	0.4
Forest Land Converted to Settlements	**49.3**	**53.9**	**58.4**	**58.6**	**58.6**	**58.6**	**58.6**
Aboveground Live Biomass	30.0	32.4	35.0	35.2	35.2	35.2	35.2
Belowground Live Biomass	5.2	5.6	6.1	6.1	6.1	6.1	6.1
Dead Wood	5.5	6.0	6.5	6.6	6.6	6.6	6.6
Litter	7.6	8.2	9.0	9.0	9.0	9.0	9.0
Mineral Soils	1.0	1.5	1.5	1.5	1.5	1.5	1.5
Organic Soils	0.1	0.2	0.2	0.2	0.3	0.3	0.3
Grassland Converted to Settlements	**5.6**	**15.8**	**9.8**	**8.8**	**7.9**	**7.4**	**7.5**
Aboveground Live Biomass	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Belowground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Wood	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Litter	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mineral Soils	4.3	13.7	8.2	7.3	6.5	6.0	6.0
Organic Soils	0.5	1.3	0.7	0.6	0.5	0.5	0.6
Other Lands Converted to Settlements	**(0.4)**	**(1.4)**	**(1.1)**	**(1.0)**	**(0.8)**	**(0.8)**	**(0.8)**
Mineral Soils	(0.4)	(1.5)	(1.1)	(1.0)	(0.9)	(0.8)	(0.8)
Organic Soils	+	0.1	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.6**	**0.3**	**0.3**	**0.1**	+	**0.1**
Mineral Soils	+	0.1	+	+	+	+	+
Organic Soils	+	0.6	0.3	0.3	+	+	+
Total Aboveground Biomass Flux	**30.4**	**32.8**	**35.5**	**35.6**	**35.6**	**35.6**	**35.6**
Total Belowground Biomass Flux	**5.2**	**5.7**	**6.1**	**6.2**	**6.2**	**6.2**	**6.2**
Total Dead Wood Flux	**5.6**	**6.1**	**6.7**	**6.7**	**6.7**	**6.7**	**6.7**
Total Litter Flux	**7.7**	**8.4**	**9.2**	**9.2**	**9.2**	**9.2**	**9.2**
Total Mineral Soil Flux	**7.0**	**20.7**	**12.0**	**10.8**	**9.8**	**9.2**	**9.2**
Total Organic Soil Flux	**1.2**	**3.4**	**1.8**	**1.6**	**1.3**	**1.2**	**1.3**
Total Net Flux	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-137: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Settlements	**0.7**	**2.2**	**1.1**	**1.0**	**0.8**	**0.8**	**0.8**
Mineral Soils	0.6	1.9	0.9	0.8	0.7	0.7	0.7
Organic Soils	0.1	0.3	0.2	0.1	0.1	0.1	0.1

Forest Land Converted to Settlements	**13.5**	**14.7**	**15.9**	**16.0**	**16.0**	**16.0**	**16.0**
Aboveground Live Biomass	8.2	8.8	9.6	9.6	9.6	9.6	9.6
Belowground Live Biomass	1.4	1.5	1.7	1.7	1.7	1.7	1.7
Dead Wood	1.5	1.6	1.8	1.8	1.8	1.8	1.8
Litter	2.1	2.2	2.5	2.5	2.5	2.5	2.5
Mineral Soils	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Converted to Settlements	**1.5**	**4.3**	**2.7**	**2.4**	**2.2**	**2.0**	**2.0**
Aboveground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	0.1	0.1	0.1	0.1	0.1
Mineral Soils	1.2	3.7	2.2	2.0	1.8	1.6	1.6
Organic Soils	0.1	0.3	0.2	0.2	0.1	0.1	0.2
Other Lands Converted to Settlements	**(0.1)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.2)**
Mineral Soils	(0.1)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.2**	**0.1**	**0.1**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.2	0.1	0.1	+	+	+
Total Aboveground Biomass Flux	**8.3**	**8.9**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**
Total Belowground Biomass Flux	**1.4**	**1.5**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Total Dead Wood Flux	**1.5**	**1.7**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
Total Litter Flux	**2.1**	**2.3**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Total Mineral Soil Flux	**1.9**	**5.6**	**3.3**	**2.9**	**2.7**	**2.5**	**2.5**
Total Organic Soil Flux	**0.3**	**0.9**	**0.5**	**0.4**	**0.4**	**0.3**	**0.3**
Total Net Flux	**15.6**	**21.0**	**19.5**	**19.1**	**18.8**	**18.6**	**18.6**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to settlements, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with conversion to settlements from forest lands and woodlands designated in the grassland, as well as (2) the impact from all land-use conversions to settlements on soil organic carbon stocks in mineral and organic soils.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter carbon stock changes for forest land converted to settlements. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023) however there is no country-specific data for settlements so the biomass, litter, and dead wood carbon stocks were assumed to be zero. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. Details for each of the carbon attributes described below are available in Domke et al. (2022) and Westfall et al. (2023).

If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

This *Inventory* also includes estimates of change in dead organic matter for standing dead, deadwood and litter. If FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011 and Westfall et al. 2023) with additional modifications for woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. See Annex 3.13 for more information about reference carbon density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic carbon stock changes are estimated for land converted to settlements according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021; Johnson and Mueller 2010) and National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015)). For federal lands, the land use history is derived from land cover changes in the NLCD. The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). Land use and some management information were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data have been incorporated from the NRI into the inventory analysis through 2017 (USDA-NRCS 2020).

NRI survey locations are classified as land converted to settlements in a given year between 1990 and 2020 if the land use is settlements but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of land converted to settlements in the early part of the time series to the extent that some areas are converted to settlement between 1971 and 1978.

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 2 method (Ogle et al. 2003) is applied to estimate carbon stock changes for mineral soils on land converted to settlements from 1990 to 2020. Data on climate, soil types, land use, and land management activity are used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Reference carbon stocks are estimated using the National Soil Survey Characterization Database (USDA-NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (USDA-NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provide a more robust sample for estimating the reference condition. Country-specific carbon stock change factors are derived from published literature to determine the impact of management practices on soil organic carbon storage (Ogle et al. 2003; Ogle et al. 2006). However, there are insufficient data to estimate a set of land use, management, and input factors for settlements. Moreover, the 2017 NRI survey data (USDA-NRCS 2020) do not provide the information needed to assign different land use subcategories to settlements, such as

turf grass and impervious surfaces, which is needed to apply the Tier 1 factors from the IPCC guidelines (2006). Therefore, the United States has adopted a land use factor of 0.7 to represent a net loss of soil organic carbon with conversion to settlements under the assumption that there are additional soil organic carbon losses with land clearing, excavation and other activities associated with development. More specific factor values can be derived in future Inventories as data become available. See Annex 3.12 for additional discussion of the Tier 2 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic carbon stock changes from 2021 to 2022 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, which is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to settlements are estimated using the Tier 2 method provided in IPCC (2006). The Tier 2 method assumes that organic soils are losing carbon at a rate similar to croplands, and therefore uses the country-specific values for cropland (Ogle et al. 2003). To estimate CO_2 emissions from 1990 to 2020, the area of organic soils in land converted to settlements is multiplied by the Tier 2 emission factor, which is 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2022 time series (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, and is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). Estimates will be recalculated in future *Inventories* when new activity data are incorporated into the analysis.

Uncertainty

The uncertainty analysis for carbon losses with forest land converted to settlements is conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux in the forest land remaining forest land category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Sources of uncertainty for mineral soil organic carbon stock changes and annual carbon emission estimates from drained organic soils include emission factors and variance associated with the NRI sample. The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For the first variance component, a Monte Carlo analysis was used to propagate uncertainties in the Tier 2 methods for the land use area and the country-specific factors or mineral and organic soils. The second variance component is associated with scaling of the data from the NRI survey to the entire area of land converted to settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992).

Uncertainty estimates are presented in Table 6-138 for each sub-source (i.e., biomass carbon, dead wood, litter, soil organic carbon in mineral soils and organic soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates are combined from the forest land converted to settlements and other land use conversions to settlements using the simple error propagation methods provided by the IPCC (2006). There are

also additional uncertainties propagated through the analysis associated with the data splicing methods applied to estimate soil organic carbon stock changes from 2021 to 2022. The combined uncertainty for total carbon stock changes in land converted to settlements ranges from 36 percent below to 36 percent above the 2022 stock change estimate of 68.2 MMT CO_2 Eq.

Table 6-138: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Settlements (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Settlements	**2.9**	**1.3**	**4.5**	**-56%**	**56%**
Mineral Soil C Stocks	2.5	0.9	4.1	-64%	63%
Federal Mineral Soil C Stocks	0.0	(0.0)	0.0	-146%	146%
Organic Soil C Stocks	0.4	0.1	0.7	-80%	80%
Forest Land Converted to Settlements	**58.6**	**35.3**	**81.9**	**-40%**	**40%**
Aboveground Biomass C Stocks	35.2	13.3	57.1	-62%	62%
Belowground Biomass C Stocks	6.1	2.3	9.9	-62%	62%
Dead Wood	6.6	2.5	10.6	-62%	62%
Litter	9.0	3.4	14.7	-62%	62%
Mineral Soil C Stocks	1.5	1.2	1.7	-19%	19%
Federal Mineral Soil C Stocks	0.0	0.0	0.0	0%	0%
Organic Soil C Stocks	0.3	0.1	0.4	-70%	70%
Grassland Converted to Settlements	**7.4**	**5.4**	**9.5**	**-27%**	**27%**
Aboveground Biomass C Stocks	0.5	0.2	0.8	-62%	60%
Belowground Biomass C Stocks	0.1	0.0	0.1	-45%	66%
Dead Wood	0.2	0.1	0.3	-51%	70%
Litter	0.2	0.1	0.3	-61%	57%
Mineral Soil C Stocks	6.0	4.1	7.9	-32%	32%
Federal Mineral Soil C Stocks	0.0	(0.0)	0.0	-194%	194%
Organic Soil C Stocks	0.5	(0.0)	1.1	-108%	108%
Other Lands Converted to Settlements	**-0.8**	**(1.1)**	**(0.4)**	**-44%**	**44%**
Mineral Soil C Stocks	-0.8	(1.1)	(0.5)	-38%	38%
Federal Mineral Soil C Stocks	0.0	(0.2)	0.1	-738%	738%
Organic Soil C Stocks	0.0	(0.1)	0.1	-511%	511%
Wetlands Converted to Settlements	**0.1**	**(0.3)**	**0.3**	**-557%**	**533%**
Mineral Soil C Stocks	0.0	0.0	0.1	-69%	69%
Federal Mineral Soil C Stocks	0.0	0.0	0.0	0%	0%
Organic Soil C Stocks	0.0	(0.3)	0.3	-1,269%	1,214%
Total: Land Converted to Settlements	**68.2**	**43.5**	**92.9**	**-36%**	**36%**
Aboveground Biomass C Stocks	**35.6**	**13.3**	**57.1**	**-62%**	**62%**
Belowground Biomass C Stocks	**6.2**	**2.3**	**9.9**	**-62%**	**62%**
Dead Wood	**6.7**	**2.5**	**10.6**	**-62%**	**62%**
Litter	**9.2**	**3.4**	**14.7**	**-62%**	**62%**
Mineral Soil C Stocks	**9.2**	**6.6**	**11.7**	**-28%**	**28%**
Organic Soil C Stocks	**1.2**	**(6.6)**	**9.1**	**-625%**	**625%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this *Inventory*.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks in forest land converted to settlements and woodland conversion associated with grassland converted to settlements. Additional recalculations are associated with incorporating new USDA-NRCS NRI data through 2017 and extending the time series using CDL and NLCD for grassland converted to settlements, cropland converted to settlements, other land converted to settlements and wetlands converted to settlements. As a result, land converted to settlements has an estimated smaller carbon loss of 7.7 MMT CO_2 Eq. on average over the time series. This represents a 19 percent decrease in carbon stock changes for land converted to settlements compared to the previous *Inventory.*

Planned Improvements

A key improvement is to develop an inventory of mineral soil organic carbon stock changes in Alaska and losses of carbon from drained organic soils in federal lands. These improvements will resolve most of the differences between the managed land base for land converted to settlements and amount of area currently included in the *Inventory* for land converted to settlements (see Table 6-139).

There are plans to improve classification of trees in settlements and to include transfer of biomass from forest land to those areas in this category. There are also plans to extend the inventory to included carbon losses associated with drained organic soils in settlements occurring on federal lands.

These improvements will be made pending prioritization of resources to expand the inventory for this source category.

Table 6-139: Area of Managed Land in Land Converted to Settlements that is not included in the current *Inventory* (Thousand Hectares)

	Area (Thousand Hectares)		
Year	LCS Managed Land Area (Section 6.1)	LCS Area Included in *Inventory*	LCS Area Not Included in *Inventory*
1990	2,865	2,865	1
1991	3,213	3,213	1
1992	3,573	3,573	1
1993	4,138	4,138	1
1994	4,703	4,702	1
1995	5,262	5,261	1
1996	5,833	5,832	1
1997	6,409	6,408	1
1998	6,929	6,928	1
1999	7,446	7,446	1
2000	7,952	7,952	1
2001	8,362	8,361	1
2002	8,696	8,695	1
2003	8,705	8,704	1
2004	8,710	8,708	2
2005	8,727	8,724	2

2006	8,691	8,688	3
2007	8,672	8,668	3
2008	8,501	8,497	4
2009	8,309	8,305	5
2010	8,130	8,124	5
2011	7,930	7,925	6
2012	7,717	7,711	6
2013	7,325	7,318	6
2014	6,942	6,935	7
2015	6,530	6,523	7
2016	6,112	6,105	7
2017	5,715	5,708	7
2018	5,201	5,194	7
2019	4,696	4,689	7
2020	4,175	4,168	7
2021	3,771	*	*
2022	3,437	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

6.12 Other Land Remaining Other Land (CRT Category 4F1)

Land use is constantly occurring, and areas under a number of differing land-use types remain in their respective land-use type each year, just as other land can remain as other land. While the magnitude of other land remaining other land is known (see Table 6-4), research is ongoing to track carbon pools in this land use. Until such time that reliable and comprehensive estimates of carbon for other land remaining other land can be produced, it is not possible to estimate CO_2, CH_4 or N_2O fluxes on other land remaining other land at this time.

6.13 Land Converted to Other Land (CRT Category 4F2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to other land each year, just as other land is converted to other uses. While the magnitude of these area changes is known (see Table 6-4), research is ongoing to track carbon across other land remaining other land and land converted to other land. Until such time that reliable and comprehensive estimates of carbon across these land-use and land-use change categories can be produced, it is not possible to separate CO_2, CH_4 or N_2O fluxes on land converted to other land from fluxes on other land remaining other land at this time.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1 and Figure 7-2). Landfills were the third largest source of anthropogenic methane (CH_4) in the United States in 2022, accounting for approximately 17.1 percent of total U.S. CH_4 emissions. Additionally, wastewater treatment and discharge, composting of organic waste, and anaerobic digestion at biogas facilities accounted for approximately 3.0 percent, 0.4 percent, and less than 0.1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions resulting from the discharge of wastewater treatment effluents into aquatic environments were estimated, along with the wastewater treatment process itself and composting. Together, these waste activities account for 6.1 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste sector is presented in Table 7-1 and Table 7-2. Overall, in 2022, waste activities generated emissions of 166.9 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions.

Emissions from landfills contributed 71.8 percent of Waste sector emissions in 2022 (see Figure 7-1) and are primarily composed of CH_4 emissions from municipal solid waste landfills. Landfill emissions decreased by 2.3 MMT CO_2 Eq. (1.9 percent) since 2021. Emissions from wastewater treatment were the second largest source of waste-related emissions in 2022, accounting for 25.6 percent of sector emissions. The remaining two sources of emissions, composting and anaerobic digestion at biogas facilities, account for 2.6 percent and less than 0.1 percent of Waste sector emissions in 2022, respectively.

Figure 7-1: 2022 Waste Sector Greenhouse Gas Sources

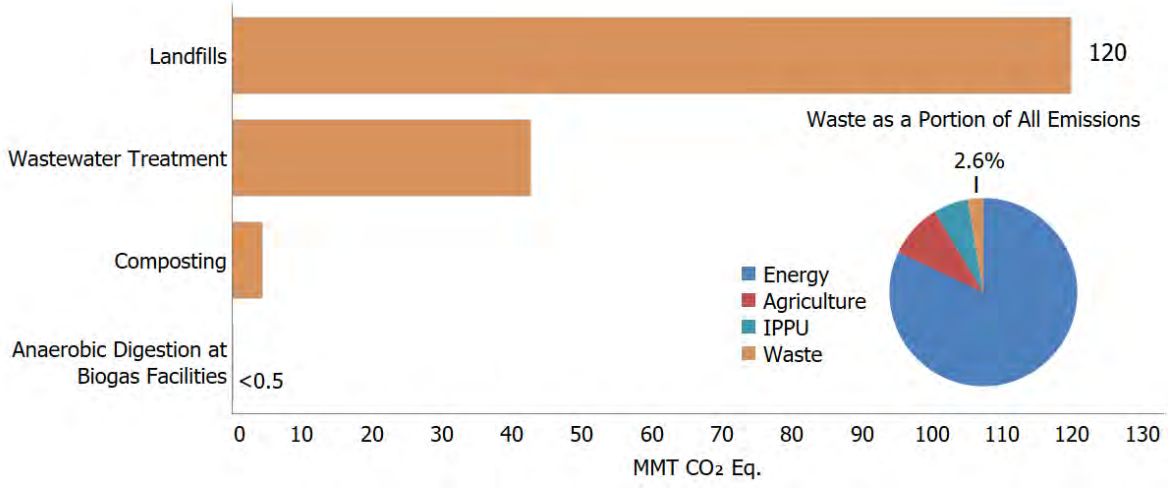

Figure 7-2: Trends in Waste Sector Greenhouse Gas Sources

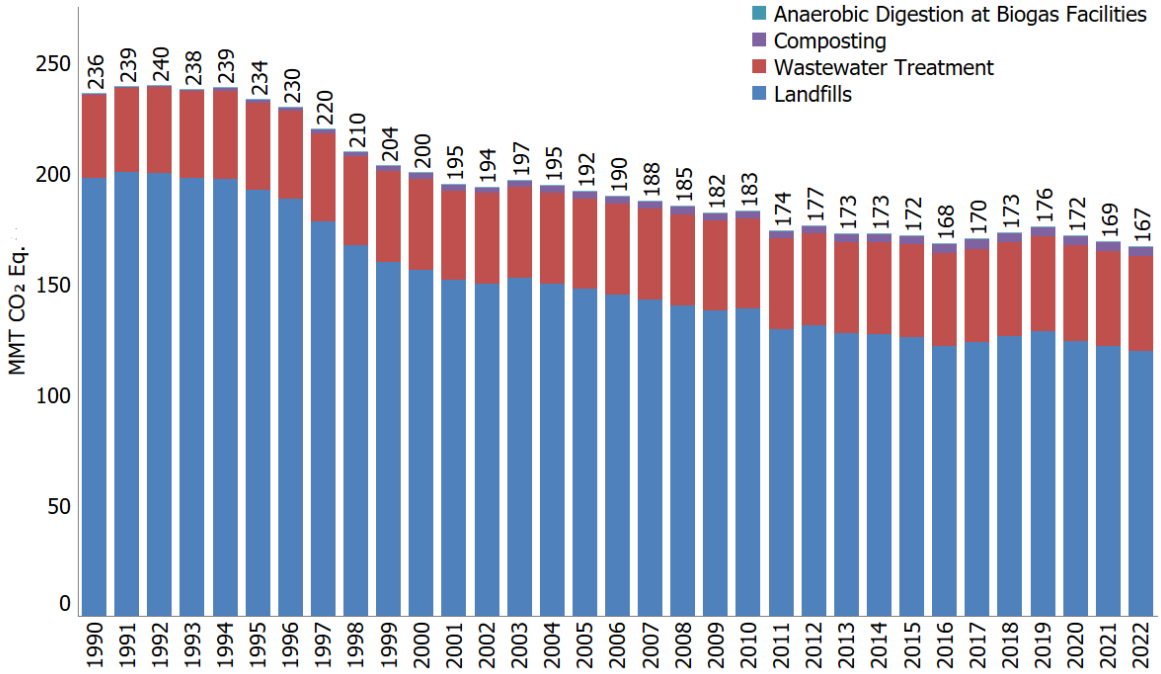

Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CH_4	**220.9**	**172.4**	**150.2**	**152.4**	**147.6**	**145.3**	**143.2**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+
N_2O	**15.1**	**19.5**	**23.0**	**23.4**	**24.1**	**23.9**	**23.7**
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Total	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CH_4	**7,889**	**6,159**	**5,365**	**5,441**	**5,271**	**5,189**	**5,113**
Landfills	7,063	5,275	4,512	4,595	4,431	4,359	4,277
Wastewater Treatment	811	809	763	755	748	738	743
Composting	15	75	90	91	92	92	92
Anaerobic Digestion at Biogas Facilities	+	+	+	1	+	+	+
N_2O	**57**	**74**	**87**	**88**	**91**	**90**	**89**
Wastewater Treatment	56	68	80	81	84	83	83
Composting	1	6	7	7	7	7	7

+ Does not exceed 0.5 kt.

Note: Totals by gas may not sum due to independent rounding.

Carbon dioxide (CO_2), CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2022 resulted in 12.7 MMT CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.5. Greenhouse Gas Precursor Emissions from the Waste sector are presented in Section 7.6.

Each year, some emission and sink estimates in the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory*'s time series (i.e., 1990 to 2021) to ensure that the trend is accurate. For the current *Inventory*, minor improvements were implemented beyond routine activity data updates, including changes to MSW and industrial waste landfill activity data, updates to production activity affecting wastewater influent, and methodological changes for CH_4 emissions from anaerobic digesters processing food waste. In total, the methodological and historic data improvements made to the Waste sector in this *Inventory* resulted in an average decrease in greenhouse gas emissions across the time series by 0.06 MMT CO_2 Eq. (0.03 percent). For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Due to lack of data availability, EPA is not able to estimate emissions associated with sludge generated from the treatment of industrial wastewater. Emissions reported in the Waste chapter for landfills, wastewater treatment, and anaerobic digestion at biogas facilities include those from all 50 states, including Hawaii and Alaska, the District of Columbia, and U.S. Territories. Emissions from landfills include modern, managed sites in most U.S. Territories except for outlying Pacific Islands. Emissions from domestic wastewater treatment include most U.S. Territories except for outlying Pacific Islands. Those emissions are likely insignificant as those outlying Pacific Islands (e.g., Baker Island) have no permanent population. No industrial wastewater treatment emissions are estimated for U.S. Territories, due to lack of data availability. However, industrial wastewater treatment emissions are not expected for outlying Pacific Islands and assumed to be small for other U.S. Territories. Emissions for composting include Puerto Rico and all states except Alaska. Some composting operations in Alaska are known, but these consist of aerated composting facilities. Composting emissions are not included from the remaining U.S. Territories, and these are assumed to be small. Similarly, EPA is not aware of any anaerobic digestion at biogas facilities in U.S. Territories but will review this on an ongoing basis to include these emissions if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to Greenhouse Gas Reporting Data

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines)* and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and sinks provided in the Waste chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from waste management and treatment activities.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. See Annex 9 "Use of EPA Greenhouse Gas Reporting Program in Inventory" for more information.

Waste Data from EPA's Greenhouse Gas Reporting Program

EPA uses annual GHGRP facility-level data in the Landfills category to compile the national estimate of emissions from Municipal Solid Waste (MSW) landfills (see Section 7.1 of this chapter for more information). EPA uses directly reported GHGRP data for net CH_4 emissions from MSW landfills for the years 2010 to 2022 of the *Inventory*. MSW landfills subject to the GHGRP began collecting data in 2010. These data are also used to recalculate emissions from MSW landfills for the years 2005 to 2009 to ensure time-series consistency.

7.1 Landfills (CRT Source Category 5A1)

In In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 7-3. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-2. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the timeframe of 1990 to the current *Inventory* year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but are used to dispose of industrial solid waste, such as RCRA Subtitle D wastes (e.g., non-hazardous industrial solid waste defined in Title 40 of the Code of Federal Regulations [CFR] in section 257.2), commercial solid wastes, or conditionally exempt small-quantity generator wastes (EPA 2016a).

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These CH_4 producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition byproducts or volatilization of biodegradable wastes (EPA 2008).

Box 7-2: Description of a Modern, Managed Landfill in the United States

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. A modern, managed landfill is EPA's interpretation of the IPCC's terminology of a managed solid waste disposal site. Municipal solid waste (MSW) landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream.

Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas);
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (e.g., final cover construction); and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the NSPS 40 CFR Part 60 Subparts WWW and XXX.[1] Additionally, state and tribal requirements may exist.

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. Net carbon dioxide flux from carbon stock changes of materials of biogenic origin in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this *Inventory*). Nitrous oxide (N_2O) emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount and composition of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas–that is not collected by a gas collection system – passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills employ similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is

[1] For more information regarding federal MSW landfill regulations, see http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm.

disposed of in a landfill and will continue for 10 to 50 or more years as the degradable waste decomposes over time.

In 2022, landfill CH_4 emissions were approximately 119.8 MMT CO_2 Eq. (4,277 kt), representing the third largest source of CH_4 emissions in the United States, behind enteric fermentation and natural gas systems. Emissions from MSW landfills accounted for approximately 84 percent of total landfill emissions (100.9 MMT CO_2 Eq.), while industrial waste landfills accounted for the remainder (18.9 MMT CO_2 Eq.). Nationally, there are significantly less industrial waste landfills compared to MSW landfills, which contributes to the lower national estimate of CH_4 emissions for industrial waste landfills. Additionally, the average organic content of waste streams disposed in industrial waste landfills is lower than MSW landfills. Estimates of operational MSW landfills in the United States have ranged from 1,700 to 2,000 facilities (EPA 2023a; EPA 2023b; EPA 2020c; Waste Business Journal [WBJ] 2016; WBJ 2010). The Environment Research & Education Foundation (EREF) conducted a nationwide analysis of MSW management and counted 1,540 operational MSW landfills in 2013 (EREF 2016). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure data is known, (EPA 2023b; WBJ 2010). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to as few as 1,540 in 2013, the average landfill size has increased (EPA 2023a; EREF 2016; BioCycle 2010). Larger landfills may have deeper cells where a greater amount of area will be anaerobic (more CH_4 is generated in anaerobic versus aerobic areas) and larger landfills tend to generate more CH_4 compared to a smaller landfill (assuming the same waste composition and age of waste). Regarding industrial waste landfills, the WBJ database includes approximately 1,100 landfills accepting industrial and/or construction and demolition debris for 2021 (WBJ 2021). Only 169 facilities with industrial waste landfills met the reporting threshold under Subpart TT (Industrial Waste Landfills) in the first year (2011) of EPA's Greenhouse Gas Reporting Program for this subpart (GHGRP codified in 40 CFR Part 98), indicating that there may be several hundred industrial waste landfills that are not required to report under EPA's GHGRP. Less industrial waste landfills meet the GHGRP eligibility threshold because they typically accept waste streams with low to no organic content, which will not decompose and generate CH_4 when disposed.

The annual amount of MSW generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The estimated annual quantity of waste placed in MSW landfills increased 10 percent from approximately 205 MMT in 1990 to 226 MMT in 2000, then decreased by 11 percent to 202 MMT in 2010, and then increased by 7 percent to approximately 217 MMT in 2022 (see Annex 3.14, Table A-233). Emissions decreased between 1990 to 2022 largely because of increased use of landfill gas collection and control systems, closure of older landfills, better management practices, and increased diversion of organics through state and local policy and regulations. The total amount of MSW generated is expected to increase as the U.S. population continues to grow. The impacts of the coronavirus (COVID-19) pandemic with respect to landfilled waste cannot be quantified as data sources such as the EPA's *Advancing Sustainable Materials Management: Facts and Figures* report have not been published for 2019 through 2022. The quantities of waste landfilled for 2019 to 2022 (presented in Annex 3.14) are extrapolated based on population growth and the last national assessment of MSW landfilled from 2013 (EREF 2016). Net CH_4 emissions from MSW landfills have decreased since 1990 (see Table 7-3 and Table 7-4).

The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper, and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 11.0 MMT in 2022 (see Annex 3.14, Table A-219). CH_4 emissions from industrial waste landfills have also remained at similar levels recently, ranging from 16.1 MMT CO_2 Eq. in 2005 to 18.9 MMT CO_2 Eq. in 2022 when accounting for both CH_4 generation and oxidation. The EPA has focused the industrial waste landfills source category on industrial sectors known to generate and dispose of by-products that are organic and contribute to CH_4 generation, which are the pulp and paper and food processing sectors. Construction and demolition (C&D) landfills, another type of industrial waste landfill, may accept waste that could degrade (e.g., treated wood), but these waste streams are unlikely to generate significant amounts of CH_4 and are therefore not as relevant to the purpose of national greenhouse gas emissions estimate. There is also a general lack of data on annual quantities of waste disposed in industrial waste

landfills, and the GHGRP Subpart TT (Industrial Waste Landfills) dataset has confirmed C&D landfills, for example, are insignificant CH_4 generators.

EPA's Landfill Methane Outreach Program (LMOP) collects information on landfill gas energy projects currently operational or under construction throughout the United States. LMOP's Landfill and Landfill Gas Energy Database contains certain information on the gas collection and control systems in place at landfills provided by organizations that are a part of the program, which can include the amount of landfill gas collected and flared. In 2022, LMOP identified 9 new landfill gas-to-energy (LFGE) projects (EPA 2023b) that began operation.

Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
MSW CH_4 Generation[a]	230.0	303.7	332.0	340.9	340.9	335.9	331.4
Industrial CH_4 Generation	13.6	17.9	20.8	20.9	21.0	21.0	21.0
MSW CH_4 Recovered[a]	(23.8)	(148.4)	(195.2)	(201.4)	(206.3)	(203.3)	(199.8)
MSW CH_4 Oxidized[a]	(20.6)	(23.6)	(29.2)	(29.6)	(29.4)	(29.5)	(30.7)
Industrial CH_4 Oxidized	(1.4)	(1.8)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)
MSW net CH_4 Emissions	185.5	131.6	107.7	109.9	105.2	103.1	100.9
Industrial CH_4 Emissions[b]	12.2	16.1	18.7	18.8	18.9	18.9	18.9
Total	**197.8**	**147.7**	**126.3**	**128.7**	**124.1**	**122.0**	**119.8**

[a] For years 1990 to 2004, the *Inventory* methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2022, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 167 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2021 (EPA 2023a).

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 7-4: CH_4 Emissions from Landfills (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
MSW CH_4 Generation[a]	8,214	10,845	11,857	12,175	12,174	11,997	11,834
Industrial CH_4 Generation	484	638	741	745	748	750	750
MSW CH_4 Recovered[a]	(851)	(5,301)	(6,970)	(7,193)	(7,367)	(7,262)	(7,135)
MSW CH_4 Oxidized[a]	(736)	(843)	(1,041)	(1,058)	(1,050)	(1,052)	(1,097)
Industrial CH_4 Oxidized	(48)	(64)	(74)	(75)	(75)	(75)	(75)
MSW net CH_4 Emissions	6,627	4,701	3,845	3,924	3,757	3,683	3,602
Industrial net CH_4 Emissions[b]	436	574	667	671	674	675	675
Total	**7,063**	**5,275**	**4,512**	**4,595**	**4,431**	**4,359**	**4,277**

[a] For years 1990 to 2004, the *Inventory* methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2022, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 167 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2021 (EPA 2023a).

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Methodology Applied for MSW Landfills

A combination of IPCC Tier 2 and 3 approaches (IPCC 2006) are used over the reported time series to calculate emissions from MSW Landfills, using two primary methods in accordance with IPCC methodological decision trees based on available data. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH_4 in a landfill that is oxidized to CO_2 as it passes through the landfill cover (e.g., soil, clay, geomembrane). This method is presented below.

Equation 7-1: Landfill Methane Generation

$$\mathrm{CH}_{4,\mathrm{MSW}} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,MSW}$	=	Net CH_4 emissions from solid waste
$G_{CH4,MSW}$	=	CH_4 generation from MSW landfills, using emission factors for DOC, k, MCF, F from IPCC (2006) and other peer-reviewed sources
R	=	CH_4 recovered and combusted
Ox	=	CH_4 oxidized from MSW landfills before release to the atmosphere, using Ox values from IPCC (2006) and other peer-reviewed or scientifically validated literature (40 CFR Part 98)

The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based on directly measured amounts of recovered CH_4 from the landfill gas and is expressed below and by Equation HH-8 in 40 CFR Part 98.343. The two parts of the equation consider the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system, and the portion that is collected. First, the recovered CH_4 is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH_4 in the landfill gas that is not captured by the collection system; this amount is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH_4 in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

The current *Inventory* uses both methods to estimate CH_4 emissions across the time series within EPA's Waste Model, as summarized in Figure 7-3 below. This chapter provides a summary of the methods, activity data, and parameters used. Additional stepwise explanations to generate the net emissions are provided in Annex 3.14.

Equation 7-2: Net Methane Emissions from MSW Landfills

$$\mathrm{CH}_{4,\mathrm{Solid\ Waste}} = [\left(\frac{R}{CE\ x\ f_{REC}} - R\right) x(1 - OX) + R\ x\ \left(1 - (DE\ x\ f_{Dest})\right)]$$

where,

$CH_{4,Solid\ Waste}$	=	Net CH_4 emissions from solid waste
R	=	Quantity of recovered CH_4 from Equation HH-4 of EPA's GHGRP
CE	=	Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA's GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used (percent)
f_{REC}	=	fraction of hours the recovery system was operating (percent)
OX	=	oxidation factor (percent)
DE	=	destruction efficiency (percent)
f_{Dest}	=	fraction of hours the destruction device was operating (fraction)

Figure 7-3: Methodologies Used Across the Time Series to Compile the U.S. Inventory of Emission Estimates for MSW Landfills

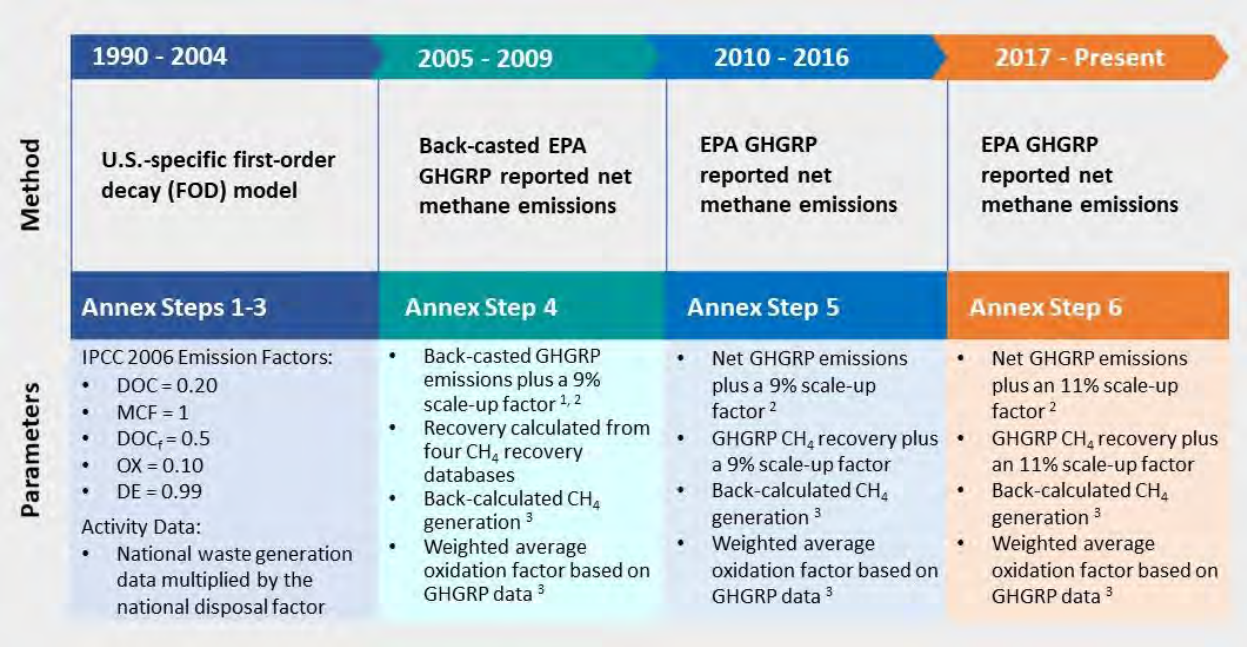

[1] The intent of the scale-up factor is to estimate emissions from landfills that do not report to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. The back-casted emissions are calculated using directly reported net methane emissions for GHGRP reporting years 2010 to 2016. The back-casted emissions are subject to change in each *Inventory* based on new reporting year reports and resubmitted greenhouse gas reports for previous years. This method is compatible with the *2006 IPCC Guidelines* because facilities reporting to the GHGRP either use the FOD method, or directly measured methane recovery data with default emission factors either directly included in the *2006 IPCC Guidelines* or scientifically validated through peer review.

[2] Emission factors used by facilities reporting to GHGRP Subpart HH are facility-specific defaults derived from peer-reviewed literature and the *2006 IPCC Guidelines*.

[3] Methane generation is back-calculated from the net MSW emissions, estimated methane recovery data, and the weighted average oxidation factor based on GHGRP Subpart HH reported data of 0.18 between 2010 to 2016, and 0.21 between 2017 to 2020, and 0.23 in 2021 and 2022.

The Waste Model is a spreadsheet developed by the IPCC for purposes of estimating methane emissions from solid waste disposal sites, adapted to the United States by the inclusion and usage of U.S.-specific parameters. The Waste Model contains activity and waste generation information from both the MSW and Industrial landfill sectors and estimates the amount of CH_4 emissions from each sector for each year of the time series, using both methods. Prior to the 1990 through 2015 *Inventory*, only the FOD method was used. Methodological changes were made to the 1990 through 2015 *Inventory* to incorporate higher tier data (i.e., CH_4 emissions as directly reported to EPA's GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The technique used to merge the directly reported GHGRP data with the previous methodology is described as the overlap technique in the Time-Series Consistency chapter of the *2006 IPCC Guidelines*. Additional details on the technique used is included in Annex 3.14, and a technical memorandum (RTI 2017).

Supporting information, including details on the techniques used to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in Annex 3.14.

Methodology Applied for Industrial Waste Landfills

Emissions from industrial waste landfills are estimated using a Tier 2 approach (IPCC 2006) and a tailored (country-specific) IPCC waste model in accordance with IPCC methodological decision trees based on available data. Activity

data used are industrial production data (ERG 2023) for two sectors (pulp and paper manufacturing, and food and beverage manufacturing) to which country-specific default waste disposal factors are applied (a separate disposal factor for each sector). The disposal factors, as described below, are based on scientifically reviewed data, and are the same across the entire time series. The emission factors are based on those recommended by the *2006 IPCC Guidelines* and are the same across the entire time series.

The FOD equation from IPCC (2006) is used via the waste model to estimate methane emissions:

Equation 7-3: Net Methane Emissions from Industrial Waste Landfills

$$\mathrm{CH}_{4,\mathrm{IND}} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,Solid\ Waste}$	=	Net CH_4 emissions from solid waste
$G_{CH4,Ind}$	=	CH_4 generation from industrial waste landfills, using production data multiplied by a disposal factor and emission factors for DOC, k, MCF, F (IPCC 2006)
R	=	CH_4 recovered and combusted (no recovery is assumed for industrial waste landfills)
OX	=	CH_4 oxidized from industrial waste landfills before release to the atmosphere (using the *2006 IPCC Guidelines* value for OX of 0.10)

The activity data used in the emission calculations are production data (e.g., the amount of meat, poultry, vegetables processed; the amount of paper produced) versus disposal data. There are currently no facility-specific data sources that track and report the amount and type of waste disposed of in the universe of industrial waste landfills in the United States. Based on this limited information, the *Inventory* methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors, thus estimates of industrial landfill emissions focused on these two sectors.

A waste disposal factor is applied to the annual quantities of key food products generated. A waste disposal factor of 4.86 percent is used for 1990 to 2009 and a factor of 6 percent is used for 2010 to the current year. The 4.86 percent disposal factor is based on available data from a 1993 Report to Congress (EPA 1993). The 6 percent waste disposal factor is derived from recent surveys of the food and beverage industry where approximately 94 percent of food waste generated is repurposed (FWRA 2016). The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills. The amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14.

Landfill CH_4 recovery is not accounted for in industrial waste landfills and is believed to be minimal based on available data collected under EPA's GHGRP for industrial waste landfills (Subpart TT), which shows that only one of the 167 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2023a). The amount of CH_4 oxidized by the landfill cover at industrial waste landfills is assumed to be 10 percent of the CH_4 generated (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for all years.

Additionally, the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) were reviewed to determine if any revisions were required to emission factors, methodologies, and assumptions underlying emission estimates for all source categories. None of the 2019 Refinements are applicable to the country-specific methodology applied for the landfills source category.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste (MSW) generated in the United States can be managed through a variety of methods. MSW that is not recycled, composted, combusted with energy recovery, or digested is assumed to be landfilled. In addition to these management pathways, waste or excess food from the food manufacturing and processing sector may be disposed through the sewerage network, used for animal feed, land application, donated for human consumption, and rendered or recycled into biofuels in the case of animal by-products, fats, oils and greases.

There have been three main sources for nationwide solid waste management data in the United States that the *Inventory* has used (see Annex 3.14, Box A-3 for comparison of estimates from these data sources):

- The *BioCycle* and Earth Engineering Center of Columbia University's SOG in America surveys [no longer published];
- The EPA's *Advancing Sustainable Materials Management: Facts and Figures* reports; and
- The EREF's *MSW Generation in the United States* reports.

The SOG surveys and, most recently EREF, collected state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. These data sources used a 'bottom-up' method. The survey asked for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown was not available, the survey asked for total tons landfilled. The data were adjusted for imports and exports across state lines so that the principles of mass balance were adhered to for completeness, whereby the amount of waste managed did not exceed the amount of waste generated. The SOG and EREF reports present survey data aggregated to the state level.

The EPA *Advancing Sustainable Materials Management: Facts and Figures* report characterizes national post-consumer municipal solid waste (MSW) generation and management using a top-down materials flow (mass balance) methodology. It captures an annual snapshot of MSW generation and management in the United States for specific products. Data are gathered from U.S. Government (e.g., U.S. Census Bureau and U.S. Department of Commerce), state environmental agencies, industry and trade groups, and sampling studies. The materials flow methodology develops MSW waste generation estimates of quantities of MSW products in the marketplace (using product sales and replacement data) and assessing waste generation by component material based on product lifespans. The data are used to estimate tons of materials and products generated, recycled, combusted with energy recovery, managed via other food waste management pathways, or landfilled nationwide. MSW that is not recycled or composted is assumed to be combusted or landfilled, except for wasted food, which uses a different methodology and includes nine different management pathways. The 2018 Facts and Figures Report (EPA 2020) uses a methodology that expanded the number of management pathways to include: animal feed; bio-based materials and/or biochemical processing (i.e., rendering); co-digestion and/or anaerobic digestion; composting/aerobic processes; combustion; donation; land application; landfill; and sewer or wastewater treatment.

In this *Inventory*, emissions from solid waste management are presented separately by waste disposal option, except for recycling of waste materials.

- **Recycling**: Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery and are presented in the stationary combustion chapter in the Energy sector. The emissions estimates for recycling are not called out separately.
- **Landfill Disposal**: Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting sections in the Waste sector of this report.
- **Anaerobic Digestion**: Emissions from anaerobic digesters are presented in three different sections depending on the digester category:
    - Emissions from on-farm digesters are included in the Agriculture sector.
    - Emissions from digesters at wastewater treatment plants are included in the Waste sector, and
    - Emissions from stand-alone digesters are also included in the Waste sector.
- **Waste Incineration**: Emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report because, in the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered.

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills when the FOD method is applied directly for 1990 to 2004 in the Waste Model and, to some extent, in the GHGRP methodology. The approach used in the MSW emission estimates assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, the FOD method as applied in this *Inventory* is not facility-specific modeling and while this approach may over- or underestimate CH_4 generation at some landfills if used at the facility-level, the result is expected to balance out because it is being applied nationwide.

There is a high degree of uncertainty associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006). There is less uncertainty in EPA's GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used.

Uncertainty also exists in the scale-up factors (both 9 percent and 11 percent) applied for years 2005 to 2016 and 2017 to 2022, respectively, and in the back-casted emissions estimates for 2005 to 2009. As detailed in RTI (2018), limited information is available for landfills that do not report to the GHGRP. RTI developed an initial list of landfills that do not report to the GHGRP with the intent of quantifying the total waste-in-place for these landfills that would add up to the scale-up factor. Input was provided by industry, LMOP, and additional EPA support. However, many gaps existed in the initial development of this Non-Reporting Landfills Database. Assumptions were made for hundreds of landfills to estimate their waste-in-place and the subsequent scale-up factors. The waste-in-place estimated for each landfill is likely not 100 percent accurate and should be considered a reasonable estimate. Additionally, a simple methodology was used to back-cast emissions for 2005 to 2009 using the GHGRP-reported emissions from 2010 to 2022. This methodology does not factor in annual landfill to landfill changes in landfill CH_4 generation and recovery. Because of this, an uncertainty factor of 25 percent is applied to the scale-up factor and years (emission estimates) the scale-up factor is applied to.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized at MSW landfills. Facilities directly reporting to EPA's GHGRP can use oxidation factors ranging from 0 to 35 percent, depending on their facility-specific CH_4 flux. As recommended by the *2006 IPCC Guidelines* for managed landfills, a 10 percent default oxidation factor is applied in the *Inventory* for both MSW landfills (those not reporting to the GHGRP and for the years 1990 to 2004 when GHGRP data are not available) and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system.

Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the *Inventory*'s CH_4 recovery databases (used for years 1990 to 2004). Four CH_4 recovery databases are used to estimate nationwide CH_4 recovery for MSW landfills for 1990 to 2009. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 to 2013 *Inventory* report (two years before the full GHGRP data set started being used for net CH_4 emissions for the *Inventory*). Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. The methodology and assumptions that go into each database differ. For example, the flare database assumes the midpoint of each flare capacity at the time it is sold and installed at a landfill; the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered. Additionally, two databases, the EIA database and flare vendor database, could no longer be updated for the entire time series due to external factors. For example, the EIA database has not been updated since 2006 because the EIA stopped collecting landfill recovery data. The EIA database has, for the most part, been replaced by the GHGRP MSW

landfills database. The flare database was populated annually until 2015, but decreasing, voluntary participation from flare vendors sharing their flare sales data for several years prior to 2015.

To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data and the EIA data are given precedence because facility data were directly reported; the LFGE data are given second priority because CH_4 recovery is estimated from facility-reported LFGE system characteristics; and the flare data are given the lowest priority because this database contains minimal information about the flare, no site-specific operating characteristics, and includes smaller landfills not included in the other three databases (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery; however, the number of unique landfills between the four databases does differ.

The *2006 IPCC Guidelines* default value of 10 percent for uncertainty in recovery estimates was used for two of the four recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the four databases in addition to the uncertainties associated with the FOD method and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5.

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary source of uncertainty with respect to the industrial waste generation and emission estimates. The approach used here assumes that most of the organic waste disposed of in industrial waste landfills that would result in CH_4 emissions consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, a straight disposal factor is applied over the entire time series to the amount produced to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the *Inventory* methodology for the pulp and paper sector. A 10 percent oxidation factor is also applied to CH_4 generation estimates for industrial waste landfills and carries the same amount of uncertainty as with the factor applied to CH_4 generation for MSW landfills. The specified probability density functions (PDFs) are assumed to be normal for most activity data and emission factors, and due to lack of data, are based on expert judgement (RTI 2004).

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. There is considerable uncertainty for the MSW landfills estimates due to the many data sources used, each with its own uncertainty factor.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	**CH_4**	**119.8**	**109.9**	**137.2**	**-8%**	**+15%**
MSW	CH_4	100.9	98.8	121.2	-2%	+20%
Industrial	CH_4	18.9	13.1	23.7	-31%	+25%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval. Individual uncertainty factors are applied to activity data and emission factors in the Monte Carlo analysis.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). QA/QC checks are performed for the transcription of the published data set (e.g., EPA's GHGRP dataset) used to populate the *Inventory* data set in terms of completeness and accuracy against the reference source. Additionally, all datasets used for this category have been checked to ensure they are of appropriate quality and are representative of U.S. conditions. The primary calculation spreadsheet is tailored from the *2006 IPCC Guidelines* waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values and calculations were verified by secondary QA/QC review. Stakeholder engagements sessions in 2016 and 2017 were used to gather input on methodological improvements and facilitate an external expert review on the methodology, activity data, and emission factors.

Category-specific checks include the following:

- Evaluation of the secondary data sources used as inputs to the *Inventory* dataset to ensure they are appropriately collected and are reliable;
- Cross-checking the data (activity data and emissions estimates) with previous years to ensure the data are reasonable, and that any significant variation can be explained through the activity data;
- Conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies; and
- Reviewing secondary datasets to ensure they are nationally complete and supplementing where necessary (e.g., using a scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP).

A primary focus of the QA/QC checks in past Inventories was to ensure that CH_4 recovery estimates were not double-counted and that all LFGE projects and flares were included in the respective project databases. QA/QC checks performed in the past for the recovery databases were not performed in this *Inventory*, because new data were not added to the recovery databases in this *Inventory* year.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[2] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with several general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. For the MSW Landfills sector, under Subpart HH of the GHGRP, MSW Landfills with gas collection are required to report emissions from their site using both a forward- (using a first order decay model as a basis) and back-calculating (using parameters specific to the landfill itself, such as measured recovery and collection efficiency of the landfill gas) methodology. Details on the forward- and back-calculation approach can be found in Annex 3.14 and 40 CFR Subpart HH of Part 98. Reporters can choose which of these two methodologies they believe best represents the emissions at their landfill and are required to submit that value as their total Subpart HH emissions. Facilities are generally not expected to switch between the two equations each year, as the emissions calculated using each method can vary greatly and can have a significant effect on emission trends for that landfill, and potentially the entire MSW Landfill sector under the GHGRP. Key checks are in place to assure that emissions are trending in a sensible way year over year for each reporting landfill.

[2] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Recalculations Discussion

Revisions to the individual facility reports submitted to EPA's GHGRP can be made at any time and a portion of facilities have revised their reports since 2010 for various reasons, resulting in changes to the total net CH_4 emissions for MSW landfills. Each *Inventory* year, the back-casted emissions for 2005 to 2009 will be recalculated using the most recently verified data from the GHGRP. Changes in these data result in changes to the back-casted emissions. The impact of the revisions to the GHGRP Subpart HH annual greenhouse gas reports resubmitted for 2017 to 2021 slightly decreased total Subpart HH reported net emissions, which decreased net MSW emissions by an average of 0.5 percent. A change in net Subpart HH reported emissions results in the same percentage change in the *Inventory* emissions for that year.

Slight revisions were also made to the food and beverage sector production data for nearly every year of the time series. The production data increased by 1 to 2 MMT per year between 1990 to 2017 and decreased by a few MMT per year between 2019 to 2021. These revisions decreased net emissions from industrial waste landfills by less than 0.1 percent between 1990 to 2010. Emissions increased slightly between 2011 to 2017 (ranging from 0.3 percent in 2011 to a high of 1.3 percent in 2017). The revisions to the production data also slightly increased emissions by an average of 0.6 percent between 2018 to 2021.

The combined changes to the MSW and industrial waste landfills activity data resulted in annual increases ranging from 0.005 percent to 0.01 percent to net emissions between 2005 to 2010. A slight decrease in net emissions is observed between 2011 to 2016 (-0.04 percent to -0.2 percent), and an increase, averaging 0.36 percent of emissions, is observed between 2017 to 2021. A 0.6 percent increase is observed for 2020, and a 0.5 percent increase is observed for 2021. Between 2005 to 2020, on average, the impact or change was very small (less than 0.1 percent).

Planned Improvements

EPA received recommendations from industry stakeholders regarding the DOC values and decay rates (k values) required to be used in the GHGRP calculations. Stakeholders have suggested that newer, more up-to-date default values considering recent trends in the composition of waste disposed in MSW landfills for both k and DOC in the GHGRP should be developed and reflected in the 2005 and later years of the *Inventory*. In response, EPA developed a multivariate analysis using publicly available Subpart HH GHGRP data, solving for optimized DOC and k values across the more than 1,100 landfills reporting to the program. The results of this analysis could help inform a current GHGRP rulemaking (87 FR 36920) where changes could be made to the default DOC and k values contained within Subpart HH, which could then be carried over to the *Inventory* emissions estimates for MSW landfills upon promulgation of any revisions to 40 CFR Part 98. This potential improvement may be long-term.

With respect to the scale-up factor, EPA received comments on revisions made to the scale-up for the 1990 to 2020 *Inventory* from a total waste-in-place approach to a time-based threshold of 50 years. Commenters noted that this time-based threshold approach does not adjust for the non-linearity of methane production of landfill gas. In response, EPA will further investigate how best to account for emissions from MSW landfills that do not report to the GHGRP, including using the FOD model for these landfills based on estimated annual waste disposed for this subset of landfills between 2005 to 2022, reverting to the total waste-in-place approach, or modifying the time-based threshold approach. Any methodological revisions to accounting for emissions from this subset of landfills will be made in the next (1990 to 2023) *Inventory*.

Relatedly, EPA will periodically assess the impact to the waste-in-place and emissions data from GHGRP facilities that have resubmitted annual reports during any reporting years, are new reporting facilities, and from facilities that have stopped reporting to the GHGRP to ensure national estimates are as complete as possible. Facilities may stop reporting to the GHGRP when they meet the "off-ramp" provisions (reported less than 15,000 metric tons of CO_2 equivalent emissions for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent emissions for 5 consecutive years). If warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the *Inventory*. EPA considered public comments received on the 1990 through 2019 *Inventory*

specific to using a time-based threshold to calculate the scale-up factor instead of a total waste-in-place approach. The rationale supporting the comments was that older, closed landfills with large quantities of waste-in-place are driving up the scale-up factor but have little impact on total methane generation. EPA assessed two time-based scenarios for developing the scale-up factor – one scenario looking at the past 30 years of waste disposed, and the second looking at the past 50 years of waste disposed. The 50-year time-based threshold was applied and resulted in the 11 percent scale-up factor used between 2017 and 2022.

EPA is planning to account for unmanaged landfills in Puerto Rico and other U.S. Territories to the landfill emissions estimates. Data limitations for historical waste received at these sites make this challenging. Presently, emissions from managed sites in Puerto Rico and Guam are accounted for in 2005 to present as part of the GHGRP Subpart HH dataset.

Box 7-4: Overview of U.S. Solid Waste Management Trends

As shown in Figure 7-4 and Figure 7-5 landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have previously been disposed in a landfill.

Figure 7-4: Management of Municipal Solid Waste in the United States, 2018

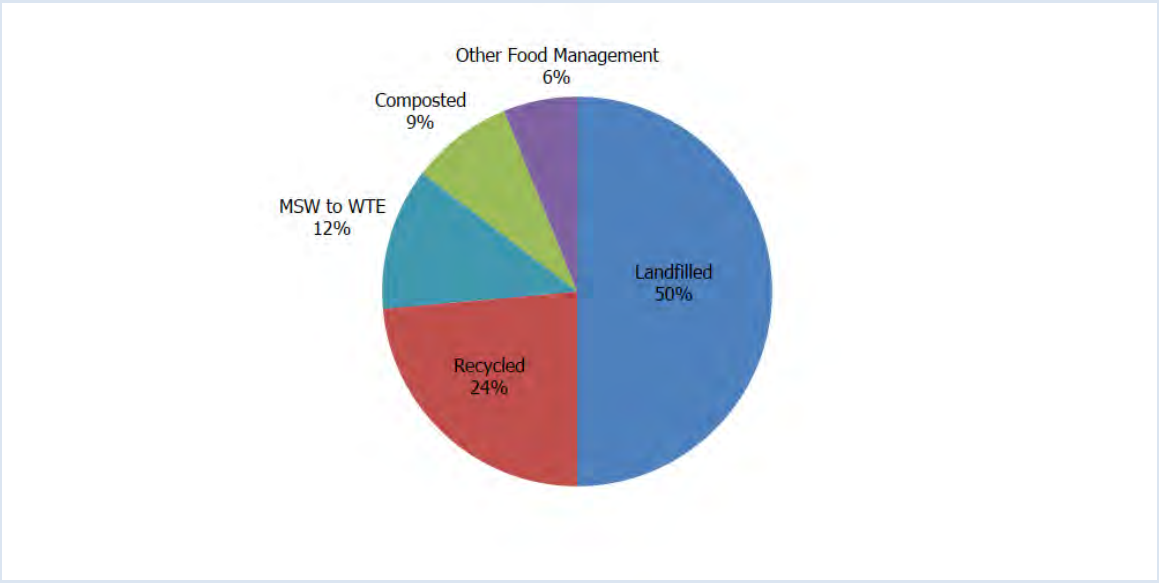

Note: 2018 is the latest year of available data. Data taken from Table 35 of EPA (2020a). MSW to WTE is combustion with energy recovery (WTE = waste-to-energy).
Source: EPA (2020b)

Figure 7-5: MSW Management Trends from 1990 to 2018

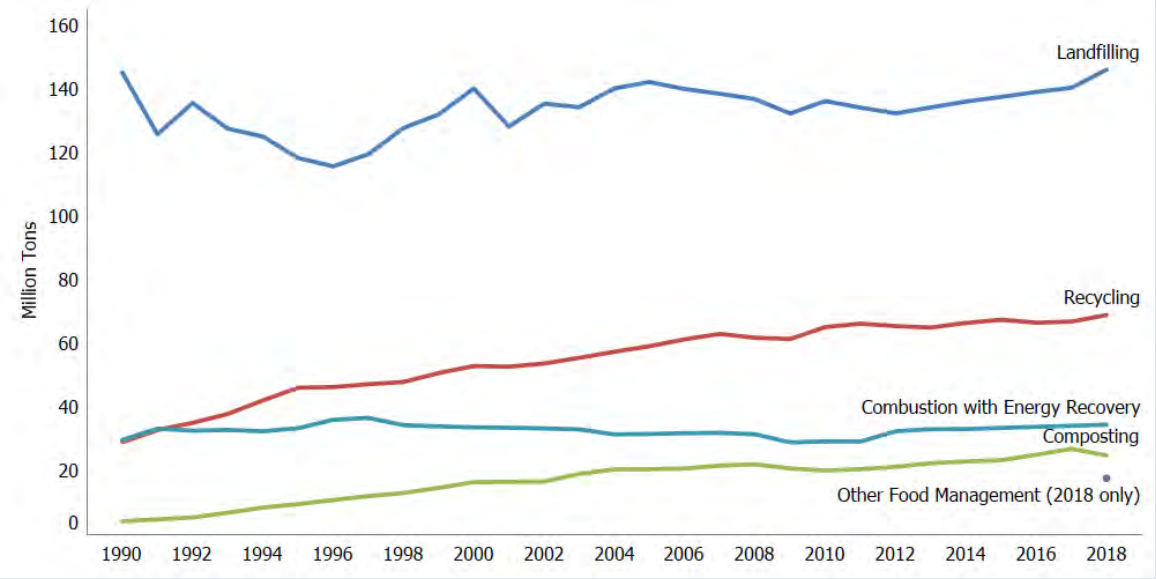

Note: 2018 is the latest year of available data. Only one year of data (2018) is available for the "Other Food Management" category.

Source: EPA (2020b). The EPA Advancing Sustainable Materials Management reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA 2020b for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request but are no longer on the EPA's Advancing Sustainable Materials Management web site.[3]

Table 7-6 presents the national-level material composition of waste disposed across typical MSW landfills in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6.

Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH_4 as they break down in a modern MSW landfill), is important for estimating greenhouse gas emissions. Increased diversion of degradable materials so that they are not disposed of in landfills reduces the CH_4 generation potential and CH_4 emissions from landfills. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste diversion through recycling and composting (see Table 7-6 and Figure 7-6). As shown in Figure 7-6, the diversion of food scraps has been consistently low since 1990 because most cities and counties do not practice curbside collection of these materials, although the quantity has been slowly increasing in recent years. Neither Table 7-6 nor Figure 7-6 reflect the frequency of backyard composting of yard trimmings and food waste because this information is largely not collected nationwide and is hard to estimate.

Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2018 (Percent)

Waste Type	1990	2005	2015	2016	2017	2018
Paper and Paperboard	30.0%	24.7%	13.3%	12.7%	13.1%	11.8%
Glass	6.0%	5.8%	5.0%	4.9%	4.9%	5.2%
Metals	7.2%	7.9%	9.5%	9.8%	9.9%	9.5%
Plastics	9.5%	16.4%	18.9%	18.9%	19.2%	18.5%
Rubber and Leather	3.2%	2.9%	3.3%	3.4%	3.5%	3.4%

Textiles	2.9%	5.3%	7.7%	8.0%	8.0%	7.7%
Wood	6.9%	7.5%	8.0%	8.8%	8.7%	8.3%
Other	1.4%	1.8%	2.2%	2.2%	2.2%	2.0%
Food Scraps	13.6%	18.5%	22.0%	22.1%	22.0%	24.1%
Yard Trimmings	17.6%	7.0%	7.8%	6.9%	6.2%	7.2%
Miscellaneous Inorganic Wastes	1.7%	2.2%	2.3%	2.3%	2.3%	2.3%

Source: EPA (2020b)

Figure 7-6: Percent of Degradable Materials Diverted from Landfills from 1990 to 2018 (Percent)

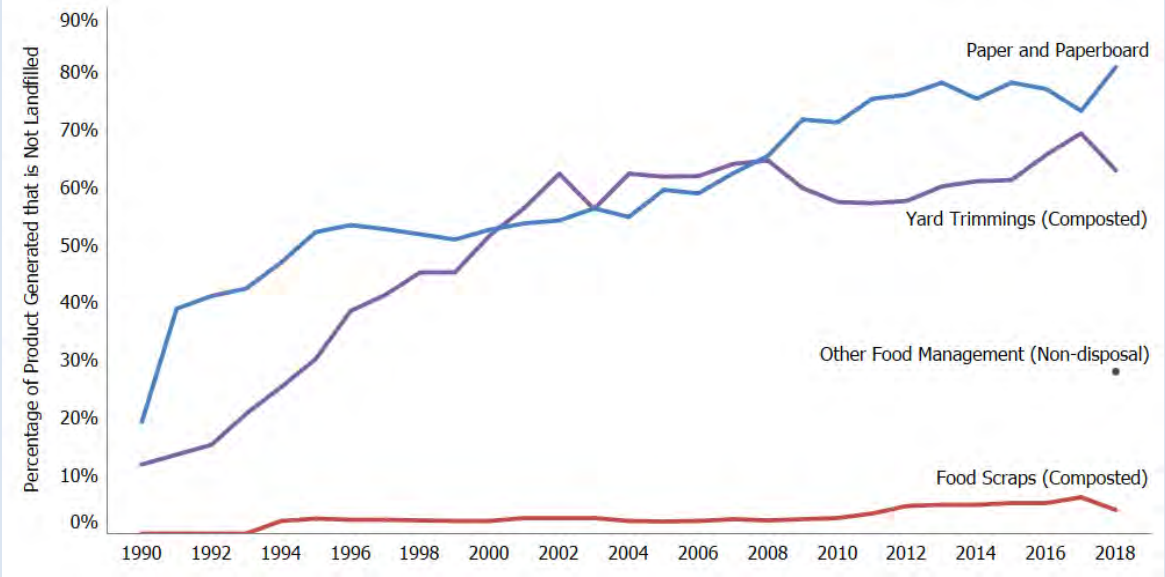

Note: The data shown in this chart are for recycling of paper and paperboard, composting of food scraps and yard trimmings, and alternative management pathways for the Other Food Management (non-disposal) category. The Other Food Management (non-disposal) category is a new addition and only one year of data are available for 2018 (28 percent of the food waste generated was beneficially reused or managed using a method that was not landfilling, recycling, or composting). The Other Food Management pathways include animal feed, bio-based materials/biochemical processing, co-digestion/anaerobic digestion, donation, land application, and sewer/wastewater treatment.

Source: EPA (2020b). The EPA Advancing Sustainable Materials reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA (2020b) for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request, but are not longer on the EPA's Advancing Sustainable Materials Management website.[4]

[3] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

[4] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

7.2 Wastewater Treatment and Discharge (CRT Source Category 5D)

Wastewater treatment and discharge processes are sources of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, nutrients, pathogenic organisms, and chemical contaminants.[5] Treatment of domestic wastewater may either occur on site, most commonly through septic systems, or off site at centralized treatment systems, most commonly at publicly owned treatment works (POTWs). In the United States, approximately 16 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2021a). Treatment of industrial wastewater may occur at the industrial plant using package or specially designed treatment plants or be collected and transferred off site for co-treatment with domestic wastewater in centralized treatment systems.

Centralized Treatment. Centralized wastewater treatment systems use sewer systems to collect and transport wastewater to the treatment plant. Sewer collection systems provide an environment conducive to the formation of CH_4, which can be substantial depending on the configuration and operation of the collection system (Guisasola et al. 2008). Recent research has shown that at least a portion of CH_4 formed within the collection system enters the centralized system where it contributes to CH_4 emissions from the treatment system (Foley et al. 2015).

The treatment plant may include a variety of processes, ranging from physical separation of material that readily settles out (typically referred to as primary treatment), to treatment operations that use biological processes to convert and remove contaminants (typically referred to as secondary treatment), to advanced treatment for removal of targeted pollutants, such as nutrients (typically referred to as tertiary treatment). Not all wastewater treatment plants conduct primary treatment prior to secondary treatment, and not all plants conduct advanced or tertiary treatment (EPA 2010).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. The resulting biomass (sludge) is removed from the wastewater (effluent) prior to discharge to the receiving stream and may be further biodegraded under aerobic or anaerobic conditions, such as anaerobic sludge digestion. Sludge can be produced from both primary and secondary treatment operations. Some wastewater may also be treated using constructed (or semi-natural) wetland systems, though this is much less common in the United States and represents a relatively small portion of wastewater treated centrally (<0.1 percent) (ERG 2016). Constructed wetlands are a coupled anaerobic-aerobic system and may be used as the primary method of wastewater treatment, or are more commonly used as a final treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants (IPCC 2014). Constructed wetlands do not produce secondary sludge (sewage sludge). Emissions from flooded lands or constructed waterbodies (not used for wastewater treatment) and lands converted to flooded lands (not used for wastewater treatment) are estimated and reported in Chapter 6, under Sections 6.8 Wetlands Remaining Wetlands and 6.9 Lands Converted to Wetlands.

The generation of N_2O may also result from the treatment of wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, proteins, and ammonia in wastewater. Ammonia N is converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic/anaerobic conditions, whereby anaerobic or facultative organisms reduce oxidized forms of nitrogen (e.g.,

[5] Throughout the *Inventory*, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

nitrite, nitrate) in the absence of free oxygen to produce nitrogen gas (N_2). Nitrous oxide is generated as a by-product of nitrification, or as an intermediate product of denitrification. No matter where N_2O is formed it is typically stripped (i.e., transferred from the liquid stream to the air and ultimately emitted to the atmosphere) in aerated parts of the treatment process. Stripping also occurs in non-aerated zones at rates lower than in aerated zones.

On-site Treatment. The vast majority of on-site systems in the United States are septic systems composed of a septic tank, generally buried in the ground, and a soil dispersion system. Solids and dense materials contained in the incoming wastewater (influent) settle in the septic tank as sludge. Floatable material (scum) is also retained in the tank. The sludge that settles on the bottom of the tank undergoes anaerobic digestion. Partially treated water is discharged in the soil dispersal system. The solid fraction accumulates and remains in the tank for several years, during which time it degrades anaerobically. The gas produced from anaerobic sludge digestion (mainly CH_4 and biogenic CO_2) rises to the liquid surface and is typically released through vents. The gas produced in the effluent dispersal system (mainly N_2O and biogenic CO_2) is released through the soil.

Discharge. Dissolved CH_4 and N_2O that is present in wastewater discharges to aquatic environments has the potential to be released into the atmosphere (Short et al. 2014; Short et al. 2017). In addition, the presence of organic matter or nitrogen in wastewater discharges is generally expected to increase CH_4 and N_2O emissions from these aquatic environments. Where organic matter is released to slow-moving aquatic systems, such as lakes, estuaries, and reservoirs, CH_4 emissions are expected to be higher. Similarly, in the case of discharge to nutrient-impacted or hypoxic waters, N_2O emissions can be significantly higher.

In summary, the principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20°C, or BOD_5. Throughout the rest of this chapter, the term "BOD" refers to BOD_5. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production, since CH_4 is produced only in anaerobic conditions. Where present, biogas recovery and flaring operations reduce the amount of CH_4 generated that is actually emitted. Per IPCC guidelines (IPCC 2019), emissions from anaerobic sludge digestion, including biogas recovery and flaring operations, where the digester's primary use is for treatment of wastewater treatment solids, are estimated and reported under wastewater treatment. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential. The methods and underlying data sources to estimate emissions from are described in further detail in the "Methodology and Time Series Consistency" section below for treatment of domestic and industrial wastewater.

Overall, treatment of wastewater emitted 42.7 MMT CO_2 Eq. in 2022. Total methane (CH_4) emissions from wastewater treatment and discharge were estimated to be 20.8 MMT CO_2 Eq. (743 kt CH_4). Methane (CH_4) emissions from domestic wastewater treatment and discharge were estimated to be 11.6 MMT CO_2 Eq. (413 kt CH_4) and 2.0 MMT CO_2 Eq. (72 kt CH_4), respectively, totaling 13.6 MMT CO_2 Eq. (485 kt CH_4) in 2022. Emissions remained fairly steady from 1990 through 2002 but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, generally including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004; U.S. Census Bureau 2021a). In 2022, CH_4 emissions from industrial wastewater treatment and discharge were estimated to be 6.7 MMT CO_2 Eq. (239 kt CH_4) and 0.5 MMT CO_2 Eq. (19 kt CH_4), respectively, totaling 7.2 MMT CO_2 Eq. (258 kt CH_4). Industrial emissions from wastewater treatment have generally increased across the time series through 1999 and then fluctuated up and correspond with production changes from the pulp and paper manufacturing, meat and poultry processing, fruit

and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries. Industrial wastewater emissions have generally seen an uptick since 2016. Table 7-7 and Table 7-8 provide CH_4 emission estimates from domestic and industrial wastewater treatment.

Nitrous oxide (N_2O) emissions from wastewater treatment and discharge in 2022 totaled 21.9 MMT CO_2 Eq. (83 kt N_2O). In 2022, domestic treatment and discharge were estimated to be 17.0 MMT CO_2 Eq. (64 kt N_2O) and 4.4 MMT CO_2 Eq. (16 kt N_2O), respectively, totaling 21.4 MMT CO_2 Eq. (81 kt N_2O). Domestic emission sources have gradually increased across the time series because of an increasing U.S. population and protein consumption. In 2022, N_2O emissions from industrial wastewater treatment and discharge were estimated to be 0.4 MMT CO_2 Eq. (1.5 kt N_2O) and 0.1 MMT CO_2 Eq. (0.3 kt N_2O), respectively, totaling 0.5 MMT CO_2 Eq. (1.8 kt N_2O). Industrial emission sources have gradually increased across the time series with production changes associated with the treatment of wastewater namely from meat and poultry processing and petroleum refining, but also with contributions from pulp and paper manufacturing and brewery industries. Table 7-7 and Table 7-8 provide N_2O emission estimates from domestic wastewater treatment.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	**22.7**	**22.7**	**21.4**	**21.1**	**21.0**	**20.7**	**20.8**
Domestic Treatment	15.1	14.6	12.3	11.9	11.7	11.4	11.6
Domestic Effluent	1.4	1.4	2.0	2.0	2.1	2.1	2.0
Industrial Treatment[a]	5.5	6.1	6.5	6.6	6.6	6.7	6.7
Industrial Effluent[a]	0.7	0.6	0.6	0.5	0.5	0.5	0.5
N_2O	**14.8**	**18.1**	**21.2**	**21.6**	**22.3**	**22.1**	**21.9**
Domestic Treatment	10.5	13.7	16.2	16.6	17.2	17.1	17.0
Domestic Effluent	3.9	3.9	4.5	4.5	4.6	4.5	4.4
Industrial Treatment[b]	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Industrial Effluent[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**37.5**	**40.7**	**42.5**	**42.7**	**43.2**	**42.7**	**42.7**

[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.
[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.
Note: Totals may not sum due to independent rounding.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	**811**	**809**	**763**	**755**	**748**	**738**	**743**
Domestic Treatment	539	521	438	426	419	407	413
Domestic Effluent	49	49	73	73	74	74	72
Industrial Treatment[a]	196	216	232	236	236	238	239
Industrial Effluent[a]	27	22	20	19	19	19	19
N_2O	**56**	**68**	**80**	**81**	**84**	**83**	**83**
Domestic Treatment	40	52	61	63	65	65	64
Domestic Effluent	15	15	17	17	17	17	16
Industrial Treatment[b]	1	1	2	2	1	1	1
Industrial Effluent[b]	+	+	+	+	+	+	+

[+] Does not exceed 0.5 kt.
[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.
[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.
Note: Totals by gas may not sum due to independent rounding

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2019) form the basis of the CH_4 and N_2O emission estimates for both domestic and industrial wastewater treatment and discharge.[6] Domestic wastewater treatment follows the IPCC Tier 2 methodology for key pathways, while domestic wastewater discharge follows IPCC Tier 2 discharge methodology and emission factors in accordance with IPCC methodological decision trees based on available data for treatment and discharge. Default factors from IPCC (2019) or IPCC (2006) are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor, though IPCC default factors are often based in part on data from or representative of U.S. wastewater treatment systems. Industrial wastewater treatment follows IPCC Tier 1 and wastewater treatment discharge follows Tier 1 or Tier 2 methodologies, again in accordance with methodological decision trees and available data, depending on the industry. EPA will continue to implement the Tier 2 discharge methodology for more industries as data are investigated and time and resource constraints allow (see the Planned Improvements section below). Similar to domestic wastewater, IPCC default factors are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. In the following cases, the source used to capture activity data changed over the time series. EPA transitioned to these newer data sources to continue estimating emissions in a way that ensured both accuracy and continuity. For example:

- Starch-based ethanol production data: the source used for 1990 to 2017 production was no longer available after 2017. A new, publicly available source was identified and is used for production in 2015-2022. However, this source does not have sufficient data for the earlier timeseries. EPA confirmed with experts familiar with the sources that combining these two sources to populate the time series was accurate (ERG 2019; Lewis 2019) and does not present any significant discontinuities in the time series.
- Brewery production data: the source used for production changed in 2007 to publish craft brewery production broken out by size but does not include data prior to 2007. Therefore, rather than estimating total production data prior to 2007 with this source, another data source was used to ensure accuracy of production data through the time series (ERG 2018b).

Refer to the Recalculations Discussion section below for details on updates implemented to improve accuracy, consistency and/or completeness of the time series.

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems. Within these centralized systems, CH_4 emissions can arise from aerobic systems that liberate dissolved CH_4 that formed within the collection system or that are designed to have periods of anaerobic activity (e.g., constructed wetlands and facultative lagoons), anaerobic systems (anaerobic lagoons and anaerobic reactors), and from anaerobic sludge digesters when the captured biogas is not completely combusted. Emissions will also result from the discharge of treated effluent from centralized wastewater plants to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries). The systems with emissions estimates are:

[6] IPCC (2019) updates, supplements, and elaborates the *2006 IPCC Guidelines* where gaps or out-of-date science have been identified. EPA used these methodologies to improve completeness and include sources of greenhouse gas emissions that have not been estimated prior to the 1990 to 2019 *Inventory*, such as N_2O emissions from industrial wastewater treatment, and to improve emission estimates for other sources, such as emissions from wastewater discharge and centralized wastewater treatment.

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C);
- Anaerobic sludge digesters (D); and
- Centralized wastewater treatment effluent (E).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic CH_4 emissions are estimated as follows:

Equation 7-4: Total Domestic CH_4 Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic } CH_4 \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D + E$$

Table 7-9 presents domestic wastewater CH_4 emissions for both septic and centralized systems, including anaerobic sludge digesters and emissions from centralized wastewater treatment effluent, in 2022.

Table 7-9: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2022, kt, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (kt)	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems (A)	215	6.0	44.4%
Centrally-Treated Aerobic Systems (B)	77	2.2	15.9%
Centrally-Treated Anaerobic Systems (C)	113	3.2	23.2%
Anaerobic Sludge Digesters (D)	8	0.2	1.7%
Centrally-Treated Wastewater Effluent (E)	72	2.0	14.9%
Total	**485**	**13.6**	**100%**

Notes: Totals may not sum due to independent rounding.

Emissions from Septic Systems:

Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 16 percent in 2022; U.S. Census Bureau 2021a) and an emission factor and then converting the result to kt/year. The method was selected in accordance with IPCC methodological decision trees in based on available data for septic systems.

U.S. population data were taken from historic U.S. Census Bureau national population totals data and include the populations of the United States and Puerto Rico (U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau 2022 and 2023; Instituto de Estadísticas de Puerto Rico 2021). Population data for American Samoa, Guam, Northern Mariana Islands, and the U.S. Virgin Islands were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2023). Table 7-10 presents the total U.S. population for 1990 through 2022. The fraction of the U.S. population using septic systems or centralized treatment systems is based on data from the *American Housing Surveys* (U.S. Census Bureau 2021a).

Methane emissions for septic systems are estimated as follows:

Equation 7-5: CH_4 Emissions from Septic Systems

$$Emissions\ from\ Septic\ Systems\ (\mathrm{U.S.\ Specific}) = \mathrm{A}$$
$$= \mathrm{US}_{POP} \times (\mathrm{T}_{SEPTIC}) \times (\mathrm{EF}_{SEPTIC}) \times 1/10^9 \times 365.25$$

Table 7-10: Variables and Data Sources for CH_4 Emissions from Septic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
EF_{SEPTIC}	Methane emission factor – septic systems (10.7)	g CH_4/capita/day	1990-2022: Leverenz et al. (2010)
$1/10^9$	Conversion factor	g to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of activity data varies over the *Inventory* time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Methane emissions from POTWs depend on the total organics in wastewater. Table 7-12 presents the total organically degradable material in wastewater, or TOW, for 1990 through 2022. The TOW was determined using BOD generation rates per capita weighted average both with and without kitchen scraps as well as an estimated percent of housing units that utilize kitchen garbage disposals. Households with garbage disposals (with kitchen scraps or ground up food scraps) typically have wastewater with higher BOD than households without garbage disposals due to increased organic matter contributions (ERG 2018a). The equations are as follows:

Equation 7-6: Total Wastewater BOD5 Produced per Capita (U.S.-Specific [ERG 2018a])

$$\mathrm{BOD}_{\mathrm{gen\ rate}}\ (\mathrm{kg/capita/day}) = \mathrm{BOD}_{\mathrm{without\ scraps}} \times (1 - \%\mathrm{kitchen\ disposal}) + \mathrm{BOD}_{\mathrm{with\ scraps}} \times (\%\mathrm{kitchen\ disposal})$$

Equation 7-7: Total Organically Degradable Material in Domestic Wastewater (IPCC 2019 [Eq. 6.3])

$$\text{TOW}\left(\frac{\text{Gg BOD}}{\text{year}}\right) = \text{US}_{POP} \times \text{BOD}_{gen\ rate} \times 365.25 \times \frac{1}{10^6}$$

Table 7-11: Variables and Data Sources for Organics in Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
$BOD_{gen\ rate}$	Total wastewater BOD produced per capita	kg/capita/day	1990-2022: Calculated
$BOD_{without\ scrap}$	Wastewater BOD produced per capita without kitchen scraps[a]	kg/capita/day	1990-2003: Metcalf & Eddy (2003) 2004-2013: Linear interpolation 2014-2022: Metcalf & Eddy (2014)
$BOD_{with\ scraps}$	Wastewater BOD produced per capita with kitchen scraps[a]	kg/capita/day	
% kitchen disposal	Percent of housing units with kitchen disposal[a]	%	1990-2013: U.S. Census Bureau (2013) 2014-2022: Forecasted from the rest of the time series
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2022: Calculated, ERG (2018a)
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
365.25	Conversion factor	Days in a year	Standard conversion
$1/10^6$	Conversion factor	kg to Gg	Standard conversion

[a] Value of activity data varies over the *Inventory* time series.

Table 7-12: U.S. Population (Millions) and Domestic Wastewater TOW (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Population	253	300	330	332	335	336	337
TOW	8,131	9,624	9,958	10,019	10,132	10,163	10,216

Sources: U.S. Census Bureau (2002); U.S. Census Bureau (2011); U.S. Census Bureau (2021b and 2022); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2023); ERG (2018a).

Methane emissions from POTWs were estimated by multiplying the total organics in centrally treated wastewater (total BOD_5) produced per capita in the United States by the percent of wastewater treated centrally, or percent collected (about 84 percent in 2022), the correction factor for additional industrial BOD discharged to the sewer system, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands),

constructed wetlands only, and anaerobic systems, and the emission factor[7] for aerobic systems, constructed wetlands only, and anaerobic systems. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

In the United States, the removal of sludge[8] from wastewater reduces the biochemical oxygen demand of the wastewater that undergoes aerobic treatment. The amount of this reduction (S) is estimated using the default IPCC (2019) methodology and multiplying the amount of sludge removed from wastewater treatment in the United States by the default factors in IPCC (2019) to estimate the amount of BOD removed based on whether the treatment system has primary treatment with no anaerobic sludge digestion (assumed to be zero by expert judgment), primary treatment with anaerobic sludge digestion, or secondary treatment without primary treatment. The organic component removed from anaerobic wastewater treatment and the amount of CH_4 recovered or flared from both aerobic and anaerobic wastewater treatment were set equal to the IPCC default of zero.

The methodological equations for CH_4 emissions from aerobic and anaerobic systems are:

Equation 7-8: Total Domestic CH_4 Emissions from Centrally Treated Aerobic Systems

$$Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (other\ than\ Constructed\ Wetlands)(B1) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ Only)(B2) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ used\ as\ Tertiary\ Treatment)(B3) = B$$

where,

Equation 7-9: Total Organics in Centralized Wastewater Treatment [IPCC 2019 (Eq. 6.3A)]

$$TOW_{CENTRALIZED}\left(\frac{\text{Gg BOD}}{\text{year}}\right) = \text{TOW} \times \text{T}_{\text{CENTRALIZED}} \times \text{I}_{\text{COLLECTED}}$$

Table 7-13: Variables and Data Sources for Organics in Centralized Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
Centrally Treated Organics (Gg BOD/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/capita/year	1990-2022: Calculated, ERG (2018a)
$T_{CENTRALIZED}$	Percent collected[a]	%	1990-2019: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2020-2022: Forecasted from the rest of the time series
$I_{COLLECTED}$	Correction factor for additional industrial BOD discharged (1.25)	No units	1990-2022: IPCC (2019) Eq. 6.3a

[7] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of domestic wastewater (B_0, 0.6 kg CH_4/kg BOD) and the appropriate methane correction factors (MCF) for aerobic (0.03) and anaerobic (0.8) systems (IPCC 2019, Table 6.3) and constructed wetlands (0.4) (IPCC 2014, Table 6.4).

[8] Throughout this document, the term "sludge" refers to the solids separated during the treatment of municipal wastewater. The definition includes domestic septage. "Biosolids" refers to treated sewage sludge that meets the EPA pollutant and pathogen requirements for land application and surface disposal.

[a] Value of this activity data varies over the time series.

Equation 7-10: Organic Component Removed from Aerobic Wastewater Treatment (IPCC 2019 [Eq. 6.3B])

$$S_{aerobic}\left(\frac{Gg}{year}\right) = S_{mass} \times \left[\left(\%\ \text{aerobic}\frac{w}{primary} \times K_{rem,aer_{prim}}\right) + \left(\%\ \text{aerobic}\frac{w}{out}\text{primary} \times K_{rem,aer_{noprim}}\right) + \left(\%\text{aerobic} + \text{digestion} \times K_{rem,aer_{digest}}\right)\right] \times 1000$$

Equation 7-11: CH_4 Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.1])

$$B1(\text{kt } CH_4/\text{year}) = [(TOW_{CENTRALIZED}) \times (\%\ \text{aerobic}_{OTCW}) - S_{aerobic}] \times EF_{aerobic} - R_{aerobic}$$

Table 7-14: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt CH_4/year)			
$S_{aerobic}$	Organic component removed from aerobic wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
S_{mass}	Raw sludge removed from wastewater treatment as dry mass[a]	Tg dry weight/year	1988: EPA (1993c); EPA (1999) 1990-1995: Calculated based on sewage sludge production change per year EPA (1993c); EPA (1999); Beecher et al. (2007) 1996: EPA (1999) 2004: Beecher et al. (2007) Data for intervening years obtained by linear interpolation 2005-2017: Interpolated 2018: NEBRA (2022), as described in ERG (2023) 2019-2022: Forecasted from the rest of the time series. Methodology for estimating sludge generated from the U.S. territories provided in ERG (2023).
% $aerobic_{OTCW}$	Percent of flow to aerobic systems, other than wetlands[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
% aerobic w/primary	Percent of aerobic systems with primary treatment and no anaerobic sludge digestion (0)	%	
% aerobic w/out primary	Percent of aerobic systems without primary treatment[a]	%	
%aerobic+digestion	Percent of aerobic systems with primary and anaerobic sludge digestion[a]	%	
K_{rem,aer_prim}	Sludge removal factor for aerobic treatment plants with primary treatment (mixed primary and secondary sludge, untreated or treated aerobically) (0.8)	kg BOD/kg sludge	1990-2022: IPCC (2019) Table 6.6a
K_{rem,aer_noprim}	Sludge removal factor for aerobic wastewater treatment plants without separate primary treatment (1.16)	kg BOD/kg sludge	

Variable	Variable Description	Units	Inventory Years: Source of Value
K_{rem,aer_digest}	Sludge removal factor for aerobic treatment plants with primary treatment and anaerobic sludge digestion (mixed primary and secondary sludge, treated anaerobically) (1)	kg BOD/kg sludge	
$EF_{aerobic}$	Emission factor – aerobic systems (0.018)	kg CH_4/kg BOD	1990-2022: IPCC (2019) Table 6.3
$R_{aerobic}$	Amount CH_4 recovered or flared from aerobic wastewater treatment (0)	kg CH_4/year	1990-2022: IPCC (2019) Eq. 6.1
1000	Conversion factor	metric tons to kilograms	Standard conversion

[a] Value of this activity data varies over the time series.

Constructed wetlands provide aerobic treatment but also exhibit partially anaerobic conditions; however, they are referred to in this chapter as aerobic systems. Constructed wetlands may be used as the sole treatment unit at a centralized wastewater treatment plant or may serve as tertiary treatment after simple settling and biological treatment. Emissions from all constructed wetland systems were included in the estimates of emissions from centralized wastewater treatment plant processes and effluent from these plants. Methane emissions equations from constructed wetlands used as sole treatment were previously described. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

For constructed wetlands, an IPCC default emission factor for surface flow wetlands was used. This is the most conservative factor for constructed wetlands and was recommended by IPCC (2014) when the type of constructed wetland is not known. A median BOD_5 concentration of 9.1 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. This median value is based on plants generally utilizing simple settling and biological treatment (EPA 2013). Constructed wetlands do not have secondary sludge removal.

Equation 7-12: CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) [IPCC 2014 (Eq. 6.1)]

$$\text{B2}\left(\frac{\text{kt CH}_4}{\text{year}}\right) = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\ \text{aerobic}_{\text{CW}})] \times (EF_{\text{CW}})$$

Equation 7-13: CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S. Specific)

$$\text{B3}\left(\frac{\text{kt CH}_4}{\text{year}}\right) = \left[\left(\text{POTW}_{\text{flow}_{\text{CW}}}\right) \times \left(\text{BOD}_{\text{CW,INF}}\right) \times 3.785 \times (\text{EF}_{\text{CW}})\right] \times \frac{1}{10^6} \times 365.25$$

Table 7-15: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs.[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012)

Variable	Variable Description	Units	Inventory Years: Source of Value
			Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2022: IPCC (2014)
Emissions from Constructed Wetlands used as Tertiary Treatment (kt CH_4/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
$BOD_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (9.1)	mg/L	1990-2022: EPA (2013)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2022: IPCC (2014)
$1/10^6$	Conversion factor	kg to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the time series.

Data sources and methodologies for centrally treated anaerobic systems are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-14: CH_4 Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 (Eq. 6.1])

$$C\left(\frac{\text{kt CH}_4}{\text{year}}\right) = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\ \text{anaerobic}) - S_{\text{anaerobic}}] \times EF_{\text{anaerobic}} - R_{\text{anaerobic}}$$

Table 7-16: Variables and Data Sources for CH_4 Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$S_{anaerobic}$	Organic component removed from anaerobic wastewater treatment (0)	Gg/year	1990-2022: IPCC (2019) Table 6.3
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0.48)	kg CH_4/kg BOD	

Variable	Variable Description	Units	Inventory Years: Source of Value
$R_{anaerobic}$	Amount CH_4 recovered or flared from anaerobic wastewater treatment (0)	kg CH_4/year	

[a] Value of this activity data varies over the time series.

Emissions from Anaerobic Sludge Digesters:

Total CH_4 emissions from anaerobic sludge digesters were estimated by multiplying the wastewater influent flow to POTWs with anaerobic sludge digesters, the cubic feet of digester gas generated per person per day divided by the flow to POTWs, the fraction of CH_4 in biogas, the density of CH_4, one minus the destruction efficiency from burning the biogas in an energy/thermal device and then converting the results to kt/year.

Equation 7-15: CH_4 Emissions from Anaerobic Sludge Digesters (U.S. Specific)

$$\mathrm{D}\left(\frac{\mathrm{kt\ CH_4}}{\mathrm{year}}\right) = \left[\left(\mathrm{POTW_{flow_{AD}}}\right) \times \frac{\mathrm{biogas\ gen}}{100}\right] \times\ 0.0283\ \times\ \left(\mathrm{FRAC_{CH_4}}\right) \times\ 365.25\ \times\ (662) \times\ (1 - \mathrm{DE}) \times \frac{1}{10^9}$$

Table 7-17: Variables and Data Sources for Emissions from Anaerobic Sludge Digesters

Variable	Variable Description	Units	Inventory years: Source of Value
Emissions from Anaerobic Sludge Digesters (kt CH_4/year)			
POTW_flow_AD	POTW Flow to Facilities with Anaerobic Sludge Digesters[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, and 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
biogas gen	Gas Generation Rate (1.0)	ft^3/capita/day	1990-2022: Metcalf & Eddy (2014)
100	Per Capita POTW Flow (100)	gal/capita/day	1990-2022: Ten-State Standards (2004)
0.0283	Conversion factor	ft^3 to m^3	Standard Conversion
$FRAC_{CH_4}$	Proportion of Methane in Biogas (0.65)	No units	1990-2022: Metcalf & Eddy (2014)
365.25	Conversion factor	Days in a year	Standard conversion
662	Density of Methane (662)	g CH_4/m^3 CH_4	1990-2022: EPA (1993a)
DE	Destruction Efficiency (99% converted to fraction)	No units	1990-2022: EPA (1998); CAR (2011); Sullivan (2007); Sullivan (2010); and UNFCCC (2012)
$1/10^9$	Conversion factor	g to kt	Standard conversion

[a] Value of this activity data varies over the time series.

Emissions from Discharge of Centralized Treatment Effluent:

Methane emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge. The BOD in treated effluent was determined by multiplying the total organics in centrally treated wastewater by the percent of wastewater treated in primary, secondary, and tertiary treatment, and the fraction of organics remaining after primary treatment (one minus the fraction of organics removed from primary treatment, secondary treatment, and tertiary treatment).

Equation 7-16: CH_4 Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$\mathrm{E}\left(\frac{\mathrm{kt\ CH_4}}{\mathrm{year}}\right) = \left(\mathrm{TOW_{RLE}} \times \mathrm{EF_{RLE}}\right) + \left(\mathrm{TOW_{Other}} \times \mathrm{EF_{Other}}\right)$$

where,

Equation 7-17: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.3D])

$$\mathrm{TOW_{EFFtreat,CENTRALIZED}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{primary} \times \left(1 - \mathrm{TOW_{rem,PRIMARY}}\right)\right] + \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{secondary} \times \left(1 - \mathrm{TOW_{rem,SECONDARY}}\right)\right] + \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{tertiary} \times \left(1 - \mathrm{TOW_{rem,TERTIARY}}\right)\right]$$

Equation 7-18: Total Organics in Effluent Discharged to Reservoirs, Lakes, or Estuaries (U.S.-Specific)

$$\mathrm{TOW_{RLE}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \mathrm{TOW_{EFFtreat,CENTRALIZED}} \times \mathrm{Percent_{RLE}}$$

Equation 7-19: Total Organics in Effluent Discharged to Other Waterbodies (U.S.-Specific)

$$\mathrm{TOW_{Other}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \mathrm{TOW_{EFFtreat,CENTRALIZED}} \times \mathrm{Percent_{Other}}$$

Table 7-18: Variables and Data Sources for CH_4 Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$\mathrm{TOW_{EFFtreat,CENTRALIZED}}$	Total organics in centralized treatment effluent[a]	Gg BOD/year	1990-2022: Calculated
$\mathrm{TOW_{CENTRALIZED}}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% primary	Percent of primary domestic centralized treatment[a]	%	1990, 1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	
$\mathrm{TOW_{rem,PRIMARY}}$	Fraction of organics removed from primary domestic centralized treatment (0.4)	No units	1990-2022: IPCC (2019) Table 6.6B
$\mathrm{TOW_{rem,SECONDARY}}$	Fraction of organics removed from secondary domestic centralized treatment (0.85)	No units	
$\mathrm{TOW_{rem,TERTIARY}}$	Fraction of organics removed from tertiary domestic centralized treatment (0.90)	No units	
$\mathrm{TOW_{RLE}}$	Total organics in effluent discharged to reservoirs, lakes, and estuaries[a]	Gg BOD/year	1990-2022: Calculated

Variable	Variable Description	Units	Source of Value
TOW_{Other}	Total organics in effluent discharge to other waterbodies[a]	Gg BOD/year	
EF_{RLE}	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114)	kg CH_4/kg BOD	1990-2022: IPCC (2019) Table 6.8
EF_{Other}	Emission factor (discharge to other waterbodies) (0.021)	kg CH_4/kg BOD	
$Percent_{RLE}$	% discharged to reservoirs, lakes, and estuaries[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2022: Set equal to 2012
$Percent_{Other}$	% discharged to other waterbodies[a]	%	

[a] Value of this activity data varies over the time series.

Industrial Wastewater CH_4 Emission Estimates

Industrial wastewater CH_4 emissions originate from on-site treatment systems, typically comprised of biological treatment operations. The collection systems at an industrial plant are not as extensive as domestic wastewater sewer systems; therefore, it is not expected that dissolved CH_4 will form during collection. However, some treatment systems are designed to have anaerobic activity (e.g., anaerobic reactors or lagoons), or may periodically have anaerobic conditions form (facultative lagoons or large stabilization basins). Emissions will also result from discharge of treated effluent to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries).

Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the *Inventory*. The main criteria used to identify U.S. industries likely to generate CH_4 from wastewater treatment are whether an industry generates high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top six industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; petroleum refining; and breweries. Wastewater treatment and discharge emissions for these sectors for 2022 are displayed in Table 7-19 below. Further discussion of wastewater treatment for each industry is included below.

Table 7-19: Total Industrial Wastewater CH_4 Emissions by Sector (2022, MMT CO_2 Eq. and Percent)

Industry	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	5.7	79.0%
Pulp & Paper	0.8	11.6%
Fruit & Vegetables	0.2	3.3%
Ethanol Refineries	0.2	2.3%
Breweries	0.1	2.0%
Petroleum Refineries	0.1	1.7%
Total	**7.2**	**100%**

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

Equation 7-20 presents the general IPCC equation (Equation 6.4, IPCC 2019) to estimate CH_4 emissions from each type of treatment system used for each industrial category.

Equation 7-20: Total CH_4 Emissions from Industrial Wastewater

$$\mathrm{CH_4\ (industrial\ sector)} = [(\mathrm{TOW}_i - \mathrm{S}_i) \times \mathrm{EF} - \mathrm{R}_i]$$

where,

CH_4 (industrial sector)	=	Total CH_4 emissions from industrial sector wastewater treatment (kg/year)
I	=	Industrial sector
TOW_i	=	Total organics in wastewater for industrial sector *i* (kg COD/year)
S_i	=	Organic component removed from aerobic wastewater treatment for industrial sector *i* (kg COD/year)
EF	=	System-specific emission factor (kg CH_4/kg COD)
R_i	=	Methane recovered for industrial sector *i* (kg CH_4/year)

Equation 7-21 presents the general IPCC equation to estimate the total organics in wastewater (TOW) for each industrial category.

Equation 7-21: TOW in Industry Wastewater Treatment Systems

$$\mathrm{TOW}_i = \mathrm{P}_i \times \mathrm{W}_i \times \mathrm{COD}_i$$

where,

TOW_i	=	Total organically degradable material in wastewater for industry *i* (kg COD/yr)
i	=	Industrial sector
P_i	=	Total industrial product for industrial sector *i* (t/yr)
W_i	=	Wastewater outflow (m^3/t product)
COD_i	=	Chemical oxygen demand (industrial degradable organic component in wastewater) (kg COD/m^3)

The annual industry production is shown in Table 7-20, and the average wastewater outflow and the organics loading in the outflow is shown in Table 7-21.

For some industries, U.S.-specific data on organics loading is reported as BOD rather than COD. In those cases, an industry-specific COD:BOD ratio is used to convert the organics loading to COD.

The amount of organics treated in each type of wastewater treatment system was determined using the percent of wastewater in the industry that is treated on site and whether the treatment system is anaerobic, aerobic or partially anaerobic. Table 7-22 presents the industrial wastewater treatment activity data used in the calculations and described in detail in ERG (2008a), ERG (2013a), ERG (2013b), and ERG (2021a). For CH_4 emissions, wastewater treated in anaerobic lagoons or reactors was categorized as "anaerobic", wastewater treated in aerated stabilization basins or facultative lagoons were classified as "ASB" (meaning there may be pockets of anaerobic activity), and wastewater treated in aerobic systems such as activated sludge systems were classified as "aerobic/other."

The amount of organic component removed from aerobic wastewater treatment as a result of sludge removal ($S_{aerobic}$) was either estimated as an industry-specific percent removal, if available, or as an estimate of sludge produced by the treatment system and IPCC default factors for the amount of organic component removed (K_{rem}), using one of the following equations. Table 7-23 presents the sludge variables used for industries with aerobic wastewater treatment operations (i.e., pulp and paper, fruit/vegetable processing, and petroleum refining).

Equation 7-22: Organic Component Removed from Aerobic Wastewater Treatment – Pulp, Paper, and Paperboard

$$S_{pulp,asb} = TOW_{pulp} \times \%\ \text{removal w/primary}$$

where,

$S_{pulp,asb}$ = Organic component removed from pulp and paper wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
TOW_{pulp} = Total organically degradable material in pulp and paper wastewater (Gg COD/yr)
% removal w/primary = Percent reduction of organics in pulp and paper wastewater associated with sludge removal from primary treatment (%)

Equation 7-23: Organic Component Removed from Aerobic Treatment Plants

$$S_{aerobic} = S_{mass} \times K_{rem} \times 10^{-6}$$

where,

$S_{aerobic}$ = Organic component removed from fruit and vegetable or petroleum refining wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
S_{mass} = Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
K_{rem} = Sludge factor (kg BOD/kg sludge)
10^{-6} = Conversion factor, kilograms to Gigagrams

Equation 7-24: Raw Sludge Removed from Wastewater Treatment as Dry Mass

$$S_{mass} = (S_{prim} + S_{aer}) \times P \times W$$

where,

S_{mass} = Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
S_{prim} = Sludge production from primary sedimentation (kg sludge/m^3)
S_{aer} = Sludge production from secondary aerobic treatment (kg sludge/m^3)
P = Production (t/yr)
W = Wastewater outflow (m^3/t)

Default emission factors[9] from IPCC (2019) were used. Information on methane recovery operations varied by industry. See industry descriptions below.

[9] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of wastewater (B_0, 0.25 kg CH_4/kg COD) and the appropriate methane correction factors (MCF) for aerobic (0), partially anaerobic (0.2), and anaerobic (0.8) systems (IPCC 2019), Table 6.3.

Table 7-20: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, Breweries, and Petroleum Refining Production (MMT)

Activity	1990	2005	2018	2019	2020	2021	2022
Pulp and Paper[a]	83.6	92.4	78.7	76.3	74.7	75.5	73.9
Meat (Live Weight Killed)	27.3	31.4	36.4	37.4	37.8	38.1	37.9
Poultry (Live Weight Killed)	14.6	25.1	29.4	30.1	30.5	30.5	31.1
Vegetables, Fruits and Juices	40.8	45.3	42.3	41.8	40.6	39.2	38.4
Ethanol Production	2.5	11.7	48.1	47.1	41.6	44.8	48.3
Breweries	23.9	23.1	21.5	21.1	21.1	21.2	21.6
Petroleum Refining	702.4	818.6	951.7	940	806.5	858.3	892.1

[a] Pulp and paper production is the sum of market pulp production plus paper and paperboard production.

Sources: Pulp and Paper – FAO (2023a) and FAO (2023b); Meat, Poultry, and Fruits and Vegetables – USDA (2023a,2023b, 2023c, 2023d, 2022a, and 2022b), ERG (2023); Ethanol – Cooper (2018) and RFA (2023a and 2023b); Breweries – Beer Institute (2011) and TTB (2022); Petroleum Refining – EIA (2023).

Table 7-21: U.S. Industrial Wastewater Characteristics Data (2022)

Industry	Wastewater Outflow (m^3/ton)	Wastewater BOD (g/L)	Wastewater COD (kg/m^3)	COD:BOD Ratio
Pulp and Paper	See Table 7-25	0.3	--	2.5
Meat Processing	5.3	2.8	--	3
Poultry Processing	12.5	1.5	--	3
Fruit/Vegetable Processing	See Table 7-26		--	1.5
Ethanol Production – Wet Mill	10[a]	1.5	--	2
Ethanol Production – Dry Mill	1.25[a]	3[b]	--	2
Petroleum Refining	0.8	--	0.45	2.5
Breweries – Craft	3.21	--	17.6	1.67
Breweries – NonCraft	1.69	--	17.6	1.67

[a] Units are gallons per gallons ethanol produced.

[b] Units are COD (g/L).

Sources: Pulp and Paper (BOD, COD:BOD) – Malmberg (2018); Meat and Poultry (Outflow, BOD) – ERG (2006a); Meat and Poultry (COD:BOD) – EPA (1997a); Fruit/Vegetables (Outflow, BOD) – CAST (1995), EPA (1974), EPA (1975); Fruit/Vegetables (COD:BOD) – EPA (1997a); Ethanol Production – Wet Mill (Outflow) – Donovan (1996), NRBP (2001), Ruocco (2006b); Ethanol Production – Wet Mill (BOD) – White and Johnson (2003); Ethanol Production – Dry Mill (Outflow and COD) – Merrick (1998), Ruocco (2006a); Ethanol Production (Dry and Wet, COD:BOD) – EPA (1997a); Petroleum Refining (Outflow) – ERG (2013b); Petroleum Refining (COD) – Benyahia et al. (2006); Petroleum Refining (COD:BOD) – EPA (1982); Breweries – Craft BIER (2021); ERG (2018b); Breweries – NonCraft ERG (2018b); Brewers Association (2016a); Breweries (Craft and NonCraft; COD and COD:BOD) – Brewers Association (2016b).

Table 7-22: U.S. Industrial Wastewater Treatment Activity Data

Industry	% Wastewater Treated On-Site	% Treated Anaerobically	% Treated Aerobically	% Treated Aerobically	
				% Treated in ASBs	% Treated in Other Aerobic
Pulp and Paper[b]	60	5.2	75.9	38.5	37.4
Meat Processing	33	33[a]	33	0	33
Poultry Processing	25	25[a]	25	0	25
Fruit/Vegetable Processing	11	0	11	5.5	5.5
Ethanol Production – Wet Mill	33.3	33.3	66.7	0	0
Ethanol Production – Dry Mill	75	75	25	0	0
Petroleum Refining	62.1	0	62.1	23.6	38.5
Breweries – Craft	0.5	0.5	0	0	0
Breweries – NonCraft	100	99	1	0	1

[a] Wastewater is pretreated in anaerobic lagoons prior to aerobic treatment.

[b] Remaining onsite treated in other treatment assumed to be non-emissive and not shown here.

Note: Due to differences in data availability and methodology, zero values in the table are for calculation purposes only and may indicate unavailable data.

Sources: ERG (2008a, 2008b); ERG (2013a); ERG (2013b); ERG (2021a).

Table 7-23: Sludge Variables for Aerobic Treatment Systems

Variable	Industry		
	Pulp and Paper	Fruit/Vegetable Processing	Petroleum Refining
Organic reduction associated with sludge removal (%)	58		
Sludge Production (kg/m^3)			
Primary Sedimentation		0.15	
Aerobic Treatment		0.096	0.096
Sludge Factor (kg BOD/kg dry mass sludge)			
Aerobic Treatment w/Primary Sedimentation and No Anaerobic Sludge Digestion		0.8	
Aerobic Treatment w/out Primary Sedimentation			1.16

Sources: Organic reduction (pulp) – ERG (2008a); Sludge production – Metcalf & Eddy (2003); Sludge factors – IPCC (2019), Table 6.6a.

Emissions from Discharge of Industrial Wastewater Treatment Effluent:

Methane emissions from discharge of industrial wastewater treatment effluent are estimated via a Tier 1 method for all industries except for pulp, paper, and paperboard in accordance with IPCC methodological decision trees in based on available data for treatment and discharge. Emissions from discharge of pulp, paper, and paperboard treatment effluent is estimated via a Tier 2 method and is described in the industry-specific data section. Tier 1 emissions from effluent are estimated by multiplying the total organic content of the discharged wastewater effluent by an emission factor associated with the discharge:

Equation 7-25: CH_4 Emissions from Industrial Wastewater Treatment Discharge

$$\mathrm{CH_4\ Effluent_{IND}} = \mathrm{TOW_{EFFLUENT,IND}} \times \mathrm{EF_{EFFLUENT}}$$

where,

$CH_4\ Effluent_{IND}$ = CH_4 emissions from industrial wastewater discharge for inventory year (kg CH_4/year)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)

$EF_{EFFLUENT}$ = Tier 1 emission factor for wastewater discharged to aquatic environments (0.028 kg CH_4/kg COD or 0.068 kg CH_4/kg BOD) (IPCC 2019)

The COD or BOD in industrial treated effluent ($TOW_{EFFLUENT,IND}$) was determined by multiplying the total organics in the industry's untreated wastewater that is treated on site by an industry-specific percent removal where available or a more general percent removal based on biological treatment for other industries. Table 7-22 presents the percent of wastewater treated onsite, while Table 7-24 presents the fraction of TOW removed during treatment.

Equation 7-26: TOW in Industrial Wastewater Effluent

$$\mathrm{TOW_{EFFLUENT,IND}} = \mathrm{TOW_{IND}} \times \%\,\mathrm{onsite} \times (1 - \mathrm{TOW_{REM}})$$

where,

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)

TOW_{IND} = Total organics in untreated wastewater for industry for inventory year (kg COD/year)

%onsite = Percent of industry wastewater treated on site (%)

TOW_{REM} = Fraction of organics removed during treatment

Table 7-24: Fraction of TOW Removed During Treatment by Industry

Industry	TOW_{REM}	Source
Pulp, Paper, and Paperboard	0.91	Malmberg (2018)
Red Meat and Poultry	0.85	IPCC (2019), Table 6.6b
Fruits and Vegetables	0.85	IPCC (2019), Table 6.6b
Ethanol Production		
Biomethanator Treatment	0.90	ERG (2008a), ERG (2006b)
Other Treatment	0.85	IPCC (2019), Table 6.6b
Petroleum Refining	0.93	Kenari, Sarrafzadeh, and Tavakoli (2010)
Breweries	0.85	IPCC (2019), Table 6.6b

Discussion of Industry-Specific Data:

Pulp, Paper, and Paperboard Manufacturing Wastewater Treatment. Wastewater treatment for the pulp, paper, and paperboard manufacturing (hereinafter referred to as "pulp and paper") industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999; Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. About 60 percent of pulp and paper mills have on-site treatment with primary treatment and about half of these also have secondary treatment (ERG 2008). In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b).

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Pulp and paper mill wastewater treated using anaerobic ponds or lagoons or unaerated ponds were classified as anaerobic (with an MCF of 0.8). Wastewater flow treated in systems with aerated stabilization basins or facultative lagoons was classified as partially anaerobic (with an MCF of 0.2, which is the *2006 IPCC Guidelines*-suggested MCF for shallow lagoons). Wastewater flow treated in systems with activated sludge systems or similarly aerated biological systems was classified as aerobic.

A time series of CH_4 emissions for 1990 through 2022 was developed based on paper and paperboard production data and market pulp production data. Market pulp production values were available directly for 1998, 2000

through 2003, and 2010 through 2021. Where market pulp data were unavailable, a percent of woodpulp that is market pulp was applied to woodpulp production values from FAOSTAT to estimate market pulp production (FAO 2023a). The percent of woodpulp that is market pulp for 1990 to 1997 was assumed to be the same as 1998, 1999 was interpolated between values for 1998 and 2000, 2000 through 2009 were interpolated between values for 2003 and 2010, and 2022 was forecasted from the rest of the time series. A time series of the overall wastewater outflow in units of cubic meters of wastewater per ton of total production (i.e., market pulp plus woodpulp) is presented in Table 7-25. Data for 1990 through 1994 varies based on data outlined in ERG (2013a) to reflect historical wastewater flow. Wastewater generation rates for 1995, 2000, and 2002 were estimated from the 2014 *American Forest and Paper Association* (AF&PA) *Sustainability Report* (AF&PA 2014). Wastewater generation rates for 2004, 2006, 2008, 2010, 2012, and 2014 were estimated from the 2016 AF&PA Sustainability Report (AF&PA 2016). Data for 2005 and 2016 were obtained from the 2018 AF&PA Sustainability Report (AF&PA 2018), data for 2018 were obtained from the 2020 AF&PA Sustainability Report (AF&PA 2020), and data for 2020 were obtained from a 2022 AF&PA sustainability update (AF&PA 2022). Data for intervening years were obtained by linear interpolation, while 2021-2022 were set equal to 2020. The average BOD concentration in raw wastewater was estimated to be 0.4 grams BOD/liter for 1990 to 1998, while 0.3 grams BOD/liter was estimated for 2014 through 2022 (EPA 1997b; EPA 1993b; World Bank 1999; Malmberg 2018). Data for intervening years were obtained by linear interpolation.

Table 7-25: Wastewater Outflow (m^3/ton) for Pulp, Paper, and Paperboard Mills

Wastewater Outflow (m^3/ton)	1990	2005	2018	2019	2020	2021	2022
Pulp and Paper	68	43	40	39	39	39	39

Sources: ERG (2013a), AF&PA (2014), AF&PA (2016), AF&PA (2018), AF&PA (2020); AF&PA (2022)

Pulp, Paper, and Paperboard Wastewater Treatment Effluent. Methane emissions from pulp, paper, and paperboard wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge.

Equation 7-27: CH_4 Emissions from Pulp and Paper Discharge (U.S. Specific)

$$Emissions\ from\ Pulp\ and\ Paper\ Discharge\ \left(\text{U. S. Specific}, \frac{\text{kt CH}_4}{\text{year}}\right) = (\text{TOW}_{\text{RLE,pulp}} \times \text{EF}_{\text{RLE}}) + (\text{TOW}_{\text{Other,pulp}} \times \text{EF}_{\text{Other}})$$

Equation 7-28: Total Organics in Pulp and Paper Effluent Discharged to Reservoirs, Lakes, Or Estuaries (U.S. Specific)

$$\text{TOW}_{\text{RLE,pulp}}\ \left(\frac{\text{Gg BOD}}{\text{year}}\right) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{RLE,pulp}}$$

Equation 7-29: Total Organics in Pulp and Paper Effluent Discharged to Other Waterbodies (U.S. Specific)

$$\text{TOW}_{\text{Other,pulp}}\ \left(\frac{\text{Gg BOD}}{\text{year}}\right) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{Other,pulp}}$$

where,

$TOW_{RLE,pulp}$	=	Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to reservoirs, lakes, or estuaries (Gg BOD/year)
EF_{RLE}	=	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114 kg CH_4/kg BOD) (IPCC 2019)
$TOW_{Other,pulp}$	=	Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to other waterbodies (Gg BOD/year)
EF_{Other}	=	Emission factor (discharge to other waterbodies) (0.021 kg CH_4/kg BOD) (IPCC 2019)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in pulp, paper, and paperboard manufacturing wastewater effluent for inventory year (Gg BOD/year)

$Percent_{RLE,pulp}$ = Percent of wastewater effluent discharged to reservoirs, lakes, and estuaries (ERG 2021b)

$Percent_{Other,pulp}$ = Percent of wastewater effluent discharged to other waterbodies (ERG 2021b)

The percent of pulp, paper, and paperboard wastewater treatment effluent routed to reservoirs, lakes, or estuaries (3 percent) and other waterbodies (97 percent) were obtained from discussions with NCASI (ERG 2021b). Data for 2019 were assumed the same as the rest of the time series due to lack of available data. Default emission factors for reservoirs, lakes, and estuaries (0.114 kg CH_4/kg BOD) and other waterbodies (0.021 kg CH_4/kg BOD) were obtained from IPCC (2019).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. Although all meat and poultry processing facilities conduct some sort of treatment on site, about 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems.

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. About half of the operations that treat and discharge wastewater use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Wastewater treated in partially anaerobic systems were assigned the IPCC default emission factor of 0.12 kg CH_4/kg BOD. Outflow and BOD data, presented in Table 7-26, were obtained from CAST (1995) for apples, apricots, asparagus, broccoli, carrots, cauliflower, cucumbers (for pickles), green peas, pineapples, snap beans, and spinach; EPA (1974) for potato and citrus fruit processing; and EPA (1975) for all other commodities.

Table 7-26: Wastewater Outflow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	Organic Content in Untreated Wastewater (g BOD/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	9.85	0.751
Fruit		
Apples	9.08	8.16
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.59	1.226
Grapes (for wine)	2.78	1.831

Sources: CAST (1995); EPA (1974); EPA (1975).

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises a very small percent of ethanol production in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other sugar or starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement and is more efficient in terms of actual ethanol production (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic sludge digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006b).

About 33 percent of wet milling facilities and 75 percent of dry milling facilities treat their wastewater anaerobically (ERG 2006b). A default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment was used to estimate the CH_4 produced from these on-site treatment systems. The amount of CH_4 recovered through the use of biomethanators was estimated, and a 99 percent destruction efficiency was used. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006b). For facilities using biomethanators, approximately 90 percent of BOD is removed during on-site treatment (ERG 2006b, 2008a). For all other facilities, the removal of organics was assumed to be equivalent to secondary treatment systems, or 85 percent (IPCC 2019).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[10] Facilities that reported using non-aerated surface impoundments or other biological treatment units (trickling filter, rotating biological contactor), which have the potential to lead to anaerobic conditions, were assigned the IPCC default emission factor of 0.05 kg CH_4/kg COD. In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product, or 0.8 m^3/ton (ERG 2013b).

Breweries. Since 2010, the number of breweries has increased from less than 2,000 to more than 8,000 (Brewers Association 2021). This increase has primarily been driven by craft breweries, which have increased by over 250 percent during that period. Craft breweries were defined as breweries producing less than six million barrels of beer per year, and non-craft breweries produce greater than six million barrels. With their large amount of water use and high strength wastewater, breweries generate considerable CH_4 emissions from anaerobic wastewater treatment. However, because many breweries recover their CH_4, their emissions are much lower.

The Alcohol and Tobacco Tax and Trade Bureau (TTB) provides total beer production in barrels per year for different facility size categories from 2007 to 2021 (TTB 2022). Because data were unavailable for 2022, EPA extrapolated from 1990 to 2021 values. For years prior to 2007 where TTB data were not readily available, the Brewers Almanac (Beer Institute 2011) was used, along with an estimated percent of craft and non-craft breweries based on the breakdown of craft and non-craft for the years 2007 through 2020.

To determine the overall amount of wastewater produced, data on water use per unit of production and a wastewater-to-water ratio were used from the Benchmarking Report (Brewers Association 2016a) for both craft and non-craft breweries. Since brewing is a batch process, and different operations have varying organic loads, full-strength brewery wastewater can vary widely on a day-to-day basis. However, the organic content of brewery wastewater does not substantially change between craft and non-craft breweries. Some breweries may collect and discharge high strength wastewater from particular brewing processes (known as "side streaming") to a POTW,

[10] Available online at https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector.

greatly reducing the organics content of the wastewater that is treated on site. Subsequently, the MCF for discharge to a POTW was assumed to be zero (ERG 2018b).

Breweries may treat some or all of their wastewater on site prior to discharge to a POTW or receiving water. On-site treatment operations can include physical treatment (e.g., screening, settling) which are not expected to contribute to CH_4 emissions, or biological treatment, which may include aerobic treatment or pretreatment in anaerobic reactors (ERG 2018b). The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment and 0 for aerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems (IPCC 2006). The amount of CH_4 recovered through anaerobic wastewater treatment was estimated, and a 99 percent destruction efficiency was used (ERG 2018b; Stier J. 2018). Very limited activity data are available on the number of U.S. breweries that are performing side streaming or pretreatment of wastewater prior to discharge.

Domestic Wastewater N_2O Emission Estimates

Domestic wastewater N_2O emissions originate from both septic systems and POTWs. Within these centralized systems, N_2O emissions can result from aerobic systems, including systems like constructed wetlands. Emissions will also result from discharge of centrally treated wastewater to waterbodies with nutrient-impacted/eutrophic conditions. The systems with emission estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C); and
- Centralized wastewater treatment effluent (D).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic N_2O emissions are estimated as follows:

Equation 7-30: Total Domestic N_2O Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic } N_2O \text{ Emissions from Wastewater Treatment and Discharge } (\text{kt}) = \text{A} + \text{B} + \text{C} + \text{D}$$

Table 7-27 presents domestic wastewater N_2O emissions for both septic and centralized systems, including emissions from centralized wastewater treatment effluent, in 2022.

Table 7-27: Domestic Wastewater N_2O Emissions from Septic and Centralized Systems (2022, kt, MMT CO_2 Eq. and Percent)

	N_2O Emissions (kt)	N_2O Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater N_2O
Septic Systems	3	0.8	3.6%
Centrally-Treated Aerobic Systems	61	16.3	76.0%
Centrally-Treated Anaerobic Systems	+	+	+
Centrally-Treated Wastewater Effluent	16	4.4	20.4%
Total	**81**	**21.4**	**100%**

+ Does not exceed 0.5 kt, 0.05 MMT CO_2 Eq., or 0.5 percent.
Note: Totals may not sum due to independent rounding.

Emissions from Septic Systems:

Nitrous oxide emissions from domestic treatment depend on the nitrogen present, in this case, in the form of protein. Per capita protein consumption (kg protein/person/year) was determined by multiplying per capita annual food availability data and its protein content. Those data are then adjusted using a factor to account for the fraction of protein actually consumed. The methodological equations are:

Equation 7-31: Annual per Capita Protein Supply (U.S. Specific)

$$\text{Protein}_{\text{SUPPLY}}\ (\text{kg/person/year}) = \text{Protein}_{\text{per capita}}/1000 \times 365.25$$

Equation 7-32: Consumed Protein (IPCC 2019 [Eq. 6.10A])

$$\text{Protein}\ (\text{kg/person/year}) = \text{Protein}_{\text{SUPPLY}} \times \text{FPC}$$

Table 7-28: Variables and Data Sources for Protein Consumed

Variable	Variable Description	Units	Inventory Years: Source of Value
Protein			
$\text{Protein}_{\text{SUPPLY}}$	Annual per capita protein supply[a]	kg/person/year	1990-2022: Calculated
$\text{Protein}_{\text{per capita}}$	Daily per capita protein supply[a]	g/person/day	1990-2022: USDA (2015)
1000	Conversion factor	g to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
FPC	Fraction of Protein Consumed[a]	kg protein consumed / kg protein available	1990-2010: USDA (2015) 2011-2020: FAO (2022) and scaling factor 2021-2022: Forecasted from the rest of the time series

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 16 percent in 2022; U.S. Census Bureau 2019), consumed protein per capita (kg protein/person/year), the fraction of N in protein, the correction factor for additional nitrogen from household products, the factor for industrial and commercial co-discharged protein into septic systems, the factor for non-consumed protein added to wastewater and an emission factor and then converting the result to kt/year. The method selected is in accordance with IPCC methodological decision trees and available data. All factors were obtained from IPCC (2019).

U.S. population data were taken from historic U.S. Census Bureau national population totals data and include the populations of the United States and Puerto Rico (U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau 2021b and 2022, Instituto de Estadísticas de Puerto Rico 2021). Population data for American Samoa, Guam, Northern Mariana Islands, and the U.S. Virgin Islands were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2023). Table 7-12 presents the total U.S. population for 1990 through 2022. The fraction of the U.S. population using septic systems, as well as centralized treatment systems (see below), is based on data from *American Housing Survey* (U.S. Census Bureau 2021a). The methodological equations are:

Equation 7-33: Total Nitrogen Entering Septic Systems (IPCC 2019 [Eq. 6.10])

$$\text{TN}_{\text{DOM}_{\text{SEPTIC}}}\left(\frac{\text{kg N}}{\text{year}}\right)$$

$$= (\text{US}_{\text{POP}} \times \text{T}_{\text{SEPTIC}}) \times \text{Protein} \times \text{F}_{\text{NPR}} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON\_septic}} \times \text{F}_{\text{IND-COM\_septic}}$$

Equation 7-34: N_2O Emissions from Septic Systems (IPCC 2019 [Eq. 6.9])

$$A\left(\frac{\text{kt } N_2O}{\text{year}}\right) = TN_{DOM\_SEPTIC} \times (EF_{SEPTIC}) \times 44/28 \times 1/10^6$$

Table 7-29: Variables and Data Sources for N_2O Emissions from Septic System

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Septic Systems			
TN_{DOM_SEPTIC}	Total nitrogen entering septic systems	kg N/year	1990-2022: Calculated
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau 2002; Instituto de Estadísticas de Puerto Rico 2021 2000-2009: U.S. Census Bureau 2011 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2022: IPCC (2019) Eq. 6.10
N_{HH}	Additional nitrogen from household products (1.17)	No units	1990-2022: IPCC (2019) Table 6.10a
$F_{NON\text{-}CON\_septic}$	Factor for Non-Consumed Protein Added to Wastewater (1.13)	No units	
$F_{IND\text{-}COM\_septic}$	Factor for Industrial and Commercial Co-Discharged Protein, septic systems (1)	No units	1990-2022: IPCC (2019)
EF_{SEPTIC}	Emission factor, septic systems (0.0045)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8a
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Nitrous oxide emissions from POTWs depend on the total nitrogen entering centralized wastewater treatment. The total nitrogen entering centralized wastewater treatment was estimated by multiplying the U.S. population by the percent of wastewater collected for centralized treatment (about 84 percent in 2022), the consumed protein per capita, the fraction of N in protein, the correction factor for additional N from household products, the factor for industrial and commercial co-discharged protein into wastewater treatment, and the factor for non-consumed protein added to wastewater.

Equation 7-35: Total Nitrogen Entering Centralized Systems (IPCC 2019 [Eq. 10])

$$\mathrm{TN_{DOM_{CENTRAL}}}\left(\frac{\text{kg N}}{\text{year}}\right) = (\mathrm{US_{POP}} \times \mathrm{T_{CENTRALIZED}}) \times \text{Protein} \times \mathrm{F_{NPR}} \times \mathrm{N_{HH}} \times \mathrm{F_{NON-CON}} \times \mathrm{F_{IND-COM}}$$

Table 7-30: Variables and Data Sources for Non-Consumed Protein and Nitrogen Entering Centralized Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau 2011 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
$T_{CENTRALIZED}$	Percent collected[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
Protein	Consumed protein per capita[a]	kg/person/year	1990-2022: Calculated
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2022: IPCC (2019), Eq. 6.10
N_{HH}	Factor for additional nitrogen from household products (1.17)	No units	1990-2022: IPCC (2019), Table 6.10a
$F_{NON-CON}$	Factor for U.S. specific non-consumed protein (1.13)	No units	

Variable	Variable Description	Units	Inventory Years: Source of Value
$F_{IND\text{-}COM}$	Factor for Industrial and Commercial Co-Discharged Protein (1.25)	No units	1990-2022: IPCC (2019) Table 6.11

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from POTWs were estimated by multiplying the total nitrogen entering centralized wastewater treatment, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands) and anaerobic systems, aerobic systems with constructed wetlands as the sole treatment, the respective emission factors for aerobic systems and anaerobic systems, and the conversion from N_2 to N_2O.

Table 7-34 presents the data for U.S. population, population served by centralized wastewater treatment plants, available protein, and protein consumed. The methodological equations are:

Equation 7-36: Total Domestic N_2O Emissions from Centrally Treated Aerobic Systems

$$Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (other\ than\ Constructed\ Wetlands)(B1) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ Only)(B2) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ used\ as\ Tertiary\ Treatment)$$

$$(B3)\ =\ B\ (kt\ N_2O/year)$$

where,

Equation 7-37: N_2O Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.9])

$$\mathrm{B1\ (kt\ N_2O/year)} = [(\mathrm{TN_{DOM\_CENTRAL}}) \times (\%\ \mathrm{aerobic_{OTCW}})] \times \mathrm{EF_{aerobic}} \times 44/28 \times 1/10^6$$

Table 7-31: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt N_2O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized systems[a]	kg N/year	1990-2022: Calculated
% $aerobic_{OTCW}$	Flow to aerobic systems, other than constructed wetlands only / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$EF_{aerobic}$	U.S.-specific emission factor – aerobic systems (0.015)	kg N_2O-N/kg N	1990-2022: IPCC (2022)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from constructed wetlands used as sole treatment include similar data and processes as aerobic systems other than constructed wetlands. See description above. Nitrous oxide emissions from

constructed wetlands used as tertiary treatment were estimated by multiplying the flow to constructed wetlands used as tertiary treatment, wastewater N concentration entering tertiary treatment, constructed wetlands emission factor, and converting to kt/year.

Equation 7-38: N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) (IPCC 2014 [Eq. 6.9])

$$B2\ \left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(TN_{DOM\_CENTRAL}) \times (\%\ \text{aerobic}_{CW})] \times EF_{CW} \times 44/28 \times 1/10^6$$

Equation 7-39: N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S.-Specific)

$$B3\ \left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(POTW\_flow\_CW) \times (N_{CW,INF}) \times 3.785 \times (EF_{CW})] \times 1/10^6 \times 365.25$$

Table 7-32: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt N_2O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2022: IPCC (2014) Table 6.7
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
Emissions from Constructed Wetlands used as Tertiary Treatment (kt N_2O/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment [a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series

Variable	Variable Description	Units	Inventory Years: Source of Value
$N_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (25)	mg/L	1990-2022: Metcalf & Eddy (2014)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2022: IPCC (2014) Table 6.7
$1/10^6$	Conversion factor	mg to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Data sources and methodologies are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-40: N_2O Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 [Eq. 6.9])

$$C\left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(TN_{DOM\_CENTRAL}) \times (\%\text{ anaerobic})] \times EF_{anaerobic} \times 44/28 \times 1/10^6$$

Table 7-33: Variables and Data Sources for N_2O Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: (EPA 1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8A
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	mg to kg	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Table 7-34: U.S. Population (Millions) Fraction of Population Served by Centralized Wastewater Treatment (percent), Protein Supply (kg/person-year), and Protein Consumed (kg/person-year)

Year	1990	2005	2018	2019	2020	2021	2022
Population	253	300	330	332	335	336	337
Centralized WWT Population (%)	75.6	78.8	82.9	83.6	84.2	84.8	83.6
Protein Supply	43.1	44.9	45.5	46	46.9	46.3	46.3
Protein Consumed	33.2	34.7	35.1	35.5	36.2	35.7	35.7

Sources: Population – U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau (2021b); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2022); U.S. Census Bureau (2023); WWTP Population – U.S. Census Bureau (2021a); Available Protein – USDA (2015), FAO (2022); Protein Consumed – FAO (2022).

Emissions from Discharge of Centralized Treatment Effluent:

Nitrous oxide emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total nitrogen in centrally treated wastewater effluent by the percent of wastewater treated in primary, secondary, and tertiary treatment and the fraction of nitrogen remaining after primary, secondary, or tertiary treatment and then multiplying by the percent of wastewater volume routed to waterbodies with nutrient-impaired/eutrophic conditions and all other waterbodies (ERG 2021a) and emission factors for discharge to impaired waterbodies and other waterbodies from IPCC (2019). The methodological equations are:

Equation 7-41: N_2O Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$D\left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(N_{EFFLUENT,IMP} \times EF_{IMP}) + (N_{EFFLUENT,NONIMP} \times EF_{NONIMP})] \times 44/28 \times 1/10^6$$

where,

Equation 7-42: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.8])

$$N_{EFFLUENT,DOM}\left(\frac{\text{kg N}}{\text{year}}\right)$$

$$= [TN_{DOM\_CENTRAL}[11] \times \%\ \text{primary} \times (1 - N_{rem,PRIMARY})] + [TN_{DOM\_CENTRAL} \times \%\ \text{secondary} \times (1 - N_{rem,SECONDARY})] + [TN_{DOM\_CENTRAL} \times \%\ \text{tertiary} \times (1 - N_{rem,TERTIARY})]$$

Equation 7-43: Total Nitrogen in Effluent Discharged to Impaired Waterbodies (U.S.-Specific)

$$N_{EFFLUENT,IMP}\ (\text{kg N/year}) = (N_{EFFLUENT,DOM} \times \text{Percent}_{IMP})/1000$$

Equation 7-44: Total Nitrogen in Effluent Discharged to Nonimpaired Waterbodies (U.S.-Specific)

$$N_{EFFLUENT,NONIMP}\ (\text{kg N year}) = N_{EFFLUENT,DOM} \times \text{Percent}_{NONIMP})/1000$$

Table 7-35: Variables and Data Sources for N_2O Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$N_{EFFLUENT,DOM}$	Total organics in centralized treatment effluent[a]	kg N/year	1990-2022: Calculated
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
1000	Conversion factor	kg to kt	Standard Conversion
% primary	Percent of primary domestic centralized treatment[a]	%	1990,1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012), respectively
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	

[11] See emissions from centrally treated aerobic and anaerobic systems for methodological equation calculating $TN_{DOM\_CENTRAL}$.

Variable	Variable Description	Units	Source of Value
			Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
$N_{rem,PRIMARY}$	Fraction of nitrogen removed from primary domestic centralized treatment (0.1)	No units	1990-2022: IPCC (2019) Table 6.10c
$N_{rem,SECONDARY}$	Fraction of nitrogen removed from secondary domestic centralized treatment (0.4)	No units	
$N_{rem,TERTIARY}$	Fraction of nitrogen removed from tertiary domestic centralized treatment (0.9)	No units	
$N_{EFFLUENT,IMP}$	Total nitrogen in effluent discharged to impaired waterbodies	kg N/year	1990-2022: Calculated
$N_{EFFLUENT,NONIMP}$	Total nitrogen in effluent discharged to nonimpaired waterbodies	kg N/year	
EF_{IMP}	Emission factor (discharge to impaired waterbodies) (0.19)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8a
$EF_{NONIMPr}$	Emissions factor (discharge to nonimpaired waterbodies) (0.005)	kg N_2O-N/kg N	
$Percent_{IMP}$	Percent of wastewater discharged to impaired waterbodies[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2022: Set equal to 2012
$Percent_{NONIMP}$	Percent of wastewater discharged to nonimpaired waterbodies[a]	%	

[a] Value for this activity data varies over the *Inventory* time series.

Industrial Wastewater N_2O Emission Estimates

Nitrous oxide emission estimates from industrial wastewater are estimated according to the methodology described in the *2019 Refinement*. U.S. industry categories that are likely to produce significant N_2O emissions from wastewater treatment were identified based on whether they generate high volumes of wastewater, whether there is a high nitrogen wastewater load, and whether the wastewater is treated using methods that result in N_2O emissions. The top four industries that meet these criteria and were added to the *Inventory* are meat and poultry processing; petroleum refining; pulp and paper manufacturing; and breweries (ERG 2021a). Wastewater treatment and discharge emissions for these sectors for 2022 are displayed in Table 7-36 below. Table 7-20 contains production data for these industries.

Table 7-36: Total Industrial Wastewater N_2O Emissions by Sector (2022, MMT CO_2 Eq. and Percent)

Industry	N_2O Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater N_2O
Meat & Poultry	0.2	47.3%
Petroleum Refineries	0.1	30.5%
Pulp & Paper	0.1	21.4%
Breweries	+	0.7%
Total	**0.5**	**100%**

+ Does not exceed 0.5 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

More recent research has revealed that emissions from nitrification or nitrification-denitrification processes at wastewater treatment, previously judged to be a minor source, may in fact result in more substantial emissions (IPCC 2019). N_2O is generated as a by-product of nitrification, or as an intermediate product of denitrification. Therefore, N_2O emissions are primarily expected to occur from aerobic treatment systems. To estimate these emissions, the total nitrogen entering aerobic wastewater treatment for each industry must be calculated. Then, the emission factor provided by the *2019 Refinement* is applied to the portion of wastewater that undergoes aerobic treatment.

The total nitrogen that enters each industry's wastewater treatment system is a product of the total amount of industrial product produced, the wastewater generated per unit of product, and the nitrogen expected to be present in each meter cubed of wastewater (IPCC equation 6.13).

Equation 7-45: Total Nitrogen in Industrial Wastewater

$$TN_{INDi} = P_i \times W_i \times TN_i$$

where,

TN_{INDi} = total nitrogen in wastewater for industry *i* for inventory year, kg TN/year
i = industrial sector
P_i = total industrial product for industrial sector *i* for inventory year, t/year
W_i = wastewater generated per unit of production for industrial sector *i* for inventory year, m^3/t product
Tni = total nitrogen in untreated wastewater for industrial sector *i* for inventory year, kg TN/m^3

For the four industries of interest, the total production and the total volume of wastewater generated has already been calculated for CH_4 emissions. For these new N_2O emission estimates, the total nitrogen in the untreated wastewater was determined by multiplying the annual industry production, shown in Table 7-20, by the average wastewater outflow, shown in Table 7-23 and the nitrogen loading in the outflow shown in Table 7-37.

Table 7-37: U.S. Industrial Wastewater Nitrogen Data

Industry	Wastewater Total N (kg N/ m^3)	Source for Total N
Pulp and Paper	0.30[a]	Cabrera (2017)
Meat Processing	0.19	IPCC (2019), Table 6.12
Poultry Processing	0.19	IPCC (2019), Table 6.12
Petroleum Refining	0.051	Kenari et al. (2010)
Breweries – Craft	0.055	IPCC (2019), Table 6.12
Breweries – NonCraft	0.055	IPCC (2019), Table 6.12

[a] Units are kilograms N per air-dried metric ton of production.

Nitrous oxide emissions from industry wastewater treatment are calculated by applying an emission factor to the percent of wastewater (and therefore nitrogen) that undergoes aerobic treatment (IPCC Equation 6.11).

Equation 7-46: N_2O Emissions from Industrial Wastewater Treatment Plants

$$N_2O\ Plants_{IND} = \left[\sum_i \left(T_{i,j} \times EF_{i,j} \times TN_{INDi}\right)\right] \times \frac{44}{28}$$

where,

$N_2O\ Plants_{IND}$ = N_2O emissions from industrial wastewater treatment plants for inventory year, kg N_2O/year
TN_{INDi} = total nitrogen in wastewater from industry *i* for inventory year, kg N/year
$T_{i,j}$ = degree of utilization of treatment/discharge pathway or system *j*, for each industry *i* for inventory year

i	=	industrial sector
j	=	each treatment/discharge pathway or system
$EF_{i,j}$	=	emission factor for treatment/discharge pathway or system j, kg N_2O-N/kg N. 0.015 kg N_2O-N/kg N (IPCC 2022)
44/28	=	conversion of kg N_2O-N into kg N_2O

For each industry, the degree of utilization (Ti,j)–the percent of wastewater that undergoes each type of treatment–was previously determined for CH_4 emissions and presented in Table 7-22.

Emissions from Industrial Wastewater Treatment Effluent:

Nitrous oxide emissions from industrial wastewater treatment effluent are estimated by multiplying the total nitrogen content of the discharged wastewater effluent by an emission factor associated with the location of the discharge. Where wastewater is discharged to aquatic environments with nutrient-impacted/eutrophic conditions (i.e., water bodies which are rich in nutrients and very productive in terms of aquatic animal and plant life), or environments where carbon accumulates in sediments such as lakes, reservoirs, and estuaries, the additional organic matter in the discharged wastewater is expected to increase emissions.

Equation 7-47: N_2O Emissions from Industrial Wastewater Treatment Effluent

$$\mathrm{N_2O\ Effluent_{IND}} = \mathrm{N_{EFFLUENT,IND}} \times \mathrm{EF_{EFFLUENT}} \times 44/28$$

where,

$N_2O\ Effluent_{IND}$	=	N_2O emissions from industrial wastewater discharge for inventory year (kg N_2O/year)
$N_{EFFLUENT,IND}$	=	Total nitrogen in industry wastewater effluent discharged to aquatic environments for inventory year (kg N/year)
$EF_{EFFLUENT}$	=	Tier 1 emission factor for wastewater discharged to aquatic environments (0.005 kg N_2O-N/kg N) (IPCC 2019)
44/28	=	Conversion of kg N_2O-N into kg N_2O

The total N in treated effluent was determined through use of a nutrient estimation tool developed by EPA's Office of Water (EPA 2019). The Nutrient Tool uses known nutrient discharge data within defined industrial sectors or subsectors, as reported on Discharge Monitoring Reports, to estimate nutrient discharges for facilities within that sector or subsector that do not have reported nutrient discharges but are likely to discharge nutrients. The estimation considers, within each sector or subsector, elements such as the median nutrient concentration and flow, as well as the percent of facilities within the sector or subsector that have reported discharges. Data from 2018 are available for the pulp, paper, and paperboard, meat and poultry processing, and petroleum refining industries. To complete the time series, an industry-specific percent removal of nitrogen was calculated using the total nitrogen in untreated wastewater. See Table 7-38.

Because data for breweries was not available, the removal of nitrogen was assumed to be equivalent to secondary treatment, or 40 percent (IPCC 2019). The Tier 1 emission factor (0.005 kg N_2O/kg N) from IPCC (2019) was used.

Table 7-38: Industrial Wastewater Nitrogen Discharged in 2018 by Sector (kg N)

Industry	N $Effluent_{IND}$ (kg N)	Industry-Specific N Removal Factor
Meat & Poultry	12,078,919	0.082
Petroleum Refineries	1,698,953	0.045
Pulp & Paper	18,809,623	1.08
Breweries[a]	1,604,878	NA

[a] Nitrogen discharged by breweries was estimated as 60 percent of untreated wastewater nitrogen.
NA (Not Available)
Source: ERG (2021a).

Uncertainty

The overall uncertainty associated with both the 2022 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (IPCC 2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, fruits and vegetable processing, ethanol production, petroleum refining, and breweries. Uncertainty associated with the parameters used to estimate N_2O emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, petroleum refining, and breweries. Uncertainty associated with centrally treated constructed wetlands parameters including U.S. population served by constructed wetlands, and emission and conversion factors are from IPCC (2014), whereas uncertainty associated with POTW flow to constructed wetlands and influent BOD and nitrogen concentrations were based on expert judgment (ERG 2021b). The specified probability density functions (PDFs) are assumed to be normal for most activity data and emission factors, and due to lack of data, are based on expert judgement (ERG 2021c).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-39. For 2022, methane emissions from wastewater treatment were estimated to be between 14.9 and 27.7 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo stochastic simulations). This indicates a range of approximately 29 percent below to 33 percent above the 2022 emissions estimate of 20.8 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 13.9 and 64.0 MMT CO_2 Eq., which indicates a range of approximately 36 percent below to 192 percent above the 2022 emissions estimate of 21.9 MMT CO_2 Eq.

Table 7-39: Approach 2 Quantitative Uncertainty Estimates for 2022 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**20.8**	**14.9**	**27.7**	**-29%**	**+33%**
Domestic	CH_4	13.6	8.8	19.3	-35%	+42%
Industrial	CH_4	7.2	4.2	11.4	-42%	+57%
Wastewater Treatment	**N_2O**	**21.9**	**13.9**	**64.0**	**-36%**	**+192%**
Domestic	N_2O	21.4	13.0	63.2	-39%	+195%
Industrial	N_2O	0.5	0.5	1.4	-0.7%	+201%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). This effort included a general or Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;

- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected trends of emission estimates; and
- Compared estimates to previous estimates to identify significant changes.

Calculation-related QC (category-specific, Tier 2) was performed for a portion of the domestic wastewater treatment discharges methodology, which included assessing available activity data to ensure the most complete publicly data set was used and checking historical trends in the data to assist determination of best methodology for filling in the time series for data that are not available annually.

All transcription errors identified were corrected and documented. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Population data were updated using the same and latest data sources as the state-level emissions inventory to create consistency across *Inventory* estimates. These changes affected the years 2020 and 2021. Protein data were updated to reflect available protein values available for 2018 through 2020 (FAO 2022). Pulp, paper, and paperboard production data were updated to reflect revised values for 2021 (FAO 2023a). Updated red meat production values for 2021, were updated based on revised data (USDA 2023a). Fruits and vegetables production values were updated for the time series (ERG 2022; USDA 2023c). Ethanol production values for 2021 were based on revised data (RFA 2023a; RFA 2023b). Petroleum refining production values for 2021 were revised based on EIA (2023). Updated values for non-craft brewery wastewater generation were included for the years 2015 and 2020, affecting the values for 2016, 2018, 2019, and 2021 (BIER 2021).

Compared to the previous *Inventory* the cumulative effect of all these recalculations had a minor impact on the overall wastewater treatment emission estimates:

- Domestic wastewater treatment and discharge CH_4 emissions decreased on average 0.2 percent over the timeseries, with 1990 through 2019 not changing and the largest decrease of 3.1 percent (0.4MMT CO_2 Eq.) in 2021.
- Domestic wastewater treatment and discharge N_2O emissions increased an average 5.6 percent over the timeseries, with 1990 through 2017 not changing and the largest increase of 6.8 percent (1.4 MMT CO_2 Eq.) in 2020.
- Industrial wastewater treatment and discharge CH_4 emissions decreased on average 0.01 percent over the timeseries, with the smallest decrease of 0.003 percent (0.0 MMT CO_2 Eq.) in 2017 and largest decrease of 0.2 percent (0.01 MMT CO_2 Eq.) in 2020.
- Industrial wastewater treatment and discharge N_2O emissions increase an average 0.02 percent over the timeseries, with the smallest increase of 0.0 percent (0.0 MMT CO_2 Eq.) in 1990 to the largest increase of 0.6 percent (0.003 MMT CO_2 Eq.) in 2021.

Over the time series, the total emissions on average increased by 0.1 percent from the previous *Inventory*. The changes ranged from the smallest increase, 0.0005 percent (0.0002 MMT CO_2 Eq.), in 2017, to the largest decrease, 2.4 percent (1.0 MMT CO_2 Eq.), in 2020.

Planned Improvements

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement them until data are available or identified:

- Continue to investigate anaerobic sludge digester and biogas data compiled by the Water Environment Federation (WEF) in collaboration with other entities as a potential source of updated activity data. Due to lack of these data, the United States continues to use another method for estimating biogas produced. This method uses the standard 100 gallons/capita/day wastewater generation factor for the United States (Ten-State Standards), which EPA believes is reasonable to estimate national emissions. However, based on stakeholder input, some regions of the United States use markedly less water due to water conservation efforts so EPA plans to investigate updated sources for this method as well.
- Investigate additional sources for estimating wastewater volume discharged and discharge location for both domestic and industrial sources. For domestic wastewater, the goal would be to provide additional data points along the time series, while the goal for industrial wastewater would be to update the Tier 1 discharge methodology to a Tier 2 methodology.
- Investigate additional sources for domestic wastewater treatment type in place data.
- Continue to review whether sufficient data exist to develop U.S.-specific CH_4 or N_2O emission factors for domestic wastewater treatment systems, including whether emissions should be differentiated for systems that incorporate biological nutrient removal operations.
- Investigate additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems.
- Evaluate literature provided by expert review commenters for potential inclusion as updates, in particular focusing on the industrial N_2O emission factor for pulp and paper wastewater treatment.
- Evaluate the use of POTW BOD effluent discharge data from ICIS-NPDES.[12] Currently only half of POTWs report organics as BOD_5 so EPA would need to determine a hierarchy of parameters to appropriately sum all loads. Using these data could potentially improve the current methane emission estimates from domestic discharge, or at least provide a comparison to the current method for QA/QC.
- Evaluate the use of POTW N effluent discharge data from ICIS-NPDES. Currently only about 80 percent of POTWs report a form of N so EPA would need to determine an appropriate method to scale to the total POTW population. EPA is aware of a method for industrial sources and plans to determine if this method is appropriate for domestic sources. Using these data could potentially improve the current nitrous oxide emissions estimates from domestic discharge, or at least provide a comparison to the current method for QA/QC.

7.3 Composting (CRT Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Composting reduces the amount of methane-generating waste entering landfills, destroys pathogens in the waste, sequesters carbon, and provides a source of organic matter. Composting can also generate a saleable product and reduce the need for chemical fertilizers when the end product is used as a fertilizer or soil amendment. This source category assumes all composting facilities are commercial, large-scale anaerobic windrow composting facilities with yard trimmings as the main waste stream composted, which aligns with findings from full-scale compost infrastructure survey data published by BioCycle (2017, 2023). Of 200 major food waste composting facilities in the United States, 75 (38 percent) use the windrow method, 45 (23 percent) use the aerated static pile method, and the remainder use other methods. The BioCycle 2023 survey received responses from facilities using aerobic composting methods (e.g., aerated static piles, in-

[12] ICIS-NPDES refers to EPA's Integrated Compliance Information System – National Pollutant Discharge Elimination System.

vessel composting) are operational in the United States, however national estimates of the material processed by these facilities are not readily available; therefore, emissions estimates by composting method are not included in this source category. Residential backyard composting is also not included in this source category.

Composting naturally converts a large fraction of the degradable organic carbon in the waste material into carbon dioxide (CO_2) through aerobic processes without anthropogenic influence. With anthropogenic influences (e.g., at commercial or large on-site composting operations), anaerobic conditions can be created in sections of the compost pile when there is excessive moisture or inadequate aeration (or mixing) of the compost pile, resulting in the formation of methane (CH_4). Methane in aerobic sections of a windrow pile is generally oxidized by microorganisms, which convert the CH_4 to CO_2 emissions. Even though CO_2 emissions are generated, they are not included in net greenhouse gas emissions for composting. Consistent with the *2006 IPCC Guidelines*, net CO_2 flux from carbon stock changes in waste material are estimated and reported under the LULUCF sector. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial carbon content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can also be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the thermophilic and secondary mesophilic stages of composting (Cornell 2007). Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

From 1990 to 2022, the amount of waste composted in the United States increased from 3,810 kt to 23,042 kt (see Table 7-42). There was some fluctuation in the amount of waste composted between 2006 to 2009 where a peak of 20,063 kt composted was observed in 2008, which decreased to 18,838 kt composted the following year, presumably driven by the economic crisis of 2009 (data not shown). Since 2009, the amount of waste composted has gradually increased, and when comparing 2010 to 2022, a 26 percent increase in waste composted is observed. Emissions of CH_4 and N_2O from composting from 2010 to 2022 have increased by the same percentage.

In 2022, CH_4 emissions from composting (see Table 7-40 and Table 7-41) were 2.6 MMT CO_2 Eq. (92 kt), and N_2O emissions from composting were 1.8 MMT CO_2 Eq. (7 kt), representing consistent emissions trends over the past several years. Composted material primarily includes yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include small-scale backyard composting and agricultural composting mainly due to the lack of consistent and comprehensive national data. Additionally, it is assumed that backyard composting tends to be a more naturally managed process with less chance of generating anaerobic conditions and CH_4 and N_2O emissions. Agricultural composting is accounted for in Chapter 5, Section 5.4 (Agricultural Soil Management) of this *Inventory*, as most agricultural composting operations are assumed to land-apply the resultant compost to soils.

The growth in composting since the 1990s and specifically over the past decade may be attributable to the following factors: (1) the enactment of legislation by state and local governments that discouraged or banned the disposal of yard trimmings and/or food waste in landfills, (2) an increase in yard trimming collection and yard trimming drop off sites operated by local solid waste management districts/divisions, (3) an increased awareness of the environmental benefits of composting, and (4) loans or grant programs to establish or expand composting infrastructure.

Most bans or diversion laws on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). California, for example, enacted a waste diversion law for organics including yard trimmings and food scraps in 1999 (AB939) that required jurisdictions to divert 50 percent of the waste stream by 2000, or be subjected to fines. Currently, 20 states representing up to 42 percent of the nation's population have enacted legislation banning yard waste from landfill disposal (U.S. Composting Council 2022). Additional initiatives at the metro and municipal level also exist across the United States. Roughly 4,713 composting facilities exist in the United States with most (57.2 percent) composting yard trimmings only (BioCycle 2017).

In the last decade, bans and diversions for food waste have also become more common. As of 2022, eight states (California, Connecticut, Massachusetts, New Jersey, New York, Orgon, Vermont, Washington) and seven local governments (Austin, TX; Boulder, CO; Hennepin County, MN; Portland, OR; New York City, NY; San Francisco, CA; Seattle, WA) had implemented organic waste bans or mandatory recycling laws to help reduce organic waste entering landfills, with most having taken effect after 2013 (U.S. Composting Council 2022). In most cases, organic waste reduction in landfills is accomplished by following recycling guidelines, donating excess food for human consumption, or by sending waste to organics processing facilities (Harvard Law School and CET 2019). An example of an organic waste ban as implemented by California is the California Mandatory Recycling Law (AB1826), which requires companies to comply with organic waste recycling procedures if they produce a certain amount of organic waste and took effect on January 1, 2015 (Harvard Law School and CET 2019). In 2017, *BioCycle* released a report in which 27 of 43 states that responded to their organics recycling survey noted that food waste (collected residential, commercial, institutional, and industrial food waste) was recycled via anaerobic digestion and/or composting. These 27 states reported an estimated total of 1.8 million tons of food waste diverted from landfills in 2016 (BioCycle 2018b). A growing number of initiatives to encourage households and businesses to compost or beneficially reuse food waste also exist.

Table 7-40: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	0.4	2.1	2.5	2.5	2.6	2.6	2.6
N_2O	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Total	**0.7**	**3.6**	**4.3**	**4.3**	**4.4**	**4.4**	**4.4**

Note: Totals may not sum due to independent rounding.

Table 7-41: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	15	75	90	91	92	92	92
N_2O	1	6	7	7	7	7	7

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process.

The emissions shown in Table 7-40 and Table 7-41 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006) in accordance with IPCC methodological decision trees and available data. Using this method, emissions are the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

Equation 7-48: Greenhouse Gas Emission Calculation for Composting

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, kt CH_4 or N_2O
M = mass of organic waste composted in kt
EF_i = emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006)
i = designates either CH_4 or N_2O

Per IPCC Tier 1 methodology defaults, the emission factors for CH_4 and N_2O assume a moisture content of 60 percent in the wet waste (IPCC 2006). While the moisture content of composting feedstock can vary significantly

by type, composting as a process ideally proceeds between 40 to 65 percent moisture (University of Maine 2016; Cornell 1996).

Estimates of the quantity of waste composted (M, wet weight as generated) are presented in Table 7-42 for select years. Estimates of the quantity composted for 1990 and 2005 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2015 (EPA 2018); estimates of the quantities composted for 2017 to 2018 were taken from EPA's *Advancing Sustainable Materials Management: 2018 Tables and Figures* (EPA 2020); the estimate of the quantity composted for 2019 to 2022 were extrapolated using the 2018 quantity composted and a ratio of the U.S. population growth for each year between 2018 and 2022 (U.S. Census Bureau 2021; U.S. Census Bureau 2022; U.S Census Bureau 2023). Estimates of waste composted by commercial facilities in Puerto Rico were provided for select years by EPA Region 2 (Kijanka 2020). This data includes amount of waste composted at three facilities in Puerto Rico for 2017, 2018, and 2019, ranging from approximately 1,200 kt to a high of 15,000 kt. The average waste composted for these years was used as the annual amount composted for the respective facility for years the facility was operational. The annual quantity of composted waste in Puerto Rico was forecasted for 2020, 2021, and 2022 using available data from prior years, assumed metro area population data near where each facility is located, and the Microsoft Excel FORECAST function to obtain annual composting estimates.

Table 7-42: U.S. Waste Composted (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Waste Composted	3,810	18,655	22,594	22,698	22,918	22,946	23,042

Uncertainty

The major uncertainty drivers are the assumption that all composting emissions come from commercial windrow facilities and the use of default emission factors (IPCC 2006) which is tied to a homogenous mixture of waste processed across the country (largely yard trimmings). Data presented by BioCycle (BioCycle 2017, 2023) confirm most composting operations use the windrow method and yard trimmings are the largest share of material composted across the country, but there are other composting methods used and waste characteristics will vary at a facility level. Additionally, there are composting operations in Puerto Rico and U.S. territories that are not explicitly included in the national quantity of material composted as reported in the EPA Sustainable Materials Management Reports because the methodological scope does not include Puerto Rico and U.S. territories. EPA took steps to include emissions from Puerto Rico and U.S. Territories beginning in the 1990 to 2020 *Inventory* and will continue to seek out additional data in future *Inventories*.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±58 percent for the Tier 1 methodology and considers the individual emission factors applied to the default emission factors and activity data.

Emissions from composting in 2022 were estimated to range between 1.8 and 7.0 MMT CO_2 Eq., which indicates a range of 58 percent below to 58 percent above the 2022 emission estimate of each gas (see Table 7-43).

Table 7-43: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4	2.6	1.1	4.1	-58%	+58%
Composting	N_2O	1.8	0.8	2.9	-58%	+58%
Composting	**Total**	**4.4**	**1.8**	**7.0**	**-58%**	**+58%**

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current *Inventory*.

Recalculations Discussion

No recalculations were performed for the 1990 to 2022 *Inventory*.

Planned Improvements

EPA recently completed a literature search on emission factors and composting systems and management techniques that were documented in a draft technical memorandum. The purpose of this literature review was to compile all published emission factors specific to various composting systems and composted materials in the United States to determine whether the emission factors used in the current methodology can be revised or expanded to account for geographical differences and/or differences in composting systems used. For example, outdoor composting processes in arid regions typically require the addition of moisture compared to similar composting processes in wetter climates. In general, there is a lack of facility-specific data on the management techniques and sum of material composted to enable the use of different emission factors. EPA will continue to seek out more detailed data on composting facilities to enable this improvement in the future.

Relatedly, EPA has received comments during previous *Inventory* cycles recommending that calculations for the composting sector be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents. At this time, EPA is not aware of any available datasets which would enable estimations to be performed at this level of granularity. EPA will continue to search for data which could lead to the development of subcategory-specific composting emission factors to be used in future *Inventory* cycles.

EPA will also continue to seek out activity data including processing capacity and years of operation for commercial composting facilities in Puerto Rico (for additional years), Guam, and other U.S. Territories for inclusion in a future *Inventory*.

7.4 Anaerobic Digestion at Biogas Facilities (CRT Source Category 5B2)

Anaerobic digestion is a series of biological processes in the absence of oxygen in which microorganisms break down organic matter, producing biogas and digestate. The biogas primarily consists of CH_4, biogenic CO_2, and trace amounts of other gases such as N_2O (IPCC 2006) and is often combusted to produce heat and power, or further processed into renewable natural gas or for use as a transportation fuel. Digester gas contains approximately 65 percent CH_4 (a normal range is 55 percent to 65 percent) and approximately 35 percent CO_2 (WEF 2012; EPA 1993). Methane emissions may result from a fraction of the biogas that is lost during the process due to leakages and other unexpected events (0 to 10 percent of the amount of CH_4 generated, IPCC 2006), collected biogas that is not completely combusted, and entrained gas bubbles and residual gas potential in the digestate. Carbon dioxide emissions are biogenic in origin and should be reported as an informational item in the Energy Sector (IPCC 2006). Volume 5 Chapter 4 of the *2006 IPCC Guidelines* notes that at biogas plants where unintentional CH_4 emissions are flared, CH_4 emissions are likely to be close to zero.

Anaerobic digesters differ based on the operating temperature, feedstock type and moisture content, and mode of operation. The operating temperature dictates the microbial communities that live in the digester. Mesophilic

microbes are present at temperatures ranging from 85 to 100 degrees Fahrenheit while thermophilic microbes thrive at temperatures ranging from 122 to 140 degrees Fahrenheit (WEF 2012). Digesters may process one or more types of feedstock, including food waste; municipal wastewater solids; livestock manure; industrial wastewater and residuals; fats, oils, and grease; and other types of organic waste streams. Co-digestion (multiple feedstocks) is employed to increase methane production in cases where an organic matter type does not break down easily. In co-digestion, various organic wastes are decomposed in a singular anaerobic digester by using a combination of wastewater solids or manure and food waste from restaurants or food processing industry, a combination of manure and waste from energy crops or crop residues (EPA 2016), or alternative combinations of feedstock. The moisture content of the feedstock (wet or dry) impacts the amount of biogas generation. Wet anaerobic digesters process feedstock with a solids content of less than 15 percent while dry anaerobic digesters process feedstock with a solids content greater than 15 percent (EPA 2020). Digesters may also operate in batch or continuous mode, which affects the feedstock loading and removal. Batch anaerobic digesters are manually loaded with feedstock all at once and then manually emptied while continuous anaerobic digesters are continuously loaded and emptied with feedstock (EPA 2020).

The three main categories of anaerobic digestion facilities included in national greenhouse gas inventories include the following:

- Anaerobic digestion at biogas facilities, or stand-alone digesters, can be industry-dedicated digesters that process waste from on industry or industrial facility (typically food of beverage waste from manufacturing), or multi-source digesters that process feedstocks from various sources (e.g., municipal food scraps, manure, food processing waste). Some stand-alone digesters also co-digest other organics such as yard waste.
- On-farm digesters manage organic matter and reduce odor generated by farm animals or crops. On-farm digesters are found mainly at dairy, swine, and poultry farms where there is the highest potential for methane production to energy conversion. On-farm digesters may also accept food waste as feedstock for co-digestion.
- Digesters at water resource recovery facilities (WRRF) produce biogas through the treatment and reduction of wastewater solids. Some WRRF facilities may also accept and co-digest food waste.

This section focuses on stand-alone anaerobic digestion at biogas facilities. Emissions from on-farm digesters are included Chapter 5 (Agriculture) and AD facilities at WRRFs are included in Section 7.2.

From 1990 to 2022, the estimated amount of waste managed by stand-alone digesters in the United States increased from approximately 988 kt to 11,947 kt, an increase of 1,109 percent. As described in the Uncertainty section, no data sources present the annual amount of waste managed by these facilities prior to 2015 when the EPA began a comprehensive data collection survey. Thus, the emission estimates between 1990 and 2014, and for 2020 to 2022 are general estimates extrapolated from data collected for years 2015 to 2019 via the EPA surveys (EPA 2018, 2019, 2021, and 2023). The steady increase in the amount of waste processed over the time series is likely driven by increasing interest in using biogas produced from waste as a renewable energy source and other organics diversion goals.

In 2022, emissions from stand-alone anaerobic digestion at biogas facilities were approximately 13,380 MT CO_2 Eq. (0.5 kt) (see Table 7-44 and Table 7-45).

Table 7-44: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (MT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4 Generation	22,129	66,388	186,507	348,699	239,720	267,603	267,603
CH_4 Recovery	(21,023)	(63,069)	(177,182)	(331,264)	(227,734)	(254,223)	(254,223)
CH_4 Emissions	**1,106**	**3,319**	**9,325**	**17,435**	**11,986**	**13,380**	**13,380**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 7-45: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4 Generation	1	2	7	12	9	10	10
CH_4 Recovery	(1)	(2)	(6)	(12)	(8)	(9)	(9)
CH_4 Emissions	**+**	**+**	**+**	**1**	**+**	**+**	**+**

+ Does not exceed 0.5 kt CH_4.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology

Methane emissions from anaerobic digestion depend on factors such as the type of waste managed, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), aeration during the digestion process, unintentional leakages, and how the biogas generated is used/combusted (e.g., flared, used on-site, used off-site).

The emissions presented in Table 7-44 were estimated using the IPCC default (Tier 1) methodology (Volume 5, Chapter 4, IPCC 2006) given in Equation 7-49 below, which applies a default leakage factor of 5 percent to the CH_4 generated, which is the product of an emission factor and the mass of organic waste processed (Equation 7-50). Only CH_4 emissions are estimated because N_2O emissions are considered negligible (IPCC 2006). Some Tier 2 data are available (annual quantity of waste digested) for the later portion of the time series (2015 and later). The methods were selected in accordance with IPCC methodological decision trees and available data on organic waste processed.

Per the *2006 IPCC Guidelines*, emissions of CH_4 from anaerobic digestion facilities due to unintentional leakages during process disturbances or other unexpected events are generally between 0 to 10 percent of the amount of CH_4 generated. When facility-specific information or data are unavailable, a 5 percent leakage factor is recommended (IPCC 2006).

Equation 7-49: Methane Emissions Calculation for Anaerobic Digestion

$$CH_4\ Emissions = L \times (G_{CH4})$$

where,

CH_4 Emissions = total CH_4 emissions in inventory year, Gg CH_4
L = leakage factor, default assumed 5 percent (IPCC 2006)
G_{CH4} = total CH_4 generation in inventory year, Gg CH_4

Equation 7-50: Methane Generation Calculation for Anaerobic Digestion

$$G_{CH4} = \sum_i (M_i \times EF_i) \times 10^{-3}$$

where,

M_i = mass of organic waste treated by biological treatment type *i*, Gg, see Table 7-46
EF = emission factor for treatment *i*, g CH_4/kg waste treated, 0.8 Mg/Gg CH_4
i = anaerobic digestion

Per IPCC Tier 1 methodology defaults, the emission factor for CH_4 assumes a moisture content of 60 percent in the wet waste (IPCC 2006). Both liquid and solid wastes are processed by stand-alone digesters and the moisture content entering a digester may be higher. One emission factor, 0.8 Mg/Gg CH_4 is applied for the entire time series (IPCC 2006 Volume 5, Chapter 4, Table 4.1).

The annual quantity of waste digested is sourced from EPA surveys of anaerobic digestion facilities (EPA 2018, 2019, 2021, and 2023). The EPA was granted the authority to survey anaerobic digestion facilities that process food waste annually through an Information Collection Request (ICR No. 2533.01). The scope includes stand-alone and

co-digestion facilities (on-farm and water resource recovery facilities [WRRF]). Four reports with survey results have been published to date:

- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results* (EPA 2018)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results* (EPA 2019)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in (2017 & 2018): Survey Results* (EPA 2021)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in (2019): Survey Results* (EPA 2023).

These reports present aggregated survey data including the annual quantity of waste processed by digester type (i.e., stand-alone, on-farm, and WRRF); waste types accepted; biogas generation and end use; and more. The amount of waste digested as reported in the survey reports were assumed to be in wet weight; the majority of stand-alone digesters were found to be wet and mesophilic (EPA 2019).

The aggregated data presented in the EPA reports are underestimates of the actual amount of processed waste and biogas produced because (1) surveys rarely achieve a 100 percent response rate and some fraction of facilities in each survey year did not respond to the survey; (2) EPA focused the surveys on facilities that primarily process food waste, although non-food waste quantities processed were also collected and reported; and (3) while the EPA has done due diligence to identify all stand-alone digesters that process food waste, EPA may not have identified all facilities across the United States and its territories.

The annual quantity of waste digested at stand-alone digesters for 1990 to 2014 (only 1990 and 2005 are shown in Table 7-46) was estimated by multiplying the count of estimated operating facilities (as presented in Table 7-47) by the weighted average of waste digested in 2015 to 2019 collected through EPA's survey data (EPA 2018, 2019, 2021, 2023). Masked survey responses of food and non-food waste processed were shared with the *Inventory* team by the EPA team leading the EPA AD Data Collection Surveys. This provided an accurate count of the number of facilities that provided annual quantities of digested waste, which matters for the weighted average. The weighted average applied to the current *Inventory* is calculated as follows for 1990 to 2014:

Equation 7-50: Weighted Average of Waste Processed

$$Weighted\ Average\ Waste\ Processed = \sum_{year} \frac{W_{year} \times Fac_{year}}{Sum\ of\ All\ Fac}$$

where,

year = the year of data for the average waste processed and count of facilities in the numerator

W = total average waste processed in the respective survey year, food and non-food waste (short tons).

Fac = the number of facilities that reported an amount of waste processed in the respective survey year. Note the number of facilities that provided an annual quantity of waste processed data was internally shared and differs from the total number of facilities that responded to the EPA surveys as presented in EPA (2018, 2019, 2021, and 2023).

The number of facilities that reported annual quantities of waste digested to the EPA survey varies by year. The masked data provided by the EPA AD survey data collection team include data for 41, 44, 42, 43, and 18 facilities between 2015 to 2019, respectively. This data was used to calculate the weighted average of waste digested of 239,709 short tons.

Estimates of the quantity of waste digested for 1990 to 2014 are calculated by multiplying the weighted average of waste digested from the masked survey data by the count of operating facilities in each year. This calculation

assumes that each facility operates continuously from the first year of operation for the remainder of the time series. Additional efforts will be made to quantify the number of operating facilities and estimates of the total waste digested by year for future Inventories as described in the Planned Improvements section.

Estimates of the quantity digested for 2015 to 2019 were taken from EPA's AD survey data (EPA 2018, EPA 2019, EPA 2021, and EPA 2023). In the 1990 to 2022 *Inventory*, the quantity of liquid, non-food waste was converted to tons using a general conversion factor of 3.8 lbs/gallon.

The EPA (2023) report provides a significant increase in data granularity for stand-alone digesters compared to earlier reports because food waste processed by the beverage sector is included as tons of food waste processed as opposed to gallons of food waste processed in prior survey years. Detail on the sources and types of the liquid food and non-food waste was not available in the 2015 to 2018 data to reliably convert the data to tons. However, the 2019 data point provides some assurance that using a general conversion factor to convert liquid waste to tons yields a more comprehensive estimate of total waste processed at stand-alone AD facilities.

The estimate of waste digested for 2020 to 2022 were extrapolated using the average of the waste digested from the 2017 to 2019 survey data (EPA 2021, 2023) as a proxy. The average did not include data from 2015 and 2016 because there is a drop in the amount of waste digested by nearly 1 million tons between 2016 and 2017. The quantities digested between 2015 and 2016 are similar, and quantities digested between 2017 and 2018 are similar. The quantity digested for 2019 is nearly twice the amount of prior EPA survey years because food waste from the beverage sector were able to be accurately converted to tons. Estimates for 2020 to 2022 will be updated as future EPA survey reports are published.

Table 7-46: Estimated U.S. Waste Digested (kt) from 1990-2022

Activity	1990	2005	2018	2019	2020	2021	2022
Waste Digested	988	2,964	8,326	15,567	10,702	11,947	11,947

The estimated count of operating facilities is calculated by summing the count of digesters that began operating by year over the time series. The year a digester began operating is sourced from EPA (2021). This assumes all facilities are in operation from their first year of operation throughout the remainder of the time series, including facilities prior to 1990. This is likely an overestimate of facilities operating per year but does not necessarily translate to an overestimate in the amount of waste processed because a weighted average of waste processed for the surveyed facilities is applied to these years. The number of facilities in 1990 to 2014 are directly used in calculating the emissions for those years.

Table 7-47: Estimated Number of Stand-Alone AD Facilities Operating from 1990-2022

Year	1990	2005	2018	2019	2020	2021	2022
Estimated Count of Operational Facilities	4	12	68	68	68	68	68

Uncertainty

The methodology applied for the 1990 to 2014 emissions estimates should be considered a starting point to build on in future years if additional historical data become available. Five years of facility-provided data are available (2015 to 2019) while the rest of the time series is estimated based on an assumption of facility counts and the 2015 to 2019 weighted average annual waste digested as calculated from survey data. The major limitations, and uncertainty drivers in the emissions estimates, are related to the uncertainty in assumptions to ensure completeness across the time series and the limitations in the EPA AD survey data, as described below:

1. The EPA AD surveys (EPA 2018; EPA 2019; EPA 2021; EPA 2023) did not receive a 100 percent response rate, meaning that the survey data represent a portion, albeit the majority, of stand-alone digesters, and annual waste processed. The methodology applied here did not attempt to estimate waste digested by facilities that did not respond to the survey, which likely underestimates the quantity of waste digested and CH_4 emissions.

2. The EPA AD survey data (EPA 2018; EPA 2019) present both food and non-food waste digested. The non-food waste was reported as liquid (gallons) and solid (tons). The quantity of liquid waste managed for 2015 and 2016, which is used as a proxy for 1990 to 2014, was converted to tons using a general conversion factor of 3.8 lbs/gallon. This may slightly over- or underestimate the quantity of waste digested and CH_4 emissions between 1990 to 2018. This conversion was not made by EPA in the survey report (EPA 2018). However, EPA (2021) did convert the liquid waste managed to tons for 2017 and 2018 using the general conversion factor of 3.8 lbs/gallon.
3. The assumption required to estimate the activity data for 1990 to 2014 may overestimate the number of facilities in operation because it assumes that each facility operates from its start year for the entire time series (i.e. facility closures are not taken into account). This introduces a large amount of uncertainty in the estimates compared to years where there is directly reported survey data. It is unclear whether this under- or over-estimates the quantity of waste digested and CH_4 emissions.
4. The most recent EPA AD survey data (EPA 2023) includes waste processed by the beverage sector, which was not presented in prior survey years. No attempts were made to separately estimate and include this waste stream in years prior to 2019 (i.e. the EPA 2023 survey). This means that annual CH_4 estimates for 1990 to 2018 are underestimated.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±54 percent for the Approach 1 methodology.

Emissions from anaerobic digestion at stand-alone biogas facilities in 2022 were estimated to be between 6,175 and 20,586 MT CO_2 Eq., which indicates a range of 54 percent below to 54 percent above the 2022 emission estimate of CH_4 (see Table 7-48). A ±20 percent uncertainty factor is applied to the annual amount of material digested (i.e., the activity data), which was developed with expert judgment (Bronstein 2021). A ±50 percent default uncertainty factor is applied to the CH_4 emission factor (IPCC 2006). Using the IPCC's error propagation equation (Equation 3.1 in IPCC 2006 Volume 1, Chapter 3), the combined uncertainty percentage is ±54 percent.

Table 7-48: Approach 1 Quantitative Uncertainty Estimates for Emissions from Anaerobic Digestion (MT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Anaerobic Digestion at Biogas Facilities	CH_4	13,380	6,175	20,586	-54%	+54%

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current *Inventory*.

Recalculations Discussion

For the current *Inventory*, a methodological change was made whereby the CH_4 emissions are considered equal to leakage from the digester network of pipes. A leakage factor of 5 percent as recommended in IPCC 2006 is applied to the CH_4 generation estimate for all years in the time series. This methodological change applies to every year in the time series and significantly reduces annual CH_4 emissions estimates. Previously the EPA AD Survey data of amount of biogas produced at AD facilities was used for the amount of gas recovered, with the remaining gas assumed to be leaked or emitted. This method calculated higher emissions estimates, which showed most of the gas generated at an AD was emitted, instead of used in biogas projects. This was inconsistent with the EPA AD Survey findings that approximately 95 percent of stand-alone AD facilities use some or all biogas onsite and the

IPCC guidance on default leakage from AD facilities. EPA will further investigate the survey data for the biogas produced data point, since it indicates very low gas utilized as compared to this revised methodology.

The weighted average of waste digested was recalculated for the current *Inventory* to incorporate EPA AD survey data from 2017 to 2019. The recalculation increased the weighted average annual waste digested from 216,494 short tons to 272,249 short tons, an approximately 25 percent increase. The weighted average is applied to the estimated count of stand-along digesters operating between 1990 to 2014 and resulted in a 26 percent increase in the amount of waste digested annually.

Additional recalculations were also made for the waste processed in 2019 to 2021. In the previous *Inventory*, the amount of waste processed for 2019 to 2021 was extrapolated based on available survey data. With the publication of survey data for 2019 (EPA 2023), the values for 2019 were replaced and the extrapolation for years 2020 to 2022 were updated. Recalculations for the amount of waste processed resulted in increases of 88 percent in 2019, 30 percent in 2020, and 45 percent in 2021.

Despite the increase of waste processed across the time series, recalculations for this *Inventory* resulted in significant decreases to the emissions estimates as compared to the previous 1990 through 2021 *Inventory*. Emissions estimates were reduced by 93 percent annually between 1990 to 2014, and between 90 to 95 percent between 2015 to 2021. For example, the net emissions estimate in 2021 decreased from 6.1 kt to 0.48 kt. The decrease in emissions is driven by the methodological change described in the first paragraph.

Planned Improvements

EPA will continue to incorporate updated survey data from future EPA AD Data Collection Surveys when the survey data are published. These revisions will change the estimated emissions for 2020 to 2022. Additionally, quality control checks on the default emission factor used to determine CH_4 generation is in process.

EPA will also reassess how best to estimate annual waste processed using proxy data for years between the EPA AD Data Collection Survey reports as needed (e.g., for 2020, 2021, 2022). The methodology described here assumes the same average amount of waste is processed each year for 2020 through 2022.

EPA continues to seek out data sources to confirm the estimated number of operational facilities by year prior to 2015 and consider how best to estimate the quantity of waste processed per year by these facilities with the goal of better estimating the annual quantity of waste digested between 1990 to 2014. Available data will also be compiled where available for facilities that did not directly respond to the EPA AD Data Collection surveys for completeness.

7.5 Waste Incineration (CRT Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the combustion of waste are accounted for in the Energy sector rather than in the Waste sector because almost all combustion of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The combustion of waste in the United States in 2022 resulted in 12.7 MMT CO_2 Eq. of emissions. For more details on emissions from the combustion of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste combustion include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided.

An analysis of the likely level of medical waste incineration emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of inventory reporting under the Paris Agreement and the UNFCCC. More information on this analysis is provided in Annex 5.

Furthermore, an analysis was conducted on the likely level of sewage sludge incineration emissions based on the total amount of sewage sludge generated and assumed percent incineration. Based on assumed amount of sludge incinerated and non-CO_2 factors for solid biomass it was determined that annual greenhouse gas emissions for sewage sludge incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of inventory reporting under the Paris Agreement and the UNFCCC. More information on this analysis is provided in Annex 5.

7.6 Waste Sources of Precursor Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of precursors to greenhouse gases. The reporting requirements of the Paris Agreement and the UNFCCC[13] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmosphere aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from waste sources for the years 1990 through 2022 are provided in Table 7-49.

Table 7-49: Emissions of NO_x, CO, NMVOC, and SO_2 from Waste (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
NO_x	84	51	73	73	76	76	75
CO	1,028	1,178	1,182	1,182	1,342	1,343	1,343
NMVOCs	870	152	156	157	173	172	172
SO_2	36	20	23	23	33	32	31

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2022 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 7-49, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Emissions Inventory System (EIS) sectors. The EIS sectors are mapped to categories more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on discussions between the EPA *Inventory* and NEI staff (see crosswalk documented in Annex 6.3).[14] EIS sectors mapped to the waste sector categories in this report include: waste disposal and recycling

[13] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[14] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1

(landfills; publicly owned treatment works; industrial wastewater; treatment, storage, and disposal facilities; waste incineration; and other).[15] As described in the NEI Technical Support Documentation (TSD) (EPA 2023b), emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing. Within the NEI, there is only one EIS sector for waste generating and handling processes, so precursor estimates are aggregated in Table 7-49 for consistency with NEI reporting. Future presentations of this data may disaggregate emissions so it better maps to reporting categories under the Paris Agreement and the UNFCCC.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022, which are described in detail in the NEI's TSD (EPA 2021). No quantitative estimates of uncertainty were calculated for this source category.

source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRT), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

[15] Precursor emissions from waste incineration were reported in the Energy sector in the previous *Inventory* but are not disaggregated from the Waste sector in this report.

8. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) “Other” sector.

9. Recalculations and Improvements

Each year, many emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised through the use of better methods and/or data with the goal of improving inventory quality and reducing uncertainties, including improving the transparency, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006) and its refinements/supplements, which state:

> *"Both methodological changes and refinements over time are an essential part of improving inventory quality. It is good practice to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors."*

When methodological changes have been implemented, the previous *Inventory's* time series (i.e., 1990 to 2021) is assessed and potentially recalculated to reflect the change, per guidance in IPCC (2006, 2019). Changes in historical data are often the result of changes in statistical data supplied by other agencies, and these changes do not necessarily impact the entire time series.

The results of all methodological changes and historical data updates made in the current *Inventory* in calculating CO_2-equivalent U.S. greenhouse gas emissions and sinks are presented in Figure 9-2, while impacts on both total and net emissions by gas are presented in Table 9-1 and Table 9-2. Collectively, these changes resulted in an average annual decrease of 114.8 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.) (1.9 percent) in net total emissions relative to the previously published *Inventory* (i.e., the 1990 to 2021 report) in units of MMT CO_2 Eq.

Figure 9-1: Impacts of Recalculations on Net Emissions

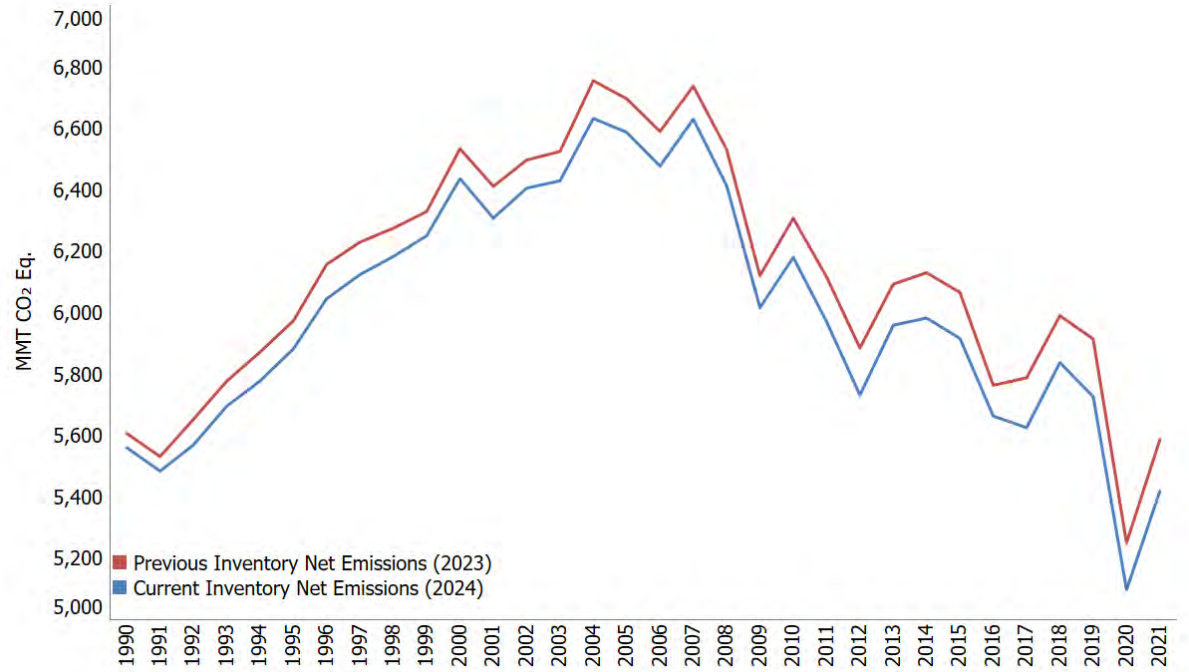

Table 9-1: Overall Impact of Recalculations by Gas Compared to Previous *Inventory*

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
CO_2	10.7	(5.3)	(15.6)	(27.7)	(25.7)	(15.0)	(4.6)
CH_4[a]	3.0	4.4	(2.6)	(13.4)	(6.9)	(7.0)	0.5
N_2O[a]	1.9	3.4	9.3	6.1	2.3	4.9	3.9
HFCs and PFCs	34.0	14.8	6.8	7.2	6.1	5.7	21.2
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Change in LULUCF Total Net Flux[b]	(95.8)	(123.0)	(148.8)	(153.4)	(120.2)	(151.4)	(133.6)
LULUCF Emissions[c]	0.0	(3.5)	(1.6)	(6.2)	(8.0)	(4.9)	(2.2)
CH_4	(0.4)	(2.8)	(1.8)	(4.4)	(6.1)	(3.8)	(2.0)
N_2O	0.4	(0.7)	0.2	(1.8)	(1.9)	(1.1)	(0.2)
Change in LULUCF Sector Net Total[d]	(95.7)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**

[a] Does not include CH_4 and N_2O emissions from LULUCF.

[b] LULUCF carbon stock change includes any C stock gains and losses from all land use and land use conversion categories

[c] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[d] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes. More detail on the impacts of recalculations on the LULUCF sector can be found in Table 9-5.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 9-2: Overall Impact of Recalculations by Sector Compared to Previous *Inventory*

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
Energy	16.8	1.6	(13.4)	(32.1)	(25.6)	(16.7)	(0.2)
IPPU	33.5	15.3	5.0	5.1	4.7	5.2	20.4
Agriculture	3.1	4.1	12.9	5.6	2.4	6.7	5.3
LULUCF	(95.8)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Waste	0.0	(0.1)	(0.5)	(0.2)	0.2	0.0	(0.1)
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 9-4 and Table 9-5 include the category-level quantitative effects of methodological changes and historical data updates made in the current *Inventory* in calculating CO_2-equivalent U.S. greenhouse gas emissions by gas across all sectors. To understand the details of any specific recalculation or methodological improvement, see the Recalculations sections within each source/sink categories' section found in Chapters 3 through 7 of this report. A discussion of *Inventory* improvements in response to review processes is described in Annex 8.

Key Recalculations and Improvements for 1990-2022 *Inventory*

The current *Inventory* includes new categories that improve completeness of the national estimates. Specifically, the current report includes CO_2 emissions from ceramics production and non-metallurgical magnesia production within other process use of carbonates category, fluorinated gases from fluorochemical production other than HCFC-22 within the fluorochemical production category, and managed forest land in Hawaii and several U.S. Territories.[1] The report also now includes SF_6 and PFCs from product uses.

The following source and sink categories underwent the most significant methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken are provided for these categories.

Table 9-3: Key Recalculations

Sector	Category	Reason for Recalculation or Improvement	Impact of Recalculation on 2021 Value	Average Impact over Time Series	
				Percent	(MMT CO_2 Eq.)
LULUCF	Forest Land Remaining Forest Land (CO_2)	Accuracy. Use of new and updated data and methods from the USFS Forest Inventory and Analysis program, see details in Chapter 6.2.	148.8	+21.7%	159.1
LULUCF	Land Converted to Grassland (CO_2)	Accuracy. Use of new activity data and methods from FIA, USDA-NRCS NRI and DayCent model, see details in Chapter 6.7.	49.2	-237.1%	53.1
LULUCF	Land Converted to Cropland (CO_2)	Accuracy. Use of new activity data and methods from FIA, USDA-NRCS NRI and DayCent model, see details in Chapter 6.5.	21.6	-36.6%	20.7

[1] American Samoa, Guam, Northern Marianas Islands, U.S. Virgin Islands, and Puerto Rico.

LULUCF	Grassland Remaining Grassland (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI, and re-calibration of the DayCent model, see details in Chapter 6.6.	0.6	+1,850.1%	10.7
Energy	Non-Energy Use of Fuels (CO_2)	Accuracy and Consistency. Use of new, updated, and recategorized data from U.S. International Trade Commission, EIA and other data sources (ACC), see details in Chapter 3.2.	28.6	-8.2%	10.1
LULUCF	Land Converted to Settlements (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI, FIA, and extended time series, see details in Chapter 6.11.	12.8	-9.3%	7.7
IPPU	Fluorochemical Production (HFCs)	Completeness. Inclusion of new subcategory fluorochemical production other than HCFC-22, see details in Chapter 4.14 and 4.15.	1.7	+58.7%	6.8
Energy	Fossil Fuel Combustion (CO_2)	Accuracy and Consistency. Use of updated data and alignment of methodology from EIA, see details in Chapter 3.1.	15.2	+0.1%	5.8
LULUCF	Cropland Remaining Cropland (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI and the OpTIS remote-sensing data, and methods to extend time series, see details in Chapter 6.4.	13.0	+26.4%	4.2
Agriculture	Agricultural Soil Management (N_2O)	Accuracy. Use of updated time series data for land representation, re-calibration of DayCent model, and updated cropland management parameters, see details in Chapter 5.4.	3.9	+1.1%	3.3
Energy	Petroleum Systems (CH_4)	Accuracy. Use of additional data from GHGRP, see details in Chapter 3.6.	1.5	-4.6%	2.5
LULUCF	Wetlands Remaining Wetlands (CO_2)	Accuracy. Use of new data and updated emissions factors, see details in Chapter 1.8.	2.3	+2.2%	2.4

Figure 9-2: Impacts of Recalculations to U.S. Greenhouse Gas Emissions and Sinks by Sector

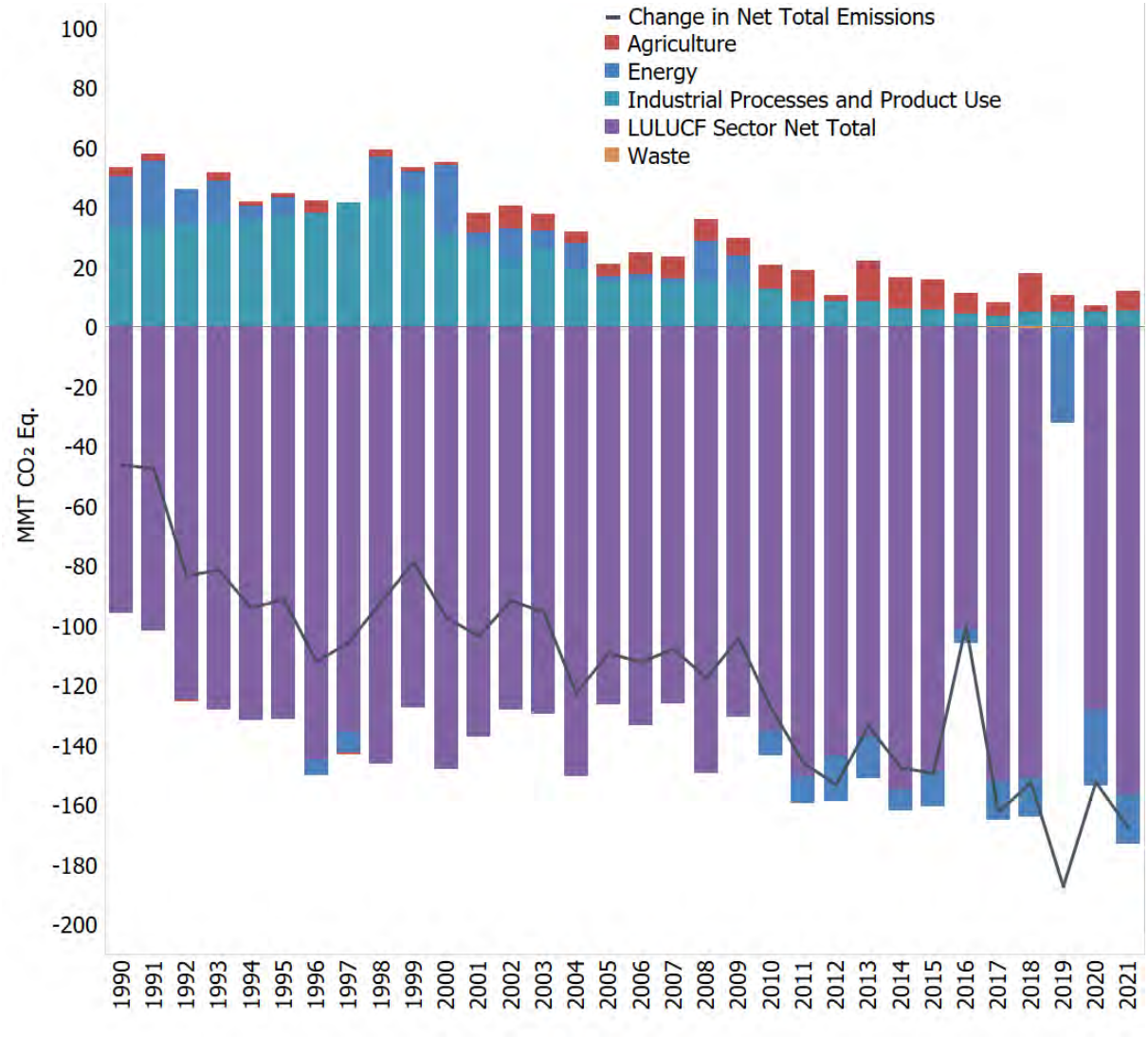

Table 9-4: Revisions to U.S. Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
CO_2	**10.7**	**(5.3)**	**(15.6)**	**(27.7)**	**(25.7)**	**(15.0)**	**(4.6)**
Fossil Fuel Combustion	*24.0*	*(3.2)*	*(1.7)*	*(3.3)*	*(3.2)*	*15.2*	*5.8*
Electric Power Sector	NC	NC	NC	NC	+	+	+
Transportation	NC	NC	0.2	0.2	0.3	1.1	0.1
Industrial	24.0	(3.2)	(3.1)	(6.1)	(5.9)	4.8	5.2
Residential	(+)	+	0.7	1.5	1.6	4.7	0.3
Commercial	(+)	+	0.5	1.0	0.8	4.5	0.2
U.S. Territories	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Non-Energy Use of Fuels	(13.3)	(3.9)	(11.1)	(21.1)	(21.5)	(28.6)	(10.1)
Natural Gas Systems	0.2	1.3	(+)	(+)	0.3	(0.4)	0.4
Cement Production	NC	NC	NC	NC	NC	NC	NC

Lime Production	NC	NC	NC	NC	NC	NC	NC
Other Process Uses of Carbonates[a]	0.9	1.0	0.6	0.6	0.6	0.6	0.8
Glass Production	0.3	(+)	NC	NC	NC	NC	+
Soda Ash Production	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Titanium Dioxide Production	NC	NC	NC	(0.1)	0.1	NC	+
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	0.2	+
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	NC	NC	NC	NC	(+)	(+)
Urea Consumption for Non-Agricultural Purposes	NC	NC	+	(+)	(+)	1.6	0.1
Phosphoric Acid Production	NC	NC	NC	NC	NC	(+)	(+)
Petrochemical Production	(1.5)	(0.5)	(2.1)	(2.2)	(1.9)	(2.5)	(1.4)
Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Lead Production	NC	NC	NC	NC	(+)	(+)	(+)
Zinc Production	NC	NC	NC	NC	NC	+	+
Petroleum Systems	0.1	(+)	(1.3)	(1.4)	(0.1)	(0.5)	(0.1)
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	+	+	NC	NC	NC	(+)	+
Liming	NC	NC	NC	NC	(+)	(0.7)	(+)
Urea Fertilization	NC	NC	(+)	+	+	+	(+)
Coal Mining	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Substitution of Ozone Depleting Substances	NC	NC	NC	NC	NC	NC	NC
Biomass and Biodiesel Consumption[b]	*NC*	*NC*	*(+)*	*(+)*	*(9.9)*	*(12.3)*	*(0.7)*
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
CH_4[d]	**3.0**	**4.4**	**(2.6)**	**(13.4)**	**(6.9)**	**(7.0)**	**0.5**
Stationary Combustion	+	(+)	+	+	(0.8)	(0.9)	(+)
Mobile Combustion	+	(0.1)	(+)	(+)	(+)	(+)	(0.1)
Coal Mining	NC	(0.4)	NC	(+)	NC	(+)	(+)
Abandoned Underground Coal Mines	NC	NC	NC	NC	NC	(0.1)	(+)
Natural Gas Systems	3.7	6.9	(4.0)	(4.9)	(5.0)	(6.8)	1.9
Petroleum Systems	(1.9)	(2.7)	(1.6)	(7.7)	(1.2)	(1.5)	(2.5)
Abandoned Oil and Gas Wells	0.1	0.2	0.2	0.1	0.2	0.3	0.2
Petrochemical Production	(0.2)	(0.1)	(0.3)	(0.4)	(0.3)	(0.4)	(0.2)
Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	+	(+)	+
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	+	+	(+)	(+)	0.1	1.5	0.1
Manure Management	0.1	0.1	1.2	0.9	0.2	0.4	0.3
Rice Cultivation	1.0	0.4	2.5	(1.2)	1.0	1.5	1.0
Field Burning of Agricultural Residues	0.1	0.2	0.1	0.2	0.1	0.1	0.1
Landfills	NC	(+)	(0.4)	(0.3)	(0.7)	(0.6)	(+)
Wastewater Treatment	(+)	(+)	(+)	(+)	(0.4)	(0.4)	(+)
Composting	NC	NC	NC	NC	NC	NC	NC
Anaerobic Digestion at Biogas Facilities	(+)	(+)	(0.2)	(0.2)	(0.2)	(0.2)	(0.1)
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels[c]	NC	NC	NC	NC	NC	NC	NC
N_2O[d]	**1.9**	**3.4**	**9.3**	**6.1**	**2.3**	**4.9**	**3.9**
Stationary Combustion	0.1	(+)	(+)	(+)	(0.1)	(0.1)	+
Mobile Combustion	+	+	0.1	0.1	+	0.1	0.1
Adipic Acid Production	NC	NC	(+)	NC	NC	NC	(+)

Nitric Acid Production	NC	NC	NC	NC	NC	NC	NC
Manure Management	1.0	0.7	(0.6)	(0.6)	(0.6)	(0.3)	0.5
Agricultural Soil Management	0.8	2.6	9.7	6.3	1.6	3.9	3.3
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wastewater Treatment	NC	NC	+	0.3	1.4	1.1	0.1
N_2O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Caprolactam, Glyoxal, and Glyoxylic Acid Production	NC	NC	NC	NC	(+)	(+)	(+)
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	NC	NC
Electronics Industry	NC	NC	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
Petroleum Systems	(+)	(+)	+	(+)	(+)	(+)	(+)
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
HFCs, PFCs, SF_6 and NF_3	**34.0**	**14.8**	**6.8**	**7.2**	**6.1**	**5.7**	**21.2**
HFCs	**8.7**	**5.4**	**3.0**	**2.7**	**2.1**	**1.9**	**6.9**
Substitution of Ozone Depleting Substances	NC	0.1	0.1	0.1	0.1	0.2	0.1
Fluorochemical Production[e]	8.7	5.3	2.9	2.6	2.0	1.7	6.8
Electronics Industry	(+)	(+)	(+)	+	(+)	+	+
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
PFCs	**17.7**	**4.2**	**3.1**	**3.3**	**2.7**	**2.8**	**9.3**
Aluminum Production	NC	NC	NC	NC	NC	+	+
Fluorochemical Production	17.5*	4.0*	2.9*	3.0*	2.5*	2.6*	9.1*
Electronics Industry	(+)	+	0.1	0.1	0.1	+	+
Substitution of Ozone Depleting Substances	NC	+	(+)	(+)	(+)	(+)	(+)
SF_6 and PFCs from Other Product Use	0.1*	0.1*	0.2*	0.2*	0.2*	0.1*	0.1*
Electrical Equipment	+	(+)	NC	(+)	+	(+)	(+)
SF_6	**7.4**	**4.7**	**0.5**	**0.6**	**0.6**	**0.4**	**4.6**
Electrical Equipment	NC	+	(0.2)	(+)	+	+	(+)
SF_6 and PFCs from Other Product Use	1.3*	1.3*	0.8*	0.6*	0.5*	0.4*	1.2*
Fluorochemical Production	5.8*	3.3*	+	+	+	+	3.3*
Electronics Industry	NC	+	+	+	+	(+)	+
Magnesium Production and Processing	0.2	0.1	NC	NC	NC	+	0.1
NF_3	**0.3**	**0.6**	**0.1**	**0.6**	**0.7**	**0.5**	**0.5**
Electronics Industry	NC	NC	+	+	+	(+)	+
Fluorochemical Production	0.3*	0.6*	0.1*	0.6*	0.7*	0.5*	0.5*
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Percent Change in Total Emissions	**0.8%**	**0.2%**	**0.0%**	**-0.4%**	**-0.4%**	**(+)**	**0.3%**
Change in LULUCF Sector Net Total[f]	(95.8)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**
Percent Change in Net Emissions	**-0.8%**	**-1.6%**	**-2.5%**	**-3.2%**	**-2.9%**	**-3.0%**	**-1.9%**

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

* Indicates a new source for the current *Inventory* year. Emissions from new sources are captured in net emissions and percent change totals.

[a] Category includes emissions from ceramics production (new subcategory, not estimated in the previous *Inventory*), other uses of soda ash, and non-metallurgical magnesia (new subcategory, not estimated in the previous *Inventory*) in the current *Inventory.*

[b] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[c] Emissions from international bunker fuels are not included in totals.

[d] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals in Table 9-4. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland

fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[e] This category was reported as HCFC-22 production in the 1990 to 2021 *Inventory*.

[f] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes. More detail on the impacts of recalculations on the LULUCF sector can be found in Table 9-5.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 9-5: Revisions to U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2017	2018	2019	2020	Average Annual Change
Forest Land Remaining Forest Land	**(153.1)**	**(164.6)**	**(170.4)**	**(169.0)**	**(162.4)**	**(153.4)**	**(160.7)**
Changes in Forest Carbon Stocks[a]	(153.3)	(161.8)	(169.1)	(163.8)	(154.6)	(148.8)	(159.1)
Non-CO_2 Emissions from Forest Fires[b]	0.3	(2.8)	(1.3)	(5.1)	(7.7)	(4.5)	(1.6)
N_2O Emissions from Forest Soils[c]	+	(+)	(+)	(+)	(+)	(+)	(+)
Non-CO_2 Emissions from Drained Organic Soils[d]	NC	NC	NC	NC	NC	NC	NC
Land Converted to Forest Land	**(1.8)**	**(1.7)**	**(2.1)**	**(2.0)**	**(2.0)**	**(2.1)**	**(1.8)**
Changes in Forest Carbon Stocks[e]	(1.8)	(1.7)	(2.1)	(2.0)	(2.0)	(2.1)	(1.8)
Cropland Remaining Cropland	**18.1**	**(2.6)**	**(1.2)**	**(4.9)**	**14.5**	**(13.0)**	**(4.2)**
Changes in Mineral and Organic Soil Carbon Stocks	18.1	(2.6)	(1.2)	(4.9)	14.5	(13.0)	(4.2)
Land Converted to Cropland	**(9.4)**	**(20.1)**	**(24.4)**	**(24.9)**	**(27.4)**	**(21.6)**	**(20.7)**
Changes in all Ecosystem Carbon Stocks[f]	(9.4)	(20.1)	(24.4)	(24.9)	(27.4)	(21.6)	(20.7)
Grassland Remaining Grassland	**15.7**	**13.2**	**17.8**	**14.2**	**10.5**	**0.9**	**10.8**
Changes in Mineral and Organic Soil Carbon Stocks	15.7	13.0	17.3	14.5	10.0	0.6	10.7
Non-CO_2 Emissions from Grassland Fires[g]	0.1	0.1	0.5	(0.3)	0.4	0.3	0.1
Land Converted to Grassland	**41.9**	**61.9**	**49.4**	**48.7**	**54.6**	**49.2**	**53.1**
Changes in all Ecosystem Carbon Stocks[f]	41.9	61.9	49.4	48.7	54.6	49.2	53.1
Wetlands Remaining Wetlands	**(4.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.9)**
Changes in Organic Soil Carbon Stocks in Peatlands	NC	NC	(0.1)	(0.1)	(0.1)	(0.2)	(+)
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(2.4)	(2.4)	(2.3)	(2.3)	(2.3)	(2.3)	(2.4)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Non-CO_2 Emissions from Peatlands Remaining Peatlands	NC	NC	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Flooded Land Remaining Flooded Land	(2.3)	(1.3)	(1.2)	(1.2)	(1.2)	(1.2)	(1.5)
Land Converted to Wetlands	**3.9**	**0.4**	**(0.1)**	**(0.1)**	**0.1**	**0.1**	**1.1**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	(+)	(+)	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Changes in Land Converted to Flooded Land	2.2	0.3	(+)	(+)	0.1	0.1	0.6
CH_4 Emissions from Land Converted to Flooded Land	1.8	0.2	(+)	(+)	+	+	0.5
Settlements Remaining Settlements	**(1.4)**	**(1.4)**	**(6.0)**	**(7.1)**	**(0.2)**	**0.2**	**(1.8)**
Changes in Organic Soil Carbon Stocks	(1.4)	(2.1)	(1.6)	(1.3)	(0.7)	(0.4)	(1.8)

Changes in Settlement Tree Carbon Stocks	(0.2)	0.4	(4.9)	(6.2)	0.1	+	(0.3)
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	NC	NC	NC	NC	NC	0.1	+
N_2O Emissions from Settlement Soils[h]	0.3	0.3	0.5	0.5	0.5	0.5	0.4
Land Converted to Settlements	**(5.2)**	**(7.9)**	**(9.7)**	**(10.9)**	**(12.2)**	**(12.8)**	**(7.7)**
Changes in all Ecosystem Carbon Stocks[f]	(5.2)	(7.9)	(9.7)	(10.9)	(12.2)	(12.8)	(7.7)
Change in LULUCF Total Net Flux[i]	**(95.8)**	**(123.0)**	**(148.8)**	**(153.4)**	**(120.2)**	**(151.4)**	**(133.6)**
Change in LULUCF Emissions[j]	**+**	**(3.6)**	**(1.6)**	**(6.2)**	**(8.0)**	**(4.9)**	**(2.2)**
CH_4	(0.4)	(2.8)	(1.8)	(4.4)	(6.1)	(3.8)	(2.0)
N_2O	0.4	(0.7)	0.2	(1.8)	(1.9)	(1.1)	(0.2)
Change in LULUCF Sector Net Total[k]	**(95.8)**	**(126.6)**	**(150.4)**	**(159.5)**	**(128.2)**	**(156.3)**	**(135.8)**
Percent Change in LULUCF Sector Net Total	**-10.9%**	**-16.2%**	**-19.7%**	**-22.7%**	**-16.5%**	**-20.7%**	**-17.0%**

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include N_2O emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[h] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.

[i] LULUCF carbon stock change includes any C stock gains and losses from all land use and land use conversion categories.

[j] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

10. References and Abbreviations

Executive Summary

BEA (2024) *2022 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2023/11).

IEA (2022) *Energy related CO_2 emissions, 2022,* International Energy Agency, Paris. Available online at: https://www.iea.org/reports/co2-emissions-in-2022.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K., Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

National Academies of Sciences, Engineering, and Medicine (2018) *Improving characterization of anthropogenic methane emissions in the United States*. Washington, DC: The National Academies Press. Available online at: https://doi.org/10.17226/24987.

National Research Council (2010) *Verifying greenhouse gas emissions: methods to support international climate agreements*. Washington, DC: The National Academies Press. Available online at: https://doi.org/10.17226/12883.

NOAA/ESRL (2024a) *Trends in Atmospheric Carbon Dioxide*. Available online at: https://gml.noaa.gov/ccgg/trends/. 05 January 2024.

NOAA/ESRL (2024b) *Trends in Atmospheric Methane.* Available online at: https://gml.noaa.gov/ccgg/trends_ch4/. 05 January 2024.

NOAA/ESRL (2024c) *Trends in Atmospheric Nitrous Oxide.* Available online at: https://gml.noaa.gov/ccgg/trends_n2o/. 05 January 2024.

UNFCCC (2014) *Report of the Conference of the Parties on its Nineteenth Session, Held in Warsaw from 11 to 23 November 2013*. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

U.S. Census Bureau (2024) U.S. Census Bureau International Database (IDB). Available online at: https://www.census.gov/programs-surveys/international-programs.html.

Introduction

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2014) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, J. Minx, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, and T. Zwickel (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1435 pp.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007*) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change.* [J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

IPCC/TEAP (2005) *Special Report: Safeguarding the Ozone Layer and the Global Climate System, Chapter 4: Refrigeration*. 2005. Available online at: https://www.ipcc.ch/site/assets/uploads/2018/03/sroc04-1.pdf.

Meinhausen, M., et al. (2017) *Historical Greenhouse Gas Concentrations for Climate Modeling (CMIP6).* Available online at: https://gmd.copernicus.org/articles/10/2057/2017/.

NOAA (2017) Vital Signs of the Planet. Available online at: http://climate.nasa.gov/causes/. Accessed on 9 January 2017.

NOAA/ESRL (2024a) *Trends in Atmospheric Carbon Dioxide*. Available online at: https://gml.noaa.gov/ccgg/trends/gr.html. March 26, 2024.

NOAA/ESRL (2024b) *Trends in Atmospheric Methane.* Available online at: https://gml.noaa.gov/ccgg/trends_ch4/. March 26, 2024.

NOAA/ESRL (2024c) *Trends in Atmospheric Nitrous Oxide.* Available online at: https://gml.noaa.gov/ccgg/trends_n2o/. March 26, 2024.

NOAA/ESRL (2024d) *Trends in Atmospheric Sulfur Hexafluoride*. Available online at: https://gml.noaa.gov/ccgg/trends_sf6/. March 26, 2024.

Rigby, M., et al. (2010) *History of Atmospheric SF_6 from 1973 to 2008.* Available online at: www.atmos-chem-phys.net/10/10305/2010. March 23, 2024.

UNEP/WMO (1999) Information Unit on Climate Change. Framework Convention on Climate Change. Available online at: http://unfccc.int.

UNFCCC (2014) *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013*. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

USGCRP (2017) *Climate Science Special Report: Fourth National Climate Assessment, Volume I.* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp, doi: 10.7930/J0J964J6. Available online at: https://science2017.globalchange.gov/.

WMO/UNEP (2018) Scientific Assessment of Ozone Depletion: 2018. Available online at: https://csl.noaa.gov/assessments/ozone/2018.

Trends in Greenhouse Gas Emissions

BEA (2024) 2022 *Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2023/11).

EIA (2020) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: http://www.eia.gov/petroleum/fueloilkerosene.

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 – 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) *2023 EPA Automotive Trends Report.* Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/automotive-trends/download-automotive-trends-report.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K., Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Census Bureau (2024) U.S. Census Bureau International Database (IDB). Available online at: https://www.census.gov/programs-surveys/international-programs.html.

U.S. Department of Agriculture, National Agricultural Statistics Service (USDA/NASS) (2023) Farm Production Expenditures Annual Summary. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington DC. Available online at: https://usda.library.cornell.edu/concern/publications/qz20ss48r?locale=en.

Energy

EIA (2024) *Monthly Energy Review, February 2024*, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2024/02).

IEA (2022) *Energy related CO_2 emissions, 2022*, International Energy Agency, Paris. Available online at: https://www.iea.org/reports/co2-emissions-in-2022.

Carbon Dioxide Emissions from Fossil Fuel Combustion

AAR (2008 through 2022) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Private communication with Dan Keen.

AISI (2004 through 2021) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

APTA (2007 through 2020) *Public Transportation Fact Book.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/resources/statistics/Pages/transitstats.aspx.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, D.C.

BEA (2024) *2022 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

BEA (1991 through 2015) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, D.C.

Benson, D. (2002 through 2004) Unpublished data. Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Browning (2022a) Addressing the Time Series Inconsistency in FHWA Data. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2022.

Browning (2022b) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2022.

Browning, L. (2020) *GHG Inventory EF Development Using Certification Data.* Technical Memo, September 2020.

Browning, L. (2019) Updated On-highway CH_4 and N_2O Emission Factors for GHG Inventory. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2019.

Browning, L. (2018a) Updated Methodology for Estimating Electricity Use from Highway Plug-In Electric Vehicles. Technical Memo, October 2018.

Browning, L. (2018b) Updated Non-Highway CH_4 and N_2O Emission Factors for U.S. GHG Inventory. Technical Memo, November 2018.

Browning, L. (2017) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Technical Memo, October 2017.

Coffeyville Resources Nitrogen Fertilizers (2012) Nitrogen Fertilizer Operations. Available online at: http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html.

Dakota Gasification Company (2006) *CO_2 Pipeline Route and Designation Information*. Bismarck, ND.

DHS (2008) Email Communication. Elissa Kay, Department of Homeland Security and Joe Aamidor, ICF International. January 11, 2008.

DLA Energy (2022) Unpublished data from the Fuels Automated System (FAS). Defense Logistics Agency Energy, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOE (1991 through 2020) *Transportation Energy Data Book*. *Edition 40*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6978. Personal Communication between Stacy Davis (DOE) and Deep Shah (ICF) for sharing selected tables from the pre-release version.

DOE (2012) *2010 Worldwide Gasification Database*. National Energy Technology Laboratory and Gasification Technologies Council. Available online at: http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html. Accessed on 15 March 2012.

DOT (1991 through 2023) *Airline Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. Available online at: http://www.transtats.bts.gov/fuel.asp.

Eastman Gasification Services Company (2011) Project Data on Eastman Chemical Company's Chemicals-from-Coal Complex in Kingsport, TN.

EIA (2024a) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035 (2024/02).

EIA (2024b) International Energy Statistics 1980-2022. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/beta/international/.

EIA (2024c) *Quarterly Coal Report: January – September 2023*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0121.

EIA (2023a) *Natural Gas Annual 2022.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0131(20).

EIA (2023b). *Petroleum Supply Annual 2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/petroleum/.

EIA (2023c) Form EIA-923 detailed data with previous form data (EIA-906/920), Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA. November 2023.

EIA (2023d) *Annual Coal Report 2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0584.

EIA (2022) "Energy use in homes." *Use of energy explained.* Available online at: https://www.eia.gov/energyexplained/use-of-energy/homes.php.

EIA (2020a) Glossary. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: https://www.eia.gov/tools/glossary/?id=electricity.

EIA (2020b) "Natural gas prices, production, consumption, and exports increased in 2019." *Today in Energy*. Available online at: https://www.eia.gov/todayinenergy/detail.php?id=37892.

EIA (2018) "Both natural gas supply and demand have increased from year-ago levels." Today in Energy. Available online at: https://www.eia.gov/todayinenergy/detail.php?id=37193.

EIA (2009a) *Emissions of Greenhouse Gases in the United States 2008, Draft Report.* Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE-EIA-0573 (2009).

EIA (2009b) *Manufacturing Consumption of Energy (MECS) 2006*. U.S. Department of Energy, Energy Information Administration, Washington, D.C. Released July 2009.

EIA (2008) *Historical Natural Gas Annual, 1930 – 2008*. Energy Information Administration, U.S. Department of Energy. Washington, D.C.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/renewable/.

EIA (2001) *U.S. Coal, Domestic and International Issues*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. March 2001.

EIA (1990-2001) *State Energy Data System*. Energy Information Administration, U.S. Department of Energy. Washington, D.C.

Environment and Climate Change Canada (2022) Personal Communication between Environment and Climate Change Canada and Vincent Camobreco for imported CO_2. March 2022.

EPA (2024) Acid Rain Program Dataset 1996-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2023) The 2023 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/automotive-trends.

EPA (2022) *Motor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/moves.

EPA (2021) The Emissions & Generation Resource Integrated Database (eGRID) 2019 Technical Support Document. Clean Air Markets Division, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available Online at: https://www.epa.gov/sites/default/files/2021-02/documents/egrid2019_technical_guide.pdf

EPA (2020) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO_2 Emission Factors – Memo.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Erickson, T. (2003) *Plains CO_2 Reduction (PCOR) Partnership*. Presented at the Regional Carbon Sequestration Partnership Meeting Pittsburgh, Pennsylvania, Energy and Environmental Research Center, University of North Dakota. November 3, 2003.

FAA (2024) Personal Communication between FAA and John Steller, Mausami Desai, and Vincent Camobreco for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). March 2024.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm.

FHWA (2015) *Off-Highway and Public-Use Gasoline Consumption Estimation Models Used in the Federal Highway Administration*, Publication Number FHWA-PL-17-012. Available online at: https://www.fhwa.dot.gov/policyinformation/pubs/pl17012.pdf.

Fitzpatrick, E. (2002) *The Weyburn Project: A Model for International Collaboration*.

FRB (2022) *Industrial Production and Capacity Utilization*. Federal Reserve Statistical Release, G.17, Federal Reserve Board. Available online at: http://www.federalreserve.gov/releases/G17/table1_2.htm.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.Marland, G. and A. Pippin (1990) "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy,* 14(4):323.

NREL (2023) "NREL Researchers Reveal How Buildings Across United States Do—and Could—Use Energy." Available online at: https://www.nrel.gov/news/features/2023/nrel-researchers-reveal-how-buildings-across-the-united-

states-do-and-could-use-energy.html#:~:text=Buildings%20are%20responsible%20for%2040,building%20stock%20is%20also%20essential.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

U.S. Aluminum Association (USAA) (2008 through 2021) U*.S. Primary Aluminum Production*. U.S. Aluminum Association, Washington, D.C.

USAF (1998) Fuel Logistics Planning. U.S. Air Force: AFPAM23-221. May 1, 1998.

U.S. Census Bureau (2001 through 2011) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Summary*. Available online at: https://www.census.gov/data/tables/time-series/econ/cir/mq325b.html.

United States Geological Survey (USGS) (2020a) *2020 Mineral Commodity Summaries: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2021b) *2021 Mineral Commodity Summary: Titanium and Titanium Dioxide*. U.S. Geological Survey, Reston, VA.

USGS (2019) *2017 Mineral Yearbook: Aluminum.* U.S. Geological Survey, Reston, VA

USGS (2014 through 2021a) *Mineral Industry Surveys: Silicon*. U.S. Geological Survey, Reston, VA.

USGS (2014 through 2021b) *Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA.

USGS (2014 through 2019) *Minerals Yearbook: Nitrogen [Advance Release*]. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/.

USGS (1991 through 2020) *Minerals Yearbook – Iron and Steel Scrap*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2015a) *Minerals Yearbook: Manufactured Abrasives Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/abrasives/.

USGS (1991 through 2015b) *Minerals Yearbook: Titanium*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2015c) *Minerals Yearbook: Silicon Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/silicon/.

USGS (1996 through 2013) *Minerals Yearbook: Silicon*. U.S. Geological Survey, Reston, VA.

USGS (1995 through 2013) *Minerals Yearbook: Lead Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995, 1998, 2000, 2001, 2002, 2007) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Stationary Combustion (excluding CO_2)

EIA (2024a) *Monthly Energy Review, February 2024*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2024b) *International Energy Statistics 1980-2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/international/data/world.

EPA (2024) Acid Rain Program Dataset 1996-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2022) *MOtor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/moves.

EPA (1997) Compilation of Air Pollutant Emission Factors, AP-42. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

Mobile Combustion (excluding CO_2)

AAR (2008 through 2023) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Private communication with Dan Keen.

ANL (2022) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET2022)*. Argonne National Laboratory. October 2022. Available online at: https://greet.es.anl.gov.

APTA (2007 through 2023) *Public Transportation Fact Book.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/resources/statistics/Pages/transitstats.aspx.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/research/stats/rail/crsum.cfm.

BEA (1991 through 2015) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, D.C.

Benson, D. (2002 through 2004) Personal communication. Unpublished data developed by the Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Browning (2022a) Addressing the Time Series Inconsistency in FHWA Data. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2022.

Browning (2022b) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2022.

Browning (2020) *GHG Inventory EF Development Using Certification Data*. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2020.

Browning, L. (2019) Updated On-highway CH_4 and N_2O Emission Factors for GHG Inventory. Memorandum from ICF to Sarah Roberts and Justine Geidosch, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2019.

Browning, L. (2018) Updated Non-Highway CH_4 and N_2O Emission Factors for U.S. GHG Inventory. Technical Memorandum from ICF International to Sarah Roberts and Justine Geidosch, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2018.

Browning, L. (2005) Personal communication with Lou Browning, "Emission control technologies for diesel highway vehicles specialist," ICF International.

BTS (2023) *Amtrak Fuel Consumption and Travel.* Bureau of Transportation Statistics, Washington, DC. Available online at: https://www.bts.gov/content/amtrak-fuel-consumption-and-travel-1.

DLA Energy (2022) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOE (1993 through 2022) *Transportation Energy Data Book Edition 40*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. Personal Communication between Stacy Davis (DOE) and Deep Shah (ICF) for sharing selected tables from the pre-release version.

DOT (1991 through 2023) Airline *Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. Available online at: http://www.transtats.bts.gov/fuel.asp.

EIA (2024) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2023) *Natural Gas Annual 2022*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0131(22).

EIA (1991 through 2022) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: http://www.eia.gov/petroleum/fueloilkerosene.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: http://www.eia.doe.gov/fuelrenewable.html.

EPA (2023) Annual Certification Test Results Report. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-test-data-vehicles-and-engines.

EPA (2022a) *Motor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/moves.

EPA (2022b) Confidential Engine Family Sales Data Submitted to EPA by Manufacturers. Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

EPA (2004) *Mobile6.2 Vehicle Emission Modeling Software*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.

EPA (1999) *Emission Facts: The History of Reducing Tailpipe Emissions.* Office of Mobile Sources. May 1999. EPA 420-F-99-017. Available online at: https://www.epa.gov/nscep.

EPA (1998) *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–1996*. Office of Mobile Sources, Assessment and Modeling Division, U.S. Environmental Protection Agency. August 1998. EPA420-R-98-009.

EPA (1994a) *Automobile Emissions: An Overview.* Office of Mobile Sources. August 1994. EPA 400-F-92-007. Available online at: https://www.epa.gov/nscep.

EPA (1994b) *Milestones in Auto Emissions Control.* Office of Mobile Sources. August 1994. EPA 400-F-92-014. Available online at: https://www.epa.gov/nscep.

Esser, C. (2003 through 2004) Personal Communication with Charles Esser, Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.

FAA (2022) Personal Communication between FAA and John Steller, Mausami Desai and Vincent Camobreco for aviation emission estimates from the Aviation Environmental Design Tool (AEDT). March 2022.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual.

FTA (2023) National Transit Database "Fuel and Energy by Mode and TOS" table. Available online at: https://data.transportation.gov/.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

IPCC (2006) 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

ICF (2006) *Revised Gasoline Vehicle EFs for LEV and Tier 2 Emission Levels.* Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

ICF (2004) *Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles*. Final Report to U.S. Environmental Protection Agency. February 2004.

RailInc (2014 through 2023) *RailInc Short line and Regional Traffic Index.* Carloads Originated Year-to-Date. November 2023. Available online at: https://public.railinc.com/.

Whorton, D. (2006 through 2014) Personal communication, Class II and III Rail energy consumption, American Short Line and Regional Railroad Association.

Carbon Emitted from Non-Energy Uses of Fossil Fuels

ACC (2023a) "U.S. Resin Production & Sales 2022 vs. 2021." Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry/resources/pips-resin-sales-and-production-cy-figures-2022-vs-2021.

ACC (2023b) *Guide to the Business of Chemistry, 2023*, American Chemistry Council. Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2023-guide-to-the-business-of-chemistry.

ACC (2022) "U.S. Resin Production & Sales 2021 vs. 2020." Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry.

ACC (2021) "U.S. Resin Production & Sales 2020 vs. 2019." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2020) "U.S. Resin Production & Sales 2019 vs. 2018." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2019) "U.S. Resin Production & Sales 2018 vs. 2017." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2018) “U.S. Resin Production & Sales 2017 vs. 2016.” Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2017) “U.S. Resin Production & Sales 2016 vs. 2015.”

ACC (2016) “U.S. Resin Production & Sales 2015 vs. 2014.”

ACC (2015) “PIPS Year-End Resin Statistics for 2014 vs. 2013: Production, Sales and Captive Use.” Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry/resin-report-subscriptions.

ACC (2014) "U.S. Resin Production & Sales: 2013 vs. 2012,” American Chemistry Council. Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

ACC (2013) “U.S. Resin Production & Sales: 2012 vs. 2011,” American Chemistry Council. Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

ACC (2003-2011) “PIPS Year-End Resin Statistics for 2010: Production, Sales and Captive Use.” Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

Bank of Canada (2023) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2022) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2021) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2020) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2019) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2018) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/.

Bank of Canada (2017) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2016) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2014) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2013) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2012) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

CIAC (2022). 2022 Economic Review of Chemistry. Available online at: https://canadianchemistry.ca/wp-content/uploads/2022/06/2022-Economic-Review-of-Chemistry23732_removed.pdf.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035 (2024/02). Available online at: https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

EIA (2021) *EIA Manufacturing Consumption of Energy (MECS) 2018.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2020) Glossary. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: https://www.eia.gov/tools/glossary/index.php?id=N#nat_Gas_Liquids.

EIA (2019) Personal communication between EIA and ICF on November 11, 2019.

EIA (2017) *EIA Manufacturing Consumption of Energy (MECS) 2014.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2013) *EIA Manufacturing Consumption of Energy (MECS) 2010.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2010) *EIA Manufacturing Consumption of Energy (MECS) 2006.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2005) *EIA Manufacturing Consumption of Energy (MECS) 2002.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2001) *EIA Manufacturing Consumption of Energy (MECS) 1998.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1997) *EIA Manufacturing Consumption of Energy (MECS) 1994.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1994) *EIA Manufacturing Consumption of Energy (MECS) 1991.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EPA (2023) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C.

EPA (2021) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2019) *Advancing Sustainable Materials Management: 2016 and 2017 Data Tables*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2019-11/documents/2016_and_2017_facts_and_figures_data_tables_0.pdf.

EPA (2018a) Advancing Sustainable Materials Management: Facts and Figures 2015, Assessing Trends in Material Generation, Recycling and Disposal in the United States. Washington, D.C.

EPA (2018b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2017) EPA's Pesticides Industry Sales and Usage, 2008 – 2012 Market Estimates. Available online at: https://www.epa.gov/sites/production/files/2017-01/documents/pesticides-industry-sales-usage-2016_0.pdf. Accessed September 2017.

EPA (2016a) Advancing Sustainable Materials Management: 2014 Facts and Figures Fact Sheet. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf.

EPA (2016b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2015) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2014a) Municipal Solid Waste in the United States: 2012 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/default/files/2015-09/documents/2012_msw_dat_tbls.pdf.

EPA (2014b) Chemical Data Access Tool (CDAT). U.S. Environmental Protection Agency, June 2014. Available online at: https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7B2D73C764-6919-404D-8C9B-61869B3330D6%7D. Accessed January 2015.

EPA (2013a) Municipal Solid Waste in the United States: 2011 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm.

EPA (2013b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2011) EPA's Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates. Available online at: https://www.epa.gov/pesticides/pesticides-industry-sales-and-usage-2006-and-2007-market-estimates. Accessed January 2012.

EPA (2009) Biennial Reporting System (BRS) Database. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at: https://www.epa.gov/enviro/br-search. Data for 2001-2007 are current as of Sept. 9, 2009.

EPA (2004) EPA's Pesticides Industry Sales and Usage, 2000 and 2001 Market Estimates. Available online at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=3000659P.TXT. Accessed September 2006.

EPA (2002) EPA's Pesticides Industry Sales and Usage, 1998 and 1999 Market Estimates, Table 3.6. Available online at https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=200001G5.TXT. Accessed July 2003.

EPA (2001) AP 42, Volume I, Fifth Edition. Chapter 11: Mineral Products Industry. Available online at: http://www.epa.gov/ttn/chief/ap42/ch11/index.html.

EPA (2000a) *Biennial Reporting System (BRS)*. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at: https://www.epa.gov/enviro/br-search.

EPA (2000b) *Toxics Release Inventory, 1998*. U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, D.C. Available online at: https://enviro.epa.gov/triexplorer/tri_release.chemical.

EPA (1999) EPA's Pesticides Industry Sales and Usage, 1996-1997 Market Estimates. Available online at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=200001IL.TXT.

EPA (1998) EPA's Pesticides Industry Sales and Usage, 1994-1995 Market Estimates. Available online at: http://www.epa.gov/oppbead1/pestsales/95pestsales/market_estimates1995.pdf.

FEB (2013) Fiber Economics Bureau, as cited in C&EN (2013) Lackluster Year for Chemical Output: Production stayed flat or dipped in most world regions in 2012. Chemical &Engineering News, American Chemical Society, 1 July. Available online at: http://www.cen-online.org.

FEB (2012) Fiber Economics Bureau, as cited in C&EN (2012) Too Quiet After the Storm: After a rebound in 2010, chemical production hardly grew in 2011. Chemical & Engineering News, American Chemical Society, 2 July. Available online at: http://www.cen-online.org.

FEB (2011) Fiber Economics Bureau, as cited in C&EN (2011) *Output Ramps up in all Regions*. Chemical Engineering News, American Chemical Society, 4 July. Available online at: http://www.cen-online.org.

FEB (2010) Fiber Economics Bureau, as cited in C&EN (2010) *Output Declines in U.S., Europe*. Chemical & Engineering News, American Chemical Society, 6 July. Available online at: http://www.cen-online.org.

FEB (2009) Fiber Economics Bureau, as cited in C&EN (2009) *Chemical Output Slipped In Most Regions* Chemical & Engineering News, American Chemical Society, 6 July. Available online at: http://www.cen-online.org.

FEB (2007) Fiber Economics Bureau, as cited in C&EN (2007) *Gains in Chemical Output Continue*. Chemical & Engineering News, American Chemical Society. July 2, 2007. Available online at: http://www.cen-online.org.

FEB (2005) Fiber Economics Bureau, as cited in C&EN (2005) *Production: Growth in Most Regions* Chemical & Engineering News, American Chemical Society, 11 July. Available online at: http://www.cen-online.org.

FEB (2003) Fiber Economics Bureau, as cited in C&EN (2003) *Production Inches Up in Most Countries,* Chemical & Engineering News, American Chemical Society, 7 July. Available online at: http://www.cen-online.org.

FEB (2001) Fiber Economics Bureau, as cited in ACS (2001) *Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole* Chemical & Engineering News, American Chemical Society, 25 June. Available online at: http://pubs.acs.org/cen.

Financial Planning Association (2006) Canada/US Cross-Border Tools: US/Canada Exchange Rates. Available online at: http://www.fpanet.org/global/planners/US_Canada_ex_rates.cfm. Accessed on August 16, 2006.

Gosselin, Smith, and Hodge (1984) "Clinical Toxicology of Commercial Products." Fifth Edition, Williams & Wilkins, Baltimore.

ICIS (2016) “Production issues force US melamine plant down” Available online at: https://www.icis.com/resources/news/2016/05/03/9994556/production-issues-force-us-melamine-plant-down/.

ICIS (2008) “Chemical profile: Melamine” Available online at: https://www.icis.com/resources/news/2008/12/01/9174886/chemical-profile-melamine/. Accessed November 2017.

IISRP (2003) “*IISRP Forecasts Moderate Growth in North America to 2007*” International Institute of Synthetic Rubber Producers, Inc. New Release. Available online at: http://www.iisrp.com/press-releases/2003-Press-Releases/IISRP-NA-Forecast-03-07.html.

IISRP (2000) "Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA" International Institute of Synthetic Rubber Producers press release.

INEGI (2006) Producción bruta total de las unidades económicas manufactureras por Subsector, Rama, Subrama y Clase de actividad. Available online at: http://www.inegi.gob.mx/est/contenidos/espanol/proyectos/censos/ce2004/tb_manufacturas.asp. Accessed on August 15, 2006.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Marland, G., and R.M. Rotty (1984) “Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-1982,” Tellus 36b:232-261.

NPRA (2002) North American Wax - A Report Card. Available online at: http://www.npra.org/members/publications/papers/lubes/LW-02-126.pdf.

U.S. Census Bureau (2021) 2017 Economic Census. Available online at: https://www.census.gov/data/tables/2017/econ/economic-census/naics-sector-31-33.html. Accessed October 2021.

U.S. Census Bureau (2014) 2012 Economic Census. Available online at: http://www.census.gov/econ/census/schedule/whats_been_released.html. Accessed November 2014.

U.S. Census Bureau (2009) *Soap and Other Detergent Manufacturing: 2007*.

U.S. Census Bureau (2004) *Soap and Other Detergent Manufacturing: 2002*. Issued December 2004. EC02-31I-325611 (RV). Available online at: http://www.census.gov/prod/ec02/ec0231i325611.pdf.

U.S. Census Bureau (1999) *Soap and Other Detergent Manufacturing: 1997*. Available online at: http://www.census.gov/epcd/www/ec97stat.htm.

U.S. International Trade Commission (2023) "Interactive Tariff and Trade DataWeb: Quick Query." Available online at: http://dataweb.usitc.gov/. Accessed September 2023.

USTMA (2022) "2021 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2022. Available online at: https://www.ustires.org/sites/default/files/21%20US%20Scrap%20Tire%20Management%20Report%20101722.pdf.

USTMA (2020) "2019 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2020. Available online at: https://www.ustires.org/sites/default/files/2019%20USTMA%20Scrap%20Tire%20Management%20Summary%20Report.pdf.

USTMA (2018) "2017 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. July 2018. Available online at: https://www.tyrepress.com/wp-content/uploads/2018/07/USTMA_scraptire_summ_2017_07_11_2018.pdf.

USTMA (2016) "2015 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. August 2016. Available online at: https://www.ustires.org/sites/default/files/MAR_028_USTMA.pdf.

USTMA (2014) "2013 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. November 2014. Available online at: https://www.ustires.org/sites/default/files/MAR_027_USTMA.pdf.

USTMA (2013) "U.S. Scrap Tire Management Summary 2005-2009." U.S. Tire Manufacturers Association. October 2011; Updated September 2013. Available online at: https://www.ustires.org/sites/default/files/MAR_025_USTMA.pdf.

USTMA (2012) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." U.S. Tire Manufacturers Association. Accessed 18 on January 2012.

Incineration of Waste

ArSova, Ljupka, Rob van Haaren, Nora Goldstein, Scott M. Kaufman, and Nickolas J. Themelis (2008) "16th Annual BioCycle Nationwide Survey: The State of Garbage in America" *BioCycle*, JG Press, Emmaus, PA. December.

Bahor, B (2009) Covanta Energy's public review comments re: *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007.* Submitted via email on April 9, 2009 to Leif Hockstad, U.S. EPA.

De Soete, G.G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control." In A. R. Van Amstel, (ed.) Proc. of the International Workshop Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control, Amersfoort, NL. February 3-5, 1993.

Energy Recovery Council (2018) Energy Recovery Council. *2018 Directory of Waste to Energy Facilities*. Ted Michaels and Karunya Krishnan. October 2018. Available online at: http://energyrecoverycouncil.org/wp-content/uploads/2019/10/ERC-2018-directory.pdf.

Energy Recovery Council (2009) "2007 Directory of Waste-to-Energy Plants in the United States." Accessed on September 29, 2009.

EIA (2019) EIA St. Louis Federal Reserve's Economic Data (FRED) Consumer Price Index for All Urban Consumers: Education and Communication (CPIEDUSL). Available online at: https://www.eia.gov/opendata/excel/.

EIA (2017) *MSW Incineration for Heating or Electrical Generation, December 2017,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035. Available online at: https://www.eia.gov/opendata/?src=-f3.

EPA (2022) Greenhouse Gas Reporting Program (GHGRP). 2022 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2020a) Advancing Sustainable Materials Management: 2018 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2020-11/documents/2018_ff_fact_sheet.pdf.

EPA (2020b) Greenhouse Gas Reporting Program (GHGRP). 2020 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2019) Advancing Sustainable Materials Management: 2016 and 2017 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2019-11/documents/2016_and_2017_facts_and_figures_data_tables_0.pdf.

EPA (2018a) Advancing Sustainable Materials Management: 2015 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2018b) Greenhouse Gas Reporting Program Data. Washington, DC: U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

EPA (2016) *Advancing Sustainable Materials Management: 2014 Fact Sheet*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf.

EPA (2015) *Advancing Sustainable Materials Management: Facts and Figures 2013 – Assessing Trends in Material Generation, Recycling and Disposal in the United States.* Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www3.epa.gov/epawaste/nonhaz/municipal/pubs/2013_advncng_smm_rpt.pdf.

EPA (2007, 2008, 2011, 2013, 2014) *Municipal Solid Waste in the United States: Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www.epa.gov/osw/nonhaz/municipal/msw99.html.

EPA (2006) *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C.

EPA (2000) *Characterization of Municipal Solid Waste in the United States: Source Data on the 1999 Update.* Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. EPA530-F-00-024.

Goldstein, N. and C. Madtes (2001) "13th Annual BioCycle Nationwide Survey: The State of Garbage in America." *BioCycle*, JG Press, Emmaus, PA. December 2001.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kaufman, et al. (2004) "14th Annual BioCycle Nationwide Survey: The State of Garbage in America 2004" Biocycle, JG Press, Emmaus, PA. January 2004.

Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.

Shin, D. (2014) Generation and Disposition of Municipal Solid Waste (MSW) in the United States–A National Survey. Thesis. Columbia University, Department of Earth and Environmental Engineering, January 3, 2014.

Simmons, et al. (2006) "15th Nationwide Survey of Municipal Solid Waste Management in the United States: The State of Garbage in America." BioCycle, JG Press, Emmaus, PA. April 2006.

USTMA (2022) "2021 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2022. Available online at: https://www.ustires.org/sites/default/files/21%20US%20Scrap%20Tire%20Management%20Report%20101722.pdf.

USTMA (2020) "2019 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2020. Available online at: https://www.ustires.org/sites/default/files/2019%20USTMA%20Scrap%20Tire%20Management%20Summary%20Report.pdf.

USTMA (2018) "2017 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. July 2018. Available online at: https://www.tyrepress.com/wp-content/uploads/2018/07/USTMA_scraptire_summ_2017_07_11_2018.pdf.

USTMA (2016) "2015 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. August 2016. Available online at: https://www.ustires.org/sites/default/files/MAR_028_USTMA.pdf.

USTMA (2014) "2013 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. November 2014. Available online at: https://www.ustires.org/sites/default/files/MAR_027_USTMA.pdf.

USTMA (2013) "U.S. Scrap Tire Management Summary 2005-2009." U.S. Tire Manufacturers Association. October 2011; Updated September 2013. Available online at: https://www.ustires.org/sites/default/files/MAR_025_USTMA.pdf.

USTMA (2012a) "Rubber FAQs." U.S. Tire Manufacturers Association. Accessed on 19 November 2014.

USTMA (2012b) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." U.S. Tire Manufacturers Association. Accessed 18 on January 2012.

van Haaren, Rob, Themelis, N., and Goldstein, N. (2010) "The State of Garbage in America." BioCycle, October 2010. Volume 51, Number 10, pg. 16-23.

Coal Mining

AAPG (1984) *Coalbed Methane Resources of the United States.* AAPG Studies in Geology Series #17.

Creedy, D.P. (1993) Methane Emissions from Coal Related Sources in Britain: Development of a Methodology. *Chemosphere,* 26: 419-439.

DMME (2023) *DGO Data Information System*. Department of Mines, Minerals and Energy of Virginia. Available online at https://www.dmme.virginia.gov/dgoinquiry/frmmain.aspx.

EIA (2023) *Annual Coal Report 2022*. Table 1. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0584.

El Paso (2009) Shoal Creek Mine Plan, El Paso Exploration & Production.

EPA (2023) Greenhouse Gas Reporting Program (GHGRP) 2022 Subpart FF: Underground Coal Mines.

EPA (2005) *Surface Mines Emissions Assessment.* Draft. U.S. Environmental Protection Agency.

EPA (1996) *Evaluation and Analysis of Gas Content and Coal Properties of Major Coal Bearing Regions of the United States*. EPA/600/R-96-065. U.S. Environmental Protection Agency.

ERG (2023). Correspondence between ERG and Buchanan Mine.

Geological Survey of Alabama State Oil and Gas Board (GSA) (2023) Well Records Database. Available online at http://www.gsa.state.al.us/ogb/database.aspx.

IEA (2022) *Coal 2022*, International Energy Agency, Paris, License: CC BY 4.0. Available online at: https://www.iea.org/reports/coal-2022.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2011) *Use of Models and Facility-Level Data in Greenhouse Gas Inventories*. Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia. Eds: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M. IGES.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

JWR (2010) *No. 4 & 7 Mines General Area Maps.* Walter Energy: Jim Walter Resources.

King, Brian (1994) *Management of Methane Emissions from Coal Mines: Environmental, Engineering, Economic and Institutional Implication of Options.* Neil and Gunter Ltd.

McElroy OVS (2023) Marshall County VAM Abatement Project Offset Verification Statement submitted to California Air Resources Board, August 2023.

MSHA (2023) Data Transparency at MSHA. Mine Safety and Health Administration. Available online at http://www.msha.gov/.

Mutmansky, Jan M. and Yanbei Wang (2000) Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions. *Mineral Resources Engineering,* 9(4).

Saghafi, Abouna (2013) *Estimation of Fugitive Emissions from Open Cut Coal Mining and Measurable Gas Content.* 13th Coal Operators' Conference, University of Wollongong, The Australian Institute of Mining and Metallurgy & Mine Managers Association of Australia. 306-313.

USBM (1986) *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*. Circular 9067. U.S. Bureau of Mines.

West Virginia Geological & Economic Survey (WVGES) (2023) Oil & Gas Production Data. Available online at http://www.wvgs.wvnet.edu/www/datastat/datastat.htm.

Abandoned Underground Coal Mines

CMOP (2023) EPA's Coalbed Methane Outreach Program, Map of US Coal Mine Methane Current Projects and Potential Opportunities. Available online at: https://www.epa.gov/cmop/map-us-coal-mine-methane-current-projects-and-potential-opportunities.

COGIS (2018) Colorado Oil and Gas Information System. Colorado Oil and Gas Commission, Department of Natural Resources. Available online at https://cogcc.state.co.us/data.html.

EPA (2004) Methane Emissions Estimates & Methodology for Abandoned Coal Mines in the U.S. Draft Final Report. Washington, D.C. April 2004.

GMI (2021) Global Methane Initiative, International Coal Mine Methane Database. Available online at: https://www.globalmethane.org/resources/details.aspx?resourceid=1981.

IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

MSHA (2023) U.S. Department of Labor, Mine Health & Safety Administration, Mine Data Retrieval System. Available online at: https://www.msha.gov/mine-data-retrieval-system..

Petroleum Systems

API (1992) *Global Emissions of Methane from Petroleum Sources*. American Petroleum Institute, Health and Environmental Affairs Department, Report No. DR140, February 1992.

BOEM (2023a) BOEM Platform Structures Online Query. Available online at: https://www.data.boem.gov/Platform/PlatformStructures/Default.aspx.

BOEM (2023b) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1947 to 2022. Download "Production Data" online at: https://www.data.boem.gov/Main/RawData.aspx.

BOEM (2023c) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1996 to 2022. Available online at: https://www.data.boem.gov/Main/OGOR-A.aspx.

BOEM (2023d) BOEM Oil and Gas Operations Reports - Part B (OGOR-B). Flaring volumes for 1996 to 2022. Available online at: https://www.data.boem.gov/Main/OGOR-B.aspx.

EIA (2023) Crude Oil Production. Energy Information Administration.

Enverus (2023) September 2023 Download. Enverus, Inc.

EPA (2023) *Greenhouse Gas Reporting Program*. U.S. Environmental Protection Agency. Data reported as of August 18, 2023.

EPA (2017) *2017 Nonpoint Oil and Gas Emission Estimation Tool*, Version 1.2. Prepared for U.S. Environmental Protection Agency by Eastern Research Group, Inc. (ERG). October 2019.

EPA (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report).* Prepared by ICF International. Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

EPA/GRI (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Natural Gas Systems

AHS (2022) U.S. Census Bureau's *American Housing Survey* (AHS). https://www.census.gov/programs-surveys/ahs.html.

CBECS (2023) Energy Information Administration's Commercial Buildings Energy Consumption Survey (CBECS). https://www.eia.gov/consumption/commercial.

CenSARA (2012) *2011 Oil and Gas Emission Inventory Enhancement Project for CenSARA States*. Prepared by ENVIRON International Corporation and Eastern Research Group, Inc. (ERG). Central States Air Resources Agencies (CenSARA). December 2012.

Cusworth, D.H., Duren, R.M., Thorpe, A.K., Pandey S., Maasakkers, J.D., Aben, I., et al. (2021). *Multisatellite imaging of a gas well blowout enables quantification of total methane emissions.* Geophysical Research Letters, 48, e2020GL090864. https://doi.org/10.1029/2020GL090864.

EIA (2023a) Natural Gas Gross Withdrawals and Production. Energy Information Administration.

EIA (2023b) October 2021 *Monthly Energy Review*. Energy Information Administration. https://www.eia.gov/totalenergy/data/monthly/archive/00352110.pdf.

Enverus (2023) September 2023 Download. Enverus, Inc.

EPA (2023a) MOVES3. https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

EPA (2023b) *Greenhouse Gas Reporting Program- Subpart W – Petroleum and Natural Gas Systems*. Environmental Protection Agency. Data reported as of August 18, 2023.

EPA (2022) Nonpoint Oil & Gas Emission estimation Tool.

EPA (1977) *Atmospheric Emissions from Offshore Oil and Gas Development and Production*. Office of Air Quality Planning and Standards, Research Triangle Park, NC. PB272268. June 1977.

Evans, D.J. & Chadwick, R.A. (2009) (eds) "Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe." *The Geological Society,* London, Special Publications, 313: 173–216. https://doi.org/10.1144/SP313.12.

FERC (2023) Form No. 2, Major Natural Gas Pipeline Annual Report. Federal Energy Regulatory Commission. https://ferc.gov/industries-data/natural-gas/industry-forms.

Fischer et al. (2018) "An Estimate of Natural Gas Methane Emissions from California Homes." *Environmental Science & Technology* 2018, *52 (17)*, 10205–10213. https://pubs.acs.org/doi/10.1021/acs.est.8b03217.

GRI/EPA (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

GTI (2019) *Classification of Methane Emissions from Industrial Meters, Vintage vs Modern Plastic Pipe, and Plastic-lined Steel and Cast-Iron Pipe*. June 2019. Gas Technology Institute and U.S. Department of Energy GTI Project Number 22070. DOE project Number ED-FE0029061.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

Illinois Office of Oil and Gas Resource Management (2022) State-level natural gas production quantities.

Indiana Division of Oil & Gas (2022) State-level natural gas production quantities.

Kansas Department of Health and Environment (2022) County-level produced water quantities.

Lamb, et al. (2015) "Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States." *Environmental Science & Technology, Vol. 49* 5161-5169.

Lavoie et al. (2017) "Assessing the Methane Emissions from Natural Gas-Fired Power Plants and Oil Refineries." *Environmental Science & Technology*. 2017 Mar 21;51(6):3373-3381. doi: 10.1021/acs.est.6b05531.

Li, H Z et al. (2022) "A national estimate of U.S. underground natural gas storage incident emissions." *Environmental Research Letters*. 17: 084013. https://doi.org/10.1088/1748-9326/ac8069.

Maasakkers, Joannes D., Mark Omara, Ritesh Gautam, Alba Lorente, Sudhanshu Pandey, Paul Tol, Tobias Borsdorff, Sander Houweling, Ilse Aben (2022). *Reconstructing and quantifying methane emissions from the full duration of a 38-day natural gas well blowout using space-based observations.* Remote Sensing of Environment. https://doi.org/10.1016/j.rse.2021.112755.

Ohio Environmental Protection Agency (2022) Well-level produced water quantities.

Oklahoma Department of Environmental Quality (2022) Well-level produced water quantities.

Pandey, S., Gautam, R., Houweling, S., van der Gon, H. D., Sadavarte, P., Borsdorff, T., et al. (2019). *Satellite observations reveal extreme methane leakage from a natural gas well blowout*. Proceedings of the National Academy of Sciences, 116, 26376– 26381. https://doi.org/10.1073/pnas.1908712116.

PHMSA (2022a) Gas Distribution Annual Data. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. Available online at: https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-gas-distribution-systems.

PHMSA (2022b) Underground Natural Gas STAR, Part C. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids.

West Virginia Department of Environmental Protection (2020) State-level natural gas production quantities.

Zimmerle et al. (2019) "Characterization of Methane Emissions from Gathering Compressor Stations." October 2019. Available at https://mountainscholar.org/handle/10217/195489.

Zimmerle et al. (2015) "Methane Emissions from the Natural Gas Transmission and Storage System in the United States." *Environmental Science and Technology, Vol. 49* 9374–9383.

Abandoned Oil and Gas Wells

Alaska Oil and Gas Conservation Commission, Available online at: https://www.commerce.alaska.gov/web/aogcc/Data.aspx.

Arkansas Geological & Conservation Commission, "List of Oil & Gas Wells - Data From November 1, 1936 to January 1, 1955."

The Derrick's Handbook of Petroleum: A Complete Chronological and Statistical Review of Petroleum Developments From 1859 to 1898 (V.1), (1898-1899) (V.2).

Enverus (2023) October 2023 Download. Enverus, Inc.

Florida Department of Environmental Protection - Oil and Gas Program, Available online at: https://floridadep.gov/water/oil-gas.

Geological Survey of Alabama, Oil & Gas Board, Available online at: https://www.gsa.state.al.us/ogb/.

GRI/EPA (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

Interstate Oil and Gas Compact Commission (2021). IDLE AND ORPHAN OIL AND GAS WELLS: STATE AND PROVINCIAL REGULATORY STRATEGIES 2021. Available online at: https://iogcc.ok.gov/sites/g/files/gmc836/f/iogcc_idle_and_orphan_wells_2021_final_web.pdf.

Kang, et al. (2016) "Identification and characterization of high methane-emitting abandoned oil and gas wells." *PNAS*, vol. 113 no. 48, 13636–13641, doi: 10.1073/pnas.1605913113.

Oklahoma Geological Survey. "Oklahoma Oil: Past, Present, and Future." Oklahoma Geology Notes, v. 62 no. 3, 2002 pp. 97-106.

Pennsylvania Department of Environmental Protection, Oil and Gas Reports - Oil and Gas Operator Well Inventory. Available online at: http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Well_Inventory.

International Bunker Fuels

Anderson, B.E., et al. (2011) *Alternative Aviation Fuel Experiment (AAFEX)*, NASA Technical Memorandum, in press.

ASTM (1989) *Military Specification for Turbine Fuels, Aviation, Kerosene Types*, NATO F-34 (JP-8) and NATO F-35. February 10, 1989.

DHS (2008) Personal Communication with Elissa Kay, Residual and Distillate Fuel Oil Consumption (International Bunker Fuels). Department of Homeland Security, Bunker Report. January 11, 2008.

DLA Energy (2023) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOT (1991 through 2013) Fuel Cost and Consumption. Federal Aviation Administration, Bureau of Transportation.

Statistics, U.S. Department of Transportation. Washington, D.C. DAI-10.

EIA (2024) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2024/02).

EPA (2020) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO_2 Emission Factors – Memo.

FAA (2024) Personal Communication between FAA and John Steller, Mausami Desai, and Vincent Camobreco for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). March 2024.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.USAF (1998) Fuel Logistics Planning. U.S. Air Force pamphlet AFPAM23-221, May 1, 1998.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. 31 Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic 32 Co-Operation and Development, International Energy Agency, Paris, France.

Wood Biomass and Biofuel Consumption

EIA (2024a) *Monthly Energy Review, February 2024*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2024b) Biofuels explained: Use of biomass-based diesel fuel. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/energyexplained/biofuels/use-of-biodiesel.php.

EPA (2023). Greenhouse Gas Reporting Program (GHGRP). 2022 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Lindstrom, P. (2006) Personal Communication. Perry Lindstrom, Energy Information Administration and Jean Kim, ICF International.

Energy Sources of Precursor Greenhouse Gases

EPA (2023a) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C.

EPA (2023b) "Criteria pollutants National Tier 1 for 1970 – 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023c) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Industrial Processes and Product Use

EPA (2014) *Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014*. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

EPA (2002) Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for Quality Assurance/Quality Control and Uncertainty Analysis, U.S. Greenhouse

Gas Inventory Program, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-007B, June 2002.

IPCC (2011) *Use of Models and Facility-Level Data in Greenhouse Gas Inventories* (Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia) eds.: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M., Pub. IGES, Japan 2011.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

Cement Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Bureau of Mines (1990 through 1993) *Minerals Yearbook: Cement Annual Report.* U.S. Department of the Interior, Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart H -National Level Clinker Production from Cement Production for Calendar Years 2014 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) *2021 Minerals Yearbook – Cement (Advance Release Tables)*. U.S. Geological Survey, Reston, VA. July 2023.

USGS (2023b) *Mineral Commodity Summaries: Cement*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023c) *Mineral Industry Surveys, Cement in December 2022*. U.S. Geological Survey, Reston, VA. (March 2023).

USGS (1995 through 2014) *Minerals Yearbook - Cement*. U.S. Geological Survey, Reston, VA.

Van Oss (2013a) 1990 through 2012 Clinker Production Data Provided by Hendrik van Oss (USGS) via email on November 8, 2013.

Van Oss (2013b) Personal communication. Hendrik van Oss, Commodity Specialist of the U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. October 28, 2013.

Lime Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Males, E. (2003) Memorandum from Eric Males, National Lime Association to William N. Irving & Leif Hockstad, Environmental Protection Agency. March 6, 2003.

Miner, R. and B. Upton (2002) Methods for estimating greenhouse gas emissions from lime kilns at kraft pulp mills. Energy. Vol. 27 (2002), p. 729-738.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Seeger (2013) Memorandum from Arline M. Seeger, National Lime Association to Leif Hockstad, Environmental Protection Agency. March 15, 2013.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart S-National Lime Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) (1996 through 2023) *Mineral Commodities Summary: Lime*. U.S. Geological Survey, Reston, VA (January 2023). Latest edition was updated in 2023 for 2022. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information.

USGS (2023b) (*2002 through 2021) Minerals Yearbook Annual Tables: Lime*. U.S. Geological Survey, Reston, VA (January 2023). Latest edition was updated in 2023 for 2021 tables. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information.

USGS (2021) *(1991 through 2018) Minerals Yearbook: Lime*. U.S. Geological Survey, Reston, VA (October 2021). Latest edition was updated in 2021 for 2018. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information. See "Archive" for editions prior to 1993.

USGS (2012) *2012* Expert Elicitation. Michael Miller, U.S. Geological Survey (2012).

Glass Production

Federal Reserve (2023) Board of Governors of the Federal Reserve System (US), Industrial Production: Manufacturing: Durable Goods: Glass and Glass Product (NAICS = 3272) [IPG3272N], retrieved from FRED, Federal Reserve Bank of St. Louis. Available at: https://fred.stlouisfed.org/series/IPG3272N. Accessed on November 21, 2023.

IPCC (2006) *2006 IPCC Guidelines* for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

RTI (2022) Expert judgment. Melissa Icenhour, RTI International. November 16, 2022.

U.S. Bureau of Mines (1991 and 1993a) Minerals Yearbook: Crushed Stone Annual Report. U.S. Department of the Interior. Washington, D.C.

U.S. Department of Energy (DOE) (2002) Glass Industry of the Future: Energy and Environmental Profile of the U.S. Glass Industry. Office of Industrial Technologies, U.S. Department of Energy. Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart N -National Glass Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2009) Technical Support Document for the Glass Manufacturing Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases. U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (1995 through 2015b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2023) *Mineral Industry Surveys: Soda Ash in January 2023*. U.S. Geological Survey, Reston, VA. November 2023. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/soda-ash-statistics-and-information.

USGS (2022) *Mineral Industry Surveys: Soda Ash in June 2022*. U.S. Geological Survey, Reston, VA. November 2022. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2021) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2020) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2019) *Mineral Industry Surveys: Soda Ash in December 2018*. U.S. Geological Survey, Reston, VA. March 2019. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2018) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. 2018. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2017) *Minerals Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

Other Process Uses of Carbonates

AISI (2018 through 2021) *Annual Statistical Report.* American Iron and Steel Institute.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kostick, D. S. (2012) Personal communication. Dennis S. Kostick, U.S. Geological Survey, Soda Ash Commodity Specialist and Gopi Manne and Bryan Lange of Eastern Research Group, Inc. October 2012.

McNeece (2023) Personal communication, Steve McNeece, Nevada Department of Environmental Quality and Amanda Chiu, U.S. Environmental Protection Agency. November 28, 2023.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Simmons (2024) Personal communication, Kristi Simmons, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency. February 9, 2024.

U.S. Bureau of Mines (1991 and 1993a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Department of the Interior. Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2023). Greenhouse Gas Reporting Program (GHGRP). Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/

United States Geological Survey (USGS) (2023a) *Mineral Industry Surveys: Soda Ash in September 2023*. U.S. Geological Survey, Reston, VA. November 2023.

USGS (2023b) *2021 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2023.

USGS (2022a) *Mineral Industry Surveys: Soda Ash in August 2022*. U.S. Geological Survey, Reston, VA. November 2022.

USGS (2022b) *2020 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2022c) *2018 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2022d) *2019 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2022.

USGS (2022e) *2018 Minerals Yearbook: Magnesium Compounds [Advanced Release]*. U.S. Geological Survey, Reston, VA. May 2022.

USGS (2022f) *2018 Minerals Yearbook: Clay and Shale [Advanced Release]*. U.S. Geological Survey, Reston, VA. March 2022.

USGS (2022g) *2018 Minerals Yearbook: Soda Ash [Advanced Release]*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021a) *Minerals Yearbook 2019: Soda Ash [Advanced Data Release of the 2019 Annual Tables]*. U.S. Geological Survey, Reston, VA. August 2021.

USGS (2021b) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2021c) 2017 *Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2021.

USGS (2021d) *2020 Mineral Commodity Summaries: Stone (Crushed).* U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020a) *Minerals Yearbook 2017: Stone, Crushed [Advanced Data Release of the 2017 Annual Tables]*. U.S. Geological Survey, Reston, VA. August 2020.

USGS (2020b) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020.

USGS (2020c) 2016 *Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2019) *Mineral Industry Surveys: Soda Ash in April 2019*. U.S. Geological Survey, Reston, VA. July 2019.

USGS (2018) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. 2018.

USGS (2017) *Mineral Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017.

USGS (1995a through 2017) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1994 through 2015b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1990 through 2002) *Minerals Yearbook: Magnesium Compounds Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1948) *Reports: Magnesite and brucite deposits at Gabbs, Nye County, Nevada*. U.S. Geological Survey, Reston, VA

Willett (2023) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency. November 21, 2023.

Willett (2017) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Mausami Desai and John Steller, U.S. Environmental Protection Agency. March 9, 2017.

Ammonia Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

Coffeyville Resources Energy, Inc. (CVR) (2008) *CVR Energy, Inc. 2008 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2022) CVR Energy, Inc. *2022 Annual Report on Form 10-K.* Available online at: https://cvrenergy.gcs-web.com/annual-report-proxy-information.

CVR (2021) CVR Energy, Inc. *2021 CVI Annual Report on Form 10-K.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2020) CVR Energy, Inc. *2020 CVI Annual Report on Form 10-K --Final*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2019) CVR Energy, Inc. *2019 CVI Form 10-K - Final*. Available online at https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2018) CVR Energy, Inc. *2018 CVI Annual Report on Form 10-K --Final*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2017) CVR Energy, Inc. *2017 CVI Annual Report on Form 10-K (Web).* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2016) CVR Energy, Inc. *2016 CVI Annual Report on Form 10-K (Web).* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2014) CVR Energy, Inc. *2014 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2015) CVR Energy, Inc. *2015 Annual Report*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2013) CVR Energy, Inc. *2013 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2012) *CVR Energy, Inc. 2012 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2011) *CVR Energy, Inc. 2011 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2010) *CVR Energy, Inc. 2010 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2009) *CVR Energy, Inc. 2009 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

EFMA (2000) *Best Available Techniques for Pollution Prevention* and *Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate. Available online at: http://fertilizerseurope.com/site/index.php?id=390.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (2011) *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2010) *Current Industrial Reports Fertilizer Materials and Related Products: 2009 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2009) *Current Industrial Reports Fertilizer Materials and Related Products: 2008 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2008) *Current Industrial Reports Fertilizer Materials and Related Products: 2007 Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b/mq325b075.xls.

U.S. Census Bureau (2007) *Current Industrial Reports Fertilizer Materials and Related Products: 2006 Summary*. Available online at: http://www.census.gov/industry/1/mq325b065.pdf.

U.S. Census Bureau (2006) *Current Industrial Reports Fertilizer Materials and Related Products: 2005 Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (2004, 2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (1998 through 2003) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Reports Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (1991 through 1994) *Current Industrial Reports Fertilizer Materials Annual Report.* Report No. MQ28B. U.S. Census Bureau, Washington, D.C.

United States EIA (2023) *Monthly Energy Review, February 2023,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2023/2).

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G -Annual Urea Production from Ammonia Manufacturing for Calendar Years 2017-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G - Annual Urea Production from Ammonia Manufacturing for Calendar Years 2011-2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C

United States Geological Survey (USGS) (2023) *2023 Mineral Commodity Summaries: Nitrogen (Fixed) - Ammonia.* January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-nitrogen.pdf.

USGS (1994-2009) *Minerals Yearbook: Nitrogen*. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/

Urea Consumption for Non-Agricultural Purposes

EFMA (2000) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

TFI (2002) *U.S. Nitrogen Imports/Exports Table.* The Fertilizer Institute. Available online at: http://www.tfi.org/statistics/usnexim.asp. August 2002.

United States Census Bureau (2001 through 2011) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/index.html.

United States Department of Agriculture (2012) Economic Research Service Data Sets, Data Sets, U.S. Fertilizer Imports/Exports: Standard Tables. Available online at: http://www.ers.usda.gov/data-products/fertilizer-importsexports/standard-tables.aspx.

U.S. EPA (2023a) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G -Annual Urea Production from Ammonia Manufacturing for Calendar Years 2017-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2023b). Greenhouse Gas Reporting Program. Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G - Annual Urea Production from Ammonia Manufacturing for Calendar Years 2011-2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States International Trade Commission (ITC) (2002) *United States International Trade Commission Interactive Tariff and Trade DataWeb, Version 2.5.0*. Available online at: http://dataweb.usitc.gov/. August 2002.

United States Geological Survey (USGS) (1994 through 2023a) *Minerals Yearbook: Nitrogen*. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/.

USGS (2023b) *Minerals Commodity Summaries: Nitrogen (Fixed) – Ammonia*. January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-nitrogen.pdf.

Nitric Acid Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Icenhour (2020) Personal communication, Melissa Icenhour, RTI International and Amanda Chiu, U.S. Environmental Protection Agency. December 3, 2020.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (2010a) *Current Industrial Reports. Fertilizers and Related Chemicals: 2009.* "Table 1: Summary of Production of Principle Fertilizers and Related Chemicals: 2009 and 2008." June, 2010. MQ325B(08)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2010b) Personal communication between Hilda Ward (of U.S. Census Bureau) and Caroline Cochran (of ICF International). October 26, 2010 and November 5, 2010.

U.S. Census Bureau (2009) *Current Industrial Reports. Fertilizers and Related Chemicals: 2008.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2004 to 2008." June, 2009. MQ325B(08)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2008) *Current Industrial Reports. Fertilizers and Related Chemicals: 2007.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2003 to 2007." June, 2008. MQ325B(07)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. EPA (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart V - National Nitric Acid Production for Calendar Years 2017 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart V - National Nitric Acid Production for Calendar Years 2010 through 2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2010) *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Nitric Acid Production Industry.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. December 2010. Available online at: http://www.epa.gov/nsr/ghgdocs/nitricacid.pdf.

U.S. EPA (1998) *Compilation of Air Pollutant Emission Factors, AP-42.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. February 1998.

Adipic Acid Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

Ard (2024) Personal communication, Howard Ard, Florida Department of Environmental Protection and Amanda Chiu, U.S. Environmental Protection Agency. February 6, 2024.

Ascend (2023) "Ascend reaches GHG abatement milestone." Available online at https://www.ascendmaterials.com/news/ascend-reaches-ghg-abatement-milestone. December 1, 2023.

C&EN (1995) "Production of Top 50 Chemicals Increased Substantially in 1994." *Chemical & Engineering News*, 73(15):17. April 10, 1995.

C&EN (1994) "Top 50 Chemicals Production Rose Modestly Last Year." *Chemical & Engineering News*, 72(15):13. April 11, 1994.

C&EN (1993) "Top 50 Chemicals Production Recovered Last Year." *Chemical & Engineering News*, 71(15):11. April 12, 1993.

C&EN (1992) "Production of Top 50 Chemicals Stagnates in 1991." *Chemical & Engineering News*, 70(15): 17. April 13, 1992.

CMR (2001) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. July 16, 2001.

CMR (1998) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. June 15, 1998.

CW (2005) "Product Focus: Adipic Acid." *Chemical Week*. May 4, 2005.

CW (1999) "Product Focus: Adipic Acid/Adiponitrile." *Chemical Week*, p. 31. March 10, 1999.

Desai (2010, 2011) Personal communication. Mausami Desai, U.S. Environmental Protection Agency and Adipic Acid Plant Engineers. 2010 and 2011.

ICIS (2007) "Adipic Acid." *ICIS Chemical Business Americas*. July 9, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Reimer, R.A., Slaten, C.S., Seapan, M., Koch, T.A. and Triner, V.G. (1999) "Implementation of Technologies for Abatement of N_2O Emissions Associated with Adipic Acid Manufacture." Proceedings of the 2nd Symposium on Non-CO_2 Greenhouse Gases (NCGG-2), Noordwijkerhout, The Netherlands, 8-10 Sept. 1999, Ed. J. van Ham et al., Kluwer Academic Publishers, Dordrecht, pp. 347-358.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Thiemens, M.H., and W.C. Trogler (1991) "Nylon production; an unknown source of atmospheric nitrous oxide." *Science* 251:932-934.

United States Environmental Protection Agency (EPA) (2021 through 2023) Greenhouse Gas Reporting Program. Subpart E Data. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2019, 2020) Greenhouse Gas Reporting Program. Subpart E, S-CEMS, BB, CC, LL Data Set (XLSX) (Adipic Acid Tab). Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2014 through 2018) Greenhouse Gas Reporting Program. Subpart E, S-CEMS, BB, CC, LL Data Set (XLSX) (Adipic Acid Tab). Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: http://www2.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2010 through 2013) Analysis of Greenhouse Gas Reporting Program data – Subpart E (Adipic Acid), Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Caprolactam, Glyoxal and Glyoxylic Acid Production

American Chemistry Council (ACC) (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

AdvanSix (2023) AdvanSix's Hopewell Facility Fact Sheet. Retrieved from: https://www.advansix.com/hopewell/about-us/ on September 13, 2023.

BASF (2023) Welcome to BASF in Freeport Texas. Retrieved from https://www.basf.com/us/en/who-we-are/organization/locations/featured-sites/Freeport.html on September 13, 2023.

ChemView (2021). Compilation of data submitted under TSCA in 2012 and 2016. Accessed April 2021. Available at https://chemview.epa.gov/chemview.

Cline, D. (2019) Firm to Clean Up and Market Former Fibrant Site. *The Augusta Chronicle*. September 9, 2019. Retrieved from https://www.augustachronicle.com.

Ecofys, et al. (2009). *Methodology for the free allocation of emission allowances in the EU ETS post 2012: Sector Report for the Chemical Industry*. Prepared by Ecofys, Fraunhofer Institute for Systems and Innovation Research, and Oko-Institut for the European Commission. November 2009. Available at https://ec.europa.eu/clima/system/files/2016-11/bm_study-chemicals_en.pdf.

ICIS (2006) Chemical Profile – Caprolactam. October 15, 2006. Available online at: https://www.icis.com/explore/resources/news/2006/10/18/2016832/chemical-profile-caprolactam/.

ICIS (2004) Chemical Profile – Caprolactam. January 5, 2004. Available online at: https://www.icis.com/explore/resources/news/2005/12/02/547244/chemical-profile-caprolactam/.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Shaw Industries Group, Inc. (Shaw) (2015) "Shaw Carpet Recycling Facility Successfully Processes Nylon and Polyester". July 13, 2015. Available online at: https://shawinc.com/Newsroom/Press-Releases/Shaw-Carpet-Recycling-Facility-Successfully-Proces/.

Textile World (2000) "Evergreen Makes Nylon Live Forever". Textile World. October 1, 2000. Available online at: https://www.textileworld.com/textile-world/textile-news/2000/10/evergreen-makes-nylon-live-forever/.

Carbide Production and Consumption

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Biscay, Nicolas & Henry, Lucile & Adschiri, Tadafumi & Yoshimura, Masahiro & Aymonier, Cyril. (2021). Behavior of Silicon Carbide Materials under Dry to Hydrothermal Conditions. Nanomaterials. 11. 1351. doi: 10.3390/nano11051351.

Environment and Climate Change Canada (ECCC) (2022), Personal Communication between Genevieve Leblanc-Power, Environment and Climate Change Canada and Mausami Desai and Amanda Chiu, U.S. Environmental Protection Agency. April 12, 2022.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (1990 through 2022) *USITC Trade DataWeb.* Available online at: http://dataweb.usitc.gov/.

USGS (1991a through 2021) *Minerals Yearbook: Manufactured Abrasives Annual Report.* U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/manufactured-abrasives-statistics-and-information.

USGS (1991b through 2021) *Minerals Yearbook: Silicon Annual Report.* U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/silicon/.

USGS (2023a) 2022 *Minerals Yearbook: Manufactured Abrasives (2022 advanced-release tables),* September 27, 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/manufactured-abrasives-statistics-and-information

USGS (2023b) *Mineral Commodity Summaries: Abrasives (Manufactured)*. U.S. Geological Survey, Reston, Va. January 2023.

USGS (2023c) *2022 Minerals Yearbook: Silicon (2022 advanced-release tables*), November 27, 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/silicon-statistics-and-information

USGS (2021a) *Mineral Commodity Summaries: Abrasives (Manufactured)*. U.S. Geological Survey, Reston, Va. January 2021. Available online at: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-abrasives.pdf.

Washington Mills (2023), North Grafton, MA. Available online at: https://www.washingtonmills.com/silicon-carbide/sic-industries. Accessed on April 4, 2023.

Titanium Dioxide Production

Gambogi, J. (2002) Telephone communication. Joseph Gambogi, Commodity Specialist, U.S. Geological Survey and Philip Groth, ICF International. November 2002.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) 2020 *Minerals Yearbook: Titanium*, 2020 tables-only release, Table 1. U.S. Geological Survey, Reston, Va. March 2023.

USGS (2023b) *Mineral Commodity Summaries: Titanium and Titanium Dioxide*. U.S. Geological Survey, Reston, Va. January 2023.

USGS (1991 through 2022) *Minerals Yearbook: Titanium.* U.S. Geological Survey, Reston, VA.

Soda Ash Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) *Mineral Commodity Summary: Soda Ash*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *Mineral Industry Surveys: Soda Ash in June 2023*. U.S. Geological Survey, Reston, VA. August 2023.

United States Geological Survey (USGS) (2022a) *Mineral Commodity Summary: Soda Ash*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2022b) *Mineral Industry Surveys: Soda Ash in June 2022*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2021) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2020) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020.

USGS (2019) *Mineral Industry Surveys: Soda Ash in April 2019*. U.S. Geological Survey, Reston, VA. July 2019.

USGS (2018a) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. Accessed September 2018.

USGS (2017) *Mineral Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017.

USGS (2016) *Mineral Industry Surveys: Soda Ash in November 2016*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2015a) *Mineral Industry Surveys: Soda Ash in July 2015*. U.S. Geological Survey, Reston, VA. September 2015.

USGS (1994 through 2015b, 2018b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995c) *Trona Resources in the Green River Basin, Southwest Wyoming.* U.S. Department of the Interior, U.S. Geological Survey. Open-File Report 95-476. Wiig, Stephen, Grundy, W.D., Dyni, John R.

Petrochemical Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

AN (2014) *About Acrylonitrile: Production*. AN Group, Washington, D.C.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, G. L. (2005 through 2010) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caroline Cochran, ICF International. September 2010.

Johnson, G. L. (2003) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caren Mintz, ICF International. November 2003.

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart X -National Petrochemical Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2008) *Technical Support Document for the Petrochemical Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases.* U.S. Environmental Protection Agency. September 2008.

U.S. EPA (2000) *Economic Impact Analysis for the Proposed Carbon Black Manufacturing NESHAP,* U.S. Environmental Protection Agency. Research Triangle Park, NC. EPA-452/D-00-003. May 2000.

HCFC-22 Production

ARAP (2010) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 10, 2010.

ARAP (2009) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 21, 2009.

ARAP (2008) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 17, 2008.

ARAP (2007) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 2, 2007.

ARAP (2006) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. July 11, 2006.

ARAP (2005) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 9, 2005.

ARAP (2004) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. June 3, 2004.

ARAP (2003) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 18, 2003.

ARAP (2002) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 7, 2002.

ARAP (2001) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 6, 2001.

ARAP (2000) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 13, 2000.

ARAP (1999) Facsimile from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger Schaefer of the U.S. Environmental Protection Agency. September 23, 1999.

ARAP (1997) Letter from Dave Stirpe, Director, Alliance for Responsible Atmospheric Policy to Elizabeth Dutrow of the U.S. Environmental Protection Agency. December 23, 1997.

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2008) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22:Emissions from 1990 through 2006." Report prepared by RTI International for the Climate Change Division. March 2008.

RTI (1997) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22: Emissions from 1990 through 1996." Report prepared by Research Triangle Institute for the Cadmus Group. November 25, 1997; revised February 16, 1998.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Production of Fluorochemicals Other Than HCFC-22

3M (2024) *3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions.* February 2024.

Daikin (2013) *Major Source Operating Permit*, Daikin America, Alabama Department of Environmental Management, August 1, 2013. http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0. (p. 11-1).

Honeywell (2012) *Part 70 Operating Permit*, Geismar Plant, Honeywell International Inc., Louisiana, Louisiana Department of Environmental Quality, Page 13, January 28, 2011. https://edms.deq.louisiana.gov/app/doc/view?doc=7812895.

Honeywell (2011) *Part 70 Operating Permit*, Baton Rouge Plant Honeywell International Inc., Louisiana Department of Environmental Quality, Page 25, October 16, 2012. https://edms.deq.louisiana.gov/app/doc/view?doc=8579001.

ICI Americas (1993) *New Permit, KLEA – 134a Plant*, ICI Americas, St. Gabriel, Louisiana, Louisiana Department of Environmental Quality, Page 44, May 28, 1993. https://edms.deq.louisiana.gov/app/doc/view?doc=1309650.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L.

Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896. Available from www.ipcc.ch. The AR6 GWPs are listed in Table 7.SM.7, which appears on page 16 of the Supplementary Material.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. The GWPs are listed in Table 8.A.1 of Appendix 8.A: Lifetimes, Radiative Efficiencies and Metric Values, which appears on pp. 731-737 of Chapter 8, "Anthropogenic and Natural Radiative Forcing."

IPCC (2007) *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

McKenna (2022) *A 3M Plant in Illinois Was the Country's Worst Emitter of a Climate-Killing 'Immortal' Chemical in 2021*, Phil McKenna, Inside Climate News, December 29, 2022. [3M Cordova IL facility.] https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/.

Perkins (1982) Perkins, B. L., *Evaluation of Environmental Control Technologies for Commercial Nuclear Fuel Conversion (UF_6) Facilities*, LA-9397-MS, October 1982 [030000442.pdf].

Rand (2007) *2004-2006 SF_6 Data Summary*, Project Memorandum Prepared by D. Knopman and K. Smythe, RAND Corporation, for the National Electrical Manufacturers Association, June 2007.

SRI Consulting (2004) *Chemical Economics Handbook (CEH) Market Research Report: Fluorocarbons*, R. Will, A. Kishi, S. Schlag. SRI Consulting, 2004.

U.S. EPA (2008) Survey of Producers of HFCs, PFCs, SF_6 and NF_3, 2008. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023a) GHGRP Data Relevant to the AIM Act, Greenhouse Gas Reporting Program. https://www.epa.gov/ghgreporting/ghgrp-data-relevant-aim-act. Last accessed 11/16/2023.

U.S. EPA (2023b) Vintaging Model for HFCs. 2023. Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023c) Estimated layer-weighted substrate production by the semiconductor industry. Office of Atmospheric Programs, Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023d) SF_6 Consumption by Users. 2023. SF_6 consumption for 3 industries, Electric Transmission and Distribution, Semiconductor Manufacturing, and Magnesium Production. Office of Atmospheric Protection, U.S. Environmental Protection Agency.

U.S. EPA (2015) Greenhouse Gas Reporting Program Report Verification. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (1995) *Protocol for Equipment Leak Emission Estimates*. Office of Air and Radiation, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Publication No. EPA-453/R-95-017. November 1995.

Vollmer et al. (2019) Vollmer, M. K., Bernard, F., Mitrevski, B., Steele, L. P., Trudinger, C. M., Reimann, S., Langenfelds, R. L., Krummel, P. B., Fraser, P. J., Etheridge, D. M., Curran, M. A. J., and Burkholder, J. B.: Abundances, emissions, and loss processes of the long-lived and potent greenhouse gas octafluorooxolane

(octafluorotetrahydrofuran, c-C4F8O) in the atmosphere, Atmos. Chem. Phys., 19, 3481–3492, https://doi.org/10.5194/acp-19-3481-2019 , 2019..

Carbon Dioxide Consumption

ARI (1990 through 2010) *CO_2 Use in Enhanced Oil Recovery.* Deliverable to ICF International under Task Order 102, July 15, 2011.

ARI (2007) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, D.C. April 20-21, 2007.

ARI (2006) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, D.C. April 20-21, 2006.

Broadhead (2003) Personal communication. Ron Broadhead, Principal Senior Petroleum Geologist and Adjunct faculty, Earth and Environmental Sciences Department, New Mexico Bureau of Geology and Mineral Resources, and Robin Petrusak, ICF International. September 5, 2003.

COGCC (2014) Monthly CO_2 Produced by County (1999-2009). Available online at: http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyCO2ProdByCounty. Accessed October 2014.

Denbury Resources Inc. (2002 through 2010) Annual Report: 2001 through 2009, Form 10-K. Available online at: http://www.denbury.com/investor-relations/SEC-Filings/SEC-Filings-Details/default.aspx?FilingId=9823015. Accessed September 2014.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

New Mexico Bureau of Geology and Mineral Resources (2006) Natural Accumulations of Carbon Dioxide in New Mexico and Adjacent Parts of Colorado and Arizona: Commercial Accumulation of CO_2. Available online at: http://geoinfo.nmt.edu/staff/broadhead/CO2.html#commercial.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart PP -National Level CO_2 Transferred for Food & Beverage Applications for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Phosphoric Acid Production

EFMA (2000) "Production of Phosphoric Acid." *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry.* Booklet 4 of 8. European Fertilizer Manufacturers Association. Available online at: http://www.efma.org/Publications/BAT%202000/Bat04/section04.asp.

Florida Institute of Phosphate Research (FIPR) (2003a) "Analyses of Some Phosphate Rocks." Facsimile Gary Albarelli, Florida Institute of Phosphate Research, Bartow, Florida, to Robert Lanza, ICF International. July 29, 2003.

FIPR (2003b) Florida Institute of Phosphate Research. Personal communication between Michael Lloyd (Laboratory Manager, FIPR, Bartow, Florida) aand Robert Lanza (ICF International) on August 2003.

Golder Associates and M3 Engineering, *Bayovar 12 Phosphate Project: NI 43-101 Updated Pre-Feasibility Study*, Issued June 28, 2016. Available at: https://www.sec.gov/Archives/edgar/data/1471603/000121716016000634/focusjune2016bayovar_techrep.htm. Accessed on October 7, 2020.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

NCDENR (2013) North Carolina Department of Environment and Natural Resources, Title V Air Permit Review for PCS Phosphate Company, Inc. – Aurora. Available online at: http://www.ncair.org/permits/permit_reviews/PCS_rev_08282012.pdf. Accessed on January 25, 2013.

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Review of Reported Facility Level Data under Subpart Z -Annual Phosphoric Acid Production from Phosphate Rock for Calendar Year 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023) *Mineral Commodity Summaries: Phosphate Rock 2023*. January 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information

USGS (2022) *Mineral Commodity Summaries: Phosphate Rock 2022*. January 2022. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information

USGS (2021a) *Mineral Commodity Summaries: Phosphate Rock 2021*. January 2021. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2021b) Personal communication between Stephen Jasinski (USGS) and Amanda Chiu (EPA) on August 25, 2021.

USGS (2020) *Mineral Commodity Summaries: Phosphate Rock 2020*. January 2020. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2019a) *Mineral Commodity Summaries: Phosphate Rock 2019*. February 2019. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2019b) Communication between Stephen Jasinski (USGS) and John Steller (EPA) on November 15, 2019.

USGS (2018) *Mineral Commodity Summaries: Phosphate Rock 2018*. January 2018. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2017) *Mineral Commodity Summaries: Phosphate Rock 2017*. January 2017. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2016) *Mineral Commodity Summaries: Phosphate Rock 2016*. January 2016. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (1994 through 2015b) *Minerals Yearbook*. *Phosphate Rock Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2012) Personal communication between Stephen Jasinski (USGS) and Mausami Desai (EPA) on October 12, 2012.

Iron and Steel Production and Metallurgical Coke Production

American Coke and Coal Chemicals Institute (ACCCI) (2021) *U.S. Coke Plants as of November 2021,* ACCCI, Washington, D.C. November 2021.

American Iron and Steel Institute (AISI) (2004 through 2023) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

Carroll (2017) Personal communication, Colin P. Carroll, Director of Environment, Health and Safety, American Iron and Steel Institute and John Steller, U.S. Environmental Protection Agency, November 2017.

Carroll (2016) Personal communication, Colin P. Carroll, Director of Environment, Health and Safety, American Iron and Steel Institute and Mausami Desai, U.S. Environmental Protection Agency, December 2016.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom996 pp.IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1995) "Volume 3: Greenhouse Gas Inventory Reference Manual. Table 2-2." *IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. IPCC WG1 Technical Support Unit, United Kingdom.

RTI (2024) Expert judgment, RTI International. April 2024.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Steiner (2008) Personal communication, Bruce Steiner, Technical Consultant with the American Iron and Steel Institute and Mausami Desai, U.S. Environmental Protection Agency, November 2008.

Tuck (2023a) Personal communication, Cris Tuck, Commodity Specialist, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency, January 24, 2023.

Tuck (2023b) Personal communication, Candice Tuck, Commodity Specialist, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency, November 30, 2023.

United States Department of Energy (DOE) (2000) *Energy and Environmental Profile of the U.S. Iron and Steel Industry*. Office of Industrial Technologies, U.S. Department of Energy. August 2000. DOE/EE-0229.EIA.

United States Energy Information Administration (EIA) (1998 through 2019) *Quarterly Coal Report: October-December*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

U.S. EIA (2021 through 2023) *Quarterly Coal Report: January – March,* Energy Information Administration, U.S. Department of Energy. Washington, D.C.

U.S. EIA (2020) *Natural Gas Annual 2019.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. September 2020.

U.S. EIA (2017b) *Monthly Energy Review*, *December 2017*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

U.S. EIA (1992) Coal and lignite production. *EIA State Energy Data Report 1992*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

United States Environmental Protection Agency (EPA) (2023). Greenhouse Gas Reporting Program. Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) *2022 Mineral Commodities Summaries: Iron and Steel.* U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *2021 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2022) *2020 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2021a) *2021 Mineral Commodities Summaries: Iron and Steel.* U.S. Geological Survey, Reston, VA. January 2021.

USGS (2021b) *2019 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2020a) *2018 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2020b) *2017 USGS Minerals Yearbook – Iron and Steel*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2020) *USGS Minerals Yearbook – Iron and Steel Scrap.* U.S. Geological Survey, Reston, VA.

Ferroalloy Production

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Onder, H., and E.A. Bagdoyan (1993) Everything You've Always Wanted to Know about Petroleum Coke. Allis Mineral Systems.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) *Mineral Industry Survey: Silicon in June 2023*. U.S. Geological Survey, Reston, VA. September 2023.

USGS (2023b) *2022 Mineral Commodity Summaries: Silicon.* U.S. Geological Survey, Reston, VA. January 2023.

USGS (2022a) *2021 Minerals Yearbook: Silicon (*tables-only release). U.S. Geological Survey, Reston, VA. September 2022.

USGS (2022b) *2020 Minerals Yearbook: Ferroalloys (tables-only release)*. U.S. Geological Survey, Reston, VA. May 2023.

USGS (2022c) *2021 Mineral Commodity Summaries*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021) *2020 Mineral Commodity Summaries: Silicon*. U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020) *2019 Mineral Commodity Summaries: Silicon*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2013a) *2013 Minerals Yearbook: Chromium*. U.S. Geological Survey, Reston, VA. March 2016.

USGS (1996 through 2022) *Minerals Yearbook: Silicon*. U.S. Geological Survey, Reston, VA.

Aluminum Production

EPA (2023) Greenhouse Gas Reporting Program (GHGRP). Envirofacts, Subpart: F Aluminum Production. Available online at: https://www.epa.gov/enviro/greenhouse-gas-subpart-f

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds.)]. Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

USGS (2023) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2022) Mineral Commodity Summaries 2022. U.S. Geological Survey, Reston VA.

USGS (2021) *2020 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2021) *2019 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2020) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2020) Mineral Industry Surveys: Aluminum in December 2020. U.S. Geological Survey, Reston VA. December 2020

USGS (2020) *2019 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2019) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2018) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2017) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2016) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2015) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2014) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2013) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2012) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2011) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2010) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2009) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2008) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2007) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2006) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2005) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1993) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1992) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1991) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1990) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Magnesium Production and Processing

ARB (2015) "Magnesium casters successfully retool for a cleaner future." California Air Resources Board News Release. Release # 15-07. February 5, 2015. Accessed October 2017. Available online at: https://www.arb.ca.gov/newsrel/newsrelease.php?id=704.

Bartos S., C. Laush, J. Scharfenberg, and R. Kantamaneni (2007) "Reducing greenhouse gas emissions from magnesium die casting." *Journal of Cleaner Production*, 15: 979-987, March.

EPA (2020) Envirofacts. Greenhouse Gas Reporting Program (GHGRP), Subpart T: Magnesium Production and Processing. Available online at: https://www.epa.gov/enviro/greenhouse-gas-customized-search. Accessed on October 2020.

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Gjestland, H. and D. Magers (1996) "Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry." #13, *1996 Annual Conference Proceedings*, International Magnesium Association. Ube City, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kramer Deborah A. (2000) "Magnesium" U.S. Geological Survey *Minerals Yearbook* – 2000.

RAND (2002) RAND Environmental Science and Policy Center, "Production and Distribution of SF_6 by End-Use Applications" Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. San Diego, CA. November 21-22, 2002.

USGS (1995 through 2023) *Minerals Yearbook: Magnesium Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis.

USGS (2010b) *Mineral Commodity Summaries: Magnesium Metal*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2010-mgmet.pdf.

USGS (2005b) Personal Communication between Deborah Kramer of the USGS and Jeremy Scharfenberg of ICF Consulting.

Lead Production

Dutrizac, J.E., V. Ramachandran, and J.A. Gonzalez (2000) *Lead-Zinc 2000*. The Minerals, Metals, and Materials Society.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Morris, D., F.R. Steward, and P. Evans (1983) *Energy Efficiency of a Lead Smelter.* Energy 8(5):337-349.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Sjardin, M. (2003) *CO_2 Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

Ullman (1997) *Ullman's Encyclopedia of Industrial Chemistry: Fifth Edition.* Volume A5. John Wiley and Sons.

United States Geological Survey (USGS) (2023a) *2022 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *2020 Minerals Yearbook, Lead – Advance Data Release*. U.S. Geological Survey, Reston, VA. July 2023.

USGS (2023c) *2022 Mineral Industries Surveys: Lead in September 2022.* U.S. Geological Survey, Reston, VA. December 2022.

USGS (2022a) *2019 Minerals Yearbook, Lead – Advance Data Release*. U.S. Geological Survey, Reston, VA. October 2022.

USGS (2022b) *2021 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021a) *2017 Minerals Yearbook, Lead – Advance Release*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2021b) *2020 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. February 2021.

USGS (2020) *2019 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2020.

USGS (2019) *2018 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2019.

USGS (2018) *2017 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2018.

USGS (2017) *2016 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2016) *2015 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2016.

USGS (2015) *2014 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. January 2015.

USGS (2014) *2013 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2014.

USGS (1994 through 2013) *Minerals Yearbook: Lead Annual Report.* U.S. Geological Survey, Reston, VA..

Zinc Production

American Zinc Recycling (AZR) (2021) Summary of Company History. Available online at https://azr.com/our-history/. Accessed on March 16, 2021.

AZR (2020) Personal communication. Erica Livingston, American Zinc Recycling and Amanda Chiu, U.S. Environmental Protection Agency. October 29, 2020.

American Zinc Products (AZP) (2021) American Zinc Products Marks First Anniversary of Zinc Production. Available online at https://americanzincproducts.com/american-zinc-products-marks-first-anniversary-of-zinc-production/. Accessed on March 1, 2022.

Befesa (2023) Personal communication. Eric Hunsberger, Befesa Zinc US Inc. and Amanda Chiu, U.S. Environmental Protection Agency. September 19, 2023.

Befesa (2022) Personal communication. Eric Hunsberger, Befesa Zinc US Inc. and Amanda Chiu, U.S. Environmental Protection Agency. November 8, 2022.

Horsehead Corp. (2016) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2015. Available online at: https://www.sec.gov/Archives/edgar/data/1385544/000119312516725704/d236839d10k.htm. Submitted on January 25, 2017.

Horsehead Corp. (2015) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2014. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000138554415000005/zinc-2014123110k.htm. Submitted on March 2, 2015.

Horsehead Corp. (2014) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2013. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000138554414000003/zinc-2013123110k.htm. Submitted on March 13, 2014.

Horsehead Corp. (2013) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2012. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000119312513110431/0001193125-13-110431-index.htm. Submitted March 18, 2013.

Horsehead Corp. (2012a) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2011. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000119312512107345/d293011d10k.htm. Submitted on March 9, 2012.

Horsehead Corp. (2012b) *Horsehead's New Zinc Plant and its Impact on the Zinc Oxide Business.* February 22, 2012. Available online at: http://www.horsehead.net/downloadAttachmentNDO.php?ID=118. Accessed on September 10, 2015.

Horsehead Corp. (2011) 10-K Annual Report for the Fiscal Year Ended December 31, 2010. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 16, 2011.

Horsehead Corp. (2010a) 10-K Annual Report for the Fiscal Year Ended December 31, 2009. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 16, 2010.

Horsehead Corp. (2010b) *Horsehead Holding Corp. Provides Update on Operations at its Monaca, PA Plant.* July 28, 2010. Available online at: http://www.horsehead.net/pressreleases.php?showall=no&news=&ID=65.

Horsehead Corp (2009) 10-K Annual Report for the Fiscal Year Ended December 31, 2008. Available online at: https://www.sec.gov/Archives/edgar/data/1385544/000095015209002674/l35087ae10vk.htm. Submitted on March 16, 2009.

Horsehead Corp (2008) 10-K Annual Report for the Fiscal Year Ended December 31, 2007. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 31, 2008.

Horsehead Corp (2007) Registration Statement (General Form) S-1. Available online at http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on April 13, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Nyrstar (2017) 2016 Clarksville Fact Sheet. Available online at: http://www.nyrstar.com/~/media/Files/N/Nyrstar/operations/melting/fact-sheet-clarksville-en.pdf. Accessed on September 27, 2017.

PIZO (2021) Personal communication. Thomas Rheaume, Arkansas Department of Energy and Environment and Amanda Chiu, U.S. Environmental Protection Agency. February 16, 2021.

PIZO (2012) Available online at http://pizotech.com/index.html. Accessed on October 10, 2012.

Recycling Today (2020) "AZR to restart for zinc recycling plant in North Carolina." March 6, 2020. https://www.recyclingtoday.com/article/american-zinc-recycling-restarting-north-carolina-plant-2020/. Accessed October 10, 2020.

Recycling Today (2017) "Horsehead announces corporate name change to American Zinc Recycling." May 3, 2017. https://www.recyclingtoday.com/article/horsehead-changes-name-american-zinc-recycling/. Accessed September 19, 2022.

Steel Dust Recycling (SDR) (2023) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. September 20 and 25, 2023.

SDR (2022) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. October 10, 2022.

SDR (2021) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. January 8, 2021.

SDR (2018) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and John Steller, U.S. Environmental Protection Agency. October 25, 2018.

SDR (2017) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and John Steller, U.S. Environmental Protection Agency. January 26, 2017.

SDR (2015) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. September 22, 2015.

SDR (2014) Personal communication. Art Rowland, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. December 9, 2014.

SDR (2013) Available online at http://steeldust.com/home.htm. Accessed on October 29, 2013.

SDR (2012) Personal communication. Art Rowland, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. October 5, 2012.

Sjardin (2003) CO_2 *Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

United States Environmental Protection Agency (EPA) (1992) "Applications Analysis Report: Horsehead Resource Development Company Inc., Flame Reactor Technology" EPA/540/A5-91/005. May 1992.

United States Geological Survey (USGS) (2023) *2023 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-zinc.pdf

USGS (2022) *2022 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021) *2021 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020) *2020 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2019) *2019 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2019.

USGS (2018) *2018 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2018.

USGS (2017) *2017 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2016) *2016 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2016.

USGS (2015) *2015 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2015.

USGS (1994 through 2014) *Minerals Yearbook: Zinc Annual Report.* U.S. Geological Survey, Reston, VA.

Viklund-White (2000) *The use of LCA for the environmental evaluation of the recycling of galvanized steel*. ISIJ International, Vol. 40. No. 3, pp 292-299.

Electronics Industry

Burton, C.S., and R. Beizaie (2001) "EPA's PFC Emissions Model (PEVM) v. 2.14: Description and Documentation" prepared for Office of Global Programs, U. S. Environmental Protection Agency, Washington, DC. November 2001.

Citigroup Smith Barney (2005) *Global Supply/Demand Model for Semiconductor*s. March 2005.

DisplaySearch (2010) DisplaySearch Q4'09 Quarterly FPD Supply/Demand and Capital Spending Report. DisplaySearch, LLC.

Doering, R. and Nishi, Y (2000) "Handbook of Semiconductor Manufacturing Technology", Marcel Dekker, New York, USA, 2000.

EPA (2023) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021*. U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-23-002.

EPA (2010) *Technical Support Document for Process Emissions from Electronics Manufacture (e.g., Micro-Electro-Mechanical Systems, Liquid Crystal Displays, Photovoltaics, and Semiconductors)*. U.S. Environmental Protection Agency, Washington, DC.

EPA (2006) *Uses and Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector.* U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-06-901.

EPA Greenhouse Gas Reporting Program (GHGRP) Envirofacts. Subpart I: Electronics Manufacture. Available online at: https://enviro.epa.gov/facts/ghg/search.html.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

ITRS (2007, 2008, 2011, 2013) *International Technology Roadmap for Semiconductors: 2006 Update*, January 2007; *International Technology Roadmap for Semiconductors: 2007 Edition,* January 2008*; International Technology Roadmap for Semiconductors: 2011, January 2012; Update, International Technology Roadmap for*

Semiconductors: 2013 Edition, Available online at: https://www.semiconductors.org/resources/2007-international-technology-roadmap-for-semiconductors-itrs/. These and earlier editions and updates are available online at: https://www.semiconductors.org/resources/?fwp_resource_types=utilization-reports&fwp_paged=2. Information about the number of interconnect layers for years 1990–2010 is contained in Burton and Beizaie, 2001. PEVM is updated using new editions and updates of the ITRS, which are published annually.

Platzer, Michaela D. (2015) *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support*. Congressional Research Service. January 27, 2015. https://fas.org/sgp/crs/misc/R42509.pdf.

SEMI – Semiconductor Equipment and Materials Industry (2021) *World Fab Forecast, June 2021 Edition.*

SEMI - Semiconductor Equipment and Materials Industry (2018) *World Fab Forecast*, *June 2018 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2017) *World Fab Forecast*, *August 2018 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2016) *World Fab Forecast*, *May 2017 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2013) *World Fab Forecast*, *May 2013 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2012) *World Fab Forecast*, *August 2012 Edition*.

Semiconductor Industry Association (SIA) (2009-2011) STATS: SICAS Capacity and Utilization Rates Q1-Q4 2008, Q1-Q4 2009, Q1-Q4 2010. Available online at: http://www.semiconductors.org/industry_statistics/semiconductor_capacity_utilization_sicas_reports/.

United States Census Bureau (USCB) (2011, 2012, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) *Historical Data: Quarterly Survey of Plant Capacity Utilization*. Available online at: https://www.census.gov/programs-surveys/qpc.html.

VLSI Research, Inc. (2012) Worldwide Silicon Demand. August 2012.

Substitution of Ozone Depleting Substances

EPA (2023a) Summary of Updates to the Unitary Air-conditioning End-uses in the Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023b) Summary of Updates to the Window Units End-use in the Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023c) Proposed Addition of Small and Large Ductless Mini-Split and Multi-Split Air Conditioning End-uses to U.S. EPA's Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023d) Proposed Updates to the Streaming Agent End-uses in U.S. EPA's Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2018) EPA's Vintaging Model of ODS Substitutes: A Summary of the 2017 Peer Review. Office of Air and Radiation. Document Number EPA-400-F-18-001. Available online at: https://www.epa.gov/sites/production/files/2018-09/documents/epas-vintaging-model-of-ods-substitutes-peer-review-factsheet.pdf.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen,

M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Electrical Equipment

CARB (2023). *California Greenhouse Gas Emission Inventory – 2023 Edition.* Accessed March 2024. Available online at: https://ww2.arb.ca.gov/ghg-inventory-data.

EPA (2022) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020*. EPA 430-R-22-003. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020.

Harnisch and Eisenhauer, "Natural CF_4 and SF_6 on Earth," GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.13, PAGES 2401-2404, JULY 1, 1998. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/98GL01779.

HIFLD (2022) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2021. Accessed September 2023. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::transmission-lines/explore?location=38.924381%2C-122.290494%2C4.78 .

HIFLD (2021) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2021. Accessed September 2022. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines.

HIFLD (2020) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2020. Accessed October 2021. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines/explore?showTable=true.

HIFLD (2019) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2019. Accessed March 2021. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines.

Hu, L., Ottinger, D., Bogle, S., Montzka, S., DeCola, P., Dlugokencky, E., Andrews, A., Thoning, K., Sweeney, C., Dutton, G., Aepli, L., and Crotwell, A. (2022) "Declining, seasonal-varying emissions of sulfur hexafluoride from the United States point to a new mitigation opportunity." *EGUsphere* [preprint]. Available online at: https://doi.org/10.5194/egusphere-2022-862.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

Levin et al. (2010) "The Global SF_6 Source Inferred from Long-term High Precision Atmospheric Measurements and its Comparison with Emission Inventories." *Atmospheric Chemistry and Physics*, 10: 2655–2662.

Middleton, B. (2000) *Cold Weather Applications of Gas Mixture (SF_6/N_2, SF_6/CF_4) Circuit Breakers: A User Utility's Perspective* [Conference Presentation]. The U.S. Environmental Protection Agency's Conference on SF_6 and the Environment: Emission Reduction Strategies, San Diego, CA, United States. Available online at: https://www.epa.gov/sites/default/files/2016-02/documents/conf00_middleton.pdf

O'Connell, P., F. Heil, J. Henriot, G. Mauthe, H. Morrison, L. Neimeyer, M. Pittroff, R. Probst, J.P. Tailebois (2002) *SF_6 in the Electric Industry, Status 2000,* CIGRE. February 2002.

Ottinger D, Averyt, M. & Harris, D. (2014). *Trends in emissions of fluorinated GHGs reported under the Greenhouse Gas Reporting Program: Patterns and potential causes*. Submitted to the Seventh International Symposium on Non-CO_2 Greenhouse Gases (NCGG-7), Amsterdam, Netherlands.

RAND (2004) "Trends in SF_6 Sales and End-Use Applications: 1961-2003," Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. RAND Environmental Science and Policy Center, Scottsdale, AZ. December 1-3, 2004.

UDI (2017) *2017 UDI Directory of Electric Power Producers and Distributors, 125th Edition*, Platts.

UDI (2013) *2013 UDI Directory of Electric Power Producers and Distributors,121st Edition*, Platts.

UDI (2010) *2010 UDI Directory of Electric Power Producers and Distributors, 118th Edition*, Platts.

UDI (2007) *2007 UDI Directory of Electric Power Producers and Distributors, 115th Edition*, Platts.

UDI (2004) *2004 UDI Directory of Electric Power Producers and Distributors, 112th Edition*, Platts.

UDI (2001) *2001 UDI Directory of Electric Power Producers and Distributors, 109th Edition*, Platts.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

SF_6 and PFCs from Other Product Use

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Workman, R.L. et al. Particle Data Group). Prog. Theor. Exp. Phys. 2022, 083C01. Available online at: https://pdg.lbl.gov/2022/reviews/rpp2022-rev-particle-detectors-accel.pdf

U.S. Department of Energy (DOE). 2022. Federal Energy Management Program (FEMP). Available online at: https://www.energy.gov/femp/federal-comprehensive-annual-energy-reporting-requirements.

Nitrous Oxide from Product Use

CGA (2003) "CGA Nitrous Oxide Abuse Hotline: CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. November 3, 2003.

CGA (2002) "CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. March 25, 2002.

Heydorn, B. (1997) "Nitrous Oxide—North America." *Chemical Economics Handbook*, SRI Consulting. May 1997.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Ottinger (2021) Personal communication. Deborah Ottinger, U.S. Environmental Protection Agency and Amanda Chiu, U.S. Environmental Protection Agency. January 7, 2021.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Tupman, M. (2002) Personal communication. Martin Tupman, Airgas Nitrous Oxide and Laxmi Palreddy, ICF International. July 3, 2002.

Industrial Processes and Product Use Sources of Precursor Greenhouse Gases

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 - 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C."

EPA (2023c) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Agriculture

Enteric Fermentation

Archibeque, S. (2011) Personal Communication. Shawn Archibeque, Colorado State University, Fort Collins, Colorado and staff at ICF International.

Crutzen, P.J., I. Aselmann, and W. Seiler (1986) Methane Production by Domestic Animals, Wild Ruminants, Other Herbivores, Fauna, and Humans. Tellus, 38B:271-284.

Donovan, K. (1999) Personal Communication. Kacey Donovan, University of California at Davis and staff at ICF International.

Donovan, K. and L. Baldwin. (1999) "Results of the AAMOLLY Model Runs for the Enteric Fermentation Model"; University of California, Davis, 1999.

Doren, P.E., J. F. Baker, C. R. Long and T. C. Cartwright (1989) Estimating Parameters of Growth Curves of Bulls, J Animal Science 67:1432-1445.

Enns, M. (2008) Personal Communication. Dr. Mark Enns, Colorado State University and staff at ICF International.

EPA (2002) Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for Quality Assurance/Quality Control and Uncertainty Analysis, U.S. Greenhouse Gas Inventory Program, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-007B, June 2002.

ERG (2021) Updated Other Animal Population Distribution Methodology. ERG, Lexington, MA.

ERG (2016) Development of Methane Conversion Rate Scaling Factor and Diet-Related Inputs to the Cattle Enteric Fermentation Model for Dairy Cows, Dairy Heifers, and Feedlot Animals. ERG, Lexington, MA. December 2016.

Galyean and Gleghorn (2001) Summary of the 2000 Texas Tech University Consulting Nutritionist Survey. Texas Tech University. Available online at http://www.depts.ttu.edu/afs/burnett_center/progress_reports/bc12.pdf. June 2009.

Holstein Association (2010) History of the Holstein Breed (website). Available online at: http://www.holsteinusa.com/holstein_breed/breedhistory.html. Accessed September 2010.

ICF (2006) Cattle Enteric Fermentation Model: Model Documentation. Prepared by ICF International for the Environmental Protection Agency. June 2006.

ICF (2003) Uncertainty Analysis of 2001 Inventory Estimates of Methane Emissions from Livestock Enteric Fermentation in the U.S. Memorandum from ICF International to the Environmental Protection Agency. May 2003.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Johnson, D. (2002) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and ICF International.

Johnson, D. (1999) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and David Conneely, ICF International.

Kebreab E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth (2008) Model for estimating enteric methane emissions from United States dairy and feedlot cattle. J. Anim. Sci. 86: 2738-2748.

Lippke, H., T. D. Forbes, and W. C. Ellis. (2000) Effect of supplements on growth and forage intake by stocker steers grazing wheat pasture. J. Anim. Sci. 78:1625-1635.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association, July 19, 2011.

Pinchak, W.E., D. R. Tolleson, M. McCloy, L. J. Hunt, R. J. Gill, R. J. Ansley, and S. J. Bevers (2004) Morbidity effects on productivity and profitability of stocker cattle grazing in the southern plains. J. Anim. Sci. 82:2773-2779.

Platter, W. J., J. D. Tatum, K. E. Belk, J. A. Scanga, and G. C. Smith (2003) Effects of repetitive use of hormonal implants on beef carcass quality, tenderness, and consumer ratings of beef palatability. J. Anim. Sci. 81:984-996.

Preston, R.L. (2010) What's The Feed Composition Value of That Cattle Feed? Beef Magazine, March 1, 2010. Available at: http://beefmagazine.com/nutrition/feed-composition-tables/feed-composition-value-cattle--0301.

Skogerboe, T. L., L. Thompson, J. M. Cunningham, A. C. Brake, V. K. Karle (2000) The effectiveness of a single dose of doramectin pour-on in the control of gastrointestinal nematodes in yearling stocker cattle. Vet. Parasitology 87:173-181.

Soliva, C.R. (2006) Report to the attention of IPCC about the data set and calculation method used to estimate methane formation from enteric fermentation of agricultural livestock population and manure management in Swiss agriculture. On behalf of the Federal Office for the Environment (FOEN), Berne, Switzerland.

U.S. Department of Agriculture (USDA) (2023) Quick Stats: Agricultural Statistics Database. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at http://quickstats.nass.usda.gov/. Accessed May-June 2023.

USDA (2022) Economic Research Service "Supply and allocation of milk fat and skim solids by product". Available online at: https://www.ers.usda.gov/data-products/dairy-data/. Accessed May 2023.

USDA (2021) Economic Research Service Dairy Data. Available online at: https://www.ers.usda.gov/data-products/dairy-data/. Accessed May 2021.

USDA (2019) *1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: https://www.nass.usda.gov/AgCensus/index.php. May 2019.

USDA (1996) Beef Cow/Calf Health and Productivity Audit (CHAPA): Forage Analyses from Cow/Calf Herds in 18 States. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at http://www.aphis.usda.gov/vs/ceah/cahm. March 1996.

USDA:APHIS:VS (2010) Beef 2007–08, Part V: Reference of Beef Cow-calf Management Practices in the United States, 2007–08. USDA–APHIS–VS, CEAH. Fort Collins, CO.

USDA:APHIS:VS (2002) Reference of 2002 Dairy Management Practices. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1998) Beef '97, Parts I-IV. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/animal_health/nahms/beefcowcalf/index.shtml#beef97.

USDA:APHIS:VS (1996) Reference of 1996 Dairy Management Practices. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1994) Beef Cow/Calf Health and Productivity Audit. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1993) Beef Cow/Calf Health and Productivity Audit. USDA–APHIS–VS, CEAH. Fort Collins, CO. August 1993. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

Vasconcelos and Galyean (2007) Nutritional recommendations of feedlot consulting nutritionists: The 2007 Texas Tech University Study. J. Anim. Sci. 85:2772-2781.

Manure Management

ASAE (1998) ASAE Standards 1998, 45th Edition. American Society of Agricultural Engineers. St. Joseph, MI.

Bryant, M.P., V.H. Varel, R.A. Frobish, and H.R. Isaacson (1976) In H.G. Schlegel (ed.)]; Seminar on Microbial Energy Conversion. E. Goltz KG. Göttingen, Germany.

Bush, E. (1998) Personal communication with Eric Bush, Centers for Epidemiology and Animal Health, U.S. Department of Agriculture regarding National Animal Health Monitoring System's (NAHMS) Swine '95 Study.

EPA (2023) AgSTAR Anaerobic Digester Database. Available online at: https://www.epa.gov/agstar/livestock-anaerobic-digester-database. Accessed August 2023.

EPA (2008) Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type Managing Manure with Biogas Recovery Systems.

EPA (2005) National Emission Inventory—Ammonia Emissions from Animal Agricultural Operations, Revised Draft Report. U.S. Environmental Protection Agency. Washington, D.C. April 22, 2005.

EPA (2002a) Development Document for the Final Revisions to the National Pollutant Discharge Elimination System (NPDES) Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (CAFOS). U.S. Environmental Protection Agency. EPA-821-R-03-001. December 2002.

EPA (2002b) Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations. U.S. Environmental Protection Agency. EPA-821-R-03-004. December 2002.

EPA (1992) Global Methane Emissions from Livestock and Poultry Manure, Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

ERG (2023) Summary of Data Processing and Proposed Integration of 2018 Beef Feedlot and Poultry Waste Management System Data into the Manure Management Greenhouse Gas Inventory. Memorandum to EPA from ERG, December 2023.

ERG (2021) Updated Other Animal Population Distribution Methodology. Memorandum to EPA from ERG.

ERG (2019) "Incorporation of USDA 2016 ARMS Dairy Data into the Manure Management Greenhouse Gas Inventory." Memorandum to USDA OCE and EPA from ERG, December 2019.

ERG (2018) "Incorporation of USDA 2009 ARMS Swine Data into the Manure Management Greenhouse Gas Inventory." Memorandum to USDA OCE and EPA from ERG, November 2018.

ERG (2010a) "Typical Animal Mass Values for Inventory Swine Categories." Memorandum to EPA from ERG. July 19, 2010.

ERG (2010b) Telecon with William Boyd of USDA NRCS and Cortney Itle of ERG Concerning Updated VS and Nex Rates. August 8, 2010.

ERG (2010c) "Updating Current Inventory Manure Characteristics new USDA Agricultural Waste Management Field Handbook Values." Memorandum to EPA from ERG. August 13, 2010.

ERG (2008) "Methodology for Improving Methane Emissions Estimates and Emission Reductions from Anaerobic Digestion System for the 1990-2007 Greenhouse Gas Inventory for Manure Management." Memorandum to EPA from ERG. August 18, 2008.

ERG (2003a) "Methodology for Estimating Uncertainty for Manure Management Greenhouse Gas Inventory." Contract No. GS-10F-0036, Task Order 005. Memorandum to EPA from ERG, Lexington, MA. September 26, 2003.

ERG (2003b) "Changes to Beef Calves and Beef Cows Typical Animal Mass in the Manure Management Greenhouse Gas Inventory." Memorandum to EPA from ERG, October 7, 2003.

ERG (2001) Summary of development of MDP Factor for methane conversion factor calculations. ERG, Lexington, MA. September 2001.

ERG (2000a) Calculations: Percent Distribution of Manure for Waste Management Systems. ERG, Lexington, MA. August 2000.

ERG (2000b) Discussion of Methodology for Estimating Animal Waste Characteristics (Summary of Bo Literature Review). ERG, Lexington, MA. June 2000.

Groffman, P.M., R. Brumme, K. Butterbach-Bahl, K.E. Dobbie, A.R. Mosier, D. Ojima, H. Papen, W.J. Parton, K.A. Smith, and C. Wagner-Riddle (2000) "Evaluating annual nitrous oxide fluxes at the ecosystem scale." Global Biogeochemical Cycles, 14(4):1061-1070.

Hashimoto, A.G. (1984) "Methane from Swine Manure: Effect of Temperature and Influent Substrate Composition on Kinetic Parameter (k)." Agricultural Wastes, 9:299-308.

Hashimoto, A.G., V.H. Varel, and Y.R. Chen (1981) "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." Agricultural Wastes, 3:241-256.

Hill, D.T. (1984) "Methane Productivity of the Major Animal Types." Transactions of the ASAE, 27(2):530-540.

Hill, D.T. (1982) "Design of Digestion Systems for Maximum Methane Production." Transactions of the ASAE, 25(1):226-230.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Morris, G.R. (1976) Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation. M.S. Thesis. Cornell University.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association July 19, 2011.

Ott, S.L. (2000) Dairy '96 Study. Stephen L. Ott, Animal and Plant Health Inspection Service, U.S. Department of Agriculture. June 19, 2000.

Robertson, G. P. and P. M. Groffman (2015) Nitrogen transformations. Soil Microbiology, Ecology, and Biochemistry, pages 421-446. Academic Press, Burlington, Massachusetts, USA.

Safley, L.M., Jr. (2000) Personal Communication. Deb Bartram, ERG and L.M. Safley, President, Agri-Waste Technology. June and October 2000.

Sweeten, J. (2000) Personal Communication. John Sweeten, Texas A&M University and Indra Mitra, ERG. June 2000.

UEP (1999) Voluntary Survey Results—Estimated Percentage Participation/Activity. Caged Layer Environmental Management Practices, Industry data submissions for EPA profile development, United Egg Producers and National Chicken Council. Received from John Thorne, Capitolink. June 2000.

USDA (2023a) Quick Stats: Agricultural Statistics Database. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: http://quickstats.nass.usda.gov/.

USDA (2023b) Chicken and Eggs 2022 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2023. Available online at: https://www.nass.usda.gov/Publications/.

USDA (2023c) Poultry - Production and Value 2022 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2023. Available online at: https://www.nass.usda.gov/Publications/.

USDA (2021a) Chicken and Eggs 2020 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2021. Available online at: http://www.nass.usda.gov/Publications/index.asp.

USDA (2021b) Poultry - Production and Value 2020 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2021. Available online at: http://www.nass.usda.gov/Publications/index.asp.

USDA (2019a) Chicken and Eggs 2018 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019b) Poultry - Production and Value 2018 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019c) Chicken and Eggs 2013-2017 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. June 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019d) 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: https://www.nass.usda.gov/AgCensus/index.php. May 2019.

USDA (2018) Poultry - Production and Value 2017 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2018. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2017) Poultry - Production and Value 2016 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2017. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2016) Poultry - Production and Value 2015 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2016. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2015) Poultry - Production and Value 2014 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2015. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2014) Poultry - Production and Value 2013 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2014. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2013a) Chicken and Eggs 2012 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2013. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2013b) Poultry - Production and Value 2012 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2013. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2012a) Chicken and Eggs 2011 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2012. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2012b) Poultry - Production and Value 2011 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2012. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2011a) Chicken and Eggs 2010 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2011. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2011b) Poultry - Production and Value 2010 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2011. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2010a) Chicken and Eggs 2009 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2010. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2010b) Poultry - Production and Value 2009 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2010. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009a) Chicken and Eggs 2008 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2009. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009b) Poultry - Production and Value 2008 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2009. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009c) Chicken and Eggs – Final Estimates 2003-2007. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 2009. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2009d) Poultry Production and Value—Final Estimates 2003-2007. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. May 2009. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2008) Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture.

USDA (2004a) Chicken and Eggs—Final Estimates 1998-2003. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2004b) Poultry Production and Value—Final Estimates 1998-2002. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1999) Poultry Production and Value—Final Estimates 1994-97. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1999. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1998) Chicken and Eggs—Final Estimates 1994-97. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1998. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1996) Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1995a) Poultry Production and Value—Final Estimates 1988-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1995. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1995b) Chicken and Eggs—Final Estimates 1988-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1995. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1994) Sheep and Goats—Final Estimates 1989-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. January 31, 1994. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA APHIS (2003) Sheep 2001, Part I: Reference of Sheep Management in the United States, 2001 and Part IV: Baseline Reference of 2001 Sheep Feedlot Health and Management. USDA-APHIS-VS. Fort Collins, CO. #N356.0702. Available online at http://www.aphis.usda.gov/animal_health/nahms/sheep/index.shtml#sheep2001.

USDA APHIS (2000) Layers '99—Part II: References of 1999 Table Egg Layer Management in the U.S. USDA-APHIS-VS. Fort Collins, CO. Available online at http://www.aphis.usda.gov/animal_health/nahms/poultry/downloads/layers99/Layers99_dr_PartII.pdf.

USDA APHIS (1996) Swine '95: Grower/Finisher Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices. USDA-APHIS-VS. Fort Collins, CO. Available online at: http://www.aphis.usda.gov/animal_health/nahms/swine/downloads/swine95/Swine95_dr_PartII.pdf.

Rice Cultivation

Baicich, P. (2013) The Birds and Rice Connection. *Bird Watcher's Digest*. Available online at: http://www.usarice.com/doclib/194/6867.pdf.

Brockwell, P.J., and R.A. Davis (2016) Introduction to time series and forecasting. Springer.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Cheng, K., S.M. Ogle, W.J. Parton, G. Pan. (2014) "Simulating greenhouse gas mitigation potentials for Chinese croplands using the DAYCENT ecosystem model." *Global Change Biology* 20:948-962.

Cheng, K., S.M. Ogle, W.J. Parton and G. Pan. (2013) "Predicting methanogenesis from rice paddies using the DAYCENT ecosystem model." *Ecological Modelling* 261-262:19-31.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." Global Biogeochemical Cycles, 24, GB1009, doi:10.1029/2009GB003544.

Deren, C. (2002) Personal Communication and Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

Fitzgerald, G.J., K. M. Scow & J. E. Hill (2000) "Fallow Season Straw and Rice Management Effects on Methane Emissions in California Rice." Global biogeochemical cycles, 14 (3), 767-776.

Fleskes, J.P., Perry, W.M., Petrik, K.L., Spell, R., and Reid, F. (2005) Change in area of winter-flood and dry rice in the northern Central Valley of California determined by satellite imagery. California Fish and Game, 91: 207-215.

Gonzalez, R. (2007 through 2014) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Hardke, J.T. (2015) Trends in Arkansas rice production, 2014. B.R. Wells Arkansas Rice Research Studies 2014. Norman, R.J. and Moldenhauer, K.A.K. (Eds.). Research Series 626, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J. (2014) Personal Communication. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Kirsten Jaglo, ICF International. September 11, 2014.

Hardke, J. (2013) Email correspondence. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Cassandra Snow, ICF International. July 15, 2013.

Hardke, J.T., and Wilson, C.E. Jr., (2014) Trends in Arkansas rice production, 2013. B.R. Wells Arkansas Rice Research Studies 2013. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 617, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J.T., and Wilson, C.E. Jr., (2013) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2012. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 609, Arkansas Agricultural Experiment Station, University of Arkansas.

Hollier, C. A. (ed), (1999) Louisiana rice production handbook. Louisiana State University Agricultural Center. LCES Publication Number 2321. 116 pp.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler (1985) "Production, Oxidation, and Emissions of Methane in Rice Paddies." *FEMS Microbiology Ecology,* 31:343-351.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, D.M., and R. Mueller (2010) The 2009 Cropland Data Layer. Photogrammetric engineering and remote sensing 76:1201-1205.

Kirstein, A. (2003 through 2004, 2006) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL and ICF International.

Klosterboer, A. (1997, 1999 through 2003) Personal Communication. Arlen Klosterboer, retired Extension Agronomist, Texas A&M University and ICF International. July 7, 2003.

Lindau, C.W. and P.K. Bollich (1993) "Methane Emissions from Louisiana First and Ratoon Crop Rice." *Soil Science,* 156:42-48.

Linquist, B.A., M.A. Adviento-Borbe, C.M. Pittelkow, C.v. Kessel, et al. (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Research*, 135:10-21.

Linscombe, S. (1999, 2001 through 2014) Email correspondence. Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center and ICF International.

LSU, (2015) Louisiana ratoon crop and conservation: Ratoon & Conservation Tillage Estimates. Louisiana State University, College of Agriculture AgCenter. Online at: www.lsuagcenter.com.

Miller, M.R., Garr, J.D., and Coates, P.S., (2010) Changes in the status of harvested rice fields in the Sacramento Valley, California: Implications for wintering waterfowl. Wetlands, 30: 939-947.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Neue, H.U., R. Wassmann, H.K. Kludze, W. Bujun, and R.S. Lantin (1997) "Factors and processes controlling methane emissions from rice fields." *Nutrient Cycling in Agroecosystems* 49: 111-117.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian. (2007) "An empirically based approach for estimating uncertainty associated with modeling carbon sequestration in soils." *Ecological Modelling* 205:453-463.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." Global Change Biology 16:810-822.

Ogle, S.M., S. Spencer, M. Hartman, L. Buendia, L. Stevens, D. du Toit, J. Witi (2016) "Developing national baseline GHG emissions and analyzing mitigation potentials for agriculture and forestry using an advanced national GHG inventory software system." In Advances in Agricultural Systems Modeling 6, *Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forestry Systems to Guide Mitigation and Adaptation*, S. Del Grosso, L.R. Ahuja and W.J. Parton (eds.), American Society of Agriculture, Crop Society of America and Soil Science Society of America, pp. 129-148.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". Glob. Planet. Chang. 19: 35-48.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." Soil Science Society of America Journal 51:1173-1179.

Särndal C-E, Swensson B, Wretman, J (1992) Model Assisted Survey Sampling. Springer, New York.

Sass, R. L. (2001) CH_4 Emissions from Rice Agriculture. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. 399-417. Available online at: http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_7_CH4_Rice_Agriculture.pdf.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner (1990) "Methane Production and Emissions in a Texas Rice Field." *Global Biogeochemical Cycles,* 4:47-68.

Sass, R.L., F.M. Fisher, S.T. Lewis, M.F. Jund, and F.T. Turner. (1994) "Methane emissions from rice fields: effect of soil texture." *Global Biogeochemical Cycles* 8:135-140.

Schueneman, T. (1997, 1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International.

Slaton, N. (1999 through 2001) Personal Communication. Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service and ICF International.

Stansel, J. (2004 through 2005) Email correspondence. Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center and ICF International.

TAMU (2015) Texas Rice Crop Survey. Texas A&M AgriLIFE Research Center at Beaumont. Online at: https://beaumont.tamu.edu/.

Texas Agricultural Experiment Station (2007 through 2014) *Texas Rice Acreage by Variety*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System. Available online at: http://beaumont.tamu.edu/CropSurvey/CropSurveyReport.aspx.

Texas Agricultural Experiment Station (2006) *2005 - Texas Rice Crop Statistics Report*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System, p. 8. Available online at: http://beaumont.tamu.edu/eLibrary/TRRFReport_default.htm.

University of California Cooperative Extension (UCCE) (2015) Rice Production Manual. Revised (2015) UCCE, Davis, in collaboration with the California Rice Research Board.

USDA (2005 through 2015) *Crop Production Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu.

USDA (2012) *Summary of USDA-ARS Research on the Interrelationship of Genetic and Cultural Management Factors That Impact Grain Arsenic Accumulation in Rice*. News and Events. Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://www.ars.usda.gov/is/pr/2012/120919.htm. September 2013.

USDA (2003) *Field Crops, Final Estimates 1997-2002*. Statistical Bulletin No. 982. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/usda/reports/general/sb/. September 2005.

USDA (1998) *Field Crops Final Estimates 1992-1997*. Statistical Bulletin Number 947 a. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/. July 2001.

USDA (1994) *Field Crops Final Estimates 1987-1992*. Statistical Bulletin Number 896. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/. July 2001.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

van Bodegom, P.M., R. Wassmann, T.M. Metra-Corton (2001) "A process based model for methane emission predictions from flooded rice paddies." *Global Biogeochemical Cycles* 15: 247-263.

Wang, J.J., S.K. Dodla, S. Viator, M. Kongchum, S. Harrison, S. D. Mudi, S. Liu, Z. Tian (2013) Agriculture Field Management Practices and Greenhouse Gas Emissions from Louisiana Soils. *Louisiana Agriculture*, Spring 2013: 8-9. Available online at: http://www.lsuagcenter.com/NR/rdonlyres/78D8B61A-96A8-49E1-B2EF-BA1D4CE4E698/93016/v56no2Spring2013.pdf.

Wassmann, R. H.U. Neue, R.S. Lantin, K. Makarim, N. Chareonsil5, L.V. Buendia, and H. Rennenberg (2000a) Characterization of methane emissions from rice fields in Asia II. Differences among irrigated, rainfed, and deepwater rice." *Nutrient Cycling in Agroecosystems*, 58(1):13-22.

Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, et al. (2000b) "Characterization of Methane Emissions from Rice Fields in Asia. III. Mitigation Options and Future Research Needs." *Nutrient Cycling in Agroecosystems*, 58(1):23-36.

Way, M.O., McCauley, G.M., Zhou, X.G., Wilson, L.T., and Morace, B. (Eds.), (2014) 2014 Texas Rice Production Guidelines. Texas A&M AgriLIFE Research Center at Beaumont.

Wilson, C. (2002 through 2007, 2009 through 2012) Personal Communication. Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service and ICF International.

Wilson, C.E. Jr., and Branson, J.W., (2006) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2005. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 540, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Branson, J.W., (2005) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2004. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 529, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., Runsick, S.K., and Mazzanti, R., (2010) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2009. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 581, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., Runsick, S.K., Mazzanti, R., (2009) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies (2008) Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 571, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Runsick, S.K., (2008) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2007. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 560, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Runsick, S.K., (2007) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2006. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 550, Arkansas Agricultural Experiment Station, University of Arkansas.

Yan, X., H. Akiyana, K. Yagi, and H. Akimoto (2009) “Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines.” *Global Biogeochemical Cycles*, 23, DOI: 0.1029/2008GB003299.

Yang, L., et al. (2018). "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies.” ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Young, M. (2013) Rice and Ducks. Ducks Unlimited, Memphis, TN. Available online at: http://www.ducks.org/conservation/farm-bill/rice-and-ducks---by-matt-young.

Agricultural Soil Management

AAPFCO (2008 through 2022) Commercial Fertilizers: 2008-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers: 1995-2007. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Cibrowski, P. (1996) Personal Communication. Peter Cibrowski, Minnesota Pollution Control Agency and Heike Mainhardt, ICF Incorporated. July 29, 1996.

Cheng, B., and D.M. Titterington (1994) "Neural networks: A review from a statistical perspective." Statistical science 9: 2-30.

Claassen, R., M. Bowman, J. McFadden, D. Smith, and S. Wallander (2018) Tillage intensity and conservation cropping in the United States, EIB 197. United States Department of Agriculture, Economic Research Service, Washington, D.C.

CTIC (2004) 2004 Crop Residue Management Survey. Conservation Technology Information Center. Available at http://www.ctic.purdue.edu/CRM/.

Del Grosso, S. J., S. M. Ogle, C. Nevison, R. Gurung, W. J. Parton, C. Wagner-Riddle, W. Smith, W. Winiwarter, B. Grant, M. Tenuta, E. Marx, S. Spencer, and S. Williams. 2022. A gap in nitrous oxide emission reporting complicates long-term climate mitigation. Proceedings of the National Academy of Sciences 119:e2200354119.

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima (2005) "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil Tillage and Research*, 83: 9-24. doi: 10.1016/j.still.2005.02.007.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." *Global Biogeochemical Cycles*, 24, GB1009, doi:10.1029/2009GB003544.

Del Grosso, S.J., T. Wirth, S.M. Ogle, W.J. Parton (2008) Estimating agricultural nitrous oxide emissions. EOS 89, 529-530.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.). Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press. Boca Raton, Florida. 303-332.

Del Grosso, S.J., W.J. Parton, C.A. Keough, and M. Reyes-Fox. (2011) Special features of the DAYCENT modeling package and additional procedures for parameterization, calibration, validation, and applications, in Methods of Introducing System Models into Agricultural Research, L.R. Ahuja and Liwang Ma, editors, p. 155-176, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. USA.

Delgado, J.A., S.J. Del Grosso, and S.M. Ogle (2009) "15N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N_2O-N emissions should be reevaluated." *Nutrient Cycling in Agroecosystems*, DOI 10.1007/s10705-009-9300-9.

Edmonds, L., N. Gollehon, R.L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaeffer (2003) "Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans." Part 1. Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping. Natural Resource Conservation Service, U.S. Department of Agriculture.

EPA (2003) Clean Watersheds Needs Survey 2000—Report to Congress, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at: http://biosolids.policy.net/relatives/18941.PDF.

EPA (1993) Federal Register. Part II. Standards for the Use and Disposal of Sewage Sludge; Final Rules. U.S. Environmental Protection Agency, 40 CFR Parts 257, 403, and 503.

Firestone, M. K., and E.A. Davidson, Ed. (1989) Microbiological basis of NO and N_2O production and consumption in soil. Exchange of trace gases between terrestrial ecosystems and the atmosphere. New York, John Wiley & Sons.

Friedman, J.H. (2001) "Greedy function approximation: A gradient boosting machine." Ann. Statist. 29 (5) 1189 – 1232.

Hagen, S. C., G. Delgado, P. Ingraham, I. Cooke, R. Emery, J. P. Fisk, L. Melendy, T. Olson, S. Patti, N. Rubin, B. Ziniti, H. Chen, W. Salas, P. Elias, and D. Gustafson. 2020. Mapping Conservation Management Practices and Outcomes in the Corn Belt Using the Operational Tillage Information System (OpTIS) and the Denitrification–Decomposition (DNDC) Model. Land **9**:408.

ILENR (1993) Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990. Office of Research and Planning, Illinois Department of Energy and Natural Resources. Springfield, IL.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. The Intergovernmental Panel on Climate Change. [T, Hiraishi, T. Krug, K. Tanabe, N. Srivastava, B. Jamsranjav, M. Fukuda and T. Troxler (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M.

Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, D.M., and R. Mueller (2010) The 2009 Cropland Data Layer. Photogrammetric engineering and remote sensing 76:1201-1205.

Little, R. (1988) "Missing-data adjustments in large surveys." *Journal of Business and Economic Statistics* 6: 287–296.

McFarland, M.J. (2001) Biosolids Engineering, New York: McGraw-Hill, p. 2.12.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26:267-286.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Mosier A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput (1998) Closing the global atmospheric N_2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle, Nutrient Cycling in Agroecosystems, 52, 225-248.

NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association, July 21, 2007.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Noller, J. (1996) Personal Communication. John Noller, Missouri Department of Natural Resources and Heike Mainhardt, ICF Incorporated. July 30, 1996.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." Global Change Biology 16:810-822.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." *Ecological Modeling* 205:453-463.

Oregon Department of Energy (1995) Report on Reducing Oregon's Greenhouse Gas Emissions: Appendix D Inventory and Technical Discussion. Oregon Department of Energy. Salem, OR.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing." *Glob. Planet. Chang*. 19: 35-48.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. *Earth Interactions* 11, Article No. 13, DOI 10.1175/EI228.1.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Pukelsheim, F. (1994) “The 3-Sigma-Rule.” American Statistician 48:88-91.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001. Scientific Investigations Report 2006-5012. U.S Department of the Interior.

Särndal C-E, Swensson B, Wretman, J (1992) Model Assisted Survey Sampling. Springer, New York.

Scheer, C., S.J. Del Grosso, W.J. Parton, D.W. Rowlings, P.R. Grace (2013) Modeling Nitrous Oxide Emissions from Irrigated Agriculture: Testing DAYCENT with High Frequency Measurements, Ecological Applications, in press. Available online at: http://dx.doi.org/10.1890/13-0570.1.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.

TVA (1991 through 1992a, 1993 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

USDA-ERS (2020) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at: http://www.ers.usda.gov/data/archive/93018/.

USDA-NASS (2023) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C., Accessed August 2023, http://quickstats.nass.usda.gov/.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2017) 2017 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2012) 2012 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH.

USDA-NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf.

USDA-NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH.

USDA-NRCS (2022) Conversation practice on cultivated croplands: A comparison of CEAP I and CEAP II survey data and modeling. United States Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/sites/default/files/2022-09/CEAP-Croplands-ConservationPracticesonCultivatedCroplands-Report-March2022.pdf.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) CEAP Cropland Farmer Surveys. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014163.

USDA-NRCS (2012) Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. U.S. Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf.

USFS (2019) Forest Inventory and Analysis Program. United States Department of Agriculture, U.S. Forest Service, https://www.fia.fs.fed.us/tools-data/default.asp.

Van Buuren, S. (2012) "Flexible imputation of missing data." Chapman & Hall/CRC, Boca Raton, FL.

Wagner-Riddle, C., Congreves, K. A., Abalos, D., Berg, A. A., Brown, S. E., Ambadan, J. T., Gao, X. & Tenuta, M. (2017) "Globally important nitrous oxide emissions from croplands induced by freeze-thaw cycles." *Nature Geosciences* 10(4): 279-283.

Wisconsin Department of Natural Resources (1993) Wisconsin Greenhouse Gas Emissions: Estimates for 1990. Bureau of Air Management, Wisconsin Department of Natural Resources, Madison, WI.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Liming

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Tepordei, V.V. (1994 through 2015) "Crushed Stone," In Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. Available online at: http://minerals.usgs.gov/minerals/.

Tepordei, V.V. (2003b) Personal communication. Valentin Tepordei, U.S. Geological Survey and ICF Consulting, August 18, 2003.

USGS (2023) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2023, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2022) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2022, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2021) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2021, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2020) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2020, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

West, T.O., and A.C. McBride (2005) "The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions," Agricultural Ecosystems & Environment 108:145-154.

West, T.O. (2008) Email correspondence. Tristram West, Environmental Sciences Division, Oak Ridge National Laboratory, U.S. Department of Energy and Nikhil Nadkarni, ICF International on suitability of liming emission factor for the entire United States. June 9, 2008.

Willett, J.C. (2023a) "Crushed Stone," In Minerals Yearbook 2021. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed November 2023

Willett, J.C. (2023b) Personal communication. Jason Willett. Preliminary data tables from "Crushed Stone," In 2022 Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. November, 2023.

Willett, J.C. (2022a) "Crushed Stone," In Minerals Yearbook 2018. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022.

Willett, J.C. (2022b) "Crushed Stone," In Minerals Yearbook 2019. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022

Willett, J.C. (2022c) "Crushed Stone," In Minerals Yearbook 2020. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022

Willett, J.C. (2022d) Personal communication. Jason Willett. Preliminary data tables from "Crushed Stone," In 2021 Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. October, 2022.

Willett, J.C. (2020a) "Crushed Stone," In Minerals Yearbook 2016. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis. Accessed November 2020.

Urea Fertilization

AAPFCO (2008 through 2022) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

AAPFCO (2000b) 1999-2000 Commercial Fertilizers Data, ASCII files. Available from David Terry, Secretary, AAPFCO.

EPA (2000) Preliminary Data Summary: Airport Deicing Operations (Revised). EPA-821-R-00-016. August 2000.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Itle, C. (2009) Email correspondence. Cortney Itle, ERG and Tom Wirth, U.S. Environmental Protection Agency on the amount of urea used in aircraft deicing. January 7, 2009.

TVA (1991 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992b) Fertilizer Summary Data 1992. Tennessee Valley Authority, Muscle Shoals, AL.

Field Burning of Agricultural Residues

Akintoye, H.A., Agbeyi, E.O., and Olaniyan, A.B. (2005) “The effects of live mulches on tomato (Lycopersicon esculentum) yield under tropical conditions.” *Journal of Sustainable Agriculture* 26: 27-37.

Bange, M.P., Milroy, S.P., and Thongbai, P. (2004) “Growth and yield of cotton in response to waterlogging.” *Field Crops Research* 88: 129-142.

Beyaert, R.P. (1996) *The effect of cropping and tillage management on the dynamics of soil organic matter*. PhD Thesis. University of Guelph.

Bouquet, D.J., and Breitenbeck, G.A. (2000) “Nitrogen rate effect on partitioning of nitrogen and dry matter by cotton.” *Crop Science* 40: 1685-1693.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer. Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Brouder, S.M., and Cassman, K.G (1990) “Root development of two cotton cultivars in relation to potassium uptake and plant growth in a vermiculitic soil.” *Field Crops Res.* 23: 187-203.

Costa, L.D., and Gianquinto, G. (2002) “Water stress and watertable depth influence yield, water use efficiency, and nitrogen recovery in bell pepper: lysimeter studies.” *Aust. J. Agric. Res.* 53: 201–210.

Crafts-Brandner, S.J., Collins, M., Sutton, T.G., and Burton, H.R. (1994) “Effect of leaf maleic hydrazide concentration on yield and dry matter partitioning in burley tobacco (Nicotiana tabacum L.).” *Field Crops Research* 37: 121-128.

De Pinheiro Henriques, A.R., and Marcelis, L.F.M. (2000) “Regulation of growth at steady-state nitrogen nutrition in lettuce (Lactuca sativa L.): Interactive effects of nitrogen and irradiance.” *Annals of Botany* 86: 1073-1080.0.

Díaz-Pérez, J.C., Silvoy, J., Phatak,S.C., Ruberson, J., and Morse, R. (2008) Effect of winter cover crops and co-till on the yield of organically-grown bell pepper (Capsicum annum L.). *Acta Hort*. 767:243-247.

Dua, K.L., and Sharma, V.K. (1976) “Dry matter production and energy contents of ten varieties of sugarcane at Muzaffarnagar (Western Uttar Pradesh).” *Tropical Ecology* 17: 45-49.

Fritschi, F.B., Roberts, B.A., Travis, R.L., Rains, D.W., and Hutmacher, R.B. (2003) “Seasonal nitrogen concentration, uptake, and partitioning pattern of irrigated Acala and Pima cotton as influenced by nitrogen fertility level.” *Crop Science* 44:516–527.

Gerik, T.J., K.L. Faver, P.M. Thaxton, and K.M. El-Zik. (1996) “Late season water stress in cotton: I. Plant growth, water use, and yield.” *Crop Science* 36: 914–921.

Gibberd, M.R., McKay, A.G., Calder, T.C., and Turner, N.C. (2003) “Limitations to carrot (Daucus carota L.) productivity when grown with reduced rates of frequent irrigation on a free-draining, sandy soil.” *Australian Journal of Agricultural Research* 54: 499-506.

Giglio, L., I. Csiszar, and C.O. Justice (2006) “Global distribution and seasonality of active fires as observed with the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors” J. Geophys. Res. 111, G02016, doi:10.1029/2005JG000142.

Giglio, L., Justice, C., Boschetti, L., Roy, D. (2015) “*MCD64A1 MODIS/Terra+Aqua Burned Area Monthly L3 Global 500m SIN Grid V006* [Data set]”. NASA EOSDIS Land Processes Distributed Active Archive Center. Accessed 2023-12-05 from https://doi.org/10.5067/MODIS/MCD64A1.006.

Halevy, J. (1976) “Growth rate and nutrient uptake of two cotton cultivars grown under irrigation.” *Agronomy Journal* 68: 701-705.

Halvorson, A.D., Follett, R.F., Bartolo, M.E., and Schweissing, F.C. (2002) “Nitrogen fertilizer use efficiency of furrow-irrigated onion and corn.” *Agronomy Journal* 94: 442-449.

Heitholt, J.J., Pettigrew, W.T., and Meredith, W.R. (1992) “Light interception and lint yield of narrow-row cotton.” *Crop Science* 32: 728-733.

Hollifield, C.D., Silvertooth, J.C., and Moser, H. (2000) "Comparison of obsolete and modern cotton cultivars for irrigated production in Arizona." *2000 Arizona Cotton Report*, University of Arizona College of Agriculture, http://ag.arizona.edu/pubs/crops/az1170/.

Hopkinson, J.M. (1967) "Effects of night temperature on the growth of Nicotiana tabacum." *Australian Journal of Experimental Agriculture and Animal Husbandry* 7: 78–82.

Huett, D.O., and Dettman, E.B. (1991) Effect of nitrogen on growth, quality and nutrient uptake of cabbages grown in sand culture. *Australian Journal of Experimental Agriculture* 29: 875-81.

Huett, D.O., and Dettman, B. (1989) "Nitrogen response surface models of zucchini squash, head lettuce and potato." *Plant and Soil* 134: 243-254.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Jacobs, J.L., Ward, G.N., and Kearney, G. (2004) "Effects of irrigation strategies and nitrogen fertilizer on turnip dry matter yield, water use efficiency, nutritive characteristics and mineral content in western Victoria." *Australian Journal of Experimental Agriculture* 44: 13-26.

Jacobs, J.L., Ward, G.N., McDowell, A.M., and Kearney, G. (2002) "Effect of seedbed cultivation techniques, variety, soil type and sowing time, on brassica dry matter yields, water use efficiency and crop nutritive characteristics in western Victoria." *Australian Journal of Experimental Agriculture* 42: 945-952.

Jacobs, J.L., Ward, G.N., McDowell, A.M., and Kearney, G.A. (2001) "A survey on the effect of establishment techniques, crop management, moisture availability and soil type on turnip dry matter yields and nutritive characteristics in western Victoria." *Australian Journal of Experimental Agriculture* 41: 743–751.

Kage, H., Alt, C., and Stűtzel, H. (2003) "Aspects of nitrogen use efficiency of cauliflower II. Productivity and nitrogen partitioning as influenced by N supply." *Journal of Agricultural Science* 141: 17–29.

Kumar, A., Singh, D.P., and Singh, P. (1994) "Influence of water stress on photosynthesis, transpiration, water-use efficiency and yield of Brassica juncea L." *Field Crops Research* 37: 95-101.

LANDFIRE (2008) Existing Vegetation Type Layer, LANDFIRE 1.1.0, U.S. Department of the Interior, Geological Survey. Accessed 28 October 2010 at http://landfire.cr.usgs.gov/viewer/.

MacLeod, L.B., Gupta, U.C., and Cutcliffe, J.A. (1971) "Effect of N, P, and K on root yield and nutrient levels in the leaves and roots of rutabagas grown in a greenhouse." *Plant and Soil* 35: 281-288.

Mahrani, A., and Aharonov, B. (1964) "Rate of nitrogen absorption and dry matter production by upland cotton grown under irrigation." *Israel J. Agric. Res.* 14: 3-9.

Marcussi, F.F.N., Bôas, R.L.V., de Godoy, L.J.G., and Goto, R. (2004) "Macronutrient accumulation and partitioning in fertigated sweet pepper plants." *Sci. Agric. (Piracicaba, Braz.)* 61: 62-68.

McCarty, J.L. (2011) "Remote Sensing-Based Estimates of Annual and Seasonal Emissions from Crop Residue Burning in the Contiguous United States." *Journal of the Air & Waste Management Association*, 61:1, 22-34, DOI: 10.3155/1047-3289.61.1.22.

McCarty, J.L. (2010) Agricultural Residue Burning in the Contiguous United States by Crop Type and State. Geographic Information Systems (GIS) Data provided to the EPA Climate Change Division by George Pouliot, Atmospheric Modeling and Analysis Division, EPA. Dr. McCarty's research was supported by the NRI Air Quality Program of the Cooperative State Research, Education, and Extension Service, USDA, under Agreement No. 20063511216669 and the NASA Earth System Science Fellowship.

McCarty, J.L. (2009) *Seasonal and Interannual Variability of Emissions from Crop Residue Burning in the Contiguous United States*. Dissertation. University of Maryland, College Park.

McPharlin, I.R., Aylmore, P.M., and Jeffery, R.C. (1992) "Response of carrots (Daucus carota L.) to applied phosphorus and phosphorus leaching on a Karrakatta sand, under two irrigation regimes." *Australian Journal of Experimental Agriculture* 32:225-232.

Mondino, M.H., Peterlin, O.A., and Garay, F. (2004) "Response of late-planted cotton to the application of growth regulator (chlorocholine chloride, CYCOCEL 75)." *Expl Agric.* 40: 381–387.

Moustakas, N.K., and Ntzanis, H. (2005) "Dry matter accumulation and nutrient uptake in flue-cured tobacco (Nicotiana tabacum L.)." *Field Crops Research* 94: 1-13.

Peach, L., Benjamin, L.R., and Mead, A. (2000) "Effects on the growth of carrots (Daucus carota L.), cabbage (Brassica oleracea var. capitata L.) and onion (Allium cepa L.) of restricting the ability of the plants to intercept resources." *Journal of Experimental Botany* 51: 605-615.

Pettigrew, W.T., and Meredith, W.R., Jr. (1997) "Dry matter production, nutrient uptake, and growth of cotton as affected by potassium fertilization." *J. Plant Nutr.* 20:531–548.

Pettigrew, W.T., Meredith, W.R., Jr., and Young, L.D. (2005) "Potassium fertilization effects on cotton lint yield, yield components, and reniform nematode populations." *Agronomy Journal* 97: 1245-1251.

PRISM Climate Group (2015) PRISM Climate Data. Oregon State University. July 24, 2015. Available online at: http://prism.oregonstate.edu.

Reid, J.B., and English, J.M. (2000) "Potential yield in carrots (Daucus carota L.): Theory, test, and an application." *Annals of Botany* 85: 593-605.

Sadras, V.O., and Wilson, L.J. (1997) "Growth analysis of cotton crops infested with spider mites: II. Partitioning of dry matter." *Crop Science* 37: 492-497.

Scholberg, J., McNeal, B.L., Jones, J.W., Boote, K.J., Stanley, C.D., and Obreza, T.A. (2000a) "Growth and canopy characteristics of field-grown tomato." *Agronomy Journal* 92: 152-159.

Scholberg, J., McNeal, B.L., Boote, K.J., Jones, J.W., Locasio, S.J., and Olson, S.M. (2000b) "Nitrogen stress effects on growth and nitrogen accumulation by field-grown tomato." *Agronomy Journal* 92:159-167.

Singels, A. and Bezuidenhout, C.N. (2002) "A new method of simulating dry matter partitioning in the Canegro sugarcane model." *Field Crops Research* 78: 151 - 164.

Sitompul, S.M., Hairiah, K., Cadisch, G., and Van Noordwuk, M. (2000) "Dynamics of density fractions of macro-organic matter after forest conversion to sugarcane and woodlots, accounted for in a modified Century model." *Netherlands Journal of Agricultural Science* 48: 61-73.

Stirling, G.R., Blair, B.L., Whittle, P.J.L., and Garside, A.L. (1999) "Lesion nematode (Pratylenchus zeae) is a component of the yield decline complex of sugarcane." In: Magarey, R.C. (Ed.), *Proceedings of the First Australasian Soilborne Disease Symposium*. Bureau of Sugar Experiment Stations, Brisbane, pp. 15–16.

Tan, D.K.Y., Wearing, A.H., Rickert, K.G., and Birch, C.J. (1999) "Broccoli yield and quality can be determined by cultivar and temperature but not photoperiod in south-east Queensland." *Australian Journal of Experimental Agriculture* 39: 901–909.

Tadesse, T., Nichols, M.A., and Fisher, K.J. (1999) Nutrient conductivity effects on sweet pepper plants grown using a nutrient film technique. 1. Yield and fruit quality. New Zealand Journal of Crop and Horticultural Science, 27: 229-237.

Torbert, H.A., and Reeves, D.W. (1994) "Fertilizer nitrogen requirements for cotton production as affected by tillage and traffic." Soil Sci. Soc. Am. J. 58:1416-1423.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2019) Quick Stats: U.S. & All States Data; Crops; Production and Area Harvested; 1990 - 2018. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, D.C. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C., Available online at: http://quickstats.nass.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Valantin, M., Gary, C., Vaissiére, B.E., and Frossard, J.S. (1999) "Effect of fruit load on partitioning of dry matter and energy in cantaloupe (Cucumis melo L.)." *Annals of Botany* 84: 173-181.

Wallach, D., Marani, A., and Kletter, E. (1978) "The relation of cotton crop growth and development to final yield." *Field Crops Research* 1: 283-294.

Wells, R., and Meredith, W.R., Jr. (1984) "Comparative growth of obsolete and modern cultivars. I. Vegetative dry matter partitioning." *Crop Science* 24: 858-872.4.

Wiedenfels, R.P. (2000) "Effects of irrigation and N fertilizer application on sugarcane yield and quality." *Field Crops Research* 43: 101-108.

Land Use, Land-Use Change, and Forestry

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Representation of the U.S. Land Base

Alaska Department of Natural Resources (2006) Alaska Infrastructure 1:63,360. Available online at: http://dnr.alaska.gov/SpatialUtility/SUC?cmd=extract&layerid=75.

Alaska Interagency Fire Management Council (1998) Alaska Interagency Wildland Fire Management Plan. Available online at: http://agdc.usgs.gov/data/blm/fire/index.html.

Alaska Oil and Gas Conservation Commission (2009) Oil and Gas Information System. Available online at: http://doa.alaska.gov/ogc/publicdb.html.

Dewitz, J., 2023, National Land Cover Database (NLCD) 2021 Products: U.S. Geological Survey data release, https://doi.org/10.5066/P9JZ7AO3.

EIA (2011) Coal Production and Preparation Report Shapefile. Available online at: http://www.eia.gov/state/notes-sources.cfm#maps.

ESRI (2008) ESRI Data & Maps. Redlands, CA: Environmental Systems Research Institute. [CD-ROM].

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States, Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2010) Revisiting the use of managed land as a proxy for estimating national anthropogenic emissions and removals. [Eggleston HS, Srivastava N, Tanabe K, Baasansuren J, (eds.)]. Institute for Global Environmental Studies, Intergovernmental Panel on Climate Change, Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. (2013) A comprehensive change detection method for updating the National Land Cover Database to circa 2011. Remote Sensing of Environment, 132: 159-175.

Nelson, M.D., Riitters, K.H., Coulston, J.W., Domke, G.M., Greenfield, E.J., Langner, L.L., Nowak, D.J., O'Dea, C.B., Oswalt, S.N., Reeves, M.C. and Wear, D.N. (2020) Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191., 191, pp.1-70.

NOAA Coastal Change Analysis Program (C-CAP) Regional Land Cover Database. Data collected 1995-present Charleston, SC: National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center. Data accessed at: www.csc.noaa.gov/landcover.

Nusser, S.M. and J.J. Goebel (1997) "The national resources inventory: a long-term multi-resource monitoring programme." Environmental and Ecological Statistics 4:181-204.

Ogle, S.M., G. Domke, W.A. Kurz, M.T. Rocha, T. Huffman, A. Swan, J.E. Smith, C. Woodall, T. Krug (2018) Delineating managed land for reporting greenhouse gas emissions and removals to the United Nations Framework Convention on Climate Change. Carbon Balance and Management 13:9.

U.S. Census Bureau (2010) Topologically Integrated Geographic Encoding and Referencing (TIGER) system shapefiles. U.S. Census Bureau, Washington, D.C. Available online at: http://www.census.gov/geo/www/tiger.

U.S. Department of Agriculture (2015) County Data - Livestock, 1990-2014. U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, D.C.

U.S. Department of Agriculture, Forest Service. (2023) Timber Product Output (TPO) Reports. https://www.fia.fs.usda.gov/program-features/tpo/

U.S. Department of Interior (2005) Federal Lands of the United States. National Atlas of the United States, U.S. Department of the Interior, Washington D.C. Available online at: http://nationalatlas.gov/atlasftp.html?openChapters=chpbound#chpbound.

United States Geological Survey (USGS), Gap Analysis Program (2012) Protected Areas Database of the United States (PADUS), version 1.3 Combined Feature Class. November 2012.

USGS (2012) Alaska Resource Data File. Available online at: http://ardf.wr.usgs.gov/.

USGS (2005) Active Mines and Mineral Processing Plants in the United States in 2003. U.S. Geological Survey, Reston, VA.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks

AF&PA (2006a and earlier) Statistical roundup. (Monthly). Washington, D.C. American Forest & Paper Association.

AF&PA (2006b and earlier) Statistics of paper, paperboard and wood pulp. Washington, D.C. American Forest & Paper Association.

AF&PA (2021) 2020 Statistics – Paper Industry – Annual Summary Data Through 2020. Washington, D.C.: American Forest and Paper Association, 54 p.

AF&PA (2023) Capacity & Fiber Consumption Survey – Paper Industry – 63rd Annual 2022-2023. Washington, D.C.: American Forest and Paper Association, 44 p.

Amichev, B.Y. and J.M. Galbraith (2004) "A Revised Methodology for Estimation of Forest Soil Carbon from Spatial Soils and Forest Inventory Data Sets." Environmental Management 33(Suppl. 1):S74-S86.

Bechtold, W.A.; Patterson, P.L. (2005) The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 85 p.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Coulston, J.W., Wear, D.N., and Vose, J.M. (2015) Complex forest dynamics indicate potential for slowing carbon accumulation in the southeastern United States. Scientific Reports. 5: 8002.

Deenik J, McClellan AT (2007) Soils of Hawai'i. Soil and Crop Management, SCM-20. College of Tropical Agriculture and Human Resources, University of Hawai'i at Manoa, Honolulu.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., Nave, L., Swanston, C. (2017) Toward inventory-based estimates of soil organic carbon in forests of the United States. Ecological Applications. 27(4), 1223-1235.

Domke, G.M., Walters, B.F., Smith, J.E., Woodall, C.W. (2022) Chapter 6: FIA Carbon Attributes. In Sampling and estimation documentation for the Enhanced Forest Inventory and Analysis Program: 2022. Westfall, J.A., Coulston, J.W., Moisen, G.G., Andersen, H.-E., eds. Gen. Tech. Rep. NRS-GTR-207, Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 129 p. https://doi.org/10.2737/NRS-GTR-207.

Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A., McRoberts, R.E. (2012) Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. Forest Ecology and Management. 270: 108-116.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

EPA (2006) Municipal solid waste in the United States: 2005 Facts and figures. Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. (5306P) EPA530-R-06-011. Available online at: http://www.epa.gov/msw/msw99.htm.

FAO. Forestry Production and Trade. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/FO. Data of Access: 13-09-2023.

Frayer, W.E., and G.M. Furnival (1999) "Forest Survey Sampling Designs: A History." Journal of Forestry 97(12): 4-10.

Freed, R. (2004) Open-dump and Landfill timeline spreadsheet (unpublished). ICF International. Washington, D.C.

Hair, D. (1958) "Historical forestry statistics of the United States." Statistical Bull. 228. U.S. Department of Agriculture Forest Service, Washington, D.C.

Hair. D. and A.H. Ulrich (1963) The Demand and price situation for forest products – 1963. U.S. Department of Agriculture Forest Service, Misc Publication No. 953. Washington, D.C.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Howard, J. L. and Liang, S. (2019) U.S. timber production, trade, consumption, and price statistics 1965 to 2017. Res. Pap. FPL-RP-701. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. and Jones, K.C. (2016) U.S. timber production, trade, consumption, and price statistics 1965 to 2013. Res. Pap. FPL-RP-679. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. (2007) U.S. timber production, trade, consumption, and price statistics 1965 to 2005. Res. Pap. FPL-RP-637. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. (2003) U.S. timber production, trade, consumption, and price statistics 1965 to 2002. Res. Pap. FPL-RP-615. Madison, WI: USDA, Forest Service, Forest Products Laboratory. Available online at: http://www.fpl.fs.fed.us/documnts/fplrp/fplrp615/fplrp615.pdf.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T.G. (eds.)]. Switzerland.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., Harrison, R.B., Guerrini, I.A., deB Richter Jr., D., Rustad, L., Lorenz, K., Chabbi, A., Miglietta, F. (2014) Current status, uncertainty and future needs in soil organic carbon monitoring. Science of the Total Environment, 468, 376-383.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Johnson, K. Domke, G.M., Russell, M.B., Walters, B.F., Hom, J., Peduzzi, A., Birdsey, R., Dolan, K., Huang, W. (2017) Estimating aboveground live understory vegetation carbon in the United States. Environmental Research Letters.

Johnson, M.G. and Kern, J.S., (2002.) Quantifying the organic carbon held in forested soils of the United States and Puerto Rico. The potential of US forest soils to sequester and mitigate the greenhouse effect, Lewis, Boca Raton, pp.47-72.

Nelson, M.D., Riitters, K.H., Coulston, J.W., Domke, G.M., Greenfield, E.J., Langner, L.L., Nowak, D.J., O'Dea, C.B., Oswalt, S.N., Reeves, M.C. and Wear, D.N. (2020) Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191., 191, pp.1-70.

Ogle, S. M., G. M. Domke, W. A. Kurz, M. T. Rocha, T. Huffman, A. Swan, J. E. Smith, C. W. Woodall, and T. Krug. (2018) Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. Carbon Balance and Management 13:9.

O'Neill, K.P., Amacher, M.C., Perry, C.H. (2005) Soils as an indicator of forest health: a guide to the collection, analysis, and interpretation of soil indicator data in the Forest Inventory and Analysis program. Gen. Tech. Rep. NC-258. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 53 p.

Oswalt, S.N., Brandeis, T.J. and Woodall, C.W., (2008). Contribution of dead wood to biomass and carbon stocks in the Caribbean: St. John, US Virgin Islands. Biotropica, 40(1), pp.20-27.

Oswalt, S.N., Smith, W.B., Miles, P.D. and Pugh, S.A. (2019) Forest resources of the United States, 2017: A technical document supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-97. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office., 97.

Perry, C.H., C.W. Woodall, and M. Schoeneberger (2005) Inventorying trees in agricultural landscapes: towards an accounting of "working trees". In: "Moving Agroforestry into the Mainstream." Proc. 9th N. Am. Agroforestry Conf., Brooks, K.N. and Folliott, P.F. (eds.). 12-15 June 2005, Rochester, MN [CD-ROM]. Dept. of Forest Resources, Univ. Minnesota, St. Paul, MN, 12 p. Available online at: http://cinram.umn.edu/afta2005/. (verified 23 Sept 2006).

Russell, M.B.; D'Amato, A.W.; Schulz, B.K.; Woodall, C.W.; Domke, G.M.; Bradford, J.B. (2014) Quantifying understory vegetation in the U.S. Lake States: a proposed framework to inform regional forest carbon stocks. Forestry. 87: 629-638.

Russell, M.B.; Domke, G.M.; Woodall, C.W.; D'Amato, A.W. (2015) Comparisons of allometric and climate-derived estimates of tree coarse root carbon in forests of the United States. Carbon Balance and Management. 10: 20.

Selmants, P.C., Giardina, C.P., Jacobi, J.D., and Zhu, Zhiliang, eds. (2017) Baseline and projected future carbon storage and carbon fluxes in ecosystems of Hawai'i: U.S. Geological Survey Professional Paper 1834, 134 p., https://doi.org/10.3133/pp1834.

Skog, K.E. (2008) Sequestration of carbon in harvested wood products for the United States. Forest Products Journal 58:56-72.

Smith, J.E., Domke, G.M. and Woodall, C.W. (2022) Predicting downed woody material carbon stocks in forests of the conterminous United States. Science of the Total Environment, 803, p.150061.

Smith, J.E., L.S. Heath, and M.C. Nichols (2010) U.S. Forest Carbon Calculation Tool User's Guide: Forestland Carbon Stocks and Net Annual Stock Change. General Technical Report NRS-13 revised, U.S. Department of Agriculture Forest Service, Northern Research Station, 34 p.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Smith, W. B., P. D. Miles, C. H. Perry, and S. A. Pugh (2009) Forest Resources of the United States, 2007. General Technical Report WO-78, U.S. Department of Agriculture Forest Service, Washington Office.

Soil Survey Staff (2020a) Gridded National Soil Survey Geographic (gNATSGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service. Available online at https://nrcs.app.box.com/v/soils.

Soil Survey Staff (2020b) Gridded National Soil Survey Geographic (gNATSGO) Database for Alaska. United States Department of Agriculture, Natural Resources Conservation Service. Available online at https://nrcs.app.box.com/v/soils.

Steer, Henry B. (1948) Lumber production in the United States. Misc. Pub. 669, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, Alice (1985) U.S. Timber Production, Trade, Consumption, and Price Statistics 1950-1985. Misc. Pub. 1453, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, Alice (1989) U.S. Timber Production, Trade, Consumption, and Price Statistics, 1950-1987. USDA Miscellaneous Publication No. 1471, U.S. Department of Agriculture Forest Service. Washington, D.C., 77.

United Nations Framework Convention on Climate Change (UNFCC) (2013) Report on the individual review of the inventory submission of the United States of America submitted in 2012. FCCC/ARR/2012/USA. 42 p.

USDA Forest Service (2022a) PNW-FIA Hawai'i Inventory Database. Last accessed: 28 September 2023. https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-hawaii-inventory-database

USDA Forest Service (2022b) PNW-FIA Pacific Islands Inventory Database. Last accessed: 28 September 2023. https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-pacific-islands-database https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-hawaii-inventory-database

USDA Forest Service (2023a) Forest Inventory and Analysis National Program: Program Features. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/program-features/index.php. Accessed 28 September 2023.

USDA Forest Service. (2023b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 28 September 2023.

USDA Forest Service. (2023c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 28 September 2023.

USDA Forest Service (2023d) Forest Inventory and Analysis National Program, FIA library: Database Documentation. U.S. Department of Agriculture, Forest Service, Washington Office. Available online at: https://www.fia.fs.usda.gov/library/database-documentation/index.php. Accessed on 28 September 2023.

U.S. Census Bureau (1976) Historical Statistics of the United States, Colonial Times to 1970, Vol. 1. Washington, D.C.

Wear, D.N., Coulston, J.W. (2015) From sink to source: Regional variation in U.S. forest carbon futures. Scientific Reports. 5: 16518.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. In press . A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104. Washington, DC: U.S. Department of Agriculture, Forest Service. 60 p. https//doi.org/10.2737/WO-GTR-104.

Westfall, J.A., Woodall, C.W., Hatfield, M.A. (2013) A statistical power analysis of woody carbon flux from forest inventory data. Climatic Change. 118: 919-931.

Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B., Will-Wolf, S. (2011b) "Status and future of the forest health indicators program of the United States." Environmental Monitoring and Assessment. 177: 419-436.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Anderson, H.-E., Clough, B.J., Cohen, W.B., Griffith, D.M., Hagan, S.C., Hanou, I.S.; Nichols, M.C., Perry, C.H., Russell, M.B., Westfall, J.A., Wilson, B.T. (2015a) The U.S. Forest Carbon Accounting Framework: Stocks and Stock change 1990-2016. Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 pp.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Zhu, Zhiliang, and McGuire, A.D., eds. (2016) Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska: U.S. Geological Survey Professional Paper 1826, 196 p., Available online at: http://dx.doi.org/10.3133/pp1826.

Forest Land Remaining Forest Land: Non-CO_2 Emissions from Forest Fires

Eidenshink, J., Schwind, B., Brewer, K., Zhu, Z.L., Quayle, B. and Howard, S. (2007) A project for monitoring trends in burn severity. Fire ecology, 3(1), pp.3-21.

French, N.H.F., W.J. de Groot, L.K. Jenkins, B.M. Rogers, E.C. Alvarado, B. Amiro, B. de Jong, S. Goetz, E. Hoy, E. Hyer, R. Keane, D. McKenzie, S.G. McNulty, B.E Law, R. Ottmar, D.R. Perez-Salicrup, J. Randerson, K.M. Robertson, and M. Turetsky (2011) "Model comparisons for estimating carbon emissions from North American wildland fire." Journal of Geophysical Research 116. 10.1029/2010JG001469

French, N.H.F., D. McKenzie, T. Erickson, B. Koziol, M. Billmire, K.A. Endsley, N.K.Y. Scheinerman, L. Jenkins, M.E. Miller, R. Ottmar, and S. Prichard (2014) "Modeling regional-scale fire emissions with the Wildland Fire Emissions Information System." Earth Interactions 18, no. 16

Giglio, L., Boschetti, L., Roy, D. P., Humber, M. L., and Justice, C. O. (2018) The Collection 6 MODIS burned area mapping algorithm and product. Remote Sensing of Environment, 217, 72-85.

IPCC (2019) Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Larkin, N. K., S. Raffuse, and T. T. Strand (2014) Wildland fire emissions, carbon, and climate: U.S. emissions inventories. For. Ecol. Manage. 317:61–69. doi:10.1016/j.foreco.2013.09.012.

MTBS Data Access: Fire Level Geospatial Data (August 2023) MTBS Project (USDA Forest Service/U.S. Geological Survey). Available online at: http://mtbs.gov/direct-download. Accessed on 15 August 2023.

Ogle, S. M., G. M. Domke, W. A. Kurz, M. T. Rocha, T. Huffman, A. Swan, J. E. Smith, C. W. Woodall, and T. Krug. (2018) Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. Carbon Balance and Management 13:9.

WFEIS (2023) Wildland Fire Emissions Inventory System, home page. https://wfeis.mtri.org/.

WFIGS (2023) WFIGS, The Wildland Fire Interagency Geospatial Service Interagency Fire Perimeters. National Interagency Fire Center. https://data-nifc.opendata.arcgis.com/datasets/nifc::wfigs-interagency-fire-perimeters/explore?location=0.000000%2C0.000000%2C1.82.

Forest Land Remaining Forest Land: N_2O Emissions from Soils

Albaugh, T.J., Allen, H.L., Fox, T.R. (2007) Historical Patterns of Forest Fertilization in the Southeastern United States from 1969 to 2004. Southern Journal of Applied Forestry, 31, 129-137(9).

Binkley, D. (2004) Email correspondence regarding the 95 percent confidence interval for area estimates of southern pine plantations receiving N fertilizer (±20%) and the rate applied for areas receiving N fertilizer (100 to 200 pounds/acre). Dan Binkley, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University and Stephen Del Grosso, Natural Resource Ecology Laboratory, Colorado State University. September 19, 2004.

Binkley, D., R. Carter, and H.L. Allen (1995) Nitrogen Fertilization Practices in Forestry. In: Nitrogen Fertilization in the Environment, P.E. Bacon (ed.), Marcel Decker, Inc., New York.

Briggs, D. (2007) Management Practices on Pacific Northwest West-Side Industrial Forest Lands, 1991-2005: With Projections to 2010. Stand Management Cooperative, SMC Working Paper Number 6, College of Forest Resources, University of Washington, Seattle.

Fox, T.R., H. L. Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson (2007) Tree Nutrition and Forest Fertilization of Pine Plantations in the Southern United States. Southern Journal of Applied Forestry, 31, 5-11.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

USDA Forest Service (2001) U.S. Forest Facts and Historical Trends. FS-696. U.S. Department of Agriculture Forest Service, Washington, D.C. Available online at: http://www.fia.fs.fed.us/library/ForestFactsMetric.pdf.

Forest Land Remaining Forest Land: Drained Organic Soils

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

STATSGO2 (2016) Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2). Available online at https://sdmdataaccess.sc.egov.usda.gov. Accessed 10 November 2016.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, DC; 2015. Available online at https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed 30 March 2022.

USDA Forest Service (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, DC; 2015. Available online at https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed 30 March 2022.

Land Converted to Forest Land

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." Global Change Biology 12:516-523.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

USDA Forest Service (2023a) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 29 September 2023.

USDA Forest Service (2023b) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 29 September 2023.

USDA-NRCS (2018) Summary Report: 2015 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

USDA-NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Land Converted to Forest Land

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." Global Change Biology 12:516-523.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

USDA Forest Service (2023b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 29 September 2023.

USDA Forest Service (2023c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 29 September 2023.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) Summary Report: 2015 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

USDA-NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Cropland Remaining Cropland

Armentano, T. V., and E.S. Menges (1986) Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology* 74: 755-774.

Brady, N.C. and R.R. Weil (1999) The Nature and Properties of Soils. Prentice Hall. Upper Saddle River, NJ, 881.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Conant, R. T., K. Paustian, and E.T. Elliott (2001) "Grassland management and conversion into grassland: effects on soil carbon." *Ecological Applications* 11: 343-355.

CTIC (2004) National Crop Residue Management Survey: 1989-2004. Conservation Technology Information Center, Purdue University, Available online at: http://www.ctic.purdue.edu/CRM/.

Daly, C., R.P. Neilson, and D.L. Phillips (1994) "A Statistical-Topographic Model for Mapping Climatological Precipitation Over Mountainous Terrain." *Journal of Applied Meteorology* 33:140-158.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management, L. Guo, A. Gunasekara, L. McConnell (eds.). American Chemical Society, Washington, D.C.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at: http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html.

Euliss, N., and R. Gleason (2002) Personal communication regarding wetland restoration factor estimates and restoration activity data. Ned Euliss and Robert Gleason of the U.S. Geological Survey, Jamestown, ND, to Stephen Ogle of the National Resource Ecology Laboratory, Fort Collins, CO. August 2002.

Friedman, J.H. (2001) "Greedy function approximation: A gradient boosting machine." Ann. Statist. 29 (5) 1189 – 1232.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S. M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F. E., Sanderman, J., Silvius, M., Wollenberg, E. & Fargione, J. (2017) "Natural climate solutions." Proceedings of the National Academy of Sciences of the United States of America 114(44): 11645-11650.

Hagen, S. C., G. Delgado, P. Ingraham, I. Cooke, R. Emery, J. P. Fisk, L. Melendy, T. Olson, S. Patti, N. Rubin, B. Ziniti, H. Chen, W. Salas, P. Elias, and D. Gustafson. 2020. Mapping Conservation Management Practices and Outcomes in the Corn Belt Using the Operational Tillage Information System (OpTIS) and the Denitrification–Decomposition (DNDC) Model. Land **9**:408

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm.

Lal, R., Kimble, J. M., Follett, R. F. & Cole, C. V. (1998) *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, MI: Sleeping Bear Press, Inc.

Little, R. (1988) "Missing-data adjustments in large surveys." *Journal of Business and Economic Statistics* 6: 287–296.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26:267-286.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006) North American regional reanalysis. Bulletin of the American Meteorological Society 87:343-360.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

NRCS (1999) Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition. Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

NRCS (1981) Land Resource Regions and Major Land Resource Areas of the United States, USDA Agriculture Handbook 296, United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Cente., Lincoln, NE, pp. 156.

Ogle, S.M., Breidt, F.J., Del Grosso, S., Gurung, R., Marx, E., Spencer, S., Williams, S., Manning, D. (2023) "Counterfactual scenarios reveal historical impact of cropland management on soil organic carbon stocks in the United States." Scientific Reports 13(1):14564.

Ogle, S. M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F. J., McConkey, B., Regina, K. & Vazquez-Amabile, G. G. (2019) "Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions." Scientific Reports 9(1): 11665.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." *Ecological Modeling* 205:453-463.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." *Global Change Biology* 12:516-523.

Ogle, S. M., et al. (2005) "Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions." *Biogeochemistry* 72: 87-121.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Paustian, K., et al. (1997a) "Agricultural soils as a sink to mitigate CO_2 emissions." *Soil Use and Management* 13: 230-244.

Paustian, K., et al. (1997b) Management controls on soil carbon. In Soil organic matter in temperate agroecosystems: long-term experiments in North America (Paul E.A., K. Paustian, and C.V. Cole, eds.). Boca Raton, CRC Press, pp. 15-49.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. *Earth Interactions* 11, Article No. 13, DOI 10.1175/EI228.1.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Pukelsheim, F. (1994) "The 3-Sigma-Rule." American Statistician 48:88-91

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

Spencer, S., S.M. Ogle, F.J. Breidt, J. Goebel, and K. Paustian. (2011) "Designing a national soil carbon monitoring network to support climate change policy: a case example for US agricultural lands." Greenhouse Gas Management & Measurement 1: 167-178.

Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.

USDA-ERS (2020) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (2018) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at: http://www.ers.usda.gov/data/archive/93018/.

USDA Forest Service. (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 07 October 2022.

USDA-FSA (2015) Conservation Reserve Program Monthly Summary – September 2015. U.S. Department of Agriculture, Farm Service Agency, Washington, D.C. Available online at: https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/sep2015summary.pdf.

USDA-NASS (2022) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C., Accessed October 2022, http://quickstats.nass.usda.gov/.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2017) 2017 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2012) 2012 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH.

USDA-NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf.

USDA-NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa, https://www.nrcs.usda.gov/sites/default/files/2022-10/2017NRISummary_Final.pdf.

USDA-NRCS (2018) CEAP Cropland Farmer Surveys. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014163.

USDA-NRCS (2012) Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. U.S. Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Land Converted to Cropland

Sampson and D. Hair, (eds.). *Forest and Global Change*, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) *Introduction to time series and forecasting*. Springer.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In *Modeling Carbon and Nitrogen Dynamics for Soil Management*, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) "Soil organic matter cycling and greenhouse gas accounting methodologies." Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: *Understanding Greenhouse Gas Emissions from Agricultural Management* (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.); *Modeling Carbon and Nitrogen Dynamics for Soil Management*. CRC Press. Boca Raton, Florida. 303-332.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) "Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States". *Carbon Balance and Management* 6:14.

Domke, G.M., et al. (2013) "From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory." *PLoS ONE* 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) "A framework for estimating litter carbon stocks in forests of the United States." *Science of the Total Environment* 557–558: 469–478.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) "Completion of the 2006 National Land Cover Database for the Conterminous United States." *PE&RS*, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) "Completion of the 2001 National Land Cover Database for the Conterminous United States." *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) "Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information." *Photogrammetric Engineering and Remote Sensing* 81: 345-354.

Houghton, R.A., et al. (1983) "Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere." *Ecological Monographs* 53: 235-262.

Houghton, R. A. and Nassikas, A. A. (2017) "Global and regional fluxes of carbon from land use and land cover change 1850–2015." *Global Biogeochemical Cycles* 31(3): 456-472.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." *Forest Science* 49(1):12-35.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) *CENTURY Soil Organic Matter Model Environment. Agroecosystem version 4.0.* Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.Ogle, S.M., Breidt, F.J., Del Grosso, S., Gurung, R., Marx, E., Spencer, S., Williams, S., Manning, D. (2023) "Counterfactual scenarios reveal historical impact of cropland management on soil organic carbon stocks in the United States." Scientific Reports 13(1):14564.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." *Global Change Biology* 12:516-523.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in *Quantitative Modeling of Soil Forming Processes.* Special Publication 39, Soil Science Society of America, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." *Global Change Biology* 21:2655-2660.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*. Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. (2023) A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-XX

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Grassland Remaining Grassland: Soil Carbon Stock Changes

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at: http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at: http://biosolids.policy.net/relatives/18941.PDF.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon (2000) Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States. U.S. Department of Agriculture, Washington, D.C. Publication number nps00-0579.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association. July 21, 2007.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. *Environmental and Ecological Statistics* 4:181-204.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 24 July 2015.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

United States Bureau of Land Management (BLM) (2014) *Rangeland Inventory, Monitoring, and Evaluation Reports*. Bureau of Land Management. U.S. Department of the Interior. Available online at: http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Grassland Remaining Grassland: Non-CO_2 Emissions from Grassland Fires

Anderson, R.C. Evolution and origin of the Central Grassland of North America: climate, fire and mammalian grazers. *Journal of the Torrey Botanical Society* 133: 626-647.

Andreae, M.O. and P. Merlet (2001) Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles* 15:955-966.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Chapin, F.S., S.F. Trainor, O. Huntington, A.L. Lovecraft, E. Zavaleta, D.C. Natcher, A.D. McGuire, J.L. Nelson, L. Ray, M. Calef, N. Fresco, H. Huntington, T.S. Rupp, L. DeWilde, and R.L. Naylor (2008) Increasing wildfires in Alaska's Boreal Forest: Pathways to potential solutions of a wicked problem. *Bioscience* 58:531-540.

Daubenmire, R. (1968) Ecology of fire in grasslands. *Advances in Ecological Research* 5:209-266.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

MTBS (2023) Burned Areas Boundaries Dataset. (2023, August – last revised). MTBS Project (USDA Forest Service/U.S. Geological Survey). Available online: https://mtbs.gov/direct-download Accessed: August 9, 2023.

Ogle, S.M., S. Spencer, M. Hartman, L. Buendia, L. Stevens, D. du Toit, J. Witi (2016) "Developing national baseline GHG emissions and analyzing mitigation potentials for agriculture and forestry using an advanced national GHG inventory software system." In Advances in Agricultural Systems Modeling 6, *Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forestry Systems to Guide Mitigation and Adaptation*, S. Del Grosso, L.R. Ahuja and W.J. Parton (eds.), American Society of Agriculture, Crop Society of America and Soil Science Society of America, pp. 129-148.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. *Environmental and Ecological Statistics* 4:181-204.

Picotte, J.J., K. Bhattarai, D. Howard, J. Lecker, J. Epting, B. Quayle, N. Benson, and K. Nelson (2020) "Changes to the Monitoring Trends in Burn Severity program mapping production procedures and data products." *Fire Ecology*. 16:16. https://doi.org/10.1186/s42408-020-00076-y.

USDA-NRCS (2015) Summary Report: 2012 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf.

Land Converted to Grassland

Asner, G.P., Archer, S., Hughes, R.F., Ansley, R.J. and Wessman, C.A. (2003) "Net changes in regional woody vegetation cover and carbon storage in Texas drylands, 1937–1999." *Global Change Biology* 9(3): 316-335.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Breshears, D.D., Knapp, A.K., Law, D.J., Smith, M.D., Twidwell, D. and Wonkka, C.L., 2016. Rangeland Responses to Predicted Increases in Drought Extremity. Rangelands, 38(4), pp.191-196.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Del Grosso, S.J., S.M. Ogle, W.J. Parton. (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management (Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. Carbon Balance and Management. 6:14.

Domke, G.M., et al. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Walters, B.F., Smith, J.E., Woodall, C.W. (2022) Chapter 6: FIA Carbon Attributes. In Westfall, J.A.; Coulston, J.W.; Moisen, G.G.; Andersen, H.-E., eds. 2022. Sampling and estimation documentation for the Enhanced Forest Inventory and Analysis Program: 2022. Gen. Tech. Rep. NRS-GTR-207, Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 129 p. https://doi.org/10.2737/NRS-GTR-207.

Epstein, H.E., Gill, R.A., Paruelo, J.M., Lauenroth, W.K., Jia, G.J. and Burke, I.C. (2002) The relative abundance of three plant functional types in temperate grasslands and shrublands of North and South America: effects of projected climate change. Journal of Biogeography, 29(7), pp.875-888.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, v. 81, no. 5, p. 345-354.

Houghton, R.A., et al. (1983) "Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere." *Ecological Monographs* 53: 235-262.

Houghton, R. A. and Nassikas, A. A. (2017) "Global and regional fluxes of carbon from land use and land cover change 1850–2015." *Global Biogeochemical Cycles* 31(3): 456-472.

Huang, C.Y., Asner, G.P., Martin, R.E., Barger, N.N. and Neff, J.C. (2009) "Multiscale analysis of tree cover and aboveground carbon stocks in pinyon-juniper woodlands." *Ecological Applications* 19(3): 668-681.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, [H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Jurena, P.N. and Archer, S., (2003) Woody plant establishment and spatial heterogeneity in grasslands. Ecology, 84(4), pp.907-919.

Lenihan, J.M., Drapek, R., Bachelet, D. and Neilson, R.P., (2003) Climate change effects on vegetation distribution, carbon, and fire in California. Ecological Applications, 13(6), pp.1667-1681.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Scholes, R.J. and Archer, S.R. (1997) Tree-grass interactions in savannas 1. Annual review of Ecology and Systematics, 28(1), pp.517-544.

Sims, P.L., Singh, J.S. and Lauenroth, W.K. (1978) The structure and function of ten western North American grasslands: I. Abiotic and vegetational characteristics. The Journal of Ecology, pp.251-285.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tarhouni, M., et al. (2016) Measurement of the aboveground biomass of some rangeland species using a digital non-destructive technique. *Botany Letters* 163(3):281-287.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." *Global Change Biology* 21:2655-2660.

United States Bureau of Land Management (BLM) (2014) *Rangeland Inventory, Monitoring, and Evaluation Reports*. Bureau of Land Management. U.S. Department of the Interior. Available online at: http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*. Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols. (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Wetlands Remaining Wetlands: CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands

Apodaca, L. (2011) Email correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. November.

Apodaca, L. (2008) E-mail correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. October and November.

Cleary, J., N. Roulet and T.R. Moore (2005) "Greenhouse gas emissions from Canadian peat extraction, 1990-2000: A life-cycle analysis." *Ambio* 34:456–461.

Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014).* Alaska Department of Natural Resources, Fairbanks, AK. Available online at http://www.dggs.dnr.state.ak.us/pubs/pubs?reqtype=minerals.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. R.K. Pachauri and L.A. Meyer (eds.). IPCC, Geneva, Switzerland.

IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report (AR4) of the IPCC*. The Intergovernmental Panel on Climate Change, R.K. Pachauri, A. Resinger (eds.). Geneva, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Szumigala, D.J. (2011) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. January 18, 2011.

Szumigala, D.J. (2008) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. October 17, 2008.

USGS (1991–2018) *Minerals Yearbook: Peat (1994–2018).* United States Geological Survey, Reston, VA. Available online at http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html.

USGS (2023a) *Minerals Yearbook: Peat (2019) Tables-only release.* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023b) *Minerals Yearbook: Peat (2020) Tables-only release.* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023c) *Mineral Commodity Summaries: Peat (1996-2023).* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023d) Email correspondence. Amanda Brioche, Mineral Commodity Specialist, USGS. August 2023.

Wetlands Remaining Coastal Wetlands: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands

Abbott, K. M., Elsey-Quirk, T., and DeLaune, R. D. (2019) Factors influencing blue carbon accumulation across a 32-year chronosequence of created coastal marshes. Ecosphere, 10(8): e02828.

Allen, J. R., Cornwell, J. C., and Baldwin, A. H. (2021) Contributions of organic and mineral matter to vertical accretion in tidal wetlands across a Chesapeake Bay subestuary. Journal of Marine Science and Engineering 9(7): 751.

Arias-Ortiz, A., Oikawa, P. Y., Carlin, J., Masqué, P., Shahan, J., Kanneg, S., ... and Baldocchi, D. D. (2021) Tidal and nontidal marsh restoration: a trade-off between carbon sequestration, methane emissions, and soil accretion. Journal of Geophysical Research: Biogeosciences, 126(12): e2021JG006573.

Arriola, J. M., and Cable, J. E. (2017) Variations in carbon burial and sediment accretion along a tidal creek in a Florida salt marsh. Limnology and Oceanography 62(S1): S15-S28.

Baustian, M. M., Stagg, C. L., Perry, C. L., Moss, L. C., and Carruthers, T. J. (2021) Long-term carbon sinks in marsh soils of coastal Louisiana are at risk to wetland loss. Journal of Geophysical Research: Biogeosciences 126(3): e2020JG005832.

Bianchi, T. S., Allison, M. A., Zhao, J., Li, X., Comeaux, R. S., Feagin, R. A., & Kulawardhana, R. W. (2013) Historical reconstruction of mangrove expansion in the Gulf of Mexico: linking climate change with carbon sequestration in coastal wetlands. Estuarine, Coastal and Shelf Science 119: 7-16.

Boyd, B. (2012) Comparison of sediment accumulation and accretion in impounded and unimpounded marshes of the Delaware Estuary. Doctoral dissertation, University of Delaware.

Boyd, B. M. and Sommerfield, C. K. (2016) Marsh accretion and sediment accumulation in a managed tidal wetland complex of Delaware Bay. Ecological Engineering, 92: 37-46.

Boyd, B. M., Sommerfield, C. K., and Elsey-Quirk, T. (2017) Hydrogeomorphic influences on salt marsh sediment

accumulation and accretion in two estuaries of the US Mid-Atlantic coast. Marine Geology, 383: 132-145.

Breithaupt, J. L., Smoak, J. M., Smith III, T. J., and Sanders, C. J. (2014) Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades. Journal of Geophysical Research: Biogeosciences, 119(10): 2032-2048.

Byrd, K. B., Ballanti, L. R., Thomas, N. M., Nguyen, D. K., Holmquist, J. R., Simard, M., Windham-Myers, L., Schile, L. M., Parker, V. T., … and Castaneda-Moya, E. (2017) Biomass/Remote Sensing dataset: 30m resolution tidal marsh biomass samples and remote sensing data for six regions in the conterminous United States: U.S. Geological Survey data release, https://doi.org/10.5066/F77943K8.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2018) A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. ISPRS Journal of Photogrammetry and Remote Sensing 139: 255-271.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2020) Corrigendum to “A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States”. ISPRS Journal of Photogrammetry and Remote Sensing 166: 63-67.

Callaway, J. C., Borgnis, E. L., Turner, R. E. & Milan, C. S. (2012a) Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuaries and Coasts 35(5): 1163-1181.

Callaway, J. C., Borgnis, E. L., Turner, R. E., Milan, C. S., Goodfriend, W., & Richmond, S. (2012b) "Wetland Sediment Accumulation at Corte Madera Marsh and Muzzi Marsh". San Francisco Bay Conservation and Development Commission.

Church, T. M., Sommerfield, C. K., Velinsky, D. J., Point, D., Benoit, C., Amouroux, D. & Donard, O. F. X. (2006) Marsh sediments as records of sedimentation, eutrophication and metal pollution in the urban Delaware Estuary. Marine Chemistry 102(1-2): 72-95.

Couvillion, B. R., Barras, J. A., Steyer, G. D., Sleavin, W., Fischer, M., Beck, H., & Heckman, D. (2011) Land area change in coastal Louisiana (1932 to 2010) (pp. 1-12). U.S. Department of the Interior, U.S. Geological Survey.

Couvillion, B. R., Fischer, M. R., Beck, H. J. and Sleavin, W. J. (2016) Spatial Configuration Trends in Coastal Louisiana from 1986 to 2010. Wetlands 1-13.

Craft, C. B., & Richardson, C. J. (1998) Recent and long-term organic soil accretion and nutrient accumulation in the Everglades. Soil Science Society of America Journal 62(3): 834-843.

Crooks, S., Findsen, J., Igusky, K., Orr, M. K. and Brew, D. (2009) Greenhouse Gas Mitigation Typology Issues Paper: Tidal Wetlands Restoration. Report by PWA and SAIC to the California Climate Action Reserve.

Crooks, S., Rybczyk, J., O’Connell, K., Devier, D. L., Poppe, K., Emmett-Mattox, S. (2014) Coastal Blue Carbon Opportunity Assessment for the Snohomish Estuary: The Climate Benefits of Estuary Restoration. Report by Environmental Science Associates, Western Washington University, EarthCorps, and Restore America’s Estuaries.

DeLaune, R. D., & White, J. R. (2012) Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: A case study of the rapidly subsiding Mississippi river deltaic plain. Climatic Change, 110(1), 297-314.

Drexler, J. Z., de Fontaine, C. S., and Brown, T. A. (2009) Peat accretion histories during the past 6,000 years in marshes of the Sacramento–San Joaquin Delta, CA, USA. Estuaries and Coasts 32: 871-892.

Drexler, J. Z., Krauss, K. W., Sasser, M. C., Fuller, C. C., Swarzenski, C. M., Powell, A., ... and Orlando, J. (2013) A long-term comparison of carbon sequestration rates in impounded and naturally tidal freshwater marshes along the lower Waccamaw River, South Carolina. Wetlands 33: 965-974.

Drexler, J. Z., Woo, I., Fuller, C. C., and Nakai, G. (2019) Carbon accumulation and vertical accretion in a restored versus historic salt marsh in southern Puget Sound, Washington, United States. Restoration Ecology 27(5): 1117-1127.

Ensign, S. H., Noe, G. B., Hupp, C. R., and Skalak, K. J. (2015) Head-of-tide bottleneck of particulate material transport from watersheds to estuaries. Geophysical Research Letters 42(24): 10-671.

Gerlach, M. J., Engelhart, S. E., Kemp, A. C., Moyer, R. P., Smoak, J. M., Bernhardt, C. E., and Cahill, N. (2017) Reconstructing Common Era relative sea-level change on the Gulf Coast of Florida. Marine Geology 390: 254-269.

Giblin, A., Forbrich, I., & LTER, P. I. E. (2018) PIE LTER high marsh sediment chemistry and activity measurements, Nelson Island Creek marsh, Rowley, MA.

Holmquist, J. R., Windham-Myers, L., Bliss, N., Crooks, S., Morris, J. T., Megonigal, J. P. & Woodrey, M. (2018) Accuracy and Precision of Tidal Wetland Soil Carbon Mapping in the Conterminous United States. Scientific reports 8(1): 9478.

Hu, Z., Lee, J. W., Chandran, K., Kim, S. and Khanal, S. K. (2012) N_2O Emissions from Aquaculture: A Review. Environmental Science & Technology 46(12): 6470-6480.

Hussein, A. H., Rabenhorst, M. C. & Tucker, M. L. (2004) Modeling of carbon sequestration in coastal marsh soils. Soil Science Society of America Journal 68(5): 1786-1795.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T., Qin, D., Plattner, G.-K., Tignor, M. Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Quantifying Uncertainties in Practice, Chapter 6. Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., Emmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., Meijer, J., Miwa, K. and Tanabe, K. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Kearney, M. S. & Stevenson, J. C. (1991) Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. Journal of Coastal Research 7(2): 403-415.

Kemp, A. C., Sommerfield, C. K., Vane, C. H., Horton, B. P., Chenery, S., Anisfeld, S., and Nikitina, D. (2012) Use of lead isotopes for developing chronologies in recent salt-marsh sediments. Quaternary Geochronology 12: 40-49.

Köster, D., Lichter, J., Lea, P. D., & Nurse, A. (2007) Historical eutrophication in a river–estuary complex in mid-coast Maine. Ecological Applications 17(3): 765-778.

Krauss, K. W., Noe, G. B., Duberstein, J. A., Conner, W. H., Stagg, C. L., and Jones, M. C. (2018) Carbon budget assessment of tidal freshwater forested wetland and oligohaline marsh ecosystems along the Waccamaw and Savannah Rivers, USA (2005–2016). US Geological Survey Data Release. https://doi.Org/10.5066/F7TM7930.

Lagomasino, D., Corbett, D. R., and Walsh, J. P. (2013) Influence of wind-driven inundation and coastal geomorphology on sedimentation in two microtidal marshes, Pamlico River Estuary, NC. Estuaries and Coasts 36: 1165-1180.

Lu, M & Megonigal, J. P. (2017) Final Report for RAE Baseline Assessment Project. Memo to Silvestrum Climate

Associates by Smithsonian Environmental Research Center, Maryland.

Lynch, J. C. (1989) Sedimentation and nutrient accumulation in mangrove ecosystems of the Gulf of Mexico. M.S. thesis, Univ. of Southwestern Louisiana, Lafayette, LA.

Luk, S. Y., Todd-Brown, K., Eagle, M., McNichol, A. P., Sanderman, J., Gosselin, K., and Spivak, A. C. (2021) Soil organic carbon development and turnover in natural and disturbed salt marsh environments. Geophysical Research Letters 48(2): e2020GL090287.

Marchio, D. A., Savarese, M., Bovard, B., & Mitsch, W. J. (2016) Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in Southwest Florida. Forests 7: 116-135.

McCombs, J. W., Herold, N. D., Burkhalter, S. G. and Robinson C. J. (2016) Accuracy Assessment of NOAA Coastal Change Analysis Program 2006-2010 Land Cover and Land Cover Change Data. Photogrammetric Engineering & Remote Sensing. 82:711-718.

McTigue, N., Davis, J., Rodriguez, A. B., McKee, B., Atencio, A., and Currin, C. (2019) Sea level rise explains changing carbon accumulation rates in a salt marsh over the past two millennia. JGR Biogeosciences.

Merrill, J. Z. (1999) Tidal Freshwater Marshes as Nutrient Sinks: particulate Nutrient Burial and Denitrification. Ph.D. Dissertation, University of Maryland, College Park, MD, 342 pp.

Miller, C. B., Rodriguez, A. B., Bost, M. C., McKee, B. A., and McTigue, N. D. (2022) Carbon accumulation rates are highest at young and expanding salt marsh edges. Communications Earth & Environment 3(1): 173.

National Marine Fisheries Service (2022). Fisheries of the United States, 2020. U.S. Department of Commerce, NOAA Current Fishery Statistics No. 2020. Available at: https://www.fisheries.noaa.gov/ national/sustainable-fisheries/fisheries-united-states.

National Oceanic and Atmospheric Administration, Office for Coastal Management (2020) Coastal Change Analysis Program (C-CAP) Regional Land Cover. Charleston, SC: NOAA Office for Coastal Management. Accessed October 2020 at www.coast.noaa.gov/htdata/raster1/landcover/bulkdownload/30m_lc/.

Noe, G. B., Hupp, C. R., Bernhardt, C. E., & Krauss, K. W. (2016) Contemporary deposition and long-term accumulation of sediment and nutrients by tidal freshwater forested wetlands impacted by sea level rise. Estuaries and Coasts 39(4): 1006-1019.

Orson, R. A., Simpson, R. L., & Good, R. E. (1990) Rates of sediment accumulation in a tidal freshwater marsh. Journal of Sedimentary Research 60(6): 859-869.

Orson, R., Warren, R. & Niering, W. (1998) Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuarine, Coastal and Shelf Science 47(4): 419-429.

Peck, E. K., Wheatcroft, R. A., and Brophy, L. S. (2020) Controls on sediment accretion and blue carbon burial in tidal saline wetlands: insights from the Oregon Coast, USA. Journal of Geophysical Research: Biogeosciences 125(2): e2019JG005464.

Poppe, K. L., and Rybczyk, J. M. (2021) Tidal marsh restoration enhances sediment accretion and carbon accumulation in the Stillaguamish River estuary, Washington. PloS one 16(9): e0257244.

Roman, C., Peck, J., Allen, J., King, J. & Appleby, P. (1997) Accretion of a New England (USA) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45(6): 717-727.

Smith, K. E., Flocks, J. G., Steyer, G. D., and Piazza, S. C. (2015) Wetland Paleoecological Study of Southwest Coastal Louisiana: Sediment Cores and Diatom Calibration Dataset. US Department of the Interior, US Geological Survey.

Thom, R. M. (1992) Accretion rates of low intertidal salt marshes in the Pacific Northwest. Wetlands 12: 147-156.

Vaughn, D. R., Bianchi, T. S., Shields, M. R., Kenney, W. F., and Osborne, T. Z. (2020) Increased organic carbon burial in northern Florida mangrove-salt marsh transition zones. Global Biogeochemical Cycles 34(5): e2019GB006334.

Villa, J. A. & Mitsch W. J. (2015) Carbon sequestration in different wetland plant communities of Southwest Florida. International Journal for Biodiversity Science, Ecosystems Services and Management 11: 17-28

Watson, E. B., and Byrne, R. (2013) Late Holocene Marsh Expansion in Southern San Francisco Bay, California. Estuaries and Coasts 36: 643-653.

Weis, D. A., Callaway, J. C., and Gersberg, R. M. (2001) Vertical accretion rates and heavy metal chronologies in wetland sediments of the Tijuana Estuary. Estuaries 24: 840-850.

Weston, N. B., Neubauer, S. C., Velinsky, D. J., & Vile, M. A. (2014) Net ecosystem carbon exchange and the greenhouse gas balance of tidal marshes along an estuarine salinity gradient. Biogeochemistry 120: 163-189.

Weston, N. B., Rodriguez, E., Donnelly, B., Solohin, E., Jezycki, K., Demberger, S., ... and Craft, C. B. (2023) Recent acceleration of wetland accretion and carbon accumulation along the US East Coast. Earth's Future 11(3): e2022EF003037.

Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land

Abril, G., Gu´erin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., et al. (2005) Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochem. Cycles 19 (GB4007), 1–16. https://doi.org/10.1029/2005GB002457.

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., et al. (2011) Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4 (9), 593–596. https://doi.org/10.1038/ngeo1211.

Davis, D. W. (1973) Louisiana Canals and Their Influence on Wetland Development. Louisiana State University and Agricultural & Mechanical College. LSU Historical Dissertations and Theses. 2386., Louisiana State University.

IPCC (2019) 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories. Wetlands, Chapter 7. Lovelock, C. E., Evans, C., Barros, N., Prairie, Y. T., Alm, J., Bastviken, D., Beaulieu, J. J., Garneau, M., Harby, A., Harrison, J. A., Pare, David, Raadal, Hanne Lerche, Sherman, B., Zhang, Chengyi, Ogle, S. M.IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.* Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). In: IPCC, Switzerland.

IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Lehner B, Reidy Liermann C, Revenga C, Vorosmarty C, Fekete B, Crouzet P, Doll P, et al. (2011b) Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. In: Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Prairie, Y. T., et al. (2017) The GHG Reservoir Tool (G-res) User guide. UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association: 38.

Teodoru, C.R., Bastien, J., Bonneville, M.C., Del Giorgio, P.a., Demarty, M., Garneau, M., et al., 2012. The net carbon footprint of a newly created boreal hydroelectric reservoir. Global Biogeochem. Cycles 26 (GB2016), 1–14. https://doi.org/10.1029/2011GB004187.

Land Converted to Wetlands: Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Abbott, K. M., Elsey-Quirk, T., and DeLaune, R. D. (2019) Factors influencing blue carbon accumulation across a 32-year chronosequence of created coastal marshes. Ecosphere, 10(8): e02828.

Allen, J. R., Cornwell, J. C., and Baldwin, A. H. (2021) Contributions of organic and mineral matter to vertical accretion in tidal wetlands across a Chesapeake Bay subestuary. Journal of Marine Science and Engineering 9(7): 751.

Arias-Ortiz, A., Oikawa, P. Y., Carlin, J., Masqué, P., Shahan, J., Kanneg, S., ... and Baldocchi, D. D. (2021) Tidal and nontidal marsh restoration: a trade-off between carbon sequestration, methane emissions, and soil accretion. Journal of Geophysical Research: Biogeosciences, 126(12): e2021JG006573.

Arriola, J. M., and Cable, J. E. (2017) Variations in carbon burial and sediment accretion along a tidal creek in a Florida salt marsh. Limnology and Oceanography 62(S1): S15-S28.

Baustian, M. M., Stagg, C. L., Perry, C. L., Moss, L. C., and Carruthers, T. J. (2021) Long-term carbon sinks in marsh soils of coastal Louisiana are at risk to wetland loss. Journal of Geophysical Research: Biogeosciences 126(3): e2020JG005832.

Bianchi, T. S., Allison, M. A., Zhao, J., Li, X., Comeaux, R. S., Feagin, R. A., & Kulawardhana, R. W. (2013) Historical reconstruction of mangrove expansion in the Gulf of Mexico: linking climate change with carbon sequestration in coastal wetlands. Estuarine, Coastal and Shelf Science 119: 7-16.

Boyd, B. (2012) Comparison of sediment accumulation and accretion in impounded and unimpounded marshes of the Delaware Estuary. Doctoral dissertation, University of Delaware.

Boyd, B. M. and Sommerfield, C. K. (2016) Marsh accretion and sediment accumulation in a managed tidal wetland complex of Delaware Bay. Ecological Engineering, 92: 37-46.

Boyd, B. M., Sommerfield, C. K., and Elsey-Quirk, T. (2017) Hydrogeomorphic influences on salt marsh sediment accumulation and accretion in two estuaries of the US Mid-Atlantic coast. Marine Geology, 383: 132-145.

Breithaupt, J. L., Smoak, J. M., Smith III, T. J., and Sanders, C. J. (2014) Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades. Journal of Geophysical Research: Biogeosciences, 119(10): 2032-2048.

Byrd, K. B., Ballanti, L. R., Thomas, N. M., Nguyen, D. K., Holmquist, J. R., Simard, M., Windham-Myers, L., Schile, L. M., Parker, V. T., … and Castaneda-Moya, E. (2017) Biomass/Remote Sensing dataset: 30m resolution tidal marsh biomass samples and remote sensing data for six regions in the conterminous United States: U.S. Geological Survey data release, https://doi.org/10.5066/F77943K8.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2018) A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. ISPRS Journal of Photogrammetry and Remote Sensing 139: 255-271.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2020) Corrigendum to “A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States”. ISPRS Journal of Photogrammetry and Remote Sensing 166: 63-67.

Callaway, J. C., Borgnis, E. L., Turner, R. E. & Milan, C. S. (2012a) Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuaries and Coasts 35(5): 1163-1181.

Callaway, J. C., Borgnis, E. L., Turner, R. E., Milan, C. S., Goodfriend, W., & Richmond, S. (2012b) "Wetland Sediment Accumulation at Corte Madera Marsh and Muzzi Marsh". San Francisco Bay Conservation and Development Commission.

Church, T. M., Sommerfield, C. K., Velinsky, D. J., Point, D., Benoit, C., Amouroux, D. & Donard, O. F. X. (2006) Marsh sediments as records of sedimentation, eutrophication and metal pollution in the urban Delaware Estuary. Marine Chemistry 102(1-2): 72-95.

Craft, C. B., & Richardson, C. J. (1998) Recent and long-term organic soil accretion and nutrient accumulation in the Everglades. Soil Science Society of America Journal 62(3): 834-843.

Crooks, S., Rybczyk, J., O'Connell, K., Devier, D.L., Poppe, K., Emmett-Mattox, S. (2014) Coastal Blue Carbon Opportunity Assessment for the Snohomish Estuary: The Climate Benefits of Estuary Restoration. Report by Environmental Science Associates, Western Washington University, EarthCorps, and Restore America's Estuaries.

Drexler, J. Z., de Fontaine, C. S., and Brown, T. A. (2009) Peat accretion histories during the past 6,000 years in marshes of the Sacramento–San Joaquin Delta, CA, USA. Estuaries and Coasts 32: 871-892.

Drexler, J. Z., Krauss, K. W., Sasser, M. C., Fuller, C. C., Swarzenski, C. M., Powell, A., ... and Orlando, J. (2013) A long-term comparison of carbon sequestration rates in impounded and naturally tidal freshwater marshes along the lower Waccamaw River, South Carolina. Wetlands 33: 965-974.

Drexler, J. Z., Woo, I., Fuller, C. C., and Nakai, G. (2019) Carbon accumulation and vertical accretion in a restored versus historic salt marsh in southern Puget Sound, Washington, United States. Restoration Ecology 27(5): 1117-1127.

Ensign, S. H., Noe, G. B., Hupp, C. R., and Skalak, K. J. (2015) Head-of-tide bottleneck of particulate material transport from watersheds to estuaries. Geophysical Research Letters 42(24): 10-671.

Gerlach, M. J., Engelhart, S. E., Kemp, A. C., Moyer, R. P., Smoak, J. M., Bernhardt, C. E., and Cahill, N. (2017) Reconstructing Common Era relative sea-level change on the Gulf Coast of Florida. Marine Geology 390: 254-269.

Giblin, A., Forbrich, I., & LTER, P. I. E. (2018) PIE LTER high marsh sediment chemistry and activity measurements, Nelson Island Creek marsh, Rowley, MA.

Hussein, A. H., Rabenhorst, M. C. & Tucker, M. L. (2004) Modeling of carbon sequestration in coastal marsh soils. Soil Science Society of America Journal 68(5): 1786-1795.

IPCC (2019) *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 4: Agriculture, Forestry, and Other Land Use. Calvo Buendia, E., Tanabe K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., & Federici, S. (eds). IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, H.S.Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (eds). IGES, Japan.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T., Qin, D., Plattner, G.-K., Tignor, M. Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. & F. Wagner (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Quantifying Uncertainties in Practice, Chapter 6. Penman, J and Kruger, D and Galbally, I and Hiraishi, T and Nyenzi, B and Emmanuel, S and Buendia, L and Hoppaus, R and Martinsen, T and Meijer, J and Miwa, K and Tanabe, K (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate

Change (IPCC): Hayama, Japan.

Kearney, M. S. & Stevenson, J. C. (1991) Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. Journal of Coastal Research 7(2): 403-415.

Kemp, A. C., Sommerfield, C. K., Vane, C. H., Horton, B. P., Chenery, S., Anisfeld, S., and Nikitina, D. (2012) Use of lead isotopes for developing chronologies in recent salt-marsh sediments. Quaternary Geochronology 12: 40-49.

Köster, D., Lichter, J., Lea, P. D., & Nurse, A. (2007) Historical eutrophication in a river–estuary complex in mid-coast Maine. Ecological Applications 17(3): 765-778.

Krauss, K. W., Noe, G. B., Duberstein, J. A., Conner, W. H., Stagg, C. L., and Jones, M. C. (2018) Carbon budget assessment of tidal freshwater forested wetland and oligohaline marsh ecosystems along the Waccamaw and Savannah Rivers, USA (2005–2016). US Geological Survey Data Release. https://doi.Org/10.5066/F7TM7930.

Lagomasino, D., Corbett, D. R., and Walsh, J. P. (2013) Influence of wind-driven inundation and coastal geomorphology on sedimentation in two microtidal marshes, Pamlico River Estuary, NC. Estuaries and Coasts 36: 1165-1180.

Lu, M & Megonigal, J.P. (2017) Final Report for RAE Baseline Assessment Project. Memo to Silvestrum Climate Associates by Smithsonian Environmental Research Center, Maryland.

Lynch, J. C. (1989) Sedimentation and nutrient accumulation in mangrove ecosystems of the Gulf of Mexico, M.S. thesis, Univ. of Southwestern Louisiana, Lafayette, La.

Luk, S. Y., Todd-Brown, K., Eagle, M., McNichol, A. P., Sanderman, J., Gosselin, K., and Spivak, A. C. (2021) Soil organic carbon development and turnover in natural and disturbed salt marsh environments. Geophysical Research Letters 48(2): e2020GL090287.

Marchio, D.A., Savarese, M., Bovard, B., & Mitsch, W.J. (2016) Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in Southwest Florida. Forests 7: 116-135.

McCombs, J.W., Herold, N.D., Burkhalter, S.G. and Robinson C.J., (2016) Accuracy Assessment of NOAA Coastal Change Analysis Program 2006-2010 Land Cover and Land Cover Change Data. Photogrammetric Engineering & Remote Sensing. 82:711-718.

McTigue, N., Davis, J., Rodriguez, A. B., McKee, B., Atencio, A., and Currin, C. (2019) Sea level rise explains changing carbon accumulation rates in a salt marsh over the past two millennia. JGR Biogeosciences.

Merrill, J. Z. (1999) Tidal Freshwater Marshes as Nutrient Sinks: particulate Nutrient Burial and Denitrification. Ph.D. Dissertation, University of Maryland, College Park, MD, 342pp.

Miller, C. B., Rodriguez, A. B., Bost, M. C., McKee, B. A., and McTigue, N. D. (2022) Carbon accumulation rates are highest at young and expanding salt marsh edges. Communications Earth & Environment 3(1): 173.

National Oceanic and Atmospheric Administration, Office for Coastal Management (2020) Coastal Change Analysis Program (C-CAP) Regional Land Cover. Charleston, SC: NOAA Office for Coastal Management. Accessed October 2020 at www.coast.noaa.gov/htdata/raster1/landcover/bulkdownload/30m_lc/.

Noe, G. B., Hupp, C. R., Bernhardt, C. E., & Krauss, K. W. (2016) Contemporary deposition and long-term accumulation of sediment and nutrients by tidal freshwater forested wetlands impacted by sea level rise. Estuaries and Coasts 39(4): 1006-1019.

Orson, R. A., Simpson, R. L., & Good, R. E. (1990) Rates of sediment accumulation in a tidal freshwater marsh. Journal of Sedimentary Research 60(6): 859-869.

Orson, R., Warren, R. & Niering, W. (1998) Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuarine, Coastal and Shelf Science 47(4): 419-429.

Peck, E. K., Wheatcroft, R. A., and Brophy, L. S. (2020) Controls on sediment accretion and blue carbon burial in

tidal saline wetlands: insights from the Oregon Coast, USA. Journal of Geophysical Research: Biogeosciences 125(2): e2019JG005464.

Poppe, K. L., and Rybczyk, J. M. (2021) Tidal marsh restoration enhances sediment accretion and carbon accumulation in the Stillaguamish River estuary, Washington. PloS one 16(9): e0257244.

Roman, C., Peck, J., Allen, J., King, J. & Appleby, P. (1997) Accretion of a New England (USA) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45(6): 717-727.

Smith, K. E., Flocks, J. G., Steyer, G. D., and Piazza, S. C. (2015) Wetland Paleoecological Study of Southwest Coastal Louisiana: Sediment Cores and Diatom Calibration Dataset. US Department of the Interior, US Geological Survey.

Thom, R. M. (1992 Accretion rates of low intertidal salt marshes in the Pacific Northwest. Wetlands 12: 147-156.

Vaughn, D. R., Bianchi, T. S., Shields, M. R., Kenney, W. F., and Osborne, T. Z. (2020) Increased organic carbon burial in northern Florida mangrove-salt marsh transition zones. Global Biogeochemical Cycles 34(5): e2019GB006334.

Villa, J. A. & Mitsch W. J. (2015) "Carbon sequestration in different wetland plant communities of Southwest Florida". International Journal for Biodiversity Science, Ecosystems Services and Management 11: 17-28.

Watson, E. B., and Byrne, R. (2013) Late Holocene Marsh Expansion in Southern San Francisco Bay, California. Estuaries and Coasts 36: 643-653.

Weis, D. A., Callaway, J. C., and Gersberg, R. M. (2001) Vertical accretion rates and heavy metal chronologies in wetland sediments of the Tijuana Estuary. Estuaries 24: 840-850.

Weston, N. B., Neubauer, S. C., Velinsky, D. J., & Vile, M. A. (2014) Net ecosystem carbon exchange and the greenhouse gas balance of tidal marshes along an estuarine salinity gradient. Biogeochemistry 120: 163-189.

Weston, N. B., Rodriguez, E., Donnelly, B., Solohin, E., Jezycki, K., Demberger, S., ... and Craft, C. B. (2023) Recent acceleration of wetland accretion and carbon accumulation along the US East Coast. Earth's Future 11(3): e2022EF003037.

Land Converted to Wetlands: Land Converted to Flooded Land

Abril, G., Gu´erin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., et al. (2005) Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochem. Cycles 19 (GB4007), 1–16. https://doi.org/10.1029/2005GB002457.

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., et al. (2011). Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4 (9), 593–596. https://doi.org/10.1038/ngeo1211.

IPCC (2019) *2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories*. Wetlands, Chapter 7. Lovelock, C. E., Evans, C., Barros, N., Prairie, Y. T., Alm, J., Bastviken, D., Beaulieu, J. J., Garneau, M., Harby, A., Harrison, J. A., Pare, David, Raadal, Hanne Lerche, Sherman, B., Zhang, Chengyi, Ogle, S. M.

IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). In: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, H.S.Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Lehner B, Reidy Liermann C, Revenga C, Vorosmarty C, Fekete B, Crouzet P, Doll P, et al. (2011b) Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. In: Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Prairie, Y. T., et al. (2017) The GHG Reservoir Tool (G-res) User guide. UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association**:** 38.

Teodoru, C.R., Bastien, J., Bonneville, M.C., Del Giorgio, P.a., Demarty, M., Garneau, M., et al. (2012). The net carbon footprint of a newly created boreal hydroelectric reservoir. Global Biogeochem. Cycles 26 (GB2016), 1–14. https://doi.org/10.1029/2011GB004187.

Settlements Remaining Settlements: Soil Carbon Stock Changes

AAPFCO (2016 through 2022) Commercial Fertilizers: 2013-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

Armentano, T. V., and E.S. Menges (1986) Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. Journal of Ecology 74: 755-774.

Brady, N.C. and R.R. Weil (1999) The Nature and Properties of Soils. Prentice Hall. Upper Saddle River, NJ, 881.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing 73(4): 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81(5):345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

NRCS (1999) Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition. Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. Environmental and Ecological Statistics 4:181-204.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997. Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model. Global Change Biology 16:810-822.

Särndal C-E, Swensson B, Wretman, J (1992). Model Assisted Survey Sampling. Springer, New York.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Settlements Remaining Settlements: Changes in Carbon Stocks in Settlement Trees

deVries R.E. (1987) A Preliminary Investigation of the Growth and Longevity of Trees in Central Park. M.S. thesis, Rutgers University, New Brunswick, NJ.

Fleming, L.E. (1988) Growth Estimation of Street Trees in Central New Jersey. M.S. thesis, Rutgers University, New Brunswick, NJ.

Frelich, L.E. (1992) Predicting Dimensional Relationships for Twin Cities Shade Trees. University of Minnesota, Department of Forest Resources, St. Paul, MN, p. 33.

IPCC (2006) *2006 IPCC Guidelines* for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

MRLC (2013) National Land Cover Database 2001 (NLCD2001). Available online at: http://www.mrlc.gov/nlcd2001.php. Accessed August 2013.

Nowak, D.J. (1986) Silvics of an Urban Tree Species: Norway maple (Acer platanoides L.). M.S. thesis, College of Environmental Science and Forestry, State University of New York, Syracuse, NY.

Nowak, D.J. (1994) Atmospheric carbon dioxide reduction by Chicago's urban forest. In: Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.). General Technical Report NE-186. U.S. Department of Agriculture Forest Service, Radnor, PA. pp. 83–94.

Nowak, D.J. (2012) Contrasting natural regeneration and tree planting in 14 North American cities. Urban Forestry and Urban Greening. 11: 374– 382.

Nowak, D.J. and D.E. Crane (2002) Carbon storage and sequestration by urban trees in the United States. Environmental Pollution 116(3):381–389.

Nowak, D.J. and E. Greenfield (2010) Evaluating the National Land Cover Database tree canopy and impervious cover estimates across the conterminous United States: A comparison with photo-interpreted estimates. Environmental Management. 46: 378-390.

Nowak, D.J. and E.J. Greenfield (2018a) U.S. urban forest statistics, values and projections. Journal of Forestry. 116(2):164–177

Nowak, D.J. and E.J. Greenfield (2018b) Declining urban and community tree cover in the United States. Urban Forestry and Urban Greening. 32:32-55.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra (2002) Brooklyn's Urban Forest. General Technical Report NE-290. U.S. Department of Agriculture Forest Service, Newtown Square, PA.

Nowak, D.J., R.E. Hoehn, D.E. Crane, J.C. Stevens, J.T. Walton, and J. Bond (2008) A ground-based method of assessing urban forest structure and ecosystem services. Arboric. Urb. For. 34(6): 347-358.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, and E. Lapoint (2013) Carbon storage and sequestration by trees in urban and community areas of the United States." Environmental Pollution 178: 229-236.

Nowak, D.J. A.R. Bodine, R.E. Hoehn, C.B. Edgar, D.R. Hartel, T.W. Lister, T.J. Brandeis (2016) Austin's Urban Forest, 2014. USDA Forest Service, Northern Research Station Resources Bulletin. NRS-100. Newtown Square, PA. 55 p.

Nowak, D.J. A.R. Bodine, R.E. Hoehn, C.B. Edgar, G. Riley, D.R. Hartel, K.J. Dooley, S.M. Stanton, M.A. Hatfield, T.J. Brandeis, T.W. Lister (2017) Houston's Urban Forest, 2015. USDA Forest Service, Southern Research Station Resources Bulletin. SRS-211. Newtown Square, PA. 91 p.

Smith, W.B. and S.R. Shifley (1984) Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois. Research Paper NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

U.S. Department of Interior (2018) National Land Cover Database 2011 (NLCD2011). Accessed online August 16, 2018. Available online at: https://www.mrlc.gov/nlcd11_leg.php.

Settlements Remaining Settlements: N_2O Emissions from Soils

AAPFCO (2016 through 2022) Commercial Fertilizers: 2013-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

Brakebill, J.W. and Gronberg, J.M. (2017) County-Level Estimates of Nitrogen and Phosphorus from Commercial Fertilizer for the Conterminous United States, 1987-2012. U.S. Geological Survey, https://doi.org/10.5066/F7H41PKX.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model. Global Change Biology 16:810-822.

Särndal C-E, Swensson B, Wretman, J (1992). Model Assisted Survey Sampling. Springer, New York.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/

Yang, L., et al. (2018). "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Settlements Remaining Settlements: Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills

Barlaz, M.A. (2008) "Re: Corrections to Previously Published Carbon Storage Factors." Memorandum to Randall Freed, ICF International. February 28, 2008.

Barlaz, M.A. (2005) "Decomposition of Leaves in Simulated Landfill." Letter report to Randall Freed, ICF Consulting. June 29, 2005.

Barlaz, M.A. (1998) "Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12:373–380.

De la Cruz, F.B. and M.A. Barlaz (2010) "Estimation of Waste Component Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data" *Environmental Science & Technology* 44:4722– 4728.

Eleazer, W.E., W.S. Odle, Y. Wang, and M.A. Barlaz (1997) "Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Environmental Science & Technology* 31:911–917.

EPA (2020) *Advancing Sustainable Materials Management: Facts and Figures 2018*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures-report.

EPA (2019) *Advancing Sustainable Materials Management: Facts and Figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures-report.

EPA (2016) *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/msw99.html.

EPA (1995) *Compilation of Air Pollutant Emission Factors*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC. AP-42 Fifth Edition. Available online at http://www3.epa.gov/ttnchie1/ap42/.

EPA (1991) *Characterization of Municipal Solid Waste in the United States: 1990 Update*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. EPA/530-SW-90-042.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman et al. (eds.). Available online at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm.

Oshins, C. and D. Block (2000) "Feedstock Composition at Composting Sites." *Biocycle* 41(9):31–34.

Tchobanoglous, G., H. Theisen, and S.A. Vigil (1993) *Integrated Solid Waste Management, 1st edition*. McGraw-Hill, NY. Cited by Barlaz (1998) "Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12:373–380.

Land Converted to Settlements

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer. Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. Carbon Balance and Management. 6:14.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) “Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments.” Global Change Biology 12:516-523.

Schimel, D.S. (1995) "Terrestrial ecosystems and the carbon cycle." Global Change Biology 1: 77-91.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." Global Change Biology 21:2655-2660.

USDA Forest Service. (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 07 October 2022.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (1997) “National Soil Survey Laboratory Characterization Data,” Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-XX.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols. (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Waste

Landfills

40 CFR Part 60, Subpart WWW (2005) Standards of Performance for Municipal Solid Waste Landfills, 60.750--60.759, Code of Federal Regulations, Title 40. Available online at: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60/subpart-WWW.

40 CFR Part 258, Subtitle D of RCRA (2012) Criteria for Municipal Solid Waste Landfills, 258.1—258.75, Code of Federal Regulations, Title 40. Available online at: https://www.ecfr.gov/cgi-bin/text-idx?node=pt40.25.258..

BioCycle (2010) "The State of Garbage in America" By L. Arsova, R. Van Haaren, N. Goldstein, S. Kaufman, and N. Themelis. *BioCycle.* December 2010. Available online at: https://www.biocycle.net/2010/10/26/the-state-of-garbage-in-america-4/.

Bronstein, K., Coburn, J., and R. Schmeltz (2012) "Understanding the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks and Mandatory GHG Reporting Program for Landfills: Methodologies, Uncertainties, Improvements and Deferrals." Prepared for the U.S. EPA International Emissions Inventory Conference, August 2012, Tampa, Florida. Available online at: https://www3.epa.gov/ttnchie1/conference/ei20/session3/kbronstein.pdf.

Czepiel, P., B. Mosher, P. Crill, and R. Harriss (1996) "Quantifying the Effect of Oxidation on Landfill Methane Emissions." *Journal of Geophysical Research*, 101(D11):16721-16730.Dou, Z.; Ferguson, J. D.; Galligan, D. T.; Kelly, A. M.; Finn, S. T.; Giegengack, R. (2016) "Assessing U.S. food wastage and opportunities for reduction." Global Food Security Volume 8, March 2016, Pages 19-26. https://doi.org/10.1016/j.gfs.2016.02.001.

EIA (2007) Voluntary Greenhouse Gas Reports for EIA Form 1605B (Reporting Year 2006). Available online at: https://www.eia.gov/environment/pdfpages/0608s(2009)index.php.

EPA (2023a) Greenhouse Gas Reporting Program (GHGRP). 2022 Amazon S3 Data. Subpart HH: Municipal Solid Waste Landfills and Subpart TT: Industrial Waste Landfills. Accessed on August 8, 2023.

EPA (2023b) Landfill Methane Outreach Program (LMOP). 2023 Landfill and Project Level Data. July 2023. Available online at: https://www.epa.gov/lmop/landfill-gas-energy-project-data.

EPA (2020a) Wasted Food Measurement Methodology Scoping Memo. July 2020. Available online at https://www.epa.gov/sites/production/files/2020-06/documents/food_measurement_methodology_scoping_memo-6-18-20.pdf.

EPA (2020b) Advancing Sustainable Materials Management: Facts and Figures 2018. December 2020. Available online at: https://www.epa.gov/sites/production/files/2020-11/documents/2018_tables_and_figures_fnl_508.pdf.

EPA (2020c) Advancing Sustainable Materials Management: Facts and Figures 2016 and 2017. November 2019. Available online at: https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf.

EPA (2018) Advancing Sustainable Materials Management: Facts and Figures 2015. July 2018. Available online at: https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2016a) Industrial and Construction and Demolition Landfills. Available online at: https://www.epa.gov/landfills/industrial-and-construction-and-demolition-cd-landfills.

EPA (2016b) Advancing Sustainable Materials Management: Facts and Figures 2014. December 2016. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smm_tablesfigures_508.pdf.

EPA (2014) Advancing Sustainable Materials Management: Facts and Figures 2014. February 2014. Available online at: https://www.epa.gov/sites/production/files/2015-09/documents/2012_msw_dat_tbls.pdf.

EPA (2008) *Compilation of Air Pollution Emission Factors, Publication AP-42*, Draft Section 2.4 Municipal Solid Waste Landfills. October 2008.

EPA (1993) *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress*, U.S. Environmental Protection Agency, Office of Air and Radiation. Washington, D.C. EPA/430-R-93-003. April 1993.

EPA (1988) *National Survey of Solid Waste (Municipal) Landfill Facilities*, U.S. Environmental Protection Agency. Washington, D.C. EPA/530-SW-88-011. September 1988.

EREF (The Environmental Research & Education Foundation) (2016) Municipal Solid Waste Management in the United States: 2010 & 2013.

ERG (2023) Production Data Supplied by ERG for 1990-2022 for Pulp and Paper, Fruits and Vegetables, and Meat. September 7, 2021.

Food Waste Reduction Alliance (FWRA) (2016) Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and Restaurants. A joint project by the Food Marketing Institute, the Grocery Manufacturers Association, and the National Restaurant Association. Available online at: https://foodwastealliance.org/wp-content/uploads/2020/05/FWRA-Food-Waste-Survey-2016-Report_Final.pdf.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Mancinelli, R. and C. McKay (1985) "Methane-Oxidizing Bacteria in Sanitary Landfills." *Proc. First Symposium on Biotechnical Advances in Processing Municipal Wastes for Fuels and Chemicals*, Minneapolis, MN, 437-450. August.

RTI (2018) Methodological changes to the scale-up factor used to estimate emissions from municipal solid waste landfills in the Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). March 22, 2018.

RTI (2017) Methodological changes to the methane emissions from municipal solid waste landfills as reflected in the public review draft of the 1990-2015 Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). March 31, 2017.

RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA). January 14, 2011.

Waste Business Journal (WBJ) (2021) Directory of Waste Processing & Disposal Sites 2021.

WBJ (2016) Directory of Waste Processing & Disposal Sites 2016.

WBJ (2010) Directory of Waste Processing & Disposal Sites 2010.

Wastewater Treatment and Discharge

AF&PA (2022) "AF&PA Members Achieve Progress on Water Stewardship Goal for 2020." American Forest & Paper Association. Available online at: https://www.afandpa.org/statistics-resources/afpa-members-achieve-progress-water-stewardship-goal-2020. Accessed July 2022.

AF&PA (2020) "2020 AF&PA Sustainability Report: Advancing the sustainability of an essential industry." American Forest & Paper Association. Available online at: https://www.afandpa.org/sites/default/files/2021-07/2020_AF-PA-Sustainability-Report.pdf. Accessed June 2021.

AF&PA (2018) "2018 AF&PA Sustainability Report: Advancing U.S. Paper and Wood Products Industry Sustainability Performance." American Forest & Paper Association. Available online at: http://sustainability.afandpa.org/wp-content/uploads/2018/06/2018SustainabilityReport_PAGES.pdf. Accessed July 2019.

AF&PA (2016) "2016 AF&PA Sustainability Report: Advancing U.S. Paper and Wood Products Industry Sustainability Performance." American Forest & Paper Association.

AF&PA (2014) "2014 AF&PA Sustainability Report." American Forest & Paper Association.

Beecher et al. (2007) "A National Biosolids Regulation, Quality, End Use & Disposal Survey, Preliminary Report." Northeast Biosolids and Residuals Association, April 14, 2007. Available online at: https://static1.squarespace.com/static/54806478e4b0dc44e1698e88/t/5480c7a2e4b0787f2c73ad81/1417725858575/NtlBiosldsRpt-AppD-FINAL.pdf. Accessed August 2021.

Beer Institute (2011) Brewers Almanac. Available online at: http://www.beerinstitute.org/multimedia/brewers-almanac.

Benyahia, F., M. Abdulkarim, A. Embaby, and M. Rao. (2006) Refinery Wastewater Treatment: A true Technological Challenge. Presented at the Seventh Annual U.A.E. University Research Conference.

BIER (2021) 2021 Benchmarking Study Trends & Observations. Available online at https://www.bieroundtable.com/publication/2021-water-and-energy-use-benchmarking-study/. Accessed September 2023.

Brewers Association (2021) Statistics: Number of Breweries. Available online at: https://www.brewersassociation.org/statistics-and-data/national-beer-stats/. Accessed August 2021.

Brewers Association (2016a) 2015 Sustainability Benchmarking Report. Available online at: https://www.brewersassociation.org/best-practices/sustainability/sustainability-benchmarking-tools. Accessed March 2018.

Brewers Association (2016b) Wastewater Management Guidance Manual. Available online at: https://www.brewersassociation.org/educational-publications/wastewater-management-guidance-manual. Accessed September 2017.

Cabrera (2017) "Pulp Mill Wastewater: Characteristics and Treatment." Biological Wastewater Treatment and Resource Recovery. InTech. pp. 119–139.

CAST (1995) Council for Agricultural Science and Technology. Waste Management and Utilization in Food Production and Processing. U.S.A. October 1995. ISBN 1-887383-02-6. Available online at: https://www.cast-science.org/publication/waste-management-and-utilization-in-food-production-and-processing/.

Climate Action Reserve (CAR) (2011) Landfill Project Protocol V4.0, June 2011. Available online at: http://www.climateactionreserve.org/how/protocols/us-landfill/.

Cooper (2018) Email correspondence. Geoff Cooper, Renewable Fuels Association to Kara Edquist, ERG. "Wet Mill vs. Dry Mill Ethanol Production." May 18, 2018.

DOE (2013) U.S. Department of Energy Bioenergy Technologies Office. Biofuels Basics. Available online at: http://energy.gov/eere/bioenergy/biofuels-basics. Accessed September 2013.

Donovan (1996) Siting an Ethanol Plant in the Northeast. C.T. Donovan Associates, Inc. Report presented to Northeast Regional Biomass Program (NRBP). (April). Available online at: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.614.856&rep=rep1&type=pdf. Accessed October 2006.

EIA (2023) Energy Information Administration. U.S. Refinery and Blender Net Production of Crude Oil and Petroleum Products (Thousand Barrels). Available online at: https://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_m.htm. Accessed August 2023.

EPA (2019) Preliminary Effluent Guidelines Program Plan 14. EPA-821-R-19-005. Office of Water, U.S. Environmental Protection Agency. Washington, DC. October 2019. Available online at: https://www.epa.gov/sites/production/files/2019-10/documents/prelim-eg-plan-14_oct-2019.pdf. Accessed July 2020.

EPA (2013) U.S. Environmental Protection Agency. Report on the Performance of Secondary Treatment Technology. EPA-821-R-13-001. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. March 2013. Available online at: https://www.epa.gov/sites/production/files/2015-11/documents/npdes_secondary_treatment_report_march2013.pdf.

EPA (2012) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2012 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2012-report-and-data#access. Accessed February 2016.

EPA (2010) U.S. Environmental Protection Agency. Nutrient Control Design Manual. U.S. Environmental Protection Agency, Office of Research and Development. Washington, D.C. EPA600-R-10-100. Available online at: https://www.epa.gov/sites/default/files/2019-08/documents/nutrient_control_design_manual.pdf. Accessed December 2023.

EPA (2008) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2008 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2008-report-and-data. Accessed December 2015.

EPA (2004) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2004 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-report-congress-2004.

EPA (2000) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2000 - Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2000-report-and-data. Accessed July 2007.

EPA (1999) U.S. Environmental Protection Agency. Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. EPA530-R-99-009. September 1999.

EPA (1998) U.S. Environmental Protection Agency. "AP-42 Compilation of Air Pollutant Emission Factors." Chapter 2.4, Table 2.4-3, page 2.4-13. Available online at: https://www.epa.gov/sites/default/files/2020-10/documents/c02s04.pdf.

EPA (1997a) U.S. Environmental Protection Agency. Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. EPA-600/R-97-091. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency. Washington, D.C. September 1997.

EPA (1997b) U.S. Environmental Protection Agency. Supplemental Technical Development Document for Effluent Guidelines and Standards (Subparts B & E). EPA-821-R-97-011. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1997.

EPA (1996) U.S. Environmental Protection Agency. 1996 Clean Water Needs Survey Report to Congress. Assessment of Needs for Publicly Owned Wastewater Treatment Facilities, Correction of Combined Sewer Overflows, and Management of Storm Water and Nonpoint Source Pollution in the United States. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C.

EPA (1993a) U.S. Environmental Protection Agency, "Anthropogenic Methane Emissions in the U.S.: Estimates for 1990, Report to Congress." Office of Air and Radiation, Washington, DC. April 1993.

EPA (1993b) U.S. Environmental Protection Agency. Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Pulp, Paper and Paperboard Point Source Category. EPA-821-R-93-019. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1993.

EPA (1993c) Standards for the Use and Disposal of Sewage Sludge. 40 CFR Part 503.

EPA (1992) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 1992 – Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C.

EPA (1982) U.S. Environmental Protection Agency. Development Document for Effluent Limitations Guidelines and standards for the Petroleum Refining. United States Environmental Protection Agency, Office of Water. EPA-440/1-82-014. Washington D.C. October 1982.

EPA (1975) U.S. Environmental Protection Agency. Development Document for Interim Final and Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Fruits, Vegetables, and Specialties Segment

of the Canned and Preserved Fruits and Vegetables Point Source Category. United States Environmental Protection Agency, Office of Water. EPA-440/1-75-046. Washington D.C. October 1975.

EPA (1974) U.S. Environmental Protection Agency. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Apple, Citrus, and Potato Processing Segment of the Canned and Preserved Fruits and Vegetables Point Source Category. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. EPA-440/1-74-027-a. March 1974.

ERG (2023) Memorandum: Improvements to the 1990-2021 Wastewater Treatment and Discharge Greenhouse Gas Inventory. February 2023.

ERG (2021a) Revised Memorandum: Improvements to the 1990-2019 Wastewater Treatment and Discharge Greenhouse Gas Inventory. March 2021.

ERG (2021b) Draft Memorandum: Improvements to the 1990-2020 Wastewater Treatment and Discharge Greenhouse Gas Inventory. July 2021.

ERG (2021c) Draft Memorandum: Expert Judgement Documentation for the Wastewater Treatment and Discharge Greenhouse Gas Inventory Uncertainties, August 2021.

ERG (2019) Memorandum: Recommended Improvements to the 1990-2018 Wastewater Greenhouse Gas Inventory. August 2019.

ERG (2018a) Memorandum: Updates to Domestic Wastewater BOD Generation per Capita. August 2018.

ERG (2018b) Memorandum: Inclusion of Wastewater Treatment Emissions from Breweries. July 2018.

ERG (2016) Revised Memorandum: Recommended Improvements to the 1990-2015 Wastewater Greenhouse Gas Inventory. November 2016.

ERG (2013a) Memorandum: Revisions to Pulp and Paper Wastewater Inventory. October 2013.

ERG (2013b) Memorandum: Revisions to the Petroleum Refinery Wastewater Inventory. October 2013.

ERG (2008a) Memorandum: Planned Revisions of the Industrial Wastewater Inventory Emission Estimates for the 1990-2007 Inventory. 10 August 2008.

ERG (2008b) Memorandum: Estimation of Onsite Treatment at Industrial Facilities and Review of Wastewater Characterization Data. 15 April 2008.

ERG (2006a) Memorandum: Recommended Improvements to EPA's Wastewater Inventory for Industrial Wastewater. Prepared for Melissa Weitz, EPA. 11 August 2006.

ERG (2006b) Memorandum: Assessment of Greenhouse Gas Emissions from Wastewater Treatment of U.S. Ethanol Production Wastewaters. Prepared for Melissa Weitz, EPA. 10 October 2006.

FAO (2023a) FAOSTAT-Forestry Database. Available online at: http://www.fao.org/faostat/en/#data/FO. Accessed September 2023.

FAO (2023b) "Pulp and Paper Capacities Report." United States. From 1998 – 2003, 2000 – 2005, 2001 – 2006, 2002 – 2007, 2003 – 2008, 2010 – 2015, 2011 – 2016, 2012 – 2017, 2013 – 2018, 2014 – 2019, 2015 – 2020, 2016 – 2021, 2017 – 2022, 2018 – 2023, 2019 – 2024, 2020-2025, 2021-2026 reports. Available online at: http://www.fao.org/forestry/statistics/80571/en/. Accessed September 2023.

FAO (2022) FAOSTAT-Food Balance Sheets. Available online at: http://www.fao.org/faostat/en/#data/FBS. Accessed September 2023.

Foley et al. (2015) *N_2O and CH_4 Emission from Wastewater Collection and Treatment Systems: State of the Science Report and Technical Report*. GWRC Report Series. IWA Publishing, London, UK.

Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. (2004) Recommended Standards for Wastewater Facilities (Ten-State Standards).

Guisasola et al. (2008) Methane formation in sewer systems. *Water Research* 42(6–7): 1421-1430.

Instituto de Estadísticas de Puerto Rico (2021) Population of Puerto Rico from 1990-1999 from "Estimados anuales poblacionales de los municipios desde 1950." Accessed February 2021. Available online at: https://censo.estadisticas.pr/EstimadosPoblacionales.

IPCC (2022) Emission factor database: Emission Factor Detail (ID:625621). The Intergovernmental Panel on Climate Change. Available online at: https://www.ipcc-nggip.iges.or.jp/EFDB/ef_detail.php.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.)]. Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kenari et. al (2010) An Investigation on the Nitrogen Content of a Petroleum Refinery Wastewater and its Removal by Biological Treatment. Journal of Environmental Health, Sciences, and Engineering. 7(1): 391-394.

Leverenz, H.L., G. Tchobanoglous, and J.L. Darby (2010) "Evaluation of Greenhouse Gas Emissions from Septic Systems." Water Environment Research Foundation. Alexandria, VA.

Lewis, A. (2019) Email correspondence. Ann Lewis, RFA to Kara Edquist, ERG. "Wet Mill vs Dry Mill Ethanol Production." August 20, 2019.

Malmberg, B. (2018) Draft Pulp and Paper Information for Revision of EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks, Waste Chapter. National Council for Air and Stream Improvement, Inc. Prepared for Rachel Schmeltz, EPA. June 13, 2018.

Merrick (1998) Wastewater Treatment Options for the Biomass-to-Ethanol Process. Report presented to National Renewable Energy Laboratory (NREL). Merrick & Company. Subcontract No. AXE-8-18020-01. October 22, 1998.

Metcalf & Eddy, Inc. (2014) Wastewater Engineering: Treatment and Resource Recovery, 5th ed. McGraw Hill Publishing.

Metcalf & Eddy, Inc. (2003) Wastewater Engineering: Treatment, Disposal and Reuse, 4th ed. McGraw Hill Publishing.

NEBRA (2022) "U.S. National Biosolids Data." Northeast Biosolids and Residuals Associations. Available online at: https://static1.squarespace.com/static/601837d1c67bcc4e1b11862f/t/62f4f5fbae32804dd9f51ef6/1660220925356/National_BiosolidsDataSummary_NBDP_20220811.pdf

Nemerow, N.L. and A. Dasgupta (1991) Industrial and Hazardous Waste Treatment. Van Nostrand Reinhold. NY. ISBN 0-442-31934-7.

NRBP (2001) Northeast Regional Biomass Program. An Ethanol Production Guidebook for Northeast States. Washington, D.C. (May 3).

Rendleman, C.M. and Shapouri, H. (2007) New Technologies in Ethanol Production. USDA Agricultural Economic Report Number 842.

RFA (2023a) Renewable Fuels Association. Annual U.S. Fuel Ethanol Production. Available online at: https://ethanolrfa.org/statistics/annual-ethanol-production. Accessed August 2023.

RFA (2023b) Renewable Fuels Association. Monthly Grain Use for U.S. Ethanol Production Report. Available online at: https://ethanolrfa.org/statistics/feedstock-use-co-product-output. Accessed August 2023.

Ruocco (2006a) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. "Capacity of Bio-Methanators (Dry Milling)." October 6, 2006.

Ruocco (2006b) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. "Capacity of Bio-Methanators (Wet Milling)." October 16, 2006.

Short et al. (2017) Dissolved Methane in the Influent of Three Australian Wastewater Treatment Plants Fed by Gravity Sewers. *Sci Total Environ* 599-600: 85-93.

Short et al. (2014) Municipal Gravity Sewers: an Unrecognised Source of Nitrous Oxide. *Sci Total Environ* 468-469: 211-218.

Stier, J. (2018) Personal communications between John Stier, Brewers Association Sustainability Mentor and Amie Aguiar, ERG. Multiple dates.

Sullivan (SCS Engineers) (2010) The Importance of Landfill Gas Capture and Utilization in the U.S. Presented to SWICS, April 6, 2010. Available online at: https://www.scsengineers.com/scs-white-papers/the-importance-of-landfill-gas-capture-and-utilization-in-the-u-s/.

Sullivan (SCS Engineers) (2007) Current MSW Industry Position and State of the Practice on Methane Destruction Efficiency in Flares, Turbines, and Engines. Presented to Solid Waste Industry for Climate Solutions (SWICS). July 2007. Available online at: https://www.scsengineers.com/wp-content/uploads/2015/03/Sullivan_LFG_Destruction_Efficiency_White_Paper.pdf.

TTB (2022) Alcohol and Tobacco Tax and Trade Bureau. Beer Statistics. Available online at: https://www.ttb.gov/beer/beer-stats.shtml. Accessed July 2021.

UNFCCC (2012) CDM Methodological tool, Project emissions from flaring (Version 02.0.0). EB 68 Report. Annex 15. Available online at: http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-06-v1.pdf/history_view.

U.S. Census Bureau (2023) International Database. Available online at: https://www.census.gov/data-tools/demo/idb/#/trends?YR_ANIM=2020&dashPages=DASH&FIPS_SINGLE=US&COUNTRY_YEAR=2022&menu=trendsViz&TREND_RANGE=1990,2022&TREND_STEP=5&TREND_ADD_YRS=&FIPS=AQ,GQ,CQ,RQ,VQ&measures=POP&CCODE=AS,GU,MP,PR,US,VI&CCODE_SINGLE=US&COUNTRY_YR_ANIM=2022. Accessed September 2023.

U.S. Census Bureau (2022) Annual Estimates of the Resident Population for the United States, Regions, States, District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2021. Available online at: https://www.census.gov/data/tables/time-series/demo/popest/2020s-national-total.html. Accessed July 2023.

U.S. Census Bureau (2021a) "American Housing Survey." Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, and 2009 reports. Table C-04-AO Plumbing, Water, and Sewage Disposal--All Occupied Units. From 2011, 2013, 2015, 2017, 2019 and 2021 reports. Available online at http://www.census.gov/programs-surveys/ahs/data.html. Accessed August 2023.

U.S. Census Bureau (2021b) Annual Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2010 to July 1, 2020. Available online at: https://www.census.gov/data/tables/time-series/demo/popest/2010s-state-total.html.

U.S. Census Bureau (2013) "American Housing Survey." Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, and 2009 reports. Table C-04-AO Plumbing, Water, and Sewage Disposal--All Occupied Units. From 2011, and 2013 reports. Available online at http://www.census.gov/programs-surveys/ahs/data.html. Accessed May 2020.

U.S. Census Bureau, Population Division (2011) Table 1. Intercensal Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2000 to July 1, 2010 (ST-EST00INT-01), Release Date: September 2011. Available online at: https://www2.census.gov/programs-surveys/popest/datasets/2000-2010/intercensal/state/st-est00int- alldata.csv.

U.S. Census Bureau, Population Division (2002) Table CO-EST2001-12-00 - Time Series of Intercensal State Population Estimates: April 1, 1990 to April 1, 2000.Available online at: https://www2.census.gov/programs-surveys/popest/tables/1990-2000/intercensal/st- co/co-est2001-12-00.pdf.

USDA (U.S. Department of Agriculture) (2023a) *Livestock Slaughter 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/r207tp32d/8p58qs65g/g445dv089/lsan0423.pdf

USDA (U.S. Department of Agriculture) (2023b) *Poultry Slaughter 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/pg15bd88s/m613p944x/ht24xx05j/pslaan23.pdf

USDA (U.S. Department of Agriculture) (2023c) *Vegetables 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/02870v86p/hq37x121v/4b29ck28c/vegean23.pdf

USDA (U.S. Department of Agriculture) (2023d) *Noncitrus Fruits and Nuts 2022 Summary*. Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/zs25x846c/zk51wx21m/k356bk214/ncit0523.pdf

USDA (U.S. Department of Agriculture) (2022a) *Potato Annual 2021 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/fx719m44h/gb19gf71k/37721m72q/pots0922.pdf

USDA (U.S. Department of Agriculture) (2022b) *Citrus Fruits 2022 Summary*. Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/j9602060k/pn89ff24k/zp38xm24q/cfrt0922.pdf

USDA (2015) U.S. Department of Agriculture. Economic Research Service. Nutrient Availability (food energy, nutrients, and dietary components). Washington D.C. Available online at: https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/food-availability-per-capita-data-system. Accessed September 2023.

U.S. Poultry (2006) Email correspondence. John Starkey, USPOULTRY to D. Bartram, ERG. 30 August 2006.

White and Johnson (2003) White, P.J. and Johnson, L.A. Editors. Corn: Chemistry and Technology. 2nd ed. AACC Monograph Series. American Association of Cereal Chemists. St. Paul, MN.

World Bank (1999) Pollution Prevention and Abatement Handbook 1998, Toward Cleaner Production. The International Bank for Reconstruction and Development/The WORLDBANK. 1818 H Street, N.W. Washington, DC. 20433, USA. ISBN 0-8213-3638-X.

Composting

BioCycle (2023) BioCycle Nationwide Survey: Full-Scale Food Waste Composting Infrastructure in the U.S. Prepared by N. Goldstein, P. Luu, and S. Motta. Available online at: https://www.biocycle.net/us-food-waste-composting-infrastructure/.

BioCycle (2018a) Organic Waste Bans and Recycling Laws to Tackle Food Waste. Prepared by E. Broad Lieb, K. Sandson, L. Macaluso, and C. Mansell. Available online at: https://www.biocycle.net/2018/09/11/organic-waste-bans-recycling-laws-tackle-food-waste/.

BioCycle (2018b) State Food Waste Recycling Data Collection, Reporting Analysis. Prepared by Nora Goldstein. Available online at: http://compostcolab.wpengine.com/wp-content/uploads/2018/11/State-Food-Waste-Recycling-Data-Collection-Reporting-Analysis.pdf.

BioCycle (2017) The State of Organics Recycling in the U.S. Prepared by Nora Goldstein. Available online at http://www.biocycle.net/17_10_06_1/0001/BioCycle_StateOfOrganicsUS.pdf.

BioCycle (2010) The State of Garbage in America. Prepared by Rob van Haaren, Nickolas Themelis and Nora Goldstein. Available online at http://www.biocycle.net/images/art/1010/bc101016_s.pdf.

Cornell Composting (1996) Monitoring Compost Moisture. Cornell Waste Management Institute. Available online at: http://compost.css.cornell.edu/monitor/monitormoisture.html.

Cornell Waste Management Institute (2007) The Science of Composting. Available online at http://cwmi.css.cornell.edu/chapter1.pdf.

EPA (2020) *Advancing Sustainable Materials Management: 2018 Tables and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf.

EPA (2018) *Advancing Sustainable Materials Management: 2015 Tables and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2016) *Advancing Sustainable Materials Management: Facts and Figures 2014*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/production/files/2016-11/documents/2014_smm_tablesfigures_508.pdf.

EPA (2014) *Municipal Solid Waste in the United States: 2012 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/default/files/2015-09/documents/2012_msw_fs.pdf.

Harvard Law School and Center for EcoTechnology (CET) (2019) Bans and Beyond: Designing and Implementing Organic Waste Bans and Mandatory Organics Recycling Laws. Prepared by Katie Sandson and Emily Broad Leib, Harvard Law School Food Law and Policy Clinic, with input from Lorenzo Macaluso and Coryanne Mansell, Center for EcoTechnology (CET). Available online at https://wastedfood.cetonline.org/wp-content/uploads/2019/07/Harvard-Law-School-FLPC-Center-for-EcoTechnology-CET-Organic-Waste-Bans-Toolkit.pdf.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan. Available online at https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf.

Kijanka (2020) Email correspondence. Kenin Kijanka, EPA Region 2 to Rachel Schmeltz, EPA HQ. "Puerto Rico Composting Operations." November 13, 2020.

University of Maine (2016) Compost Report Interpretation Guide. Soil Testing Lab. Available online at: https://umaine.edu/soiltestinglab/wp-content/uploads/sites/227/2016/07/Compost-Report-Interpretation-Guide.pdf.

U.S. Census Bureau, Population Division (2023) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2022 (NST-EST2022-POP). Available online at https://www.census.gov/data/tables/time-series/demo/popest/2020s-state-total.html.

U.S. Census Bureau, Population Division (2022) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2021 (NST-EST2021-POP). Available online at https://www.census.gov/data/datasets/time-series/demo/popest/2020s-national-total.html.

U.S. Census Bureau (2021) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2010 to July 1, 2019; April 1, 2020; and July 1, 2020 (NST-EST2020). Available online at https://www.census.gov/programs-surveys/popest/technical-documentation/research/evaluation-estimates/2020-evaluation-estimates/2010s-totals-national.html.

U.S. Composting Council (2022) State and City Organics Bans, as of June 2021. Accessed on September 29, 2022. Available at https://www.compostingcouncil.org/page/organicsbans.

U.S. Composting Council (2010) Yard Trimmings Bans: Impact and Support. Prepared by Stuart Buckner, Executive Director, U.S., Composting Council. Available online at https://cdn.ymaws.com/www.compostingcouncil.org/resource/resmgr/images/advocacy/Yard-Trimmings-Ban-Impacts-a.pdf.

Anaerobic Digestion at Biogas Facilities

Bronstein, Kate (2021) Expert Judgement Uncertainty of quantity of materials digested. RTI International, Solid Waste Management GHG Expert.

EPA (2023) Anaerobic Digestion Facilities Processing Food Waste in the United States (2019): Survey Results. April 2023 EPA 530-R-23-003. April 2023. Available online at https://www.epa.gov/system/files/documents/2023-04/Anaerobic_Digestion_Facilities_Processing_Food_Waste_in_the_United_States_2019_20230404_508.pdf.

EPA (2021) Anaerobic Digestion Facilities Processing Food Waste in the United States (2017 & 2018): Survey Results. January 2021 EPA/903/S-21/001. Available online at https://www.epa.gov/sites/default/files/2021-02/documents/2021_final_ad_report_feb_2_with_links.pdf.

EPA (2020) Types of Anaerobic Digesters: Common Ways to Describe Digesters. Available online at https://www.epa.gov/anaerobic-digestion/types-anaerobic-digesters.

EPA (2019) Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results. September 2019 EPA/903/S-19/001. Available online at https://www.epa.gov/sites/production/files/2018-08/documents/ad_data_report_final_508_compliant_no_password.pdf.

EPA (2018) Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results. May 2018 EPA/903/S-18/001. Available online at https://www.epa.gov/sites/production/files/2019-09/documents/ad_data_report_v10_-_508_comp_v1.pdf.

EPA (2016) Frequently Asked Questions About Anaerobic Digestion. Available online at https://www.epa.gov/anaerobic-digestion/frequent-questions-about-anaerobic-digestion#codigestion.

EPA (1993) Anthropogenic Methane Emissions in the U.S.: Estimates for 1990, Report to Congress. Office of Air and Radiation, Washington, DC. April 1993.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan. Available online at https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf.

Water Environment Federation (WEF) (2012) What Every Operator Should Know about Anaerobic Digestion. Available online at https://www.wef.org/globalassets/assets-wef/direct-download-library/public/operator-essentials/wet-operator-essentials---anaerobic-digestion---dec12.pdf.

Waste Incineration

RTI (2009) Hospital/Medical/Infectious Waste Incinerators: Summary of Requirements for Revised or New Section 111(d)/129 State Plans Following Amendments to the Emission Guidelines. Available online at https://nepis.epa.gov/Exe/ZyPDF.cgi/P1009ZW6.PDF?Dockey=P1009ZW6.PDF.

Waste Sources of Precursor Greenhouse Gas Emissions

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 - 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Recalculations and Improvements

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland. IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Abbreviations

ABS	Acrylonitrile butadiene styrene
AC	Air conditioner
ACC	American Chemistry Council
AEDT	FAA Aviation Environmental Design Tool
AEO	Annual Energy Outlook
AER	All-electric range
AF&PA	American Forest and Paper Association
AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
AFOLU	Agriculture, Forestry, and Other Land Use
AFV	Alternative fuel vehicle
AGA	American Gas Association
AGR	Acid gas removal
AHEF	Atmospheric and Health Effects Framework
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AIM Act	American Innovation and Manufacturing Act
AISI	American Iron and Steel Institute
ALU	Agriculture and Land Use
ANGA	American Natural Gas Alliance
ANL	Argonne National Laboratory
APC	American Plastics Council
API	American Petroleum Institute
APTA	American Public Transportation Association
AR4	IPCC *Fourth Assessment Report*
AR5	IPCC *Fifth Assessment Report*
AR6	IPCC *Sixth Assessment Report*
ARI	Advanced Resources International
ARMA	Autoregressive moving-average
ARMS	Agricultural Resource Management Surveys
ASAE	American Society of Agricultural Engineers
ASLRRA	American Short-line and Regional Railroad Association
ASR	Annual Statistical Report
ASTM	American Society for Testing and Materials
AZR	American Zinc Recycling
BCEF	Biomass conversion and expansion factors
BEA	Bureau of Economic Analysis, U.S. Department of Commerce
BIER	Beverage Industry Environmental Roundtable
BLM	Bureau of Land Management
BoC	Bureau of Census
BOD	Biological oxygen demand
BOD5	Biochemical oxygen demand over a 5-day period
BOEM	Bureau of Ocean Energy Management
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BOF	Basic oxygen furnace
BRS	Biennial Reporting System
BSEE	Bureau of Safety and Environmental Enforcement
BTS	Bureau of Transportation Statistics, U.S. Department of Transportation
Btu	British thermal unit
C	Carbon
C&D	Construction and demolition waste
C&EN	Chemical and Engineering News
CAAA	Clean Air Act Amendments of 1990
CAFOS	Concentrated Animal Feeding Operations
CAGR	Compound Annual Growth Rate
CaO	Calcium oxide
CAPP	Canadian Association of Petroleum Producers
CARB	California Air Resources Board
CBI	Confidential business information
C-CAP	Coastal Change Analysis Program
CDAT	Chemical Data Access Tool
CEAP	USDA-NRCS Conservation Effects Assessment Program
CEFM	Cattle Enteric Fermentation Model
CEMS	Continuous emission monitoring system
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CH_4	Methane
CHAPA	California Health and Productivity Audit
CHP	Combined heat and power
CI	Confidence interval
CIGRE	International Council on Large Electric Systems
CKD	Cement kiln dust
CLE	Crown Light Exposure
CMA	Chemical Manufacturer's Association
CMM	Coal mine methane
CMOP	Coalbed Methane Outreach Program
CMR	Chemical Market Reporter
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COGCC	Colorado Oil and Gas Conservation Commission
CONUS	Continental United States
CRF	Common Reporting Format
CRM	Component ratio method
CRP	Conservation Reserve Program
CSRA	Carbon Sequestration Rural Appraisals
CTIC	Conservation Technology Information Center
CVD	Chemical vapor deposition
CWNS	Clean Watershed Needs Survey
d.b.h	Diameter breast height
DE	Digestible energy

DESC	Defense Energy Support Center-DoD's Defense Logistics Agency
DFAMS	Defense Fuels Automated Management System
DGGS	Division of Geological & Geophysical Surveys
DHS	Department of Homeland Security
DLA	DoD's Defense Logistics Agency
DM	Dry matter
DOC	Degradable organic carbon
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOM	Dead organic matter
DOT	U.S. Department of Transportation
DRE	Destruction or removal efficiencies
DRI	Direct Reduced Iron
EAF	Electric arc furnace
EDB	Aircraft Engine Emissions Databank
EDF	Environmental Defense Fund
EER	Energy economy ratio
EF	Emission factor
EFMA	European Fertilizer Manufacturers Association
EJ	Exajoule
EGR	Exhaust gas recirculation
EGU	Electric generating unit
EIA	Energy Information Administration, U.S. Department of Energy
EIIP	Emissions Inventory Improvement Program
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EREF	Environment Research & Education Foundation
ERS	Economic Research Service
ETMS	Enhanced Traffic Management System
EV	Electric vehicle
EVI	Enhanced Vegetation Index
FAA	Federal Aviation Administration
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agricultural Organization database
FAS	Fuels Automated System
FCCC	Framework Convention on Climate Change
FEB	Fiber Economics Bureau
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FGD	Flue gas desulfurization
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
FIADB	Forest Inventory and Analysis Database
FIPR	Florida Institute of Phosphate Research
FOD	First order decay
FOEN	Federal Office for the Environment
FOKS	Fuel Oil and Kerosene Sales
FQSV	First-quarter of silicon volume
FSA	Farm Service Agency
FTA	Federal Transit Authority
FTP	Federal Test Procedure
g	Gram
G&B	Gathering and boosting
GaAs	Gallium arsenide
GCV	Gross calorific value
GDP	Gross domestic product
GEI	Gulfwide Emissions Inventory
GHG	Greenhouse gas
GHGRP	EPA's Greenhouse Gas Reporting Program
GIS	Geographic Information Systems
GJ	Gigajoule
GOADS	Gulf Offshore Activity Data System
GOM	Gulf of Mexico
GPG	Good Practice Guidance
GRI	Gas Research Institute
GSAM	Gas Systems Analysis Model
GTI	Gas Technology Institute
GWP	Global warming potential
ha	Hectare
HBFC	Hydrobromofluorocarbon
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HDDV	Heavy duty diesel vehicle
HDGV	Heavy duty gas vehicle
HDPE	High density polyethylene
HF	Hydraulically fractured
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HFE	Hydrofluoroether
HHV	Higher Heating Value
HMA	Hot Mix Asphalt
HMIWI	Hospital/medical/infectious waste incinerator
HTF	Heat Transfer Fluid
HTS	Harmonized Tariff Schedule
HVAE	High Voltage Anode Effects
HWP	Harvested wood product
IBF	International bunker fuels
IC	Integrated Circuit
ICAO	International Civil Aviation Organization
ICBA	International Carbon Black Association
ICE	Internal combustion engine
ICR	Information Collection Request
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IGES	Institute of Global Environmental Strategies
IISRP	International Institute of Synthetic Rubber Products
ILENR	Illinois Department of Energy and Natural Resources
IMO	International Maritime Organization
IPAA	Independent Petroleum Association of America
IPCC	Intergovernmental Panel on Climate Change

IPPU	Industrial Processes and Product Use
ISO	International Organization for Standardization
ITC	U.S. International Trade Commission
ITRS	International Technology Roadmap for Semiconductors
JWR	Jim Walters Resources
KCA	Key category analysis
kg	Kilogram
kt	Kiloton
kWh	Kilowatt hour
LDPE	Low density polyethylene
LDT	Light-duty truck
LDV	Light-duty vehicle
LEV	Low emission vehicles
LFG	Landfill gas
LFGTE	Landfill gas-to-energy
LHV	Lower Heating Value
LKD	Lime kiln dust
LLDPE	Linear low density polyethylene
LMOP	EPA's Landfill Methane Outreach Program
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas(es)
LTO	Landing and take-off
LULUCF	Land Use, Land-Use Change, and Forestry
LVAE	Low Voltage Anode Effects
M&R	Metering and regulating
MARPOL	International Convention for the Prevention of Pollution from Ships
MC	Motorcycle
MCF	Methane conversion factor
MCL	Maximum Contaminant Levels
MCFD	Thousand cubic feet per day
MDI	Metered dose inhalers
MDP	Management and design practices
MECS	EIA Manufacturer's Energy Consumption Survey
MEMS	Micro-electromechanical systems
MER	Monthly Energy Review
MGO	Marine gas oil
MgO	Magnesium oxide
MJ	Megajoule
MLRA	Major Land Resource Area
mm	Millimeter
MMBtu	Million British thermal units
MMCF	Million cubic feet
MMCFD	Million cubic feet per day
MMS	Minerals Management Service
MMT	Million metric tons
MMTCE	Million metric tons carbon equivalent
MMT CO_2 Eq.	Million metric tons carbon dioxide equivalent
MODIS	Moderate Resolution Imaging Spectroradiometer
MoU	Memorandum of Understanding
MOVES	U.S. EPA's Motor Vehicle Emission Simulator model
MPG	Miles per gallon
MRLC	Multi-Resolution Land Characteristics Consortium
MRV	Monitoring, reporting, and verification
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MT	Metric ton
MTBE	Methyl Tertiary Butyl Ether
MTBS	Monitoring Trends in Burn Severity
MVAC	Motor vehicle air conditioning
MY	Model year
N_2O	Nitrous oxide
NA	Not applicable; Not available
NACWA	National Association of Clean Water Agencies
NAFTA	North American Free Trade Agreement
NAHMS	National Animal Health Monitoring System
NAICS	North American Industry Classification System
NAPAP	National Acid Precipitation and Assessment Program
NARR	North American Regional Reanalysis Product
NAS	National Academies of Sciences, Engineering, and Medicine
NASA	National Aeronautics and Space Administration
NASF	National Association of State Foresters
NASS	USDA's National Agriculture Statistics Service
NC	No change
NCASI	National Council of Air and Stream Improvement
NCV	Net calorific value
ND	No data
NE	Not estimated
NEH	National Engineering Handbook
NEI	National Emissions Inventory
NEMA	National Electrical Manufacturers Association
NEMS	National Energy Modeling System
NESHAP	National Emission Standards for Hazardous Air Pollutants
NEU	Non-Energy Use
NEV	Neighborhood Electric Vehicle
NF_3	Nitrogen trifluoride
NFI	National forest inventory
NGL	Natural gas liquids
NGO	Non-Governmental Organization
NID	National inventory of Dams
NIR	National Inventory Report
NLA	National Lime Association
NLCD	National Land Cover Dataset
NMOC	Non-methane organic compounds
NMVOC	Non-methane volatile organic compound
NMOG	Non-methane organic gas
NO	Not occurring
NO_2	Nitrogen dioxide

NO_x	Nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
NOF	Not on feed
NPDES	National Pollutant Discharge Elimination System
NPP	Net primary productivity
NPRA	National Petroleum and Refiners Association
NRBP	Northeast Regional Biomass Program
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Laboratory
NRI	National Resources Inventory
NSCEP	National Service Center for Environmental Publications
NSCR	Non-selective catalytic reduction
NSPS	New source performance standards
NWS	National Weather Service
OAG	Official Airline Guide
OAP	EPA Office of Atmospheric Programs
OAQPS	EPA Office of Air Quality Planning and Standards
ODP	Ozone depleting potential
ODS	Ozone depleting substances
OECD	Organization of Economic Co-operation and Development
OEM	Original equipment manufacturers
OGJ	Oil & Gas Journal
OGOR	Oil and Gas Operations Reports
OH	Hydroxyl radical
OPEC	Organization of Petroleum-Exporting Countries
OMS	EPA Office of Mobile Sources
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OTA	Office of Technology Assessment
OTAQ	EPA Office of Transportation and Air Quality
OVS	Offset verification statement
PADUS	Protected Areas Database of the United States
PAH	Polycyclic aromatic hydrocarbons
PCA	Portland Cement Association
PCC	Precipitate calcium carbonate
PDF	Probability Density Function
PECVD	Plasma enhanced chemical vapor deposition
PET	Polyethylene terephthalate
PET	Potential evapotranspiration
PEVM	PFC Emissions Vintage Model
PFC	Perfluorocarbon
PFPE	Perfluoropolyether
PHEV	Plug-in hybrid vehicles
PHMSA	Pipeline and Hazardous Materials Safety Administration
PI	Productivity index
PLS	Pregnant liquor solution
PM	Particulate matter
POTW	Publicly Owned Treatment Works
ppbv	Parts per billion (10^9) by volume
ppm	Parts per million
ppmv	Parts per million (10^6) by volume
pptv	Parts per trillion (10^{12}) by volume
PRCI	Pipeline Research Council International
PRP	Pasture/Range/Paddock
PS	Polystyrene
PSU	Primary Sample Unit
PU	Polyurethane
PVC	Polyvinyl chloride
PV	Photovoltaic
QA/QC	Quality Assurance and Quality Control
QBtu	Quadrillion Btu
R&D	Research and Development
RECs	Reduced Emissions Completions
RCRA	Resource Conservation and Recovery Act
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
RMA	Rubber Manufacturers' Association
RPA	Resources Planning Act
RTO	Regression-through-the-origin
SAE	Society of Automotive Engineers
SAGE	System for assessing Aviation's Global Emissions
SAIC	Science Applications International Corporation
SAN	Styrene Acrylonitrile
SAR	IPCC Second Assessment Report
SCR	Selective catalytic reduction
SCSE	South central and southeastern coastal
SDR	Steel dust recycling
SEC	Securities and Exchange Commission
SEMI	Semiconductor Equipment and Materials Industry
SF_6	Sulfur hexafluoride
SIA	Semiconductor Industry Association
SiC	Silicon carbide
SICAS	Semiconductor International Capacity Statistics
SNAP	Significant New Alternative Policy Program
SNG	Synthetic natural gas
SO_2	Sulfur dioxide
SOC	Soil Organic Carbon
SOG	State of Garbage survey
SOHIO	Standard Oil Company of Ohio
SSURGO	Soil Survey Geographic Database
STMC	Scrap Tire Management Council
SULEV	Super Ultra Low Emissions Vehicle
SWANA	Solid Waste Association of North America
SWDS	Solid waste disposal sites
SWICS	Solid Waste Industry for Climate Solutions
TA	Treated anaerobically (wastewater)
TAM	Typical animal mass
TAME	Tertiary amyl methyl ether
TAR	IPCC Third Assessment Report
TBtu	Trillion Btu
TDN	Total digestible nutrients
TEDB	Transportation Energy Data Book

TFI	The Fertilizer Institute
TIGER	Topologically Integrated Geographic Encoding and Referencing survey
TJ	Terajoule
TLEV	Traditional low emissions vehicle
TMLA	Total Manufactured Layer Area
TOW	Total organics in wastewater
TPO	Timber Product Output
TRI	Toxic Release Inventory
TSDF	Hazardous waste treatment, storage, and disposal facility
TTB	Tax and Trade Bureau
TVA	Tennessee Valley Authority
UAN	Urea ammonium nitrate
UDI	Utility Data Institute
UFORE	U.S. Forest Service's Urban Forest Effects model
UG	Underground (coal mining)
U.S.	United States
U.S. ITC	United States International Trade Commission
UEP	United Egg Producers
ULEV	Ultra low emission vehicle
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAA	U.S. Aluminum Association
USAF	United States Air Force
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
USITC	U.S. International Trade Commission
VAIP	EPA's Voluntary Aluminum Industrial Partnership
VAM	Ventilation air methane
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VOCs	Volatile organic compounds
VS	Volatile solids
WBJ	Waste Business Journal
WEF	Water Environment Federation
WERF	Water Environment Research Federation
WFF	World Fab Forecast (previously WFW, World Fab Watch)
WGC	World Gas Conference
WIP	Waste-in-place
WMO	World Meteorological Organization
WMS	Waste management systems
WRRF	Water resource recovery facilities
WTE	Waste-to-energy
WW	Wastewater
WWTP	Wastewater treatment plant
ZEVs	Zero emissions vehicles

Why is nitrate contamination a concern?

Nitrate is an acute contaminant, meaning that health effects can occur immediately (I.e. within hours or days) of short-term exposure. Too much nitrate in your body makes it harder for red blood cells to carry oxygen. While most people recover quickly, this can be very dangerous for infants and some adults. Particularly vulnerable populations may include infants under the age of 6 months, pregnant women or those with specific health concerns. Infants exposed to high amounts of nitrate may develop “blue baby syndrome.” This illness is rare, but it can be fatal. Infants may be especially vulnerable if they are fed with formula mixed with well water that has a high nitrate concentration.

Southeast Minnesota Groundwater

Minnesota Petition Frequently Asked Questions for Nitrates <https://epa.gov/mn/southeast-minnesota-groundwater#faqs>

Learn more about nitrate contamination <https://cfpub.epa.gov/watertrain/pdf/sdwa.pdf> (pdf).

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Managing Manure To Improve Air and Water Quality

Marcel Aillery, Noel Gollehon, Robert Johansson, Jonathan Kaplan*, Nigel Key, and Marc Ribaudo

Abstract

Animal waste from confined animal feeding operations is a potential source of air and water quality degradation from evaporation of gases, runoff to surface water, and leaching to ground water. This report assesses the potential economic and environmental tradeoffs between water quality policies and air quality policies that require the animal agriculture sector to take potentially costly measures to abate pollution. A farm-level analysis of hog farms estimates the economic and environmental tradeoffs that occur when policies are designed to address pollutant flows to one environmental medium without considering flows to another medium. A national analysis addresses the broader impacts of coordinated (water and air) policies, including long-term structural adjustments and welfare impacts on both producers and consumers. The report also analyzes the potential implications of adding air quality regulations to existing Clean Water Act regulations in the Chesapeake Bay watershed, where a limited land base increases producers' costs of meeting manure management requirements.

Keywords: Animal waste, nitrogen, ammonia, water quality, nutrient management plan, manure management costs, price and quantity adjustments, CAFO.

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Summary

U.S. environmental laws tend to focus on a single environmental medium (e.g., Clean Water Act, Clean Air Act, and Endangered Species Act). When a single pollution source can simultaneously affect more than one environmental medium, a single-medium approach to pollution control can confound policymakers concerned with economic efficiency. An uncoordinated set of policies that independently address different pollution issues can result in unnecessary and unanticipated economic and environmental costs.

Animal agriculture is facing just this situation. Animal agriculture produces a variety of pollutants, including organic matter, urea, ammonia, nitrous oxide, phosphorus, methane, carbon dioxide, pathogens, antibiotics, and hormones. Regulations to restrict animal farm emissions to the water might inadvertently increase emissions to the air, and vice versa.

What Is the Issue?

In 2003, EPA introduced revised Clean Water Act regulations to better protect surface waters from nutrients from concentrated animal feeding operations (CAFOs). When applying manure to crop or pasture land (the primary disposal method), CAFOs now must follow a nutrient management plan that specifies a manure application rate that minimizes the threat to water quality. The cost to farmers of meeting this requirement can be relatively high, primarily from moving manure to an adequate land base. A logical response by producers operating under a nitrogen-based plan might be to reduce the nitrogen content of manure spread on fields by enabling nitrogen to volatilize into the atmosphere from uncovered lagoons or by applying animal waste to land without incorporating it into the soil. But doing so also releases ammonia emissions into the air. As animal feeding operations are the primary source of ammonia in the United States, air quality regulations might require some States to regulate ammonia emissions from animal feeding operations.

What Did the Study Find?

Air and water quality regulations would be most cost effective if implemented simultaneously. This would allow farmers to select the most appropriate mix of practices that satisfy environmental quality goals while maximizing net returns. If environmental policies are uncoordinated, farmers may have to make costly changes to practices more than once before both environmental goals can be met.

To meet a water quality goal, farmers tend to use practices that increase ammonia emissions to the air. Similarly, the practices used to meet an air quality goal would tend to increase nitrogen losses from fields to ground and surface waters. Meeting both air and water quality goals would likely cost more than meeting either air or water goals.

Depending on how the air quality regulations are applied, this could have two impacts on CAFOs and water quality. First, farms identified as CAFOs might need to increase the amount of land on which they spread manure in

order to continue to meet nutrient application standards. This could be particularly costly in a region where animal concentrations are high and cropland available for spreading manure is relatively scarce. For example, requiring CAFOs in the Chesapeake Bay watershed to control ammonia emissions would increase producer costs of land-applying manure by $4 million per year. Failure to account for these costs when developing an ammonia regulation could lead to the false conclusion that the policy is efficient.

Second, an uncoordinated approach could reduce water quality. If ammonia reductions were required of both CAFOs and smaller farms, the water quality benefits from the regulations restricting CAFOs' nitrogen emissions might be diluted by increased nutrient applications on the smaller farms, which have no such nitrogen restrictions. In the Chesapeake Bay watershed, for example, the nutrient content of manure produced on farms not covered by a nitrogen application standard would more than double if ammonia restrictions were applied to all animal feeding operations. This would increase the risk of nitrogen runoff into the Chesapeake Bay.

Anticipating the different forms and pathways that nitrogen takes can keep air quality and water quality policies from working at cross purposes. Then, true solutions—like diet manipulation (to reduce the amount of nitrogen excreted by animals) or industrial uses of manure—might become clearer.

How Was the Study Conducted?

The study used three separate but related analyses to capture the full range of economic decisions (and consequences) that result from farmers' meeting environmental regulations. Data from the 1998 Agricultural Resources Management Survey of hog producers were used to estimate the tradeoffs that occur at the farm level when policies are designed to address pollutant flows to one environmental medium without considering flows to another medium. The broader impacts of coordinated policies, including the welfare impacts on both producers and consumers and regional shifts in production, were examined with a national model of the agriculture sector that tracks nitrogen losses to the environment. A case study of the Chesapeake Bay watershed was used to demonstrate the problems that hypothetical ammonia reductions would have for farms meeting the CAFO regulations in a region where land for spreading manure is relatively scarce, and for resource managers trying to reduce nitrogen loads.

At the heart of all three analyses are nitrogen loss coefficients that are derived from a mass-balance accounting of nitrogen in manure. These were obtained from EPA, and enabled us to estimate tradeoffs in nitrogen losses to the air and nitrogen applied to land as different manure management practices are employed.

Chapter 1
Introduction

U.S. agriculture produces affordable food and fiber for domestic use and export and contributes significantly to the economic base of rural communities. But many agricultural activities also produce pollutants that can harm the environment. For example, animal production generates byproducts such as organic matter, urea, ammonia, nitrous oxide, phosphorus, methane, carbon dioxide, pathogens, antibiotics, and hormones. Without proper management, these materials can degrade surface water, ground water, and soils. Environmental policy aims to improve the management of agricultural systems such that environmental harm is minimized.

Mitigating pollution problems can challenge policymakers when more than one environmental medium is affected by a single pollution source. The correction of a single problem without simultaneously addressing others may not increase societal welfare as much as anticipated, and may even decrease it. Thus, an uncoordinated set of policies that independently address different pollution issues could result in unnecessary losses in societal welfare. Scientists and program managers are also aware of these tradeoffs. However, environmental laws often focus on only one environmental medium (Clean Water Act, Clean Air Act, Endangered Species Act). Such narrowly focused programs may harbor large opportunity costs, especially with high interdependence in pollution flows between different environmental media (U.S. EPA, 1996).

Animal agriculture, in particular, has faced increasing environmental regulations in recent years. Growth and concentration in the industry over the past several decades has prompted concerns over environmental degradation in areas where production facilities are clustered. Concentrated animal feeding operations (CAFOs) have been regulated since 1974 under the Clean Water Act. CAFO regulations were strengthened in 2003 to reduce the threat of nutrients entering surface water, and were the subject of an earlier ERS study (Ribaudo et al., 2003). But these regulations do not require control of potential air emissions from CAFOs. Confined animal operations are the largest source of ammonia emissions in the United States (Abt Associates, 2000). Ammonia emissions have long been encouraged as a justifiable byproduct of meeting water quality goals (Sweeten et al., 2000). Lagoons, for instance, are commonly used to store and treat manure waste from swine operations. These storage systems volatilize nitrogen, thereby reducing its concentration in lagoon effluent and reducing the cost of meeting land application requirements. But, the volatilized nitrogen compounds escape into the air, creating odors, contributing to fine particulates (haze), and hastening global climate change (National Research Council, 2003). Only recently has ammonia loss been viewed as a potential problem in terms of air quality (Sweeten et al., 2000).

The current uncoordinated approach to air and water quality protection has potentially costly implications for both animal producers and society in general. Some animal feeding operations already subject to water quality regulations may soon be required to meet ammonia emission regulations. Technologies adopted to reduce water pollution may be inadequate for

meeting both water quality and ammonia requirements, and might have to be abandoned or modified, at some cost, to comply with both sets of regulations.

Smaller operations not required to meet Clean Water Act regulations might be required to meet air quality regulations. If they change manure management practices to reduce ammonia emissions, the nitrogen content of the operations' manure will increase. If manure applications to the land remain unchanged, the risk of nitrogen runoff to water resources increases. A more coordinated approach to environmental quality protection could avoid these unintended consequences.

Research Objectives

This report assesses the potential economic and environmental tradeoffs between air and water quality when the animal sector is required to take potentially costly measures to abate pollution. To date, only a few analyses have discussed the cross-media problem (Helfand, 1994; Hohmann, 1994; Resources for the Future, 1996), and none explore the theoretical or empirical tradeoffs inherent in cross-media environmental policy. We extend this literature by acknowledging that multiple pollutants from animal feeding operations may enter different media; pollution control technologies effective in one environmental medium may conflict with technologies to control pollutants to other media. Examining the implications of regulating across environmental media may help guide future air and water quality regulations and improve the performance of existing policies.

To accomplish these objectives, this report:

- Reviews some of the potential pollution problems attributable to animal waste, the physical relationships inherent in the waste stream that complicate efficient manure management policy, and the environmental policy regime facing animal agriculture.
- Estimates the tradeoffs that occur at the farm level for hogs when policies are designed to address pollutant flows to one environmental medium without considering flows to another medium. This analysis best captures the production decisions that an individual producer makes when faced with market signals and regulatory requirements in the context of the farm's capital and resource bases.
- Analyzes the national impacts of coordinated policies, including the welfare impacts on both producers and consumers. This accounts for the price effects and regional adjustments missing from the farm-level analysis.
- Analyzes the implications of adding air quality regulations to existing Clean Water Act (CWA) regulations in a region where a limited land base increases the costs of meeting manure management requirements. This case study of the Chesapeake Bay watershed demonstrates how the costs of meeting CWA requirements are affected if ammonia emissions must also be reduced. It also demonstrates how water quality might be affected if ammonia reductions are required on farms not covered under the CWA.

Chapter 2
Animal Agriculture and the Environment

The U.S. animal sector has undergone major structural changes over the past several decades, the result of domestic and export market forces, technological changes, and industry adaptations. The number of large confined production units has expanded, while animal production and feed production are increasingly separated. The total number of animal units increased by about 10 percent between 1987 and 1997, while the number of animal feeding operations (AFOs) decreased by more than half (Gollehon et al., 2001).

Growing concerns about the potential impacts of these changes on environmental quality have spurred local, State, and Federal action. Complaints about water quality and air quality (primarily odor) fuel most of the conflicts between the animal sector and the general population. The Environmental Protection Agency (U.S. EPA) revised Clean Water Act regulations in 2003 for controlling runoff of manure nutrients from the largest AFOs. At the State level, North Carolina entered a legal agreement with the State's largest swine producers to develop innovative waste management strategies that would replace uncovered lagoon and sprayfield systems as a means of storing and treating waste from large hog operations, in order to prevent a repeat of the massive damage to water resources caused by Hurricane Floyd in 1995 (Williams, 2004). Rules on the handling of poultry litter now protect water supplies in eastern Oklahoma, which has witnessed a sharp increase in large poultry operations (Cody, 2003). The South Coast Air Quality Management District in California has introduced new rules for handling and disposing of dairy manure in order to reduce ammonia emissions that have affected heavily populated areas downwind (Wilson, 2004). Iowa, Pennsylvania, Arkansas, and Kentucky are among States that have introduced rules for curbing water pollution, ammonia, and odor from AFOs (Patton and Seidl, 1999; U.S. EPA, 2002).

Environmental Impacts of Animal Production

The major source of environmental degradation from AFOs is waste products (manure, urine, and bedding material). Pollution from animal waste includes runoff of nutrients, organic matter, and pathogens to surface water, leaching of nitrogen and pathogens to ground water, volatilization of gases and odors to the atmosphere, and emissions of fine particulates. Pollutants can originate at several stages of production, including:

- Production houses where animals are confined;
- Manure storage structures such as tanks, ponds, and lagoons;
- Land where manure is applied.

The focus of this report is primarily on the various forms of nitrogen generated by manure. Nitrogen moves freely between the soil, air, and water, and

there is a high degree of interdependence between the forms and paths it takes. Nitrogen from manure is therefore capable of affecting the quality of more than one environmental medium.

Nitrogen Products From Animal Production

Nitrogen is found throughout the environment. It is required by all living things and is a critical crop nutrient. Seventy-eight percent of the atmosphere consists of elemental nitrogen gas (N_2), which is inert, does not affect environmental quality, and is unavailable to living organisms. However, during the past 50 years, large amounts of reactive N have been added to terrestrial systems—including ammonia, ammonium, nitric oxide, nitrogen dioxide, nitrate, and nitrite—through combustion of fossil fuels and production/application of synthetic and organic fertilizer (Follett and Hatfield, 2001). Reactive forms of nitrogen pose a potential threat to environmental quality because of their ability to combine with other compounds and create environmental problems (see box, "Ammonia and Nitrate in the Environment," p. 6). Emissions of reactive nitrogen from AFOs are substantial, and their control represents an important objective in improving environmental quality (NRC, 2003).

Water-Air Interactions

Emissions of nitrogen to water and to the atmosphere are not independent events, but are linked by the biological and chemical processes that produce the various nitrogen compounds (fig. 2-1). Nitrogen enters the system in animal feed. Some of the nitrogen is retained in the animal products (meat, milk, eggs), but as much as 95 percent is excreted in urine and manure (Follett and Hatfield, 2001).

Manure can collect in or under the production house for a few hours or several years, depending on the collection system. Production houses are ventilated to expel gases that are emitted, including ammonia. The manure is eventually removed from the house to a storage structure (lagoon, tank, pit, or slab) and stored anywhere from a few days to many months. Losses of nitrogen to air and water can occur during this time, depending on the system and the extent of contact with rain and wind. The stored manure is eventually transported to fields where it is applied. Losses to air and water from the field vary, depending on application method and rate. Nitrogen in the field helps produce crops, which may in turn be fed to animals, thus completing the cycle. Nitrogen lost to the air eventually returns to earth, where it can be a source of plant nutrients, or contribute to runoff or leaching to water resources.

The form nitrogen takes in its journey from animal to field depends on a host of factors, including storage technology, manure moisture content, temperature, air flow, pH, and the presence of micro-organisms. Reducing nitrogen movement along one path by changing its form will increase nitrogen movement along a different path (NRC, 2003). For example, reducing ammonia losses from a field to the atmosphere by injecting waste directly into the soil increases the amount of nitrogen at risk of moving to water resources as nitrate (Oenema, 2001; Abt Associates, 2000). Ignoring the interactions of the nitrogen cycle in developing manure management policies could lead to unintended and adverse effects on environmental quality.

Figure 2-1

Nitrogen follows many pathways in a livestock operation

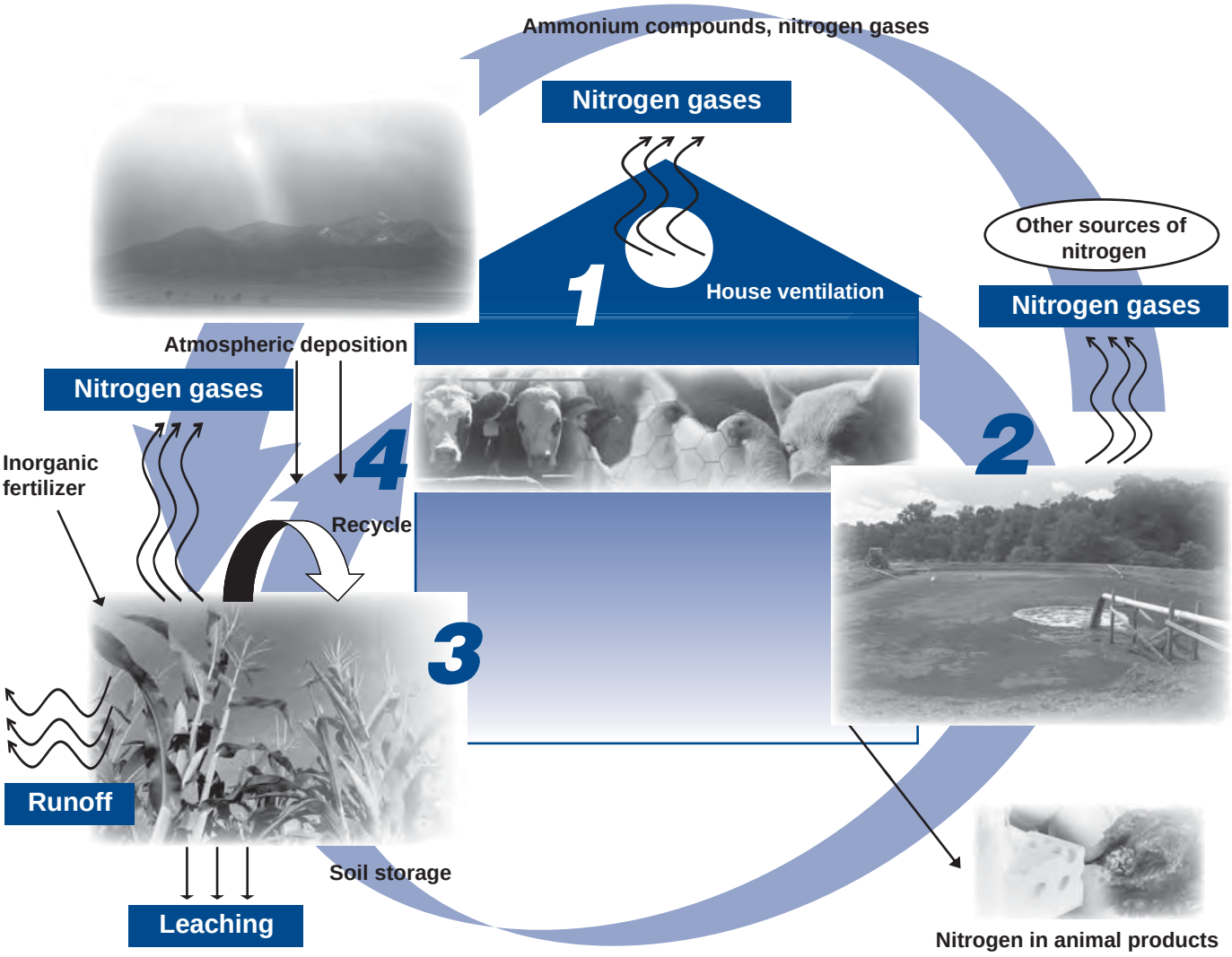

The nitrogen cycle is a complex one, without a beginning, middle, or end. The principle of mass-balance ensures that the amount of nitrogen in a closed system is constant. Thus, any action to divert it from one pathway must necessarily transfer it into another. In this stylized figure:

1. Animals in the "house" release nitrogen in three ways: they produce manure (which then enters a storage system); they store nitrogen internally, which is bound in animal products distributed to markets; and they produce gases (directly and indirectly in manure production), which are released as air emissions;

2. Manure is stored in lagoons, tanks, pits, or other structures before being transported to fields for use as fertilizer;

3. Manure nitrogen applied to fields may be stored in the soil, leached into groundwater, run off into surface water, volatilize into air emissions, and be bound in crops; or

4. Nitrogen bound in crops may be used for feed for the animals, and the cycle begins again.

Nitrogen also enters and exits the system through intermediate pathways. For example, some of the nitrogen released into the air will settle back on the fields (deposition) and some new nitrogen will be added in the form of commercial fertilizer and nitrogen deposition from other sources.

Ammonia and Nitrate in the Environment

Two nitrogen compounds of particular environmental concern are ammonia and nitrate. Ammonia is a pungent gas that is a potential health hazard to humans and livestock. Nitrogen in animal manure can be converted to ammonia by a combination of hydrolysis, mineralization, and volatilization (Oenema et al., 2001). Once in the atmosphere, ammonia can be converted rapidly to ammonium aerosol by reactions with acidic compounds such as nitric acid or sulfuric acid. As an aerosol, ammonium contributes directly to fine particulates, the source of haze in the atmosphere. Gaseous ammonia that is not converted to ammonium is removed from the atmosphere by dry deposition, while ammonium aerosol is primarily removed from the atmosphere by rain or snow. Atmospheric deposition can cause ecological problems by changing plant communities through nutrient enrichment and soil acidification. Large quantities of ammonia are emitted from animal operations each year, making up 50 to 70 percent of annual ammonia emissions from all sources in the United States (NRC, 2003).

Nitrate is a highly soluble compound that is an important plant nutrient. In water, it can degrade water quality by spurring eutrophication. Nitrate can be a human or animal health hazard in drinking water if in high enough concentrations. The U.S. EPA has established a maximum contaminant level for drinking water of 10 ppm for nitrate-nitrogen. Nitrate enters water resources through runoff or leaching from fields receiving manure, or from leaks in manure storage structures.

Economic Relationships in Animal Waste Management

Farmers consider an array of factors when deciding about farm management and conservation practices. Production decisions are based on market prices, the farm's resources, available technologies, management skill, and expectations about weather. But incentives to consider environmental quality in the balance are often lacking.

How an animal feeding operation manages waste determines the paths of nitrogen and other manure constituents from production to disposal. Many practices are available for reducing gaseous emissions, runoff, and leaching (see box, "Manure Management Strategies"), but manure management practices with strictly public benefits (benefits realized off the farm) will be little used unless economic and regulatory conditions change.

Environmental policy incentives can be subsidies that favor a set of practices (technology incentives), requirements that certain practices be used (technology standards), or requirements that particular farm-level environmental goals be achieved (performance standards) (Ribaudo, Horan, and Smith, 1999). In each case, the farmer will choose that set of practices that maximizes net returns while taking into account the financial incentives or constraints introduced by policy. Whether environmental goals are subse-

Manure Management Strategies

Diet and health—Feed additives and improved nutrient utilization in animals' diets can simplify manure management at all stages of handling and disposal by reducing the amount of nutrients in waste (CAST, 2002; Abt, 2000). The goals of feed management are to match nutrient needs of animals more closely with nutrients in feed. Animal genetics, phase feeding (altering feed to match the age or production level of animals), and amino acid supplements are management tools that are currently available to animal producers.

Chemical addition—Chemicals can be added to manure during its collection in order to bind odorous compounds and to reduce ammonia emissions by lowering pH. For example, field tests indicate that alum can reduce ammonia emissions by 75-97 percent when added to poultry litter (Moore et al., 2000). Alum also increases the nitrogen content of litter that is eventually spread on fields, potentially increasing ammonia emissions from fields and loss of nitrate to water resources.

Air treatment—Trapping air vented from production houses and treating it before discharge to the atmosphere can reduce odorous compounds, ammonia, and other gases. Treatment processes include ozonation and biofilters (Jacobson et al., 1999). These processes do not affect the nitrogen content of manure.

Solid-liquid separation—Separating urea from solid fecal matter either mechanically or with sedimentation basins avoids some of the reactions that cause the formation of ammonia and odor. Separation also simplifies waste handling and disposal (Jacobson et al., 1999). While reducing ammonia emissions, separation preserves nitrogen in liquid and solid wastes, potentially increasing losses to air and water when eventually applied to fields.

Tank covers—Covering storage tanks can greatly reduce the discharge of ammonia to the atmosphere, primarily by altering pH and preventing the formation of ammonia (Jacobson et al., 1999). Storage tanks can be covered with a roof, concrete lid, or flexible plastic cover. The surface of the stored waste can also be covered with straw or other materials (polystyrene foam, air-filled clay balls). This material serves as a medium for micro-organisms that act as a biofilter. While reducing ammonia emissions, covers also increase the nitrogen content of effluent that is eventually spread on fields, increasing the potential for both ammonia emissions and loss of nitrate to water resources.

Lagoon covers—Plastic covers that float on the lagoon surface or that are tented over lagoons can greatly decrease gaseous emissions (Jacobson et. al.,1999, Arogo et al., 2002). Some systems (anaerobic digesters) also capture methane and use it as a biofuel to generate electricity. Covering a lagoon prevents the formation of ammonia by lowering the pH, but increases the nitrogen content of the effluent that is eventually sprayed on fields. While ammonia emissions from fields sprayed with lagoon effluent might increase, the net effect is a reduction in ammonia emissions from both lagoon storage and field applications. However, the risk of nitrate loss to water increases.

Manure incorporation and injection—Rapidly incorporating manure into the soil, either by plowing or disking solids after spreading or injecting liquids and slurries directly into the soil, reduces odor and ammonia emissions (Abt, 2000; Arogo et al., 2002). But, this also increases the nitrogen available for crops in the soil, and thus the risk of nitrate runoff to water resources.

Comprehensive nutrient management—Following a comprehensive nutrient management plan when applying manure and commercial fertilizer to land can reduce potential losses of nitrate to water resources through runoff or leaching (USDA, NRCS, 2005). Nutrient management matches nutrient applications to crop needs so that as few nutrients as possible are lost to the environment. Individual components include testing manure and the soil for nutrient content, calibrating application equipment, balancing crop needs with commercial fertilizer, and recordkeeping. Plans can account for atmospheric losses of nitrogen from animal operations, as well as atmospheric deposition of nitrogen on cropland.

quently met depends on how well the incentives are designed by the resource agency.

Policy Regime for Animal Waste

The major Federal environmental law currently affecting animal feeding operations is the Clean Water Act. AFOs concentrate animals, feed, manure, and urine in a small land area. Feed is brought to the animals rather than their grazing in pastures, fields, or on rangeland. The Clean Water Act specifies that AFOs may be covered by the National Pollutant Discharge Elimination System (NPDES) program (U.S. EPA, 2003). NPDES permits are required by point sources (facilities that discharge directly to water resources through a discrete ditch or pipe) before they can discharge into navigable waters. The permits specify a level of treatment for each effluent source. The regulations set thresholds for size categories based on the number of animals confined at the operation for a total of 45 days or more in any 12-month period.

Concentrated animal feeding operations (CAFOs) are AFOs that are designated by the U.S. EPA or State authority as requiring a point-source discharge permit. We estimate the number of potential CAFOs by using the December 2004 EPA specifications of CAFOs (see box, "EPA Size Thresholds") based on operation size. Large operations are considered CAFOs. Medium-sized operations *can* be designated CAFOs if a manmade ditch, pipe, or similar device carries manure or wastewater from the operation to surface water or the animals come into contact with surface water that runs through the confinement area, or the operation is designated by the permitting authority (typically the State). Even a small operation can be designated a CAFO by the permitting authority if it is found to be a significant source of pollution and it meets the above conditions.

The NPDES permits for CAFOs contain technology-based effluent limit guidelines for the production area and for the land receiving manure. A CAFO must have a nutrient management plan, covering the land receiving manure, that specifies an application rate for manure nitrogen or phosphorus based on the agronomic needs of the crops. EPA estimated that about 15,500 AFOs would be defined or designated as CAFOs (U.S. EPA, 2003).[1] This represents about 5 percent of U.S. AFOs, but covers about 60 percent of all confined animals.

Atmospheric emissions of pollutants are regulated by the Clean Air Act (CAA). The CAA authorizes regulatory programs primarily for protecting human health. EPA has recently initiated development of regulations for reducing fine particulates in the atmosphere (referred to as PM2.5, for particles less than 2.5 microns in size). The Clean Air Act requires State, local, and tribal governments to identify areas not meeting national air quality standards for fine particles (one of the six criteria pollutants regulated under the Act) (U.S. EPA, 2005). States with designated non-attainment areas must submit plans by February 2008 that outline how they will meet the standards by 2010. This regulation could affect animal operations because ammonia is a major precursor of fine particulates. Controlling ammonia from animal operations would be a likely priority in non-attainment areas with high concentrations of animals (U.S. EPA, 2000).

[1]A recent court ruling has brought into question how many CAFOs will actually need NPDES permits. It may be less than 15,500.

EPA size thresholds

Animal sector	Size threshold (number of animals)		
	Large CAFOs	Medium CAFOs	Small CAFOs
Cattle or cow/calf pairs	1,000 or more	300 - 999	Fewer than 300
Mature dairy cattle	700 or more	200 - 699	Fewer than 200
Veal calves	1,000 or more	300 - 999	Fewer than 300
Swine (over 55 pounds)	2,500 or more	750 - 2,499	Fewer than 750
Swine (under 55 pounds)	10,000 or more	3,000 - 9,999	Fewer than 3,000
Turkeys	55,000 or more	16,500 - 54,999	Fewer than 16,500
Laying hens or broilers (liquid manure handling systems)	30,000 or more	9,000 - 29,999	Fewer than 9,000
Chickens other than laying hens (other than a liquid manure handling system)	125,000 or more	37,500 - 124,999	Fewer than 37,500
Laying hens (other than a liquid manure handling system)	82,000	25,000 - 81,999	Fewer than 25,000

Source: U.S. Environmental Protection Agency.

Also covering air pollution is the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), enacted in 1980 to provide broad Federal authority to respond to releases of hazardous substances that might endanger public health. Section 103 of CERCLA requires that the person in charge of a facility immediately notify the National Response Center as soon as he has knowledge of any release in quantities equal to or greater than the "reportable quantity" (e.g., for ammonia, 100 pounds in a 24-hour period) of a hazardous substance. EPA is authorized to require remedial action when appropriate. Although CERCLA is focused on hazardous wastes from industrial plants, the increased size and consolidation of animal feeding operations may make their ammonia and hydrogen sulfide emissions subject to the notification provisions (U.S. EPA, 2005).

Neither the Clean Air Act nor CERCLA currently recognize CAFOs for regulatory purposes. There is no reason to expect that either of these laws would be applied to the same set of operations required by the Clean Water Act to meet nutrient application standards.

While environmental policies may not explicitly recognize the compound (air and water) effects of manure management practices, these interactions are well known to soil and animal scientists. NRCS specifically recognizes the potential air quality impacts of manure management practices that could be included in a Comprehensive Nutrient Management Plan (CNMP). A CNMP is a conservation plan unique to AFOs that addresses natural resource concerns dealing with soil erosion, manure, and organic byproducts and their potential impacts on water quality (USDA, NRCS, 2005). A CNMP must meet strict technical standards. NRCS recommends that AFOs consider the impact of selected conservation practices on air quality during

the CNMP development process. However, NRCS does not currently maintain technical standards for practices that address air quality concerns, so they are not included in a CNMP. In addition, CNMPs are not required of AFOs under EPA regulations. The nutrient management plan that permitted CAFOs must implement is not the same as a CNMP.

Multi-Path Emissions Have Unique Economic Implications

Pollution imposes costs on society that are not borne by the polluter. Thus, pollution control policies can increase societal welfare. Literature on the design of pollution control policies has almost exclusively focused on the control of one specific pollutant (Baumol and Oates, 1988; Tietenberg, 1990). The assumption that there is no interaction between pollutants, either in production or once emitted, is a strong one. Practical experience shows that this is not often the case.

When a production activity creates multiple pollutants or pollutes more than one environmental medium, correcting a single problem can lead to further resource misallocations (Lipsey and Lancaster, 1956). For example, Weinberg and Kling (1996) showed that addressing two pollution externalities associated with irrigation policy can increase welfare, even when the policies are introduced independently. However, there are situations where acting independently can lead to lower welfare than if one pollution problem was not addressed at all. Coordination of policies would ensure that an optimal mix of pollution control is achieved. Coordination is particularly important when policies are in conflict. When policies are complementary, addressing one pollutant tends to move the other in the desired direction. When policies are in conflict, addressing only one could worsen the other, even to the point of reducing overall economic welfare. Reducing soil erosion and improving water quality is an example of policies that can be in conflict (Conner et al., 1995; Lakshminarayan et al., 1995).

The multi-pollutant, multi-effect nature of air pollution has led to serious consideration of coordinated policies. For example, concern over the emission of acidic sulfur and nitrogen compounds in Europe led to separate protocols for reducing emissions of sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds. Because of the synergistic effects of these pollutants in the atmosphere, and the multiple impacts on environmental quality (soil and water acidification, eutrophication, ozone formation), a combined approach offers the best means of achieving cost-effective control (Metcalfe et al., 1998; Michaelis, 1992).

One consequence of an uncoordinated approach is uncertainty about future regulations and how they might affect production. Uncertainty complicates a firm's investment decisions, in light of the significant adjustment costs and irreversibility of investment that capital expenditures generally entail (Lee and Alm, 2004). Policies in conflict would be particularly prone to this. If technologies and management measures implemented by CAFOs to meet water pollution regulations turn out to be in conflict with the goal of reducing air emissions, some of these measures might have to be abandoned, at significant cost to producers.

The compound and multi-pollutant nature of nitrogen flows in the environment suggests the importance of coordinated, rather than piecemeal, control (Bull and Sutton, 1998; Baker et al., 2001). In our chosen case of nitrogen from manure, CWA regulations require CAFOs to meet a nutrient standard for land application. This generally means more land is required for spreading manure than has been used in the past, an expensive proposition for many large farms (Ribaudo et al., 2003). One rational management response under a nitrogen standard is to encourage volatilization of manure nitrogen (e.g., use of uncovered lagoons, surface application to fields) to reduce the nitrogen content in waste, thus allowing higher application rates on cropland and reducing the amount of land needed for spreading (Sweeten et al., 2000). But, such a strategy would increase atmospheric emissions of ammonia and worsen air quality. Environmental policies that simultaneously consider all the environmental consequences of manure nitrogen may increase social welfare relative to single-medium policies when pollutant emissions are interdependent. Zilberman et al. (2001) cite the multi-path nature of animal waste as one reason why current policies are inadequate. A policy focused on nitrogen applications to land allows the buildup of other potential pollutants in the soil, such as phosphorus, and ignores problems such as odor and dust.

Ammonia Coefficients Used in This Report

While there are growing concerns over ammonia emissions to the atmosphere, the science behind developing a national ammonia emissions inventory and assessing ammonia management practices is lacking (NRC, 2003). According to the NRC, "There is a general paucity of credible scientific information on the effects of mitigation technology on concentrations, rates, and fates of air emissions from AFOs, (p. 5)." Much of this has to do with lack of appropriate monitoring technologies and procedures for measuring emissions from a nonpoint source.

However, we are not trying to estimate national emissions, but to assess tradeoffs in the nitrogen cycle (fig. 2-1). Recent research on manure management has provided useful information on the nature of these tradeoffs. We used as our starting point the manure management "trains" (MMT) developed by EPA (2004). This inventory of currently used animal production and manure management systems takes a mass balance or systems approach that is central to our study. However, these MMTs did not include management practices for reducing ammonia emissions. We adapted MMTs for systems incorporating recognized ammonia reduction technologies by using reduction efficiencies reported in the published scientific literature to redirect nitrogen along the appropriate paths. Table 2-1 shows the ammonia losses and the nitrogen available for crops for a set of common production and manure handling systems (with and without ammonia-reducing practices) that are used in this report to assess tradeoffs. The ammonia-reduction efficiency of lagoon covers (Jacobson et al., 1999; Arogo et al., 2002.; Oenema et al., 2001), incorporation (Moore and Meisinger, 2003; Hatfield, 2003; Jacobson et al.,1999; Abt, 2000) and alum (Moore et al., 2000) were obtained from the literature.

We make several assumptions to simplify our analysis.. We assume all CAFOs regulated under the Clean Water Act must adopt nitrogen-based nutrient management plans. An unknown number will probably have to adopt a phosphorus-based plan instead. Under such a plan, manure nitrogen

Table 2-1
Manure management systems and nitrogen losses

Animal	System	N excreted	Losses from building	Losses from storage	Losses from field	Total losses to air	Total available for crops
				Pounds N/head/year			
Hogs	Lagoon, uncovered	18.3	4.9	9.5	0.8	15.2	3.1
Hogs	Lagoon, covered	18.3	4.9	0.5	2.8	8.2	10.1
Hogs	Deep pit, surface apply	18.3	6	0	2.6	8.6	9.7
Hogs	Deep pit, incorporate	18.3	6	0	0.4	6.4	11.9
Dairy	Flush barn, surface apply	220	44	125	11.2	180.2	39.8
Dairy	Flush barn, incorporate	220	44	125	2.8	171.8	48.2
Dairy	Daily spread, surface apply	220	15.2	2.2	37.7	55.1	164.9
Dairy	Daily spread, incorporate	220	15.2	2.2	8.3	25.7	194.3
Poultry	Surface apply	0.9	0.18	0.03	0.17	0.38	0.51
Poultry	Incorporate	0.9	0.18	0.03	0.04	0.25	0.65
Poultry	Alum, surface apply	0.9	0.03	0.04	0.21	0.28	0.62
Fed beef	Solid storage, surface apply	102	0	20.8	13.8	34.6	67.4
Fed beef	Solid storage, incorporate	102	0	20.8	0.7	21.5	80.5

Source: U.S. EPA; Jacobson et al.; Arogo et al.; Oenema et al.; Moore and Meisinger; Hatfield; Jacobson et al.; Abt; Moore et al.

is generally applied at rates less than crop needs, so supplemental commercial nitrogen fertilizer is required (Ribaudo et al., 2003). Incentives to encourage nitrogen losses to the atmosphere would not exist in this case. Subsequently reducing ammonia emissions would not pose increased risks to water quality as long as compensating adjustments in supplemental commercial nitrogen fertilizer are made and the increased nitrogen content of manure does not exceed crop needs.

The Clean Air Act and CERCLA are national laws, but whether they affect animal operations depends on local conditions (non-attainment area in the Clean Air Act) or characteristics of individual operations (daily ammonia emissions under CERCLA). While these laws currently have only limited impacts on animal feeding operations, we do not attempt to forecast which regions or types of operations might be required to reduce ammonia emissions. Our goal is to demonstrate potential tradeoffs that could be important to farmers and to resource managers wherever animal feeding operations are required to meet water quality and/or air quality goals.

We also do not consider the fate of atmospheric nitrogen in our analyses. Atmospheric nitrogen can travel long distances, and our models cannot track its movement. Industrial and mobile sources also contribute significant amounts of atmospheric nitrogen. Accounting for atmospheric deposition would likely reduce the manure nitrogen application rates under a nutrient management plan used in our analyses, but would not alter our basic findings.

Chapter 3
Water-Air Tradeoffs at the Farm Level

A farm-level perspective allows us to look at the economic decisions individual producers make to meet environmental goals, given previous management choices and farm characteristics. We examine the hog sector because it exemplifies the changes to scale, structure, and location that have occurred in the confined animal sector since the 1960s. In 1982, there were 175,284 farms with confined hogs, containing 6.3 million animals (USDA, ERS, 2005). By 1997, the number of farms had shrunk 64 percent to 63,723, while the number of hogs on these farms increased to 8.2 million (USDA, ERS, 2005). These larger facilities (in terms of animal units) are not necessarily larger in terms of cropland. Thus, 51 percent of the recoverable nitrogen (nitrogen remaining after manure handling and storage) in confined hog manure in 1997 was estimated to be in excess of crop needs at the farm level (Gollehon et al., 2001).

Most confined hog operations use either a slurry pit system or a liquid lagoon system for managing manure. Slurry systems store undiluted, untreated manure in watertight tanks or pits until it can be land applied. Storage can be either under the house or outdoors. The stored slurry is surface applied to fields by sprayer trucks or wagons, or incorporated into the soil with chisel plows behind nurse tanks, or directly injected into the soil with drag hoses. Most ammonia emissions from these systems are from the field where manure is applied (U.S. EPA, 2004).

Lagoon systems use open holding ponds to treat diluted manure for an extended period of time. Lagoons stabilize organic matter, reduce the nutrient mass that must be land applied, and vent a large quantity of the manure nitrogen as ammonia. Some of the diluted lagoon liquid is used to flush the production houses. The “digested” lagoon liquid is eventually sprayed on cropland. Lagoons are used primarily in warmer climates where the anaerobic processes can take place year round. Lagoon systems emit more ammonia per animal unit to the atmosphere than do slurry systems (U.S. EPA, 2004).

Because of the high cost of transporting manure relative to the value of the nutrients in the manure, farmers have an incentive to overapply manure to land located near their livestock facilities. The amount of manure generated on CAFOs and its estimated nutrient content indicate that 82 percent of hog CAFOs were overapplying manure nitrogen in 1998 (Ribaudo et al., 2003). Farmers can reduce threats to water quality by testing soil and manure for nutrient content, and applying nutrients at rates consistent with the agronomic needs of crops. Such an approach could force farmers to spread manure on more land, often requiring manure to be transported greater distances from the hog facility (Ribaudo et al., 2003). Farmers faced with nitrogen application restrictions through a required nutrient management plan—but not ammonia emission restrictions—might try to reduce the nitrogen content of manure as a means of reducing the amount of land

needed for spreading, and limiting hauling costs. The nitrogen content of manure can be reduced by promoting the creation of ammonia and its volatilization to the atmosphere. This can be done by storing manure in uncovered lagoons and by surface applying slurry rather than injecting it (Sweeten et al., 2000). For example, the nitrogen available to crops in lagoon liquid is 70 percent lower when coming from an uncovered lagoon rather than a covered lagoon.

If, on the other hand, farmers face restrictions in ammonia emissions but not runoff, they can reduce emissions by adopting storage structures and management methods that reduce manure's contact with the air and maintain a low pH. Preventing the formation of ammonia preserves the nitrogen content of manure, increasing the availability of nitrogen for crops, as well as the risk of nitrogen loss to surrounding waters if the land base receiving lagoon liquid stays the same.

To examine the effect of potentially conflicting policies on a farmer's production decisions, we constructed a hog farm economic model. We evaluate three scenarios: (1) a nitrogen application standard as part of a nutrient management plan required by the 2003 CAFO regulations under the Clean Water Act, (2) a hypothetical ammonia emission standard based on available emission abatement technologies, and (3) a coordinated policy that meets both land application and ammonia emission standards. A positive mathematical programming model with calibrated cost functions captures the essential farm-level tradeoffs between air emissions and water discharges of nitrogen (see Appendix A—web only—for details). Farmers maximize profits given input prices, output prices (hogs and crops), regulatory requirements, and available cropland by choosing a manure management technology, the amount of land on which to spread manure, the acreage of each crop to plant, the amount of commercial fertilizer to purchase, and the number of hogs to produce. We assumed that the basic manure storage system (pit or slurry) would not change.

In the model, nitrogen enters through the feed ration and is retained by the animals or excreted in manure. Once excreted, the nitrogen may be released into the atmosphere through ammonia emissions or preserved in the manure storage and handling system until it is applied to cropland. Nitrogen enters cropland through commercial and manure fertilizer applications. The crop retains some nitrogen, some is bound in the soil substrate, and some is released directly into the environment through air emission and water runoff. Water quality impacts are assumed to be directly related to the amount of nitrogen applied to cropland that is in excess of crop needs, after losses to the atmosphere. Air emissions are derived from total animal production and the type of storage/handling technology employed by the animal feeding operation.

The model is calibrated with data from the 1998 USDA-ARMS survey of hog operations, the most recent survey for hogs. In the analysis, eight representative CAFOs are depicted, corresponding to four major hog producing regions (East Corn Belt, West Corn Belt, Mid-Atlantic, and South and West) and two major manure storage technologies (lagoon and pit). We consider two technological options currently available to hog farms that influence the level of ammonia released to the air: the injection of manure into the soil and covering lagoons.

Single-Medium Environmental Policies

Baseline

Model results indicate how the two single-medium policies and a joint multimedia policy would alter farmers' decisions affecting production, input levels, nitrogen to soil and air, and the use of emission technologies relative to the baseline year 1998—the year of the survey to which the model is calibrated. Baseline costs and profits reflect production decisions made in the absence of any regulatory constraints. In the baseline year, all hog manure was applied onfarm to corn, soybean, and other crops at a rate 7.3 times greater than the nitrogen-based agronomic rate (table 3-1, column 1). This rate reflects the quantity of manure produced by farms relative to the amount of land on which manure was spread in 1998 and the crops reported as receiving manure. In the baseline year, about 10 times more ammonia nitrogen is released from manure storage facilities (lagoons and pits) than from fields. Total nitrogen released to the air in the form of ammonia (361,000 tons) is about twice the total quantity of manure nitrogen applied to crops and almost three times the quantity that is not absorbed by the crops. The high level of nitrogen released as ammonia implies that there is a significant potential for increasing manure nitrogen available for crops. We assume that both excess nitrogen and ammonia emissions in the baseline exceed environmental standards; i.e., further increases in either one would result in unacceptable degradations in environmental quality.

Wide geographical differences in application rates reflect the relative abundance of cropland on which manure is applied. Lagoon operations, located primarily in the Mid-Atlantic, apply manure nitrogen at 9.2 times the agronomic rate, on average, compared with 5.5 times the agronomic rate for pit operations, located primarily in the Corn Belt regions. Livestock operations in the Corn Belt tend to be more integrated with crop production than elsewhere,

Table 3-1
Production, profits, emissions, and technology adoption under nitrogen application standard (NAS), ammonia nitrogen standard (ANS), and both

	Base	NAS		ANS		NAS+ANS	
Item			*% chg.*		*% chg.*		*% chg.*
Hogs (*mil. cwt.*)	119.10	117.96	-0.96	118.26	-0.70	115.61	-2.93
Total profits (*mil. $*)	3,700	3,487	-5.77	3,426	-7.40	3,187	-13.87
Hog enterprise profits (*mil. $*)	3,047	2,837	-6.89	2,805	-7.93	2,568	-15.72
Ammonia N - storage (*1,000 tons*)	327.5	325.3	-0.68	203.3	-37.91	198.8	-39.29
Ammonia N - field (*1,000 tons*)	33.8	34.9	3.38	53.1	57.16	52.1	54.15
Ammonia N - total (*1,000 tons*)	361.3	360.2	-0.30	256.4	-29.02	250.9	-30.55
Excess N - soil (*1,000 tons*)	137.7	0.0	-100.00	246.4	78.95	0.0	-100.00
Application rate (*factor of agronomic rate*)	7.3	1.0	-86.38	17.6	140.37	1.0	-86.38
Manure transport costs *(mil. $)*	0.0	205.6	-	0.0	0.00	231.9	-
Manure N on-farm (*1,000 tons*)	183.6	51.8	-71.81	284.6	55.02	42.3	-76.96
Manure N off-farm (*1,000 tons*)	0.0	127.7	-	0.0	0.00	235.7	-
Cover lagoon (*% farms, all farms*)	0.00	0.00	0.00	36.42	-	36.42	-
Inject manure (*% land, all farms*)	25.56	22.55	-11.78	37.66	47.33	37.46	46.54

so they generally have more cropland available on the farm for spreading manure (McBride and Key, 2003). For pit operations, the amount of excess nitrogen applied to land that is not absorbed by crops is about the same amount of nitrogen released to the air as ammonia. Lagoon operations, in contrast, release far more nitrogen into the air, primarily from the lagoon itself.

Nitrogen Application Standard

The CAFO rules require farmers to follow a nutrient management plan that eliminates excess applications of nitrogen. In our first scenario, we assume each hog operator must meet a nitrogen application standard. Farmers adjust their operations to meet this standard at least cost. CAFOs increase the share of their own land on which they apply manure, decrease the share of the land cultivated using chemical fertilizer, and increase shipments of manure off-farm to conform to this standard. As a result, total profits from the hog enterprise and the whole farm (accounting for crop production) decline about 6.9 percent and 5.8 percent (table 3-1, column 2).

Economic impacts are not distributed equally between the major manure handling technologies. Hog profits for farms using slurry systems decline 9.9 percent, versus 4.9 percent for farms using lagoon systems (table 3.2, column 2). Pit operations suffer larger losses because slurry manure contains more nitrogen than lagoon liquid. Even though pit farms tend to have more land available for spreading manure, the high nitrogen content of

Table 3-2
Production, profits, emissions, and technology adoption under nitrogen application standard (NAS), ammonia nitrogen standard (ANS), and both, by storage technology

	Base	NAS		ANS		NAS+ANS	
Item			*% chg.*		*% chg.*		*% chg.*
Lagoon operations							
Hogs (*mil. cwt.*)	70.76	70.52	-0.34	69.92	-1.18	68.50	-3.20
Total profits (*mil. $*)	2,019	1,929	-4.47	1,778	-11.95	1,686	-16.50
Hog enterprise profits (*mil. $*)	1,827	1,738	-4.88	1,586	-13.22	1,494	-18.26
Ammonia N - storage (*1,000 tons*)	255.0	254.1	-0.34	130.8	-48.69	128.2	-49.74
Ammonia N - field (*1,000 tons*)	14.8	14.7	-0.34	40.7	175.05	39.8	169.43
Ammonia N - total (*1,000 tons*)	269.8	268.8	-0.34	171.5	-36.43	168.0	-37.73
Excess N - soil (*1,000 tons*)	42.4	0.0	-100.00	136.3	221.64	0.0	-100.00
Application rate (*factor of agronomic rate*)	9.4	1.0	-89.31	25.4	171.11	1.0	-89.31
Cover lagoon (*% farms, lagoon farms*)	0.00	0.00	0.00	76.70	-	76.70	-
Pit operations							
Hogs (*mil. cwt.*)	48.34	47.44	-1.86	48.34	0.00	47.11	-2.54
Total profits (*mil. $*)	1,681	1,558	-7.33	1,648	-1.94	1,501	-10.71
Hog enterprise profits (*mil. $*)	1,220	1,099	-9.91	1,220	0.00	1,074	-11.91
Ammonia N - storage (*1,000 tons*)	72.5	71.2	-1.86	72.5	0.00	70.7	-2.54
Ammonia N - field (*1,000 tons*)	19.0	20.2	6.27	12.4	-34.54	12.3	-35.52
Ammonia N - total (*1,000 tons*)	91.5	91.4	-0.17	85.0	-7.17	82.9	-9.39
Excess N - soil (*1,000 tons*)	95.3	0.0	-100.00	110.2	15.53	0.0	-100.00
Application rate (*factor of agronomic rate*)	5.5	1.0	-81.88	10.7	93.27	1.0	-81.88
Inject manure (*% land, pit storage farms*)	48.67	42.93	-11.79	71.70	47.31	71.32	46.54

the slurry means they must still transport large amounts of manure off the farm, and incur high hauling costs.

The nitrogen application standard effectively eliminates excess nitrogen applied to the soil. The nutrient application standard also induces a 3.4-percent increase in the quantity of ammonia nitrogen emitted from fields (table 3-1, column 2), mainly because more land is receiving manure and because farmers that had been injecting slurry switch to surface application to use more manure and minimize off-farm transportation costs. However, the net effect of the policy on ammonia nitrogen emissions is very small, due mainly to the small decline in hog production. Hog production on each farm declines because of the increase in production costs relative to market prices for hogs (which are assumed constant). There is no real tradeoff between air quality and nitrogen available for crops because farmers were generally not taking steps to preserve the nutrient content of manure by preventing atmospheric losses in the first place. This suggests that large hog producers treat manure as a waste to be disposed of rather than a valuable source of nutrients.

Ammonia Nitrogen Limit

We also consider ammonia nitrogen limits based on the minimum levels obtainable employing currently available abatement technologies (lagoon covers and manure injection). For this policy simulation, manure nutrient application standards for protecting water quality are assumed not to exist. For pit operations, ammonia nitrogen emissions are constrained to 10 percent above the minimum obtainable if all manure is injected. For lagoon operations, ammonia emissions are constrained to 20 percent above what is obtainable if lagoons are covered. These limits were chosen so that costs to producers of meeting the emission standards are in the same range as under CAFO application standards and so that pit and lagoon operations face similar regulatory costs under the joint policy (next scenario). The constraint on ammonia emissions is in the form of a percentage reduction in net N emissions per pig.[1]

The ammonia nitrogen standard induces pit operations to switch from surface application to injection on some land, and induces some lagoon operations to cover their lagoons. The ammonia standard results in a 38-percent decline in ammonia emissions from manure storage facilities (the largest source of emissions) and a 57-percent increase in emission from fields, for a net decline in ammonia emissions of 29 percent (table 3-1, column 5). The increase in emissions from fields results because more lagoons are covered, which raises the nutrient content of the lagoon liquid applied to fields, resulting in greater nitrogen volatilization. The ammonia standard resulted in a 79-percent increase in excess nitrogen applied to soil—revealing an important tradeoff between water and air quality. For pit operations, the standard does not affect the profitability of the hog enterprise, so there is no hog production response (table 3-2). On the other hand, profits for operations with lagoons decline over 13 percent, resulting in a decline in production of about 1.2 percent, with no marketwide price effects accounted for.

[1]Another option would have been to place a direct restriction on the entire farm. This would provide a different incentive to the farmer than the per-unit output restriction, and would likely result in a different outcome (Helfand, 1991). How different is an empirical question, but the direction of change would be the same.

Additional Simulations

To explore the tradeoffs between water and air emissions in more detail, we perform two more simulations. First, we examine how the levels of excess soil nitrogen and ammonia nitrogen vary for different nitrogen application standards applied to CAFOs (fig. 3-1). The application standard is incrementally tightened from 50 percent greater than the agronomic rate to full implementation (where manure must be applied at the agronomic rate for all crops). Reducing the allowable nitrogen application rate (moving from right to left along the x-axis) results in a large decrease in the excess nitrogen applied to the soil, but almost no change in the amount of ammonia released. Farms were not conserving manure nutrients prior to the CAFO regulations, so the nitrogen application standards had little impact on air emissions. With no ammonia limits, tightening the nitrogen application standards to improve water quality produces only a minimal tradeoff in terms of lower air quality.

A much different outcome occurs if hypothetical restrictions are placed only on ammonia emissions and CAFOs do not have to meet nutrient application standards (fig. 3-2). A significant tradeoff between water and air quality would occur with increasing restrictions on ammonia emissions and no restrictions on nutrient application rates. Moving toward full implementation of emissions-reducing technologies (lagoon covers and manure injection) causes a large increase in excess soil nitrogen. Since there is no incentive to apply at agronomic rates, and spreading on more land would increase costs, manure nutrients are overapplied.

With no ammonia limits, tightening the nitrogen application standards to improve water quality produces only a minimal tradeoff in terms of lower air quality.

Coordinated (Air and Water) Environmental Policies

Relative to either of the single-medium policies, the joint policy is quite costly in terms of profits (column 7, tables 3-1 and 3-2). Hog operation and total farm profits decline by 15.7 percent and 13.9 percent relative to the base year. Production decreases about 3 percent. However, this policy

Figure 3-1

Tradeoff between ammonia nitrogen emissions and excess soil nitrogen under varying soil nitrogen standards

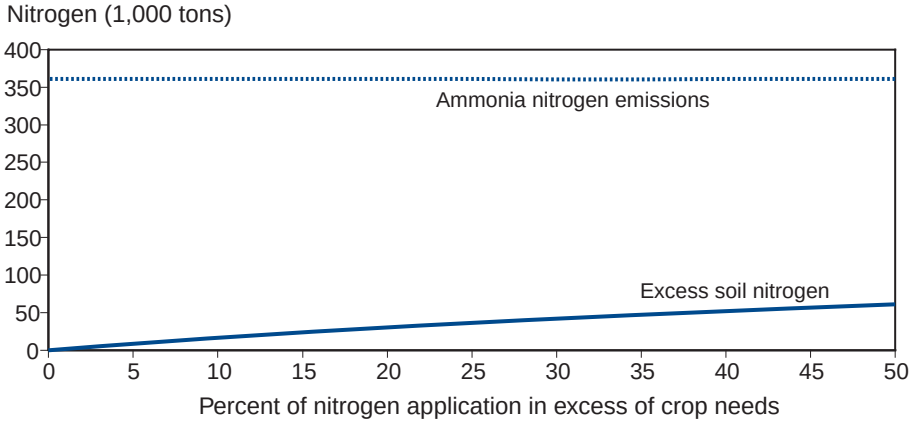

Note: Ammonia emitted to the atmosphere measured in terms of nitrogen.

Figure 3-2

Tradeoff between ammonia nitrogen emissions and excess soil nitrogen under varying ammonia nitrogen standards

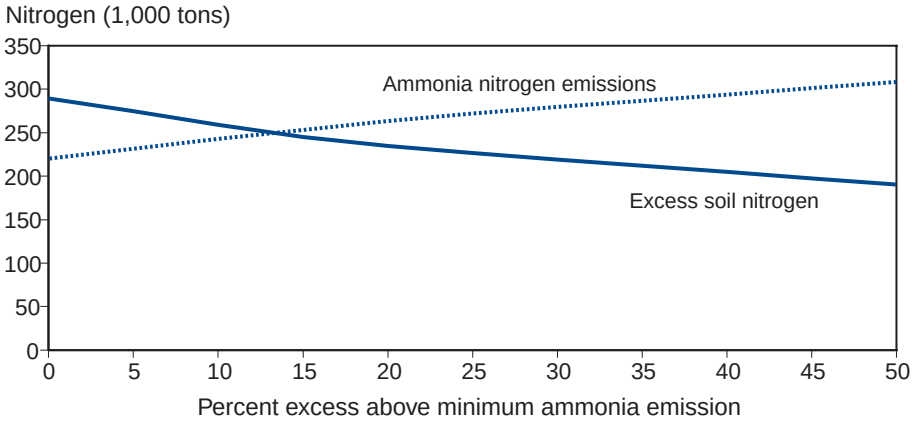

Note: Minimum ammonia emission based on all operations adopting emissions-reducing management practices.

reduces ammonia nitrogen by about 30 percent relative to the levels under the CAFO regulations alone, and eliminates excess nutrient applications. Lagoon operations suffer the largest decline in profits, with hog profits declining 18.3 percent, compared with 11.9 percent for pit operations.

An indication that the individual policies could be in conflict is that the least-cost mix of technologies for addressing either an ammonia policy or a water policy is not the same as the mix of technologies that best meets a joint policy goal. Meeting the land application goal results in a decrease in the amount of manure that is injected, contrary to what would be required to meet the ammonia emission reduction goal. Similarly, meeting the ammonia reduction goal would result in a large increase in nitrogen applications that are in excess of crop needs.

This result implies that applying one policy after the other would result in higher costs than applying both simultaneously. To meet the ammonia emission goal after first implementing nitrogen application standards, manure injection on pit operations would have to increase 66 percent, rather than the 46 percent if the goals had been met simultaneously. This additional 20 percent of land requiring injection is the direct cost of implementing policies piecemeal rather than jointly. This land had been injected before the implementation of any policy, but shifted to surface application in response to the nutrient application regulations. To shift back to injection imposes a cost that would have been avoided if the policies had been implemented simultaneously. For lagoon operators, this conflict does not occur. Meeting the nutrient application standards first would not require any subsequent changes in storage technology to meet the coordinated policy goals (lagoons remain uncovered).

Farm-Level Decisions Have National Implications

This farm-level analysis highlights the economic and environmental tradeoffs that can occur with single-medium environmental policies as they are

applied to hog farms. The two single-medium policies induce different responses. An ammonia emission standard alone would induce farmers to apply more excess nitrogen to the soil—a result likely to diminish water quality through increased nitrogen runoff and leaching. By itself, a nitrogen application standard to protect water quality does not have as dramatic an impact on ammonia emissions, but it does encourage an increase in surface application of manure, which increases potential ammonia losses from fields. Meeting both excess nitrogen and ammonia standards would be more costly than either single-medium policy.

Decisions made at the farm level are just the start of policy impacts. An operator who adopts waste management practices in response to regulatory requirements may also see an increase in production costs. Increased costs of production would, in turn, reduce the number of animals produced. When many hog farmers are affected by a policy change, new production levels may alter the market price of animal products and inputs (feedgrains, for example). Price changes springing from environmental regulations affect consumers and other sectors of the economy, and may cause animal producers to make further changes in their operations.

Chapter 4
National Effects of Coordinated Manure Management

Having examined the implications of addressing nitrogen concerns over water and air quality for one farm-level sector, we now take a larger view. The implications of coordinated (air and water) policies across regions and animal/crop sectors must account for interactions between crop and animal production and their subsequent economic and environmental impacts. Here, potential changes in commodity prices and shifts in production among regions are estimated assuming (1) adoption of land application standards for manure generated on concentrated animal feeding operations (CAFOs) and/or (2) reductions in nitrogen emissions to air from manure generated on all animal feeding operations (AFOs). Some consequences of national policy can only be viewed at this scale of analysis. Tradeoffs are not limited to the farm, but extend to regions and consumers. Market adjustments can produce contrary outcomes, even without the complication of conflicting single-medium policies.

At any level of analysis, adjustments to environmental policies entail increased costs to the producer. The magnitude of this increase depends on a number of factors, including the amount of manure transported for application, the availability of cropland for applying manure nutrients, the willingness of crop producers to substitute manure nutrients for commercial fertilizer, and regional heterogeneity in crop and animal production. Again, we consider current manure spreading regulations both independent of and in coordination with potential ammonia emission regulations across regions and sectors.[1] Specifically, we assess the environmental and economic implications of:

(1) Impacts of the 2003 Clean Water Act regulations for the spreading of animal manure on cropland for CAFOs (*Water*);

(2) Hypothetical reductions in atmospheric nitrogen emissions from animal feeding operations by 10-40 percent in the absence of manure nutrient application standards (*Air10, Air20, Air30,* and *Air40*); and

(3) CAFO water quality regulations plus AFO nitrogen emission regulations (10-40 percent reductions) in each region (*WaterAir10, WaterAir20, WaterAir30,* and *WaterAir40*).

We are looking for tradeoffs associated with implementing policies piecemeal rather than jointly, and indications that the different environmental goals (air quality vs. water quality) move the animal sector along different adjustment paths. Hence, we look at ammonia restrictions in the absence and presence of existing CAFO regulations for the protection of surface-water quality.

Simulating Coordinated Environmental Policies

We use the U.S. Regional Agricultural Sector Model (see Appendix B, web only) to assess secondary price and quantity effects between crop and animal

[1]Here, though, we evaluate both nitrogen and phosphorus application standards. Because each region in the model is large, there is sufficient land to assimilate manure nitrogen in the baseline, meaning there is no overapplication. A nitrogen standard alone would result in no change in the model results.

production (USMP; House et al., 1999) at the national and regional levels (fig. 4-1). We simulate restrictions on manure nutrient use on cropland and on nitrogen emissions from animal production.[2] The model estimates nitrogen emissions to the atmosphere, which allows us to constrain ammonia emissions directly. This model has also been used in previous analyses of the Clean Water Act (Ribaudo et al., 2003; Kaplan et al., 2004).

Various crop rotation, tillage, production and technology adjustments can be made to meet the nitrogen application or ammonia emission constraints. The composition of cropping or animal production could change to alter the amount of manure nutrients demanded or supplied. Storage, handling, or application technologies can reduce ammonia emissions or alter the nitrogen content of manure. Our model selects the optimal combination of technology, crop, and animal changes across the sectors and regions in order to minimize the net cost to society of meeting the different environmental policies. This includes changes in net returns for producers and changes in consumer surplus for purchasers of agricultural products. Storage, handling, and application technologies available in the model for meeting the CAFO nutrient standards and for reducing AFO emissions of nitrogen are consistent with those in the farm-level analysis.[3] We also consider treatment of poultry litter with aluminum sulfate (alum) to reduce nitrogen storage losses and to decrease the bioavailability[4] of phosphorus. Our baseline for comparison (*Base*) uses the USDA 2010 baseline projections for prices and production (USDA, WAOB, 2003) (table 4-1).

What Might We Expect?

CAFOs represent 4.5 percent U.S. feeding operations, but the quantity of manure generated by these facilities exceeds 200 million tons—more than 47 percent of the U.S. total (table 4-2). While the Corn Belt has the most AFOs and CAFOs and generates the most manure, the concentration of

Figure 4-1
USDA farm production regions

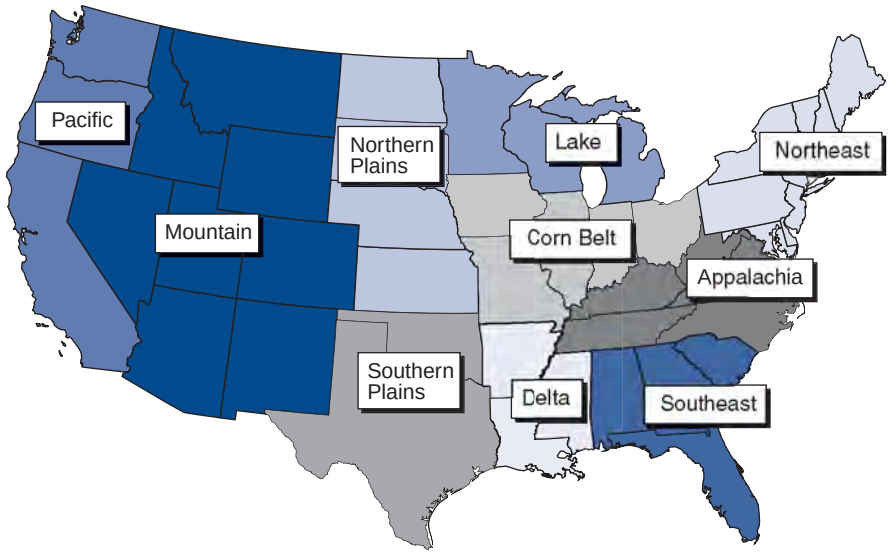

Source: Economic Research Service, USDA.

[2]Manure generation is calculated according to Kellogg et al. (2000); crop nutrient demands by region are calculated using the Environmental Policy Integrated Climate Model (EPIC; Mitchell et al., 1998).

[3]We assume a crop producer willingness to accept manure of 30 percent, meaning that approximately 30 percent of available cropland in each region will utilize manure nutrients (USDA, ERS, 2003b). Alternative levels of manure utilization have been considered, but are not included here.

[4]Bioavailability of phosphorus refers to the amount of phosphorus in runoff that is available for aquatic and terrestrial plant growth.

Table 4-1
Policy scenarios for simulation analysis

Scenario	Manure nutrient spreading standards for CAFOs	Reduction in nitrogen emissions for AFOs
Base	No	No
Water	Yes	No
WaterAir10	Yes	10%
WaterAir20	Yes	20%
WaterAir30	Yes	30%
WaterAir40	Yes	40%
Air10	No	10%
Air20	No	20%
Air30	No	30%
Air40	No	40%

Table 4-2
Baseline for policy simulations

	AFOs						CAFOs		
							Operations	Manure	
Region	Operations	Total manure	Nitrogen runoff	Nitrogen leached	Nitrogen emissions	Phosphorus runoff	Share of total	Share of total	
		Million tons			*Million pounds*		*Percent*		*Tons/acre*
NE	31,350	39.10	32.60	0.17	189.61	5.46	1.59	16.45	0.45
LS	52,498	61.54	72.50	0.80	362.55	12.30	1.64	26.68	0.43
CB	71,252	83.75	87.60	1.02	517.85	25.98	3.18	39.49	0.34
NP	26,087	71.13	80.05	0.82	371.35	15.42	4.77	62.91	0.64
AP	22,776	78.32	120.49	2.01	571.36	34.81	7.46	65.95	2.88
SE	12,635	24.35	126.97	0.67	187.64	21.87	10.97	43.48	1.43
DS	12,252	19.66	33.33	0.34	137.95	9.86	7.48	39.44	0.44
SP	10,500	48.42	72.65	0.43	263.98	17.01	7.00	38.77	0.62
MT	7,780	33.52	80.45	0.09	215.23	14.69	8.43	70.22	0.89
PS	7,654	39.53	118.55	0.18	283.10	16.40	14.85	60.49	2.50
US	254,784	499.31	825.19	6.52	3,100.62	173.78	4.47	47.44	0.72

Northeast (NE) = CT, DE, MA, MD, ME, NH, NJ, NY, PN, RI, VT; Lake States (LS) = MI, MN, WI; Corn Belt (CB) = IA, IL, IN, MO, OH; Northern Plains (NP) = KS, ND, NE, SD; Appalachia (AP) = KY, NC, TN, VA, WV; Southeast (SE) = AL, FL, GA, SC; Delta States (DS) = AR, LA, MS; Southern Plains (SP) = OK, TX; Mountain (MT) = AZ, CO, ID, MT, NM, NV, UT, WY; Pacific States (PS) = CA, OR, WA).

CAFO manure per cropland acre is greatest in the Appalachia, Southeast, and Pacific regions. Therefore, we would expect land application standards for CAFO manure nutrients to result in greater production adjustments in these relatively land-scarce regions. On the other hand, because all animal feeding operations are subject to ammonia emission policies in our analysis, regions with large numbers of animals, such as the Corn Belt, are likely to be more affected by such policies.

What We Found

Higher production costs from meeting environmental standards result in changes to production levels, both animal production (fig. 4-2) and cropped acres (fig. 4-3). Animal production would fall under all scenarios, but to different degrees across sectors.[5] Dairy production would remain relatively unchanged (reductions of less than 1 percent), but reductions in beef

[5]We elected to focus on the results for a 10-percent reduction in ammonia emissions (*Water, WaterAir10, and Air10*). At higher levels of constraints on air emissions, it is likely that producers would consider many alternative technologies, which are not feasible to model at this point.

Figure 4-2

Changes in animal production by policy

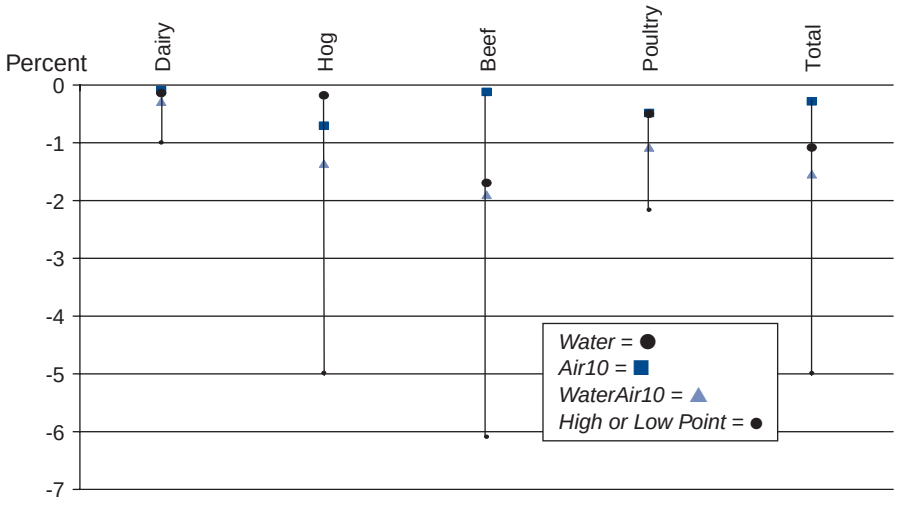

Figure 4-3

Change in cropped acres by region and policy

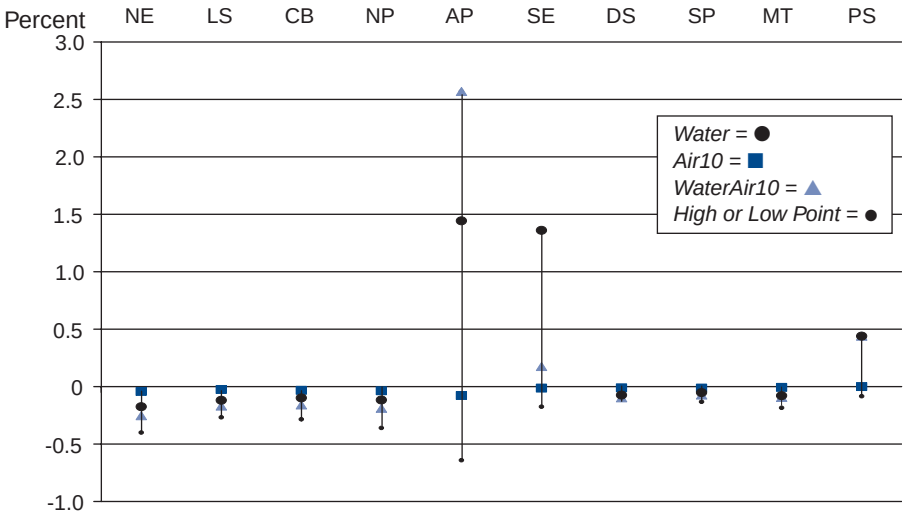

Northeast (NE) = CT, DE, MA, MD, ME, NH, NJ, NY, PN, RI, VT; Lake States (LS) = MI, MN, WI; Corn Belt (CB) = IA, IL, IN, MO, OH; Northern Plains (NP) = KS, ND, NE, SD; Appalachia (AP) = KY, NC, TN, VA, WV; Southeast (SE) = AL, FL, GA, SC; Delta States (DS) = AR, LA, MS; Southern Plains (SP) = OK, TX; Mountain (MT) = AZ, CO, ID, MT, NM, NV, UT, WY; Pacific States (PS) = CA, OR, WA).

production would range from 0.1 percent (*Air10*) to 6.1 percent (*Air40*). Hog production would also exhibit a wide range of production changes.

Beef and hogs exhibit greater reductions because the cost of meeting some environmental constraints are higher. Many hog CAFOs are in regions with limited land for spreading manure (such as Appalachia), and would require expensive emission abatement technologies (covering lagoons). Much of feedlot beef production is in regions where crop demand for nutrients would

be relatively low (such as the Southern Plains); under a nutrient application standard, adjustment costs are high. On the other hand, beef producers could meet the ammonia emission constraint-only scenarios (*Air10* through *Air40*) at relatively low cost. The combined scenarios (*WaterAir10* through *WaterAir40*) would be the most costly, primarily because of the high transportation costs borne by CAFOs to meet the land application requirements when atmospheric emissions are constrained, increasing the nitrogen content of manure.

Dairy CAFOs generally have more land available for spreading, which keeps hauling costs down. The ammonia abatement measures for poultry are generally less costly than for other sectors. In addition, poultry litter has a higher nutrient value-to-weight ratio, so it would be less costly to haul.

At greater reductions in air emissions, the combined scenario (e.g., *WaterAir40*) can have a smaller impact on costs in all animal sectors than the air-only scenario (e.g., *Air40*) because the increased nutrient value of manure would increase the amount AFOs receive for their manure from crop producers, mitigating land application costs (crop producers are assumed to pay for manure).

Under two scenarios (*Water* and *WaterAir10*), the incentive to increase cropped acres where the CAFO manure application standard is most binding (Appalachia, Southeast, and Pacific) boosts cropped acres by 0.5 to 2.5 percent (fig. 4-3). For all other scenarios, cropped acres would fall as demand for feedgrain declines with decreasing animal production.

Technology Adjustments

Technology adoption would be influenced by the policy requirements and the relative costs of the management practices, determined by factors such as mix of animals, dominant production technologies, and cropland available for spreading manure. Consequently, total regional expenditures on practices for meeting environmental goals would adjust after simulated adjustments in production levels have taken place (table 4-3). Under the *Water* scenario, where only the CAFO regulations for protecting water quality are simulated, CAFOs would develop and implement nutrient management plans that minimize the cost of spreading manure. Hauling manure to cropland would be the predominant cost. If restrictions are placed on ammonia emissions from animal feeding operations, producers would begin using alum, incorporating/injecting manure, and covering their lagoons. The costs of these alternative storage, handling, treatment, and application technologies would increase as required reductions in ammonia emissions increase. Expenditures would be highest when both air and water quality goals have to be met (*WaterAir10-40*) because more actions to manage manure must be taken.

The producers' cost per animal unit for each scenario reveals the same relationship between the air and water scenarios as in the farm-level analysis. The sum of the costs of the CAFO regulation scenario (*Water*) and the hypothetical ammonia-only regulation scenarios (*Air*) would be less than the cost of the joint policy scenarios (*WaterAir*) that achieve the same level of

Table 4-3
Net manure storage, handling, treatment, hauling, and application costs

Region[1]	*Water*	*WaterAir10*	*WaterAir20*	*WaterAir30*	*WaterAir40*	*Air10*	*Air20*	*Air30*	*Air40*
					$ million				
NE	9.28	40.40	46.62	53.12	59.52	2.51	5.58	20.53	36.22
LS	34.55	77.76	92.87	110.90	127.56	3.97	8.03	20.41	58.08
CB	52.33	138.30	161.11	193.86	212.70	8.77	21.43	73.79	142.73
NP	129.26	127.38	137.11	132.13	201.74	2.78	9.38	33.20	139.40
AP	6.08	34.73	57.79	95.40	161.42	8.20	18.80	37.54	71.58
SE	23.24	29.33	41.64	53.96	66.75	5.53	16.47	27.93	39.65
DS	13.70	25.71	33.28	41.74	55.50	5.12	13.82	23.02	34.73
SP	47.35	47.65	56.24	74.11	54.49	1.73	7.05	16.68	61.33
MT	96.99	97.14	97.10	99.32	92.66	1.36	3.14	5.44	5.57
PS	121.69	124.00	124.37	126.57	128.76	2.27	4.87	7.73	17.15
Total U.S. cost	534.46	742.39	848.12	981.11	1,161.10	42.23	108.56	266.27	606.42
U.S. cost per AU ($)	4.99	6.96	7.96	9.31	11.19	0.39	1.01	2.52	5.89

[1] Northeast (NE) = CT, DE, MA, MD, ME, NH, NJ, NY, PN, RI, VT; Lake States (LS) = MI, MN, WI; Corn Belt (CB) = IA, IL, IN, MO, OH; Northern Plains (NP) = KS, ND, NE, SD; Appalachia (AP) = KY, NC, TN, VA, WV; Southeast (SE) = AL, FL, GA, SC; Delta States (DS) = AR, LA, MS; Southern Plains (SP) = OK, TX; Mountain (MT) = AZ, CO, ID, MT, NM, NV, UT, WY; Pacific States (PS) = CA, OR, WA.

ammonia reduction. Again, this indicates that the policies are in conflict. The optimal economic adjustments to the different environmental policies would involve tradeoffs; i.e., strategies for addressing ammonia control may make nutrient standards for CAFOs more costly and vice versa.

Regional Shifts

Examining the pattern of geographic shifts in production following our policy simulations provides further evidence that addressing ammonia and water goals independently rather than jointly would impose additional costs on producers. These shifts result from many simultaneous economic forces, reflecting relative costs of meeting regulations, animal mix, and resource base. As expected, meeting two environmental goals rather than one would impose additional costs on the sector and would result in a larger reduction in production. The CAFO regulations alone could reduce production by about 1.2 million animal units (table 4-4). Simultaneously reducing ammonia losses by 20 percent could reduce production by an additional 650,000 animal units (a total loss of 1.85 million).

Most regions would follow this same pattern; production losses would be greatest when both environmental regulations are in place. However, in the Mountain, Appalachian, Northern Plains, and Pacific regions, production would be higher under the joint regulations than under the *Water* scenario. In these regions, the costs associated with closing operations and losing production that would have occurred under the *Water* scenario could be avoided if the water and ammonia regulations are implemented simultaneously rather than independently.

Table 4-4
Changes in regional production

Region[1]	*Base*[2]	*Water*	*WaterAir10*	*WaterAir20*	*Air10*	*Air20*
			Million AU			
NE	4.176	-0.004	-0.123	-0.144	0.015	-0.068
LA	7.847	-0.099	-0.302	-0.359	0.045	0.110
CB	16.874	-0.375	-1.550	-1.725	-0.137	-0.251
NP	19.461	-0.848	-0.549	-0.648	-0.121	-0.643
AP	14.284	-0.323	-0.164	-0.225	-0.101	0.079
SE	3.871	0.005	0.019	-0.013	-0.043	-0.033
DL	3.082	-0.020	-0.120	-0.151	-0.053	-0.046
SP	21.224	0.400	0.729	0.880	0.042	-0.141
MN	10.365	0.450	0.651	0.755	0.041	0.254
PA	7.149	-0.358	-0.262	-0.220	0.006	0.082
US	108.333	-1.172	-1.671	-1.850	-0.306	-0.657

[1] Northeast (NE) = CT, DE, MA, MD, ME, NH, NJ, NY, PN, RI, VT; Lake States (LS) = MI, MN, WI; Corn Belt (CB) = IA, IL, IN, MO, OH; Northern Plains (NP) = KS, ND, NE, SD; Appalachia (AP) = KY, NC, TN, VA, WV; Southeast (SE) = AL, FL, GA, SC; Delta States (DS) = AR, LA, MS; Southern Plains (SP) = OK, TX; Mountain (MT) = AZ, CO, ID, MT, NM, NV, UT, WY; Pacific States (PS) = CA, OR, WA).

[2] Baseline values are taken from 2010 USDA baseline projections (USDA, 2003).

Environmental Implications

Environmental impacts result from changing manure management at the farm level, but also from changing the number of animals raised in each region. As AFOs adopt storage, handling, treatment, and application technologies to reduce ammonia emissions, the reductions in nitrogen runoff (from land application constraints) would gradually diminish. Runoff could even increase above baseline levels, supporting the findings of the farm-level analysis (fig. 4-4). With nutrient application standards in place on CAFOs (*Water*), nitrogen runoff would fall by about 12 percent. As restrictions on ammonia emissions are imposed, nitrogen runoff could increase. When emissions are reduced 40 percent, runoff would be about 7 percent lower than the baseline. Many of the environmental gains attributable to the CAFO regulations would disappear, primarily because non-CAFO operations are not subject to land application constraints. Manure spread on land from these operations would have higher nitrogen content due to technological changes adopted to reduce air emissions. Not restricting land application to agronomic rates would therefore increase nitrogen runoff. Again, policies addressing pollution to only one medium could increase emissions to a different medium. Without land application restrictions in place at all, reducing ammonia emissions would increase overall nitrogen runoff, even with fewer animals.[6]

Phosphorus runoff is a leading cause of surface-water eutrophication (overenrichment of nutrients causing algal blooms). While phosphorus is not part of the nitrogen cycle, manure contains high levels of this nutrient and meeting a nitrogen standard may still result in an overapplication of phosphorus (Ribaudo et al., 2003). This can degrade water resources so that they are unfit for swimming, boating, or fishing. Manure phosphorus, along with nitrogen, is a focus of the Clean Water Act's CAFO regulations. Under most simulated policies, phosphorus discharges would fall substantially (fig. 4-4). In the model, phosphorus applications are restricted under the CAFO regu-

[6] Some of the nitrogen applied to cropland leaches to ground water, which is an important source of drinking water in many areas. The policies examined would have little impact on nitrogen leaching nationally (see fig. 4-4).

Figure 4-4

Change from baseline in ammonia and nutrient losses to the environment, U.S.

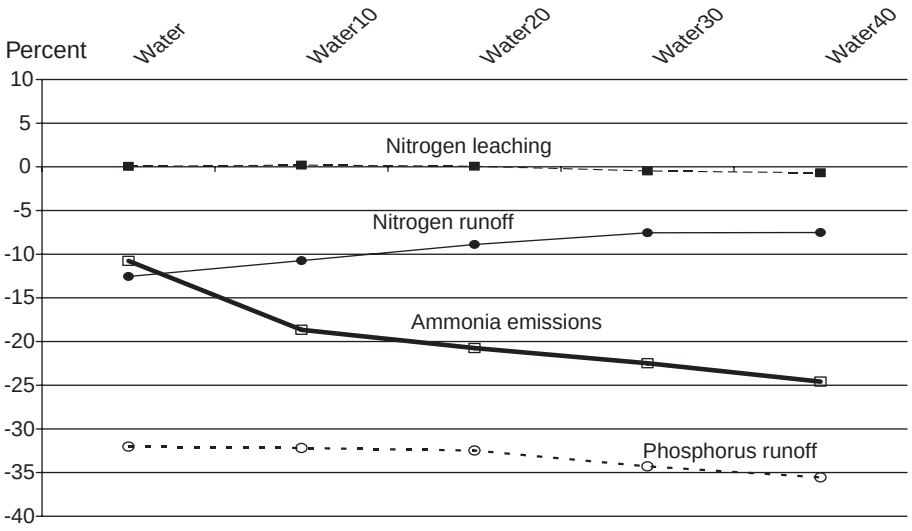

lations when phosphorus is the limiting nutrient (posing greatest environmental threat). Also, one of the practices for reducing ammonia emissions—adding alum to poultry litter—would further limit the loss of phosphorus to water.

Economic Implications From Market Interactions

The farm-level analysis assumed constant prices, so the costs of meeting single-medium or joint policies would be borne fully by animal operations. However, animal production would be expected to fall under all scenarios (fig. 4-2) as producers adjust to increased production costs brought about by more intensive manure management. Such changes would likely lead to higher commodity prices, transferring some of the burden of higher costs to consumers (table 4-5). Crop producers would also be affected by what happens in the animal sector. Corn and soybeans are important feedgrains for animal production, and fewer animals being produced would dampen corn and soybean prices. In addition, policies to protect water quality could increase corn and soybean acres in some regions (receiving manure), which would also reduce prices.

Economic tradeoffs from a joint rather than uncoordinated policy approach can only be inferred from our results. The livestock sector would seemingly benefit from a joint policy versus uncoordinated policy. Reductions in net returns for any one of the joint policies would be less than for the *Water* scenario. Costs to the livestock sector from implementing only the CAFO regulations could have been reduced if hypothetical ammonia reductions had been required at the same time.

Table 4-5
Economic impacts and nitrogen reductions

	Water	*WaterAir10*	*WaterAir20*	*WaterAir30*	*WaterAir40*
			Change (million units)		
Nitrogen reductions (lbs. runoff, leaching, and air emissions)	1,169	1,553	1,599	1,653	1,779
Net returns to crop production ($)	449	328	307	267	196
Net returns to livestock production ($)	-897	-700	-724	-566	-268
Consumer surplus ($)	-402	-786	-876	-1,304	-2,053
Returns to agriculture and consumer surplus ($)	-850	-1,158	-1,293	-1,602	-2,125

Summary

A national manure management policy affecting a significant share of animal feeding operations would affect prices, producer net returns, and consumers. The environmental and economic impacts would vary greatly by region and animal type. The ability of the different sectors and regions to respond to the direct costs of water and air quality regulations depends on the size and structure of the agricultural operations, regional characteristics like available cropland, and responsiveness to price changes by the crop and animal sectors.

National results generally confirm farm-level results. Policies aimed at reducing ammonia emissions from animal manure would result in technological and production adjustments that could, in the aggregate, lead to increased discharge of nitrogen into surface and ground waters. This outcome is explored further for the Chesapeake Bay watershed.

Chapter 5
Impact of Spatial Factors on the Costs of Manure Management:
A Case Study of the Chesapeake Bay Watershed

The costs associated with meeting USDA goals and U.S. EPA regulations for improved manure management depend not only on individual farm conditions and national markets, but on spatial considerations concerning the location of animal operations and cropland available for manure application. Where animal production is concentrated, producers may face competition for suitable land to apply manure, which can increase the cost of meeting application requirements by forcing manure to be hauled longer distances (Ribaudo et al., 2003). Implementing hypothetical ammonia emission controls on farms meeting nutrient standards could increase the competition for land by increasing the nutrient content of manure. Among U.S. areas where manure nutrient production exceeds the assimilative capacity of the land are several county clusters within the Chesapeake Bay watershed (Gollehon et al., 2001) (fig. 5-1). We present this case study to demonstrate how the costs of meeting Clean Water Act requirements might be affected if ammonia emission regulations are also imposed.

The Chesapeake Bay is among the largest and most biologically rich estuaries in the world. The declining health of this ecosystem in recent decades has prompted Federal and State initiatives to reduce nutrient loading from tributaries that drain the watershed. Nutrient discharges to waters in the region have resulted in eutrophication and related ecological shifts that harm wildlife and aquatic resources (Preston and Brakebill, 1999). Manure from confined animal operations has been identified as a primary source of both nutrient runoff to water bodies and local air emissions (Follett and Hatfield, 2001). A joint effort by watershed States to reduce nitrogen loadings is addressing all sources of nitrogen. The potential cost is high. The plan to upgrade 66 of Maryland's major sewage treatment plants will cost between $750 million and $1 billion, and would provide only a third of the nitrogen reductions needed for Maryland to meet its commitment (Maryland Department of Natural Resources, 2004).

The Chesapeake Bay watershed (CBW), spanning over 160 counties in 6 States, includes 66,600 farms with an estimated 8.5 million acres of land potentially available to receive manure. Approximately 15,900 farms in the CBW had confined animals in 1997, with an average daily inventory of about 1.6 billion pounds of feedlot beef, dairy, swine, and poultry (USDA, 1999). These animals produce roughly 93,000 tons of recoverable manure nitrogen, 44,000 tons of recoverable manure phosphorus, and 100,000 tons of ammonia-N annually. Even if confined animal operations fully utilized the crop and pasture land under their control for manure application, excess nutrients would remain. Applying manure at agronomic rates to meet water quality goals would require moving significant quantities of manure off animal producing farms.

Figure 5-1

Location of manure production in Chesapeake Bay watershed, 1997

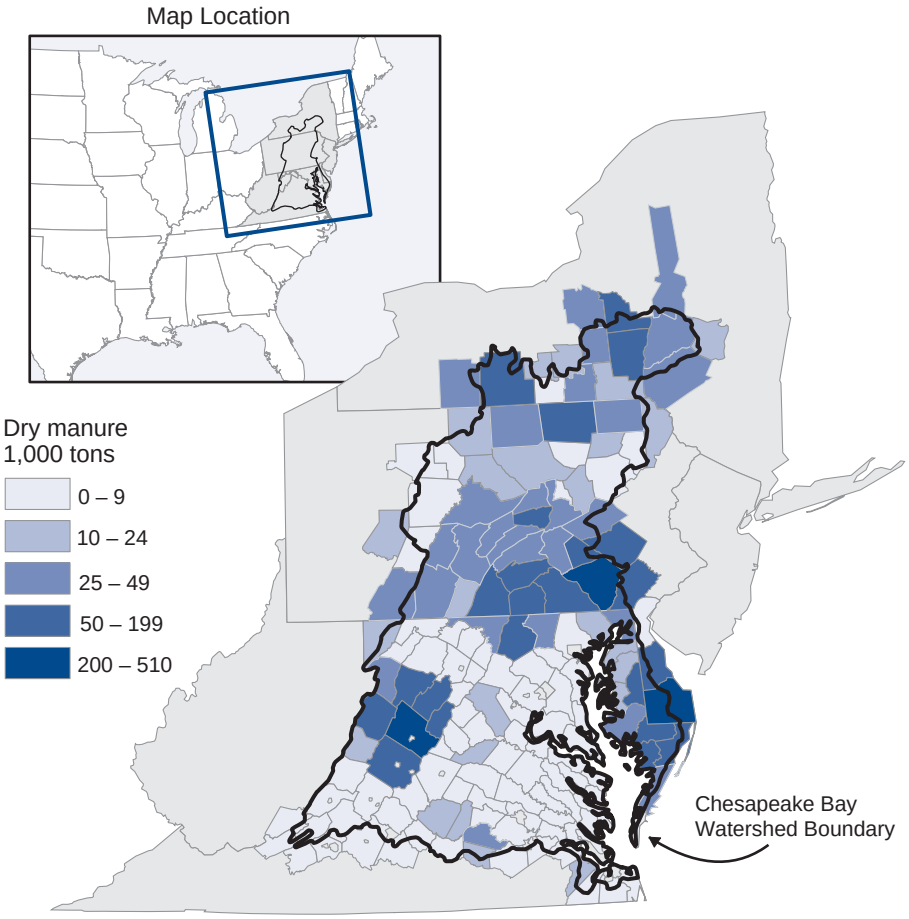

Source: Economic Research Service, USDA.

The effect of alternative behavioral assumptions on the willingness of farmers to accept manure as a substitute for commercial fertilizer was examined in Ribaudo et al. (2003) for all confined animal operations in the CBW. Results from that study indicate that if farmland application is the primary disposal method, implementing nutrient management regulation poses significant challenges where animal production is concentrated. Only about half the manure produced CBW-wide can be used onfarm given current technologies and crop mixes. The feasibility of land application as a regional manure management strategy depends on the willingness of landowners to accept manure on farmland, the nutrient assimilative capacity of the regional cropland base, and the nutrient standard in effect. Ribaudo et al. estimated that more than 30 percent of CBW crop farms would need to accept manure in order to land-apply all the manure produced in the CBW at a rate based on the nitrogen needs of crops (under reasonable hauling distance assumptions).

The CBW case study uses a regional modeling framework designed to capture spatial considerations in manure production and land availability for manure spreading (see Appendix C, web only). The model and its results reflect a

regional planning perspective in evaluating key cost determinants and alternative policy strategies at the watershed scale.

We assume that farms meeting nutrient application standards will apply manure at a rate based on a **nitrogen** standard for cropland and pastureland. Farms in locations with high phosphorus concentrations in the soil and runoff vulnerability may be required to base manure applications on a phosphorus standard, which generally decreases manure applied per acre (Ribaudo et al., 2003). While the effects of manure land application on phosphorus-limiting soils is an important concern in the Chesapeake Bay region, air emission controls interact primarily with manure-nitrogen concentrations. Thus, our focus is on changes in costs to meet a nitrogen standard.[1] We assume the willingness to accept manure by crop producers is 30 percent.

[1]Increasing the nitrogen content of manure by adopting emission controls does not increase the acreage needed for land application when meeting a phosphorus standard. In fact, the increased nitrogen in the manure reduces the supplemental nitrogen usually required.

Determining the effect of emission control technologies on representative manure handling systems for the CBW required two steps. First, the quantities of total manure excreted were estimated from quantities of recoverable manure nitrogen available in the watershed (Aillery et al., 2005) and estimates of ammonia-N losses at the facility and field levels (appendix table D-1). This estimation process—from the field back to the animal—provides consistent estimates of manure nitrogen and ammonia emissions for a baseline situation. (Estimated values for selected systems commonly used in the CBW are provided in appendix table D-2.) In the second step, quantities of manure nitrogen available for plant use and changes in ammonia emissions were estimated from the animal to the field with the addition of emission control technologies by a manure-handling system. Nitrogen losses by system (see chapter 2) were converted to losses as a share of recoverable manure for direct inclusion in the model (appendix table D-3). An example of the estimation process to calculate nitrogen losses and crop availability under alternative emission control technologies is provided in appendix table D-4.

Land Application of Manure With Ammonia-N Reductions

We compare costs to the CBW animal sector of land-applying manure, and the water quality impacts, of four scenarios:

Case A—CAFOs meet nitrogen-based land application standards for water quality improvement, without consideration of ammonia-N emissions (current Clean Water Act policy);

Case B—CAFOs meet nitrogen-based land application standards for water quality improvement, with the addition of ammonia-N reducing technologies and practices;

Case C—All AFOs adopt ammonia-N emission controls for air quality improvements, while CAFOs continue to meet land application standards;

Case D—All AFOs adopt ammonia emission controls and meet land application standards.

For purposes of this analysis, methods of controlling ammonia emissions include the following:

- ***Incorporation/injection.*** Manure is incorporated or injected on 100 percent of acres receiving manure from poultry, dairy, and feedlot beef operations in the included farm set. We assume that lagoon liquid from dairies and feedlot beef operations is surface applied so that it is possible to inject the liquid with current technologies; swine lagoon waste is generally sprayed and is not typically incorporated. Under current conditions, incorporation is assumed to occur on 40 percent of CBW cropland for soil-nutrient retention and odor control, based on data from the ARMS hog and dairy surveys. This practice reduces ammonia emissions on acres currently treated. We assume the crop mix on land receiving manure does not change.
- ***Lagoon covers.*** Impervious lagoon covers are added to all dairy, swine, and feedlot beef operations using lagoon-based manure storage systems. The base model assumption is that no lagoons are covered.
- ***Alum.*** Alum is added to all poultry operations as an additive to the manure in the poultry house. The base model assumption is no alum use.

Case A—CAFO land application standards, with NO ammonia controls. The annual cost of meeting regulations for improved manure management to protect water quality is estimated to be $30 million[2] when only CAFOs meet land application standards (fig. 5-2). CAFOs account for roughly 19 percent of the total modeled manure in the CBW. The distribution of CAFO farms varies significantly across CBW counties, with the share of AUs on CAFO operations ranging from 0 (for about half the counties) to as high as 80 percent in some counties. The manure from non-CAFO farms is assumed to be applied on the source farm without the benefit of a nutrient management plan. Ammonia-N emissions from manure produced on all AFOs in the watershed total an estimated 100,000 tons, including 78,000 tons from animal production and manure storage facilities and 22,000 tons from field applications (fig. 5-3).

[2]Results here are very similar but not identical to those in Ribaudo et al., with the differences due to model and data improvements.

Case B—CAFO land application standards, with CAFO ammonia controls. The estimated cost to CAFOs for managing manure increases by $18 million relative to Case A (fig. 5-2). This reflects both the cost of implementing ammonia-controlling practices ($9 million) and the increased cost of applying manure according to a nutrient management plan ($9 million). Land application costs increase as a larger land area (more than doubled) is required to accommodate the nitrogen-enriched manure (fig. 5-4).

The addition of ammonia emission controls on CAFOs would reduce emissions by about 12,000 tons, relative to Case A, representing 12 percent of total animal emissions basinwide (fig. 5-3).

Case C—All AFO ammonia controls, with CAFO land application standards. Requiring all AFOs to control ammonia emissions would result in a CBW-wide reduction in emissions of 43 percent, 30,000 tons more than in Case B (fig. 5-3). The additional cost to implement air emission controls through expanded use of alum, lagoon covers, and incorporation on all AFOs, relative to Case A, is an estimated $41 million (fig. 5-2).

The threat of nitrogen runoff from CAFOs remains unchanged because the change in nitrogen content of manure is considered in the development of

the nutrient management plans (fig. 5-3). However, the same cannot be said for non-CAFOs, which are not required to follow a nutrient management plan. Non-CAFOs are assumed to spread their manure on land near the production facility without a nutrient management plan, at an estimated cost of $80 million (not shown in fig. 5-2). If these operations do not adjust the amount of land receiving manure, the doubling of the nitrogen content of manure would increase the threat of runoff to the Bay.[3] Potential impacts on water quality would be an unintended consequence of the air quality policy if additional steps are not taken to address manure nutrient over-application.

Case D—All AFO ammonia controls, with AFO land application standards implemented simultaneously. A requirement that all AFOs follow a nutrient management plan in conjunction with meeting ammonia controls would likely limit the threat to water quality in the Bay while reducing ammonia emissions, but at an increased cost to producers. The decline in ammonia emissions is about 9,000 tons more than achieved under Case C (fig. 5-3). The lower field emissions under Case D reflect the overall reduction in field losses achieved by applying all manure at agronomic rates, in contrast to Case C where most of the manure (81 percent) is assumed to be applied at rates substantially above crop needs. The total estimated cost for

[3]The actual effect on water quality in the Bay will depend on the rate of nutrient loading from applied (and over-applied) manure, and the rate and location of nitrogen deposition from air emissions. The science behind these issues continues to evolve.

Figure 5-2

Annual costs of meeting nutrient application standards with alternative emission controls on CAFOs and AFOs, Chesapeake Bay Watershed*

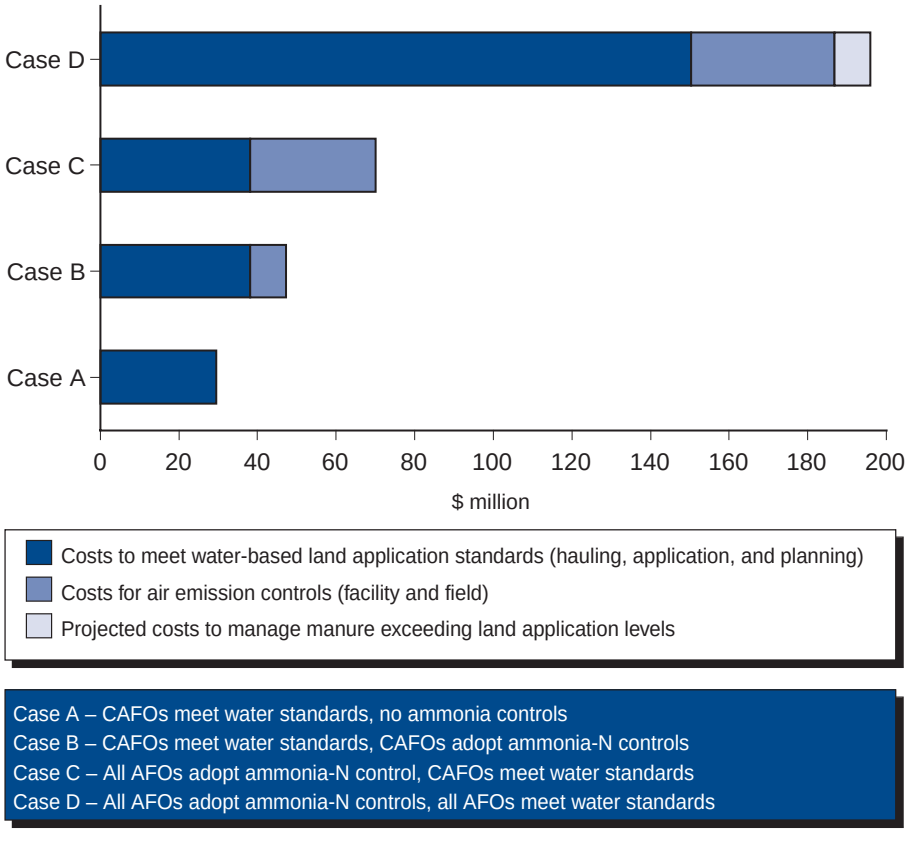

*Assumes a nitrogen standard for manure land application with 30 percent of farmland accepting manure.

Source: Economic Research Service, USDA.

Figure 5-3

Ammonia-N emissions with alternative emission controls for CAFOs and AFOs, Chesapeake Bay Watershed*

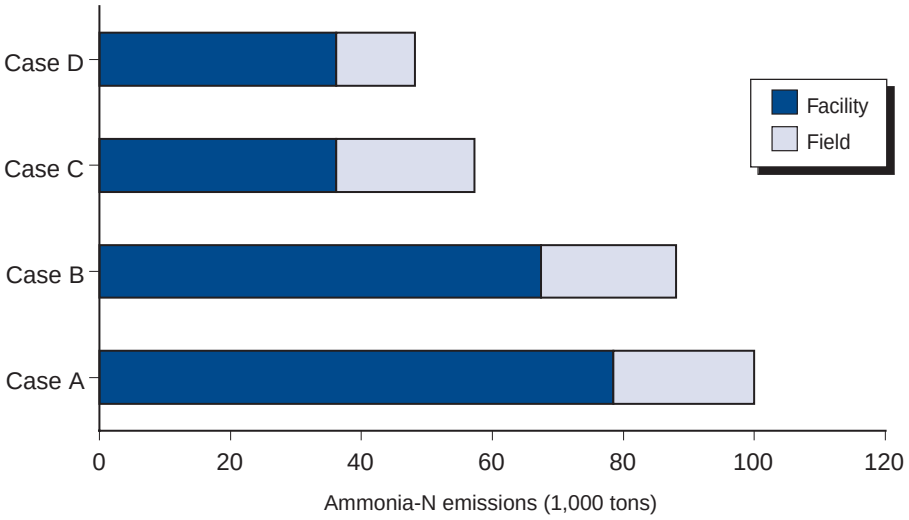

Case A – CAFOs meet water standards, no ammonia controls
Case B – CAFOs meet water standards, CAFOs adopt ammonia-N controls
Case C – All AFOs adopt ammonia-N control, CAFOs meet water standards
Case D – All AFOs adopt ammonia-N controls, all AFOs meet water standards

*Assumes a nitrogen standard for manure land application with 30 percent of farmland accepting manure.

Source: Economic Research Service, USDA.

managing manure to meet ammonia control and land application requirements exceeds $186 million (fig. 5-2). Most of this reflects the implementation of nutrient management plans on all AFOs and a 75-percent increase in the number of acres receiving manure in an environment of intense competition for land (fig. 5-4). Land application costs on non-CAFO operations increase by an estimated $32 million.

An additional cost is for dealing with excess nitrogen for which no land is available within the CBW. Based on model simulations, the CBW has insufficient land to receive all manure when all AFOs are both controlling ammonia emissions and following a nutrient management plan, given an assumed farmer willingness to accept manure of 30 percent.

Various disposal strategies exist for handling this basinwide surplus, like increasing the willingness of crop farmers to accept manure (assumed to be 30 percent in this case study), increasing manure diverted to industrial processes, adjusting the diet of animals to reduce manure nutrients, reducing the number of animals, or transporting manure beyond the 100-mile limit assumed in the model. The latter option may be the least expensive. States have recognized the need to move manure extended distances to comply with nutrient regulations, and some offer a transportation subsidy. Delaware, for example, provides transportation assistance of $18 per ton (Rohrer, 2004). For illustrative purposes, if we assume that all the surplus manure in the model could be transported to land outside the CBW for application

Figure 5-4

Acres receiving manure from CAFOs and AFOs with alternative air emission controls, Chesapeake Bay Watershed*

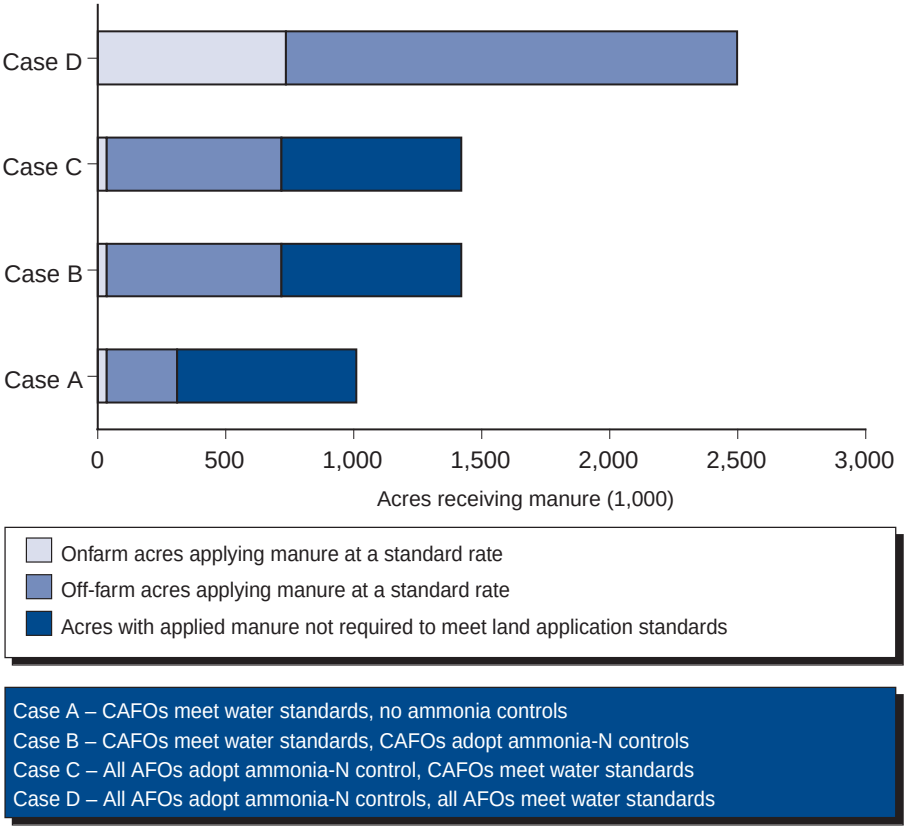

*Assumes a nitrogen standard for manure land application with 30 percent of farmland accepting manure.

Source: Economic Research Service, USDA.

and/or other disposal at $18 per ton, disposal of all AFO manure produced in the CBW would exceed $9 million annually (fig. 5-2).

Reducing the region's animal units to a level where all manure could be land applied is a costly alternative. This approach would require as much as a 7-percent reduction in the number of animals in the CBW. With an average regional return per animal unit of $1,339[4], the annual costs of reducing the number of animals, plus land application of the manure produced, would total about $150 million at a willingness to accept of 30 percent.

Conclusions

Our analysis brings to light a key challenge in achieving air and water quality goals: strides to meet one goal may impede the other, as nitrogen is either applied to farmland via manure or emitted to the atmosphere. Animal producers in the Chesapeake Bay watershed required to meet regulations and guidelines for water quality protection face significant costs for managing manure. New air emission controls, if implemented, would increase costs to the animal sector. The higher nitrogen content of applied manure would pose a challenge to those producers with limited land,

[4]The value of production by animal unit is determined by using USDA baseline projections for 2010 (USDA. 2003). These projections are in turn processed through the USMP model (see Appendix B, web only) to convert animal production into animal units and to account for production cycles. For our purposes, we use gross value minus variable costs per AU to represent the opportunity cost of decreasing production.

requiring longer hauling distances to access adequate land. For other farmers needing nutrients, the nutrient-rich manure can be a resource.

Widely adopted ammonia emission controls could encourage overapplication of manure-nitrogen on non-CAFOs, to the detriment of water quality. Extending land application standards to non-CAFOs would substantially reduce nitrogen available for runoff, but substantially increase the total cost of air and water pollution abatement. The actual effect on water quality in the Bay will depend on nutrient loadings from applied (and overapplied) manure, and the deposition from airborne nitrogen.

Under current Federal regulations for land application of manure, the cost of air emission control reflects both the cost of control practices as well as the increased costs of meeting land application standards due to the higher nitrogen content of manure. Assessments that address practice implementation costs alone may substantially underestimate the full impact of air emissions control on the animal sector.

Cost impacts would be greatest where animal production is concentrated and manure quantities approach or exceed the assimilative capacity of the existing land base, increasing competition for land needed for manure spreading. Under these conditions, reliance on land application alone as a regional manure management solution may not be feasible. Other measures—such as increasing landowner willingness to accept manure, developing industrial applications for manure, subsidizing the long-range transport of manure out of the watershed, or even reducing animal stocks—may play a role in dealing with a regional surplus of manure nutrients.

Chapter 6
Summary and Implications for Policy and Research

Addressing the pollution problems generated by production activities can challenge policymakers concerned with economic efficiency when more than one environmental medium is affected by a single pollution source. This is true of many environmental issues. Coordinating policy so that all potential pollution issues are addressed simultaneously has been shown in the literature to be more efficient than dealing with each issue in an uncoordinated fashion, particularly when correcting one environmental problem worsens another (policies conflict). This report illustrates the tradeoffs in environmental quality by focusing on livestock and poultry production. Nitrogen in manure from animals on feeding operations can take a number of forms; reducing one form of nitrogen to protect one environmental medium can increase the amount of another form moving to a different medium.

Current environmental policies often fail to account for these interactions between media, as is the case with animal waste policies. Revised Clean Water Act regulations focus on managing land application of manure to reduce pollution of surface water. Restricting manure nutrient applications to agronomic rates can reduce manure's threat to water quality, but imposes costs on producers, primarily increased manure hauling costs. These costs can be reduced with manure handling and application strategies that promote the creation of ammonia and its loss to the atmosphere.

Ammonia emissions are a source of haze in the atmosphere, and a potential threat to human health. Recent lawsuits, court decisions, and consent agreements have induced some States to start regulating emissions under the Clean Air Act; the Comprehensive Environmental Response, Compensation and Liability Act; and State laws.

Tradeoffs Between Air and Water Quality Are Prevalent in Manure Nitrogen Management

Tradeoffs between air and water quality exist at the farm, regional, and national level. However, the magnitude varies, depending on baseline assumptions and scale of analysis. The farm-level analysis found that CAFO regulations for reducing nitrogen runoff had only a small impact on ammonia emissions in the hog sector. Hog operations had generally adopted practices that released ammonia to the atmosphere prior to the CAFO regulations (open lagoons and surface manure application), so there was little opportunity to further increase these emissions. Model results suggest that some operations that had been incorporating slurry (presumably for odor control) would start surface-applying manure in order to reduce the amount of land needed to receive manure, but this effect was relatively small. At the national level, implementing the CAFO water quality regulations could actually reduce ammonia emissions. Estimated reductions in animal numbers outweighed any small increase in per-unit ammonia emissions.

On the other hand, when we assumed hypothetical restrictions on ammonia emissions in the absence of the CAFO regulations, excess nitrogen applications (the cause of nitrogen losses to water) increased dramatically at the farm level, and to a lesser degree at the regional and national levels. Animal operations reduced ammonia emissions by covering lagoons and incorporating manure. Excess manure nitrogen applications that existed in the baseline increased as nitrogen in manure was conserved by preventing losses to the atmosphere and land applied to the same acres.

Uncoordinated Policies Impose Extra Costs on Farmers

CAFO regulations and the hypothetical ammonia reduction regulations provide much different incentives to farmers, and so encourage different management practices. Furthermore, neither set of management practices is the most economical for addressing a joint policy where both water quality and ammonia emission goals are set. Farms that adopt a set of practices to meet the CAFO water quality requirements might need to adopt a different set to meet both water and air requirements. The cost of changing practices could be avoided under a coordinated policy. A producer may even be reluctant to comply with new regulations for fear that the rules may change in the future. (Our models do not account for uncertainty or for the economic implications of "sunk" costs for adopting a set of waste-handling technologies and then having to adopt a new set.)

These differences in production costs have broader implications for the agricultural sector. Overall impacts for animal producers, crop producers, and consumers change considerably when hypothetical ammonia reduction goals are added to the CAFO regulations. Some of the regional shifts in production predicted for the CAFO regulations do not occur under a coordinated policy. This implies that some of the adjustment costs from a sequential (uncoordinated) implementation of regulations would have been avoided if they had been introduced together.

Unintended Consequences Can Lessen Environmental Gains

Should ammonia emission standards induce farmers to adopt manure management practices that reduce nitrogen emissions, the manure applied to land will have a higher nitrogen content. Depending on how the air quality regulations are applied, this can have two impacts on CAFOs and water quality. First, those farms identified as CAFOs may need to increase the amount of land they are spreading on to meet nutrient application standards if they are also required to reduce ammonia emissions. This can be particularly costly in a region where animal concentrations are high and cropland available for spreading manure is relatively scarce. In our analysis of the costs of spreading manure in the Chesapeake Bay watershed, nitrogen content of manure substantially increased when ammonia restrictions were introduced, increasing the costs of meeting nitrogen application standards. The higher cost of meeting water quality regulations might not be accounted for in an assessment of the cost of air quality regulations.

Second, a failure to coordinate water and air policies could lead to a loss of water quality benefits. If Clean Air Act or CERCLA requirements result in States requiring ammonia reductions on smaller farms as well as CAFOs, the water quality benefits of the CAFO regulations could be diluted by excess nutrient applications on the smaller farms. This was the case in both our regional and national analyses. Without regulations on spreading manure at agronomic rates, farms reducing ammonia emissions would be more likely to overapply manure, thus increasing nitrogen discharged to surrounding waters. It would be difficult to achieve ammonia emission reductions and still maintain water quality gains of the CAFO regulations if water quality regulations were not extended to smaller operations. Doing so would increase the costs to producers and consumers, but provide greater environmental improvements.

In our analyses, we have not assumed a relative value of air quality changes versus water quality changes. Monetary values associated with improved health and visibility from reduced ammonia emissions, and improved recreation and drinking water benefits from reduced nitrate runoff, have not been estimated at the national scale. These values would help policymakers respond appropriately to ammonia emissions and nitrogen runoff from animal feeding operations. For example, if water quality improvements are valued much less than air quality improvements, the "unintended consequence" of increased nitrogen runoff from an uncoordinated ammonia control policy may be of little concern.

Other Tradeoffs May Be Important

While we focus on the ammonia-nitrate tradeoffs, other interactions have a bearing on current environmental concerns. For example, animal operations are a primary source of the greenhouse gases methane and nitrous oxide. The former is not part of the nitrogen cycle. Its sources are the animal itself (enteric processes) and anaerobic storage. Nitrous oxide, which is part of the nitrogen cycle, is emitted primarily from fields where nitrogen is applied and from dry-waste-handling systems that have aerobic conditions. Commercial fertilizer is the primary source of agricultural nitrous oxide.

Policies that influence the number of animals, manure handling and storage systems, and the amount of nitrogen applied to land also influence greenhouse gas emissions. For example, if a nitrogen runoff-ammonia scenario reduces the number of beef cattle by 2 percent, methane emissions from beef cattle also decline 2 percent. Considering potential conflicts and synergies between policies aimed at visibility, health, water quality, and global climate change would be complex and costly, but could avoid unnecessary costs to the sector and to society as a whole.

Reducing Nitrogen at the Source Can Address Multiple Problems

Not creating pollution in the first place avoids the problems posed by conflicting policies. In the case of nitrogen and AFOs, increasing the efficiency of nutrient conversion to animal products can reduce nitrogen in waste. This would reduce the threats to air and water quality, and make

addressing either or both by managing manure less costly. Major advances are being made in feed efficiency through animal genetics, herd management, phase feeding, and feed formulation.

Another onfarm option involves technology for separating manure into liquid and solid wastes. Each component has a different nutrient content and may be handled differently so that the overall cost for meeting water quality and air quality goals may be reduced.

Another option is to remove manure as quickly as possible from the animal facility and to use it as an input elsewhere. Manure is currently being used to produce commercial fertilizer and energy, and research is underway to identify other potential uses. Atmospheric emissions may be more easily controlled in an industrial setting where contact with air and water can be minimized, and emissions from a ventilation system can be filtered. Current cost and demand conditions have not yet spurred wide-scale development of such industrial options. However, as environmental concerns increase and local, State, and Federal governments deal with manure issues, the costs of manure management are also likely to rise, making industrial options for manure more viable.

This report takes a stylized approach to mass balance, focusing on one set of compounds (nitrogen) and two environmental media (surface water and air quality). A more complete analysis would consider atmospheric deposition of nitrogen (bringing in nitrogen emissions from other sources), greenhouse gases, and groundwater contamination. A full accounting of all the controls necessary to meet additional environmental issues would likely increase the cost to producers, but the magnitude would depend on the interactions between the different pollutant flows, and the degree to which manure handling technologies can address multiple problems. However, the essential link between production and environmental quality, and the tradeoffs between different policy approaches, would likely be similar to those suggested by these results.

References

Abt Associates. 2000. *Air Quality Impacts of Livestock Waste*. Report prepared for U.S. EPA Office of Policy. Bethesda, MD.

Aillery, M. N. Gollehon, and V. Breneman. (2005), "Technical Documentation of the Regional Manure Management Model for the Chesapeake Bay Watershed," Technical Bulletin No. 1913, Economic Research Service, U.S. Department of Agriculture, March, www.ers.usda.gov/publications/tb1913/

Arogo, J., P.W. Westerman, A.J. Heber, W.P. Robarge, and J.J. Classen. 2002. *Ammonia Emissions from Animal Feeding Operations*. National Center for Manure and Animal Waste Management, North Carolina State University, Raleigh, NC.

Baker, L.A., D. Hope, Y. Xu, and J. Edmonds. 2001. "Multicompartment Ecosystem Mass Balances as a Tool for Understanding and Managing the Biogeochemical cycles of Human Ecosystems," *The Scientific World* 1(S2):802-808.

Baumol, W., and W. Oates. 1988. *The Theory of Environmental Policy*. Cambridge University Press, Cambridge, MA.

Borton, L.R., C.A. Rotz, H.L. Person, T.M. Harrigan and W.G. Bickert. 1995. "Simulation to Evaluate Dairy Manure Systems." *Applied Engineering in Agriculture* 11:301-310.

Bull, K.R., and M.A. Sutton. 1998. "Critical Loads and the Relevance of Ammonia to an Effects-Based Nitrogen Protocol," *Atmospheric Environment* 32(3):565-572.

Carmichael, J.J., and K.M. Strzepek. 2000. "A Multi-Organic-Pollutant Simulation/Optimization Model of Industrial and Municipal Wastewater Loading to a Riverine Environment," *Water Resource Research* 36(5): 1325-1332.

Cody, C. 2003. "Farmers told to stop spreading litter." *Arkansas Democrat-Gazette*, April 29.

Conner, J.D., Perry, G.M. and R.M. Adams. 1995. "Cost-Effective Abatement of Multiple Production Externalities," *Water Resources Research* 31(7):1789-96.

Council for Agricultural Science and Technology (CAST). 2002. "Animal Diet Modification to Decrease the Potential for Nitrogen and Phosphorus Pollution." Issue Paper 21 (July).

De Lucia, R., E. McBean, and J. Harrington. 1978. "A Water Quality Planning Model with Multiple Time, Pollutant, and Source Capabilities," *Water Resources Research* 14(1):9-14.

Feinerman, E., D. Bosch, and J. Pease. 2004. "Manure Application and Nutrient Standards," *American Journal of Agricultural Economics* 86(1):14-25.

Fleming, R., B. Babcock, and E. Wang. 1998. "Resource or Waste? The Economics of Swine Manure Storage and Management" *Review of Agricultural Economics* 20(1):96-113.

Follett, R.F., and J.L. Hatfield. 2001. *Nitrogen in the Environment*. Elsevier Press, Amsterdam, The Netherlands. 329 pp.

Foreman, L.F. 2001. *Characteristics and Production Costs of U.S. Corn Farms*. SB-974, U.S. Department of Agriculture, Economic Research Service, Aug.

Foreman, L.F., and J. Livezey. 2002. *Characteristics and Production Costs of U.S. Soybean Farms*. SB-974-4, U.S. Department of Agriculture, Economic Research Service, March.

Gollehon, N., M. Caswell, M. Ribaudo, R. Kellogg, C. Lander, and D. Letson. 2001. *Confined Animal Production and Manure Nutrients.* AIB-771, U.S. Department of Agriculture, Economic Research Service, June.

Hatfield, J. 2003. *Air Quality Primer*. Draft report.

Helfand, G.E. 1994. "Pollution Prevention as Public Policy: An Assessment," *Contemporary Economic Policy* 12(Oct.):104-113.

Hohmann, H. 1994. "Cross-Media Pollution and International Law," *Natural Resources Journal* 34(Summer):535-561.

House, R.M., H. McDowell, M. Peters, and R. Heimlich. 1999. "Agriculture Sector Resource and Environmental Policy Analysis: An Economic and Biophysical Approach," in *Environmental Statistics: Analyzing Data for Environmental Policy*, John Wiley and Sons: New York, NY.

Howitt, R.E. 1995. "Positive Mathematical Programming," *American Journal of Agricultural Economics* 77(2):329-42.

Innes, Robert. 2000. "The Economics of Livestock Waste and Its Regulation," *American Journal of Agricultural Economics* 82(1):97-117.

Jacobson, L.D., R. Moon, J. Bicudo, K. Janni, S. Noll, G. Shurson, J. Zhu, D. Schmidt, C. McGinley, P. Goodrich, R. Nicolai, C. Clanton, K. Davis, L. Brosseau, J. Bruns, C. Pijoan, and T. Blaha. 1999. *Generic Environmental Impact Statement on Animal Agriculture; A Summary of the Literature Related to air quality and Odor (H)*. Report prepared for Minnesota Environmental Quality Board, Minnesota Dept. of Agriculture.

Johansson, R.C., and J.D. Kaplan. 2004. "A Carrot and Stick Approach to Environmental Improvement: Marrying Agri-Environmental Payments and Water Quality Regulations," *Agriculture and Resource Economics Review* 31(1):91-104.

Kaplan, J.D., R.C. Johansson, and M.A. Peters. 2004. "The Manure Hits the Land: Economic and Environmental Implications When Land Application of Nutrients is Constrained," *American Journal of Agricultural Economics* 86(3):688-700.

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon. 2000. *Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States*.

Natural Resources Conservation Service and Economic Research Service, USDA.

Lakshminarayan, P.G., S.R. Johnson, and A. Bouzaher. 1995. "A Multi-objective Approach to Integrating Agricultural Economic and Environmental Policies," *Journal of Environmental Management* 45:365-378.

Lee, A.I., and J. Alm. 2004. "The Clean Air Act Amendments and Firm Investment in Pollution Abatement Equipment," *Land Economics* 80(3):433-447.

Lence, B. 1991. "Weighted Sum Transferable Discharge Permit Programs for Control of Multiple Pollutants," *Water Resources Research* 27(12):3019-3027.

Lipsey, R.G., and K. Lancaster. 1956. "The General Theory of Second Best," *Review of Economic Studies* 24(1):11-32.

Maryland Department of Natural Resources. 2004. "Governor Ehrlich's Chesapeake Bay Watershed Restoration Fund." Press release for Chesapeake Bay Watershed Restoration Fund. www.dnr.state.md.us/dnrnews/pressrelease2004/talking_points.pdf#search='chesapeake%20bay%20watershed%20restoration%20fund'

Massey, R., J. Zulovich, J. Lory, and A. Millmier. 2004. "Agronomic and Economic Impacts of Lagoon-Based Swine Operations Complying With the Proposed EPA Zero Discharge Rule." www.agebb.missouri.edu/commag/crops/massey/present/discharge/sld001.htm.

Metcalfe, S.E., R.G. Derwent, J.D. Whyatt, and H. Dyke. 1998. "Nitrogen Deposition and Strategies for the Control of Acidification and Eutrophication Across Great Britain," *Water, Air, and Soil Pollution* 107:121-145.

Michaelis, P. 1992. "Global Warming: Efficient Policies in the Case of Multiple Pollutants," *Environmental and Resource Economics* 2(1):61-77.

Mitchell, G., R.H. Griggs, V. Benson, and J. Williams. 1998. *Environmental Policy Integrated Climate Model*. Texas A&M University. www.brc.tamus.edu/epic/.

Moore, P., and J. Meisinger. 2003. "Air Quality Issues: Poultry". Working paper in J. Hatfield (ed.), *Air Quality Primer*. Draft report.

Moore, P.A., Jr., T.C. Daniel, and D.R. Edwards. 2000. "Reducing phosphorus runoff and inhibiting ammonia loss from manure with aluminum sulfate," *Journal of Environmental Quality* 29(1):37-49.

Nagurney, A., Kanwalroop, K. and J.K. Stranlund. 1997. "General Multi-Product, Multi-Pollutant Market Pollution Permit Model: A Variational Inequality Approach," *Energy Economics* 19(1): 57-76.

National Research Council. 2003. *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs*. Ad Hoc Committee on Air Emissions from Animal Feeding Operations, Committee on Animal Nutrition, National Research Council, National Academy Press, Washington, DC.

Oenema, O., A. Bannink, S.G. Sommer, and G.L. Velthof. 2001. "Gaseous Nitrogen Emissions from Livestock Farming Systems," in Follett, R.F. and J.L. Hatfied (eds.), *Nitrogen in the Environment: Sources, Problems, and Management*. Elsevier Press, Shannon, Ireland.

Patton, M., and A. Seidl. 1999. *Matrix of State Level Policies for Animal Feeding Operations*. Agricultural and Resource Policy Report, Dept. of Agricultural and Resource Economics, Colorado State Univ., Ft. Collins, CO.

Pease, J., B.A. Pelletier, and D. Kenyon. 2001. "Poultry Litter Transport Alternatives for Land Application in Virginia." Selected paper presented at the Annual Southern Agricultural Economics Association meetings, Ft. Worth, TX, Jan. 29-31.

Preston, S.D., and J.W. Brakebill. 1999. *Application of Spatially Referenced Regression Modeling for the Evaluation of Total Nitrogen Loading in the Chesapeake Bay Watershed*. USGS Water-Resources Investigations Report 99-4054, U.S. Geological Survey, Reston, VA.

Randhir, T.O., and J.G. Lee. 1997. "Economic and Water Quality Impacts of Reducing Nitrogen and Pesticide Use in Agriculture," *Agricultural and Resource Economics Review* 26(1):39-51.

Resources for the Future. 1996. "Cross-Media Pollution and the Chesapeake Bay," *Resources* 124 (Summer).

Ribaudo, M., N. Gollehon, M. Aillery, J. Kaplan, R. Johansson, J. Agapoff, L. Christensen, V. Breneman, and M. Peters. 2003. *Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Nutrients to Land*. AER-824, U.S. Department of Agriculture, Economic Research Service.

Ribaudo, M., A. Catteneo, and J. Agapoff. 2004. "Cost of Meeting Manure Nutrient Application Standards in Hog Production: The Roles of EQIP and Fertilizer Offsets," *Review of Agricultural Economics* 26(4):430-444.

Ribaudo, M.O., R.D. Horan, and M.E. Smith. 1999. *Economics of Water Quality Protection from Nonpoint Sources: Theory and Practice*. AER-782, U.S. Department of Agriculture, Economic Research Service.

Ribaudo, M., N. Gollehon, and J. Agapoff. 2003. "Land Application of Manure by Animal Feeding Operations: Is More Land Needed?" *Journal of Soil and Water Conservation* 58:(1):30-38.

Rohrer, W. 2004. "Delaware Nutrient Relocation Program." Presentation at Finding Solutions to Excess Nutrients in Animal Manure and Poultry Litter Conference, Beltsville, MD, Nov. 30.

Röhm, O., and S. Dabbert. 2003. "Integrating Agri-Environmental Programs into Regional Production Models: An Extension of Positive Mathematical Programming," *American Journal of Agricultural Economics* 85(1):254-265.

Roos, K.F., M.A. Moser, and A.G. Martin. 1999. "Agstar Charter Farm Program: Experience with Five Floating Lagoon Covers." Paper presented at the Fourth Biomass Conference of the Americas, Oakland, CA, Aug. 29-Sept. 2.

Smith, R.A., G.E. Schwarz, and R.B. Alexander. 1997. "Regional interpretation of water-quality monitoring data," *Water Resources Research* 33: 2781-2798.

Sweeten, J. 2001. "Animal Production and Air Quality." Paper presented at Agricultural Outlook Forum 2001, Alexandria, VA, Feb.

Sweeten, J., L. Erickson, P. Woodford, C. Parnell, T. Kendall, T. Coleman, R. Flocchini, C. Reeder, J. Master, W. Hambleton, G. Bluhm, and D. Tristao. 2000. *Air Quality Research and Technology Transfer White Paper and Recommendations for Concentrated Animal Feeding Operations.* Report for USDA Agricultural Air Quality Task Force, Washington, DC.

Tietenberg, T. 1990. "Economic Instruments for Environmental Regulation," *Oxford Review of Economic Policy* 6(1):17-33.

U.S. Department of Agriculture, Economic Research Service. 2005. "Confined Animal and Manure Data System." www.ers.usda.gov/data/manure/

U.S. Department of Agriculture, Economic Research Service. 2003. *Agricultural Resources and Environmental Indicators*, AH-722

U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS). 2003. *Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans: Part I.*

U.S. Department of Agriculture, Natural Resources Conservation Service. 2005. "Draft Comprehensive Nutrient Management Planning Technical Guidance," *National Planning Procedures Handbook*, Subpart B, Part 600.51. /www.nrcs.usda.gov/programs/afo/cnmp_guide_600.51.html .

U.S. Department of Agriculture, Natural Resources Conservation Service. 1999. "Nutrient Management." NRCS Conservation Practice Standard 590.

U.S. Department of Agriculture, World Agricultural Outlook Board (WAOB). 2003. "USDA Agricultural Baseline Projections to 2010," Staff Report WAOB-2003-1, U.S. Department of Agriculture, Office of the Chief Economist, Washington, DC.

U.S. Environmental Protection Agency. 2000. *Air Pollution Regulatory Assessment for Animal Feeding Operations*. Office of Air Quality Planning and Standards, Research Triangle Park, NC.

U.S. Environmental Protection Agency. 2004. *National Emission Inventory-Ammonia Emissions from Animal Husbandry Operations*. Draft report www.epa.gov/ttnchie1/ap42/ch09/related/nh3inventorydraft_jan2004.pdf.

U.S. Environmental Protection Agency. 2003. "National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitations Guidelines and Standards for Concentrated Animal Feeding Operations: Final Rule," *Federal Register* 69(Feb.):7175-7274.

U.S. Environmental Protection Agency. 2001. *Emissions from Animal Feeding Operations*. Draft report, Emissions Standards Division, Office of Air Quality and Planning and Standards, Research Triangle Park, NC.

U.S. Environmental Protection Agency. 1996. *Preventing Pollution Through Regulations: The Source Reduction Review Project: An Assessment*. EPA-742-R-96-001. Office of Prevention, Pesticides, and Toxic Substances, Washington, DC.

U.S. Environmental Protection Agency. 2005. *Recommendations for Areas to be designated "Nonattainment" for the Fine Particle National Air Quality Standards*. Office of Air Quality Planning and Standards. http://www.epa.gov/pmdesignations/documents/120/factsheet.htm.

U.S. Environmental Protection Agency, Office of Water. 1998. *National Water Quality Inventory: 1996 Report to Congress*. EPA841-R-97-008. Washington, DC.

U.S. Environmental Protection Agency. 2002. *State Compendium: Programs and Regulatory Activities Related to Animal Feeding Operations*. Tetra Tech, Fairfax, VA.

Weinberg, M., and K.L. Kling, 1996. "Uncoordinated Agricultural and Environmental Policy Making: An Application to Irrigated Agriculture in the West," *American Journal of Agricultural Economics* 78 (1):66-78.

Williams, M. 2004. "Progress of Identifying and Installing Potential Environmentally Superior Technologies per Agreements Between the North Carolina Attorney General, Smithfield Foods, Premium Standard Farms, and Frontline Farmers." Presentation at public meeting, July 14. North Carolina State University, Raleigh, NC. www.cals.ncsu.edu/waste_mgt/smithfield_projects/smithfieldsite.htm

Wilson, J. 2004. "AQMD Moves to Corral Cow Pollution," *Los Angeles Times*, June 17.

Wolfsohl, K. 2003. "A Big Stink: Small communities fight big farms." *Progressive Farmer* (July):28-29.

Zilberman, D., A. Ogishi, and M. Metcalfe. 2001. "Innovative Policies for Addressing Livestock Waste Problems," *White Paper Summaries*, National Center for Manure and Animal Waste Management, pp. 51-53.

Appendix A
Modeling the Farm Level

Linear Program To Calculate Dual Values

Positive mathematical programming (PMP) is used to calibrate the farm-level model to base year data without having to add constraints that cannot be justified by economic theory. PMP takes advantage of the fact that it is easier to collect information about outputs and inputs at the farm level than information about costs. The observed output and input levels result from a complicated decision process based in part on a cost function that is known to the farmer but difficult or impossible to observe directly. Some costs—perhaps associated with the environment, risk, or technology—may be hidden to the researcher even when a detailed survey instrument is available. PMP incorporates information about unobservable costs by using a quadratic cost function that approximates the true underlying cost function.

There are three steps to the PMP calibration (Howitt, 1995). In the first step, a constrained linear programming model is used to derive dual values associated with the "calibration constraints." In the second step, the dual values are used to parameterize a calibrated quadratic objective function. In the third step, the calibrated model is used for economic analysis, by imposing environmental policy constraints.

In the first step, the linear objective is to maximize total net revenues:

$$(1) \qquad \max_{X1_{ir}} \sum_r \sum_i X1_{ir}(P_{ir} - C_{ir}),$$

where $X1_{ir}$ is the level of each output i in region r. The cost of producing each output is $C_{ir} = \sum_j Ai_{jr}W_{jr}$, where A_{ij}r is the amount of input j required to produce a unit of output and W_{jr} is the input price. The optimization is subject to $j \times r$ resource constraints:

$$(2) \qquad \sum_i A_{ijr}X_{ir} \le \sum_i A_{ijr}X0_{ir}, \forall\ j,r$$

where $X0_{ir}$ is the initial observed activity level, so that $\sum_i A_{ijr}X0_{ir}$ is the initial level of input j.

Inputs include land, capital, feeder pigs, feed corn, feed soy, and chemical nitrogen fertilizer. Outputs include hogs, corn, soybeans, and "other crops" (defined as the value of all other crops produced). All three crops can be produced under three fertilization regimes: (1) chemical fertilizer, (2) manure fertilizer applied to the surface, or (3) manure fertilizer injected into the soil. We use the extension of PMP developed by Röhm and Dabbert (2003) to allow for a greater policy response between crop fertilization regimes than between crops. To do so, we define three "variant activities" (chemical fertilizer, manure-spread, and manure-injected) for each crop and impose calibration

constraints that distinguish between variant activities and the total activity for each crop. In practice, this approach results in greater substitution between, for example, corn fertilized by spreading manure and corn fertilized by injecting manure, than between corn and "other crop" production.

The calibration constraints for each activity are:

$$(3) \qquad X1_{ir} \le X0_{ir}(1+\varepsilon_1), \forall\ i,r \quad dual: \hat{\lambda}_{i,r}$$

where ε_1 is a small perturbation (see Howitt, 1995). Following Röhm and Dabbert, we include three additional calibration constraints corresponding to each set of variant activities. For corn activities, the additional calibration constraint is:

$$(4) \qquad \sum_{i \in cv} x1_{ir} \le \sum_{i \in cv} x0_{ir}(1+\varepsilon_2), \forall\ i,r \quad dual: \hat{\lambda}_{corn,r}$$

where *cv* is the set of corn variant activities: *cv* = {corn - chemical fertilizer, corn - spread manure, corn - injected manure}. There are two additional constraints analogous to equation 4 corresponding to soybean variant activities, sv, and other crops variant activities, *ov*.

From the 1998 ARMS survey and other sources, we observe prices P_{ir}, W_{ir}, the output levels $X0_{ir}$, and most of the input-output coefficients A_{ijr} (see Appendix tables A1-A4 for details). It would be desirable to include manure nitrogen as an input. However, we do not observe manure application rates, only the amount of land on which manure is applied.

Estimate Calibrated Quadratic Cost Function

In step 2 we define quadratic total variable costs as $\frac{1}{2}\hat{Q}_{ir}X_{ir}^2$, where $\hat{Q}ir = (\hat{\lambda}_{ir} + \hat{\lambda}_{crop,r} + C_{ir}) / X0_{ir}$, $\hat{\lambda}_{ir}$, are the estimated dual values associated with equation 3 the calibration constraints, and $\hat{\lambda}_{crop,r}$, are the estimated dual values associated with equation 4 the calibration constraints for each crop activity: crop $\in \{corn, soybean, other\}$ Since equation 4 applies only to crops, $\hat{Q}_{ir} = (\hat{l}_{ir} + C_{ir}) / X0_{ir}$ for *i=hogs*. The objective in step 2 is to maximize total net revenues:

$$(5) \qquad \max_{X2_{ir}} \sum_r \sum_i P_{ir}X2_{ir} - \frac{1}{2}\hat{Q}_{ir}X2_{ir}^2$$

subject to the resource constraints:

$$(6) \qquad \sum_i A_{ijr}X2_{ir} \le \sum_i A_{ijr}X0_{ir}, \forall\ j,r$$

Solution of the non-linear optimization problem defined by equations 5 and 6 results in the initial output levels $X0_{ir}$.

Estimate Activity Levels for Policy Scenarios Using Calibrated Cost Function

Having characterized the farmer's non-linear optimization problem that results in the observed initial values, the final step is to impose policy constraints and compare solutions to the initial values. The policies we consider are the CAFO nitrogen application constraint and a hypothetical ammonia emission constraint. Farms can respond to policy constraints by adjusting input and output levels. Pit storage operations can vary the amount of land on which they inject versus surface-apply manure slurry in order to alter the ammonia emitted to the air and the nutrients available to plants. Lagoon operations can cover their lagoons to reduce air ammonia emissions. EQIP payments can enter the farmer's decision problem by reducing costs of abiding by the CAFO rules.[1]

[1]We assume for this analysis that CAFOs do not receive EQIP payments.

First we incorporate into the optimization a manure transportation cost that depends on how the manure is stored and handled. Prior to implementation of the CAFO manure application rules, farmers had little incentive to transport manure off-farm, and few did. According to the 1998 survey, fewer than 2 percent of farms transported manure off-farm. The CAFO manure application rules require farmers to apply manure at a rate that plants can absorb. In response to the CAFO rules, farmers without adequate cropland will need to transport some manure off-farm (Ribaudo et al., 2003).

For the policy analysis, the farmer's objective is:

$$(7)\quad \max_{x3_{ir}\,\mathrm{cov}_r} \sum_r \sum_i P3_{ir} X3_{ir} - \frac{1}{2}\hat{Q}_{ir} X3_{ir}^2 - (1 - EQIP) MTC_r - COV_r \times \kappa \times X3_{hogs,r}$$

where MTC_r is the cost of transporting manure off-farm, which is a function of technology choices that affect that nutrient availability to the crop—and consequently the amount of land on which the manure must be spread. Farms eligible for EQIP payments receive a share of the manure transportation costs and receive a per acre subsidy for land on which they apply manure at the agronomic rate. *EQIP* is defined as the share of manure transportation costs financed by EQIP. The per-acre EQIP subsidy is expressed as a per-unit subsidy and appears in the optimization as a higher price *P3*. The decision by lagoon farms to cover their lagoon is reflected in the binary choice variable COV_r (1 if covered, 0 otherwise). The cost of covering a lagoon is simply a cost κ per unit of hog output.

Manure transportation costs depend on the nutrient content of the manure (how it was stored), how it is applied (injected or spread), the availability of land on which to apply the manure, and what crops it is applied to. Estimates for the transportation costs per hundredweight of hog are based on a transportation cost model proposed by Fleming et al. (1998) (see Appendix table A-5 for details). Manure transportation costs equal the quantity of hogs used to produce manure transported off-farm, $hogs\_off_r$, multiplied by the manure transportation costs per hundredweight of hog. Manure transportation costs are distinguished for lagoon operations, which may or may not cover their lagoons:

(8) $$MTC_r = hogs\_off_r (COV_r * T_{cover,r} + (1 - COV_r) * T_{uncov,r}),$$

and for pit storage operations which may inject (versus surface-apply) manure into some portion of the land on which manure is applied:

(9) $$MTC_r = hogs\_off_r (INJ_r * T_{inject,r} + (1 - INJ_r) * T_{surf,r}),$$

where transportation costs per hundredweight of hog produced, $T_{e.r}$, depend on the manure storage and handling technology $e \in$ {covered, uncovered, surface-applied, injected}.

For lagoon operations, COV_r is a binary choice variable. For pit storage operations, INJ_r is the share of manure-applied cropland on which manure is injected:

(10) $$INJ_r = \sum_{i \in mi} A3_{i,land,r} X3_{i,r} \Big/ \sum_{i \in m} A3_{i,land,r} X3_{ir},$$

where m is the set of manure crop activities (corn, soybean and other crops, either spread or injected) and mi is the set of all cropping activities on which manure is injected.

The quantity of hogs that produce manure applied off-farm equals the total hogs produced minus the number of hogs required to produce the nitrogen from manure applied on-farm:

(11) $$hogs\_off_r = X3_{hogs,r} - \left(manrate_r \sum_{i \in m} X3_{ir} A_{i,fertN,r} \left(\frac{COV_r}{NH_{cov}} + \frac{1 - COV_r}{NH_{uncov}}\right)\right).$$

The number of hogs required to produce the nitrogen from manure applied on-farm equals the manure nitrogen used on-farm divided by the manure nitrogen available to crops per hundredweight of hogs, NH_e (which depends on the cover technology). The manure nitrogen used on-farm equals the pounds of manure nitrogen applied on-farm if it were applied at an agronomic rate $\sum_{i,m} X3_{ir} A_{i,fertN,r}$ (the rate at which chemical fertilizers are applied) multiplied by the factor $manrate_r$. From the survey we observe the average rate at which manure is applied to receiving land, but we do not know the rate applied to individual crops. Consequently, we assume that farmers apply manure at the same observed factor, $manrate_r$, above the agronomic rate for all crops.

There is an analogous equation for pit storage operations.

(12) $$hogs\_off_r = X3_{hogs,r} - \left(manrate_r \sum_{i \in m} X3_{ir} A_{i,fertN,r} \left(\frac{INJ_r}{NH_{inject}} + \frac{1 - INJ_r}{NH_{surf}}\right)\right)$$

Policy 1: Nitrogen application constraint. CAFO rules require a nutrient management plan that requires growers to apply manure nitrogen at or below the rate at which plants can absorb (the agronomic rate). This policy is imposed by constraining $manrate_r$ to be less than or equal to 1.

Policy 2: EQIP payments. The effect of EQIP payments can be modeled by adjusting the share of off-farm manure transportation costs borne by EQIP and by adjusting the per-unit subsidy for crops produced in accordance with CAFO application guidelines.

Policy 3: Ammonia nitrogen emission constraint. Hypothetical ammonia emissions regulations are modeled by imposing a limit, *Amlimit*, on the quantity of nitrogen from ammonia per-unit of hog produced. Nitrogen emissions per unit of hog produced, AmN_e, depend on manure storage and handling technologies. The ammonia emission constraint is:

$$(13) \qquad COV_r * AmN_{Cover} + (1 - COV_r) * AmN_{Uncover} \leq Amlimit$$

for lagoon operations and:

$$(14) \qquad INJ_r * AmN_{Inject} + (1 - INJ_r) * AmN_{Surface} \leq Amlimit$$

for pit storage operations. Note that the ammonia emission constraint does not depend on the quantity of manure transported off-farm. The application method (spread/inject) is assumed to be the same on-farm and off-farm.

Appendix table A-1

Initial production, $X0_{ir}$

Outputs	Units	Value	Source
Corn fertilizer	100 bushels	*	USDA ARMS Survey 1998
Corn manure surface	100 bushels	*	USDA ARMS Survey 1998
Corn manure inject	100 bushels	*	USDA ARMS Survey 1998
Soy fertilizer	100 bushels	*	USDA ARMS Survey 1998
Soy manure surface	100 bushels	*	USDA ARMS Survey 1998
Soy manure inject	100 bushels	*	USDA ARMS Survey 1998
Other fertilizer	$ (value of production)	*	USDA ARMS Survey 1998
Other manure surface	$ (value of production)	*	USDA ARMS Survey 1998
Other manure inject	$ (value of production)	*	USDA ARMS Survey 1998
Hogs	cwt	*	USDA ARMS Survey 1998

* Estimated mean value varies by region and size of operation.

Appendix table A-2

Output price, P_{ir}

Outputs	Units	Value	Source
Corn (all)	$/100 bushels	284	NASS - (average price 1997-99)
Soy (all)	$/100 bushels	700	NASS - (average price 1997-99)
Other (all)	-	1	-
Hogs	$/cwt	46.92	NASS -(average price 1997-99)

Appendix table A-3

Input price, W_{jr}

Inputs	Units	Value	Source
Land	$/acre	68.2	NASS Agricultural Land Values Final Estimates 1998, Statistical Bulletin Number 957 (national average) (use 7% of land value as rental rate)
Capital	$	1	(by definition)
Feeder pigs	$/cwt	80.25	NASS - (average price 1997-99)
Feed corn	$/100 bushels	284	NASS - (average price 1997-99)
Feed soy	$/100 bushels	700	NASS - (average price 1997-99)
Fertilizer - N	$/lb.	0.185	Ribaudo et al., 2003

Appendix table A-4

Resource use, A_{ijr}

Input-output	Units	Value	Source
Land-corn	acres/100 bushels	*	USDA ARMS Survey 1998
Land-soy	acres/100 bushels	*	USDA ARMS Survey 1998
Land-other	acres/$	*	USDA ARMS Survey 1998
Capital-corn	$/100 bushels	49.3	Foreman, 2001
Capital-soy	$/100 bushels	127	Foreman, and Livezey, 2002
Capital-other	Share of value	0.17	Same share as corn
Capital-hogs	$/CWT.	*	USDA ARMS Survey 1998
Feed corn-hogs	100 bushels /CWT.	*	USDA ARMS Survey 1998
Feed soy-hogs	100 bushels /CWT.	*	USDA ARMS Survey 1998
Feeder pigs-hogs	CWT/CWT	*	USDA ARMS Survey 1998
Fertilizer-N-corn	lbs./ 100 bushels	80.0	Kellogg et al., 2000.
Fertilizer-N-soy	lbs./ 100 bushels	236.7	Kellogg et al., 2000.
Fertilizer-N-other	lbs./ $	0.282	Same rate as corn

* Estimated mean value varies by region and size of operation.

Appendix table A5

Manure off-farm transportation net costs by region and manure storage and handling technology, T_{re}

Manure storage /handling technology	Eastern Cornbelt	Western Cornbelt	Mid-Atlantic	South and West
		Dollars/cwt of hogs		
Lagoon				
Uncover	1.33	1.36	2.01	2.15
Cover	5.32	5.38	6.57	6.83
Pit				
Surface	1.20	1.25	2.29	2.53
Inject	1.61	1.66	2.82	3.08

Source: Estimated. Base manure handling costs from Fleming et al. 1998. Unit mile cost from USDA, NRCS, 2003 C*osts Associated with Development and Implementation of Comprehensive Nutrient Management Plans*. Lagoon cover costs from Massey, et al. *Agronomic and economic impacts of lagoon based swine operations complying with the proposed EPA zero discharge rule*.

Appendix table A-6

Nitrogen available to crops and nitrogen ammonia emissions by manure storage and handling technology

Manure storage/ handling techology	Soil nitrogen available to plants, $Npercwt_e$	Air ammonia emissions from house and storage	Air ammonia emissions from land application	Total air ammonia emissions, AmN_e
		Lbs/cwt		
Lagoon				
Uncover	1.53	7.21	0.42	7.62
Cover	5.07	2.69	1.39	4.08
Pit				
Surface	4.83	3.00	1.32	4.32
Inject	5.95	3.00	0.20	3.20

Source: US EPA *National Emission Inventory--Ammonia Emission from Animal Husbandry Operations*, 2004.

Appendix table A-7

EQIP payments per unit of output by crop and region

Crop	Uni	Eastern Cornbelt	Western Cornbelt	Mid-Atlantic	South and West
Corn	$/100 bu	8.87	8.28	53.00	49.70
Soybean	$/100 bu	27.44	24.44	85.62	86.92
Other	Share of value	0.05	0.11	0.13	0.17

Source: Estimated using EQIP program data, Farm Service Agency, USDA.

Appendix B
USMP Model

The USMP model accounts for production of major crops (corn, soybeans, sorghum, oats, barley, wheat, cotton, rice, hay, and silage) and confined animals (beef, dairy, swine, and poultry), comprising approximately 75 percent of crop production and more than 90 percent of livestock and poultry production in the United States. USMP is a comparative-static, spatial, and market equilibrium model that incorporates agricultural commodity, supply, demand, environmental impacts, and policy measures. The model permits agricultural sectors to adjust to nutrient standards for air and water by substituting across space, production activities, and cropping and tillage practices with varying input requirements.

Crop and animal production choices are linked to edge-of-field environmental variables using the Environmental Policy Integrated Climate Model (EPIC), which uses a daily time step to simulate weather, hydrology, soil temperature, erosion-sedimentation, nutrient cycling, tillage, crop management and growth, and pesticide movements to the field's edge (Mitchell et al., 1998). The transport of nutrients, pesticides, and sediment across the landscape is calibrated to USGS estimates of regional pollutant loads (Smith, Schwartz, and Alexander, 1997).

Estimates of CAFO and AFO spreading practices on hog operations taken from Ribaudo, Gollehon, and Agapoff (2003) allow us to account for prior land application of manure in the simulations. Accordingly, CAFOs are assumed to spread manure on the nearest 155 acres and the smaller AFOs are assumed to spread manure on the nearest 90 acres. While these numbers are not necessarily representative of the range of production conditions across the Nation, we feel that these are reasonable for initial estimates of the environmental effects of excess manure application at the Farm Production Region scale. The above levels provide a lower bound on the estimated costs from meeting nutrient standards since many livestock facilities have little or no land on which to spread manure (Kaplan, Johansson, and Peters, 2004). Given the acres currently receiving manure nutrients, we calculate the quantity of manure nutrients in excess of the crop requirements on those acres. These excess nutrients are subject to leaching, runoff, and volatilization, similar to commercial fertilizers.

Manure transportation costs are determined using the Fleming et al. (1998) formulation in conjunction with regional and species-specific cost coefficients from the literature (Borton et al., 1995; Pease et al., 2001). The costs to develop a nutrient management plan, and to test periodically for manure nutrient composition and soil nutrient content are also included using USDA estimates (USDA, NRCS, 2003). Current market values for commercial nitrogen and phosphorus are used to calculate the savings from substituting manure nutrients for commercial fertilizers. The costs of using manure nutrients (testing, transporting, and applying) as fertilizers are covered by the livestock sectors. The savings in forgone commercial nutrient purchases by cropping enterprises are included in the returns to crop production.

Appendix C
Modeling Manure Management in the Chesapeake Bay Watershed

Our model is designed to minimize the total regional costs of manure management, transport, and application for use on agricultural lands in the Chesapeake Bay Watershed (CBW), given the existing structure and scale of the animal industry, and the current manure storage technology. The regional specification captures the element of competition for a limited land base by modeling access to spreadable land, requiring adequate area for land application of manure produced, and computing the associated hauling costs. Technologies that limit ammonia-N emissions alter regional competition by changing the costs and manure nutrient content across manure systems and animal types. Explicit modeling of competition for land on which to spread manure is a central feature of the regional model that is not captured in existing farm-level models.

The model was developed to: (1) provide a mechanism to track manure and related nutrient flows within the basin, from farm to site application and use, (2) compute the regional costs of land-applying manure, given the manure movement dictated by the nutrient uptake, and (3) provide a framework for evaluating alternative technologies that limit ammonia-N emissions, given land-application rates to meet a water-quality standard.

The county serves as the primary modeling unit for the regional model. The county-level specification provides consistency with Census of Agriculture data and other data, while permitting differentiation of institutions and regulatory conditions across county and State political boundaries within the watershed. County and local data are used to capture heterogeneity in technologies and land-quality conditions across the region, though our model may not represent the conditions on any particular farm.

The model is designed to minimize the regional cost of applied manure, subject to total manure produced and the land available for manure applications. Total regional costs of applied manure include transporting the manure, applying it to the land, implementing a nutrient management plan, implementing ammonia-reducing technology, based on 1997 production numbers. The model allocates manure flows between source and destination counties in the watershed to minimize the costs of hauling and applying manure, selected treatment costs, and costs of nutrient management plan development, given constraints on ammonia emissions and nutrient application rates. For a more detailed description of the water-based model, see Appendix 4-A in Ribaudo et al. (2003) or the technical documentation in Aillery and Gollehon (2004).

Including Air Emissions in the Modeling Framework

The regional modeling framework developed for manure management and water-quality policy analysis was extended to consider air emission measures. Air emissions were incorporated into the modeling framework by (1) adjusting the manure-nutrient content, (2) including treatment costs, and (3) calculating levels of ammonia emissions.

Changes in manure N content were calculated based on manure-nutrient adjustments by species, type of manure-handling system, and ammonia reduction measures. Changes in the N content of manure impact both the level of manure-N excess that must be transferred off confined animal farms and the rate of applied manure under an N-standard. Thus, implementation of policies to address air emissions issues will affect costs to the animal sector of meeting water-quality regulations.

The costs of emission control policies reflect the individual treatment costs for the three ammonia-reducing technologies considered-alum, incorporation into the soil, and lagoon covers-weighted by the share of acreage by species and manure system type, and use shares by treatment. Emissions were calculated by treatment scenario at both the storage facility (pre-haul) and field levels, for both regulated and non-regulated farms. Facility emissions are exogenous to the model, based on total manure production allocated across manure storage systems. Field emissions on regulated farms are calculated based on endogenously derived values for total land-applied manure (net industrial uses and that exceeding land capacity) and rate of applied manure in receiving counties. Field emissions on non-regulated farms were calculated from that portion of manure not explicitly addressed in the model optimization.

Model Data

Three primary data sources form the basis of the CBW model data set: the 1997 Census of Agriculture and the National Land Cover Dataset from USGS form the basic model structure and the National Emission Inventory from EPA is the source of the ammonia-N emission values. Farm-level Census data were used to generate county-level measures of animal operations and animal-units, total manure production, surplus recoverable manure, manure-nutrient content, and potential assimilative capacity of the land for applied manure nutrients. The National Land Cover Dataset was used to define the spatial pattern of land available for manure spreading and to simulate the spatial distribution of livestock operations (Ribaudo et al., 2003).

Model data on ammonia-N emissions were developed from system loss values presented in EPA's National Emission Inventory (NEI). For each manure-handling system, ammonia-N loss and retention are reported for animal confinement area, manure storage area, and land application area, based on a mass-balance approach. Starting from an excreted level of nitrogen in the manure, each unit of nitrogen will be either lost to the atmosphere or applied to the land for crop use.[1] Ammonia losses were aggregated for CBW model use based on losses from animal confinement

[1] This assumption ignores direct discharge to water and accidental spills, which are believed to be non-significant.

and manure storage areas (termed "facility" losses) and subsequent losses during field application (termed "field losses"). The coefficients for ammonia-N losses were then derived at the facility and field levels, with losses expressed as a share of manure nitrogen available to the crop (and not as a share of excreted levels).

The shares of ammonia-N losses were then mapped to recoverable manure nitrogen available for plant use from Kellogg et al., (2000) to estimate the ammonia-N losses at each stage of the manure handling system.[2] Excreted manure nitrogen levels were derived from this mapping procedure for 1997 animal stocks in the CBW. For scenarios evaluating alternative technologies to reduce ammonia-N emissions, the process operated in reverse. From the calculated excreted nitrogen quantities, revised facility and field losses were subtracted to estimate a revised level of nitrogen available for crop use relative to the values in Kellogg et al., which constitute the core of the model data.

[2] The values in Kellogg et al. were derived from the Census of Agriculture and are the basis for manure estimates in the model.

Production Cost Data

The NRCS Cost and Capabilities Assessment was the primary source of cost data for nutrient management plan components (USDA, NRCS, 2003). Manure hauling and application charges were based on published literature (Pease et. al., 2001; Fleming et. al., 1998), supplemented with data from the NRCS Cost and Capabilities Assessment. Transportation charges reflect a base rate per wet ton (loading/unloading and application) and hauling cost per ton-mile, by hauling mode and distance interval. Application costs are incorporated within hauling charges for lagoon and slurry systems; an additional charge was included for dry manure application. Per-acre costs of manure incorporation/injection were based on an Iowa State Farm Survey (2001). The baseline values assume that 40 percent of cropland acres currently incorporate manure, derived from information obtained in the ARMS hog and dairy surveys.

Chemical fertilizer costs were based on reported 1997 NASS prices, based on representative fertilizer products for the northeast States (USDA, NASS 2001). Cost-savings for reduced field application costs (under an N-standard) of $5 per acre were from Fleming, 1998. Annual costs associated with improved manure management practices to reduce ammonia-N emissions were: alum–$26.77 per poultry animal unit (AU) plus the additional hauling costs from adding an additional 10 percent to the weight of the litter; lagoon covers–$0.72 per AU for biofilter covers and $5.76 per AU for impervious covers; and incorporation/injection–$6.00 per acre. For a detailed description of the cost data see Appendix 4-A in Ribaudo et al. (2003) or the technical documentation in Aillery and Gollehon (2004).

For these systems, the share of N lost in each stage of the manure system was derived using a mass-balance approach based on manure management systems described by EPA (detailed in Chapter 2). Implementation of manure management practices to reduce ammonia-N emissions affects air emissions at different stages in the system. Alum affects the emissions from confinement structures while lagoon covers affect emissions from manure storage systems. These practices, which reduce ammonia emissions at the facility level prior to field application, actually increase volatilization during

land application with surface application methods due to the manure's higher nitrogen content and expanded acreage requirements.

Incorporation/injection is a manure management practice that reduces ammonia emissions at the field level only. Field treatments can be used in combination with facility reduction practices or alone. In general, reducing the losses of nitrogen to the atmosphere increases the nitrogen level of manure available for crop use, and net reductions in emissions need to consider interactive effects from a broader systems perspective. Appendix table D-3 presents the model's assumptions regarding the changes in ammonia emissions and changes in the nitrogen level of the manure available for crop use. Appendix table D-4 presents examples of derived facility and field emissions using the coefficients in Appendix table D-3 for the major CBW manure systems in Appendix table D-2.

Appendix D
Data and Computation Tables

Appendix table D1

Base representative systems and ammonia-N emissions for use in the CBW model, by animal type and manure system type

	Representative system		
Animal type	Lagoon	Slurry	Dry/litter
Dairy	Flush barn, surface applied	Pond storage, surface applied	Dry, solids system, surface applied
Feedlot beef	Flush barn, surface applied	Pond storage, surface applied	Dry, solids system, surface applied
Swine	Daily flush, surface irrigate	Deep pit, surface applied	Minor technology (used values for dry feedlot beef system)
Poultry	Not considered	Not considered	Broiler house, surface-applied litter
	Facility emissions coefficients (share of N available to the crop)		
Dairy	4.242	0.637	0.309
Feedlot beef	4.242	0.637	0.309
Swine	4.725	0.621	0.309
Poultry	n/a	n/a	0.417
	Field emissions coefficients (share of N available to the crop)		
Dairy	0.282	0.209	0.0205
Feedlot beef	0.282	0.209	0.0205
Swine	0.274	0.274	0.0205
Poultry	n/a	n/a	0.333

Appendix table D-2

Manure ammonia-N production and losses for selected animal types and manure management systems for the CBW, baseline scenario

Animal type	Example manure system	Excreted nitrogen	Facility loss as ammonia-N	Field loss as ammonia-N	Nitrogen available for plant use
	Pounds per AU				
Dairy	Dry/Litter	99.2	20.25	13.43	65.5
Feedlot beef	Slurry	85.8	29.61	9.72	46.5
Swine	Lagoon	248.5	195.74	11.35	41.4
Poultry	Dry/Litter	421.8	100.5	80.26	241.0

Appendix table D-3

Ammonia-N emission and manure nitrogen changes with evaluated manure system improvements for use in the CBW model, by animal type and manure system type

Animal type	Item	Lagoon	Slurry	Dry/litter
Manure Management System Change: Alum to poultry litter (coefficients expressed as a share of N available to the crop)				
Poultry	Facility emissions	n/a	n/a	-0.679
Poultry	Field emissions	n/a	n/a	0.213
Poultry	Applied manure nitrogen	n/a	n/a	0.2125
Manure Management System Change: Biofilter Lagoon Cover (coefficients expressed as a share of N available to the crop)				
Dairy, feedlot beef, and swine	Facility emissions	-0.264	n/a	n/a
Dairy, feedlot beef, and swine	Field emissions	0.979	n/a	n/a
Dairy, feedlot beef, and swine	Applied manure nitrogen	0.979	n/a	n/a
Manure Management System Change: Impervious Lagoon Cover (coefficients expressed as a share of N available to the crop)				
Dairy, feedlot beef, and swine	Facility emissions	-0.627	n/a	n/a
Dairy, feedlot beef, and swine	Field emissions	2.326	n/a	n/a
Dairy, feedlot beef, and swine	Applied manure nitrogen	2.326	n/a	n/a
Manure Management System Change: Incorporate/Inject Manure (coefficients expressed as a share of N available to the crop)				
Dairy and feedlot beef	Facility emissions	0.0	0.0	0.0
Dairy and feedlot beef	Field emissions	-0.75	-.80	-0.18
Dairy and feedlot beef	Applied manure nitrogen	0.212	0.233	0.06
Swine	Facility emissions	0.0	0.0	0.0
Swine	Field emissions	n/a	n/a	-0.18
Swine	Applied manure nitrogen	n/a	n/a	0.06

Appendix table D-4

Manure ammonia-N production and losses for selected animal types and manure management systems for the CBW, Ammonia-N reduction scenarios

Animal type	Example manure system	Scenario	Excreted nitrogen	Facility loss as ammonia-N	Field loss as ammonia-N	Nitrogen available for plant use
	Pounds per AU					
Poultry	Dry/litter	Alum	421.8	32.26	97.27	292.2
Swine	Lagoon	Impervious cover	248.5	73.01	37.74	152.2
Dairy	Dry/litter	Incorporation	99.2	20.25	11.02	68.0

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Cattle & Beef – Sector at a Glance

Updated: 5/22/2025 **Contact:** Russell Knight

In this section

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Cattle production is the most important U.S. agricultural industry, consistently accounting for the largest share of total cash receipts for agricultural commodities. In 2024, U.S. cattle production represented about 22 percent of the $515 billion in total cash receipts for agricultural commodities. With rich agricultural land resources, the United States has developed a beef industry that is largely separate from its dairy sector. The U.S. beef industry is unique when compared with countries (like India) that produce beef from water buffalo, which are used as dual-purpose animals. In addition to having the world's largest fed-cattle industry, the United States is also the world's largest total consumer of beef—primarily high-value, grain-fed beef. The U.S. beef cattle industry is often divided into two production sectors: cow-calf producers and cattle feeding.

U.S. Cattle Production

Cattle Cycle

The cattle cycle describes a period of time (8–12 years) when the national cattle herd—the total number of all cattle and calves—begins its first year of growth after a period of decline. Then, the herd size will peak after several years of growth, or expansion, and then it will decline for several years before it starts to expand again, starting a new cycle. It is influenced by the combined effects of: cattle prices and input costs that drive cow-calf producer profitability; the gestation period for cattle; the time needed for raising calves to market weight; and climate conditions. Specifically, if cattle prices and producer revenues are expected to rise, producers may expand their herds; if revenues are expected to decline substantially, producers might reduce their herds by culling older cows and keeping fewer heifers to replace or add to older cows in their herd. Also, cow-calf producers' response to profit fluctuations may appear delayed because of the lengthy gestation period for cattle, relative to hogs and poultry. The total number of beef cattle in the United States is highly dependent on the stage in the cattle cycle.

Adverse climate, like persistent dry conditions leading to drought, can diminish pasture conditions and reduce harvested feed supplies, which can alter a cycle's direction and duration. For example, the last full cattle cycle began in 2004 with 94.4 million head of cattle and calves, including both beef and dairy cattle. The herd expanded for 3 years to 96.6 million head, until increasing feed and energy prices caused producers to reduce their herds. Then, drought conditions decreased pasture and forage availability, forcing producers to further cull cows and limit heifer retention at a more rapid pace, increasing contraction from 2011 through 2014.

By late 2013 and early 2014, grazing conditions improved and feed prices decreased. However, as each year's calf crop shrank (as the number of beef cows declined), progressively fewer feeder calves were placed in feedlots and, subsequently, fed to a particular weight and marketed for slaughter. These combined effects increased feeder calf prices, which helped to improve cow-calf profitability. A 7-year liquidation of the national cattle herd ended January 1, 2014, at 88.2 million cattle and calves, which was the smallest herd size since 1952. Since then, the cattle herd has grown to a peak of 94.7 million head in 2019. As of January 1, 2025, the herd has decreased by 8 percent since the peak to 86.7 million cattle head. The USDA, National Agricultural Statistics Service (NASS) provides information on cattle inventory in its semi-annual Cattle reports.

Figure 1. Cattle and cow inventories, 1970–2025

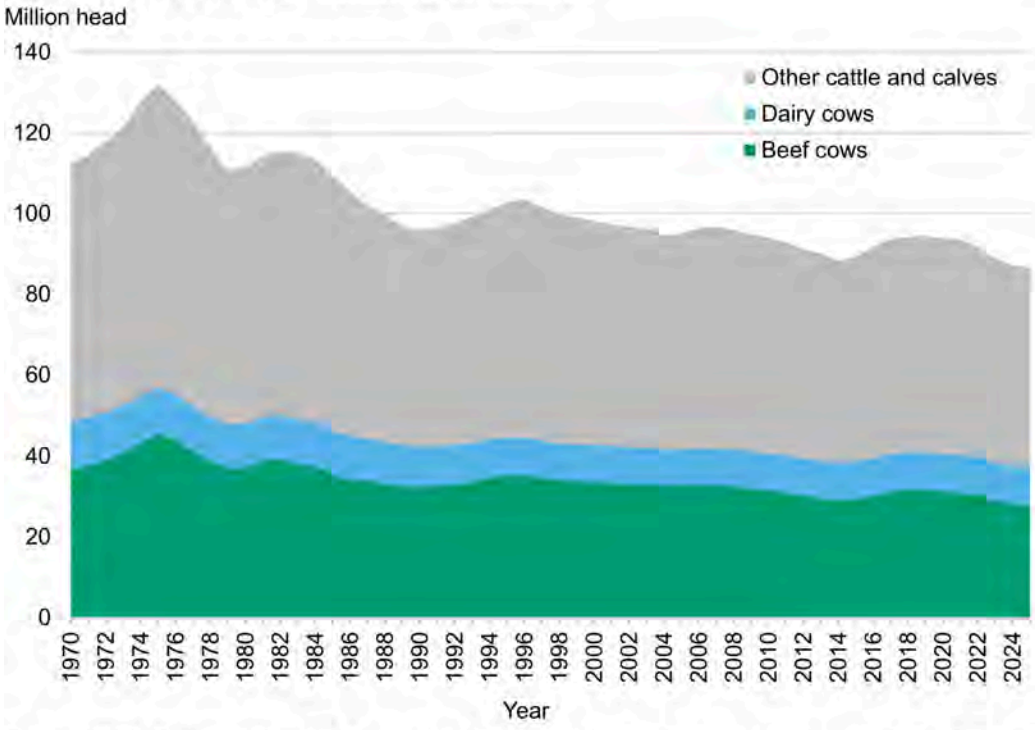

Source: USDA, Economic Research Service calculations using USDA, National Agricultural Statistics Service, Cattle report.

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Cow-Calf Operations

Cow-calf operations mainly maintain a herd of beef cows for raising calves. Most calves are born in spring and weaned at 3 to 7 months. Following the weaning stage, calves can move through the value chain in several different ways. Some of the female calves (heifers) and male calves (bulls) may be retained in the herd or sold to another producer. If additional pasture forage is available at weaning, then some calves may be retained for further grazing and growth until the following spring when the calves would be sold. Throughout the United States, cow-calf operations are located on land that is not typically suited or needed for crop production. These operations depend on range and pasture forage conditions, which in turn depend on the area's variations of average rainfall and temperature. Beef cows graze on forage from grasslands to maintain themselves and raise a calf with very little, if any, grain input. The cow is maintained on pasture year-round, as is the calf until the calf is weaned. Based on USDA, NASS 2022 Census of Agriculture data, the average beef cow herd is about 47 head. Operations with 50 or fewer head likely coexist alongside other income streams, or the operations provide supplemental income to off-farm employment. Operations with 100 or more beef cows compose 10.5 percent of all beef operations and 60.5 percent of the beef cow inventory.

Cattle Feeding

When calves are weaned, producers must decide if they should retain some heifers and bull calves to replace older cows and bulls or to expand their herds. The remaining bulls are castrated to become steers, and together with the remaining heifers not kept in the herd for breeding, are sold into the feeding system for slaughter. This marks the beginning phase of beef production. There are different ways for these new steers and heifers designated for slaughter to grow to market weight. After being weaned, the calves may enter a stocker program, where the calves will graze on grass for 3 to 4 months before being placed in a feedlot. Another option is to move calves into a 30- to 60-day preconditioning program. Within this program, the calves go through an animal health protocol (for deworming, dehorning, and vaccinating) so calves can then be started on feed to ensure they are healthy in the next stage of the value chain. Another option is for the calves to be backgrounded for 90–120 days, placed in pens or lots—and fed dry forage, silage, and grain before entering a feedlot.

A feedlot provides a confined area for feeding steers and heifers on a ration of grain, silage, hay, and/or protein supplement to produce a carcass that will meet the USDA quality grade of Select or better for the slaughter market. The USDA, Agricultural Marketing Service (AMS) grades beef as whole carcasses in two ways: (1) quality grades for tenderness, juiciness, and flavor; and (2) yield grades for denoting the amount of usable lean meat on the carcass. The quality grades are Prime, Choice, and Select. The length of time a calf spends in a feedlot can range from 90 to 300 days depending on the weight and age of the calf at the time of placement, genetics, weather, feed rations, and desired carcass grade. Average gain is from 2.5–4 pounds per day on about 6 pounds of dry-matter feed per 1 pound of gain. Although most of a calf's nutrients come from grass until the calf is weaned, feedlot rations are generally 70–90 percent grain and protein concentrates.

Cattle feeding operations are concentrated in the Great Plains region but are also located in parts of the Corn Belt, Southwest, and Pacific Northwest regions. Feedlots with sales of 1,000-head or fewer comprise most of U.S. feedlot operations, but these smaller feedlots manage a relatively small share of total fed cattle marketed for slaughter. Further, based on the 2022 Agricultural Census, feedlots with sales of 1,000 or more cattle on feed represent 7 percent of total feedlots, but they market about 88 percent of fed cattle. Feedlots with sales of 5,000 or more cattle on feed market around 77 percent of fed cattle. The industry continues to shift toward a small number of very large, specialized feedlots that are focused on raising high-quality cattle for a particular market—such as markets requiring cattle that are not treated with hormones and not fed beta agonists. USDA, NASS provides monthly Cattle on Feed reports.

Policy

Federal Government assistance provided to the cattle sector is limited to emergency measures approved for a specific scope and time period. Federal assistance addresses the needs of producers suffering losses due to: drought, hot weather, disease, insect infestation, flood, fire, hurricane, earthquake, severe storms, extreme cold, or other natural disasters. See the Disaster Assistance Programs section of USDA's Farm Service Agency (FSA) website for information on current programs.

The sector trends toward fewer and large enterprises, which brings environmental issues to the forefront of public policy regarding the U.S. livestock industry. As animal density (i.e., the number of animals per unit of land area) increases, so do concerns about air and water quality, the occupational health of livestock workers, and waste management. The U.S. Environmental Protection Agency reports the environmental requirements for the production of livestock in Animal Feeding Operations .

Any product that is used as an animal-feed ingredient is regulated by the U.S. Food and Drug Administration (FDA) . The FDA Center for Veterinary Medicine distributes uniform feed-ingredient definitions and feed-labeling standards to ensure the safe use of animal foods.

Cattle are also affected by other government policies and programs related to animal health, food safety, and mandatory price reporting.

U.S. Beef and Cattle Trade

- Beef Exports
- Beef Imports
- Live Cattle Trade

Trade

Based on estimates from the USDA, Foreign Agricultural Service's Production, Supply and Distribution data, the United States continues to be the world's largest beef producer and consumer, by total volume, since the series began in 1960. To support consumer demand, the United States is the second largest importer, a majority of which is destined for blending into ground beef. Also, overseas demand for high quality beef has allowed the United States to sit among the top four exporting countries since the series began.

The year-to-year variation in U.S. beef imports and exports is correlated with the U.S. cattle cycle. When the size of the cattle herd begins to contract, more domestic cows are slaughtered, adding more lean trimmings (90 percent lean) available for grinding into ground beef. Further, there will

likely be more heifers added to feedlots adding fattier trimmings (50 percent lean) need to blend with leaner trimmings from cows. However, as the herd contraction slows down and begins the process of expanding, fewer cows and heifers are destined for slaughter. This has the effect of growing demand for imported lean beef trimmings. For additional information on the dynamics of imported beef products and how they change over time, see the special article, “An Assessment of U.S. Beef Imports” in Livestock, Dairy, and Poultry Outlook: July 2023.

The amount of U.S. beef exported is mainly affected by volume of domestic beef production, which reflects the current stage in the cattle cycle. Similarly, beef traded in the global marketplace responds to the volume of beef produced around the world. See UDSA, ERS Sector at a Glance web page for information on the cattle cycle.

Figure 2. U.S. beef trade, 1990–2024



Source: USDA, Economic Research Service calculations using data from U.S. Department of Commerce, Bureau of the Census

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Bovine Spongiform Encephalopathy Effects on U.S. Cattle and Beef Trade

In May 2003, the United States banned Canadian cattle imports following Canada's first case of bovine spongiform encephalopathy (BSE). In July 2005, U.S. imports of Canadian cattle resumed for cattle younger than 30 months old (for immediate slaughter or for finishing in a U.S. feedlot). In

November 2007, USDA expanded cattle imports to include live cattle of all ages from Canada and any other country that was recognized as presenting a minimal risk of introducing BSE into the United States. Currently, Canada is the only minimal-risk country designated by the United States. All animals born after Canada's 1997 feed ban are eligible to be imported into the United States. For the latest requirements for exporting U.S. live animals and animal products by country destination, visit USDA's Animal and Plant Health Inspection Service (APHIS) animal and animal product export information. Also, for the latest information about importing live animals into the United States, visit animal and animal product import information.

Simultaneously, in December 2003, the discovery of the first U.S. BSE case in a dairy cow imported from Canada led many U.S. trading partners to restrict some U.S. beef products or to completely ban all U.S. beef and cattle. Two more cases of BSE in the United States were subsequently reported—in Texas (June 2005) and in Alabama (March 2006). The reported BSE cases significantly altered U.S. beef export patterns in 2004. Japan, South Korea, China, and various other countries ceased importing U.S. beef and beef products for several years. Although Mexico and Canada initially closed their borders to U.S. beef imports, they reopened trade within a matter of months.

In 2011, U.S. beef exports reached 2.8 billion pounds in carcass-weight equivalents, which surpassed 2003's historic record of 2.5 billion pounds. In 2013, the World Organization for Animal Health upgraded the United States' BSE status to "negligible risk"—the highest status available—based on the U.S. history with the disease, the implementation and enforcement of the U.S. feed ban, and the USDA, BSE surveillance system. For the latest details on the export eligibility and requirements for U.S. beef to specific countries, see USDA, Food Safety and Inspection Service (FSIS) Import & Export Library.

Want more information?

- Economic Impacts of Feed-Related Regulatory Responses to Bovine Spongiform Encephalopathy(Livestock, Dairy, and Poultry Outlook, September 2008).
- An Economic Chronology of Bovine Spongiform Encephalopathy in North America (Livestock, Dairy, and Poultry Outlook, June 2006).
- Did BSE Announcements Reduce Beef Purchases?(Report No. ERR-34, December 2006)

Information on BSE from other USDA agencies:

- Animal and Plant Health Inspection Service
- Food Safety and Inspection Service

Beef Exports

In 2024, U.S. beef exports slowed for the second year since setting a record in 2022. Beef exports dropped to 3.003 billion pounds, about 1 percent below 2023 levels and a 15-percent decline from the record set in 2022. The main reasons for the decline were less domestic beef production since 2022, robust domestic demand, and expensive U.S. beef prices relative to competitors in overseas markets.

In 2024, the top five U.S. beef export markets comprised 78 percent of total beef exports (by volume): Japan, South Korea, China, Mexico, and Canada. The two largest beef markets accounted for about 42 percent of U.S. beef exports (Japan and South Korea). The third largest market was China, accounting for 16 percent of beef exports. Mexico and Canada combined to account for nearly 20 percent of total U.S. beef exports.

Figure 3. Percent shares of U.S. beef export markets in 2024

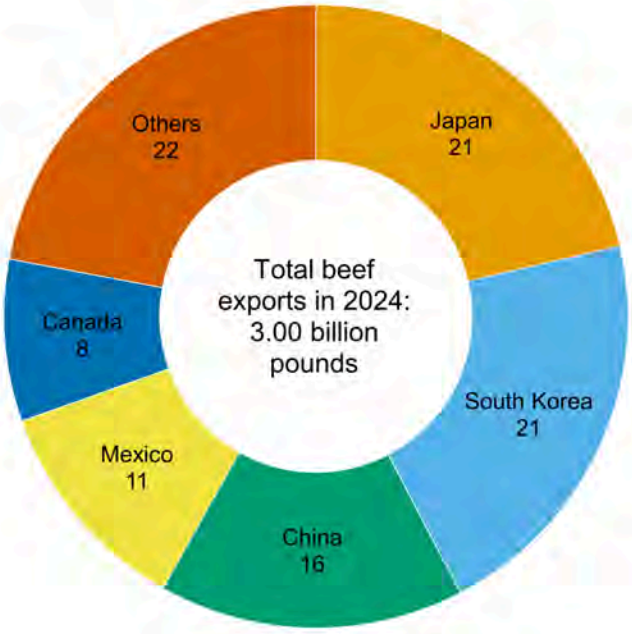

Note: Data labels indicate the percent share of total exports. Total may not add to 100 due to rounding.
Source: USDA, Economic Research Service calculations using data from U.S. Department of Commerce, Bureau of the Census.

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Beef Imports

U.S. beef imports set a new record in 2024 totaling 4.635 billion pounds, more than 24 percent above the previous record in 2023. Australia, the largest beef supplier, accounted for 24 percent of total U.S. beef imports in 2022. The U.S. second and third largest beef sources were Canada and Brazil, providing about 22 and 15 percent of U.S. beef imports, respectively. Mexico, the fourth major supplier, shipped 13 percent of U.S. beef imports. New Zealand, the fifth major source, supplied 12 percent of the U.S. beef import needs. In February 2020, the United States lifted the ban on fresh beef imports from Brazil. Since lifting import restrictions, imports from Brazil have grown more than four times.

There are specific tariff-rate quotas (TRQ) for Australia, New Zealand, Argentina, Uruguay, and other countries not otherwise listed. Specific to Australian beef, it enters the United States with no tariff and then a larger tariff of 21.1 percent is then applied to imports above the TRQ limit. All other beef imports within the TRQ enter at a minimal tariff rate of 4.4 cents per kilogram and then a larger tariff of 26.4 percent is then applied to imports above the TRQ limit. Beef imports from Canada and Mexico are exempt from the TRQ due to the U.S.-Mexico-Canada free trade agreement. For additional information, refer to the USDA, Foreign Agricultural Service (FAS) International Agricultural Trade Report: Reviewing the Tariff-Rate Quotas for U.S. Beef Imports.

Figure 4. Percent shares of U.S. beef import sources in 2024

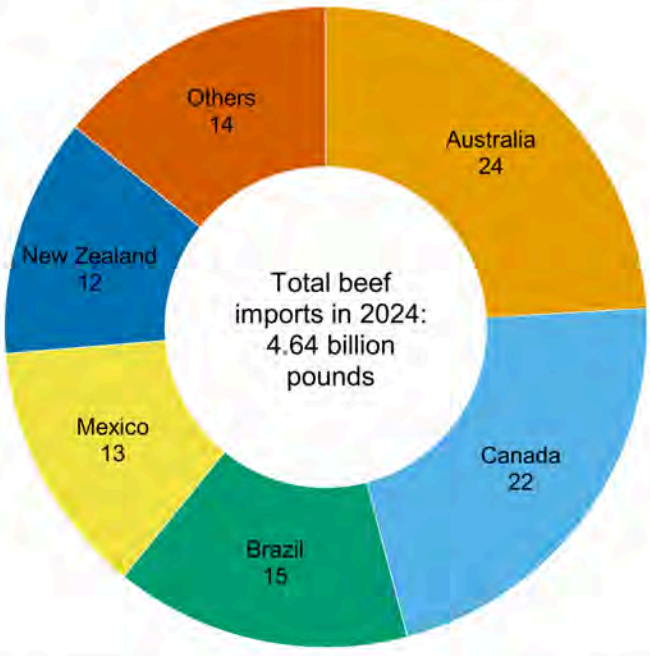

Note: Data labels indicate the percent share of total imports. Total may not add to 100 due to rounding.
Source: USDA, Economic Research Service calculations using data from U.S. Department of Commerce, Bureau of the Census.

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Live Cattle Trade

Traditionally, the United States imports more cattle than it exports. Canada and Mexico are the only significant cattle suppliers to the U.S. market because of their geographical proximity and because of how their cattle and beef sectors complement the U.S. sector. From 2020 to 2024, Mexico provided about 62 percent of U.S. cattle imports, and nearly all the imports were lighter-weight cattle intended for U.S. stocker or feeder operations. Of the cattle imported from Canada over the same time period, about 75 percent were designated for immediate slaughter; on average, 63 percent of these cattle were fed steers and heifers and 37 percent were cows and bulls. About 23 percent of the cattle imported from Canada went to U.S. feedlot operations. Lastly, nearly 2 percent of cattle imported from Canada were used for breeding.

Effective November 22, 2024, USDA implemented a restriction on the importation of cattle and bison originating from or transiting through Mexico upon discovery of New World Screwworm (NWS) in cattle in the Mexican state of Chiapas. On February 1, 2025, the USDA, APHIS announced the resumption of cattle and bison imports from Mexico under a new protocol. The handling of cattle imports under the new protocol constricted the flow of feeder cattle import volumes. After February 1st, it took 6 weeks for imports to grow to an average weekly import volume of about 68 percent of prior-year levels.

On May 11, 2025, USDA reinstated the suspension on the importation of cattle and bison originating from or transiting through Mexico. NWS was detected in remote farms with minimal cattle movement as far north as Oaxaca and Veracruz, about 700 miles away from the U.S. border. This import suspension will persist on a month-by-month basis, until a significant window of containment is achieved.

U.S. cattle exports are primarily destined for Canada and Mexico, but the volume exported and the relative percentages exported to North America and other destinations can vary year to year. From 2020 to 2024, the United States has primarily exported feeder cattle to both Canada (79 percent) and Mexico (12 percent), in addition to some breeding cattle. However, new markets for U.S. dairy and beef cattle for breeding have emerged the last 5 years. These markets include Vietnam, Turkey, Pakistan, Saudi Arabia, and Thailand.

For the latest trade data, see Livestock and Meat International Trade Data. These reports contain monthly and annual data for imports and exports of live cattle, hogs, sheep, and goats. The tables only display quantities. The beef and veal, pork, and lamb and mutton data are reported on a carcass-weight-equivalent basis. Breakdowns by country are included. For the current U.S. meat and animal trade outlook, see the USDA, ERS Livestock, Dairy, and Poultry Outlook report and the USDA, FAS semi-annual Livestock and Poultry: World Markets and Trade reports.

Figure 5. U.S. live cattle imports by use, 2012–2024

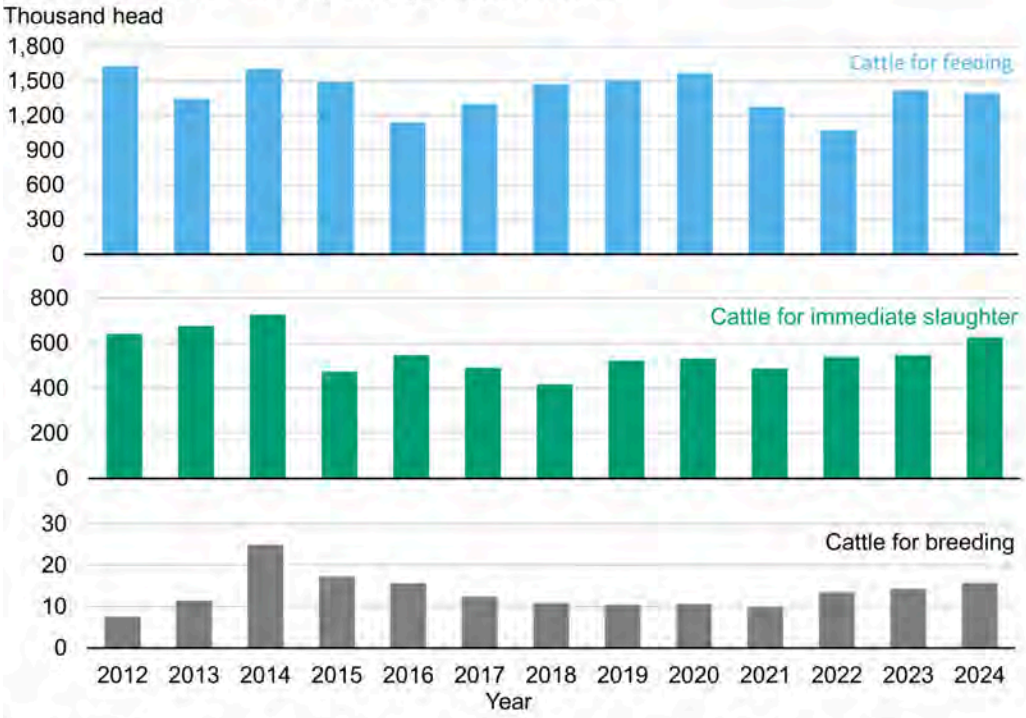

Source: USDA, Economic Research Service calculations using data from U.S. Department of Commerce, Bureau of the Census.

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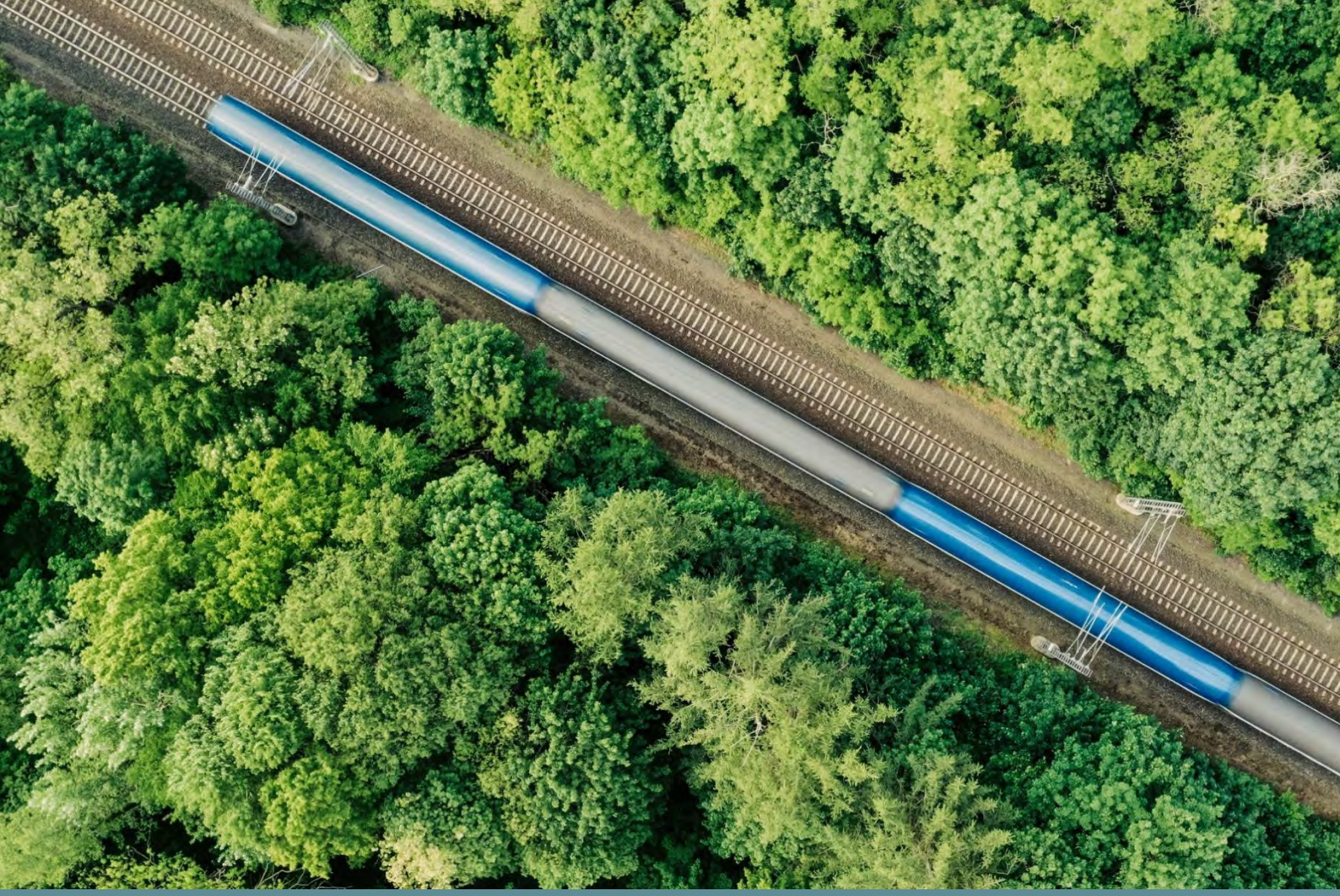

Towards EU climate neutrality

Progress, policy gaps and opportunities

Assessment Report 2024

European Scientific Advisory Board on Climate Change

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About the European Scientific Advisory Board on Climate Change

The European Scientific Advisory Board on Climate Change is an independent scientific advisory body providing the EU with scientific knowledge, expertise and advice relating to climate change. The Advisory Board identifies actions and opportunities to achieve the EU's climate neutrality target by 2050. The Advisory Board was established by the European Climate Law of 2021 with a mandate to serve as a point of reference for the EU on scientific knowledge relating to climate change by virtue of its independence and scientific and technical expertise.

The members of the Advisory Board are:

- Ottmar Edenhofer (Chair)
- Jette Bredahl Jacobsen (Vice-Chair)
- Laura Díaz Anadón (Vice-Chair)
- Maarten van Aalst
- Constantinos Cartalis
- Suraje Dessai
- Vera Eory
- Edgar Hertwich
- Lena Kitzing
- Elena López-Gunn
- Lars J. Nilsson
- Keywan Riahi
- Joeri Rogelj
- Nicolaas Schrijver
- Jean-Francois Soussana

The Advisory Board is supported in the execution of its tasks by a secretariat, hosted by the European Environment Agency.

Recommendations

The European Union (EU) is committed to reducing its greenhouse gas (GHG) emissions to net zero by 2050 at the latest and to aiming to achieve net-negative emissions thereafter. To ensure the EU and its Member States remain on track to meet their climate objectives, the European Climate Law foresees a regular assessment of progress made towards them, together with an assessment of whether EU and national measures are consistent with the climate neutrality objective. This process should be supported by the best available and most relevant scientific evidence, including reports from the European Scientific Advisory Board on Climate Change (hereafter "the Advisory Board"). With this report, the Advisory Board presents its recommendations for achieving the EU's climate targets, as shown in Figure 1 and further detailed below.

Figure 1 Overview of the Advisory Board's recommendations

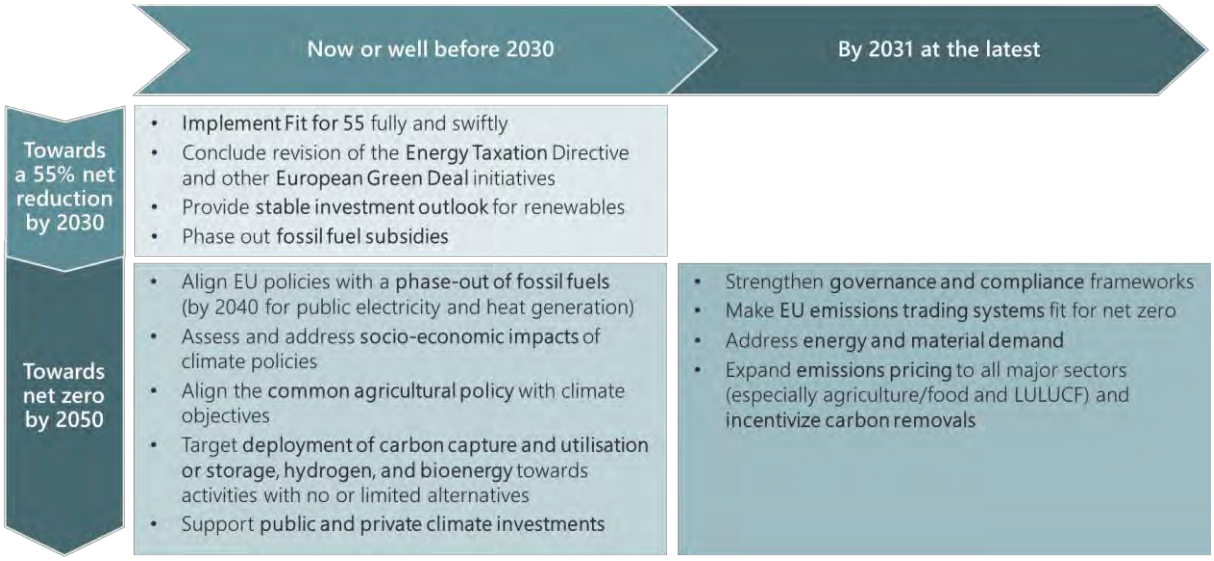

Source: Advisory Board (2024)

1. Achieving the EU's 2030 climate target: fully implement the Fit for 55 package and conclude outstanding European Green Deal initiatives

1.1 Fully and swiftly implement the Fit for 55 package

Key recommendation 1 - Member States should urgently adopt and implement national measures to increase the pace of emissions reductions and reverse the declining EU carbon sink in time. If necessary, the European Commission should take enforcement action to ensure that Member States' updated national energy and climate plans (NECPs) fully comply with the requirements set out in the Governance Regulation.

The EU has substantially reduced its net GHG emissions since 2005. But the pace of reductions needs to increase considerably (to more than twice the average rate over 2005-2022) if the EU is to achieve its 2030 target (a net decrease in GHG emissions of at least 55% compared to 1990) and climate neutrality by 2050. Additional efforts are required in all sectors, especially in the land use, land use change and forestry (LULUCF) sector, where the carbon sink has decreased sharply since 2015.

With the European Green Deal and the Fit for 55 package, the EU has substantially strengthened its climate policies to bring about such an acceleration and reach its 2030 target, as a milestone towards climate neutrality.

Achieving the 2030 target depends on **rapid, robust and effective implementation of the Fit for 55 package**, in particular at the national level: central elements of the package – such as the Effort Sharing Regulation (ESR), the LULUCF Regulation, the Renewable Energy Directive (RED III) and the Energy Efficiency Directive (EED) set out general objectives, whose achievement primarily relies on ambitious national policies and measures.

These measures should be included in Member States' NECPs which are currently being updated. So far, Member States have not sufficiently complied with their obligations regarding NECPs, both in terms of process and content. The European Commission's assessment of the draft updated NECPs found that their collective ambition was insufficient to achieve the EU's 2030 targets. Many draft updates did not include sufficient information or were submitted late, and not all Member States have set up permanent multi-level dialogues or conducted public consultations on their plans.

- Member States' updated NECPs, which must be submitted by 30 June 2024, should fully reflect the new EU legislative framework and demonstrate enough ambition to enable achievement of the EU's energy and climate objectives.
- All Member States must rapidly adopt and implement the updated NECPs' planned measures to have a chance of achieving the necessary emissions reductions in time.
- The European Commission should ensure the updated NECPs are fully compliant with the Governance Regulation, in terms of both their content and the process supporting their set-up and implementation, and take enforcement action if necessary.

1.2 Conclude pending legislative initiatives under the European Green Deal

Key recommendation 2 - The Advisory Board recommends that the EU adopts pending legislative initiatives aimed at supporting the required emissions reductions. This includes in particular the revision of the Energy Taxation Directive (ETD).

– To contribute to further emissions reductions, EU legislators should conclude the Fit for 55 package by adopting an ambitious revision of the ETD which would align energy taxation with the EU's climate objectives. In particular, the revision should set higher minimum tax rates for fossil fuels and remove environmentally harmful tax exemptions, such as for aviation, maritime and professional road transport fuels, as part of a full and urgent phase-out of fossil fuel subsidies (see key recommendation 4).
– Several initiatives could deliver additional emissions reductions but they have yet to be concluded. These include some launched or planned under the European Green Deal's sectoral strategies (e.g. the Farm to Fork Strategy, the Sustainable and Smart Mobility Strategy, the 2020 circular economy action plan (CEAP 2)), as well as a number of initiatives introduced after the Fit for 55 package (e.g. the revision of carbon dioxide (CO_2) emission performance standards for heavy-duty vehicles (HDVs) and the Net-Zero Industry Act). EU legislators should conclude the legislative process related to these initiatives, while maintaining a high level of environmental ambition.

Key recommendation 3 - Both EU and national policy-makers should provide a stable investment outlook for renewable energy by adopting pending legislation and implementing existing policies.

– Timely adoption and implementation of the electricity market reform, the Net-Zero Industry Act and the Critical Raw Materials Act should reinforce long-term investment signals to support the scale-

up in wind and solar photovoltaics (PV). These acts complement the REPowerEU plan, the RED III, the Trans-European Networks for Energy (TEN-E) regulation and the EU action plan for grids, which aim at overcoming key bottlenecks in the roll-out of renewable energy sources (RES), including inadequate electricity networks and administrative permitting. Mechanisms supporting RES need to be stable, offer a long-term market outlook, and find a balance between least-cost RES at scale and nurturing technological innovation. Better use of public funds will be key in this respect, e.g. through de-risking tools and tailored financing solutions (see key recommendation 11).

1.3 Phase out fossil fuel subsidies

Key recommendation 4 - The Advisory Board recommends urgently and fully phasing out fossil fuel subsidies in the EU, in line with existing commitments.

- Member States should fully and urgently phase out fossil fuel subsidies. In line with the 8th Environment Action Programme (8th EAP), they should set a deadline for phasing out such subsidies, and their updated NECPs should include a clear plan and timeline to achieve this.
- Fossil fuel subsidies supporting vulnerable households should be redirected towards well-targeted interventions that adequately address regressive effects while maintaining an incentive for energy savings and a shift towards RES.
- The EU rules affecting state aid for companies should become more consistent with EU climate goals and be brought in line with the Aarhus Convention, notably to safeguard public access to justice.

2. Towards climate neutrality by 2050: address remaining policy inconsistencies and gaps

Assuming swift and effective implementation of the European Green Deal, the Advisory Board has identified opportunities for further policy action to help the EU achieve climate neutrality. The recommendations below are primarily aimed at strengthening the EU policy framework post 2030. However, some of the actions suggested should start before then to reduce the risk of carbon lock-in, decrease the probability of abrupt changes in the EU economy, and help the EU exceed its 55% reduction target by 2030.

2.1 Remove policy inconsistencies

Key recommendation 5 - The EU policy framework should be made fully consistent with the climate neutrality objective and the phase-out of fossil fuels in the EU.

- The European Climate Law requires the European Commission to check that any draft measure or legislative proposal is consistent with EU climate goals. These checks have been done on many, but not all, relevant measures and proposals; they should apply to the delegated and implementing acts under the Fit for 55 package and the European Green Deal, as well as other measures such as climate-relevant state aid decisions and communications.
- EU policies should be better aligned with the 2050 climate neutrality objective, notably in the fields of energy infrastructure and markets (e.g. TEN-E and the internal energy market framework), finance (e.g. the EU Taxonomy), industrial emissions (e.g. the Industrial Emissions Directive) and competition (e.g. state aid rules).
- Practices within the EU policy framework, such as scenario-building for the planning and development of cross-border energy infrastructure, should be consistent with EU pathways to climate neutrality. According to these, fossil fuel use decreases sharply and is almost fully phased out from EU's public electricity and heat generation by 2040.

– The use of carbon capture technologies and hydrogen should not lead to fossil gas infrastructure lock-ins (see key recommendation 10).

2.2 Further improve existing policies

Key recommendation 6 - The Advisory Board recommends strengthening EU climate governance and compliance frameworks.

– The upcoming revisions of the Governance Regulation and the European Climate Law represent an opportunity to improve the existing governance framework for climate action in the EU. In particular, national long-term strategies (LTSs) should be subject to an iterative review process (like the current process with draft and final NECPs), and the link between LTSs and NECPs should be strengthened. The requirement to set up permanent multi-level energy and climate dialogues should be reinforced, and the establishment of national climate advisory bodies should be mandatory.
– The EU should also consider more effective compliance mechanisms, in particular for Member States' obligations to reduce emissions from sectors outside the EU Emissions Trading System for stationary installations and aviation (EU ETS), i.e. under the Effort Sharing and LULUCF Regulations.

Key recommendation 7 - The two EU emissions trading systems must be made fit for net zero.

– The functioning of the EU ETS when the emissions cap for stationary installations approaches or equals zero must be clarified shortly, including the potential role of carbon removals. The EU should also develop alternatives to free allocation to address the risk of carbon leakage for sectors not yet covered by the Carbon Border Adjustment Mechanism (CBAM), especially as the cap further reduces towards zero.
– The initial years of operation of the EU emissions trading system for buildings, road transport and additional sectors (EU ETS 2) should help inform future adjustments and design choices. After 2030, the system should aim for a carbon price signal high enough to incentivise emissions reductions in line with reaching EU climate neutrality, and for an increasing convergence of the carbon price between the two emissions trading systems. This should be accompanied by well-provisioned and targeted measures to address adverse socio-economic effects, based on a thorough analysis of the expected impacts (see key recommendation 8).

Key recommendation 8 - To ensure a just transition and effective implementation, EU policies should build on systematic impact assessments and *ex post* evaluations of the socio-economic aspects of climate policies and measures in specific contexts.

– More systematic and context-specific impact assessments and *ex post* evaluations (e.g. considering local and national needs) should help reinforce synergies between EU social and climate policies and improve climate policy narratives. They should also help design compensatory measures like the Social Climate Fund and the Just Transition Fund. Assessments should be transparent and include public consultations. By informing and engaging citizens and other stakeholders, consultations can increase public support for climate policies and measures.

Key recommendation 9 - The Advisory Board recommends providing stronger incentives for climate action in the agricultural sector and food system, including through the upcoming revision of the common agricultural policy (CAP).

– The CAP should be better aligned with EU climate goals. This could include (i) a standalone emissions reduction objective; (ii) moving towards mandatory good practices that support methane (CH_4) and nitrous oxide (N_2O) reductions and soil carbon increases; and (iii) shifting CAP support

away from emission-intensive agricultural practices, including livestock production, and towards lower-emitting products, carbon removals, environmental services and economic diversification.
- In parallel, the EU should strengthen measures to encourage healthier, more plant-based diets, and develop a strategy for a just transition to a food system consistent with climate neutrality.
- The EU should start preparations now with a view to extending the EU emissions pricing regime to the agricultural/food and LULUCF sectors to incentivise further climate action in these areas (see key recommendation 13).
- The actions recommended (reforming the CAP, introducing emissions pricing and strengthening measures to encourage healthier, more sustainable diets) should be pursued in parallel and in a coherent manner to avoid conflicting policy signals. This would be consistent with the EU approach for other sectors, where carbon pricing is combined with other policy instruments such as minimum performance standards and subsidies.

Key recommendation 10 - The deployment of carbon capture and utilisation/storage (CCU/CCS), hydrogen, and bioenergy should be targeted towards activities with no or limited alternative mitigation options.

- CCU/CCS, indirect electrification through the use of hydrogen, and the use of bioenergy are less efficient or have higher sustainability risks compared to other mitigation pathways such as energy efficiency improvements and direct electrification. EU policies in support of CCU/CCS, hydrogen and bioenergy should be better targeted towards applications with no or very limited other mitigation options.

Key recommendation 11 - The EU should take further policy action to drive the required increase in public and private investments in climate mitigation.

- The reporting methodology under the Multiannual Financial Framework (MFF) (i.e. 7-year EU budget) should be improved to track more accurately EU expenditures that contribute to climate action, and to identify spending on potentially harmful activities.
- The EU should consider continuing the common debt approach under the current Recovery and Resilience Facility (RRF) beyond 2026 to increase investors' certainty and boost EU public investment in climate action.
- To boost private investments, the supply of bankable climate mitigation projects must be increased. To this end, policies should address technology-specific risks and funding gaps by speeding up permitting, removing regulatory uncertainties, and providing tailored financing incentives and solutions where investments are not yet profitable with the current carbon price trajectory.

2.3 Develop new policies

Key recommendation 12 - The Advisory Board recommends pursuing more ambitious reductions in energy and material demand through new and strengthened policies.

- EU policies should incentivise more vigorously the reduction of energy and material demand (in mobility, housing, material use and diets), both through efficiency improvements and behavioural changes. To enable this, policies should establish structures and introduce end-use innovations which increase the quality, affordability and convenience of lower-emissions products and services. The European Green Deal sectoral strategies have several initiatives which could contribute to this (e.g. a legislative framework of sustainable food systems, a regulation on railway infrastructure and

revision of the Combined Transport Directive, mandatory green public procurement requirements), but these remain to be proposed/adopted (see key recommendation 2).

Key recommendation 13 - The Advisory Board recommends expanding the EU GHG pricing regime to all major sectors (including agricultural/food, LULUCF and upstream fossil fuel operations) and providing EU-level incentives for carbon removals.

- The EU should start preparations now with a view to introducing pricing instruments in the agricultural/food and LULUCF sectors, in order to incentivise emissions reductions and carbon removals. Such instruments should reflect the specific characteristics of these sectors, including the technical complexity of measuring emissions and removals, attributing them to land management and mitigation actions, the differences in the permanence of various natural removals and the risk of international leakage. Their impact – in particular on small farms and farms in vulnerable regions – should be assessed *ex ante*, and potentially adverse economic, social and environmental impacts should be addressed to ensure a just and fair transition. This could be done in different ways directly targeting the problems at hand. The CAP budget or revenues from such pricing mechanisms could be used to finance redistributive measures, and to support climate mitigation and adaptation efforts. The EU carbon removal certification framework (CRCF), which is currently being developed, could serve as a first step towards a robust monitoring, reporting and verification system for such instruments.
- The EU should address upstream emissions from fossil fuel extraction and handling, both domestically and related to imported fossil fuels. Building on the Methane Regulation, it should consider expanding the EU ETS to fugitive emissions from domestic fossil fuel operations, and in parallel introduce a border adjustment mechanism for upstream GHG emissions from fossil fuel imports. Pricing upstream emissions from fossil fuels would also contribute to the necessary phase-out of fossil fuels in the EU (see key recommendation 5).

Summary

Context and objectives of the report

Under the European Climate Law, the EU should regularly track progress towards its climate objectives and assess whether its policies are consistent with achieving these goals

The Paris Agreement sets out the goal of strengthening the global response to the threat of climate change by holding global warming to well below 2° C and pursuing efforts to limit it to 1.5°C, relative to pre-industrial levels. As its contribution to this goal, the EU is legally committed, under the European Climate Law, to reduce its GHG emissions to net zero by 2050 at the latest, and to aim to achieve negative emissions thereafter. The law also sets the intermediate target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels.

On 12 December 2023, a comprehensive assessment of the progress made by the global community towards the goals of the Paris Agreement – the first global stocktake – was concluded at the 28th Conference of the Parties under the UN FCCC in Dubai. This process resulted in a call for accelerated action, recognising the need for deep, rapid and sustained emissions reductions in line with 1.5°C pathways. Similarly, to ensure the EU remains on track to meet its climate objectives, the European Climate Law foresees a regular stocktake of progress towards the law's objectives, including an assessment of whether EU measures are consistent with these goals.

The EU has significantly strengthened its climate policies (primarily through the Fit for 55 package) to reach its 2030 target and to respond to new challenges posed by a rapidly changing international environment. Achieving climate neutrality by 2050 will require further development of climate policies.

To achieve its 55% reduction target by 2030, the EU has significantly revised its climate policy framework in the past 3 years, primarily through the Fit for 55 package. In addition, the European Commission launched several sectoral strategies and actions to achieve further GHG emissions reductions. These include the Sustainable and Smart Mobility Strategy, the Farm to Fork Strategy, the Biodiversity and Forest Strategies, and the CEAP 2.

In parallel, several developments in the socio-economic and geopolitical context in which the EU is pursuing its climate objectives have provided strong arguments to accelerate the transition, to reduce the EU's dependence on imported fossil fuels and to strengthen its position to benefit from clean energy and the industries of the future:

- The 2020-2021 COVID-19 pandemic and the 2021-2022 energy crisis resulting from Russia's war of aggression against Ukraine resulted in distorted supply chains, high inflation and greater attention to security, including supply of energy and raw materials. The economic slowdown and large support measures in the context of the pandemic, as well as the energy crisis, have reduced EU Member States' fiscal leeway. Furthermore, higher interest rates have increased financing costs.
- The global race for green investments has accelerated with the US Inflation Reduction Act and due to strategic rivalry with China, leading to a re-evaluation of China's dominance in key strategic sectors and products which threatens the EU's long-term competitiveness and resilience.

In response to these developments, measures have been introduced at the EU level to enhance economic and security-related elements of the climate transition, such as the REPowerEU plan and the Green Deal

Industrial Plan. Member States have also put in place a range of policies that will shape future GHG emissions trends in the EU.

In the context of this strengthened EU climate policy framework, this report aims to provide the EU with scientific advice on policy actions that can support the achievement of climate neutrality by 2050 at the latest.

With this report, the European Scientific Advisory Board on Climate Change (hereafter Advisory Board) aims to advise EU policy-makers on how to make the EU's policies and measures 'fit for net zero', by flagging up areas for improvement and gaps in the current framework. To that end, it assesses the progress made towards the EU's climate objectives, as well as the consistency of EU policies with the climate neutrality objective. Where sufficient scientific evidence is available, it also puts forward recommendations to address these gaps. By doing so, the Advisory Board aims to provide an independent input to the stocktake process established at EU level under the European Climate Law, in complement to existing assessments by the European Environment Agency (EEA, the annual Trends and Projections reports (EEA, 2023p)) and the European Commission (the Climate Action Progress Report (EC, 2023ax)).

This report is an integral part of the Advisory Board's effort to provide scientific advice on existing and proposed EU measures and their consistency with the EU's climate objectives, and to identify actions and opportunities to successfully achieve these targets, in line with the mandate set out in the European Climate Law (EU, 2021c).

The report provides a first general assessment of progress and policy consistency in different sectors (energy supply, industry, transport, buildings, agriculture and LULUCF) and for cross-cutting issues (pricing of emissions and rewarding removals, just transition and public engagement, finance and investments, innovation, governance, and skills and capacity building) (see Figure 2 below). All recommendations include explanations of the evidence and rationale supporting them.

Figure 2 Scope of the progress and policy consistency assessment

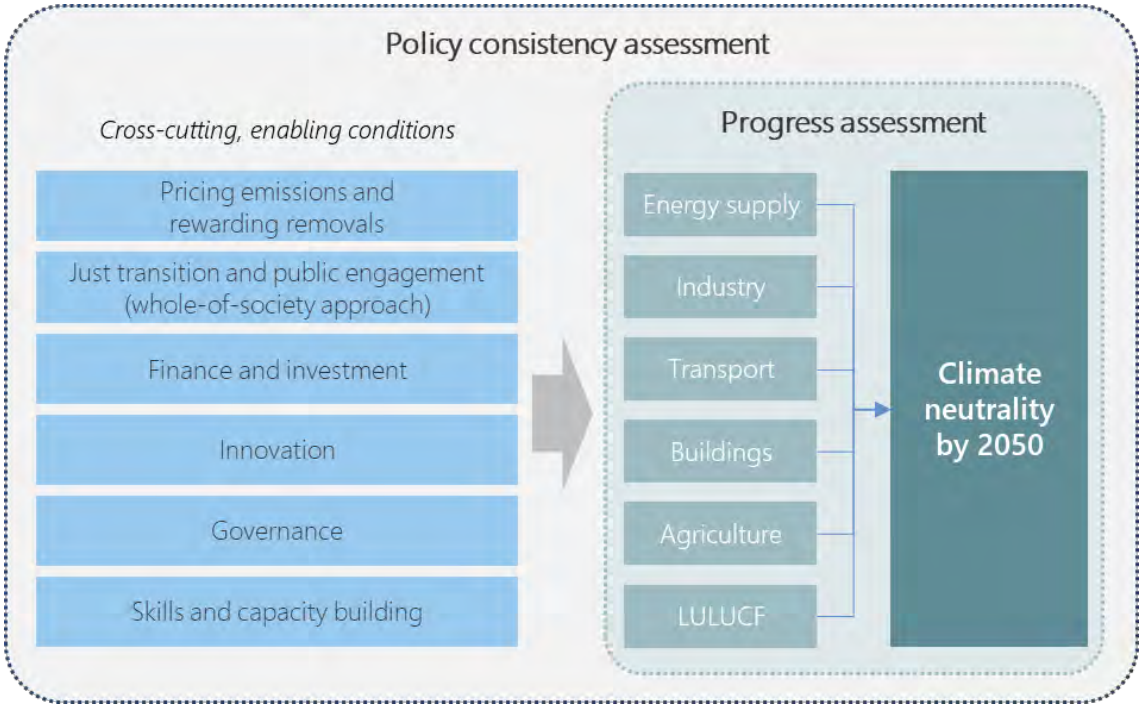

Source: Advisory Board (2024).

Given the broad scope of an analysis addressing progress towards meeting climate objectives in the EU, the Advisory Board chose to limit its assessment to the EU level and did not include specific Member State-level analysis. Progress and consistency of policies with climate objectives at the national level are regularly assessed by the European Commission and other stakeholders, such as national climate advisory bodies established in certain Member States ([1]).

In addition to objectives on climate mitigation, the European Climate Law sets out an obligation for the relevant EU institutions and Member States to ensure continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change. Although climate adaptation is not specifically covered in this report, the Advisory Board highlights its importance both as a critical issue on its own and because of potential synergies between adaptation and mitigation measures.

Analytical approach

For each of the six sectors covered by the analysis (see Chapters 4-9 of the report), the Advisory Board performed the following two main tasks:

1. An assessment of **progress**, based on the analysis of relevant indicators and their comparison with indicative benchmarks.
2. An assessment of the **consistency** of relevant existing or recently adopted policies in each sector with the EU's climate objectives, starting from the assessed progress and based on a thorough review of recent scientific and expert findings.

To assess progress across the different sectors, the Advisory Board identified 76 indicators specific to the different sectors. It then compared historical trends with indicative benchmarks for 2030 and 2050 derived from existing EU targets and objectives, as well as European Commission scenarios and other scientific scenarios used by the Advisory Board to prepare its recommendations for the determination of an EU-wide 2040 climate target and a GHG budget for 2030-2050 (ESABCC, 2023b).

For its assessment of policy consistency in the different sectors, the Advisory Board assessed whether EU policies are (or can be expected to be) sufficiently driving the required changes to deliver the necessary GHG emissions reductions. This assessment led to identifying four main types of gaps or inconsistencies: **policy gaps** (no policies in place to address the required change), **ambition gaps** (the policies in place are not ambitious enough to deliver the required change), **implementation gaps** (policies are not implemented adequately), and **policy inconsistencies** (policies provide counterproductive incentives).

The assessment was based on a thorough review of recent scientific findings, reports and data from international organisations (such as the International Energy Agency (IEA)) and from European institutions (e.g. European Court of Auditors (ECA), European Commission and its Joint Research Centre (JRC)). The Advisory Board also considered insights from reports and data from non-governmental organisations, think tanks and industry, provided they were underpinned by robust and credible analysis. Given the difficulties inherent to the *ex ante* assessment of impacts of newly adopted policies, some level of judgement was involved in translating the available evidence into expectations of gaps. The sources used are referenced throughout the report.

(1) The European Climate Law invites each Member State that has not done so yet to establish a national climate advisory body.

For the cross-cutting issues (Chapters 10-15 of the report), the assessment mainly focused on policy consistency, based on the same approach as for the sectoral assessments.

Based on its analysis of progress and consistency, the Advisory Board drew conclusions on:

1. '**needs**' – changes required to deliver the necessary emissions reductions (or removals) in line with a meaningful contribution to EU climate neutrality;
2. '**gaps**' – barriers in the current policy framework that must be addressed to deliver the required changes;
3. '**recommendations**' – policy options recommended to overcome the identified gaps.

Figure 3 Structure of the Advisory Board conclusions

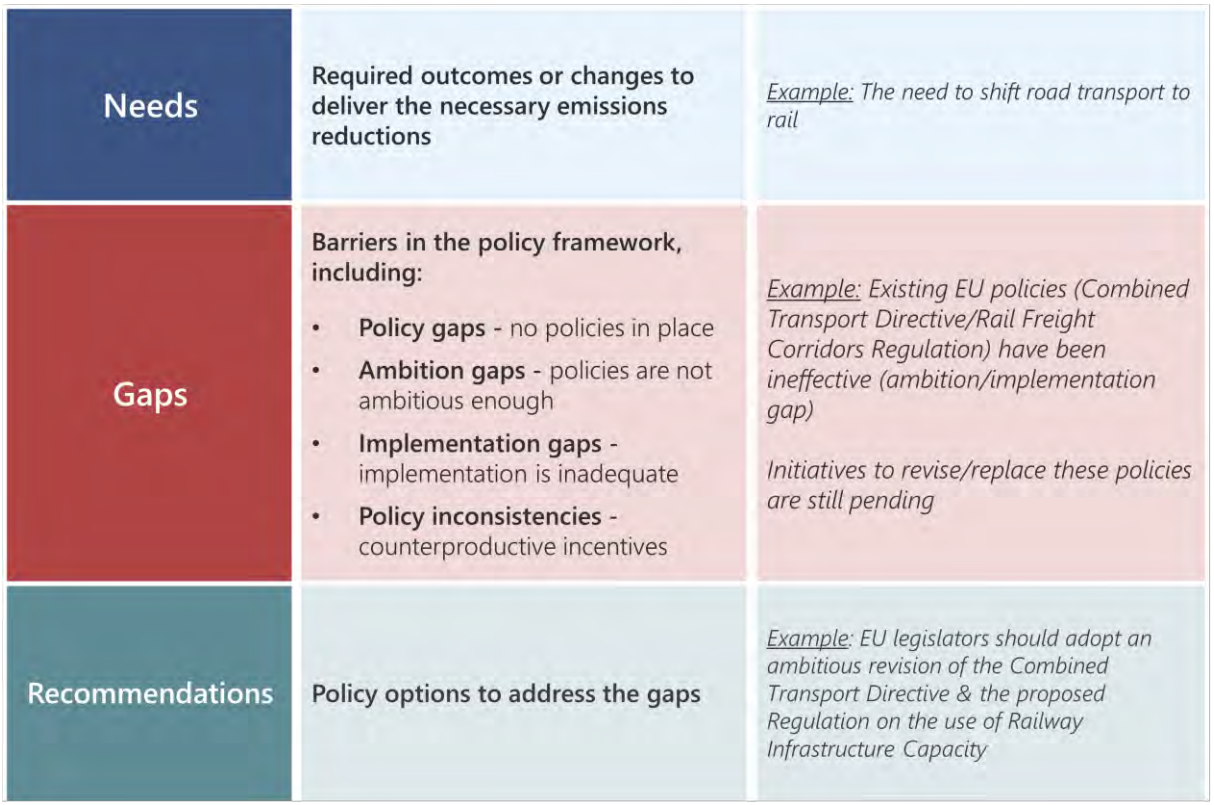

Source: Advisory Board (2024).

While the Advisory Board's assessment of progress and policy consistency draws on a large body of scientific and grey literature, it is not fully comprehensive. It focuses on selected progress indicators and their respective indicative benchmarks, EU policies, and does not consider Member State policies. It uses a sectoral approach but does not address sectoral interactions in detail, although some cross-cutting topics which are important across many sectors are included. Because of these limitations, the findings and recommendations of the report do not exhaust the list of EU-level actions that may be needed to achieve climate neutrality by 2050. Nevertheless, the report does provide an overview of some key areas where further policy action can help move the EU closer to meeting its climate goals, based on existing evidence.

1. Achieving the EU's 2030 climate target: fully implement the Fit for 55 package, conclude pending European Green Deal initiatives, and address implementation gaps

The Advisory Board makes the following recommendations to the EU to ensure the 55% reduction objective for 2030 is reached or exceeded, as further detailed below:

1. Fully and swiftly implement the Fit for 55 package.
2. Conclude pending legislative initiatives under the European Green Deal.
3. Phase out fossil fuel subsidies.

1.1 Fully and swiftly implement the Fit for 55 package

Key recommendation 1 - Member States should urgently adopt and implement national measures, to increase the pace of emissions reductions and reverse the declining EU carbon sink in time. If necessary, the European Commission should take enforcement action to ensure that Member States' updated NECPs fully comply with the requirements set out in the Governance Regulation.

The EU has substantially reduced its net GHG emissions since 2005 and largely exceeded its 20% reduction target by 2020, compared to 1990.

In 2022, the EU had reduced its net GHG emissions by 31% compared to 1990 levels. It surpassed the 20% reduction target for 2020, and trends over the past 5 years show an increase of average emissions reductions. Consumption-based CO_2 emissions decreased at a similar pace to territorial CO_2 emissions in the 2010-2020 period.

While recent emissions reductions have accelerated, achieving the EU's 55% objective for 2030 requires a significant increase in the pace of reductions to more than twice the 2005-2022 average.

While encouraging, the observed trends are not sufficient to indicate that the EU is on track to meet its climate targets: achieving these requires the pace of emissions reductions to increase even further (see Figure 4). To reach the EU's 55% reduction target by 2030, average annual reductions during the 2022-2030 period should be more than twice those observed on average in 2005-2022.

For the time being, Member States' latest projections show that net GHG emissions would be reduced by only 49% by 2030, with current and planned policies at the national level (see Figure 4). According to the European Commission's assessment of the draft updated NECPs submitted in 2023, the measures they include would result in net emissions reductions of 51% by 2030, compared to 1990, which is still short of the 55% objective. Additional efforts would be required in all sectors, particularly those covered by the Effort Sharing Regulation (buildings, transport and agriculture) and the LULUCF sector. The biggest step change is needed in the latter, where the carbon sink has been sharply decreasing since 2015.

These projections do not yet fully reflect the expected impact of the Fit for 55 package or the final updated NECPs, which must be submitted in 2024. But they underline the crucial importance of rapid and effective implementation of the strengthened EU climate policy framework.

Figure 4 Overall progress towards the EU's 2030 and 2050 objectives since 2005

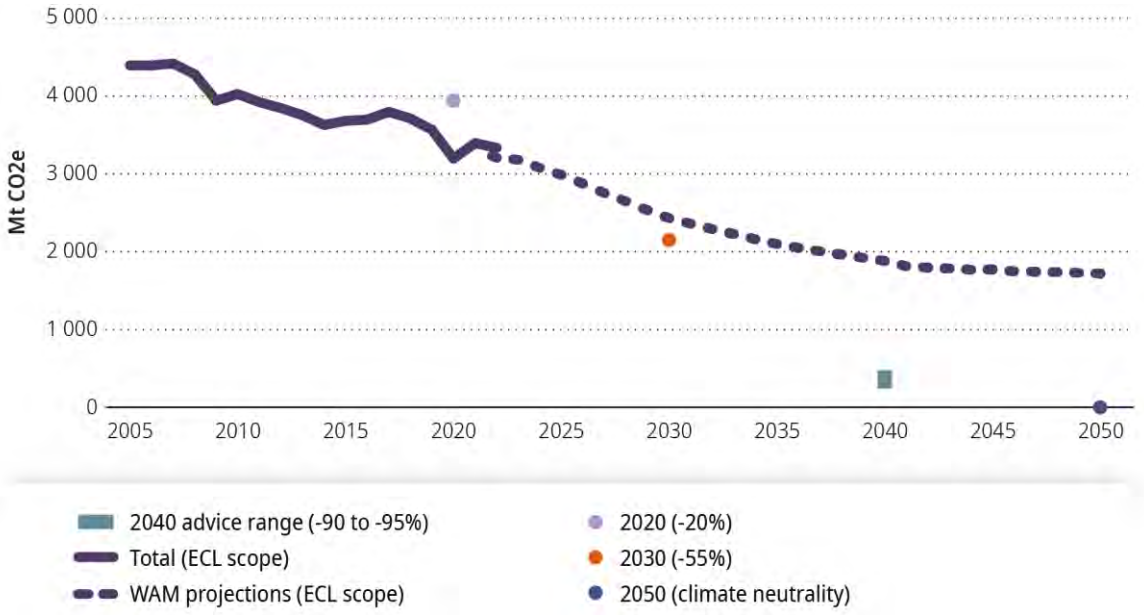

Notes: WAM: projections 'with additional measures'. These reflect the expected impacts of existing policies and additional ones that Member States were expecting to adopt at the time the projections were made. The projections do not necessarily reflect all the recently adopted elements of the Fit for 55 package. The 2040 range corresponds to the 90-95% reduction compared to 1990 recommended by the Advisory Board. Except for the 2020 target, the scope considered for the GHG emissions includes all domestic emissions and removals, 64% of the international maritime emissions reported in the GHG inventory, and all international aviation emissions reported in the GHG inventory (see Box 1 in Chapter 3 for more information). The 2020 target includes gross domestic GHG emissions (excluding LULUCF) and international aviation.

Sources: Historic GHG emissions: EU GHG inventory (EEA, 2023f). WAM projections: Member States' March 2023 submissions to the European Commission under the Governance Regulation (EEA, 2023m).

To enable the significant acceleration of emissions reductions required to achieve the 55% target by 2030, the EU strengthened its climate policy framework substantially, in particular with the Fit for 55 package. Delivery of this package will depend on rapid, robust and effective implementation, especially at the national level.

A wide range of EU climate and energy policies have been adopted or revised in recent years to support the necessary acceleration of GHG emissions reductions, primarily under the Fit for 55 package. Central elements of this package set out overall objectives for Member States (the Effort Sharing Regulation, the LULUCF Regulation) or at EU level (the RED III and the EED) that must be achieved primarily through policies and measures at the national and subnational levels.

Member States are required to outline their overall strategies as well as concrete policies and measures to achieve the EU energy and climate objectives in their NECPs, including an overview of the investments needed to reach the national objectives, and a clear plan and timeline to phase out fossil fuel subsidies. Under the Governance Regulation, Member States must update their NECPs to align them with recent policy developments, including the Fit for 55 package. Draft updates had to be submitted by June 2023, and final updates are due by June 2024.

So far, Member States have not sufficiently complied with their obligations regarding NECPs, both in terms of process and content. Many Member States did not fully comply with the Governance Regulation

under the first NECP cycle in 2020 (**implementation gap**): several submissions were late and did not include the minimum required content (e.g. lacking sufficiently detailed information on investment needs and the expected socio-economic impacts of planned measures), and not all Member States ensured permanent multi-level engagement as required. The EU is also in breach of the Aarhus Convention in relation to public engagement in the NECP process (**implementation gap**). The European Commission's assessment of the draft updated NECPs in 2023 found that, despite steps in the right direction, the collective ambition of NECPs was insufficient to achieve the Fit for 55 package's objectives. Many draft updates did not include sufficient information or were submitted late, and not all Member States had set up permanent multi-level dialogues nor conducted public consultations on the plans.

- ➔ **Member States' updated NECPs, which must be submitted by 30 June 2024, should fully reflect the new EU legislative framework and demonstrate enough ambition to enable achievement of the EU's energy and climate objectives.**
- ➔ **All Member States must proceed with rapid adoption and implementation of the planned measures outlined in their updated NECPs to have a chance of achieving the necessary reductions in time.**
- ➔ **The European Commission should ensure that Member States' updated NECPs are fully compliant with the Governance Regulation – in terms of both their content and the process supporting their set-up and implementation – and take enforcement action if necessary** (see Chapter 14, recommendation G1)**.**

1.2 Conclude pending legislative initiatives under the European Green Deal

Key recommendation 2 - Adopt pending legislative initiatives which aim to support the required emissions reductions, including the ETD.

While almost all the Fit for 55 package's legislative proposals have now been adopted, the revision of the ETD put forward by the European Commission is still pending. The current ETD is not aligned with the EU's climate ambitions, as it gives preferential treatment to GHG emission-intensive energy carriers compared to less emission-intensive alternatives. It also includes harmful tax exemptions for aviation, maritime and professional road transport, agriculture, energy-intensive industries and heating of buildings (**policy inconsistency**). Adopting the revision as proposed would go a long way to addressing the inconsistencies identified. However, by the end of 2023, legislators had made limited progress towards this, making it the only proposal from the original Fit for 55 package (published in July 2021) that had not been adopted yet.

- ➔ **To contribute further emissions reductions, EU legislators should conclude the Fit for 55 package by adopting an ambitious revision of the ETD, aligning energy taxation with the EU's climate objectives. In particular, the revision should set higher minimum tax rates for fossil fuels and remove environmentally harmful tax exemptions (for aviation, maritime and professional road transport, agriculture, heating of buildings and energy-intensive industries), as part of a full and urgent phase-out of fossil fuel subsidies** (see key recommendation 4, and Chapter 10, recommendation C5).

Since the Fit for 55 package was published in July 2021, the European Commission has made further legislative proposals aimed at accelerating GHG emissions reductions. These include revisions of the Energy Performance of Buildings Directive (EPBD) and of CO_2 emission performance standards for HDVs, as well as a Methane Regulation. It also launched initiatives to boost clean technologies and make the EU more competitive and autonomous, in particular the Net-Zero Industry Act, the Critical Raw Materials Act, and the reform of the electricity market design, as well as the hydrogen and decarbonised gas

market package. Most of these proposals were at advanced stages of the legislative process by the end of 2023.

However, progress on the operationalisation of the different sectoral strategies under the European Green Deal (e.g. the Farm to Fork Strategy, the Sustainable and Smart Mobility Strategy, the CEAP 2) has been slower, with many initiatives still in the legislative process or not yet proposed by the European Commission. These remain to be converted into ambitious EU legislation.

➔ **EU legislators should conclude the legislative process on the other pending initiatives under the European Green Deal, such as the revised CO_2 emission performance standards for HDVs, while maintaining a high level of environmental ambition** (see Chapter 4, recommendation E4; Chapter 5, recommendation I3; Chapter 6, recommendation T2; Chapter 7, recommendation B1; Chapter 8, recommendation A3).

Key recommendation 3 - Provide stable investment outlooks for renewable energy by adopting pending legislation and implementing existing policies.

The deployment of solar PV and wind energy needs to accelerate across the EU to achieve the 42.5% renewable energy objective for 2030 and to lead to a net-zero electricity system by 2040 at the latest. Progress is challenged by changing investment landscapes as well as inadequate infrastructure planning and development, spatial planning and permitting, workforce skills, and supply chains. This lowers investment certainty and affects system planning and decision-making (e.g. in PV and wind value chains, as they are not yet adjusted to the required deployment and industry growth).

EU policies have been adapting to this challenge, in particular through the REPowerEU plan, the RED III, the TEN-E Regulation and the EU action plan for grids. Several of the above-mentioned pending legislative initiatives also aim to improve the investment framework for renewables, including the electricity market reform, the Net-Zero Industry Act and the Critical Raw Materials Act.

➔ **Timely adoption and implementation of the electricity market reform, the Net-Zero Industry Act and the Critical Raw Materials Act should reinforce long-term investment signals to support the scale-up in wind and solar PV. Mechanisms supporting RES must be stable, offer a long-term market outlook, and find a balance between least-cost RES at scale and nurturing technological innovation. Better use of public funds will be key in this respect, e.g. through de-risking tools and tailored financing solutions** (see Chapter 4, recommendation E4).

1.3 Phase out fossil fuel subsidies

Key recommendation 4 - Phase out fossil fuel subsidies in line with existing commitments.

Fossil fuel subsidies undermine the climate transition, by hindering the reorientation of private financial flows towards climate mitigation, locking in GHG emissions from fossil fuel-dependent infrastructure, and reducing the public budget available to support climate investments.

The EU and its Member States have repeatedly committed to phasing out fossil fuel subsidies, for which they are required to set a deadline under the 8th EAP. Despite these commitments, fossil fuel subsidies remained relatively stable in the last decade (around €50 billion per year), and even increased sharply in 2022, in the context of the energy crisis (€120 billion). Only a minority of Member States currently have, in their NECPs, clear plans and timelines for phasing out such subsidies (**implementation gap**).

➔ **Fossil fuel subsidies should be phased out fully and urgently. Member States should include clear plans and timelines to achieve this in their updated NECPs** (see Chapter 12, recommendation F2).

➔ **Fossil fuel subsidies supporting vulnerable households should be redirected towards well-targeted interventions that adequately address regressive effects while maintaining an incentive for energy savings and a shift towards RES** (see Chapter 12, recommendation F2).

Fossil fuel subsidies continue being channelled through state aid approved by the European Commission. While the Temporary Crisis and Transition Framework includes a very positive opening for more public investment towards a net-zero economy, it is not fully consistent with the EU climate neutrality objectives. Adopted in response to the energy crisis, the Temporary Crisis Framework of March 2022 and its successor the Temporary Crisis and Transition Framework of March 2023 allow Member States to shield fossil fuel power plant operations and energy-intensive companies from high and volatile energy prices. Despite its temporary and crisis-led nature, the framework provisions keep being extended, allowing vast public support which is inconsistent with the energy transition (**policy inconsistency**). In addition, by restricting public rights to internal administrative review of state aid decisions, the EU is in breach of the Aarhus Convention in relation to access to justice (**implementation gap**).

➔ **EU state aid rules affecting national support measures for EU companies should be made more consistent with EU climate goals and brought in line with the Aarhus Convention, notably to safeguard public access to justice** (see Chapter 4, recommendation E1).

2. Towards climate neutrality by 2050: address remaining policy inconsistencies and gaps

Looking beyond 2030, emissions reductions in the EU will need to accelerate even faster to achieve climate neutrality by 2050. Building on the Fit for 55 package, the EU can become climate neutral by 2050 through several well-identified actions and opportunities. Early action on these could bring multiple benefits.

While the recent strengthening of the EU climate policy framework is expected to go a long way towards achieving the EU's 2030 target – provided that it is implemented swiftly and effectively – becoming climate neutral by 2050 at the latest will require further policy developments.

The Advisory Board identified several remaining policy options that can help the EU achieve the necessary emissions reductions to deliver on its long-term climate objectives. The board makes the following recommendations to the EU, as further detailed below:

1. Remove remaining inconsistencies of EU policies with climate objectives.
2. Further improve existing policy instruments.
3. Develop new policies.

Certain decisions made today have long-lasting effects and might strongly impact the EU's ability to reach its climate neutrality objective in time, for example, when linked with a risk of fossil fuel lock-in. Therefore, although the recommendations below are primarily aimed at strengthening the EU policy framework post 2030, some of the recommended actions should start already in the coming years. This would provide multiple benefits, including avoiding lock-ins, reducing the risk of abrupt changes in the EU economy, supporting the achievement of the 2030 objective and potentially even enabling this goal to be exceeded (thereby decreasing the EU's cumulative emissions until 2050 and thus increasing the fairness of its contribution to global mitigation).

2.1 Remove policy inconsistencies

Key recommendation 5 - Make EU policies fully consistent with the EU climate neutrality objective and the phase-out of fossil fuels in the EU.

The European Climate Law requires the European Commission to check that draft measures and legislative proposals are consistent with EU climate goals. These checks have been done on many, but not all, relevant measures, including at least two delegated acts with high climate relevance (i.e. acts establishing taxonomy criteria for sustainable investment and defining renewable transport fuels) (**implementation gap**).

➔ **The European Commission should assess more systematically the consistency of any draft measure or legislative proposal with the climate neutrality goals as set out in the European Climate Law. This also applies to the delegated and implementing actions under the Fit for 55 package and European Green Deal, as well as other measures such as climate-relevant state aid decisions and communications** (see Chapter 14, recommendation G3).

Scenarios towards net-zero emissions in the EU imply that fossil fuel use decreases sharply and is almost fully phased out from public electricity and heat generation by 2040. While the revised EU ETS provides a strong signal to this end, not all EU policies are consistent with a progressive phase-out of fossil fuels in future energy systems (e.g. the TEN-E Regulation, the proposed Gas Directive and Gas Regulation, state aid rules, and the EU Taxonomy). Due to the necessary speed of change in the energy sector, decisions made today risk costly infrastructural and contractual carbon lock-ins (**policy inconsistency**).

The 10-year network development plan (TYNDP) process, which informs today's energy infrastructure investment decisions across Europe and beyond, is not yet in line with the EU 2050 climate neutrality objective as required under the revised TEN-E Regulation (**implementation gap**).

➔ **EU policies should be better aligned with the 2050 climate neutrality objective, notably in the fields of energy infrastructure and markets (for example, TEN-E and the internal energy market framework), finance (e.g. the EU Taxonomy), industrial emissions (for instance, the Industrial Emissions Directive) and competition (e.g. state aid rules)** (see Chapter 4, recommendation E1).

➔ **Practices within the EU policy framework, such as scenario-building for cross-border infrastructure planning and development, should be consistent with EU pathways to climate neutrality. According to these, fossil fuel use decreases sharply and is almost fully phased out from EU's public electricity and heat generation by 2040** (see Chapter 4, recommendation E1).

➔ **Application of CCU/CCS technologies and hydrogen should not lead to unnecessary fossil gas infrastructure lock-ins** (see Chapter 4, recommendations E6 and E7).

2.2 Further improve existing policies

Key recommendation 6 - Strengthen the EU climate governance and compliance frameworks.

The Governance Regulation requires Member States to develop national LTSs and to ensure consistency between their NECPs and LTSs. However, the LTS governance process does not foresee an iterative review process as is currently provided for the NECPs. The regulation also does not require the European Commission to thoroughly check whether the NECPs are consistent with national LTSs. Therefore, the regulation does not sufficiently ensure that the NECPs are consistent with the LTSs, nor that the latter are adequate to enable achievement of the EU's long-term objectives (**ambition gap**). Furthermore, the provisions on multi-level climate and energy dialogues are not sufficiently clear regarding the permanent and systematic nature of stakeholder engagements (**ambition gap**).

The current provisions of the European Climate Law are not sufficient to incentivise the establishment by Member States of independent national climate advisory bodies (**ambition gap**). These could play a particular role in the NECP preparation process at the national level, but this role is currently not yet foreseen in the Governance Regulation (**ambition gap**).

➔ **The upcoming revisions of the Governance Regulation and European Climate Law represent an opportunity to improve the existing governance framework for climate action in the EU. In particular, (i) the national LTSs should be subject to an iterative review process (similar to the current process for NECPs) and the link between LTSs and NECPs should be strengthened, (ii) the requirement to set up permanent multi-level energy and climate dialogues should be reinforced, and (iii) the establishment of independent national climate advisory bodies should be made mandatory** (see Chapter 14, recommendations G1, G3 and G4).

The ESR sets annual binding targets at national level for domestic GHG emissions not covered by EU ETS or the LULUCF Regulation. The 5-year cycle of formal compliance checks under ESR leads to a substantial time lag between the emissions and the compliance assessment's conclusions, which risks undermining its effectiveness (**ambition gap**).

➔ **The EU should consider more effective compliance mechanisms, in particular for Member States' obligations to reduce emissions from sectors outside the EU ETS, i.e. under the Effort Sharing and LULUCF Regulations** (see Chapter 14, recommendation G2).

Key recommendation 7 - Make the two EU emissions trading systems fit for net zero.

Successive revisions have strengthened EU ETS. However, there is not yet a clear strategy to prepare the carbon market for when the cap – which determines the amount of emission allowances allocated to the market – reaches zero, which will occur before 2040 (**policy gap**).

Furthermore, whereas free allocation will be gradually phased out for sectors covered by the new CBAM (even if only by 2034), it will continue for sectors considered to be exposed to carbon leakage which are not covered by the CBAM. This risks creating distortions and complexities, and could reduce mitigation incentives for consumers and downstream industries (**ambition gap**). Furthermore, the number of allowances available for free allocation will decrease rapidly and eventually reach zero in line with the cap. Free allocation is therefore not a long-term solution to address the risk of carbon leakage.

➔ **The functioning of EU ETS when the emissions cap for stationary installations is approaching or equalling zero needs to be clarified shortly (including the potential role of carbon removals). The EU should also develop alternatives to free allocation to address the risk of carbon leakage for sectors not yet covered by the CBAM, especially as the cap further reduces towards zero** (see Chapter 10, recommendations C1 and C2).

The introduction of a separate scheme for buildings and road transport will substantially increase the share of EU GHG emissions covered by an EU-wide carbon price, and provides an additional incentive for emissions reductions in those sectors. However, if the system's carbon price exceeds €45/tonne of carbon dioxide equivalent (tCO_2e), a predefined number of additional emissions allowances will be released on the market, on top of the original cap. As most models predict that prices well above €45/tCO_2e will be needed to deliver the required reductions in the sectors covered, this mechanism is likely to be triggered. This would *de facto* increase the emissions budget under the system, and could jeopardise the envisaged GHG emissions reductions of 62% by 2030 (compared to 2005) (**ambition gap**). This would require more ambitious national measures to achieve the reduction targets under the

ESR which could be riskier, given the weaknesses in the governance and compliance framework described above.

The split between the two emissions trading systems can be justified for pragmatic reasons in the short term. In the longer term, having different prices for 1 tonne of CO_2 might fail to encourage emissions reductions where they are least expensive. It could also create distortions and perverse incentives, e.g. by discouraging electrification of energy uses if electricity (covered by the EU ETS) is subject to a higher carbon price than fuels used for heating of buildings (covered by the EU ETS 2) (**ambition gap**).

➔ **The initial years of operation of EU ETS 2 should help inform future adjustments and design choices. After 2030, the system should aim for a carbon price signal high enough to incentivise emissions reductions in line with reaching EU climate neutrality, and for an increasing convergence of the carbon price between the two emissions trading systems** (see Chapter 10, recommendation C3). **This should be accompanied by well-provisioned and targeted measures to address adverse socio-economic effects, based on a thorough analysis of the expected impacts** (see key recommendation 8)**.**

Key recommendation 8 - Base EU policies on a systematic impact assessment and *ex post* evaluations of the socio-economic impact of climate policies and measures to ensure a just transition and effective implementation.

Despite the many benefits of climate mitigation (e.g. reduced dependency on energy imports, improved air quality and human health, avoided costs of inaction), climate policy measures can have disruptive and regressive socio-economic impacts, placing a disproportionate burden on low-income households and vulnerable groups. The net-zero transition relies on properly understanding and addressing its costs and benefits at household, community and wider society levels.

Many EU policies build on a limited recognition and narrow understanding of the socio-economic impacts that could arise from climate policy implementation, particularly in relation to inequality. This limitation suggests that the connection between EU climate and social policies could be reinforced (**ambition gap**).

This also partly explains why the narratives surrounding climate policy instruments do not pay due attention to their co-benefits as well as local needs and values (**ambition gap**).

➔ **More systematic and context-specific impact assessments and *ex post* evaluations (e.g. considering local and national needs) should help reinforce synergies between EU social and climate policies and improve climate policy narratives. They should also help design compensatory measures such as the Social Climate Fund and the Just Transition Fund. Assessments should be transparent and include public consultations. By informing and engaging citizens and other stakeholders, consultations increase public support for climate policies and measures** (see Chapter 11, recommendations W1, W2 and W3; Chapter 15, recommendation S2).

Key recommendation 9 - Provide stronger incentives for climate action in the agricultural sector and food system, including through the upcoming revision of the CAP.

The lack of emissions reductions in the agricultural sector since 2005 highlights the need for stronger incentives in this sector. The CAP is the EU's flagship agricultural policy, which aims to deliver on 10 key objectives including on climate action. However, its effective contribution to GHG emissions reductions is uncertain at best. Its goal, among others, to contribute to mitigation is largely qualitative and forms part of a broader set of agri-environment objectives (**ambition gap**).

The CAP's green architecture provides opportunities for Member States to promote sustainable practices, but the emphasis given to climate change mitigation is largely discretionary and difficult to quantify *ex ante* (**ambition gap**).

Furthermore, the CAP continues to provide financial support to emission-intensive agricultural practices such as livestock production, rather than focusing on the transition to less emission-intensive activities (**policy inconsistency**).

- ➔ **The CAP should be better aligned with the EU climate objectives. This could include (i) a standalone emissions reduction objective, (ii) moving towards mandatory good practices that support CH_4 and N_2O reductions and soil carbon increases, and (iii) shifting CAP support away from emission-intensive agricultural practices, like livestock production, and towards lower-emitting products, carbon removals, environmental services, and economic diversification** (see Chapter 8, recommendation A1).
- ➔ **In parallel, the EU should strengthen measures to encourage healthier, more plant-based diets, and develop a strategy for a just transition to a food system consistent with the climate neutrality objective** (see Chapter 8, recommendation A3).
- ➔ **The EU should start preparations now with a view to extending the emissions pricing regime to the agricultural/food and LULUCF sectors to incentivise further climate action in these areas** (see key recommendation 13)**.**
- ➔ **The recommended options (reforming the CAP, introducing emissions pricing and strengthening measures to encourage healthier, more sustainable diets) should be pursued in parallel and in a coherent manner to avoid conflicting policy signals. This would be consistent with the EU approach for other sectors, where carbon pricing is combined with other policy instruments such as minimum performance standards and subsidies.**

Key recommendation 10 - Target the deployment of CCU/CCS, hydrogen and bioenergy towards activities with no or limited alternative mitigation options.

CCU/CCS, indirect electrification through renewable hydrogen and its derivatives, and bioenergy are less efficient or raise sustainability concerns compared to other mitigation pathways, such as energy efficiency improvements and direct electrification. Even so, they remain necessary to achieve deep emissions reductions in sectors where direct electrification is technically challenging (e.g. in aviation and maritime transport and energy-intensive industries).

A harmonised carbon price applied across all sectors would ensure that the most efficient mitigation options are prioritised, and that less efficient options are only applied where there is a lack of alternatives, provided that the price signal is not distorted by other interventions such as subsidies. However, this is currently not the case:

- Different sectors are subject to different carbon prices, which distorts the level playing field for different mitigation pathways. For example, electricity production is currently subject to the highest price under the EU ETS, whereas the absence of a pricing mechanism in agriculture and LULUCF means that bioenergy is not covered by any carbon price. As a result, the EU carbon pricing regime favours bioenergy use over electrification technologies (**policy gap/inconsistency**).
- EU policies support CCU/CCS, including CO_2 infrastructure, but do not currently target their deployment to applications with no, or limited, other mitigation options (**policy gap**).
- The EU's massive policy support for the hydrogen value chain does not sufficiently reflect the techno-economic limits of hydrogen and its most efficient uses in an integrated and decarbonised energy system (**policy gap**).

- The promotion of bioenergy under the REDI and II has resulted in substantial volumes of national subsidies for bioenergy use, even in sectors where available mitigation options (e.g. electricity and low-temperature heat production) are more efficient and carry lower land-use and biodiversity risks (**policy inconsistency**).

➔ **EU policies in support of CCU/CCS, bioenergy and hydrogen should be better targeted towards applications with no, or very limited, other mitigation options** (see Chapter 4, recommendations E6 and E7; Chapter 6, recommendation T4; Chapter 9, recommendations L1, L2 and L3).

Key recommendation 11 - More policy action is needed to increase public and private investments in climate mitigation.

Annual investments in climate mitigation need to be multiplied more than fourfold (from €200-300 billion per year in recent years to €1,250-1,400 billion a year up to 2030). This requires a reorientation of existing investments and an increase in overall investments in the energy and transport sectors (by at least €500bn per year). Given the magnitude of the investment gap, a concerted effort by both public and private sectors is needed.

The EU aims to spend 30% of its long-term budget (the MFF) and at least 37% of the RRF's national envelopes on climate action. However, flaws in the methodology for tracking climate spending results in over-reporting and, in the case of the MFF, does not capture spending on potentially harmful activities (**ambition gap**).

Reporting under the RRF is more robust as it applies the 'do no significant harm' principle, in line with the EU Taxonomy. However, the facility is expected to cease after 2026 and there is no clarity on whether it will be succeeded by a similar instrument, which limits the outlook for investors (**policy gap**).

The investment gap also needs to be closed through Member States' public budgets. Their fiscal space is however constrained by high expenditures to tackle recent crises, increased competition for public budgets, higher interest rates, and the EU's fiscal rules set out in the Stability and Growth Pact. Recent changes to state aid rules provide more leeway for Member States to support mitigation projects. However, this could fragment the internal market, and measures to address this (the proposed Strategic Technologies for Europe Platform) have insufficient budget (**ambition gap**).

➔ **The reporting methodology under the MFF should be improved to track more accurately EU expenditures that contribute to climate action, and to identify spending on potentially harmful activities** (see Chapter 12, recommendation F2).

➔ **The EU should consider continuing the common debt approach under the current RRF beyond 2026 to increase investors' certainty and boost EU public investment in climate action** (see Chapter 12, recommendation F3).

The private sector will need to make a substantial contribution to achieve the required level of climate-related investments. This must be driven by sufficiently ambitious EU policies that address technology-specific risks and funding gaps, to increase the supply of bankable climate mitigation projects. Measures could include regulations, carbon pricing and – where investments are not yet profitable under current carbon pricing trajectories – other tailored financial incentives and solutions. In addition, the policy framework must address permitting, access to capital, long-term regulatory visibility, supply chains and labour availability.

➔ **EU policies should address technology-specific risks and funding gaps by speeding up permitting, removing regulatory uncertainties, and providing tailored financial incentives and solutions where investments are not yet profitable with the current carbon price trajectory** (see Chapter 12).

2.3 Develop new policies

Key recommendation 12 - Pursue more ambitious reductions in energy and material demand through new and strengthened policies.

The Advisory Board's advice on a 2040 target highlighted that pathways with more emphasis on demand-side measures have multiple co-benefits compared to those prioritising supply-side technological solutions. So far, the EU policy framework has primarily concentrated on supply-side, technology-focused measures, and much less on initiatives aimed at moderating consumption of GHG-intensive products and services. The latter are either absent (e.g. no dedicated policies to moderate transport demand, to promote healthy diets, etc.) (**policy gap**) or ineffective (for instance, a lack of progress in reducing energy demand, achieving a modal shift, or increasing material circularity) (**ambition/implementation gaps**).

Several sectoral strategies under the European Green Deal include initiatives to address the issue, but many of these have not yet been proposed (e.g. a legislative framework of sustainable food systems) or adopted (such as the Regulation on the Use of Railway Infrastructure Capacity and the revision of the Combined Transport Directive). Furthermore, some of these initiatives are primarily focused on voluntary consumer responsibility, which is unlikely to be effective on its own (**ambition gap**).

➔ **EU policies should incentivise more vigorously the reduction of energy and material demand (in mobility, housing, material use and diets), both through efficiency improvements and behavioural changes. To enable this, policies should establish structures and introduce disruptive end-use innovations which increase the quality, affordability and convenience of lower-emissions products and services. The European Green Deal sectoral strategies include several initiatives that could contribute to this, but these remain to be proposed/adopted** (see key recommendation 1, Chapter 3, recommendations E2 and E3; Chapter 5, recommendations I2 and I3; Chapter 6, recommendations T1 and T2; Chapter 7, recommendations B1, B2 and B4; Chapter 8, recommendation A3; Chapter 11, recommendation W2).

Key recommendation 13 - Expand the EU GHG pricing regime to all major sectors (including agricultural/food, LULUCF and upstream fossil fuel operations), and provide EU-level incentives for carbon removals.

The recent revision of the EU ETS Directive substantially extends the scope of the EU GHG pricing regime, from 36% of total emissions and removals today to 74% by the end of this decade. However, the remaining 26% would still be excluded from any EU-wide GHG pricing regime (**policy gap**).

Most of this gap is due to the absence of an EU-level pricing mechanism in the agricultural and LULUCF sectors. The European Commission is currently studying ways of introducing some form of pricing mechanism in these areas but has not yet tabled a formal proposal. A GHG pricing mechanism for the agricultural/food and LULUCF sectors would provide a clear financial incentive for farmers and forest managers to reduce emissions and increase removals, and for consumers to reduce consumption of GHG-intensive agricultural products. It would also address the uneven distribution of incentives for biomass use versus carbon removal and reduce the risk of intra-EU leakage of agricultural and LULUCF-related emissions.

➔ **The EU should start preparations now with a view to expanding the pricing regime of EU GHG emissions to all major emitting sectors, including agricultural/food and LULUCF. For these areas, pricing instruments should incentivise both emissions reductions and carbon removals. Instruments should reflect the specific characteristics of the agricultural/food and LULUCF sectors. This includes the technical complexity of measuring emissions and removals, attributing them to land management and mitigation actions, differences in the permanence of various natural removals, and the risk of international leakage. The impact – in particular on small farms and farms in vulnerable regions – should be assessed *ex ante* and potentially adverse economic, social and environmental impacts addressed to ensure a just and fair transition. This could be done in different ways directly targeting the problems at hand. The CAP budget or revenues from such pricing mechanisms could be used to finance redistributive measures and to support climate mitigation and adaptation efforts** (see Chapter 8, recommendation A2; Chapter 9, recommendations L3 and L4; Chapter 10, recommendation C4).

Fugitive emissions from fossil fuel extraction and handling are not covered by the EU ETS and, until recently, were not covered by any other EU reduction policy (**policy gap**). The Methane Regulation aims to address this gap, but its ambition level will depend on the implementing acts to be adopted by the European Commission. It does not set a price on upstream GHG emissions from fossil fuel extraction and handling, either in the EU or abroad. As a result, climate externalities are not fully internalised in the price of fossil fuels supplied to the EU market (**policy gap**).

The emission intensity of oil and gas extraction and handling could be lowered considerably by setting a price on upstream emissions in the energy sector. Expanding the EU ETS to fugitive emissions from fossil fuel operations within the EU, and setting up a border adjustment mechanism (reflecting the EU ETS price) on upstream GHG emissions from fossil fuels imports, would incentivise fossil fuel exporters to adopt adequate regulations; it could take into account comparable reduction efforts outside the EU (e.g. the CH_4 emission charge under the US Inflation Reduction Act). The Methane Regulation could serve as a first step towards a robust monitoring, reporting and verification system for such instruments.

➔ **The EU should address upstream emissions from fossil fuel extraction and handling, both domestically and related to fossil fuels imported into the EU. Building on the Methane Regulation, it should consider expanding the EU ETS to fugitive emissions from domestic fossil fuel operations. In parallel, a border adjustment mechanism should be introduced for upstream GHG emissions from fossil fuel imports** (see Chapter 4, recommendation E9)**. Pricing upstream emissions from fossil fuels would also contribute to the required phase-out of these fuels in the EU** (see key recommendation 5).

1 Introduction

1.1 Context

The European Climate Law (EU, 2021c) sets out legally binding objectives for the EU to reduce its GHG emissions by at least 55 % by 2030 (compared to 1990), to reach net zero GHG emissions by 2050 at the latest, and to aim to achieve negative emissions thereafter. Achieving the 2030 and 2050 climate objectives under the European Climate Law requires GHG emission reductions at an unprecedented rate and scale, which will need to be driven by a comprehensive portfolio of ambitious and effective policies covering all sectors of the economy. To put the EU on track towards the 2030 – 55 % objective, the European Commission has proposed a wide range of policies under the European Green Deal (EC, 2019c) and the Fit for 55 package (EC, 2021m), building on the existing climate and energy *acquis*, which helped the EU to achieve its climate and energy objectives for 2020.

Since the launch of the Fit for 55 package, the broader socioeconomic and geopolitical context in which the EU is pursuing its climate objectives has become increasingly challenging. The COVID-19 pandemic in 2020–2022 and subsequent recovery have resulted in global supply shortages and inflation. These worsened following the start of Russia's war of aggression against Ukraine, which resulted in historically high energy prices in the EU and increased food prices globally. High levels of inflation led to a cost-of-living crisis in the EU and undermined the international competitiveness of EU businesses – notably in energy-intensive sectors (ESABCC, 2023a). As a response to the increasing inflation, central banks increased interest rates and therefore the cost of capital, which further increased overall investment costs. Furthermore, the economic slowdown and various support measures in the context of the COVID-19 pandemic and the energy crisis have led to a surge in public debt. This constrains the available budgetary space of the various EU Member States, which are facing competition in allocating scarce public budgets between the climate transition, digitalisation, military expenditure and investments in social infrastructure. In parallel, the global race for green investments accelerated when the Biden administration adopted the US Inflation Reduction Act, which risks drawing investments in green technologies away from the EU. China's dominance in key strategic low-carbon technologies (IEA, 2023j) also continues to threaten the long-term competitiveness and resilience of the EU. These developments have made the EU's climate transition more challenging, and have made the need for a cost-effective, fair and just transition more important than ever.

On the other hand, these developments also provide strong arguments to accelerate the transition, notably to reduce the EU's dependence on imported fossil fuels, to increase its strategic autonomy in important areas and to strengthen its position in the race towards the industries of the future. In line with these arguments, the European Commission took further steps to enhance the EU climate policy framework. In response to the energy crisis triggered by Russia's aggression, it launched the REPowerEU plan (EC, 2022p), which aims to reduce the EU's dependence on Russian fossil fuels, including by reducing energy demand and increasing the domestic renewable energy supply. In 2023, after the launch of the Inflation Reduction Act in the United States, the European Commission launched a Green Deal Industrial Plan to enhance the competitiveness of Europe's net zero industry (EC, 2023u).

At the time of publication of this report, the legislative proposals under the Fit for 55 package have been adopted (with the exception of the revision of the ETD), and political attention is increasingly shifting towards implementation and the post-2030 climate policy framework. The European Climate Law requires the European Commission to put forward a legislative proposal for an intermediate 2040 reduction objective within 6 months after the first global stocktake, which implies in spring 2024 at the latest. To this end, it launched a public consultation on the 2040 target and related climate policy

framework in spring 2023 (EC, 2023z). The European Climate Law requires the European Commission's proposal to consider, among other things, the advice of the Advisory Board, which was published on 15 June 2023 and recommends a reduction objective of 90–95 % by 2040 (compared to 1990), in combination with increased efforts outside the EU to achieve a fair contribution towards the 1.5 °C objective and climate neutrality by 2050 (ESABCC, 2023b).

1.2 Objective of the report

The main objective of this report is to advise EU policymakers on how to make the EU policy framework fit for net zero, by flagging potential gaps in the current framework to be addressed in order to keep the 2030 and 2050 climate objectives within reach. Where sufficient scientific evidence is available, the report also puts forward policy recommendations to address these gaps. To serve its purpose, the report focuses on two key research questions.

— To what extent is the EU on track towards achieving its climate objectives? This step makes it possible to identify areas where progress is lagging, which could be an indication of a lack of sufficiently ambitious and effective policies, or policy inconsistencies.
— To what extent are EU policies consistent with the objectives of the European Climate Law, and where is there a need for policy change to ensure such consistency?

This report is an integral part of a broader effort of the Advisory Board to provide scientific advice on existing and proposed Union measures and their coherence with EU climate objectives, and to identify actions and opportunities needed to successfully achieve those objectives, as mandated by the European Climate Law. It provides a broad overview of progress and policy consistency, across sectors and cross-cutting issues. Specific topics raised in this report will be elaborated on in subsequent, in-depth reports, such as the dedicated report on carbon dioxide removal (CDR), which is planned for publication in 2024 (ESABCC, 2022a). The Advisory Board also intends to provide periodical updates of this report.

With this first edition of the report, the Advisory Board in particular wishes to provide input to the discussions on the post-2030 EU climate policy framework, which are expected to accelerate in the after the publication of the European Commission's proposal for a 2040 GHG emission reduction objective. It is also intended as an input for new EU legislators, including the new European Commission, who will come into office after the 2024 European elections.

There are existing reports that assess progress towards the EU climate and energy objectives, including the EEA's annual Trends and Projections reports (EEA, 2023p) and the European Commission's annual Climate Action Progress reports (EC, 2023ax). For the latter, the scope of the 2023 edition was expanded to meet the requirements of the European Climate Law, which mandates the European Commission to, by 30 September 2023 and every 5 years thereafter:

— assess the collective progress made by all Member States towards the achievement of the 2050 climate neutrality objective;
— review the consistency of Union measures with that objective;
— assess the consistency of national measures – those that are identified as relevant to the achievement of the 2050 climate neutrality objective – with that objective.

Although the 2023 Climate Action Progress report does include highly relevant information on progress towards climate neutrality at both the EU and national levels, as well as recent policy developments, it does not include a systematic assessment of the consistency of EU policies with the objectives of the

European Climate Law ([2]). With the present report, the Advisory Board wishes to complement the reports by the EEA and the European Commission, by providing its own, independent assessment.

1.3 Scope of the report

This first edition of the report focuses on progress towards and policy consistency with the climate neutrality objective for 2050, with at least 55 % GHG emission reduction as a first milestone. Where possible (through availability and comparability of data), the assessment will also consider progress required by 2040, based on the Advisory Board's advice on the 2040 reduction objective.

The assessment will cover all major GHGs –CO_2, CH_4, N_2O and fluorinated gases (F-gases) – and all major emitting sectors of the EU economy, including energy systems, industry, transport (including international bunker fuels), buildings, agriculture and the LULUCF sector. The waste sector is not treated as a separate sector, but the consistency of waste policies is included under the industrial chapter in the context of the circular economy. Technological emission removals are not covered in this edition of the report but will be covered in a dedicated report on CDR in early 2024. In addition to this sectoral perspective, the report covers several cross-cutting issues, including carbon pricing, a fair and just transition, public engagement, finance and investments, innovation, governance, labour, skills and capacity building. The assessment in this report focuses on progress and policy consistency at the EU level and does not provide a detailed assessment of specific developments within the different Member States of the EU.

Climate adaptation, although an integral part of the European Climate Law, is not covered by this first edition of the report. The Advisory Board intends to publish a dedicated report on progress towards and policy consistency with the EU's climate adaptation objectives in the future.

The Advisory Board intends to broaden and deepen the scope of its assessment in subsequent updates of this report.

1.4 Outline

The report is structured as follows. Chapter 2 describes the underlying methodology that was used for the assessment. Chapter 3 provides a short overview of overall progress towards the EU's climate mitigation objectives. Chapters 4 to 9 describe progress towards and policy consistency with the climate objectives in each of the major emitting sectors, namely energy supply (Chapter 4), industry (Chapter 5), transport (Chapter 6), buildings (Chapter 7), agriculture (Chapter 8) and the LULUCF sector (Chapter 9). Chapters 10 to 14 cover cross-cutting issues including pricing GHG emissions and rewarding removals (Chapter 10), the need for a whole-of-society approach (which covers a fair and just transition and public engagement; Chapter 11), finance and investments (Chapter 12), innovation (Chapter 13), climate governance (Chapter 14) and labour, skills and capacity-building (Chapter 15).

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[2] The report states that 'for the first time this year this report assesses progress under the European Climate Law, including the collective progress made by Member States towards the EU's goal to achieve climate-neutrality by 2050', without referring to the issue of policy consistency. The report does acknowledge in general terms that there is scope to further improve the consistency of EU policies with climate objectives, and briefly refers to the updated better regulation instruments. However, it does not include a systematic overview of the consistency of existing EU policies with these objectives.

2 Methodology

2.1 Assessment framework

Achieving deep GHG emission reductions across all sectors of the economy will require a combination of different solutions – both demand- and supply-focused – that are often interlinked, as well as a broad supporting framework to facilitate those solutions. To structure the progress and policy consistency assessment, the Advisory Board has developed a framework that structures these different elements into:

- **GHG emission reductions**, which represent the GHG emission reductions (or, in the LULUCF sector, net emission removals) that would need to be achieved in each sector by 2050 as a contribution to the economy-wide climate neutrality objective;
- **outcomes**, the main results that need be obtained both on the demand side and on the supply side, to drive GHG emission reductions in line with the required GHG emission reductions;
- **mitigation levers**, which are physical changes that, all other things being equal, are certain to contribute to the achievement of the outcomes;
- **enabling conditions**, either physical or non-physical changes that do not directly contribute to the achievement of the outcomes but can facilitate (and are in some cases crucial for) the activation of one or more mitigation levers.

This approach – which was inspired by the UK Climate Change Committee's monitoring framework (UK CCC, 2022) – is illustrated in Figure 5 (based on the assessment framework for the transport sector).

Figure 5 Illustration of the assessment framework based on its application to the transport sector

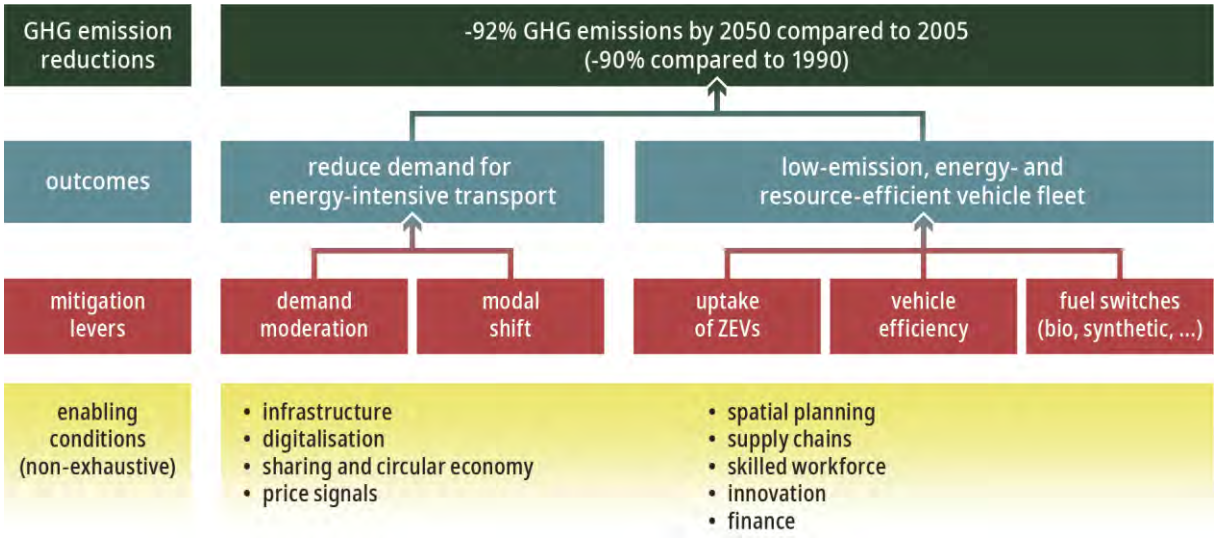

Source: Advisory Board (2024).

The GHG emission reductions required by 2050 for each sector are primarily based on the European Commission's scenarios that underpin the EU's 2030 and 2050 climate objectives, or – where available – on specific sectoral targets in official EU documents. For example, – 90 % by 2050 compared with 1990 for the transport sector is based on the European Green Deal communication (EC, 2019c).

The outcomes, mitigation levers and enabling conditions draw on the mitigation pathways presented in the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6) (IPCC, 2022d), complemented by insights from similar assessment frameworks developed by national advisory bodies in Europe.

2.2 Methodology for the progress assessment

Progress tracking based on indicators

To assess whether the EU is on track towards its climate objectives, the Advisory Board used an indicator-based approach which was inspired by similar existing assessments (Boehm et al., 2023, ECNO, 2023, Velten et al., 2021). Several indicators were selected to track progress on overall GHG emission reductions, outcomes, mitigation levers and some (but not all) of the enabling conditions (shown in Figure 6). This selection was made taking into account (i) the need for completeness (covering the required GHG emission reductions, outcomes and most of the mitigation levers), (ii) representativeness (indicators that representatively reflect progress on the related contribution, outcome, mitigation lever or enabling condition) and (iii) data availability. The relationship between the assessment framework described above and the indicators to track progress is illustrated in Figure 6, based on the assessment framework for the transport sector. Indicators are labelled based on the title of their respective capters (e.g. O1 to O3 for indicators discussed under Chapter 3 'Overall progress', T1 to T6 for indicators discussed under Chapter 6 'Transport', etc.).

Figure 6 Illustration of indicators (white boxes) for tracking progress based on their application to the transport sector

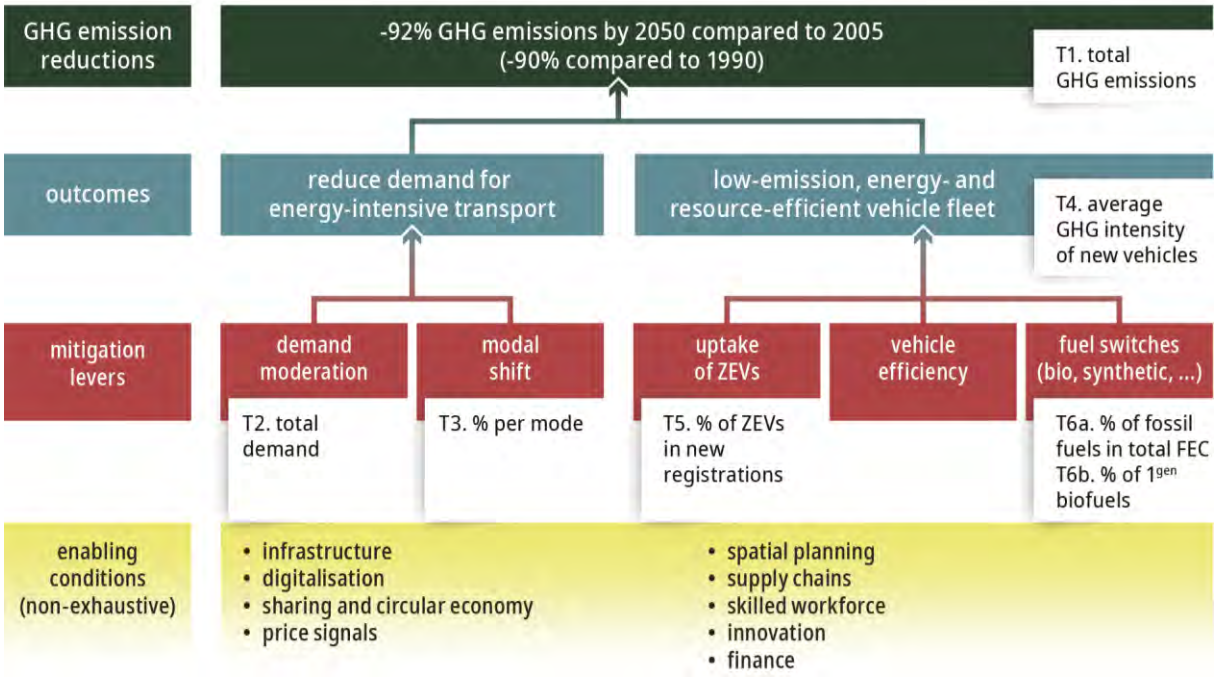

Source: Advisory Board (2024).

Comparing historical progress with linear trajectories towards 2030 and 2050 benchmarks

For each of the selected indicators, it was assessed whether historical developments are progressing at a sufficient pace to meet specific benchmarks for 2030 and 2050. More specifically, their average annual rate of change in the past (e.g. the average annual GHG emission reductions in megatonnes of CO_2e), or the average annual increase in solar PV capacities in gigawatts (GW) was compared with the required average annual rate of change to meet benchmarks set for 2030 and 2050 (which implies linear progress towards those benchmarks).

Historical progress was measured based on data from 2005 onwards, or – where 2005 data was not available – from the most recent year for which data was available. Tracking progress on GHG emission reductions is based on the average annual reduction between 2005 and 2022. For other indicators, recent historical progress was calculated as the average annual rate of change for the last 5-year period for which data is available. In some cases, an earlier 5-year period was taken, to exclude years with outlier values. This is particularly the case for indicators in the transport sector, which showed non-representative values in 2020 and 2021 due to the COVID-19 pandemic. Historical data is primarily based on official databases, including Eurostat, the EU GHG inventories and data from the EEA. In some cases, this was complemented with data from sectoral federations.

The 2030 and 2050 benchmarks for each indicator were based on a cascading set of possible sources (in descending order of priority):

1. legally binding objectives, which are embedded in EU legislation,
2. political objectives, which are objectives not embedded in EU legislation but politically endorsed by EU institutions such as the European Council, the Council of the European Union or the European Parliament,
3. proposed objectives, which are objectives put forward by the European Commission (either in legislative proposals or in strategic documents) but are not (yet) endorsed or approved by the other EU institutions,
4. outputs of the European Commission's scenarios that underpin the EU climate objectives, notably the scenarios underpinning the Fit for 55 package (EC, 2021v), the scenarios underpinning the 2020 Climate Target Plan (EC, 2020s) ([3]), and the scenarios from the in-depth assessment accompanying the 2018 LTS 'A Clean Planet for all' (EC, 2018e) ([4]); here, priority was given to the most recent scenarios.

Five categories of progress

The final step in the progress assessment methodology is to compare the ratio of the required rates of change (based on linear trajectories towards each chosen benchmark) to the recent historical rate of change ([5]). This ratio is referred to as the '**required change**'. Depending on this required change, each indicator is assigned to one of five categories of progress, as shown in Table 1.

([3]) For the Fit for 55 and Climate Target Plan scenarios, the MIX scenario was used as a source for the benchmarks. For most indicators, the difference in the outputs for 2030 across the different policy scenarios is very limited.

([4]) The 2018 in-depth analysis is based on the EU-28. Where necessary, values were recalibrated for the EU-27 based on the EU-27/EU-28 ratio in 2015.

([5]) For indicators that are heading in the wrong direction, the final ratio was inverted (recent historical rate of change / required rate of change) to better represent the magnitude of the divergence between the historical and required future rates of change. The ratio was also inverted for some indicators that put an upward pressure on GHG emissions, but whose benchmarks still allowed for a positive rate of change in the future, to better reflect progress. For example, under the European Commission's scenarios, transport demand is projected to increase further in the future, but at a much slower rate

Table 1 Categories of progress

On track	The required change is ≤ 1.
Almost on track	The required change is between 1 and 1.5.
Somewhat off track	The required change is between 1.5 and 2.
Considerably off track	The required change is ≥ 2.
Wrong Direction	The required change is < 0.

Note: The required change is calculated as the ratio of the required rates of change (based on linear trajectories towards each chosen benchmark) to the recent historical rate of change. For indicators that are heading in the wrong direction or that put upward pressure on GHG emissions on GHG emissions but whose benchmarks still allow a positive rate of change in the future, the ratio was inverted to calculate the rate of change (see footnote (5) for more details).

Source: Advisory Board (2024).

This assessment is based on both the required change until 2030 and the required change between 2031 and 2050. The progress category for 2031–2050 is by default limited to the category assigned to the period up to 2030. If, for example, progress is considerably off track towards the 2030 benchmark, but adequate to be consistent with the trajectory between 2031 and 2050 (because the benchmarks expect most progress up to 2030, and a slowdown after that), the indicator will be considered considerably off track for 2031–2050 too.

An overview of progress in the six different sectors covered by this report, including the categorisation of progress for each of the selected indicators, is included in a summary table at the end of each chapter. A full overview of the sources and assumptions underlying the progress assessment is included in Annex I.

Limitations of the progress assessment methodology

In practice, no legal, political or proposed objectives are in place for most indicators, and the benchmarks are therefore based on the outputs of the European Commission's scenarios that underpin the EU's overall climate objectives. The Advisory Board acknowledges that the detailed outputs of these scenarios are not intended as specific objectives that need to be achieved, and that there are several possible pathways towards achieving the climate objectives for 2030 and 2050. However, it is nevertheless useful to compare progress with these scenario outputs because the non-attainment of the benchmark for one indicator would require outperformance in other indicators to attain the overall objective. If most indicators within a sector are off track compared with these scenarios, it could be a strong indication that the sector in general is not progressing in line with the EU's overall climate objectives.

It is also important to note that the overall methodology to track progress is based on benchmarks that are set by EU institutions and the European Commission in particular, without questioning the validity or adequacy of those benchmarks.

than the observed rate of change in 2015–2019. Under the standard methodology, the required change would be ≤ 1 and therefore the indicator would be categorised as 'on track'. To prevent this unrepresentative outcome, for these types of indicators the ratio to determine the required rate of change was inverted.

Finally, the progress assessment is based on linear trajectories towards the benchmarks up to 2030, and between the benchmarks for 2030 and 2050. Using such linear trajectories is a simplification which does not consider the following.

— The uptake of new technologies is non-linear. It is usually characterised by an S-shaped curve, when uptake is slow at the beginning and then accelerates strongly, to slow down again as the market saturates.
— A non-linear GHG reduction trajectory would need to be followed between 2030 and 2050, to be consistent with the 90–95 % reduction objective for 2040 as recommended by the Advisory Board (ESABCC, 2023b). To reflect this, the progress assessment for some indicators ([6]) will also refer to the progress required to be consistent with the scenarios that underpin the recommended 90–95 % reduction objective for 2040. When this is the case, it will be explicitly specified throughout the report.

2.3 Methodology for the policy consistency assessments

Focus on internal and horizontal policy consistency

Policy consistency is a broad concept that can be interpreted in different ways, at different levels and across different dimensions. At a minimal level, it implies that there are no contradictions or counteractive signals in the policy framework, implying a neutral coexistence between different policies and policy objectives. At a more comprehensive level, it could also refer to the presence of policies that are mutually reinforcing, therefore resulting in synergies, which is also often referred to as policy coherence (Evans et al., 2023; Lenschow et al., 2018; Rogge and Reichardt, 2016). Furthermore, policy consistency can be assessed internally within a specific policy domain (e.g. whether EU climate policies are consistent with its climate objectives), horizontally across different policy domains (e.g. whether EU transport policies are consistent with the EU climate objectives) and vertically across different governance levels (e.g. whether national policies are consistent with the EU climate objectives) (Evans et al., 2023).

The scope of the policy consistency assessment for this report is summarised in Table 2. This assessment is focused on identifying potentially counterproductive EU policies, which hinder progress towards its climate objectives, and on assessing the suitability of EU policies to achieve those objectives, but does not go as far as assessing synergies between different policies (for lack of available evidence in existing literature). Furthermore, it focuses on consistency across the internal and horizontal dimensions, and therefore includes an assessment of EU policies in other policy areas (e.g. agriculture, transport, energy) that can have a substantial impact on GHG emissions. The consistency of specific national policies ('vertical consistency') with the EU climate objectives is beyond the scope of this report.

([6]) Depending on availability and comparability of data.

Table 2 Scope of the policy consistency assessment

	Internal	Horizontal	Vertical
Lack of conflicts	EU climate policies do not conflict with the EU climate objectives	EU non-climate policies do not conflict with the EU climate objectives	(Sub-)national policies do not conflict with EU climate objectives
Adequacy of policies	EU climate policies are adequate to deliver on the EU climate objectives	EU non-climate policies are adequate to deliver on the EU climate objectives	(Sub-)national policies are adequate to deliver on the EU climate objectives
Synergies between policies	EU climate policies are mutually reinforcing	EU climate and non-climate policies are mutually reinforcing	EU and (sub-)national policies are mutually reinforcing

Notes: The scope of this report is included in the green box. The grey text illustrates aspects of policy consistency that are not included in the scope of this report.

Source: Advisory Board (2024), adapted from Evans et al. (2023).

Consistency assessment based on the overall assessment framework

The methodology to assess policy consistency is based on the overall assessment framework described in Section 2.1. In short, the Advisory Board has assessed to what extent EU policies are (or can be expected to be) sufficiently driving the various mitigation levers and enabling conditions to achieve the outcomes and eventually the required GHG emission reductions. The aim of this assessment is to identify:

- **policy gaps**, when there are no EU policies in place to drive the required change in the specific mitigation lever or enabling conditions;
- **policy inconsistencies**, understood as cases where EU policies are providing incentives that counteract the required change in the relevant mitigation levers or enabling conditions;
- **ambition gaps**, which means there are EU policies in place to target the relevant mitigation lever or enabling condition, but their overall ambition level – in terms of either their objectives or their delivery mechanisms – is considered to be insufficient to achieve the outcomes;
- **implementation gaps**, which means there are ambitious EU policies in place, but implementation at the EU, national or subnational level has been ineffective so far.

Focus on existing and new key EU policies

The consistency assessment was carried out both for existing EU policies that have already been in force for several years (and therefore can be assessed *ex post* to some extent) and for new EU policies that have been recently adopted or are still under development (and of which therefore only an *ex ante* assessment is possible). The latter category includes the various new policies and revisions of existing legislation under the Fit for 55 package (EC, 2021m), other relevant strategies under the European Green Deal (e.g. the Farm to Fork Strategy (EC, 2020f), the Sustainable and Smart Mobility Strategy (EC, 2020k), the CEAP 2 (EC, 2020g)), REPowerEU (EC, 2022p) and the Green Deal Industrial Plan (EC, 2023u). As many of these policies are very recent (or even not yet fully adopted), the assessment of their consistency is preliminary.

Given the wide scope of this report, the assessment focuses on the key EU policies that the Advisory Board considers to be most relevant to the EU climate objectives. Going back to our building block

framework in Figure 5, it also focuses on key mitigation levers and some but not all enabling conditions. Whereas this does not constitute an exhaustive, comprehensive analysis of all EU policies that might affect the climate transition, the approach should provide a reasonably broad and robust overview of policy consistency at the EU level.

Assessment based on existing literature and independent assessment reports

The Advisory Board has based its assessment primarily on existing studies and reports that assess the consistency of EU policies with its 2030 and 2050 climate objectives. A wide variety of literature was consulted to this end, based on the following hierarchy:

1. scientific, peer-reviewed literature, with an effort to include evidence from recent publications (2019 or after),
2. reports and assessments by independent official institutions and organisations, including European organisations such as the ECA, the EEA, Science Advice for Policy by European Academies (SAPEA), the European Academies Science Advisory Council (EASAC), and international organisations including the IEA and the Organisation for Economic Co-operation and Development (OECD),
3. the European Commission's own data and impact assessments, including reports and studies by the JRC and the European University Institute/Florence School of Regulation,
4. reports and studies written or commissioned by other, independent research institutes and think tanks.

Although a wide range of literature was consulted to underpin the consistency assessment, it does not constitute a full review of all relevant available literature on the wide range of topics covered in this report. The Advisory Board has striven to give its assessment a broad scientific foundation by prioritising sources that are also synthesis assessments based on extensive literature reviews, including IPCC AR6, and by combining the joint expertise of its 15 members.

3 Overall progress

3.1 Progress on reducing greenhouse gas emissions

In 2022, total net greenhouse gas emissions in the EU (including emissions from international aviation) had decreased by 31% compared to 1990 (EEA, 2023p). Overall, the EU has managed to structurally reduce its GHG emissions by more than 1 Gt CO_2e, or 24 %, between 2005 and 2022 (based on proxy data), as shown in Figure 7. GHG emissions reduced by on average 62 Mt CO_2e per year in 2005–2022.

Figure 7 Indicator O1 – overall progress towards the EU's 2030 and 2050 GHG emission reduction objectives

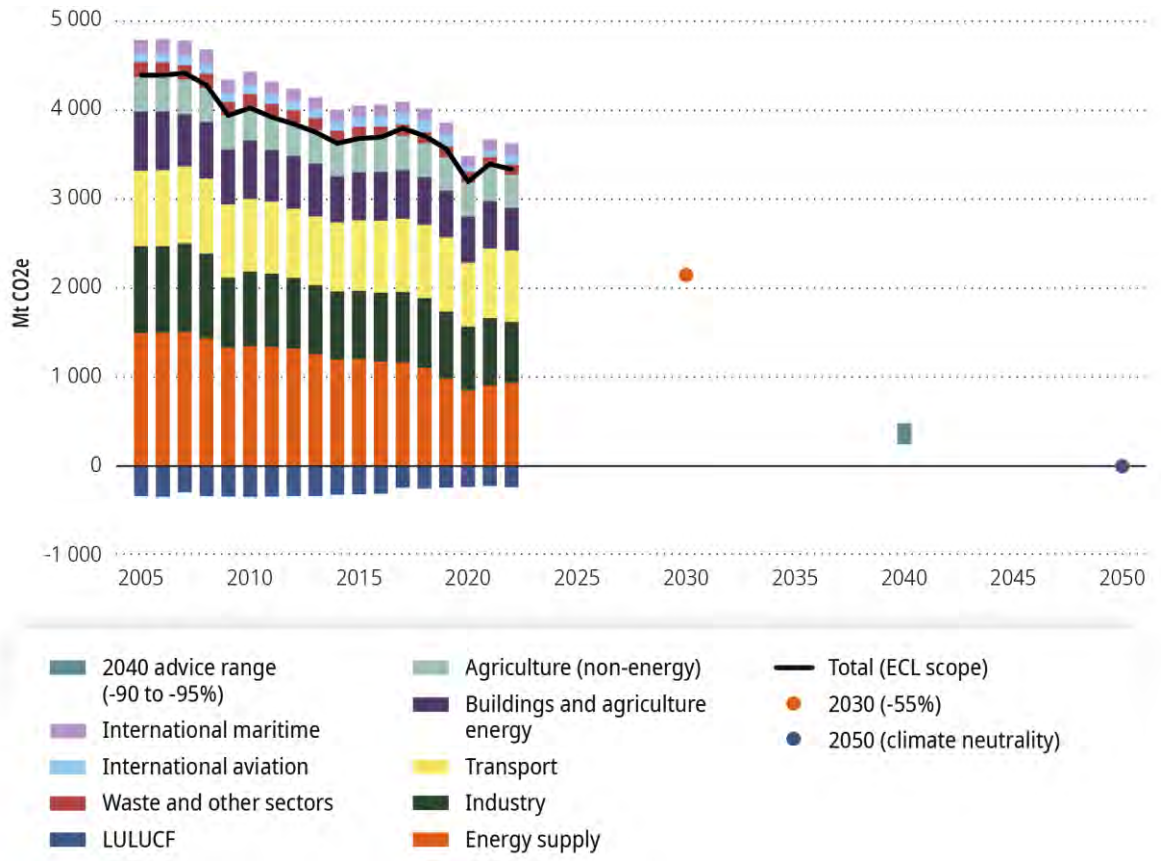

Notes: Historic emissions up to 2021 from the EU GHG inventory, with 2022 data based on proxy data received from the EEA. The 2030 -55% objective and 2040 90-95% range were calculated based on a reduction from 1990 historic emission levels, the 2050 objective is set at zero in line with the EU's climate neutrality objective. Indicators are labelled based on the title of their respective capters (e.g. O1 to O3 for indicators discussed under Chapter 3 'Overall progress', T1 to T6 for indicators discussed under Chapter 6 'Transport', etc.)

Sources: GHG inventories (EEA, 2023f)

While this is substantial progress, the pace of reductions must accelerate even further for the EU to remain on track towards its current 2030 and 2050 climate objectives (see Box 1 on the assumed scope of the GHG reduction objectives under the European Climate Law). Between 2022 and 2030, emissions would need to reduce by on average 141 Mt CO_2e per year, more than a doubling of the reduction trend observed since 2005. After 2030, the pace of reductions would need to remain high, at an average of 106 Mt CO_2e per year, towards the 2050 climate neutrality objective. To achieve the recommended 90–

95 % objective for 2040, GHG emission reductions would even need to accelerate to on average 171–198 Mt CO_2e per year in 2031–2040. A promising development is that GHG reductions have been accelerating in recent years (– 94 Mt CO_2e per year in 2018–2022), a trend that had already started in 2018–2019, before COVID-19 and the energy crisis. Furthermore, the deployment of key decarbonisation technologies such as solar energy, battery electric vehicles (BEVs) and heat pumps is picking up pace.

Box 1 Scope of the reduction objectives under the European Climate Law

The European Climate Law covers all emissions and emission removals regulated by Union law. The scope of the objectives under the European Climate Law is therefore considered to include all domestic emissions and emission removals (including LULUCF), and parts of international maritime and aviation transport.

For maritime transport, the 2021 emissions that are expected to be covered by the EU ETS ('at berth', intra-EU and 50 % of extra-EU maritime transport) correspond to 64 % of the international maritime emissions reported in the GHG inventory (EC, 2023k; EEA, 2023f). Therefore, 64 % of all international maritime emissions as reported in the GHG inventories (from 1990 to 2022) are assumed to be covered by the European Climate Law.

For aviation, the current EU ETS Directive covers in principle all flights arriving at and departing from airports located in the European Economic Area. However, it also provides a temporary derogation for extra-EU flights until 2026, thereby de facto limiting the EU ETS to intra-EU flights. Without further changes to the legislation, the EU ETS will again apply to both intra- and extra-EU flights as of 1 January 2027. However, Article 28b(3) of the directive requires the European Commission to – where appropriate – submit a proposal to apply the EU ETS to all flights departing from airports located in states in the European Economic Area. This would closely correspond with the GHG emissions for international aviation currently reported in the EU GHG inventories. The Advisory Board has therefore – by approximation – considered that international aviation emissions as reported in the EU GHG inventories correspond with the scope of the European Climate Law.

Whereas this report focuses on territorial (or production-based) emissions, in line with the objectives of the European Climate Law, Eurostat data on the EU's carbon footprint indicates that, in 2010–2020, consumption-based CO_2 emissions decreased on a par with production-based (or territorial) CO_2 emissions (Eurostat, 2023l). For the period before 2010, other studies have found that the technology-adjusted carbon footprint ([7]) of the EU and some of its Member States was below its territorial emissions (Jakob, 2022; Kander et al., 2015; Jiborn et al., 2018).

From a sectoral perspective (shown in Figure 8), GHG emission reductions between 2005 and 2022 were achieved primarily in energy supply (– 565 Mt CO_2e, – 38 %), followed by industry (– 290 Mt CO_2e, – 30 %) and buildings (– 183 Mt CO_2e, – 28 %). Progress in emission reductions has been considerably slower in the transport (– 47 Mt CO_2e, – 5 %) and agricultural sectors (– 19 Mt CO_2e, – 5 %). The LULUCF sector has been a net sink of GHG emissions; however, the size of the sink reduced by almost 30 % (– 98 Mt CO_2e).

([7]) This considers both embedded emissions of products imported into the EU and emissions avoided by exporting relatively GHG-efficient products from the EU.

Figure 8 Sectoral GHG emissions in 2005 and 2022

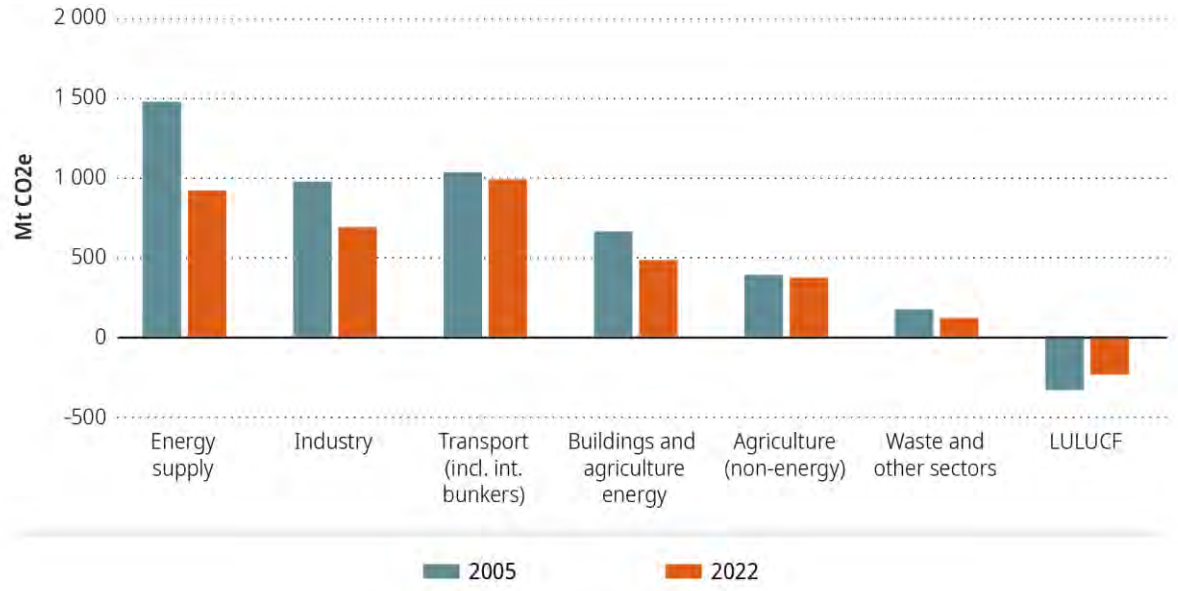

Notes: 2005 emissions based on the EU GHG inventory, 2022 emission data based on proxy data received from the EEA. Energy supply includes common reporting format (CRF) categories 1.A.1 and 1.B. Industry includes CRF categories 1.A.2 and 2. Transport includes CRF categories 1.A.3, emissions from international aviation (CRF memo item) and 64% of emissions from international shipping (CRF memo item). Buildings and agriculture energy include CRF category 1.A.4. Agriculture (non-energy) includes CRF category 3. LULUCF includes CRF category 4. Waste and other sectors includes CRF categories 1.A.5 and 5.

Sources: GHG inventories (EEA, 2023f)

3.2 Progress on energy efficiency and phasing out fossil fuels

As shown in Figure 9, in 2005–2021 the EU reduced its use of primary energy (– 12 %) and final energy (– 7 %), thereby achieving the 2020 energy efficiency target of 20 % set out under the EED (EU, 2012). However, the achievement of the 2020 target was in large part due to the COVID-19 pandemic. Without this external shock, the EU would not have reduced its energy demand sufficiently to achieve its 2020 objective, making it the only area where the EU had underdelivered its 2020 climate targets (EEA, 2022i). The average pace of reduction in final energy use in 2005–2021 (– 53 terawatt-hours (TWh) per year) would need to increase fivefold (– 265 TWh per year) in 2022–2030 to achieve the legally binding objective of 763 million tonnes of oil equivalent (Mtoe) (which corresponds to 8 874 TWh) under the revised EED (EU, 2023e). The latest EEA Trends and Projections report states that the Member States' latest projections – which date from 2019 – would only reduce final energy use to 885 Mtoe (10 293 Twh) by 2030, which is well above the newly agreed legal objective (EEA, 2023p). Such acceleration depends on energy efficiency policies; the complexities and challenges of this are addressed in more detail in Section 4.3.

Figure 9 Indicator O2 - progress in reducing primary and final energy consumption

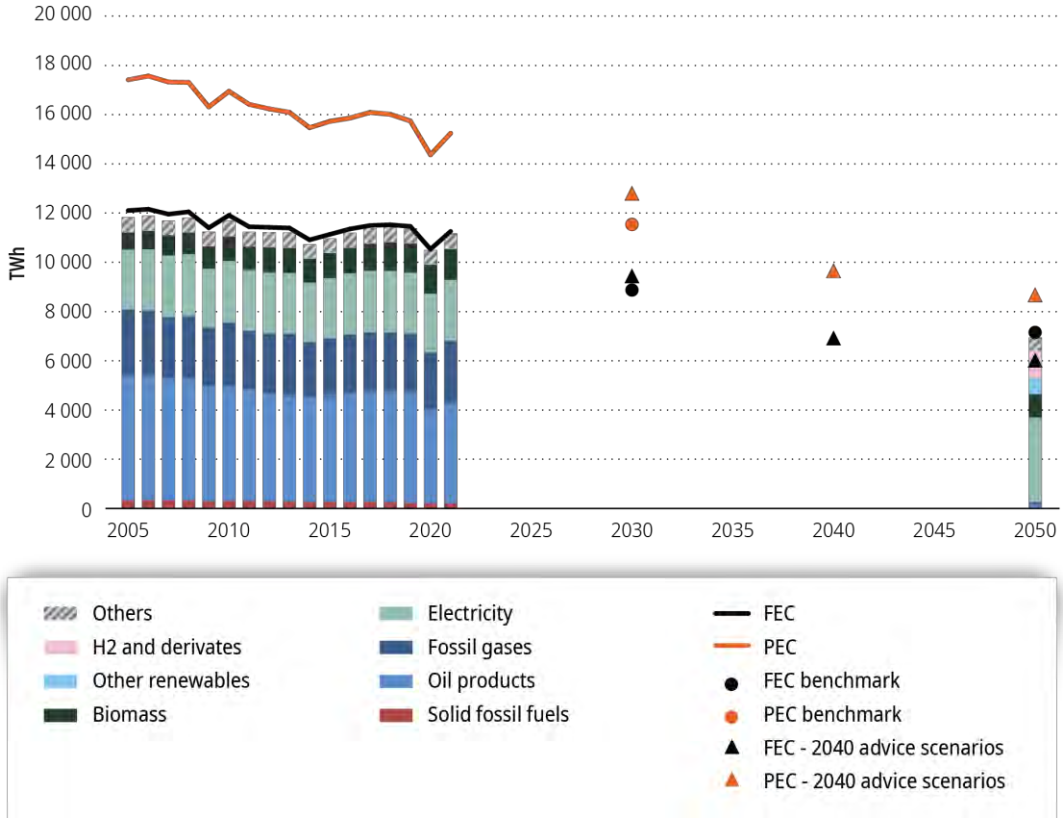

Notes: Historic energy use based on Eurostat energy balances. 2030 benchmarks based on the targets in the revised EED, while 2050 benchmarks based on the MIX Scenario from the Climate Target Plan impact assessment (Figure 17 & 37). Triangles represent the values of the scenarios underpinning the Advisory Board's advice on a 2040 reduction objective. Values converted to TWh.

Sources: Eurostat energy balances (2023b), revised EED (EU, 2023e), Climate Target Plan impact assessment (EC, 2020s), Advisory Board advice on a 2040 reduction objective (ESABCC, 2023b).

The share of fossil fuels in gross inland consumption ([8]) fell from 77 % in 2005 to 68 % in 2021, mainly achieved by a decrease in the use of solid fuels (– 5 percentage points (pp)) and oil products (– 5 pp), whereas the share of fossil gas increased (+ 2 pp). In 2021, the majority of the EU's gross inland energy use was still largely based on fossil fuels, notably oil products (33 %), fossil gas (24 %) and solid fossil fuels (12 %). To be consistent with the European Commission's scenarios that underpin the EU climate objectives, the phase-out rate for fossil fuels (on average – 0.6 pp per year in 2005–2021) would need to double up to 2030 (on average – 1.2 pp per year) and even more than triple thereafter (– 2 pp per year). By 2050, coal use would need to be phased out completely, whereas the use of oil (10 %) and fossil gas (7 %) would need to be reduced to less than 25 % of today's levels.

([8]) This includes non-energy use, but excludes energy use in international aviation and maritime transport.

Figure 10 indicator O3 - EU gross inland energy consumption

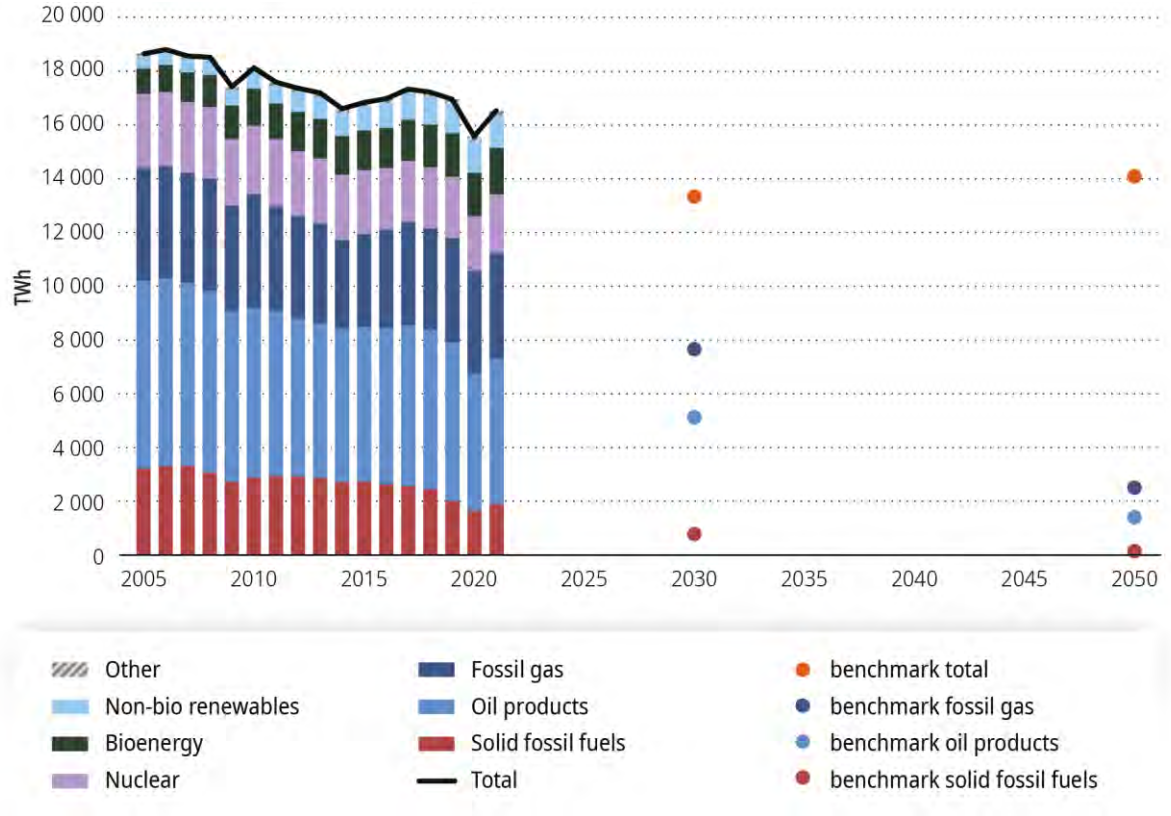

Notes: Historic energy use up to 2021 based on Eurostat energy balances. 2030 and 2050 benchmarks based on the MIX scenario of the Climate Target Plan impact assessment (figure 36). Peat and peat products included under solid fossil fuels, oil shale and oil sands included under oil products. The 'others' category includes waste and imports/exports of electricity and heat. All values have been converted to TWh.

Sources: Eurostat energy balances (2023b), Climate Target Plan impact assessment (EC, 2020s).

3.3 Progress on policy development

In 2019, the European Commission launched the European Green Deal as a strategic agenda to make the EU the first climate-neutral continent in the world (EC, 2019c). It initiated an extensive revision of the EU's policy and legal framework, with new legislation, revisions to existing legislation and additional funding all required to ensure consistency with the EU's climate ambitions. A key part of this was the Fit for 55 package, which was published in July 2021 and included a range of legislative proposals to put the EU on track towards the 2030 – 55 % objective (EC, 2021m).

While not an exhaustive list of all legislation and policy proposals stemming from the European Green Deal, Table 3 illustrates that the EU has already made substantial progress on several major pieces of legislation to align its policy and legal framework with its climate objectives. Many of the measures in the table have already been adopted at the time of writing, with those related to transport, effort sharing, carbon pricing, and finance and investments generally being the most advanced of all policy areas. Most of these adopted measures are already in force, while others, such as the EU ETS 2 and the Social Climate Fund, will come into effect in the coming years. Other policy areas are significantly less advanced and are still under negotiation between the institutions, notably many of the policies contained in the European Commission's recent Green Deal Industrial Plan and the CEAP 2. Although it is clear from this

table that climate policy and legislative development have greatly accelerated since 2019, it remains to be seen whether this pace will be maintained in the coming years.

This overview illustrates the substantial progress that has been made over the last few years in developing policies to set the EU on track towards its climate objectives. However, achieving the targets set by the European Climate Law not only depends on having certain legislation or policies in place, but requires them to be sufficiently ambitious, strong and comprehensive to deliver on the change required in the coming decades. Nor does this broad overview give insights into potential challenges or gaps in the implementation of different policies, which ultimately depends on the collective efforts and resources committed by the EU and Member States. This report therefore aims to provide a more comprehensive overview of the EU's progress towards climate neutrality by assessing current and future policies, identifying potential gaps or inconsistencies in their design and implementation, and providing recommendations on how to build on the progress that has been achieved to date on the path to climate neutrality.

Table 3 Summary overview of progress on the adoption of climate-relevant policies

Topic	Initiative	Legislative status
Carbon pricing and effort sharing	EU ETS for stationary installations (revision)	Adopted
	EU ETS 2 for buildings, road transport and additional sectors	Adopted
	Carbon Border Adjustment Mechanism	Adopted
	Effort Sharing Regulation (revision)	Adopted
Energy	Renewable Energy Directive (revision)	Adopted
	Energy Efficiency Directive (recast)	Adopted
	TEN-E Regulation (revision)	Adopted
	REPowerEU plan	Adopted
	EU electricity market design (revision)	Tabled
	Hydrogen and decarbonised gas market package	Close to adoption
	Methane Regulation	Close to adoption
	Energy Taxation Directive (revision)	Tabled
Buildings	Energy Performance of Buildings Directive (recast)	Close to adoption
	Construction Products Regulation (revision)	Close to adoption
Industry	Batteries Regulation	Adopted
	F-Gas Regulation (revision)	Close to adoption
	Net-Zero Industry Act	Tabled
	Critical Raw Materials Act	Close to adoption
	Industrial Emissions Directive (revision)	Close to adoption
	Ecodesign for Sustainable Products Regulation	Close to adoption
	Packaging and Packaging Waste Regulation (revision)	Tabled
	Waste Framework Directive (revision)	Tabled
	Right to Repair Directive	Tabled
	Green Claims Directive	Tabled
Transport	CO_2 emission standards for cars and vans (revision)	Adopted
	Alternative Fuels Infrastructure Regulation	Adopted
	ReFuelEU Aviation Regulation	Adopted

Topic	Initiative	Legislative status
	Carbon Offsetting and Reduction Scheme for International Aviation	Adopted
	EU ETS for aviation (revision)	Adopted
	FuelEU Maritime Regulation	Adopted
	CO_2 emission standards for heavy-duty vehicles (revision)	Tabled
	End-of-life vehicles Regulation (revision)	Tabled
	Trans-European Transport Network Regulation (revision)	Close to adoption
	Regulation on the use of railway infrastructure capacity in the single European railway area	Tabled
	Combined Transport Directive (revision)	Tabled
Carbon removal	Certification framework for carbon removals	Tabled
Agriculture	Sustainable food systems legislative framework	Announced
Land use	LULUCF Regulation (revision)	Adopted
	Nature Restoration Law	Close to adoption
	Soil Health Law	Tabled
Finance and investment	Taxonomy Regulation (for sustainable investment)	Adopted
	Social Climate Fund	Adopted
	Just Transition Fund	Adopted
	European Green Bond Regulation	Adopted

Notes: Measures are classed as 'adopted' if the legislative process has been fully completed, 'close to adoption' if interinstitutional/trilogue agreement has been reached, 'tabled' if at a different stage of the legislative process and 'announced' when they have been announced (e.g. in one of the sectoral strategies under the European Green Deal or in the European Commission's annual work programme) but a formal proposal has not yet been tabled by the European Commission.

4 Energy supply

Key messages

Despite substantial progress since 2005, the rate of reductions in the energy supply sector needs to increase to be consistent with the overall 2030 – 55 % objective.

The energy supply sector has reduced its GHG emissions by 38 % since 2005, as shown in Figure 11. However, the average rate of reduction up to 2030 needs to increase by a factor of 1.6 compared with 2005–2022 to be consistent with the European Commission's scenarios underpinning the 2030 – 55 % reduction objective. At the same time, the sector's output in terms of electricity generation would need to increase considerably to enable the electrification of end use sectors.

To decarbonise the EU's energy supply in the long term, the end use electrification rate has to pick up and reach annual increases of 1 pp, so that at least one third of end use demand is electrified by 2030. Non-biomass RES need to be scaled up, mainly by doubling the annual rate of solar power capacity installation and a fivefold increase in the annual rate of offshore wind installation. This needs to be accompanied by increases in the annual rate of CH_4 emission reduction in the energy sector by a factor of 1.4, and in the annual rate of reduction of fossil fuel use in electricity generation by a factor of 1.5. To underpin this changing energy supply structure, it is estimated that annual electricity grid investment must increase by at least a factor of 1.5 to reach nearly EUR 60 billion per year, with a large share of new investment directed towards distribution grids (low and medium voltages).

Figure 11 Indicator E1 – overall progress in reducing GHG emissions in the energy supply sector

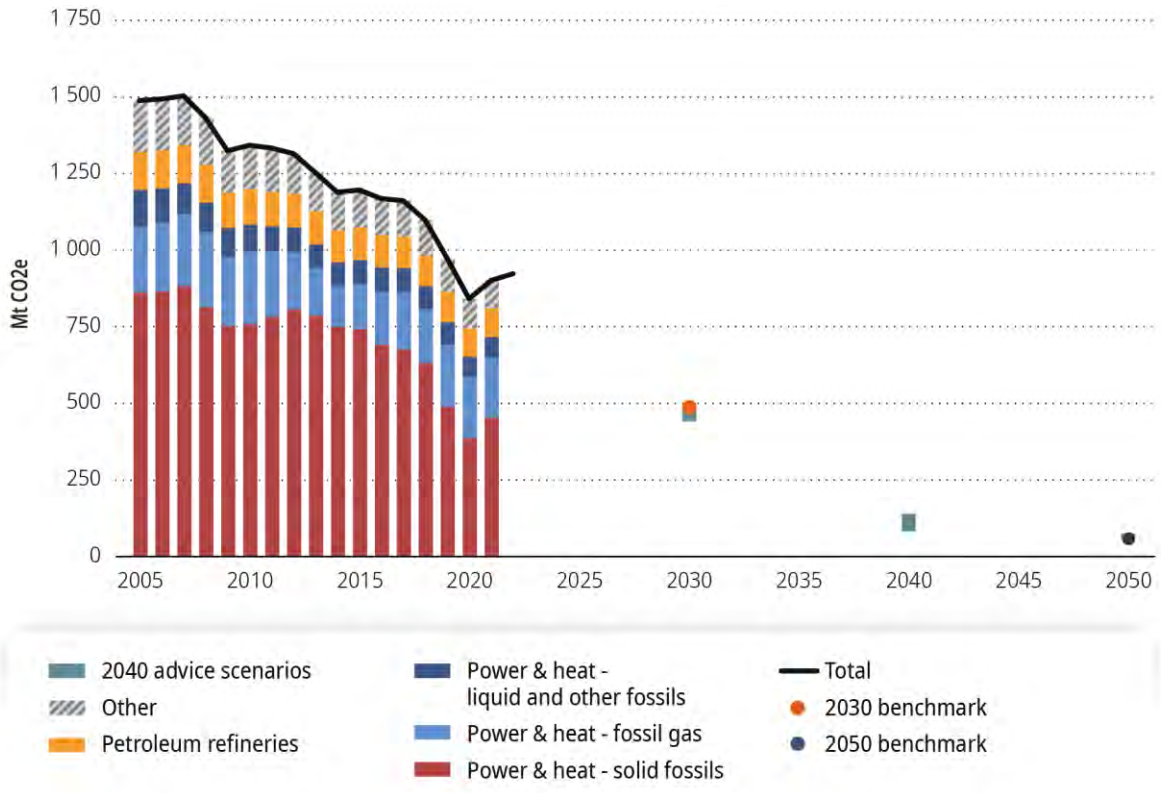

Sources and Notes: See Figure 13 for detailed sources and notes.

The decline in coal and fossil gas is too slow as a result of insufficient price signals, continuing subsidies and inconsistencies in the EU policy framework.

Needs. To be consistent with the European Commission's scenarios underpinning the 2050 climate neutrality objective, the EU needs to sharply decrease the use of fossil fuels (see Section 3.2), and almost fully phase out the use of coal and fossil gas in public electricity and heat generation by 2040 The share of oil in energy supply also needs to decline. Oil decline is not covered in this chapter given its relatively small share in the overall EU (non-transport) energy supply structure.

Gaps. The revised EU ETS provides a strong signal to phase out fossil fuel use in public electricity and heat production. However, not all EU policies are consistent regarding the declining role of fossil gas in future energy systems (e.g. the TEN-E Regulation, the proposed Gas Directive and regulation, State aid rules and the EU Taxonomy), and, because of the necessary speed of change in the energy sector, decisions made today are risking costly infrastructural and contractual carbon lock-ins **(policy inconsistency)**.

Recommendation E1. Practices within the EU policy framework, such as the scenarios and assumptions used in cross-border infrastructure planning and development, should be consistent with EU pathways to climate neutrality. According to these, fossil fuel use decreases sharply and is almost fully phased out from EU's public electricity and heat generation by 2040 ([9]). In this respect, and with a view to helping the EU avoid costly carbon lock-in effects, EU policies should be better aligned with net zero goals, notably in the field of energy infrastructure and markets (e.g. TEN-E, the internal energy market framework), finance (e.g. the EU Taxonomy), industrial emissions (e.g. the industrial emission directive) and competition (e.g. State aid rules).

The EU's target for final energy demand reduction is fit for net zero, but achieving it calls for energy efficiency – including its multiple benefits – to be better measured and understood, and for the energy efficiency first principle to be systematically put into practice.

Needs. The EU needs to substantially increase and accelerate energy savings in both primary and final energy consumption to reach the 2030 targets under the EED (see also Section 3.2).

Gaps. Energy efficiency is the only area where the EU made insufficient progress to achieve its 2020 target (which was met thanks to the impact of the COVID-19 pandemic). Progress was hampered by, among other things, insufficient understanding and measurement of energy efficiency and its multiple benefits as part of planning and reporting under the EED and energy retrofit investment schemes. Understanding issues also led to insufficient operationalisation of the energy efficiency first principle so far **(implementation gap)**. While the EED aims to reinforce the application of the energy efficiency first principle, it sets a very high investment value (EUR 100 million) threshold, which means that many relevant projects will be exempted from assessment of energy efficiency solutions, including demand-side resources and system flexibilities **(ambition gap)**.

Recommendation E2. To achieve the 2030 energy efficiency targets under the EED, EU policies should foster public awareness of the multiple benefits of energy efficiency, such as energy security and health, and increase common understanding and measurement of energy efficiency under the EED. To this end, policies should be informed by insights from the energy efficiency obligation schemes and the coordinated measures to reduce demand for fossil gas.

([9]) Any remaining fossil gas share in the EU's 2040 energy mix for public electricity and heat generation is marginal.

Recommendation E3. Putting the energy efficiency first principle into practice should be mandatory for all energy infrastructure projects advancing energy system integration. The investment value threshold set out in Article 3 of the EED should be lowered.

The deployment of solar PV and wind energy needs to accelerate across the EU and lead to a net zero electricity system by 2040 at the latest. Progress is challenged by changing investment landscapes, and by inadequate infrastructure planning and development, spatial planning, issuing of permits, workforce skills and supply chains.

Needs. The EU needs to massively scale up solar PV and wind energy deployment, with a view to decarbonising electricity supply by 2040 at the latest. The considerable obstacles to accelerating and enabling deployment must be urgently overcome, including electricity grid infrastructure development, permit-issuing, supply chain and workforce barriers.

Gaps. EU policies have been adapting to this challenge, among others, through the REPowerEU plan, new permit-issuing rules, the revised RED III, legislative proposals on the electricity market design and the Net-Zero Industry Act. The RED III, including the newly adopted target of a 42.5 % renewable energy share in final energy consumption and the electricity market reform are mostly in place, the RES value chain reinforcement is still under negotiation **(policy gap)**. This lowers investment certainty and affects system planning and decision-making, for instance in PV and wind value chains, as they have not yet been adjusted to the required deployment and industry growth. Moreover, while changes to the design of RES support schemes allow adaptive improvements, they may also increase investment risks and decrease investors' certainty.

Recommendation E4. EU policies reflecting the growth needs in wind and solar PV need to be adopted and implemented without further delay with a view to reinforcing long-term investment signals. To attract investment, support schemes for RESs need to (i) be stable, (ii) offer a long-term market outlook and (iii) find a balance between least-cost RES at scale and nurturing technological innovation. The long-term investment outlook should be reinforced through the 2023–2024 NECP process, which can reveal national ambitions regarding RES investments including, for example, volumes of auctions measured against the pace of progress required to achieve climate neutrality by 2050.

The topic of bioenergy is discussed in Section 9.5 (see enabling condition "Keep biomass demand within sustainable limits").

Although the European Commission endorsed system integration as a strategic direction in 2020, the EU still lacks long-term planning for a transformation of the energy system as a whole. Policy support is needed to boost direct electrification, digitalisation and non-fossil flexibility options. These mitigation options require distribution system operators (DSOs) and regulators to adapt fast. Direct electrification should be prioritised over indirect electrification (e.g. hydrogen) to avoid conversion losses.

Needs. Cost-effective decarbonisation requires energy system integration through RES-based electrification and digitalisation. The share of electricity in the EU's energy use needs to double by 2040, which means the recent trend needs to be reversed. By 2030, the flexibility needs of the EU electricity system will more than double from today's level. To meet them, demand-side response, grid expansion and innovation, storage and dispatchable generation need to be upscaled. Distribution system operations play a key role in this process, but the network operators and regulators need to adapt fast.

Gaps. Despite the endorsement of the system integration as a strategic direction by the European Commission in 2020, the EU still does not plan and operate the energy system as a whole **(implementation gap)**, as pointed out by the Advisory Board in its previous contribution on decarbonised and resilient EU energy infrastructure (ESABCC, 2023c). This risks locking in options that are not viable beyond 2030 as the EU moves towards a decarbonised energy system. Carbon lock-ins increase long-term mitigation costs and delay the net zero transition. Digitalisation of the energy sector was embedded in an EU action plan in October 2022 and is synergetic with existing and new EU policies (e.g. the RED III, the EED, the EPBD, the Net-Zero Industry Act) that aim at encouraging direct electrification, demand response, and district heating and cooling. EU policies so far have not sufficiently activated new players (e.g. aggregators, active consumers), the roles of transmission and distribution system operators and regulatory authorities, and dynamic pricing and business models (e.g. virtual power plants)**.** The impact of the new laws including the electricity market reform in terms of upscaling demand response and storage is still uncertain. The EU's massive policy support to the hydrogen value chain does not sufficiently reflect the techno-economic limits of hydrogen and its role in the integrated and decarbonised energy systems **(policy gap)**.

Recommendation E5. The EU should improve energy system integration through better energy infrastructure planning and development and through urgently delivering on new policies to bring about direct electrification and non-fossil flexibilities in line with the energy efficiency first principle.

Recommendation E6. EU policies should better target hydrogen deployment, prioritising well-defined uses that cannot be directly electrified, notably in industrial processes (see Chapter 5 'Industry') and fuels for some modes of transport (mostly aviation and shipping; see Chapter 6 'Transport').

EU policies support CCU/CCS without a strategy for targeting their deployment to applications that have no of very limited other mitigation options.

Needs. Fossil fuel phase-out is a priority for the decarbonisation of EU energy systems. By 2050, CCU/CCS needs to play only a limited role in energy supply. This is because of the limitations of CCU/CCS such as its capital intensity and impacts on the energy system. The value chain of CCU/CCS across the EU is not yet mature and needs to be developed only where non-fossil alternatives are not viable.

Gaps. Several EU policies support CCU/CCS, including CO_2 infrastructure (e.g. REPowerEU plan, hydrogen strategy, TEN-E Regulation, Innovation Fund, Net-Zero Industry Act proposal, State aid rules), without targeting their deployment to applications with no or limited other mitigation options. Residual emissions (e.g. in agriculture or industry) that motivate the use of carbon capture and storage (CCS) are currently not defined at the EU or Member State level **(policy gap)**.

Recommendation E7. Carbon capture and utilisation or storage are less efficient or have higher sustainability risks compared to other mitigation pathways such as renewable energy deployment. EU policies in support of the CCU/CCS should be better targeted towards applications with no or very limited other mitigation options (see Chapter 5 'Industry' and Chapter 9 'Land use, land use change and forestry').

Progress in development and roll-out of innovative energy technologies is too slow to unlock the decarbonisation of the EU energy supply. To remain a front runner in innovative energy technologies, the EU has to increase its efforts in research, development and market scale-up of innovative renewable energy and flexibility sources.

Needs. The EU needs to improve support of research and innovation, and accelerate market scale-up of innovative renewable energy technologies. Other technologies such as concentrated solar power, geothermal energy and innovative storage concepts could contribute significantly more to EU energy supply if innovation hurdles and inadequate value chains were addressed.

Gaps. Despite the strategic policy direction towards the market upscaling of innovative renewable energy technologies, they show slow progress in market roll-out because of immature markets and inadequate value chains involving high upfront costs and significant technical risks, among other reasons.

Recommendation E8. The EU should review its allocation of research and development (R & D) spending to technologies, considering their expected and potential future contributions to the energy mix. This can also include support to build up value chains and workforce skills (see Chapter 13 'Innovation' and Chapter 15 'Labour, skills, and capacity building').

The largest sources of CH_4 emissions from the energy sector were subject to a major EU policy gap until the agreement on the EU regulation on CH_4 emissions from the energy sector in November 2023. The new regulation is a step in the right direction, but the actual ambition of the new rules is yet to be defined. The EU should also consider expanding the EU ETS to fugitive emissions from domestic fossil fuel operations, and in parallel introduce a border adjustment mechanism for upstream GHG emissions from fossil fuel imports.

Needs. By 2050 at the latest, the EU needs to eliminate fugitive CH_4 emissions from coal and fossil gas operations and from biomass combustion, which are the largest sources of energy-related CH_4 emissions. Fugitive CH_4 emissions are currently not systematically measured and can continue many years after oil, gas or coal operations have ceased. Until recently, fugitive CH_4 emissions in the energy sector have not been addressed by EU policies. The new EU regulation on CH_4 emissions from the energy sector aims to address this gap and could become a crucial instrument in EU energy supply decarbonisation. At the time of writing of this report, no agreed legislative text had been published, however. The regulation's scope also covers non-EU operators exporting fossil fuels to the EU. In this regard, the new law offers an opportunity for the EU to support global decarbonisation efforts.

Gaps. The new EU regulation on CH_4 emissions in the energy sector requires monitoring, reporting and verification measures to be put in place only by 2027, and maximum CH_4 intensity values by 2030. The ambition of the applicable thresholds, including the minimum detection limits and the maximum CH_4 intensity values, will depend on the implementing acts to be adopted by the European Commission. This indicates a delay and ambition uncertainties in EU policies on reducing energy-related CH_4 emissions. The regulation does not put a price on leaking upstream emissions and does not align with similar international initiatives **(policy gap)**.

Recommendation E9. The EU should address upstream emissions from fossil fuel extraction and handling, both domestically and related to imported fossil fuels imported into the EU. Building on the Methane Regulation, it should consider expanding the EU ETS to fugitive emissions from domestic fossil fuel operations, and in parallel introduce a border adjustment mechanism for upstream GHG emissions from fossil fuel imports. Pricing upstream emissions from fossil fuels would also contribute to the required phase-out of fossil fuels in the EU.

4.1 Scope and sectoral assessment framework

Scope

This chapter focuses on the energy supply sector, which includes electricity and (public) heat production, and fossil fuel extraction, processing (e.g. refining), transport and distribution (including fugitive emissions).

The interplay between energy supply and demand is a key factor in the clean energy transition, as demand-side responses can enable greater renewable energy penetration and more efficient energy uses. Therefore, the policy consistency assessment in the chapter goes beyond energy supply, and also considers broader aspects of energy demand. The demand for energy in end use sectors and specific policies to address this are further elaborated on in the dedicated chapters (see Chapter 5 'Industry', Chapter 6 'Transport' and Chapter 7 'Buildings').

Greenhouse gas emission reductions required in the energy supply sector to reach climate neutrality

According to the European Commission's policy scenarios underpinning the 2050 climate neutrality objective, the energy supply sector will need to achieve near-zero GHG emissions by 2050 (zero emissions in electricity, > 90 % reductions in other supply sectors), before considering negative emission technologies. The use of fossil fuels for public electricity and heat generation would need to be almost fully phased out by 2040, resulting in zero emissions from those activities by that date at the latest. (EC, 2018a, EC, 2020h). This is also consistent with the IPCC scenarios, which see the energy supply sector reach net zero emissions well before other sectors of the economy on the path to climate neutrality by 2050 (IPCC, 2022g).

Assessment framework for the energy supply sector

Outcomes. Two main outcomes are considered for the assessment: reduced GHG emissions from energy supply, and reduced energy demand.

Mitigation levers. To achieve these outcomes, six main mitigation levers were identified based on IPCC AR6 and other scientific literature.

- **Energy efficiency.** Bring down energy sector needs, including energy conversion and distribution losses, through fossil fuel phase-out, deployment of RESs and direct electrification. Beyond energy supply, energy efficiency depends on end use sectors and their efficient consumption of energy in sufficient quantities.
- **Fossil fuel phase-out.** Substantially lower the use of fossil fuels compared with today by decommissioning of coal, gas and oil facilities, and limited carbon abatement/removal in specific cases. Given the low demand for oil in the energy sector (less than 5 % in 2021 according to (Eurostat, 2023b), the phase-out of oil is addressed in sectoral analyses in Chapters 5–7.
- **Fast roll-out of renewable energy at scale.** Significantly increase and accelerate deployment of RESs, mainly wind and solar PV, but also dispatchable non-biomass renewables. Bioenergy deployment, subject to stringent sustainability criteria and the energy efficiency first principle, also contributes to a net zero energy system.
- **System integration.** Coordinated planning and operation of the energy system as a whole, across multiple energy carriers, infrastructures and consumption sectors (European Commission,) should focus on (i) zero-carbon flexibility solutions, such as storage and advanced control tools, and (ii) direct electrification of end uses, including light-duty transport, space heating and cooking.

— **Targeted carbon capture and utilisation/storage.** Apply CCU/CCS in a number of industrial processes and the fossil fuel electricity sector where non-fossil mitigation options have been exhausted, based on a scientifically led definition of residual emissions.
— **Reduction of CH_4 emissions.** CH_4 mitigation options in energy supply include leak detection and repair in fossil gas operations, and CH_4 recovery.

Enabling conditions. In addition, seven enabling conditions have been identified as key to at least one of the mitigation levers described above. Two sector-specific enabling conditions are addressed in this chapter.

— **Infrastructure.** Energy system planning should include identifying net zero projects, scaled-up investment in electricity grids at all voltage levels, and faster issuing of permits for renewable energy infrastructure within the bounds of sustainability.
— **Market signals.** Regulatory certainty, long-term investment signals and well-functioning wholesale and retail markets can stimulate the expansion of variable energy sources and their integration with non-fossil flexibility solutions.

Some other cross-cutting enabling conditions, which are discussed in other chapters of this report (price signals, public engagement and a just transition, finance, innovation and a skilled workforce) are also relevant to the energy supply sector, as shown in Figure 12. This figure also shows the indicators (shown in the white boxes) that were selected to track progress in the energy supply sector.

Figure 12 Assessment framework for the energy supply sector

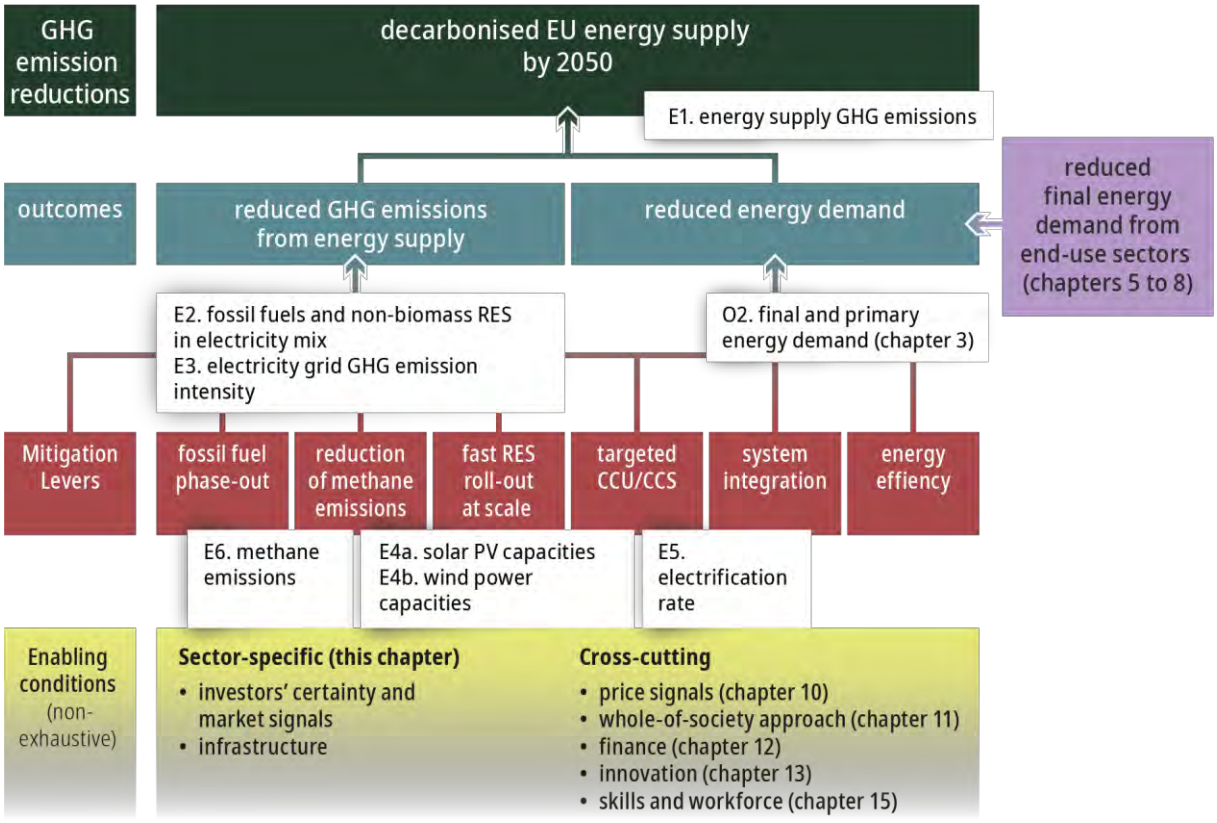

Source: Advisory Board (2024).

4.2 Emission reduction progress

The energy supply sector reduced its GHG emissions by 565 Mt CO_2e (– 38 % or – 33 Mt CO_2e per year) between 2005 and 2022 (see Figure 13). Between 2005 and 2020, there was a decrease of 648 Mt CO_2e (– 43 % or – 43 Mt CO_2e per year), followed by a rebound in GHG emissions in 2021 (+ 60 Mt CO_2e) and 2022 (+ 22 Mt CO_2e). The reduction until 2021 was mainly achieved by reduced coal use for electricity and heat production (– 407 Mt CO_2e, 70 % of the total decrease), with smaller emission reductions in other parts of the energy supply sector. The use of coal for electricity generation was mainly replaced by solar and wind electricity, and to a lesser extent by increased biomass use. If the average annual reduction experienced between 2005 and 2022 in the energy supply sector (– 33 Mt CO_2e per year) is maintained, the energy supply contribution will be sufficient to ensure net zero emissions by 2050. However, because the sector must decarbonise faster than other sectors, an acceleration of emission reductions to on average 54 Mt CO_2e per year (or by a factor of 1.6 compared with 2005–2022) is required to reach the 2030 benchmark. In pathways consistent with the 90–95 % objective recommended by the Advisory Board, the rate of reductions will then need to remain between 35 and 41 Mt CO_2e per year in 2031–2040.

Figure 13 Indicator E1 – overall progress in reducing GHG emissions in the energy supply sector

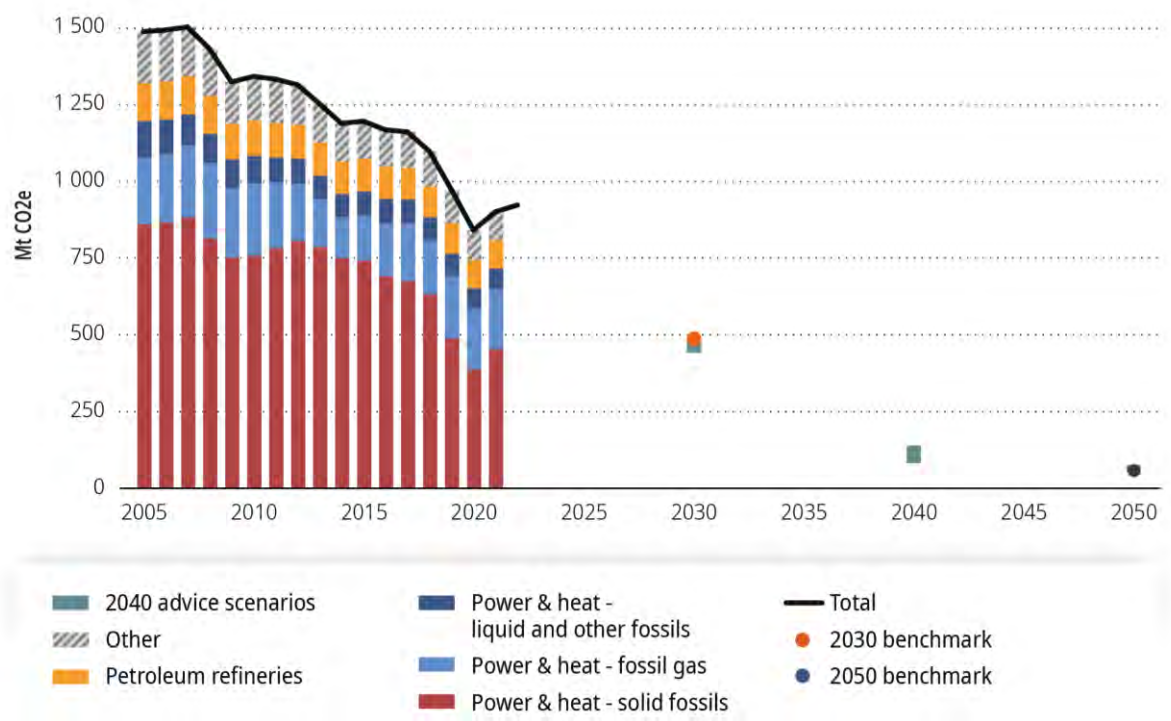

Notes: Historic emissions up to 2021 from the EU GHG inventory, with 2022 data based on proxy date reported by Member States to the EEA. Historic emissions include all GHG emissions from energy industries (CRF category 1.A.1) and fugitive emissions from fuels (CRF category 1.B). The 'other' category includes emissions from mining, fuel production other than petroleum refining, and gas distribution. The 2030 benchmark is based on the Fit for 55 MIX scenario and includes CO_2 emissions from electricity, heat and the "energy branch" and CH_4 emissions from energy use. The 2040 advice range is based on the scenarios which underpin the Advisory Board's 2040 advice. The 2050 benchmark is based on the 1.5TECH scenario of the in-depth analysis accompanying a Clean Planet for all (recalibrated for EU27 based on 2015 data), and includes all GHG emissions from electricity production, refineries and energy-related fugitive emissions.

Sources: GHG inventories (EEA, 2023f), Fit for 55 MIX scenario (EC, 2021v), Advisory Board 2040 advice scenarios (ESABCC, 2023b), in-depth analysis accompanying a Clean Planet for All (EC, 2018e).

4.3 Outcomes 1 and 2: decarbonised energy supply and reduced energy demand

Lever: energy efficiency

The EU target for final energy demand reduction is fit for net zero, but attention should be paid to energy intensity and emission intensity of energy supply as well as common metrics and understanding of energy efficiency concepts and benefits.

As described in Section 3.2, additional efforts are needed to achieve the legal objective of reducing the EU's final energy consumption to maximum 8 874 TWh in 2030.

The EU's energy demand is driven by many factors, including seasonal temperature changes, price signals and the structure of the EU economy. The flagship EU policy instrument driving energy demand reduction is the EED (EU, 2012), revised in 2023, which sets out EU energy efficiency targets for 2030. The agreed targets are final energy consumption of no more than 740 Mtoe (8 606 TWh) and primary energy consumption of no more than 960 Mtoe (11 165 TWh) at the EU level in 2030, which translates into a 40 % reduction in final energy consumption relative to the 2007 modelling projections for 2030(EU, 2023e). The new target is in line with the energy demand projections in the 2040 scenarios assessed by the Advisory Board (ESABCC, 2023b), and the Advisory Board therefore considers it to be fit for net zero.

In terms of final energy demand savings, the EED sets out energy efficiency obligation schemes, a flagship instrument in support of the EU energy efficiency target so far (EC, 2021g). The EU Member States should achieve cumulative end use energy savings up to 2030, with annual savings of at least 0.8 % of final energy consumption by the end of 2023, increasing gradually to 1.9 % from 2028 (EU, 2023e). This measure focuses on final energy consumption, and 'can be designed in a variety of ways to meet national needs, and to fit within very different policy mixes' (Fawcett et al., 2019). The success of final energy demand savings depends on the public's acceptance of ambition levels and its adoption of the saving measures they trigger (Fawcett et al., 2019; IPCC, 2022g; Wagner et al., 2020).

Regarding both primary and final energy consumption, delivery of the 2030 energy efficiency target will benefit from the application of the energy efficiency first principle (see Box 2). That principle was introduced to the EU policy framework in 2015 (EC, 2015b) and reiterated in the European Climate Law, with limited impact so far because, among other reasons, the stakeholders do not understand how to translate it into concrete action across the sectors (EC, 2021g). As Von Malmborg (2023) concludes, the 'energy efficiency first principle is constantly disputed in a struggle for interpretation, meaning and implementation'. This issue also affects pan-European energy system planning in support of infrastructure investment decisions; so far, that planning has not been sufficiently driven by the energy efficiency first principle (ESABCC, 2023c).

Box 2 Definition of energy efficiency first principle

The **energy efficiency first principle** in EU policy framework means 'taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand response initiatives and more efficient conversion, transmission and distribution of energy, whilst still achieving the objectives of those decisions' according to Article 2 of the Governance Regulation (EU, 2018e).

It is therefore a good sign that the principle is clarified and its application encouraged under the revised EED (EU, 2023e). However, Article 3 of the revised EED, which aims to operationalise the energy efficiency principle, sets a very high investment value threshold (EUR 100 million) to trigger the assessment of energy efficiency solutions including demand-side resources and system flexibilities. In practice, major infrastructure projects may be split into smaller investments below the threshold set; see, for instance, information on projects of common interest (PCI) available through the PCI Transparency Platform (EC and CINEA, 2023).

Putting the energy efficiency first principle into practice is stifled by lack of a common understanding of energy efficiency-related concepts and measurements, including the diversity of scientific observations, for example in terms of energy conversion efficiency of biofuel generation (Van Den Oever et al., 2022; IPCC, 2022g). It is generally difficult 'to define and measure' efficiency, which can be understood as a ratio between primary and final energy, between economic growth and energy consumption, or between energy savings and lower energy consumption (Dunlop and Völker, 2023). Misinterpretations and the lack of a harmonised approach have weakened annual monitoring of progress under the EU energy efficiency policies so far. Standardising of calculation methodologies as well as defining baselines and the savings additionality have challenged the implementation of the EED; so has assessing of behavioural effects (Renders et al., 2021).

Energy efficiency improvement towards 2030 depends on policy, on public awareness of the measurement and on governance (see also Chapters 11 'Whole-of-society approach' and 14 'Climate governance'). In this respect, experience from the EU gas demand reduction measure offers valuable insight. As an exceptional EU-led policy instrument fostering energy savings, it was put in place in response to fossil gas supply disruptions triggered by the Russian invasion of Ukraine. The European gas demand reduction plan communication (EC, 2022n), followed by the Council regulation on coordinated demand reduction measures for gas (EU, 2022b), set a voluntary (mandatory in emergencies) 15 % target for reducing Member States' gas consumption between summer 2022 and spring 2023 (with the average consumption between 2017 and 2022 as a baseline). The target has been extended to end of March 2024 (Council of the EU, 2023b). Modelling contributions, taking account of the disruption caused by the Russian invasion of Ukraine, highlights the benefit of EU energy demand reduction measures (10 % from transport and buildings sectors were assumed) for both the economy and the environment of the EU in the long run, including its potential to reverse the current headwinds facing the EU economy (Liu et al., 2023).

Lever: coal and fossil gas phase-out

Coal in energy supply decreases, but fossil gas decline is too slow

As described in Section 3.2, the phase-out of fossil fuels in the overall energy mix (across all sectors) needs to double by 2030 and even triple thereafter (compared with 2005–2021) to be consistent with the European Commission's scenarios underpinning the EU climate objectives.

Figure 14 displays the historical and benchmark shares of fossil-based and RES in EU electricity generation. The fossil fuel share has fallen from 52 % in 2005 to 36 % in 2021, while the renewable electricity share (excluding from biomass) has increased from 14 % to 32 %. In the 5 years from 2017 to 2021, the share of fossil fuels fell by 1.7 pp per year on average, while the share of renewables rose by 1.7 pp ([10]). Looking ahead, meeting the EU's climate goals for 2030 and 2050 (as represented by the Fit

([10]) The assessment of recent trends in these indicators excludes 2022 because in that year output from hydroelectric and nuclear plants was exceptionally low owing to a combination of hot, dry weather and technical outages (IEA, 2023h). The resultant increase in fossil fuel generation (from coal) is not expected to be repeated as plant operations return to normal and the capacity of other renewables continues to expand.

for 55 MIX scenario (EC, 2021v)) implies slightly accelerating the annual decline in fossil fuel share (to – 1.9 pp up to 2030) and accelerating the increase in renewable energy share (to + 1.8 pp) in the EU's electricity mix. However, this would need to happen in the context of increasing electricity demand, and therefore the deployment of renewable generation capacity would need to increase considerably (see indicator E4 below).

Based on the scenarios considered by the Advisory Board in the context of its advice on the 2040 target, wind and solar PV will account for 79–82 % of the electricity mix in 2040. The use of fossil fuels, notably coal and fossil gas, for public electricity and heat generation will be almost phased out in 2040, with the remaining emissions abated through carbon capture or CDR. The 2040 advice range refers to the final electricity consumption from the six scenarios assessed in the Advisory Board's 2040 advice that achieved 2040 emission reductions of 90–95 % while remaining within identified environmental risk levels.

In the scenarios from the Advisory Board's advice on an EU 2040 target and accompanying GHG budget, the acceleration to 2030 is more rapid compared with the benchmark, with the renewable share 16 pp. higher (and fossil share 2 pp. lower). The scenarios from the Advisory Board report also see continued rapid deployment of renewable generation beyond 2030, with its share reaching 88 % by 2040 and 95 % by 2050 (compared with 71 % in the Fit for 55 MIX scenario). By contrast, the fossil fuel share in 2040 falls to 1 % in the Advisory Board report scenarios, compared with a 13 % share in the European Commission's Fit for 55 benchmark.

Figure 14 Indicator E2 – shares of fossil-based and renewable energy sources (excluding biomass) in the total electricity mix

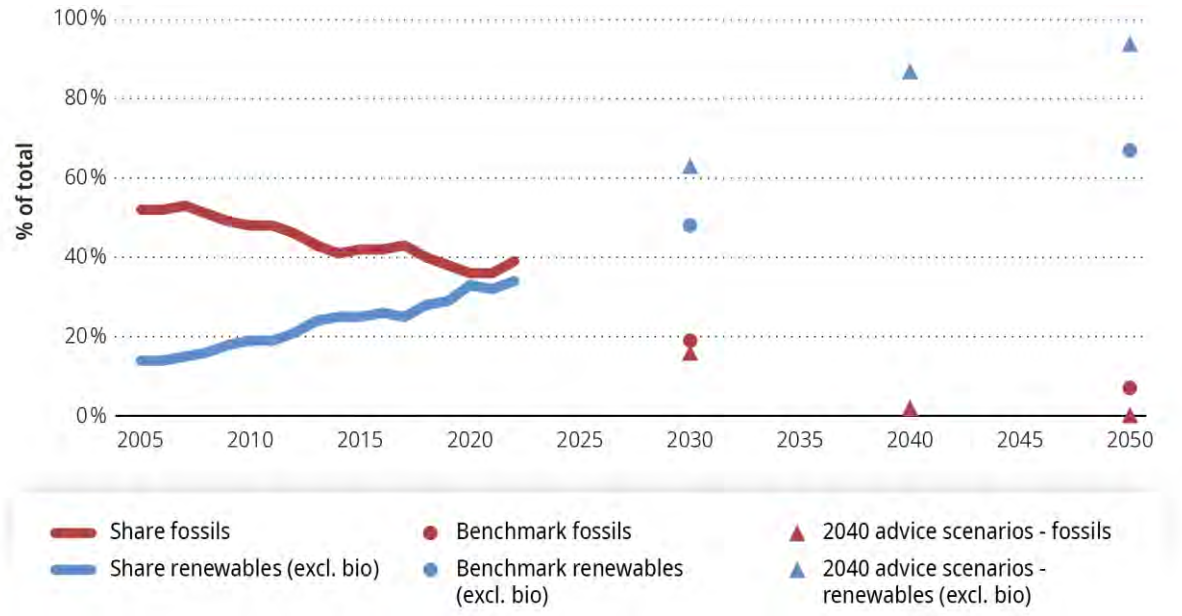

Notes: Historic data refers to gross electricity generation reported in the Eurostat energy balances. The 2030 benchmark and breakdown are based on the Fit for 55 MIX scenario. The 2050 benchmarks are based on the MIX Scenario from the Climate Target Plan impact assessment (see figure 46). For 2040, the benchmark refers to the High renewable energy iconic pathway of the Advisory Board's 2040 advice.

Sources: Eurostat energy balances (2023b), Climate Target Plan impact assessment (EC, 2020s), Fit for 55 MIX scenario (EC, 2021v), Advisory Board 2040 advice (ESABCC, 2023b).

The average grid GHG intensity (shown in Figure 15) declined steadily from 2005, until a rebound in 2021 and 2022 due to a combination of factors including record low volumes of hydro and nuclear electricity generation (ESABCC, 2023a). As a result, the decarbonisation rate of the electricity grid averaged 0 g CO_2e per kilowatt-hours (kWh) in 2018–2022. It needs to accelerate to 6 g CO_2/kWh in 2023–2030 to be consistent with the scenarios underpinning the Fit For 55 package. This decarbonisation rate (which is an increase from before 2015) needs to be maintained while increasing overall electricity consumption due to the electrification of end use sectors. The scenarios assessed in the Advisory Board's advice on an EU 2040 target envisage both a faster decarbonisation rate (21–23 g CO_2/kWh) and more electricity consumption than the Fit For 55 benchmark. Under both of the European Commission's scenarios that underpin the climate neutrality objective, like the scenarios underpinning the Advisory Board's 2040 advice, the electricity sector should already be fully decarbonised by 2040.

Figure 15 Indicator E3 – average intensity of greenhouse gas emissions from electricity grids

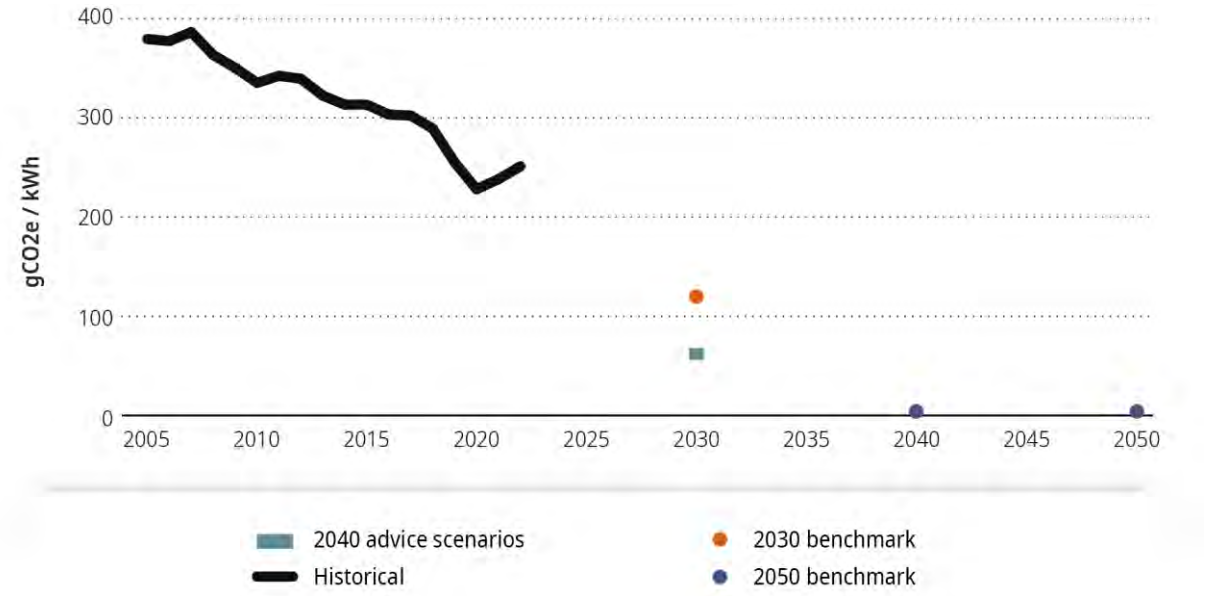

Notes: 2030 benchmark is based on the Fit for 55 MIX scenario. 2050 benchmark based on the 1.5TECH and 1.5LIFE scenarios from the in-depth analysis accompanying a Clean Planet for all (recalibrated for EU27), *excluding* negative emissions from carbon removal technologies. 2040 advice range based on the 6 scenarios that underpin the Advisory Board's 2040 advice. In these cases, negative emissions from carbon removal technologies are *included*, but are not a major contributor to the scenarios' near-zero GHG intensity in 2040. Both the 2040 range and the 2050 benchmark are close to 0 (below 5gCO_2e/kWh) as of 2040 (the 2040 range data point is "hidden" by the 2050 benchmark marker).

Sources: EEA (2023j), Fit for 55 MIX scenario (EC, 2021v), in-depth analysis accompanying a Clean Planet for all (EC, 2018e), Advisory Board 2040 advice scenarios (ESABCC, 2023b)

So far, coal phase-out commitments at the national level have not been sufficiently supported by EU policies.

Twenty-one EU Member States are currently participating in a governmental initiative called the Powering Past Coal Alliance (PPCA), established in 2017 (PPCA, 2017), which encourages its EU members to phase out coal by 2030 at the latest. However, early evidence from the crises induced by the COVID-19 pandemic and the Russian invasion of Ukraine indicates that policymakers tend to support incumbent energy industries to increase energy security (Zakeri et al., 2022). Moreover, not all EU Member States had a clear pre-war commitment to phasing out coal (IPCC, 2022g); there are still a few that do not

envisage their coal power plants closing before 2050. The lack of a clear commitment is not consistent with the EU's net zero target.

The EU Member States commitment to phasing out coal in energy supply can be accompanied by transition measures including phase-out roadmaps, divestment strategies, compensation mechanisms for early power plant closures, labour market measures for coal workers and substantial support for structural change in coal-mining regions (IPCC, 2022g; Jakob et al., 2020; Rosenbloom et al., 2020). The EU's efforts in this area will benefit from continued and reinforced carbon pricing under the EU ETS, the revised energy taxation directive (ETD; see also Chapter 10 'Pricing emissions and rewarding removals') and support under the just transition programmes that encourage public support for coal phase-out policies and increase the pressure on policymakers for swift and definitive action (see Chapter 11 'Whole-of-society approach' and Chapter 14 'Climate governance'). In addition, the revisions of the EU industrial emissions directive (EC, 2022t) and the European Pollutant Release and Transfer Register regulation (EC, 2022z) are an opportunity to increase EU policy coherence, notably between pollution reduction and climate policy instruments. While the installations prompted by the industrial emissions directive account for around 40 % of EU GHG emissions and there are strong interconnections between climate change and pollution (EEA, 2022k), the EU's industrial emission policy under the directive currently makes an incoherent contribution to the EU's climate objectives. It does not sufficiently exploit the synergies between depollution and decarbonisation; in other words, it does not build on the increasing interlinkages between climate policy measures, such as carbon pricing and energy efficiency targets, or on industrial policy measures such as the best available techniques mandated under the industrial emissions directive (EC, 2022h).

The EU's stance on the role of fossil gas is ambiguous, leading to costly infrastructural and institutional lock-ins, and delayed fossil fuel phase-out.

Locking fossil gas into the EU's energy infrastructure and business operations perpetuates GHG emissions and implies additional costs linked to stranded assets, energy imports and carbon capture infrastructure (IPCC, 2022g) ([11]). Despite the vulnerabilities linked to the negative impacts of fossil gas on climate change and energy independence, the role of fossil gas in EU energy systems has still not been clearly addressed at the EU level.

The EU **State aid rules** authorise new investment in fossil gas as long as it is CCU/CCS ready, which means it could be qualified as low-carbon gas in the future (see Chapter 12 'Finance and investments'). They recognise fossil gas's role in a transitional period (EC, 2022ab), which confirms the ambiguous stance of the EU, torn between the need for rapid fossil fuel phase-out and the costs of stranded fossil gas assets and business models, underpinned by newly signed long-term import contracts. In addition, fossil fuel subsidies continue being channelled through the Temporary Crisis and Transition Framework. Adopted in response to the energy crises, the Temporary Crisis Framework of March 2022, and its successor the Temporary Crisis and Transition Framework of March 2023, allow Member States to shield fossil fuel power plant operations and energy-intensive companies from the high and volatile energy prices. Despite its supposedly temporary and crisis-led nature, the framework provisions keep being extended, allowing vast public support inconsistent with energy transition. Beyond the fossil fuel subsidy concern, the Temporary Crisis and Transition Framework includes also very positive opening for more public investment towards net-zero economy (see Section12.4). Member States' fiscal choices, some of which qualify as state aid (see e.g. Nowag et al. (2021), leading to **fossil fuel subsidies** more than

([11]) As pointed out by Seto et al (2016): 'Carbon lock-in is a special case of path dependency, which is common in the evolution of complex systems. However, carbon lock-in is particularly prone to entrenchment given the large capital costs, long infrastructure lifetimes, and interrelationships between the socioeconomic and technical systems involved. Further, the urgency of efforts to avoid dangerous climate change exacerbates the liability of even small lock-in risks'.

doubled between 2021 and 2022 to reach at least EUR 123 billion, and fossil gas subsidies tripled (to EUR 46 billion in 2022; EC, 2023) (see also Section 12.3).

The above ambiguity regarding the fossil fuel phase-out is also demonstrated under the **Taxonomy Regulation** and its delegated acts (EU, 2022a). They allow energy generation from fossil gas to be labelled as a sustainable activity owing to its transitional capacity 'to accelerate the shift from more polluting activities, such as coal generation, towards a climate-neutral future, mostly based on renewable energy sources'. The use of fossil gas to generate electricity or heat is compliant with the taxonomy criteria as long as it replaces other fossil fuels and meets specific emission and efficiency thresholds. These thresholds are too high, however, potentially leading to exaggerated capacity additions, given that electricity generation from such plants should be marginal in the decarbonised energy systems, even if emissions can be captured through CCU/CCS (ESABCC, 2023b) (see also Section 12.6).

Another example is the revised **TEN-E Regulation**, which, despite its stated target of discontinuing support to fossil fuels, allows new fossil gas investment – for instance, in repurposed infrastructure blending fossil gas with hydrogen or biomethane as a transitional activity – until the end of 2029. Electrolysers producing hydrogen from fossil gas can be eligible for the status of PCI / project of mutual interest as long as they meet GHG emission thresholds, which can be achieved through CCU/CCS. They represent a risk in terms of the EU's path to net zero, linked to the low maturity of CCU/CCS projects and the lack of coordination in their deployment to abate fossil gas emissions in energy supply.

The proposed recast of the **Gas Directive** (EC, 2021ag), under discussion at the time of writing of this report, sends a generally positive signal that the new EU policies aim to phase out fossil gas, including a time limit for the duration of long-term contracts for unabated fossil gas (2049, or earlier for willing Member States) ([12]). This overall policy direction is, however, called into question by the specific proposed EU measures that allow up to 5 % hydrogen blended with fossil gas to flow through cross-border infrastructure under Article 20 of the proposed recast of the gas regulation (EC, 2021ag), and lenient criteria for low-carbon hydrogen, that is, hydrogen produced from non-renewable sources with at least 70 % GHG emission reduction (European Parliament, 2023a). These measures risk extending the fossil fuel business case, with costly lock-in effects.

Moreover, regarding fossil gas emissions, the above EU laws and plans to upscale deployment of so-called low-carbon gases (i.e. gases not produced from RES but producing 70 % less GHG emissions than fossil gas across their full life cycle (EC, 2021ag)) are not consistent with carbon neutrality. Moreover, the connection between fossil gas installations, and actual CCU/CCS deployment is currently weak (see the targeted CCU/CCS lever below). The lack of robust connection between fossil gas installations and abatement projects can lead to a **slowdown of energy transition** because of ill-identified investment priorities and carbon **lock-in effects**. Moreover, there has been little progress in defining, identifying and prioritising carbon capture or CDR in those application areas for which alternative emission reductions, e.g. through fuel switching or decommissioning, are not viable (Buck et al., 2023; Lund et al., 2023); see 'Lever: targeted carbon capture and utilisation/storage') below.

In this context, the EU's policy would be more effective if it focused on **phasing out fossil fuel deployment** rather than fossil fuel emissions (e.g. through CCU/CCS). It is therefore regrettable that the EU policy framework does not openly address the shift in operations in the fossil gas sector towards the phase-down of traditional activities (Szabo, 2022), including the impacts of a decreasing customer base on gas system operators. While protection of fossil gas customers from rising tariffs is proposed by the

([12]) The EU Member States' short-term energy security considerations triggered in 2021 have resulted in new liquefied natural gas infrastructure being built and planned (EC, 2023bb) and long-term fossil gas contracts signed between the Member States and global suppliers.

European Parliament (European Parliament, 2023a), a systematic approach to the decline of the fossil gas economy and the rise of new business models is absent. This in turn has impacts ranging from local decision-making on the demand side (e.g. homeowners choosing between a gas boiler and a heat pump) to supply-side geopolitical considerations and contracting. Notably, the EU needs a new vision to underpin fossil fuel phase-out roadmaps and divestment strategies, in line with Article 10 of the European Climate Law, which puts forward voluntary sectoral roadmaps towards climate neutrality (EU, 2021c), and considering regulatory approaches to repurposing and decommissioning fossil gas infrastructure (ACER, 2022a), as well as other measures also outlined in the discussion of coal at the beginning of this subsection.

Lever: fast roll-out of renewable energy sources at scale

Solar PV and wind need to scale up massively across the EU and lead to a decarbonised electricity system by 2040 at the latest. Further progress remains challenging because of changing investment landscapes, inadequate infrastructure planning and development, and workforce and supply chain shortages.

Solar PV represented around 6% of renewable energy supply and 1% of gross final energy consumption in the EU in 2021 (EEA, 2023n). However, its annual installation rate has been rising since 2015 and is expected to continue. In 2018–2022, on average 22 GW of capacity was added each year, with a clear upward trend within that period, driven in particular by distributed solar installation, that is, by homes and businesses rather than at utility scale (IEA, 2023h). The current installed solar PV capacity of 160 GW across the EU needs to nearly quadruple to reach the REPowerEU target of 600 GW by 2030 (EC, 2022p). As Figure 16 suggests, installation of solar PV capacity is generally on track with pathways that were thought consistent with delivering climate neutrality in older scenarios, particularly if the acceleration observed in recent years continues into the future. The faster deployment of this technology provides an opportunity to either increase the EU's rate of decarbonisation or compensate for slower development of other mitigation options. Forward-looking scenarios have also tended to revise solar PV capacity upwards over time, which in part explains why the more recent scenarios (such as the European Commission's REPowerEU scenario and selected scenarios from the Advisory Board's recent advice on an EU 2040 target) have higher capacities than earlier estimates (such as the Fit for 55 MIX scenario and the 1.5TECH scenario in 'a Clean Planet for all') ([13]).

([13]) Other explanations for higher PV estimates include REPowerEU's emphasis on the need to reduce reliance on imported fossil gas, and the Advisory Board's emphasis on reducing emissions by 2040 (to 90–95 % below the 1990 level) rather than aiming for a slower path towards climate neutrality by 2050.

Figure 16 Indicator E4a – annual solar PV capacity additions

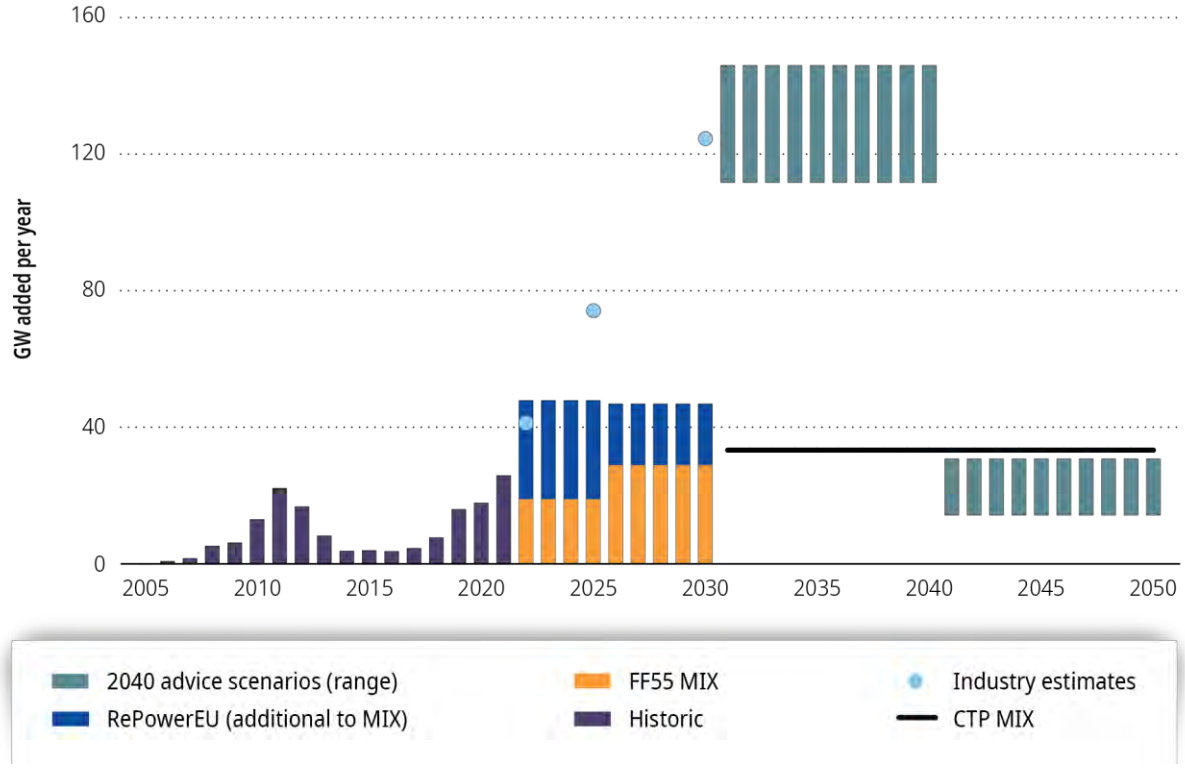

Notes: Historic annual additions based on solar production capacity data from Eurostat (nrg_inf_epcrw). The 2030 benchmarks are based on the European Commission's Fit for 55 MIX and REPowerEU scenarios for solar PV. Post-2030, the bars show the average annual additions needed to reach the total capacity foreseen in the Advisory Board's 2040 advice. Diamonds show the estimated annual additions in selected years from the medium outlook scenarios of SolarPower Europe.

Sources: Eurostat (2023d), REPowerEU staff working document (EC, 2022p), Advisory Board 2040 advice (ESABCC, 2023b), SolarPower Europe EU market outlook 2022-2026 (SolarPower Europe, 2022a).

Wind represented around 16% of the renewable energy supply and 3% of gross final energy consumption in the EU in 2021 (EEA, 2023n). Wind electricity has been increasing at a rate of over 5 % annually in recent years, with 19 GW added in 2022, mostly onshore (EEA, 2023p). Unlike solar PV, new capacities in wind have been added at a slower pace recently (see figure 17); this has been attributed to serious bottlenecks, primarily linked to the issuing of permits and changing investment landscapes. While the pace of annual capacity additions in wind shows signs of recovery, projected capacity this decade appears set to remain below the level envisaged by the Fit for 55 and REPowerEU scenarios.

Figure 17 illustrates that the installed wind capacity across the EU, currently 236 GW, needs to more than double to reach the REPowerEU target of 510 GW by 2030. The installed offshore wind capacity (16.3 GW EU-wide in 2022) needs to nearly quadruple to reach 60 GW in 2030 as set out in the EU strategy on offshore renewable energy (EC, 2020d), and to grow even more to reach the recently agreed political target of about 111 GW of offshore renewable generation capacity in each of the EU's five sea basins by 2030 (EC, 2023an). This would be in line with the latest EU policy direction under REPowerEU, which emphasises the benefits of offshore wind, referring to its higher public acceptability than onshore wind (EC, 2022m). Nevertheless, in the short term, onshore wind is expected to account for three quarters of new wind capacity additions in the EU (WindEurope, 2023).

Figure 17 Indicators E4b and E4c – annual wind electricity capacity additions

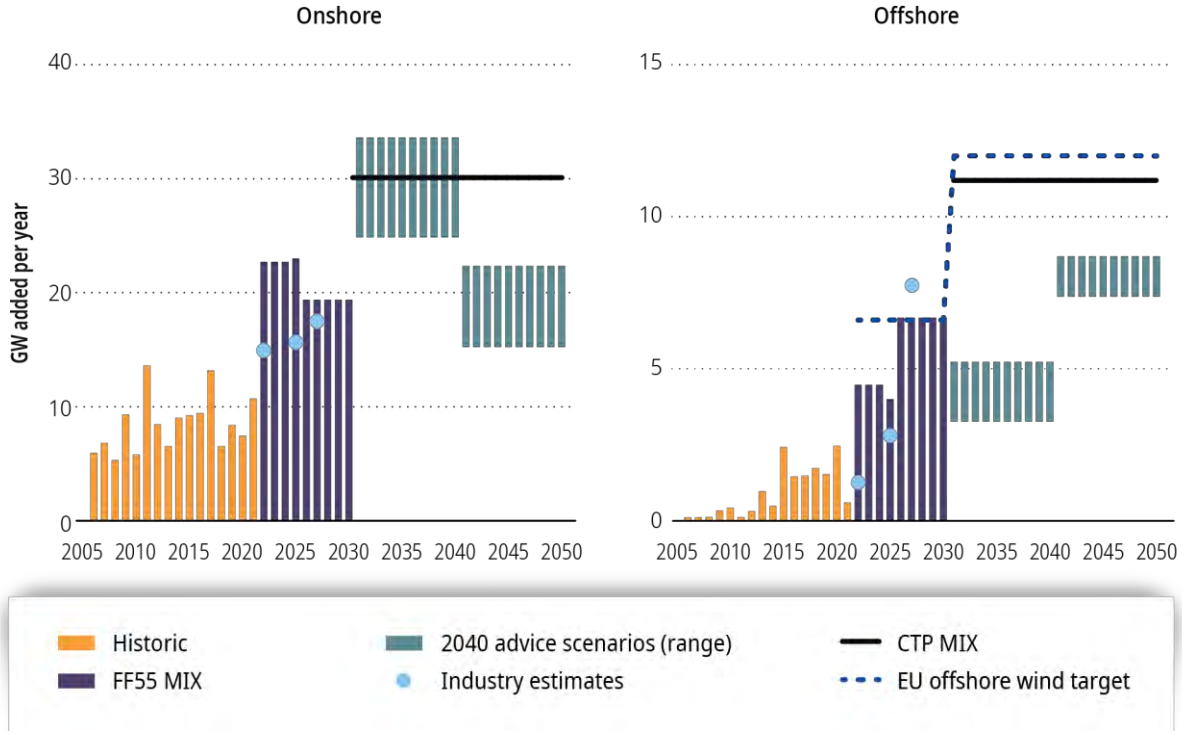

Notes: Historic annual additions based on wind production capacity data from Eurostat. 2030 benchmarks are based on the European Commission's Fit for 55 MIX scenario (available data for REPowerEU does not distinguish between onshore and offshore wind). Post-2030, lines show the average annual additions in the Climate Target Plan MIX scenario and Offshore Renewable Energy Strategy, while bars show the average annual additions needed to reach the total capacity foreseen in the Advisory Board's 2040 advice. Diamonds show the estimated annual additions in selected years from the outlook scenarios of WindEurope.

Sources: Eurostat (2023d), Fit for 55 MIX scenario (EC, 2021v), Climate Target Plan impact assessment (EC, 2020s), Offshore Renewable Energy Strategy (EC, 2020d). Advisory Board 2040 advice (ESABCC, 2023b), WindEurope market outlook 2023-2027 (WindEurope, 2023).

Progress in PV and wind deployment remains challenging because of changing investment landscapes, inadequate infrastructure planning and development, inadequate spatial planning, and workforce and supply chain shortages.

The EU policy framework identifies solar PV and wind energy as priority energy sources. Since 2009 they have been promoted mostly under the consecutive renewable energy directives. The Renewable Energy Directive that is currently in force (RED II) (EU, 2018b) recognises that 'the promotion of the use of renewable energy in the electricity sector, the heating and cooling sector and the transport sector are effective tools, together with energy efficiency measures, for reducing GHG emissions in the [EU] and the [EU]'s energy dependence' (RED II, recital 4, EC, 2021e). Through renewable energy directives, the EU established the 2020 and 2030 binding targets for the minimum share of renewables in the energy mix. The recently agreed target of 42.5 % RES share in EU energy mix is welcome and needs to support early decarbonisation of the EU electricity systems, which is a key milestone in the projected net zero pathways. RepowerEU targets for wind and solar PV are higher than those assumed under Fit for 55 scenarios, which is a good thing from climate mitigation and energy security perspectives. To account for the increased targets, the EU's overall long-term investment signals and strategic planning, including

modelling in support of decision-making (e.g. PV and wind value chains), still needs to be adjusted to the required deployment of PV and wind, and growth of the industry (Haegel et al., 2023; IEA, 2022g).

To address the specific wind industry hurdles, the European Commission tabled a European wind power action plan in October 2023 (EC, 2023s). It aims to address some of the key **bottlenecks** impeding the fast roll-out of wind power that can be attributed to infrastructure, investors' certainty and market signals, public engagement, workforce and supply chains. Barriers to deployment can also be identified in the solar PV sector, and should be addressed as well (see Section 4.4 below and Chapters 14 'Climate governance' and 15 'Labour, skills and capacity building').

EU policies to promote biomethane risk extending the use of fossil fuels, delaying electrification and lead to higher fugitive emissions.

The REPowerEU plan (EC, 2022m) has the ambition to increase the production and use of biomethane tenfold (compared to 2021) to reach 35 billion cubic metres per year by 2030. However, this has potentially negative impacts in terms of extended use of fossil fuels (e.g. through blending of biomethane with fossil gas, and dedicated infrastructure investment) and stalled electrification. Constraints on large-scale local availability of sustainable biomethane feedstock, together with transport and fugitive emissions, can lead to high emissions of biomethane along the value chain (Bakkaloglu et al., 2022; ICCT et al., 2021). The EU legislation in force, the REPowerEU plan (EC, 2022m), do not sufficiently address these risks. Neither do the European Commission proposals for a regulation on methane emissions reduction in the energy sector (EC, 2021af) or the gas package proposals (EC, 2021ag, 2021ab). For instance, CH_4 emissions from biomethane are not covered by the regulation on methane emissions reduction in the energy sector (Council of the EU, 2023a).

A broader assessment of bioenergy use and related policies is included in Section 9.5. An assessment of EU policies on transport biofuels is included in Chapter 6 'Transport'.

For the EU to remain the front runner in innovative renewable energy technologies that will enable more effective pathways to carbon neutrality, a concerted effort of research, development and market scale-up is required.

Some renewable energy technologies, e.g. ocean energy (wave and tidal), concentrated solar power, geothermal energy and other new and innovative RESs, currently contribute only marginally to the overall EU renewable energy mix. This may present untapped potential that could possibly contribute to the future energy system, including through dispatchable load contribution, which is needed for wind and PV system integration (IEA, 2023i). Geothermal technologies, for example, can be efficient in decarbonising heating and cooling systems (IPCC, 2022g).

Innovative RES are currently supported under the EU policy framework, including the RED III, EU research and infrastructure funding and the EU's offshore renewable energy strategy (EC, 2020d). Barriers to their scale-up persist, however, including immature markets, high upfront costs and significant technical risks (IPCC, 2022g). Market scale-up of innovative renewable technologies developed with EU support, such as through Horizon programmes, is currently too slow to put the EU on the path to climate neutrality (see also Chapter 12 'Finance and investments'). For instance, only about 10 % of the total R & D expenditure in the EU goes to the energy sector, or 0.02 % of the EU's gross domestic product (GDP), and most of it goes to incumbent energy sources such as fossil fuels and nuclear power (IEA, 2022c). As further explained in Chapter 13 'Innovation', significant scale-up in R & D spending in support of RESs is urgently needed for the EU to achieve its climate neutrality objectives.

The European Commission's strategic ambition to have 1 GW of installed ocean energy capacity by 2030 and 40 GW by 2050, driven by the EU's technological leadership in this field (EC, 2020d), could support

the overall progress in decarbonising the EU's energy system. The slow progress in the implementation of the EU's offshore renewable energy strategy, however, results in low levels of ocean energy being deployed and industrial leadership in ocean energy shifting to non-EU jurisdictions (Ocean Energy Europe, 2023; Ramos et al., 2021).

In this context it is positive that offshore renewable and geothermal energy technologies feature among the strategic net zero technologies in the European Commission's proposal for a framework of measures to strengthen Europe's ecosystem for manufacturing net zero technology products, that is, the Net-Zero Industry Act proposal (EC, 2023ao). The EU should strive to remain the front runner in innovative renewable energy technologies that will enable more effective pathways to carbon neutrality, through a concerted effort of research, development and market scale-up.

Box 3 Nuclear power

In 2021 around 25 % of the EU's electricity demand was met by nuclear power plants located in 13 EU Member States. Nuclear electricity generation in the EU has been generally decreasing since 2006. In 2022 nuclear power plant output decreased to unprecedented levels as a result of drought and technical issues [– 18 % compared with 2021, according to EEA, (2023)]. Based on the MIX policy scenario in the climate target plan, nuclear power could account for about 15 % of the EU's overall electricity generation in 2030 and 10 % in 2050 (EC, 2020s).

In its recent advice on aligning policy responses to rising energy prices with the long-term climate neutrality objective (ESABCC, 2023a), the Advisory Board acknowledged that delaying the closure of existing nuclear reactors can be a supportive tool to ensure additional low-carbon energy supply in the short term if it is cost-effective and if safety can be sufficiently guaranteed. Given the long lead times of new nuclear power plants (10 to 15 years), a further expansion of this technology cannot be expected to contribute to achieving the EU's 2030 climate targets. Furthermore, social acceptability remains an issue in several countries. In terms of the potential contribution of nuclear power to the 2050 climate neutrality target, climate change impacts on the EU's future energy security should be considered and weighed against risk factors and other impacts. In 2022 a wide and persistent lack of precipitation in combination with heatwaves affected several regions in Europe. This in turn led to historically low hydropower outputs, and reduced generation by thermal power stations – including nuclear reactors – due to a lack of cooling water (Toreti et al., 2022). In addition, low water levels in some of the EU's main waterways disrupted fuel supplies to coal-fired power plants (Gillespie and Sorge, 2022). These events show that climate change – which makes extreme weather events such as drought more frequent and intense – requires a rethinking of the drivers of and solutions for the EU's energy security in the future, including technologies that have in the past been considered highly reliable.

Lever: system integration

Despite the endorsement of system integration as a strategic direction by the European Commission in 2020, the EU still lacks coordination in its planning and operation of the energy system as a whole. While policymaking focuses on upscaling low-carbon fuels, including hydrogen, it does not sufficiently target them to priority sectors. Other pillars of the EU's energy system integration strategy such as digitalisation, energy efficiency and distributed resources need further policy and implementation support.

System integration is defined by the European Commission in the dedicated strategy (EC, 2020l) as the coordinated planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures and consumption sectors. There are six pillars of the European Commission's energy system integration strategy:

- a more circular energy system, with energy efficiency first at its core,
- accelerated electrification of energy demand, building on a largely renewables-based electricity system,
- more renewable and low-carbon fuels, including hydrogen, for priority sectors,
- energy markets more fit for decarbonisation and distributed resources,
- more integrated energy infrastructure,
- a digitalised energy system and a supportive innovation framework.

New EU policies and funding support have been directed to the **hydrogen** economy, which plays a central role in all recent European Commission energy strategies (EC, 2023q, 2022m, 2020c). New fuels and energy carriers such as hydrogen appear in all climate target plan policy scenarios in significant quantities after 2030 and are crucial to achieving climate neutrality by 2050. However, the EU's targeting of hydrogen to priority sectors, as part of the EU's energy system integration strategy, is not progressing fast enough.

Key policies from the European Commission include the EU hydrogen strategy (EC, 2020c), the REPowerEU plan (EC, 2022m), the proposals for a revised regulation and directive (EC, 2021al, 2021m) addressing the internal markets for renewable and fossil gases and for hydrogen (the 'gas package'), and the revised TEN-E Regulation (EU, 2022e). The European Commission has set out the rules enabling hydrogen to be treated as a RES under the RED III (EU, 2023f). It has also tabled a proposal to set up an EU Hydrogen Bank (EC, 2023r). The proposed electricity market design reform may define the role of hydrogen in EU energy systems: notably its potential as an energy carrier for non-electrified uses and as a flexibility source in electricity markets.

The currently limited hydrogen market (8 Mt in 2022; EC, 2023) in the EU is dominated by unabated fossil gas-based hydrogen for the refining and ammonia industries. According to the European Commission, 'hydrogen may provide an alternative fuel for transport, heating and industry where direct electrification might face challenges' (EC, 2020a). The REPowerEU plan envisages a ramp-up in production of renewable hydrogen from nearly zero in 2022 to 20.6 Mt (about 680 TWh, half domestic and half imported) by 2030. The MIX policy scenario sees a ramp-up of the installed electrolyser capacity to 12–13 GW by 2030, 40–70 GW in 2035 and 528–581 GW in 2050. Hydrogen and, to a smaller extent, its derivatives are expected to account for 71 % of all renewable and low-carbon gases in 2050.

To enable hydrogen uptake, five supply corridors totalling about 28 000 km are planned to be created by 2030 as a 'European hydrogen backbone'. By 2040, the backbone is expected to grow to almost 53 000 km, consisting of about 60 % repurposed infrastructure and 40 % new hydrogen pipelines. The European Commission expects the total investment needed to produce, transport and consume 20.6 Mt of renewable hydrogen and its derivatives by 2030 to be in the range of EUR 835 billion to

EUR 971 billion. Within the EU the estimated costs include EUR 200 billion to EUR 300 billion for additional renewable electricity production, EUR 50 billion to EUR 75 billion for electrolysers, EUR 28 billion to EUR 38 billion for EU-internal pipelines, EUR 6 billion to EUR 11 billion for storage and EUR 1.2 billion for upscaling electrolyser-manufacturing capacities (EC, 2023r). The European Commission estimates that 150–210 GW of additional renewable capacity to generate electricity at low cost is needed to make renewable hydrogen competitive with its fossil alternatives (EC, 2023r).

The IPCC highlights that hydrogen production processes (power to gas and vice versa) and hydrogen storage can bring short- and long-term flexibility to the electricity system, replacing fossil gas-based electricity generation in this respect. However, the economic benefits of flexible power-to-gas plants, energy storage and other flexibility options will depend on the locations of variable RESs, storage sites, gas, hydrogen and electricity networks. Electricity use in producing hydrogen for storage (power to gas) and its subsequent reconversion to electricity is very resource-intensive because of the low round-trip efficiency of the process. The use of fossil gas in the production of hydrogen will only be feasible if it involves carbon capture and storage (CCS) or CDR (IPCC, 2022g).

Hydrogen from fossil gas with CCU/CCS (sometimes still referred to as 'blue' hydrogen, and termed 'low-carbon' hydrogen in recent EU policy documents) is associated with higher GHG emission intensity than fossil gas combustion, notably because of fugitive CH_4 emissions associated with the increased demand for fossil gas driven by CCS applications (Howarth and Jacobson, 2021; Novotny, 2023); see also the levers 'reduction of methane emissions' and 'Lever: targeted carbon capture and utilisation/storage' below.

Regarding non-electrified uses, such as heating buildings, 'delivered cost of heat from hydrogen would be much higher than the cost of delivering heat from heat pumps, which could also be used for cooling. Repurposing gas grids for pure hydrogen networks will also require system modifications such as replacement of piping and replacement of gas boilers and cooking appliances … with safety and performance concern'. Scenarios assessed by the IPCC show a 'very modest role for hydrogen in buildings by 2050' (IPCC, 2022b).

Overall, there are remaining challenges around hydrogen-based energy carriers. Economically and environmentally viable options, including efficient hydrogen transport, storage and conversion technologies, are currently not widely available but may become so in the future thanks to, among other things, further research and market scale-up. **Targeted hydrogen deployment** could provide a practical safeguard in support of the EU's energy transition. Priority should be given to well-defined uses that cannot be electrified, notably in industrial processes and fuels for some transport modes. Blending fossil gas with hydrogen and using fossil gas in the production of hydrogen should be avoided, considering the risks of infrastructural carbon lock-ins, risks of CH_4 leakages (see 'Lever: reduction of methane emissions' below) and limited CCU/CCS availability (see 'reduction of remaining emissions' below) in line with the energy efficiency first principle.

Moreover, other aspects of the EU energy system integration are less advanced. This weakness can be attributed to, among other things, the methodologies and assumptions behind the pan-European energy infrastructure planning and development (see also Section 4.4). The key scenarios underpinning the identification of EU energy infrastructure gaps and priority projects have been found to be misaligned with the EU's climate neutrality objective and do not incorporate future climate projections (ESABCC, 2022b). They underestimate the potential of integrated energy infrastructure, including electrification driven by energy efficiency first, and innovative flexibility options such as digitally enabled demand response (ESABCC, 2023c, 2022b).

Accelerated electrification of energy demand is not yet on track to reach the EU's climate objectives.

The share of electricity in the EU's total final energy use has increased slightly from 21 % in 2005 to 23 % in 2021. In the most recent 5-year period for which data is available (2017–2021), the share even decreased slightly (see Figure 18).

Electrification needs to increase considerably, to align with the trajectories towards overall climate neutrality by 2050. The electrification of end use is one of the key levers to achieve the EU's climate targets for 2030 and 2050. In the European Commission's scenarios that underpin these targets, electricity represents at least 30 % of final energy demand by 2030, and almost 50 % by 2050. The increasing share under these scenarios is driven by the uptake of heat pumps in buildings, the electrification of industrial processes and the further electrification of transport, while other forms of electricity use would see reductions due to energy efficiency improvements.

Electrification is also a key feature of all pathways assessed in the Advisory Board's 2040 advice. Electricity reaches 50% of final energy demand by 2040 and 60% by 2050 in the pathways that achieve a 90-95% emissions reduction, while remaining within specified environmental risk levels. Pathways with similar emissions reduction but lower electrification rates were found to rely more heavily on bioenergy or carbon removal (through CCUS technology or expansion of the land sink (ESABCC, 2023b).

Figure 18 Indicator E5 – electrification rate (share of electricity in final energy use)

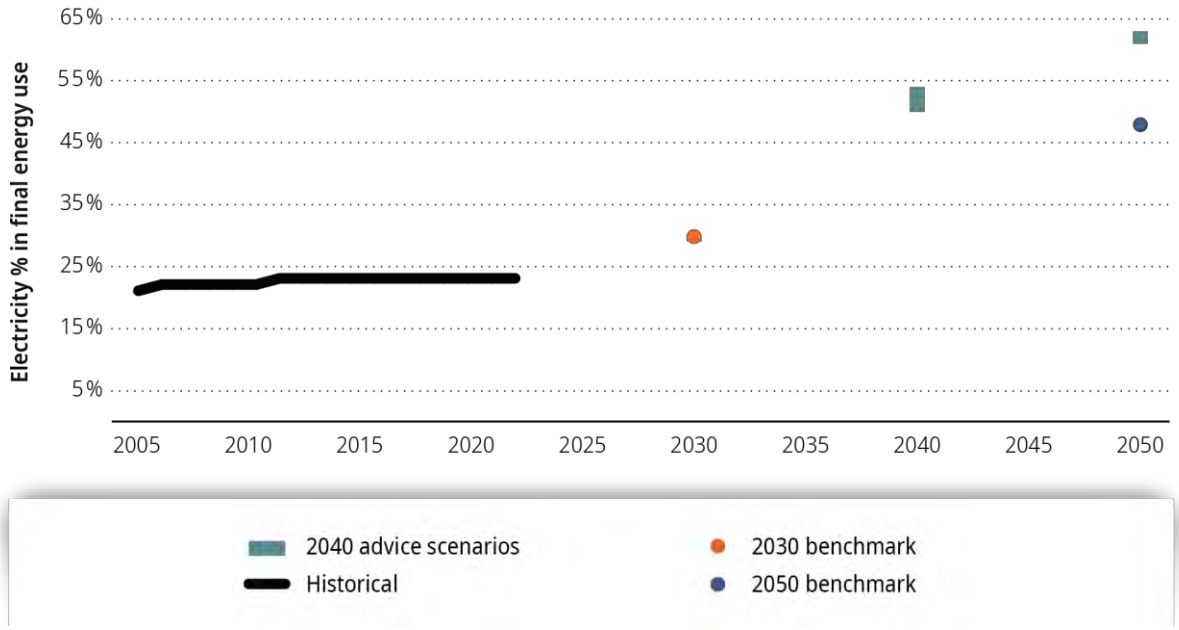

Notes: Historic share is calculated as the share of electricity in final energy use based on the Eurostat energy balances. The 2030 benchmark is based on the Fit for 55 MIX scenario. The 2050 benchmark is based on the MIX Scenario from the Climate Target Plan impact assessment (see figure 37). The 2040 advice range based on the 6 scenarios that underpin the Advisory Board's 2040 advice.

Sources: Eurostat energy balances (2023b), Climate Target Plan impact assessment (EC, 2020s), Fit for 55 MIX scenario (EC, 2021v), Advisory Board 2040 advice scenarios (ESABCC, 2023b).

Electrification can be direct (e.g. through heat pumps or electric vehicles) or indirect (e.g. through hydrogen or synthetic fuels), but it usually means replacing fossil fuel applications (Haegel et al., 2023). Direct and indirect electrification can increase the flexibility of the EU electricity system, which is increasingly reliant on variable wind and solar PV energy production. However, indirect electrification through, for example, production of renewable hydrogen comes with energy losses during conversion process, and hence reduces overall efficiency of energy supply (IPCC, 2022g; JRC, 2022a).

By 2030, the EU electricity system will need more than double the flexibility it has today. Distribution system operations play a key role in meeting them, but DSOs and regulators need to adapt fast.

The recent EEA and ACER (2023) report shows that by 2030, an increase by 240 % of variable renewable energy generation compared with 2021 levels, corresponding to three main target-reaching scenarios of the EU Climate Target Plan (EC, 2021w) will require more than the doubling of the flexibility needs existing in 2021 across the EU electricity system ([14]). Several solutions that provide the required flexibility in highly electrified systems include cross-border grid links, demand-side management, storage, dispatchable generation and grid efficiency. At the heart of many of these solutions is the distribution system.

The operation of the many distribution systems is diversely regulated across Europe, providing highly different investment environments. Distribution system operations have been subject to relatively little direct involvement at the EU level so far, apart from the EU unbundling and consumer protection rules. This is changing, as the Fit for 55 legal changes and the REPowerEU plan put distribution networks in the spotlight (EC, 2022m). Closer EU cooperation in this area is timely, as DSOs share increasing uncertainties due to the integration of distributed energy resources, increasing investment needs, and opportunities in the form of **flexibility services** that they could facilitate. As with the transmission assets, shifting the operating paradigm of DSOs should encourage regulators to reflect on how to adapt so that they identify missing solutions and encourage flexibility services as a cost-efficient investment. For instance, there is growing evidence that the regulatory framework is often positively tilted towards capital expenses rather than operating expenses, which may discourage flexibility services (Ruiz et al., 2023). Moreover, the system needs study conducted under the TYNDP insufficiently grasps the potential benefits of **demand-side response**, as it is based on the premise that 'only a small portion of consumers, or no consumers at all, will be flexible in the future' (ACER, 2023a). This observation could explain the fact that, despite a substantial roll-out of smart meters in the residential sector across the EU (54 % of households had smart meters in 2022 according to ACER and CEER (2022), demand-side response still plays a marginal role in wholesale electricity markets and ancillary services (ACER, 2022; ACER and CEER, 2022). This is despite the fact that, following its inclusion in the electricity regulation, demand-side response is emerging as potentially the cheapest technology to ensure that systems are reliable (ACER, 2022b).

([14]) Over 2015–2021, the average daily, weekly and annual flexibility needs were 157 TWh, 128 TWh and 130 TWh, respectively. In 2030, when variable renewable energyinstalled capacity should be at least 3.4 times higher than in 2021, daily, weekly and annual flexibility needs are estimated to reach 362 TWh, 242 TWh, and 168 TWh, respectively. Essentially, for daily, weekly and annual flexibility needs this means an increase of 138 % (2.4-fold increase), 77 % (1.8-fold increase) and 28 % (1.3-fold increase), compared to the situation in 2021' (ACER and CEER, 2022).

EU policies for energy system digitalisation and non-fossil sources of flexibility require urgent, target-driven implementation.

Implementation of **the EU action plan on digitalisation of energy system** (EC, 2022k) can help mostly zero-carbon flexible energy resources, such as bidirectional charging of electric vehicles, virtual power plants and energy communities, participate in the wholesale markets. The European Commission expects these solutions to satisfy 90 % of the flexibility needs in the EU's electricity grids by 2050, namely 580 GW (EC, 2022k).

The action plan's delivery depends on the EU Member States overcoming multiple policy, technological and behavioural barriers, some of which could be tackled by the EU policymakers in the upcoming revision of the ETD (Voulis et al., 2019) by encouraging **energy efficiency first** demand response and sector coupling.

Moreover, in the **Net-Zero Industry Act** proposal (EC, 2023ao), the European Commission puts forward an expansion of the EU's 'manufacturing capacity for energy efficient technologies, such as heat pumps and smart grid technologies, that help the EU reduce and control its energy consumption' (EC, 2023ao). This is a very positive development, as the proposal announces a step change in EU policies at the electricity distribution level, which is where connecting prosumers and managing the demand side increase system flexibility and lead to better energy system integration.

In March 2023 the European Commission issued its **recommendations on energy storage** (EU, 2023a), which, among other things, encourage EU Member States and system operators to identify their flexibility needs and create an inducive framework for storage. This is an important development from a system integration perspective, especially as different storage solutions have different material and carbon footprints and different timescales (short, medium and long terms).

The revised **TEN-E Regulation** (EU, 2022e) covers cross-border electricity links, which are key flexibility solutions for the EU by 2030 and beyond (JRC, 2023b). It also covers smart grid projects that can become PCI.

The **RED II** (EU, 2018b) assists renewable self-consumers, including their aggregation and storage systems, and requires DSOs to assess the potential of district heating or cooling to provide system services, including demand response and storing of excess electricity from renewable sources. The **RED III** (EU, 2023f) introduces indicative storage and demand-side flexibility targets and defines co-located energy storage projects. While the new provisions are a step change in terms of zero-carbon flexibility frameworks, the EU's experience suggests that such indicative targets may not be sufficient to drive fast transformational change.

The **electricity market design** reform proposal (EC, 2023ar) puts forward objectives to deliver on (among other things) electricity system flexibility needs through low-carbon solutions and new support schemes for non-fossil flexibility through demand-side response and storage.

Lever: reduction of methane emissions

The largest sources of CH_4 emissions from energy sector have been subject to a major EU policy gap until the adoption of the EU regulation on CH_4 emissions from the energy sector. The new EU regulation is a step in the right direction, but the actual ambition of the new rules is yet to be defined. The EU should also extend the EU ETS to cover CH_4 emissions from the energy sector and align its policy in this area with the US measures under the Inflation Reduction Act, while encouraging other jurisdictions to tackle CH_4 emissions from the energy sector.

CH_4 is a potent GHG with high global warming potential (IPCC, 2007b). The energy supply sector is the third-biggest source of CH_4 emissions in the EU (11 % of total), after agriculture (55 % of total) and waste (23 %). The largest sources of CH_4 in the energy sector in 2021, as shown in Figure 19, are fugitive emissions from coal mining and handling (37 %), fossil gas operations (25 %) and emissions from biomass combustion in the residential sector (17 %) (EEA, 2022f). Fugitive emissions have fallen by an average of 3 Mt CO_2e per year since 2005, while emissions related to combustion have remained stable. However, fugitive emissions are currently not systematically measured and can continue many years after oil, gas or coal operations have ceased (EEA, 2022f). Moreover, the reporting of CH_4 emissions from closed or abandoned coal mines in the EU has not been reliable to date (ECA, 2022a).

Fugitive emissions from gas pipelines and bioenergy make it difficult to reach the EU's net zero target by deploying fossil gas in combination with carbon capture (EC, 2020c) and biomethane. Remaining emissions from continued use of fossil fuels, including fossil gas with CCU/CCS-based hydrogen, and from bioenergy include large amounts of fugitive emissions (IEA, 2023g). CH_4 leaks occur not only in the EU but also outside it, linked to EU fossil gas imports.

Nevertheless, the European Commission's analysis considered that fugitive emissions in the energy sector can be largely eliminated by 2050 (EC, 2018d). The analysis identifies 8 Mt CO_2e of potential mitigation in the production, transmission and distribution of oil and fossil gas. However, the mitigation potential from decreasing fuel consumption is much greater, with the 1.5LIFE scenario in 'A clean planet for all' estimating a reduction of 15 Mt CO_2e (the difference in 2050 between the baseline and the 1.5LIFE scenarios, excluding the 8 Mt CO_2e of supply-side mitigation). Global CH_4 emission reductions of 45 % by 2030, according to United Nations Environment Programme and the Climate and Clean Air Coalition, could avoid nearly 0.3 °C of global warming by 2045 (UNEP and CCAC, 2021).

While until 2024 there has been no specific policy aimed at eliminating CH_4 emissions from energy supply at the EU level, the EU has been a leading partner in the Global Methane Pledge signed at the 26th Conference of the Parties (COP26) in November 2021 (UNFCCC, 2021). By joining the pledge, countries commit to collectively reduce CH_4 emissions by at least 30 % below 2020 levels by 2030. The pledge was followed up with the Energy Pathway in June 2022, in which the EU committed to 'endeavour to reduce the methane emissions from the entire value chain of oil and gas production and consumption, including by promoting appropriate international monitoring, reporting, and verification standards; by providing technical assistance and investment for methane emission reduction along the fossil fuel value chain; and by supporting lower-GHG emissions oil and gas production and consumption' (EC, 2022r). Further policy progress in regulating CH_4 emissions is enabled by increasingly reliable data thanks to, among others, the EU's Copernicus Earth observation system (Copernicus and ECMWF, 2023).

Figure 19 Indicator E6 – energy-related methane emissions

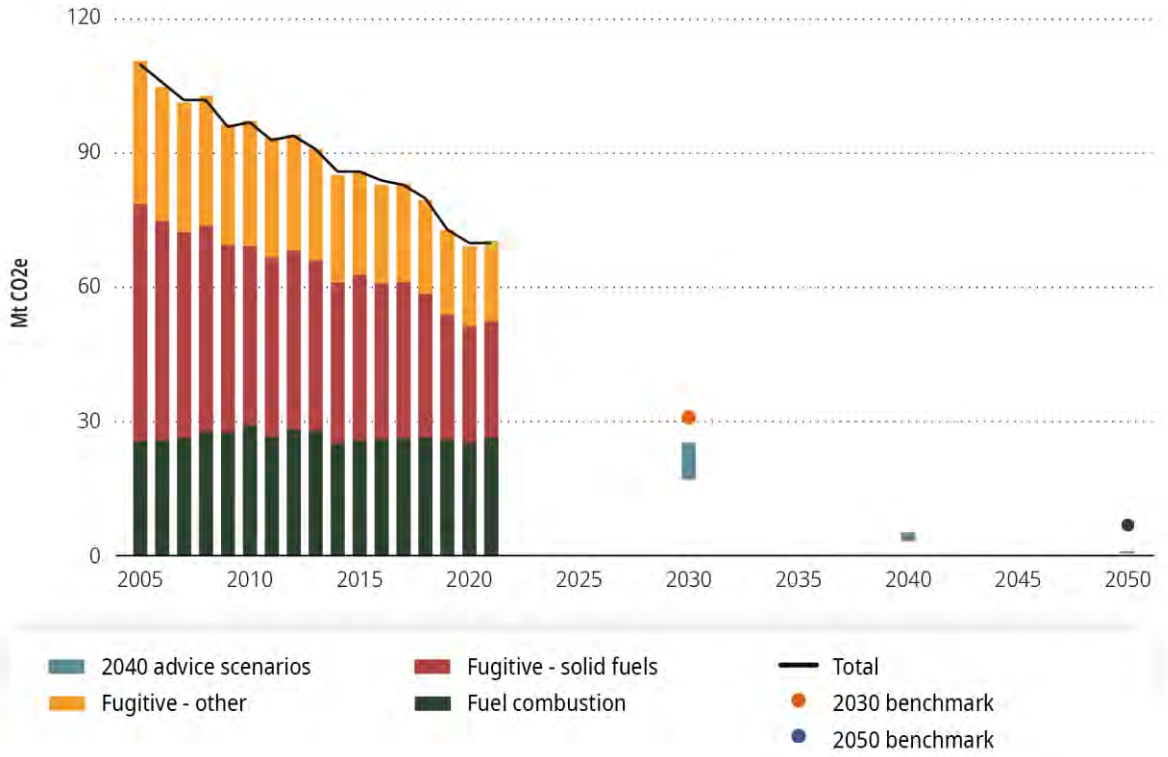

Notes: Historic data refers to CH_4 emissions from fuel combustion (CRF category I.A) and fugitive emissions (CRF category I.B) reported in the EU GHG inventory. 2030 benchmark refers to the same emissions scope under the Fit for 55 MIX scenario. 2050 benchmark is based on the 1.5LIFE scenario from the in-depth analysis accompanying a Clean Planet for All (see table 3, recalibrated for EU27 based on 2015 emissions). 2040 advice range is based on the scenarios which underpin the Advisory Board's 2040 advice, calculated as total CH_4 emissions less those from agriculture, land use and waste.

Sources: GHG inventories (EEA, 2023f), Fit for 55 MIX scenario (EC, 2021v), in-depth analysis accompanying A Clean Planet for All (EC, 2018e), Advisory Board 2040 advice scenarios (ESABCC, 2023b).

In this context, the new EU regulation on CH_4 emissions from the energy sector (EC, 2021af), which was agreed by the EU co-legislators at the end of 2023 (Council of the EU, 2023a), is set to become a crucial instrument in decarbonising the EU's energy supply. The regulation introduces new requirements for the oil, gas and coal sectors to measure, report and verify CH_4 emissions and to put in place emission mitigation measures, including detecting and repairing CH_4 leaks and limiting venting and flaring. The regulation also puts forward global monitoring tools to ensure transparency on CH_4 emissions from imports of oil, gas and coal into the EU. Given that the EU imports fossil fuels, the act will apply to both EU and non-EU operations. The European Commission's implementing acts will be essential, as they will define, among other things, the maximum CH_4 intensity values and minimum detection limits. Administrative penalties for infringing the regulation, including non-compliance with the set thresholds, will apply. The power to impose penalties lies with the Member States (Council of the EU, 2023a).

The new regulation could therefore be a first step to expanding the scope of the EU ETS to upstream emissions in the energy sector. In the future, a financial charge equal to the price level of the EU ETS could be levied on fossil fuel imports exceeding the EU CH_4 standards. This would de facto establish a border adjustment mechanism on upstream emissions in the energy sector (Clausing et al., 2023). In addition, the EU continues to strive for an internationally coherent approach, concerting its actions with other major policy initiatives to regulate energy-related CH_4 emissions, notably the 'Methane Emissions

Reduction Program' and 'Royalties on All Extracted Methane' under the US Inflation Reduction Act (CRS, 2022), and incentivising non-EU countries to implement adequate oil and gas regulations.

The new rules on monitoring, reporting and verification measures will only bind exporters to the EU starting from 2027, and maximum CH_4 intensity values will apply from 2030. The agreed regulation's impact will be most prominent when it comes to new contracts signed between EU importers and non-EU suppliers of fossil fuels; the parties under existing contracts are only encouraged to 'do their best' (Council of the EU, 2023a). Given the urgent need to reduce CH_4 emissions along the fuel value chain and the long-term nature of fuel import contracts, the implementation delays indicate an ambition gap under the new regulation and are a reminder of the risks and costs of contractual lock-ins.

Lever: targeted carbon capture and utilisation/storage

EU policies support CCU/CCS without targeting deployment to applications with no other mitigation option.

Fossil fuel phase-out in the EU should be the priority of decarbonising the EU's energy systems. It also necessitates identifying and defining those uses of fossil fuels that cannot be replaced by renewables.

The EU policies address remaining emissions by promoting CCU/CCS. In 2009 the EU put in place a directive on the geological storage of CO_2, called the CCS directive (EU, 2009a). Activities listed in Annex I of the EU ETS Directive, including in energy supply, are exempted from surrendering allowances for CO_2 that is captured and geologically stored in line with the CCS directive (Article 12 of the EU ETS Directive). Emissions related to the transport and storage of CO_2 are also covered by the CCS directive to ensure all emissions remain covered. With the latest revision, the exemption from surrendering allowances has been extended to CO_2 that is captured and used in such a way that it becomes permanently chemically bound in a product so that it does not enter the atmosphere under normal use, including any normal activity taking place after the end of the life of the product (EU, 2023c). Combined with the observed increases in the EU ETS allowance price since 2018, this provides a considerable financial incentive for CCU/CCS.

Carbon capture is also a key technology in the EU hydrogen strategy (EC, 2020c) and the EU energy sector integration strategy (EC, 2020l). Capital-intensive infrastructure required for CCU/CCS, including CO_2 transport networks, is supported under the revised TEN-E Regulation (EU, 2022e). Moreover, national investment in CCU/CCS technologies, including for power plants, is compatible with EU State aid rules (EC, 2022i).

The EU funds CCU/CCS through, among other means, the Innovation Fund (EC, 2023al), the Horizon Europe programme and the Connecting Europe Facility. CCU/CCS projects supported under the Innovation Fund can originate from electricity and heat generation facilities as well as energy-intensive industries. The proposal for the Net-Zero Industry Act aims to address some core drivers of investments in net zero technology manufacturing, which include fossil gas-based hydrogen with CCU/CCS. It also includes a binding target for EU carbon storage: the annual injection capacity should reach at least 50 Mt CO_2 by 2030 (EC, 2023ao).

Other specific EU policies have been put in place to incentivise the demand for – and therefore development of – CCU-based fuels, including specific fuel mandates under ReFuelEUAviation, the GHG intensity objective under FuelEU maritime and the general objective of reducing the GHG intensity of transport fuels under the RED III (see Chapter 6 'Transport').

The European Commission is planning to publish a dedicated EU strategy for CC(U)S deployment by the end of 2023, which aims to cover industrial carbon management through the transport, use and storage of CO_2 (EC, 2023d).

Several techno-economic aspects of CCU/CCS deployment guide our assessment of the above EU policies in terms of their consistency with climate neutrality.

— Firstly, the contribution of CCU/CCS to the decarbonisation of energy supply depends on costly investment, so that the highest possible rate of carbon emissions can be captured. The standard rate of 90 % observed so far is much lower than the technically feasible rate of over 99 % (Bolscher et al., 2019; Brandl et al., 2021; Holz et al., 2021; IEAGHG, 2019). In practice, projects supported with EU funds, for example the Innovation Fund, are not required to meet the 90 % capture threshold (CINEA, EC, 2023), which leads to remaining ('residual') emissions.
— Secondly, fugitive CH4 emissions are associated with the increased demand for fossil gas driven by CCS applications (see 'Lever: system integration' and 'Lever: reduction of methane emissions' above).
— Thirdly, facilities equipped with CCU/CCS are more energy intensive and may increase cooling water usage significantly compared with their unabated counterparts (IEA, 2023a; IPCC, 2022g).
— Fourthly, there is an inverse correlation between the level of CCU/CCS deployment in energy generation and the need to expand electricity transmission. As explained by Holz et al., 2021, 'as coal- and gas-fired power plants using CCS are located at existing electricity nodes, there is less reinforcement needs for the grid when this type of generation contributes to the supply of electricity than in the case where renewable deployment is larger'.
— Fifthly, only limited long-term geological storage capacity for CO2 is accessible so far across the EU. The mismatch between capture and storage capacity and the failure of coordination in Europe are growing (EC, 2023ao; Simon et al., 2022). The lack of a thorough CCU/CCS value chain identification and mapping has been highlighted in a recent contribution by the JRC (EC JRC et al., 2022).
— Sixthly, EU and national governments will be in charge of developing infrastructure for the transport and storage of CO2, including financing, issuing permits and regulating liabilities (IPCC, 2022g). CO2 infrastructure will be required to provide industrial installations with access to new, low-emission energy carriers and feedstocks (e.g. electricity, low-emission hydrogen) and CO2 storage sites. The need for new infrastructure can be limited through the geographical clustering of industrial activities ((Chiappinelli et al., 2021; Wyns and Khandekar, 2020)
— Finally, studies indicate that CCS has relatively little advantage over a system without CCS in terms of energy system costs (Holz et al., 2021; IPCC, 2022g); further insight into the system costs and benefits of CCU/CCS applications could be part of the TYNDP process (ESABCC, 2023c).

Residual emissions are currently not well defined at the EU or Member State level. Recent studies indicating that without standards for what can be reasonably deemed residual emissions the achievement of the EU's 2050 climate neutrality target is at risk (Buck et al., 2023; Lund et al., 2023).

It is therefore key for EU policymaking to consider the above policy and socioeconomic aspects, the benefits of other mitigation options in line with the energy efficiency first principle, and the limited availability and uncertainties inherent to CCU/CCS and sustainable CDR (Krause et al., 2020; Rogelj et al., 2021). Swift policy correction in this area can avoid the risks linked to the path dependence of EU energy innovation funding and institutional design (see e.g. Meckling et al., 2022). EU policies should target CCU/CCS at priority applications with no alternatives, that is, sectors unable to achieve net zero emissions without CCU/CCS (see e.g. European University Institute., 2022).

4.4 Enabling conditions

Enabling condition: infrastructure

Growth in the share of solar and wind in the EU's electricity mix depends on their rapid integration into electricity grids (IPCC, 2022g) which remains a key challenge in the EU. Connection delays, congestion

management work and the costs of curtailing renewable energy because of inadequate electricity grid infrastructure remain considerable and are expected to grow (see for example EC, 2020; ENTSO-E, 2022; Kryszk et al., 2023). This is largely due to administrative and grid aspects of increasingly complex system planning and management. For instance, the permit-granting process for large renewable energy projects can take up to 9 years in some EU Member States (EC, 2022a). According to a study by the European Commission, administrative and grid issues already make up about 46 % of all identified barriers and this share is expected to rise in the future (EC, 2022a). In this light, for electricity network, renewable energy generation, and storage investment to grow more quickly we identify the following EU policy directions.

Faster permits for renewable energy sources

Renewables acceleration areas and other new rules for faster issuing of permits for RESs should go hand in hand with other environmental policies. Project developers and local policymakers can increase fairness and avoid opposition by embracing early and carefully designed public and stakeholder engagement processes.

The numerous barriers to issuing permits for renewable energy infrastructure projects are well identified in institutional and academic literature (EC et al., 2022; IEA, 2023i; Kitzing et al., 2021; Schumacher, 2019). Permission and administrative procedures enabling renewable energy projects have recently entered the centre stage of EU energy policy. The key EU policy instruments in place to address them are the RED II and III, and the European Commission recommendation on speeding up permit-granting procedures for renewable energy projects and facilitating power purchase agreements (EC, 2022d). In May 2022 the European Commission proposed an urgent amendment to the RED II, targeted at speeding up permit procedures as part of the REPowerEU plan (EC, 2022p). While the amendment process is still ongoing, in December 2022 the Council of the EU adopted an emergency regulation laying down a framework to accelerate the deployment of renewable energy (EU, 2022c). It established temporary rules to accelerate the permit-granting process for RESs, especially solar, storage, repowering assets and heat pumps. The emergency rules include a clause on overriding public interest that aims to accelerate the granting of permits, and so do the recently adopted RED III (EU, 2023f) and the European wind power action plan (EC, 2023s).

The RED III (EU, 2023f) increases the ambition to facilitate issuing permits for renewable energy infrastructure projects through (among other means) the introduction of renewables acceleration areas, shortening lead times for issuing permits and extending the overriding public interest clause beyond the temporary framework. In the meantime, technical assistance from the RRF supports EU Member States in reforming their administrations that grant renewables permits (European Commission, 2022e; see also 'investors' certainty and market signals' subsection). EU lawmakers should provide clear guidance on when the above measures are to be effectively implemented; according to the IEA, ambiguity in this respect risks further delays in renewables deployment (IEA, 2023i).

It is paramount that these policies do not compromise on other environmental policy objectives, notably biodiversity protection. Accordingly, the designation of renewables acceleration areas under the RED III needs to be subject to technology-specific environmental impact assessments, and to safeguarding the balance between nature restoration and the siting choices for net zero infrastructure development. Moreover, locally rooted public engagement plays a pivotal role in accelerating RES roll-out. As pointed out by Kirkegaard et al. (2023) in the context of wind energy projects, 'success … heavily depends on how society engages with the development of wind power infrastructure'. Project developers and local policymakers can increase fairness and avoid opposition by embracing early and carefully designed engagement processes following good practice described by institutions, practitioners and scientists (see e.g. EC, 2022d; RGI, 2023; Segreto et al., 2020). These processes can enrich local project planning

and execution, including technology choices, by means of co-design and cooperation (e.g., Kirkegaard et al., 2023). Nevertheless, despite good practices being available, the public is often excluded from decision-making in climate matters (Citizens' Observatory for Green Deal Financing, 2023; EPRS, 2023). This weakness partly explains the European Commission's observation that 'the lack of public acceptance of renewable energy projects is another significant barrier to their implementation in many Member States' (EC, 2022d). It is therefore welcome that, in its recommendation on speeding up permit-granting procedures for renewable energy projects and facilitating power purchase agreements (EC, 2022d), the European Commission provides Member States with guidance on good practices in public engagement and encourages them to facilitate participation by citizens, energy companies and local communities, for example by passing the benefits to local communities and simplifying granting permits for renewable energy communities.

Identification of missing projects for a decarbonised electricity system

Energy regulators do not focus sufficiently on identifying cost-efficient but currently missing solutions, including anticipatory investments.

Most electricity transmission projects are regulated. National regulatory frameworks within EU Member States provide the same return to all electricity transmission infrastructure projects in the country, irrespective of their individual risk profile or impact (ACER, 2023b) The EU policy framework recognises different, often high, risk profiles of energy infrastructure projects needed to achieve EU climate targets; for example, projects of cross-border importance, such as most offshore grids. The EU regulation on guidelines for trans-European energy infrastructure – the TEN-E Regulation as recently revised (EU, 2022e) – allows favourable regulatory treatment of such projects, for instance faster issuing of permits and financial incentives. However, some project categories falling under the TEN-E Regulation, such as storage and hydrogen, are often unregulated, so the national regulatory authorities may not have any power to grant them favourable treatment (ACER, 2023b). Risk management aspects of investment in regulated and unregulated assets are an emerging concern for rapid decarbonisation of the EU's electricity grid. ACER has recently suggested that, to improve the incentives framework, regulators' focus should be shifted from project risk mitigation or compensation for transmission system operators to prioritising the identification of cost-efficient but currently missing solutions (ACER, 2023b). Such missing solutions could be identified as part of the TYNDP.

Investment in electricity grids at all voltage levels

EU electricity grid investment needs to increase by a factor of 1.5 from current levels, with a big part of new investment directed towards distribution (low- and medium-voltage) grids.

The observed average investments between 2017 and 2021 are about EUR 40 billion to EUR 45 billion per year (ETIP Wind et al., 2021; IEA, 2022c). According to the REPowerEU plan, an additional EUR 29 billion (ca. EUR 3.6 billion per year) of electricity grid investment is needed by 2030 'on top of what is needed to realise the objectives of the Fit for 55 proposals' (EC, 2022m). The estimates of needs for Fit for 55 range from an additional EUR 2.2 billion per year in the MIX-50 scenario to EUR 7.7 billion per year in MIX and EUR 9.6 billion per year in ALLBNK (EC, 2020p). The European Commission estimates put forward in October 2022 as part of the communication 'Digitalising the energy system – EU action plan' indicate that at least EUR 58.4 billion per year of electricity grid investment is needed between 2020 and 2030 (EC, 2022k).Based on this, it can be assumed that, to meet the EU's 2030 climate objectives, investment in the EU's electricity grid needs to increase by a factor of 1.5 from current levels. However, this assumption should be considered with care, as the estimated ranges of current and needed investment levels in EU electricity grids vary significantly, and call for more consistent and reliable data. There is a consensus, however, about the need to significantly ramp up investment in electricity networks

across the EU, with a big part of new investment directed towards distribution (low- and medium-voltage) grids (see for example Prettico et al., 2021; EC, 2022c).

EU-wide system planning aligned with EU climate targets

The TYNDP is not yet in line with the EU's 2050 climate neutrality objective.

The EU internal energy market policy requires the European networks of transmission system operators for electricity and for gas to develop TYNDPs. As a European electricity and gas grid infrastructure investment roadmap, the TYNDP will link, support and complement national grid development plans and will be connected to the national energy and climate action plans. The TYNDP will inform today's energy infrastructure investment decisions, and hence play a pivotal role in the EU's path to its 2050 climate neutrality target. The TYNDP process does not sufficiently address the transformational changes and rapid reductions in GHG emissions that are necessary to achieve the EU's climate neutrality and climate resilience targets by 2050 (ESABCC, 2022b). This observation pertains to the entire TYNDP process, in particular the scenario development, system needs assessment and cost–benefit analysis, as well as the subsequent selection of PCI and projects of mutual interest. To address this weakness, the Advisory Board recommends that priority be systematically given to full decarbonisation, energy efficiency and infrastructure resilience to changing climate, in particular through rapid and widespread electrification combined with demand-side flexibility (ESABCC, 2023c).

Enabling condition: investors' certainty and market signals

The EU's internal energy market is the most interconnected energy market worldwide. There is abundant scholarly literature explaining the fundamentals of its functioning (see for example Meeus, 2020). Well-functioning wholesale and retail markets lead to lower prices for consumers and enable investment in energy systems decarbonisation (see for example IEA, 2022d). The recent fall in wind and solar PV deployment costs as well as geopolitical disruptions in the energy markets have led the EU Member States to revisit the premises of the current legal framework of the internal energy market. The planned market reforms (EC, 2023ar) will go hand in hand with the EU ETS as well as energy taxation and capacity remuneration mechanisms.

While the political negotiations on the EU's electricity market reform (EC, 2023ar) are ongoing, recent academic contributions (EEA and ACER, 2023b; European University Institute, 2022; Glachant, 2022; Grubb et al., 2022; IEA, 2022d) agree that (among other things) the uptake of innovative zero-carbon energy solutions should be encouraged through market design changes (e.g. higher temporal granularity), grid congestion should be tackled and capacity remuneration mechanisms should be reformed.

Capacity mechanisms

The EU can reduce its reliance on fossil fuels to ensure reliability of the energy system by favouring non-fossil resources such as demand-side response and storage to ensure adequate supply.

An opportunity to phase out fossil fuel subsidies becomes evident when scrutinising the existing rules governing so-called capacity mechanisms, which remunerate availability of energy generators to ensure energy system reliability. Energy system reliability can be defined as resource adequacy in which the demand for and supply of energy are always in balance. Capacity mechanisms deployed across the EU aim to ensure that electricity supply is sufficient during peak periods by remunerating producers for the availability of resources. In practice, so far most capacity mechanisms in the EU remunerate fossil fuel thermal generation plants (70 % of contracted capacity in 2022; ACER, 2022). These translate to substantial fossil fuel subsidies given that in 2021 the total incurred or projected costs of capacity

mechanisms in the EU reached nearly EUR 5 billion and they are expected to increase to nearly EUR 7 billion in 2023 (ACER, 2022b).

While their overall design is at the discretion of EU Member States, capacity mechanisms must comply with the principles set out in the electricity regulation (EU 2019/943). They must also be in line with the EU's internal market rules, and the state aid rules in particular (regarding state aid, see also Chapters 12 'Finance and investments' and 14 'Climate governance'). Until their revision in 2022, the state aid guidelines for energy and environment did relatively little to encourage capacity mechanisms to remunerate other sources of resource adequacy than fossil fuels (Hancher and Maria Salerno, 2021a; Nowag et al., 2021). A general overhaul of the current rules may be expected under the electricity market reform, creating an opportunity for the EU to encourage non-fossil adequacy resources such as demand-side response and storage.

Supply chains

Vulnerabilities in the EU's supply chains for renewable energy and electrification put the transition in many sectors at risk. Recent EU policies aim to address this challenge by boosting domestic manufacturing and promoting the reuse of secondary raw materials.

The EU's transition to climate neutrality entails energy and material supply substitution processes, which rely on secure supply chains of raw materials and technical components of clean technologies. These substitution processes and material reliance have profound impacts on, and are impacted by, global trade and geopolitics (EC, 2023be; Lowe and Drummond, 2022). The supply chain disruptions due to the COVID-19 pandemic and the Russian invasion of Ukraine illustrated Europe's vulnerabilities in this regard (Accenture, 2022; WindEurope and Eurofer, 2023).

In 2022 the REPowerEU plan called for 'action on the supply side to create the capacity and framework to roll out and produce renewables' (EC, 2022m). It focuses on strengthening supply chains for solar, wind and heat pump technologies. In this vein, the EU co-legislators work on future EU regulation to diversify and monitor the EU's imports of critical raw materials in order to reduce strategic dependencies, and to improve sustainability and circularity within supply chains (EC, 2023as); see also Chapter 5 'Industry'. Resilient and transparent wind industry supply chains, and de-risking financial exposure linked to supply disruptions are also in the focus of the EU wind power action plan (EC, 2023s). These policy initiatives make a very promising contribution to EU energy supply decarbonisation.

4.5 Summary tables

Table 4 Progress summary – energy supply

Indicator	Reference period	Historical progress	Required up to 2030		Required in 2031–2050
E1: GHG emissions	2005–2022	– 33 Mt CO_2e/yr	– 55 Mt CO_2e/yr		– 24 Mt CO_2e/yr
E2: electricity generation mix					
E2a: % of fossils	2017–2021	– 1.7 pp/yr	– 1.9 pp/yr		– 0.6 pp/yr
E2b: % of non-bio renewables	2017–2021	+ 1.7 pp/yr	+ 1.8 pp/yr		+ 0.9 pp/yr
E3: electricity GHG intensity	2018–2022	– 10 g CO_2e/kWh/yr	– 16 g CO_2e/kWh/yr		– 12 g CO_2e/kWh/yr [a]
E4: renewables capacity deployment					
E4a: solar PV	2018–2022	+ 22 GW/yr	+ 25 GW/yr Fit for 55	+ 48 GW/yr REPowerEU	+ 34 GW/yr
E4b: onshore wind	2018–2022	+ 10 GW/yr	+ 21 GW/yr		+ 30 GW/yr
E4c: offshore wind	2018–2022	+ 1.5 GW/yr	+ 6 GW/yr		+ 11 GW/yr
E5: electrification rate	2017–2021	– 0.04 pp/yr	+ 0.9 pp/yr		+ 0.9 pp/yr
E6: energy-related methane emissions	2017–2021	– 3 Mt CO_2e/yr	– 4 Mt CO_2e/yr		– 1 Mt CO_2e/yr

Legend

On track	The required change [b] is ≤ 1.
Almost on track	The required change [b] is between 1 and 1.5.
Somewhat off track	The required change [b] is between 1.5 and 2.
Considerably off track	The required change [b] is ≥ 2.
Wrong direction	The required change [b] is < 0.

[a] Required in 2031–2040 in order to reach near- zero GHG intensity by 2040.
[b] See Section 2.2 for more details on how the required change is calculated.

Table 5 Policy consistency summary - energy supply

Policy inconsistencies	– Not all EU policies are consistent regarding the role of fossil gas in future energy systems (e.g. the TEN-E Regulation, the proposed Gas Directive and regulation, State aid rules and the EU Taxonomy).
Policy gaps	– The EU's massive policy support to the hydrogen value chain does not sufficiently reflect the techno-economic limits of hydrogen and its role in integrated and decarbonised energy systems. – Residual emissions (from so-called hard-to-abate sectors) are currently not defined at the EU or Member State level. – Fugitive CH_4 emissions in the energy sector have not been addressed by EU policies (dedicated regulation in the lawmaking process). – The electricity market reform including support to non-fossil electricity system flexibility sources (e.g. demand response) and the RES value chain reinforcement (Net-Zero Industry Act) are in the lawmaking process.
Ambition gaps	– The EED reinforces the application of the energy efficiency first principle but sets a very high threshold, which means that many relevant projects are exempt from assessment of energy efficiency solutions, including demand-side resources and system flexibilities.
Implementation gaps	– Diverse understandings and measurements of energy efficiency and its multiple benefits under the EED and energy retrofit investment schemes have led to insufficient operationalisation of the energy efficiency first principle so far. – The EU still lacks planning and operation of the energy system as a whole. – Market upscaling of innovative renewable energy technologies is making slow progress.

5 Industry

Key messages

Industrial GHG emissions reduced by 30 % in 2005–2022, partially driven by lowered production in emission-intensive industries. Achieving climate neutrality requires a transition to new, zero-emission technologies in combination with lowered demand for GHG-intensive materials.

The industry sector reduced its GHG emissions by 30 % in 2005–2022 (see Figure 20), while its gross added value increased by 33 %. In GHG-intensive sectors (iron and steel, cement, and chemicals), reductions were mainly driven by lowered production, while their use levels and GHG intensities ([15]) remained relatively stable. The increase in gross value added, in combination with declining production levels in GHG-intensive industries, suggests a shift of activities to less GHG-intensive subsectors.

Figure 20 Indicator I1 – overall progress in reducing industrial GHG emissions

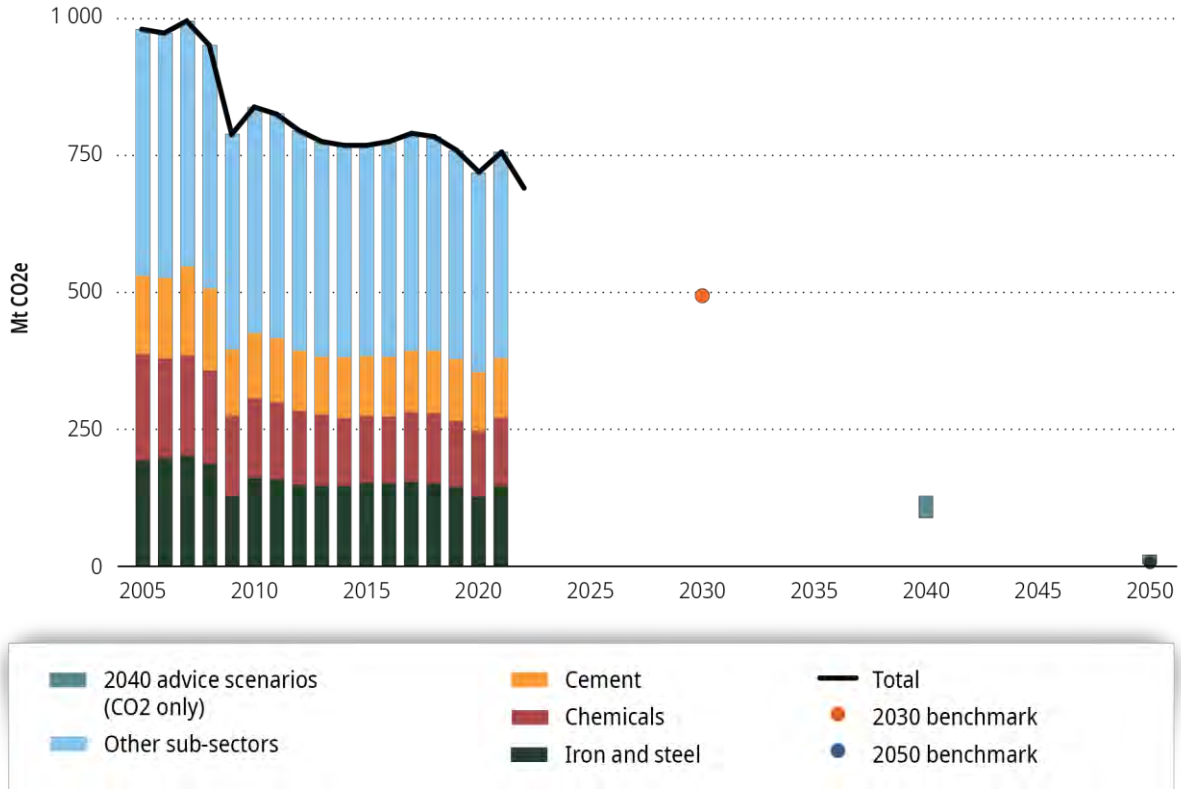

Source: see Figure 23 for detailed sources and notes.

The average annual reduction in 2005–2022 (by 17 Mt CO_2e per year) needs to accelerate (to 24 Mt CO_2e per year in 2023–2030 and 21 Mt CO_2e per year in 2031–2050) to be consistent with the trajectories towards the overall 2030 and 2050 reduction objectives. A steeper reduction rate would be required to achieve the recommended 90–95 % GHG emission reductions by 2040. Achieving deep reductions in industry while avoiding carbon leakage to outside the EU requires a transition towards low- and zero-

([15]) The GHG intensities of steel, cement and chemicals are also dependent on the production mix and quality grade (e.g. steel alloy grades, clinker content in cements, share of finer chemicals in the total production mix). For lack of available data, the Advisory Board was not able to assess the impact of this on the observed GHG intensities.

emission industrial production technologies in combination with lowered demand for GHG-intensive materials. Such technologies are currently under development, and several pilot and demonstration projects have been launched in recent years, bringing the sector closer to faster emission reductions.

More action is needed to accelerate the transition towards a circular economy and curb demand for GHG-intensive materials.

Needs. Demand for GHG-intensive materials can be limited through an overall reduction in product demand (e.g. by increasing lifetimes and repairability), increased material efficiency and enhanced material circularity. This would allow faster emission reductions at overall lower costs, while reducing pressures on expanding renewable electricity, hydrogen and CCS infrastructures, as well as waste handling. Policies that could support such demand-side measures include product standards, price policies (e.g. a carbon price that is passed along the value chain) and waste policies. So far, the EU has made very little progress in increasing the circular use of materials, and demand for key GHG-intensive materials (steel, cement and base organic chemicals) has remained relatively stable.

Gaps. Demand management and material efficiency have until recently remained largely unaddressed by EU policies. The 2015 circular economy action plan (CEAP 1) and the strategy on plastics mainly targeted recycling, with little focus on solutions upstream in the waste hierarchy **(policy gap)**. Similarly, the Ecodesign Directive has been mainly focused on energy efficiency and, whereas product circularity has been added in recent years, its scope remained limited to energy products **(policy gap)**. Recent policies are steps in addressing this gap, including the 2019 Directive on Single Use Plastics and CEAP 2 which has a broader scope than CEAP 1 (including product design, durability, repairability, reusability and recyclability). Although a clear improvement, the effectiveness of the latter will depend on the specific actions included in the plan, most of which have only been adopted recently (e.g. the Ecodesign for Sustainable Products Regulation) or still under negotiation (e.g. the End-of-life vehicles Regulation).

In parallel, high levels of free allocation to industry in combination with the lack of a carbon price on imports, as well as the exclusion of the waste sector under the EU ETS, have undermined the incentive for such demand-side measures **(ambition and policy gaps)**. The most recent revision of the EU ETS partially addresses this gap by gradually shifting from free allocation to a CBAM for specific sectors as a carbon leakage prevention measure, and the potential inclusion of the waste sector as of 2028 (while taking into account the potential diversion of waste to landfill or exports to third countries). See also Chapter 10 'Pricing emissions and rewarding removals'.

Recommendation I1. The Advisory Board recommends that EU co-legislators complete the legislative decision process on the various actions under the CEAP 2 without watering down the provisions, in order to accelerate the transition towards a circular EU economy, which would contribute to climate neutrality.

Recommendation I2. The EU should further develop alternatives to free allocation for addressing the risk of carbon leakage. The European Commission should, among other things, monitor the introduction of the CBAM, with a view to expanding it to more products and sectors, as envisaged in the CBAM regulation (see also Chapter 10 'Pricing emissions and rewarding removals'). In addition to relying on price signals, it would be prudent to explore other policy measures to support the demand management and efficiency of materials, such as through spatial planning (see also Section 7.5), standards or public procurement.

Dedicated policies are needed to help low-emission industrial technologies reach full maturity ([16])**.**

Needs. So far, limited progress has been made in reducing the GHG intensity of key GHG-intensive materials (iron and steel, cement, and chemicals), and achieving deep reductions by 2050 in these subsectors will require a large-scale shift towards new, low-emission production processes. Promising production technologies are currently under development but have not yet reached full maturity. These include, among others, hydrogen direct reduction of iron ore, CCS for cement, and electrification, hydrogen and sourcing of non-fossil carbon in the chemicals industry. Their development and deployment will need to be accelerated and scaled up. Dedicated policies are required to support new low-emission technologies throughout each stage of their development. For other industrial sectors, emissions are mainly related to heat production, which can be reduced through direct electrification, complemented with other forms of renewable heat (e.g. based on hydrogen and biomass). In all cases, the transition to a low-emission industry depends on sufficient access to decarbonised electricity, hydrogen and – for sectors with high process emissions, such as cement – CCS infrastructure (see also Chapter 4 'Energy supply').

Gaps. Past EU policies have been mainly focused on supporting basic R & D (e.g. Horizon Europe), pilots and demonstration (NER 300 and the Innovation Fund) and the large-scale diffusion of mature technologies (the EU ETS), but dedicated policies to support early deployment / market formation have been largely absent **(policy gap)** (see also Chapter 13 'Innovation', and particularly Section 13.3). Recent (proposed) EU policies aim to address this gap, including by providing direct financial support ((carbon) contracts for difference or fixed premium contracts under the Innovation Fund), and by creating lead markets (planned mandatory green public procurement requirements and the proposed Ecodesign for Sustainable Products Regulation under CEAP 2). Given how recent these new policies are, the Advisory Board has not yet been able to assess their (expected) effectiveness.

Recommendation I3. Dedicated EU policies should (continue to) provide support for the development and deployment of new, low-emission industrial technologies at each stage of their development. The new support mechanisms under the Innovation Fund and the various initiatives under the CEAP 2 should be implemented and closely monitored to ensure they provide adequate support for the early deployment of such technologies.

5.1 Scope and sectoral assessment framework

Scope

This chapter covers both the energy- and process-related GHG emissions from the EU industrial sector (CRF categories I.A.2 and 2 in the GHG inventories). It includes F-gases and emissions from construction activities but excludes emissions from petroleum refining and fossil fuel extraction (which are included in Chapter 4 'Energy supply'). Emissions from waste treatment are not included in the emission data, but some waste-related policies are included in the policy consistency assessment, given their links with the circular economy.

The industrial sector is a heterogeneous group of subsectors, each of which has its own characteristics. Whereas this chapter covers the entire industrial sector, a particular focus is put on the top three emitting

([16]) Full maturity is assumed to be reached when such technologies reach technology readiness level 9: 'actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)' (EC, 2014).

subsectors (iron and steel, cement and chemicals), which jointly accounted for almost half of total industrial GHG emissions in the EU in 2021 (see Figure 21).

Figure 21 Industrial GHG emissions in 2021 per subsector (Mt CO_2e and % of total)

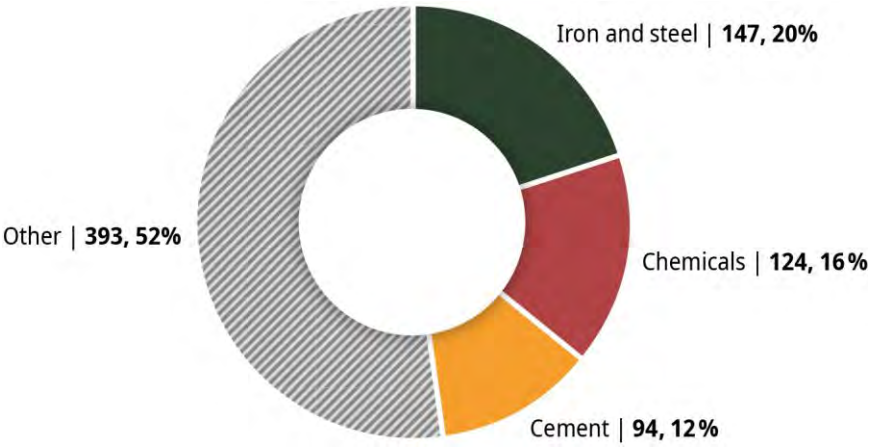

Notes: GHG emissions for iron and steel are based on the 2023 EU GHG inventory, and includes both energy- (CRF category 1.A.2.a) and process emissions (CRF category 2.C.1) but excludes emissions from blast furnace gases which are combusted for electricity production, which is instead reported under the 'energy supply' sector (CRF category 1.A.1) in the GHG inventory. GHG emissions for chemicals include both energy- (CRF category 1.A.2.c) and process emissions (CRF category 2.B). GHG emissions for cement are based on verified EU ETS data accessed via the EEA EU ETS data viewer (installations with main activity code 29). These emissions are slightly underestimated as they don't include installations without in-house clinker production. 'Other sectors' is calculated as the difference between total industrial emissions (CRF categories 1.A.2 and 2) and the emissions of iron and steel, cement, and chemicals.

Sources: GHG inventories (EEA, 2023f), EEA EU ETS data viewer (EEA, 2023g)

Greenhouse gas emission reductions required in the industry sector to reach climate neutrality

Under the 1.5TECH and 1.5LIFE scenarios of the European Commission's in-depth analysis accompanying the 2018 LTS 'A clean planet for all' (EC, 2018e), industrial CO_2 emissions are expected to reduce by almost 90 % by 2050 compared to 2005. Under the more recent 2020 Climate Target Plan impact assessment (EC, 2020s) , total industrial GHG emissions are expected to reduce by 90–93 % by 2050 compared to 2005. Nevertheless, some limited residual emissions would remain in 2050 (65–95 Mt CO_2e), which need to be counterbalanced by emission removals either within or outside the industrial sector to achieve overall climate neutrality. This is also in line with the latest IPCC AR6 Illustrative Mitigation Pathways, which see deep reductions but still a certain level of residual industrial GHG emissions in most scenarios by 2050 (IPCC, 2022h).

Assessment framework for the industry sector

The selection of outcomes, mitigation levers and enabling conditions is primarily based on the industry chapter (chapter 11 of the contribution of Working Group III) of IPCC AR6 (IPCC, 2022h).

Outcomes. IPCC AR6 has identified six major mitigation pathways (see levers below) for the industry sector that could reduce emissions by reducing overall demand for GHG-intensive materials, and by decarbonising industrial production processes (IPCC, 2022h). Based on this, the following two outcomes were identified as a basis for tracking progress and policy consistency in the industry sector:

— **lowering demand** for GHG-intensive materials,
— a shift towards **low-carbon industrial production processes**.

Mitigation levers. To achieve these outcomes, six main mitigation levers were identified, which largely correspond with the six main mitigation pathways of IPCC AR6. A split was made between marginal efficiency improvements and fuel switches within existing production processes, on one hand, and the switch to new, climate-friendly production processes, on the other hand. The selected levers are as follows.

— An overall **reduction in product demand** can be achieved through smarter system design, sufficiency measures (e.g. more compact housing, and fewer and more compact vehicles, both of which are also linked with spatial planning at the urban and territorial scales; see also Section 7.5), the sharing economy and enhanced product lifetimes (through higher durability and repairability).
— A further reduction in demand for GHG-intensive materials can be achieved through **material efficiency** (e.g. lightweighting, 3D printing, near-net shaping and avoiding over-dimensioning) and **material substitution** (e.g. substitution of supplementary cementitious materials for clinker-based cement).
— A high level of **material circularity** at end of life can be achieved through a higher level of repurposing and high-quality recycling, facilitated by product design, appropriate waste sorting and collection, and adequate recycling capacities.
— Continued **energy efficiency improvements** and **fuel switches (including electrification)** within existing production processes can contribute to further reducing emissions in the short to medium term without major changes required to industrial infrastructure.
— In some subsectors – including major emitters such as the iron and steel and chemicals sectors – the potential for further efficiency improvements and fuel switches within existing production processes is limited. For these sectors, **a shift towards new, climate-friendly production processes** will be needed to achieve deep GHG emission reductions.
— The application of end-of-pipe **carbon capture** combined with geological storage (**CCS**) or utilisation (**CCU**) will be required for industrial processes that have no alternative mitigation option (e.g. cement production, in which 60 % of total emissions relate to unavoidable CO_2 emissions from calcium carbonate decomposition).

The first three levers are also often referred to as circular economy measures.

Enabling conditions. In addition, six enablers were identified that could support the six levers. These enablers are based on the key policy approaches and strategies identified by IPCC AR6, complemented by insights from other studies on industrial decarbonisation.

— **Price signals** – e.g. by means of carbon-pricing policies – can steer both consumer's choices and industrial producers' investment and operational decisions (see also Chapter 10 'Pricing emissions and rewarding removals').
— **Transition plans and strategies** are needed to coordinate the different policy domains affecting the industrial sector, and to guide policy design and investments.
— **RD & D and innovation** are necessary to enable the development and improvement of new technologies that can facilitate further emission reductions.
— **Lead markets** (or market pull) and **financial support** are considered highly effective (or even a prerequisite) to allow new technologies to bridge the gap between first commercialisation and large-scale deployment.
— **Infrastructure** planning, financing and construction will be required to provide industrial installations with an adequate supply of new, low-emission energy carriers and feedstocks (e.g. electricity, hydrogen) and CO_2 storage sites. Given the overlap with the energy supply sector, this

enabling condition is assessed in Chapter 4 'Energy supply'. The need for new infrastructure can be limited through the geographical clustering of industrial activities, which would also facilitate the exchange and valorisation of by-products between different installations (Chiappinelli et al., 2021; Wyns and Khandekar, 2019).

— **International competitiveness** needs to be safeguarded to ensure that EU GHG emission reductions are achieved by real emission reductions and not merely by displacing industrial activities to areas outside the EU (carbon leakage), and to attract the required investments in new climate-friendly production technologies and infrastructures.

Some other cross-cutting enabling conditions, which are discussed in other chapters of this report (whole-of-society approach, finance and a skilled workforce), are also relevant to the industry sector, as shown in Figure 22. This figure also shows the indicators (shown in the white boxes) that were selected to track progress in the industry sector.

Figure 22 Assessment framework for the industry sector

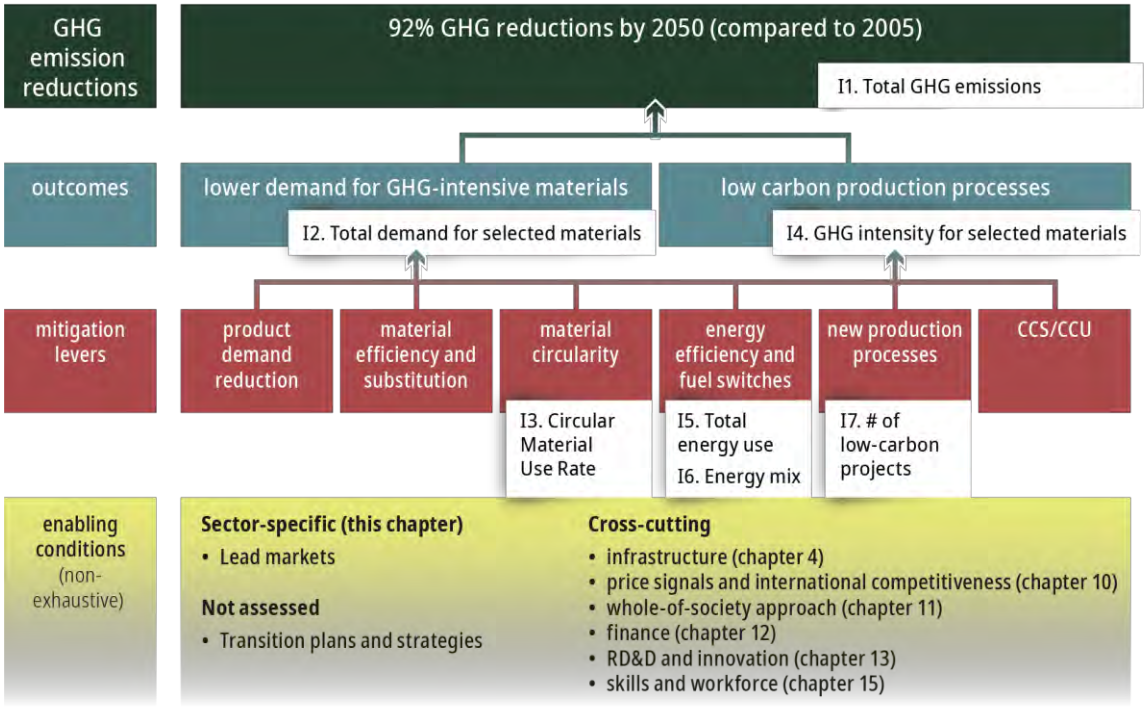

Source: Advisory Board (2024).

5.2 Emission reduction progress

Total industrial GHG emissions decreased by 30 % in 2005–2022 (see Figure 23). The sharpest reduction occurred in 2007–2010, mainly because of production decreases in the iron and steel and cement sectors in the context of the economic crisis and N_2O abatement measures in the chemicals industry (EEA, 2023f; EEA ETC/CM, 2022). After that, the pace of reductions slowed until 2020. A period of volatility then followed the COVID-19 pandemic, when emissions dropped, then partially rebounded in 2021, and fell again in 2022 amid high energy prices and curtailed production levels (ESABCC, 2023a). While emissions decreased, the gross value added of EU industry increased by 33 % in real terms from 2005 to 2021 (Eurostat, 2023m). When considering specific industrial subsectors, considerable reductions occurred in

2005–2021 in the iron and steel sector (– 24 %), the chemicals sector (– 36 %) and the cement sector (– 23 %), with less steep reductions in other industrial subsectors (– 16 %) (see Figure 23).

The average annual reduction in 2005–2022 (– 17 Mt CO_2e per year) needs to accelerate to – 24 Mt CO_2e per year in 2023–2030 and – 19 Mt CO_2e per year in 2031–2050 to be consistent with the trajectories towards the overall 2030 and 2050 reduction objectives. A steeper reduction rate would be required to achieve the recommended 90–95 % GHG emission reductions by 2040.

Figure 23 Indicator I1 – overall progress in reducing industrial GHG emissions.

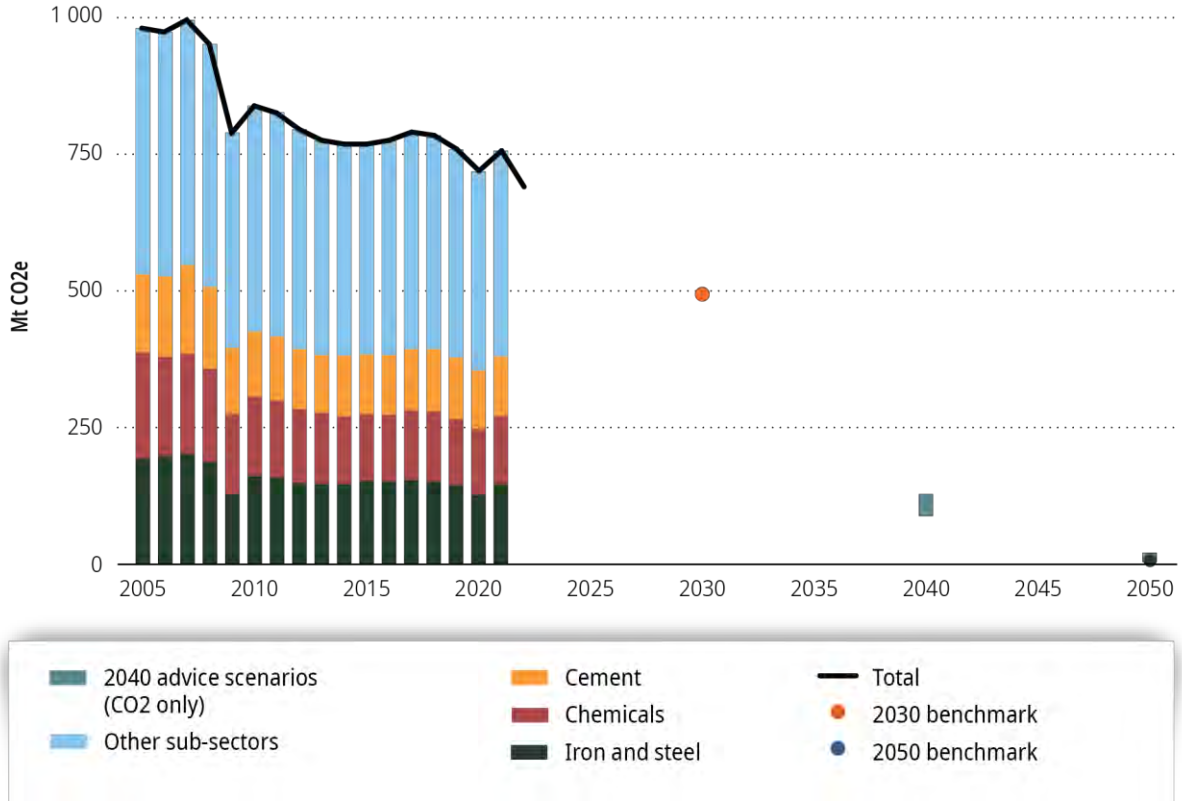

Notes: Historic GHG emissions based on the EU GHG inventory and verified EU ETS data (see figure 21 for more info, including on the split between different sub-sectors). The 2030 benchmark is based on the European Commission's Fit for 55 MIX scenario, as the sum of industrial energy-related CO_2 emissions, non-LULUCF non-energy CO_2 emissions, and non-CO_2 emissions from industry, AC & refrigeration and 'other sectors'. The 2050 benchmark is based on the MIX scenario from the Climate Target Plan impact assessment (see figures 9 and 65), and includes industrial energy and process CO_2 and non-CO_2 emissions. The 2040 advice range is based on the scenarios which underpin the Advisory Board's 2040 advice, and includes CO_2 emissions only.

Sources: GHG inventories (EEA, 2023f), EEA EU ETS data viewer (EEA, 2023g), Fit for 55 MIX scenario (EC, 2021v), Climate Target Plan impact assessment (EC, 2020s), Advisory Board 2040 advice scenarios (ESABCC, 2023b).

5.3 Outcome 1: lower demand for greenhouse gas-intensive materials

Demand-side measures have substantial potential to reduce GHG emissions while providing several other co-benefits.

The GHG reduction potential of measures that reduce the demand for GHG-intensive materials could be substantial. A 2020 report by the International Resource Panel found that material efficiency measures could reduce the life cycle GHG emissions of residential buildings and passenger vehicles by 35 % and 40 % respectively by 2050 compared with a scenario that only pursues supply-side mitigation measures (IRP, 2020). Two reports by Material Economics came to similar conclusions and found that increased material efficiency and high-quality material recirculation could reduce emissions from major industrial sectors in the EU by more than half. Most of the required measures would be at relatively low cost (< EUR 50/t CO_2e) or even profitable, provided that specific barriers are removed (Material Economics, 2019, 2018). Furthermore, these measures would not only reduce GHG emissions but also contribute to mitigating biodiversity loss and pollution, whereas a GHG reduction strategy solely focused on supply-side measures might worsen other environmental problems such as biodiversity loss, pollution and waste (Potoćnik and Teixeira, 2022).

Slow progress has been made so far in curtailing material demand and increasing material circularity.

Figure 24 shows estimates of the use and production of steel, cement and chemicals in the EU, illustrating a pattern that largely follows economic cycles. The demand for these GHG-intensive materials decreased in 2008–2009 in the context of the economic crisis, and, although it has recovered somewhat since 2015, overall demand has been relatively stable in recent years. Production of steel, cement and base organic chemicals have followed similar cyclical trends, although there are some differences in the change in trade balance. For example, growth in steel demand in recent years has largely been met by increased imports, leading to the development of a negative trade balance. For cement, this trade balance has become positive, while the negative trade balance for chemicals has largely remained stable.

There is no publicly available data on the use and production of GHG-intensive industrial products under the European Commission's scenarios that underpin the EU climate objectives, and therefore no benchmark for this indicator was set. However, the EU's 8th EAP does include a legally binding (but unquantified) broader objective to 'significantly reduce the EU's material and use footprint by 2030' (EC, 2022q), which might also require a reduction in the overall use of GHG-intensive materials.

The circular material use rate represents the share of recycled materials in the total amount of materials used by the EU economy and is therefore a good proxy indicator of the circularity of an economy. As Figure 25 illustrates, the rate has been increasing very slowly in recent years; it went from 10.8 % in 2010 to 11.7 % in 2021.

The European Commission has announced its ambition to double the circular material use rate by 2030 (EC, 2020g). This would require a more than a tenfold increase in the recently observed average annual rate of change by (from on average + 0.1 pp per year in 2017–2021 to on average + 1.3 pp per year in 2021–2030). Given the scale of the required acceleration, this will probably need a combination of increasing recycling and declining overall material demand.

Figure 24 Indicator I2 – production, use and trade balance of steel, cement and base organic chemicals

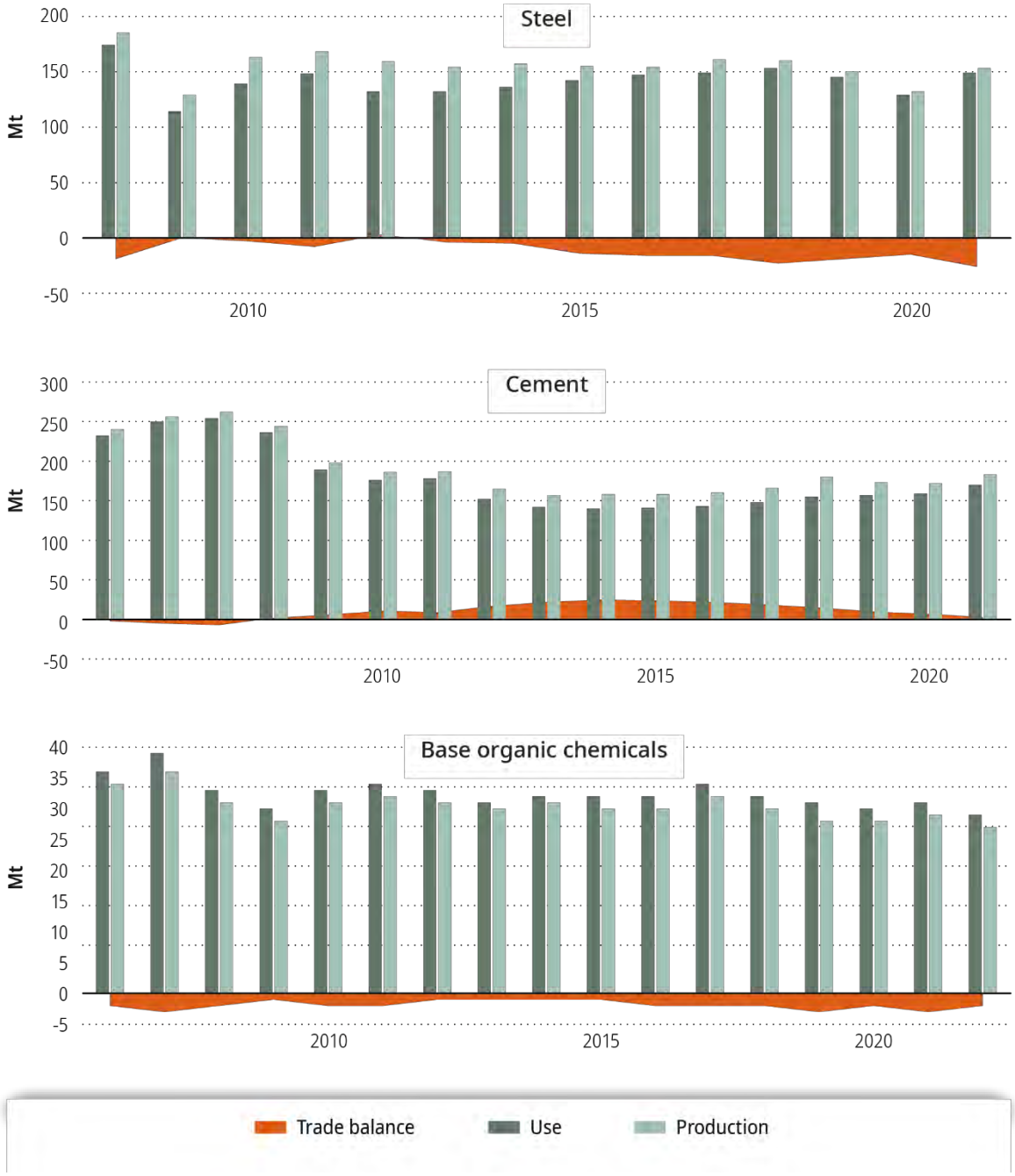

Notes: Steel production and use data is from Eurofer's annual activity report. Production refers to crude steel outputs, whereas use refers to apparent steel consumption (which includes steel that is stocked and not used immediately). The steel trade balance (exports minus imports) is based on data from Eurostat (DS-059268). The trade balance does not fully reflect the balance between production and use, which is partially due to material losses between crude steel output and total finished steel production (with the latter being lower than total steel use since 2015, which is consistent with the observed negative trade balance). Cement production and use received by mail from Cembureau, trade data based on Eurostat (DS-059268). Base organic chemicals data on production, import and export estimated based on Eurostat (DS-056120), use calculated as production + import – export.

Sources: Eurofer annual activity report (Eurofer, 2022), Eurostat (2023c, 2023d)

Figure 25 Indicator I3 – circular material use rate in the EU

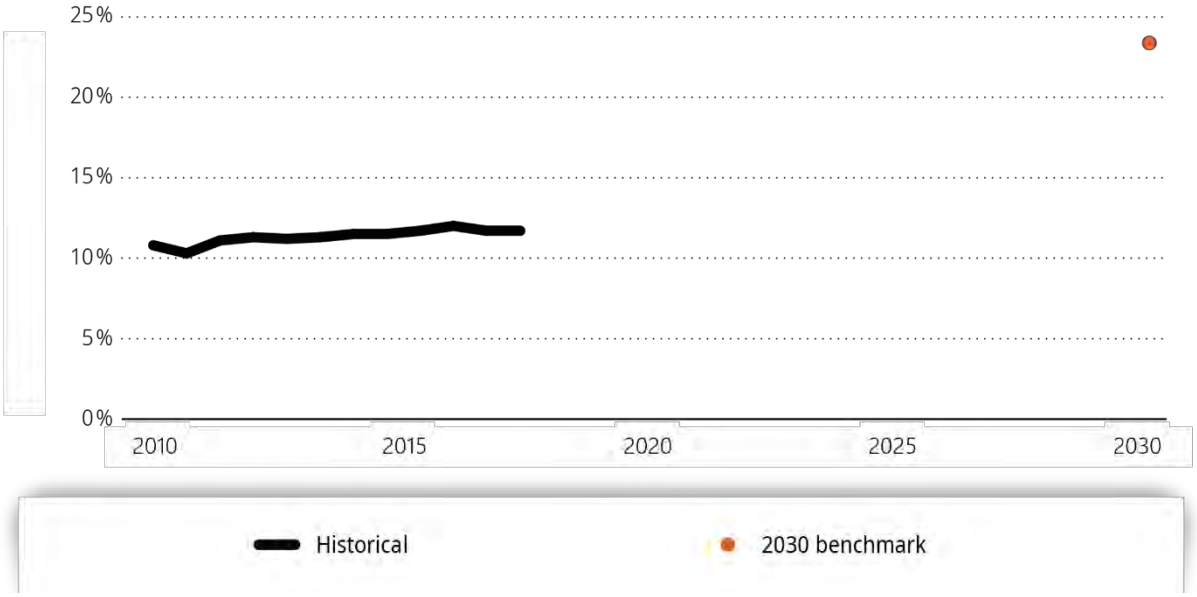

Sources: Eurostat (2023a) (historic), Circular Economy Action Plan 2 (EC, 2020g) (benchmark).

Improvements to the EU circular economy policy framework are still under development.

In the period to 2020, EU policies to decarbonise the industry sector mainly focused on supply-side solutions to address negative consequences of production, neglecting demand-side options (Pantzar and Suljada, 2020). Efforts to address the demand side have long been limited to voluntary information provision (e.g. on eco-labels) and voluntary green public procurement. However, the impact of such voluntary approaches is likely to remain limited unless combined with other, stronger policies such as pricing policies (e.g. carbon pricing) or regulations (EEA, 2022h; Pantzar and Suljada, 2020; SAPEA, 2020). The uptake of green public procurement practices in EU Member States has also been limited (Axelsson et al., 2023; Sapir et al., 2022).

In 2015, the European Commission launched CEAP 1, which included 54 specific actions (EC, 2015a). However, these measures have not been effective at curbing demand for GHG-intensive materials (see indicator I2) or at increasing the circularity of materials (see indicator I3). One of the major shortcomings that have been identified is the focus on waste management at the end of life of products rather than product system design and lifetime decisions, which determine much of a product's environmental impact (Friant et al., 2020; IRP, 2020; Watkins and Meysner, 2022; ECA, 2023a).

Similarly, the Ecodesign Directive (2009/125/EC) largely focuses on energy efficiency, although other dimensions such as product durability and repairability have been added over time (Barkhausen et al., 2022). Nevertheless, its scope remains limited, covering mainly energy-related products. A broader range of product standards covering recyclability has been identified as necessary to reverse the growing variety of composites, alloys and additives that prevent high-quality, closed-loop recycling of GHG-intensive materials (Chiappinelli et al., 2021; Neuhoff et al., 2019).

Finally, the lack of consistent price signals has been identified as a barrier to a more circular economy and an overall reduction in demand for materials. Inconsistencies include the exclusion of waste treatment from the EU ETS and the free allocation of allowances to GHG-intensive industry as a means to prevent carbon leakage in combination with a lack of carbon pricing on imported materials (see Chapter 10 'Pricing emissions and rewarding removals').

In more recent years, several steps were taken to address these gaps. In 2019, the EU adopted the Single-Use Plastics Directive (EU, 2019a), which introduced measures to reduce the use of 10 single-use items made from plastics. These include bans on those items where sustainable alternatives are easily available and affordable. This could also contribute to GHG emission reductions, as alternatives have, or can have, a substantially lower carbon footprint (– 75 % for bioplastics, ≥ 85 % for multi-use items (Di Paolo et al., 2022)).

The European Commission also launched CEAP 2 under the European Green Deal, including 35 additional actions (of which about half are legislative) to boost the circular economy (EC, 2020g). At the time of the publication of this report, most of these proposals have already been published by the European Commission but the legislative process is still ongoing. CEAP 2 takes on a broader approach towards the circular economy than CEAP 1, extending the focus of its actions to areas upstream in the waste hierarchy, such as product design, durability, repairability, reusability and recyclability. Furthermore, as about half of the actions under the plan are legally binding measures, it shows an increasing recognition of the need to use legally binding measures to strengthen the transition towards a circular economy. Finally, it also aims to improve the monitoring framework to track progress on the transition towards a circular economy (Johansson, 2021; Pantzar and Suljada, 2020; Watkins and Meysner, 2022). Although the plan itself is not binding on Member States, achieving its objectives will require ambitious and effective policies at the national and subnational levels. Several legislative proposals under CEAP 2 will become binding at the national level, including the Ecodesign for Sustainable Products Regulation (EC, 2022v), the revision of the Construction Products Regulation (EC, 2022x), the revision of the Vehicle End-of-life Directive (EC, 2023at), the revision of the Packaging and Packaging Waste Regulation (EC, 2022y), and the revision of the EU Waste Framework Directive (EC, 2023aq). These proposals are currently still in the legislative process or have been adopted only recently (see Table 3), and a detailed assessment of their consistency with the EU's climate objectives goes beyond the scope of this report.

Circularity also plays an important role in alleviating supply chain challenges, which have recently affected EU net zero industries and risk complicating the EU's transition to climate neutrality. The challenge stems from, among other factors, the high concentration of strategic minerals and supply chains in a few countries, and in particular China, which dominates supply chains of key critical materials (e.g. copper, lithium, nickel, cobalt and rare earth minerals) and net zero technologies (e.g. solar PV and batteries) (ECA, 2023d; IEA, 2023j, 2022f). Such concentration raises concerns that geopolitical factors could disrupt the supply chain required for the net zero transition (IPCC, 2022g). The combination of the EU's limited own extraction, processing and production capacities, high dependence on imports from a limited number of trading partners, strong incentives in other regions of the world to attract investments in battery supply chains and projected strong increases in demand globally makes it particularly vulnerable to supply chain disruptions (ECA, 2023d; IEA, 2023j). The EU policy framework is currently responding to this challenge: the EU raw materials initiative launched in 2008, led to the adoption of Critical Raw Materials Resilience roadmap in 2020 (EC, 2020j), including the EU list of critical raw materials. The REPowerEU plan announced increased EU innovation funding to 'reduce materials consumption, enhance recyclability of renewable energy equipment and substitute critical raw materials' (EC, 2022p) in line with CEAP 2. In 2023, as part of its Green Deal Industrial Plan, in response to the US Inflation Reduction Act it proposed a Critical Raw Materials Act (EC, 2023ac) and Net-Zero Industry Act (EC, 2023ao), which contain objectives aimed at boosting the EU's domestic supply chains for critical raw materials and its manufacturing of strategic net zero technologies respectively. Both proposals are currently still in the legislative process (see Table 3), and a detailed assessment of their consistency with the EU's climate objectives goes beyond the scope of this report.

The revision of the EU ETS Directive in combination with the CBAM Regulation (EU, 2023c, 2023n) is expected to result in better internalisation of the carbon cost in end use products, which supports the

different mitigation levers to reduce demand for GHG-intensive industrial products. However, as this is only introduced gradually and for specific sectors, the EU ETS does not yet ensure that the climate cost of producing a product is fully reflected in the product's price. That may potentially result in overconsumption. In addition, the revised EU ETS Directive requires the European Commission to assess the extension of the system to waste incineration by 2026, with a view to including it as of 2028 (see Chapter 10 'Pricing emissions and rewarding removals' for more details). This assessment should consider, among other topics, the potential diversion of waste towards landfill or increased exports to non-EU countries, which would lead to higher overall emissions (EU, 2023c).

5.4 Outcome 2: low-emission production processes

Progress on decarbonising industrial production is slow. New technologies are under development.

Estimates suggest that the GHG intensity of the selected GHG-intensive materials (steel, cement and chemicals) in the EU has been relatively stable or even slightly increasing, and observed trends in total emissions have been driven mainly by changes in production levels rather than reductions in emission intensity (see Figure 26).

- The emission intensity of steel production decreased slightly (– 5 %) between 2008 and 2021. The 21 % decrease in total GHG emissions was thus mainly driven by lower production levels, rather than decarbonisation of the production process.
- The emission intensity of (clinker-based) cement increased slightly in 2005–2015 before starting to decline again. By 2021, the emission intensity was at the same level as 2005, whereas total GHG emissions reduced by 23 % in the same period as a result of lower production levels. Whereas this assessment only accounts for the emission intensity of clinker-based cements, the sector has developed its own GHG-monitoring methodology, which also considers the replacement of clinker-based cement with supplementary cementitious materials. Using this methodology, the sector reports that the gross emission intensity of cementitious products in the EU decreased from 0.65 t CO_2e per tonne of cementitious product in 2005 to 0.61 t CO_2e per tonne in 2020 (Cembureau, 2023).
- A similar picture emerges for base organic chemicals. A slight reduction in the average GHG intensity (– 5 % in 2013–2022) only contributed about one third of the decrease in total emissions (– 14 %), with reduced production levels accounting for the large majority of emission reductions.

Final energy use in EU industry (shown in Figure 27) decreased in 2007–2010 in the context of the economic crisis but has remained relatively stable since (between 2 700 and 2 800 TWh per year). In the most recent 5-year period (2017–2021), there was even a slight increase in final energy use (on average + 0.8 TWh per year), although it is expected that 2022 data will show a considerable drop in final energy use linked to product curtailment due to the energy crisis (ESABCC, 2023a).

Under the European Commission's scenarios that underpin the EU's climate objectives, industrial energy use would need to reduce by on average 38 TWh per year up to 2030 (– 57 TWh per year under REPowerEU), which requires a reversal of recently observed trends.

Figure 26 Indicator I4 – GHG intensity of steel, cement and base organic chemicals in the EU

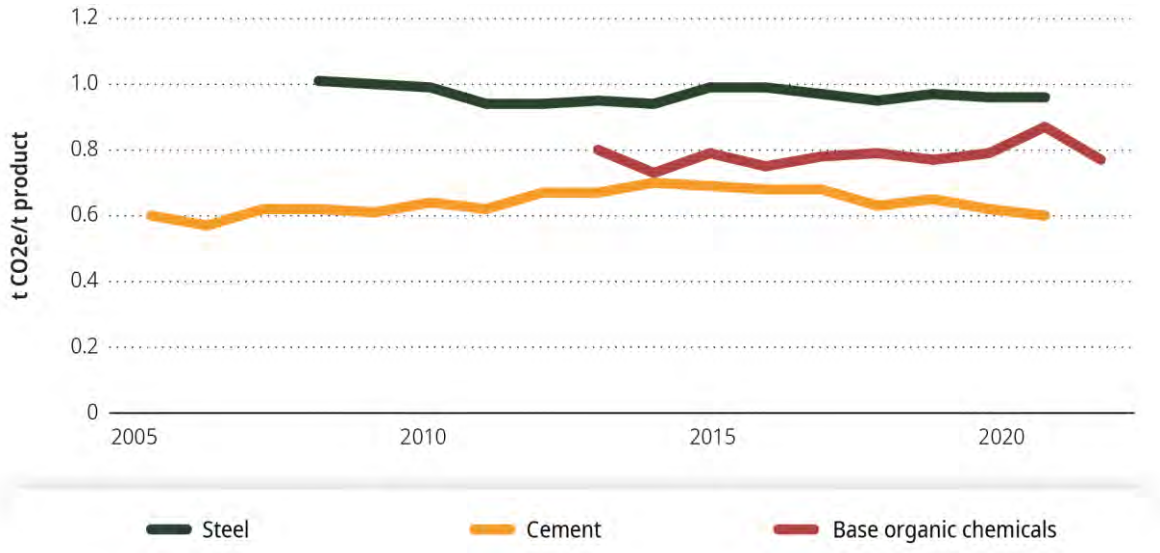

Notes: Advisory Board's estimates based on sectoral GHG emissions (see sources and notes under Figure 23) and production data (see sources and notes under Figure 24) for the iron and steel, cement, and base organic chemicals sectors.

Figure 27 Indicator I5 – final industrial energy use

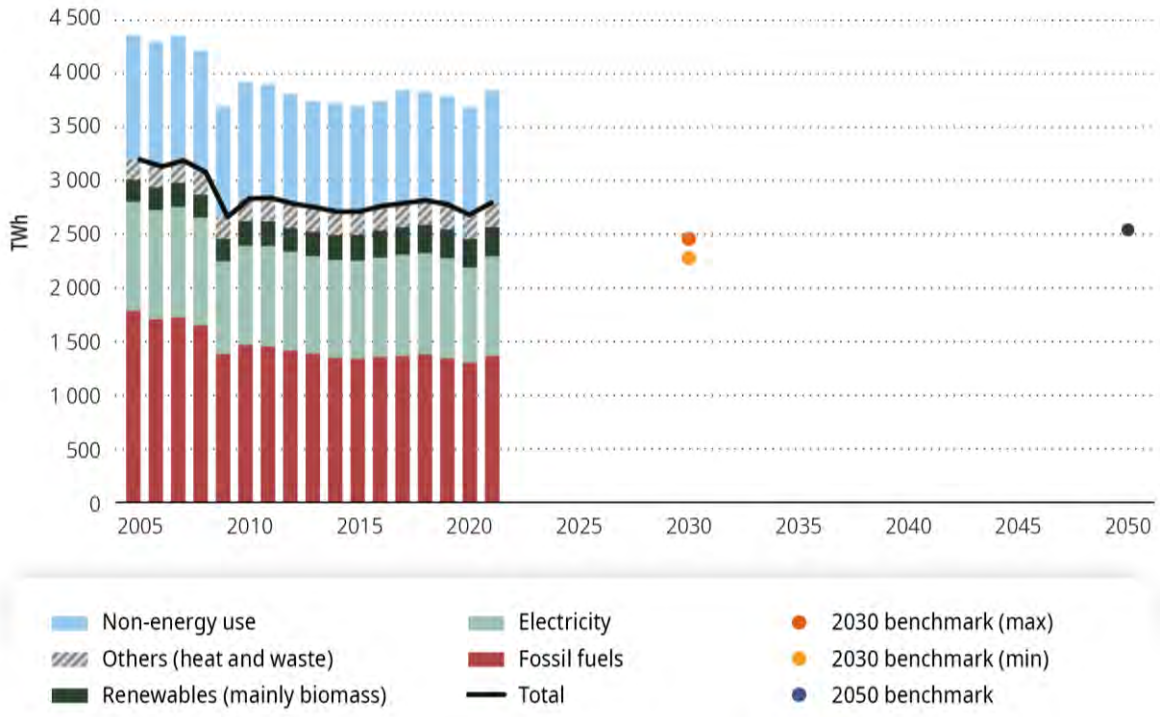

Notes: The max and min 2030 benchmarks based on the Fit for 55 MIX scenario and REPowerEU scenario respectively. The 2050 benchmark is based on the MIX scenario from the Climate Target Plan impact assessment (see Figure 67). All values were converted from kilotonnes of oil-equivalent to TWh.

Sources: Eurostat energy balances (2023b), Fit for 55 MIX scenario (EC, 2021v), REPowerEU staff working document (EC, 2022p), Climate Target Plan impact assessment (EC, 2020s).

In relative terms, the share of fossil fuels in final industrial energy use has been slightly declining, from 56 % in 2005 to 49 % in 2021, as shown in Figure 28. This was mainly replaced by (predominantly bio-based) renewable energy (from 6 % in 2005 to 10 % in 2021) and to a lesser extent electricity (from 32 % in 2005 to 33 % in 2021). However, the phase-out of fossil fuels has stalled in recent years, with their share stable at 49 % since 2015.

To be consistent with the European Commission's scenarios that underpin the EU climate objectives, the use of fossil fuels needs to be further reduced by 2030 and almost completely phased out by 2050. On the other hand, the uptake of renewables (other than renewable electricity) needs to double (from + 0.1 pp per year in 2017–2021 to + 0.2 pp per year until 2050), and the declining trend in the share of electricity (on average – 0.1 pp per year in 2017–2021) needs to be reversed (+ 0.3 pp per year until 2030; + 0.7 pp per year until 2050).

Figure 28 Indicator I6 – relative shares of fossil fuels, renewables and electricity in industrial final energy use (excluding non-energy use)

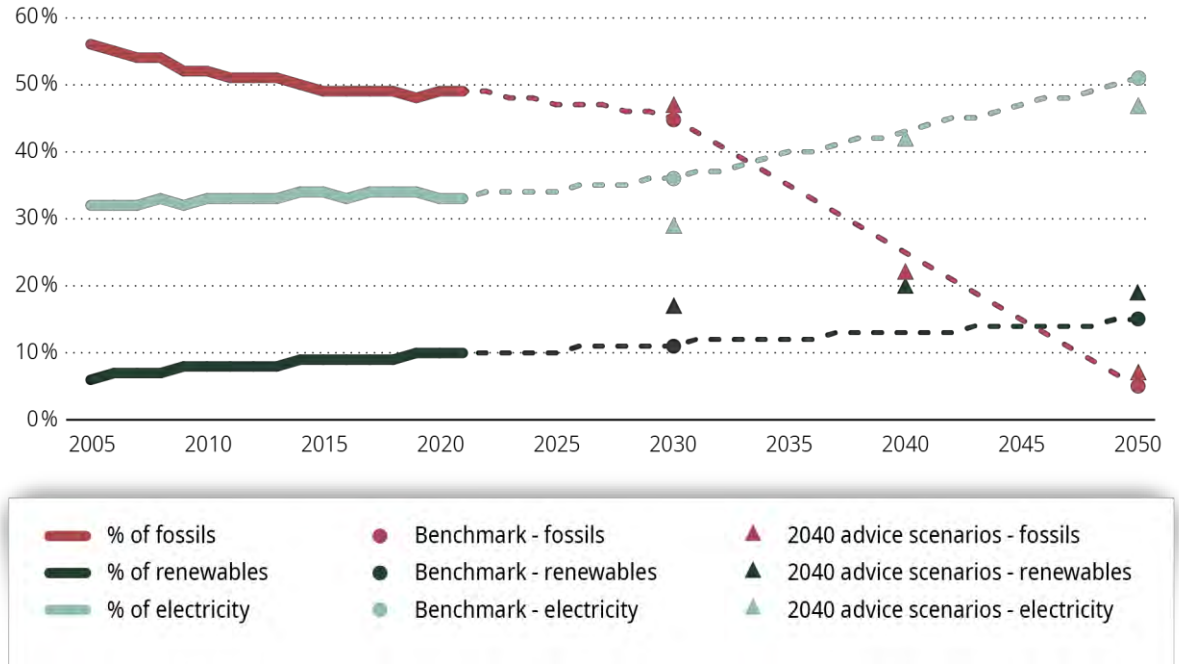

Notes: 2030 and 2050 benchmarks are based on the MIX scenario from the Climate Target Plan impact assessment (see figure 67). The 2040 advice values are based on the scenarios which underpin the Advisory Board's 2040 advice. The linear trajectories are shown to increase the readability of the figure, but do not imply that the Advisory Board recommends a linear trajectory towards the benchmarks.

Sources: Eurostat energy balances (2023b), Climate Target Plan impact assessment (EC, 2020s), Advisory Board 2040 advice scenarios (ESABCC, 2023b).

Although incremental efficiency improvements and fuel switches remain important to further bring down industrial GHG emissions, achieving deep reductions (> 90 %) by 2050 will require a shift towards new, low-emission industrial production processes. Several new technologies are currently under development in the various subsectors, but most of them have not yet reached commercial maturity. These include, among others, hydrogen direct reduction of iron ore, carbon capture for cement, and electrification, hydrogen and sourcing of non-fossil carbon in the chemicals industry.

Over the last few years, projects have emerged in the EU steel sector to research, develop and test low-emission and low-carbon production technologies. According to the Green Steel Tracker (summarised

in Figure 29) on 15 September 2023, 48 such projects were currently in development, of which more than half (28) related to full-scale industrial production plants (LeadIT, n.d.). Most of these projects are focused on the direct reduction of iron production route (23 direct reduction of iron projects + 12 projects to provide these with the required hydrogen), either by means of hydrogen or using fossil gas as a transitional fuel. Only two projects relate to carbon capture, which until recent years had been considered a key mitigation pathway for the steel sector.

Figure 29 Indicator I7a – low-carbon projects in the steel sector by technology group and project scale

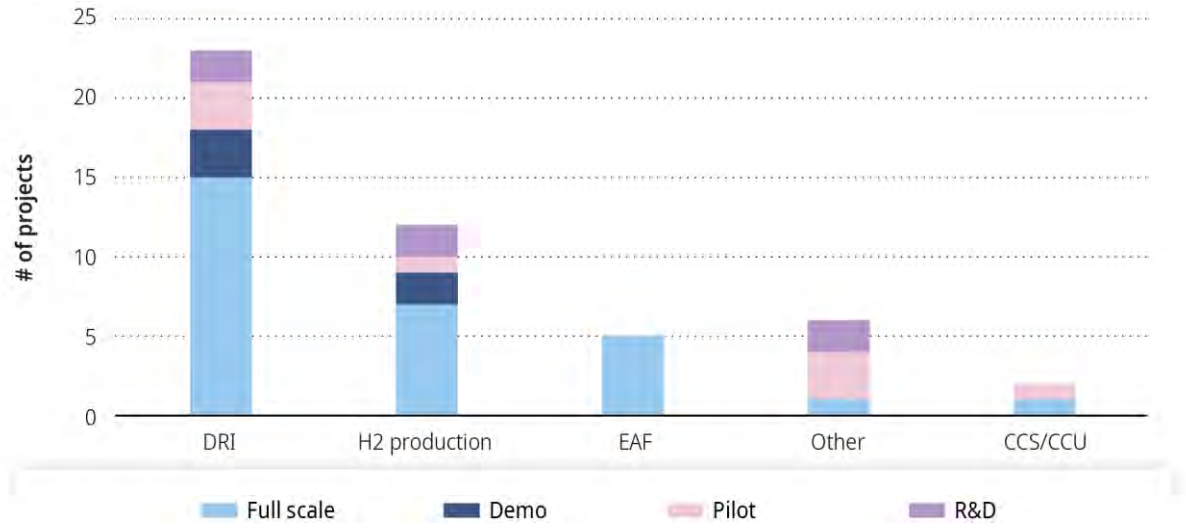

Source: Green Steel Tracker database (LeadIT, forthcoming).

The cement sector in the EU has reported 63 low-carbon projects currently under development or in operation in the EU, as shown in Figure 30. However, in contrast to the steel sector, only a small minority of these relate to full-scale projects, whereas most of the projects are still in the R & D (22) or pilot (24) phase. In terms of mitigation routes, more than half of the projects relate to carbon capture, reflecting the limited options for reducing the sector's high share of process emissions.

Figure 30 Indicator I7b – number of low-carbon projects in the cement sector by technology group and project scale

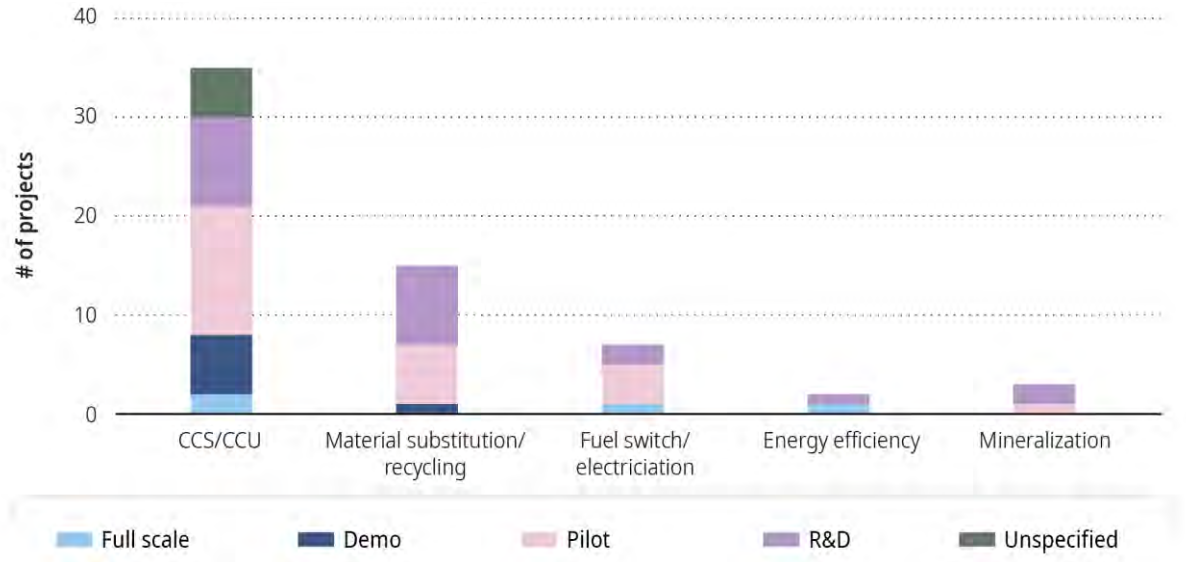

Source: Cembureau's online map of innovation projects (Cembureau, n.d.).

The chemical sector has reported 85 low-carbon projects that have already started in the EU, with another 86 currently planned ([17]), as shown in Figure 31. These projects cover a wide range of technologies, reflecting the different mitigation options available to the chemicals sector. The bulk of the projects relate to renewable energy, but these include many on-site solar PV parks, which are likely to contribute only a small share of those sites' energy needs. Chemical and mechanical recycling is also well represented, as are projects related to the use of low-emission hydrogen (and derivates) and the application of CCS/CCU technologies. Electric cracking is only being pursued by two projects. The sector overview does not provide consolidated information regarding the scale of the various projects, unlike the steel and cement sectors.

Figure 31 Indicator I7c – number of low-carbon projects in the chemicals sector by technology group and status

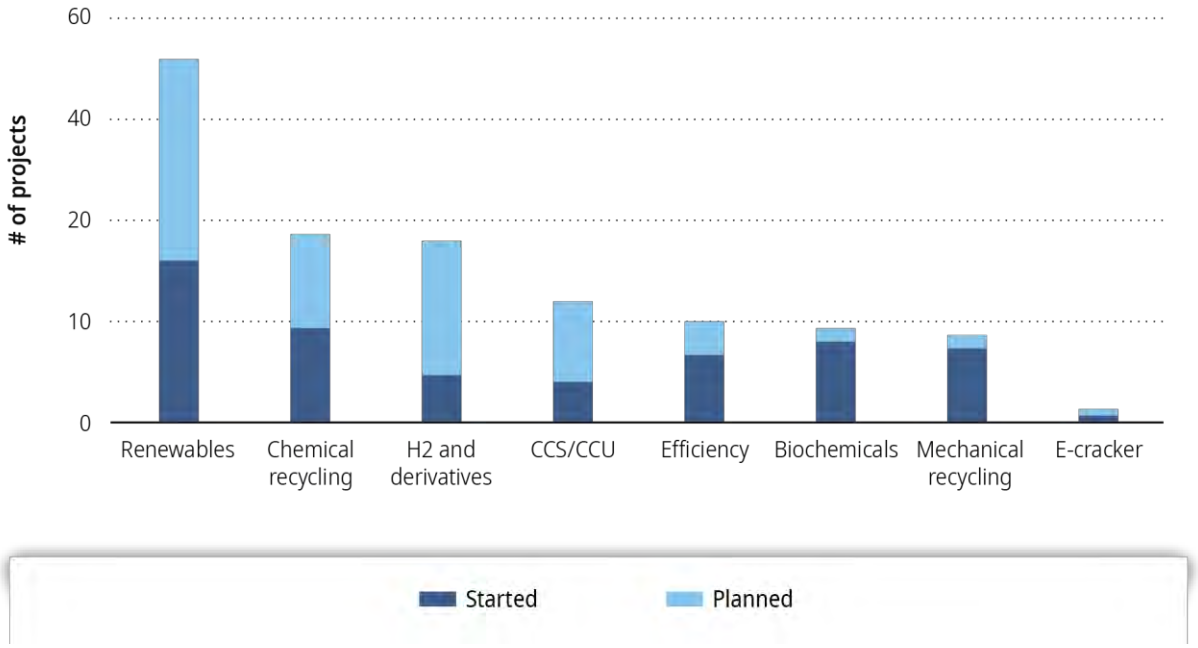

Source: CEFIC's online map of low-carbon technology projects (CEFIC, n.d.).

Dedicated policies are needed to accelerate the development and deployment of low-emission technologies.

Since 2005, the EU ETS has been the EU's flagship policy to reduce GHG emissions and spur low-carbon technologies in the industrial sector. Although the latest revision has substantially reinforced the system, there are justifications for combining it with complementary measures to bring forward and reduce the cost of immature technologies, which often face a competitive disadvantage, as society is currently locked in GHG-intensive technologies in terms of infrastructure, institutions and markets (see Section 10.2). This provides a justification for combining carbon pricing with a range of complementary policies to support new low-emission technologies, throughout each step of their development (R & D, prototype, pilot or demonstration, early deployment or market formation, and maturity and diffusion).

In the past, the EU has actively supported the early stages through dedicated research programmes (e.g. Horizon 2020 and Horizon Europe). Since its revision in 2018 and more recently in 2023, the EU ETS is

([17]) Projects related to renewable power purchasing agreements and the installation of combined heat and power units were not included in the overview.

also expected to become more effective in supporting the pilot and demonstration phase (through the Innovation Fund) as well as the diffusion of low-emission technologies once they reach full maturity (via a stronger carbon price signal). In addition, several measures are taken at the EU level to reinforce the EU electricity grid and develop infrastructure for hydrogen and CO_2 (see Chapter 4 'Energy supply' for more details), which are important enabling conditions for the deployment of low-emission industrial technologies. However, until recently, dedicated policies to support technologies in the phase of early deployment/market formation have been largely lacking or ineffective due to their voluntary nature and limited implementation at the national level (as described in more detail later in this section). Such policies are important for technologies to improve their reliability and cost-competitiveness through learning effects (Chiappinelli et al., 2021; Material Economics, 2022; Neuhoff et al., 2019; Nilsson et al., 2021; Vogl et al., 2021; Wyns and Khandekar, 2019).

The creation of lead markets allows innovations to be tailored to customer needs, to gain experience and therefore to improve quality, reliability and cost-competitiveness (Neuhoff et al., 2019). There are several options to create such lead markets, such as green public procurement, labels and product standards (Chiappinelli et al., 2021; Neuhoff et al., 2019; Nilsson et al., 2021; Sapir et al., 2022). However, Vogl et al. (2021) have cautioned about the limited effectiveness and practical complexity of lead markets in the context of decarbonising the steel sector, while recognising they can help to reduce the required subsidy volumes and aid the global diffusion of new production methodologies (as they would also incentivise EU importers to reduce their GHG intensity). Vogl et al. therefore conclude that direct financial support mechanisms such as carbon contracts for difference (CCfDs; see later in this section) are a more effective approach to supporting green steel production, in case the EU ETS does not create sufficient incentives. Policies to create lead markets can still be warranted, to serve other policy goals such as creating international demand for green steel and thereby driving climate action in non-EU countries.

Until recently, there have been few EU policies that aim to create lead markets for climate-friendly industrial products. New and revised policies under the European Green Deal include several measures which could address this.

As public procurement accounts for around 15 % of the EU's GDP, green public procurement could be an effective tool to create demand for low-emission materials (Axelsson et al., 2023; Sapir et al., 2022). The EU directive on public procurement (EU, 2014) allows the (voluntary) inclusion of green criteria in public procurement processes, and in 2022 the European Commission provided a list of good practices to encourage their use. However, so far their application remains rare, at less than 5 % of all public procurement contracts. The main barriers identified are their voluntary nature, public authorities' preference for short-term lowest-cost options, limited know-how and lack of established environmental criteria/assessment methodologies, lack of coordination between different ministries at the national level, and lack of a monitoring and reporting mechanism to track progress on green public procurement practices (Axelsson et al., 2023; Sapir et al., 2022). Under CEAP 2, the European Commission is planning to tackle these issues by proposing minimum mandatory green public procurement criteria and targets in sectoral legislation, phase in compulsory reporting to monitor the uptake of green public procurement, and continue supporting capacity building and sharing of best practices (EC, 2020g). Green public procurement obligations are included amongst others in the proposed Ecodesign for Sustainable Products Regulation, the proposed revision of the Construction Products Regulation, and the proposed Packaging and Packaging Waste Regulation. Whereas these planned policies seem to address most of the barriers identified, their effectiveness will depend on their final form and implementation in the coming years.

A second group of tools to create lead markets are labels that nudge climate-aware consumers into low-carbon choices, and product standards that regulate the GHG intensity of produced materials. So far, EU

labelling and standardisation requirements have been mainly focused on safety, functionality and – in some cases – energy efficiency, and their potential to create demand for low-carbon products has remained largely unused (Chiappinelli et al., 2021; Neuhoff et al., 2019; Wyns and Khandekar, 2020). The sustainable products initiative under CEAP 2 aims to increase the circularity and reduce the climate impact of products sold in the EU, with priority given to high-impact intermediary products such as steel, cement and chemicals. This would be operationalised through the proposed Ecodesign for Sustainable Products Regulation (EC, 2022v) – which would replace the Ecodesign Directive (EU, 2009b). Once adopted, it would have to be elaborated in secondary legislation with specific rules for specific product groups. A preliminary study by the JRC identified a shortlist of intermediary products, including GHG-intensive products such as steel and chemicals, but excluding plastics and construction products (including cement), as these would be covered by other legislative initiatives (JRC, 2023a). One of these initiatives is the proposed revision of the Construction Products Regulation (EC, 2022x), which sets a range of minimum requirements that construction products sold on the EU market need to adhere to, including a requirement to "address – in accordance with the state of the art – minimising whole-life-cycle greenhouse gas emissions". Given the broad and generally defined criteria in the proposed Ecodesign for Sustainable Products Regulation and proposed revision of the Construction Products Regulation, their effectiveness in creating lead markets for low carbon industrial products is difficult to assess *ex ante* and will largely depend on the outcome of the legislative process and subsequent implementation.

In addition to creating lead markets, new technologies could be supported by direct financial support by the EU and its Member States, which could cover investment or operational costs. CCfDs have been recommended to provide operational support for three reasons: firstly, they make it possible to provide adequate levels of support for new, low-carbon, but more costly technologies, without the need to increase the carbon price for the entire economy. Secondly, they increase investor certainty by providing a predictable, long-term level of support, which would also reduce financing costs ([18]). Finally, they reduce public expenditures and avoid windfall profits if the carbon price increases in future years (Chiappinelli et al., 2021; Neuhoff et al., 2019; Vogl et al., 2021). On the downside, there is a risk that CCfDs could lead to overcompensation, depending on the ability of producers to pass on the cost premium for low-carbon technologies. Furthermore, if CCfDs are allocated through tendering – which would be the most efficient approach – they would put regions with lower access to low-cost, renewable electricity at a disadvantage. Additional transitional support might be required for such regions to ensure a just transition towards climate-friendly industry (Vogl et al., 2021).

The recent revision of the EU ETS Directive introduces the possibility for the Innovation Fund to support decarbonisation projects through contracts for difference, CCfDs and fixed premium contracts (EU, 2023c), and a first call for green hydrogen production is planned to be launched soon (EC, 2023v). The effectiveness of these measures will become clearer in the coming years.

In addition, the European Commission has recently proposed several initiatives to (financially, among other ways) support the production of green hydrogen (mainly the Net-Zero Industry Act and EU Green Hydrogen Bank; see Chapter 4 'Energy supply'), which could also contribute to the decarbonisation of the industry sector. The revised 2022 State aid guidelines on energy and climate also include a range of options for Member States to (financially) support the decarbonisation of their industries (EC, 2022i). However, Member States' budgetary abilities have been constrained in recent years, and increasing the available public budget for climate-related State aid faces multiple challenges (see also Section 12.5).

([18]) For electrification technologies, they might need to be complemented by other measures to shield early movers from volatile electricity prices to achieve this goal.

Finally, article 22a of the recently adopted RED III (EU, 2023f) introduced legally binding objectives for Member States to increase the share of renewables in industrial energy and feedstock use. Firstly, Member States are required to 'endeavour' to increase the share of renewable sources in both the final industrial energy use and the use of energy sources for feedstock purposes by at least 1.6 pp per year. Secondly, they must ensure that at least 42 % of total hydrogen use in 2030 for energy and non-energy purposes in the industrial sector comes from renewable fuels of non-biological origin. Whereas the first requirement only imposes an effort obligation on Member States, the second requirement imposes a result obligation. In response to the RED III, Member States are expected to implement additional policies in the coming years to promote the uptake of renewable energy and feedstocks in the industry sector, including by supporting the deployment of new industrial technologies.

5.5 Summary tables

Table 6 Progress summary - industry

Indicator	Reference period	Historical progress	Required up to 2030	Required in 2031–2050
I1: GHG emissions	2005–2022	– 17 Mt CO_2e/yr	– 29 Mt CO_2e/yr	– 21 Mt CO_2e/yr
I2: total material use				
I2a: steel	2017–2021	Stable	No benchmark	No benchmark
I2b: cement	2017–2021	+ 6 Mt/yr	No benchmark	No benchmark
I2c: high-value chemicals	2017–2021	– 0.7 Mt/yr	No benchmark	No benchmark
I3: circular material use rate	2017–2021	+ 0.1 pp/yr	+ 1.3 pp/yr	No benchmark
I4: GHG intensity				
I4a: steel	2017–2021	– 0.8 kg CO_2e/t/yr	No benchmark	No benchmark
I4b: cement	2018–2022	– 18 kg CO_2e/t/yr	No benchmark	No benchmark
I4c: high-value chemicals	2018–2022	– 6 kg CO_2e/t/yr	No benchmark	No benchmark
I5: final energy use	2017–2021	+ 0.8 TWh/yr	– 38 TWh/yr	Stable
I6: energy mix				
I6a: % of fossil fuels	2017–2021	Stable	– 0.4 pp/yr	– 2 pp/yr
I6b: % of renewables	2017–2021	+ 0.1 pp/yr	+ 0.2 pp/yr	+ 0.2 pp/yr
I6c: % of electricity	2017–2021	– 0.1 pp/yr	+ 0.3 pp/yr	+ 0.7 pp/yr
I7: low-carbon projects				
I7a: steel	2023	48	No benchmark	No benchmark
I7b: cement	2023	63	No benchmark	No benchmark
I7c: high-value chemicals	2023	85	No benchmark	No benchmark

Legend

On track	The required change ([a]) is ≤ 1.
Almost on track	The required change ([a]) is between 1 and 1.5.
Somewhat off track	The required change ([a]) is between 1.5 and 2.
Considerably off track	The required change ([a]) is ≥ 2.
Wrong direction	The required change ([a]) is < 0.

([a]) See Section 2.2 for more details on how the required change is calculated.

Table 7 Policy consistency summary - industry

Policy gaps	– Demand management and materials efficiency have until recently remained largely unaddressed by EU policies (e.g. CEAP 1 which mainly targeted recycling). This is better addressed under CEAP 2, but the legislative measures thereunder are not yet adopted. – Dedicated policies to support early deployment / market formation of low-emission technologies have been largely missing in the past. New policies have been put in place (e.g. the introduction of contracts for difference and CCfD's under the Innovation Fund) or are under development (e.g. the Ecodesign for Sustainable Products Regulation).
Ambition gaps	– High levels of free allocation to industry in combination with the lack of a carbon price on materials imports, and the exclusion of the waste sector under the EU ETS have undermined the carbon price signal that could trigger such demand-side measures. The gradual introduction of a CBAM to replace free allocation is expected to address this gap, at least for the sectors covered by it. Waste incineration might be included under the EU ETS as of 2028.

6 Transport

Key messages

The pace of GHG emission reductions in the EU transport sector needs to at least double to align with the EU's climate objectives.

As shown in Figure 32, the EU has not managed to structurally reduce the GHG emissions of its transport sector since 2005. There have been improvements in vehicle efficiency and the GHG intensity of transport fuels, but these have been offset by increased overall transport demand (in particular for aviation) and – in more recent years – the shift towards heavier, less-efficient passenger cars. A substantial decrease occurred in 2020 (– 20 % compared to 2019) in the context of the COVID-19 pandemic, but emissions have largely rebounded since then (– 4 % in 2022 compared to 2019). In recent years, the share of zero-emission vehicles (ZEVs) in new sales has been increasing, in particular in the passenger car segment; which is expected to lower GHG emissions in the coming years.

The average rate of reduction since 2005 (by 2 Mt CO_2e per year) needs to increase more than tenfold to be consistent with the trajectories towards the overall 2030 – 55 % objective (– 26 Mt CO_2e per year in 2023–2030), and even more so after 2030 to be consistent with the 90 % reduction objective for transport GHG emissions by 2050 (– 31 Mt CO_2e per year in 2031–2050). Even steeper reductions (– 52 Mt CO_2e per year) would be required in 2031–2040 to be consistent with the scenarios underpinning the recommended 90–95 % reduction objective for 2040.

Figure 32 Indicator T1 – overall progress in reducing transport GHG emissions

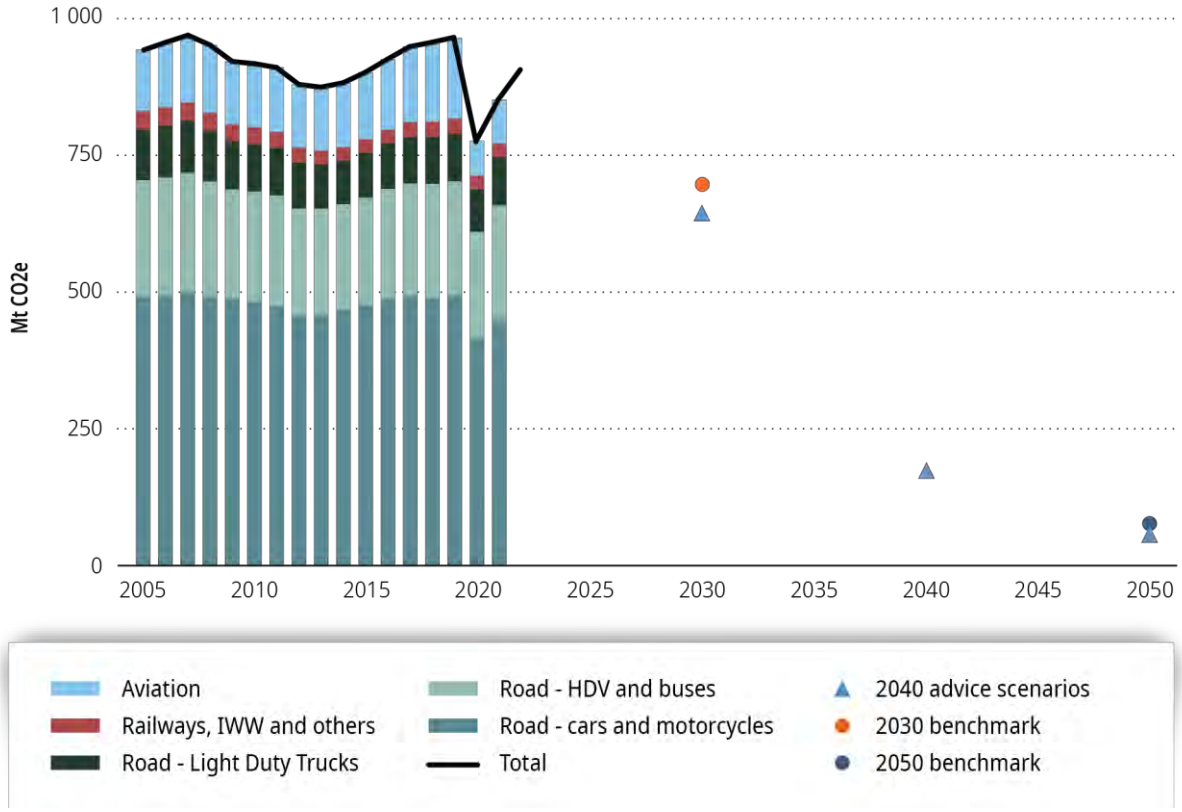

Sources: See Figure 34 for detailed sources and notes.

Moderate growth in overall transport demand and encourage a modal shift.

Needs. The growth in overall transport demand in the EU needs to slow down, and part of the remaining demand should shift towards lower-emission transport modes (e.g. from aviation and road to rail and inland waterways (IWW) to be consistent with the scenarios that underpin the EU's 2030 and 2050 climate objectives. Activating demand-side mitigation levers in parallel with decarbonisation of supply is important to reduce pressure on constrained resources, to accelerate emission reductions and to reduce emissions in subsectors where supply-side decarbonisation technologies are not yet proven at scale (e.g. synthetic fuels). Whereas such demand-side levers primarily rely on (sub)national policies, these can be supported by EU policies, in particular when considering cross-boundary transport flows.

Gaps. Moderation of overall transport demand is not considered as an option in the EU's Sustainable and Smart Mobility Strategy **(policy gap)**. Furthermore, EU policies to support a modal shift (the Combined Transport Directive, the Rail Freight Corridors Regulation, the Trans-European Transport Network (TEN-T) regulation) have so far had little success owing to lack of ambition (e.g. outdated provisions in the Combined Transport directive that prevent digitalised workflows, lack of adequate delivery mechanisms in the Rail Freights Corridors Regulation, lack of an overview of current and future required capacities of intermodal terminals under the TEN-T regulation) **(ambition gap)** and incomplete and heterogeneous implementation at the Member State level **(implementation gap)**. Recent proposals by the European Commission (the 2021 proposal to revise the TEN-T regulation, the recent proposals for a regulation on the use of railway capacities and the revision of the Combined Transport Directive) aim to address these gaps. Given how recent they are, the Advisory Board has not been able to assess the adequacy of these proposals.

Recommendation T1. EU policies should seek to curb growth in overall transport demand, for example by supporting more efficient spatial planning at the (sub)national level where possible (see also Section 7.5).

Recommendation T2. EU policies should also more effectively support a modal shift by tackling non-market barriers that hinder a shift towards lower-emission transport modes, including operational and regulatory barriers, infrastructural bottlenecks, and lack of available and integrated data. To this end, EU legislators should adopt an ambitious revision of the Combined Transport Directive and the regulation on the use of railway infrastructure capacities. In parallel, both overall demand moderation and a modal shift should be further facilitated through a further alignment of pricing policies with climate objectives (see recommendations T5 and T6).

Promote uptake of the most efficient ZEVs.

Needs. The share of ZEVs in new registrations has been increasing in recent years, but the increase needs to accelerate to achieve the EU's objectives, in particular for vans and HDVs. Adequate charging/refuelling infrastructure and the availability of critical raw materials and batteries are the two main prerequisites for accelerated uptake of ZEVs.

Gaps. The EU has put in place several policies to increase the uptake of ZEVs. These include strengthened CO_2 emission performance standards for passenger cars and vans (adopted) and HDVs (proposed, currently under negotiation), the Alternative Fuel Infrastructure Regulation to enhance charging and refuelling infrastructure (adopted) and the revised Clean Vehicles Directive (adopted). In addition, EU State aid guidelines allow Member States to provide financial support for the purchase of ZEVs. Whereas these policies can effectively accelerate the uptake of ZEVs, they currently do not incentivise efficiency (smaller, more efficient vehicles) within the segment of ZEVs **(ambition gap)**, and might even incentivise

the uptake of larger, less-efficient ZEVs **(policy inconsistency)**, increasing pressure on the already constrained availability of critical resources.

Recommendation T3. EU policies that incentivise the uptake of ZEVs should prioritise the uptake of energy- and resource-efficient ZEVs.

Prioritise direct electrification where possible, and promote biofuels only from sustainable feedstocks.

Needs. Achieving the required reductions by 2050 will require deep GHG reductions in all transport modes, and an acceleration of the trend in phasing out fossil fuel use. Direct electrification is an energy-efficient option with relatively low sustainability concerns. However, despite recent improvements in battery technology, decarbonising aviation, maritime and (specific segments of) heavy-duty road transport will probably require the use of low-carbon fuels, including synthetic fuels and sustainable biofuels.

Gaps. The RED III, ReFuelEU Aviation and FuelEU Maritime set specific objectives for the uptake of low-carbon fuels in the transport sector, while limiting the potential contribution of biofuels with high negative spillover risks. Nevertheless, concerns remain, as these policies continue to promote some biofuels with potentially high indirect effects, such as fuels made from food and feed crops (up to 7 %), intermediate crops and specific types of animal fats (so-called "category 3 animal fats") **(ambition gap)**. Furthermore, there are well-founded suspicions of fraud in the labelling of biofuels as sustainable **(implementation gap)**. This illustrates that the risk of spillover effects is inherent to biofuels, as impacts can be indirect (e.g. demand for fuel can contribute to land use change far away from a specific supply chain), and their sustainably available supply is constrained.

Recommendation T4. EU policies should prioritise direct electrification in the transport sector where possible. Given their limited availability, the use of sustainable biofuels and hydrogen-based fuels should be promoted for only those transport modes for which direct electrification is not suitable, such as aviation, long-haul shipping and possibly some cases of heavy-duty road transport. These policies should only promote the use of biofuels made from truly sustainable feedstocks, reflecting their overall limited availability.

Further align EU pricing policies in the transport sector with the EU's climate objectives (see also Chapter 10 'Pricing emissions and rewarding removals')**.**

Needs. Consistent EU pricing policies are needed to incentivise emission reduction options across all possible transport choices, including demand moderation, a shift towards lower-emission transport modes, and the uptake of ZEVs and low-carbon transport fuels. Such policies need to be accompanied by measures to address potentially adverse social impacts (see Chapter 11 'Whole-of-society approach').

Gaps. Recent policy developments are expected to improve the alignment of the EU's pricing policies in the transport sector with its climate objectives. The revised EU ETS will gradually phase out free allocation for aviation and extend the system to maritime transport by 2026, while introducing a separate EU ETS 2 for (amongst others) road transport fuels in 2027 or 2028. The revised Eurovignette Directive (adopted) mandates a shift from time-based to distance-based road pricing, which would better internalise externalities. The proposed revision of the ETD would limit current exemptions for commercial transport fuels, and for aviation and maritime transport.

However, gaps remain even when taking these recent developments into account. The price difference between the EU ETS and the EU ETS 2 (which is more likely due to the 'soft' price cap under the latter) would continue to promote fossil fuel use over electrification in the transport sector **(policy inconsistency)**. Furthermore, extra-EU aviation and half of extra-EU maritime transport remains exempt from the EU ETS **(policy gap)**. Finally, progress on the adoption of the ETD proposal has been slow, and current exemptions are still in force **(policy inconsistency)**.

Recommendation T5. In the short term, the proposed revision of the ETD should be adopted to phase out exemptions for commercial, aviation and maritime transport.

Recommendation T6. In the longer term (after 2030), carbon price levels between the EU ETS and the EU ETS 2 should converge to level the playing field between electrified and fuel-based transport (see also Chapter 10 'Pricing emissions and rewarding removals').

6.1 Scope and sectoral assessment framework

Scope

This chapter covers all activities that result in transport GHG emissions as reported under the United Nations Framework Convention on Climate Change (UNFCCC), including:

- emissions from road, rail, domestic navigation and domestic aviation, and other transport (CRF category I.3 – energy use in transport);
- emissions from international aviation and international maritime transport (on the basis of bunker fuels sold in the EU, which would cover all outgoing voyages and 'at berth' fuel consumption; reported as memo items in the GHG inventory).

Transport by active modes (walking, cycling, etc.) is not covered in the data shown in this chapter.

Throughout the chapter, it is further specified whether data shown includes international bunker fuels or not.

Greenhouse gas emission reductions required in the transport sector to reach climate neutrality

The European Green Deal (EC, 2019c) states that the transport sector will have to reduce its emissions by 90 % ([19]) by 2050 (compared to 1990, which implies a reduction of 92 % compared to 2005) as a contribution to the overall climate neutrality objective. The European Commission's LTS A Clean Planet for all (EC, 2018e) presents a similar reduction level, with transport emissions reduced by 89–90 % by 2050 under the 1.5TECH and 1.5LIFE scenarios (compared to 1990). Scenarios underpinning the Advisory Board's recent report on a greenhouse target for 2040 suggest that CO_2 emissions in transport could be reduced by up to 79 % by 2040 and 93 % by 2050 (compared to 1990) ([20]).

By 2030, the European Commission's scenarios that underpin the overall 55 % reduction objective require transport emissions excluding international aviation and maritime to reduce by 29 % compared

([19]) This includes international aviation, but not international maritime. Emissions from international maritime should reduce by 80 % by 2050 compared to 1990 (see footnote 8 of SWD(2020) 331 final).

([20]) Based on reductions in domestic transport emissions from the 90–95 % reduction scenarios assessed by the ESABCC, combined with an illustrative reduction for aviation based on the Sustainable and Smart Mobility Strategy.

to 2005. Emissions from international aviation and maritime transport would peak in 2025, and return to 2005 levels by 2030.

Assessment framework for the transport sector

The selection of outcomes, mitigation levers and enabling conditions is primarily based on the transport chapter (chapter 10 of the contribution of Working Group III) (IPCC, 2022j). Whereas the IPCC covers the challenges and opportunities to decarbonise the transport sector at a global level, its findings also apply to the EU context.

Outcomes. IPCC AR6 highlights a growing awareness that achieving the necessary GHG emission reductions in the transport sector will require a combination of demand management with new technologies. In line with this, two main outcomes are considered for the assessment:

- **curbing demand for emission-intensive transport**, which covers the need both to moderate overall demand (e.g. through digitalisation) and to switch part of it from emission-intensive to lower-emission transport modes,
- **decarbonising the transport fleet** through scaling up ZEV and fuel technologies, and improving the energy and resource efficiency of vehicles (in order to reduce emissions and resource use along the whole supply chain).

Mitigation levers. To achieve these outcomes, five main mitigation levers were identified, based on the different mitigation pathways described in IPCC AR6.

- An overall **moderation of transport demand** would lower GHG emissions, and can be pursued through a range of measures, including changes in infrastructure and spatial planning (referred to as 'urban form' in IPCC AR6), promoting changes in travel habits, shorter supply chains and digitalisation trends.
- A **modal shift** from emission-intensive (e.g. cars, lorries, planes) to lower-emission (e.g. rail, maritime and waterways, active transport) transport modes – including through multimodality – can contribute to GHG emission reductions, if the shift leads to an overall reduction in the activity of the most GHG-intensive transport modes (road and air).
- The uptake of **ZEVs** is a key lever to decarbonise the transport sector, and notably road transport. Electromobility has the potential to rapidly reduce GHG emissions, especially when combined with low-carbon electricity supply (see Chapter 4 'Energy supply'), but might need to be complemented by other types of ZEVs such as hydrogen-powered fuel cell electric vehicles or low-carbon fuels (see the final lever below) in specific circumstances.
- More **energy-efficient vehicles** can reduce GHG emissions both directly (lower tailpipe emissions) and indirectly (lower emissions from electricity production in the case of BEVs), fuel refining in case of internal combustion engine vehicles (ICEVs)). Similarly, more **resource-efficient vehicles** can indirectly reduce emissions from car manufacturing, including battery manufacturing (in the case of BEVs).
- For those subsectors that cannot be (fully) electrified, **a switch towards non-fossil, low-carbon fuels** can be used to achieve deep GHG emission reductions. This is particularly the case for the aviation and maritime sectors, and for some parts of heavy-duty road transport in particular circumstances. For these sectors, advanced bio- and hydrogen-based fuels (e.g. synthetic jet fuels for aviation, methanol and ammonia for maritime transport) are emerging as viable options, with the first pilot projects already in or close to operation today (IPCC, 2022g). The contributions of such fuels to atmospheric GHG concentrations depend strongly on their the types of inputs used (e.g. the type of biomass feedstock, hydrogen and CO_2 used) and their production processes.

Enabling conditions. In addition, the Advisory Board identified seven enabling conditions (based on IPCC AR6) that can facilitate one or several of the levers described above.

- **Transport infrastructure** such as road, rail and waterway networks, cycling infrastructure and airport capacities is an important driver of overall transport demand and modal choices (IPCC, 2022j). Charging and refuelling infrastructure is a crucial enabler to facilitate the rapid uptake of ZEVs and non-fossil transport fuels in the transport system, in particular to increase user-friendliness and overcome range anxiety (IPCC, 2022j).
- **Price signals** determine the cost of use for different transport modes, vehicle technologies and fuel types, and can therefore enable both overall demand moderation and shifts to lower-emission transport modes, technologies and fuels. They include, for example, carbon prices, road charging, fuel taxes, congestion charges and parking fees. In general, transport GHG emissions are highly inelastic, at least in the short term (IPCC, 2022j). However, there are also indications that price elasticity increases over time and is three to four times larger if the price change is driven by persistent policies rather than market fluctuations. This is because policy-induced changes are expected to cause a more structural, long-term price increase than short-term fuel market price fluctuations, and are therefore more likely to trigger behavioural change and steer investment decisions (Andersson, 2019; Rivers and Schaufele, 2015).
- **Spatial planning** refers to the physical characteristics of human settlements, including their shape, size, density and configuration. It determines the need, time, space and cost of travel, which in turn can drive transport demand and modal choices (IPCC, 2022j) (see also Section 7.5).
- The **sharing economy** refers both to traditional mobility concepts such as carpooling and to more recent developments such as vehicle sharing and mobility as a service. There is still much uncertainty about the net effect of shared mobility on net emissions, although there is growing evidence that structural, large-scale behavioural change through shared mobility can indeed facilitate emission reductions (IPCC, 2022j).
- The **circular economy** could support emission reductions in the transport sector by reducing the amount of materials that need to be transported (through lower material use) and by reducing the distance across which these need to be transported (through more local value chains) ([21]). However, the net impact is still uncertain, as some evidence suggests that reductions in material use from more efficient product design are offset by increased consumer demand. Furthermore, the collection of waste streams for recycling purposes might also increase transport demand (IPCC, 2022j).
- **Digitalisation** can enable transport emission reductions in several ways (IPCC, 2022j). It enables teleworking and teleconferencing, which reduce travel demand. It also enables online shopping, although the net impact of this on transport emissions can be either positive or negative. Finally, it can support smart mobility, which could reduce transport demand and increase efficiency.

Some other cross-cutting enabling conditions, which are discussed in other chapters of this report (whole-of-society approach, finance, innovation and a skilled workforce), are also relevant to the transport sector, as shown in Figure 33. This figure also shows the indicators (shown in the white boxes) that were selected to track progress in the transport sector.

([21]) A similar impact could be achieved by other measures to shorten supply chains.

Figure 33 Assessment framework for the transport sector

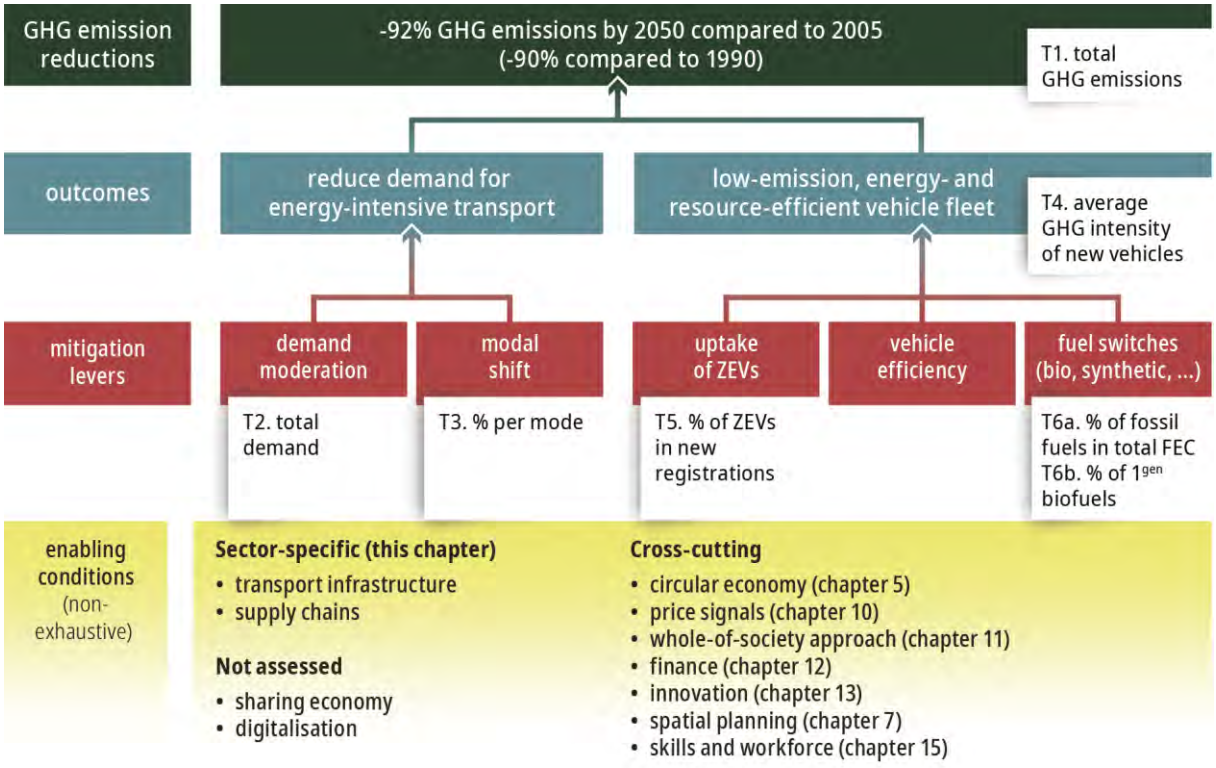

Source: Advisory Board (2024).

6.2 Emission reduction progress

The EU has not managed to structurally reduce the emissions of its transport sector since 2005. A breakdown is shown in Figure 34. There were some reductions in 2008–2013, triggered at least partially by the economic crisis of 2008–2010. However, emissions have increased again since 2014, and by 2019 emissions were 2.4 % above 2005 levels. This increase was mainly caused by a strong growth in aviation emissions (+ 31 % by 2019 compared to 2005) combined with very limited reductions in other transport modes (– 1.5 % in 2019 compared to 2005) ([22]). The underlying drivers of the limited decrease in non-aviation emissions are an overall increase in transport activity and the lack of a modal shift to low-emitting transport modes, which have largely offset any improvements from efficiency improvements and fuel switches. The observed increase in car GHG emissions in the years preceding 2020 was mostly due to an increasing share of larger and heavier cars, such as sport utility vehicles (EEA, 2022d).

The COVID-19 pandemic caused a significant reduction in transport emissions in 2020, notably in emissions from aviation and cars. Although there was a partial rebound in 2021–2022, they were still 6 % below 2019 levels in 2022 (based on proxy data). Eurostat quarterly GHG emission data shows that this rebound continued in Q1 2023 (Eurostat, 2023q).

The average rate of emission reduction since 2005 (– 2 Mt CO_2e per year) needs to accelerate more than tenfold to be consistent the trajectories towards the overall 2030 – 55 % objective (– 26 Mt CO_2e per

([22]) Emissions including international aviation but excluding international maritime, in line with the 90 % reduction objective put forward by the European Green Deal.

year in 2023–2030), and even further after 2030 to be consistent with the 90 % reduction objective for transport GHG emissions by 2050 (– 31 Mt CO_2e in 2031–2050) as set out in the European Green Deal. In pathways consistent with the 90–95 % objective recommended by the Advisory Board, the reduction rate for 2031–2040 would need to be even higher (– 52 Mt CO_2e per year).

Figure 34 Indicator T1 – overall progress in reducing transport GHG emissions (including international aviation, excluding international maritime)

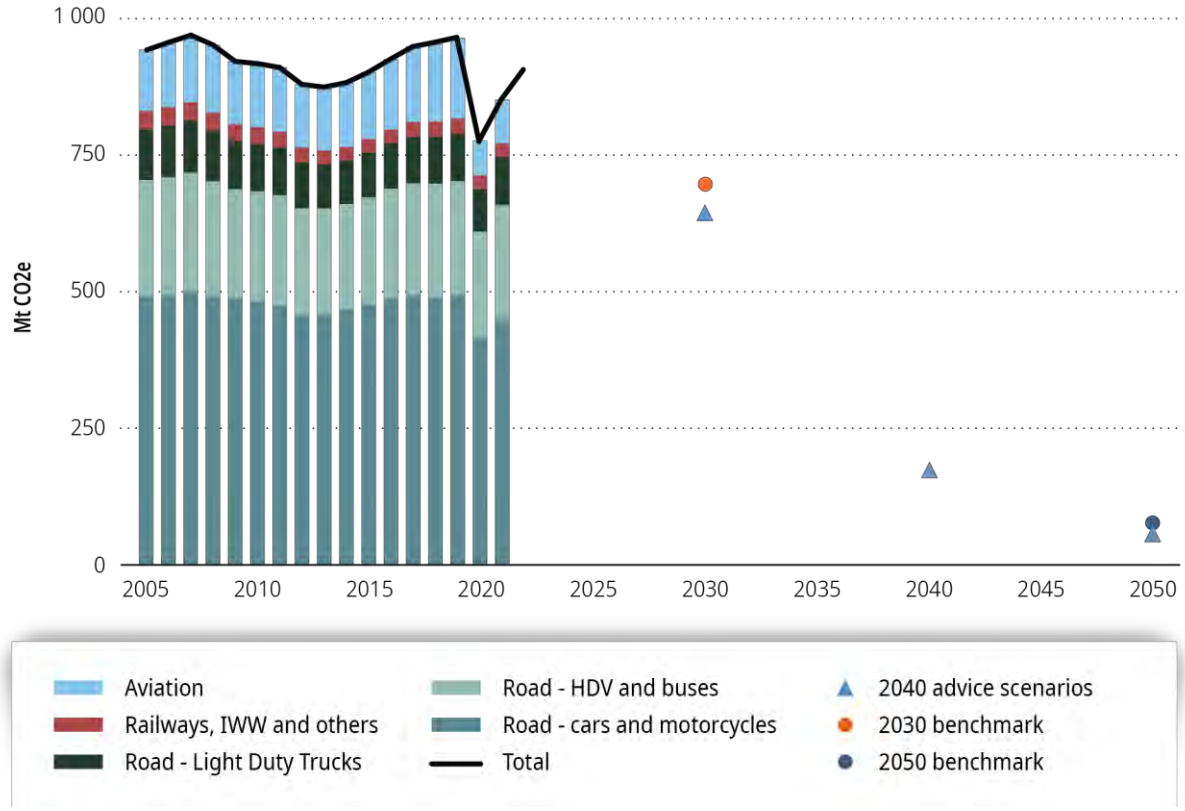

Notes: Historic emissions up to 2021 from the EU GHG inventory, with 2022 data based on proxy data reported to the EEA. 2030 benchmark based on the Fit for 55 MIX scenario. 2050 benchmark is calculated as a 90% reduction compared to 1990 as put forward by the European Green Deal and Sustainable and Smart Mobility Strategy thereunder. The 2040 advice range represents average domestic transport emission levels in the scenarios which underpin the Advisory Board's 2040 advice, combined with an illustrative path for aviation based on the Sustainable and Smart Mobility Strategy. All data includes international aviation but excludes international maritime transport, in line with the 90% reduction objective by 2050.

Sources: EU GHG inventory (EEA, 2023f), Fit for 55 MIX scenario (EC, 2021v), Sustainable and Smart Mobility Strategy (EC, 2020k), Advisory Board 2040 advice scenarios (ESABCC, 2023b).

6.3 Outcome 1: reduce demand for emission-intensive transport

Lever: demand moderation

Both transport and freight demand have been increasing at a rate that is not in line with the European Commission's scenarios that underpin the EU's climate objectives.

Total passenger transport (including domestic and intra-EU aviation, but excluding water-based transport and extra-EU aviation because consistent data is lacking) increased from 2005, with an acceleration after 2013, before a sudden drop in 2020 linked to the COVID-19 crisis (see Figure 35).

About three quarters of the observed increase in 2005–2019 is due to higher demand per capita, with the remaining growth linked to the EU's increasing population. In relative terms, growth has been strongest for aviation (+ 62 % in 2005–2019), followed by rail (+ 23 %) and private road transport (+ 11 %). Total transport by bus and coach declined slightly (– 2 %). Under the European Commission's scenarios underpinning the EU's climate objectives, transport demand would continue to increase, but the average rate of increase would decrease by more than half compared to 2015–2019 until 2030, and then slow further in 2031–2050.

Figure 35 Indicator T2a – passenger transport demand

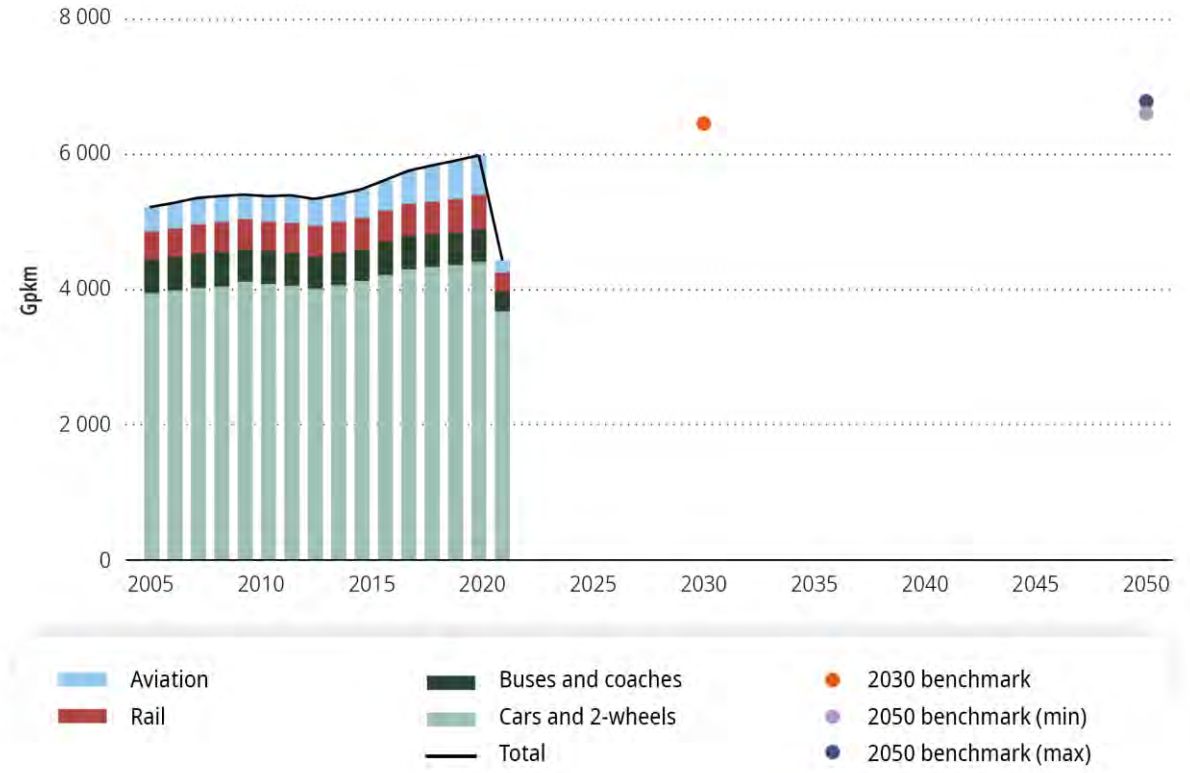

Notes: The 2030 benchmark is based on the Fit for 55 MIX scenario. The 2050 benchmarks are based on the 1.5TECH and 1.5LIFE scenarios of the in-depth analysis accompanying a Clean Planet for All (see figure 45, recalibrated for EU27 based on 2015 data). All data includes domestic and intra-EU aviation, but excludes extra-EU aviation, IWW and intra-EU maritime transport. All data expressed in billion passenger-kilometers (Gpkm).

Sources: Statistical pocketbook on transport 2022 (EC, 2022al), Fit for 55 MIX scenario (EC, 2021v), in-depth analysis accompanying A Clean Planet for All (EC, 2018e)

Figure 36 displays total freight transport demand, excluding aviation and maritime freight. Demand dropped following the economic crisis in 2008–2010 but rose steadily from 2013 until a limited drop in 2020 linked to the COVID-19 crisis. The relative increase was considerably higher for road transport (+ 11 % in 2005–2019) than for rail transport (+ 3 % in 2005–2019), whereas the volume of freight transported by IWW remained stable. Similarly to passenger transport, the European Commission's scenarios underpinning the EU's climate objectives assume a continued growth in freight transport demand but at a slower pace, in particular after 2030.

Figure 36 Indicator T2b – total freight transport demand

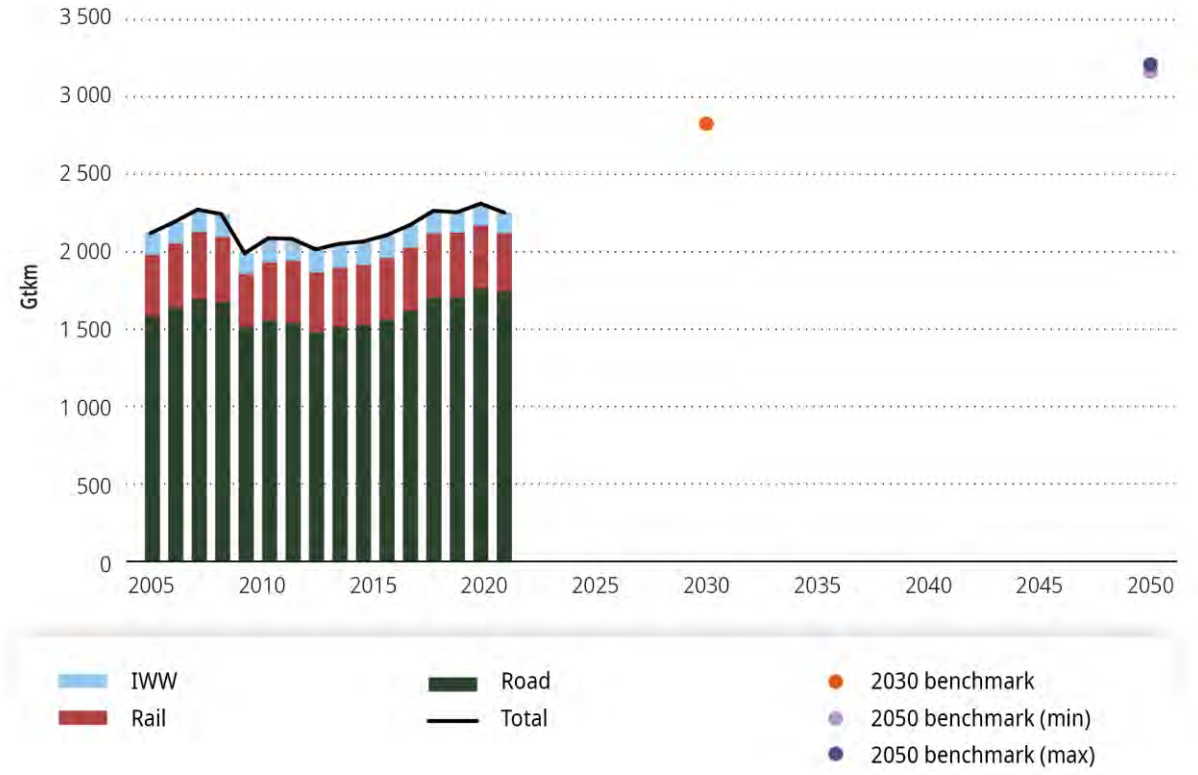

Notes: The 2030 benchmark is based on the Fit for 55 MIX scenario. The 2050 benchmarks are based on the 1.5TECH and 1.5LIFE scenarios of the in-depth analysis accompanying a Clean Planet for All (see figure 45, recalibrated for EU27 based on 2015 data). All data includes domestic and intra-EU aviation, but excludes extra-EU aviation, IWW and intra-EU maritime transport. Domestic maritime transport in 2030 was filtered out of the MIX scenario data based on the 2015 ratio between IWW and domestic maritime transport. All data expressed in billion tonne-kilometers (Gtkm).

Sources: Statistical pocketbook on transport 2022 (EC, 2022al), Fit for 55 MIX scenario (EC, 2021v), in-depth analysis accompanying A Clean Planet for All (EC, 2018e)

The EU's overall strategy to reduce transport GHG emissions does not aim to moderate demand.

The EU's overall strategy to reduce GHG emissions in the transport sector has been to focus exclusively on modal shifts and technological, supply-side improvements, without considering the option of curbing growth in demand. The 2011 White Paper on transport (EC, 2011) – which formed the overarching strategy for EU transport policies between 2012 and 2022 – had the objective of allowing continued transport growth while reducing GHG emissions by 60 % by 2050 thanks to a combination of modal shifts, increased efficiency and technological changes. It explicitly excluded the option of curbing mobility to achieve emission reductions. This overall strategy was maintained in the European Commission's Sustainable and Smart Mobility Strategy (EC, 2020k), which is the EU's overarching mobility strategy under the European Green Deal. It states that the greening of the mobility system, through modal shifts and technological changes, must be a new licence for the transport sector to grow, thereby confirming that the strategy will not aim to moderate or curb transport growth. So far, this strategy has proven ineffective in reducing GHG emissions, as incremental efficiency improvements and fuel switches have been outpaced by increased transport demand (see Section 6.2).

As transport demand has historically been strongly correlated with household income and overall economic activity (IPCC, 2022j), there is a risk that efforts to reduce overall transport demand could lead to reduced economic activity and corresponding income losses. Nevertheless, there are several enabling conditions that policymakers could activate to decouple this correlation (IPCC, 2022j). For instance, spatial planning policies that encourage more compact urban forms and reduce the distances people need to travel to work, education or services can also have positive economic and social co-benefits. A large body of literature (see Puga (2010) and Rosenthal and Strange (2004) for overviews) has found that density and spatial clustering of economic activity is linked to higher productivity, incomes and innovation – referred to as 'agglomeration economies'. The exact causes of agglomeration economies can vary, although research has generally pointed to how densification leads to the development of deeper labour markets, supply chain efficiencies, greater opportunities for knowledge spillover between workers and companies, and closer access to goods and services. While these benefits can come with trade-offs that must also be managed through spatial planning policies, such as congestion, pollution and higher land/housing prices (Duranton and Puga, 2020), there are synergies with other policy areas that can help to mitigate these trade-offs (e.g. reduced congestion from modal shifts, and lower pollution from uptake of ZEVs and renewable energy technologies).

Lever: modal shift

The EU has so far not managed to achieve a shift towards lower-emission transport modes.

Over the past decade, the increase in overall transport demand (both passenger and freight) has not been accompanied by notable shifts towards low-emission transport modes. As seen in Figure 37, road transport remained dominant in demand in inland transport, both for passenger and freight transport. Its share has even slightly increased in recent years. This trend is not in line with the European Commission's scenarios underpinning the EU climate objectives, which would require a decrease in the overall share of road in both passenger and freight transport by 2030 and 2050.

Figure 37 Indicator T3a – share of road transport in total motorised inland transport (excluding aviation and maritime, excluding active transport modes)

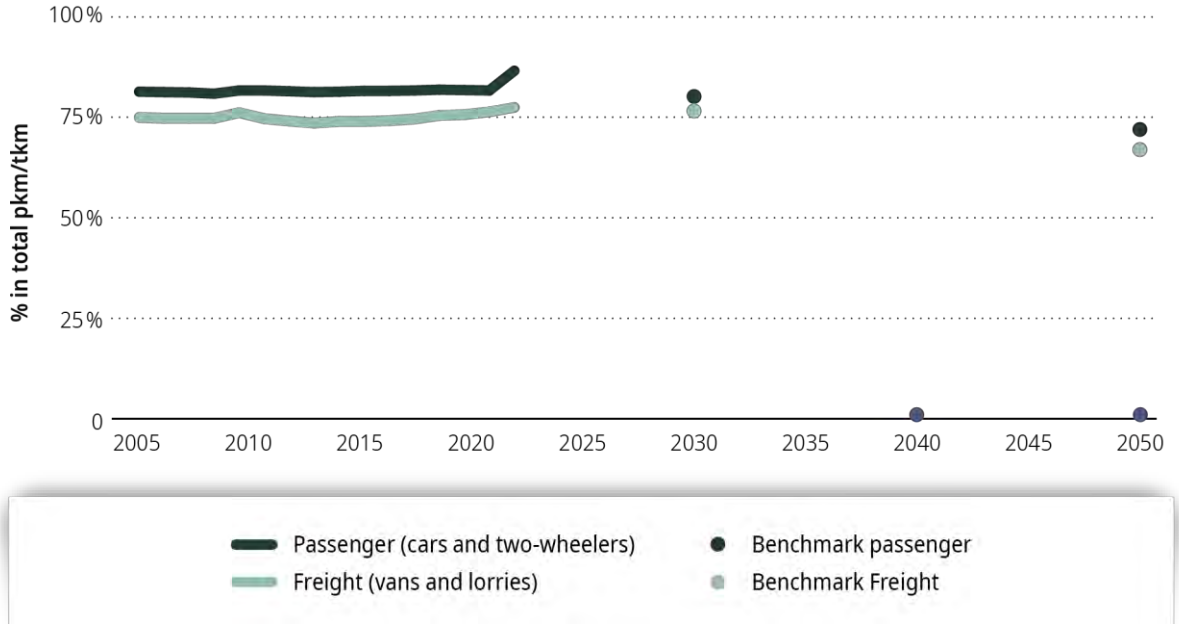

Notes: 2030 benchmark based on the Fit for 55 MIX scenario. 2050 benchmarks based on the 1.5TECH and 1.5LIFE scenarios of the in-depth analysis accompanying a Clean Planet for All (see figures 45 and 46, recalibrated for EU27 based on 2015 data).

All shares expressed as percentage of passenger-kilometers or percentage of tonne-kilometers in total motorised transport by road, rail or IWW. Aviation and international maritime are excluded, to filter out the effect of substantial growth in international (extra-EU) transport. Active transport modes (walking, cycling) are also excluded for lack of data. The 1.5TECH and 1.5LIFE scenarios do not provide a split between private and public road transport, so the share of buses and coaches has been assumed to remain at 9% under these scenarios.

Sources: Statistical pocketbook on transport 2022 (EC, 2022al), Fit for 55 MIX scenario (EC, 2021v), in-depth analysis accompanying A Clean Planet for All (EC, 2018e)

As mentioned in Section 6.2, there has been a particular increase in passenger aviation transport (see Figure 38). Between 2015 and 2019, intra-EU aviation grew by on average 33 Gpkm per year. This rate of increase is not in line with the European Commission's scenarios underpinning the EU's climate objectives, which anticipate growth of only 2 Gpkm per year until 2030 and 5–12 Gpkm per year thereafter.

Figure 38 Indicator T3b – intra-EU passenger transport by air

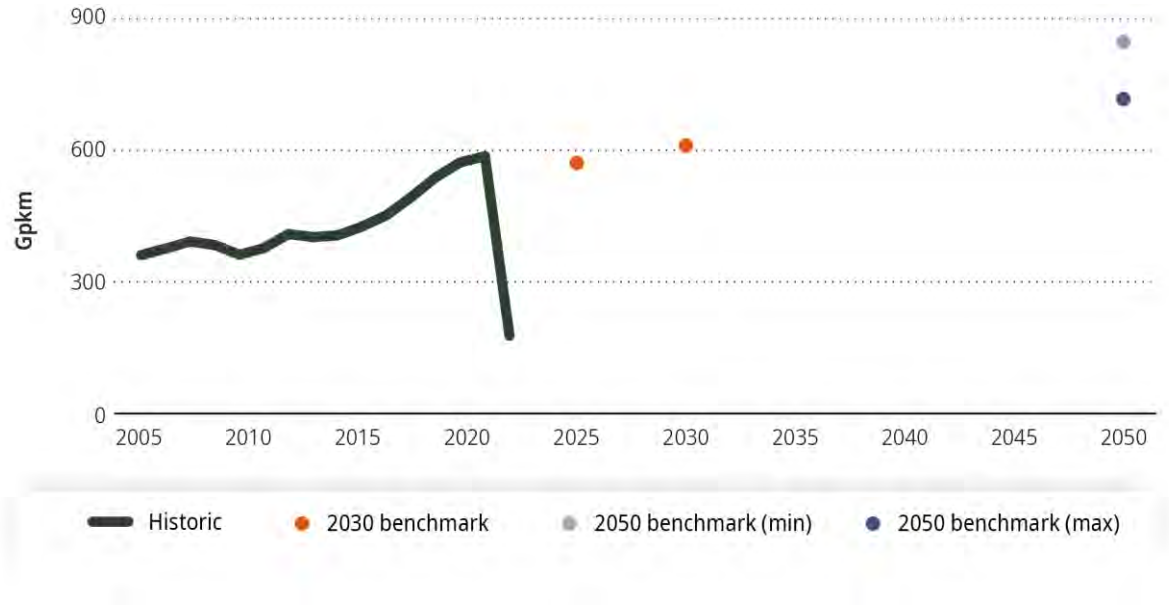

Notes: The 2030 benchmark is based on the Fit for 55 MIX scenario. The 2050 benchmarks are based on the 1.5TECH and 1.5LIFE scenarios of the in-depth analysis accompanying a Clean Planet for All (see figure 45, recalibrated for EU27 based on 2015 data).

Sources: Statistical pocketbook on transport 2022 (EC, 2022al), Fit for 55 MIX scenario (EC, 2021v), in-depth analysis accompanying A Clean Planet for All (EC, 2018e)

The Sustainable and Smart Mobility Strategy has put forward specific objectives to substantially increase passenger transport by high-speed rail (+ 100 % by 2030 and + 200 % by 2050 compared to 2015), and freight transport by rail (+ 50 % by 2030 and + 100 % by 2050 compared to 2015) and IWW (+ 25 % by 2030 and + 50 % by 2050 compared to 2015). As reflected in Figure 39, achieving these objectives would need a substantial acceleration of the observed annual rate of change in 2015–2019 for high-speed rail (+ 33 %) and rail freight transport (+ 600 %), and a reversal of the declining trend observed for IWW.

Figure 39 Indicator T3c – passenger transport by high-speed rail, and freight transport by rail and IWW

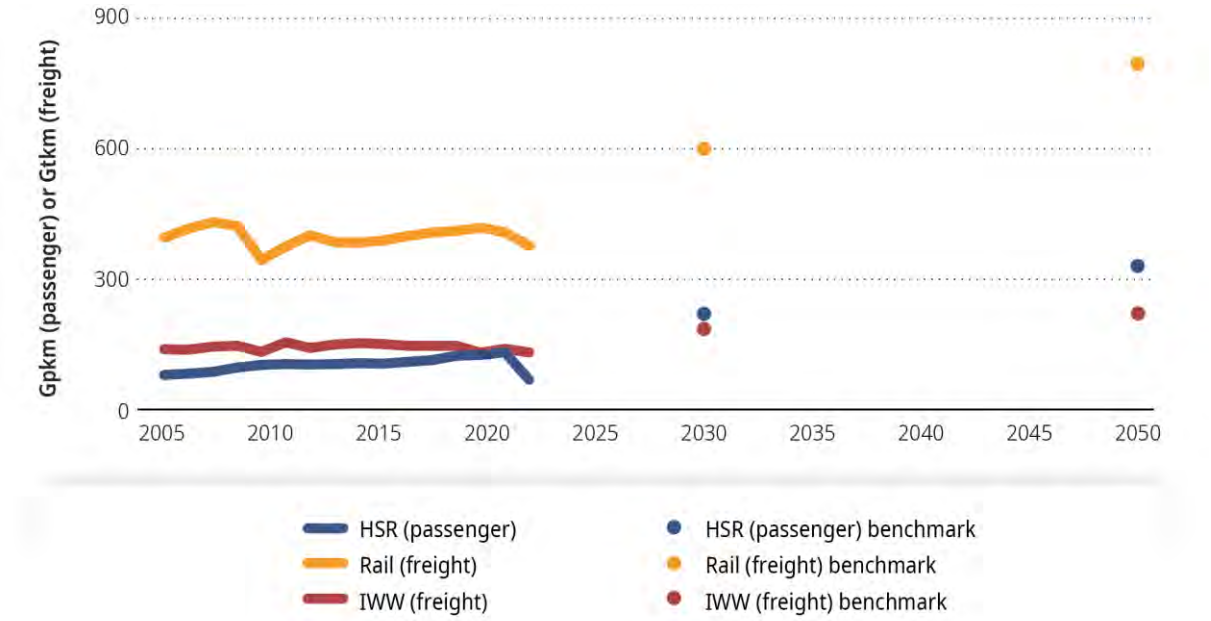

Sources: Statistical pocketbook on transport 2022 (EC, 2022al), Sustainable and Smart Mobility Strategy (EC, 2020k)

EU policies to trigger a modal shift have been ineffective.

In the past, the EU has put several policies in place to shift transport from road to rail and IWW. The 2011 White Paper on transport (EC, 2011) already included an objective to achieve a 50 % shift of medium-distance intercity passenger and freight journeys from road to rail and waterborne transport by 2050. However, as evidenced above, so far these objectives have not been achieved. Several causes have been identified for this lack of progress, including persistent operational and regulatory barriers (e.g. lack of interoperability, insufficient coordination and information sharing, lack of accessible data), infrastructural bottlenecks (hindered by high investment needs and low investment capacities), lack of available and integrated data and digital platforms, and higher costs of lower-emission transport modes (either perceived or effective) (ECA, 2023b; Finger et al., 2021; Pastori et al., 2018; Serafimova et al., 2022).

Several EU policies are already in place that address these issues, but so far they have been ineffective and insufficiently aligned with the EU climate ambitions. The Combined Transport Directive (EU, 1992), which governs intermodal freight transport in the EU, has not yet been revised since its inception in 1992, and both the European Commission and the ECA have assessed it as outdated and ineffective at promoting intermodal transport in the EU (EC, 2021s; ECA, 2023b). Key issues identified are legal requirements for paper documentation (preventing digitalised workflows) and a minimum threshold of 100 km for the non-road leg (which limits the scope of the directive). Furthermore, the implementation of the directive by Member States has been heterogeneous, which creates uncertainty for logistics operators. The Rail Freight Corridors Regulation (EU, 2010b) aims to boost the competitiveness of rail freight by creating transnational rail freight corridors but has been found to be insufficiently effective. Reasons include shortcomings within the regulation itself (e.g. the lack of adequate tools to deliver on its objectives, and the absence of an entity in the governance framework that transcends national interests) as well as how it was implemented at the national level (e.g. heterogeneous implementation

due to lack of sufficiently clear rules, stakeholders approaching it as a tick-box exercise rather than implementing it in a way conducive to achieving its objectives) (EC, 2021f; Finger et al., 2021).

Finally, until recently EU pricing policies did not effectively support the modal shift. The Eurovignette Directive (EU, 1999) has not – except in a few specific cases – promoted a shift of freight towards lower-emission transport modes. Among the reasons cited are road charges applied under the directive being too low or insufficiently differentiated to trigger a substantial shift, and the lack of sufficient, reliable and efficient alternative transport modes (Gomez and Vassallo, 2020). The EU ETS has put the highest real carbon price (after accounting for free allocation) on electrified transport – such as the majority of rail transport, in which electricity accounts for 75 % of final energy use (Eurostat, 2023b) – whereas aviation has received most of its allowances for free, and road transport fuels have been excluded altogether. The ETD puts relatively high minimum energy tax rates on road transport fuels, but this is undermined by an exemption that allows lower rates for commercial passenger and freight transport. It also completely exempts aviation and maritime transport from energy taxation (see Chapter 10 'Pricing emissions and rewarding removals' for more details on the EU ETS and the ETD).

Several steps have been taken in recent years to address these issues. The Eurovignette Directive was revised in 2022 to expand its scope and to ensure better internalisation of transport externalities (EU, 2022d). The European Commission also announced a range of both legislative and non-legislative initiatives under the Sustainable and Smart Mobility Strategy and the Fit for 55 package, including an action plan to boost long-distance and cross-border passenger rail (EC, 2021k), a revision/replacement of the Rail Freight Corridors Regulation (EC, 2023av), a revision of the Combined Transport Directive (EC, 2023ap), a revision of the TEN-T regulation (see Section 6.5 below), the creation of a new EU ETS 2 for (amongst others) road transport, and a revision of the ETD (Chapter 10 'Pricing emissions and rewarding removals') ([23]). It is a positive development that the European Commission has acknowledged the need for additional efforts to achieve a modal shift and has taken steps in that direction, but it is too soon to assess whether these will be sufficiently effective, notably because these initiatives have not yet been adopted by the co-legislators (the TEN-T Regulation, a regulation on the use of railway infrastructure capacity that would replace the Rail Freight Corridors Regulation, the revision of the Combined Transport Directive) or will start to operate in the future (the EU ETS 2). Other reasons for concern are the lack of progress in the revision of the ETD (which, under the European Commission's proposal, would aim to tax the most environmentally harmful fuels the most and remove certain tax exemptions for fossil fuels, including transport fuels), and the 'soft' price cap under the EU ETS 2 (see Chapter 10 'Pricing emissions and rewarding removals').

When striving for a modal shift to reduce GHG emissions, it is important to consider the total aggregate impact, as measures to promote a modal shift (e.g. the construction of a new railway line) may lead to overall increases in transport demand (Kemp, 2016). Overall, the GHG reduction potential of a modal shift is largest where population density is large, whereas it is limited in more remote areas (Pastori et al., 2018). Furthermore, according to the ECA, urban mobility accounts for only 23 % of total transport emissions (ECA, 2020c). Consequently, although a modal shift in European cities could make significant contributions towards other environmental and societal objectives such as improved air quality, reduced noise nuisance, more efficient and safe mobility, it would yield only limited GHG emission reductions compared with modal shifts in intercity travel.

([23]) For a full overview, see the action plan annex to the Sustainable and Smart Mobility Strategy (EC, 2020k).

6.4 Outcome 2: low-emission and efficient transport fleet

Levers: uptake of zero-emission and efficient vehicles

The average CO_2 intensity of new vehicles is decreasing thanks to the uptake of ZEVs, but the rate of that uptake needs to accelerate to remain on track towards the 2035 objectives.

As shown in Figure 40, the average GHG intensity of new passenger vehicles declined in 2005–2015, but rebounded in 2016–2019 owing to a shift from diesel to petrol and the increased market share of sport utility vehicles and other larger and heavier cars (EEA, 2020). As of 2020, the GHG intensity started to decline again thanks to the increasing market share of plug-in hybrid electric vehicles (PHEVs) and BEVs, a trend that continued in 2021 and 2022. Progress in reducing the CO_2 intensity of new vans has been slower than for passenger cars. It declined steadily in 2005–2016, but then stagnated as a result of an increase in the average mass, engine capacity and size of vans. The downward trends resumed as of 2021 thanks to the uptake of zero-emission electric vans (EEA, 2023c).

HDV manufacturers have been required to monitor and report the CO_2 emission intensity of new vehicles since 2019 (EU, 2018d). Reported data so far shows that the average CO_2 intensity for new HDVs sold in 2019 to mid-2020 was 52.75 g CO_2 per tkm (EEA, 2022d). Current legislation requires this intensity to decrease by 15 % by 2025 and 30 % by 2030 (EU, 2019f). In 2023, the European Commission has proposed to increase the objective for 2030 to – 45 %, and to achieve a 65 % reduction by 2035 and a 90 % reduction by 2040 (EC, 2023ar). At the time of writing this report, the European Commission proposal had not yet been adopted by the Council and the European Parliament, and no data beyond 2020 on the average GHG intensity was yet available. Once more up-to-date data is available, it will be possible to assess the progress made and the required acceleration to remain on track towards the objectives set out in EU legislation.

Recent years have witnessed a breakthrough of BEVs on the European **passenger car** market, as illustrated in Figure 41. Their share in new registrations increased from less than 1 % in 2017 to more than 13 % in 2022. In the same period, the share of PHEVs increased from less than 1 % to almost 10 %, meaning that in 2022 more than 23 % of new passenger cars registered in the EU had a plug. Nevertheless, the uptake needs to accelerate even further (from on average + 3 pp in 2018–2022 to on average + 7 pp in 2023–2035) for the EU to achieve the binding objective of 100 % ZEVs by 2035 as set out under the revised CO_2 emission performance standards for cars and vans (EU, 2023k). Preliminary data from the European Automobile Manufacturers Association shows that the share of ZEVs in new car sales continued to increase in 2023 in line with earlier trends (12 % in January–April 2023 compared with 9 % in January–April 2022) (ACEA, 2023).

The uptake of battery electric **vans** seems to be following a similar trajectory, although with a few years' delay compared with passenger cars. The share of ZEVs (predominantly BEVs) among newly registered vans increased from less than 1 % in 2017 to 5 % by 2022, increasing by on average 1 pp per year in 2018–2022. This rate should increase to on average 8 pp per year in 2023–2035 to achieve 100 % ZEVs by 2035.

Figure 40 Indicator T4 – average GHG intensity of new passenger cars and vans (g CO_2/km)

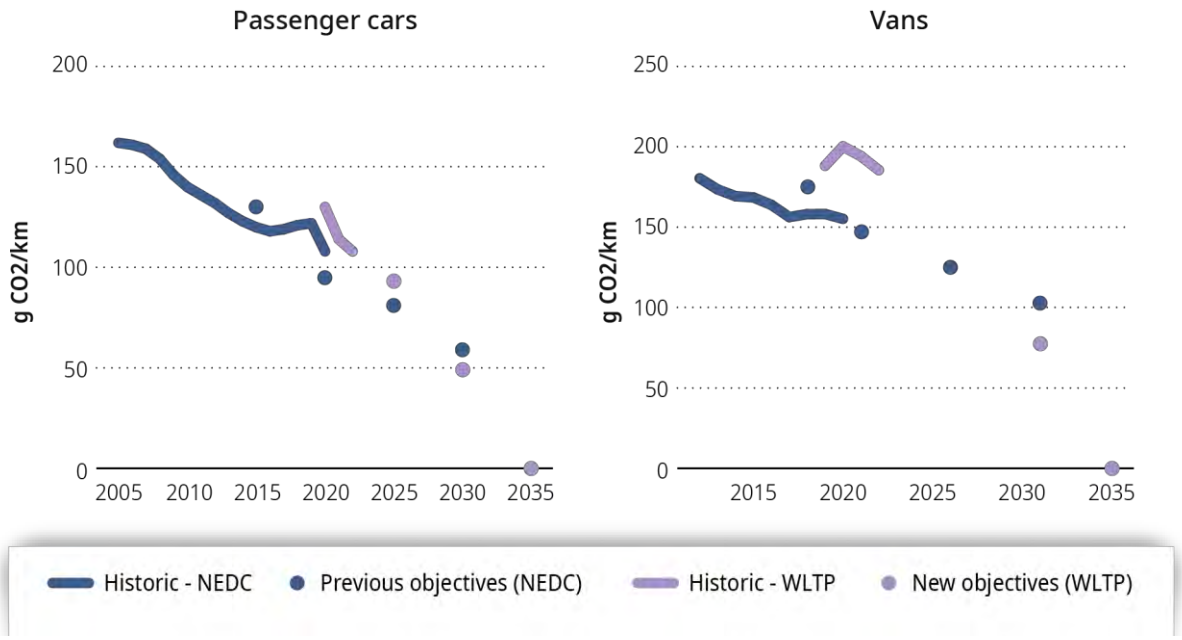

Notes: Historic data is based on EEA data on emission intensity according to the New European Driving Cycle (data available up to 2020) and the Worldwide Harmonised Light Vehicle Test Procedure (data available as of 2020). The objectives are based on the CO_2 emission performance standards for passenger cars and vans.

Sources: EEA (2023c, 2023d) , CO_2 emission performance standards for passenger cars and vans (EU, 2019d, 2023k).

Figure 41 Indicator T5a – share of ZEVs in new registrations of passenger cars and vans

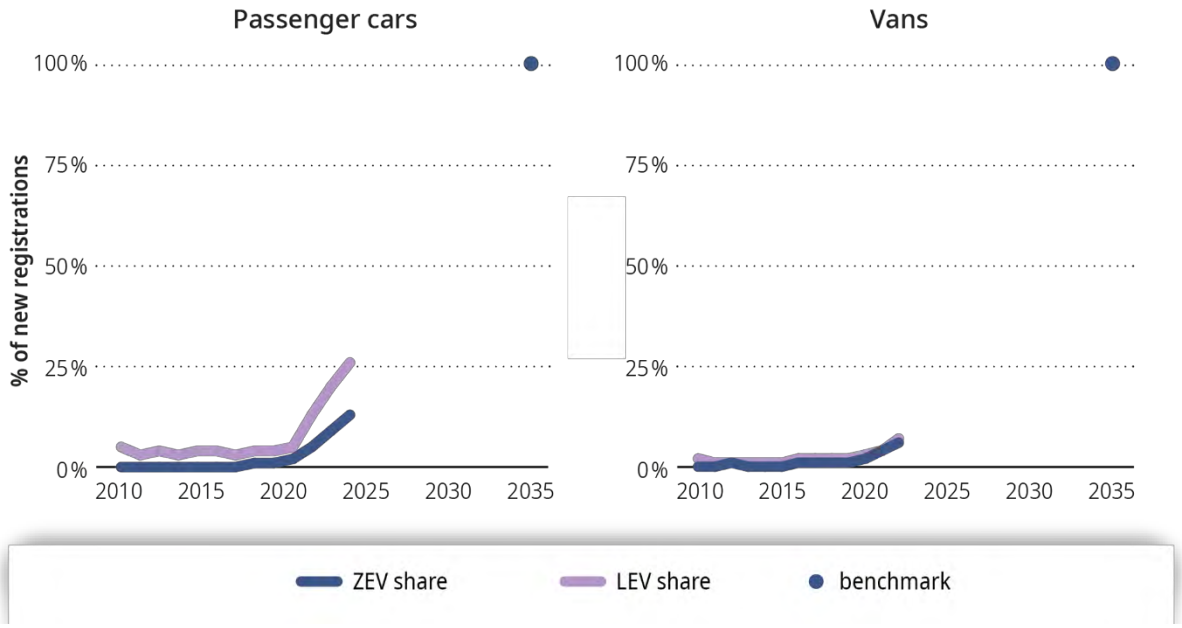

Notes: LEV refers to the share of low-emission vehicles, which primarily constitutes PHEVs, with a smaller contribution of CNG/LNG vehicles

Sources: European Alternative Fuels Observatory (EC, 2023ab), CO_2 emission performance standards for passenger cars and vans (EU, 2023k).

For **HDVs** (shown in Figure 42), the uptake of ZEVs has been slower, reflecting a lower maturity level ([24]) of zero-emission technologies for this segment. According to Eurostat, the share of ZEVs in new vehicle registrations was still very low in 2021 at 0.29 % for tractor trailers and 0.15 % for lorries (Eurostat, 2023b). The average annual rate of uptake would have to increase more than tenfold to have 80 000 zero-emission lorries in the EU fleet by 2030 as envisaged by the Sustainable and Smart Mobility Strategy.

Figure 42 Indicator T5b – total number of zero-emission lorries in the total EU fleet

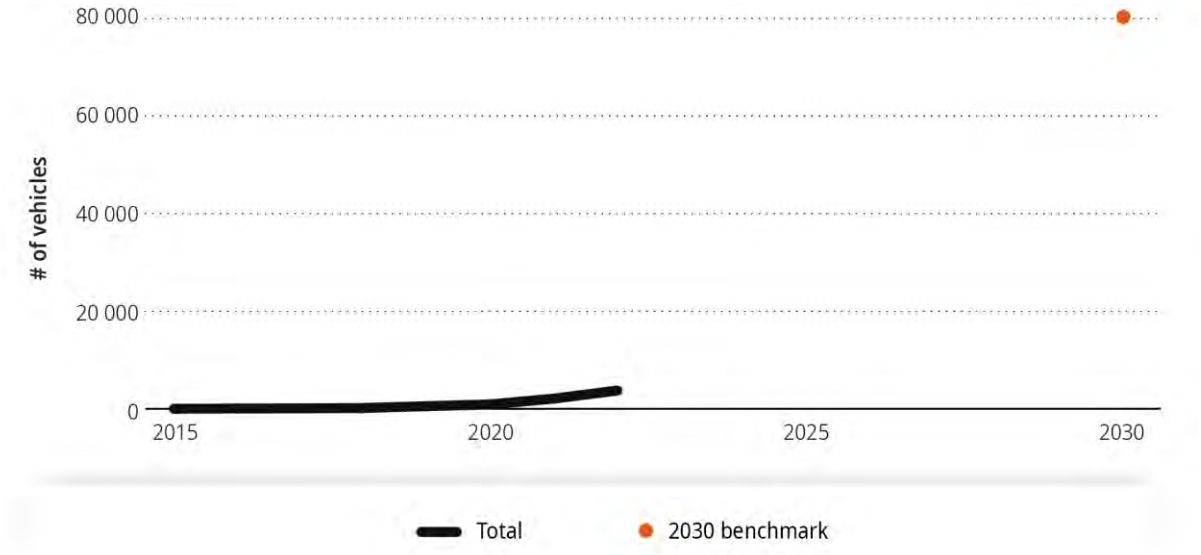

Sources: European Alternative Fuels Observatory (EC, 2023ab), Sustainable and Smart Mobility Strategy (EC, 2020k).

Overall, ZEV technology is relatively new, and its uptake could be expected to follow a non-linear, S-shaped trajectory (see also Section 2.2). Therefore, although recent historical rates of change are not sufficient compared with the linear trajectories towards the objectives for 2030/2035, developments have been positive, and future years will need to clarify whether the deployment will accelerate as the technology matures. However, so far, the acceleration has not yet started, with the annual increase of ZEV shares in passenger cars relatively stable at 3 pp per year.

EU standards are an effective tool to drive the uptake of ZEVs, but currently fail to incentivise efficiency within the ZEV segment.

Emission performance standards for new vehicles have been the main tool in the EU policy toolbox to drive the uptake of ZEVs and increase vehicle efficiency. The most recent revision of the CO_2 emission performance standards for passenger cars and vans targets a 55 % reduction in CO_2 intensity for cars (50 % for vans) by 2030 (compared to the 2021 objective), and a de facto ban on the sale of non-ZEVs as of 2035 (EU, 2023k). Assuming an average 15-year lifetime for ICEVs, this should result in a completely zero-emission car and van fleet by 2050. The decrease in average CO_2 intensity suggests the policy instrument has been effective. The observed uptake of ZEVs in recent years is particularly promising with a view to achieving rapid emission reductions in the sector.

([24]) In particular, the relatively low energy density of batteries requires a trade-off between the range and the weight (and price) of battery electric HDVs.

However, while current emission performance standards incentivise energy efficiency within the segment of ICEVs and a switch from ICEVs to ZEVs, they do not provide an incentive (in addition to the electricity price) to increase efficiency within the segment of ZEVs (e.g. by prioritising the development and sale of compact, energy- and resource-efficient models). On the contrary, recent analysis (Gómez Vilchez et al., 2023; Thies et al., 2022) has cautioned that the current legislation incentivises car manufacturers to prioritise the development and sale of larger ZEVs over more compact ZEVs in two ways. Firstly, the calculation method to measure compliance with the CO_2 performance standards considers the mass of a vehicle, which means that replacing a large ICEV with a large ZEV will contribute more towards reaching the overall average CO_2 standard than replacing a compact ICEV by a compact ZEV. Secondly, ZEVs are still more costly to produce and have lower profit margins than ICEVs. Car manufacturers will therefore be more inclined to develop ZEVs for their larger car segment, as overall profit margins in that segment are higher (because there is less price elasticity in that market segment). Similarly, current State aid guidelines do not require Member States to differentiate financial support for clean vehicles as a function of their energy efficiency and resource efficiency (e.g. battery pack size), and most Member States are not doing this at the moment (IEA, 2023f). Currently, larger models including sport utility vehicles account for the majority (60 %) of all BEV models on the EU market (IEA, 2023e).

From a narrow perspective, faster electrification of the segment of larger vehicles is beneficial for the climate, as it yields the highest direct emission reductions. However, from a broader perspective the trend towards large electric vehicles is worrisome, as larger vehicles are more resource- and energy-intensive. On average, large BEVs weigh 50 % more, are 20 % less energy efficient and require 70 % more critical raw materials than smaller BEVs (IEA, 2023e). This increases their life cycle environmental footprint both directly (from higher electricity use) and indirectly (from higher resource use). Furthermore, the focus on larger, less efficient BEVs also undermines the overall availability and affordability of BEVs, as they add pressure on the constrained availability of critical raw materials, which is a key driver of their production cost. Reducing the average vehicle size is – together with the development of new battery types – a key pathway to moderate demand for (and therefore enhance the security of supply of) critical raw materials, which is a prerequisite to enable worldwide electrification of the transport fleet (IEA, 2023e).

For HDVs, emission standards were first introduced in 2019 (EU, 2019f), and currently revised under the Fit for 55 package (EC, 2023ar). The European Commission's proposal aims to reduce the average CO_2 intensity of new HDVs by 45 % by 2030 and 90 % by 2040 (compared to 2020 levels) and expands the scope to cover additional vehicle types such as buses and coaches (which would need to become zero-emission by 2030). A first independent assessment (not peer-reviewed) by the International Council on Clean Transport has found that, despite its overall high level of ambition, the regulation would lead to only 64 % GHG emission reductions by 2050 (compared to 1990), which falls short of the 90 % reduction envisaged by the European Green Deal (Mulholland and Rodriguez, 2023).

In addition to CO_2 emission performance standards, the EU also promotes the uptake of clean and energy-efficient road transport vehicles through public procurement, by means of mandatory minimum targets for each Member State set out in the Clean Vehicles Directive (EU, 2019c). Furthermore, in its Sustainable and Smart Mobility Strategy (EC, 2020k), the European Commission announced further proposals to boost the uptake of ZEVs in corporate and urban fleets. To date, to the Advisory Board's knowledge, no further actions in this domain have been taken.

Further action is needed to ensure security of supply and reduce the environmental impact of critical raw materials and batteries.

Battery technology and production costs have improved substantially over the last decade, and the overall expectation is that costs will continue to decrease with technological advances and economies

of scale, even when taking into account raw material price increases (Mauler et al., 2021). As a result, the total cost of ownership of passenger car BEVs has decreased and is approaching parity with ICEVs in at least some market segments (IEA, 2022a). These developments have also increased the technological feasibility and economic competitiveness of battery electric HDVs (Bhardwaj and Mostofi, 2022; Nykvist and Olsson, 2021), and several lorry manufacturers are currently offering commercial BEV models or are planning to do so in the coming years (Mollière, 2023).

However, key bottlenecks in their large-scale deployment persist, such as the lack of available charging infrastructure (see Section 6.5) and the availability of critical raw materials and batteries (ECA, 2023d; Hao et al., 2019; IEA, 2021b). The EU is in a particularly vulnerable position, due to its limited domestic capacity to extract and process critical raw materials and produce batteries. Furthermore, global value chains are concentrated in just a few countries, primarily China, which produces 75 % of all lithium ion batteries and is home to 70 % of the production capacity for cathodes and 85 % of the production capacity for anodes (ECA, 2023d; IEA, 2022b). Finally, there is strong competition between different regions in the world to attract private investment in clean technology value chains – including battery production – as illustrated by the US Inflation Reduction Act. The combination of the EU's limited own extraction, processing and production capacities and its high dependence on imports from a limited number of trading partners with strong incentives in other regions of the world to attract investments in battery supply chains, and projected strong increases in demand globally, makes it very vulnerable to supply chain disruptions.

The European Commission is aware of this challenge and has taken several initiatives to tackle the issue. In 2017, it launched a European Battery Alliance, which is a platform for cooperation with key industrial stakeholders, interested Member States, the European Investment Bank (EIB) and the scientific community to build up battery technology and production capacity in the EU (EC, 2017). In 2018, it followed up with a Strategic Action Plan on Batteries, which listed a range of actions to further build up a competitive EU battery value chain (EC, 2018a). In 2023, as part of its Green Deal Industrial Plan in response to the US Inflation Reduction Act, it proposed a Critical Raw Materials Act (EC, 2023ac) and Net-Zero Industry Act (EC, 2023ao), which contain objectives aimed at boosting the EU's domestic supply chains for critical raw materials and manufacturing of strategic net zero technologies (respectively), including for batteries.

A recent report by the ECA (ECA, 2023d) has found that the European Commission's promotion of an EU industrial policy on batteries has been largely effective, despite some shortcomings regarding monitoring, and regarding coordination and targeting of support. Furthermore, it concluded that projected battery production capacity (based on companies' announcements) would be largely sufficient to meet projected EU battery demand for 2025 and 2030. However, it also warned that the actual deployment of this production capacity is subject to several risks, including time lags, and battery manufacturers reversing on their investment plans because of increasing costs in the EU or more attractive financial conditions offered in regions outside the EU. Furthermore, it warned that access to raw materials remains a major strategic challenge for the EU's battery value chain, which faces a looming global shortage of some key raw materials as of 2030. As a result, the EU might not be able to supply sufficient batteries to achieve its objective of 100 % of new cars and vans sold being ZEVs as of 2035. It would therefore have to rely on considerable imports from other regions of the world, which would undermine its security of supply and would outsource investments and jobs in clean technologies.

IPCC AR6 also highlights the need to address adverse impacts of battery production such as GHG emissions, non-climate environmental impacts and labour rights (IPCC, 2022g). There are several possible approaches to pursue this, which can also increase the EU's resilience against supply chain disruptions, such as such as prioritising smaller, more resource-efficient vehicles, increased recycling or

repurposing of batteries (Ioakimidis et al., 2019; Iturrondobeitia et al., 2022; Unterreiner et al., 2016) and switching to alternative battery types (Feng et al., 2022).

Lever: fuel switches

Progress in phasing out fossil transport fuels has been too slow, and relied heavily on first-generation biofuels with high indirect land use change (ILUC) risks.

The share of fossil fuels in the transport energy mix (shown in Figure 43) decreased only slightly from 98 % in 2005 to 93 % by 2021. This reduction was almost exclusively achieved by a shift from fossil fuels to biofuels, whereas the share of electricity remained very small (from 1.4 % in 2005 to 1.5 % in 2021).

The European Commission's scenarios that underpin the EU climate objectives would require an acceleration of this trend, notably after 2030. This would require a combination of direct electrification and the use of low-carbon fuels (hydrogen and related derivates, and sustainable biofuels). Under the MIX scenario underpinning the Climate Target Plan (EC, 2020s), about 80 % of passenger cars and 70 % of vans would be electric ([25]) by 2050. For HDVs, the feasible share would be lower, with 18 % BEVs and 26 % PHEVs by 2050. Regarding the total energy mix for transport (including aviation and maritime), the share of fossil fuels would decline to 14 % by 2050, to be replaced by electricity (21 % by 2050), hydrogen and related derivates (41 % by 2050) and biofuels (24 % by 2050). However, since the publication of the Climate Target Plan, significant advances have been made regarding electrification technologies, which would make even greater electrification of road freight transport more feasible than it was considered a few years ago, including for HDVs. Nevertheless, low-carbon fuels would still be required to decarbonise international maritime and aviation transport (ESABCC, 2023b).

Biofuels made from food and feed crops (hereafter referred to as first-generation biofuels) accounted for the majority of the biofuels used in the transport sector (EEA, 2022j). Figure 44 displays their absolute volumes, showing that their use increased by almost 60 % in 2011–2019, after which it reduced slightly in parallel with overall lower energy use in the context of the COVID-19 pandemic ([26]). Under the European Commission's scenarios that underpin the EU climate objectives, their use could only increase slightly until 2030, and then phase out completely by 2050.

([25]) The majority (70 % of passenger cars, 63 % of vans) would be fully electric (BEV), with a small minority of PHEVs.

([26]) These figures are based on the SHARES summary results, and only take into account biofuels which meet the minimum GHG savings and sustainability criteria set out in the Renewable Energy Directive.

Figure 43 Indicator T6a – share of fossil fuels in transport energy use (including international bunker fuels)

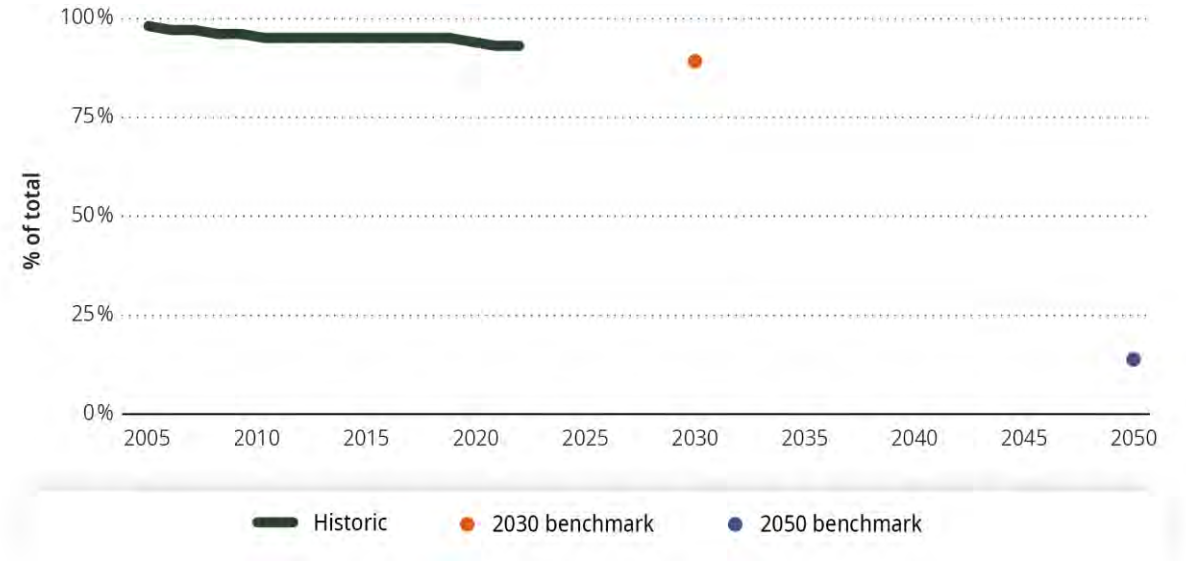

Notes: 2030 and 2050 benchmarks based on the MIX scenario from the Climate Target Plan impact assessment.

Sources: Eurostat energy balances (2023b), Climate Target Plan impact assessment (EC, 2020s).

Figure 44 Indicator T6b – use of first-generation biofuels in the transport sector

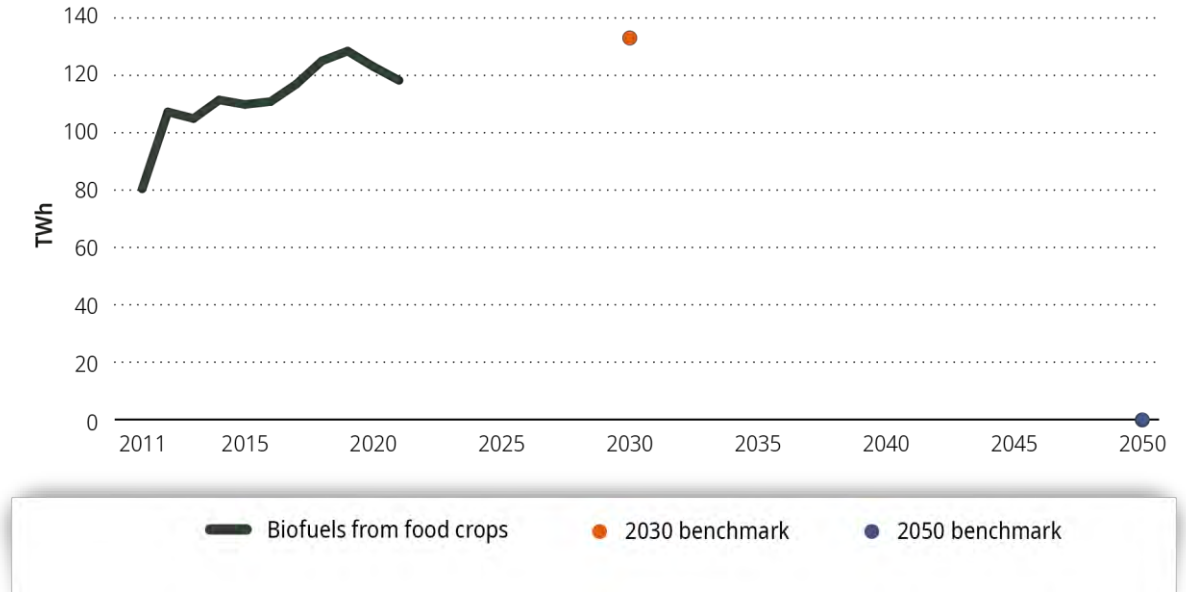

Notes: Historic data based on the EU SHARES tool database. The 2030 and 2050 benchmarks are based on the MIX scenario from the Climate Target Plan impact assessment (see figures 77 and 79). Values converted from Mtoe to TWh

Sources: EU SHARES database (Eurostat, 2023r), Climate Target Plan impact assessment (EC, 2020s).

EU policies continue to promote transport biofuels, which have inherent spillover risks.

Since 2003, EU policies have actively incentivised the use of biofuels in the transport sector (EU, 2003). However, awareness has since increased about the high risk of harmful ILUC effects from EU biofuel policies, which could have a net effect of increasing atmospheric GHG concentrations (see e.g. Valin et al., 2015). This led to more stringent rules under the RED II of 2018 (RED II), which increased the total renewable target for transport to 14 % by 2030 but set a cap on the potential contribution of food- and feed-based biofuels at a maximum of 7 % after 2020 ([27]), and required a phase-out by 2030 of the promotion of biofuels made from feedstocks with a high ILUC risk (EU, 2018b).

The Renewable Energy Directive was recently revised (RED III) as part of the Fit for 55 package (EU, 2023). One major change in the agreed outcome is the option for the EU Member States to pursue either a renewable energy target (29 % by 2030) or a GHG intensity reduction target (– 14.5 % by 2030 under the RED III) in the transport sector. The latter option could result in considerably higher overall GHG savings at a considerably lower cost than the renewable energy objective (Christensen, 2021; Baldino and Searle, 2021). Furthermore, the 7 % cap on food- and feed-based biofuels was maintained, as was the required phase-out of fuels made from high-ILUC feedstocks. However, there are concerns that this cap does not sufficiently tackle the problem. The directive continues to promote first-generation biofuels (up to 7 %) and does not stipulate a full phase-out of these fuels (even if they are assumed to be fully phased out by 2050 under the European Commission's scenarios underpinning the 2050 climate neutrality objective). Furthermore, the International Council on Clean Transport has warned that intermediate crops ([28]) are not covered by the 7 % cap, and certain types of them could cause ILUC emissions of the same order of magnitude as regular food and feed crop biofuels. Even more, because they are relatively low-cost to produce, they warn of a potential paradox that the increased renewable energy objective would lead to a high uptake of biofuels from intermediate food and feed crops, thereby reducing overall GHG emissions savings (Baldino and Searle, 2021; Christensen, 2021; Searle, 2021). Furthermore, despite previous warnings by the ECA (ECA, 2016) and reports commissioned by non-governmental organisations (van Grinsven et al., 2020), the issue of fraud in the labelling of biofuels persists (Moskowitz et al., 2023).

In addition to the RED III, the Fit for 55 package also introduced two separate pieces of legislation to decarbonise the fuel mix in the aviation (ReFuelEU Aviation) (EU, 2023q) and maritime sectors (FuelEU Maritime) (EU, 2023p). The first one sets a mandatory requirement for aircraft operators to use a minimum share of 2 % sustainable aviation fuels by 2025, increasing to 6 % by 2030 and 70 % by 2050 (with specific subtargets for synthetic aviation fuels). For maritime fuels, another approach was chosen, which requires their average GHG intensity to decrease by 2 % by 2025, 6 % by 2030 and 80 % by 2050 (compared with a reference value of 91.16 g CO_2e/MJ). Given the lack of progress in these sectors, it is encouraging that separate legislation has been put in place to drive GHG emission reductions in aviation and maritime transport. However, the first assessments have warned they risk reintroducing issues with the sustainability of the biofuels they promote. Whereas ReFuelEU Aviation is more stringent than the RED III on some types of biofuels (e.g. by excluding fuels made from intermediate crops), it does not apply a cap on waste oils and animal fats (which are restricted under the RED III). A report commissioned by a non-governmental organisation has warned that this could increase demand for fuels made from category 3 animal fats, which could drive indirect emission increases by triggering a shift to fossil feedstocks in other sectors such as the chemicals sector (Malins, 2023). The FuelEUMaritime regulation is more stringent than the RED III with regard to fuels made from food and feed crops (which cannot

([27]) Or 1 pp higher than the 2020 value in a specific Member State, whichever value is lower.
([28]) Defined as crops that are not grown as the main crop as per Article 2 (40) of RED II.

count towards the targets under the regulation) but does not put restrictions on biofuels from other feedstocks with high ILUC risks.

The remaining concerns described above highlight the challenge of designing and implementing policies that can effectively promote the use of sustainable biofuels while avoiding potential negative spillover effects. This is because those spillover effects are in large part inherent to biofuels, as impacts can be indirect (e.g. demand for fuel can increase overall demand for agricultural commodities, thereby contributing to land use change far away from a specific supply chain), and their sustainably available supply is constrained.

There are strong arguments for prioritising direct electrification over the use of hydrogen- and bio-based fuels.

There are in total three alternatives to fossil fuels in the transport sector: direct electrification, hydrogen and its derivatives, and sustainable biofuels. A report by Trinomics for the European Parliament (Trinomics, 2023b) found that direct electrification is the most energy efficient and has the lowest sustainability concerns of these three alternatives, even if it also faces potential constraints on raw materials for batteries. Hydrogen-based fuels and biofuels can also deliver substantial GHG emission reductions, but their scalability is constrained by limited availability of the required inputs (sustainable feedstocks for biofuels, zero-emission electricity for hydrogen, and biogenic or atmospheric CO_2 for synthetic fuels), their cost-competitiveness and their technological readiness.

As all transport modes need to be significantly decarbonised to achieve the 90 % reduction objective, there is thus a strong argument for prioritising direct electrification and reserving the use of hydrogen-based fuels and sustainable biofuels for transport modes that are technologically difficult to electrify directly. These include aviation, long-haul shipping and, in some circumstances, heavy-duty road transport (IPCC, 2022j; Trinomics, 2023b).

The study by Trinomics (2023) also compares sustainable biofuels with hydrogen and its derivatives. Whereas sustainable biofuels are more affordable (currently, but probably also in the longer term), they have the disadvantage of facing more stringent availability limitations than hydrogen-based fuels. These constraints are expected to continue in the longer term, as there will be competing demand for biogenic carbon from other sectors. This increases the importance of limiting policy incentives to sustainably sourced biofuels. On the other hand, hydrogen-based fuels are less subject to sustainability constraints, but are more expensive, at a lower technological readiness level and energy-inefficient to produce, which limits their scalability at least in the short to medium term. However, the prospects of future cost reductions through technological improvements, economies of scale and increased availability of zero-emission electricity could improve their scalability in the medium to longer term.

6.5 Enabling condition: transport infrastructure

The EU provides considerable support for transport infrastructure through a range of funds, including the Cohesion Fund, the European Regional Development Fund, the Connecting Europe Facility and the RRF. The Advisory Board has not assessed whether the investments in transport infrastructure under these funds have been consistent with the EU's climate objectives and in particular its ambitions to achieve a shift towards lower-emission transport modes.

The TEN-T regulation is a specific EU policy instrument to develop a consistent, efficient, multimodal, and high-quality transport infrastructure across the EU (EU, 2013b). However, a recent report by the ECA (ECA, 2023b) has criticised the fact that the current regulation does not require an analysis of the adequacy of existing intermodal terminals and the need for future terminals to meet current and

potential future traffic flows. It also does not require the collection of information on the digitalisation of terminal infrastructure, which would allow logistics operators to share information efficiently. Furthermore, Member States have made insufficient progress in ensuring the compliance of their infrastructure with the technical requirements set out in the TEN-E Regulation. In 2021, the European Commission published a proposal for a revision of the TEN-T regulation, with the aim of aligning it with the European Green Deal and the ambition to achieve a 90 % GHG emission reduction in transport by 2050 (EC, 2021ah). Specific measures in the proposal include obligations for Member States to allow faster speeds (at least 160 km/h) on all passenger lines on main TEN-T rail stretches, make it possible for lorries to be transported by train, connect large airports to rail, and increase the number of multimodal transport hubs for freight and multimodal stations for passengers. It would also address the shortcomings described above, by requiring better information on terminal location and digitalisation, and including more means for the European Commission to ensure proper implementation at the Member State level (ECA, 2023b). At the time of publication of this report, the European Parliament and the Council had reached a provisional agreement on the proposal.

The lack of available charging infrastructure has been identified as a key bottleneck to achieving rapid and large-scale electrification of the transport fleet (Nykvist and Olsson, 2021; Osieczko et al., 2021; Shoman et al., 2023). To address this, in 2023 the EU adopted the Alternative Fuels Infrastructure Regulation, which sets binding minimum national targets for charging infrastructure (EU, 2023o). Although it is generally recognised as an effective tool to ensure adequate charging infrastructure, an independent assessment (not peer-reviewed) by the International Council on Clean Transport has warned that the targets for HDV charging stations are insufficiently ambitious, as they are based on conservative estimates of the deployment of heavy-duty BEVs (Basma and Rodriguez, 2021).

6.6 Summary tables

Table 8 Progress summary - transport

Indicator	Reference period	Historical progress	Required up to 2030	Required in 2031–2050
T1: GHG emissions	2005–2022	– 2 Mt CO_2e/yr	– 26 Mt CO_2e/yr	– 31 Mt CO_2e/yr
T2: transport demand				
T2a: passenger	2015–2019	+ 92 Gpkm/yr	+ 41 Gpkm/yr	+ 10 to + 17 Gpkm/yr
T2b: freight	2015–2019	+ 51 Gtkm /yr	+ 46 Gtkm/yr	+ 18 to + 19 Gtkm/yr
T3: modal shares				
T3a: % of cars in passenger transport [a]	2015–2019	Stable	– 0.2 pp/yr	–0.2 pp/yr
T3b: % of lorries in freight transport [a]	2015–2019	+ 0.6 pp/yr	– 0.4 pp/yr	–0.2 pp/yr
T3c: aviation passenger transport	2015–2019	+ 33 Gpkm/yr	+ 2 Gpkm/yr	+ 5 to + 12 Gpkm/yr
T3d: high-speed rail passenger transport	2015–2019	+ 5 Gpkm/yr	+ 8 Gpkm/yr	+ 5 Gpkm/yr
T3e: rail freight transport	2015–2019	+ 2 Gpkm/yr	+ 17 Gpkm/yr	+ 10 Gpkm/yr
T3f: inland waterway freight transport	2015–2019	– 2 Gpkm/yr	+ 4 Gpkm/yr	+ 2 Gpkm/yr
T4: road vehicle CO_2 intensities				
T4a: passenger cars (new sales)	2018–2022	– 9 g CO_2/km/yr	– 7 g CO_2/km/yr	– 10 g CO_2/km/yr [b]
T4b: vans (new sales)	2018–2022	– 1 g CO_2/km/yr	– 8 g CO_2/km/yr	– 16 g CO_2/km/yr [b]
T5: uptake of ZEVs				
T5a: passenger cars (% in new sales)	2018–2022	+ 3 pp/yr	+ 7 pp/yr (to reach 100 % by 2035)	
T5b: vans (% in new sales)	2018–2022	+ 1 pp/yr	+ 8 pp/yr (to reach 100 % by 2035)	
T5c: lorries (number of ZEVs in total fleet)	2018–2022	+ 729/yr	+ 9 526/yr	No benchmark
T6: fuel mix				
T6a: % of fossil fuels	2017–2021	– 0.4 pp/yr	– 0.5 pp/yr	– 4 pp/yr
T6b: % of first-generation biofuels	2017–2021	+ 0.4 pp/yr	+ 0.04 pp/yr	– 0.6 pp/yr

Legend

On track	The required change [c] is ≤ 1.
Almost on track	The required change [c] is between 1 and 1.5.
Somewhat off track	The required change [c] is between 1.5 and 2.
Considerably off track	The required change [c] is ≥ 2.
Wrong direction	The required change [c] is < 0.

[a] Inland transport, excluding aviation and maritime transport volumes.
[b] To achieve the legally binding objectives for 2035 (cars and vans) or 2040 (lorries).
[c] See Section 2.2 for more details on how the required change is calculated.

Table 9 Policy consistency summary - transport

Policy inconsistencies	– Current CO_2 emission performance standards incentivise car manufacturers to prioritise larger, less efficient vehicles within the segment of ZEVs. – The price cap mechanism under the EU ETS 2 increases the likelihood of a lower price than under the EU ETS, which undermines electrification in the transport sector. – The ETD continues to provide exemptions for commercial transport fuels, and for aviation and maritime. The proposed revision to tackle this has not yet been adopted. – The RED III, ReFuelEU Aviation and FuelEUMaritime continue to promote some biofuels with potentially high indirect effects, such as fuels made from food and feed crops, intermediate crops and category 3 animal fats.
Policy gaps	– There are no dedicated policies or strategies to curb overall transport demand; moderation of overall transport demand is not considered as an option in the EU's Sustainable and Smart Mobility Strategy. – Extra-EU aviation and half of extra-EU maritime transport remains exempt from the EU ETS.
Ambition gaps	– EU policies to promote a modal shift (the Combined Transport Directive, the Rail Freight Corridors Regulation, the TEN-T regulation) are not yet aligned with the European Green Deal. The European Commission has launched several initiatives to address this gap, including a revision of the TEN-T regulation (provisional agreement reached), a regulation on the use of railway infrastructure capacities (proposed but not yet adopted) and a revision of the Combined Transport Directive (proposed but not yet adopted).
Implementation gaps	– Implementation of the Rail Freight Corridor Regulation and the Combined Transport Directive has been incomplete and heterogeneous across the EU. – There are well-founded suspicions of fraud in the labelling of transport biofuels as sustainable under RED III.

7 Buildings

Key messages

The GHG emission trend in the EU buildings sector is not in line with the EU's climate objectives. Putting it on track towards climate neutrality can be accelerated by a shift to zero-emission buildings and deep energy retrofits of existing buildings, combined with reducing the floorspace and energy demand.

GHG emissions in the buildings sector have decreased by 27.5 % (– 11 Mt CO_2e per year on average) between 2005 and 2022 (Figure 45). However, to be consistent with the European Commission's scenarios that underpin the overall 2030 – 55 % objective, the average rate of GHG emission reductions would need to almost triple in 2023–2030 to 31 Mt CO_2e per year. Achieving that scale of emission reductions in the coming years requires a deep energy retrofit of the EU building stock in combination with a rapid switch from fossil to zero- or low-carbon heating technologies.

Figure 45 Indicator B1 – overall progress in reducing GHG emissions from the EU tertiary and residential buildings

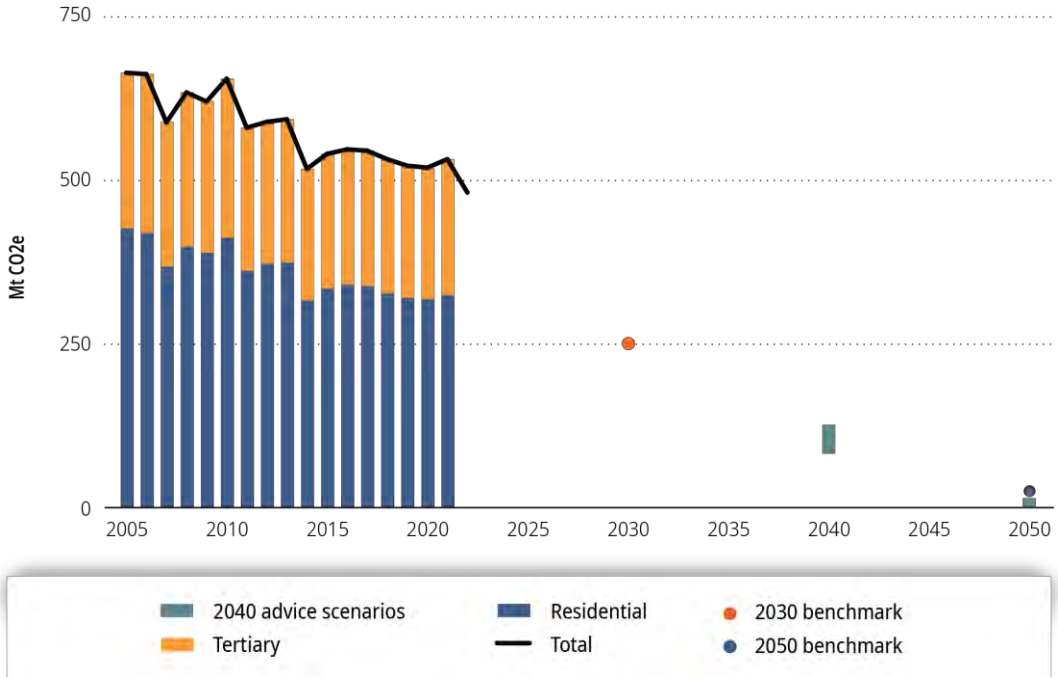

Sources: See Figure 47.

The rate and depth of renovation must increase fast while managing distributional impacts.

Needs. Around three quarters of EU buildings were built before 1990. Most of the buildings (85–95 %) standing in the EU today will also be there in 2050. Around 75 % of buildings in the EU are energy inefficient. Improving the energy performance of the existing buildings can reduce the final energy demand, but the pace and depth of building energy retrofits so far is not sufficient to meet the EU's climate targets by 2030 and 2050. The EU needs to overcome multiple barriers to deep energy retrofits,

including stifled price signals, split incentives ([29]), and obstacles linked to the building sector's high heterogeneity in terms of building types, sizes and operational uses. In addition, skills shortages are acute in the construction sector (see Chapter 15 'Labour, skills and capacity building'). Policy design needs to account for the socioeconomic impacts of measures to decarbonise buildings in the context of a just transition (see Chapter 11 'Whole-of-society approach').

Gaps. EU policies so far have not overcome barriers to wide-scale and deep energy retrofits of buildings **(implementation gap)**. The recast of the EPBD aims to address this gap, notably through the gradual introduction of minimum energy performance standards to trigger renovation of the worst-performing buildings, a definition of deep renovation and the introduction of building renovation passports. The introduction of the EU ETS 2 covering energy use in buildings will support energy retrofits but is not in itself a solution to the persisting barriers. Constraints on distribution, organisation, administrative capacity, investment, and data go beyond the insufficient price signals. The quality and ambition of the EU's long-term renovation strategies are not sufficient to guide the required building renovation towards the 2050 climate neutrality objective **(implementation gap)**.

Recommendation B1. The EU ETS 2 should be accompanied by the swift adoption and effective implementation of an ambitious EPBD recast addressing:

— organisational, administrative capacity and investment barriers, for instance through one-stop shops and energy performance contracting,
— regressive socioeconomic impacts, such as through the Social Climate Fund and actions set out in the European Commission's Recommendation (EU) 2023/2407 of 20 October 2023 on energy poverty (see Chapter 11 'Whole-of-society approach')
— skilled workforce availability (see Chapter 15 'Labour, skills, and capacity building').

Recommendation B2. The long-term renovation strategies should be improved and contribute to the national LTSs under the EU climate Governance Regulation (see Chapter 14 'Climate governance').

In most cases, decarbonisation of heating and cooling is most efficiently achieved through direct electrification based on the accelerated deployment of heat pumps. District heating has also an important role to play.

Needs. Fossil fuels and biomass dominate the heating sources for the EU's building stock. Space heating and water heating represent around 80 % of the building energy demand across the EU. Heating, cooling, ventilation, and hot water solutions in the EU building stock need to reflect the changing climatic conditions, advancements in net zero technologies, and direct electrification benefits from efficiency and system perspectives. Heat pumps deliver heat at a higher efficiency than combustion fuel boilers and usually rely on increasingly renewables-dominated electricity grid supply. Very efficient appliances reduce energy demand and hence reduce the need for expanding electricity supply. The EU needs to keep up the momentum created by the energy crisis, which led to a massive uptake of heat pumps.

Gaps. So far, EU policies have been moderately successful in driving non-fossil fuel switching. This is thanks to, among other factors, subsidies to fossil gas allowed under the ETD and EU State aid rules **(policy inconsistency)**, a lack of system integration (see Chapter 4 'Energy supply') and insufficiently robust EU standards leading to incremental energy efficiency improvements and lock-in effects **(policy gap)**.

([29]) A split incentive may occur in the case of rented properties, that is, principal/agent problems in which the tenant benefits from the decarbonisation investment made by the landlord.

Recommendation B3. To maintain the current rate of heat pump uptake and, where relevant, shift to innovative district heating, EU policies should create a conducive framework including carbon pricing, energy taxation (see Chapter 10 'Pricing emissions and rewarding removals), energy system integration guided by the energy efficiency first principle (see outcome 1 subsection below and Chapter 4 'Energy supply') and robust supply chains including available skilled workforces (see Chapter 15 'Labour, skills, and capacity building'). It should support timely and robust local heating and cooling plans, which are required under the EED. The roll-out of heat pumps should be considered in the context of better-integrated social and climate policies (see Chapter 11 'Whole-of-society approach').

Reducing the demand for energy and materials over the life cycle of buildings is an important lever for a fair and just transition. To this end, EU policies can provide information and guidance to national policies, for example in the field of taxation and planning.

Needs. Buildings' energy and materials demands have been increasing overall, as a result of changes in demography, climatic conditions and use of building. The EU's **floor area** has been increasing more than could be justified by the EU's population growth. Reducing the demand for energy and materials, known as sufficiency, relies on widely available measures such as compact cities, shared spaces, voluntary demand reduction, and nature-based solutions such as green roofs that can bring multiple benefits including climate resilience and well-being. In this respect, sufficiency-led **reduction of floor space demand** is one of the most impactful measures to reduce buildings' environmental footprint, including embodied energy and carbon.

Gaps. The revised EED and the EPBD before recast do not explicitly aim to leverage sufficiency, but include provisions that will encourage it, such as the consumer information and empowering programmes. The EU does not prominently guide urban/spatial planning and taxation towards energy and material sufficiency **(ambition gap)**. The EPBD recast aims to tackle buildings' embodied carbon and energy, which could encourage better use of existing buildings rather than new construction.

Recommendation B4. The EU should strongly encourage reduction in demand for energy and materials by promoting sufficiency in the pre-use phase, that is, through urban and territorial spatial planning and building codes, as well as the use phase, that is, through digital solutions, awareness-raising and sharing good practice, for example on land value taxation, and through adequate carbon pricing under the EU ETS 2 (see Chapter 10 'Pricing emissions and rewarding removals'). Innovative policy measures could also incentivise building occupants' behaviour to drive energy and resource savings through, for example, energy saving feed-in tariffs and personal carbon allowances, perhaps based on experience from regulatory sandboxes, since a large proportion of emissions comes from the building operations phase.

Reliable, granular and comparable data on building performance and on the multiple benefits of energy efficiency investment are urgently needed to underpin policy measures.

Needs. When embedded in appropriate policies, reliable building performance data can contribute to (i) attracting private investment, (ii) creating new markets and infrastructure, (iii) innovating to reduce building life cycle emissions, (iv) spurring behavioural changes and (v) better tracking of EU policy progress. The EU increasingly relies on energy performance certificate (EPC) data for tracking the progress and implementation of renovation policies and funding.

Gaps. So far, EU policies have not sufficiently facilitated collection and sharing of reliable, granular, comparable and interoperable information on the energy performance, investments in energy efficiency

and multiple benefits of efficient building stock, such as indoor air quality **(policy gap)**. The EPC schemes are of uneven quality and have limitations in terms of reliability, as they are based on data derived from the physical properties of buildings rather than energy demand driven by occupancy behaviour **(ambition gap)**. The recent EPBD recast aims to address this gap.

Recommendation B5. The EPBD recast and follow-up to the EU action plan on digitalisation of energy system should allow better use of the EPCs and minimum energy performance standards and should make it possible to unlock the benefits of data in the context of energy system integration (see Chapter 4 'Energy supply'). The EPBD recast should be implemented swiftly so that national databases on the energy performance of buildings are established and the role of the EU Building Stock Observatory is reinforced. The data collected should be based on actual performance and go beyond the energy parameters, so it includes at least environmental quality, thermal comfort, sufficiency and circularity, as well as building resilience aspects. This should help improve the policy narratives accompanying building decarbonisation measures (see also Chapter 11 'Whole-of-society approach').

7.1 Scope and sectoral assessment framework

Scope

This chapter covers all residential and tertiary buildings. In tracking progress, it covers all direct emissions from fuel combustion in buildings, and energy-related emissions from the agricultural sector. Emissions from district heating and the production of electricity that is used in buildings are covered in the energy supply sector. Emissions from the construction and maintenance of buildings, and F-gases from heating and cooling installations, are reported in the industry sector. For policy consistency, this chapter also considers the role of buildings in the broader energy system.

Greenhouse gas emission reductions required in buildings to reach climate neutrality

Under the 1.5TECH and 1.5LIFE scenarios of the European Commission's in-depth analysis accompanying the 2018 LTS 'A clean planet for all' (EC, 2018e), and under the more recent MIX scenario of the 2020 climate target plan impact assessment (EC, 2020s), buildings sector emissions are reduced by approximately > 95 % by 2050 compared with 2005. The very few remaining emissions in 2050 need to be counterbalanced by emission removals to achieve overall climate neutrality. This is also in line with the latest IPCC AR6 illustrative mitigation pathways, which show deep reductions from buildings in most scenarios by 2050 (IPCC, 2022b).

Assessment framework for the buildings sector

The following building blocks were identified to achieve the required GHG reductions in the buildings sector by 2050.

Outcomes. Based on the latest IPCC assessment report, the following two outcomes were identified as a basis for tracking progress and policy consistency in the buildings sector (IPCC, 2022b):

- **lowering energy and material demand**
- shifting towards **efficient and decarbonised energy supply**.

Mitigation levers. To achieve these outcomes, and building on the IPCC approach, the assessment of the EU policies relevant to buildings follows the sufficiency, efficiency, renewables framework (IPCC, 2022b). **Sufficiency** can be understood as reducing the demand for energy services and materials, often through better use of existing space or the building materials, **efficiency** as continuous short-term

marginal technological improvements, and **renewables** as reducing the environmental impacts of supplying energy and materials.

In this context, the following levers for the contribution of buildings to the EU's overall GHG emission reductions have been identified.

- **Deep retrofits and zero-emission new buildings.** Thermal efficiency retrofits of existing envelopes should be followed up by replacing the heating, ventilation and air conditioning and backed up with demand-side measures through digitalisation and the integration of renewable energy, retrofits and new builds in line with zero-emission building standards, in other words buildings with very high energy performance. The remaining energy demand should be covered mainly by local RESs.
- **Heat pumps.** Switch fuel to renewable heating and cooling through heat pumps, and highly efficient district heating, solar thermal, geothermal and sufficiency-led cooling solutions such as indirect evaporative cooling.
- **Energy and material sufficiency.** Reduce demand for space and resources, for example by downsizing dwellings and increasing co-habitation. Make better use of available floorspace rather than construct new buildings.
- **Sustainable construction.** This has a strong link to material sufficiency. Consider and reduce buildings' embodied carbon and emissions, notably through, for example, extending the lifespan of existing buildings while increasing the intensity of building use, reducing the amount of materials required for each unit of newly built floor area (material efficiency), use innovative construction materials and reduce the GHG intensity of material production.

While the EU 2050 vision suggests renewable **hydrogen** and hydrogen blends with fossil gas have a role to play in heating buildings (EC, 2018d), the IPCC warns against it because 'the delivered cost of heat from hydrogen would be much higher than the cost of delivering heat from heat pumps, which could also be used for cooling. Repurposing gas grids for pure hydrogen networks will also require system modifications such as replacement of piping and replacement of gas boilers and cooking appliances, a factor cost to be considered when developing hydrogen roadmaps for buildings. There are also safety and performance concerns with domestic hydrogen appliances … scenarios assessed show a very modest role for hydrogen in buildings by 2050' (IPCC, 2022g).

Enabling conditions. In addition, seven enabling factors have been identified as key to at least one of the mitigation levers described above. They are finance and investments, quality and use of data, prosumers and positive energy buildings and districts, pricing emissions, skills and workforce, whole-of-society approach and innovation. Some of these enabling conditions are assessed in other chapters throughout the report, as shown in Figure 46. The four sector-specific enablers addressed in this chapter are:

- **urban and spatial planning**, for example design of urban and rural settlements enabling reduced demand for floor space, faster deployment of renewables and better adaptive capacities;
- **prosumers and positive energy buildings and districts**, for example adapting electricity grids through infrastructure investment facilitating access to the grid, and enabling buildings to have an active role in electricity system reliability (demand response) through digital and smart solutions integrating energy storage systems, such as on-site batteries and seasonal heat storage;
- **quality and use of data**, for example improving the availability, quality and use of EPCs, digitalising buildings data systems, and integrating data on the multiple benefits of building retrofits into investment decision-making;
- **public and private investment**, for example better use of public funds with a focus on additionality and alleviation of negative socioeconomic impacts; technical assistance and one-stop shops for the crowding-in of private funding; support to sufficiency; and fiscal incentives led by a just transition.

The assessment framework for the buildings sector, including the selected indicators to track progress for this sector (see white boxes), is shown in Figure 46.

Figure 46 Assessment framework for the buildings sector

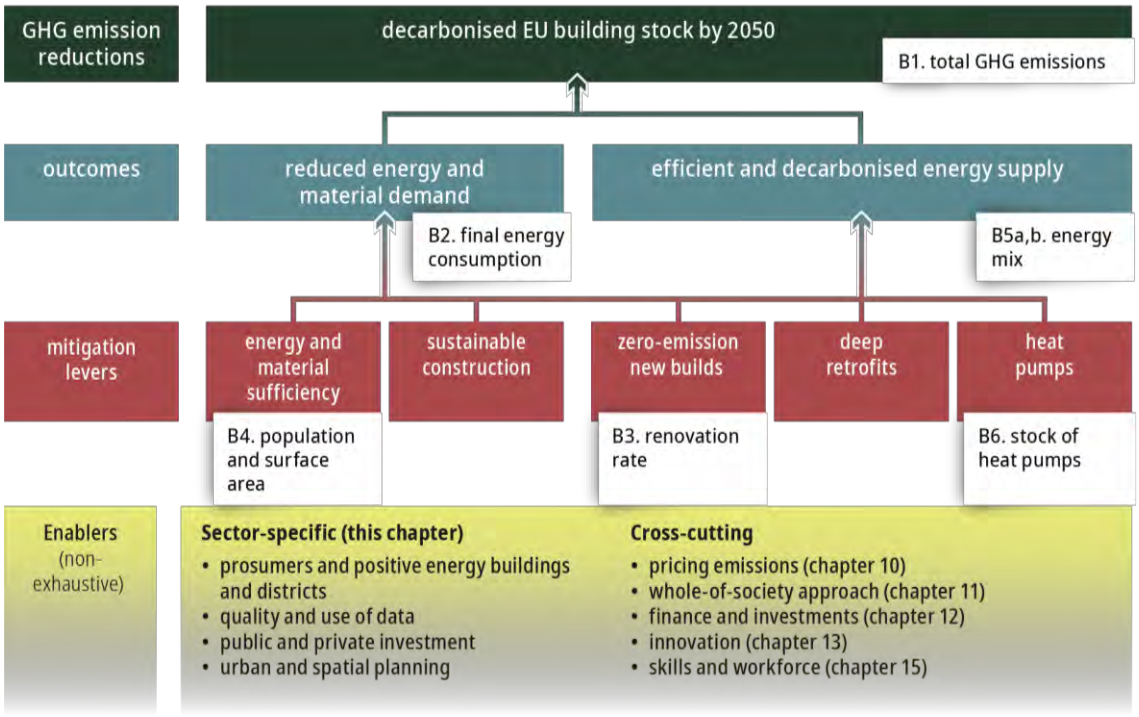

Source: Advisory Board (2024).

7.2 Emission reduction progress

GHG emissions in the buildings sector ([30]) decreased by 27.5 % (– 11 Mt CO_2e per year on average) between 2005 and 2022. Despite consistent emission reductions since 2005, the sector is not on track compared with the European Commission scenarios that underpin the EU 2030 climate target. The buildings sector's contribution would require the average rate of GHG emission reductions to almost triple in 2023–2030 (to – 31 Mt CO_2e per year) compared with 2005–2022 (see Figure 47).

The emission reduction so far is primarily a result of decarbonising the energy mix and in particular a reduction in the use of oil products (Eurostat, 2023e). Energy is being used more efficiently in buildings (see indicator B4 below), but these efficiency gains are counteracted by shrinking household sizes, more floor area per person (see indicator B3), more electric appliances and increased demand for energy services driven by economic activity. The emission reductions required from the buildings sector by 2030 can be achieved through an accelerated deep energy retrofit of the European building stock in combination with a rapid switch from to efficient, non-fossil heating and cooling technologies.

([30]) This refers to emissions from energy use in the residential sector, the commercial sector (which includes institutions and public services) and agriculture. Although agriculture is not the focus of this chapter, these agricultural emissions are included for comparability with the European Commission analysis, which aggregates energy-related emissions from the three sectors. According to the EU GHG inventory, agriculture has accounted for 6–7 % of these emissions historically.

Figure 47 Indicator B1 – overall progress in reducing GHG emissions from the EU buildings sector

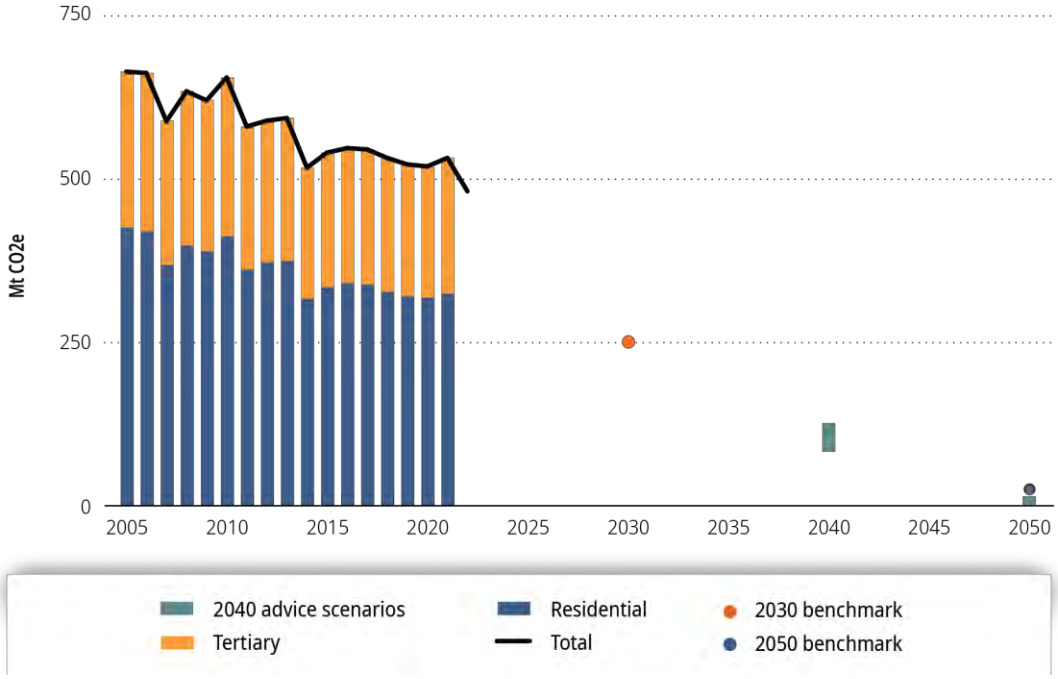

Notes: Historic data refers to GHG emissions from residential and tertiary sectors (including energy use in agriculture) from the EU GHG inventory. 2030 benchmark refers to residential & tertiary CO_2 emissions from the Fit for 55 MIX scenario. 2040 advice range refers to energy-related CO_2 emissions in the residential and tertiary sector in the scenarios that underpin the Advisory Board's 2040 advice, with original data (which does not include agriculture) adjusted upwards for comparability with the other series (assuming the share of agricultural energy in overall emissions from these sectors remains at the 2021 level as per GHG inventory). 2050 benchmark refers to residential and tertiary sector CO_2 emissions reported in the in-depth analysis accompanying A Clean Planet for All, recalibrated for EU27.

Sources: EU GHG inventory (EEA, 2023f), Fit for 55 MIX scenario (EC, 2021v), Advisory Board 2040 advice scenarios (2023d), In-depth analysis accompanying A Clean Planet for All (EC, 2018e) (Figure 91)

7.3 Outcome 1: reduced energy and material demand

Final energy demand in residential and tertiary buildings does not show a clear declining trend in Figure 48. Significant energy demand reductions are required by 2030 to meet benchmarks consistent with the EU's 2030 climate target underpinned by the REPowerEU plan. The Fit or 55 benchmark would require residential use to fall by 29 % by 2030 compared with the 2021 level, and by 18 % in the tertiary sector. Greater reductions (– 34 % and – 23 % respectively) are envisaged in the REPowerEU scenario. The reduction level consistent with the revised EED lies somewhere between these two levels (EC, 2022a; EU, 2023a) ([31]).

([31]) According to the REPowerEU staff working document (European Commission, 2022a), the Fit for 55 proposals are consistent with reducing final energy consumption (from all sectors) by 9 % in 2030 compared with a reference scenario. The European Commission REPowerEU plan would increase this to 13 %. The revised EED sets a target of 11.7 % compared with the projections of the EU reference scenario, but does not specify the contribution of the residential and service sectors.

Figure 48 Indicator B2 – final energy consumption in the residential and tertiary sectors

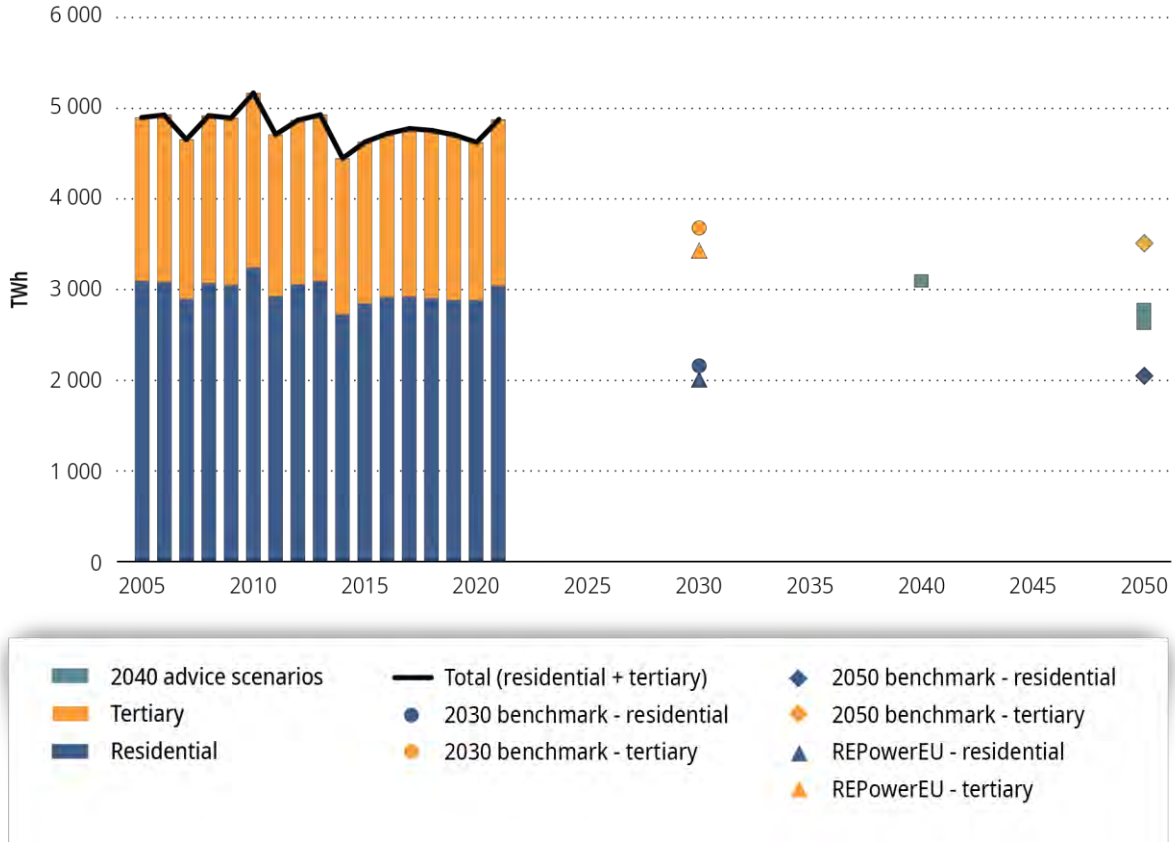

Notes: Tertiary sector final energy consumption includes energy from commercial, public, and agricultural buildings. 2030 benchmark and REPowerEU figures refer to energy consumption consistent with the Fit for 55 and REPowerEU scenarios. 2050 benchmark based on the MIX scenario from the Climate Target Plan. All sources include ambient heat harnessed by heat pumps.

Sources: Eurostat energy balances (2023b), REPowerEU staff working document (EC, 2022p) (Table 10), Climate Target Plan (EC, 2020s).

Despite the need to reduce buildings' energy demand, most EU Member States are not on track to meet their energy use targets for 2030 as set in their respective long-term renovation strategies (EC, 2023ba). Regarding the **drivers of energy use by residential and tertiary buildings**, a number of studies suggest that the stability of overall consumption over the past 20 years is in fact due to a variety of countervailing factors, with increased demand related to rising incomes and activity, broadly cancelled out by efficiency improvements driven by energy retrofits, and efficient appliances and new buildings. In the residential sector, Tsemekidi Tzeiranaki et al. (2019) find that energy consumption up to 2016 declined slightly in spite of rising population and incomes, smaller household sizes and increased floor area per capita, aided in part by climatic conditions (fewer heating degree days). They also find that energy efficiency in the residential sector improved, even after adjusting for climatic and economic effects. However, the approximate balance between increased demand and improved efficiency appears to have broken down in more recent years. Reductions in energy consumption have slowed since 2016 (particularly in the residential sector) and most recently appear to have reversed, with energy consumption increasing sharply in 2021. Final energy consumption for heating has fallen steadily since 2005, with the reduction reaching 16 % by 2019 (Odyssee-Mure project, 2023). After controlling for climate effects, this reduction falls to 8 %, suggesting that around half of it is due to a warming

climate ([32]). The reduction in energy consumption for heating has far outweighed the increased consumption for cooling in absolute terms (Odyssee-Mure project, 2023). While cooling represents a modest fraction of energy use in buildings today, it is increasing, and studies suggest that it could account for 8–9 % of energy use in residential and non-residential buildings by 2050 (EEA, 2022b).

Regarding material demand, according to the European Commission, the material demand in the EU buildings sector driven by construction activities accounts for about 50 % of all extracted material and is responsible for over 35 % of the EU's total waste generation. GHG emissions from material extraction, manufacturing of construction products, and construction and renovation of buildings are estimated at 5–12 % of total national GHG emissions across the EU. Greater material efficiency could save 80 % of those emissions (EC, 2023c).

Lever: deep retrofits and zero-emission new builds

Improving the energy performance of the existing buildings is a key driver of reduced final energy consumption but its pace is not sufficient to meet the EU climate targets by 2030 and 2050.

Around three quarters of EU buildings were built before 1990 (EC, 2021i). With the building stock's renewal rate at 1.2 % annually, most of the buildings (85–95 %) standing today in the EU will be there also in 2050. Around 75 % of buildings in the EU are energy inefficient according to current standards (EC, 2021j). Buildings in EPC class A represent a negligible share of the EU building stock (EC, 2021al). Whereas a significant portion of EU buildings are renovated to some extent every year, the depth of the renovation is often very limited. The currently observed retrofits across the EU are dominated by shallow retrofits: incremental changes to energy performance as part of building renovations (EC, 2022f). Only 0.2 % of residential buildings (and 0.3 % of non-residential buildings) are deeply renovated each year. Deep energy retrofits go beyond upgrading of a heating source, and transform the building to zero-emission standard while also improving the occupants' well-being, the dwelling's resilience and the integration of the energy system. To achieve the – 55 % objective, the average renovation rate should be doubled (EC, 2020s) as presented in Figure 49 (indicator B3) below.

The energy retrofits may be part of wider non-energy renovations to address comfort, safety or maintenance issues. Around 15 % of Europeans live in dwellings with leaking roofs or damp walls, floors or foundations, and between 5 % and 39 % live in buildings with rot in the window frames or floors (EEA, 2022a). The available building data is insufficient to indicate the respective energy and non-energy aspects of building renovations, including the depth of energy retrofits and the renovation rate itself (see Section 7.5).

The renovation wave strategy, the EPBD in force and the expected changes under the EPBD recast are intended to encourage deeper energy renovations. The changes included in the revised EPBD (EC, 2021ac) – for instance the introduction of minimum energy performance standards for existing buildings, and tools supporting staged deep renovation, such as a renovation passport towards the zero-emission standard (see Box 4) – go in the right direction in terms of the decarbonisation of buildings. It is too early, however, to comment on the ambition of the EPBD recast or on the delivery of new measures and their overall effectiveness. Its timely implementation will be of the essence, supported by the EU ETS 2. The price signals of the EU ETS and the EU ETS 2, will increase considerably should the progress with the deep retrofits be too slow (see Chapter 10 'Pricing emissions and rewarding removals').

([32]) Controlling for climate effects involves assuming that the number of heating and cooling degree days stands at the long-term average, and adjusting heating and cooling demand accordingly.

Figure 49 Indicator B3 – residential annual renovation rate and depth

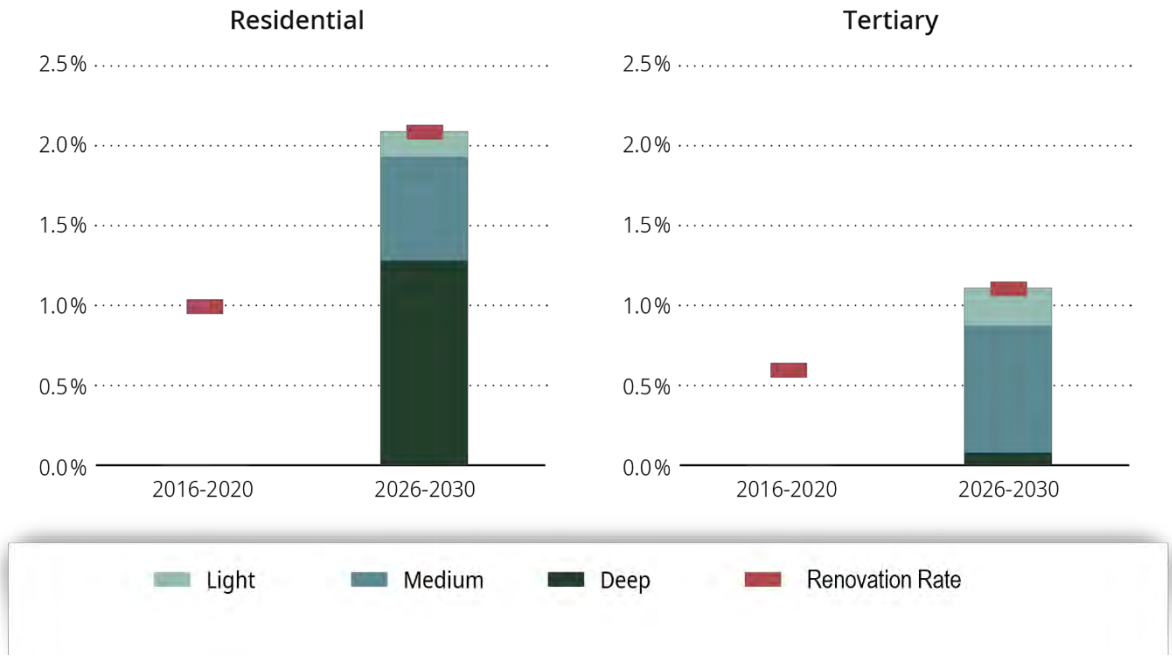

Notes: 2016-2020 benchmark data is based on historic data, with 2026-2030 renovation rates and depth for residential and tertiary sectors based on Type 1 renovations (i.e. 'improvement of thermal integrity of buildings through renovation of the building shell') from the MIX scenario of the Climate Target Plan impact assessment. A comparable breakdown of renovation depth is not available for the 2016-2020 benchmark, with only the total renovation rate available.

Sources: Climate Target Plan impact assessment (EC, 2020s) (Figure 53 and Figure 54)

Box 4 From nearly zero-energy to zero-emission buildings

The EPBD recast replaces the **nearly zero-energy** building standard with **zero-emission buildings**, which becomes the new standard for new buildings, the level to be attained by a deep renovation as of 2030 and the vision for the building stock in 2050. It defines a zero-emission building as 'a building with a very high energy performance in line with the energy efficiency first principle, and where the very low amount of energy still required is fully covered by energy from renewable sources at the building or district or community level where technically feasible (notably those generated on-site, from a renewable energy community or from renewable energy or waste heat from a district heating and cooling system)' (EC, 2021ac).

Nearly zero-energy building remains the standard for new buildings until the application of the zero-emission building standard, and becomes the level to be attained by a deep renovation until 2030 (EU, 2010a). It does not require that RES cover the entirety of building energy needs. The specific performance requirement expressed by a numeric indicator of primary energy use in kWh/(m2/y) are defined by the EU Member States.

Ambitious standards underpinned by robust calculation methodologies for zero-emission new builds are urgently needed.

From 2021 all new buildings should be nearly zero-energy under the EPBD in force. The nearly zero-energy buildings requirement has been a strong efficiency standard at the EU level, but there is no

uniform approach to its implementation across the EU Member States (D'Agostino et al., 2021a; Tagliapietra et al., 2019) ([33]). The standard is a cost-optimum-driven benchmark level of energy performance (kWh/m^2/y) per building type depending on the climatic zone as established by the European Commission (EC, 2016a). A recent assessment of national implementation shows that levels applied in practice are generally lower than those set out by the European Commission, because, among other reasons, different Member States apply different methods to calculate energy flow (D'Agostino et al., 2021a). Moreover, performance requirements of new buildings do not reflect the best available techniques, new materials, behavioural aspects of energy consumption and an integrated approach to building construction (D'Agostino et al., 2021a; Economidou et al., 2020; IPCC, 2022b). The European Commission's proposal for a revised EPBD (EC, 2021ac) requires all new buildings to be zero-emission as of 2030 (see Box 4). The actual **ambition of the revised standards** for new buildings will depend on thresholds of total annual primary energy use and the corresponding calculation methodologies yet to be set out. Energy demand variations due to occupants' behaviour can be significant, so energy performance measurement is more accurate if based on actual consumption, that is, real-world behaviour and building performance rather than a theoretical value, especially when the operation phase is the critical contributor to the total carbon emissions (Zhang and Asutosh, 2023). Advanced digital building management systems offer such dynamic measurements and help bridge the gap between design goals and actual building energy performance (IPCC, 2022b).

The EU needs better long-term planning of its building stock decarbonisation.

The need for better building data and control through digital tools stems also from the findings on the **long-term renovation strategies** for building stock decarbonisation by 2050 required under the EPBD. Such long-term roadmaps, if properly developed, can address the need for careful planning of building renovations (see for example Re Cecconi et al., 2022; Salvia et al., 2021). However, according to the European Commission, the long-term renovation strategies are not robust enough, so 'there is a lack of a clear pathway to deliver on climate neutrality [and] lack of a coherent framework to allow Member States to develop and plan their building decarbonisation' (EC, 2021j). The level of ambition of the strategies is not always in line with the 2050 decarbonisation goals (EC, 2023ba). To improve the long-term strategic planning for building stock decarbonisation under the EPBD, the EU can rely on more harmonised reporting, better planning, and better building data and control through digital tools (Pasichnyi et al., 2019; Salvia et al., 2021) as part of the national building renovation plans ([34]) under the EPBD recast. Such improved long-term planning and reporting could boost sufficiency measures, for example through bioclimatic design of buildings and efficient consumption of space (IPCC, 2022b), and integration of multiple benefits of building retrofits including better indoor air quality, disaster prevention and protection against climate-related hazards. It has to be underpinned by capacity building for municipal administrations, funding identification and coordination within multilevel governance as part of EU climate governance delivery mechanisms (Salvia et al., 2021 see also Chapters 14 'Climate governance' and 15 'Labour, skills and capacity building').

Lever: energy and material sufficiency

Reduction of demand for energy services and floor space has multiple benefits beyond emission reduction, but its potential is largely untapped across the EU. The EU should encourage sufficiency both in the pre-use phase (e.g. through urban and spatial planning) and in buildings use (e.g.

([33]) For example, the average non-renewable primary energy demand for a new single-family houses varies from as low as 15 kWh/m2/y) to 95 kWh/m2/y in different Member States, with an EU-level average of 52 kWh/m2/y (EC, 2023ba).

([34]) Article 3 of the EPBD recast changes the term 'long-term renovations strategies' to 'national building renovation plans'.

through digital solutions, sufficiency-led progressive housing taxation, and adequate energy tax rates under the ETD and carbon price under the EU ETS 2.

There is a growing scientific consensus regarding the untapped benefits of **reduction of demand for energy services and building materials**, in other words energy and material sufficiency (IPCC, 2022b). Sufficiency-led policies that aim to make better use of existing buildings (Gaspard et al., 2023) can address urban challenges such as energy security, air pollution, ageing populations, social alienation and demographic pressures on (Hook et al., 2023; JRC, 2021c, 2019a; Zannakis et al., 2019). In terms of energy savings, policies focusing on energy sufficiency complement energy efficiency policies (Bertoldi, 2022).

By encouraging cohabitation and higher density per unit of surface area, for example through spatial planning, building codes and taxation, sufficiency measures help to reduce the demand for new accommodation and thus reduce the sector's pressure on resources (see for example Berrill et al., 2021; IRP, 2020; Ivanova and Büchs, 2022). At the city level, compact cities and nature-based solutions, such as for cooling services, can be part of structural sufficiency (Bibri 2020; EEA 2022g) (see also 'Enabling condition: urban and spatial planning' in Section 7.5 below). Building occupants' behaviour driving energy and resource savings can be encouraged by digital tools, such as smart meters, and could be incentivised by innovative policy measures, for instance energy saving feed-in tariffs and personal carbon allowances (Bertoldi, 2022).

Looking at buildings use in the EU, there is no sign of energy and material sufficiency. The trend in building use in recent decades, notably fewer people occupying bigger dwellings, has placed upward pressure on energy consumption and emissions, as Figure 50 demonstrates. Although the total population increase has been modest (+ 3 % since 2005), there have been greater increases in the average floor space per dwelling (which currently stands at 90 m^2) and a reduction in average household size (from 2.4 people in 2010 to 2.3 people today). Between 2020 and 2021 almost all Member States increased their floor area (+ 3 % on average; EC, 2023). The annual number of dwellings for which building permits were granted in the EU increased by a factor of more than 1.3 between 2010 and 2022 (forthcoming).

EU policies do not explicitly focus on energy and material sufficiency in buildings; see for example the renovation wave strategy (EC, 2020b). Moreover, energy price interventions available to EU Member States under the European Commission's State aid guidelines (EC, 2022i), including fossil fuel subsidies (see Section 12.5), and the ETD (see Section 10.5) have been muting financial incentives for sufficiency measures (see for example ESABCC, 2023a). Accordingly, the first round of NECPs have only marginally included building-related sufficiency measures (Zell-Ziegler et al., 2021). Regarding the most recent EU policies, the revised EED and the EPBD recast include provisions that encourage sufficiency, such as consumer information and empowering programmes (EU, 2023e). The upcoming implementation of the EU ETS2 and the ETD revision could also provide sufficiency incentives.

Figure 50 Indicator B4 – population and surface area of homes and businesses

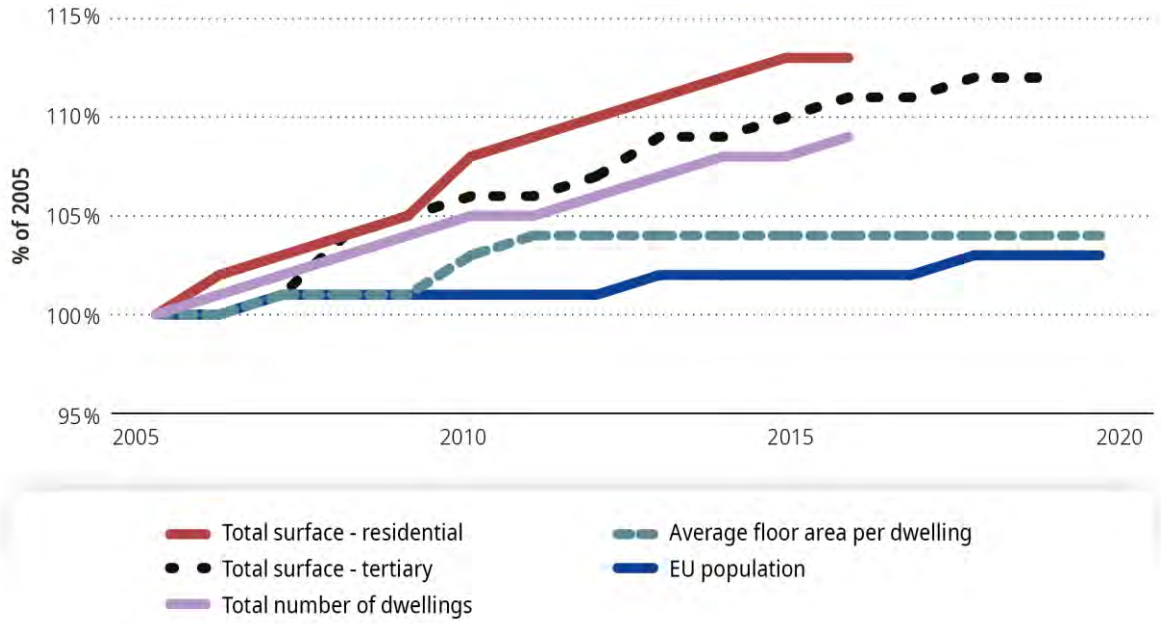

Notes: Data on total number of dwellings and total residential area is only available until 2016, and fragmented.

Sources: European Building Stock Observatory (EC DG Energy, 2023) (total surface – residential, total number of dwellings), Odyssee database (Odyssee-Mure project, 2023) (average floor area per dwelling, total surface – tertiary excluding agriculture), Eurostat (2023) (population, average household size).

Drive sufficiency through housing taxation.

In addition to EU-led measures, national and subnational authorities play a role in driving sufficiency through housing taxation. A recent analysis of the EU Member States' fiscal systems indicates a low level of recurrent property taxation combined with significant tax deductibility for mortgage interest payments, which is often not capped. A significant fraction of the tax income from real estate is from transaction taxes (OECD, 2022). Current taxes favour homeownership for high-income households and indeed increasing home sizes with rising income. They lead to large wealth gains for property owners, and distort households' decisions (JRC, 2019). They adversely affect the efficiency of land and floor space uses and the supply of affordable housing (OECD, 2022). Housing taxation may also be too rigid to encourage residential mobility, for example through transaction taxes and the failure to update property values for recurring taxes, which both constitute tax incentives to stay in large residences even when a family becomes smaller as children or spouses move out (DIW, 2021). Housing taxation also has sizeable distributional impacts (OECD, 2022) and may affect the vulnerability of lower-income households ([35]) (see Chapter 11 'Whole-of-society approach'). Reduced transfer taxes, transfer tax waivers, regular revaluation of taxable values and bonus payments for older couples who sell their houses have been proposed as measures to increase the availability of housing for younger families (Lorek and Spangenberg, 2019; Thomas et al., 2019. The OECD also suggests using housing taxation to provide incentives for energy efficiency upgrades. Both the opportunities and the risks of housing taxation reforms have been recognised in the European Semester process, in which the European Commission

([35]) Lower-income households often live in poorly insulated dwellings and spend a large share of their income on energy and housing. This means they are disproportionately exposed to carbon taxes and stringent building standards (see for example Muellbauer, 2023).

found that 'shifting part of the tax burden from labour to other types of taxes, including environmental and immovable property taxation, while duly taking account of the distributional impact of such a shift, would support the green transition and boost sustainable growth and job creation' (EC, 2023n). Land value taxation ([36]) is also linked to enhanced equity and efficiency of property taxation and may consist of green variants such as split-rate taxes ([37]) that encourage greater urban density and hence boost sufficiency (Muellbauer, 2023; OECD, 2022; Schwerhof et al., 2022). The links between housing taxation, EU climate mitigation efforts and equity need further examination, with a view to guiding Member States' fiscal choices.

Lever: sustainable construction

EU policies do not yet sufficiently leverage resource efficiency and circularity, including extending buildings' lifespans and increasing the intensity of building use, to address embodied carbon and emissions from buildings.

Extending buildings' lifespans and improving building use are among the best ways to lower embodied emissions from buildings (EEA, 2022i; Hertwich, Edgar et al., 2019; IPCC, 2022c, Saenz de Guinoa et al, 2022) and turn parts of the building stock into a temporary carbon sink. In addition, opportunities for material efficiency in the building and construction sector exist at various other levels, with design being one of the key points for intervention. Design is shaped by building codes, which in turn reflect the applicable building policies.

Better building design could address EU buildings' rapidly increasing cooling needs. Use of thermochromic energy-efficient building coating (see for example Butt et al., 2021 and green roofs and facades are among sustainable solutions to this challenge, as they reduce both the heat gains of buildings and the heat island effect (Akbari et al., 2016; EEA, 2021a; IPCC, 2022b). Furthermore, significant life cycle GHG emission reductions are linked to compact, low-rise buildings (IPCC 2022b; Pomponi et al.) and (re)use of recycled and new materials with lower energy and emission intensity than normal ones, for instance replacing concrete with wood and lowering the share of Portland cement thanks to the use of alternative binding materials (IRP, 2020). In the choice of materials, green public procurement, recycled content mandates and virgin material taxation have a role to play (IRP, 2020), and could be facilitated by EU policies (see also Section 5.3).

The EPBD recast is building on an assumption that 'minimizing the whole life-cycle greenhouse gas emissions of buildings requires resource efficiency and circularity', with a new requirement to consider the life cycle global warming potential of new buildings (EC, 2021ac). The life cycle requirement is reinforced by the proposals for the new construction products regulation (EC, 2022x) and for the ecodesign regulation establishing a framework for sustainable products (EC, 2022u). The proposed acts are underpinned by the EU's CEAP 2 (EC, 2020g) and include a mix of policy instruments, mainly regulation and information including standards, labelling and data harmonisation.

The inclusion of embodied GHG emission considerations in the EU building policy framework is a very promising development in terms of 2050 climate neutrality objectives. If the new legal framework proves to be sufficiently robust, leading to timely implementation of standards that have no implementation loopholes and cover key GHG-emitting activities, it can drive the material sufficiency aspect of building

([36]) Land value taxation is a type of property taxation that falls on the unimproved value of land, as opposed to standard property taxation, which takes the total value of property, including structures built upon it, as the tax base (see for example Barbosa and Skipka, 2019).

([37]) According to the OECD (2022), 'split-rate taxes are a hybrid of pure land value taxes and regular recurrent taxes on immovable property, where both the land and improvements on the land are taxed, but land is typically taxed at a higher rate'.

decarbonisation. For this to happen, significant learning and know-how need to be developed along the buildings value chain (see e.g. Michalak and Michałowski, 2022); see also Chapter 15 'Labour, skills and capacity building'.

7.4 Outcome 2: efficient and decarbonised energy supply of buildings

Space heating and water heating represent around 80 % of the energy consumption of residential buildings in the EU (Eurostat, 2023h). Space heating relies mostly on direct use of fossil fuels (EC, 2021j) and is the largest fossil gas consumer in the EU (EC, 2021j). While the share of coal and oil products in residential buildings' consumption has been falling since 2005, no such trend has been observed for fossil gas.

The share of fossil fuels in the energy mix has been declining steadily since 2005, as shown in Figure 51. However, at the current pace (– 0.6 pp per year in 2017–2021), fossil fuels would still account for 42 % of the mix in 2030. The pace of reduction needs to quadruple (to – 2.4 pp per year in 2022–2030) to be consistent with the European Commission scenarios underpinning the 2030 target. Accelerating the phase-out mainly requires a large-scale replacement of fossil fuel boilers by heat pumps, as reflected in the increasing shares of electricity (from + 0.1 pp per year in 2017–2022 to + 1.3 pp per year in 2022–2030) and non-bio renewables, which include ambient heat harnessed by heat pumps (from + 0.3 pp per year in 2017–2021 to + 1 pp per year in 2022–2030). The share of bioenergy has increased from 13 % in 2005 to 17 % in 2012, but has been relatively stable since. Similarly, the share of district heating was relatively stable around 8–9 % in 2005–2021. The shares of both bioenergy and district heating would remain stable until 2050 under the European Commission's decarbonisation scenarios.

Figure 51 Indicator B5a – energy mix in the residential sector

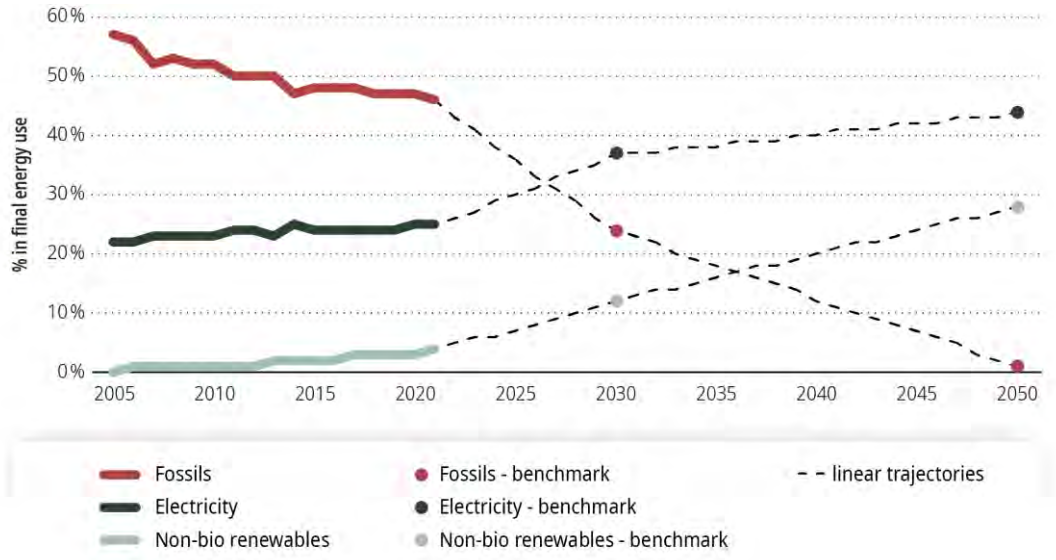

Notes: Benchmark data is based on the MIX scenario from the Climate Target Plan impact assessment. The linear trajectories are shown to increase the readability of the figure, but do not imply that the Advisory Board recommends a linear trajectory towards the benchmarks.

Sources: Eurostat energy balances (2023b), Climate Target Plan impact assessment (EC, 2020s) (Figure 55).

A similar observation can be made about the tertiary sector (see Figure 52, indicator B5b). The share of fossil fuels has declined by 18 % since 2005, although the rate of decline has slowed down in recent years (on average – 0.1 pp per year in 2017–2021). The phase-out needs to accelerate (to, on average, – 2 pp per year in 2022–2030 and – 1 pp per year in 2031–2050) to be consistent with the European Commission scenarios underpinning the EU climate objectives. Under these scenarios, they would mainly be replaced by electricity and non-bio renewables (e.g. ambient heat), whereas the share of bioenergy and district heating would remain relatively stable until 2050.

The RED III (Article 15a) introduced a new indicative national 2030 benchmark of at least 49 % of renewable energy in the buildings sector (EU, 2023f). To achieve the 2030 climate targets, RES roll-out and fossil fuel phase-out need to accelerate.

Figure 52 Indicator B5b – energy mix in the tertiary sector

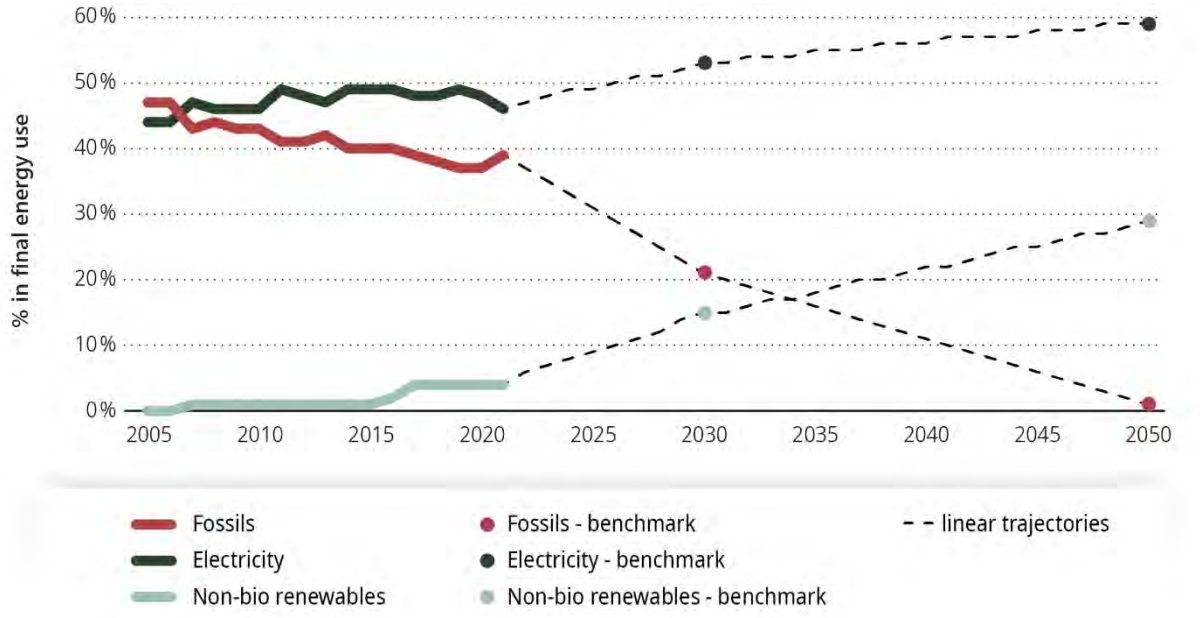

Notes: Benchmark data is based on the MIX scenario from the Climate Target Plan impact assessment. The linear trajectories are shown to increase the readability of the figure, but do not imply that the Advisory Board recommends a linear trajectory towards the benchmarks.

Sources: Eurostat (2023b), Climate Target Plan impact assessment (EC, 2020s) (Figure 55).

Lever: heat pumps

So far, EU policies have been moderately successful in driving non-fossil fuel switching. Scaling-up of heat pumps and other sustainable heating and cooling sources should accelerate.

Fossil fuels and biomass dominate heating sources in the EU's building stock (EC, 2021j), which is a problem from climate and wider environmental perspectives (see also Chapter 4 'Energy supply' and Chapter 9 'Land use, land use change and forestry'). Net zero transition requires the EU to foster direct electrification of buildings (see Chapter 4 'Energy supply'). This process can be driven by heating source replacement, such as a heat pump taking place of a gas boiler. Heat pumps can be used individually or in conjunction with heat networks and can provide both heating and cooling. This latter function is especially important in the light of experienced and expected rises in temperatures. Heat pumps operate best in highly efficient buildings; hence, their installation should usually be accompanied by insulation and other measures characterising deep building retrofits. Heat pumps can be combined with on-site

renewable electricity generation such as solar PV panels and can be backed up by storage solutions (IRENA, 2022b). Their fast and wide-scale roll-out across the EU is a necessity to achieve climate neutrality by 2050. As highlighted by the IPCC, this means 'banning the sale of new fossil fuel-fired boilers, as well as making heat pumps and very efficient appliances standard technologies' (IPCC, 2022b).

The EU heat pump market has grown significantly since 2015, with an acceleration since 2020 (see Figure 53). If the stock of heat pumps continues to grow at its current rate, the EU is on track to achieve the REPowerEU objective of installing 10 million new units by 2026 (EC, 2022m). However, further acceleration will be needed to meet the objective of 41.5 million units installed by 2030.

Figure 53 Indicator B6 - stock of heat pumps (million units) compared with REPowerEU objective

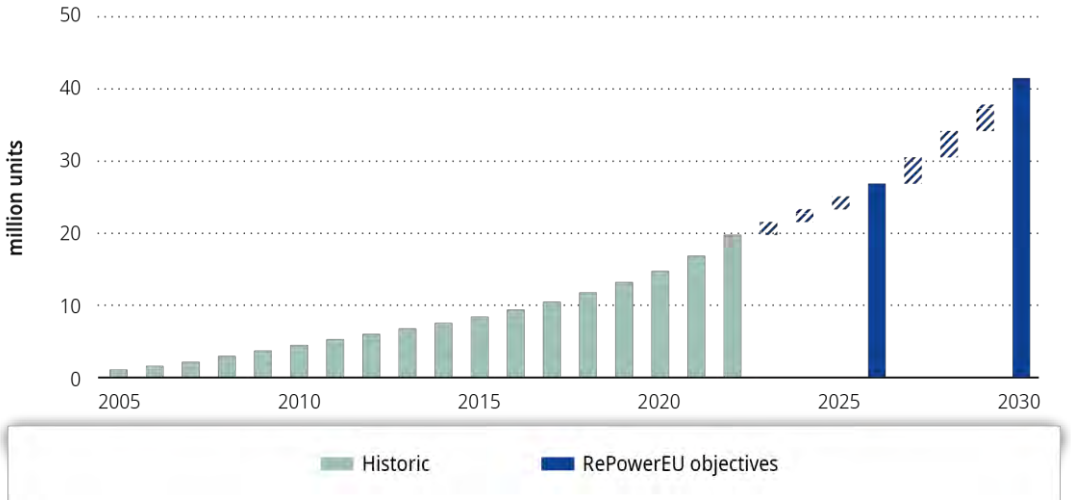

Notes: Dashed bars extrapolating the annual average growth required to meet REPowerEU objectives.

Sources: European Heat Pump Association (EHPA, 2023), REPowerEU Staff Working Document (EC, 2022p).

So far, however, EU policies have been only moderately successful in driving non-fossil fuel switching. This is because, among other reasons, the ETD and EU State aid rules allow subsidies to fossil gas (see Sections 10.5 and 12.3). EU standards and requirements for boilers, driven mainly by the EPBD and the ecodesign directive, have contributed to a decline in heating energy consumption, thanks to, for instance, efficient fossil gas boilers. Moreover, a recent review of scientific contributions regarding EU energy efficiency policies for buildings by Economidou et al. (2020) points out discrepancies in ambition among Member States' efficiency levels for heating and cooling.

A step change in decarbonisation of heating and cooling has been triggered by the European Green Deal and Fit for 55 package, further reinforced by the REPowerEU strategy. The relevant policy landscape is changing drastically following the revisions of heating and cooling product-specific regulations under the ecodesign and energy labelling framework, the EPBD, the RED II, the EED and the ETD, and new measures such as the emergency measure on issuing permits for renewables under Article 122 of the Treaty on the Functioning of the European Union, reforms under the electricity market design proposals (EC, 2023ar), and the proposals for a Net-Zero Industry Act (EC, 2023ao) and for a Critical Raw Materials Act (EC, 2023ac). Heat pumps are listed among net zero technologies under the Net-Zero Industry Act proposal, and an EU heat pump strategy is under preparation. The European Commission warns that 'without a dedicated EU action plan, 22 million old individual heating appliances and several thousand large old fossil-based heating units are at risk of being replaced by fossil boilers' (EC, 2023aj).

Local heating and cooling planning, newly required under the EED for all municipalities with over 45 000 inhabitants, could become a key tool in shifting to sustainable heating and cooling, provided it is properly implemented and expanded to smaller municipalities, with a sense of urgency reflecting the approaching increases in costs of heating with fossil fuel boilers (see Chapter 10 'Pricing emissions and rewarding removals' and Section 14.3 on the importance of multilevel dialogues).

7.5 Enabling conditions

Enabling condition: urban and spatial planning

The EU should systematically promote the integration of climate change considerations into urban and spatial planning, for instance through land use efficiency, the compact city approach and the better use of existing buildings, leading to reduced energy demand and CO_2 emissions, higher RES deployment, climate resilience and societal well-being.

Urban and spatial planning can bring considerable benefits in terms of increased building and land use efficiency leading to, among other things, reduced demand for floor space, faster deployment of renewables and greater capacities of urban and rural settlements to adapt (Devine-Wright, 2015; Kitzing et al., 2021; Nowak et al., 2022; Wiehe et al., 2020). In cities, spatial planning for compact urban form can enable reduced energy demand and changes in service provision, including walkable neighbourhoods and mixed land use, encouraging socio-behavioural change towards active transport (IPCC, 2022k). Urban and spatial planning can also enable electrification and the integration of energy systems (see Chapter 4 'Energy supply') into urban infrastructure. Finally, the IPCC also points out the potential synergies between several sustainable development goals and sustainable land use and urban planning, such as greener spaces, reduced air pollution, improved access to services and opportunities, and demand-side mitigation including shifts to balanced, sustainable, healthy diets (IPCC, 2022l).

Despite the benefits above, many cities in EU Member States are expanding in a dispersed, low-density manner. Such urban sprawl poses difficulties for sustainable land use and the construction of more compact communities, and result in additional transportation needs (Urban Agenda for the EU, 2021).

Rooted deeply in national and subnational decision-making, spatial planning is generally outside the EU's direct field of competence. Nevertheless, it contributes to and has interconnections with several EU policies and initiatives related to climate change, such as the European Green Deal, biodiversity strategy, forest strategy, soil strategy and Nature Restoration Law, strategy on adaptation to climate change, green infrastructure strategy, EU zero pollution action plan, new European Bauhaus initiative, new European mobility framework and the EED. Urban and spatial planning approaches may influence – either enhance or reduce – the potential of the above policies and initiatives to contribute to climate neutrality. Important current initiatives are the mission on climate-neutral and smart cities (EC, 2021; Huovila et al., 2022) with the recent signing of the first climate city contracts, and the European urban initiative (EUI, 2023) which supports urban areas of all sizes with innovative actions, capacity and knowledge building, policy development and communication on sustainable urban development, including greening cities, constructing and renovating in a spirit of circularity and carbon neutrality, adapting and transforming buildings for affordable housing solutions, and regenerating urban spaces.

The orientation for strategic spatial planning is provided by the *Territorial Agenda 2030 – A future for all places*, which was adopted in 2020 as a strategic framework document to support policy responses for societal transformation towards a carbon-/climate-neutral economy. It underlines the importance of balanced territorial development to deal with climate change, to reduce regional vulnerabilities to climate change and to develop capacities for mitigating and adapting to the impacts of climate change (Ministers responsible for Spatial Planning and Territorial Development and/or Territorial Cohesion,

2021). The territorial agenda 2030 promotes actions for stopping net land take by 2050, sustainable land use, open spaces and public green areas, preventing urban sprawl, restoring degraded land and coastal areas, combating deforestation and implementing green infrastructure. It is important to note that the EU territorial agenda 2030 promotes place-based policies for urban regeneration and sustainable urban planning, and considers the application of different geographic approaches, for example using functional urban areas, cross-border areas or urban–rural linkages. A widely recognised trend in the approaches is the creation of functional planning regions that address such flows as commuting patterns, economic relations, river basins, energy networks and others (Nadin and Fernández-Maldonado, 2023). To this end, it is important to assess the potential impact of all placed-based policies and geographic approaches to sectors that contribute to emissions of GHGs, such as transport, energy, agriculture and buildings. Whereas the principle of a place-based approach can support effective climate change mitigation and adaptation plans, functional urban areas may result in additional car-based mobility and land uptake, and should for this reason be treated with caution.

The EU cohesion policy also has a strong sustainable urban development dimension, which is strongly related to climate. For 2021–2027, the urban dimension of cohesion policy has been strengthened, with its policy objectives focusing on a smarter, greener, more connected and more social Europe and a Europe closer to citizens. A minimum of 8 % of the European Regional Development Fund resources in each Member State must be invested in priorities and projects selected by cities themselves and based on their own sustainable urban development strategies. In particular, the focus on a greener Europe refers to a resilient Europe transitioning from a low-carbon towards a net zero-carbon economy, promoting a clean and fair energy transition, green and blue investment, the circular economy, climate change mitigation and adaptation, risk prevention and management, and sustainable urban mobility.

The EU can further support sustainable spatial planning through sharing good practice, building the capacity of local and public authorities, and disseminating guidelines linked to, for example, the European Regional Development Fund and other cohesion policy programmes (ESPON, 2021), and the European Semester process could encourage Member States to improve their spatial planning. There are several EU funding streams addressing sustainable urban planning, such as Urbact IV (which is co-funded by EU cohesion policy funds and aims to enhance the institutional capacity of public authorities (URBACT, 2023) or the European Urban Initiative (EUI, 2023).

Enabling condition: prosumers and positive energy buildings and districts

Net zero transition requires energy system integration allowing buildings to actively participate in the energy system.

The IPCC highlighted the role of market and business models that encourage energy prosumers ([38]), fostering local energy generation and consumption and allowing buildings to actively participate in the energy system. With regard to energy system integration (see Chapter 4 'Energy supply'), new services (e.g. aggregated load management for demand response, peer-to-peer exchanges, energy services companies) will need to complement and to some extent replace the traditional supply of energy services. In this respect energy communities play an increasingly important role (IPCC, 2022b). New services and energy prosumers are encouraged by the falling costs of building-integrated renewables,

([38]) 'Prosumption exists in numerous types and forms: for example, it can be only one household, a group of tenants in a multi-family building or an energy cooperative with participants from the local community. They can produce renewable electricity, heat or both, and some combine this with supporting the grid infrastructure or providing energy storage. Prosumers can apply different ownership structures and business models, which may be run by volunteers or, in the case of larger projects, by paid staff' (EEA, 2022e).

heat pumps and storage technologies, to enable their wide-scale roll-out (D'Agostino et al., 2021; IPCC, 2022c, Ines et al, 2020).

Building-integrated renewable energy infrastructure makes it possible to generate electricity and heat and export them to local networks when they exceed on-site demands. The positive energy balance can be defined at the building or neighbourhood level and could be promoted in parallel with measures aiming to reduce the GHG emissions from building-related uses (EASAC, 2021a). Positive energy districts and compact neighbourhoods could be built on the basis of a 'wider vision of urban sustainability that foresees innovative solutions for street lighting, urban mobility, waste, and public safety' (D'Agostino et al., 2021a; Zakeri et al., 2022). Such integrated planning will further encourage prosumers, energy communities and other citizen-led contribution to climate neutrality.

Positive energy buildings require the roll-out and use of digital building automation and control systems (IPCC, 2022b) as well as smart grids for energy sharing. Notably, distribution networks (low and medium voltage) and business models need to be adjusted to enable the active participation of positive energy buildings. In addition, stationary electric battery storage can unlock unprecedented levels of demand management (see 'Lever: system integration' in Section 4.3).

EU policies, such as the REPowerEU plan and the renovation strategy, recognise the role of prosumers, energy communities and positive energy buildings in the net zero transition. The EU laws enabling individual and collective prosumers and positive energy buildings include the RED III, the EPBD and its recast, the EED and the EU's internal energy market framework. The total number of prosumers in the EU Member States and the EU is not known, because of monitoring gaps (EEA, 2022e). The fragmented available data suggests that number of prosumers is increasing rapidly in some EU Member States. Regarding prosumer-driven demand response, in 2022 only nine EU Member States had given aggregated residential end users access to the wholesale, balancing and ancillary electricity markets (ACER and CEER, 2022). Reasons include, among others, the inadequate national implementation of the EU laws and persisting market participation barriers (Campos et al., 2020; EASAC, 2021a; EC, 2023ag; Magrini et al., 2020; Moura and Brito, 2019; Reis et al., 2013). Given the slow pace of residential demand-side response (ACER and CEER, 2022), the RED III, the European Commission proposals for a Net-Zero Industry Act and reform of the electricity market's design, and the EU action plan on digitalisation of the energy system could accelerate infrastructure development, enabling prosumers, positive energy buildings and system integration. The newly established Energy Communities Repository (EC, 2023x) and the Rural Energy Communities Advisory Hub (EC, 2023bc) are very welcome in this context.

Enabling condition: quality and use of data

Reliable, granular and comparable data on building performance and the multiple benefits of energy efficiency investment are urgently needed to underpin policy measures.

Data availability and comparability are important for decarbonising the building stock, because data is relevant to several aspects of effective policies, including (i) evidence-based policy development and progress assessment, (ii) leveraged private investment in energy retrofits, (iii) energy system integration, new business models and infrastructure, and (iii) behavioural changes thanks to available information (EEFIG, 2023; IPCC, 2022b; Runge-Metzger and Van Ierland, 2019). Why data matters in EU building decarbonisation can be demonstrated by the EPCs, which can inform building owners and induce them to undertake energy renovation. According to Building Performance Institute Europe, 'there is an increasing reliance on EPC data for tracking the progress and the implementation of renovation policies and funding. Yet the uneven quality and reliability of national EPC schemes, coupled with the lack of public trust in the generic list of recommendations may hinder the goal of the EPC to encourage additional investments in energy efficiency' (BPIE, 2023).

The European Commission's assessment of the first long-term renovation strategies and the NECP progress reports concluded that the required data concerning decarbonisation of buildings provided by Member States varies in nature, which makes it difficult to compare the effect of the different national measures and assess their cumulative and quantitative impact. An additional complexity was detected in terms of some key indicators' definitions (EC, 2023, 2022, see also Section 4.3 under 'Lever: energy efficiency'). There is a consensus among practitioners, academia and policymakers that EU does not have sufficient and comparable information on the energy performance and other linked parameters of its building stock (EASAC, 2021; EC and EEFIG, 2023; JRC, 2021a).

EPC limitations in terms of reliability of data based on the physical properties of buildings has also been highlighted by the IPCC in the context of energy demand driven by occupancy behaviour (IPCC, 2022b). To further improve data relevant to occupancy and demand patterns, there is a need for a 'social science-based research to investigate how buildings with the same EPC differ statistically in terms of their measured consumption' (Ali et al., 2020). The task of filling this data gap can be helped by smart electricity meters that quantify the load patterns of electric appliances, for example by using disaggregation techniques (EASAC, 2021a).

Similarly, better data is needed to underpin the consideration of non-energy benefits, such as comfort, health and reduced energy poverty, in designing energy efficiency programmes so that they are adjusted to the customers' needs and therefore to stimulate demand for building renovation efforts (EC and EEFIG, 2022). According to the Energy Efficiency Financial Institutions Group convened by the European Commission (2022), identifying multiple benefits, collecting data on them and evaluating them strengthen the connection between energy efficiency investing and impact investing, as well as decision-making by financial institutions. Thus it can make investing in buildings' energy efficiency more attractive to private investors (see 'Enabling condition: private investment' below).

The EU policy measures driving the collection and use of this essential data include the EPBD, the Infrastructure for Spatial Information in Europe directive (EU, 2007), non-legislative initiatives such as the EU Building Stock Observatory and Odyssee-Mure database (ADEME et al., 2023), the renovation wave strategy (EC, 2020h) and the EU action plan on digitalisation of the energy system (EC, 2022k). Regarding spatial planning and urban land use efficiency, it is the EU Copernicus programme that provides an insight complementary to the building-level data (EEA, 2023e; Schiavina et al., 2022)

The EPBD recast strengthens the role of the EU Building Stock Observatory as the EU database for data related to building renovation, EPC and smart readiness indicators. Importantly, a step change in this respect could be driven by the EU action plan on digitalisation of the energy system (EC, 2022k), which recognises the need for seamless data exchanges 'supporting smart energy buildings as a source of renewable energy production and flexibility in the energy system, and making the data from buildings available to define business cases for renovation' (EC, 2022k). It includes putting in place a common European energy data space for improving access to, exchange of and reuse of data. These developments are still at early stage of delivery but have significant potential to contribute to decarbonising the building stock across the EU.

Enabling condition: private investment

EU policies need to better leverage private investment in the energy efficiency of buildings and avoid lock-in risks linked to shallow retrofits.

Decarbonising EU's building stock by 2050 requires the scaling-up of private investment to meet estimated additional investment needs of EUR 90 billion per year (EC, 2020h). Estimates by the JRC indicate that across the EU around EUR 15 billion per year are allocated to energy efficiency in buildings (JRC, 2019a). The energy efficiency investment gap is well documented in academic publications (see e.g.

Bertoldi et al., 2021) and reflected in several EU policy documents (see e.g. EC, 2020f). It points to the great heterogeneity of the buildings sector, which is subject to, among other challenges, split incentives, inadequate information about costs and benefits of energy retrofit investment, loss aversion, complex decision-making processes, long pay-back periods and high transaction costs that hamper private investment (Economidou et al., 2020; IPCC, 2022c, Perez Navarro et al, 2023). For those reasons, technical support is often the key enabler to attract private investment in the energy efficiency of buildings, as it helps to overcome the various organisational and other non-financial obstacles such as the split incentive dilemma and the need for investment aggregation.

Analysis of the recovery and resilience plans submitted by the EU Member States to the European Commission in 2022 shows that 'most of the spending on energy efficient renovations goes to schemes that have the objective to achieve, on average, a medium-depth level renovation, which amounts to at least 30 % primary energy saving' (EC, 2022f). In 2022 a flagship technical support to Member States was launched under the RRF regulation (EU, 2021a), with a focus on (i) renovation along thematic areas of the Renovation Wave, including energy poverty alleviation, public buildings and the wider renovation ecosystem; (ii) the implementation of planning tools, especially long-term renovation strategies and recovery plans; and (iii) the implementation of cohesion policy funding for building renovation.

The rather shallow depth of energy retrofits in the Member States' plans under the RRF appears to echo the technical screening criteria (TSC) for sustainable economic activities set out in the delegated act supplementing the Taxonomy Regulation (EU, 2020). The TSC for renovation of existing buildings require building renovation to comply with the applicable requirements for major renovations under the EPBD or to lead to a reduction of primary energy demand of at least 30 %. Such shallow energy retrofits may not be aligned with the EU's climate neutrality objective and may create dangerous lock-ins (see for example Schütze and Stede, 2021) unless they are part of a staged intervention, for instance under a building renovation passport leading to a deep retrofit while recognising the complexity of such investment (BPIE, 2017; Sesana et al., 2020; Villarejo et al., 2021). Voluntary building renovation passports will be introduced in the EPBD recast.

Regarding the new construction, acquisition and ownership of buildings, the criteria are somewhat more robust, as, for buildings constructed in 2022 and after, they go beyond the current EPBD requirements (EC, 2021b).

Several EU funding schemes aim to bridge the investment gap by supporting the retrofitting of buildings. Such support ranges from research and market uptake to large-scale retrofits as part of the EU cohesion policy. In the 2014–2020 programming period, the cost-effectiveness of the EU cohesion policy spending on energy efficiency in buildings (about EUR 14 billion over the period) was rather low because of inadequate targeting of investments through grants with low additionality, that is, crowding out private investment that would probably have happened anyway. Moreover, the monitoring system in place did not make it possible to measure energy savings triggered by the investment (ECA, 2020a). Both weaknesses – lack of additionality, and inadequate data about impact – perpetuate the challenge of attracting private finance to invest in the energy efficiency of buildings.

To make better use of public funds, some EU funding programmes (e.g. L'Instrument Financier pour l'Environnement (LIFE), Horizon, InvestEU) develop, test and scale up financing schemes and business models such as on-bill financing, one-stop shops and energy performance contracting, in line with the IPCC findings (IPCC, 2022c, Sequeira, & Gouveia, 2022, Pardalis et al, 2022). They also provide financial guarantees and project development assistance to energy efficiency investment at building portfolio

levels ([39]). These are promising efforts to leverage private investment through public funds, but they should go hand in hand with fiscal policy within the EU Member States, supported by the upcoming revision of the ETD (EC, 2021y) and the State aid guidelines to discourage further use of fossil gas as a heating source for buildings (see also Sections 10.5 and 12.3).

([39]) For instance, the European Local Energy Assistance programme created under Horizon 2020 and implemented by the EIB leverages private investment in the energy efficiency of buildings (EIB, 2023a). The EIB is also crowding in private finance to sustainable infrastructure for buildings by providing financial guarantees under the InvestEU programme. The overall InvestEU Fund budget guarantee of EUR 26.2 billion is expected to trigger EUR 372 billion of public and private investment in all sectors between 2021 and 2027 (EU, 2023h).

7.6 Summary tables

Table 10 Progress summary - buildings

Indicator	Reference period	Historical progress	Required up to 2030	Required in 2031–2050
B1: GHG emissions	2005–2022	– 11 Mt CO_2e/yr	– 29 Mt CO_2e/yr	– 11 Mt CO_2e/yr
B2: final energy use				
B2a: residential	2017–2021	+ 29 TWh/yr	– 98 to – 113 TWh/yr	– 35 to – 42 TWh/yr
B2b: tertiary	2017–2021	+ 23 TWh/yr	– 36 to – 47 TWh/yr	– 15 to – 21 TWh/yr
B3: Type 1 renovation rate				
B3a: residential buildings	2016-2020	+ 1 %/yr	+ 2.1 %/yr	*No benchmark*
B3b: tertiary buildings	2016-2020	+ 0.6 %/yr	+ 1.1 %/yr	*No benchmark*
B4: built surface				
B4a: residential surface area	2012–2016	+ 128 km^2/yr	*No benchmark*	*No benchmark*
B4b: tertiary surface area	2015–2019	+ 23 km^2/yr	*No benchmark*	*No benchmark*
B5: fuel mix				
T5a: % of fossils in residential final energy consumption	2017–2021	– 0.6 pp/yr	– 2.4 pp/yr	– 1.1 pp/yr
T5b: % of fossils in tertiary final energy consumption	2017–2021	– 0.1 pp/yr	– 1.9 pp/yr	– 1.0 pp/yr
B6: heat pumps (total stock)	2018–2022	+ 2 million/yr	+ 2.7 million/yr	*No benchmark*

Legend

On track	The required change ([a]) is ≤ 1.
Almost on track	The required change ([a]) is between 1 and 1.5.
Somewhat off track	The required change ([a]) is between 1.5 and 2.
Considerably off track	The required change ([a]) is ≥ 2.
Wrong direction	The required change ([a]) is < 0.

([a]) See Section 2.2 for more details on how the required change is calculated.

Table 11 Policy consistency summary - buildings

Policy inconsistencies	– Subsidies to fossil gas persist as they are allowed under the Energy Taxation Directive and EU state aid rules
Policy gaps	– In terms of heating and cooling decarbonisation, lack of system integration and insufficiently robust EU standards have led to incremental energy efficiency improvements and lock-in effects. – The EPBD recast aiming to tackle buildings' embodied carbon and energy, which could encourage better use of the existing buildings rather than new construction, has not yet been adopted. – EU policies have not sufficiently facilitated collection and sharing of reliable, granular, comparable and interoperable information on the energy performance, energy efficiency investment and multiple benefits of efficient building stock, such as indoor air quality.
Ambition gaps	– The revised EED and the EPBD before recast do not explicitly aim to leverage sufficiency. – The EU does not prominently guide urban and spatial planning and taxation towards energy and material sufficiency. – The EPC schemes are of uneven quality and have limitations in terms of reliability, as they are based on data derived from the physical properties of buildings rather than energy demand driven by occupancy behaviour.
Implementation gaps	– EU policies so far have not overcome barriers to wide-scale and deep energy retrofits of buildings. – The quality and ambition of the EU's long-term renovation strategies are insufficient to guide the required building renovation towards the 2050 climate neutrality objective.

8 Agriculture

This chapter covers non-CO_2 greenhouse emissions associated with the production of crops and livestock, and the relationship of these emissions with the food system. Some aspects of agriculture are dealt with in Chapters 9 and 10. Chapter 9 'Land use, land use change and forestry' covers emissions, removals and storage of GHGs on land, including in forests and agricultural soils. Chapter 10 'Pricing emissions and rewarding removals' contains a dedicated section discussing how emissions and removals from agriculture and land use can be incorporated into an emission-pricing regime.

Key messages

Emissions from agriculture have remained largely unchanged since 2005, and reductions are needed to align with the EU's climate objectives.

Today, non-CO_2 emissions from agriculture account for 11 % of the EU's total net GHG emissions ([40]). They have remained largely unchanged since 2005. Although the sector is regarded as having lower mitigation potential than other parts of the economy, emission reductions can be achieved and are identified in pathways consistent with EU and global climate goals. EU-level pathways examined by the European Commission and by the Advisory Board suggest that a reduction of around 30 % below 2005 levels by 2050 could be achieved largely through supply-side measures identified in the literature, and around 60 % in the most ambitious pathways featuring additional demand-side action.

Figure 54 Indicator A1 – overall progress in reduction of agricultural non-CO_2 emissions

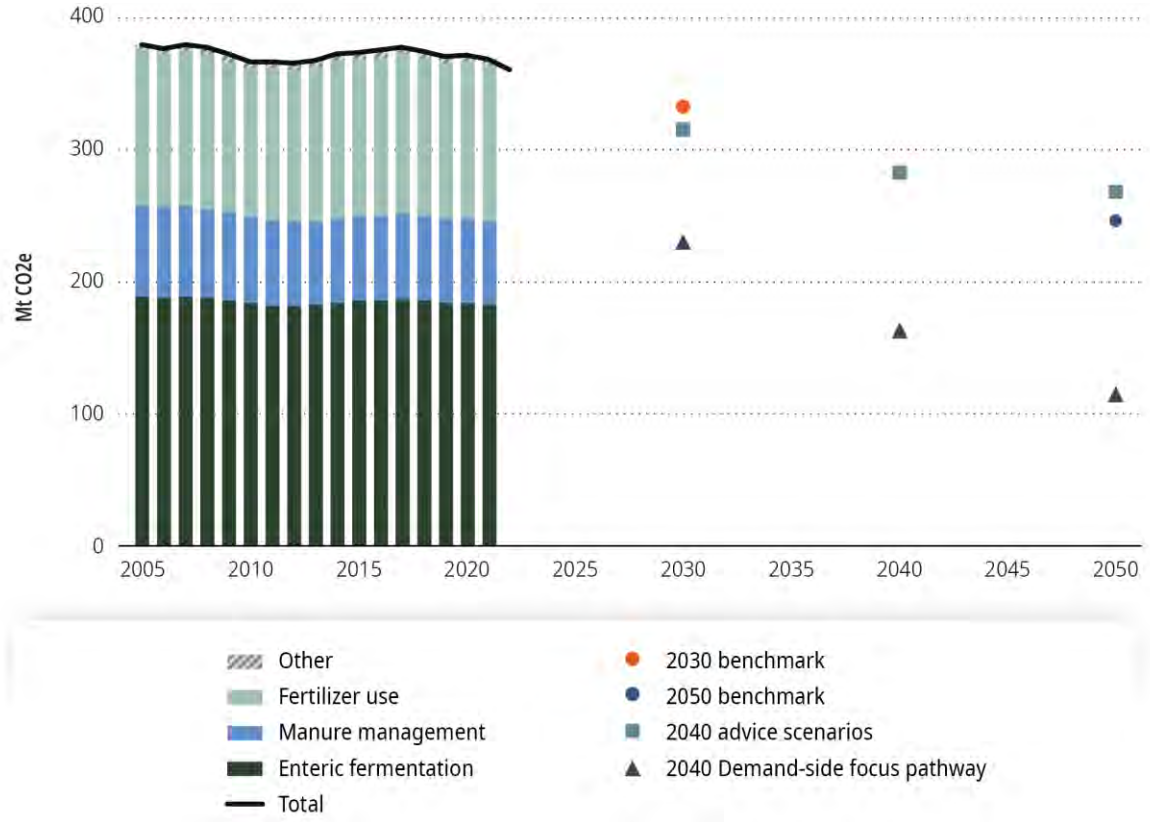

Source and Notes: See Figure 56 for detailed sources and notes.

([40]) This excludes emissions from energy use in agriculture, which are covered in other chapters. CO_2 emissions from agriculture (apart from its energy use) are minor (2–3 % of the sector's GHG emissions).

Ambitious climate targets, and the policies and incentives for achieving them, should be at the heart of the EU's CAP.

Needs. GHG emissions from agriculture need to be reduced to a level consistent with the EU's climate neutrality objective. The EU and Member States therefore need to adopt and implement policies and incentives consistent with this level of ambition.

Gaps. Within the CAP, the aim of contributing to climate change mitigation is largely qualitative and forms part of a broader set of agri-environmental objectives (also covering adaptation, soil and biodiversity preservation, and animal welfare) **(ambition gap)**. The CAP's climate and environment aims are pursued by Member States in their CAP Strategic Plans (CSPs), where the emphasis given to climate change mitigation is largely discretionary and difficult to quantify *ex ante* **(ambition gap)**. Although the 2023–2027 CAP includes some mandatory good practices (conditionality), the CAP still provides direct support to emission-intensive agricultural practices such as livestock production rather than focusing financial support on the transition to less emission-intensive activities **(policy inconsistency)**. Emissions from agriculture are also not covered by a GHG emission-pricing regime **(policy gap)**.

Recommendation A1. The CAP should be reformed to include standalone emission reduction objectives in addition to obligations to pursue other environmental and sustainability objectives.

— The CAP should move towards mandatory good practices with greater clarity about their mitigation outcomes. Land management rules (both statutory management requirements and conditionality under the CAP) and criteria for eco-schemes should be strengthened and defined more concretely to ensure that they are more closely related to positive environmental outcomes and that their mitigation impact can be estimated quantitatively.
— The EU should shift CAP support away from emission-intensive agricultural practices, including livestock production, and towards lower-emitting products, environmental services and economic diversification (see Chapter 11 'Whole-of-society approach'). In parallel, the EU should strengthen measures to encourage healthier, more plant-based diets, and develop a framework for just transition to an agricultural sector consistent with the climate neutrality objective.

Recommendation A2. A system for estimating and pricing agricultural emissions targeting the source should be introduced, complemented by policies that seek to ensure that more sustainable, healthier food choices are available to consumers at all income levels. This could be activity-based (rewarding specific activities) or results-based (such as a cap-and-trade system based on verified emission estimates). Their socioeconomic impact of emissions pricing – in particular on small farms and farms in vulnerable regions – should be assessed *ex ante,* and potentially adverse economic, social and environmental impacts should be addressed to ensure a just and fair transition. See also next recommendation, on sustainable food systems, and Chapter 10 'Pricing emissions and rewarding removals'.

EU policies on agriculture and biofuels should also better reflect the need to maintain and expand the area of forests and wetlands for carbon sequestration purposes (see Chapter 9 'Land use, land use change and forestry').

The Farm to Fork Strategy should be translated into concrete policies for delivering a sustainable food system, reducing food waste and encouraging healthy, plant-based diets.

Needs. From a strictly climate mitigation perspective, reductions in the production and consumption of GHG-intensive agricultural products (especially livestock products) need to go hand in hand, otherwise emission reduction efforts risk being offset by increased imports (displacing emissions to other countries) or exports (maintaining EU emissions in spite of consumption changes).

From a broader perspective, there is a need to shift towards healthier diets, reducing the over-consumption of animal products and increasing the consumption of plant products, since these are associated with lower emissions. Ensuring sustainable production and consumption of food – as well as reduced food waste – also requires further action in the middle part of the agri-food value chain (food processing, distribution and retail companies), given its influence on food product availability, accessibility and affordability, marketing strategies and information provision.

Gaps. The overarching framework for climate action in the food system is the Farm to Fork Strategy, published in 2020. At the time of writing, however, the European Commission has not made a proposal on some of its key initiatives (such as the legislative framework for a sustainable food system, and rules on labelling and sustainable public procurement of food). In other cases, proposed legislation has not yet been adopted by policymakers (such as targets on food waste reduction) **(policy gap)**. The Farm to Fork Strategy has been criticised for lacking quantified objectives (and delivery mechanisms for achieving the objectives that it has) and for its reliance on monitoring and labelling requirements and information provision measures. This represents an **ambition gap** (and a **policy gap**, since, at the time of writing, the European Commission has not yet released its proposal on some of the topics announced in the strategy). Other **ambition gaps** identified in food system governance include the expected low impact of the EU Code of Conduct on Responsible Food Business and Marketing Practices, the food waste reduction targets of the Waste Framework Directive revision proposal (which falls short of the 50 % reduction target of the Farm to Fork Strategy) and the revised Industrial Emissions Directive, which postpones stronger controls on emissions from intensive livestock production to 2030 at the earliest.

Recommendation A3. Policies should encourage and incentivise the sale and marketing of, and access to, healthier, more plant-based foods, the reduction of food waste and a sustainable food culture.

- In the middle of the food chain, EU-level food policy should go beyond voluntary codes of conduct and explore binding regulations and incentives to improve the sector's climate performance (for example on food waste) and empower consumers to make more sustainable choices (for example through regulation of labelling and marketing).
- Additional policies should be considered to encourage and improve access to more sustainable, healthier diets, paying particular attention to the influence of the social environment on food choices. Action on sustainable public procurement of food is an example of this. Other opportunities should be identified.

Needs. Reducing agricultural emissions implies shifting away from bioenergy for uses that can be decarbonised by other means (see Chapter 6 'Transport').

Gaps. Continued promotion of first-generation biofuels in EU energy policy also represents a **policy inconsistency** in applications where electrification offers a lower-emitting route to decarbonisation.

Recommendation A4. Future revision of EU energy policies should limit support for biofuels to areas that cannot reasonably be decarbonised by other means.

8.1 Scope and sectoral assessment framework

Scope

This chapter covers all non-energy related emissions from agriculture as reported under the UNFCCC (CRF category 3), primarily CH_4 and N_2O emissions from livestock and N_2O emissions from fertiliser use ([41]).

- Energy-related emissions in the agricultural sector are included in the buildings (space heating), transport (rolling equipment) and industry (food processing) sectors respectively.
- CO_2 emissions and emission removals from agricultural soils and forestry are included in the LULUCF sector.

Greenhouse gas emission reductions required in the agricultural sector to reach climate neutrality

Today, non-CO_2 emissions from agriculture account for 11 % of net EU GHG emissions. There is an overall scientific consensus that the cost-effective mitigation potential in agricultural non-CO_2 emissions is limited compared to the reduction potential of energy-related CO_2 in other sectors, if production and consumption patterns remain unchanged (Fellmann et al., 2021), but also that emission reductions from this sector are an important element of achieving both global and EU climate goals (JRC, 2023c; IPCC, 2022a; Leahy et al., 2020).

Although the European Green Deal does not specify the extent of climate mitigation expected from the agricultural sector, the sector's non-CO_2 emissions are reduced by 30–45 % below 2005 levels by 2050 in scenarios underpinning the European Commission's analysis (EC, 2018e, 2020s). Scenarios assessed in the Advisory Board's recent report on a GHG target for 2040 suggest that a 23–57 % reduction could be achieved by 2040, depending on the extent of demand-side action, including a shift to sustainable, healthy diets ([42]).

The European Commission's scenarios see agricultural emissions remaining essentially flat up to 2030 (– 3 % compared to 2022), JRC analysis has identified supply-side options equivalent to a 20 % reduction ([43]) (Pérez Dominguez et al., 2020) and the Advisory Board's 2040 analysis suggests a reduction of at least 10 % below the 2022 level could be achieved by 2030.

Climate change impacts might undermine the capacity of the agricultural sector to deliver on all these different objectives, and therefore the sector will also have to enhance its resilience against these impacts.

Assessment framework for the agriculture sector

Outcomes. Achieving the mitigation contribution described above requires some combination of the following two outcomes.

- **Reduced production and demand for GHG-intensive agricultural products.** Reducing production of the most GHG-intensive products will lower EU GHG emissions, while lower

([41]) In CRF category 3 (which excludes energy-related emissions in agriculture), CO_2 emissions typically account for 2–3 % of total GHG emissions.

([42]) This refers to emission reductions compared to 2015 at 'R10' geographical wider Europe ('R10') geographical resolution (all of Europe). The range encompasses the pathways underpinning the Advisory Board's 90-95% recommendation (23%-26%) as well as the reductions achievable in Demand-side focus pathway which has a greater focus on healthy & sustainable diets (-57%)

([43]) Figures 17 and 21 of Pérez Dominguez et al. (2020) identify approximately 75 Mt CO_2e of mitigation at the EU-27 level though measures such as feed additives, anaerobic digestion, winter cover crops and fallowing histosols.

consumption will reduce the market for them (as well as bringing health benefits in general). The two must go hand in hand to ensure that climate policy objectives are not counteracted by international trade. The issue of emission leakage (the movement of activity and emissions to locations with laxer climate regulation) is discussed in Chapter 10 'Pricing emissions and rewarding removals'.

— **Lower GHG-intensity of agricultural production in the EU.** This would deliver additional emission reductions.

Levers. To achieve these outcomes, five main levers were identified based on the agriculture, forestry and other land use chapter of IPCC AR6 (contribution of Working Group III) (IPCC, 2022a) ([44]).

— **Low-emission livestock production.** CH_4 emissions can be reduced by measures to reduce emissions from enteric fermentation (the digestion process of ruminant livestock such as cattle) and by improved manure management.
— **Low-emission crop production.** This would reduce N_2O emissions from fertiliser use (and CH_4 emissions from rice cultivation).
— **Reduced livestock production** and **sustainable and healthy diets.** These would reduce EU GHG emissions both directly (reduced livestock emissions) and indirectly (reduced demand and production of feed crops), provided that reduced meat and dairy demand and reduced livestock production happen simultaneously in the EU.
— **Reduced food waste.** This would also reduce EU emissions provided that reduced demand leads to reduced domestic production.
— **Minimise demand for biofuel crops.** According to the IPCC, it is not possible to precisely determine the scale of bioenergy (and BECCS) deployment at which negative impacts outweigh benefits, given the multiple interactions with food, land and energy systems. Minimising demand for biofuel crops is therefore included since this determines overall demand for (and therefore production of) agricultural crop production.

Enablers. In addition, eight enablers were identified that would facilitate the five levers described above.

— **Price signals and incentives** can support all the abovementioned levers, both on the demand side and on the supply side.
— **Information provision and education** can help consumers to reduce food waste and make informed food choices, which can contribute to more sustainable and healthy diets. However, they are insufficient on their own and need to be combined with other, more stringent types of policies.
— Cultural and social values might hinder the adoption of more sustainable diets and or more GHG-efficient agricultural practices. Therefore, it is necessary to promote **supportive social and cultural values** to enable the transition, for example by highlighting the various co-benefits (such as the health benefits of more sustainable diets), by working with the social context in which food is produced and consumed.
— Adequate access to **finance** combined with GHG-pricing incentives can enable an acceleration of the uptake of sustainable agricultural practices. While some mitigation measures in the agricultural sector relate to changes in management practices and can be implemented without large

([44]) Relevant topic headings in the IPCC chapter's agriculture and food sections (7.4.3–7.4.5) include the phrases 'soil carbon management', 'enteric fermentation', 'crop nutrient management', 'manure management', 'bioenergy and BECCS', 'sustainable healthy diets' and 'reduce food loss and waste'.

investments ([45]), others require considerable upfront investments. Rates of adopting these measures could be slow without available finance, even if price signals are implemented.

— European farmers, farm advisory agents and other professionals providing services to farmers (e.g. vets, or feed and fertiliser suppliers) need to be equipped with the required **skills and know-how** to implement different mitigation practices in an effective and efficient way, and need to be supported by industries.
— Some options for reducing GHG emissions require additional RD & D and **innovation**, especially in order to become affordable and deployable at scale. The IPCC gives several examples including ongoing innovations in crop breeding (e.g. through gene-editing technologies), feed additives and genomic selection to reduce enteric CH_4 in livestock, and further developments in precision agriculture (the use of sensors and satellites to improve crop yields, animal production and manage inputs more effectively) and remote sensing (IPCC, 2022a).
— The **regulatory framework on food and feed safety** needs to be aligned with the ambitions to reduce food losses and food waste and to enable novel, low-GHG-emission food and feed types (e.g. insect-based protein) to enter the market, without compromising public health or animal welfare.
— Overall, improved **yields** using the same amount of resources or less at the farm level can reduce overall GHG emissions, but only if they do not lead to higher aggregate production.

The assessment framework for the agriculture sector – including the selected indicators to track progress for this sector (see white boxes) – is shown in Figure 55.

Aside from the mitigation measures summarised in Figure 55, there are a number of climate action and broader environmental measures whose impact on overall GHG emissions is less certain. Organic farming has the potential to reduce emissions directly per unit land due to higher soil carbon sequestration (counted under LULUCF) and lower N_2O emissions from fertiliser use. However, it also leads to lower productivity, which could lead to additional land used for agricultural production if demand remains unchanged (EEA, 2022h; EC, Joint Research Centre et al., 2021; Skinner et al., 2014; Tuomisto et al., 2012). Similarly, evidence about shorter value chains is mixed, and could lead to both decreases and increases in emissions depending on specific circumstances (EEA, 2022h).

([45]) For example, the European Commission Target Plan (Figure 71) estimated that 12 Mt CO_2e of agricultural non-CO_2 emissions could be abated at a cost of up to EUR 5/t, while a further 35 Mt CO_2e could be abated at a cost of up to EUR 100/t (EC, 2020s). More detailed abatement cost curves for European agriculture are estimated by the JRC (JRC, 2020b).

Figure 55 Assessment framework for the agricultural sector

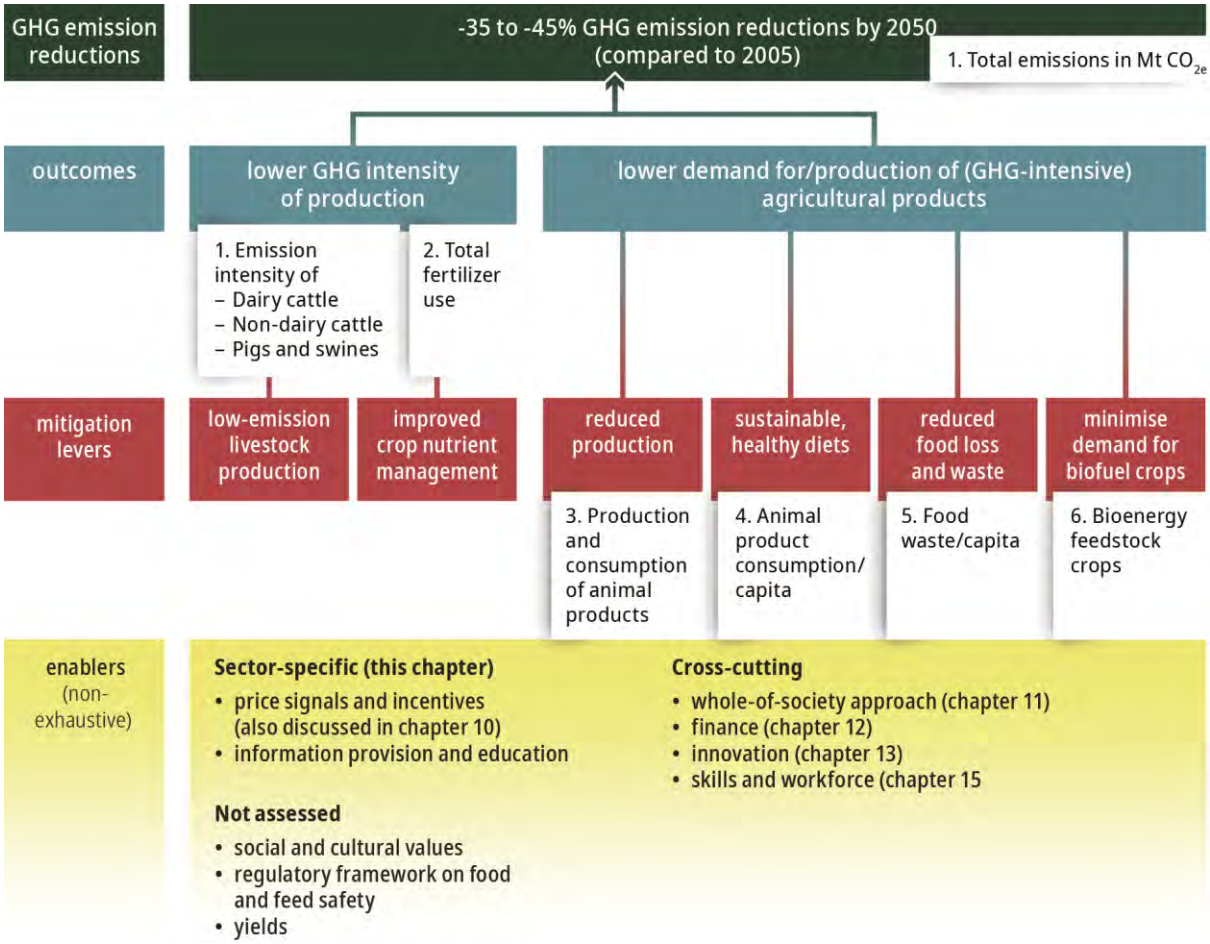

Source: Advisory Board (2024)

8.2 Emission reduction progress

In the 1990s, agricultural non-CO_2 emissions in current EU Member States were considerably higher than today's levels (average 420 Mt CO_2e per year). However, the EU has not achieved consistent annual reductions in agricultural emissions since 2005 (see Figure 56).

Emissions decreased slightly in 2007–2012 but rebounded again until 2017 before starting a new but modest downward trend. By 2022, emissions were 5 % below 2005 levels. In 2005–2022, emissions reduced by on average 1 Mt CO_2e per year. This rate would need to accelerate to on average 3.5 Mt CO_2e per year to put the sector on track towards reaching modest reductions by 2030 that are in line with the European Commission's reduction scenarios. After that, the average pace of emission reductions would need to accelerate further (to 4 Mt CO_2e per year) to reach the 35 % emission reductions (compared with 2005) presented in the European Commission's scenarios underpinning the EU climate objectives.

Scenarios underpinning the 90–95 % recommendation of the Advisory Board reduce emissions more quickly, by 17 % in 2030 and 26 % in 2040 compared with 2005 levels. Greater emission reductions than this (63 % below 2005 levels by 2050) are achieved in the demand-side focus pathway assessed by the Advisory Board, which has a particular focus on healthy and sustainable diets in line with the recommendations of the EAT-Lancet European Commission (Willett et al., 2019).

Direct livestock emissions (excluding emissions related to feed production) account for two thirds of agricultural non-CO_2 emissions, which consist mainly of enteric CH_4 emissions (50 % of total) and CH_4 and N_2O emissions from animal manure (17 % of total) (EEA, 2023f). The other third of total agricultural emissions are N_2O emissions related to fertiliser use on crop- and grasslands, a substantial proportion of which is also related to feeding livestock ([46]). These shares remained relatively stable throughout 2005–2021.

Figure 56 Indicator A1 – overall progress in reduction of agricultural non-CO_2 emissions

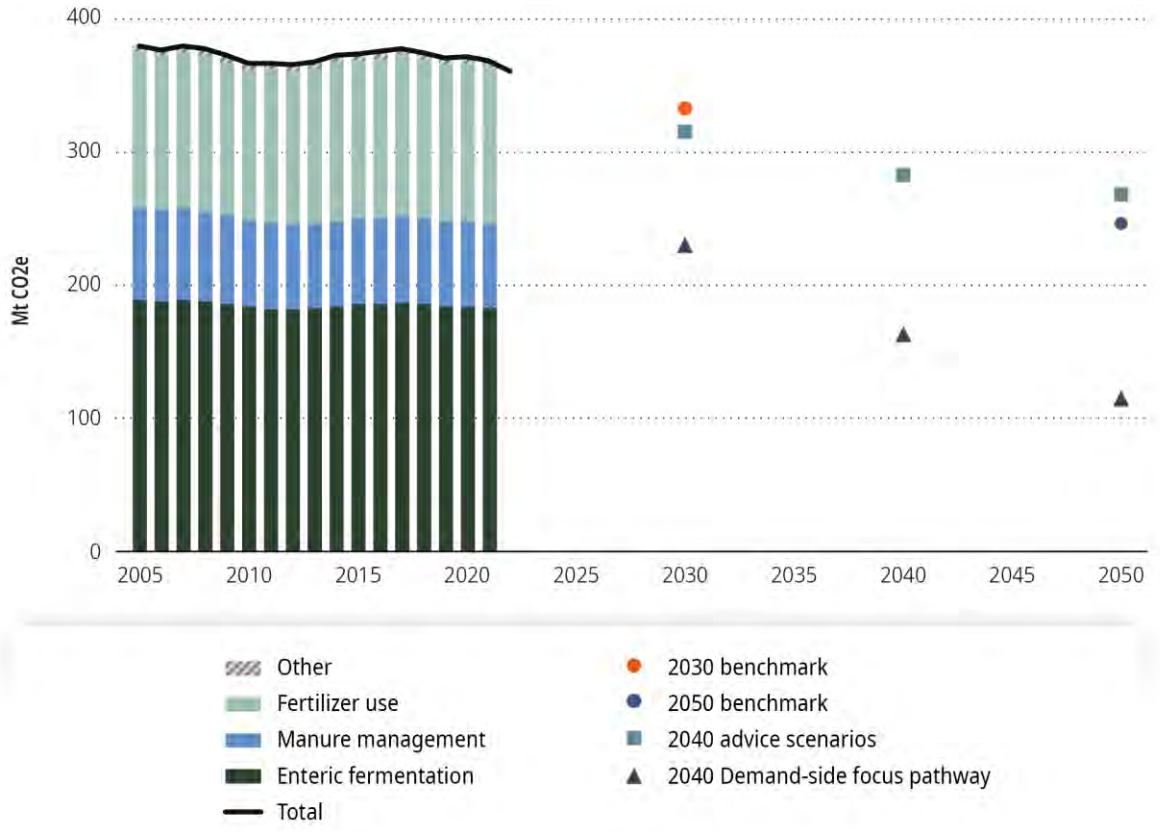

Notes: Historic emissions to 2021 from the EU GHG inventory, with 2022 data based on proxy data reported to the EEA. 2030 benchmark based on the MIX scenario underpinning the Fit for 55 package, with 2050 benchmark based on the MIX scenario from the Climate Target Plan impact assessment. 2040 advice refers to average agricultural non-CO_2 emissions in the scenarios which underpin the Advisory Board's 2040 advice. Data for demand-side focus pathway is downscaled from wider Europe (R10 region) resolution to EU27 for comparability. The Advisory Board's 2040 advice describes the demand-side focus pathway in greater detail.

Sources: EU GHG inventory (EEA, 2023f), Fit for 55 MIX scenario (EC, 2021v), Climate Target Plan impact assessment (EC, 2020s) (Figure 19), Advisory Board's 2040 advice (ESABCC, 2023b).

([46]) For example, Guyomard et al. (2021) state that more than 60 % of the EU's agricultural area is used for feeding animals.

8.3 EU food and agriculture policies, and movement towards a whole-system perspective

EU policies affect agricultural emissions mainly through the CAP and the more recent farm to fork Strategy. This section examines each of these and considers the extent to which EU policies constitute a consistent approach to reducing GHG emissions within a broader context of environmental, social and sustainability goals.

Common agricultural policy

The CAP primarily supports food production, incomes and environmental outcomes.

The CAP is the EU's overall agricultural policy. It was established in 1962 and revised most recently in 2021 (covering 2023–2027) (EC, 2023e). Its founding objectives include increasing agricultural productivity, and ensuring fair incomes for the agricultural community and affordable food for consumers (EU, 2016). These objectives are still central to the CAP today, but the scope has gradually broadened to include environmental concerns, and the design of financial support has changed accordingly. It currently represents 35 % of the total EU budget, making it the largest budget item (EEA, 2022h).

The CAP for 2023–2027 requires Member States to set targets, including on climate action, under a new pledge-and-review system.

The CAP regulation for 2023–2027 (EU, 2021d) establishes a pledge-and-review process (often referred to as a performance- and results-based approach) whereby each Member State produces a CSP, sets targets and reports progress (with regular reviews by the European Commission). The regulation also establishes a series of objectives and indicators that Member States are to use, including on climate change mitigation and adaptation. The climate indicators include targeting and monitoring the share of land covered by measures to reduce emissions, store carbon or adapt to climate change, and investments in renewable energy capacity (measured in megawatts). Member States use these indicators to set their own targets and milestones, and must aim to make a 'greater overall contribution' to the achievement of environment and climate objectives than in 2014–2020 (Article 105 of EU (2021d)).

Implementation of the CSPs is subject to an annual review meeting and biennial performance review by the European Commission. If the review reveals a significant shortfall with respect to its milestones or targets, the European Commission may ask it to submit an action plan detailing remedial actions.

The majority of the CAP budget is not dedicated to climate change mitigation per se.

For 2023–2027, the majority of the CAP budget (75 % of pillar I and 65 % of pillar II) will continue to be spent on agricultural activities that do not per se contribute to climate mitigation, although there is some mainstreaming of climate action into the CAP via environmental **conditionality** requirements. These are largely based on the greening criteria of the 2013–2020 CAP but are now mandatory for all beneficiaries of CAP support. They include climate-relevant criteria such as requirements to maintain or protect grassland, wetland, peatland and soil cover.

Reviews such as those by the EEA (2022h) and Pe'er et al. (2022) argue that the CAP, overall, continues to consolidate rather than phase out conventional GHG-intensive farming practices. Even with a switch to area-based payments as the dominant approach (rather than direct payments, which subsidise production volume), the tendency in the EU is to use intensive farming methods to maximise income. The CAP therefore continues to indirectly provide considerable subsidies to food production practices that can result in high GHG emissions. In addition, the revised CAP will continue to subsidise the livestock

sector, including through coupled support ([47]), which is a direct subsidy for GHG-intensive food products and undermines the goal of having food products reflect their true costs.

Dedicated green spending accounts for a growing proportion of the budget.

Although it does not account for the majority of spending, the green share of the CAP has increased over time. During 2014–2020, over a quarter of the CAP budget was assigned to climate change mitigation and adaptation, and consequently representing half of the EU's total climate spending (ECA, 2021). For 2023–2027, 40 % of the CAP budget is 'expected' to contribute to the achievement of climate-related objectives (recital 94 of EU (2021d)). The climate share of the budget will be tracked by the European Commission, with progress towards the indicative 40 % climate-mainstreaming target encouraged through annual review meetings and biennial performance reviews between the European Commission and Member States (EC, 2022g; EU, 2021d).

The CAP's 'green architecture' consists of mandatory environmental criteria and voluntary incentives.

Measures under the CAP that promote climate action and environmental protection are referred to as its green architecture. According to Guyomard et al. (2023), this consists of three main elements.

— Conditionality requirements are mandatory for all CAP beneficiaries.
— Eco-schemes and agri-environment climate measures are additional support that farmers can receive in exchange for implementing additional sustainability practices. Eco-schemes must represent at least 25 % of pillar I budget allocations (direct income support) over 2023–2027, and agri-environment climate measures must represent at least 35 % of pillar II (rural development funding).

There are considerable concerns regarding the likelihood that the green architecture will deliver additional climate action.

Although the CAP's green architecture provides significant opportunities for Member States to address both climate and biodiversity challenges, its delivery mechanism is primarily based on voluntary efforts. Independent assessments indicate that these are unlikely to be effective for the reasons given below.

The conditionality requirements consist mainly of broadly defined principles, which allow a high degree of flexibility for Member States, including broad exemptions (Guyomard et al., 2023; Matthews, 2021; Pe'er et al., 2022). Furthermore, ensuring compliance with these requirements, in terms of both monitoring and enforcement, remains a weak point (Pe'er et al., 2019). Guyomard et al. (2023) argue that the ambition of these measures cannot be truly appreciated without knowing about the implementation choices made by Member States. For example, Ecorys et al. (2023) point out that it is difficult to estimate the carbon sequestration effect of the requirement to maintain permanent grassland, since the definition of this term varies between Member States.

Similarly, the possible eco-schemes are defined in general terms in EU legislation, leaving their elaboration up to Member States. As a result, they risk funding (or continuing to fund) measures with very limited added value from an environmental perspective, which would de facto make them additional income support mechanisms under the guise of being environmental schemes (Matthews, 2021; Pe'er et al., 2022). Scientists have therefore made specific recommendations about developing eco-schemes, including avoiding support for practices that can be harmful to one of the environmental objectives of

([47]) 'Coupled support' refers to support payments to farmers that are linked to the level of production.

the CAP, and focusing the bulk of the budget on measures with high added (environmental) value on multiple dimensions (climate, biodiversity, etc.) (Pe'er et al., 2022).

The governance of the CAP allows Member States a great deal of flexibility. This arrangement provides opportunities for Member States to take climate action, but little incentive to be ambitious. An approach incorporating national flexibility can be advantageous, given the heterogeneous character of the agricultural sector and national geographies, but only if that flexibility does not come at the expense of ambition. The new CAP regulation requires Member States to set targets to achieve its specific objectives (which include climate action) but does not specify the ambition level of these targets (other than the requirement that they be more ambitious than in the past). Therefore, Member States arguably have an incentive to keep their ambition levels low in order to avoid having to justify themselves and develop potential remedial action during their performance reviews with the European Commission (Matthews, 2021).

Furthermore, although the European Commission can make recommendations on the CSPs, Member States are not obliged to adhere to them as long as they are in compliance with the broadly defined legal requirements of the CAP. Finally, national CAP budgets are pre-allocated under the MFF, regardless of the ambition levels of their CSPs, which leaves the European Commission with neither carrot nor stick to enhance their environmental ambition levels (Matthews, 2021).

It is also likely that many national administrations will lack the capacity and know-how to develop and implement ambitious CSPs, despite the technical assistance offered by the European Commission (Matthews, 2021; Pe'er et al., 2022).

This lack of incentive is confounded by a lack of quantified objectives that need to be met (as also evidenced by the lack of benchmarks that could be found for this report), and the few quantified objectives put forward by the Farm to Fork Strategy have yet to be endorsed either legally or politically. This means that the European Commission cannot refer to such targets as an argument for more ambition.

As a result, the impact of the new CAP on climate change mitigation is difficult to assess quantitatively, as the European Commission acknowledges in its summary assessment of the final CSPs submitted in 2022 (covering 2023–2027) (EC, 2023bf). In general, this assessment and the detailed mapping analysis underpinning it (Ecorys et al., 2023) are able to identify efforts that should contribute to mitigation, but are not able to estimate outcomes in terms of reduced emissions. For example, they identify efforts to support agroforestry and improve nutrient management, which should increase carbon sequestration or reduce N_2O emissions. Livestock emissions are identified as a priority area in 20 CSPs, but only 12 include a target, leading to an EU average of only 9 % of livestock units being covered by commitments to reduce GHG emissions or ammonia. The ability of the European Commission to reach these kinds of conclusions is in part due to the national recommendations formulated as part of the Farm to Fork Strategy including a request to set 'national reference values' for Green Deal targets such as reducing pesticide use and nutrient loss (Annex I of EC (2020r)). The summary assessment also acknowledges that further work is needed to support quantification of the CSPs' impacts and suggests that this is ongoing as Member States prepare to implement amended CSPs ([48]).

([48]) The European Commission's summary assessment (published 23 November 2023) covers the CSPs submitted and approved up to the end of 2022. However, Member States are required to assess (and potentially amend) their CSPs in light of the ESR and the LULUCF regulation. The summary assessment indicates that 18 amendments had been submitted, and 9 had been adopted by the European Commission, as of 4 October 2023.

Farm to Fork Strategy

The Farm to Fork Strategy is the European Green Deal's overarching strategy for pursuing a sustainable food system (EC, 2020f). Its main aims are to 'reduce the environmental and climate footprint of the EU food system and strengthen its resilience, ensure food security in the face of climate change and biodiversity loss, and lead a global transition towards competitive sustainability from farm to fork and tapping into new opportunities' (EC (2020f), p. 4).

The lack of an overarching strategy for the EU agri-food system had been identified by the scientific community as a major gap in the EU policy mix (EC, Group of Chief Scientific Advisors, 2020; SAPEA, 2020). The scientific community has generally welcomed the Farm to Fork Strategy as an important step in the right direction, while pointing out several shortcomings (EEA, 2022h; König and Araújo-Soares, 2021; Moschitz et al., 2021; Schebesta and Candel, 2020).

The strategy includes six environmental targets, of which the most relevant to lowering GHG emissions from the EU agricultural sector are reducing fertiliser use by 20 % and increasing the share of organic farming to 25 %, both by 2030 (EC, 2020f). As noted earlier in this chapter, while organic farming has the potential to reduce emissions directly per unit of land, it can increase overall land use (and therefore emissions) on account of lower productivity.

The Farm to Fork Strategy also announced 27 initiatives – both legislative and non-legislative – to deliver on its objectives, with mixed results so far in terms of ambition and delivery.

These aims, targets and initiatives reflect previous criticisms concerning the lack of clear and quantified environmental objectives under the CAP (Matthews, 2021). The Farm to Fork Strategy does not have a single delivery mechanism to achieve its objectives. Instead, the European Commission's approach has been to enhance food- and sustainability-related aspects of other initiatives. Some new legislation has been adopted (on the Farm Sustainability Data Network). Some legislation has been proposed by the European Commission but not yet adopted by the Parliament and Council (food waste reduction, corporate governance framework). The European Commission has also taken some non-legislative action (CAP recommendations, a voluntary code of conduct on responsible food business and marketing). However, the European Commission has not yet delivered several proposals announced in the Farm to Fork Strategy, including on sustainable food systems, public procurement, food labelling and regulation of feed additives. The list below details progress on the initiatives most relevant to climate change mitigation.

— The legislative framework for sustainable food systems was due to appear before the end of 2023 but has not been published at time of writing. Its stated aim is to promote policy coherence at the EU and national levels, mainstream sustainability in all food-related policies and strengthen the resilience of food systems. However, although the inception impact assessment recognises many of the challenges and bottlenecks – including the lack of financial incentives, of internalisation of externalities, and of a clear and common objective – there are signals that the upcoming proposal will be limited to a voluntary labelling scheme, and some limited mandatory measures for public procurement practices (EC, 2021t; Euractiv, 2023).
— In agriculture, outputs linked to the strategy include recommendations (featuring a dedicated climate section) to each Member State for consideration when drafting its CAP CSP (EC, 2020r), and the establishment of the Farm Sustainability Data Network to improve the collection of farm-level environmental and social data (Council and Parliament of the EU, 2023a). However, the proposal to revise legislation on feed additives (which could facilitate efforts to reduce livestock CH_4 emissions) has not been tabled at time of writing (European Parliament, 2023c).

— In the middle of the food chain (processing, wholesale, retail, hospitality and food services), a voluntary code of conduct on responsible food business and marketing practices has been produced and signed by a number of companies and associations, accompanied by individual pledges (discussed further in the next subsection) (EC, 2021o). Large companies (including in the food sector) would also be affected by requirements to incorporate climate and sustainability into their corporate strategies under the Directive on corporate sustainability due diligence (political negotiations are ongoing at time of writing (European Parliament, 2023b)).
— Regarding sustainable food consumption, the Farm to Fork Strategy mentions minimum mandatory criteria for sustainable food procurement, and sustainability labelling for food products. The European Commission consulted on both of these issues during 2021 and 2022 (EC, 2021an) but has not made a proposal at the time of writing.
— Regarding reduction of food waste, the European Commission proposed a revision of the Waste Framework Directive that would include a 10 % food waste reduction target in processing and manufacturing, and a 30 % per capita target among retailers, restaurants, food services and households (EC, 2023aq). At time of writing, this is being negotiated at the political level, with the possibility that some targets will be weakened, postponed or narrowed in scope (European Parliament, 2023d).

Towards a whole-system approach

According to the IPCC, a food system approach enables the identification of cross-sectoral mitigation opportunities, including both technological and behavioural options (IPCC, 2022e). Taking a whole-system approach to EU agriculture and food policies would involve exploring options for mitigation by producers, consumers and intermediate links in the food supply chain, and ensuring that a coherent approach is taken to balancing the different environmental, economic and social demands placed on the agricultural sector.

On farming, in addition to the CAP and the Farm to Fork Strategy, emissions from the largest pig and poultry farms are governed under the Industrial Emissions Directive. In November 2023, the European Parliament and Council agreed a revision of this directive that will expand the number of farms covered (Council and Parliament of the EU, 2023b). In its original proposal, the European Commission estimated that a revised directive would reduce CH_4 emissions by 7.4 Mt CO_2e per year ([49]) (equivalent to around 3.2 % of annual agricultural CH_4 emissions) (EC, 2022ae). However, the politically agreed revision is considerably less ambitious than this, since it covers fewer pig and poultry farms and excludes cattle entirely, although it mandates the European Commission to produce an assessment of how best to address CH_4 emissions from cattle by 2026. The functioning of the directive's implementation will be reviewed every 5 years starting in 2028. However, the new rules on animal farming will only start to be applied from 2030.

The middle part of the agri-food value chain (food processing, distribution and retail companies) plays a vital role in the transition given its influence on food product availability, accessibility and affordability, marketing strategies and information provision. Aside from energy-related emissions (which are addressed in other chapters), actors in the middle of the supply chain can reduce emissions directly through improvements in the packaging, conservation and GHG intensity of food, and indirectly through their influence on consumers and producers. An effective policy mix should include targeting those in the middle of the agri-food value chain, through a combination of voluntary measures and

([49]) Conversion from 265 000 t of CH_4 per year using the 100-year global warming potential given in the IPCC Fifth Assessment Report (IPCC, 2013).

more stringent types of policy (carbon pricing and regulations, including on advertising practices, standards and financial incentives) to achieve the necessary scale of change.

While the Farm to Fork Strategy addresses the middle part of the agri-food value chain, it does so primarily through soft policies such as voluntary agreements. However, there is limited scientific evidence to lead one to expect such an approach to have a significant impact on its own. An EEA report on Europe's food system gives the example of the EU Code of Conduct on Responsible Food Business and Marketing Practices (EEA, 2022h). Firstly, the code of conduct has become more general and less concrete than originally envisaged, as illustrated by the deletion of references to avoiding advertising cheap meat. Secondly, it relies completely on self-regulation and voluntary pledges, and signatories have a high degree of choice about to which of the aspirational objectives they want to commit. Despite the high level of subscription to the code (130 signatories in mid 2022, representing a considerable share of the EU market), its overall impact is expected to be low. This is also confirmed by the European Commission's own 2022 mapping report, which concludes that, although the commitments made under the initiative are generally aligned with the Farm to Fork Strategy (and in some cases anticipate EU regulation on deforestation-free supply chains), there is room for improvement concerning their level of ambition and specificity (EC, 2022ag).

Shifting to sustainable food consumption and production is an essential part of climate policy in food and agriculture.

Aside from the multiple benefits of sustainable and healthy diets, several studies have pointed out that a strategy focusing exclusively on supply-side reductions risks being undermined by trade-related leakage effects (e.g. (Henderson and Verma, 2021; Zech and Schneider, 2019)). The importance of sustainable food consumption, including its health and environmental benefits, is recognised in the EU farm to fork Strategy, and in IPCC AR6, which finds that a transition to more plant-based consumption (including more pulses, fruits and vegetables) and reduced consumption of animal-based foods (in particular from ruminant animals) has considerable potential to reduce GHG emissions both directly (reduced enteric and manure-related emissions) and indirectly (reduced land and inputs needed for feed production). In addition, it could enhance public health and bring a range of other environmental co-benefits (biodiversity, reduced air, soil and water pollution). Potential trade-offs relate mainly to the risk of adverse economic and social impacts on the livestock sector, which would need to be well managed to ensure a just transition (IPCC, 2022a). Up to now, EU policies to encourage sustainable diets have focused primarily on information provision and voluntary codes of conduct, but these measures are not sufficient by themselves. Further action of this kind, on food labelling and public procurement, is promised in the Farm to Fork Strategy, although these at time of writing these proposals have not yet been tabled (see subsection 'Farm to Fork Strategy' above).

More ambitious policies to encourage healthy, sustainable diets, such as the introduction of emission pricing, would also have to be managed carefully, taking into account the social environment and economic implications for low-income consumers (see 'Lever: sustainable, healthy diets' below and Chapter 11 'Whole-of-society approach').

However, studies have warned that the farm to fork Strategy's goals of reducing fertiliser use and expanding organic farming risk displacing production and related environmental pressures outside the EU, if not accompanied by reduced demand for the most GHG-intensive products, which can be achieved through more sustainable and healthy diets and reduction of food waste (Bremmer et al., 2021; EC, Joint Research Centre et al., 2021; Matthews, 2021). **Climate change impacts are already affecting crop and livestock productivity in the EU**, and are projected to reduce crop productivity in parts of southern Europe and to improve conditions for growing crops in northern Europe in some years. Furthermore, increased intensity and frequency of extreme weather events are expected to negatively affect

agriculture in the EU overall (EEA, 2019). Reduced productivity risks undermining mitigation ambitions, as it could require increased inputs (including land use) to continue to meet demand, as well as risking maladaptation.

Achieving the ambitions of the European Green Deal will also require a **just transition in the agricultural sector**. Millions of farmers across the EU will need to change their farming practices, and this will require investments and lead to increased costs/reduced income in the short term. On the other hand, it is also recognised that in a broader sense the European Green Deal can improve farmers' incomes and resilience by reducing environmental damage and providing new income streams (e.g. bio-economy feedstocks, payment for carbon sequestration) and reduce costs (resource efficiency and circular economy) (Matthews, 2021; NESC, 2023). As discussed above, the mix of policies that would deliver a Green Deal-based transition in agriculture is not yet agreed. Nevertheless, a report commissioned by the Institute for European Environmental Policy attempts to identify who might benefit in a hypothetical transition, and who might be negatively affected (IEEP, 2021). The report indicates that potential beneficiaries include farmers and businesses able to exploit markets such as products with higher value added (nuts, fruit and vegetables), higher-welfare livestock products, organic products, ecosystem service and carbon sequestration markets, and recreation, amenity and hospitality activities. Those who may be negatively affected include some livestock producers and workers in meat-processing industries, suppliers of agrochemical inputs and producers with high reliance on these inputs, as well as famers unable to take advantage of growing markets or new support schemes.

Given the limited investment capacity and low profitability of many (mainly smaller-scale) farms in the EU, active policies will be needed to ensure the transition to a greener agricultural sector will be fair. In terms of building a policy approach for just transition (in the CAP beyond 2027), the Institute for European Environmental Policy report recommends combining better use of CAP basic payments to support environmental sustainability, development of new income streams and markets for sustainable activities, thorough preparatory work including building capacity and skills in the agricultural sector, and enhanced engagement to identify and address multiple dimensions of fairness (e.g. towards multiple stakeholders along the food supply chain, and those initially disadvantaged in the transition).

This need is not sufficiently reflected in the CAP. Although its latest revision has increased the overall environmental ambitions, its overall budget has remained unchanged in nominal terms, meaning that the additional requirements are not met by additional means (Matthews, 2021). Furthermore, CAP subsidies have been biased towards larger farms by the 'per hectare' basis of direct income support, and the system does not have any dedicated instruments to address potentially uneven social repercussions resulting from a sustainability transition (EEA, 2022h).

The Farm to Fork Strategy is a step forward in this regard, putting the aim of a just transition at the centre of its strategic goals. However, as with other objectives of the strategy, the main shortcoming is the lack of an effective delivery mechanism to achieve this objective (EEA, 2022h).

8.4 Outcome 1: lower greenhouse gas intensity of production

The GHG intensity of EU agriculture has remained largely unchanged over the past 10 years, as measured by GHG emissions per tonne of production in the livestock sector, and by use of nitrogen fertiliser per hectare in crop cultivation (as a proxy for intensity of N_2O emissions).

As discussed above, the reformed CAP for 2023–2027 is expected to consolidate rather than challenge existing high-GHG-intensity production practices, since these continue to be subsidised while the encouragement of more sustainable practices through the green architecture is largely voluntary or at Member State discretion.

Lever: low-emission livestock production

The emission intensity of livestock has remained largely unchanged over the past 10 years. Livestock production can become less emission-intensive through improved manure management and measures to reduce emissions from enteric fermentation.

In the livestock sector, the data shown in Figure 57 indicates an increase in GHG emission intensity for beef of 3 % by 2020, compared with 2010, which has partially offset the 4 % reduction in production levels (leading to an overall emission reduction of 2 %). By 2020, the direct emission intensity was about 15 kg CO_2e/kg product.

The direct emission intensity of dairy products and pig meat fell by 11 % and 6 % respectively over the same period. However, the improvements in GHG emission intensity were offset by increased production, which resulted in a quasi-stabilisation of total GHG emissions.

It should be noted, though, that these indicators only cover direct emission intensity and do not take into account indirect emissions from feed production. Feed production can cause considerable GHG emissions due to land use, fertiliser use and transport. JRC data (JRC, 2023) shows that about 50 % of all cereal supply (own production + imports) in the EU is used for feed purposes, indicating that the indirect GHG emissions of feed production constitute a large part of the livestock total GHG impact. For oilseed crops and related products, the share of total supply use for feed is even higher, at 66 %. With 50 % of total oilseed product supply coming from imports, the use of this feed type could be linked to significant indirect emissions – including those due to deforestation – outside the EU.

CH_4 emissions per unit of output can be reduced by focusing on two areas, namely enteric fermentation and manure management, as discussed by Reisinger et al. (2021) and the IPCC (2022a).

Enteric fermentation is a natural part of the digestion process of several species of livestock such as cattle, sheep and goats (ruminant species). The resultant CH_4 emissions account for half of total agricultural GHG emissions in the EU ([50]). A range of options exist to reduce these emissions, including changes to the feeding mix and the addition of feed additives. Other measures that can reduce emissions from both enteric fermentation and manure are optimising herd composition (fewer non-productive animals), improved animal health, livestock breeding and genetics to improve overall efficiency, and precision livestock-farming technologies. It is difficult to give a precise estimate of these measures' mitigation potential, given their inherent differences and varying technological maturity. Nevertheless, Reisinger et al. (2021) estimate potential reductions of 20–50 %, while the IPCC (2022a) reports that the reductions in the literature range from 16 % to 70 % for chemically synthesised CH_4 inhibitors, and also notes the large potential of additives derived from plants and algae. Potential co-benefits include enhanced resilience against climate change impact and higher productivity, whereas potential trade-offs include poor permanence of mitigation, ecological impacts associated with changes in feed mix, and potential toxicity and reduced animal welfare.

([50]) Emissions expressed in terms of CO_2 equivalent using 100-year global warming potential as per EEA (2023f).

Figure 57 Indicator A2 – livestock products: total production and GHG emissions (left axis), and GHG emission intensity (right axis)

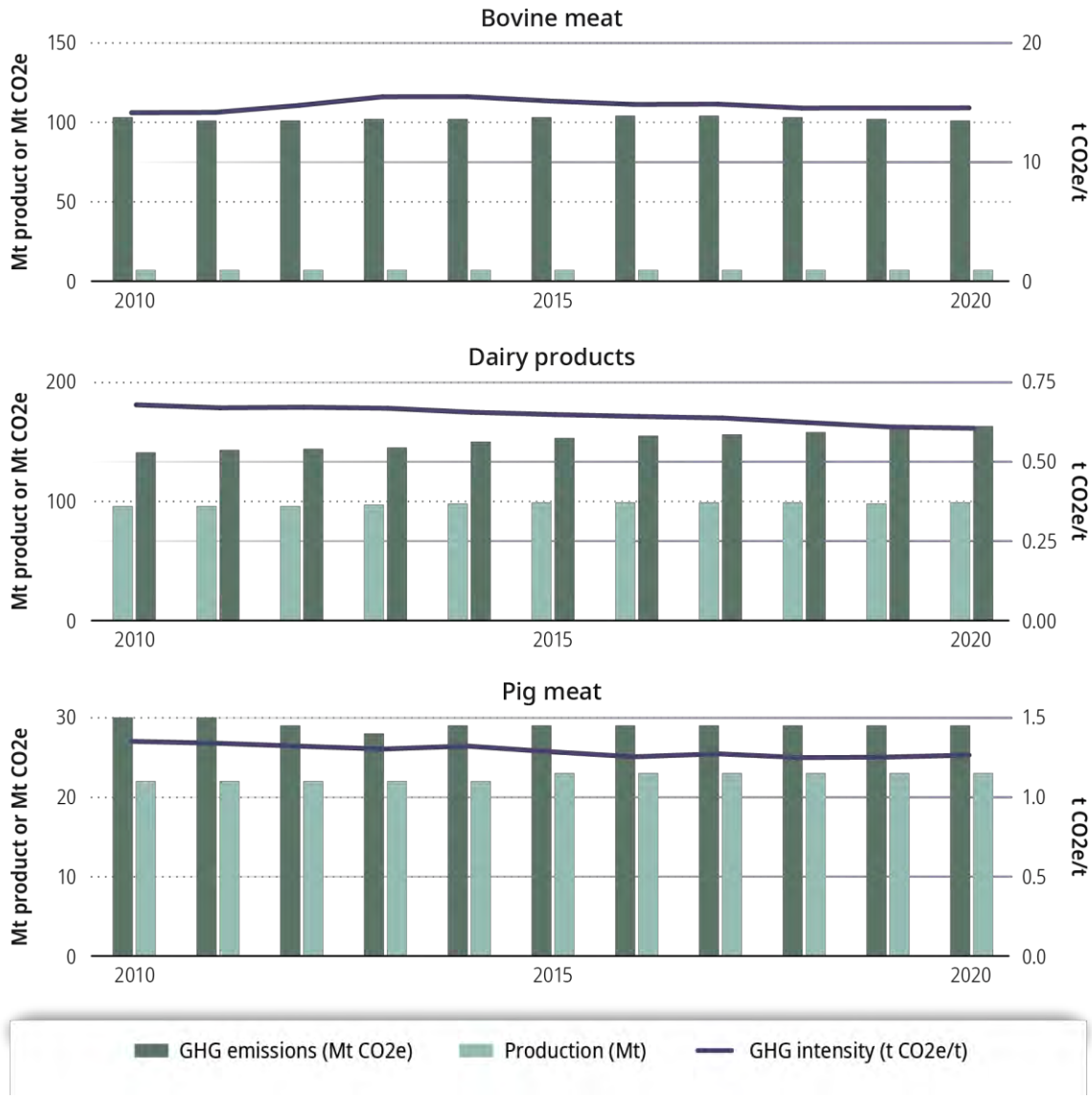

Notes: GHG emission intensity calculated as emissions/production.

Sources: EU CRF tables (EEA, 2023h), FAO Food Balances (FAO, 2023)

CH_4 emissions from manure management are the third most important source of EU agricultural emissions (accounting for around 17 %) (EEA, 2023k). Changes in manure management can contribute to reductions in both CH_4 and N_2O emissions. The main reduction options – in addition to those mentioned in the previous paragraph – are switches in manure management systems (e.g. anaerobic digestion and slurry acidification), the application of nitrification and urease inhibitors to stored manure or urine patches, improved manure removal and storage systems, changes in grazing and housing practices, and changes in the feeding mix. Potential co-benefits are renewable energy production (biogas), improvements to the fertiliser potential of manure, additional income streams for farmers, and improved air and water quality from reduced ammonia emissions. Potential trade-offs include increased N_2O emissions from manure application to poorly drained or wet soils, trade-offs between N_2O and ammonia emissions, potential eco-toxicity associated with some measures, and increased incentives to maintain livestock herd numbers.

At the EU-28 level (including the United Kingdom), JRC modelling estimates that 21 Mt CO_2e of mitigation can be achieved at a carbon price of EUR 100/t CO_2e through a combination of anaerobic digestion, low nitrogen feeding, feed additives and vaccination against methanogenic bacteria (Figure 17 of Pérez Dominguez et al. (2020)) ([51]).

Lever: low-emission crop production

Crop cultivation techniques that use synthetic fertiliser less intensively can reduce emissions as well as enhancing resilience to climate change impacts and improving soil, air and water quality.

N_2O emissions from agricultural soils are the second-highest contributor to GHG emissions from agriculture, accounting for 31 % (EEA, 2023k). In crop cultivation, the use of fertilisers (shown in Figure 58) has been increasing steadily (+ 10 %) between 2009 and 2017. However, since the peak in 2017, fertiliser use has been reducing in absolute volumes (kt N). The efficiency of fertiliser use (measured as the percentage of applied nitrogen that is harvested as crops) varies from year to year but appears to be improving gradually over time.

On average, fertiliser use reduced by 180 kt N per year in 2017–2021. This average rate of decline would need to accelerate by 75 % in absolute value (– 310 kt N per year) in 2022–2030 to achieve the objective of the Farm to Fork Strategy to reduce total fertiliser use by 20 % by 2030 (EC, 2020f). The shares of inorganic and organic fertilisers have remained relatively stable since 2005, at 66 % and 34 % respectively.

Figure 58 Indicator A3 – total fertiliser use (left axis) and nitrogen use efficiency (right axis) in the EU agriculture sector

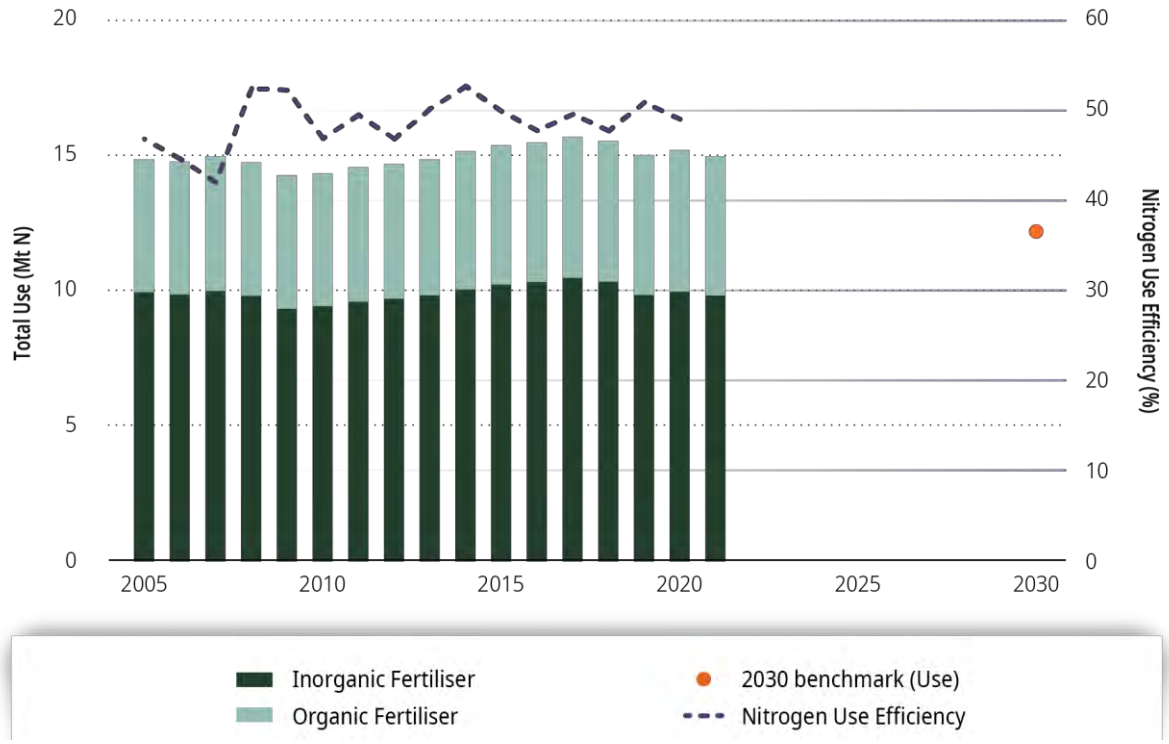

Notes: 2030 objective based on the European Commission's Farm to Fork Strategy.

Sources: EU CRF tables (EEA, 2023h) (Fertiliser Use), Ludemann et al. (2023) (Nitrogen Use Efficiency), Farm to Fork Strategy (EC, 2020f)

([51]) GHGs in Pérez Dominguez et al. (2020) are expressed using the 100-year global warming potential from the IPCC Fourth Assessment Report (IPCC, 2007a).

Improved crop nutrient management could lower N_2O emissions from fertiliser use in the agricultural sector. At the EU-28 level, JRC modelling estimates that 65 Mt CO_2e of mitigation can be achieved at a carbon price of EUR 100/t CO_2e through measures including fallowing histosols, growing winter cover crops and using nitrogen inhibitors (Pérez Dominguez et al., 2020)[52]. More broadly, options mentioned by the IPCC (2022a) include improved crop rotation practices increasing biological nitrogen fixation by legumes used as main crops (grain legumes, alfalfa) or as cover crops, optimised fertiliser application rates and timing (including precision application technologies), improved manure-spreading machinery, the reduction of inorganic fertiliser use by better utilising the nutrients in organic fertilisers, the application of nitrification and urease inhibitors, and better overall efficiency in crop production (e.g. reduced soil compaction and degradation, optimised irrigation, improved crop health).

Potential co-benefits are emission reductions in other sectors (due to lower mineral fertiliser production and increased carbon sequestration in agricultural soils), improved soil, air and water quality (due to less nitrate leaching, eutrophication and ammonia emissions), and better climate resilience due to increased water-holding capacity of the soil (if soil carbon is increased). In addition to improving biological nitrogen fixation, improved cropping systems with a higher share of grain legumes could also provide plant-based proteins for supporting the shift towards more sustainable diets, or replace soybeans that are imported for feed from non-EU areas undergoing tropical deforestation. Trade-offs relate to the potential reduction in yields in specific circumstances, which could therefore lead to negative impacts from ILUC either within or outside the EU, if the food, feed and bioenergy crop demand is not reduced simultaneously.

8.5 Outcome 2: reduced production and consumption of GHG-intensive agricultural products

While Outcome 1 focused on the intensive margin (reducing the GHG intensity of each product), Outcome 2 focuses on the extensive margin (reducing the production and consumption of GHG-intensive products).

As noted in the subsection 'Towards a whole-system approach' above, production and consumption need to be addressed jointly, otherwise emission reduction efforts risk being offset by increased imports (displacing emissions to other countries) or exports (maintaining EU emissions in spite of consumption changes). Several food and agricultural products are internationally traded commodities. For example, the EU is a net exporter of beef, pig meat, dairy products and cereals.

Lever: reduced livestock production

Agricultural emissions in the EU come predominantly from livestock production (two thirds of emissions) and N_2O emissions associated with growing crops (over half of which are used for feed purposes (JRC, 2023)).

The main contributors to emissions from livestock production are dairy cattle (40 % of total), non-dairy cattle (36 % of total) and pigs (10 % of total) (EEA, 2023h). Over the past 10 years, data on production and consumption of these products (summarised in Figure 59) indicates an increasing production to consumption ratio. The EU is a net exporter of beef, dairy products and pig meat (FAO, 2023), and since 2005 exports of each have grown by more than imports (although both have increased). Slight decreases in consumption of pig meat and beef have therefore not led to a similar reduction in production volumes, and the increase in dairy consumption has been outpaced by dairy production. Overall, increases in

[52] GHGs in Pérez Dominguez et al. (2020) are expressed using the 100-year global warming potential from the IPCC Fourth Assessment Report (IPCC, 2007a).

production have been achieved through improved productivity, with the total herd size declining for dairy cattle and pigs (stable since 2013) and relatively stable for non-dairy cattle.

Total beef consumption decreased in 2010–2020 (by 1 Mt). Production decreased in line with consumption until 2013, but then decoupled from consumption and started to increase again. The herd size fluctuated slightly and was 1 % lower in 2020 than in 2010. The ratio between production and herd size might be explained by a shift towards slaughtering cattle at a later age, which is also supported by the lower ratio of slaughtering to herd size observed in the United Nation's Food and Agriculture Organisation (UN FAO) Corporate Statistical Database (FAOSTAT) data.

The consumption of dairy products increased by 6 Mt between 2010 and 2020 but was outpaced by an increase in production of 22 Mt. Production increases were mainly driven by improved productivity due to genetic selection (larger animals with higher milk production per head), while the total herd size decreased by 1 million head.

Figure 59 Indicator A4 – total production and consumption of livestock products (left axis) and herd sizes (right axis)

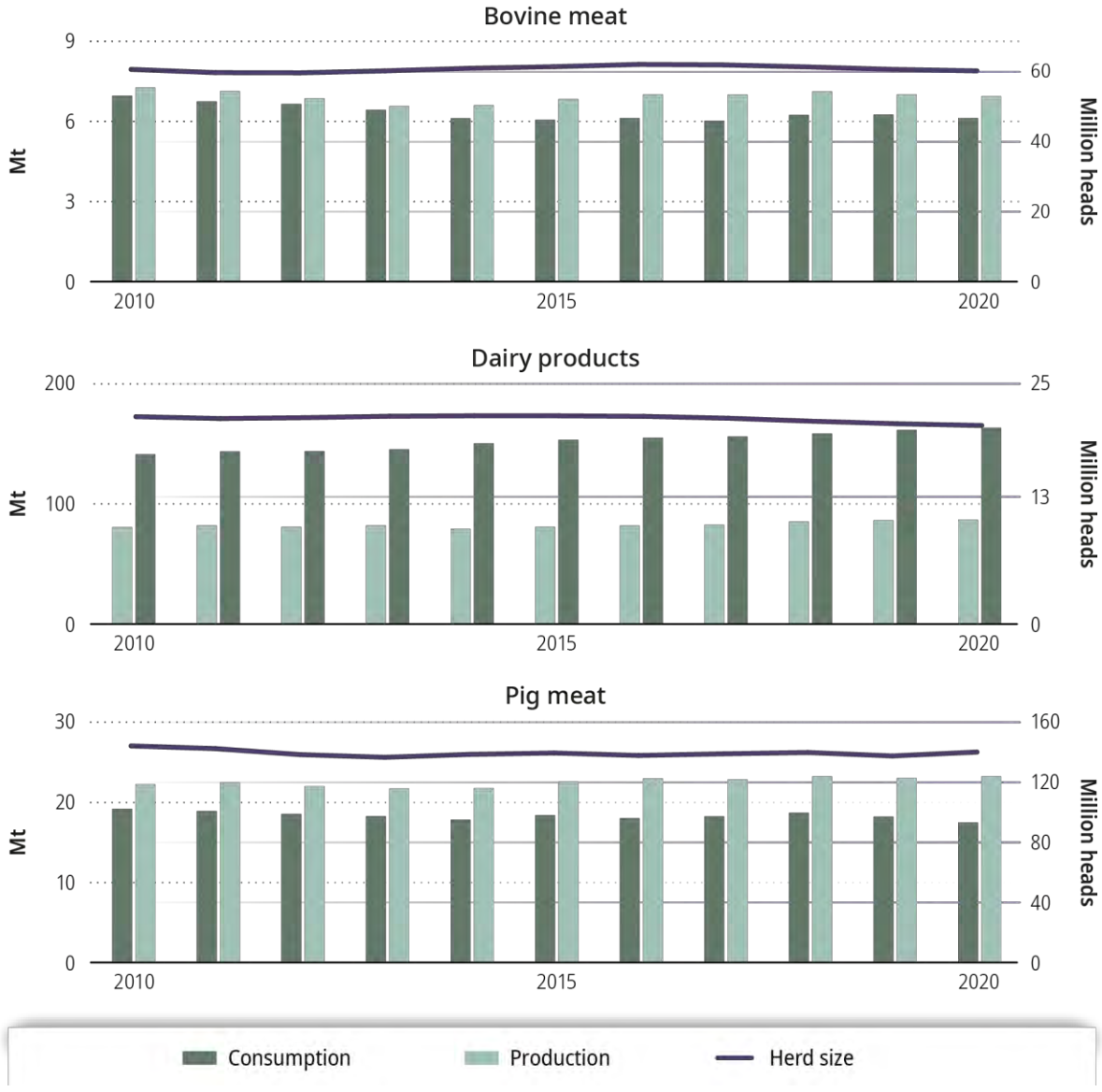

Sources: EU CRF tables (EEA, 2023h) (Herd Size), FAO Food Balances (2023) (Consumption & Production)

Despite a reduction in pig meat consumption (by 2 Mt in 2010–2020), production levels increased by 1 Mt. This increase in production was achieved through higher productivity, as the total herd size decreased only slightly in the same period, by 3 %.

To be beneficial for the global climate, lower production of GHG-intensive products will have to be matched by a shift to more sustainable, plant-based diets (addressed in the next section). Such a change should be possible given that agricultural production in the EU is supported by the CAP, which could be reformed to become more ambitious on climate change and provide greater support to low-emission production and environmental stewardship (see subsection 'Common agricultural policy' above).

Lever: sustainable, healthy diets

The health and environmental benefits of sustainable diets are recognised in the EU Farm to Fork Strategy. EU policies to encourage sustainable diets focus primarily on information provision and voluntary codes of conduct, but these measures are not sufficient by themselves.

Despite the heterogeneity of production practices, it is generally true that meat from ruminant animals has the highest GHG emissions (20–50 kg CO_2e per 100 g of protein), followed by other meat and fish (5–8 kg) and dairy (3–11 kg) (Poore and Nemecek (2018), Figure 1) ([53]). For ruminant livestock, a large share of emissions come from CH_4. However, meat (in particular, beef) has higher emissions than other products even when CH_4 emissions are excluded (Ritchie, 2020).

As mentioned above ('Towards a whole-system approach'), shifting to healthier, sustainable, more plant-based diets is important both because of the health and environmental benefits, and because an exclusively supply-side approach risks being undermined by trade-related leakage effects. According to data from the UN FAO shown in Figure 60 ([54]), the average consumption of beef and pig meat per capita has fallen over the last 10 years, although the trend seems to have stagnated and even slightly rebounded in the second half of the period. The observed average reduction in bovine meat consumption in 2016–2020 of 0.01 kcal per person per day would have to accelerate to 0.14 kcal per person (a more than 18-fold increase) to align with a linear trajectory towards the 2050 benchmark. On the positive side, the reduction of pig meat consumption (– 1.3 kcal per person per day on average in 2016–2020) is well on track towards the 2050 benchmark of 0.6 kcal per person per day in 2021–2050.

In contrast to the consumption of meat, the average consumption of dairy products has been increasing in the last 10 years.

The benchmark used for this assessment is the most ambitious ('diet 5') of five possible diet scenarios included in the in-depth analysis supporting the European Commission's 2018 LTS. This scenario could deliver reductions of around 100 Mt CO_{2e} in 2050, reduces animal-based calorie intake by around a third between 2013 and 2050, and would be consistent with reaching meat consumption in line with recommended diets by 2070 (EC, 2018e). Therefore, even though it is the most ambitious of all the scenarios assessed, it still reaches recommended diets only 20 years after the EU's deadline to achieve climate neutrality. The benchmark should therefore be considered as a strict minimum, and further (and faster) reductions in animal product consumption would be recommended. This would not only contribute to further GHG emission reductions but also be recommendable from a health perspective. For example, the World Cancer Research Fund has issued a recommendation to limit the consumption

([53]) Figures refer to mean values. For dairy, the low value refers to milk and the high value to cheese.

([54]) The UN FAO database provides information on average animal product consumption per capita in different countries and regions, including for the EU-27. This data is based on consumer surveys, and the values are therefore estimates with some degree of uncertainty.

of red meat ([55]) to a maximum of 525–750 g per week to reduce cancer risks (WCRF, forthcoming). This would imply a reduction of 30–50 % compared with the average red meat consumption in the EU-27 of 1.1 kg per person per week in 2020 (FAO, 2023).

Figure 60 Indicator A5 – average animal product consumption

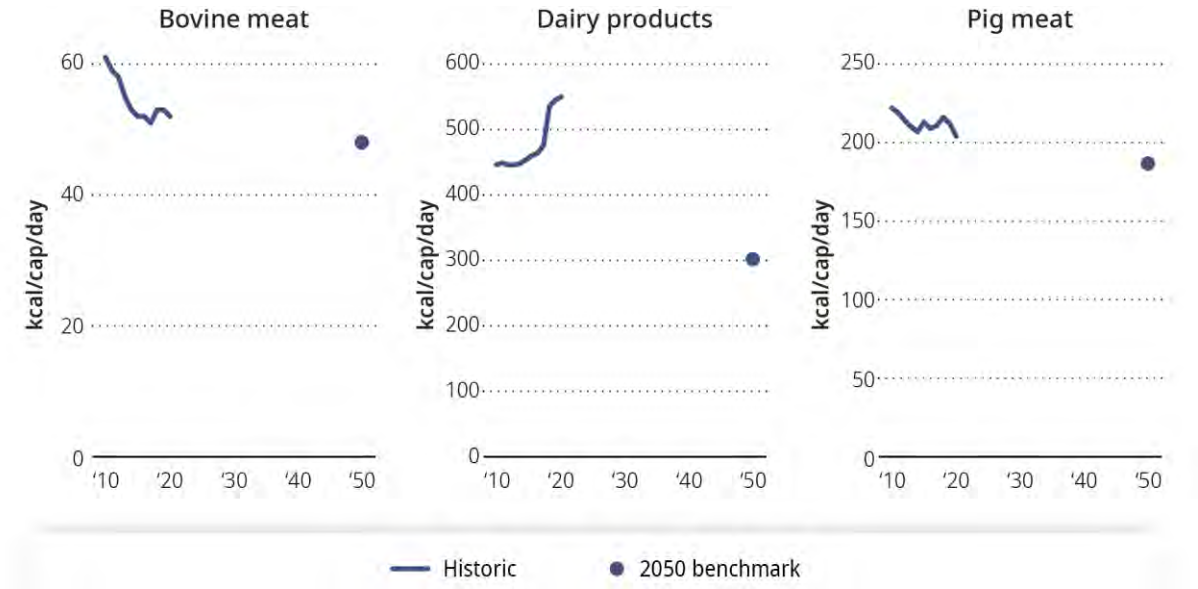

Notes: 2050 benchmarks based on 'Diet 5' from the in-depth analysis accompanying A Clean Planet for All.

Sources: FAO Food Balances (2023) (historic), In-depth analysis accompanying A Clean Planet for All (EC, 2018e) (Figure 76) (benchmark).

Looking at the issue of sustainable and healthy diets more broadly, the European Commission's Farm to Fork Strategy states that current EU food consumption patterns are unsustainable on both health and environmental grounds, citing evidence that 950 000 deaths a year and 16 million lost healthy life-years can be attributed to unhealthy diets. The strategy therefore calls for promoting sustainable food consumption and facilitating the shift to healthy, sustainable diets.

To this end, it proposes empowering consumers to make healthy and sustainable food choices, improving the availability and price of sustainable food and putting in place tax incentives to encourage healthy diets.

One criticism of the Farm to Fork Strategy is that it **remains vague on definitions and lacks quantified objectives for the shift towards sustainable and healthy consumption patterns**. It uses several general concepts such as 'food sustainability', 'sustainable (agri-)food system' and 'sustainable agricultural practices' without being specific about what they mean. This absence of clear definitions can lead to diverging interpretations, lack of a clear and common vision of the desired end goal, and therefore an increased risk of policy inconsistencies. This is evidenced by the EEA's analysis of the consultation responses to the Sustainable food system framework initiative, which found that stakeholders have different understandings of what a sustainable food system would look like (EEA, 2022h). Similarly, the strategy lacks quantified objectives for its demand-side ambitions (with the

([55]) Under World Cancer Research Fund International's interpretation of red meat, this includes beef, pork, lamb, mutton, horse and goat.

exception of reducing food waste by 50 % by 2030) which makes it difficult to track progress and hold policymakers accountable for the delivery of the objective (EEA, 2022h).

Overall, consumer choices are constrained by food product availability, accessibility and affordability, marketing strategies, and psychological (e.g. habits) and sociocultural (e.g. norms) factors. **Pricing policies could be among the most effective tools but are largely absent from the Farm to Fork Strategy.** The advisory bodies' reports found that pricing policies can be effective to steer consumer demand and ensure that food prices reflect their true costs of production and consumption (EEA, 2022h; EC, Group of Chief Scientific Advisors, 2020; SAPEA, 2023). The Farm to Fork Strategy acknowledges the importance of **tax incentives**, stating they 'should also drive the transition to a sustainable food system and encourage consumers to choose sustainable and healthy diets' (EC (2020f), p. 14). It refers to the ability of Member States to differentiate value added tax (VAT) levels to support specific types of more sustainable foodstuffs. However, the 2022 EEA report found that, at the national level too, there is an almost complete absence of favourable taxation schemes for sustainable consumer food products (EEA, 2022h).

One possible way to address this at the EU level while taking into account the EU's limited powers in the field of taxation is to apply **emission pricing** to the agri-food system (see Chapter 10 'Pricing emissions and rewarding removals' for a discussion of this). The European Commission is considering this option, and launched a survey in June 2023 to gather expert views on how such a system should be organised (EC, 2023bd). In order to have an impact on consumer behaviour, an emission-pricing regime would have to ensure that price incentives favouring low-emission food choices are eventually passed through to the end consumer.

There is a general consensus that introducing emission pricing for food would be regressive, because low-income households spend a larger share of their income on food (Kehlbacher et al. (2016), Klenert et al. (2023) and a number of studies reviewed by Temme et al. (2020)). Temme et al. (2020) suggest that a combination of taxes and subsidies could reduce regressive effects and may enable consumers to change to a more healthy and sustainable diet without additional cost. Modelling by Klenert et al. (2023) supports this conclusion, estimating that a EUR 50/t CO_2e tax on meat would cost the lowest quintile of consumers EUR 72 per year (around 0.6 % of total food expenditure), that recycling the revenue into reduced VAT for fruit and vegetables would reduce this cost to EUR 15, and that recycling the revenue as a lump sum transfer would reduce inequality by returning EUR 13–350 to the lowest income quintile (the range depending on whether the transfer goes to all households or only the poorest quintile).

Pricing policies promoting healthier diets (while ensuring access to healthy food for all) can also be justified on health grounds, with Temme et al. (2020) suggesting that this rationale may increase public acceptability. Predominantly plant-based diets such as the EAT-Lancet diet (Willett et al., 2019) have been designed with objective of improving both health and sustainability outcomes.

Given the evidence outlined above, policies based on emission pricing can in principle incentivise shifts from red to white meat, and to more plant-based diets, while achieving positive outcomes for health, climate and inequality. However, the use of emission pricing or taxes without complementary policies could lead to unintended health outcomes. For example, it could encourage consumers to switch to lower-quality meats, or to sugary products that are not emission-intensive (Kehlbacher et al., 2016; Klenert et al., 2023).

The Farm to Fork Strategy places a great emphasis on **improved information provision** as a key driver of consumer behaviour change (although the European Commission has not yet published the announced proposals at time of writing). The overall approach focuses on providing better information to consumers (e.g. through labelling), in the expectation that they will make well-informed and rational

choices towards more healthy and sustainable diets (EEA, 2022h; SAPEA, 2023). According to a number of recent reports by EU advisory bodies (EEA, 2022h; EC, Group of Chief Scientific Advisors, 2020; SAPEA, 2020, 2023), soft policies such as information provision, sensibilisation and choice architecture ('nudging') can support the required shifts in consumer behaviour but are insufficient on their own to drive the required change. As discussed above ('Towards a whole-system approach'), the EU code of conduct on responsible food business and marketing practices has had mixed results so far in facilitating a shift towards healthy and sustainable diets.

Regarding the **social, cultural and behavioural aspects of food consumption**, SAPEA (2023) and other studies such as those by Eker et al. (2019) and Wendler and Halkier (2023) point to the importance of the social environment (i.e. the fact that dietary change is not merely carried out by isolated individuals). Wendler and Halkier go further, arguing that the social aspect (essentially whether a plant-based diet is considered more or less normal) could have a greater influence on meat consumption than an individual's intention to change their diet. In this respect, measures such as improving the sustainability of public procurement (suggested in the Farm to Fork Strategy) can also have an important role to play.

In conclusion, the introduction of price-based policies to encourage healthy and sustainable diets appears to be the main element missing from the EU's farm to fork policy. If well designed, it could be introduced with a modest regressive effect, or even be a financial benefit to low-income consumers. Therefore, the introduction of more binding measures such as regulations and financial incentives appears necessary but should be combined with further efforts to enhance information provision and education about sustainable and healthy diets as part of a broad policy mix.

Lever: reduced food loss and waste

EU policies to reduce food waste are in preparation, and the recent establishment of a monitoring system is an important first step. However, the proposed targets are less ambitious than the aims of the Farm to Fork Strategy.

Reducing food loss and waste could deliver considerable emission reductions. Currently, food waste represents approximately 15 % of the total GHG footprint of the EU food system (EEA, 2022h). Reducing food losses and waste could reduce emissions both directly (by reducing agricultural production, food processing and transport) and indirectly (by making land available that could be used for biomass production or carbon sequestration). Food loss and waste take place across the entire agri-food value chain, and in particular the distribution and (post-)consumption stages. Options to reduce them include incentives to reduce business- and consumer-level waste, active marketing of cosmetically imperfect products, improved information provision and regulation of unfair business practices. Potential co-benefits are reduced environmental stress and improved food security.

Before the adoption of the Farm to Fork Strategy, food waste was already considered in a number of EU-level policies and strategies. The European Commission proposed a series of actions under the 2015 Circular Economy Action Plan (EC, 2015a), and the 2018 Waste Framework Directive (EU, 2018a) included obligations for Member States to reduce food waste (without any quantified objective), to measure food waste levels and to report on progress made. To this end, in 2019 the European Commission adopted a common food waste measurement methodology (EC, 2019a) to ensure harmonised food waste monitoring and reporting across Member States.

The Farm to Fork Strategy puts forward a concrete, quantified objective of reducing food waste per capita by 50 % by 2030. Recently, it also published a proposal to revise the Waste Framework Directive (EC, 2023aq), which sets legally binding objectives for Member States to reduce food waste. Under the proposal, food waste in processing and manufacturing would need to be reduced by 10 % by 2030, and food waste in the retail, distribution, restaurant and food services and households would need to be

reduced by 30 % by 2030 (both compared to 2020, in kilograms per capita). No objective is set for primary producers, which accounted for 11 % of total food waste in 2020. Given that the objective does not cover all food waste and sets targets below the overall 50 % reduction objective, it is highly uncertain that it will be sufficient to meet that objective. The European Commission acknowledged this ambition gap but argued that lower targets were needed to ensure feasibility, and that targets can be revised upwards in the event of sufficient progress.

Data collected under the common food waste measurement methodology in Figure 61 shows that in 2020 the EU wasted on average 131 kg of fresh food per capita, most of it during the consumption phase: 53 % of the total waste was generated by households and 9 % in the restaurant sector. Under its Farm to Fork Strategy, the European Commission is committed to halving this by 2030, in line with sustainable development goal 12.3 (EC, 2020f). Data for 2021 will bring further clarity about whether the EU is moving in the right direction and at an adequate pace to achieve this objective.

Figure 61 Indicator A6 – food waste in the EU in 2020, per source (left) and compared to the 2030 benchmark (right)

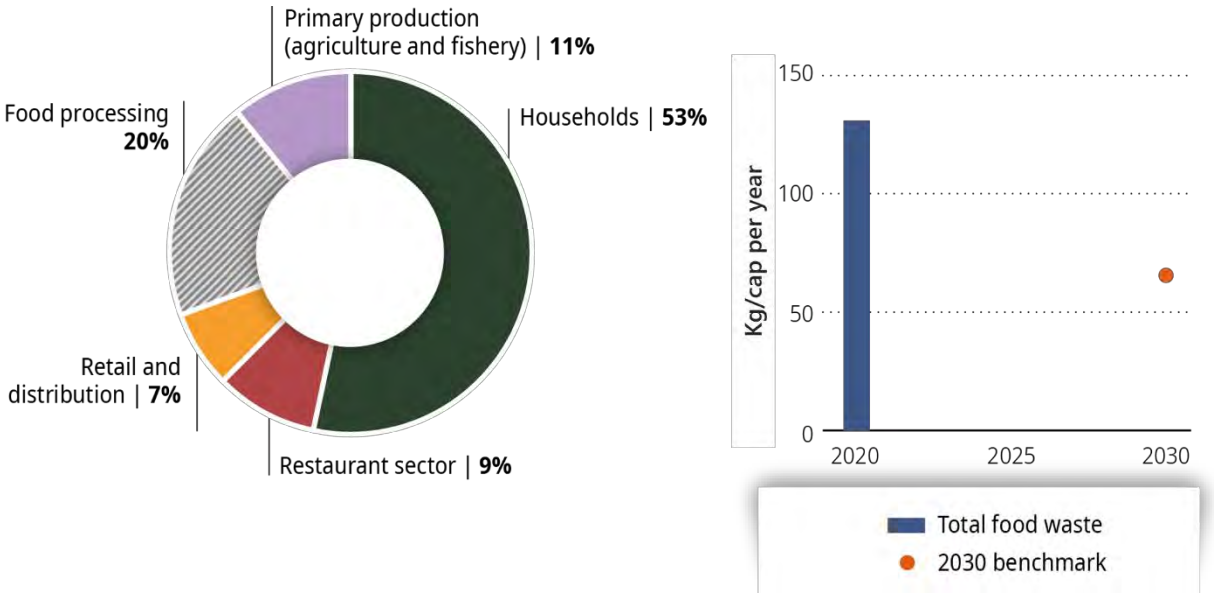

Notes: Food waste during the primary production of foods excludes pre-harvesting food losses. 2030 benchmark based on the European Commission's Farm to Fork Strategy.

Sources: Eurostat (2023i) (2020 data), Farm to Fork Strategy (EC, 2020f) (benchmark).

Lever: minimise demand for biofuel crops

In the long term, use of food crops for first-generation biofuels is expected to decline thanks to advances in electric vehicles and second-generation biofuel technology. However, first-generation biofuel production may continue to grow in the short term as a result of renewable fuel mandates.

The use of bioenergy can lead to either increased or reduced emissions, depending on the scale of deployment, the conversion technology, what fuel it displaces and how/where the biomass is produced (IPCC, 2022i). In particular, some of the GHG emissions and other sustainable development impacts associated with demand for bioenergy cannot be observed or measured directly, because it is entangled with a large number of other changes in agricultural markets at both the global and local levels (Valin et

al., 2015). This chapter considers the influence of bioenergy markets on the EU agricultural sector, while Chapter 6 (on transport) examines EU bioenergy policies in general.

The use of agricultural crops as feedstock for biofuels has been increasing since 2005 as the result of EU policies promoting the use of biofuels to decarbonise the transport sector (see Section 6.4, under 'Lever: fuel switches'). The increase was strongest in 2005–2010, after which it slowed down. Nevertheless, by 2021 the absolute volumes of cereal crops and vegetable oils used as biofuel feedstocks more than tripled compared with 2005. Whereas the share of cereal crops used for biofuel production is relatively small (4 % of total), a large minority (40 %) of the total vegetable oil use in 2021 in the EU was linked to biofuel production.

Under the European Commission's MIX scenario underpinning the 55 % reduction objective, the use of food crops for biofuel production would continue to increase up to 2030 at a rate of 0.9 Mt fresh material per year, faster than the observed trend in 2016–2021 (0.4 Mt fresh material per year). After 2030, the MIX scenario envisages continued growth in production of bioenergy feedstocks overall, but largely from non-food crops (lignocellulosic grass) and agricultural residues. Total food crop use for biofuel production should be 66 % below 2021 levels by 2050. Given recent declines in the cost of both batteries and variable renewable generation technologies (IPCC, 2022g), more up-to-date scenarios may find that EU climate targets can be met with lower production and bioenergy use than that set out in the MIX scenario.

Figure 62 Indicator A7 – use of agricultural products as bioenergy feedstocks

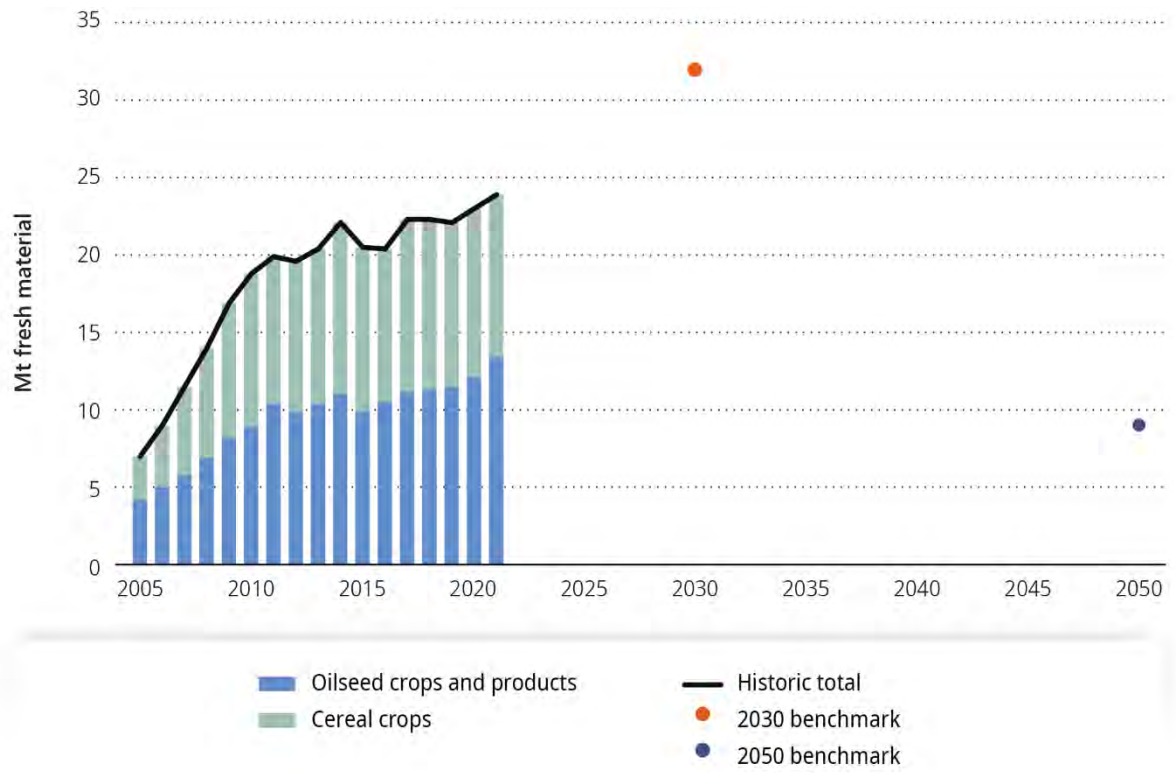

Sources: JRC Medium-term outlook commodity flows (Gurría Albusac et al., 2021) (historic), Climate Target Plan impact assessment MIX scenarios (EC, 2020s) (Figure 79) (benchmarks).

8.6 Summary tables

Table 12 Progress summary - agriculture

Indicator	Reference period	Historical progress	Required up to 2030	Required in 2031–2050
A1: GHG emissions	2005–2022	– 1 Mt CO_2e/yr	– 3.5 Mt CO_2e/yr	– 4 Mt CO_2e/yr
A2: livestock GHG intensity				
A2a: beef	2016–2020	– 73 kg CO_2e/kg/yr	No benchmark	No benchmark
A2b: dairy products	2016–2020	– 9 kg CO_2e/kg/yr	No benchmark	No benchmark
A2c: pig meat	2016–2020	+3 kg CO_2e/kg/yr	No benchmark	No benchmark
A3: total fertiliser use	2017–2021	–179 kt N/yr	– 313 kt N/yr	No benchmark
A4: livestock production				
A4a: beef	2016–2020	Stable	No benchmark	No benchmark
A4b: dairy products	2016–2020	+ 2 Mt/yr	No benchmark	No benchmark
A4c: pig meat	2016–2020	Stable	No benchmark	No benchmark
A5: livestock product consumption				
A5a: beef	2016–2020	– 3 kcal per person y^{-1}	No benchmark	– 50 kcal per person/yr
A5b: dairy products	2016–2020	+ 7 777 kcal per person/yr	No benchmark	– 2 970 kcal per person/yr
A5c: pig meat	2016–2020	– 468 kcal per person/yr	No benchmark	– 204 kcal per person/yr
A7: food waste	2020	131 kg per person/yr [a]	– 7 kg/cap/yr	No benchmark
A7: bioenergy feedstock crops	2017–2021	+ 0.4 Mt FM/yr	+ 0.9 Mt FM/yr	– 1.2 Mt FM/yr

Legend

On track	The required change [b] is ≤ 1.
Almost on track	The required change [b] is between 1 and 1.5.
Somewhat off track	The required change [b] is between 1.5 and 2.
Considerably off track	The required change [b] is ≥ 2.
Wrong direction	The required change [b] is < 0.

[a] Only data for one year available; not possible to compare with required progress.
[b] See Section 2.2 for more details on how the required change is calculated.

Table 13 Policy consistency summary – agriculture

Policy inconsistencies	– Support to emission-intensive agricultural practices such as livestock production continues under the CAP through area-based and, in some cases, production-linked payments. – EU energy policy continues to promote first-generation biofuels.
Policy gaps	– GHG emissions from agriculture are not covered by an emission-pricing system. – Several initiatives announced in the Farm to Fork Strategy have not yet been adopted as final legislation. In some cases, the initial proposal from the European Commission has not been published.
Ambition gaps	– Emission reduction targets and objectives under the CAP are combined with general agri-environmental objectives and are largely qualitative. – Emphasis on mitigation in Member States' CAP CSPs is largely discretionary. Expected mitigation outcomes are difficult to quantify. – The Farm to Fork Strategy lacks delivery mechanisms and relies on non-binding measures (such as information provision). – The impact of recent food and agriculture initiatives such as the EU Code of Conduct on Responsible Food Business and Marketing Practices, food waste reduction targets in the Waste Framework Directive revision proposal and the revised industrial emissions directive are expected to be low.

9 Land use, land use change and forestry

Key messages

The observed decrease in the net carbon sink in the LULUCF sector needs to be reversed to be consistent with the EU climate objectives. Several complementary options are available to achieve this.

Figure 63 displays the overall levels of emissions and removals from the LULUCF sector. The net sink in the LULUCF sector has been in decline since 2010 and was a third lower in 2021 than in 2005. The decline was predominantly caused by reduced CO_2 removals by EU forests, driven by slower forest growth, natural disturbances and increased demand for woody biomass (see indicator L6 for more details). The carbon sink has declined, removing on average 6 Mt CO_2 less every year in 2005–2022. This trend needs to be reversed so that the sink will remove on average an additional 8 Mt CO_2 each year in 2023–2030 to meet the legally binding target of 310 Mt CO_2e net removals per year by 2030, and to be consistent the European Commission scenarios underpinning the 2050 climate neutrality objective.

Figure 63 Indicator L1 – overall progress in reducing emissions (positive values) and increasing removals (negative values) in the LULUCF sector

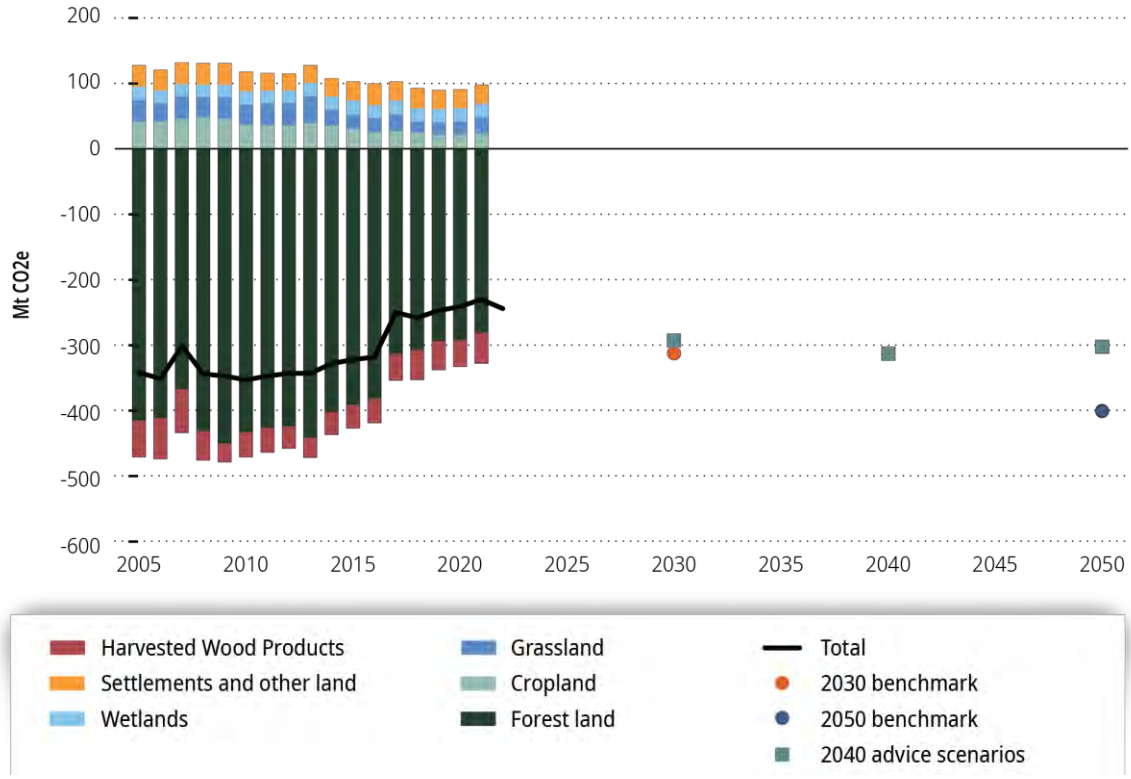

Sources and Notes: See Figure 65 for detailed sources and notes.

The Advisory Board has explored four possible pathways to reverse the downward trend in the LULUCF sink: maintain and expand forests and wetland areas, increase the carbon sink in existing forests, reduce GHG emissions and increase removals in crop- and grasslands, and improve the resilience of ecosystems to current and projected climate change impacts. These solutions are not mutually exclusive, and a combination of all four might be required to achieve the required net removals in 2030 and beyond. The conclusions of the assessment for each pathway are summarised below.

The potential to maintain and expand the area of forests and wetlands is undermined by EU policies on agriculture and biofuels, which are driving land use for agricultural production.

Needs. Maintaining and expanding the area of forests and wetlands has substantial potential to increase the net sink in the LULUCF sector. Its potential is constrained by land availability, which is largely determined by demand for other competing land uses such as human settlements and agricultural production. More efficient spatial planning (see also Section 7.5), lower production of livestock products (which accounts for approximately 65 % of total agricultural land use), reduced food waste and lower production of biofuels made from feed and food crops are all enabling conditions that can reduce demand for these land uses and therefore increase the land available for carbon sequestration.

Gaps. Even if the total area of agricultural land in the EU has slightly decreased, several EU policies are putting upward pressure on demand for agricultural land, which undermines the potential to maintain and expand forest and wetland areas. As described in Chapter 8 'Agriculture', the current CAP continues to financially support livestock production **(policy inconsistency)**, which drives demand for land for feed production. Similarly, the CAP continues to financially support the cultivation of organic soils and marginal lands, which might be better suited to carbon sequestration **(policy inconsistency)**. The CAP does have a mandatory requirement to preserve wetlands (good agricultural and environmental condition (GAEC) 2), but over half of the EU Member States have opted to delay its implementation to 2024 or 2025. The CAP also allows support mechanisms (eco-schemes) for the restoration of wetlands, but these are used to only a limited extent by Member States **(implementation gap)**. The objectives of the Farm to Fork Strategy to reduce fertiliser use (by 20 %) and increase the share of organic farming (to 20 %) have direct local environmental benefits, but risk reducing yields and therefore increasing demand for land (either in the EU or abroad) if demand for agricultural products is not reduced in parallel **(policy gap)**. It also includes an ambitious (non-binding) objective to reduce food waste per capita by 50 % by 2030, but the proposed legal objectives under the Waste Framework Directive fall short of achieving this **(ambition gap)**. Finally, as described in Chapter 6 'Transport', EU biofuel policies continue to incentivise demand for specific biofuel types that drive demand for agricultural land **(policy inconsistency)**.

Recommendation L1. EU policies on agriculture and biofuels should better reflect the need to maintain and expand the area of forests and wetlands for carbon sequestration purposes. The upcoming revision of the CAP should reduce support for livestock production, which is a major driver of demand for agricultural land. Similarly, EU biofuel policies should cease to promote the use of biofuels with high ILUC risks, and in particular first-generation biofuels (see also Chapter 6 'Transport'). Finally, the EU should leverage its competence to support more efficient spatial planning at the (sub)national level (see also Section 7.5).

The carbon sink in EU forests is under pressure from multiple factors, including wood demand. To keep aggregate demand for biomass within sustainable limits while ensuring sufficient supply, incentives for bioenergy use should be better targeted towards end use sectors with limited other mitigation options.

Needs. The decline in the EU forest carbon sink is driven by several, interlinked factors including forest age, climate change impacts and harvesting practices (which affect carbon sequestration both in living biomass and in forest soils). There is an ongoing scientific debate on the role of EU biomass policies in driving the observed decline in the carbon sink (through increased harvesting), and the climate mitigation impact of (forest) biomass use in general. This impact strongly depends on the source and end use of forest biomass, but there is also a need to limit the aggregate demand to the sustainably available supply of forest biomass.

Gaps. Subsequent revisions of the Renewable Energy Directive have made incentives for biomass use for energy conditional on increasingly stringent sustainability criteria, minimum GHG savings thresholds and adherence to the cascading principle. Furthermore, the incentives for bioenergy use are expected to be counterbalanced by the incentive coming from the LULUCF Regulation, and Member States will have to report on the compatibility of their bioenergy policies with their targets under the LULUCF Regulation. Nevertheless, some reasons for concern remain. Firstly, specific exemptions **(ambition gap)** and monitoring and compliance issues (including fraud) **(implementation gap)** risk undermining the effectiveness of the sustainability criteria and provisions on the cascading principle under the RED III. Secondly, so far, Member States have provided insufficient information for the European Commission to assess the compatibility between projected bioenergy demand and sustainably available supply **(implementation gap)**. Furthermore, the incentives for using forest biomass for energy purposes versus maximising the LULUCF carbon sink continue to be unevenly distributed in the absence of a financial incentive for land managers to reduce emissions and increase removals in the LULUCF sector **(policy gap)** (see also Chapter 10 'Pricing emissions and rewarding removals'). Finally, the aggregate demand for biomass is currently projected to (substantially) exceed sustainably available supply. As a result, the EU risks either increasing biomass harvesting levels beyond what is sustainable (thereby undermining the LULUCF net sink) or increasing the import of biomass from regions outside the EU (thereby exporting environmental pressures to outside the EU). This risk could be mitigated by better targeting incentives for biomass use to sectors that have limited other mitigation options. However, key EU policies such as the RED III ([56]) do not differentiate incentives for bioenergy use as a function of other available mitigation options for each end use **(policy gap)**.

Recommendation L2. EU policies should better target incentives for bioenergy use towards end uses with limited mitigation options, to reduce the risk that aggregate demand will exceed sustainably available supply.

Recommendation L3. The EU should start preparations now with the view to introduce a GHG pricing instrument in the LULUCF sector, as to provide a financial incentive for forest managers to reduce emissions and increase removals. This would counterbalance current price incentives for biomass use (see also Chapter 10 'Pricing emissions and rewarding removals').

The potential of reducing CO2 emissions and emission removals in other land use categories (mainly agricultural land) remains under-addressed by EU policies.

Needs. Reducing net CO_2 emissions in non-forest land use categories (e.g. through sustainable soil carbon management practices and agroforestry) can contribute to increasing the overall LULUCF net sink, which is particularly important given the challenges in increasing the forest carbon sink. Whereas net emissions from these non-forest land use categories have reduced by 24 % compared to 2005, they have partially rebounded in recent years. To be consistent with the European Commission's scenarios that underpin the 2030 – 55 % objective, their net emissions need to be reduced by 12 % by 2030 and 75 % by 2050 compared to 2021.

Gaps. The CAP is the strongest policy driver of agricultural land use decisions. It includes both mandatory (e.g. GAECs 1 and 2 on wetland and grassland preservation) and voluntary (e.g. eco-schemes to support 'carbon farming' ([57]) and agroforestry) provisions that aim to reduce emissions from and increase

([56]) The exception is electricity-only generation, which cannot receive new or renewed support except when used in specific just-transition regions with high dependence on solid fossil fuels, as a temporary measure in outermost regions and territories, or in combination with CCS.

([57]) See (EC, 2021u) for an overview of the different practices covered under this term.

emission removals in agricultural soils. However, there are reasons for concern about the effectiveness of these measures. The mandatory requirement on the maintenance of grasslands (GAEC 1) does not prevent agricultural practices that lead to high soil carbon emissions from grasslands **(ambition gap)**. Whereas most Member States have set targets on carbon storage in soil and biomass, only eight of them included voluntary eco-schemes to incentivise carbon farming, often with low levels of ambition **(implementation gap)**. The assessment result is more positive for agroforestry, with a majority of Member States supporting it either directly or indirectly under the CAP. However, the effectiveness of these national support schemes is still suboptimal owing to their limited scope (which relates to a more general concern about the expected effectiveness of eco-schemes; see also Chapter 8 'Agriculture') **(implementation gap)**.

The agriculture and LULUCF sectors are currently still excluded from the EU GHG-pricing regime, which also implies a lack of an overall financial incentive for farmers and land managers to enhance CDR **(policy gap)**. The Carbon Removal Certification Framework, which is currently under development, might create such an incentive, but only to the extent that it creates a voluntary market.

Recommendation L4. Overall, EU policies should provide stronger incentives to trigger emission reductions and removals in all land use categories, including agricultural soils. This could be achieved by making better use of the potential of the CAP, and by pricing GHG emissions and rewarding removals in the LULUCF sector (see also recommendation L3 above and Chapter 10 'Pricing emissions and rewarding removals'). The Advisory Board will publish a dedicated report on the topic of CDR in 2024, including more detailed recommendations on how they should be governed and incentivised at the EU level.

Climate adaptation is crucial to maintain and possibly even increase the net sink in the LULUCF sector. At the same time, even with increased adaptation efforts, the future of the net sink is uncertain.

Needs. The LULUCF sink is increasingly under pressure from natural disturbances, which are exacerbated by climate change, a trend that is projected to worsen in the future. This highlights the need for increased adaptation efforts, such as (in many places) shifting conifer monocultures to mixed-species or broadleaf forests. Such adaptation efforts might decrease the sink in the short term (as maladapted species are harvested) but would increase it in the future (as newly established trees grow and losses from natural disturbances are reduced). Furthermore, it highlights the need to account for uncertainty when relying on removals in the LULUCF sector to achieve overall climate objectives.

Gaps. The assumptions that underpin the LULUCF objective for 2030 did not account for the uncertain effects of climate change and related natural disturbances on the development of the sink **(policy gap)**. The European Climate Risk Assessment will include an assessment of the potential impacts of climate change on the forestry sector, which can provide a good knowledge basis for the future.

Recommendation L5. To cope with the uncertainties of climate change, the EU and its Member States should increase efforts on adaptation.

Recommendation L6. In parallel, the EU should develop a contingency strategy to manage the potential impacts of climate change on the LULUCF net sink. The contingency strategy should include an assessment of the potential development of the LULUCF sink under different climate change scenarios and explore the potential for further reductions in residual emissions or increases in technological emission removals to cope with a further decline in the LULUCF sink.

9.1 Scope and sectoral assessment framework

Scope

This chapter covers all GHG emissions and removals by the EU LULUCF sector, as reported to the UNFCCC under CRF category 4. It focuses particularly on emissions and removals by forests (afforestation, deforestation and forest management), which is by far the largest land use category in terms of net GHG removals, but also the main driver behind the observed decline in the net sink observed over the last decade (see Section 9.2 below). Emissions and GHG removals in other land use categories (crop-, grass-, wet- and peatlands) are also covered under this chapter, but in less detail. The Advisory Board will publish a separate, dedicated report on CDR in 2024, which will cover the topic in more detail, as well as the removal of CO_2 from the atmosphere through novel technologies such as BECCS and direct air carbon capture and storage (DACCS).

Emissions and removals in the LULUCF sector are governed by the LULUCF Regulation (EU, 2023j), which allocates binding targets to Member States. Each Member State will have to implement policies at the national level to achieve these objectives. If a Member State does not achieve its national objective, it can make use of several flexibilities set out in the regulation. Achieving the regulation's objective depends on policies to be defined by each Member State. The European Commission's assessment of the draft updated NECPs found that the majority of those draft updated do not show sufficient ambition and action on the LULUCF sector, with only very few Member States showing a concrete pathway to reach their national net removal targets (EC, 2023p). In aggregate, Member States' action in the sector would still lead to a gap of -40 to -50 Mt CO_2e compared to the 2030 target.

Whereas ambitious national action will be crucial for achieving the 2030 LULUCF objective, the policy consistency assessment in this chapter focuses on to what extent other EU policies facilitate or hamper the achievement of this objective.

Greenhouse gas emission reductions and removals required in the LULUCF sector to reach climate neutrality

Achieving overall climate neutrality requires a balance between anthropogenic GHG emissions ('residual emissions') and the removal of GHGs from the atmosphere. Currently, CDR in the LULUCF sector is the only available option to remove GHGs from the atmosphere at a large scale. In the future, this is expected to be complemented by CDR technologies such as BECCS and DACCS (IPCC, 2018).

The LULUCF sector in the EU is a net sink, removing 230 Mt CO_2e from the atmosphere in 2021 (EEA, 2023f). The EU has set a legally binding objective under the LULUCF Regulation to reach an annual net sink of 310 Mt CO_2 by 2030 (EU, 2023j). The impact assessment for that regulation states that, in order to achieve overall climate neutrality by 2050, net removals in the LULUCF sector should increase to 400 Mt CO_2e by 2050 (EC, 2021r). This corresponds to the 400 Mt CO_2e upper limit of the range of GHG removals in the LULUCF considered to be feasible under the Advisory Board's advice on the EU's 2040 reduction objective (ESABCC, 2023b), considering future impacts of climate change. Under those scenarios where net reductions reach 90–95 % by 2040, the LULUCF sink increases to approximately 300 Mt CO_2e by 2030, with a slight further increase by 2040 (325 Mt CO_2e), after which it levels off by 2050.

Assessment framework for the LULUCF sector

The following building blocks were identified to achieve the required net GHG removals in the LULUCF sector by 2050.

Outcomes. IPCC AR6 has identified several mitigation pathways (see mitigation levers below) that can reduce GHG emissions and increase GHG removals in forests and other ecosystems (IPCC, 2022a). Overall, these pathways aim to achieve either of the following goals, which have been selected as outcomes for the assessment in this chapter.

— **Maintain or expand the surface area of carbon-rich land use categories**, that is, land use categories with high carbon stocks or carbon sink ([58]) potential, primarily forests and wetlands.
— **Reduce emissions and increase emission removals** within each land use category.

Mitigation levers. To achieve these outcomes, five main levers were identified ([59]), which largely correspond to the main mitigation pathways included in Sections 7.4.2 and 7.4.3 of Working Group III's contribution to AR6 (IPCC, 2022a).

1. **Reducing deforestation and forest degradation** can reduce GHG emissions in the LULUCF sector on a short timescale (IPCC, 2022a). Whereas globally the highest potential lies in tropical forests, deforestation is still occurring in the EU-27 as well, causing approximately 30 Mt of CO_2e emissions each year (EEA, 2023h).
2. **Afforestation, reforestation and forest ecosystem restoration** can increase GHG emission removals. The level of emission removals per hectare is relatively low in the initial years, but then increases over time as trees start to grow. In the longer term, removals decrease again as forests reach maturity (EEA, 2023o).
3. **Avoiding conversion and degradation of wetlands and other organic soils** avoids high emissions per hectare on a short timescale, whereas **restoring** these land types can increase removals over a longer timescale (Humpenöder et al., 2020; IPCC, 2022a).
4. **Improved forest management** can increase the carbon stocks in existing managed forests, through a variety of practices such as longer rotations, less intensive harvests, continuous-cover forestry, change of species and provenances, and increasing resilience to avoid the risk of hazards (e.g. fires, windfall, pests and diseases) (IPCC, 2022a).
5. Certain agricultural practices can increase carbon sequestration on agricultural lands, both in the soil and in above-ground biomass. These include **sustainable agricultural soil management practices** (e.g. cover crops, reduced tillage, residue retention and improved water management) and **agroforestry** (the integration of woody vegetation on agricultural land used for grazing or crop production) (IPCC, 2022a; Kay et al., 2019; Sykes et al., 2020).

In addition to increasing the carbon stock in living biomass, some of the practices under levers 1, 2 and 4 can also increase carbon stocks in forest soils (see Box 5).

Enabling conditions. In addition, the following enablers were identified, which could support the various levers. This list is not exhaustive.

— The availability of land determines the potential for the expansion of land use categories with high carbon sequestration potential such as forests and wetlands (Searchinger et al., 2022b). It can be increased by **more efficient spatial planning** to reduce land take and urban sprawl (Metternicht,

([58]) A carbon stock is the total amount of carbon stored in an ecosystem, either in biomass or in soils. A carbon sink is the annual increase in the total carbon stock, in other words the amount of carbon that is removed from the atmosphere and added to the biosphere carbon stock in a certain year.

([59]) The conservation and restoration of grasslands is included as a mitigation pathway in the IPCC AR6, but not included as a mitigation lever in this chapter. This is because most of Europe's climate is suitable for forest ecosystems, which have a higher carbon sequestration potential than grasslands. Whereas reducing the conversion of grasslands to croplands can reduce emissions (and conversely the restoration of croplands to grasslands can increase removals), the conversion of crop- or grasslands to forests has an even higher GHG mitigation potential.

2018). Similarly, **reduced livestock production** (which require large amounts of land for feed production) (Leip et al., 2015) and **reduced food waste** (Philippidis et al., 2019) can reduce the area of land required for agricultural production.

- Keeping the **demand for biomass for GHG mitigation purposes** ([60]) **within sustainable limits** can support the mitigation levers in two ways. Keeping demand for woody biomass within sustainable limits avoids overharvesting of managed forests, which would lead to a decrease in the forest carbon sink (and even risking turning it into a source). Reduced demand for crops for biofuel production can reduce the land required for agricultural production, thereby increasing the land available for, for example, afforestation.
- **Price signals and financial incentives** can influence decisions on land use and land management (Kim and Langpap, 2015).
- **Enhancing climate adaptation/resilience** is key to maintaining the carbon stock and sink activity in EU forests and ecosystems, which are currently already under pressure from climate change impacts (Forzieri et al., 2022; Patacca et al., 2023). For example, the decrease in the forest carbon sink observed in recent years is partly due to natural disturbances such as pest outbreaks (bark beetles), storms and wildfires, all of which are projected to become more frequent and more intense as a result of climate change. Improving the resilience of forest and ecosystems against such disturbances can mitigate future carbon losses.

There are strong links between climate mitigation, climate adaptation, and biodiversity preservation and restoration. In most cases, there is potential for strong synergies. For example, maintaining and restoring carbon-rich ecosystems such as forests and wetlands contribute to climate mitigation, climate adaptation and biodiversity objectives. However, in some cases trade-offs might also occur; for example, rewetting afforested land might be beneficial from a nature and biodiversity perspective, but would reduce the carbon sink in the LULUCF sector. Although a detailed assessment of such potential synergies and trade-offs is beyond the scope of this report, it is important to taken them into account when developing policies affecting the LULUCF sector.

Finally, it is important to note that all land use categories are subject to carbon saturation, which means their potential to serve as a carbon sink will decrease over time and finally reach zero (EEA, 2023o). When this will occur depends on the type of land use, the point of departure and the specific measures taken to increase the carbon sink. From a policy perspective, this means that, whereas the LULUCF sector can contribute to climate neutrality by 2050, it cannot continue to offset residual emissions forever, and therefore provides only a temporary solution for residual emissions.

The assessment framework for the LULUCF sector – including the indicators selected to track progress for this sector (see white boxes) – are shown in Figure 64.

([60]) That is, demand for biomass to replace fossil fuels and feedstocks and other GHG-intensive materials.

Figure 64 Assessment framework for the LULUCF sector

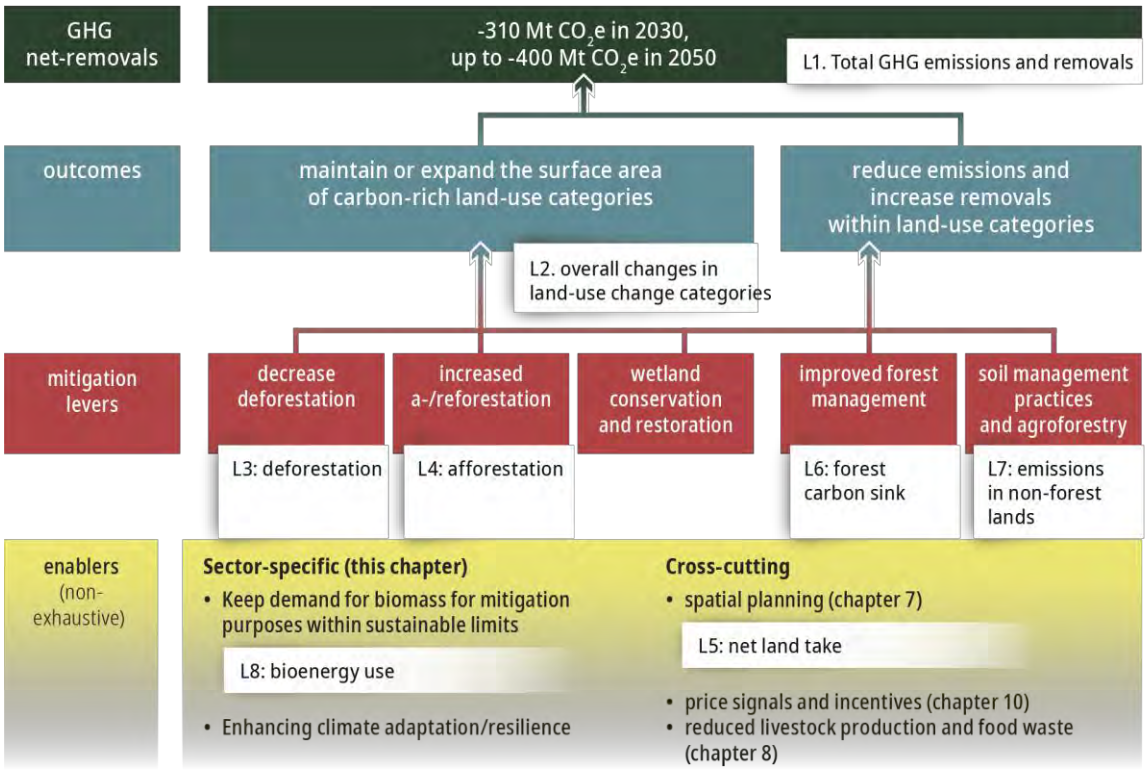

Source: Advisory Board (2024).

9.2 Emission reduction progress

As shown in Figure 65, the EU LULUCF sector is a net sink of GHG emissions, with gross emission removals in forest lands and in harvested wood products larger than the GHG emissions from other land use categories. However, after relative stability in 2005–2013, the net sink has been declining rapidly in the last 10 years, and in particular since 2016. By 2021, the total net sink had decreased by approximately one third (removing 112 Mt CO_2e less) compared to 2005. The reduction in the net sink was predominantly caused by a reduced carbon sink in EU forests (removing 134 Mt CO_2e less in 2021 than in 2005), which was driven by slower forest growth, natural disturbances and increased harvesting (see Figure 69 for more details). Proxy data for 2022 indicates a slight increase in the net sink compared to 2021.

The trend observed in the last decade would need to be reversed for the EU to meet the legally binding objective for 2030 (310 Mt CO_2e net removals). After 2030, the sink should be further increased to align with the European Commission scenarios underpinning the 2050 climate neutrality objective, and the scenarios underpinning the Advisory Board's advice on a 2040 reduction objective and the 2030–2050 GHG emission budget.

Figure 65 Indicator L1 – overall progress in reducing emissions (positive values) and increasing removals (negative values) in the LULUCF sector

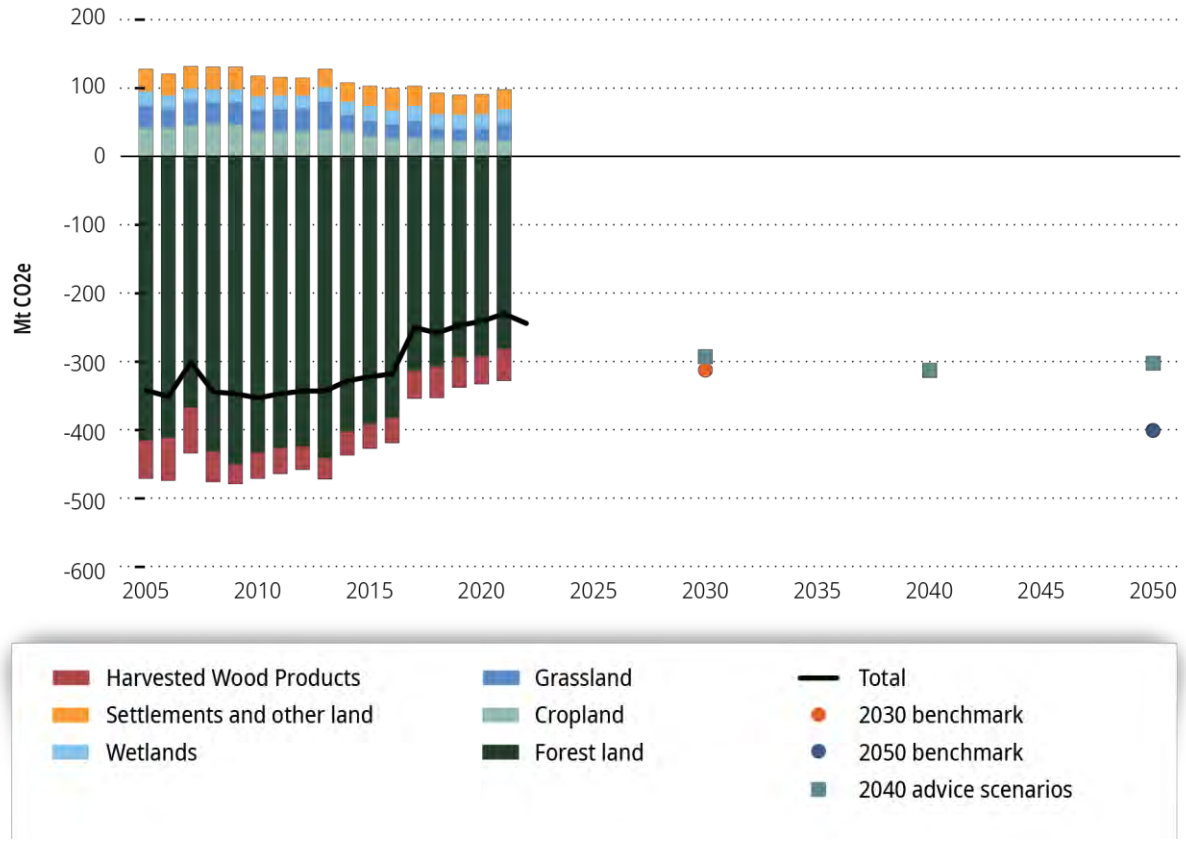

Notes: Historic data from the EU GHG inventory, with 2022 data based on proxy data reported to the EEA. 2030 benchmark based on the legally binding objective under the LULUCF regulation, while 2050 benchmark based on the impact assessment accompanying the revised LULUCF regulation. 2040 advice values are based on the scenarios that underpin the Advisory Board's 2040 advice.

Sources: EU GHG inventory (EEA, 2023f), LULUCF regulation impact assessment (EC, 2021d), Advisory Board 2040 advice scenarios (ESABCC, 2023b).

9.3 Outcome 1: maintained or expanded surface area of carbon-rich land use categories (forests and wetlands)

Progress on expanding forest and wetland areas

There have been limited changes in total area for each land use category since 2005.

As shown in Figure 66, there have been relatively limited changes in the total area for each land use category since 2005. The most noticeable change has been a decrease in cropland (– 6 million ha, or – 5 % compared to 2005) and an equal increase in settlements (+ 3 million ha, or + 13 % since 2005) and forest land (+ 3 million ha, or + 2 % compared to 2005). The area of wetlands has also increased, but to a lesser extent (+ 0.2 million ha, or + 1 % compared to 2005).

Figure 66 Indicator L2 – change in surface area per land use category (2021 compared with 2005)

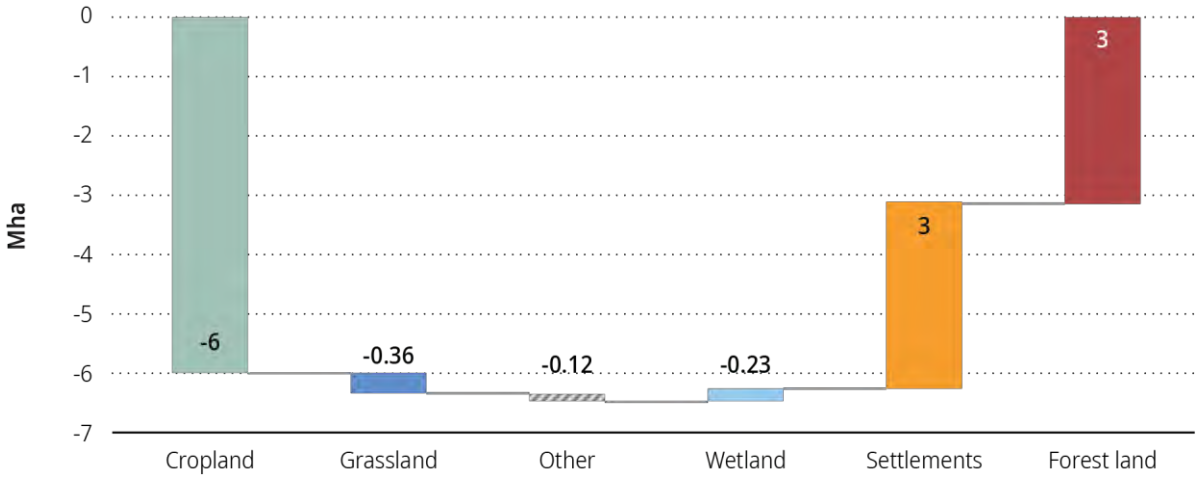

Notes: No benchmarks were found for 2030 or 2050.

Source: EU CRF tables (EEA, 2023h)

Net afforestation declined in 2005–2010 and has remained relatively stable since, driven by declining afforestation in combination with stable deforestation.

Whereas the total surface of forest land has increased since 2005, the rate at which it increased (the net afforestation rate) declined in 2005–2010 as a result of decreasing afforestation and stable deforestation, as shown in Figure 67. Both afforestation and deforestation have been relatively stable since.

Figure 67 Indicators L3 and L4 – afforestation and deforestation in the EU

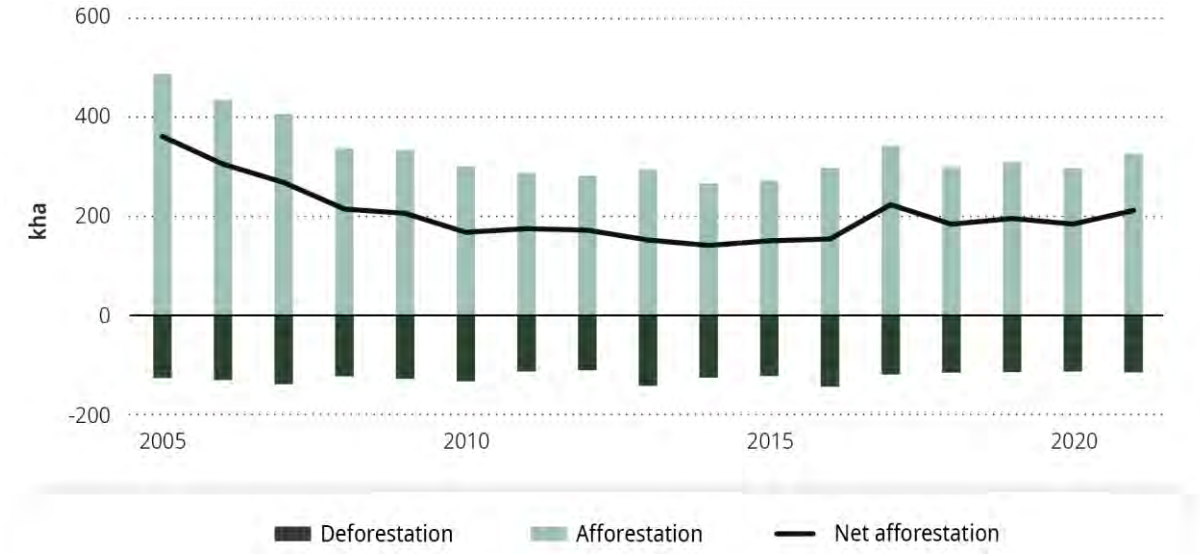

Notes: No benchmarks were found for 2030 or 2050

Source: EU CRF tables (EEA, 2023h)

The EU Biodiversity Strategy includes a pledge to plant 3 billion additional trees by 2030, for which a roadmap was included under the Forest Strategy (EC, 2021n, 2020e). To achieve this objective, the EU would need to plant on average 333 million additional trees per year in 2022–2030. However, 2 years

after the pledge only 12.5 million additional trees have been reported as planted, which is far below the required rate (EEA, forthcoming). The Advisory Board has not been able to assess whether this low figure is due to lack of planting or lack of reporting. Furthermore, even if the objective is achieved, it will only make a modest contribution to the LULUCF sink, generating 15 Mt CO_2e of additional removals by 2050 (Korosuo et al., 2023).

A faster reduction of deforestation would be a quick win to increase the LULUCF carbon sink in the short term, whereas increased afforestation increases the carbon sink gradually over time, as it takes time for young forests to sequester carbon (Korosuo et al., 2023). About half of the deforestation observed in 2005–2021 is driven by the expansion of settlements (EEA, 2023h). Decreasing net land take (see indicator L5) could therefore be expected to contribute to decreasing deforestation.

The decrease in net land take for settlements has slowed down in recent years.

As shown in Figure 68, the total surface of settlement area increased by 13 % in 2005–2021, but the rate at which it did so fell between 2005 and 2017 (EEA, 2023h). However, since then the rate has been relatively stable. The downward trend over the longer term needs to be continued to put the EU on track towards achieving no net land take by 2050, in accordance with the ambition of the 7th Environmental Action Programme (EU, 2013a). An even faster decrease could support the overall LULUCF objective by reducing deforestation (see indicator L4 in Figure 67) and increase the surface land available for carbon sequestration.

Figure 68 Indicator L5 – annual increase in settlement area (as proxy for net land take)

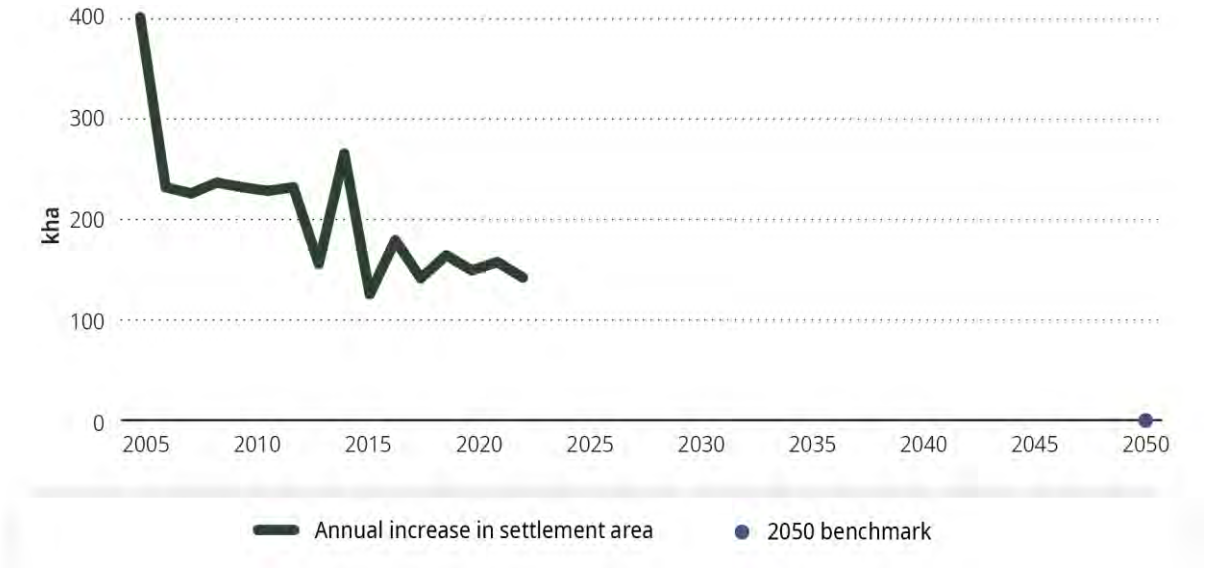

Sources: EU CRF Tables (EEA, 2023h) (historic), 7th Environment Action Programme (EU, 2013a) (benchmark)

Consistency of EU policies

EU policies are driving land use for agricultural production, thereby reducing the potential for maintaining and expanding forests and wetlands.

Section 9.1 identified several enabling conditions that could reduce the demand for land for settlements and agricultural production, thereby reducing pressure on carbon-rich land use categories and increasing the amount of land available for their expansion.

Whereas spatial planning is predominantly a (sub)national competence, there are some areas where EU policies can facilitate more efficient spatial planning, which could, among other effects, reduce land demand for human settlements. These are further discussed in Section 7.5.

The EU has more competences in other areas such as agriculture, transport and energy, which could be used to limit land for agricultural production (including for biofuel crops) and therefore increase the amount of land available for carbon sequestration. However, as further detailed below, there are some EU policies in these policy domains that put upward pressure on land demand for agricultural production.

For example, livestock production is particularly land-intensive: animal feed accounts for 61 % of the EU's total cereal production (EEA, 2023o), and livestock systems (including feed production) occupy around 65 % of total agricultural land (or 28 % of the EU's total land surface) (Leip et al., 2015). Reducing livestock production would not only reduce emissions directly (less GHG emissions from enteric fermentation and manure) and indirectly (less fertiliser use for feed crop production) but could also free up substantial amounts of land that could be used for carbon sequestration (e.g. afforestation). However, there are few EU policies in place that aim to reduce demand for livestock products, and the current CAP continues to financially support livestock production (see also Chapter 8 'Agriculture').

The CAP does include a number of provisions to maintain and increase the area of grass-, wet- and peatlands (EU, 2021d). Firstly, the minimum environmental requirements under the CAP include the mandatory requirement to maintain permanent grassland (GAEC 1) and the protection of wet- and peatlands (GAEC 2). Secondly, Member States can (financially) support the rewetting of wet- and peatlands, and the establishment, maintenance and extensive use of grasslands, through eco-schemes and agri-environmental measures. However, there are several elements of the CAP that undermine its effectiveness at expanding or even maintaining the area of carbon-rich land use categories. Firstly, the overall approach of the CAP is to provide payments per hectare of land cultivated. This approach incentivises farmers to continue to cultivate organic soils, which causes high CO_2 emissions, and to cultivate less productive land, which might be more suitable for afforestation and the restoration of grasslands and wetlands (EEA, 2022h). Furthermore, the majority of EU Member States have chosen to delay the implementation of GAEC 2 (on the conservation of peatlands) to 2024 or 2025 (EC, 2022aa). Finally, some peatland-rich Member States have not included any voluntary support schemes for rewetting peatlands, and in those that have done so the schemes are not expected to lead to substantial changes in land management practices (Birdlife Europe and EEB, 2022; Midler et al., 2023).

As further described in Chapter 8 'Agriculture', the Farm to Fork Strategy includes a range of objectives to reduce local environmental pressures from agricultural production, such as increasing the share of organic farming and reducing the use of mineral fertilisers. However, whereas such measures can reduce environmental impacts (including GHG emissions) locally, they are also expected to result in lower yields (JRC, 2021b). Therefore, unless they are complemented by policies to reduce demand for agricultural products (which are largely missing regarding reduced livestock consumption; see Chapter 8 'Agriculture'), they risk increasing overall land demand for agricultural production either in the EU or abroad.

Finally, EU policies in the domain of transport fuels continue to incentivise the demand for (and therefore production of) crop-based biofuels, which contribute further to land demand for agricultural production (see also Section 6.4, under 'Lever: fuel switches', and Section 8.5, under 'Lever: minimise demand for biofuel crops').

Even if there has been a slight decline in the total area of croplands in the EU (– 5 % since 2005; see Figure 66), the abovementioned policies put upward pressure on the area of land required for

agricultural production. Changes to these policies could reduce this pressure, freeing up larger areas of land available for carbon sequestration through afforestation/reforestation and wetland restoration.

9.4 Outcome 2: reduced emissions / increased removals within land use categories

Progress on increasing removals in EU forests

Despite the increasing forest area, the net carbon sink in EU forests is declining. The decline needs to be reversed to be consistent with the scenarios underpinning the EU climate objectives.

Despite the net afforestation occurring in the EU (see indicators L3 and L4 in Figure 67), the forest carbon sink has been declining rapidly, primarily because of a slowing down of the annual growth in living biomass which accounts for > 80 % of the total forest carbon sink (see Figure 69). In the last 5 years, the net carbon sink in forests declined by on average 8 Mt CO_2e per year. This trend would need to be reversed to be consistent with the scenarios underpinning the EU climate objectives. Under the MIX scenario of the Climate Target Plan, the forest carbon sink would need to increase to 380 Mt CO_2e by 2030 and 450 Mt CO_2e by 2050.

Box 5 The role of forest soils in the carbon sink and stock

As shown in Figure 69, growth in living biomass accounts for the large majority (between 80 % and 90 % in 2005–2021) of the total forest carbon sink, with deadwood, litter and soils accounting for the remaining 10–20 %. However, forest soils represent the largest carbon stock in forests, with a total carbon content estimated to be 2.5 times larger than the carbon stock in tree biomass (see footnote 58 for the difference between the carbon sink and the carbon stock) (De Vos et al., 2015). Furthermore, the role of forest soils as a carbon sink and stock can be further increased through forest management practices.

The French National Research Institute for Agriculture, Food and Environment launched a study (Augusto and Boča, 2022) to identify the characteristics of forests that would optimise carbon sequestration in soils. It found that it is important to have a significant amount of tree biomass in forests, which would produce a lot of debris (leaves, needles and dead roots) that contributes to the carbon stock in the soil. Furthermore, forests made up of a mixture of two species can store more carbon than forests with a single species, provided that the mixed forests grow faster than the single-species ones. But it is the characteristics of the dominant tree species in combination with the climate zone and soil type that most control the capacity of forests to store carbon in soils. Even though some questions remain to be further explored in more detail, the results of the study show that encouraging a significant biomass of trees, through extensive management or a mixture of species, is a practice that should be encouraged provided that the environmental risks to which the forest is exposed are carefully assessed (fires, drought, etc.). Above all, it is important to choose the species of trees carefully, favouring species ecologically adapted to the climate and soil of the region where they are planted.

Figure 69 Indicator L6 – changes in the forest carbon sink

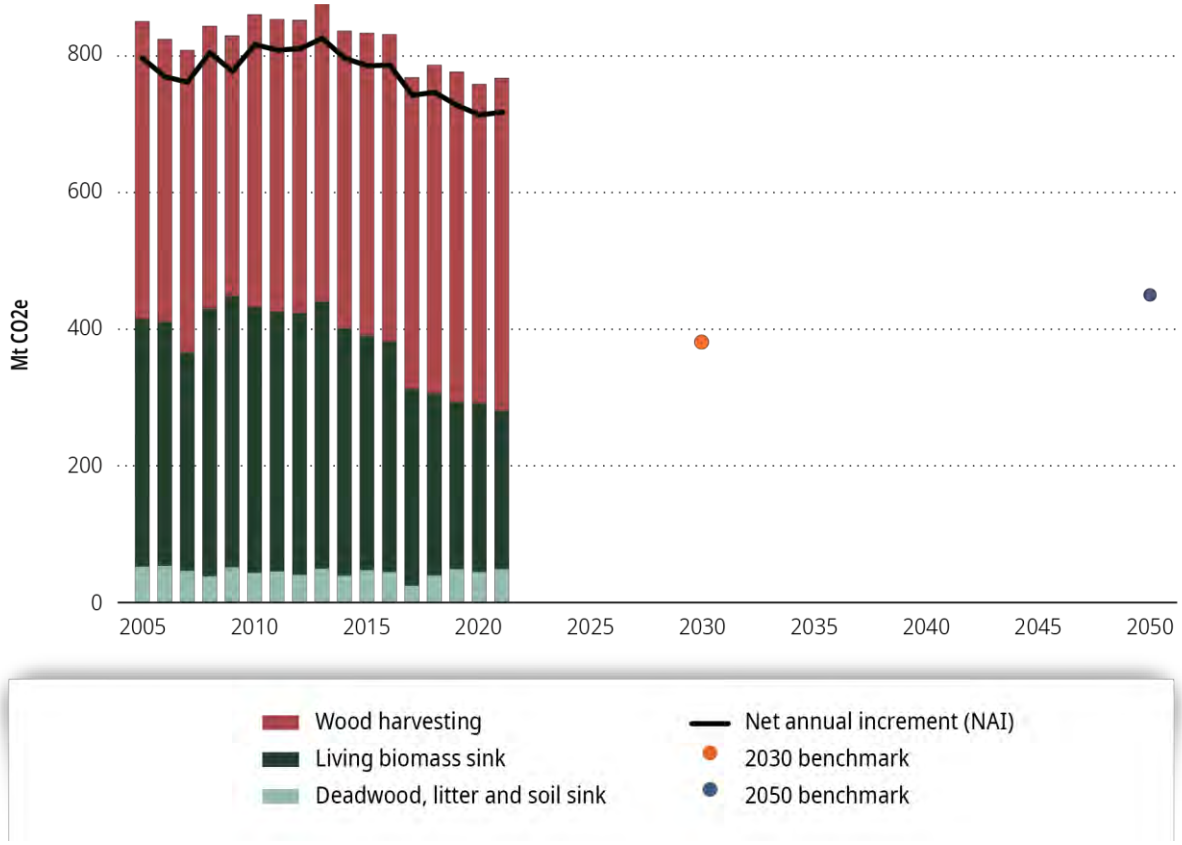

Notes: Wood harvesting data converted from m^3 to Mt CO_2e based on standard conversion factors. The Net Annual Increment was approximated as the sum of the forest carbon sink and wood harvesting. 2030 and 2050 benchmarks are based on the MIX scenario from the Climate Target Plan impact assessment.

Sources: EU GHG inventory (EEA, 2023h). FAO Statistics on Forestry Production and Trade (2020), Climate Target Plan impact assessment (EC, 2020s) (Figure 10).

The decline in the forest carbon sink is driven by multiple, interlinked drivers, including forest age, biomass demand and climate change impacts.

Forests have long production cycles (from 15 to more than 250 years), which means that changes in the forest sink over a few years could be (but are not necessarily) compatible with long-term sustainable forest management. The observed decline in the carbon sink in the last 10 years is caused by several underlying trends, including a slowdown in net afforestation (see indicators L3 and L4 in Figure 67 above), a decrease in gross annual increment (that is, forest biomass growth before taking into account natural mortality and harvesting), increased mortality (worsened by natural disturbances) and increased harvesting (Korosuo et al., 2023). This is also illustrated in Figure 69, which shows a declining net annual increment (NAI) ([61]) since 2013, and an increase in wood harvesting. These trends are driven by multiple, interlinked drivers.

([61]) The NAI is defined as the gross annual increment (gross forest growth) minus the natural mortality. Part of the NAI is harvested; the remaining biomass growth represents the net carbon sink. See Figure 2 in (Korosuo et al., 2023) for more details. Natural disturbances have an impact on both natural mortality (e.g. if a tree is burned in a wildfire) and harvesting

— **Forest age** determines the forest growth rate (EEA, 2023o). Trees grow slowly when they are young, resulting in a small annual carbon sink. The growth rate then accelerates as they grow older (which increases the carbon sink), after which it starts to slow down again as the tree reaches maturity. As a result, the average age of a forest determines the forest growth rate and consequently the carbon sink. Furthermore, forest age also influences harvesting rates, as forest managers are likely to harvest trees when they reach a certain size. Finally, forests with older trees are also more vulnerable to natural disturbances, which could result in carbon stock losses and related emissions both directly and indirectly (see Figure 70). As forests in the EU do not have even age structures, there will be fluctuations in the carbon stock and sink, even if management and growth conditions are unchanged.
— **Biomass demand** is a driver of harvesting rates (De Oliveira Garcia et al., 2018), and increased biomass demand could therefore lead to a net decrease in the forest carbon sink and even a net decrease in the carbon stock (in which case it would result in net emissions). On the other hand, it is argued by some that biomass demand could also incentivise afforestation and forest management practices that improve forest productivity, which would increase the carbon sink (Berndes et al., 2022), although other research found no or only weak evidence to support this claim (Giuntoli and Searle, 2019). It is also suggested that biomass supply could be increased through forest management practices without affecting long-term carbon storage (Gylling et al., 2023) but, again, the aggregate effect necessarily depends on the specifics.
— **Climate change** is expected to increase the frequency and intensity of natural disturbances that undermine the sink potential of EU forests either directly (increased mortality) or indirectly (increased sanitary or salvage logging) (Korosuo et al., 2023; Seidl et al., 2017). Forest management practices to adapt forests to projected climate change impacts can increase resilience against such disturbances but might require increased harvesting in the shorter term (see also Section 9.5 for more details).

Figure 70 Overview of drivers affecting the forest carbon sink and carbon stock

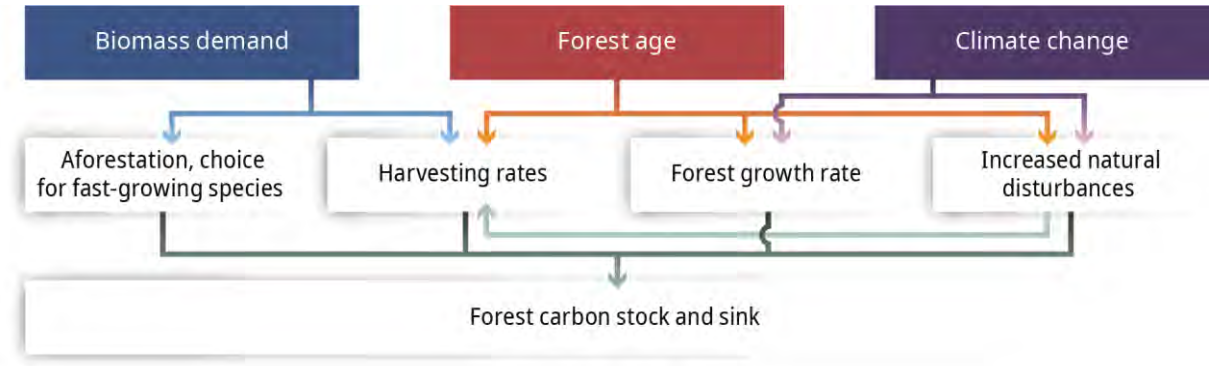

Source: Advisory Board (2024).

Increasing the forest carbon sink is possible only by reducing the share of the NAI that is harvested, either by increasing the NAI more than the increase in harvested woody biomass or by decreasing harvesting compared with the NAI. This would require more effort than the traditional concept of sustainable forest management, which is understood as ensuring that harvesting does not exceed the NAI (Korosuo et al., 2023).

(when a tree is cut for sanitary or salvage purposes). There is an inverse correlation between natural mortality and harvesting, as the non-harvesting of trees will eventually increase natural mortality and vice versa. In its assessment, the Advisory Board has assumed a constant natural mortality for simplicity.

Consistency of EU policies with the aim of increasing the forest carbon sink

The observed decrease in the forest carbon sink has been linked to EU bioenergy policies and the increasing occurrence of natural disturbances, exacerbated by climate change. These topics – including the role of EU policies – are assessed in more detail in Section 9.5 below, as they are relevant to the overall LULUCF sector.

Progress on reducing emissions and increasing removals in other land use categories

Net emissions are decreasing, but the pace needs to double beyond 2030.

Although forests make up the largest share of the LULUCF sector, reducing net emissions in other land use categories can contribute to enhancing the overall sink. Between 2005 and 2021, net GHG emissions in these other land use categories decreased by 24 %, as shown in Figure 71. This was mainly achieved by reductions of soil carbon emissions in croplands (– 46 %, – 19 Mt CO_2e), grasslands (– 23 %, – 8 Mt CO_2e) and settlements (– 14 %, – 5 Mt CO_2e), whereas emissions from wetlands increased slightly (+ 5 %, + 1 Mt CO_2e). However, reported data show a rebound in emissions in recent years. The average pace of reductions in the last 5 years (1.5 Mt CO_2e) would need to be maintained until 2030, and then double (to 3 Mt CO_2e per year) to be consistent with the European Commission scenarios underpinning the EU climate objectives.

Figure 71 Indicator L7 – net GHG emissions in non-forest land use categories

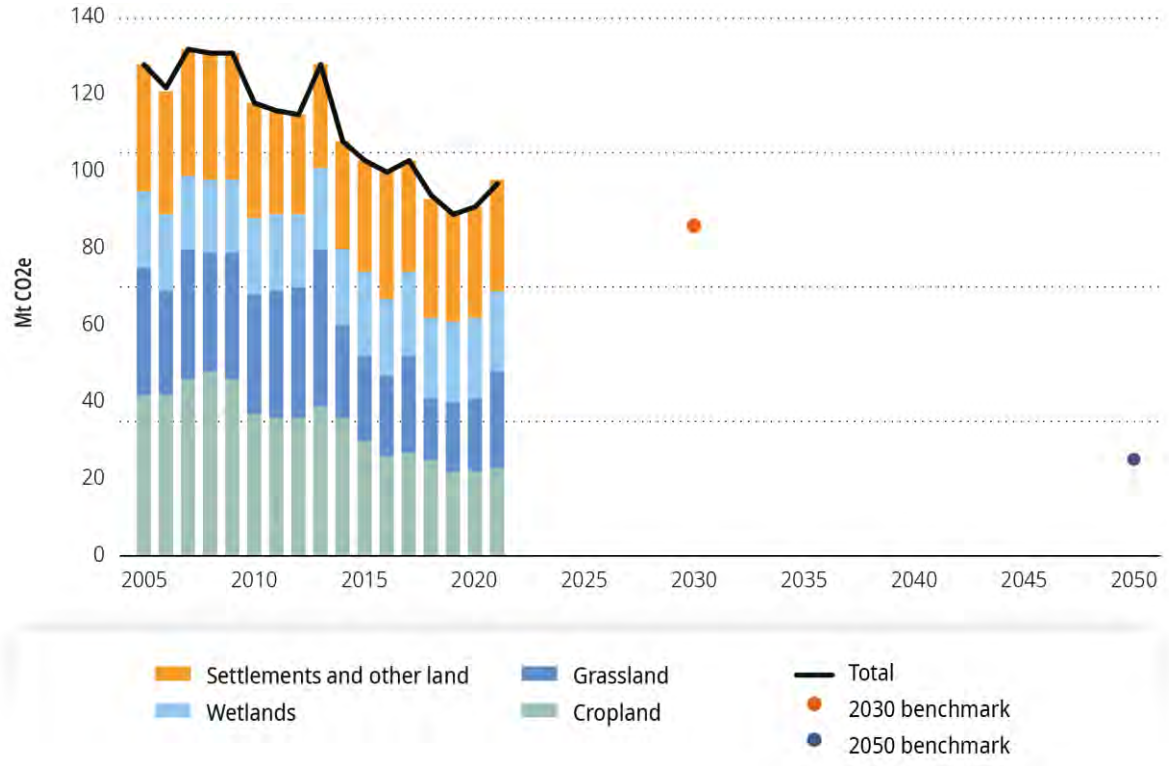

Notes: 2030 and 2050 benchmarks are based on the MIX scenario from the Climate Target Plan impact assessment.

Sources: EU GHG inventory (EEA, 2023h), Climate Target Plan impact assessment (EC, 2020s) (Figure 10).

Consistency of EU policies with the aim of reducing emissions from other land use categories

The EU has few policies to incentivise carbon sequestration in crop- and grasslands.

Whereas there are several agricultural practices to enhance carbon sequestration in crop- and grasslands, there are currently only a few EU policies to incentivise this. The CAP does allow Member

States to support such measures under eco-schemes, but only eight Member States have chosen to do so (EC, 2022aa). Furthermore, permanent grasslands are defined in such a way that the mandatory requirement on the maintenance of permanent grasslands (GAEC 1) does not prevent ploughing and tilling, which are agricultural practices that lead to high soil carbon emissions from grasslands. Regarding agroforestry, some positive policy developments can be observed compared with the pre-2020 CAP. From 2007 to 2020, direct payments under the CAP were conditional on a maximum tree density (50 trees/ha in 2007–2013, 100 trees/ha in 2014–2020), which incentivised farmers to remove trees from arable land in order to receive such payments. This condition was removed in the CAP after 2020, which is positive for the promotion of agroforestry (Mosquera-Losada et al., 2023). Furthermore, the amount of national support schemes for agroforestry under the CAP has also increased. In 2007–2013, only five Member States supported agroforestry under the CAP, which increased slightly to eight Member States in 2014–2020. Under the latest CAP, 17 Member States have included eco-schemes to support agroforestry in their CSPs, either directly (4 Member States) or indirectly through support for landscape features (13 Member States), making it one of the most widely employed schemes (Buratti-Donham et al., 2023). Nevertheless, some room for improvement remains, as the national support schemes do not cover all types of agroforestry or support all phases (preservation of traditional systems, implementation of new systems and management of those new systems) (Buratti-Donham et al., 2023; Mosquera-Losada et al., 2023).

Furthermore, there is currently no (financial) incentive at the EU level for the agriculture and LULUCF sectors to enhance CDR. The European Commission recently took initiatives to start addressing this gap, including a proposal for a Union certification framework for carbon removals (EC, 2022w), and steps to explore the possibility of establishing a mandatory, separate emissions trading system for GHG emissions and removals in the land sector (EC, 2023bd). Both initiatives are described in more detail in Section 10.6.

The Advisory Board's upcoming report on CDR will provide a more detailed assessment and policy recommendations to enhance CDR, including in agricultural soils.

9.5 Enabling conditions

Keep biomass demand within sustainable limits

Biomass use can be an important mitigation lever, but can also have a negative impact on ecosystems, including on the net sink in the LULUCF sector.

According to IPCC AR6 (IPCC, 2022g), biomass has the potential to be a high-value and large-scale mitigation option, and could be particularly valuable for sectors with limited alternatives to fossil fuels (e.g. aviation, energy-intensive industry), for the production of chemicals and other products, and, potentially, in CDR by means of BECCS or biochar. However, the long-term role of bioenergy in low-carbon energy systems is uncertain because of sustainability concerns about traditional biomass and first-generation biofuels – which can have far-reaching impacts on food production, forestry, water use, land use and overall ecosystems – and cost-effectiveness concerns about more advanced biofuels.

In line with the IPCC guidelines for GHG inventories (IPCC, 2006), when biomass is harvested this is counted as an emission under the LULUCF sector. When the harvested biomass is then combusted for energy purposes, it is 'zero-rated', meaning that it is assigned an emission factor of zero, although biogenic GHG emissions are still reported as a memo item. This means that, whereas bioenergy can contribute to GHG emissions in other sectors, it can at the same time undermine the sink in the LULUCF sector (and thus achievement of the LULUCF objective). This is less of a risk when the harvested biomass is used as a material instead of being combusted (in which case it is reported as a sink under the

harvested wood product" category) or when bioenergy is combined with CCS (BECCS, in which case it should be accounted as a removal under CRF category I.C).

Bioenergy use in the EU has doubled since 2005 and is projected to more than double again by 2050 under the European Commission's decarbonisation scenarios.

The EU started to promote the use of biofuels in the electricity and transport sectors in the early 2000s (EU, 2001, 2003), and has continued to do so under the renewable energy directives, the EU ETS and the ESR.

Since 2005, bioenergy use has doubled from about 900 TWh in 2005 to 1 800 TWh in 2021 (see Figure 72). This was mainly driven by increased use for electricity and heat production (+ 512 TWh) and in 'other sectors' (mainly building heating, + 178 TWh), followed by the transport (+ 158 TWh) and industry sectors (+ 55 TWh). Based on the most recent data (2021), it is mainly used as input for electricity and heat production (41 %), followed by building heating (34 %), transport (14 %) and industry (11 %). Bioenergy is the main source of all renewable energy in the EU, accounting for 59 % of all renewable energy use in 2021 (EC, 2023bh).

As shown in Figure 72, the European Commission's scenarios underpinning the EU climate objectives assumed that bioenergy use could increase by 10 % between 2015 and 2030. However, in reality this increase was already exceeded in 2021. After 2030, the scenarios assumed, bioenergy use would again increase substantially, to double by 2050 compared with 2030, driven mainly by increased use in the power and heat sector combined with CCS (about 500 TWh more than in 2021) and in the transport sector (about 325 TWh more than in 2021, mainly for aviation and maritime transport). The total bioenergy use by 2050 under the European Commission's scenarios (> 2 800 TWh) would exceed the 20 EJ (or 2 500 TWh) ' high feasibility' threshold used for the Advisory Board's advice on the 2040 target (which is based on the High availability scenario from Ruiz et al (2019)).

Figure 72 Indicator L8 - bioenergy use

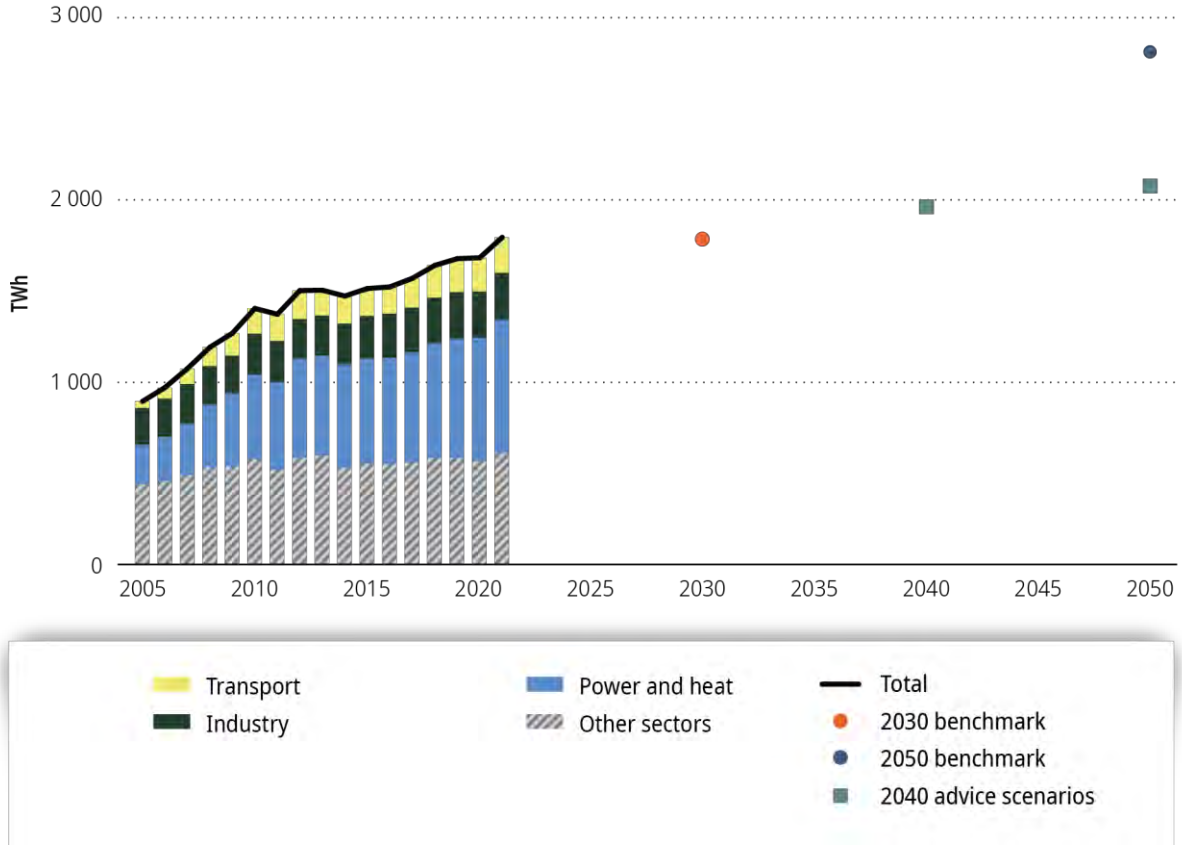

Notes: Historic data refers to final energy use in the industry, transport and other sectors, and transformation input for the power and heat sector. The "other sectors" is primarily dominated by residential buildings (ca. 85% of "other sectors'" bioenergy use in 2021), but also includes the tertiary and agriculture sector. 2030 and 2050 benchmarks are based on the MIX scenario of the Climate Target Plan impact assessment. 2040 advice range refers to the average bioenergy use in the scenarios which underpin the Advisory Board's advice for a 90-95% emissions reduction by 2040.

Sources: Eurostat energy balances (2023b), Climate Target Plan impact assessment (EC, 2020s) (Figure 77), Advisory Board 2040 advice scenarios (ESABCC, 2023b).

The increase in bioenergy contributed to an increase in forest biomass demand. At least 45 % of the increased forest biomass demand was met by increased harvesting.

The JRC has published data on woody biomass supply and demand for 2009 until 2017 (JRC, 2022b), which is shown in Figure 73. In that period, demand for woody biomass increased by more than 25 % (193 million m^3), primarily owing to an increase in demand for energy use (121 million m^3). At least 45 % of the increased demand in 2009–2017 was met by increased harvesting, with another 22 % being met through additional supply from unknown sources (which could also include harvesting). Only one third of the additional demand is known to have been met from additional secondary supply, which includes residues from wood-processing industries and post-consumer wood. The available data therefore shows a correlation between increased demand for woody biomass – primarily for energy purposes – and an increase in harvesting, which in its turn has contributed to the reduction of the forest carbon sink (see indicator L6 in Figure 69).

Whereas the JRC data covers only the period up to 2017, UN FAO data indicates that harvesting continued to increase, with volumes 8 % higher in 2021 than in 2017 (FAO, 2020). Similarly, Eurostat data indicates that the consumption of solid primary biofuels have increased with an additional 13 % by 2021 compared to 2017 (Eurostat, 2023b).

Figure 73 Supply (shown as positive values) and demand (shown as negative values) for woody biomass

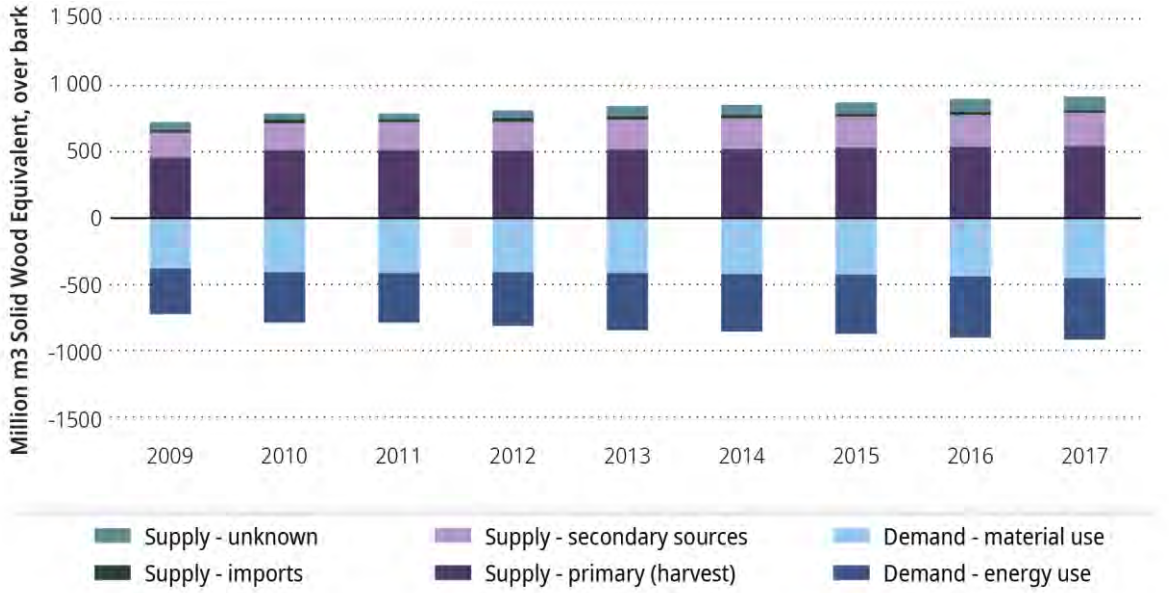

Source: Wood Resource Balances (JRC, 2022b)

The scientific debate on the consistency of EU bioenergy policies with the EU's overall climate objectives is ongoing.

There is an ongoing debate about the role of EU biomass policies in driving the observed decline in the LULUCF carbon sink (in particular in the forest carbon sink), and the mitigation impact of bioenergy in general. The most critical voices within the scientific community (see e.g. EASAC 2017; Blattert et al. 2023; Norton et al. 2019; Searchinger et al. 2022; Brack 2017) argue that the promotion of bioenergy by EU policies is the main culprit of the decreasing carbon sink and will put the EU climate targets for 2030 and 2050 out of reach. They argue that the use of primary woody biomass for energy production often increases atmospheric GHG concentrations in the short to medium term, and it can take up to decades or even centuries before it has a net mitigation effect. Finally, they have also warned that the promotion of bioenergy puts the EU biodiversity targets at risk. They have therefore called for a halt to policy support for the use of bioenergy from primary woody biomass, including stepping away from the zero-rating approach for bioenergy.

On the other side of the debate, there are scientific researchers who are more supportive of the promotion of bioenergy (see e.g. Berndes, Cowie, and Pelkmans 2022; Berndes et al. 2016). They emphasise that, in many cases, bioenergy can already make a substantial net contribution to climate mitigation in the short term and will continue to be necessary for the EU to achieve its climate objectives for 2030 and 2050. Their main arguments are that bioenergy often uses waste streams from value chains that use biomass as material in which carbon is stored for a longer time (e.g. sawnwood, pulp and paper). Furthermore, they point out that forest management has a greater climate benefit than forest conservation, as regular harvesting and replanting of trees contributes to maintaining the forest carbon

sink in the longer term, whereas the sink would saturate over time under the conservation approach. Related to this, they argue it is more appropriate to assess the mitigation impacts of forest harvesting at the landscape level instead of at the level of a specific forest stand, as under sustainable management practices it is appropriate to harvest specific forests stands when the trees reach maturity. Furthermore, they counter-argue that bioenergy use is in fact not zero-rated in GHG inventories, as the emissions are counted in the LULUCF sector, and that counting emissions at the point of combustion would therefore result in double counting. Finally, harvesting might also be appropriate from a climate adaptation perspective, for example to replace maladapted species, to reduce the amount of biomass at risk of being lost in natural disturbances or to remove wood after such disturbances (Korosuo et al., 2023).

It is highly likely that a trade-off is needed between, on the one hand, maintaining/increasing forest harvesting and biomass supply and, on the other, maintaining/increasing the forest carbon sink.

In an ideal world, the EU would be able to increase the net emissions sink in forests, while maintaining or even increasing current harvesting levels to supply other sectors with forest biomass to substitute for fossil fuels and other GHG-intensive materials. This would require the NAI in EU forests to outpace the increase in harvesting levels (see indicator L6). However, current forest management practices are projected to increase harvesting while decreasing the NAI (both of which are driven by ageing forests), and as a result the forest carbon sink is projected to decrease to 240 Mt CO_2 in 2030 and 207 Mt CO_2 in 2050 (Korosuo et al., 2023; Pilli et al., 2022). It is therefore highly unlikely that the EU can achieve its LULUCF objectives for 2030 and 2050 without major and immediate changes to current forest management practices.

There are several options possible to increase the NAI, including decreasing deforestation, increasing afforestation, specific management practices to increase gross annual increment and increasing the resilience of forests against natural disturbances. However, the impact of these options will only materialise over decades, with only modest impacts in the timeframe up to 2050. Reducing harvesting is therefore one of the rare options to maintain or increase forest carbon sinks in the short to medium term. However, this also has its downsides, as forest biomass supply supports mitigation in other sectors, allows stronger forest growth in the future and might be required in the context of climate adaptation (JRC, 2021a; Korosuo et al., 2023).

It is therefore highly likely that the EU will have to make a trade-off between maintaining/increasing current harvesting levels and maintaining/increasing the forest carbon sink. The first option would increase biomass supply to other sectors, increase the forest carbon sink in the longer term (provided that harvested trees are replanted) and possibly also contribute to climate adaptation (if harvested trees are replaced with better-adapted species). However, it might also cause the EU to miss its 2030 LULUCF target, result in a smaller sink in 2050 and undermine the EU's biodiversity objectives. The second option would enhance the carbon sink in the short to medium term and is also preferable from a biodiversity perspective. However, it would reduce the carbon sink in the longer term (as the forest carbon stock saturates) and would reduce domestic supply to other end use sectors. In certain cases, it might also make forests more vulnerable to natural disturbances. The different options are also likely to have different socioeconomic impacts, which would need to be taken into consideration, but these have not been assessed within the scope of this report.

Recent literature suggests that, in the short to medium term, limiting harvesting is a more effective climate change mitigation action than increasing harvests to produce more bioenergy and wood-based materials (partly because wood is currently mainly used in short-lived products such as packaging and paper) (JRC, 2021a; Korosuo et al., 2023). The climate benefit of biomass use can be strengthened if wood is used in longer-lived products such as construction materials, which would diversify the income

stream and increase the harvested wood products sink in the LULUCF sector. Nevertheless, even for such uses, the majority of studies conclude that within a short to medium time frame (up to 2050) the mitigation potential provided by the material substitution effect is unlikely to compensate for the reduction of the carbon sink in forests affected by increased harvesting (JRC, 2021a).

The EU has taken steps to mitigate the potential adverse impacts of bioenergy, but concerns remain. In particular, there is a high risk that biomass demand (driven by EU policies) will exceed sustainably available supply.

The EU strives to address the potential adverse impacts of bioenergy production, for example through sustainability criteria and minimum GHG emissions savings for biomass set out in Renewable Energy Directive in 2009, which became increasingly stringent under the RED II and the RED III. Only biomass use that adheres to these criteria can contribute to the EU's renewable energy objectives and be eligible for financial support mechanisms (including the exemption from surrendering allowances under the EU ETS). The RED III has further strengthened this sustainability framework, by expanding it to more (smaller) installations, by excluding biomass from areas that were previously old-growth forests, and by excluding biomass harvested in a way that exceeds maximum thresholds for large clear-cuts. Although this sustainability framework is certainly useful to prevent the worst adverse impacts of biomass use, its overall effectiveness remains uncertain because of monitoring and compliance issues, including risks of fraud (Mai-Moulin et al., 2021; Mather-Gratton et al., 2021; Sikkema et al., 2021). Furthermore, as described in more detail in Chapter 6 'Transport', despite this framework, EU policies continue to promote certain types of biofuels that have a high risk of negative spillover effects.

In addition to the sustainability criteria framework, the RED III also requires Member States to design support mechanisms for bioenergy in line with the cascading principle and prohibits direct financial support for the use of specific, high-value wood types for bioenergy production. However, several implicit and explicit exemptions from these rules (e.g. the possibility of continuing to provide non-direct financial support such as tax cuts for the use of high-value wood for energy production) risk undermining their effectiveness.

The RED III also aims to improve the consistency of the EU's bioenergy policies and the objective of the LULUCF Regulation to increase the carbon sink. It does so by introducing a requirement for Member States to ensure that the domestic production of biomass for energy is consistent with their targets under the LULUCF Regulation. To this end, Member States need to assess in their NECPs the compatibility of overall projected forest biomass energy use with their respective targets under the LULUCF Regulation, and a description of the national measures and policies put in place to ensure compatibility with those targets. Member States are also required to report on those policies and measures in their biennial national energy and climate progress reports submitted under the Governance Regulation. These provisions are generally a step in the right direction to improve the consistency between the RED III and the LULUCF Regulation, but their effectiveness will depend on implementation by Member States. The European Commission's 2023 Bioenergy sustainability report (EC, 2023bh) – a biennial requirement under the Governance Regulation – found that so far Member States have not provided sufficiently granular information to allow a comprehensive insight on projected bioenergy demand and sustainably available supply. Similarly, the assessment of the draft updated NECPs found that most of them don't include information on the domestic supply of forest biomass for energy purposes, nor the projected use of forest biomass for energy purposes in 2021-2030 (EC, 2023p).

Furthermore, there continues to be an uneven distribution of incentives for the different possible uses of forest biomass. The current EU policy framework provides a direct, financial benefit for certain private actors to use bioenergy (e.g. operators that are exempted from surrendering allowances under the EU ETS or benefiting from national biomass support schemes). However, in the absence of an emission-

pricing mechanism in the LULUCF sector (see also Section 10.6), the financial cost of the biomass use (in the form of a reduced carbon sink) is solely at the expense of the Member State. As a result, the climate benefit of bioenergy use is privatized, whereas the climate cost (in the form of a reduced carbon sink) is socialised.

Finally, the EU policy framework on bioenergy does not consider its potential impact on the aggregate demand for biomass compared with the sustainably available supply. Some researchers have questioned the feasibility of the European Commission's scenarios with regard to potential sustainable biomass supply (Searchinger et al., 2022a), and several assessments have cautioned that biomass demand – driven by climate and energy policies – is projected to exceed sustainably available domestic supply (EEA, 2023o; Material Economics, 2021). This could result in three outcomes, each of which is to be avoided:

— the EU would harvest more biomass than is sustainable, with negative impacts on, among other things, biodiversity and the LULUCF net sink;
— the EU would not be able to meet demand for biomass, and therefore specific sectors with limited alternative mitigation options would risk being unable to reduce their GHG emissions enough to be compatible with the overall climate neutrality target;
— the EU would meet the increased demand by substantial increases in biomass imports, thereby exporting environmental pressures (including GHG emissions) associated with biomass production.

To avoid these outcomes, the aggregate demand for biomass needs to stay within ecological boundaries, while ensuring that end uses with limited mitigation options have sufficient access to sustainably sourced biomass to decarbonise by 2050 at the latest. This could be achieved by targeting incentives for bioenergy towards end uses that have limited other mitigation options, and by promoting the efficient and circular use of biomass overall. However, EU policies do little to target bioenergy towards demand centres with limited alternatives to fossil fuels (Malico et al., 2019). Whereas the RED III (EU, 2023f) does prioritise material use over biomass use for energy, regarding end uses it only excludes (new or renewed) support for electricity-only installations. It does not further differentiate between end uses based on the availability of other renewable energy or climate mitigation options. A better-targeted use of biomass could be achieved by putting a price on emissions in the LULUCF sector at a level similar to the carbon prices in other sectors (the EU ETS and the EU ETS 2). This would create an incentive to use biomass where its value is highest, that is, where it is hardest to replace.

Enhance climate adaptation

Climate change is projected to undermine the LULUCF sink by increasing the frequency and intensity of natural disturbances.

Research has found that – despite strong interannual variation – natural disturbances are increasingly damaging EU forests ([62]), thereby undermining their climate mitigation potential (Forzieri et al., 2022; Patacca et al., 2023; Seidl et al., 2017; Senf and Seidl, 2020). There is growing evidence that climate change is one of the underlying drivers of this trend and is expected to worsen it in the future (Forzieri et al., 2022; Patacca et al., 2023); there is some evidence that climate change has increased maximum wind speeds during extreme wind events, and models predict that such events will occur more frequently in the future. Whereas improved fire suppression policies have reduced damages from forest fires in recent decades, climate change is expected to increase the intensity and frequency of extreme fire events. Finally, climate change is increasing the damage expected from bark beetle outbreaks, both by increasing the bark beetle population and by reducing the resistance of trees to beetle infestations (e.g.

([62]) Expressed as volume of forest biomass loss per year.

due to droughts). Further increases in disturbance-caused mortality risk further undermining the net sink in EU forests and could even transform them into a net source of emissions.

Whereas climate change is expected to increase the frequency and intensity of natural disturbances, it might also improve carbon sequestration in some regions and forest types through warming and CO_2 fertilisation (Forzieri et al., 2022). The overall impact is expected to be mainly negative in arid and temperate forests (southern and central Europe) whereas it might be overall positive for boreal forests (northern Europe). Pilli et al. (2022) expect climate change to lead to an overall increase in forest growth in broadleaved forests (in particular in northern European regions) and an overall decrease in coniferous forests, but concludes that the overall impact of climate change on the aggregate EU forest sink is highly uncertain and could be either positive or negative. For example, assuming continuation of current management practices, the EU forest carbon sink could range between 100 and 400 Mt CO_2e by 2050 (compared to 280 Mt CO_2e in 2021) depending on climate change impacts.

Forests' resilience can be enhanced by changing forest management practices, but, even then, the future of the LULUCF net sink remains uncertain.

The findings above highlight the need for climate adaptation efforts to safeguard the net sink in the LULUCF sector. Several forest management options exist that could improve the resilience of EU forests against climate change impacts. One recommended option is to shift from conifer monocultures to mixed forests and broadleaved species. Such practices might decrease the LULUCF sink in the shorter term (as maladapted tree species are harvested, to be replaced by more resilient species) but would enhance the sink over the longer term (as the newly planted trees grow and future losses from natural disturbances are reduced (Korosuo et al., 2023). However, even if improved forest management practices can increase the mitigation potential and resilience of EU forests, their effect might still be outpaced by increased damage caused by natural disturbances (Patacca et al., 2023).

The importance of climate adaptation – but also of accounting for uncertainty induced by climate change – is illustrated by the sudden drop in the forest carbon sink in the late 2010s, which was driven by natural disturbances, among other causes ([63]). In its impact assessment regarding the revised LULUCF Regulation (EC, 2021r), the European Commission had assumed that the LULUCF net sink could be maintained at the average 2016–2018 level (268 Mt CO_2e) until 2030 without substantial additional efforts. Moreover, it assumed around 40 Mt CO_2 of additional removals could be achieved through a range of relatively inexpensive near-term actions including improved forest management and set-aside of organic soils, which formed the basis for the 310 Mt CO_2e objective. Whereas the impact assessment acknowledged the potential exacerbation of natural disturbances by climate change and biodiversity loss, it did not account for this in its scenarios that underpinned the proposed objective. Since the assumptions were made, net removals in the LULUCF sector have dropped drastically, to only 230 Mt CO_2e in 2021. As a result, the additional effort required has almost doubled (from 42 Mt assumed in 2021 to 80 Mt CO_2e today).

This highlights the need to account for the uncertainties from climate change when setting climate reduction objectives for the LULUCF sector. This could be based on the European Climate Risk Assessment, which is currently under development and expected to be published in spring 2024.

([63]) Pattaca et al. (2023) estimate that the loss of forest biomass due to natural disturbances was on average 50 million m^3/yr in 2010–2015, and then started to increase to on average 100 million m^3/yr in 2018–2020, mainly due to increased extreme wind events and bark beetle outbreaks. Based on standard conversion factors (between 0.8 and 1 t CO_2 per tonne of forest biomass, depending on the tree species), this would have decreased the forest sink by 40–50 Mt CO_2e in 2018–2020 compared to 2010–2015. According to the EU GHG inventory, the total forest carbon sink decreased from on average 420 Mt CO_2e/yr in 2010–2015 to on average 300 Mt CO_2e/yr in 2018–2020. Natural disturbances would thus be responsible for a large minority (33–40 %) of the decrease in the carbon sink.

Furthermore, it shows that the > 400 Mt CO_2e net removals by 2050 under the European Commission's scenarios might not be achievable. In that case, more technological removals of emissions or further reductions in residual emissions will be required to achieve overall climate neutrality.

9.6 Summary tables

Table 14 Progress summary - LULUCF

Indicator	Reference period	Historical progress	Required up to 2030	Required in 2031–2050
L1: GHG emissions and removals [a]	2005–2022	+ 6 Mt CO_2e/yr	– 8 Mt CO_2e/yr	– 5 Mt CO_2e/yr
L2: land-use changes				
L2a: forests	2005–2021	+ 194 kha/yr	No benchmark	No benchmark
L2b: wetlands	2005–2021	Stable	No benchmark	No benchmark
L3: deforestation	2017–2021	– 3 kha/yr	No benchmark	No benchmark
L4: afforestation	2017–2021	– 4 kha/yr	No benchmark	No benchmark
L5: net land take	2017–2021	Stable	No benchmark	– 5 kha/yr
L6: forest carbon sink [a]	2017–2021	+ 8 Mt CO_2e/yr	– 11 Mt CO_2e/yr	– 4 Mt CO_2/yr
L7: emissions in non-forest lands [a]	2017–2021	– 1.5 Mt CO_2e/yr	– 1.3 Mt CO_2e/yr	– 3.1 Mt CO_2e/yr
L8: bioenergy use [b]	2017–2021	+ 56 TWh/yr	Stable/no further increase	+ 52 TWh/yr

Legend

On track	The required change [c] is ≤ 1.
Almost on track	The required change [c] is between 1 and 1.5.
Somewhat off track	The required change [c] is between 1.5 and 2.
Considerably off track	The required change [c] is ≥ 2.
Wrong direction	The required change [c] is < 0.

[a] Positive values represent an increase in emissions or a reduction in removals. Negative values represent a decrease in emissions or an increase in removals.

[b] Given the expected adverse impacts if bioenergy use exceeds sustainably available supply, indicator L8 is considered to be on track if bioenergy use remains below a linear trajectory to the benchmark values, and off track if it risks exceeding that linear trajectory.

[c] See Section 2.2 for more details on how the required change is calculated.

Table 15 Policy consistency summary – LULUCF

Policy inconsistencies	– EU policies (CAP support for livestock production and the cultivation of organic soils and marginal lands, EU biofuel policies) put upward pressure on the demand for agricultural land, reducing land available for afforestation/reforestation and wetland restoration.
Policy gaps	– The objectives of the Farm to Fork Strategy to reduce fertiliser use (– 20 %) and increase the share of organic farming (to 20 %) have direct local environmental benefits, but risk reducing yields and therefore increasing demand for land (either in the EU or abroad) if demand for agricultural products is not reduced in parallel. – Agriculture and LULUCF are currently still excluded from the EU carbon-pricing regime. Therefore there is no EU-wide (financial) incentive for farmers and land managers to reduce GHG emissions and enhance CDR. It also implies that the incentives for using forest biomass for energy purposes versus maximising the LULUCF carbon sink continue to be unevenly distributed between private and public actors. – There is a genuine risk that aggregate biomass demand will exceed sustainably available supply. Key EU policies such as the RED III do not target incentives for bioenergy towards end uses that have limited alternative mitigation options. – The assumptions that underpin the LULUCF objective for 2030 did not account for the uncertainty of the effects of climate change and related natural disturbances on changes in the sink.
Ambition gaps	– Specific exemptions risk undermining the effectiveness of the sustainability criteria and provisions on the cascading principle under the RED III. – Under the CAP, the mandatory requirement on the maintenance of grasslands (GAEC 1) does not prevent agricultural practices that lead to high soil carbon emissions from grasslands
Implementation gaps	– So far, Member States have provided insufficient information in their NECPs and national energy and climate progress reports to assess the compatibility between projected bioenergy demand and sustainably available supply. – The CAP does include a mandatory requirement to preserve wetlands (GAEC 2), but over half of EU Member States have opted to delay its implementation to 2024 or 2025. It allows support mechanisms (eco-schemes) for the restoration of wetlands, but these are used to only a limited extent by Member States. Similarly, whereas most Member States have set targets for carbon storage in soil and biomass, voluntary eco-schemes to incentivise carbon farming have been implemented by few Member States, often with low levels of ambition. – Monitoring and compliance issues (including fraud) risk undermining the effectiveness of the sustainability criteria and provisions on the cascading principle under the RED III.

10 Pricing emissions and rewarding removals

Key messages

Achieving climate neutrality requires a policy mix with a sufficiently high, credible and consistent price signal for GHG emissions.

By internalising the externalities of GHG emissions in the market (making the polluter pay), carbon pricing is an effective tool to incentivise producers and service providers to shift towards lower-emission processes, and to incentivise consumers to reduce their consumption of GHG-intensive products and services. It also enables emission reductions to occur where they are most cost-effective. Carbon pricing therefore achieves predefined climate policy goals at the lowest cost ([64]).

Carbon pricing also needs to be complemented by measures to address social impacts and other market failures and to support investments in infrastructure and innovative new technologies, as well as action to prevent carbon leakage (where production and emissions relocate to places not subject to ambitious climate policies). The appropriate complementary measures are different for each sector and policy issue, and are discussed in the other chapters of this report.

In the EU ETS, the carbon-pricing signal needs to be credible so that producers and consumers are empowered to make long-term investments to reduce emissions.

Needs. Carbon pricing systems' efficiency hinges on a stable, long-term regulatory environment to incentivise low-emission investments. Interventions should therefore aim to stabilise expectations about future renegotiations of rules and targets for the carbon market (e.g. price caps, market stability reserve (MSR)), and ideally be based on clear rules.

Gaps. Successive revisions of the EU ETS have increased both the level of the carbon price and its resilience to economic shocks (such as the COVID-19 pandemic). By further accelerating the decline in emissions, the latest (Fit for 55) revision of the EU ETS Directive brings forward the end of the supply of allowances for stationary installations to 2040.

However, there is not yet a clear strategy to prepare the carbon market and relevant sectors for this **(policy gap)**. EU ETS governance, including the existing stability mechanisms, is yet to be adjusted to account for such scarcity of allowances and their effects on allowance price volatility, and ultimately the producers and consumers concerned. The potential contribution of carbon capture and utilisation (CCU) and CDR as well as international linking under the EU ETS is also unclear ([65]).

Recommendation C1. Discussion on carbon pricing in the sectors covered by the EU ETS needs to begin urgently, given the need to provide certainty for long-term investments.

Questions that need to be clarified include the amount and timing of allowances to be issued after 2030; the future design of the MSR; the relationship between EU ETS and other carbon markets, such as the EU ETS 2 and potentially third-country carbon markets; and the appropriate way to incorporate CDR. A very low, or net zero, cap does not require the replacement of a cap-and-trade system when permits for carbon removal can compensate for residual emissions. However, net negative emissions might require

([64]) In this chapter, 'carbon pricing' refers to the pricing of GHG emissions (including non-CO_2 emissions).

([65]) The revised ETS directive (Article 30(5)) requires the European Commission to produce a report on these matters, accompanied by a legislative proposal where appropriate, by 31 July 2026.

new incentive schemes for sustainable removals. The Advisory Board will consider this issue further in future work, including a report on carbon removal, which is planned for publication in 2024.

The risk of carbon leakage needs to be addressed, without undermining the incentive to reduce emissions.

Needs. Successive reviews of the EU ETS have increased the carbon price (to about EUR 90/t CO_2e in recent years), which is projected to increase further towards and beyond 2030. This increases the incentive for emission reductions, but also the **risk of carbon leakage**. EU policies need to adequately address this risk, while maintaining a strong incentive to reduce emissions.

Gaps. The EU's traditional response has been to issue free allowances to sectors considered exposed to the risk of carbon leakage**.** However, several assessments raise concerns that free allocation creates distortions and complexities, and there is uncertainty concerning its overall impact on the carbon market. Free allocation can also reduce the incentive for mitigation action by consumers and downstream industries (see Chapter 5 'Industry', Chapter 6 'Transport' and Chapter 7 'Buildings'). Replacing it with auctioning of allowances, combined with a carbon border adjustment mechanism (CBAM), would restore this incentive. Ultimately, free allocation cannot be sustained in the longer run, as the ETS cap – and therefore the number of allowances available for free allocation – will decline rapidly to reach zero before 2040.

The CBAM is superior to free allocation, as it applies carbon pricing to both domestic and imported products (thereby also maintaining a stronger incentive for demand-side measures), and does not conflict with the projected decline in the ETS cap. However, the CBAM will be only phased in gradually (from 2026 to 2034), does not yet cover all ETS sectors or address the risk of carbon leakage for EU exporters, and might be circumvented switching imports from raw materials to more refined products (which are not covered by the mechanism). Continued issuing of free allowances for some sectors up to 2030 and beyond represents an **ambition gap**.

Recommendation C2. The EU should further develop alternatives to free allocation for addressing the risk of carbon leakage, to maintain adequate protection even when the cap reduces further. To this end:

— the European Commission should monitor the introduction of the CBAM carefully, with a view to expanding it to more products and sectors, as stipulated in the CBAM regulation;
— the EU should in parallel engage in diplomatic efforts to introduce comparable carbon pricing in the EU's major trading partners.

The European Commission should also conduct or encourage further research into the extent of carbon leakage in recent years, the effectiveness of successive EU ETS reforms in preventing it, and potential policy options other than those mentioned above.

The EU ETS 2 (covering fuel use in buildings, transport and additional sectors) will need to be reformed to provide a stronger, more predictable price signal and greater convergence between the two emission trading systems.

Needs. The EU ETS 2 needs to put a price on emissions of GHGs that is high enough and credible enough to spur a target-consistent trajectory of emission reductions in the relevant sectors.

Gaps. While the original EU ETS appears to have reached a sufficiently high carbon price and ambitious trajectory, **it is unclear whether the EU ETS 2 will be stringent enough to meet its target** of reducing emissions by 43 % below 2005 levels by 2030. Modelling studies suggest that the carbon price in these

sectors could reach well in excess of the EUR 45/t CO_2e soft price cap agreed in the revised EU ETS Directive. This would cause additional allowances to be released on to the market, thereby de facto weakening the emissions cap and jeopardising achievement of the target **(ambition gap)**.

Decarbonising these sectors while keeping the carbon price low will require additional measures by the EU and Member States, such as addressing non-market barriers in the transport and buildings sectors (see key messages of Chapters 6 'Transport'and 7 'Buildings'). The coverage of the EU ETS 2 overlaps with the sectors covered by individual Member State targets under the ESR. Therefore, the potential release of new allowances (in response to the soft price cap) will increase the reliance on Member States implementing additional policies (in these or other sectors) in order to achieve their ESR targets (potential **implementation gap**) (see Chapter 14 'Climate governance').

Maintaining two separate emissions trading systems creates distortions and perverse incentives. The EU ETS and the EU ETS 2 have different carbon prices, caps and governance regimes. In the short term, this difference can be justified for pragmatic reasons. The EU ETS has been developing continuously for nearly 20 years, while actors in the buildings and road transport sectors will experience emissions trading for the first time under the EU ETS 2. However, maintaining multiple prices and systems weakens the cost-effectiveness of carbon pricing as a way of encouraging emission reductions where they are least expensive **(policy inconsistency)**. One example of this is electrification of the buildings and transport sectors, which is both encouraged by subjecting fossil fuels in heating and road transport to the EU ETS 2 carbon price and discouraged by subjecting electricity to a (higher) carbon price under the EU ETS.

Recommendation C3. The EU ETS 2 should be reformed for after 2030 to give greater certainty regarding the overall quantity of allowances and strength of the emission price signal associated with fuel use in transport, buildings and the other sectors covered. Including these sectors in the EU ETS (or other options for linking the two systems) should also be considered.

The EU ETS 2 will operate only from 2027 (potentially 2028). Hence, its initial years should be used as a trial period to inform design choices in later trading phases after 2030. Key parameters to monitor will include the level and volatility of the allowance price, the amount of additional allowances released in response to potentially high prices, the functioning of the auctioning, monitoring and reporting systems, the impact on carbon prices and energy taxes at the Member State level, and the system's effect on the uptake of emission reduction measures.

After 2030, the EU ETS 2 should, at a minimum, feature a carbon price high enough to achieve an emission reduction target consistent with the EU's climate neutrality goal, and enhanced credibility so that it is clear to participants whether it will resemble a traditional cap-and-trade system (in which quantity is fixed and prices could be high) or a carbon tax (in which prices are predictable but there is less certainty over the resultant emission reductions).

The European Commission should also propose options for increasing convergence between the two emissions trading systems. Options include creating a single emissions trading system (with a single emissions cap, carbon price and set of governance arrangements ([66])), and more gradual options such as allowing trading between the two systems so that their prices converge over time.

([66]) The ETS Directive (Article 30i) requires the European Commission to report on the implementation of EU ETS 2 by January 2028, and to assess by October 2031 the feasibility of integrating its sectors into EU ETS 1.

Expand coverage of emission pricing to missing sectors, including agriculture and land use.

Needs. All major sources of GHG emissions and opportunities for removals need to be covered by a price incentive to reduce emissions and increase removals.

Gaps. Although the recent Fit for 55 package more than doubles the scope of EU carbon-pricing policies, **some sectors are still not covered by explicit emission pricing (ambition gap / policy gap)**. Plans to include or expand the coverage of carbon pricing (including pricing of non-CO_2 GHG emissions) are at different stages of maturity. There is no EU-level price on emissions in **agriculture/food, forestry** and **land use**, which suffer from an overall lack of incentives to reduce emissions and increase removals (see Chapter 8 'Agriculture' and Chapter 9 'Land use, land use change and forestry'). The European Commission is currently studying ways of introducing some form of emission-pricing mechanism in these sectors. Municipal **waste** incineration may be incorporated into emission trading (in accordance with the ETS Directive), taking into account the risk of diverting waste streams to landfill or third countries. In **aviation**, intra-EU flights are covered by the EU ETS; expansion to extra-EU flights is dependent on further legislation and the development of the international carbon offsetting and reduction scheme for international aviation **(implementation gap)**.

Recommendation C4. The EU should start preparations now with a view to introducing pricing instruments in the agricultural/food and LULUCF sectors, in order to incentivise emissions reductions and carbon removals. These instruments need to take into account the technical complexity of measuring emissions and removals, and attributing them to land management and mitigation actions, as well as differences in the permanence of various natural removals. Discussions on the development of carbon removal certification for land, and pricing of non-CO_2 emissions in agriculture, should therefore explore these complexities, focus on solutions that are scientifically robust and feasible, and convert the solutions into concrete legislative proposals for after 2030. Policymakers will need to pay particular attention to whether land-based carbon removal should be rewarded as part of a system for pricing of non-CO_2 emissions in agriculture, or whether non-CO_2 emissions and carbon removal should be treated separately. They should also take account of the possibility that such carbon-pricing efforts will be affected by emission leakage through international trade (see also Chapters 8 'Agriculture' and 9 'Land use, land use change and forestry').

For international aviation, the EU should ensure that the same carbon price applies to all outgoing flights (including to third-country destinations), whether through the EU ETS, the carbon offsetting and reduction scheme for international aviation (CORSIA) or a combination of the two (see also Chapter 6 'Transport').

Reform energy taxation so that relative price signals are consistent with climate goals.

Needs. Effective carbon prices in the EU today can vary from zero to over EUR 100/t CO_2e, depending on the Member State, activity and fuel use. This can mean that some cost-effective options for reducing emissions are not pursued, while costlier options may need to be considered instead.

A lot of the difference in effective carbon prices is due to implicit carbon pricing (meaning taxes levied for other reasons, such as excise duties). While differences are justifiable (because climate policy is not the only goal of taxation), instances where the tax system actively encourages climate-damaging activities need to be removed.

Gaps. The current ETD permits energy tax differentials that are inconsistent with climate goals. For example, fossil fuels can be taxed less than electricity. In some cases, activities that are not covered by

explicit carbon pricing (such as agriculture and extra-EU flights) can also be exempted from energy taxation entirely **(policy inconsistency)**.

Recommendation C5. The EU should adopt the proposed reform of the ETD and consider further options for aligning taxation and incentives to reduce emissions.

Adoption of the revised Fit for 55 ETD proposed by the European Commission would go a long way towards addressing inconsistencies between energy taxation and climate policy. It would remove exemptions (the ability to tax energy use below established minimum rates), tax fuels based on energy content (rather than volume) and establish a hierarchy whereby carbon-intensive fuels are taxed the most.

Further improvements could be introduced, such as taxing electricity based on the carbon content of the energy used to produce it (this is an option for Member States but not an obligation in the European Commission's proposal).

Carbon-pricing policies need to be complemented by redistributive policies to mitigate adverse social impacts, and by measures to address market failures and support investments in infrastructure and innovative new technologies.

Needs. Carbon pricing provides social benefits by reducing the impacts of climate change and fossil fuel consumption, as well as reducing dependence on fossil fuel imports. However, in most cases carbon pricing is regressive (a heavier burden falls on people with low incomes and certain vulnerable groups). Therefore, it needs to be accompanied by complementary or compensation measures that can alleviate its burden without undermining its effectiveness. These include targeting non-market barriers to reducing emissions (thereby lowering abatement costs and hence the carbon price needed to achieve a given level of emission reduction) and recycling revenues from carbon pricing to make low-emission substitutes available, accessible and affordable for vulnerable groups (see Chapter 11 'Whole of Society Approach'). Carbon-pricing revenues should also continue to fund the development and deployment of innovative new technologies with the aim of bringing their prices down to the point where they would be competitive at the prevailing carbon price.

Gaps. Under the revised ETS Directive, Member States must spend all the revenue they receive from auctioning ETS allowances for climate and energy-related purposes, including the decarbonisation of energy and transport, RD & D of innovative new technologies, energy efficiency, providing support to vulnerable households and compensating sectors exposed to carbon leakage. Nevertheless, **ambition gaps** exist. While the potential revenue from carbon pricing will expand once the CBAM begins to collect payments from 2026, there is no requirement to spend these proceeds on climate- and energy-related purposes. Replacing the remaining free ETS allowance allocations with auctioning would further increase revenues earmarked for energy and climate purposes.

Recommendation C6. Resources for climate and energy-related expenditure should be expanded by ending the free allowance allocation in the EU ETS and requiring revenues collected by the CBAM to be spent for climate- and energy-related purposes.

10.1 Scope and overview

This chapter provides an overview of the role of carbon prices in the EU climate policy mix, and assesses the consistency of the main policies that affect the pricing signal. Carbon pricing in this sense refers to the collection of economic measures that affect the cost of emitting GHGs. It includes both explicit measures designed to reduce emissions (such as the EU ETS) and implicit measures that act as de facto carbon prices (such as taxes on energy).

Other forms of regulation that affect GHG emissions are considered in Chapter 13 on governance, as well as in earlier sectoral chapters. The distributional consequences of carbon pricing (and of climate policies in general) are considered in Chapter 9 on whole-of-society approaches.

10.2 The role of carbon pricing in the policy mix

Carbon pricing as climate policy

There is a consensus in the relevant literature that a sufficiently high carbon price plays an important role in reducing GHG emissions and achieving climate neutrality (ECB, 2022; IEA, 2022e; IMF, 2019; Koch et al., 2022; OECD, 2021). Carbon pricing can incentivise reductions cost-effectively, since it enables the market (both producers and consumers) to identify and exploit the most cost-effective way to reduce emissions. It also incentivises investment in low-carbon technologies, and generates additional fiscal revenues, which can be recycled to finance complementary policies or compensation measures, alongside decarbonisation.

Carbon pricing as fiscal policy

The tax system can be used as a means to correct externalities, hence providing (dis)incentives to induce behavioural change, for example by discouraging smoking, or by encouraging innovation and investment.

When it comes to influencing GHG emissions, some policy measures price emissions explicitly, while others, such as excise taxes on fuel, act as implicit carbon prices. The latter are typically not designed to control GHG emissions in the first place, and are not calculated as a price per tonne of CO_2 equivalent, but nevertheless put a price on emissions at the margin.

Carbon pricing is therefore capable of raising revenue to compensate low-income households or finance green infrastructure while aligning price incentives with climate goals. However, by reducing GHG emissions, successful carbon prices run the risk of undermining their own revenue base in the long term as the economy decarbonises (EEA, 2022g). Therefore, carbon pricing should not be understood as a traditional fiscal instrument, feeding national budgets sustainably with revenue streams. However, carbon pricing can be used together with other fiscal instruments to reduce horizontal and vertical inequality (Hänsel et al., 2022).

Carbon pricing within the EU

In the EU today, carbon pricing is applied through several overlapping measures at both the European and national levels.

The EU ETS is an EU-wide cap-and-trade system, which was created in 2005 following several failed attempts to establish an EU-wide carbon and energy tax (Delbeke and Vis, 2019). At the time (and still today) decisions on taxation required unanimity among Member States, whereas environmental measures such as a cap-and-trade system required only qualified majority approval.

Environmental taxes are not set at the EU level, although they are subject to some common rules as part of the EU's single market, including the minimum tax rates set out in the ETD. However, the ETD has not been revised since 2003, in part because any reforms need to be approved unanimously (EP, 2021).

According to Eurostat data, environmental taxes in the EU consist primarily of energy taxes, although explicit carbon taxes also exist in 14 Member States (Eurostat, 2022a). Environmental taxes represent 5.5 % of government revenues from taxation and social contributions in the EU. While the vast majority of this share (78 % in 2021) comes from energy taxes, revenue from the auctioning of EU ETS allowances represented 6.4 % of total energy tax revenue in 2020. However, the share of environmental taxation in total tax revenue has been falling since 2009 (i.e. revenues have risen more slowly than GDP and overall tax revenue). Environmental taxes are most often levied per unit of physical consumption and are fixed in nominal terms. Hence, their real value tends to fall over time unless adjusted for inflation or gradually adapted (EC, 2021q; Eurostat, 2013).

Carbon pricing combined with complementary policy instruments

While carbon pricing is traditionally acknowledged as the cost-effective way to achieve an emission reduction objective (Jenkins (2014) citing earlier literature), there is an ongoing debate about how ambitious climate targets are best achieved by including carbon pricing within a wider policy mix (Goulder and Parry, 2008; Jaffe et al., 2005; Koch et al., 2022).

Such research indicates that the theoretically cost-optimal solution is not always feasible or sufficient because of market failures, which justify complementing emission pricing with other policy instruments such as standards, bans or subsidies ([67]). Market failures hindering the uptake of potentially cost-effective mitigation options include imperfect information, split incentives ([68]), principal–agent relationships, network externalities or insufficient R & D investments (see Hood (2011) for a more complete overview). Addressing these market failures though complementary measures can therefore improve the effectiveness and reduce the cost of a carbon-pricing regime, by improving the uptake of theoretically low-cost mitigation measures. Examples of other instruments include minimum efficiency standards and labelling, building codes, or policies and incentives for expanding vehicle charging infrastructure.

The need to bring forward and reduce the cost of immature technologies is also often cited as a justification for supplementing carbon pricing with other measures (Kalkuhl et al., 2012). A policy combination can be justified because current societies are locked in to high-emitting technologies in terms of infrastructure, institutions and markets. Furthermore, incumbent emitting technologies have been able to reach very low costs through decades of learning, economies of scale and increasing returns through network effects, which place new technologies at a competitive disadvantage at the beginning of their lifetimes. For example, Stiglitz (2019) points out that high carbon prices may be needed to switch to low-emission technologies, but maintaining them may not require such high carbon prices once these same effects take hold for the new technologies.

Combining carbon pricing with complementary measures can also be justified when there are multiple market failures to be addressed simultaneously (e.g. reduce GHG pollution, encourage innovation,

([67]) 'Market failure' means when decisions based on market prices do not generate an efficient allocation of resources because of market distortions such as externalities. Externalities are costs or benefits incurred by third parties by production or consumption. Pollution is an example of a negative externality. Education is an example of a positive externality (because it benefits society as well as the individual student).

([68]) 'Split incentives' means when the costs and benefits of an action accrue to different people, for instance in the building sector, where renovations would be the responsibility of the landlord, but the benefits in terms of energy savings would accrue to the tenant.

address distributional concerns, raise revenue). For example, Kalkuhl et al. (2013) demonstrate a second-best situation in which carbon pricing is effective in reducing emissions, while a complementary renewable energy subsidy limits the resultant energy price increase. Some authors (e.g. Stiglitz, 2019) raise concerns about the level of carbon prices because of their political consequences. Some command-and-control regulation can lower the level of explicit carbon tax required to achieve a given emission reduction, and thereby reduce the adverse distributional consequences of the tax. However, the overall economic costs – often hidden – will increase and have to be paid by consumers or producers.

Use of revenues from carbon pricing

Targeting the use of carbon-pricing revenues is one way to combine the price-incentive effect of carbon pricing with other objectives (such as redistribution to low-income groups, or funding innovation). This is also a core feature of the EU ETS. In the Fit for 55 revision of the ETS Directive, Member States are required to spend their share of the revenues from allowance auctioning on climate- and energy-related purposes, which can include investing in decarbonisation of energy and transport, R & D and energy efficiency, providing support to vulnerable households or transport users, and compensating sectors exposed to carbon leakage (EU, 2023c) ([69]). In addition, a share of allowances is managed at the EU level (rather than by Member States) for improving energy efficiency and modernising energy systems in lower-income Member States (Modernisation Fund), and supporting innovation in low- and zero-carbon technologies (Innovation Fund). The new EU ETS 2 features a Social Climate Fund to be spent by Member States on similar purposes (including temporary direct income support for vulnerable households and transport users), funded by a combination of auctioning revenues and national co-financing.

Following the revision of the ETS Directive, there are two remaining opportunities for increased revenue recycling in EU carbon-pricing policies. Firstly, there is currently no requirement for Member States or the EU to spend CBAM revenues on energy and climate-related purposes (although a recital in the CBAM regulation mentions the need for the EU budget to support adaptation in least developed countries) (EU, 2023n). Legislation on the use of the EU's own resources ([70]) created by the CBAM is still being debated but, at the time of writing, does not contain such a requirement (EP, 2023). Secondly, replacement of free allocation in the EU ETS by auctioning, would create additional revenues to be used for climate- and energy-related purposes.

Data covering 2013–2020 indicates that Member States spent 75 % of their auctioning revenues on climate- and energy-related purposes between 2013 and 2020. However, five Member States did not meet this requirement individually (EEA, 2023q).

Carbon pricing under Fit for 55

The de facto approach to carbon pricing in the EU and its Member States has also been to integrate explicit carbon pricing into a broader portfolio of climate and non-climate policies, taxes and subsidies. With the proposals of the European Green Deal, the EU is attempting to expand carbon pricing to areas not already covered. The rest of this chapter considers carbon pricing under the Green Deal, in particular the EU ETS, the EU ETS 2 and the reform of the ETD.

([69]) 'Carbon leakage' refers to the displacement of emissions to regimes outside the EU where climate governance is laxer. According to the directive, Member States must seek to limit compensation to leakage-exposed sectors to 25 % of the revenues or below (and provide justification if this share is higher). The list of eligible spending areas is in Article 10(3) of the ETS Directive.

([70]) EU 'own resources' are sources of revenue for the EU budget (as opposed to carbon-pricing revenues that can be spent by Member States).

10.3 EU Emissions Trading System (energy supply, industry, international transport and maritime)

The EU ETS has been the EU's climate flagship policy since 2005. Since then, it has been revised multiple times, resulting in an extended scope, a more ambitious emission cap, more stringent allocation rules and increased recycling of auctioning revenues for climate purposes. The latest revision of the EU ETS was concluded in 2023, based on the European Commission's proposal under the Fit for 55 package. It had the following key outcomes.

- **Extension of the system to the maritime sector, to be concluded by 2026.** Furthermore, the European Commission is mandated to consider the extension of the system to waste incineration by 2026, with a view to include the sector as of 2028.
- **Further tightening of the emissions cap.** This is to be done both by increasing the annual linear reduction factor (from the current 2.2 % to 4.4 % by 2028) and by imposing two one-off reductions in 2024 and 2026. As a result, the current directive would reduce the cap to zero by around 2040.
- **Adjusting the MSR**. The MSR consists of ETS allowances that have been withdrawn from the market but can be released back into it under certain conditions. The latest adjustments include maintaining the current ('accelerated') rate at which allowances enter the MSR, capping the maximum size of the MSR at 400 million allowances from 2024, and gradually invalidating excess MSR allowances above that level (EU, 2023b).
- **Gradual transition from free allocation to a carbon border adjustment mechanism (CBAM) for specific sectors.** The aim is to shield the relevant sectors against the risk of carbon leakage.
- **More rapid phase-out of free allocations for the aviation sector.** This is to be implemented by 2026.
- **Changes to the distribution of auctioning revenues.** These include an increase in the volumes of the Modernisation Fund and the Innovation Fund, and a requirement for Member States to spend all of their auctioning revenues (or an equivalent amount) on climate- and energy-related purposes.
- **Creation of EU ETS 2, a parallel emissions trading system for buildings and road transport and other sectors.** This is discussed in Section 10.4.

The progressive tightening of the EU ETS cap, together with other reforms, has caused the carbon price to increase considerably over time, from EUR 5/t CO_2e in the mid 2010s to EUR 80–90/t CO_2e in recent years. It has remained at higher levels despite external shocks such as the COVID-19 pandemic and the energy crisis in 2021–2022 (Bruninx and Ovaere, 2022; Pahle et al., 2023). As a result, the incentive that the EU ETS provides for GHG emission reductions is stronger now than ever before.

Continued effort is needed to combat carbon leakage without undermining the carbon price signal.

While auctioning is the default allocation methodology under the EU ETS, a substantial proportion of EU ETS allowances (48 % of total supply in 2013–2020) are allocated for free, mainly to sectors that are considered to be exposed to the risk of carbon leakage (EC, 2023g).

The rationale behind free allocation is that these sectors are considered unable to pass on the cost of the EU ETS to their customers downstream in the value chain without losing competitiveness and thus market share to non-EU producers that do not face a comparable carbon cost ([71]). As a result, the EU ETS could lead to displacement of production (and related GHG emissions) to outside the EU. To prevent this, ETS firms in certain sectors are given a certain amount of allowance (based on benchmarks) for free.

([71]) This applies both to EU firms that are competing on the EU market with non-EU producers that import their products into the EU and to EU firms that export their products and are competing with non-EU producers outside the EU.

This should reduce the actual carbon cost they face, thereby reducing the need to pass this cost through to their customers.

Free allocation therefore risks weakening the incentive for demand-side mitigation measures (such as improved material efficiency or material substitution) by reducing the need for firms to pass through the ETS cost through to their customers. In addition, several assessments have suggested that free allocation creates distortions in the carbon market, the extent of which continues to be debated in the literature. There is debate over whether or not free allocation affects firms' production and mitigation decisions (Teixidó et al., 2019; Venmans, 2016; Zaklan, 2023), and over the extent to which it has enabled windfall profits through over-allocation of allowances or passing carbon costs on to consumers (Cludius et al., 2020; Neuhoff and Ritz, 2019).

Recent EU ETS reforms extended the use of free allocations into trading phase IV (2021-2030). The revision introduced more dynamic allocation benchmarks by aligning free allowances with actual production levels. Still, substantial free allocations are permitted to continue until 2030. For 2021–2030, sectors that are considered exposed to the risk of carbon leakage (and thus eligible for continued free allocation) account for 94 % of total industrial GHG emissions under the EU ETS (EC, 2019e), and over 40 % of the aggregated ETS cap is projected to be allocated for free (ECA, 2020b) ([72]).

In the first two phases of the EU ETS (up to 2013), the scientific literature did not find significant evidence of carbon leakage caused by the EU ETS (Cludius et al., 2020; Hintermann et al., 2020; Verde et al., 2019). However, studies that include more recent data do find (non-causal) evidence of carbon leakage (while confirming the lack of such effects prior to 2013). A study by the European Central Bank (ECB) (2023a) observes that emission reductions in EU ETS industries within the EU were more than offset by a simultaneous rise in emissions from the same industrial sectors outside the EU, and that sourcing high-emission inputs from within the EU translates into a competitive disadvantage. Similarly, De Beule et al. (2022) found (non-causal) evidence of investment leakage, meaning that multinational enterprises respond to more stringent climate policy by investing outside the EU. The risk of carbon leakage strongly depends on the development of climate policies in other major economies outside the EU. In that respect, it is positive to note that uptake of cap-and-trade systems and carbon taxes is increasing, including in emerging economies (World Bank, 2023). Furthermore, there is some evidence that the adoption of carbon pricing in one country can explain the subsequent adoption of carbon pricing in other countries (Linsenmeier et al., 2023).

To further address the risk of carbon leakage, the EU adopted the CBAM that will start to operate as of 2026. Under this mechanism, a price equivalent to the ETS price is put on imports of certain carbon-intensive products and their precursors ([73]) into the EU. It will be phased in gradually between 2026 and 2034, with a corresponding phase-out of free allocation for the same products under the EU ETS ([74]). For sectors that are exposed to the risk of carbon leakage but not (yet) covered by the CBAM, free allocation will continue. This means that free allocation will coexist with the CBAM, and a substantial share of the allowances under the EU ETS cap is still expected to be allocated for free until at least 2030.

The newly adopted CBAM could reduce carbon leakage by ensuring that both domestic production and imports face a carbon price (meaning that all suppliers to the EU market have an incentive to reduce emissions). Its introduction – combined with a corresponding phase-out of free allocation – would also provide a stronger incentive for demand-side mitigation measures (e.g. material efficiency or substitution), as it would ensure that the carbon cost is passed down the value chain.

([72]) Before taking into account the impact of the CBAM, which is expected to reduce this share.

([73]) Cement, iron and steel, aluminium, fertilisers, electricity and hydrogen.

([74]) For example, in 2026, a carbon price will be levied on imported steel based on 2.5 % of its climate impact, and the amount of allowances allocated to EU steel producers will be decreased by an equal 2.5 %. This share increases to 5 % in 2027, 10 % in 2028, 22.5 % in 2029, 48.5 % in 2030 and so on, to reach 100 % by 2034.

On the other hand, even with the introduction of the CBAM, removing free allocation could place EU exporters at a disadvantage if they are competing in third-country markets against firms that are not subject to a carbon price (Evans et al., 2020). Furthermore, both the European Commission (2023f) and the ECB (2023a) point out that it may be necessary to expand the CBAM's coverage further downstream. Otherwise, there may be an incentive to avoid the carbon price by switching from importing raw materials to importing more refined products. To this end, the product scope will be reviewed during the scheme's transitional phase.

Because of the rapid decline of the ETS cap – which is expected to reach zero before 2040 – the allowances available for free allocation will become more and more scarce. This means that in any case the EU needs to consider further alternatives to free allocation to address the issue of carbon leakage. One option is a further extension of the CBAM, which has the additional advantage that it can sharpen incentives to reduce emissions (Jakob, 2023). However, this would still leave the issue of EU exporters unresolved. This underlines the need for (i) climate policies to encourage innovation, scale-up and cost reduction for zero emission technologies so that they become the more competitive choice; and (ii) the EU to pursue diplomatic efforts to encourage carbon pricing in the EU's trading partners and ensure a level playing field and strong mitigation incentives for both imports and exports.

Preparations must start now to make the EU ETS fit for 2040.

With the Fit for 55 revision of the EU ETS Directive, the emissions cap is expected to reach zero by 2039 ([75]). Specifically, the increase in the emissions cap's annual linear reduction factor, eventually to 4.4 % from 2028 onwards, and the lack of a sunset clause for this provision, combined with the invalidation of allowances held in the MSR above a level of 400 million (equivalent to 31 % of verified EU ETS emissions in 2022) ([76]) are decisive reform elements.

Still, both the European Commission's long-term scenarios and the scenarios underpinning the Advisory Board's 2040 advice indicate considerable residual GHG emissions in 2040 in sectors covered by the EU ETS (in particular in industry and in international aviation and maritime transport), which means demand for allowances will not reduce to zero.

This brings the 'endgame' of the EU ETS in sight, raising questions about how governance and stability mechanisms must be adjusted to account for trade frictions under low liquidity (Pahle et al., 2023).

The possible consequences of the latest revision (assuming there are no further reforms of the EU ETS governance) are explored by Pahle et al. (2023). They include more rapid emission reductions and banking of allowances as participants anticipate the future scarcity of allowances. In an optimistic outcome, this could drive investment in green technologies, thereby reducing the demand for allowances. However, considering potential impacts beyond modelling, the price of allowances could become increasingly high and volatile, calling the political credibility of the ETS into question.

There are numerous options available to policymakers for avoiding the outcome described above. In principle (and without prejudging future advice of the Advisory Board or forthcoming political discussions) these could include the following.

— **Increasing liquidity.** This could be done by expanding the scope of the EU ETS, for example by including smaller operators and other sectors (such as agriculture and waste, or linking with the new

([75]) The 2039 extrapolation excludes aviation.

([76]) The ETS Directive establishes the 'invalidation' of allowances above 400 million, but also stipulates that legislators could revise this in the light of a hypothetical European Commission proposal based on the annual review of the functioning of the European carbon market.

EU ETS 2 covering transport and buildings); or by linking to emissions trading systems elsewhere in the world (FTI consulting, 2023; Ferrari, 2023; Pahle et al., 2023).

- **Incorporating CDR into the ETS.** This will require a governance framework that balances the need to scale up carbon removal technologies against the risks associated with relying on these technologies and the risk of crowding out emission reduction as the primary means for achieving climate neutrality (Strefler et al., 2021) ([77]).
- **Further regulatory changes.** These may include adjustments to the cap or MSR, shifting to a more price-based approach by introducing floor and ceiling prices, or replacing the EU ETS with a carbon tax.
- **Establishment of a carbon central bank.** It could perform some combination of all the above, with the intention of keeping carbon prices or net emissions within a trajectory consistent with EU policy goals (Edenhofer et al., 2023; Rickels et al., 2022).

By agreeing to a steeper, stricter emission reduction path, the latest revision of the ETS Directive has ushered in the endgame of the ETS and placed it within current investment horizons. This in turn increases the urgency of addressing questions around the future of climate governance, in particular the EU ETS, in a credible way (Dolphin et al., 2023). The next scheduled review of several of the abovementioned issues related to the EU ETS Directive and the MSR is due in (July) 2026, and further assessment of the different options for post-2030 governance needs to start now. The Advisory Board will contribute to this in future work, including its upcoming report on carbon removal, which is planned for publication in 2024.

10.4 EU Emissions Trading System 2 (buildings and road transport)

The revised ETS Directive creates a separate EU ETS 2 for buildings and road transport and additional sectors (mainly smaller industry) (EU, 2023c). By introducing an additional emissions trading system, the EU has significantly enhanced its policy architecture; EU carbon pricing, and monitoring and reporting of emissions are expanded to additional sectors; and additional fiscal revenues will be generated by auctioning emission allowances issued under the new system. This in turn enables further spending on climate- and energy-related purposes (including support to vulnerable groups through a dedicated Social Climate Fund). However, design features of the system make it difficult to predict its contribution to achieving the EU's 2030 climate target. Most of this difficulty relates to uncertainties related to the soft price cap set at EUR 45/t CO_2e in the initial years of the system.

The EU ETS 2 expands the coverage of carbon pricing.

The EU ETS 2 will become operational in 2027 (or 2028, in the event of exceptionally high fuel prices), with data collection and reporting starting in 2025. In the impact assessment accompanying the original EU ETS 2 proposal, the European Commission stated that the EU ETS 2 should operate as part of a broader policy mix to decarbonise the transport and building sector, given the existence of non-market barriers such as split incentives, lack of information and lack of access to finance (EC, 2021al). EU co-legislators have therefore decided that, at least until 2030, the sectors covered by the EU ETS 2 will also continue to be covered by the ESR, thereby supporting Member States in meeting their ESR targets.

The implementation of an EU-wide carbon-pricing mechanism in the road transport and buildings sectors is an important step forward, which is expected to drive further GHG emission reductions. As

([77]) CO_2 that is captured and stored geologically is exempt from the requirement to surrender EU ETS allowances (according to Article 12 of the EU ETS Directive). The Fit for 55 revision of the directive extends this exemption to GHGs that have been captured and utilised, mandating the European Commission to develop implementing legislation on how to ensure that the utilised GHGs do not enter the atmosphere.

pointed out by the German scientific platform on climate protection (WPKS, 2022), it strengthens climate governance in several different ways compared to having these sectors are governed only by national measures contributing to ESR targets. Firstly, the EU ETS 2 provides direct incentives to lower emissions by means of the price signal. Secondly, it introduces a compliance mechanism that reduces the reliance on each Member State's bespoke policies and measures as an incentive for reducing emissions, and on the ESR compliance procedure (see Section 14.2).

The EU ETS 2 carbon price is uncertain.

The emissions cap and auctioning of allowances in the EU ETS 2 will be calculated so as to achieve a 43 % emission reduction in regulated sectors (combined) by 2030 (compared to 2005 levels). This is consistent with these sectors' contribution to an overall 55 % emission reduction target as per the European Commission's MIX scenario (EC, 2021c). In the buildings and road transport sectors, there is considerable uncertainty about price elasticities and future market developments, and it is not clear *ex ante* how actual prices may develop. The original European Commission proposal estimated allowance prices of between EUR 48 and EUR 80, with the lower estimate assuming there are more complementary emission reduction measures to accompany the carbon price (EC, 2021c). However, other studies suggest a carbon price of EUR 200–300 in the absence of sufficient accompanying measures (Abrell et al., 2022; Agora Energiewende, 2023; Rickels et al., 2023).

Price formation under the EU ETS 2 is regulated in several ways, either using a rule-based procedure or by direct intervention of the European Commission. To prevent sudden price peaks in the starting phase of the system, auction volumes will be frontloaded (130 % of volumes for 2027). The frontloading mechanism is 'cap neutral', as quantities will be deducted from auctioning volumes between 2029 and 2031. Additional allowances will be released if the allowance price exceeds EUR 45/t CO_2e for two consecutive months (the soft price cap in initial years of the system). These additional allowances will come from a separate MSR, which will be endowed initially with 600 million allowances (equivalent to 80 % of the sectors' target-consistent emissions for 2030 ([78])). Unlike the EU ETS, for which surplus allowances already in circulation were placed in the MSR, the initial reserve for the EU ETS 2 will contain allowances that are additional to the quantity calculated to be consistent with the 43 % reduction target.

It is also not clear how many allowances will be released on to the market if the soft price cap is exceeded. According to the directive, the first triggering of the cap would result in the release of 20 million allowances (equivalent to 3 % of the sectors' target-consistent 2030 emissions[78]). Additional tranches of 20 million, 50 million or 150 million allowances could be released on to the market several times depending on how allowance prices develop (explained in the directive's Article 30h).

There are significant risks to the EU's climate targets and social compatibility.

If the EU ETS 2 fails to meet its 43 % reduction target, there is a considerable risk that the EU will fail to reach its 2030 target under the ESR. This places pressure back on Member States to address the shortfall by adopting further national policies and measures in ESR sectors, either in transport and buildings or in other sectors such as agriculture and land use. The ESR features a flexibility mechanism, which grants Member States the option to sell any surplus of their reductions under the ESR sectors to others to efficiently achieve compliance. However, it is unclear *ex ante* whether sufficient annual emission allocations will be available to fill potential emission gaps, in particular given ESR's slow-acting and relatively weak compliance mechanisms (see Section 14.2).

([78]) See Table 46 of European Commission (2021c).

In this context, Member States that already have ambitious carbon prices covering EU ETS 2 sectors should maintain them, since this would help mitigate the risks of not meeting national obligations under the ESR and increase the predictability of investment decisions. Furthermore, the introduction of the EU ETS 2 will reduce the risk of intra-EU carbon leakage by placing an EU-wide floor on the level of ambition.

If the EU ETS 2 prices reach the higher end of price projections, the distributional impacts of uncompensated carbon pricing can be significant. In the course of the Fit for 55 package, the EU has decided to establish a Social Climate Fund to mitigate adverse effects of the EU ETS 2 on vulnerable groups (see Section 11.4 for a detailed explanation). Each Member State is eligible for a specified maximum share of Social Climate Fund funding based on a 'solidarity' formula (EU (2023l), Annex I). However the size of the fund is capped at EUR 65 billion, irrespective of the value of the carbon price. While the Social Climate Fund has been broadly welcomed by stakeholders (EurActiv, 2023), it remains unclear at this stage whether the combination of the fund and national auction revenues will be sufficient to balance distributional concerns and vulnerability issues in the EU ETS 2 context (Pahle, 2023).

The underlying logic of having two separate emissions trading systems merits revisiting beyond 2030.

As discussed above, the EU will, from 2027, operate two separate emissions trading systems, each with separate carbon prices, caps, allowance allocation methods, and systems for managing the price or quantity of allowances. This appears suboptimal, since the underlying logic of carbon pricing is to allow the market to identify and incentivise the most cost-effective emission reductions wherever they might be. One example of this is electrification of the buildings and transport sectors, which is encouraged on the one hand by subjecting fossil fuels in heating and transport to the EU ETS 2 carbon price, but discouraged on the other hand by subjecting electricity to a (probably higher) carbon price under the EU ETS.

There may be political, economic and administrative reasons for maintaining separate carbon markets at least in the short term. These include the fact that EU ETS is a tried and tested system that has been refined over nearly 20 years, while emissions trading may be new to the participants in the EU ETS 2. Furthermore, price changes in the buildings and transport sectors may be more salient to consumers than in the EU ETS sectors (since consumers purchase both heating and transport fuel directly). This provides a political (and distributional) rationale for policymakers' decision to introduce the EU ETS 2 in a more gradual manner, in particular given uncertainties over the EU ETS 2 carbon price and the likely success of policymakers in reducing it through complementary mitigation measures in these sectors.

However, the case for maintaining separate markets is likely to weaken over time, firstly because policymakers and the public will gain experience of operating the EU ETS 2, and secondly because (other things being equal) the EU ETS cap will shrink towards net zero (or net negative emissions), placing a very high price on some carbon emissions and causing attention to shift to the sectors that continue to emit. Options for merging the two markets include the creation of a single emissions trading system (a single price, cap and set of governance arrangements). Alternatively, policymakers could consider more gradual convergence options involving linking (the possibility of importing allowances from one system to the other under certain conditions) (Edenhofer et al., 2022).

10.5 Energy Taxation Directive

Taxation of the embodied emissions in energy varies across Europe.

Effective carbon prices within the EU (the prices created by fuel excise taxes, carbon taxes and emission allowances combined) can vary widely between Member States and between different sectors and applications. This is mostly because taxation is decided primarily at the Member State level, and partly because taxation serves numerous policy objectives apart from climate policy goals.

While a comprehensive survey of effective carbon taxes within the EU is beyond the scope of this chapter, a number of key characteristics are noted here.

- There are **substantial differences in effective carbon taxation between Member States and between sectors**. Transport fuels (diesel and petrol) face relatively high implicit carbon prices compared with other sectors, ranging between Member States from less than EUR 150/t CO_2 to over EUR 350/t CO_2 (Matthes and Graichen, 2022). These prices consist overwhelmingly of excise duties rather than explicit carbon taxes (OECD, 2023a). However, there are numerous sectoral reductions and exemptions. For example, agriculture and energy-intensive industries pay the least tax relative to the amount of energy they consume (Trinomics, 2020).
- **Explicit carbon taxes are levied in 14 Member States** according to Eurostat (2022a), while the European Commission estimates that 7 Member States have carbon taxes covering the buildings and transport sectors, with prices in 2020 ranging from EUR 19 to EUR 115 per tonne of CO_2 (EC, 2021c)
- **Tax rates sometimes favour carbon-intensive choices.** For example, effective carbon rates for coal are much lower than the rates for gasoline and diesel quoted above. Although most coal uses are subject to explicit carbon pricing under the EU ETS (around EUR 90 at time of writing), excise duties for coal are much lower (ranging from EUR 0 to EUR 25/t CO_2) (OECD, 2023a). Similarly, electricity is taxed more highly than gas per kWh (Rosenow et al., 2023).

The ETD aims to harmonise tax levels but is not aligned with the EU's climate objectives.

The Energy Taxation Directive (2003/96/EC) sets minimum taxation levels across Europe to ensure that the internal market can function effectively. It was introduced in 2003 with one of its main objectives being to harmonise energy taxation, avoid the distortions between different energy carriers (such as gas and electricity) and avoid energy tax competition across Europe. This harmonisation is ultimately aimed at strengthening the internal market by addressing possible distortions from the relocation of energy-intense businesses to beneficial tax regimes.

In 2011, the European Commission proposed to restructure the ETD to reflect both energy content and emissions. Following 4 years of unsuccessful negotiations, the proposal was withdrawn, as Member States were unable to reach a unanimous agreement. In 2019, the European Commission published an evaluation report on the ETD (EC, 2019b), concluding that energy taxation can be an important part of the economic incentives that steer energy transition. Considering the need for an updated ETD, the Council invited the European Commission to analyse and evaluate potential options, with a view to publishing a proposal for a revision.

The European Commission's proposal to update the ETD aims to address this misalignment.

In 2021, as part of the Fit for 55 package, the European Commission proposed a revision of the ETD to 'remove outdated exemptions and reduced rates that currently encourage the use of fossil fuels' (EC, 2021ai). It would introduce a new scale of tax rates based on the energy content and environmental

performance of the fuels and broadens the tax base to include more products in its scope, such as electricity, hydrogen and sustainable biofuels. Some of the main changes can be summarised as follows.

— Fuels and electricity would be taxed according to their energy content and environmental performance, rather than their volume. This change aims to help consumers to make more climate-cautious choices.
— A simpler product categorisation would be introduced, to simplify taxation and ensure that the most harmful fuels are taxed in the highest tax band.
— Exemptions for certain fuel uses, such as home heating, would be phased out, and so would the option for Member States to tax agricultural energy use at zero, thereby removing the possibility of taxing fossil fuels below specified minimum rates.
— Fossil fuels used for intra-EU transport by air or sea should no longer be exempt from energy taxation.

The proposal would tax energy use and price GHG emissions with a wider scope than the current ETD. One of the main challenges is to find ways to align EU-wide energy taxation with climate policy objectives. Low tax rates on fossil fuels increase the relative cost of switching to cleaner technologies and can delay the energy transition. According to the proposal, conventional fossil fuels (i.e. petrol, gas, oil) will be subject to the top minimum rate of EUR 10.75/GJ when used as motor fuel and EUR 0.9/GJ when used for heating. The next category applies to fuels such as fossil gas and liquefied petroleum gas, which will be taxed at a lower rate for a transition period of 10 years. In this transition period, a minimum rate of EUR 7.17/GJ will be charged when they are used in transport and EUR 0.6/GJ for heating. After the 10-year transition period, they will be taxed at the same rate as conventional fossil fuels. Electricity will be taxed at the lowest minimum rate, EUR 0.15/GJ, regardless of its use ([79]). Low-carbon hydrogen can also benefit from the same rate for a transition period of 10 years (EC, 2021z).

The European Commission proposal builds on the *ex post* evaluation of the ETD in 2017, which, in line with the better regulation guidelines, assessed the performance of the directive against the basic principles of relevance, effectiveness, efficiency, coherence and EU added value (EC, 2019b). The evaluation identified significant shortcomings in both the directive and its implementation. On effectiveness (i.e. progress made towards achieving policy objectives), the ETD was found to have made only a limited contribution to smooth functioning of the internal market, given the absence of an indexation mechanism and the multiple exceptions granted in certain industries. In terms of relevance and coherence, the ETD shows a gap between the needs of EU climate targets and the objectives the ETD was designed to address back in 2003 (for example, it enables electricity to be taxed more highly than fossil gas). The potential of synergies from the alignment of fiscal polies with policies in the domains of energy and transport remains unexploited. In the meantime, policy gaps and inconsistencies in implementation hamper the achievement of EU climate objectives.

Without a revision, the ETD undermines the effectiveness of the EU's carbon-pricing regime.

At the time of the writing of this report, progress on the revision of the ETD is limited, in part because of the requirement for revision to be approved by unanimity among Member States (as opposed to the qualified majority required for most Fit for 55 legislation). As previous sections of this chapter point out, taxes are not the only type of carbon price signal operating in the EU, and the Fit for 55 package should see a deepening and extension of explicit carbon pricing in several sectors. Nevertheless, the ETD in its current form enables the continuation of energy tax rates that run counter to the EU's climate goals by

([79]) Article 13 of the proposal also permits Member States to adopt a tiered approach to the taxation of energy inputs into electricity production, whereby taxation would reflect the input's relative carbon intensity.

taxing carbon-intensive energy carriers more lightly than low-carbon alternatives or by prolonging disparities in the carbon tax signals between Member States or different sectors of the economy. The ETD should therefore be revised in a manner similar to the European Commission proposal in order to correct these policy inconsistencies.

Additional opportunities for aligning energy taxation with climate goals include taxing electricity differently depending on its source (e.g. coal, wind) and offering preferential tax treatment for electrified transport or shore-side electricity for ships ([80]). The European Commission proposal allows Member States to exploit these opportunities by applying exemptions to these cases but stops short of giving them EU-wide preferential treatment.

10.6 Remaining gaps in the EU carbon-pricing regime

This section discusses emission pricing in agriculture and LULUCF. More general discussions of options for managing emissions and removals in these sectors can be found in Chapters 8 and 9, respectively.

With the most recent revision of the ETS Directive, the EU's carbon-pricing regime is extended to the maritime sector, road transport and fuels for heating in buildings. It might also be extended to (municipal) waste incineration as of 2028, based on an assessment by the European Commission to be carried out by 2026 (see Section 10.3).

As a result, the share of EU emissions and removals that are covered by an EU-wide carbon price will increase from 36 % at the time of writing ([81]) to 73 % in the second half of the 2020s (74 % if the EU ETS is extended to waste incineration) ([82]). However, the remaining 26 % (795 Mt CO_2e emissions and 230 Mt CO_2e removals in 2021) would remain excluded from any EU-wide carbon-pricing mechanism by 2030. Most of this carbon price gap, illustrated in Figure 74, is related to the absence of an EU carbon-pricing mechanism for the agriculture and LULUCF sectors, and the remainder is due to the partial exclusion of certain sectors (international aviation and maritime; non-CO_2 emissions from energy production, transport and combustion; and some smaller sectors including waste landfilling, wastewater treatment, etc.).

As all sectors will need to contribute to the 2050 climate neutrality objective, this gap should be addressed. Applying a carbon-pricing mechanism to the agriculture and LULUCF sectors would provide a clear financial incentive for farmers and forest managers to reduce emissions and increase removals, and for consumers to reduce the consumption of GHG-intensive agricultural products (see Chapter 8 'Agriculture'). It would also reduce the potential for intra-EU leakage ([83]) of emissions related to agriculture, forestry and other land use (Stepanyan et al., 2023), and address the uneven distribution of incentives for biomass use versus carbon removal (see Chapter 9 'Land use, land use change and forestry').

([80]) Shore-side power allows ships to turn off their engines (powered by tax-exempted fossil fuels) and connect to the electricity grid, thereby reducing local air pollution, and potentially GHG emissions, compared with using electricity generated on board the ship.

([81]) Hydrofluorocarbon emissions are currently covered by the F-gas regulation, which is considered to be a cap-and-trade system, and are therefore covered by a carbon or GHG price.

([82]) Based on the latest available data on GHG emissions and removals in 2021.

([83]) displacement of activity to regions with laxer climate policies

Figure 74 Scope of EU-wide carbon-pricing mechanisms (% of 2021 EU-wide GHG emissions and removals)

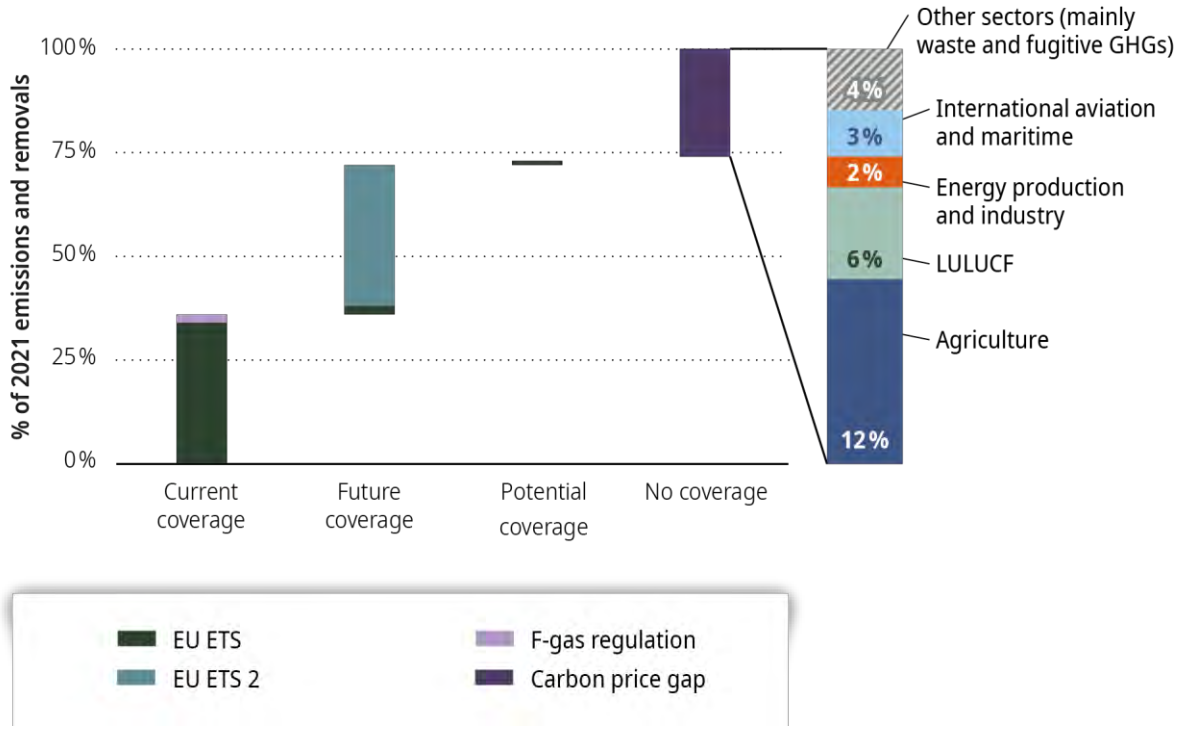

Notes: Agriculture includes both energy (CRF category I.A.3.c) and non-energy (category 3) GHG emissions. Energy production and industry include fugitive GHG emissions (category I.B). The denominator for determining the share is all EU GHG emissions and removals (both expressed as positive values) in 2021, including emissions from international aviation and bunkers but excluding indirect CO_2 emissions, as reported in the latest GHG inventories.

Sources: For the numerator: current coverage based on verified EU ETS data and the reported emissions from hydrofluorocarbons in the 2023 EU GHG inventory; future coverage under the EU ETS based on intra-EU, 'at berth' and half of extra-EU CO_2 emissions as reported by (EC, 2023k); future coverage under the EU ETS 2 based on the reported GHG emissions under the 2023 EU GHG inventory for road transport (CRF category I.A.3.b), the residential sector (category I.A.4.a) and the commercial/institutional sector (I.A.4.b); potential coverage based on an estimated 52 Mt CO_2e from waste incineration (this is an estimation, as the majority of waste incinerators recover energy and are therefore reported under the broader 'energy production' sector in GHG inventories); breakdown of the carbon price gap based on the 2023 EU GHG inventory data.

For **CDR**, the European Commission has proposed a certification framework based on four "QU.A.L.ITY" criteria (Quantification, Additionality, Long-term storage, and 225ustainability) (EC, 2022w). However, each of these criteria represents a key conceptual challenge to carbon pricing in land use (forestry and agricultural soils), as articles such as those by McDonald et al. (2023) and Wells et al. (2023) point out. It is challenging scientifically to quantify emissions and removals, and even more so to prove causality between management actions and carbon fluxes, due to the heterogeneity of the systems involved. Demonstrating additionality is also challenging because detailed checks may be needed to ensure that changes are the result of mitigation actions that go beyond existing requirements. Long-term storage cannot be guaranteed for land-based mitigation because carbon stored in soils and vegetation is inherently non-permanent and can be released by fire, natural disturbances, and changes in climate conditions or land management. This implies that land-based emission reductions and removals cannot be considered equivalent to other types of mitigation or removal unless sophisticated systems are put in place to ensure that the mitigation continues over time. Sustainability is challenging, since it involves

ensuring that carbon-pricing incentives incorporate (or at least do not conflict with) several other environmental and social objectives. Despite these challenges, excluding land-based carbon fluxes from carbon pricing can create a loophole (Isermeyer et al., 2021), for example by incentivising the use of straw for energy (to avoid CO_2 emissions from fossil fuels) while failing to incentivise the carbon sequestration benefits of returning it to the field.

When it comes to pricing **non-CO_2 emissions in agriculture**, some of the same challenges apply – in particular, heterogeneity – and the need for on-site measurement if emissions and mitigation are to be calculated accurately. Isermeyer et al. (2021) provide a review of practical options. For CH_4 emissions associated with livestock, they suggest emission pricing could work by introducing a default emission value per ruminant animal (e.g. cattle, goats and sheep). For N_2O, pricing could be based on the nitrogen surplus calculated at the farm level (the difference between annual nitrogen inputs and outputs) or by subjecting sales of nitrogen fertiliser to a carbon price. When introducing emission pricing in agriculture, the same risks of carbon leakage apply as those discussed in the context of the CBAM above and will need to be taken into account.

Options for designing a carbon tax in agriculture have been considered by the Danish climate council (Klimarådet, 2023), and at the time of writing the government of New Zealand is developing a system to commence mandatory emissions reporting in 2024 and carbon pricing in 2025 (He Waka Eke Noa, 2022; New Zealand government, 2022; O'Connor, 2023). The New Zealand proposal contains a number of interesting design choices that could inform ongoing discussions among the European Commission and European stakeholders. Emission reporting will occur at the farm level, through the use of standardised calculation tools whereby the cost per farm will be a function of estimated CH_4 and N_2O emissions, with discounts awarded for specified mitigation actions. The initial scheme will apply separate emission prices for CH_4 and N_2O, as well as rewarding certain carbon sequestration activities. In this way, the proposal appears to resemble an emissions tax and incentive scheme for encouraging sectoral mitigation, rather than a cap-and-trade market based around tradable tonnes of verified CO_2e emissions and removals. However, the New Zealand government has stated that its eventual aim is to include scientifically validated forms of on-farm carbon sequestration in its national emissions trading system covering other sectors of the economy. Introducing carbon pricing in agriculture also raises issues of international trade and emission 'leakage' (Henderson and Verma, 2021; Zech and Schneider, 2019). The general economic principles of this question are the same as those discussed in Section 10.3 in the context of the EU ETS and the CBAM. However, questions specific to agriculture will also need to be considered and addressed.

At the EU level, the European Commission is currently exploring options for pricing emissions and rewarding removals in the land sector, including through surveying the public (EC, 2023bd), commissioning research (EC, 2023am) and holding discussions in the expert group on carbon removal (EC, 2023af). As part of this effort, a study by Trinomics (2023a) examined a number of options for introducing an emissions trading system in agriculture, exploring the pros & cons of different "points of obligation" including farm-level, upstream (producers and importers of fertilizer and feed), and downstream (meat and dairy processors). It found that an on-farm point of obligation is likely to be the most complex administratively but may provide the most direct incentive to reduce emissions. The study also stressed that "vertical arrangements" could be put in place to incentivise mitigation along the value chain. For example this could incentivise manufacturers and importers to produce and supply low-emission feed and fertilizer, and incentivise food producers to substitute away from the highest emitting animal products. Emissions pricing can also involve action further down the "farm to fork" value chain (such as differentiated VAT rates). These kinds of action are considered in Chapter 8 on agriculture. The Trinomics study also points out that administrative costs, combined with economies of scale, may mean that large farms benefit the most from the opportunity to generate credits from mitigation actions, implying that ways to limit adverse impacts on small farms will need to be identified.

The European Commission's deliberation needs to be followed up by a concrete legislative proposal, with a view to extending carbon pricing to the agricultural and LULUCF sectors after 2030. The Advisory Board will consider this issue further in future work, including a report on carbon removal expected to be published in 2024.

10.7 Summary table

Table 16 Policy consistency summary – pricing emissions and rewarding removals

Policy inconsistencies	– Differences in the carbon price between the EU ETS and the EU ETS 2 introduce discrepancies such as subjecting electricity and fuels to different carbon prices in the buildings and transport sectors. – The ETD allows fossil fuels to be taxed less than electricity.
Policy gaps	– The EU does not yet have a clear strategy to prepare the carbon market and relevant sectors for the era of very low emissions and the prospect of the allowance supply reaching zero by 2040 – Agriculture/food and land use are not covered by explicit carbon pricing.
Ambition gaps	– The latest reform of the EU ETS does not phase out free allowances completely. They continue in industrial sectors not covered by the CBAM. – The EU ETS 2 may fall short of its own 2030 target because of uncertainties concerning the level of the carbon price, and design features that may de facto loosen the cap. – Not all revenue from carbon pricing is allocated to climate action. While EU ETS revenues must be used for specified climate action purposes, a similar requirement for CBAM revenues has not been confirmed at the time of writing. In the EU ETS, replacing free allocation with auctioning would release additional revenue.
Implementation gaps	– Potential gap: the risk of the EU ETS 2 missing its target places pressure on Member States to increase the stringency of national policies and measures in pursuit of national ESR targets. – Legislation enabling the expansion of the EU ETS to extra-EU flights is yet to be proposed.

11 Whole-of-society approach

*The title of this chapter is inspired by the first global stocktake under the UNFCCC, which highlighted that '**carefully designed climate action** can generate significant benefits and can help to minimize disruptions by taking a whole-of-society approach informed by local context. Equity should enable greater ambition and increase the likelihood of meeting the goals of the Paris Agreement' (UNFCCC, 2023, own emphasis).* ***Given that several climate policy measures recommended in this report are likely to have regressive social impacts, at least in the short term, the Advisory Board raises a few points for attention in support of a careful design of the EU climate policies.***

Key messages

EU climate policies should be accompanied by more systematic ex ante and ex post measurements of their distributional and wider socioeconomic impacts in specific contexts. Co-benefits of climate mitigation policy measures such as health, well-being and climate resilience, as well as trade-offs, should be duly considered and better integrated in the EU's policymaking.

Needs. To allow a transition to societies with a high level of well-being in a net zero EU, EU climate policy cycles need to be informed by the distributional and wider socioeconomic impacts of their various measures in specific contexts, such as rural/urban and gender-specific aspects. Identifying climate policy co-benefits ([84]) and unintended harms provides policymakers with a more comprehensive picture of what is at stake, and allows science-based positive framing of policy. By informing and engaging citizens and other stakeholders, consultations can increase public support for climate policies and measures.

Gaps. Despite the better regulation toolbox being equipped with instructions regarding the assessment of distributional and wider socioeconomic impacts, EU climate policies have not always been accompanied by systematic measurement of such impacts **(implementation gap)**. Moreover, the evidence of climate policy co-benefits such as better health, social cohesion and energy security, as well as possible trade-offs, is often overlooked in impact assessments. For that reason, policymakers across the EU often lack sufficient understanding of the socioeconomic impacts of the policies they put forward.

Recommendation W1. More systematic and context-specific impact assessments and *ex post* evaluations (e.g. considering local and national needs) should help reinforce synergies between EU social and climate policies and improve climate policy narratives. Assessments should be transparent and include public consultations. Trade-offs and co-benefits of climate policy measures should be duly considered and better integrated in the EU's policymaking. The European Commission's communication on 'Better assessing the distributional impact of Member States' policies' (2022), provides welcome guidance for the Member States, and should go hand in hand with integrated socioeconomic assessments, including those conducted by the European Commission for all relevant draft EU policies and measures.

Climate policies driving societal and behavioural changes can be supported by better narratives that are tailored to local contexts and built on evidence regarding the expected costs and benefits.

Needs. Many demand-side mitigation measures build on people's willingness to adopt innovative or otherwise disruptive solutions, usually triggered by understanding of the related costs and benefits at

([84]) Climate policy co-benefits are the multiple benefits that are additional to avoided climate change costs.

the household, community, or wider society level. EU climate policies need to leverage behavioural and societal changes in consumption patterns.

Gaps. The narratives surrounding climate policy instruments tend to be focused on GHG emission reduction and cost-effectiveness, without due attention paid to their co-benefits or to local needs and values **(ambition gap)**.

Recommendation W2. EU climate policies across sectors should be better supported by narratives that respond to local needs and values, informed by data on both costs and benefits of climate policy measures.

Regressive impacts of climate policies can be attenuated by well-designed and well-resourced social policy measures.

Needs. Many climate policy instruments carry a risk of disadvantaging lower-income households and vulnerable groups, for instance through green gentrification, restricting access to energy services, higher prices of goods and loss of jobs. Since the perceived fairness of EU climate policies will determine whether they are implemented successfully, EU policies need to address regressive social impacts of climate policy measures, taking into account various dimensions of social inequalities including location (e.g. rural, urban, remote), income, gender, ethnicity, race, age and (dis)ability.

Gaps. EU climate and social policies are not sufficiently complementary so far. Few EU climate policies are informed by *ex ante* assessments of their possible socioeconomic impacts **(policy gap)**. This may affect the design and funding of social compensation instruments; for example, it is uncertain if the Social Climate Fund will be sufficient to offset the expected regressive impacts of the EU ETS 2. Adequate targeting of compensation measures is attracting increasing attention within the EU, linked to the risk of perverse incentives in fossil fuel consumption; for example, the recent energy subsidies deployed across the EU in response to high energy prices to protect consumers accounted for EUR 195 billion in 2021–2022, with the lion's share categorised as fossil fuel subsidies (for the need to phase out fossil fuel subsidies, see Section 12.3). The risks of such policy responses were flagged by the Advisory Board in its previous contribution (ESABCC, 2023a).

Recommendation W3. Synergies between EU social policies and climate policies should be strengthened, and the measures compensating for regressive impacts of climate policy instruments, such as the Social Climate Fund and Just Transition Fund, should be adequately targeted and resourced. At the national level, the European Commission's recommendation of October 2023 should be followed by all Member States, as it provides a welcome basis for defining and tackling energy poverty, calling on Member States to ensure coherence across policies, in particular between energy and social policies.

11.1 Fair and just transition in a challenging context

The EU is moving towards net zero while dealing with the cost-of-living crisis, income disparities and constrained fiscal space.

Since the European Green Deal communication in 2019 (EC, 2019c), the socioeconomic and geopolitical context in which the EU is pursuing its climate objectives has become increasingly challenging. The COVID-19 pandemic in 2020–2022 and subsequent recovery have resulted in global supply shortages and inflation (Lebastard et al., 2023). These worsened in the wake of Russia's war of aggression against Ukraine, which resulted in historically high energy prices in the EU and increased food prices globally.

High levels of inflation (see Figure 75) led to a cost-of-living crisis in the EU and undermined the international competitiveness of EU businesses, notably in energy-intensive sectors (ESABCC, 2023a). A recent Eurofound survey sheds light on the resulting hurdles for the European workforce, such as struggles to make ends meet and poor job security, as well as declining trust in public institutions (Eurofund, 2023).

Figure 75 Euro area inflation and its main components, October 2013 to October 2023 (%)

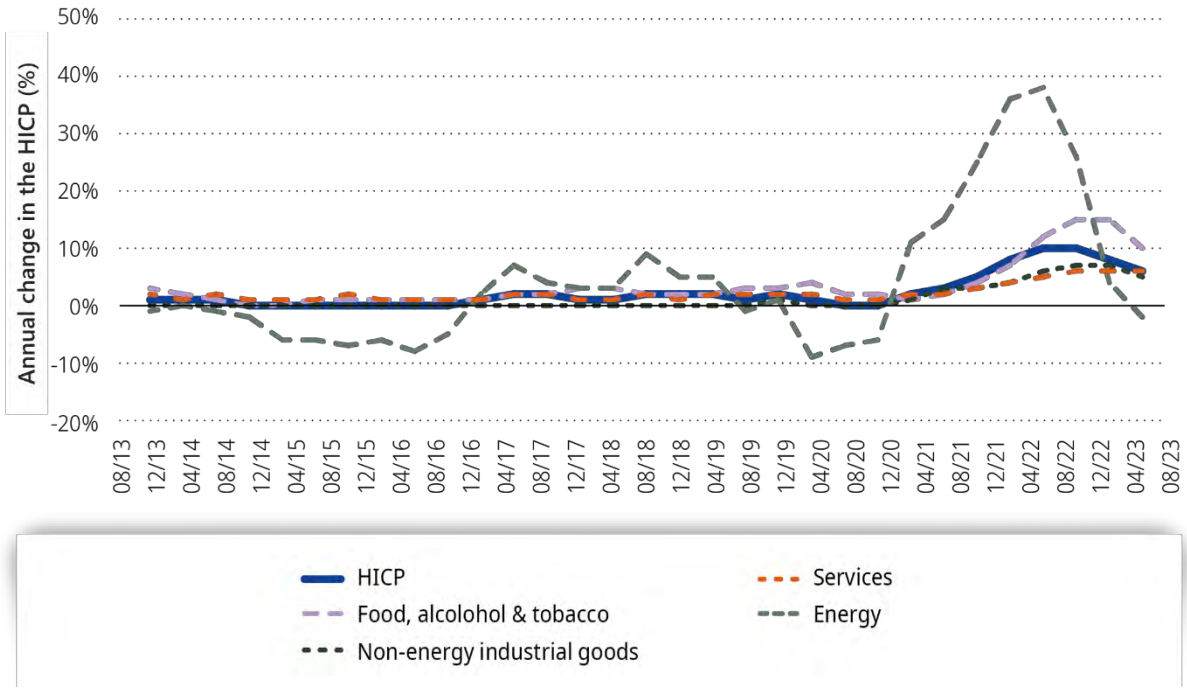

Source: Eurostat (2023n)

As a response to the increasing inflation, the ECB has increased interest rates to a record high level since the euro was established in 1999. The ECB's benchmark deposit rate went up to 4 % in September 2023, from 0.5 % in September 2019 (ECB, 2023b). Central banks' interest rates have increased investment financing costs, that is, cost of capital. Increases in the cost of capital are exacerbated by financial risks linked to, for example, geopolitical and policy uncertainties (IEA, 2023b). High financing costs can discourage investment spending, while the opposite is needed on the EU's pathway to climate neutrality (see Chapter 12 'Finance and investments').

Furthermore, the economic slowdown and various support measures in the context of COVID-19 and the energy crisis led to a surge of government debt across the EU in 2020, and, although the EU's government debt to GDP ratio is decreasing, the available fiscal space of the EU Member States is more constrained today than it was in 2019 (Eurostat, 2023k). High interest rates set by the ECB increase costs in public debt management (Claeys and et al., 2023), further constraining the fiscal space of EU Member States. This in turn affects social transfers that reduce the high disparities in income in the EU Member States ([85]). The contribution of social transfers to the total median annual disposable income per inhabitant across the EU in 2022 is presented in Figure 76.

([85]) In 2022, the Gini coefficient for the EU was 29.6. The Gini coefficient is based on the comparison of cumulative proportions of the population against cumulative proportions of income they receive, and it ranges between 0 in the case of perfect equality and 100 in the case of perfect inequality .

Figure 76 Mean equivalised disposable income and share of social transfers

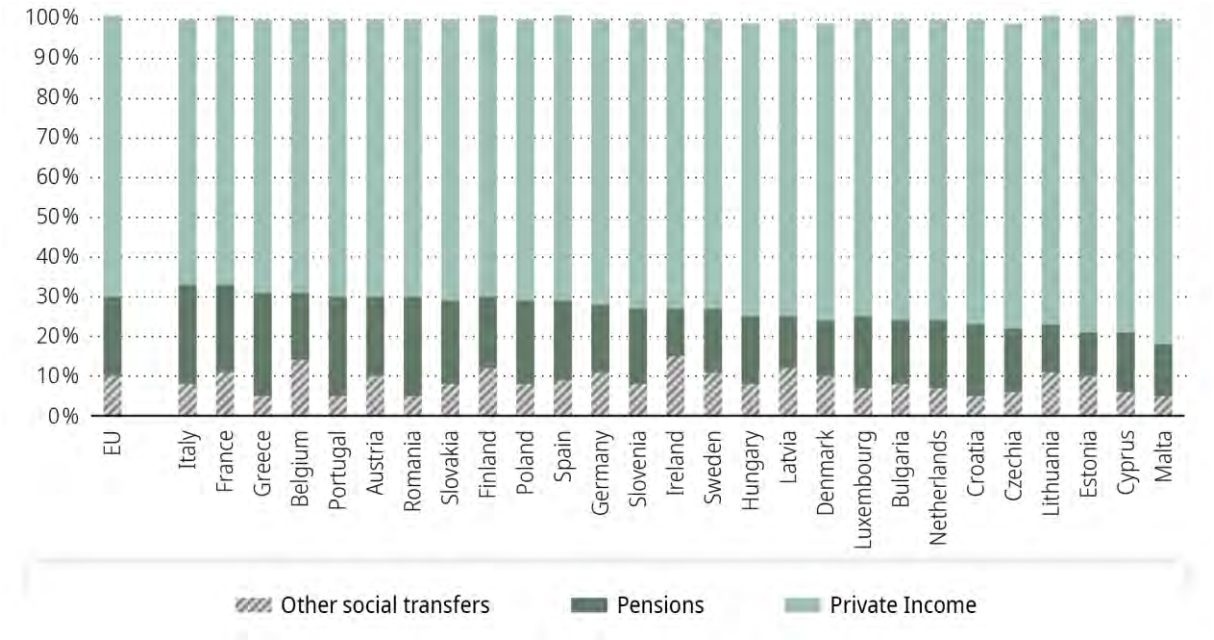

Notes: Categories estimated based on mean income including/excluding pensions and social transfers

Source: Adapted from Eurostat (2023p) (codes ilc_di03, ilc_di13, ilc_di14)

The pressure on social transfers to ensure redistributive equality is likely to grow together with the introduction and strengthening of some climate policy instruments, notably carbon pricing. It will be exacerbated by an ageing EU population (EC, 2021a) and competitiveness pressures.

The above considerations indicate that the EU's path towards climate neutrality is particularly exposed to the socioeconomic impacts of the climate policies.

11.2 Transition to high-well-being societies

To allow a transition to high-well-being societies in a net zero EU, EU climate policy cycles need to be informed by the distributional and wider socioeconomic impacts of their various measures in specific contexts. Co-benefits of climate policy measures need due consideration and better integration in the EU's policymaking.

According to the IPCC, 'ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries, including shifting of income and employment during the transition from high to low emissions activities' . At the EU level, the better regulation toolbox (EC, 2021a) provides the European Commission with instructions regarding socioeconomic, including distributional, impact assessment of the proposed policies and measures. Moreover, in September 2022 the European Commission issued guidance to Member States on 'Better assessing the distributional impact of Member States' policies' (EC, 2022l).

However, recent EU analyses demonstrate that there is no systematic measurement of distributional and wider socioeconomic impacts of EU climate policies, and that there is a need to improve policymakers' understanding of such impacts (EEA and Eurofund, 2021; EPRS, 2023). Limited recognition and narrow understanding of the negative socioeconomic impacts that could arise from implementing climate policy measures are particularly acute in relation to the various dimensions of inequality (EPRS, 2023).

In addition, co-benefits of climate policy measures are often not sufficiently considered (Buchholz et al., 2020; Karlsson et al., 2020; Weitzel et al., 2023). This may be because of the difficulties in quantifying, illustrating or monetising such benefits. Without due consideration of the co-benefits, the EU may forgo some of the opportunities linked to the positive framing and science-based support to policymaking offering a 'comprehensive picture of what is at stake' (Karlsson et al., 2020). A tendency to focus policy assessments on direct market cost values may lead to neglecting more systemic solutions for which market prices are difficult to evaluate, but that advance societies towards a new idea of prosperity and the achievement of the sustainable development goals (Buchholz et al., 2020; Creutzig et al., 2022).

Better data and understanding of distributional and wider socioeconomic impacts of climate policy design and implementation, based on experience and forward-looking assessment tools, can help advance the EU's fair and just transition. Information generated through systematic measurement of socioeconomic impacts can inform policy design and help to improve it. In this way, it will allow for adaptive feedback loops across policy instruments linking ex ante assessments and ex post evaluations (see also Section 14.3). Thanks to that, EU policies will be more fit to reduce social inequalities in a net zero economy, making the most of multiple benefits of climate action, such as health and well-being (see for example EEA and Eurofund, 2021).

11.3 Better narratives for societal and behavioural changes

Climate policies driving societal and behavioural changes can be supported by narratives that are tailored to local contexts and built on evidence regarding the expected costs and benefits.

Apart from the equity considerations, the whole-of-society approach links strongly to demand-side mitigation (IPCC, 2022b, 2022f) and its untapped potential highlighted in terms of GHG emission reduction in the sectoral analyses of this report. Demand-side mitigation options are considered to increase well-being (Creutzig et al., 2022), and can be activated by, among others, non-technological measures in climate action including professional advice and awareness raising, community approaches and demonstrative interventions at a local scale (IPCC, 2022f; Niamir et al., 2020). Many of them build on people's willingness to adopt innovative or otherwise disruptive solutions, usually triggered by their understanding of the related benefits at the household, community or wider society level (see for example Maestre-Andrés et al., 2019; Van Der Linden et al., 2021). In this respect, non-technological measures such as considering societal readiness levels in the preparation of net zero transition plans and measures (Bernstein et al., 2022; Büscher et al., 2023) can be supported by technology, such as smart devices.

In the context of energy and buildings, behavioural interventions such as social comparison, goal setting, and labelling have the potential to significantly reduce the energy consumption of private households (Andor and Fels, 2018). Half of the 12 % drop in fossil gas consumption in EU buildings between 2019 and 2022 is attributed to behaviour changes. Voluntary energy consumption reduction can be further leveraged through EU policies, for example by encouraging better use of existing buildings (Bertoldi, 2022; Gaspard et al., 2023). Moreover, considering behavioural factors represents a promising way to mitigate excessive rebound effects after renovation (EEA, 2023a).

In agriculture, informing and educating consumers helps them to reduce food waste and choose sustainable and healthy diets. While some cultural and social values might hinder the adoption of more sustainable diets, policies can appeal to supportive values; for example, they can invoke health by highlighting the multiple benefits of sustainable diets.

So far, however, as described in sectoral chapters 4-9, EU climate policies have not sufficiently leveraged behavioural and societal changes in consumption patterns. This can be attributed to, among other

influences, narratives surrounding climate policy instruments, which tend to be focused on GHG emission reduction and cost-effectiveness, without paying due attention to their multiple benefits or to local values and core beliefs (Rietig, 2019). For example, building retrofits triggered by the EPBD have not been sufficiently embedded in appealing narratives so far, often for lack of reliable data regarding the multiple benefits of deep energy retrofits of the building stock, such as job creation, energy poverty alleviation, public health, energy security and environmental sustainability (EC, 2021j).

Increased policy integration of multiple benefits at the EU level has been announced in the renovation wave strategy and the ensuing initiatives such as the New European Bauhaus (EC, 2022f). The New European Bauhaus aims at facilitating and steering the transformation of our societies alongside the values of sustainability, aesthetics and inclusion. It devises a delivery mechanism to spur such new lifestyles and future-proof the built environment (EC, 2023ay). The EPBD recast (EC, 2021ac) refers to wider benefits of energy efficiency and reinforces their contribution of those benefits to society through several provisions, for example as part of the proposed building renovation passport. The proposed revision fosters digitalisation of buildings through, for example, a smart readiness indicator, which can support behavioural changes, for instance by improving building users' access to data.

In energy supply, in locations where RES and energy demand reduction are perceived predominantly as remedies for air pollution, low-quality employment or energy dependence on imported fuels, prospects linked to these multiple benefits, rather than climate action, engage citizens in transformative changes (IPCC, 2022g; Mata Pérez et al., 2019). Following Russia's invasion of Ukraine in February 2022, European Commission communications emphasised the benefit of energy security linked to measures increasing the roll-out of renewable energy and encouraging energy savings (EC, 2022a). That made the EU policies in these areas relatable and understood by the wider public who were enduring the energy crisis and geopolitical instability.

In this context, EU climate policies across sectors could benefit from better narratives informed by data and tailored to local needs.

11.4 Attenuated regressive impacts

Regressive impacts of climate policies can be attenuated by well-designed and well-resourced social policy measures.

The perceived fairness of EU climate policies will determine whether they are implemented successfully (IMF, 2023; ECA, 2022; EPRS, 2023b). The climate transition exposes fairness issues. Many climate policy instruments, whether regulatory (e.g. standards) or economic (e.g. carbon taxes), carry a risk of disadvantaging lower-income households and vulnerable groups, for instance through green gentrification, restricting access to energy services and – as in the case of fossil fuel workers – loss of jobs (see e.g. Zakeri et al., 2022). Climate policies bring also substantial long-term benefits to societies, such as lower energy bills, higher thermal comfort and improved air quality, with positive outcomes in terms of health and well-being. They also avoid the immense economic and social costs of climate inaction (see for example IPCC, 2022h). Lower-income households and vulnerable groups tend to be exposed more to these costs and benefits (EEA and Eurofund, 2021; IPCC, 2022l).

The around 10 % of EU citizens who cannot afford to heat or cool their homes properly often occupy low-performing buildings that lead to high energy costs (Eurostat, 2023o; Thomson et al., 2019). Moreover, the inability to maintain thermal comfort at home is also likely to coincide with health issues for residents. The problem of energy poverty in conjunction with unhealthy living conditions is common

across the EU (IEA, 2020) and is reflected in the definitions of 'energy poverty' and 'vulnerable households' ([86]) in the Social Climate Fund regulation (EU, 2023m). The proposal for a revised ETD (EC, 2021y) includes a simplified definition linking vulnerability only to disposable income ([87]). Vulnerability in the context of high energy bills goes beyond the disposable income consideration, however. Social inequalities in the context of climate change mitigation are also linked to, among other factors, spatial location (e.g. rural/urban) gender, ethnicity, age and disability (IPCC, 2022f).

The sizeable socioeconomic impacts of climate policy measures call for a strong link between climate policies and social policies. This link has been found insufficient in recent analyses conducted by the EEA, Eurofound and the European Parliament's think tank (EEA and Eurofund, 2021; EPRS, 2023)

Stronger links between social and climate policies would be in line with the existing EU climate policy aspiration to leave no-one behind, repeatedly affirmed by EU leaders, in the context of just transition policy (EU, 2021b). EU efforts in this context include energy products and electricity used by vulnerable households being exempted from taxes under the proposed ETD, the European Commission's recommendation on energy poverty (EC, 2023i), and the setting-up of the Energy Poverty Advisory Hub (EC, 2023y) and the European Commission on Energy Poverty and Vulnerable Consumers Coordination Group (EC, 2022a). Together with the Social Climate Fund (EU, 2023m), these initiatives have the potential to mitigate some socioeconomic risks linked to energy prices and the cost of compliance with high energy performance standards and carbon pricing under the EU ETS and the EU ETS 2.

The Social Climate Fund (see also Box 6) is an example of using revenue from carbon emissions trading to address the equity and distributional impacts of carbon-pricing instruments. As such, it will be of utmost importance that it is targeted and resourced appropriately, so that it can fulfil its objectives. While it is positive that the Social Climate Fund budget can be increased through transfers from other funds, there are concerns that its reliance on EU ETS revenues may lead to insufficient finance for the fund (EESC, 2021). Moreover, experience from the Just Transition Fund suggests that the implementation of the public consultation requirement when developing national/local plans guiding the fund's disbursement can be challenging and is not to be taken for granted (EC, 2023bg).

In addition to the above initiatives, including the Social Climate Fund and the Just Transition Fund, the EU has put in place several social policy measures that can help attenuate regressive impacts of EU climate policies. Their adequate resourcing and targeting can be supported by closer interaction between social and climate policies, including better recognition of climate policies' socioeconomic impacts (see Section 11.3 above).

Box 6 Social Climate Fund

Adopted in May 2023, the EU regulation establishing a Social Climate Fund (EU, 2023m) aims to contribute to a socially fair transition towards climate neutrality by addressing the social impacts of including GHG emissions from buildings and road transport within the scope of the EU ETS. Its specific objective is to 'support vulnerable households, vulnerable micro-enterprises and vulnerable transport

([86]) Energy poverty for the purposes of the Social Climate Fund is defined as 'household's lack of access to essential energy services that underpin a decent standard of living and health, including adequate warmth, cooling, lighting, and energy to power appliances, in the relevant national context, existing social policy and other relevant policies'; 'vulnerable households' means 'households in energy poverty or households, including low income and lower middle-income ones, that are significantly affected by the price impacts of the inclusion of greenhouse gas emissions from buildings within the scope of the EU ETS Directive 2003/87/EC and lack the means to renovate the building they occupy' (Article 1 of the Social Climate Fund regulation).

([87]) Vulnerable households under the proposed ETD are households below the 'risk of poverty' threshold, defined as 60 % of the national median equivalised disposable income.

users, through temporary direct income support and through measures and investments intended to increase the energy efficiency of buildings, decarbonisation of heating and cooling of buildings, including through the integration in buildings of renewable energy generation and storage, and to grant improved access to zero- and low-emission mobility and transport' (Article 3). The Social Climate Fund resources will come from EU ETS 2 revenues covering buildings and transport and should reach up to EUR 65 billion between January 2026 and December 2032. This amount can be topped up with resources from EU funds under shared management, and it can also partly be transferred to such funds, at the request of a Member State. The Social Climate Fund will be disbursed based on the social climate plans prepared by the Member States through a participatory process in which local and regional authorities, economic and social partners, civil society organisations, youth organisations and other stakeholders are involved (Article 5). The first plans should be submitted to the European Commission in mid-2025 and the Social Climate Fund will put into operation in 2026.

11.5 Summary table

Table 17 Policy consistency summary – whole-of-society approach

Policy gaps	– EU climate and social policies are not sufficiently complementary so far. Few EU climate policies recognise their negative socioeconomic impacts, and even fewer identify ways to address them.
Ambition gaps	– The narratives surrounding climate policy instruments tend to be focused on GHG emission reduction and cost-effectiveness, without due attention paid to their co-benefits or to local needs and values.
Implementation gaps	– Despite the Better Regulation toolbox being equipped with instructions regarding the assessment of distributional and wider socioeconomic impacts, EU climate policies have not always been accompanied by systematic measurement of such impacts.

12 Finance and investments

Key messages

As an estimate, investments in clean energy and transport need to at least quadruple to achieve the EU's climate goals. This can be achieved by increasing the absolute level of investments in these sectors towards an annual average of EUR 1 241 billion (an increase of about EUR 500 billion) and reorienting all existing investments in these sectors towards mitigation technologies.

Needs. The European Commission's modelled scenarios estimate that investments related to mitigation in energy and transport sectors need to reach an average annual level of about EUR 1 241 billion over 2021–2030, to achieve the EU's climate objectives. According to recent research (IPCC, EIB, Bloomberg New Energy Finance (BNEF)), only a small share of current investments in energy and transport is climate related (about EUR 200–300 billion per year). Given this evidence, the Advisory Board estimates that investments in mitigation technologies in energy and transport need to increase by at least a factor of four (as illustrated in Figure 77 below), through a combination of increasing total investments in energy and transport (by at least EUR 500 billion annually) and redirecting existing finance flows towards mitigation technologies. Given the size and scope of the investment gap, a concerted effort by both public and private sectors is required.

Gaps. The above estimates are based on a variety of sources with different scopes and levels of granularity. Currently, there is insufficient information available on the investments required to fund the transition towards climate neutrality. There is also a lack of available indicators to track progress at the sectoral level. This knowledge gap is mainly due to the lack of a harmonised methodology for identifying and estimating climate-related investment needs **(policy gap)**.

Recommendation F1. The EU should strive for a more granular and accurate overview of required and actual investments in climate mitigation to monitor and assess progress. Specific recommendations on how to effectively increase both public and private climate investments are included in the key messages below.

Fossil fuel subsidies need to be phased out completely and urgently. The share of subsidies that is aimed at supporting vulnerable households should be well targeted, without undermining the incentives for energy efficiency and savings or the shift towards RES.

Needs. Fossil fuel subsidies hinder the reorientation of private financial flows towards climate mitigation and increase the risk of locking in GHG emissions. They also reduce the public budget available to support climate investments. Therefore, they need to be phased out rapidly, as also called for in the COP26 Glasgow Climate Pact, the European Green Deal and the 8th EAP.

Gaps. Despite repeated political commitments, EU State aid guidelines continue to allow fossil fuel subsidies **(policy inconsistency)**. Fossil fuel subsidies remained relatively stable in the last decade (around EUR 50 billion per year), and even increased sharply in 2022 (to EUR 120 billion) in the context of the energy crisis. The 8th EAP requires the European Commission and Member States to set a deadline for the phasing out of fossil fuel subsidies consistent with the 1.5 °C objectives, but so far only a few Member States have enacted laws or set out clear plans that specify how and by when this will be achieved **(implementation gap)**.

Recommendation F2. Member States should clearly specify in their updated NECPs how and by when they will phase out fossil fuel subsidies, including a clear trajectory towards a full phase-out by a specific year in the immediate future. The European Commission should assess during their review of these NECPs whether this requirement is met.

Support measures for vulnerable households that constitute a fossil fuel subsidy should be transformed into well-targeted interventions that do not undermine the incentive for energy savings or the shift towards RES (see also Section 11.4).

The EU budget aims to make a significant contribution towards reaching the required investments needed to reach climate neutrality. However, this is hindered by flaws in the methodology for tracking climate-related spending and by the lack of information about what happens after the RRF ends, which increases uncertainty.

Needs. The EU budget needs to contribute towards the EU's climate objectives, by supporting investments in climate action and avoiding investments in GHG-intensive activities (in other words, by climate mainstreaming). Furthermore, the EU has committed to spending at least 30 % of its long-term budget under the MFF and at least 37 % of the RRF on climate-related objectives. Combined, this corresponds to an estimated average of EUR 83 billion a year of EU public budget to be spent on climate action in 2021–2027.

Gaps. There are substantial flaws in the methodology applied to track the spending of the EU budget on climate action, which result in overestimating the EU budget's contribution towards the EU's climate objectives **(ambition gap)**. These include the reliance on high-level coefficients in combination with overly optimistic assumptions about the climate impact of spendings (with the CAP a primary example), the lack of an *ex post* assessment of whether budgets planned for or committed to climate action were actually spent on that, and a lack of reporting about spending on activities that increase GHG emissions; such reporting would be in line with the 'do no significant harm' principle. The methodology applied under the RRF is more robust, as it is partially aligned with the EU Taxonomy to prevent harmful investments, but it still relies on coefficients in tracking climate contribution **(ambition gap)**. Furthermore, the RRF itself is expected to cease after 2026 and it is not clear whether it will be succeeded by a similar instrument, reflecting a lack of long-termism **(policy gap)**.

Recommendation F3. The reporting methodology to track climate spending under the EU budget should be improved to more accurately track expenditures that effectively contribute towards the EU's climate objectives. The reporting methodology should also track spending on activities that breach the 'do no significant harm' principle; for example, it could do this by aligning with the principles of the EU Taxonomy framework.

Recommendation F4. The EU should consider continuing the approach of the current RRF beyond 2026. The framework is financed by common debt and supports the EU budget, to boost EU public investment, strengthen the EU's sovereignty and accelerate the climate transition.

State aid rules have been relaxed to allow increased spending by Member States in response to the pandemic and the energy crisis. However, their fiscal space is constrained by increased demands on public expenditures, decreasing revenues and the fiscal rules set out in the Stability and Growth Pact. Member States' divergent fiscal headroom increases the risks of fragmentation in the single market. The EU's response to this risk (the Strategic Technologies for Europe Platform) has so far been inadequate.

Needs. In addition to the EU budget, Member States also need to increase their climate spending to close the investment gap. State aid rules need to strengthen the single market and support the further development of mitigation technologies, addressing the investment gap in the energy and transport sectors.

Gaps. The potential for increasing Member State borrowing to support investment needs related to the transition to climate neutrality is limited by the requirements of the Stability and Growth Pact. Despite calls from policymakers and experts to provide specific rules for climate-related public investments, the European Commission's recent proposal to reform the Stability and Growth Pact does not differentiate investments related to the climate transition **(ambition gap)**.

In the meantime, the relaxation of State aid rules increases the risk of fragmenting the EU single market. Proposals from European Commission to address this (the proposed Strategic Technologies for Europe Platform, as a first step towards an EU Sovereignty Fund) include too limited a budget (EUR 10 billion compared with more than EUR 300 billion per year in State aid in 2021) to be sufficiently effective **(ambition gap)**.

Recommendation F5. A rapid phase-out of fossil fuel subsidies (see recommendation F2) would increase Member States' revenues or reduce their expenditures, which could then be reoriented to finance climate investments. A structural common fiscal capacity based on a common debt (see recommendation F4) would help to mitigate the risk of fragmenting the single market.

The private sector will need to deliver most of the required climate-related investments. This needs to be driven by ambitious EU policies, to build a pipeline of bankable projects across the EU.

Needs. Given the magnitude of the investment gap and the difficulty of increasing (both EU and national) public spending on climate, the private sector will need to make a substantial contribution to achieve the required level of climate-related investments. This needs to be driven by sufficiently ambitious EU policies to improve the bankability of climate-related investments, and by tailored financing solutions. There is also a need for an effective policy mix that addresses standards and regulations, support infrastructure, faster issuing of permits, technical assistance and capacity building. Stable investment conditions and better use of public funds will play a key role in this respect (see also Chapters 4–10). Various policy options are discussed in other chapters of this report, and in particular in Chapters 0–8 on the different sectors and Chapter 10 'Pricing emissions and rewarding removals'.

Claims on sustainable investments need to be based on harmonised and science-backed frameworks.

Needs. Sustainable investments (taking into account environmental, social and governance (ESG) criteria) and green bonds have become increasingly popular in recent years. The increasing appetite of the market for these financial products can contribute to the financing of required climate-related investments, provided that they are based on credible and transparent sustainability criteria to avoid greenwashing.

Gaps. In the past, the environmental integrity and credibility of sustainable investments and green bonds could not be ensured, for lack of a harmonised, robust classification system. The EU aims to address this with the development of the EU Taxonomy framework in 2020, and the EU Green Bond Standard in 2023. While these are overall steps in the right direction, the EU Taxonomy labels certain fossil gas activities as sustainable. Despite the specific criteria, that increases the risk of fossil fuel lock-ins **(policy inconsistency)**. Furthermore, whereas many private entities in the EU will have to report on the alignment of their investments and activities with the EU Taxonomy, there is no requirement to meet a minimum degree of alignment. Such alignment's contribution to shifting investments towards sustainable activities will thus primarily rely on investors' preferences. Similarly, the green bond standard is voluntary, and its effectiveness will therefore depend on whether bond issuers will choose to apply it in the future. So far, green bonds issued under NextGenerationEU are not necessarily aligned with the EU Taxonomy and the EU Green Bond Standard, which reduces transparency on the use of proceeds and can undermine credibility in the credit market, resulting in higher borrowing costs **(ambition gap)**.

Recommendation F6. The regular updates of the TSC of the EU Taxonomy should lead towards full alignment of the EU Taxonomy with the climate neutrality objective and treat investments in natural gas as non-sustainable, to avoid the risk of creating lock-ins.

Recommendation F7. As a minimum, the European Commission should start to apply the EU Green Bond Standard to green bonds issued to finance NextGenerationEU, to strengthen reporting transparency on the use of proceeds and foster market confidence, which can result in lower borrowing costs.

12.1 Context, scope and overview

The Paris Agreement, IPCC AR6 and the European Green Deal emphasise the role of finance as a critical enabling factor for the achievement of ambitious climate objectives (UNFCCC, 2015; EC, 2019c; IPCC, 2022n). Achieving the objectives of the European Green Deal would require a substantial increase in investments, the magnitude of which would require mobilising both the public and the private sector. The current economic context, characterised by slower economic growth, constrained public budgets, inflation and elevated interest rates, affects the EU's capacity to finance the climate transition (see also Section 1.1).

The aim of this chapter is to assess progress in financing the climate transition in the EU, and to what extent EU policies are driving the necessary mobilisation of public and private finance. It starts with an overview of current and required investments in the climate transition, based on available data. It then provides an assessment of the potential and required policies to mobilise the EU budget, national public budgets and private capital to reach the required investments. It then proceeds to assess progress and policies on the phase-out of fossil fuel subsidies, and the potential roles of the EU Taxonomy and green bond market to close the climate investment gap. A thorough assessment of the EU's progress towards

achieving its commitments on climate finance is beyond the scope of this report, but it is briefly discussed in Box 7 'international climate finance'.

Box 7 international climate finance

The EU remains committed to supporting the developed economies' goal of jointly mobilising USD 100 billion per year up to 2025 to support developing economies. Between 2014 and 2021, EU support to developing countries increased by 50 %, reaching EUR 23 billion a year, which includes contributions from the EU budget, Member States and the EIB. In 2021, over 54 % of EU funding to developing economies was related to climate adaption or a combination of climate mitigation and adaptation, and almost half of the funding was in the form of grants (EEA, 2023j). Currently there is limited public information available on the uses of funding reported under EU contributions to international climate finance. This hinders the assessment of policy effectiveness. More detailed reporting on a project-by-project basis would improve transparency and could attract more interest from private funding initiatives.

In its advice on an EU 2040 objective, the Advisory Board has identified the need for the EU to contribute to climate mitigation outside the EU, to close the gap between what it can feasibly do to reduce domestic net emissions and what it should do in line with its fair share towards the global 1.5 °C objective (ESABCC, 2023b). This could be achieved by, among other methods, providing finance for climate mitigation projects outside the EU.

12.2 Progress on climate-related investments

Assessing progress in climate-related investments faces methodological challenges.

This section aims to assess progress towards financing the climate transition in the EU by comparing actual with required climate-related investments (also referred to as investment needs). Investment needs are widely used as an indicator for measuring the required system change (when compared with current flows and asset bases). They usually focus on investments required to realise new infrastructure. One of the benefits of this indicator is that it is relatively easy to compare with private sector investment flows. However, it also has limitations, as it does not capture the need to build institutional capacity to strengthen knowledge and skills; nor does it measure needs for investment to address economic losses due to physical climate risks or investment needs related to adaptation (IPCC, 2022m).

There are two main challenges in assessing progress in climate-related investments. Firstly, there is no clear and verifiable definition of what constitutes climate finance flows or climate-related investments. This presents a difficulty in estimating progress and identifying investment gaps, as using different definitions can lead to different conclusions (Yeo, 2019). Boundaries between private and public finance can also be unclear, as private climate-related investments often benefit from public support in the form of co-financing, guarantees or fiscal measures (Weikmans and Roberts, 2019). In addition, the accuracy of modelled investment needs is also influenced by multiple, inherent sources of uncertainty. One source of uncertainty is change in technology costs, such as the levelised cost of energy of different renewable energy technologies. The relatively high share of investments since the early 2000s in the renewables sector has contributed to the rapidly declining technology costs of solar PV and wind in more recent years ("Energy Transition Investment Trends 2023," ; IEA and IRENA, 2017). Cost reductions could free up investment and financing capacities for potential use in other climate-related activities. Another source of uncertainty about financing needs is the interplays between:

— the economic growth rate,
— the link between growth and energy demand, including rebound effects of energy efficiency gains,
— changes in variables such as fossil fuel prices, inflation and real interest rates (IPCC, 2018).

Since 2020 the European Commission has prepared multiple estimates on different investment needs for achieving specific strategies (e.g. the hydrogen strategy and REPowerEU). Estimated investment needs varied considerably, partly because of rapid changes in the macroeconomic context (COVID-19, energy crisis, inflation) and technology costs, but also because different definitions and methodologies were applied in different periods (EEA, 2023l). The lack of a unified methodology to estimate investment needs undermines comparability and makes it challenging to accurately track progress.

The progress assessment in this chapter is based on the best available data on historical and required climate-related investments within the EU, covering both public and private sources of funding. As the different sources use different definitions and scopes, and given the inherent uncertainties described above, the results should be interpreted as an indicative estimate to illustrate the order of magnitude.

Climate-related investments in the EU need to at least quadruple, both by reorienting existing investments and by increasing total energy investments.

IPCC AR6 estimated that total investments supporting climate mitigation in Europe ([88]) were on average about EUR 220 billion per year in 2017–2020 ([89]). This would need to increase to EUR 960 billion per year (which represents more than a quadrupling) until 2030 to be consistent with pathways that limit global warming to well below 2 °C (IPCC, 2022n) (see Figure TS.25).

The EIB's estimates of climate-related investments in the EU are in the same order of magnitude, increasing from about EUR 240 billion in 2019–2020 to about EUR 310 billion in 2021. It concludes that current spending on climate mitigation needs to increase significantly to achieve climate neutrality by 2050 (EIB, 2023b). BNEF also reports an increase in climate-related investments in the EU, from on average EUR 70 billion per year in 2011–2019 to almost EUR 200 billion in 2022 (BNEF, 2023). Both the EIB and BNEF have identified an increase in climate-related investments in recent years, which is mainly driven by the increased uptake of electric vehicles, the deployment of solar and wind energy, and energy efficiency improvements (FS-UNEP and BNEF, 2018).

Finally, the European Commission's scenarios that underpin the EU climate objectives also include data on historical and required investments. The MIX scenarios of the impact assessments accompanying the climate target plan and the Fit for 55 package estimate that overall investments in energy and transport need to increase by 62 %, from an average of EUR 764 billion per year in 2011–2022 to EUR 1 241 billion per year on average in 2021–2030. Under the REPowerEU plan, investments would need to increase even further to about EUR 1 276 billion per year up to 2030. The scenario data does not distinguish between climate- and non-climate-related energy investments (EC, 2023l, 2020a, 2022p). However, given the need to fully decarbonise the energy system, all future investments should be aligned with European climate targets. This is also consistent with the IPCC data described above, which estimated that climate-related investments in Europe would need to increase to almost EUR 1 trillion per year to be compatible with 'well below 2 °C' pathways (with even higher investment needs likely for compatibility with 1.5 °C pathways).

All the sources above cover different scopes in terms of geography, years and sectors/technologies, as summarised in Table 18.

([88]) This include some countries beyond the EU-27: Norway, Switzerland, Turkey and the United Kingdom.
([89]) All values are converted into 2022 euro.

Table 18 Overview of the scopes of the different data sources used for assessing investment needs

Data source	Scope
IPCC AR6	– 2017–2020 average for Europe (including non-EU countries) – Energy supply: low-emission electricity generation and electricity grids – End use sectors: energy efficiency in buildings and industry, transport
EIB	– 2019–2021 data for EU-27 – Energy supply: renewable energy – End use sectors: energy efficiency, sustainable transport – Others: climate-related R&D, forestry (very low share in total investments)
BNEF	– 2022 data for EU-27 – Energy supply: renewables, nuclear, hydrogen (electrolysis, storage and pipelines), energy storage, CCS – End use sectors: ZEVs and recharging/refuelling infrastructure, heat pumps – Others: sustainable materials
European Commission climate target plan and Fit for 55	– Average 2011–2020 data for EU-27 – Energy supply: all electricity generation (RESs, fossil, nuclear), electricity grid, boilers, production and transport of new fuels – End use sectors: energy-related investments in residential, tertiary and industry sectors, all vehicles and recharging/refuelling infrastructure in transport

Based on the available data, the Advisory Board estimates that climate-related investments need to at least quadruple, from between about EUR 200 billion and EUR 300 billion per year in recent years to about EUR 1 000 billion per year up to 2030, as illustrated in Figure 77. This would require the redirection of existing investment flows into the energy system, as well as an overall increase in energy and transport investments (+ EUR 500 billion per year ([90])).

([90]) The EUR 500 billion a year of investments in energy and transport exclude the additional investments required for REPowerEU (EUR 35 billion a year) and the Net-Zero Industry Act (EUR 12 billion a year). Including these figures would increase the additional investments needed (for example, the ECB (2023c) has estimated the required additional invesmtents to achieve the objectives of the European Green Deal and Net-Zeron Industry Act at EUR 620 billion a year). The 2023 climate action progress report (EC, 2023ax) advises against adding these figures, given their different scopes, timeframes and estimation methods.

Figure 77 Historical versus required climate-related energy investments

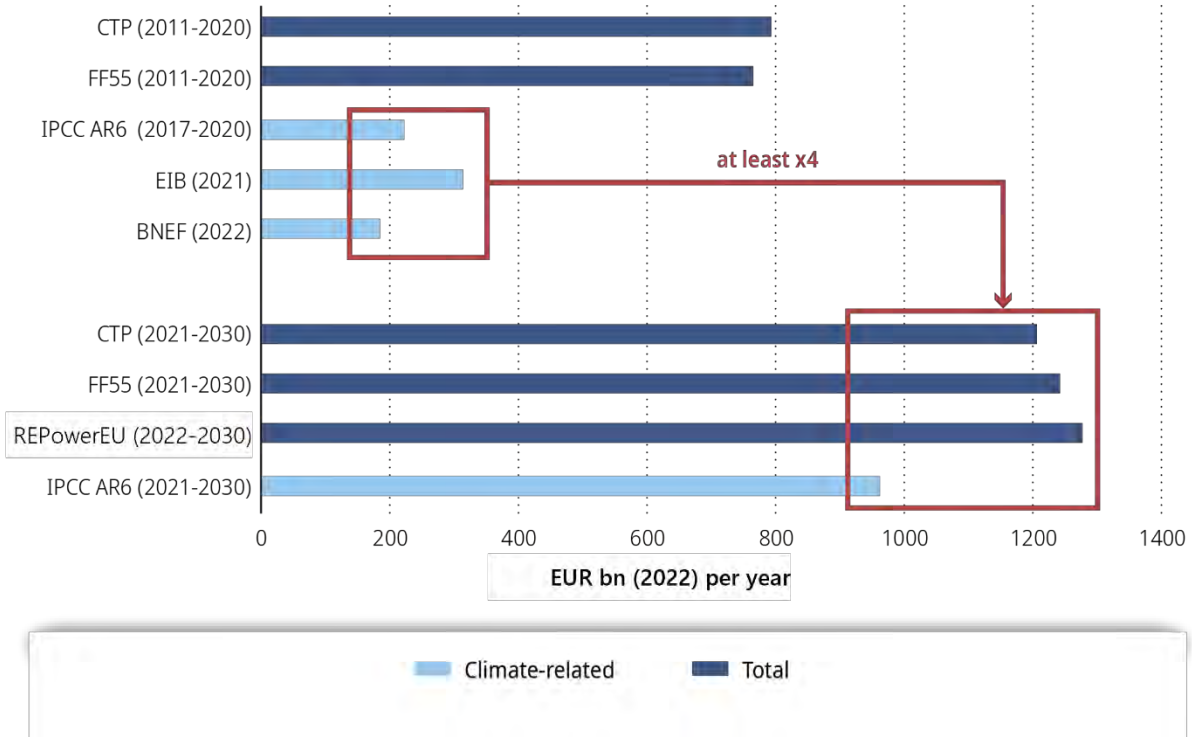

Notes: CTP is based on the Climate Target Plan impact assessment, FF55 data is based on the Net-Zero Industry Act staff working document. REPowerEU data includes an additional €300 billion on top of FF55. All data is converted to 2022 euro values.

Sources: Climate Target Plan impact assessment (EC, 2020s) (Table 46), staff working document accompanying REPowerEU (EC, 2022s), Net-Zero Industry Act staff working document (EC, 2023l) (Table 9), IPCC (2022l) (Figure TS.25), EIB Investment Report 2022/2023 (2023b) (Figure 31), BNEF (2022).

Meeting the investment needs requires a combined effort of the public and private sector.

The magnitude of the total investment flows in the real economy can be approximated by the gross fixed capital formation, which includes investments in both tangible assets (notably infrastructure and equipment) and intangible assets (intellectual property) (Eurostat, 2022c). Current gross fixed capital formation is estimated at about EUR 2.8 trillion (approximately 23 % of the EU's GDP) (Eurostat, 2022c). This suggests that the EU has sufficient investment capacity to meet its climate objectives, but that it would require redirecting approximately 30–40 % of the current total investment flows towards climate mitigation projects, or less if gross fixed capital formation is increased through climate mitigation. It should be emphasised here that these investments lead to later savings of expenditure on fossil fuels and climate damage and hence should not be misread as costs of mitigation. The magnitude of the gap is beyond the sole capacity of either the public or the private sector and will require a combined effort by both.

The EU action plan on financing sustainable growth outlines the overarching strategy to meet the required investments.

The European Commission's overall approach to meet the required investments is outlined in the 2018 action plan on financing sustainable growth, which was updated in 2020 as a follow-up to the European Green Deal (EC, 2018c). It outlines 10 action points in three categories:

— actions to redirect capital flows towards a more sustainable economy (including actions such as the EU Taxonomy classification system, the development of an EU Green Bond Standard and the sustainable Europe investment plan (also referred to as the Green Deal investment plan),
— actions to mainstream sustainability into risk management,
— actions to foster transparency and long-termism (including the revision of the non-financial reporting directive, which is now referred to as the corporate sustainability reporting directive).

Whereas a full assessment of this action plan is beyond the scope of this report, some of its components (the EU Taxonomy framework, the green bond standard and the green deal investment plan) are assessed in more detail in subsequent sections.

12.3 Fossil fuel subsidies

Fossil fuel subsidies persist and have even increased in the context of the energy crisis.

Several sources report on fossil fuel subsidies in the EU, including the European Commission's annual state of the energy union report (EC, 2023aw), Member States' annual national energy and climate progress reports, and independent assessments by organisations such as the EEA and the OECD (OECD and IISD, 2023; EEA, 2023i). As shown in Figure 78, the EU has made little progress towards phasing out fossil fuel subsidies. Reported fossil fuel subsidies remained stable between 2010 and 2020 at around EUR 50 billion per year. In 2022, they more than doubled to ca. EUR 120 billion, as governments provided substantial amounts of support to both households and businesses to mitigate the impact of the energy crisis.

Figure 78 Changes in fossil fuel subsidies in the EU

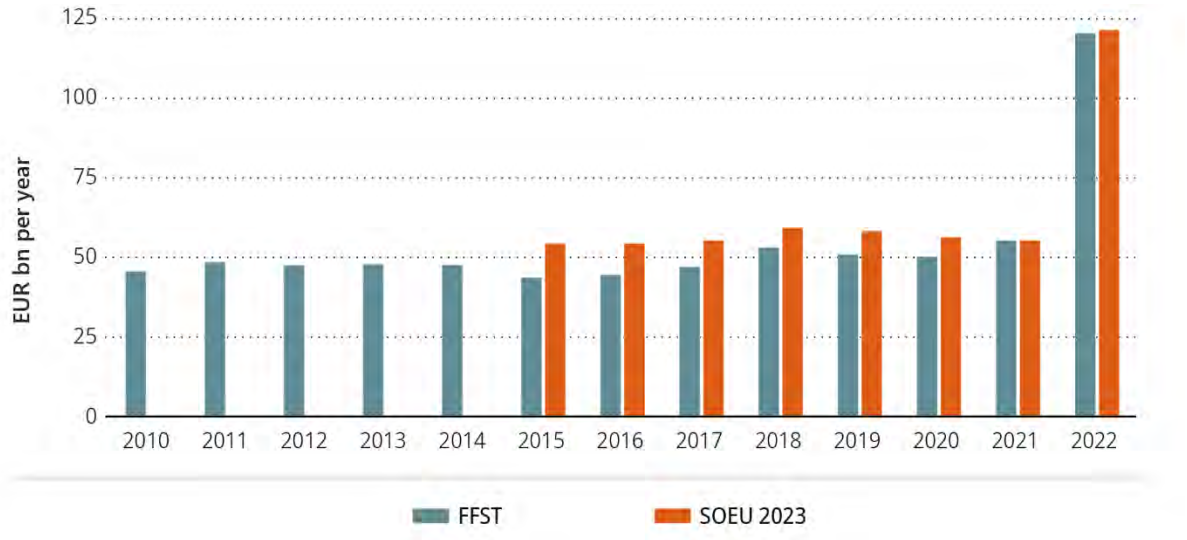

Sources: Fossil Fuel Subsidy Tracker (OECD and IISD, 2023), EC (2023aw)

The share of fossil fuel subsidies in total energy subsidies reduced gradually from 31 % in 2015 to 26 % in 2021, as they remained stable while other types of energy subsidies increased. However, in 2022 the share of fossil fuel subsidies in total energy subsidies rebounded to 31 %, and in absolute amounts fossil fuel subsidies (EUR 123 billion in 2023) exceeded the amount of subsidies for RES (EUR 87 billion in 2022) (EC, 2023aw).

In addition to these fossil fuel subsidies, the EU and its Member States have provided other forms of energy subsidies to shield households and businesses from the impacts of the energy crisis. The IEA tracked more than EUR 325 billion in total support to reduce energy bills during 2022 in the EU (IEA, 2023d). Similarly, the European Commission reports that overall energy subsidies increased from about EUR 200 billion in 2018–2021 to between EUR 350 billion and EUR 390 billion in 2022 (including EUR 112 billion to 'all energies', which also includes fossil fuels) (EC, 2023aw). Although not all this spending is captured by the definition of 'fossil fuel subsidies' as applied by the European Commission and the OECD, the Advisory Board has assessed that in many cases it has distorted the price signal, which reduced the incentive for making energy efficiency investments, rationalising energy consumption or switching to RES (ESABCC, 2023a). Furthermore, these expenditures have not always been well targeted towards the most vulnerable consumers and have posed a substantial fiscal burden on Member States (EC, 2023n).

There is no clear phase-out plan or deadline for the majority of fossil fuel subsidies.

The eighth EAP requires the European Commission and Member States to 'set a deadline for the phasing out of fossil fuel subsidies consistent with the ambition of limiting global warming to 1.5 °C' (EC, 2022q). Member States are required to include in their biennial national energy and climate progress reports an assessment of progress towards phasing out energy subsidies, in particular for fossil fuels (EU, 2018e). According to these reports, although many Member States confirm their intention to phase out fossil fuel subsidies, only five Member States have enacted laws or clear plans that specify how and by when (EEA, 2023i). For more than half of all fossil fuel subsidies, there is either no end-date or an end-date after 2030 (EC, 2023aw).

Fossil fuel subsidies can hinder the climate transition by undermining the reorientation of private investments, reducing the available budget for public investments and locking in fossil fuels.

Fossil fuel subsidies ([91]) are a major obstacle to the transition towards climate neutrality. By lowering the cost of fossil fuel use, they hinder the required reorientation of financial flows towards non-fossil, climate-friendly alternatives. Furthermore, they also decrease the amount of public funding that is available to finance the climate transition. By supporting the use and financing of fossil fuel-related assets, they lock in future GHG emissions, which is inconsistent with emission pathways necessary to reach the Paris Agreement goals. This inconsistency exposes investors and asset owners to the risk of stranded assets (Semieniuk et al., 2022). A rapid phase-out of fossil fuel subsidies is therefore considered to be a top priority to close the climate investment gap. In line with international commitments such as the COP26 Glasgow Climate Pact, both the European Green Deal and the 8th EAP call for the phase-out of subsidies for fossil fuels.

12.4 Mobilising the EU budget

Approximately EUR 580 billion of EU funds are earmarked for climate action for 2021–2027.

The EU's long-term budget (referred to as the MFF) totals EUR 1.2 trillion for 2021–2027. It has the aim of supporting the long-term objectives of the EU, including the climate transition. For 2021–2027, the EU committed to spending 30 % of the MFF (EUR 360 billion) on climate action, compared with at least 20 % in 2014–2020 (EC, 2016b). NextGenerationEU is the EU's recovery instrument to support its economic recovery after the COVID-19 pandemic. It provides an additional budget of EUR 800 billion for 2021–2026. The vast majority of this (EUR 723 billion) will be spent through the RRF, in the form of

([91]) Fossil fuel subsidies exist in different forms, including price/income support (e.g. price caps), tax reductions (e.g. lower rates, exemptions and rebates) and direct transfers (e.g. energy vouchers and direct subsidies).

grants and loans to support investments. Member States are required to spend at least 37 % of the funds they receive via the RRF on climate-related investments and reforms (EU, 2021a). The European Commission reported that all Member States have exceeded this threshold, and that in total 40 % (or EUR 203 billion) will be spent on climate-related activities. The European Commission has assessed that the EU plans to spend EUR 578 billion of its total budget (MFF and RRF) on climate action in 2021–2027 (on average about EUR 72 billion per year) (EC, 2023ax).

The discussions on the revision of the MFF for the period after 2027 will start in the next few years. Some experts have already flagged the need to increase the overall budget and reorient spendings, in particular to support the EU's climate and energy objectives (Franco-German working group on EU institutional reform, 2023). NextGenerationEU and the RRF, however, are currently intended to cease by the end of 2026, with no follow-up instrument planned. This would lead to a substantial drop in EU public climate spending after 2026.

The effectiveness of the EU budget is undermined by flaws in the methodology to track climate spending.

The methodology for estimating climate spending in the MFF is based on coefficients (EC, 2016b) ([92]) that are applied to the planned expenditure on different intervention fields, as a proxy for their expected contributions towards climate change mitigation and climate change adaptation. The main advantage of this approach is the light administrative burden and ease of use. More specifically, the European Commission uses three coefficients (EC, 2016b):

— a 100 % coefficient is applied to programmes that are expected to have a significant climate impact;
— a 40 % coefficient is applied to planned spending that is expected to make a 'moderate' contribution to climate objectives;
— a 0 % coefficient is applied to projects with an insignificant contribution.

Overall, this methodology implies significant approximations in estimating expected contribution to climate objectives, as the Rio markers do not enable precise quantification of the monitored spending (Cremins and Kevany, 2018). A high-percentage coefficient is applied to budget items that are expected to contribute more positively to climate objectives, and a low-percentage coefficient is applied to budget items from which little benefit is expected in terms of climate.

A report by the ECA (2022c) identified several flaws in this methodology, which can be summarised as follows.

— It allowed for overly optimistic assumptions about the relevance of certain expenditures to climate action. The CAP is a prime example: it accounted for EUR 100 billion of EU climate spending in 2014–2020 (half of the EU's total climate spending in that period), even though it had little impact on actual agricultural GHG emissions (ECA, 2021). For 2021–2027, the CAP continues to account for a substantial share of total EU climate spending (EUR 146 billion, or 25 % of the total), even though it is unlikely to deliver substantial GHG emission reductions (see Chapter 8 'Agriculture').
— It does not track potentially negative climate impacts of EU budget expenditures. The ECA's recommendation to enhance reporting under the MFF by identifying spending with potential negative impacts on climate was not accepted by the European Commission (EC, 2022ac).
— Reporting on climate spending is primarily based on *ex ante* plans, without checking *ex post* if planned climate spending was realised.

([92]) These are based on the Rio markers for climate, developed by the OECD in 2018.

— It allowed for inconsistencies, with similar types of projects receiving different coefficients, illustrating the subjectivity involved and the unclear criteria. For example, rail transport projects in the trans-European network funded by the Connecting Europe Facility were assigned a 100 % coefficient in estimating climate contribution, whereas similar projects under the European Regional Development Fund or the Cohesion Fund were assigned only a 40 % coefficient.

Overall, the ECA report (ECA, 2022c) concludes that, for 2014–2020, these flaws resulted in an overestimation of climate spending by at least EUR 72 billion (33 % of the total EUR 216 billion climate spending reported by the European Commission). The majority (80 %) of this is linked to an overestimation of the climate contribution of the CAP. It furthermore concluded that, despite some limited improvements, these flaws continue to undermine accurate reporting on climate spending under the 2021–2027 MFF.

The methodology used for the EU's RRF, which is the core of NextGenerationEU, has been updated to reflect definitions from the EU's sustainable finance taxonomy including the 'do no significant harm' principle. However, the methodology used to track spending on climate objectives remains broadly unchanged and continues to rely on coefficients (Baccianti, 2023). The recent review of the RRF by the ECA (ECA, 2023c) finds that the current performance monitoring framework does not sufficiently capture performance on climate and other intended objectives.

The European Commission also does not differentiate between spending on climate change mitigation and climate change adaptation. Aggregating both climate objectives under a single reporting line means that it is not possible to reliably estimate progress towards meeting investment needs for each objective. The lack of relevant and reliable reporting on investments that support climate adaption objectives hinders the mainstreaming of climate resilience across the EU policies that are supported by intervention instruments funded through the EU budget.

The EU budget on its own is insufficient to close the investment gap, even when taking into account the crowding-in effect.

The EUR 578 billion of the EU budget that is earmarked for climate action is a substantial amount, but on its own insufficient to meet the total required investment identified in Section 12.2. One of the three key pillars of the Green Deal investment plan is therefore to use the EU budget as a lever to crowd in private and other (national) public investments. One mechanism is InvestEU, which provides the EIB and other multilateral banks with an EU budget guarantee to allow them to increase their risk taking and to crowd in additional investments. With this approach, it aims to double the impact of the EU budget for climate action, and to mobilise EUR 1 trillion for climate investments over 2021–2030 (EC, 2020s).

Although generally welcoming it as a step in the right direction, independent analysts have warned that it will not be sufficient to cover the required investment needs. The independent think tank Bruegel (2020) assessed that, even if the EUR 1 trillion objective is achieved, it will only cover up to one third of the required investments. When considering the investment needs identified in Section 12.2 (which showed that climate-related investments would need to increase by roughly EUR 1 trillion per year), the Green Deal investment plan will cover only 10 % of total investment needs. The gap becomes even larger when taking into account that not everything classed as climate spending in the EU budget will actually contribute to the climate mitigation objectives, given the flaws in the monitoring methodology explained above.

12.5 Mobilising national budgets

State aid guidelines have been loosened and allow more public climate funding at the national level, but they are not yet fully aligned with the EU's climate objectives and risk undermining the single market.

The national budgets of EU Member States can also play an important role, especially in supporting investments in mitigation enablers, stimulating demand for net zero technologies and implementing adaptation projects. Some types of support might, however, be subject to EU State aid rules ([93]).

In recent years, EU State aid rules have been adjusted several times, which has resulted in, among other things, more leeway for Member States to financially support the climate transition. After a first temporary adjustment in 2020–2022 (in the context of the COVID-19 pandemic), State aid rules were temporarily relaxed in 2022–2023 by means of the temporary crisis and transition framework, to support investments supporting the green transition and alleviate the impact of the energy crisis (EC, 2022j). A positive element of this temporary framework is that the European Commission has abandoned its usual technology-neutral approach in order to allow selective subsidies for net zero technologies such as batteries, solar panels, wind turbines, heat pumps, electrolysers and CCU/CCS, as well as related critical raw materials. This is a welcome development because, as explained by Anadón et al., 2022, 'in a context of innovation and structural change, policies will almost always advantage some technologies more than others. It is better to choose deliberately rather than accidentally, supporting innovation in low-carbon directions. Some policies intended to be neutral can have a bias towards incumbents, and incremental change'.

Meanwhile, the guidelines on state aid for climate, environmental protection and energy were also revised in 2022 to align them with the European Green Deal (EC, 2022i). As these guidelines are recent and have not yet been widely applied (owing to the temporary framework in force until 2025), the Advisory Board was not able to do a full assessment of these guidelines. Nevertheless, some inconsistencies with the EU's climate neutrality objective can already be highlighted. The guidelines do not ban support for fossil fuels. Instead, they allow further public funding in the form of tax incentives and capacity mechanisms for fossil gas operations under specific conditions, further relaxed under the temporary crisis framework (EC, 2023m) (see also Section 12.5)

A final concern is that, although State aid can address urgent investment needs, too much flexibility can also lead to market fragmentation, disadvantaging smaller Member States with less-developed capital markets and weaker economies. A long-term European strategy to finance the energy transition necessitates a stronger single market that gives businesses better access to finance across all Member States. To address this, the European Commission President, Ursula von der Leyen, launched the idea of an EU Sovereignty Fund. A first step to test this concept is the Strategic Technologies for Europe Platform, which was proposed in June 2023. The proposal includes the allocation of an additional EUR 10 billion to targeted programmes, including InvestEU, Horizon Europe and the Innovation Fund (EC, 2023d). However, the amount of available funding is dwarfed by comparison with the state support programmes approved by the European Commission, which have increased substantially in recent years to EUR 335 billion in 2021 (EC, 2023d).

([93]) State aid is defined as an advantage in any form conferred by national public authorities to undertakings on a selective basis, and is generally prohibited by the EU law (Article 107 of the Treaty on the Functioning of the EU). There are some exceptional circumstances in which State aid is not only allowed but also encouraged as a beneficial intervention from a socioeconomic perspective. Over the years, the European Commission's powers to set rules and make decisions about State aid have expanded, notably in terms of the exceptional circumstances in which State aid by the EU Member States is justified.

Member States' investment capacities are constrained by the recent crises and the EU's fiscal policy framework.

As previously described (see Sections 1.1 and 11.1), Member States' budgetary space has been substantially constrained in recent years by higher expenditures, lower economic growth and increasing interest rates.

One way to address this would be for Member States to increase borrowing to finance climate-related investments. However, the current EU fiscal policy framework, as recorded in the Maastricht Treaty (1992) and the Stability and Growth Pact (1997), aims to preserve fiscal discipline within the EU, by requiring Member States to limit their annual deficit to maximum 3 % of their GDP, and the aggregate debt to 60 % of their GDP (Karagounis et al., 2015). Whereas these rules might be recommendable from a fiscal perspective – as potential negative externalities from a spiralling debt crisis would have a direct systemic effect across the EU – they also limit the ability of Member States to borrow additional money to finance climate investments, even if such investments are recommendable from a long-term perspective. There have therefore been several calls to adjust the fiscal policy framework, for instance by allowing Member States to exclude investments related to the climate transition from the calculated deficit- and debt-to-GDP ratios (Darvas and Wolff, 2023). The rules of the Stability and Growth Pact were suspended for 2020–2023 to allow Member States to address the impacts of the COVID-19 pandemic and, subsequently, the energy crisis. In 2023, the European Commission published a proposal to revise the EU's fiscal rules, building on the Maastricht Treaty (EC, 2023d). However, although it allows for a more gradual (up to 7 years) fiscal adjustment path, it does not provide any specific treatment for public expenditures on climate action (Bruegel, 2023).

Another possible way for Member States to increase their climate spending without increasing their overall debt would be to increase revenues or decrease other public spending. However, this option also faces challenges. Increasing revenues, for instance by raising taxes, is politically difficult, and also risks undermining a Member State's competitiveness given the absence of a fiscal union. Decreasing expenditures might also be challenging, given that multiple other societal challenges also warrant increased public spending (e.g. digitalisation, social infrastructure or increased military spending in the context of the current geopolitical tensions) (EEA, 2023l).

The assessment above highlights the challenge of substantially increasing national public spending on the climate transition. One possible way forward that can contribute to solving this conundrum is a rapid phase-out of fossil fuel subsidies, as further described in Section 12.3.

12.6 Mobilising private finance

Private finance will need to make a substantial contribution to close the investment gap.

The magnitude of the investment gap as described in Section 12.2, and the challenges of increasing public climate spending (see Sections 12.4 and 12.5), highlight the importance of private finance to close the investment gap. Different sources have estimated the required ratio of private to public climate investments ranging from 2:1 to 5:1, which implies that the private sector would need to deliver 66–83 % of the total required climate-related investments. However, wide variations could be possible between EU Member States. For example, the EIB projected that in central and eastern Europe about 60 % of additional investments will be funded from public sources and the share will be only 37 % in western and northern Europe (EEA, 2023l).

The mobilisation of private finance requires ambitious policies to improve the bankability of climate-related investments.

Private actors generally seek positive returns on investments, and the required increase in private finance flows will not materialise unless policies provide favourable conditions for climate-related investments that can generate a sufficient supply of bankable projects. This can be facilitated by streamlining permit-issuing processes, carbon-pricing mechanisms, financial incentives (e.g. tax credits, public guarantees), technical assistance, institutional capacity building, standards and regulations, as well as enabling conditions such as infrastructures and regulatory stability. Such policies are covered in other chapters throughout this report, in particular Chapters 0–8 on the different sectors and Chapter 10 'Pricing emissions and rewarding removals'. The overarching conclusion of these chapters is that the EU's overall climate policy has been strengthened in recent years, although further improvements remain necessary (see Section 7.5, under 'Enabling condition: private investment').

In the domain of financial policies, private finance can be further mobilised towards climate investments by phasing out fossil fuel subsidies (see Section 12.3) and labelling (see Section 12.7).

The popularity of sustainable investments is growing, but their impact depends on a robust classification mechanism.

While scaling up climate finance remains a challenge, investments that take into account ESG sustainability criteria (measured following self-regulated standards) are increasingly popular (Maiti, 2021). A recent market analysis (Bloomberg, 2022) suggests that global ESG assets may surpass USD 50 trillion by 2025, compared with USD 35 trillion in 2020, with Europe remaining one of the most important markets. The primary ESG approaches focus on exclusion criteria, with shareholder activism and corporate engagement also gaining traction (GSIA, 2020). However, research indicates that ESG investing by itself is not enough to yield meaningful climate outcomes (Kölbel et al., 2020). ESG strategies and reporting tools are not sufficient to understand the tangible impact of the financial sector claiming to advance environmental and social outcomes climate change.

The EU Taxonomy provides a harmonised framework to label activities as 'environmentally sustainable', including certain types of fossil gas activities.

The European Commission has identified the need for more robust assessment and standardisation of ESG methodologies to understand climate and other environmental impacts (EC, 2018a). Responding to the challenge of a fragmented market for ESG ratings, which to a large extent remains self-regulated (Jonsdottir et al., 2022; Charlin et al., 2022), the European Commission launched the EU Taxonomy, which is a classification system with harmonised criteria for labelling economic activities as environmentally sustainable. For an economic activity to be classified as environmentally sustainable, it must (i) contribute to at least one of six sustainability objectives (which include climate change mitigation and adaptation), (ii) without significantly harming any of the other six objectives (referred to as the 'do no significant harm' principle), (iii) while complying with minimum social safeguards. To expand the utility of the EU Taxonomy, the regulation introduced two additional categories of activities qualifying as environmentally sustainable: enabling activities ([94]) and transitional activities ([95]).

([94]) Enabling activities are economic activities that enable other activities to make a substantial contribution to at least one of the six environmental objectives, if it does not lead to a lock-in of assets that undermine long-term environmental goals, and has a substantial positive environmental impact based on life cycle considerations.

([95]) Transitional activities are activities that can be considered to contribute substantially to climate objectives if their GHG emissions are substantially lower than the sector or industry average, they do not hamper the deployment of low-carbon alternatives and they do not lead to a lock-in of carbon intensive assets, considering the economic lifetimes of those assets.

Whereas the EU Taxonomy regulation sets out the overall framework, the specific criteria (referred to as TSC) are set out by the European Commission through delegated acts. To remain relevant to the latest research and market developments, these TSC are subject to regular review by the European Commission to reflect technological progress, ensuring that sectors and activities can be added or deleted through amendments to the regulation. The first act to be adopted under the EU Taxonomy regulation was the Climate Delegated Act (EC, 2021b), which established the TSC for the first two objectives of the EU Taxonomy: climate change mitigation and climate change adaptation. This initial delegated act covered about 40 % of EU-domiciled publicly listed companies, which are responsible for roughly 80 % of direct GHG emissions in Europe. One year later, the European Commission adopted a Complementary Climate Delegated Act (EC, 2022b), which established the TSC for fossil gas and nuclear activities. These allow the labelling of certain fossil gas activities as transitional activities contributing to climate change mitigation, provided they meet certain criteria (e.g. such activities would need to remain below certain emission intensity and energy efficiency thresholds). However, these thresholds are too high, and, even if the emissions can be lowered through CCU/CCS, such electricity plants should be marginal in the decarbonised energy systems (ESABCC, 2023b); see also Section 4.3, under 'Lever: coal and fossil gas phase-out' and 'Lever: targeted carbon capture and utilisation/storage'. Another example of the TSC under the EU Taxonomy potentially jeopardising the net zero transition pertains to the depth of building renovation, where reducing primary energy demand by 30 % can be considered sustainable without necessarily linking it to staged deep retrofits (see Section 7.5, under 'Enabling condition: private investment').

While an in-depth analysis of the TSC is beyond the scope of this report, the Advisory Board notes that not all EU Taxonomy thresholds for economic activities are currently in line with climate neutrality (see for example (Schütze and Stede, 2021). In this respect, it is important that the European Commission initiate regular updates of the criteria in line with Article 19 of the EU Taxonomy regulation (EU, 2020).

Initial data shows large differences between sectors' alignment with the current TSC in the EU Taxonomy.

The Corporate Sustainability Reporting Directive ([96]) (EC, 2021l) and Sustainable Finance Disclosure Regulation (EC, 2018b) require certain entities to disclose information on the degree of alignment of their activities with the EU Taxonomy. However, they do not include a legal obligation for those entities to reach a minimum degree of alignment. Whereas the EU Taxonomy, the directive and the regulation are thus important steps forward to increase transparency and credibility, their effectiveness in shifting investments towards sustainable activities will purely rely on investors' preferences, which will also be determined by the bankability and marketability of sustainable investments.

Based on the data reported so far, there are large differences in different economic sectors' alignment with the EU Taxonomy (see Figure 79). On a positive note, in the real estate and utilities sectors (the latter of which includes the electricity sector) a large share of capital expenditure is already eligible under the EU Taxonomy, reflecting the plethora of available options for investments in projects that can potentially meet the TSC. However, for other key relevant sectors such as industry, materials, energy ([97]) and finance, only 30 % of capital expenditure can be eligible under the EU Taxonomy. For these sectors, there is still much room for improvement to shift existing investment flows towards sustainable activities.

([96]) This will replace the 2014 Non-Financial Reporting Directive.

([97]) This includes non-regulated energy companies, primarily in the oil and gas industry.

Figure 79 Eligibility of different sectors' revenues and capital expenditure under EU taxonomy

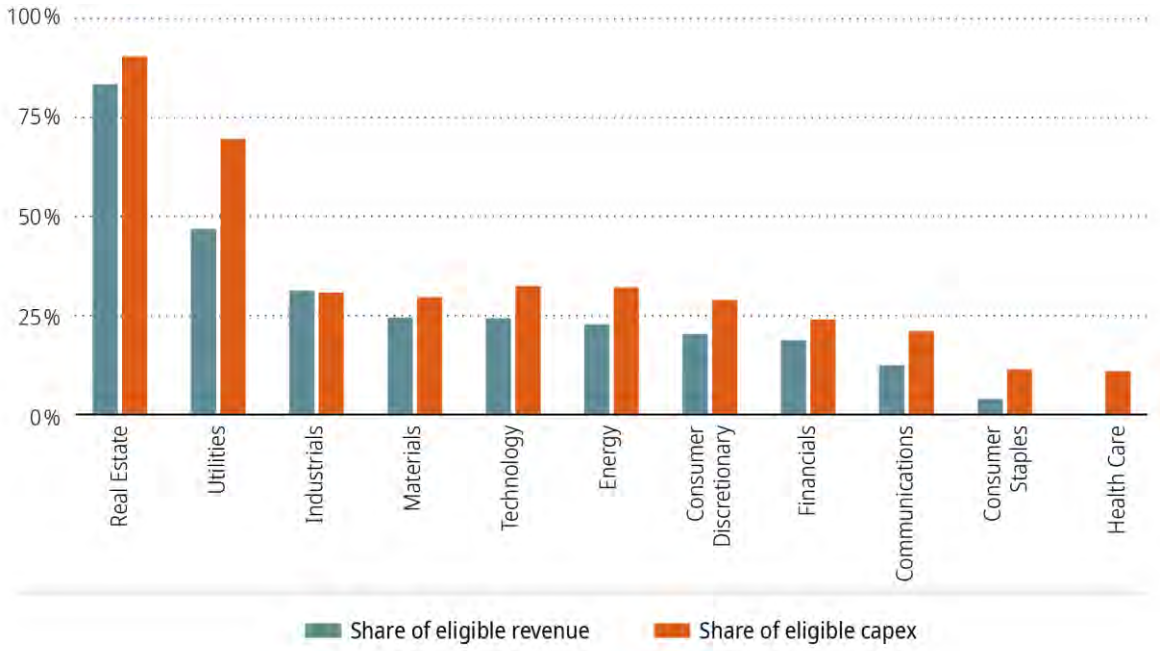

Source: Bloomberg terminal, based on company reported data (BNEF, 2022)

12.7 EU green bond market

Green bonds could provide an opportunity to scale up climate finance, provided their additionality and environmental integrity are ensured.

Green bonds are fixed-income investment securities that provide financing to sustainable projects run by either companies or governments. Since the EIB inaugurated the green bond market in 2007 with the first climate awareness bond, the market has seen significant growth. In 2022 European companies and governments raised EUR 241 billion issuing green bonds, which represented 47 % of the global proceeds in that year. However, their share in the total EU bond market remains relatively low at 7 % (see Figure 80). Most assets financed with green bonds have been in renewables (21 % of the issuance activity), clean transport (16 %), and clean technologies and buildings (11 %) (Bloomberg, 2023).

The rapid rise of climate-related bond issuances could present an opportunity for scaling up climate finance (IPCC, 2022m). This is particular the case in the EU, as the European capital market relies more on debt instruments than on shareholder equity to finance new projects (Gaud et al., 2007). However, their actual impact depends greatly on their environmental integrity and additionality (Shishlov and Censkowsky, 2022). So far, this is not ensured: there is no common definition of or assessment framework for what constitutes a green bond. They are currently labelled as such based on criteria defined by the rating agent used by the bond issuer (Ehlers et al., 2022). This increases the risk of greenwashing.

Another limitation of green bonds is that they provide limited incentives for corporations to phase out harmful activities. This can be attributed to the design of the green bonds: it addresses only green projects, which on many occasions form only a small part of the overall activities in a diversified corporate structure.

Figure 80 Development of the EU green bond market

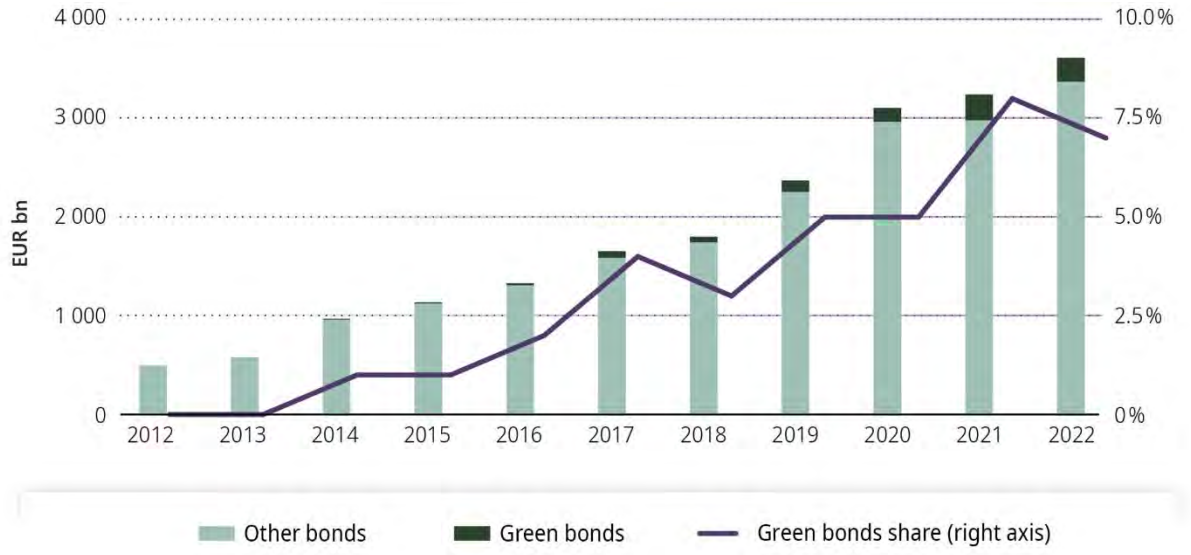

Source: Bloomberg terminal (Bloomberg, 2023)

The EU green bond standard could improve the transparency and credibility of green bonds, but is only voluntary. Its effectiveness will depend on the degree to which it is applied.

To address the fragmentation in the green bond market, the European Commission proposed in 2021 a European green bond standard, which was finally adopted in October 2023 (EC, 2021ae). Overall, the standard is aligned with the EU Taxonomy framework described in Section 12.6. The application of this harmonised standard is, however, strictly voluntary, and its effectiveness will therefore depend on the degree to which it is applied by bond issuers.

NextGenerationEU is largely (up to EUR 250 billion, representing almost 30 % of the total) funded by the issuance of green bonds, which will make the European Commission the largest green bond issuer in the world. However, these bonds currently do not follow the requirements of the EU Taxonomy, which also means they are not aligned with the European Green Bond Standard. This reduces transparency on the use of proceeds and can undermine credibility in the credit market, resulting in higher borrowing costs (Larcker and Watts, 2020; Löffler et al., 2021; Partridge and Medda, 2020).

12.8 Summary table

Table 19 Policy consistency summary – finance and investments

Policy inconsistencies	– EU State aid rules still allow fossil fuel subsidies. – The Stability and Growth Pact does not treat investment related to the climate transition differently from other types of investment.
Policy gaps	– There is no reporting on EU budget expenditure on activities that breach the 'do no significant harm' principle of the EU Taxonomy. – There is no structural, long-term common fiscal capacity based on a common EU debt (beyond the RRF).
Ambition gaps	– EU policies do not sufficiently encourage the creation of bankable projects that would attract private investment. – The Strategic Technologies for Europe Platform has so far been inadequate because of its limited budget (EUR 10 billion, compared with more than EUR 300 billion per year of State aid in 2021). – Only soft EU policy measures encourage EU Member States to phase out fossil fuel subsidies. – There are substantial flaws in the methodology for tracking EU spending on climate action, which undermine the EU budget's contribution to the EU climate objectives.
Implementation gaps	– Only a few Member States have enacted laws or clear plans that specify how and by when the phase-out of fossil fuel subsidies will be achieved.

13 Innovation

Key messages

A more ambitious policy on research, development and deployment (RD & D) is needed to accelerate innovation and support competitiveness.

Needs. The EU aspires to be a global leader in climate ambition, action and innovation. This requires increasing investments in climate-related RD & D, and both private and public sectors have a role to play in supporting this objective. The EU needs to make RD & D investments and enact additional demand policies that stimulate innovation and crowd in private investment. Spending on innovation needs to increase, to ensure that Europe remains competitive in the global landscape of clean technologies. Planned expenditure on R & D across all research areas (not just climate related), including through the European Green Deal, continues to fall short of the 3 % GDP target that was set back in 2010 and reiterated in 2021. Despite the increasing needs for cleaner technologies across all sectors, public funding on innovation stagnated over the last decade, at 0.8 % of the EU-27's GDP in 2021 compared with 0.8 % of the EU-27's GDP back in 2011.

Gaps. The main EU policy instruments aiming to catalyse private investment are Horizon Europe and the Innovation Fund. One of their main focuses is climate-related technologies; however, their administrative complexity hinders the crowding-in of private investments **(implementation gap)**. Public funding instruments can sometimes be slow in reacting to the changing needs of the fast-paced global clean technology arena. This should be monitored at the EU level, particularly beyond early-stage research **(policy gap)**. For example, public funding in the United States took many years to begin providing more substantial support for RD & D in energy storage.

Recommendation In1. There is a role for increasing various forms of public climate-related RD & D investments, including supporting private sector activity. They need to be distributed strategically, encouraging the participation of start-ups and small and medium-sized enterprises. Increased RD & D investments are needed to ensure that the EU can remain in a position to invent, patent and commercialise the mitigation technologies of tomorrow. The administrative complexity of the EU's funding instruments can be streamlined in order to encourage the participation of small and medium-sized enterprises and start-ups, given that they often lack the resources to participate in time-intensive and complex processes. Spending on climate- and energy-related technologies currently represents only about 9 % of total spending on innovation. An effective policy mix that combines instruments such as carbon pricing, fiscal incentives and grants can direct a larger amount of public and private RD & D towards technologies that directly contribute to the climate neutrality objective (please see Chapter 10 'Pricing emissions and rewarding removals').

Currently there is a significant funding gap for projects that are towards the end of the RD & D process, the demonstration stage, and for commercial deployment. Policies that support innovation need to ensure that there is sufficient investment to give them a chance to cross the 'valley of death'.

Needs. While the EU originates more than 30 % of all top scientific publications, there is a significant lag in innovative solutions for clean energy. Part of the disconnect between scientific excellence and commercialisation can be attributed to the scarcity of funding at the demonstration and early commercialisation stages. Climate technology projects that evolve from the early stages of R & D and

prototyping towards piloting have fewer sources of funding available than those in other subject areas and in other countries.

Gaps. Current policy intervention instruments focus their support at the two ends of the RD & D process, the early R & D stage and the late maturity and diffusion stage (the former through the European Research Council and Horizon Europe, and the latter through pricing and other demand-pull incentives). This policy mix leaves a funding gap for climate technology manufacturing or deployment projects aiming to complete the piloting and demonstration stage and move towards the early deployment of clean technologies **(policy gap)**. This funding gap is further widened by the relative lack of support from venture capital, as this concept remains less developed in Europe than in the United States, for instance **(policy gap)**.

Recommendation In2. Access to finance needs to address all the stages of the RD & D process and across to deployment, as innovation is only as close to market as the weakest link in the development process. The current system of support for RD & D could give additional attention to the demonstration and early commercialisation phases in the forms of additional grants, loans, loan guarantees and government procurement. The combination of increased investments in R & D (recommendation In1) and in demonstration and commercialisation through additional tools and market-pull policies, such as carbon prices and other, more targeted, incentives, can help attract additional venture capital and other types of investments.

Across the EU, funding support for innovation and early deployment needs to further diversify and support a wide range of early stage technologies with high mitigation potential in industry, some transport applications, agriculture and food, and CDR.

Needs. The EU's leadership position in mitigation technologies is underpinned by a strong position in a small number of mature technologies such as wind power and rail transport. Strengthening Europe's strategic autonomy in key sectors, which could reduce its exposure to various geopolitical risks, requires developing a portfolio of early-stage clean technologies to support the transition. Some of that may involve developing capabilities in parts of the supply chain for climate technologies that are more mature, but also in sectors where there are currently fewer mature technologies, including agriculture, some key industries and CDR. Europe lags behind international peers in the development of emerging technologies, such as lithium-ion batteries and electrolytes used in hydrogen production, in terms of its relative position over time in the number of patents for those technologies.

Gaps. The Net-Zero Industry Act aims to partially address the need to strengthen the knowledge and industrial manufacturing capacity in key technologies, but an explicit link to the earlier stages of the innovation process could help strengthen the EU's position **(policy gap)**. Policy instruments such as the strategic energy technology plan, which aims to strengthen collaborations between industry and research, also need to address behavioural barriers to innovation such as the fear of failure, emphasising the value of the knowledge generated when trying to innovate, and the value of sharing that knowledge **(ambition gap)**.

Recommendation In3. Policy intervention instruments such as the revamped strategic energy technology plan should strengthen collaborations and networks in novel technologies with high mitigation potential, encouraging knowledge sharing and the wider dissemination of lessons learned.

Innovation policies need to crowd in private investments, fostering closer collaborations between private and public knowledge organisations.

Needs. The innovation cycle needs to accelerate. This requires stronger collaborations between private and public knowledge organisations. Longer-term frameworks, including incentives and regulations, are needed in order to successfully crowd in more private investments in early-stage technologies with high mitigation potential. When potential future support is unpredictable, there is a risk that a project may be ended prematurely owing to lack of resources, and the knowledge generated may be lost. Policies supporting innovation need to prioritise learning, iteratively upscale, engage the private sector, disseminate knowledge and create robust demand.

Gaps. Policy instruments on innovation need to foster collaborations between private and public knowledge organisations, creating opportunities for building stronger collaborations **(policy gap)**. The existing EU funding architecture offers limited predictability beyond 2030, which increases uncertainty for long-term projects **(ambition gap)**. The Net-Zero Industry Act aims to increase the EU's manufacturing capacity in strategic technologies to reach at least 40 % of domestic needs; however, the existing reporting mechanisms offer limited means to track progress towards achieving this target **(policy gap)**. It is also unclear if the same level of coverage is needed to advance the EU's transition in a way that is just and that increases the resiliency of supply chains.

Recommendation In4. The revamped strategic energy technology plan needs to foster a closer collaboration between private and public actors and broader dissemination of the knowledge generated, so that more private investments can crowd in. In order to monitor progress towards the policy objectives of the Net-Zero Industry Act, relevant and reliable information is needed on investments across the supply chains of key climate technologies and on asset deployment.

Innovation should not be seen as an argument for postponing climate action.

Innovation cycles typically take decades from first proposal to full commercialisation. While an important enabler, R & D alone cannot be considered a panacea. Innovation can bring important benefits in, for example, reducing costs and improving efficiency. However, expected developments of new technologies should not be relied upon to delay action or social innovation that can curb emissions.

13.1 Scope

According to IPCC AR6 (contribution of Working Group III, Chapter 16) innovation in climate mitigation technologies, encompassing the process from R & D to technology deployment, has seen 'enormous activity and significant progress in recent years' in supporting system transitions to limit warming. This is evidenced by the recent rapid cost reductions and diffusion of climate-friendly products such as the electric car, the solar panel and the heat pump. Technological challenges remain in a range of economic activities including freight, agriculture, shipping and aviation, metallurgy (steel and aluminium) and cement production. These sectors rely on burning fossil fuels or using them as feedstock, as mitigation alternatives either do not exist or are not available at the necessary scale.

The development of new decarbonisation technologies and the improvement of existing ones are essential to move towards a carbon-neutral economy in a cost-efficient way, while simultaneously pursuing economic growth opportunities that strengthen productivity (IPCC, 2022, (Grassano et al., 2020) and driving the economy's overall competitiveness (Anadón et al., 2017). The last few decades of experience with low-carbon technologies show that a combination of technology-push investments and

policies with demand-pull interventions to create or grow early markets is needed in order to accelerate technology unit cost reductions and scale up more rapidly. A recent synthesis of experience with policies shaping innovation in clean energy technologies around the world also shows that policies need to be adaptive, make choices, address questions about inclusion and justice, and harness tipping points in cost reductions (EEIST, 2022). To some extent, these insights are already reflected in some European policy efforts: investments in mitigation technologies have taken centre stage in the recent RRF, REPowerEU, Net-Zero Industry Act and Green Deal industrial plan. However, a number of policy areas need to be further addressed in order to accelerate innovation in clean technologies to continue supporting the competitiveness of European industry.

13.2 Progress on innovation

Methodology to track progress

Tracking progress on innovation remains challenging because innovation is a complex process that cannot be understood using one or even multiple metrics, each of which has limitations. In addition, the relationship between policy inputs (e.g. finance, education) and intermediate outputs (i.e. patents, pilot projects) is sometimes unclear (Moaniba et al., 2018). Policy objectives such as more affordable energy, industrial transformation and economic growth are hard to attribute to specific inputs (Grubb et al., 2021), although evidence is growing (Peñasco et al., 2021) that a range of indicators can be used as proxies for innovation, including RD & D investments, publications, funding and follow-on investments.

Total research and development spending

The EU is falling short on its objective of spending 3 % of its GDP on R & D.

The EU has a long-standing objective to increase spending towards R & D to at least 3 % of the GDP (Lisbon 2000 strategy and Europe 2020 strategy). This objective does not include any specific target for increasing R & D spending on energy and climate.

The ratio of R & D to GDP is also known as R & D intensity (Eurostat, 2021), and data about the EU and other major economies are shown in Figure 81. This ratio increased marginally in the EU during 2011–2021, rising from 2.02 % in 2011 to 2.31 % in 2020 but decreasing in 2021 to 2.27 %. The slight decrease in R & D intensity between 2020 and 2021 could be explained by the GDP rebound in 2021 after the significant drop in 2020 as a result of the COVID-19 pandemic. To compare it to the situation before the COVID-19 crisis, the R & D intensity of the EU saw a marginal increase from 2.02 % to 2.19 % between 2011 and 2019. In other words, over 2011–2021, the EU as a whole made limited progress in increasing R & D expenditure towards the 3 % target pledged in the Europe 2020 strategy.

In contrast, over the same decade, R & D intensity trends were different (and in some cases more dynamic) in other parts of the world. Between 2011 and 2021, R & D intensity in the United States increased from 2.76 % in to 3.45 %, and in China from 1.78 % to 2.4 %. Japan's remained consistently above 3.10 %. As a result, the EU is progressively falling behind other regions on R & D spending. That gap can erode competitiveness in strategic sectors such as energy and international transport. It is estimated that the energy sector represents about a tenth of the EU's total R & D expenditure, or 0.02 % of its GDP (IEA, 2023i).

Higher spending on R & D both in energy and beyond requires higher contributions from both public and private participants, and public spending needs to become more effective at crowding in private investments (Becker, 2015). An analysis of R & D expenditure by source of funds shows that about two thirds of the total expenditure within the EU is funded by the private sector whereas almost one third is funded by EU and Member State resources. According to the data from Eurostat, as evidenced in

Figure 82, the main development over 2011–2021 was a fall in the share of funding by the public sector from 37 % to 34 %, with a corresponding increase for the private sector from 63 % to 66 %.

Figure 81 Gross domestic expenditure on research and development, 2010–2021

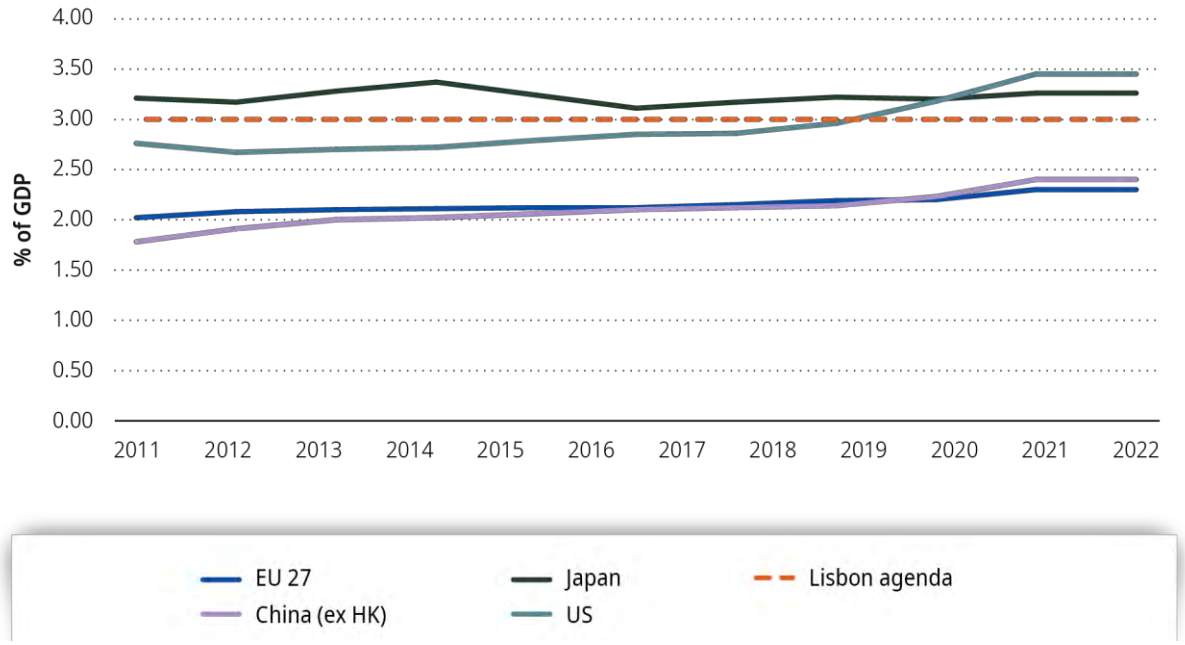

Sources: Eurostat (2023j), OECD (2023c) (US, Japan and China).

Figure 82 EU-27 R & D spending in the public and private sectors

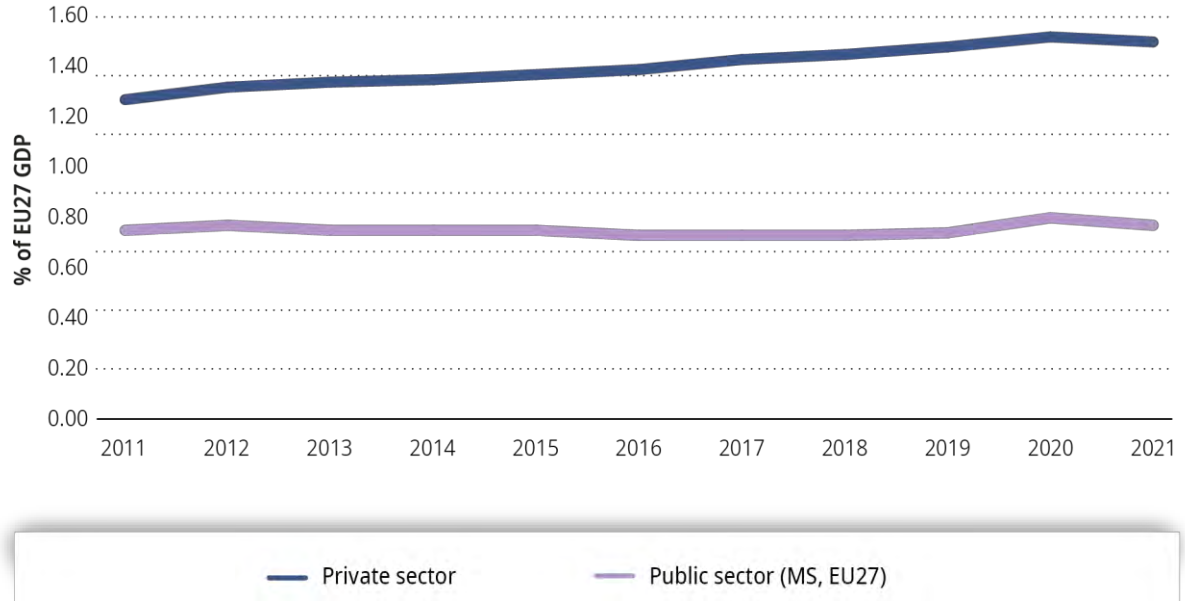

Notes: Eurostat's statistics on R&D expenditure are compiled using guidelines laid out in the Frascati manual 2015, published in 2015 by the OECD. Public spending includes funding from both member states and the EU budget.

Source: Eurostat (2023j)

Research on energy R & D finds no evidence that increases in energy R & D draw out (or crowd out) R & D resources from other sectors (Goldstein et al., 2020; Popp and Newell, 2012). Moreover, other research, focused on public funding for defence R & D, shows evidence of public investments crowding in private investments (Noriega et al., 2018). Public institutions funding energy R & D and engaging with small companies have been associated, in some cases causally, with improved patenting outcomes or follow-on investments by firms.

Climate-related patenting

Climate-related patenting in the EU is slowing down.

Patents in climate-related technologies ([98]) have been increasing over the last 10 years, with European companies targeting high-value inventions with international protection, which suggests growing confidence in their competitiveness in the global energy technology market. However, the absolute number of EU patent filings related to climate change mitigation has stagnated more recently. The decline in patenting activity in 2019 may reflect the maturity of some technologies such as solar PV, bioethanol and wind (IEA, 2020), combined with low energy prices at the time (Probst et al., 2021).

Figure 83 Share of climate patents among all EU filings and the global market share of the EU in climate-related patents

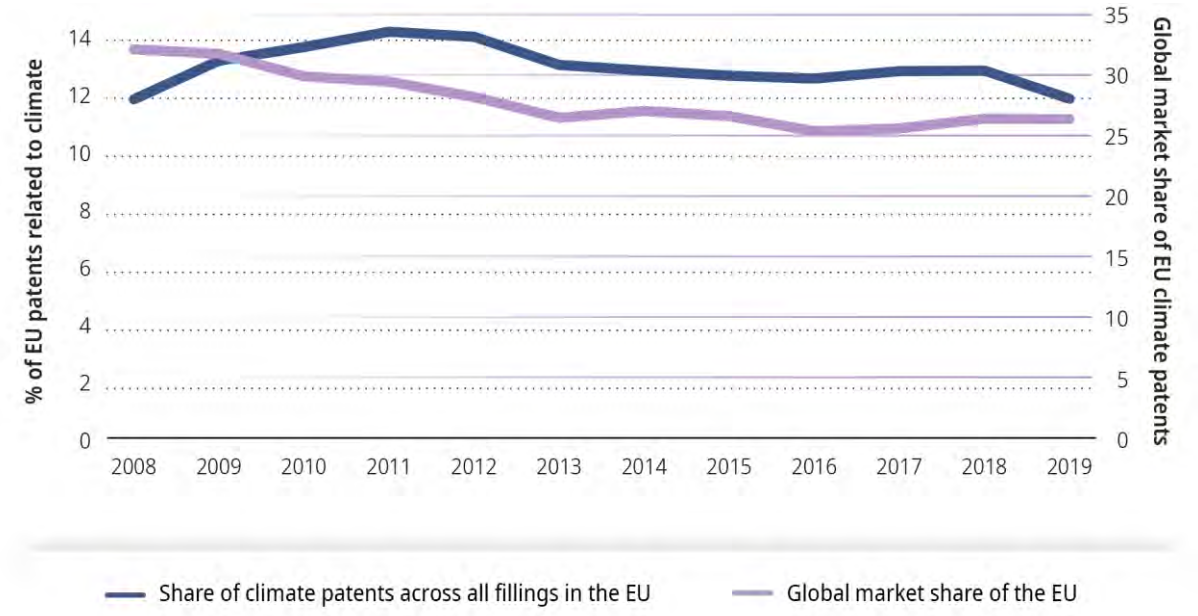

Notes: Patents related to climate change mitigation include: Energy generation through RES: geothermal, hydro, oceanic, solar (PV and thermal), wind; Energy generation of nuclear origin fusion and fission; Technologies for efficient electrical power generation, transmission or distribution Reactive power compensation, efficient operation of power networks; Technologies for the production of fuel of non-fossil origin Biofuels, from waste. Technologies with potential or indirect contribution to GHG emissions mitigation; Energy storage (batteries, ultracapacitors, flywheels), hydrogen technology, fuel cells, etc.; and other energy conversion or management systems reducing GHG emissions.

Source: OECD (2023b)

([98]) The definition of climate-related technologies in the OECD database used for the analysis of patent trends includes the following sectors: solar, wind, hydro, geothermal, marine, sustainable biomass and waste to energy, biofuels and smart energy technologies (such as smart grids, energy efficiency and electric vehicles).

A closer examination of the share of climate-related patents in the overall number of patent filings in the EU suggests a loss of momentum, as this share initially increased from 11.9 % in 2008 to reach 14.3 % in 2011 and then reverted to near the starting point (Figure 83). This has a direct impact on the share of EU climate patents in the global market, as evidenced by the decline in the EU's market share from 32.2 % in 2008 to 26.4 % in 2019. Given that most new investments in clean energy technologies are expected to take place outside the EU, it is unlikely that this trend will reverse without a decisive change in the policy mix. Overall, the recent trends in climate-related patent filings and R & D expenditure suggest that the EU contributes less to the development of new green technologies than its ambition would suggest. As previously mentioned, patents have well-known limitations as an innovation metric, but can be helpful to identify and compare trends.

13.3 Policy consistency on innovation

Need for more public–private cooperation

At every stage of the RD & D process, both public and private sector actors play critical roles. The role of governments encompasses education, R & D funding, tax incentives, providing network infrastructure, protecting intellectual property, supporting exports, helping small and medium-sized enterprises, providing the regulatory framework, and shaping, and in some cases creating, early markets (Roberts and Geels, 2019).

In addition to increased funding, it is also important to take a more holistic and deliberate approach to shaping technology innovation to address the climate challenge in a way that advances societal goals (including climate mitigation) and is inclusive and just. Public investment in enabling infrastructure could support such an approach, increasing the probability that innovations will succeed (IPCC, 2022o). Research on public RD & D investments in the energy sector shows that these investments are generally associated with positive impacts on environmental, technological, innovation and competitiveness outcomes (Peñasco et al., 2017). There is also a growing literature indicating that, at least in the energy sector, public funding and tax incentives for RD & D are useful to small and medium-sized enterprises.

Given the magnitude and speed of the change needed, there are also indication that the institutions supporting and coordinating energy innovation need to better enable the fast commercialisation of technologies; in many cases, the time between the invention of a technology and its wide diffusion has spanned decades (Stephan et al., 2017). There is also evidence of a valley of death after R & D, when technology risks are high but investment costs increase. Finally, some analysis suggests that at some times the outcomes of start-ups in energy were not as positive as those in biotech and IT, reinforcing the need for additional types of finance to scale up and commercialise new energy technologies (Gaddy et al., 2016).

Public funding for key technologies lagging behind

Public funding of RD & D is lagging behind on key technologies that are necessary for the transition towards climate neutrality, such as batteries and hydrogen. Batteries are a key technology that enables the decarbonisation of the transport sector, but also serves for energy storage in the energy supply sector; this is also recognised in the 2018 strategic action plan on batteries. According to Figure 84, public funding for RD & D in batteries has accounted for a relatively constant share of 9 % of total public expenditure on RD & D. The battery industry in the EU lags behind the growing global competition (Lebedeva et al., 2021), suggesting that a bigger effort in some storage areas may be valuable. The early investment associated with large-scale production allowed Asia to scale up and retain technological leadership in battery technologies (IEA, 2021b).

Hydrogen is also a key enabler in reducing emissions in industry (see Section 5.4) and long-range transport (see Section 6.4 under 'Lever: fuel switches', and for increasing flexibility in the energy supply sector (see Section 4.3 under 'Lever: system integration'). To realise this potential, more intense innovation is needed along the entire hydrogen supply chain, including electrolysers, to improve performance and reduce costs. Despite the significant increase in the proportion of spending on hydrogen-related RD & D from almost zero in 2000 to 7.9 % of the total spending in 2021, current levels of spending on deployment (EUR 621 billion) are about half the amount required (EUR 1 370 billion) to reach the REPowerEU targets of producing 10 million tonnes and importing an additional 10 million tonnes by 2030 (EC, 2022ad). This could suggest that additional support for early deployment could be helpful in complementing the R & D increases.

At the same time, public funding for fossil fuel RD & D including CCS remained above 5 % of the total energy RD & D budget between 2000 and 2021 (estimated total) (Figure 84). This support is inconsistent with the EU's pledge to phase out fossil fuel subsidies (EEA, 2023i). Reorienting funding away from fossil fuels and towards mitigation technologies would reduce funding gaps in key enabling technologies and also send a strong signal that the EU prioritises energy security and climate mitigation.

Figure 84 Public spending on RD & D by sector

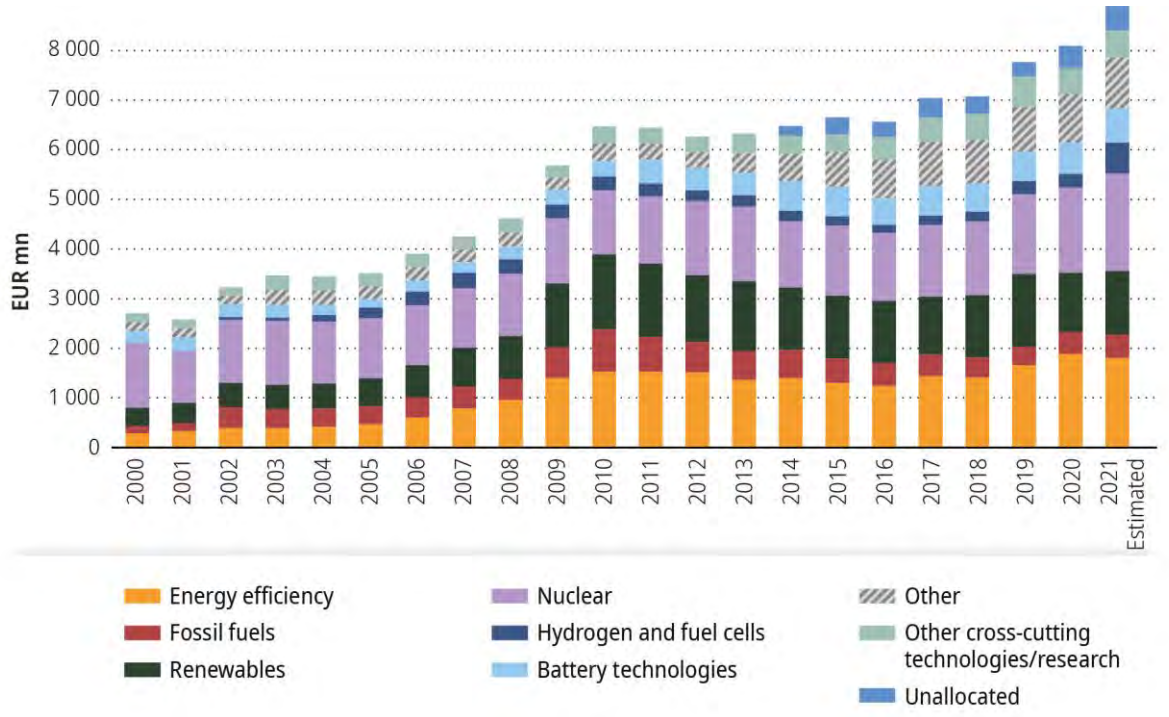

Notes: Data collected at member state and EU level, in 2021 euro values.

Source: IEA (2023c) (indicator: 'Public R&D spending').

Persisting risk of funding gaps at the demonstration and early deployment stages

The RD & D process can be summarised in the following five key stages (IPCC, 2022o), which can vary in duration, as the pathway to maturity can be long and success is not guaranteed.

1. **R & D.** Creative work is undertaken on a systematic basis in order to increase the stock of knowledge, and this knowledge is applied to devise new applications and solutions.
2. **Prototype.** A research project is developed into a design and then into a prototype for a new device (e.g. a furnace that produces steel using hydrogen instead of fossil fuels).
3. **Pilot.** The first demonstration examples of a new technology are introduced at the size of a full-scale commercial unit (e.g. installing a carbon capture system at a cement plant).
4. **Early deployment.** At this stage, there is still a cost and performance gap between the new technology and established ones (e.g. electric versus combustion engine cars). Policy needs to address this to level the playing field.
5. **Maturity and diffusion.** As deployment progresses at scale, the product moves into the mainstream as a common consumer choice for new purchases (e.g. LED lamps).

The EU has a range of funding programmes to support climate-related innovation across all stages, including Horizon Europe, the Innovation Fund, the LIFE programme, the European Institute of Innovation and Technology, the European Innovation Council, InvestEU, the Connecting Europe Facility and Breakthrough Energy Europe. The availability of funding through these programmes across the main stages of the RD & D process (R & D, prototype, pilot, early deployment, and maturity and diffusion), is summarised in Figure 85. Despite the plethora of available mechanisms, there is a material funding gap at the middle stage of the RD & D process (pilot stage).

Figure 85 Available public funding by stage of the RD & D process

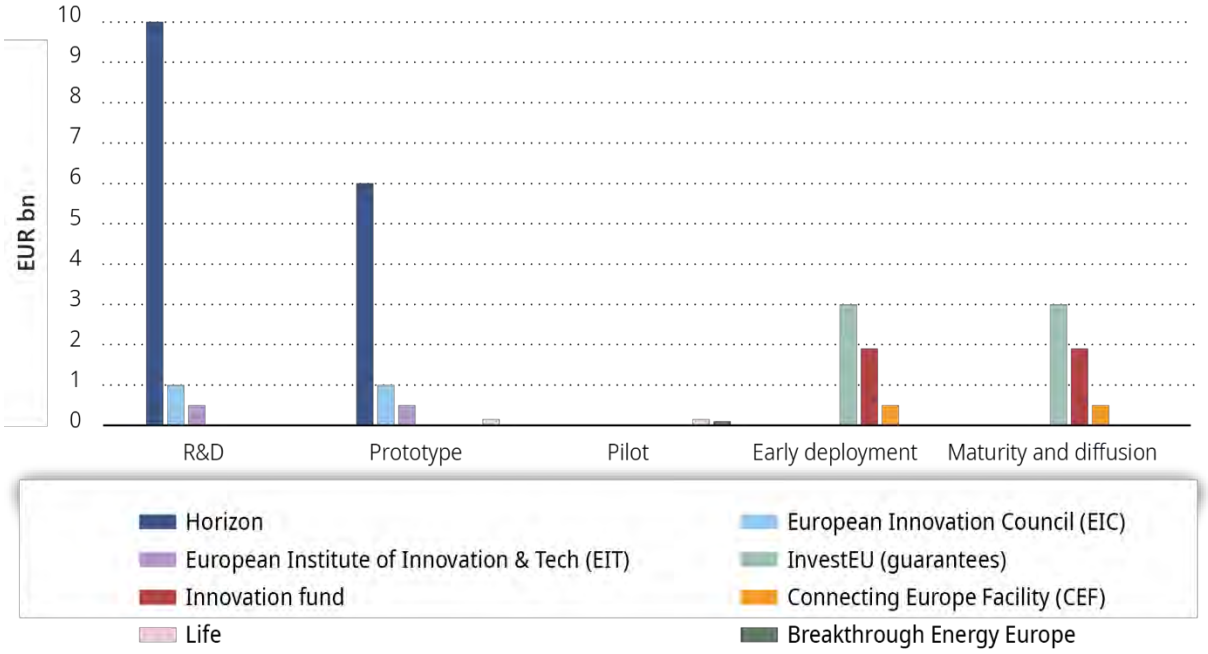

Notes: Annualised estimates for the period 2021 – 2027, except from the Innovation fund which is annualized for the period 2020-2030 and the Breakthrough Energy Europe which spans over the 2018-2023 period, in 2022 EUR values.

Sources: Policy documents for corresponding programmes (CINEA, 2021; EC, 2024, 2023ak, 2021p, 2019d, 2023bi; EIT, 2024; Wallace, 2019)

The venture capital financing model, used to overcome the valley of death in biotech and software technology, has not been as suitable for hardware start-ups in energy, because of their higher capital intensity and their dependence on network infrastructure. The current venture capital model and private finance do not sufficiently cover the need to pilot energy technologies at scale (Nemet and Greene, 2022). As Figure 86 demonstrates, investment in EU companies that specialise in clean technologies ([99]) lags behind that in the United States. This includes seed, series A, series B and growth investments. More specifically, in 2022 the EU invested only about 0.06 % of its GDP in clean tech start-ups whereas in the United States this investment amounted to 0.16 % of GDP.

Figure 86 Investments in cleantech across Europe and the United States (% of GDP)

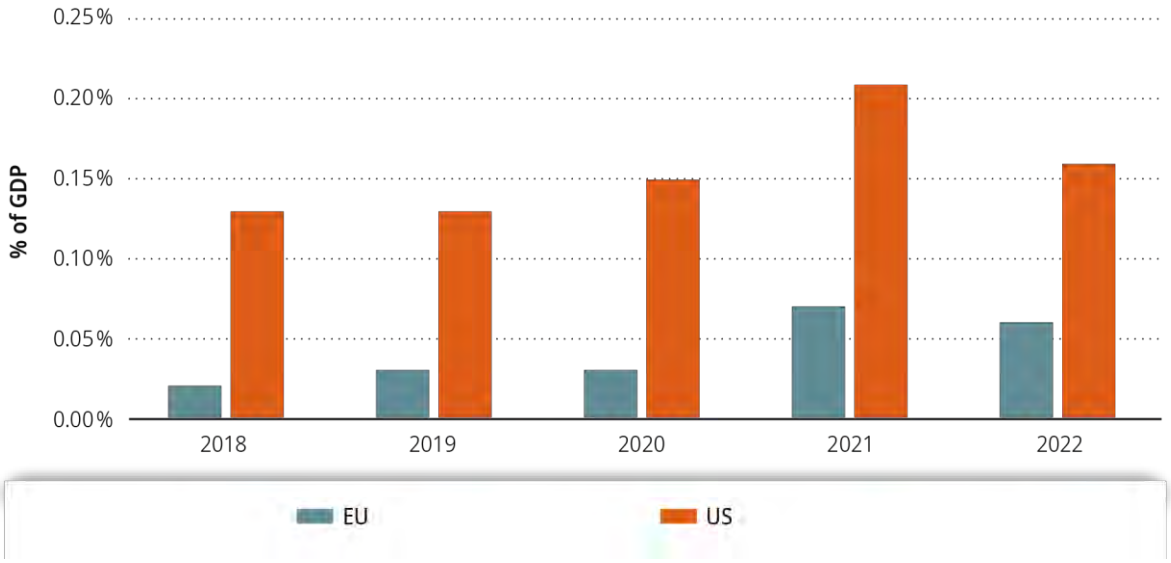

Notes: All values are expressed in 2022 Euros. Includes funding in Seed, Series A, Series B and Growth investments. For a full definition of cleantech technologies please see footnote 97.

Source: Cleantech for Europe (forthcoming).

Need to diversify early-stage research and development to boost competitiveness

According to the recent joint publication by the IEA and the European Patent Office (IEA, 2021a), countries are specialising nationally in honing their competitive edge in specific technologies and collaborating internationally to foster regional technology advantages. In this respect, Europe ranks first in wind renewables and railways, two mature sectors, whereas sectors that are at an inflection point in their growth, such as batteries, hydrogen and carbon capture, are more developed in regions outside Europe. EU policies that support RD & D need to address a broader range of technologies that might currently stand at a low technology readiness level but have a high mitigation potential. This would enable Europe to remain competitive in ownership and control of the intellectual property necessary to enable the transition in sectors where mitigation alternatives to carbon abatement are limited.

([99]) The cleantech category in transport includes the following technologies: fuel cells, electric vehicle charging, ride sharing, micro-mobility, fleet management and route efficiency. Cleantech in energy includes wind power, solar power, geothermal, nuclear, energy storage, biofuels and hydrogen. Cleantech in agriculture includes precision agriculture, indoor farming, increasing crop yields, decreasing food waste, cultured meats and alternative proteins. Cleantech in industry includes biochemicals, process electrification, circular economy, recycling and innovative materials. Cleantech in buildings includes insulation, energy efficiency systems, heat pumps and waste heat reuse. Other cleantech activities also include satellite imagery, carbon offsetting, carbon accounting, weather forecasting and climate modelling.

Figure 87 Technology advantages of global innovation centres

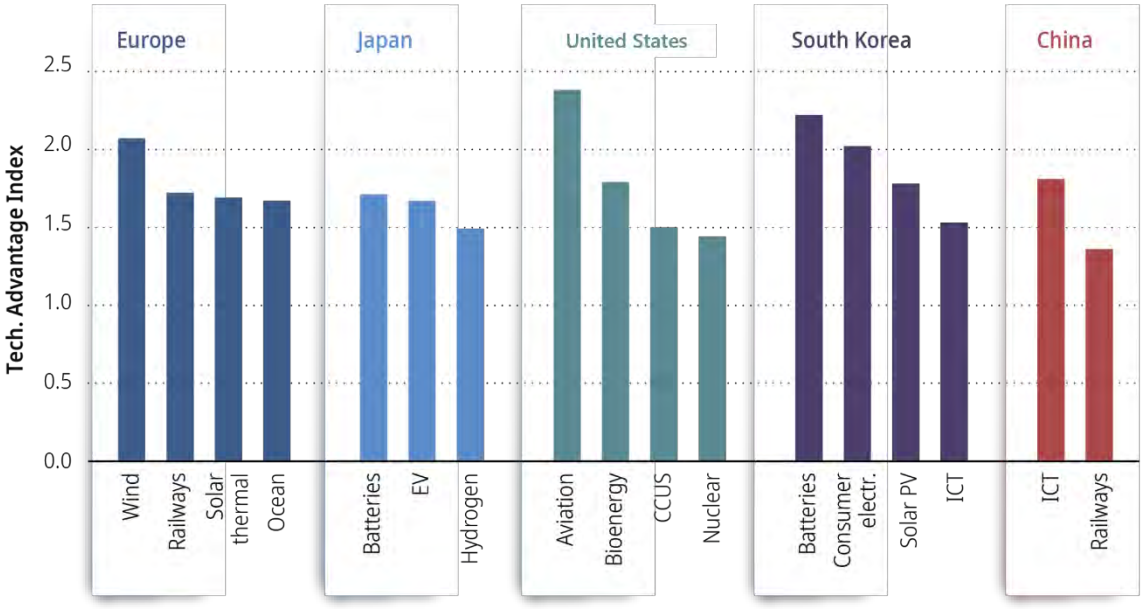

Notes: The technology advantage index indicates a country's specialisation relative to its overall innovation capacity. It is defined as a country's share of international patent fillings in a particular filed of technology divided by the country's share in all fields. A value above one reflects a country's specialisation in a given technology.

Sources: Adapted from IEA (2021a, p. 18).

13.4 Summary table

Table 20 Policy consistency summary – Innovation

Policy gaps	– Public funding instruments can be slow in reacting to the changing needs of the fast-paced global clean technology arena. – There is a significant funding gap for projects aiming to complete the piloting stage and move towards the early deployment of clean technologies. – This funding gap is further widened by the lack of sufficient support from venture capital, as this concept remains less developed in Europe than in the United States – The Net-Zero Industry Act aims to partially address this, strengthening manufacturing capacity in key technologies, but it remains silent on innovation aspects. – Policy instruments on innovation treat private and public knowledge organisations separately, which hinders the opportunity to build stronger collaborations. – The Net-Zero Industry Act aims to increase the EU's manufacturing capacity in strategic technologies to reach at least 40 % of domestic needs; however, the existing reporting mechanisms offer limited means to track progress towards achieving this target.
Ambition gaps	– Policy instruments, such as the strategic energy technology plan, that aim to strengthen industry and research collaborations need to address behavioural barriers to innovation such as the fear of failure, emphasising the value of sharing the knowledge generated. – The existing EU funding architecture offers limited predictability beyond 2030, which increases uncertainty for long-term projects.
Implementation gaps	– While Horizon Europe and the Innovation fund aim to catalyse private investment in climate-related technologies, their administrative complexities hinder the crowding-in of private investments

14 Climate governance

Key messages

National energy and climate plans, LTSs and progress reports are pivotal to the delivery of the EU's climate policies. Their timeliness and quality can be further improved.

Needs. Achieving the EU's climate goals depends on the delivery mechanisms embedded in the Governance Regulation, notably the NECPs and LTSs. The NECPs are required to be in line with the LTSs. Long-term planning is fundamental to climate policies, as it helps to assess and manage the socioeconomic impacts of the transition. The NECPs are an important source of information regarding the ambition and progress of the EU Member States in achieving milestones on the path to net zero, such as reductions in fossil gas, phase-out of fossil fuel subsidies, sustainable sourcing of biomass and demand-side mitigation policies. Without timely and full implementation of the Governance Regulation, the EU risks underdelivering on its climate ambition, including its mitigation and reporting commitments under the Paris Agreement.

Gaps. Many of the NECPs are delayed and not all LTSs were submitted by January 2020, which indicates an **implementation gap** under the Governance Regulation. The 10-year frame of the NECPs seems too short to ensure policy consistency with 2050 objectives, and the connection between the NECPs and LTSs is based on weak consistency processes **(ambition gap)**. The quality of information on some of the key milestones on the EU's path to net zero included in the first NECPs submitted, and their updates so far, is insufficient to allow the European Commission to assess the consistency of national policies and measures with climate neutrality **(implementation gap)**.

Recommendation G1. The European Commission should rigorously enforce the Governance Regulation to ensure its full and timely implementation by all EU Member States. LTSs should become subject to EU-level reviews with country-specific recommendations, and lay the basis for the NECPs. The European Commission should encourage the Member States to include all relevant information in their updated NECPs and progress reports, notably the following: use of public funds to leverage private finance for climate-related projects (Chapter 12), fossil fuel phase-out plans (Chapter 4), demand mitigation measures (Chapter 7), projected biomass energy use and compliance with the LULUCF Regulation and sustainability and GHG criteria under the RED III (Chapter 4 and 9) and commitment to phase out fossil fuel subsidies (Chapter 12).

Rigorous enforcement of the Governance Regulation should go hand in hand with effective compliance mechanisms embedded in other parts of EU climate legislation. There is a concern that the compliance mechanisms in the ESR are currently too weak.

Needs. Beyond the Governance Regulation, the key role of Member States' compliance with the EU law in climate matters is an imperative highlighted in all chapters of this report. While some acts have more effective compliance mechanisms than others, there is a concern that such mechanisms under the ESR are particularly feeble. According to the European Commission's assessment, aggregated projections by Member States show that the planned measures would reduce EU-wide emissions covered by the ESR by 32 % in 2030 compared with 2005 levels, far short of the EU-wide target to reduce emissions in 2030 by 40 % compared with 2005 levels.

Gaps. The 5-year cycle of the ESR's formal compliance checks leads to a substantial time lag between detected non-compliance and automatic penalties and, if still needed, any enforcement action

(ambition gap). The first comprehensive review will take place in 2027, but academic contributions already warn against the looming compliance deficit and the resulting launch of a formal infringement procedure by the European Commission beyond 2032.

Recommendation G2. The EU should make the Member States' progress towards their respective binding targets set under the ESR more visible to the public and put in place stronger compliance mechanisms to ensure sufficient emission reductions in the non-ETS sectors.

Access to information and public participation at the EU level can be further improved for increased transparency, democratic legitimacy and public understanding of the net zero transition. The consistency and coherence of EU climate and competition policies should be improved.

Needs. Participation, transparency and good communication are essential to climate policy design and effective implementation with minimal public climate-related discontent. The Governance Regulation requires Member States to ensure that the public is given full access to information and effective opportunities to participate in the preparation of the NECPs and LTSs. The European Climate Law requires the European Commission to assess on any relevant draft policy or measure for consistency with climate neutrality, which reinforces the impact assessment requirement under the better regulation rulebook applicable to the European Commission. The EU and its Member States are Parties to the Aarhus Convention: the United Nations Economic European Commission for Europe Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters.

Gaps. Deficits in transparency and in public engagement are observed in NECP preparation at the national level **(implementation gap)**. Moreover, despite the impact assessment practice having improved significantly in 2022 thanks to the climate neutrality checks, far-reaching non-legislative acts establishing taxonomy criteria for sustainable investment and defining some renewable transport fuels have not been accompanied by appropriate impact assessments including public consultation and climate neutrality checks **(implementation gap)**. In addition, the EU is in breach of the Aarhus Convention in relation to access to justice in state aid matters and public engagement in the NECP process **(implementation gap)**.

Recommendation G3 The transparency and democratic legitimacy of climate policies should be strengthened by rigorous enforcement of the European Climate Law and the Governance Regulation. Relevant far-reaching acts should be systematically accompanied by impact assessments including public consultations and climate neutrality consistency assessments. This also applies to the upcoming non-legislative acts, namely delegated and implementing regulations supplementing the gas package legislation and the Methane Regulation (see also Chapter 4 'Energy supply'), as well as the legislative proposals under the CAP and the next MFF with their implementing acts. They should be transparent and follow the procedural steps embedded in the European Climate Law and the Better Regulation rulebook, without undue recourse to exceptional circumstances in which effective public consultations can be omitted. Access to information, and access to administrative and judicial procedures for members of the public to challenge decisions taken by the European Commission on State aid measures, should be improved to ensure the effective safeguarding of fundamental human rights, including the right to a high level of environmental protection.

Weak participatory governance at the local and national levels undermines coordination and societal trust in EU climate policies. This calls for better implementation of a permanent climate and energy dialogue in each EU Member State.

Needs. According to the IPCC, subnational actors are important for mitigation because municipalities and regional governments have jurisdiction over climate-relevant matters such as land use, waste and urban policy, and are able to experiment with climate solutions and forge partnerships to leverage enhanced climate action. Article 11 of the Governance Regulation mandates each Member State to establish a permanent multilevel climate and energy dialogue, in which local authorities, civil society organisations, the business community, investors, other relevant stakeholders and the public engage and discuss options for energy and climate policies in the context of the NECPs and LTSs. The needs for multilevel governance and coordinated action are increasingly apparent in the EU's sectoral policies, for example under the new obligations for the Member States to conduct heating and cooling assessments as part of the NECP process and for municipalities with over 45 000 inhabitants to prepare local heating and cooling plans. Article 3 of the European Climate Law invites EU Member States to establish national climate advisory bodies, responsible for providing expert scientific advice on climate policy to the relevant national authorities. Such advisory bodies at the national level can be tasked with (i) providing the relevant authorities with expert scientific advice on climate policy, (ii) monitoring policy and (iii) supporting the multilevel climate and energy dialogue.

Gaps. Recent analyses indicate that multilevel climate and energy dialogues in some Member States are of poor quality. The uncertainty over the quality of implementation of Article 11 of the governance regulation pertains to (i) the number of Member States with permanent multilevel dialogues, (ii) the involvement of all required stakeholder categories and (iii) the coverage of topics discussed. The Committee of the Regions points out that the dialogues are often not permanent and the NECPs are not always in tune with subnational climate policies **(implementation gap)**. The European Climate Law only encourages the Member States to establish national climate advisory bodies, without making such bodies mandatory and no link to such bodies is made in the procedural obligations of the NECPs, for example as part of the multilevel climate and energy dialogues **(ambition gap)**.

Recommendation G4. Building on the insight available through the EU multilevel cooperation initiatives, and taking into account the voices of the Committee of the Regions, civil society, local authorities, and scientists, the European Commission should strive to ensure stronger compliance with Article 11 of the Governance Regulation so that every Member State has a permanent multilevel climate and energy dialogue in place, allowing coordinated and informed climate action at the EU, regional, national and local levels. The Advisory Board recommends that all EU Member States that have not done so yet should establish independent climate advisory bodies. The upcoming revision of the Governance Regulation should enable a stronger connection to the European Climate Law in this respect.

14.1 Policy planning for target delivery

The EU climate governance can be improved and made fit for 2050 through the upcoming revisions of the European Climate Law and the Governance Regulation.

The **European Climate Law** sets the EU climate neutrality target by 2050 and provides an overall sense of the EU policy direction towards 2050 climate neutrality and the interim targets (ref). The corresponding policy delivery mechanisms are embedded in the **Governance Regulation**. While it is too early to assess EU climate governance effects in terms of delivering the 2030 and 2050 climate targets (Schoenefeld and Knodt, 2021), scientists and stakeholders are already warning that the EU's

climate governance is not fit for the radical transformation ahead of the EU in view of its 2050 climate neutrality target (EC, 2023ai; Hancher, 2022; Kulovesi and Oberthür, 2020; Oberthür et al., 2023). The upcoming revisions of both acts can improve the EU's climate governance and make it fit for 2050.

The EU's net zero transition can be facilitated by the swift adoption of a science-led 2040 target.

Climate laws enable mitigation by, among other measures, setting targets and enhancing regulatory certainty (IPCC, 2022p). According to the European Climate Law (Article 4), the intermediate 2040 target is to be set based on a European Commission proposal made no later than June 2024. The Advisory Board issued its recommendations regarding the 2040 target (ESABCC, 2023c) in June 2023. The swift adoption of a science-led 2040 target is important to guide the EU's transition to climate neutrality through the post-2030 policy framework. The adoption of a 2040 target should open up the process of revising the existing legislation so that it is fit for after 2030, reflecting the linked revision clauses, for example under Article 15 of the ESR (EU, 2018c).

Target delivery relies on long-term planning and an EU-level overview of key milestones on the path to net zero.

The EU's climate governance is based on the mandatory planning, monitoring and reporting processes carried out by the EU Member States and the European Commission (Kulovesi and Oberthür, 2020). To deliver on the climate targets underpinned by the EU energy union strategy, which are binding on the EU, the Member States plan the climate policy measures and embed them into their NECPs and LTSs. Long-term climate strategies, including the impact assessments of their socioeconomic aspects (Annex IV of the Governance Regulation), can enable a whole-of-society approach (see Chapter 11) and contribute to the delivery of the climate ambition under the Paris Agreement (UNFCCC, 2023). These plans and strategies are submitted to the European Commission, which assesses if their respective contributions are, on aggregate, sufficient to deliver on the EU's ambition. Through progress reports, the EU Member States allow the European Commission to monitor and assess progress towards targets. In this sense, the European Commission is the guardian of the EU's collective ambition and progress, and is expected to take action should the achievement of the EU's climate targets be at risk (Oberthür, 2019). As part of this process, the European Commission reports the overall progress to the European Parliament and is responsible to it, in line with Article 18 of the Treaty on European Union, and Articles 233–234 of the Treaty on the Functioning of the European Union.

The first NECPs were submitted to the European Commission in 2020. By mid 2023, the EU Member States were to submit their updated versions and progress reports. Many of them are delayed, which is partly because of legal changes driven by the Fit for 55 package, and the resulting adjustments at the national level. Late submission of NECPs risk delaying their assessment and follow-up. The final NECPs are due in June 2024.

The EU cannot afford any further delay to climate action, and needs to provide **long-term policy signals** based on long-term plans for the net zero transition. In this respect, the 10-year time frame of the NECPs seems too short to ensure policy consistency with 2050 objectives. This gap can be bridged by stronger links between the NECPs and the LTSs, which have a 30-year span. Despite the requirement for NECPs to be in line with the LTSs under Article 15 of the Governance Regulation, such consistency may be meaningless in practice given the way the LTSs are developed in the first place. They are not subject to iterative dialogue between the Member States and the European Commission, as the NECPs are. The European Commission merely checks their collective ambition regarding achieving climate goals at the EU level. Moreover, the LTS update clause under Article 15 of the Governance Regulation relies on an arbitrary trigger (i.e. 'where necessary'), effectively weakening the relevance of the LTSs and their already feeble links to the NECPs. The LTSs therefore need a more prominent place in the EU's climate

governance than they currently have. They need to be submitted by all EU Member States – which is already an obligation but is not fulfilled (EC, 2022af) – and become subject to EU-level reviews with country-specific recommendations so they can lay a robust foundation for the NECPs.

Finally, the NECP process is an important source of information regarding the progress and ambition of each EU Member State in achieving milestones on the path to net zero, such as targeted deployment of fossil gas, the phase-out of fossil fuel subsidies, sustainable deployment of bioenergy, and policies and measures in non-ETS sectors including demand-side mitigation policies. It is vital to learn from the first assessment of NECPs, when not all relevant information was included by all Member States; for example, only six Member States included a timeline to phase out some of the existing fossil fuel subsidies, and the NECPs lacked 'details on how to supply the required sustainable biomass, by feedstock and origin and trajectories for forest biomass, and how they are aligned with measures to maintain and increase the carbon sink' (EC, 2020q, p. 24). Moreover, in the assessment of NECP progress reports conducted in 2023, the European Commission observed that the reported information, notably pertaining to building stock decarbonisation and investment, was often incomplete and inconsistent and was thus not helpful for drawing EU-wide conclusions (EC, 2023j). As highlighted earlier in this report, the European Commission can encourage Member States to include the following information in their updated NECPs: fossil fuel phase-out plans, with a focus on the declining business case for fossil gas (Chapter 4); national ambitions regarding RES investments, to give investors a better overview, e.g. volumes of auctions measured against the required pace of progress (Chapter 4); building-related data and sufficiency measures (Chapter 7); compatibility aspects in terms of the projected use of forest biomass energy compared with the targets under the LULUCF Regulation and with sustainability and GHG criteria under the RED III (Chapters 4 and 9); finance and investment data and commitments to phase out fossil fuel subsidies (Chapter 12); and ways public participation and permanent multilevel engagement are facilitated (Section 14.3).

14.2 Compliance and enforcement

Enforcement of EU climate legislation is necessary in cases of non-compliance.

The European Commission examines the NECPs and progress reports, assessing both compliance with EU law and the effectiveness of national climate policies and measures (Higham et al., 2021). Should it identify a gap in ambition, policy or progress, the European Commission issues recommendations to the relevant Member State. It is for the Member State to decide on how to act on the recommended corrective course, and for the European Commission to take the necessary follow-up. If this iterative process does not lead to compliance, the European Commission may decide to initiate **infringement procedures** (Schlacke et al., 2022; Monti and Martinez Romera, 2020). It is therefore up to the European Commission to 'continue to ensure that all relevant legislation is rigorously enforced' in the context of the EU's climate governance (EC, 2019c). In this role the European Commission is supported by other EU institutions (such as the European Parliament) and bodies and by other stakeholders, enabled by transparent and participatory policy and governance. EU-level enforcement is a poor alternative to well-designed policy adoption and implementation, however. As pointed out by legal scholars and practitioners, the EU's infringement procedures are often cumbersome and too lengthy to offer timely remedies in climate-relevant non-compliance cases (Hancher, 2022; Monti and Martinez Romera, 2020; Oberthür et al., 2023). For instance, in September 2022 the European Commission took the first step of the official infringement procedure by sending letters of formal notice to the four Member States that had not submitted their LTSs by January 2020 in line with Article 15 of the Governance Regulation (EC, 2022af). Enforcement of EU law at the national level is outside the scope of this report.

Stronger public visibility of the Member States' progress towards their respective binding targets set under the ESR, combined with stronger compliance mechanisms, is needed to ensure sufficient emission reductions in the non-ETS sectors.

Beyond the Governance Regulation, Member States' compliance with the EU law in climate matters plays a key role. That is an imperative highlighted in all chapters of this report. While some acts have more effective compliance mechanisms than others, there is a concern that such mechanisms under the **ESR** ([100]) are particularly feeble. Meeting the binding emission reduction targets for the non-ETS sectors under the ESR relies on the implementation of sectoral policies (see e.g. Runge-Metzger and Van Ierland, 2019). EU policies in this area need to be complemented by ambitious climate action at the national and subnational levels. The ESR emission reduction targets are therefore the EU's main compliance tool to ensure sufficient reductions in the non-ETS sectors on the path to net zero.

The progress towards targets is checked through an annual assessment (Article 8 of the ESR). Should the reported progress, after taking account of the multiple flexibilities at the Member State's disposal, be deemed insufficient, the European Commission opens an iterative dialogue with the Member State that may lead to a corrective action. The annual cycles have limited public visibility, however, compared with similar processes such as the European Semester.

In addition to the annual progress reporting and the dialogue, every 5 years (in 2027 for 2021–2025, and in 2032 for 2026–2030, as set out in Article 9 of the ESR) the European Commission conducts compliance checks, with automatic penalties in the form of emission budget adjustments and transfer prohibitions applicable in the event of excess GHG emissions (ref). Since no direct monetary sanctions are laid down and there is no price estimate in terms of EUR/tonne of CO_2eq in bilateral transfers, Member States have limited visibility of the costs of not achieving their national reduction objectives. This lack of direct financial incentive is exacerbated by a substantial time lag between a detected case of non-compliance and any potential enforcement actions. As a result, the final determination of non-compliance leading to a formal infringement procedure may only start in 2032, and, considering the long lead times of administrative and judicial procedures, any resulting remedy would not be effective in terms of timely emission reductions.

Although the first compliance check will only start in 2027, academic contributions already warn against the looming compliance deficit and the resulting necessity of enforcement action (see e.g. Peeters and Athanasiadou, 2020). This concern grows when the problem is considered together with the EU Climate Action Progress Report (EC, 2023j), in which the European Commission indicates that Member States' aggregated projections show that EU-wide ESR emissions would reduce by 32 % in 2030 compared with 2005 levels, including planned measures, which is 8 pp below the EU-wide target set for 2030 in the ESR.

([100]) The ESR aims to reduce GHG emissions in sectors outside the EU ETS (about 60 % of total GHG emissions) by 40 % by 2030 compared with 2005. This overall objective is translated into legally binding national targets, which are differentiated based on Member States' GDPs per capita, ranging from – 10 % to – 50 %. Each Member State is assigned annual emission allocations based on a linear trajectory towards its target. Member States have to ensure that their annual emissions in relevant sectors do not exceed these annual allocations. They can use a range of flexibility mechanisms to achieve compliance in a cost-effective way, including banking, borrowing and trading of allocations and limited flexibilities with the EU ETS and the LULUCF sector.

14.3 Assessments, public participation, and multilevel dialogue

Democratic legitimacy enabled by public participation, transparency and access to justice are essential to effective climate policies. Climate neutrality consistency checks required under the European Climate Law are key in this respect and should be further mainstreamed.

Participation, transparency and good communication are essential to climate policy design and effective implementation with minimal climate-related public discontent (IPCC., 2022p). Public engagement improves the democratic legitimacy and wider understanding of EU climate policies (see for example ESABCC, 2023; IMF, 2023). Article 10 of the Governance Regulation requires the EU Member States to engage the public in the preparation of the NECPs and LTSs. Article 9 of the European Climate Law requires the European Commission to 'facilitate an inclusive and accessible process at all levels … for the exchange of best practice and to identify actions to contribute to the achievement of the objectives of' the European Climate Law. In line with Article 6 of the European Climate Law, the European Commission 'shall assess the consistency of any draft measure or legislative proposal, including budgetary proposals, with the climate-neutrality objective … and the [EU] 2030 and 2040 climate targets before adoption' (EU, 2021c). Climate neutrality consistency checks and public consultation feed into impact assessment and are 'required for [European] Commission initiatives that are likely to have significant economic, environmental or social impacts or which entail significant spending, and where the [European] Commission has a choice of policy options' (EC, 2021e).

Impact assessments including public and stakeholder consultations are required under the EU policymaking rules known as 'better regulation', developed on the basis of the interinstitutional agreement between the European Parliament, the Council and the European Commission on better lawmaking adopted in 2016 (EP et al., 2016). It is very positive that the European Commission has updated its better regulation instruments to ensure that new EU policies are consistent with climate targets, and applies these climate neutrality checks on new proposals since 2022. This practice has not been applied to proposals submitted before 2022 (e.g. as part of the impact assessment to the EU Taxonomy Climate Delegated Act) and should be further mainstreamed. Many EU delegated acts of binding and general application (Hancher, 2022) are highly relevant to EU's net zero transition. Supposed to supplement or amend certain *non-essential* elements of the legislated acts, they are not systematically accompanied by impact assessments, however. The omission to conduct an impact assessment may be justified in exceptional circumstances set out in the better regulation toolbox (EC, 2021a). It is not always clear, however, whether the omission to conduct a fully-fledged impact assessment and climate neutrality checks was indeed justified as in the cases of e.g. in the delegated act defining what constitutes renewable hydrogen in transport fuels (EC, 2023h). Moreover, the lack of the dedicated, formal impact assessments goes beyond the delegated acts; e.g. the European Commission evoked previous impact assessments and public consultations under the 2030 climate target plan, the revision of the EU ETS Directive, and other relevant initiatives under the European Green Deal to justify that the social climate plan regulation proposal was not accompanied by a dedicated impact assessment (EC, 2021ad). The need to include systematic assessment of distributional and socioeconomic impacts of draft climate policies and measures has been highlighted in chapter 11 Section 11.2.

In parallel, transparency and public engagement deficits have been observed in the NECP preparation at the national level (European Commission, 2023a). These deficits impact also the EU-level part of the NECP process, in particular the draft NECP assessment by the European Commission, which has been found in breach of the Aarhus Convention (ECE, 2021). As a follow-up, the European Commission has provided a guidance to the EU Member States (EC, 2022c) for the update of NECPs, and sent a remedial action plan to the Aarhus Convention Compliance Committee in 2022 (ref). While it is not certain yet how the guidance has led to reducing the transparency and public engagement deficits in the ongoing

NECP cycle, the civil society have raised concerns regarding this matter in April 2023 (Civil society organisations, 2023).

In this context, the transparency and democratic legitimacy of the EU and national climate policies could be strengthened by a rigorous and timely enforcement of climate neutrality consistency assessments and public consultation clauses in the European Climate Law and the Governance Regulation. Relevant far-reaching acts should be systematically accompanied by formal, dedicated impact assessments. In particular, the upcoming non-legislative acts i.e. delegated and implementing regulations supplementing the gas package legislation and the Methane Regulation (see Chapter 4 'Energy supply'), as well as the legislative proposals under the CAP and the next MFF with their implementing acts, need to be transparent and follow the procedural steps embedded in the European Climate Law and the Better Regulation rulebook, without undue recourse to exceptional circumstances in which full impact assessments can be omitted.

While impact assessments are an important *ex ante* insight into the proposed measures, they need to go hand in hand with *ex post* evaluations and fitness checks in line with better regulation guidelines and toolbox (EC, 2021a), as highlighted also in Section 11.2.

Finally, democratic legitimacy of climate policy depends also on effective **access to justice** in climate matters. Not only can climate litigation affect the outcome and ambition of the overall climate governance (IPCC, 2022p), but also courts in democratic jurisdictions 'possess strong claims to democratic legitimacy in the climate litigation cases as a result of their institutional capacity to weigh intergenerational harms and responsibly assess scientific claims.' (Kuh, 2020). While an analysis of the role of climate litigation in the EU climate policies is out of scope of this report, the Advisory Board flags its concern regarding access to justice in EU State aid control matters. The exclusive competence of the European Commission in State aid control has considerably expanded over time (Schneider, 2023). The European Commission's regulations, communications, and decisions in this area are not subject to the same level of legal guarantees as applicable to other areas of EU law (Council of the EU, 2015). This weakness is particularly acute in the context of the streamlined State aid rules under the crises-induced temporary framework approval which led to significant spending in energy and industry sectors. The scale of State aid indicates its potentially far-reaching consequences for EU's net zero transition (see also Section 12.5). Nevertheless, challenging the European Commission's decisions to approve state financial assistance before the Court of Justice of the EU is difficult for citizens and non-governmental organisations due to, among other impediments, such as timely access to information and high admissibility threshold of the claims, notably restricted to parties 'individually and directly concerned by the decision' (ClientEarth, 2023; Delarue and Bechtel, 2021; Hancher and Maria Salerno, 2021b; Winter, 2020). Due to the legal and procedural obstacles linked to state-aid, the EU was found in breach of the Aarhus Convention in 2021 (ACCC, 2021). The European Commission is in search of the solution to ensure full compliance of its State aid regime with the Aarhus Convention (EC, 2023t). Future policy development in this area is an opportunity to increase transparency and public engagement in EU policies with a view of achieving the climate neutrality objective by increasing consistency and coherence of EU climate and competition policies.

Permanent multilevel dialogue can help to coordinate climate policies development and implementation. Coordinated development of the local heating and cooling plans required under the EED is urgently needed to avoid further carbon lock-ins and attenuate impact of price increases triggered by the EU emission trading policies. The national climate advisory bodies can act as convenors supporting the multilevel dialogue on national climate policy.

According to the IPCC, 'sub-national actors are important for mitigation because municipalities and regional governments have jurisdiction over climate-relevant sectors such as land use, waste and urban policy; are able to experiment with climate solutions; and can forge partnerships with the private sector and internationally to leverage enhanced climate action'. (…) Sub-national institutions play a complementary role to national institutions by developing locally-relevant visions and plans, addressing policy gaps or limits in national institutions, building local administrative structures and convening actors for place-based decarbonisation' (IPCC, 2022p). Multilevel stakeholder involvement and decentralisation of decision-making ('the closest to the citizens the better') are all part of adaptive and fair climate transition frameworks (Willis et al., 2022; Anadón et al., 2022). Moreover, community approaches and other types of 'bottom-up approach driven by citizen engagement' (IPCC, 2022b) have significant benefits in terms of delivering climate justice and driving behavioural and societal transformation (IPCC, 2022f).

While many climate policies are decided at the EU level and implemented by the Member States, the Governance Regulation highlights the need for coordinated action, combining both legislative and non-legislative acts at the EU, regional, national and local levels. Under its article 11 it mandates each Member State to establish a permanent ([101]) 'multilevel climate and energy dialogue pursuant to national rules, in which local authorities, civil society organisations, business community, investors and other relevant stakeholders and the general public are able actively to engage and discuss the different scenarios envisaged for energy and climate policies, including for the long term, and review progress, (…)' discussing the NECPS and the LTS. The needs for multilevel governance are increasingly apparent in the EU sectoral policies, notably under the EED obligation for the Member States to conduct heating and cooling assessment as part of the NECP process and for municipalities with over 45 000 inhabitants prepare local heating and cooling plans (EU, 2023e). EU cities networks call for national- and EU-level adjustments to ensure adequate technical and financial resourcing of local authorities to develop such plans transparently and independently so that they deliver for net zero in coordination with other parts of the energy systems (EnergyCities, 2022), in line with art. 25 of the EED (EU, 2023e).

There is a concern however regarding poor quality of the multilevel climate and energy dialogues in some Member States (CoR, 2023b) and significant uncertainty over the quality of art. 11 of the Governance Regulation implementation based on the reporting under the NECP process (NECPlatform, 2023). The European Commission's assessment of the first round of the NECPs focused on a regional cooperation in the context of multilevel dialogues, although specified that, in an unprecedented process, 'several' Member States organised local, regional, sectoral workshops to discuss the content of their final NECP with stakeholders (EC, 2020i). The uncertainty surrounding the updates to the NECPs pertains to the number of Member States enabling such exchanges on a permanent basis, the involvement of all required stakeholder categories, and the coverage of topics discussed (NECPlatform, 2023). The weakness pointed out by the Committee of the Regions also links to the permanent nature of the dialogues and the limited integration of NECPs with subnational climate policies (CoR, 2023a).

([101]) The permanence of multilevel climate and energy dialogues is mentioned in the preamble, but not in the art. 11 of the governance regulation.

The EU supports permanent multilevel climate and energy dialogues through funding under the LIFE programme (EC, 2021x). Moreover, the EU policies foster broader multilevel governance and bottom-up action for net zero transition through initiatives such as the Covenant of Mayors for climate and energy (EC, 2023w) and the urban agenda for the EU (EC, 2021ak). The European Commission launched also the European Climate Pact and supports the Energy Communities Repository (EC, 2023x) and the Rural Energy Community Advisory Hub (EC, 2023bc).

Moreover, multilevel climate and energy dialogues can be supported by national **climate advisory bodies.** As set out in the European Climate law, such bodies can play an important role in convening stakeholders and providing expert scientific advice on climate policy to the relevant authorities (Evans and Duwe, 2021). They can also monitor relevant policy developments (EEA, 2021b). Despite being encouraged to do so, not all the Member States have established an independent climate advisory body so far.

14.4 Summary table

Table 21 Policy consistency summary – climate governance

Ambition gaps	– The 10-year frame of the NECPs seems too short to ensure policy consistency with 2050 objectives, and the connection between the NECPs and LTS is based on weak consistency processes. – The five-year cycle of the ESR formal compliance checks leads to a substantial time lag between a detected non-compliance and automatic penalties, and if still need be, any potential enforcement action. The first comprehensive review will take place in 2027; but academic contributions warn already against the looming compliance deficit and the resulting launch of a formal infringement procedure by the European Commission beyond 2032. – The European Climate Law only encourages the Member States to establish national climate advisory bodies, without making them mandatory and no link to such bodies is made in the NECP procedural obligations e.g., as part of the multilevel climate and energy dialogues.
Implementation gaps	– Many of the NECPs are delayed and not all LTS were submitted. – The quality of information on some of the key milestones on the EU's path to net zero included in first submitted NECPs, their updates and progress reports, is insufficient to allow the European Commission to assess consistency of national policies and measures with climate neutrality. – Transparency and public engagement deficits are observed in the NECP preparation at a national level. – The EU is in the breach of Aarhus Convention in relation to access to justice in state aid matters and public engagement in NECP process. – Moreover, despite the impact assessment practice having improved significantly in 2022 thanks the climate neutrality checks, far-reaching non-legislative acts establishing taxonomy criteria for sustainable investment and defining some renewable transport fuels have not been accompanied by appropriate impact assessments including public consultation and climate neutrality checks. – Recent analyses indicate poor quality of multilevel climate and energy dialogues in some Member States. The uncertainty over the quality of art. 11 of the Governance Regulation implementation pertains to: (i) the number of Member States with permanent multilevel dialogue, (ii) the involvement of all required stakeholder categories and (iii) the coverage of topics discussed. The Committee of the Regions points out to the weakness in terms of the permanent nature of the dialogues and the limited integration of NECPs with subnational climate policies.

15 Labour, skills and capacity building

Key messages

The transition to net zero will require a profound shift in the structure of the labour force. Ambitious sectoral targets will create new employment opportunities in many sectors, although skills shortages are already acute in the European economy and will deepen if not addressed by tailored policy measures to train and upskill the workforce.

Needs. The transition to net zero will require a profound shift in the European labour market: new jobs will be created in some sectors, while existing jobs will require new types of skills and competencies. Labour shortages are already acute across Europe and may worsen without additional supply, particularly in the energy systems and construction sectors; while upskilling, certification, and cross-cutting digital and interpersonal skills will be required across the workforce. Policy development and climate investments will create additional demands on the skills and capacity of public administration, while a transition to sustainable farming practices also requires the provision of appropriate support, advice and training to farm managers.

Gaps. The EU has put in place programmes and funding to address skills shortages in priority sectors, and to improve skills and capacity in public administration; while the Farm Advisory System exists to provide training and advice to farm managers. Although design and implementation of education and training schemes is largely the responsibility of member states, there are some remaining policy gaps at a European level, particularly regarding workforce mobility and mutual recognition of qualifications in the construction sector **(policy gap)**. Low participation in training in some key sectors (e.g. buildings, agriculture) also limits the opportunities to upskill and enhance knowledge exchange relevant to the transition **(implementation gap)**.

Recommendation S1. Investments in education, training and skills should be targeted to upskilling and improved mobility in the construction, renewable energy systems sectors; as well as cross-cutting skills like digitalisation and interpersonal skills. The EU should also support – for example, through the Technical Support Instrument and other funding schemes – skills and capacity-building projects aimed at enhancing the ability of public administrations to implement climate policies and investments. Further efforts are needed to ensure that the national Farm Advisory Systems provide appropriate support, advice and training to farm managers regarding sustainable farming practices and mitigation measures; as well as to increase awareness and uptake of training opportunities among farmers.

Training and reskilling are important to support and provide opportunities to those who may be negatively affected by the transition, such as coal and fossil gas workers. While the EU provides support under the Just Transition Fund, doubts remain over whether the design and ambition of this mechanism fully reflect the scale of transition in some regions and sectors.

Needs. In parallel, well-funded and -tailored employment and reskilling programmes are needed for workers in fossil fuel sectors that may be negatively impacted by the transition; to minimise distributional and regional impacts, and to ensure that the employment opportunities presented by the transition remain open to all.

Gaps. The EU has put in place a Just Transition Fund to support regions and occupations whose workforce will be negatively impacted by the transition; however, experience of previous reskilling initiatives suggests that issues around the eligibility criteria, funding and limited systemic measurement

of outcomes has limited their impact **(ambition & implementation gap).** Transition schemes for workers in the fossil gas sector are also largely still absent at the EU level **(policy gap)**.

Recommendation S2. Further efforts are required to address weaknesses identified in the design and implementation of just transition programmes: particularly in ensuring that eligibility criteria and funding are targeted towards those workers and regions at greatest risk; to improve measurement of impacts and outcomes; and to increase participation in training by affected groups.

15.1 Workforce and skill needs in the net zero economy

The EU's transition to net zero will require a workforce with both the capacity and skills to deliver on targets across a range of sectors, including in construction/buildings, energy systems and agriculture. European climate policies to date have already created growth in sectors associated with the transition like renewable energy systems, and although research generally suggests that aggregate employment levels in the European economy are not likely to increase significantly under the Fit for 55 targets, there will be a profound shift in the structure of the labour force between sectors, occupations, required skillsets and regions (EC, 2022ai; Borgonovi et al., 2023).

For sectors linked to the net zero transition, workers will be required in a range of operational, manufacturing, installation, engineering and research roles (Eurostat, 2023f). Employment in wind energy is expected to grow from 300 000 in 2022 to 450 000 in 2030 (WindEurope, 2022). Direct employment in solar is also expected to increase from 200 000 in 2021, to almost 460 000 by 2030 under REPowerEU's target of 750GW (SolarPower Europe, 2022b), while the battery sector requires approximately 800 000 workers to be retrained or upskilled by 2025 (EC, 2023ah). More technicians and craftspeople will be needed to renovate millions of buildings to zero-emission standard (D'Agostino et al., 2021b; EASAC, 2021b), with an estimated 4 million construction workers needing to develop energy efficiency-related skills according to European Construction Sector Observatory (2020) ([102]).

The European Commission lists skills shortages among the key barriers to the EU's net zero transition, notably the locally-available labour force and its skills, including digital literacy (EC, 2022m, 2022ah). The EU already faces a shortage of skilled workers in the construction sector, which is expected to worsen 'as a consequence of green transition'. In addition, demand and supply for renewable energy technicians (including those with software skills) is imbalanced across the EU (ELA, 2023). For instance, up to 30 % of companies in offshore renewables reported experiencing skills shortages in 2020, primarily in research, engineering and technician roles (EC, 2020c). The uniqueness of net zero transition jobs may make them difficult to fill at first due to the small size of the dedicated occupational labour market (ELA, 2023; IPCC, 2022g). It will also be important that EU employment policy measures remain adaptive and anticipate market needs, e.g. in terms of innovation and circular use of materials given that recycling, remanufacturing and reuse offer greater employment opportunities than landfilling or incineration (IRENA, 2022a).

([102]) As much as 60 % of expenditure on home energy efficiency retrofits could go towards labour creating 12–18 jobs per million euro of investment, more than in other areas of energy policy (IEA, 2020). For instance, according to JRC, if 'renovation rate increased to 3 % within 10 years and maintained thereafter (…) the associated impact on employment would be approximately 55 millions of full-time equivalent job places' (JRC, 2020a). Moreover as highlighted in the Renovation Wave strategy decarbonisation of buildings requires also public administration to develop the necessary skills in the area (EC, 2020h)

Beyond specific occupations, there is also a need for cross-cutting skills to drive and manage the adoption of new technologies, with a particular emphasis on improved digital and interpersonal skills. For instance, public engagement is increasingly important for energy and engineering workers during the planning and permitting processes for RES developments, while construction workers play a more active role in advising consumers and encouraging them to make more sustainable choices (e.g. the choice of a heat pump vs. a fossil heating system). Improving the advisory, communication, and digital skills of the existing workforce can therefore be an important enabler for wider societal change (Borgonovi et al., 2023; EGFSN, 2021).

15.2 Construction and energy systems workers

The EU has put in place several programmes to address the skills shortages in the construction and energy systems sectors, and the ambition of the Green Deal industrial plan in addressing the skills gap is promising in this respect. Further investments in upskilling, improved workforce mobility and mutual recognition of qualifications between Member States can help to address skills shortages in these sectors.

In July 2023 there have been 13 EU funding instruments for upskilling and reskilling (EC, 2023aa), notably the European skills agenda (EC, 2020o), the Just Transition programme, the REPowerEU plan (EC, 2022m) with its sectoral strategies (e.g. EU Solar PV Industry Alliance under the EU (EC, 2022o)), the RRF, the Just Transition Fund, the InvestEU programme, BUILD UP skills initiative, the European Social Fund Plus (EC, 2023ad) and Erasmus+. The European Year of Skills 2023 also aimed to address skills shortages with an ambition to 'give a fresh impetus to lifelong learning, empowering people and companies to contribute to the green and digital transitions, supporting innovation and competitiveness' (EC, 2023ae).

The European skills agenda supports large-scale skills partnerships in strategic sectors under the Pact for Skills. Launched in 2020, the Pact for Skills is a shared engagement model for companies, workers, national, public authorities, social partners, cross-industry and sectoral organisations, education and training providers, chambers of commerce and employment services. The European skills agenda is complemented by the European Education Area (Council of the European Union, 2021) including the digital education action plan (EC, 2020m). 'Enhancing skills' is also one of the four pillars in the European Commission's Green Deal industrial plan, which contains several proposals to address skills shortages and improve workforce mobility in strategic industries (EC, 2023u).

The revised EPBD (EC, 2021ac), in line with the renovation wave strategy (EC, 2020h), also addresses workforce skills in the context of decarbonising the buildings sector. It requires Member States to put in place measures and financing to promote education and training to ensure 'a sufficient workforce with the appropriate level of skills corresponding to the needs in the building sector' (EC, 2021ac). Moreover, reskilling and up-skilling of workers, education, job-seeking initiatives are explicitly mentioned among funding areas for the Member States to use the revenues from emission trading under the revised EU ETS Directive (EU, 2023c). The 2023 Net-Zero Industry Act proposal sets out workforce-related measures for net zero technologies (EC, 2023ao).

While it is still too early to assess the impact of these initiatives, there are barriers to increasing participation in upskilling and training among construction workers, including the time and mode of training, the predominance of small and medium-sized enterprises with low training budgets in the sector, and low consumer demand (ECSO, 2020). In the construction sector roundtable organised as part of the Pact for Skills in 2020, participating stakeholders indicated that 'high mobility of the construction workforce can help address local skills shortages' (EC, 2020q); yet they pointed out that mobility is hindered by the lack of mutual recognition of qualifications amongst EU Member States, due to

differences in training systems and legislation. As a way forward the stakeholders suggested 'a uniform assessment of workers and an automatic recognition of qualifications on a voluntary basis' (EC, 2020q). Currently the EU directive on the recognition of professional qualifications (EU, 2005) does not explicitly target construction workers, as they depend on national policy. Further EU support to Member States for reinforcing qualification recognition and facilitating the mobility of professionals in the construction and related sectors could help to address the skilled workforce gap (European Construction Sector Observatory, 2018).

As part of the REPowerEU chapters in recovery and resilience plans, EU Member States can include 'an accelerated requalification of the workforce towards green and related digital skills' (EU, 2023i). Moreover, building capacity of local authorities to streamline permitting for renewable energy projects is one of the RRF flagships providing technical support to the EU Member States (EC, 2022ak). The RED III aims at facilitating mutual recognition of installer skills, identifying skilled workforce shortages, and creating a database of trained certified installers of renewable technologies and demand response and storage systems (EU, 2023f). The database is expected to help increase public trust in such interventions. The REPowerEU plan (EC, 2022m) dedicates special attention to skills for the hydrogen economy, announcing a launch of a large project in this area supported by EU funding streams. There are positive signals under the EU action plan on digitalising the energy system (EC, 2022k), that incites the Member States to use the funds through available EU programmes to support upskilling and reskilling of the workforce for the digitalisation of the energy value chain, including through university-level upskilling programmes and partnerships.

15.3 Fossil fuel workers and just transition

Training and reskilling is also important to support and provide opportunities to those who may be negatively affected by the transition, such as coal and other fossil gas workers. While the EU provides support under the Just Transition Fund, doubts remain over whether the design and ambition of this mechanism fully reflect the scale of transition in some regions and sectors.

Employment increases and skills shortages in these sectors contrasts with declining employment in sectors negatively impacted by the transition, particularly the coal sector. Based on industry data between 2010 and 2018, coal jobs in the EU decreased by 32 % from 239 400 to 161 930 (JRC, 2021d), and employment in the 'mining of coal and lignite' sector is projected to fall by a further 89 % under the Fit for 55 targets. Such jobs, including coal mining, are estimated to cover around 5 % of employment in the EU (EC, 2022aj). While employment growth in other sectors could provide job opportunities for coal or other fossil fuel workers, there are substantial challenges that must be overcome to ensure that these workers can avail of these opportunities. These include a relative dissimilarity between existing job profiles and those required in other sectors, low participation in education/training schemes, and spatial mismatches between where jobs are gained and lost (Borgonovi et al., 2023). These challenges in the coal sector are compounded by more general trends, where the shift to renewable energy is associated with declining demand for manual workers and greater demand for technical and professional workers (Marin and Vona, 2019).

In line with the principles of a just transition, efforts to phase out fossil fuels must be accompanied by investments in workers and communities that are likely to experience a contraction in labour demand or significant structural change. However, the geographic concentration of the coal sector often requires a broader focus: since renewable jobs are often outside of coal regions, a straightforward reskilling and reemployment of coal workers in renewable energy sector may not be possible, and a just transition may also require support for broader economic and regional development (IPCC, 2022g). Therefore, the effectiveness of these investments depends on strong social dialogue processes and coordination

between government, economic actors and civil society; necessary not only from an equity perspective and to ensure that appropriate support is provided to communities, but also to maintain wider public support for the transition (Anadón et al., 2022; ILO, 2015; IPCC, 2022g).

At the EU level, the Just Transition Fund (EU, 2021b) provides retraining opportunities to workers who bear the costs of the structural transformation (Marin and Vona, 2019), particularly coal, shale and peat workers. However, the ECA has found that EU support to coal regions to date has had a limited focus and impact on job creation, and observed lower levels of participation in training initiatives among affected workers than initially targeted. They also highlighted weaknesses in data collection and impact measurement, which made it difficult to assess the impact of investments (ECA, 2022a). These challenges also reflect some of the issues discussed in Chapter 11 (Whole of Society Approach) and Chapter 14 (Climate Governance), particularly the lack of systematic assessments of the socioeconomic impacts of EU climate policies and weaknesses in participatory decision-making. For example, an evaluation of the Just Transition Fund, taking into account lessons learned from its predecessor Initiative for Coal Regions in Transition, found remaining weaknesses in its current design and targeting. In particular, the study highlighted the eligibility criteria for potential Just Transition Fund projects and stakeholders, the restrictive nature of which was found to be 'inadequate for determining the worst-off' in the transition; insufficient and volatile funding; and differences in administrative capacity between regions as limiting factors of the current Just Transition Fund (Moesker and Pesch, 2022). As a result, there are doubts about whether the design and ambition of these initiatives match the scale of the transition required.

Transition schemes for workers in the fossil gas sector are also largely still absent at the EU level. The gas industry, along with public service and trade unions, have recently called to create 'momentum that ensures a Just Transition for gas workers across Europe' (Eurogas et al., 2023). The EU should address the declining fossil gas activities and any resulting employment impacts (Cedefop, 2023) in an open and proactive fashion (in line with the findings and recommendations regarding gas in chapter 4), and aim to create upskilling and reskilling opportunities for high-quality jobs in non-fossil fuel (and preferably even energy transition) activities.

15.4 Public administration

Effective and efficient public administration is crucial for the implementation of climate policies. This rapid policy development can place additional demands on member states' public administrations, while skills and capacity shortages also constrain public climate investments.

Effective and efficient public administration is an enabler of the transition to a climate-neutral society, and the policies discussed throughout this report will place significant demands on public administration at the local, national and European levels: from energy and infrastructure permitting (Chapter 4 'Energy supply') and spatial planning policies (Section 7.5 under 'Enabling condition: urban and spatial planning'); to public investment, procurement (Chapter 12) and climate governance (Chapter 14). Increased funding for climate-related investments will also create additional demands on the public sector to plan and deliver projects, meaning that capacity or skills shortages can constrain the effectiveness of these investments. These challenges have already been highlighted in relation to local government: for example, 69 % of municipalities in the EIB's 2022 Municipalities Survey reported skills shortages to be a barrier to their investments in climate mitigation and adaptation infrastructure, with particular shortages highlighted in relation to environmental and climate assessment, engineering, legal and digital skills (EIB, 2023c). The European Commission has identified a need for 'a multidisciplinary approach to policymaking, strong coordination and planning capacities across all levels of public administration' (EC, 2023o), while other studies have highlighted skills shortages in the planning systems and legal systems as barriers to implementing climate investments and policies (EGFSN, 2021).

The EU provides direct support to some Member States for capacity building and skills in public administration under the cohesion policy, and more widely via the Technical Support Instrument (TSI), which responds to requests from member states with tailored advice and technical support for climate and other reform policies. Member states can also request funding for public sector skills and digitalisation projects under various funding streams, including the RRF, Horizon Europe and the Digital Europe Programme (EC, 2021aj). The European Commission's recent communication on 'Enhancing the European Administrative Space' (ComPAct) also aims to support member states in enhancing capacity in public administration, and contains a pillar dedicated to supporting public administration in delivering on climate policies (e.g. provision of technical support and guidance, disseminating best practices, exchange and peer-learning opportunities for administrators) (EC, 2023o), although the impact of these proposals has yet to be assessed.

15.5 Agriculture

Although the CAP 2023–2027 contains more ambitious targets for training and knowledge exchange among farm managers than its predecessor, available insight so far shows that more effort is needed to increase interest in and uptake of these initiatives. With greater emphasis on sustainability, the Farm Advisory System can support farm managers in the transition to net zero.

The transition to more sustainable farming systems and the implementation of mitigation practices (see Chapter 8 'Agriculture') will require investment in skills, training and innovation for farmers and agricultural workers. Agriculture remains a large employer within the EU, with 8.7 million people working directly in agricultural production in 2020 (Eurostat, 2022b), although employment in agriculture has been falling since 2005. The agricultural workforce's unique demographic and socioeconomic characteristics presents additional challenges in the sector's resilience and ability to adapt to the transition. The agricultural workforce is older than sectors, with just 11 % of farm managers under the age of 40 in 2020. There is also a significant gender imbalance, and only 32 % of farm managers in 2020 were women (27 % of farmers under the age of 30) (EC, 2023bj). Finally, just 32 % of farm managers in 2016 have received agricultural training (9 % with full agricultural training), although this percentage represents an increase over the previous decade (EC, 2020n).

As one of its objectives, the 2023–2027 CAP recognises that *'*support for knowledge exchange, training, advice and innovation is key for securing smart and sustainable agriculture, forestry and rural areas', and the current CAP builds on the instruments established in the 2014–2020 period, particularly the requirement for Member States to put in place Farm Advisory Systems to provide hands-on advice and training on a range of financial, technical and environmental topics. The CAP continues to promote the agricultural European Innovation Partnerships (EIP-AGRI), supplemented by funding from Horizon Europe. This supports collaborations between farmers, foresters, scientists and rural businesses aimed at developing and testing innovative solutions to socioeconomic and environmental challenges, including the development/adoption of sustainable farming practices and agri-environment schemes. The European CAP Network has been established alongside these as a forum to disseminate research, examples of best practice and lessons learned from EIP-AGRI projects across Europe. The European Commission's review of Member States' CAP strategic plans for 2023–2027 highlighted and welcomed member states' ambition for fostering the agricultural knowledge and innovation systems: 6 million targeted participants in different knowledge and training initiatives over the period (up from the previous target of 2.9 million), as well as a threefold increase in agricultural European Innovation Partnerships to 6 600 (EC, 2023b). Within the wider sector, the Pact for Skills partnership for the agri-food industry was launched in 2022 to address skills challenges in the wider agri-food sector. These challenges include global value chain disruptions, increasing competition, climate change, urbanisation, changing consumer demands, and generational renewal (EC, 2022ah).

However, the European Commission's evaluation of the previous CAP programme highlights several challenges that may continue into the current implementation period. Due to slow implementation of the previous programme, just 23 % of the amount planned for knowledge exchange and training measures in the previous plan was spent by 2020, while only 1.22 million farmers (42 % of the 2020 target) ultimately availed of these initiatives. Interest in training was reportedly low among farmers, with the time and opportunity cost of participation identified as a major barrier to uptake, along with poor awareness or promotion of available initiatives. In particular, the evaluation highlighted very limited engagement by "hard-to-reach" farmers with these initiatives, a category which often includes the types of smaller and less-profitable farms that are least resilient in the transition to net zero (EC, 2022e). Other authors have similarly identified long working hours among European farmers as a barrier to their participation in training, as well as to their willingness to adopt new farming practices or additional mitigation measures (Murphy, 2022).

While the European Commission's review of CAP strategic plans for 2023–2027 (EC, 2023b) welcomes the emphasis from member states on practical and interactive knowledge exchange mechanisms (e.g. on-farm demonstrations, peer-to-peer learning, EIP-AGRI projects etc.), it expressed 'doubts on whether the overall level of support planned by Member States is in line with the increased ambition on knowledge sharing and innovation'. Upskilling in the sector, particularly in relation to climate resilience and adaptation, will require a more concerted effort to reach and engage farmers, particularly those "hard-to-reach" farmers who have not traditionally engaged with education and training systems before. As identified by the European Commission's evaluation of the previous programme, there also needs to be increased training of farm advisors themselves, particularly with regard to climate adaption and mitigation practices required in the transition to net zero.

15.6 Summary table

Table 22 Policy consistency summary – labour, skills and capacity building

Policy gaps	– Implementation of education and training schemes is mainly a national competence, although some policy gaps remain at a European level, particularly with regard to workforce mobility and mutual recognition of qualifications in the construction sector – Transition schemes for workers in the fossil gas sector are largely still absent at the EU level.
Ambition gaps	– The EU has put in place a Just Transition Fund to support regions and occupations whose workforce will be negatively impacted by the transition; however, experience of previous reskilling initiatives suggests that issues with eligibility criteria, funding and limited systemic measurement of outcomes can limit their impact.
Implementation gaps	– Low participation in education/training schemes in some sectors (e.g. buildings, fossil fuel regions, agriculture) also limits the opportunities to develop skills and enhance knowledge exchange relevant to the transition

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Abbreviations

8th EAP	8th Environment Action Programme
ACER	European Union Agency for Cooperation of Energy Regulators
Advisory Board	the European Scientific Advisory Board as established under the European Climate Law
AR6	6th Assessment Report of the IPCC
BECCS	bioenergy with carbon capture and storage
BEV	battery electric vehicle
BNEF	Bloomberg New Energy Finance
CAP	common agricultural policy
CBAM	Carbon Border Adjustment Mechanism
CCfD	carbon contract for difference
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCU/CCS	carbon capture and utilisation/storage
CDR	carbon dioxide removals
CEAP 1	The circular economy action plan of 2015
CEAP 2	The circular economy action plan of 2020
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP26	26th Conference of the Parties under the UNFCCC
CRF	common reporting format used for the GHG inventories reported to the UNFCCC
CSP	CAP Strategic Plan
DACCS	direct air carbon capture and storage
DSO	distribution system operator
EASAC	European Academies Science Advisory Council
ECA	European Court of Auditors
ECB	European Central Bank
EEA	European Environment Agency
EED	Energy Efficiency Directive
EIB	European Investment Bank
EIP-AGRI	agricultural European Innovation Partnerships
EPBD	Energy Performance of Buildings Directive
EPC	energy performance certificate
ESG	environmental, social and governance
ESR	Effort Sharing Regulation
ETD	Energy Taxation Directive
EU	European Union
EU ETS	EU Emissions Trading System
EU ETS 1	The EU ETS for stationary installations (chapter III of Directive 2003/87/EC)
EU ETS 2	The EU ETS for buildings, road transport and additional sectors (chapter IVa of Directive 2003/87/EC)
FAOSTAT	Corporate Statistical Database of the UN FAO
F-gas	fluorinated gas

GAEC	good agricultural environmental condition
GDP	gross domestic product
GHG	greenhouse gas
Gpkm	billion passenger-kilometres
Gtkm	billion tonne-kilometres
GW	Gigawatt
HDV	heavy-duty vehicle
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
ILUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
IWW	inland waterways
JRC	Joint Research Centre
kWh	kilowatt-hour
LIFE	L'instrument Financier pour l'Environnement
LTS	long-term strategy
LULUCF	land use, land use change and forestry
MFF	Multiannual Financial Framework
MSR	Market Stability Reserve
Mtoe	million tonnes of oil equivalent
N_2O	nitrous oxide
NAI	net annual increment, which represents the gross forest growth minus natural mortality
NECP	national energy and climate plan (see Governance Regulation (EU) 2018/1999)
OECD	Organisation for Economic Co-operation and Development
PCI	project of common interest
PHEV	plug-in hybrid electric vehicle
pp	percentage points
PV	photovoltaics
R & D	research and development
RD & D	research, development and deployment
RED II	the revised Renewable Energy Directive of 2018 (Directive 2018/2001/EU)
RED III	the revised Renewable Energy Directive of 2023 (Directive EU/2023/2413)
RES	renewable energy sources
RRF	Recovery and Resilience Facility
SAPEA	Science Advice for Policy by European Academies
TEN-E	Trans-European Networks for Energy
TEN-T	Trans-European networks for transport
TSC	technical screening criteria (under the EU Taxonomy)
TWh	terawatt hours
TYNDP	10-year network development plan
UN FAO	United Nations Food and Agriculture Organisation
UNFCCC	United Nations Framework Convention on Climate Change
VAT	value added tax
yr	year
ZEV	zero-emission vehicle

Bibliography

Abrell, J., et al., 2022, Optimale Zuteilung des CO2-Budgets der EU: Eine Multi-Modell-Bewertung, Kopernikus Projekt Ariadne (https://ariadneprojekt.de/media/2022/06/Ariadne-Analyse_CO2-Budget-Multi-Modell-Bewertung_Juni2022.pdf).

ACCC, 2021, Case ACCC/C/2015/128 European Union, (https://unece.org/env/pp/cc/accc.c.2015.128_european-union).

Accenture, 2022, From Disruption to Reinvention – The future of supply chains in Europe (https://www.accenture.com/us-en/insights/strategy/ukraine-future-supply-chains-europe).

ACEA, 2023, 'New car registrations: +17.2% in April, battery electric 11.8% market share' (https://www.acea.auto/pc-registrations/new-car-registrations-17-2-in-april-battery-electric-11-8-market-share/#:~:text=Despite%20a%204.3%25%20growth%20in,year%20to%207.4%25%20in%202023.) accessed 19 June 2023.

ACER, 2022a, Future Regulatory Decisions on Natural Gas Networks: Repurposing, Decommissioning and Reinvestments, No ACER/OP/DO/13/2017/LOT 2/RFS 05, Agency for the Cooperation of Energy Regulators (https://www.acer.europa.eu/Media/News/Documents/Future%20Regulation%20of%20Natural%20Gas%20Networks%20-%20Final%20Report%20DNV.pdf).

ACER, 2022b, Security of EU electricity supply in 2021: Report on Member States approaches to assess and ensure adequacy, European Union Agency for the Cooperation of Energy Regulators (https://acer.europa.eu/Publications/ACER_Security_of_EU_Electricity_Supply_2021.pdf).

ACER, 2023a, DECISION No 04/2023 OF THE EUROPEAN UNION AGENCY FOR THE COOPERATION OF ENERGY REGULATORS of 27 February 2023 on the European Resource Adequacy Assessment for 2022, (https://www.acer.europa.eu/Individual%20Decisions/ACER_Decision_04-2023_ERAA_2022.pdf).

ACER, 2023b, Report on Investment Evaluation, Risk Assessment and Regulatory Incentives for Energy Network Projects, European Union Agency for the Cooperation of Energy Regulators (https://acer.europa.eu/Publications/ACER_Report_Risks_Incentives.pdf).

ACER and CEER, 2022, Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2021 Energy Retail and Consumer Protection Volume, European Union Agency for the Cooperation of Energy Regulators and the Council of European Energy Regulators (https://www.acer.europa.eu/Publications/MMR_2021_Energy_Retail_Consumer_Protection_Volume.pdf).

ADEME, et al., 2023, 'Odyssee-Mure' (https://www.odyssee-mure.eu/).

Agora Energiewende, 2023, 'Der CO2-Preis für Gebäude und Verkehr. Ein Konzept für den Übergang vom nationalen zum EU-Emissionshandel' (https://www.agora-energiewende.de/fileadmin/Projekte/2023/2023-26_DE_BEH_ETS_II/A-EW_311_BEH_ETS_II_WEB.pdf).

Akbari, H., et al., 2016, 'Local climate change and urban heat island mitigation techniques – The state of the art', Journal of Civil Engineering and Management 22(1), pp. 1-16 (DOI: 10.3846/13923730.2015.1111934).

Ali, U., et al., 2020, 'A data-driven approach to optimize urban scale energy retrofit decisions for residential buildings', Applied Energy 267, p. 114861 (DOI: 10.1016/j.apenergy.2020.114861).

Anadón, L. D., et al., 2017, 'Integrating uncertainty into public energy research and development decisions', Nature Energy 2(5), p. 17071 (DOI: 10.1038/nenergy.2017.71).

Anadón, L. D., et al., 2022, Ten Principles for Policy Making in the Energy Transition, Cambridge, UK (https://eeist.co.uk/eeist-reports/ten-principles-for-policy-making-in-the-energy-transition/).

Andersson, J. J., 2019, 'Carbon Taxes and CO2 Emissions: Sweden as a Case Study', American Economic Journal: Economic Policy 11(4), pp. 1-30 (DOI: 10.1257/pol.20170144).

Andor, M. A. and Fels, K. M., 2018, 'Behavioral Economics and Energy Conservation – A Systematic Review of Non-price Interventions and Their Causal Effects', Ecological Economics 148, pp. 178-210 (DOI: 10.1016/j.ecolecon.2018.01.018).

Association négaWatt, 2022, 'The material impacts of an energy transition based on sufficiency, efficiency, and renewables', (https://www.negawatt.org/IMG/pdf/220608_ecee_the-material-impacts-of-an-energy-transition-based-on-sufficiency-efficiency-and-renewables.pdf).

Augusto, L. and Boča, A., 2022, 'Tree functional traits, forest biomass, and tree species diversity interact with site properties to drive forest soil carbon', Nature Communications 13(1), p. 1097 (DOI: 10.1038/s41467-022-28748-0).

Axelsson, K., et al., 2023, Green Public Procurement: a lever for mitigating European greenhouse gas emissions, Stockholm Environment Institute https://doi.org/10.51414/sei2023.013

Baccianti, C., 2023, 'EU Climate Funding Tracker', Agora, (https://www.agora-energiewende.org/data-tools/eu-climate-funding-tracker) accessed 25 June 2023.

Bakkaloglu, S., et al., 2022, 'Methane emissions along biomethane and biogas supply chains are underestimated', One Earth 5(6), pp. 724-736 (DOI: 10.1016/j.oneear.2022.05.012).

Baldino, C. and Searle, S., 2021, Changes to the Renewable Energy Directive revision and ReFuel EU proposals: Greenhouse gas savings and costs in 2030, ICCT Briefing, International Council on Clean Transportation (Changes to the Renewable Energy Directive revision and ReFuel EU proposals: Greenhouse gas savings and costs in 2030).

Barbosa, R. and Skipka, S., 2019, 'Tax housing or land?: distributional effects of property taxation in Germany', Tax housing or land?: distributional effects of property taxation in Germany. Working Paper, CESifo Working Paper, 2019/8039.

Barkhausen, R., et al., 2022, 'Review and Analysis of Ecodesign Directive Implementing Measures: Product Regulations Shifting from Energy Efficiency towards a Circular Economy', Sustainability 14(16), p. 10318 (DOI: 10.3390/su141610318).

Barnes, J., et al., 2022, 'Energy communities as demand-side innovators? Assessing the potential of European cases to reduce demand and foster flexibility', Energy Research & Social Science 93, p. 102848 (DOI: 10.1016/j.erss.2022.102848).

Basma, H. and Rodriguez, F., 2021, 'Alternative fuels infrastructure in Europe: electric trucks and buses can't wait another decade' (https://theicct.org/alternative-fuels-infrastructure-in-europe-electric-trucks-and-buses-cant-wait-another-decade/) accessed 4 July 2023.

Becker, B., 2015, 'Public R&D Policies and Private R&D Investment: A Survey of the Empirical Evidence', Journal of Economic Surveys 29(5), pp. 917-942 (DOI: 10.1111/joes.12074).

Berndes, G., et al., 2016, Forest biomass, carbon neutrality and climate change mitigation, From Science to Policy, European Forest Institute https://doi.org/10.36333/fs03

Berndes, G., et al., 2022, The use of forest biomass for climate change mitigation: dispelling some misconceptions, IEA Bioenergy (https://www.ieabioenergy.com/wp-content/uploads/2020/08/The-use-of-biomass-for-climate-change-mitigation-dispelling-some-misconceptions-August-2020-Rev1.pdf).

Bernstein, M. J., et al., 2022, 'The Societal Readiness Thinking Tool: A Practical Resource for Maturing the Societal Readiness of Research Projects', Science and Engineering Ethics 28(1), p. 6 (DOI: 10.1007/s11948-021-00360-3).

Berrill, P., et al., 2021, 'Linking Housing Policy, Housing Typology, and Residential Energy Demand in the United States', Environmental Science & Technology 55(4), pp. 2224-2233 (DOI: 10.1021/acs.est.0c05696).

Bertoldi, P., et al., 2021, 'How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU', WIREs Energy and Environment 10(1) (DOI: 10.1002/wene.384).

Bertoldi, P., 2022, 'Policies for energy conservation and sufficiency: Review of existing policies and recommendations for new and effective policies in OECD countries', Energy and Buildings 264, p. 112075 (DOI: 10.1016/j.enbuild.2022.112075).

Bhardwaj, S. and Mostofi, H., 2022, 'Technical and Business Aspects of Battery Electric Trucks—A Systematic Review', Future Transportation 2(2), pp. 382-401 (DOI: 10.3390/futuretransp2020021).

Bibri, S. E., et al., 2020, 'Compact city planning and development: Emerging practices and strategies for achieving the goals of sustainability', Developments in the Built Environment 4, p. 100021 (DOI: 10.1016/j.dibe.2020.100021).

Birdlife Europe and EEB, 2022, Peatlands and wetlands in the new CAP: too little action to protect and restore, Policy briefing (https://www.birdlife.org/wp-content/uploads/2022/04/Analysis-Peatlands-Wetlands-CAP-strategic-plans-April2022.pdf).

Blattert, C., et al., 2023, 'Climate targets in European timber-producing countries conflict with goals on forest ecosystem services and biodiversity', Communications Earth & Environment 4(1), p. 119 (DOI: 10.1038/s43247-023-00771-z).

Bloomberg, 2023, 'Green bonds boom in first half of 2023 | Insights', Bloomberg Professional Services, 27 July 2023 (https://www.bloomberg.com/professional/blog/green-bonds-boom-in-first-half-of-2023/) accessed 24 November 2023.

BNEF, 2022, 'New Energy Outlook' (https://bnef.turtl.co/story/neo-2022/page/1?teaser=yes) accessed 12 June 2023.

BNEF, 2023, 'Energy Transition Investment Trends 2023', BNEF (https://about.bnef.com/energy-transition-investment/).

Boehm, S. et al., 2023, 'State of climate action 2023', Berlin and Cologne, Germany, San Franciso, CA and Washington, DC: Bezos Earth Fund, Climate Action Tracker, Climate Analytics, ClimateWorks Foundation,

NewClimate Institute, the United Nations Climate Change High-Level Champios, and Worls Resources Institute (https://doi.org/10.46830/irpt.23.00010.)

Bolscher, H., et al., 2019, High Level Report: CCUS in Europe, CCUS Projects Network (https://ccuszen.eu/sites/default/files/HLR%20_CCUS-in-Europe.pdf).

Borgonovi, F., et al., 2023, The effects of the EU Fit for 55 package on labour markets and the demand for skills, OECD Social, Employment and Migration Working Papers No 297 https://dx.doi.org/10.1787/6c16baac-en.

BPIE, 2017, BUILDING RENOVATION PASSPORTS: CONSUMER'S JOURNEY TO A BETTER HOME, (https://bpie.eu/wp-content/uploads/2017/09/Factsheet_D-170918_Final-2.pdf), Buildings Performance Institute Europe.

BPIE, 2023, Conceptualising iBRoad2EPC: Can Energy Performance Certificates be upgraded to include Building Renovation Passport elements?, Building Performance Institute Europe (https://www.bpie.eu/publication/conceptualising-ibroad2epc-can-epcs-be-upgraded-to-include-building-renovation-passport-elements/).

Brack, D., 2017, Woody biomass for Power and Heat. Impact on the global climate, Research Paper, Chatham House (https://www.chathamhouse.org/2017/02/woody-biomass-power-and-heat).

Brandl, P., et al., 2021, 'Beyond 90% capture: Possible, but at what cost?', International Journal of Greenhouse Gas Control 105, p. 103239 (DOI: 10.1016/j.ijggc.2020.103239).

Bremmer, J., et al., 2021, Impact assessment of EC 2030 Green Deal targets for sustainable crop production, Wageningen Economic Research. Report 2021-150. https://doi.org/10.18174/558517 .

Bruegel, 2020, 'A trillion reasons to scrutinise the Green Deal Investment Plan', (https://www.bruegel.org/blog-post/trillion-reasons-scrutinise-green-deal-investment-plan) accessed 21 November 2023

Bruegel, 2023, 'Fiscal rule legislative proposal: what has changed, what has not, what is unclear?', Bruegel | The Brussels-based economic think tank (https://www.bruegel.org/analysis/fiscal-rule-legislative-proposal-what-has-changed-what-has-not-what-unclear) accessed 21 November 2023.

Bruninx, K. and Ovaere, M., 2022, 'COVID-19, Green Deal and recovery plan permanently change emissions and prices in EU ETS Phase IV', Nature Communications 13(1), p. 1165 (DOI: 10.1038/s41467-022-28398-2).

Buchholz, W., et al., eds., 2020, Ancillary benefits of climate policy: new theoretical developments and empirical findings, Springer, Cham, Switzerland.

Buck, H. J., et al., 2023, 'Countries' long-term climate strategies fail to define residual emissions', Nature Climate Change 13(4), pp. 317-319 (DOI: 10.1038/s41558-023-01614-7).

Buratti-Donham, J., et al., 2023, 'Transforming food systems towards agroecology – a critical analysis of agroforestry and mixed farming policy in 19 European countries', Agroecology and Sustainable Food Systems 47(7), pp. 1023-1051 (DOI: 10.1080/21683565.2023.2215175).

Büscher, M., et al., 2023, 'Making Response-Ability: Societal Readiness Assessment for Sustainability Governance', Sustainability 15(6), p. 5140 (DOI: 10.3390/su15065140).

Butt, A. A., et al., 2021, 'Investigating the energy saving potential of thermochromic coatings on building envelopes', Applied Energy 291, p. 116788 (DOI: 10.1016/j.apenergy.2021.116788).

Campos, I., et al., 2020, 'Regulatory challenges and opportunities for collective renewable energy prosumers in the EU', Energy Policy 138, p. 111212 (DOI: 10.1016/j.enpol.2019.111212).

Cedefop, 2023, Skills in transitions: the way to 2035., European Centre for the Development of Vocational Training., LU (https://data.europa.eu/doi/10.2801/438491).

CEFIC, 'Low-carbon technologies projects' (https://cefic.org/low-carbon-projects-map/) accessed 27 July 2023.

Cembureau, 2023, Activity report 2022 (https://www.cembureau.eu/media/m3jcyfre/cembureau-activity-report-2022-light.pdf).

Charlin, V., et al., 2022, 'ESG ratings: an industry in need of a major overhaul', Journal of Sustainable Finance & Investment 0(0), pp. 1-19 (DOI: 10.1080/20430795.2022.2113358).

Chiappinelli, O., et al., 2021, 'A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions', Climate Policy 21(10), pp. 1328-1346 (DOI: 10.1080/14693062.2021.1922340).

Christensen, A., 2021, Transportation Carbon Intensity Targets for the European Union - Road and Aviation sectors., Report for the International Council on Clean Transport (https://theicct.org/wp-content/uploads/2021/12/GAMS-EU-fuels-modeling-consultant-report-Aug2021.pdf).

CINEA, 2021, 'Connecting Europe Facility 2021-2027 adopted', European Climate, Infrastructure and Environment Executive Agency, 20 July 2021, Brussels (https://cinea.ec.europa.eu/news-events/news/connecting-europe-facility-2021-2027-adopted-2021-07-20_en) accessed 10 January 2024.

CINEA, EC, 2023, Innovation Fund (INNOVFUND) Call for proposals Innovation Fund call for Large-Scale Projects (INNOVFUND-2022-LSC), (https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/innovfund/wp-call/2022/call-fiche_innovfund-2022-lsc_en.pdf).

Citizens' Observatory for Green Deal Financing, 2023, No recovery without citizens. Why public involvment is key to Europe's green transformation. (https://counter-balance.org/uploads/files/2023_06_20_No-recovery-without-citizens_why-public-involvement-is-key-to-Europes-green-transformation.pdf).

Civil society organisations, 2023, Public Participation in Climate Policies; NECP revision process, (https://caneurope.org/content/uploads/2023/04/CSO-Letter-Public-Participation-NECPs.pdf).

Claeys, G. and et al., 2023, The rising cost of European Union borrowing and what to do about it, No Policy Brief 12/2023, Bruegel (https://www.bruegel.org/sites/default/files/2023-06/PB%2012%202023.pdf).

Clausing, K. A., et al., 2023, How an international agreement on methane emissions can pave the way for enhanced global cooperation on climate change, (https://www.piie.com/sites/default/files/2023-06/pb23-7.pdf), Peterson Institute for International Economics.

Cleantech for Europe, 'EU Cleantech Annual Briefing 2022' (https://www.cleantechforeurope.com/publications/cleantech-annual-briefing-2022) accessed 16 November 2023.

ClientEarth, 2023, Access to justice in State aid matters in EU Member States Where do NGOs stand? (https://www.clientearth.org/media/x4javzkp/clientearth-study-access-to-justice-in-state-aid-matters-in-eu-member-states-where-do-ngos-stand.pdf).

Cludius, J., et al., 2020, 'Ex-post investigation of cost pass-through in the EU ETS - an analysis for six industry sectors', Energy Economics 91, p. 104883 (DOI: 10.1016/j.eneco.2020.104883).

Copernicus and ECMWF, 2023, 'Global carbon dioxide and methane monitoring' (https://atmosphere.copernicus.eu/ghg-services).

CoR, 2023a, Local and regional authorities in the governance of the energy union, European Committee of the Regions, Commission for the Environment, Climate Change and Energy, (https://cor.europa.eu/en/engage/studies/Documents/Local%20and%20regional%20authorities%20in%20the%20governance%20of%20the%20energy%20union/LRAs%20in%20energy%20governance_draft%20study%20with%20cover.pdf).

CoR, 2023b, Towards a multilevel Green Deal governance: the revision of the Governance of the Energy Union and Climate Action Regulation - draft opinion, Opinion Number CDR 903/2023, European Committee of the Regions.

Council and Parliament of the EU, 2023a, 'Farm Sustainability Data Network: Council and Parliament reach provisional political agreement' (https://www.consilium.europa.eu/en/press/press-releases/2023/06/29/farm-sustainability-data-network-council-and-parliament-reach-provisional-political-agreement/) accessed 30 November 2023.

Council and Parliament of the EU, 2023b, 'Industrial emissions: Council and Parliament agree on new rules to reduce harmful emissions from industry and improve public access to information' (https://www.consilium.europa.eu/en/press/press-releases/2023/11/29/industrial-emissions-council-and-parliament-agree-on-new-rules-to-reduce-harmful-emissions-from-industry-and-improve-public-access-to-information/) accessed 3 December 2023.

Council and Parliament of the EU, 2023c, Press release: Council and Parliament strike deal on energy efficiency directive (https://www.consilium.europa.eu/en/press/press-releases/2023/03/10/council-and-parliament-strike-deal-on-energy-efficiency-directive/) accessed 15 May 2023.

Council of the EU, 2015, Council Regulation (EU) 2015/1589 of 13 July 2015 laying down detailed rules for the application of Article 108 of the Treaty on the Functioning of the European Union (codification) (OJ L 248, 24.9.2015, pp. 9–29).

Council of the EU, 2023a, Climate action: Council and Parliament reach deal on new rules to cut methane emissions in the energy sector, (https://www.consilium.europa.eu/en/press/press-releases/2023/11/15/climate-action-council-and-parliament-reach-deal-on-new-rules-to-cut-methane-emissions-in-the-energy-sector/#:~:text=The%20regulation%20introduces%20new%20requirements,and%20limiting%20venting%20and%20flaring.).

Council of the EU, 2023b, Council formally adopts 15% gas demand reduction target, Council of the European Union (https://www.consilium.europa.eu/en/press/press-releases/2023/03/30/council-formally-adopts-15-gas-demand-reduction-target/).

Council of the European Union, 2021, Council Resolution on a strategic framework for European cooperation in education and training towards the European Education Area and beyond (2021-2030), (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021G0226(01)).

Cremins, A. and Kevany, L., 2018, 'An introduction to the implementation of Green Budgeting in Ireland', Staff Paper, Irish Government Economic & Evaluation Service.

Creutzig, F., et al., 2022, 'Demand-side solutions to climate change mitigation consistent with high levels of well-being', Nature Climate Change 12(1), pp. 36-46 (DOI: 10.1038/s41558-021-01219-y).

CRS, 2022, Inflation Reduction Act Methane Emissions Charge: In Brief, Congressional Research Service (https://crsreports.congress.gov/product/pdf/R/R47206#:~:text=The%20IRA%20methane%20charge%20applies,including%20methane%2C%20to%20EPA's%20GHGRP.).

D'Agostino, D., et al., 2021a, 'Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe', Energy Strategy Reviews 36, p. 100680 (DOI: 10.1016/j.esr.2021.100680).

D'Agostino, D., et al., 2021b, 'Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe', Energy Strategy Reviews 36, p. 100680 (DOI: 10.1016/j.esr.2021.100680).

Darvas, Z. and Wolff, G. B., 2023, 'A Green Fiscal Pact for the EU: increasing climate investments while consolidating budgets', Climate Policy 23(4), pp. 409-417 (DOI: 10.1080/14693062.2022.2147893).

De Beule, F., et al., 2022, 'The pollution haven effect and investment leakage: The case of the EU-ETS', Economics Letters 215, p. 110536 (DOI: 10.1016/j.econlet.2022.110536).

De Oliveira Garcia, W., et al., 2018, 'Increasing biomass demand enlarges negative forest nutrient budget areas in wood export regions', Scientific Reports 8(1), p. 5280 (DOI: 10.1038/s41598-018-22728-5).

De Vos, B., et al., 2015, 'Benchmark values for forest soil carbon stocks in Europe: Results from a large scale forest soil survey', Geoderma 251-252, pp. 33-46 (DOI: 10.1016/j.geoderma.2015.03.008).

Delarue, J. and Bechtel, S. D., 2021, 'Access to justice in State aid: how recent legal developments are opening ways to challenge Commission State aid decisions that may breach EU environmental law', ERA Forum 22(2), pp. 253-268 (DOI: 10.1007/s12027-021-00665-7).

Delbeke, J. and Vis, P., 2019, Towards a Climate-Neutral Europe: Curbing the Trend, Routledge, London.

Devine-Wright, P., ed., 2015, Renewable energy and the public: from NIMBY to participation, Routledge, London.

Di Paolo, L., et al., 2022, 'Carbon Footprint of Single-Use Plastic Items and Their Substitution', Sustainability 14(24), p. 16563 (DOI: 10.3390/su142416563).

DIW, 2021, Reform der Immobilienbesteuerung: Bodenwerte belasten und Privilegien streichen. DIW Wochenbericht 27 / 2021, S. 463-470, (https://www.diw.de/de/diw_01.c.821131.de/publikationen/wochenberichte/2021_27_3/reform_der_immobilienbesteuerung__bodenwerte_belasten_und_privilegien_streichen.html), DIW Wochenbericht.

Dolphin, G., et al., 2023, 'A net-zero target compels a backward induction approach to climate policy', Nature Climate Change 13(10), pp. 1033-1041 (DOI: 10.1038/s41558-023-01798-y).

Dunlop, T., 2019, 'Mind the gap: A social sciences review of energy efficiency', Energy Research & Social Science 56, p. 101216 (DOI: 10.1016/j.erss.2019.05.026).

Dunlop, T. and Völker, T., 2023, 'The politics of measurement and the case of energy efficiency policy in the European Union', Energy Research & Social Science 96, p. 102918 (DOI: 10.1016/j.erss.2022.102918).

Duranton, G. and Puga, D., 2020, 'The Economics of Urban Density', Journal of Economic Perspectives 34(3), pp. 3-26 (DOI: 10.1257/jep.34.3.3).

EASAC, 2017, Multi-functionality and sustainability in European Union's forests, EASAC Policy Report No 32, European Academies Science Advisory Council, Halle (Saale), Germany (https://easac.eu/fileadmin/PDF_s/reports_statements/Forests/EASAC_Forests_web_complete.pdf).

EASAC, ed., 2021a, Decarbonisation of buildings: for climate, health and jobs, EASAC Secretariat, Deutsche Akademie der Naturforscher Leopoldina - German National Academy of Sciences, Halle (Saale).

EASAC, ed., 2021b, Decarbonisation of buildings: for climate, health and jobs, EASAC Secretariat, Deutsche Akademie der Naturforscher Leopoldina - German National Academy of Sciences, Halle (Saale).

EASAC, 2023, The Future of Gas, No 46, European Academies' Science Advisory Council (https://easac.eu/fileadmin/user_upload/EASAC_Future_of_Gas_Web.pdf).

EC, 2011, White Paper - Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system (COM(2011) 144 final).

EC, 2014, Horizon 2020 - work programme 2014-2015. General Annexes. G. Technology readiness levels (TRL), Extract from Commission Decision C(2014)4995 (https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf)

EC, 2015a, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — Closing the loop — an EU action plan for the circular economy (COM(2015) 614 final).

EC, 2015b, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank — a Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy COM/2015/080 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2015:80:FIN).

EC, 2016a, Commission Recommendation (EU) 2016/1318 of 29 July 2016 on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings C/2016/4392 (OJ L 208, 2.8.2016, p. 46–57).

EC, 2016b, 'Supporting climate action through the EU budget — European Commission', European Commission (https://ec.europa.eu/clima/policies/budget/mainstreaming_en) accessed 18 September 2023.

EC, 2017, 'European Battery Alliance' (https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-battery-alliance_en) accessed 26 June 2023.

EC, 2018a, Annex 2 to the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committe of the Regions. Europe on the move: Sustainable Mobility for Europe: safe, connected and clean (COM(2018) 293 final).

EC, 2018b, 'Commission legislative proposals on sustainable finance: Proposal for a regulation on disclosures relating to sustainable investments and sustainability risks and amending Directive (EU) 2016/2341', European Commission - European Commission

(https://ec.europa.eu/info/publications/180524-proposal-sustainable-finance_en) accessed 11 March 2020.

EC, 2018c, Communication from the Commission to the European Parliament; the European Council, the Council, the European Central Bank, the European Economic and Social Committee and the Committee of the Regions. Action Plan: financing sustainable growth (COM(2018) 097 final).

EC, 2018d, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank 'A clean planet for all: a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy' (COM(2018) 773 final).

EC, 2018e, In-depth analysis in support of the Commission Communication COM(2018) 773: a clean planet for all — a European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy (https://knowledge4policy.ec.europa.eu/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en).

EC, 2019a, Commission Delegated Decision (EU) 2019/1597 of 3 May 2019 supplementing Directive 2008/98/EC f the European Parliament and of the Council as regards a common methodology and minimum quality requirements for the uniform measurement of levels of food waste ((EU) 2019/1597).

EC, 2019b, Commission staff working document: evaluation of the Council directive 2003/96/EC of 27 October 2003 restructuring the Community framework for the taxation of energy products and electricity, No SWD(2019) 329 (https://taxation-customs.ec.europa.eu/news/commission-report-evaluation-energy-taxation-directive-2019-09-12_en).

EC, 2019c, Communication from the Commission. The European Green Deal (COM/2019/640 final).

EC, 2019d, 'The European Commission, European Investment Bank and Breakthrough Energy Ventures establish a new €100 million fund to support clean energy investments', 29 May 2019, Brussels (https://ec.europa.eu/commission/presscorner/detail/fr/IP_19_2770).

EC, 2019e 'Adoption of the Delegated Decision on the carbon leakage list for 2021-2030' (https://climate.ec.europa.eu/news-your-voice/news/adoption-delegated-decision-carbon-leakage-list-2021-2030-2019-02-15_en) accessed 22 November 2023a.

EC, 2020a, Commission Staff Working Document — impact assessment accompanying the document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — stepping up Europe's 2030 climate ambitions — investing in a climate neutral future for the benefit of our people (SWD(2020) 176 final — Part 1/2).

EC, 2020b, Commission Staff Working Document Impact Assessment accompanying the document Proposal for a Regulation of the European Parliament and of the Council on guidelines for trans-European energy infrastructure and repealing Regulation (EU) No 347/2013 SWD(2020) 346 final, (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12382-Trans-European-energy-infrastructure-revision-of-guidelines_en).

EC, 2020c, Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions — A hydrogen strategy for a climate-neutral Europe (COM(2020) 301 final).

EC, 2020d, Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions — An EU strategy to harness the potential of offshore renewable energy for a climate neutral future (COM(2020) 741 final).

EC, 2020e, Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions 'EU Biodiversity Strategy for 2030. Bringing nature back into our lives' (COM(2020)380 final, Brussels, 20.5.2020).

EC, 2020f, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Region 'A farm to fork strategy for a fair, healthy and environmentally friendly food system' (COM(2020) 381 final).

EC, 2020g, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A new Circular Economy Action Plan. For a cleaner and more competitive Europe (COM(2020) 98 final).

EC, 2020h, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions — A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives (COM/2020/662 final), (https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662), European Commission.

EC, 2020i, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions — an EU-wide assessment of National Energy and Climate Plans Driving forward the green transition and promoting economic recovery through integrated energy and climate planning, COM/2020/564 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1600339518571&uri=COM%3A2020%3A564%3AFIN).

EC, 2020j, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions — Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability COM/2020/474 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474).

EC, 2020k, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'Sustainable and smart mobility strategy — putting European transport on track for the future' (COM(2020) 789 final).

EC, 2020l, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions 'Powering a climate-neutral economy: An EU Strategy for Energy System Integration (COM(2020) 299 final).

EC, 2020m, 'Digital Education Action Plan (2021-2027)' (https://education.ec.europa.eu/focus-topics/digital-education/action-plan).

EC, 2020n, EU Agriculture in Numbers - Performance on the nine specific objectives of the CAP, Factsheet (https://agriculture.ec.europa.eu/system/files/2020-05/analytical-factsheet-eu-level_en_0.pdf) accessed 6 October 2023.

EC, 2020o, European Skills Agenda for sustainable competitiveness, social fairness and resilience, (https://ec.europa.eu/migrant-integration/sites/default/files/2020-07/SkillsAgenda.pdf).

EC, 2020p, Impact Assessment accompanying the document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committe and the Committee

of the Regions + Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people, No SWD(2020)176 Final (https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=SWD:2020:176:FIN) .

EC, 2020q, Pact for Skills. Report from the roundtable for the construction ecosystem., European Commission (https://ec.europa.eu/social/BlobServlet?docId=23282&langId=en).

EC, 2020r, Recommendations to the Member States as regards their strategic plan for the Common Agricultural Policy, No COM(2020) 846 final (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0846).

EC, 2020s, Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people (European Commission 2030 Target Plan and accompanying impact assessment), No COM(2020) 562 (https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=SWD:2020:176:FIN).

EC, 2021a, 'Better regulation' toolbox – November 2021 edition, European Commission, Brussels, Belgium (https://commission.europa.eu/system/files/2023-02/br_toolbox-nov_2021_en.pdf).

EC, 2021b, Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives (OJ L 442, 9.12.2021, p. 1–349).

EC, 2021c, Commission Staff Working Document: Impact Assessment Accompanying the document Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757, No SWD(2021) 601 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021SC0601).

EC, 2021d, Commission Staff Working Document - Impact Assessment Report Accompanying the document 'Proposal for a Regulation of the European Parliament and the Council amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review', No SWD(2021) 609 final, European Commission, Brussels (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD:2021:0609:FIN).

EC, 2021e, Commission Staff Working Document Better Regulation Guidelines, SWD(2021) 305 final, (https://commission.europa.eu/system/files/2021-11/swd2021_305_en.pdf).

EC, 2021f, Commission Staff Working Document. Evaluation of Regulation (EU) No 913/2010 concerning a European rail network for competitive freight (SWD(2021) 134 final).

EC, 2021g, Commission Staff Working Document Impact Assessment Report accompanying the Proposal for a Directive of the European Parliament and of the Council on energy efficiency (recast), (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12552-EU-energy-efficiency-directive-EED-evaluation-and-review_en).

EC, 2021h, Commission Staff Working Document Impact Assessment Report accompanying the Proposal for a Directive of the European Parliament and of the Council on energy efficiency (recast) SWD(2021)

623 final, (https://eur-lex.europa.eu/resource.html?uri=cellar:c20a8b93-e574-11eb-a1a5-01aa75ed71a1.0001.02/DOC_1&format=PDF).

EC, 2021i, Commission Staff Working Document: Impact Assessment Report accompanying the Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast) SWD(2021) 453, (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12910-Energy-efficiency-Revision-of-the-Energy-Performance-of-Buildings-Directive_en).

EC, 2021j, Commission Staff Working Document Impact Assessment Report accompanying the Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast) SWD(2021) 453 final PART 1/4, (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12910-Energy-efficiency-Revision-of-the-Energy-Performance-of-Buildings-Directive_en).

EC, 2021k, Communication from the Commission to the European Parliament and the Council. Action Plan to boost long distance and cross-border passenger rail. (COM(2021) 810 final).

EC, 2021l, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - EU taxonomy, corporate sustainability reporting, sustainability preferences and fiduciary duties: directing finance towards the European Green Deal (COM(2021) 188, Brussels, 21.4.2021).

EC, 2021m, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'Fit for 55: delivering the EU's 2030 climate target on the way to climate neutrality' (COM(2021) 550 final).

EC, 2021n, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions 'New EU Forest Strategy for 2030' (COM (2021)572 final).

EC, 2021o, EU code of conduct on responsible food business and marketing practices (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0846).

EC, 2021p, Horizon Europe: The EU Research & Innovation Programme 2021-2027, European Commission (https://research-and-innovation.ec.europa.eu/system/files/2022-06/ec_rtd_he-investing-to-shape-our-future_0.pdf).

EC, 2021q, Impact assessment report, accompanying the document. Proposal for a Council Directive restructuring the Union framework for the taxation of energy products and electricity (recast), No SWD(2021) 641 final (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021SC0641).

EC, 2021r, Impact Assessment Report accompanying the document Proposal for a Regulation of the European Parliament and the Council amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review, No SWD(2021) 609 final (https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=SWD:2021:609:FIN).

EC, 2021s, Inception Impact Assessment. Revision of the Combined Transport Directive, (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=PI_COM:Ares(2020)3896535).

EC, 2021t, Inception impact assessment. Sustainable food system framework initiative, (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13174-Sustainable-EU-food-system-new-initiative_en).

EC, 2021u, 'List of potential agricultural practices that eco-schemes could support' (https://agriculture.ec.europa.eu/system/files/2021-01/factsheet-agri-practices-under-ecoscheme_en_0.pdf).

EC, 2021v, 'Policy scenarios for delivering the European Green Deal' (https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en) accessed 10 August 2023.

EC, 2021w, 'Policy scenarios for delivering the European Green Deal' (https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en) accessed 23 November 2022.

EC, 2021x, Programme for the Environment and Climate Action (LIFE) Call for proposals, LIFE Clean Energy Transition (LIFE-2021-CET), (https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/life/wp-call/2021-2024/call-fiche_life-2021-cet_en.pdf).

EC, 2021y, Proposal for a Council Directive restructuring the Union framework for the taxation of energy products and electricity (recast) (COM(2021) 563 final).

EC, 2021z, Proposal for a Council Directive restructuring the Union framework for the taxation of energy products and electricity (recast)., No COM/2021/563 final (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0563).

EC, 2021aa, Proposal for a Directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652, COM/2021/557 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0557).

EC, 2021ab, Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen, COM/2021/803 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0803&qid=1640002501099).

EC, 2021ac, Proposal for a Directive of the European Parliament and of the Councilon the energy performance of buildings (recast) COM/2021/802 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52021PC0802).

EC, 2021ad, Proposal for a Regulation of the European Parliament and of the Council establishing a Social Climate Fund, COM(2021) 568 final.

EC, 2021ae, Proposal for a regulation of the European Parliament and of the Council on European green bonds (COM (2021) 391 final of 6 July 2021).

EC, 2021af, Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942, COM(2021) 805 final, (https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:805:FIN).

EC, 2021ag, Proposal for a Regulation of the European Parliament and of the Council on the internal markets for renewable and natural gases and for hydrogen (recast), COM/2021/804 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A804%3AFIN&qid=1640001545187).

EC, 2021ah, Proposal for a Regulation of the European Parliament and of the Council on Union guidelines for the development of the trans-European transport network, amending Regulation (EU) 2021/1153 and Regulation (EU) No 913/2010 and repealing Regulation (EU) 1315/2013 (COM(2021) 812 final).

EC, 2021ai, Review of the Energy Taxation Directive (ETD): Questions and Answers (https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3662).

EC, 2021aj, Supporting public administrations in EU Member States to deliver reforms and prepare for the future., Publications Office, LU.

EC, 2021ak, Urban Agenda for the EU Multi-level governance in action 2021 Update, (https://www.citiesforum2023.eu/docs/Urban/Urban%20Agenda%20for%20the%20EU%20-%20Brochure%202021.pdf).

EC, 2021al, Commission Staff Working Document Impact Assessment Report accompanying the document Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757 {COM(2021) 551 final} - {SEC(2021) 551 final} - {SWD(2021) 557 final} - {SWD(2021) 602 final}, (https://eur-lex.europa.eu/resource.html?uri=cellar:7b89687a-eec6-11eb-a71c-01aa75ed71a1.0001.01/DOC_1&format=PDF).

EC, 2021am, 'EU Mission: Climate-Neutral and Smart Cities' (https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en) accessed 8 June 2022.

EC, 2021an, 'Sustainable EU food system - new initiative', European Commission - Have your say (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13174-Sustainable-EU-food-system-new-initiative_en) accessed 30 November 2023c.

EC, 2022a, Commission Decision (EU) 2022/589 of 6 April 2022 establishing the composition and the operational provisions of setting up the Commission Energy Poverty and Vulnerable Consumers Coordination Group (OJ L 112, 11.4.2022, p. 67–72).

EC, 2022b, Commission Delegated Regulation (EU) 2022/1214 of 9 March 2022 amending Delegated Regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities (Text with EEA relevance) (OJ L).

EC, 2022c, Commission Notice on the Guidance to Member States for the update of the 2021-2030 national energy and climate plans (2022/C 495/02), (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX%3A52022XC1229%2802%29&from=EN).

EC, 2022d, Commission Recommendation on speeding up permit-granting procedures for renewable energy projects and facilitating Power Purchase Agreements C/2022/3219 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM%3AC%282022%293219&qid=1653033569832).

EC, 2022e, Commission Staff Working Document - Evaluation of the CAP's impact on knowledge exchange and advisory activities, No SWD(2022) 137 final (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/2132-EU-farm-policy-evaluation-of-its-impact-on-knowledge-exchange-and-advisory-activities_en).

EC, 2022f, Commission Staff Working Document Analysis of the national long-term renovation strategies SWD(2022) 375 final, European Commission (https://energy.ec.europa.eu/system/files/2022-12/SWD-Analysis-of-2020-LTRS.PDF).

EC, 2022g, Commission Staff Working Document Climate Mainstreaming Architecture in the 2021-2027 Multiannual Financial Framework. SWD(2022) 225 final, (https://commission.europa.eu/system/files/2022-06/swd_2022_225_climate_mainstreaming_architecture_2021-2027.pdf).

EC, 2022h, Commission Staff Working Document Impact Assessment Report Accompanying the documents Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) and Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste and Proposal for a Regulation of the European Parliament and of the Council on reporting of environmental data from industrial installations and establishing an Industrial Emissions Portal SWD(2022) 111 final, (https://environment.ec.europa.eu/publications/proposal-revision-industrial-emissions-directive_en).

EC, 2022i, Communication from the Commission – Guidelines on State aid for climate, environmental protection and energy 2022 (C/2022/481), (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022XC0218(03)), European Commission.

EC, 2022j, Communication from the Commission Temporary Crisis Framework for State Aid measures to support the economy following the aggression against Ukraine by Russia 2022/C 131 I/01.

EC, 2022k, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Digitalising the energy system - EU action plan (COM/2022/552 final).

EC, 2022l, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions — better assessing the distributional impact of Member States' policies COM/2022/494 final, European Commision (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A494%3AFIN&qid=1664539714709).

EC, 2022m, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'REPowerEU Plan' (COM(2022) 230 final of 18 May 2022).

EC, 2022n, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions — 'save gas for a safe winter', (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0360&from=EN).

EC, 2022o, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions EU Solar Energy Strategy (COM(2022)221).

EC, 2022p, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions 'REPowerEU plan' (COM (2022) 230 final of 18 May 2022).

EC, 2022q, Decision (EU) 2022/591 of the European Parliament and of the Council of 6 April 2022 on a General Union Environment Action Programme to 2030 (Decision (EU) 2022/591).

EC, 2022r, EU-US Joint Press Release on the Global Methane Pledge Energy Pathway, (https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3793).

EC, 2022s, Implementing the REPowerEU action plan: investment needs, hydrogen accelerator and achieving the bio-methane targets, No SWD(2022) 230 final, European Commission (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230).

EC, 2022t, Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) and Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste COM(2022) 156 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0156).

EC, 2022u, Proposal for a Regulation establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC (COM(2022) 142).

EC, 2022v, Proposal for a Regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC (COM(2022)142).

EC, 2022w, Proposal for a Regulation of the European Parliament and of the Council establishing a Union certification framework for carbon removals (COM(2022) 672 final).

EC, 2022x, Proposal for a Regulation of the European Parliament and of the Council laying down harmonised conditions for the marketing of construction products, amending Regulation (EU) 2019/1020 and repealing Regulation (EU) 305/2011 (COM(2022)144).

EC, 2022y, Proposal for a Regulation of the European Parliament and of the Council on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC (COM/2022/677 final).

EC, 2022z, Proposal for a Regulation of the European Parliament and of the Council on reporting of environmental data from industrial installations and establishing an Industrial Emissions Portal COM(2022) 157 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52022PC0157).

EC, 2022aa, Proposed CAP Strategic Plans and Commission obeservations. Summary overview for 27 Member States (https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans_en).

EC, 2022ab, 'Questions and answers: Guidelines on State aid for climate, environmental protection and energy 2022' (https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_566).

EC, 2022ac, Replies of the European Commission to the European Court of Auditors' Special Report 'Climate spending in the 2014-2020 EU Budget: not as high as reported'., European Commission (https://www.eca.europa.eu/Lists/ECAReplies/COM-Replies-SR-22-09/COM-Replies-SR-22-09_EN.pdf) accessed 17 November 2023.

EC, 2022ad, Report from the Commission to the European Parliament and the Council: Progress on competitiveness of clean energy technologies (COM(2022) 643 f inal).

EC, 2022ae, 'Revised EU rules on Industrial Emissions', European Commission - European Commission (https://ec.europa.eu/commission/presscorner/detail/en/QANDA_22_2239) accessed 3 December 2023.

EC, 2022af, 'September Infringements package: key decisions' (https://ec.europa.eu/commission/presscorner/detail/en/inf_23_4367) accessed 1 December 2024.

EC, 2022ag, 'Study on commitments pledged under the EU Code of Conduct on responsible food business and marketing practices' (https://food.ec.europa.eu/system/files/2023-03/f2f_sfpd_coc_report_mapping_2022.pdf).

EC, et al., 2022, Technical support for RES policy development and implementation: simplification of permission and administrative procedures for RES installations (RES simplify): interim report., Publications Office, LU.

EC, 2022ah, The Pact for Skills A Skills Partnership for the Agri-Food Ecosystem, (https://ec.europa.eu/social/main.jsp?langId=en&catId=1517&furtherNews=yes&newsId=10171).

EC, 2022ai, The possible implications of the green transition for the EU labour market., Publications Office, LU (https://data.europa.eu/doi/10.2765/583043).

EC, 2022aj, The possible implications of the green transition for the EU labour market., European Commission's Directorate-General for Economic and Financial Affairs, LU (https://data.europa.eu/doi/10.2765/583043).

EC, 2022ak, TSI 2023 Flagship Technical Support Project RENEWABLE PERMITS, (https://reform-support.ec.europa.eu/system/files/2022-05/2023%20Flagships%20Techical%20Support%20projects%20-%20rewable%20energy.pdf).

EC, 2022al, EU transport in figures: statistical pocketbook 2022., Publications Office, LU. doi:10.2832/92929
https://op.europa.eu/en/publication-detail/-/publication/f656ef8e-3e0e-11ed-92ed-01aa75ed71a1

EC, 2023a, Annual report on taxation 2023: review of taxation policies in Member States, No doi: 10.2778/982557 (https://op.europa.eu/s/y1Kk).

EC, 2023b, Approved 28 CAP Strategic Plans (2023-2027) - Summary overview for 27 member states, European Commission (DG ARD) (https://agriculture.ec.europa.eu/system/files/2023-06/approved-28-cap-strategic-plans-2023-27.pdf).

EC, 2023c, 'Buildings and construction' (https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en).

EC, 2023d, Call for evidence and public consultation launched on industrial carbon management under European Green Deal, (https://energy.ec.europa.eu/news/call-evidence-and-public-consultation-launched-industrial-carbon-management-under-european-green-2023-06-09_en).

EC, 2023e, 'CAP at a glance' (https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-glance_en) accessed 19 September 2023.

EC, 2023f, 'Carbon Border Adjustment Mechanism' (https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en) accessed 9 October 2023.

EC, 2023g, 'Carbon leakage' (https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage_en) accessed 9 October 2023.

EC, 2023h, Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin (OJ L 157, 20.6.2023).

EC, 2023i, Commission Recommendation (EU) 2023/2407 of 20 October 2023 on energy poverty C/2023/4080, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202302407), European Commission.

EC, 2023j, Commission Staff Working Document Assessment of progress towards the objectives of the Energy Union and Climate Action Accompanying the document Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Commitee of the Regions State of the Energy Union 2023 Report (pursuant to Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action) {COM(2023) 650 final}, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD%3A2023%3A646%3AFIN&qid=1698236844015).

EC, 2023k, Commission Staff Working Document. Full-length report accompanying the document Fourth Annual Report from the European Commission on CO2 Emissions from Maritime Transport (period 2018-2021) (SWD(2023) 54 final).

EC, 2023l, Commission Staff Working Document. Investment needs assessment and funding availabilities to strengthen the EU's Net-Zero technology manufacturing capacity (SWD(2023) 68 final).

EC, 2023m, Communication from the Commission Temporary Crisis and Transition Framework for State Aid measures to support the economy following the aggression against Ukraine by Russia 2023/C 101/03 (C/2023/1711), (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.C_.2023.101.01.0003.01.ENG&toc=OJ%3AC%3A2023%3A101%3ATOC), European Commission.

EC, 2023n, Communication from the Commission to the European Parliament, the Council, the European Central Bank, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank. 2023 European Semester - Spring Package (COM(2023) 600 final).

EC, 2023o, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committe of the Regions - Enhancing the European Administrative Space (ComPAct), No COM(2023) 667 final, European Commission, Brussels (https://commission.europa.eu/system/files/2023-10/Communication_Enhancing%20the%20European%20Administrative%20Space.pdf).

EC, 2023p, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. EU wide assessment of the draft updated National Energy and Climate Plans - An important step towards the more ambitious 2030 energy and climate objectives under the European Green Deal and RePowerEU (COM(2023) 796 final).

EC, 2023q, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the European Hydrogen Bank, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0156&qid=1682349760946).

EC, 2023r, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'on the European Hydrogen Bank'

(COM(2023)156 final), (https://energy.ec.europa.eu/system/files/2023-03/COM_2023_156_1_EN_ACT_part1_v6.pdf), European Commission.

EC, 2023s, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions European Wind Power Action Plan, (https://energy.ec.europa.eu/system/files/2023-10/COM_2023_669_1_EN_ACT_part1_v8.pdf), European Commision.

EC, 2023t, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions on the findings adopted by the Aarhus Convention Compliance Committee in case ACCC/C/2015/128 as regards state aid: Analysing the implications of the findings and assessing the options available {SWD(2023) 307 final}, (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52023DC0307).

EC, 2023u, Communication From the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions - A Green Deal Industrial Plan for the Net-Zero Age (COM(2023) 62 final).

EC, 2023v, 'Competitive bidding. A new tool for funding innovative low-carbon technologies under the Innovation Fund' (https://climate.ec.europa.eu/eu-action/funding-climate-action/innovation-fund/competitive-bidding_en#pilot-auction) accessed 11 August 2023.

EC, 2023w, 'Covenant of Mayors - Europe' (https://eu-mayors.ec.europa.eu/en/home) accessed 11 August 2023.

EC, 2023x, 'Energy Communities Repository' (https://energy-communities-repository.ec.europa.eu/index_en).

EC, 2023y, 'Energy Poverty Advisory Hub' (https://energy-poverty.ec.europa.eu/about-us/vision-and-mission_en).

EC, 2023z, 'EU climate target for 2040' (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13793-EU-climate-target-for-2040_en) accessed 24 August 2023.

EC, 2023aa, 'EU funding instruments for upskilling and reskilling', Employment, Social Affairs & Inclusion (https://ec.europa.eu/social/main.jsp?catId=1530&langId=en).

EC, 2023ab, European Alternative Fuels Observatory, (https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27) accessed 28 November 2023.

EC, 2023ac, European Critical Raw Materials Act, No COM(2023) 160, European Commission, Brussels, Belgium (https://single-market-economy.ec.europa.eu/publications/european-critical-raw-materials-act_en).

EC, 2023ad, 'European Social Fund Plus' (https://ec.europa.eu/european-social-fund-plus/en).

EC, 2023ae, 'European Year of Skills 2023' (https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-year-skills-2023_en).

EC, 2023af, 'Expert group on carbon removals' (https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/expert-group-carbon-removals_en) accessed 20 October 2023.

EC, 2023ag, Exploring the main barriers and action drivers for the uptake of energy communities: Take-aways from our policy workshop, European Commission, DG Energy (https://energy-communities-

repository.ec.europa.eu/energy-communities-repository-news-and-events/energy-communities-repository-news/exploring-main-barriers-and-action-drivers-uptake-energy-communities-take-aways-our-policy-workshop-2023-06-05_en).

EC, 2023ah, Green Deal Industrial Plan - Plugging the Skills Gap, Factsheet (https://op.europa.eu/en/publication-detail/-/publication/38990ae2-f07f-11ed-a05c-01aa75ed71a1?pk_campaign=OPNewsletter_June2023&pk_source=EUP) accessed 6 October 2023.

EC, 2023ai, 'Have your say: Energy Union and climate action – Review report on the Governance Regulation - results' (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13799-Energy-Union-and-climate-action-Review-report-on-the-Governance-Regulation/feedback_en?p_id=32230584).

EC, 2023aj, 'Heat pumps' (https://energy.ec.europa.eu/topics/energy-efficiency/heat-pumps_en#:~:text=EU%20Heat%20Pump%20Action%20Plan,-There%20is%20an&text=The%20action%20plan%20will%20aim,and%20fine%2Dtune%20the%20initiative.).

EC, 2023ak, 'Innovation Fund - European Commission' (https://cinea.ec.europa.eu/programmes/innovation-fund_en) accessed 10 January 2024.

EC, 2023al, Innovation Fund Auction Terms and Conditions, (https://climate.ec.europa.eu/system/files/2023-08/innovationfund_pilotauction_termsandconditions_en.pdf).

EC, 2023am, 'Looking at how to mitigate emissions from agriculture' (https://climate.ec.europa.eu/news-your-voice/news/looking-how-mitigate-emissions-agriculture-2023-11-13_en) accessed 20 November 2023.

EC, 2023an, Member States agree new ambition for expanding offshore renewable energy (news announcement) (https://energy.ec.europa.eu/news/member-states-agree-new-ambition-expanding-offshore-renewable-energy-2023-01-19_en) accessed 28 July 2023.

EC, 2023ao, Net Zero Industry Act, No COM(2023) 161 (https://single-market-economy.ec.europa.eu/publications/net-zero-industry-act_en).

EC, 2023ap, Proposal for a directive of the European Parliament and of the Council amending Council Directive 92/106/EC as regards a support framework for intermodal transport of goods and Regulation (EU) 2020/1056 of the European Parliament and the Council as regards calculation of external costs savings and generation of aggregated data (COM(2023) 702 final).

EC, 2023aq, Proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste (COM(2023) 420 final).

EC, 2023ar, Proposal for a Regulation of the European Parliament and of the Council amending Regulations (EU) 2019/943 and (EU) 2019/942 as well as Directives (EU) 2018/2001 and (EU) 2019/944 to improve the Union's electricity market design, COM(2023) 148 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0148&qid=1679410882233), European Commission.

EC, 2023as, Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020 COM/2023/160 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160).

EC, 2023at, Proposal for a Regulation of the European Parliament and of the Council on circularity requirements for vehicle design and on management of end-of-life vehicles, amending Regulations (EU) 2018/858 and 2019/1020 and repealing Directives 2000/53/EC and 2005/64/EC (COM(2023) 451 final).

EC, 2023au, Proposal for a Regulation of the European Parliament and of the Council 'on the effective coordination of economic policies and multilateral budgetary surveillance and repealing Council Regulation (EC) No 1466/97' (COM(2023) 240 final), (https://economy-finance.ec.europa.eu/system/files/2023-04/COM_2023_240_1_EN.pdf), European Commission.

EC, 2023av, Proposal for a regulation of the European Parliament and of the Council on the use of railway infrastructure capacity in the single European railway area, amending Directive 2012/34/EU and repealing Regulation (EU) No 913/210 (COM(2023) 443/2).

EC, 2023aw, Report from the Commission to the European Parliament and the Council — 2023 Report on Energy Subsidies in the EU (COM(2023) 651 final).

EC, 2023ax, Report from the Commission to the European Parliament and the Council. EU Climate Action Progress Report 2023 (COM(2023) 653 final).

EC, 2023ay, Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions — New European Bauhaus Progress Report COM(2023) 24 final, European Commission (https://new-european-bauhaus.europa.eu/system/files/2023-01/CP-003%20-%20Report%20from%20the%20Commission%20%28EN%29%20Part%201.pdf).

EC, 2023ba, Report on renovation of the national stock of residential and non-residential buildings and on nearly zero-energy buildings. Annex to the Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions State of the Energy Union Report 2023 COM(2023) 650 final (https://energy.ec.europa.eu/system/files/2023-10/COM_2023_650_2_EN_annexe_autre_acte_part1_v5.pdf).

EC, 2023bb, REPowerEU: One year later, (https://energy.ec.europa.eu/system/files/2023-05/EU_REPowerEU.pdf), European Commission.

EC, 2023bc, 'Rural Energy Community Advisory Hub' (https://rural-energy-community-hub.ec.europa.eu/index_en).

EC, 2023bd, 'Share your views: putting a price on emissions and rewarding carbon removals in the land sector' (https://climate.ec.europa.eu/news-your-voice/news/share-your-views-putting-price-emissions-and-rewarding-carbon-removals-land-sector-2023-06-27_en) accessed 6 July 2023.

EC, 2023be, Study on the critical raw materials for the EU 2023: final report., Publications Office, LU.

EC, 2023bf, Summary of the CAP Strategic Plans for 2023-2027: joint effort and collective ambition, No COM(2023) 707 final (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2023:707:FIN).

EC, 2023bg, 'The Just Transition Mechanism: making sure no one is left behind' (https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism_en).

EC, 2023bh, Union Bioenergy Sustainability Report (COM(2023) 650 final).

EC, 2023bi, 'LIFE programme - European Commission' (https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/life-programme_en) accessed 10 January 2024b.

EC, 2023bj, 'Young Farmers', Common agricultural policy - young farmers (https://agriculture.ec.europa.eu/common-agricultural-policy/income-support/young-farmers_en) accessed 6 October 2023.

EC, 2024, 'European Innovation Council' (https://eic.ec.europa.eu/index_en) accessed 10 January 2024.

EC and CINEA, 2023, PCI Transparency Platform, (https://ec.europa.eu/energy/infrastructure/transparency_platform/map-viewer/main.html) accessed 20 December, 2023.

EC DG Energy, 2023, EU Building Stock Observatory, (https://building-stock-observatory.energy.ec.europa.eu/database/) accessed 28 November 2023.

EC and EEFIG, 2022, Multiple benefits of energy efficiency investments for financial institutions: final report: October 2021., European Commission, Energy Efficiency Financial Institutions Group (EEFIG) (https://data.europa.eu/doi/10.2833/205185).

EC, Group of Chief Scientific Advisors, 2020, Towards a Sustainable Food System: moving from food as a commodity to food as more of a common good: independent expert report., Publications Office, LU (https://data.europa.eu/doi/10.2777/282386).

EC, Joint Research Centre, et al., 2021, Modelling environmental and climatic ambition in the agricultural sector with the CAPRI model: exploring the potential effects of selected farm to fork and biodiversity strategies targets in the framework of the 2030 climate targets and the post 2020 Common Agricultural Policy, Publications Office of the European Union (https://data.europa.eu/doi/10.2760/98160).

EC JRC, et al., 2022, Clean Energy Technology Observatory, Carbon capture utilisation and storage in the European union: status report on technology development, trends, value chains and markets: 2022, Joint Research Centre (https://op.europa.eu/en/publication-detail/-/publication/13eafc68-64a2-11ed-92ed-01aa75ed71a1/language-en/format-PDF/source-search).

ECA, 2016, The EU system for the certification of sustainable biofuels, Special report, European Court of Auditors (https://www.eca.europa.eu/en/publications/SR16_18).

ECA, 2020a, Energy efficiency in buildings: greater focus on cost-effectiveness still needed, Special report No 11, European Court of Auditors (https://www.eca.europa.eu/Lists/ECADocuments/SR20_11/SR_Energy_efficiency_in_buildings_EN.pdf).

ECA, 2020b, Special Report 18/2020: The EU's Emissions Trading System: free allocation of allowances needed better targeting, No 18/2020 (https://www.eca.europa.eu/en/publications?did=54392).

ECA, 2020c, Sustainable Urban Mobility in the EU: No substantial improvement is possible without Member States' commitments, Special Report No 06/2020 (https://op.europa.eu/webpub/eca/special-reports/urban-mobility-6-2020/en/#:~:text=Urban%20areas%20account%20for%2023%20%25%20of%20CO2%20emissions%20from%20transport.).

ECA, 2021, Common agricultural policy and climate: Half of EU climate spending but farm emissions are not decreasing, Special Report No 16, European Court of Auditors (https://www.eca.europa.eu/Lists/ECADocuments/SR21_16/SR_CAP-and-Climate_EN.pdf).

ECA, 2022a, EU support to coal regions Limited focus on socio-economic and energy transition, European Court of Auditors. Special report 22/2022 (https://www.eca.europa.eu/en/publications?did=62373).

ECA, 2022b, Review 01/2022: Energy taxation, carbon pricing and energy subsidies - European Court of Auditors, No Review 01/2022, European Court of Auditors, Brussels (https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=60760).

ECA, 2022c, Climate spending in the 2014-2020 EU budget - Not as high as reported, Special Report No 09/2022, European Court of Auditors, Luxembourg (https://www.eca.europa.eu/en/publications?did=61103).

ECA, 2023a, Circular Economy. Slow transition by member states despite EU action, Special report No 17/2023, European Court of Auditors (https://www.eca.europa.eu/ECAPublications/SR-2023-17/SR-2023-17_EN.pdf).

ECA, 2023b, Intermodal freight transport. EU still far from getting freight off the road, Special Report No 2023/08, European Court of Auditors.

ECA, 2023c, Special report 26/2023: The Recovery and Resilience Facility's performance monitoring framework (http://www.eca.europa.eu/en/publications/sr-2023-26).

ECA, 2023d, The EU's industrial policy on batteries: New strategic impetus needed, Special report No 15/2023 (https://www.eca.europa.eu/en/publications/SR-2023-15).

ECB, 2022, Fiscal policies to mitigate climate change in the euro area, ECB economic bulletin, issue 6/2022, European Central Bank (https://www.ecb.europa.eu/pub/economic-bulletin/articles/2022/html/ecb.ebart202206_01~8324008da7.en.html).

ECB, 2023a, Benefits and costs of the ETS in the EU, a lesson learned for the CBAM design, No 2764 (https://ideas.repec.org/p/ecb/ecbwps/20232764.html).

ECB, 2023b, 'Key ECB interest rates' (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/key_ecb_interest_rates/html/index.en.html) accessed 14 December 2023.

ECB, 2023c, 'A Kantian shift for the capital markets union' (https://www.ecb.europa.eu/press/key/date/2023/html/ecb.sp231117~88389f194b.en.html) accessed 30 October 2023.

ECE, 2021, Decision VII/8f concerning compliance by the European Union with its obligations under the Convention, (https://unece.org/sites/default/files/2021-12/Decision_VII.8f_eng.pdf), Economic Commission for Europe.

ECNO, 2023, 'Flagship Report: State of EU progress to climate neutrality. An indicator-based assessment across 13 building blocks for a climate neutral future', the European Climate Neutrality Observatory (https://www.ecologic.eu/19265)

Economidou, M., et al., 2020, 'Review of 50 years of EU energy efficiency policies for buildings', Energy and Buildings 225, p. 110322 (DOI: 10.1016/j.enbuild.2020.110322).

Ecorys, et al., 2023, Mapping and Analysis of CAP Strategic Plans Assessment of joint efforts for 2023-2027 (https://data.europa.eu/doi/10.2762/71556).

ECSO, 2020, Improving the human capital basis, European Construction Sector Observatory (https://single-market-economy.ec.europa.eu/document/download/6637d5a4-c932-4492-904d-caf5f1878264_en) accessed 28 November 2023.

Edenhofer, O., et al., 2022, 'Four ways to make the European Commission's carbon pricing proposal fitter for 55', in: Greening Europe's post-COVID-19 recovery, Bruegel, Brusselsn ISBN: 978-9-078910-53-4.

Edenhofer, O., et al., 2023, 'On the Governance of Carbon Dioxide Removal – a Public Economics Perspective', Rochester, NY (https://dx.doi.org/10.2139/ssrn.4422845).

EEA, 2019, Climate change adaptation in the agriculture sector, No 04/2019, European Environment Agency (https://www.eea.europa.eu/publications/cc-adaptation-agriculture).

EEA, 2020, 'Monitoring of CO2 emissions from passenger cars – Regulation (EU) 2019/631 — European Environment Agency, Copenhagen, Denmark' (https://www.eea.europa.eu/data-and-maps/data/co2-cars-emission-18) accessed 29 September 2020.

EEA, 2021a, Nature-based solutions in Europe: Policy, knowledge and practice for climate change adaptation and disaster risk reduction, EEA Report No 1/2021, Europe Environment Agency (https://www.eea.europa.eu/publications/nature-based-solutions-in-europe).

EEA, 2021b, The contribution of national advisory bodies to climate policy in Europe — European Environment Agency, EEA Briefing No 02/2021, European Environment Agency (https://www.eea.europa.eu/publications/the-contribution-of-national-advisory/).

EEA, 2022a, 'Building renovation: where circular economy and climate meet', European Environment Agency (https://www.eea.europa.eu/publications/building-renovation-where-circular-economy) accessed 10 October 2022.

EEA, 2022b, Cooling buildings sustainably in Europe: exploring the links between climate change mitigation and adaptation, and their social impacts, European Environment Agency (https://www.eea.europa.eu/publications/cooling-buildings-sustainably-in-europe) access 15 December 2023.

EEA, 2022c, 'Cooling buildings sustainably in Europe: exploring the links between climate change mitigation and adaptation, and their social impacts', European Environment Agency (https://www.eea.europa.eu/publications/cooling-buildings-sustainably-in-europe) accessed 28 November 2022.

EEA, 2022d, Decarbonising road transport — the role of vehicles, fuels and transport demand, EEA Report No 2/2022, EEA (https://www.eea.europa.eu/publications/transport-and-environment-report-2021).

EEA, 2022e, Energy prosumers in Europe — Citizen participation in the energy transition, Publication No 01/2022, European Envionment Agency (EEA) (https://www.eea.europa.eu/publications/the-role-of-prosumers-of).

EEA, 2022f, Methane emissions in the EU: the key to immediate action on climate change, European Environment Agency, Copenhagen, Denmark (https://www.eea.europa.eu/publications/methane-emissions-in-the-eu) accessed 5 February 2023.

EEA, 2022g, The role of (environmental) taxation in supporting sustainability transitions (https://www.eea.europa.eu/publications/the-role-of-environmental-taxation).

EEA, 2022h, Transforming Europe's food system — Assessing the EU policy mix. Report No 14/2022, European Environment Agency, Copenhagen (https://www.eea.europa.eu/publications/transforming-europes-food-system).

EEA, 2022i, Trends and projections in Europe 2022, Publication No 10/2022, European Environment Agency, Copenhagen (https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2022).

EEA, 2022j, 'Use of renewable energy for transport in Europe' (https://www.eea.europa.eu/ims/use-of-renewable-energy-for) accessed 23 June 2023.

EEA, 2022k, Zero pollution monitoring assessment, EEA Web Report No 03/2022, European Environment Agency (https://www.eea.europa.eu/publications/zero-pollution).

EEA, 2023a, Accelerating the energy efficiency renovation of residential buildings — a behavioural approach, briefing, European Environment Agency, Copenhagen, Denmark (https://www.eea.europa.eu/publications/accelerating-the-energy-efficiency/) accessed 02 December 2023.

EEA, 2023b, 'Climate and Energy in the EU' (https://climate-energy.eea.europa.eu/) accessed 15 August 2023.

EEA, 2023c, 'CO2 emissions from new passenger cars' (http://co2cars.apps.eea.europa.eu/) accessed 12 December 2023.

EEA, 2023d, 'CO2 performance emissions of new vans in Europe' (https://www.eea.europa.eu/en/analysis/indicators/co2-performance-emissions-of-new) accessed 17 September 2023.

EEA, 2023e, 'Copernicus Land Monitoring Service' (https://land.copernicus.eu/) accessed 13 March 2023.

EEA, 2023f, 'EEA greenhouse gases - data viewer' (https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer) accessed 10 August 2023.

EEA, 2023g, 'EU Emissions Trading System (ETS) data viewer' (https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1) accessed 10 August 2023.

EEA, 2023h, 'European Union CRF tables 1990-2021' (https://www.eea.europa.eu/publications/annual-european-union-greenhouse-gas-2/european-union-crf-tables-1990-2021/view) accessed 28 June 2023.

EEA, 2023i, 'Fossil fuel subsidies' (https://www.eea.europa.eu/en/analysis/indicators/fossil-fuel-subsidies) accessed 14 November 2023.

EEA, 2023j, Greenhouse gas emission intensity of electricity generation in Europe, (https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1).

EEA, 2023k, 'Greenhouse gas emissions from agriculture in Europe' (https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-agriculture) accessed 10 November 2023.

EEA, 2023l, Investments in the sustainability transition: leveraging green industrial policy against emerging constraints, EEA Briefing, European Environment Agency, Copenhagen (https://www.eea.europa.eu/publications/investments-into-the-sustainability-transition/) accessed 15 November 2023.

EEA, 2023m, 'Member States' greenhouse gas (GHG) emission projections' (https://www.eea.europa.eu/en/datahub/datahubitem-view/4b8d94a4-aed7-4e67-a54c-0623a50f48e8) accessed 9 January 2024.

EEA, 2023n, 'Share of energy consumption from renewable sources in Europe (8th EAP)' (https://www.eea.europa.eu/ims/share-of-energy-consumption-from) accessed 15 November 2023.

EEA, 2023o, The European biomass puzzle. Challenges, opportunities, and trade-offs around biomass production and use in the EU, No EEA Report 08/2023 (https://www.eea.europa.eu/publications/the-european-biomass-puzzle).

EEA, 2023p, Trends and projections in Europe 2023. EEA Report 07/2023, European Environment Agency, Copenhagen (https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2023).

EEA, 2023q, 'Use of auctioning revenues generated under the EU Emissions Trading System' (https://www.eea.europa.eu/ims/use-of-auctioning-revenues-generated) accessed 10 July 2023.

EEA, 'Mapmytree' (https://mapmytree.eea.europa.eu/) accessed 8 August 2023.

EEA and ACER, 2023a, 'Flexibility solutions to support a decarbonised and secure EU Electricity System', European Environment Agency. EEA/ACER Report 09/2023 (https://www.eea.europa.eu/en/newsroom/news/rapid-growth-in-renewables-calls).

EEA and ACER, 2023b, Flexibility Solutions to Support a Decarbonised and Secure EU Electricity System. EEA/ACER Report 09/2023 (https://www.eea.europa.eu/publications/flexibility-solutions-to-support) European Envionment Agency and European Union Agency for the Cooperation of Energy Regulators.

EEA ETC/CM, 2022, ETC/CME Report: trends and projections in the EU ETS 2022. ETC CM Report 2022/5 (https://www.eionet.europa.eu/etcs/etc-cm/products/etc-cm-report-2022-05/@@download/file/ETC%20Eionet%20report%205%202022.pdf).

EEA and Eurofund, 2021, Exploring the social challenges of low-carbon energy policies in Europe, No Briefing No 11/2021 (https://www.eea.europa.eu/publications/exploring-the-social-challenges-of).

EEFIG, 2023, Collecting and monitoring data on energy efficiency investments and financing across EU Member States and targeted economic sectors: final report. DOI number 10.2833/114382 Energy Efficiency Financial Institutions Group (EEFIG), LU (https://data.europa.eu/doi/10.2833/114382).

EEIST, 2022, 'Ten Principles for Policy Making in the Energy Transition | Department of Land Economy', EEIST flagship report (https://www.landecon.cam.ac.uk/news/eeist-project-launches-flagship-report-ten-principles-policy-making-energy-transition) accessed 7 November 2023.

EESC, 2021, Social Climate Fund, European Economic and Social Committee (https://www.eesc.europa.eu/en/our-work/opinions-information-reports/opinions/social-climate-fund) accessed 15 November 2023.

EGFSN, 2021, Skills for Zero Carbon: The Demand for Renewable Energy, Residential Retrofit and Electric Vehicle Deployment Skills to 2030, Expert Group on Future Skills Needs, Dublin, Ireland

(https://www.skillsireland.ie/all-publications/2021/5119-dete-egfsn-skills-for-zero-carbon-web_.pdf) accessed 14 November 2023.

Ehlers, T., et al., 2022, 'The pricing of carbon risk in syndicated loans: Which risks are priced and why?', Journal of Banking & Finance 136, p. 106180 (DOI: 10.1016/j.jbankfin.2021.106180).

EHPA, 2023, European heat pump market and statistics report, 2023 (https://www.ehpa.org/european-heat-pump-market-and-statistics-report-2023/).

EIB, 2023a, 'ELENA – European Local ENergy Assistance' (https://www.eib.org/en/products/advisory-services/elena/index.htm) accessed 08 December 2023.

EIB, 2023b, Investment report 2022/2023. Resilience and renewal in Europe. (https://doi.org/10.2867/307689). European Investment Bank.

EIB, 2023c, The state of local infrastructure investment in Europe: EIB municipalities survey 2022 2023., European Investment Bank, Frankfurt (https://data.europa.eu/doi/10.2867/84744).

EIT, 2024, 'European Institute of Innovation & Technology (EIT) | EIT' (https://eit.europa.eu/) accessed 10 January 2024.

Eker, S., et al., 2019, 'Modelling the drivers of a widespread shift to sustainable diets', Nature Sustainability 2(8), pp. 725-735 (DOI: 10.1038/s41893-019-0331-1).

ELA, 2023, Report on labour shortages and surpluses: 2022., European Labour Authority, LU. DOI 10.2883/50704

Energy Efficiency Watch, 2022, The missing 'why' – how narratives can improve energy efficiency and security in Europe. Key results from the Energy Efficiency Watch 4 project. (https://fedarene.org/the-missing-why-how-narratives-can-improve-energy-efficiency-and-security-in-europe-key-results-from-eew4/) accessed 04 December 2023.

EnergyCities, 2022, Human capacity in local governments: the bottleneck of the building stock transition (https://energy-cities.eu/wp-content/uploads/2022/06/EnergyCities_PolicyPaper_CapacityNeeds_EN_FINAL.pdf) accessed 30 September 2023.

ENTSO-E, 2022, European Resource Adequacy Assessment, European Network of Transmissions Systems Operators for Electricity, Brussels, Belgium. (https://www.entsoe.eu/outlooks/eraa/2022/) accessed 9 October 2023.

EP, et al., 2016, Interinstitutional Agreement between the European Parliament, the Council of the European Union and the European Commission on Better Law-Making (OJ L 123, 12.5.2016, p. 1–14) (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016Q0512(01)).

EP, 2021, Review of the Energy Taxation Directive, European Parliament Think Tank (https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2021)662636) accessed 6 October 2023.

EP, 2023, 'Procedure File: 2021/0430(CNS) | Legislative Observatory | European Parliament' (https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2021/0430(CNS)&l=en).

EPRS, 2023, Policy instruments to tackle social inequalities related to climate change (https://www.europarl.europa.eu/RegData/etudes/STUD/2023/740081/IPOL_STU(2023)740081_EN.pdf) accessed 17 October 2023.

ESABCC, 2022a, Annual work programme 2023, European Scientific Advisory Board on Climate Change (https://climate-advisory-board.europa.eu/about/description-of-the-ecl-and-the-legal-mandate/2023-work-programme-of-the.pdf/@@display-file/file).

ESABCC, 2022b, Towards a climate-neutral and climate-resilient EU energy infrastructure: advice on scenario guidelines for trans-European networks for energy + European Scientific Advisory Board on Climate Change (https://climate-advisory-board.europa.eu/reports-and-publications/towards-a-climate-neutral-and-climate-resilient-eu-energy-infrastructure-recommendations-to-acer).

ESABCC, 2023a, Aligning policy responses to rising energy prices with the long-term climate neutrality objective, European Scientific Advisory Board on Climate Change (https://climate-advisory-board.europa.eu/reports-and-publications/addressing-the-energy-crisis-while-delivering-on-eus-climate-objectives-recommendations-to-policy-makers/2023-02-07-recommendationspolicyresponsesenergycrisisclimateneutrality.pdf/@@display-file/file).

ESABCC, 2023b, Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050, European Scientific Advisory Board on Climate Change (https://climate-advisory-board.europa.eu/reports-and-publications/scientific-advice-for-the-determination-of-an-eu-wide-2040).

ESABCC, 2023c, Towards a decarbonised and climate-resilient EU energy infrastructure: recommendations on an energy system-wide cost-benefit analysis, European Scientific Advisory Board on Climate Change (https://climate-advisory-board.europa.eu/reports-and-publications/towards-a-decarbonised-and-climate-resilient-eu-energy-infrastructure-recommendations-on-an-energy-system-wide-cost-benefit-analysis).

ESPON, 2021, Cross-fertilisation of cohesion policy and spatial planning. Policy brief (https://www.espon.eu/cohesion-policy-and-spatial-planning) accessed 22 November 2023.

ETIP Wind, et al., 2021, Getting fit for 55 and set for 2050. Electrifying Europe with wind energy., ETIP Wind, Brussels, Belgium (https://etipwind.eu/publications/getting-fit-for-55/) accessed 14 December 2023.

EU, 1992, Council Directive 92/106/EEC of 7 December 1992 on the establishment of common rules for certain types of combined transport of goods between Member States (Directive 92/106/EEC).

EU, 1999, Directive 1999/62/EC of the European Parliament and of the Council of 17 June 1999 on the charging of heavy goods vehicles for the use of certain infrastructures (OJ L 187, 20.7.1999, p. 42-50).

EU, 2001, Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market (Directive 2001/77/EC).

EU, 2003, Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport (Directive 2003/30/EC).

EU, 2005, Directive 2005/36/EC of the European Parliament and of the Council of 7 September 2005 on the recognition of professional qualifications (consolidated).

EU, 2007, Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE) (OJ L 108, 25.4.2007, p. 1–14).

EU, 2009a, Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (OJ L 140, 5.6.2009, p. 114–135).

EU, 2009b, Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast) (Text with EEA relevance) (OJ L 285, 31.10.2009, p. 10–35).

EU, 2010a, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast) (OJ L 153, 18.6.2010, p. 13–35).

EU, 2010b, Regulation (EU) No 913/2010 of the European Parliament and of the Council of 22 September 2010 concerning a European rail network for competitive freight (Regulation (EU) No 913/2010).

EU, 2011, Regulation (EU) No 1227/2011 of the European Parliament and of the Council of 25 October 2011 on wholesale energy market integrity and transparency Text with EEA relevance (OJ L 326, 8.12.2011, p. 1–16).

EU, 2012, Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (OJ L 315, 14.11.2012, p. 1-56).

EU, 2013a, Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet' (OJ L 354, 28.12.2013, pp. 171-200).

EU, 2013b, Regulation (EU) No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU. (OJ L 348, 20.12.2013, p. 1-128).

EU, 2014, Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement and repealing Directive 2004/18/EC (Directive 2014/24/EU).

EU, 2016, Consolidated version of the Treaty on the Functioning of the European Union#Part Three - Union Policies and Internal Actions#Title III - Agriculture and Fisheries#Article 39 (ex Article 33 TEC) (http://data.europa.eu/eli/treaty/tfeu_2016/art_39/oj/eng).

EU, 2018a, Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (text with EEA relevance) (OJ L 150, 14.6.2018, p. 109-140).

EU, 2018b, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (OJ L 328, 21.12.2018, p. 82–209).

EU, 2018c, Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013 (OJ L 156, 19.6.2018, p. 26-42).

EU, 2018d, Regulation (EU) 2018/956 of the European Parliament and of the Council of 28 June 2018 on the monitoring and reporting of CO2 emissions from and fuel consumption of new heavy-duty vehicles ((EU) 2018/956).

EU, 2018e, Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action (OJ L 328, 21.12.2018, p. 1-77).

EU, 2019a, Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment (OJ L 155, 12.6.2019, p. 1-19).

EU, 2019b, Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast) (OJ L 158, 14.6.2019, p. 125–199).

EU, 2019c, Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles.

EU, 2019d, Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011 (OJ L 111, 25.4.2019, p. 13-53).

EU, 2019e, Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast) (OJ L 158, 14.6.2019, p. 54–124).

EU, 2019f, Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC (OJ L 198, 25.7.2019, p. 202–240).

EU, 2020, Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (OJ L 198, 22.6.2020, p. 13-43).

EU, 2021a, Regulation (EU) 2021/241 of the European Parliament and of the Council of 12 February 2021 establishing the Recovery and Resilience Facility (OJ L 57, 18.2.2021, p. 17–75).

EU, 2021b, Regulation (EU) 2021/1056 of the European Parliament and of the Council of 24 June 2021 establishing the Just Transition Fund (OJ L 231, 30.6.2021, p. 1–20).

EU, 2021c, Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality (OJ L 243, 9.7.2021, p. 1–17).

EU, 2021d, Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013 (http://data.europa.eu/eli/reg/2021/2115/oj/eng).

EU, 2022a, Commission Delegated Regulation (EU) 2022/1214 of 9 March 2022 amending Delegated Regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities

(C/2022/631), (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2022.188.01.0001.01.ENG).

EU, 2022b, Council Regulation (EU) 2022/1369 of 5 August 2022 on coordinated demand-reduction measures for gas (OJ L 206, 8.8.2022, p. 1–10).

EU, 2022c, Council Regulation (EU) 2022/2577 of 22 December 2022 laying down a framework to accelerate the deployment of renewable energy (OJ L 335, 29.12.2022, p. 36–44).

EU, 2022d, Directive (EU) 2022/362 of the European Parliament and of the Council of 24 February 2022 amending Directives 1999/62/EC, 1999/37/EC and (EU) 2019/520, as regards the charging of vehicles for the use of certain infrastructures (OJ L 69, 4.3.2022, p. 1-39).

EU, 2022e, Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure (OJ L 152, 3.6.2022, p. 45–102).

EU, 2023a, Commission Recommendation of 14 March 2023 on Energy Storage – Underpinning a decarbonised and secure EU energy system ((2023/C 103/01)).

EU, 2023b, Decision (EU) 2023/852 of the European Parliament and of the Council of 19 April 2023 amending Decision (EU) 2015/1814 as regards the number of allowances to be placed in the market stability reserve for the Union greenhouse gas emission trading system until 2030 (Text with EEA relevance) (OJ L).

EU, 2023c, Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system.

EU, 2023d, Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015-1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system (Directive (EU) 2023/959).

EU, 2023e, Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast) ((EU) 2023/1791).

EU, 2023f, Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.

EU, 2023g, Directive of the European Parliament and of the Council on energy efficiency and amending Regulation (EU) 2023/955 (recast) (2021/0203 (COD)).

EU, 2023h, 'InvestEU Fund' (https://investeu.europa.eu/what-investeu-programme/investeu-fund_en).

EU, 2023i, Regulation (EU) 2023/435 of the European Parliament and of the Council of 27 February 2023 amending Regulation (EU) 2021/241 as regards REPowerEU chapters in recovery and resilience plans and amending Regulations (EU) No 1303/2013, (EU) 2021/1060 and (EU) 2021/1755, and Directive 2003/87/EC (2023/435).

EU, 2023j, Regulation (EU) 2023/839 of the European Parliament and of the Council of 19 April 2023 Amending Regulation (EU) 2018/841 as regards the scope, simplifying the reporting and compliance rules, and setting out the targets of the Member States for 2030, and Regulation (EU) 2018/1999 as

regards improvements in monitoring, reporting, tracking of progress and review (Regulation (EU) 2023/839).

EU, 2023k, Regulation (EU) 2023/851 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition (OJ L 110, 25.4.2023, p. 5–20).

EU, 2023l, Regulation (EU) 2023/955 of the European Parliament and of the Council of 10 May 2023 establishing a Social Climate Fund and amending Regulation (EU) 2021/1060 (OJ L 130, 16.5.2023, p. 1–51).

EU, 2023m, Regulation (EU) 2023/955 of the European Parliament and of the Council of 10 May 2023 establishing a Social Climate Fund and amending Regulation (EU) 2021/1060 (OJ L 130, 16.5.2023, p. 1–51).

EU, 2023n, Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism ((EU) 2023/956).

EU, 2023o, 'Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU (Text with EEA relevance)' (https://eur-lex.europa.eu/eli/reg/2023/1804/oj) accessed 27 September 2023.

EU, 2023p, Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Regulation (EU) 2023/1805).

EU, 2023q, Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation) (Regulation (EU) 2023/2405).

EUI, 2023, 'European Urban Initiative - Who we are' (https://www.urban-initiative.eu/what-european-urban-initiative) accessed 17 October 2023.

Euractiv, 2023, 'EU food systems law to lean on green labeling, procurement' (https://www.euractiv.com/section/agriculture-food/news/eu-food-systems-law-to-lean-on-green-labelling-procurement/) accessed 6 July 2023.

EurActiv, 2023, 'Why adopting the Social Climate Fund is the right choice for the EU', www.euractiv.com (https://www.euractiv.com/section/energy-environment/opinion/why-adopting-the-social-climate-fund-is-the-right-choice-for-the-eu/) accessed 22 November 2023.

Eurofer, 2022, European Steel in Figures 2022 (https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2022/European-Steel-in-Figures-2022-v2.pdf) accessed 12 October 2023.

Eurofund, 2023, Living and working in Europe 2022., European Foundation for the Improvement of Living and Working Conditions, LU (https://data.europa.eu/doi/10.2806/65484).

Eurogas, et al., 2023, Challenges and Opportunities for Employment in the Gas Sector in the Context of the European Energy Transition: Ensuring a Just Transition for Workers (https://www.eurogas.org/wp-content/uploads/2023/01/Syndex_Final_Report_January_2023.pdf) accessed 14 September 2023.

European Construction Sector Observatory, 2018, Strengthening the Internal Market for Construction (https://single-market-economy.ec.europa.eu/document/download/71536b81-b70a-48ff-8edb-a75447548d1c_en) accessed 05 January 2024.

European Construction Sector Observatory, 2020, Improving the human capital basis, European Commission (https://single-market-economy.ec.europa.eu/document/download/6637d5a4-c932-4492-904d-caf5f1878264_en) accessed 25 November 2023.

European Parliament, 2023a, draft EP resolution on the proposal for a directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen - recast (2021/0425(COD)).

European Parliament, 2023b, 'Legislative proposal on Corporate Sustainability Due Diligence | Legislative Train Schedule', European Parliament (https://www.europarl.europa.eu/legislative-train/theme-an-economy-that-works-for-people/file-legislative-proposal-on-sustainable-corporate-governance) accessed 30 November 2023.

European Parliament, 2023c, 'Revision of Regulation (EC) No 1831/2003 on additives for use in animal nutrition (REFIT) | Legislative Train Schedule', European Parliament (https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-revisio-of-the-feed-additives-regulation) accessed 30 November 2023.

European Parliament, 2023d, 'Revision of the EU waste framework directive - textiles and food waste | Legislative Train Schedule', European Parliament (https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-revision-of-the-eu-waste-framework) accessed 1 December 2023.

European University Institute, 2022, The 5th EU electricity market reform: a renewable jackpot for all Europeans package?, (https://data.europa.eu/doi/10.2870/407931), Publications Office.

European University Institute., 2022, The role of CCUS on the EU road to climate neutrality. Policy Brief., Publications Office, LU (https://fsr.eui.eu/publications/?handle=1814/73595) accessed 14 September 2023.

Eurostat, 2013, Environmental taxes. A statistical guide, No ISSN 2315-0815 (https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-gq-13-005).

Eurostat, 2021, 'Energy intensity of GDP in chain linked volumes (2010) [NRG_IND_EI]' (https://ec.europa.eu/eurostat/databrowser/view/NRG_IND_EI__custom_930709/default/table) accessed 22 May 2021.

Eurostat, 2022a, Environmental tax statistics - detailed analysis (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Environmental_tax_statistics_-_detailed_analysis) accessed 6 October 2023.

Eurostat, 2022b, Farmers and the agricultural labour force - statistics, Eurostat (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farmers_and_the_agricultural_labour_force_-_statistics) accessed 4 September 2023.

Eurostat, 2022c, 'Gross fixed capital formation by AN_F6 asset type' (https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_an6&lang=en) accessed 18 July 2022.

Eurostat, 2023a, Circular material use rate by material type, ENV_AC_CURM (https://ec.europa.eu/eurostat/databrowser/view/ENV_AC_CURM/default/table?lang=en) accessed 28 November 2023.

Eurostat, 2023b, 'Complete energy balances (NRG_BAL_C)' (https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en) accessed 24 October 2023.

Eurostat, 2023c, 'Degree of urbanisation: background' (https://ec.europa.eu/eurostat/web/degree-of-urbanisation/background) accessed 13 March 2023.

Eurostat, 2023d, Electricity production capacities by main fuel groups and operator, NRG_INF_EPC (https://ec.europa.eu/eurostat/databrowser/view/NRG_INF_EPC/default/table?lang=en) accessed 28 November 2023.

Eurostat, 2023e, 'Energy balance visualisation tool', Energy balance visualisation tool (https://ec.europa.eu/eurostat/cache/infographs/energy_balances/enbal.html) accessed 24 April 2023.

Eurostat, 2023f, Environmental economy – statistics on employment and growth, (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Environmental_economy_%E2%80%93_statistics_on_employment_and_growth&oldid=583805#Employment_by_environmental_domain) accessed 22 July 2023.

Eurostat, 2023g, EU trade since 2002 by CPA 2.1 (DS-059268), (https://ec.europa.eu/eurostat/databrowser/view/ds-059268/legacyMultiFreq/table?lang=en) accessed 20 November 2023.

Eurostat, 2023h, Final energy consumption in the residential sector by use, EU, 2021, nrg_bal_c (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households) accessed 15 September 2023.

Eurostat, 2023i, Food waste and food waste prevention by NACE Rev. 2 activity - tonnes of fresh mass, ENV_WASFW (https://ec.europa.eu/eurostat/databrowser/view/env_wasfw/default/table?lang=en) accessed 28 November 2023.

Eurostat, 2023j, GERD by sector of performance, RD_E_GERDTOT (https://ec.europa.eu/eurostat/databrowser/product/page/rd_e_gerdtot) accessed 28 November 2023.

Eurostat, 2023k, Government deficit/surplus, debt and associated data, gov_10dd_edpt1 (https://ec.europa.eu/eurostat/databrowser/view/gov_10dd_edpt1/default/table?lang=en) accessed 14 September 2023.

Eurostat, 2023l, 'Greenhouse gas emission statistics - carbon footprints' (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_carbon_footprints) accessed 26 September 2023.

Eurostat, 2023m, 'Gross value added and income by A*10 industry breakdown' (https://ec.europa.eu/eurostat/databrowser/view/NAMA_10_A10__custom_1841738/bookmark/table?lang=en&bookmarkId=45bdc71c-47da-4f49-b799-3d8855e3ddb0) accessed 17 October 2023.

Eurostat, 2023n, HICP - monthly data (annual rate of change), PRC_HICP_MANR (https://ec.europa.eu/eurostat/databrowser/view/PRC_HICP_MANR/default/table?lang=en) accessed 28 November 2023.

Eurostat, 2023o, Inability to keep home adequately warm - EU-SILC survey, ILC_MDES01 (https://ec.europa.eu/eurostat/databrowser/view/ILC_MDES01/default/table?lang=en).

Eurostat, 2023p, Median equivalised disposable income and magnitude of social transfers (PPS per inhabitant, 2022), ILC_DI03, ILC_DI13, ILC_DI14 (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:F1Median_equivalised_disposable_income_and_magnitude_of_social_transfers_(PPS_per_inhabitant,_2022).png) accessed 28 November 2023.

Eurostat, 2023q, Quarterly greenhouse gas emissions in the EU (ENV_AC_AIGG_Q), (https://ec.europa.eu/eurostat/databrowser/view/env_ac_aigg_q/default/table?lang=en) accessed 21 November 2023.

Eurostat, 2023r, Short assessment of renewable energy sources (SHARES), (https://ec.europa.eu/eurostat/documents/38154/4956088/SUMMARY-results-SHARES_2021.xlsx/a3ec29ed-95d3-8dfd-6f2f-4acd1eafdc91?t=1673009663750) accessed 21 November 2023.

Eurostat, 2023s, Sold production, exports and imports (DS-056120), (https://ec.europa.eu/eurostat/databrowser/view/DS-056120__custom_7015045/bookmark/table?lang=en&bookmarkId=f30845e4-5f1c-467b-a26a-133f3a366f9d) accessed 16 September 2023.

Evans, N., et al., 2023, Policy consistency: What it means, how to measure it, and links with other processes., Policy Paper, Ecologic (https://www.ecologic.eu/19265) accessed 22 June 2022.

Evans, N. and Duwe, M., 2021, Climate governance systems in Europe: the role of national advisory bodies, Ecologic Institute, Berlin (https://www.ecologic.eu/sites/default/files/publication/2021/Evans-Duwe-Climate-governance-in-Europe-the-role-of-national-advisory-bodies-2021-Ecologic-Institute.pdf) accessed 22 June 2022.

Evans, S., et al., 2020, Border Carbon Adjustments and Industrial Competitiveness in a European Green Deal, Energy Policy Research Group, University of Cambridge (https://www.jstor.org/stable/resrep30378) accessed 15 October 2023.

FAO, 2020, FAO Statistics on Forestry Production and Trade, FOASTAT-Forestry (https://www.fao.org/faostat/en/#data/FO), FAOSTAT.

FAO, 2023, FAO Food Balances, (https://www.fao.org/faostat/en/#data/FBS) accessed 29 June 2023, FAOSTAT.

Fawcett, T., et al., 2019, 'Energy efficiency obligation schemes: their future in the EU', Energy Efficiency 12(1), pp. 57-71 (DOI: 10.1007/s12053-018-9657-1).

Fellmann, T., et al., 2021, 'Greenhouse gas mitigation technologies in agriculture: Regional circumstances and interactions determine cost-effectiveness', Journal of Cleaner Production 317, p. 128406 (DOI: 10.1016/j.jclepro.2021.128406).

Feng, T., et al., 2022, 'Life cycle assessment of lithium nickel cobalt manganese oxide batteries and lithium iron phosphate batteries for electric vehicles in China', Journal of Energy Storage 52, p. 104767 (DOI: 10.1016/j.est.2022.104767).

Ferrari, A., 2023, 'Is the reformed ETS fit for the new EU climate ambition?', Florence School of Regulation (https://fsr.eui.eu/is-the-reformed-emissions-trading-system-fit-for-the-new-eu-climate-ambition/) accessed 16 October 2023.

Finger, M., et al., 2021, The Governance of Rail Freight Corridors, European University Institute. DOI 10.2870/800530 (https://op.europa.eu/en/publication-detail/-/publication/96fe7ce8-8088-11eb-9ac9-01aa75ed71a1).

Forzieri, G., et al., 2022, 'Emerging signals of declining forest resilience under climate change', Nature 608(7923), pp. 534-539 (DOI: 10.1038/s41586-022-04959-9).

Franco-German working group on EU institutional reform, 2023, Sailing on High Seas: Refoming and Enlarging the EU for the 21st Century, Paris-Berlin (https://www.auswaertiges-amt.de/blob/2617206/4d0e0010ffcd8c0079e21329bbbb3332/230919-rfaa-deu-fra-bericht-data.pdf) accessed 20 September 2023.

Friant, M. C., et al., 2020, 'A typology of circular economy discourses: Navigating the diverse visions of a contested paradigm', Resources, Conservation and Recycling 161, p. 104917 (DOI: 10.1016/j.resconrec.2020.104917).

FS-UNEP and BNEF, 2018, Global trends in renewable energy investment 2018, Frankfurt School-United Nations Environment Programme and Bloomberg New Energy Finance, Frankfurt, Germany (Global trends in renewable energy investment 2018).

FTI consulting, 2023, 'Approaching the ETS Endgame in Europe - Get Ready for EU', https://getready4.eu/ (https://getready4.eu/approaching-the-ets-endgame-in-europe/) accessed 16 October 2023.

Gaddy, B., et al., 2016, Venture capital and cleantech: the wrong model for clean energy innovation, MIT Energy Initiative, Cambridge, MA (https://energy.mit.edu/publication/venture-capital-cleantech/) accessed 29 September 2023.

Gaspard, A., et al., 2023, 'Introducing sufficiency in the building sector in net-zero scenarios for France', Energy and Buildings 278, p. 112590 (DOI: 10.1016/j.enbuild.2022.112590).

Gaud, P., et al., 2007, 'Debt-equity choice in Europe', International Review of Financial Analysis 16(3), pp. 201-222 (DOI: 10.1016/j.irfa.2006.08.003).

Gillespie, T. and Sorge, P., 2022, 'German power plants warn of coal shortage amid low river levels. Bloomberg' (https://www.bloomberg.com/news/articles/2022-09-02/german-power-plants-warn-of-coal-shortage-amid-low-river-levels?leadSource=uverify%20wall) accessed 3 October 2023.

Giuntoli, J. and Searle, S., 2019, Does bioenergy demand improve forest management?, White Paper, International Council on Clean Transportation (https://theicct.org/sites/default/files/publications/ICCT_bioenergy_demand_20190719.pdf).

Glachant, J.-M., 2022, 'Electricity market reform is no silver bullet for Europe's energy crisis', EurActiv, 16 December 2022 (https://www.euractiv.com/section/electricity/opinion/electricity-market-reform-is-no-silver-bullet-for-europes-energy-crisis/).

Glicker, J., et al., 2022, POSITIVE ENERGY NEIGHBOURHOODS DRIVERS OF TRANSFORMATIONAL CHANGE (https://www.bpie.eu/wp-content/uploads/2022/06/OpenLab-Positive-Energy-Neighbourhoods_9.pdf) accessed 18 November 2023.

Goldstein, A., et al., 2020, 'Patenting and business outcomes for cleantech startups funded by the Advanced Research Projects Agency-Energy', Nature Energy 5(10), pp. 803-810 (DOI: 10.1038/s41560-020-00683-8).

Gomez, J. and Vassallo, J. M., 2020, 'Has heavy vehicle tolling in Europe been effective in reducing road freight transport and promoting modal shift?', Transportation 47(2), pp. 865-892 (DOI: 10.1007/s11116-018-9922-3).

Gómez Vilchez, J. J., et al., 2023, 'The new electric SUV market under battery supply constraints: Might they increase CO2 emissions?', Journal of Cleaner Production 383, p. 135294 (DOI: 10.1016/j.jclepro.2022.135294).

Görlach, B., et al., 2022, A fair and solidarity-based EU Emissions Trading System for Buildings and Road Transport, Kopernikus Projekt Ariadne (https://ariadneprojekt.de/media/2022/06/Ariadne-Report_ETS2-SCF_June2022.pdf) accessed 12 October 2023.

Goulder, L. H. and Parry, I. W. H., 2008, 'Instrument Choice in Environmental Policy', Review of Environmental Economics and Policy 2(2), pp. 152-174 (DOI: 10.1093/reep/ren005).

Grassano, N., et al., 2020, The 2020 EU Industrial R&D Investment Scoreboard, Publications Office of the European Union, Luxembourg (https://iri.jrc.ec.europa.eu/sites/default/files/2020-12/EU%20RD%20Scoreboard%202020%20FINAL%20online.pdf) accessed 20 December 2022.

Grubb, M., et al., 2021, 'Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation', Environmental Research Letters 16(4), p. 043007 (DOI: 10.1088/1748-9326/abde07).

Grubb, M., et al., 2022, Separating electricity from gas prices through Green Power Pools: Design options and evolution. Working paper 193, Institute for New Economic Thinking (https://www.ineteconomics.org/research/research-papers/separating-electricity-from-gas-prices-through-green-power-pools-design-options-and-evolution) accessed 20 November 2022.

GSIA, 2020, 'Trends Report 2020 | GSIA' (https://www.gsi-alliance.org/trends-report-2020/) accessed 23 November 2023.

Gurría Albusac, P., et al., 2021, Medium-term Outlook commodity flows, (http://data.europa.eu/89h/310ee8b3-a2bf-4cd7-9ae8-52582708bb1a), Joint Research Centre.

Guyomard, H., et al., 2021, 'Review: Why and how to regulate animal production and consumption: The case of the European Union', Animal 15, p. 100283 (DOI: 10.1016/j.animal.2021.100283).

Guyomard, H., et al., 2023, 'How the Green Architecture of the 2023–2027 Common Agricultural Policy could have been greener', Ambio 52(8), pp. 1327-1338 (DOI: 10.1007/s13280-023-01861-0).

Gylling, M., et al., 2023, Potential Danish biomass production and utilization in 2030, DCA Report No 2019, University of Copenhagen, Danish Centre for Food and Agriculture (https://static-curis.ku.dk/portal/files/373616325/DCArapport219.pdf).

Haegel, N. M., et al., 2023, 'Photovoltaics at multi-terawatt scale: Waiting is not an option', Science 380(6640), pp. 39-42 (DOI: 10.1126/science.adf6957).

Hancher, L., 2022, 'EU Energy Governance—Moving Targets and Flexible Ambitions between Opacity and Opportunism?', Yearbook of European Law, p. yeac010 (DOI: 10.1093/yel/yeac010).

Hancher, L. and Maria Salerno, F., 2021a, 'State aid in the energy sector', in: Hancher, L. and Piernas López, J. J. (eds), Research Handbook on European State Aid Law, Edward Elgar Publishing.

Hancher, L. and Maria Salerno, F., 2021b, 'State aid in the energy sector', in: Hancher, L. and Piernas López, J. J. (eds), Research Handbook on European State Aid Law, Edward Elgar Publishing. https://doi.org/10.4337/9781789909258.00011

Hänsel, M. C., et al., 2022, 'Optimal carbon taxation and horizontal equity: A welfare-theoretic approach with application to German household data', Journal of Environmental Economics and Management 116, p. 102730 (DOI: 10.1016/j.jeem.2022.102730).

Hao, H., et al., 2019, 'Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment', Nature Communications 10(1), p. 5398 (DOI: 10.1038/s41467-019-13400-1).

He Waka Eke Noa, 2022, Recommendations for pricing agricultural emissions: report to ministers, No ISBN No: 978-0-473-63459-9, He Waka Eke Noa, New Zealand (https://hewakaekenoa.nz/report/).

Henderson, B. and Verma, M., 2021, Global assessment of the carbon leakage implications of carbon taxes on agricultural emissions, OECD, Paris (https://www.oecd-ilibrary.org/agriculture-and-food/global-assessment-of-the-carbon-leakage-implications-of-carbon-taxes-on-agricultural-emissions_fc304fad-en) accessed 26 October 2023.

Henze, V., 2022, 'ESG May Surpass $41 Trillion Assets in 2022, But Not Without Challenges, Finds Bloomberg Intelligence | Press | Bloomberg LP', Bloomberg L.P.

Hertwich, Edgar, et al., 2019, Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future, Zenodo (https://zenodo.org/record/3542680) accessed 14 August 2020.

Higham, C., et al., 2021, Accountability mechanisms in climate change framework laws, (https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2021/11/Accountability-mechanisms-in-climate-change-framework-laws.pdf), Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy.

Hintermann, B., et al., 2020, The effect of climate policy on productivity and cost pass-through in the German manufacturing sector, Working Paper No 2020/11, WWZ Working Paper (https://www.econstor.eu/handle/10419/240420) accessed 9 October 2023.

Holz, F., et al., 2021, 'A 2050 perspective on the role for carbon capture and storage in the European power system and industry sector', Energy Economics 104, p. 105631 (DOI: 10.1016/j.eneco.2021.105631).

Hood, C., 2011, Summing up the parts: combining policy instruments for least-cost climate mitigation strategies, IEA.

Hook, J. N., et al., 2023, 'Minimalism, voluntary simplicity, and well-being: A systematic review of the empirical literature', The Journal of Positive Psychology 18(1), pp. 130-141 (DOI: 10.1080/17439760.2021.1991450).

Howarth, R. W. and Jacobson, M. Z., 2021, 'How green is blue hydrogen?', Energy Science & Engineering 9(10), pp. 1676-1687 (DOI: 10.1002/ese3.956).

Humpenöder, F., et al., 2020, 'Peatland protection and restoration are key for climate change mitigation', Environmental Research Letters 15(10), p. 104093 (DOI: 10.1088/1748-9326/abae2a).

Huovila, A., et al., 2022, 'Carbon-neutral cities: Critical review of theory and practice', Journal of Cleaner Production 341, p. 130912 (DOI: 10.1016/j.jclepro.2022.130912).

ICCT, et al., 2021, Life-cycle Greenhouse Gas Emissions of Biomethane and Hydrogen Pathways in the European Union, International Council on Clean Transportation, Washington DC, US (https://theicct.org/wp-content/uploads/2021/10/LCA-gas-EU-white-paper-A4-v5.pdf) accessed 4 September 2023.

IEA, 2020, Energy Efficiency 2020, International Energy Agency, Paris, France (https://www.iea.org/reports/energy-efficiency-2020/energy-efficiency-jobs-and-the-recovery).

IEA, 2021a, Patents and the energy transition - Global trends in clean energy technology innovation April 2021, International Energy Agency, Paris (https://www.iea.org/reports/patents-and-the-energy-transition).

IEA, 2021b, The role of critical minerals in clean energy transitions, World Energy Outlook Special Report, International Energy Agency, Paris (https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions).

IEA, 2022a, 'Electric Vehicles: Total Cost of Ownership tool' (https://www.iea.org/data-and-statistics/data-tools/electric-vehicles-total-cost-of-ownership-tool) accessed 26 June 2023.

IEA, 2022b, Global EV Outlook 2022. Securing supplies for an electric future., International Energy Agency, Paris (https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf).

IEA, 2022c, 'Investment spending on electricity grids, 2015-2021' (https://www.iea.org/data-and-statistics/charts/investment-spending-on-electricity-grids-2015-2021).

IEA, 2022d, Steering Electricity Markets Towards a Rapid Decarbonisation, International Energy Agency. (https://www.iea.org/reports/steering-electricity-markets-towards-a-rapid-decarbonisation), IEA.

IEA, 2022e, Steering Electricity Markets towards a Rapid Decarbonisation, (https://www.iea.org/reports/steering-electricity-markets-towards-a-rapid-decarbonisation), IEA.

IEA, 2022f, The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report, International Energy Agency, Paris, France (https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf).

IEA, 2022g, Wind Electricity, International Energy Agency, Paris, France (https://www.iea.org/reports/wind-electricity).

IEA, 2023a, CCUS Policies and Business Models Building a commercial market, International Energy Agency, Paris (https://iea.blob.core.windows.net/assets/d0cb5c89-3bd4-4efd-8ef5-57dc327a02d6/CCUSPoliciesandBusinessModels.pdf).

IEA, 2023b, Cost of Capital Observatory, Paris (https://www.iea.org/reports/cost-of-capital-observatory/dashboard).

IEA, 2023c, Energy Technology RD&D Budgets, (https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2).

IEA, 2023d, 'Fossil fuels consumption subsidies 2022' (https://www.iea.org/reports/fossil-fuels-consumption-subsidies-2022)

IEA, 2023e, Global EV outlook 2023. Catching up with climate ambitions, International Energy Agency (https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf).

IEA, 2023f, 'Global EV Policy Explorer' (https://www.iea.org/data-and-statistics/data-tools/global-ev-policy-explorer) accessed 27 June 2023.

IEA, 2023g, Global Methane Tracker 2023, International Energy Agency, Paris (https://www.iea.org/reports/global-methane-tracker-2023).

IEA, 2023h, Renewable energy market update: outlook for 2023 and 2024 (https://www.iea.org/reports/renewable-energy-market-update-june-2023).

IEA, 2023i, Renewables 2022. Analysis and forecast to 2027., International Energy Agency, Paris, France (https://iea.blob.core.windows.net/assets/ada7af90-e280-46c4-a577-df2e4fb44254/Renewables2022.pdf).

IEA, 2023j, The State of Clean Technology Manufacturing., International Energy Agency (https://iea.blob.core.windows.net/assets/0a421001-6157-436d-893c-c37eeab54967/TheStateofCleanTechnologyManufacturing.pdf).

IEA and IRENA, 2017, Perspectives for the energy transition: investment needs for a low-carbon energy system, International Energy Agency and International Renewable Energy Agency, Paris (https://www.irena.org/publications/2017/Mar/Perspectives-for-the-energy-transition-Investment-needs-for-a-low-carbon-energy-system) accessed 13 August 2019.

IEAGHG, 2019, Zero-emission carbon capture and storage in power plants using higher capture rates, International Energy Agency (https://documents.ieaghg.org/index.php/s/CLIZIvBI6OdMFnf).

IEEP, 2021, Just transition in the EU agriculture and land use sector, Institute for European Environmental Policy (https://ieep.eu/publications/just-transition-in-the-eu-agriculture-and-land-use-sector/).

ILO, 2015, Guidelines for a just transition towards environmentally sustainable economies and societies for all, International Labour Organization, Geneva, Switzerland. ISBN 978-92-2-130627-6 (https://www.ilo.org/global/topics/green-jobs/publications/WCMS_432859/lang--en/index.htm).

IMF, 2019, Fiscal Monitor, October 2019: How to Mitigate Climate Change, ISBN 978-1-51351-532-8 (https://www.imf.org/en/Publications/FM/Issues/2019/09/12/fiscal-monitor-october-2019).

IMF, 2023, Support for Climate Action Hinges on Public Understanding of Policy, (https://www.imf.org/en/Blogs/Articles/2023/02/09/support-for-climate-action-hinges-on-public-understanding-of-policy) accessed 12 November 20223.

Ioakimidis, C., et al., 2019, 'Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios', Sustainability 11(9), p. 2527 (DOI: 10.3390/su11092527).

IPCC, 2006, 2006 IPCC guidelines for national greenhouse gas inventories, Institute for Global Environmental Strategies, Hanawa, Japan. ISBN 4-88788-032-4 (https://www.ipcc-nggip.iges.or.jp/public/2006gl/).

IPCC, 2007a, Changes in Atmospheric Constituents and in Radiative Forcing. Chapter 2 of Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Intergovernmental Panel Climate Change (https://www.ipcc.ch/report/ar4/wg1/).

IPCC, 2007b, Climate Change 2007: Working Group I: The Physical Science Basis, (https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html).

IPCC, 2013, Anthropogenic and Natural Radiative Forcing. Chapter 8 of Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC (https://www.ipcc.ch/report/ar5/wg1/).

IPCC, 2018, Global warming of 1.5 °C, Intergovernmental Panel on Climate Change, Geneva (http://www.ipcc.ch/report/sr15/).

IPCC, 2022a, 'Agriculture, Forestry and Other Land Uses (AFOLU)'. Chapter 7 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022b, 'Buildings', Chapter 9 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022c, Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2022d, Climate Change 2022: Mitigation of Climate Change - Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate (https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/).

IPCC, 2022e, 'Cross-sectoral perspectives'. Chapter 12 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022f, 'Demand, Services and Social Aspects of Mitigation'. Chapter 5 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022g, 'Energy Systems'. Chapter 6 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022h, 'Industry'. Chapter 11 in IPCC 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022i, 'Mitigation pathways compatible with long-term goals'. Chapter 3 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022j, 'Transport'. Chapter 10 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022k, 'Urban Systems and Other Settlements'. Chapter 8 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022l, Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change -Summary for Policy Makers, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022m, 'Investment and Finance'. Chapter 15 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022n, Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change -Technical Summary, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022o, 'Innovation, Technology Development and Transfer'. Chapter 16 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2022p, 'National and sub-national policies and institutions.', Chapter 13 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IRENA, 2022a, Renewable Energy and Jobs Annual Review 2022, International Renewable Energy Agency and International Labour Organization. ISBN 978-92-9260-364-9 (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Sep/IRENA_Renewable_energy_and_jobs_2022.pdf?rev=7c0be3e04bfa4cddaedb4277861b1b61).

IRENA, 2022b, Renewable solutions in end-uses: Heat pump costs and markets, International Renewable Energy Agency, Abu Dhabi, UAE. ISBN 978-92-9260-486-8 (https://www.irena.org/Publications/2022/Nov/Renewable-solutions-in-end-uses-Heat-pump-costs-and-markets).

IRP, 2020, Resource efficiency and climate change. Material efficiency strategies for a low-carbon future, International Resource Panel (https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change).

Isermeyer, F., et al., 2021, 'Integrating agriculture into carbon pricing', Thünen Working Paper 136a (https://ideas.repec.org/p/ags/jhimwp/310017.html).

Iturrondobeitia, M., et al., 2022, 'Environmental Impact Assessment of LiNi 1/3 Mn 1/3 Co 1/3 O 2 Hydrometallurgical Cathode Recycling from Spent Lithium-Ion Batteries', ACS Sustainable Chemistry & Engineering 10(30), pp. 9798-9810 (DOI: 10.1021/acssuschemeng.2c01496).

Ivanova, D. and Büchs, M., 2022, 'Implications of shrinking household sizes for meeting the 1.5 °C climate targets', Ecological Economics 202, p. 107590 (DOI: 10.1016/j.ecolecon.2022.107590).

Jaffe, A. B., et al., 2005, 'A tale of two market failures: Technology and environmental policy', Ecological Economics 54(2), pp. 164-174 (DOI: 10.1016/j.ecolecon.2004.12.027).

Jakob, M., et al., 2020, 'The future of coal in a carbon-constrained climate', Nature Climate Change 10(8), pp. 704-707 (DOI: 10.1038/s41558-020-0866-1).

Jakob, M., 2022, Handbook on Trade Policy and Climate Change, Edward Elgar Publishing Ltd. (https://doi.org/10.4337/9781839103247).

Jakob, M., 2023, 'The political economy of carbon border adjustment in the EU', Oxford Review of Economic Policy 39(1), pp. 134-146 (DOI: 10.1093/oxrep/grac044).

Jenkins, J. D., 2014, 'Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design?', Energy Policy 69, pp. 467-477 (DOI: 10.1016/j.enpol.2014.02.003).

Jiborn, M., et al., 2018, 'Decoupling or delusion? Measuring emissions displacement in foreign trade', Global Environmental Change 49, pp. 27-34 (DOI: 10.1016/j.gloenvcha.2017.12.006).

Johansson, N., 2021, 'Does the EU's Action Plan for a Circular Economy Challenge the Linear Economy?', Environmental Science & Technology 55(22), pp. 15001-15003 (DOI: 10.1021/acs.est.1c06194).

Jonsdottir, B., et al., 2022, 'Barriers to Using ESG Data for Investment Decisions', Sustainability 14(9), p. 5157 (DOI: 10.3390/su14095157).

JRC, 2019a, Accelerating energy renovation investments in buildings: financial and fiscal instruments across the EU., Publications Office, LU (https://dx.doi.org/10.2760/086805).

JRC, 2019b, Housing taxation: a new database for Europe. JRC Working Papers on Taxation and Structural Reforms No 08/2019, Joint Research Centre (https://joint-research-centre.ec.europa.eu/system/files/2019-10/jrc118277.pdf).

JRC, 2020a, Building energy renovation for decarbonisation and Covid-19 recovery: a snapshot at regional level., Publications Office, LU (https://dx.doi.org/10.2760/08629).

JRC, 2020b, Economic assessment of GHG mitigation policy options for EU agriculture, (https://publications.jrc.ec.europa.eu/repository/handle/JRC120355).

JRC, 2021a, Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution (https://publications.jrc.ec.europa.eu/repository/handle/JRC124374).

JRC, 2021b, Modelling environmental and climatic ambition in the agricultural sector with the CAPRI model: exploring the potential effects of selected farm to fork and biodiversity strategies targets in the framework of the 2030 climate targets and the post 2020 common agricultural policy, JRC Technical Report, Joint Research Centre, Publications Office of the European Union, Luxembourg (https://data.europa.eu/doi/10.2760/98160).

JRC, 2021c, Progress of the Member States in implementing the energy performance of Building Directive., Joint Research Centre, European Commission (https://data.europa.eu/doi/10.2760/914310).

JRC, 2021d, Recent trends in EU coal, peat and oil shale regions., European Commission, LU (https://data.europa.eu/doi/10.2760/510714).

JRC, 2022a, The role of hydrogen in decarbonisation energy scenarios: views on 2030 and 2050., Publications Office, LU (https://dx.doi.org/10.2760/899528).

JRC, 2022b, 'Wood Resource Balances of European Union and Member States. Years 2009-2017' (https://knowledge4policy.ec.europa.eu/sites/default/files/WRB_EU_v2021.pdf) accessed 26 September 2023.

JRC, 2023a, Ecodesign for sustainable products regulation - preliminary study on new product priorities. (https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2023-01/Preliminary%20ESPR%20WP%20Report_MERGED_CLEAN_.pdf) accessed 15 October 2023.

JRC, 2023b, Flexibility requirements and the role of storage in future European power systems., Publications Office, LU (https://data.europa.eu/doi/10.2760/384443) accessed 9 July 2023.

JRC, 2023c, GHG emissions of all world countries: 2023., Publications Office, LU (https://doi.org/10.2760/953322).

JRC, 2023d, 'Medium-term outlook commodity flows' (https://datam.jrc.ec.europa.eu/datam/mashup/AGRI_MTO_FLOWS/index.html) accessed 29 June 2023.

Kalkuhl, M., et al., 2012, 'Learning or lock-in: Optimal technology policies to support mitigation', Resource and Energy Economics 34(1), pp. 1-23 (DOI: 10.1016/j.reseneeco.2011.08.001).

Kalkuhl, M., et al., 2013, 'Renewable energy subsidies: Second-best policy or fatal aberration for mitigation?', Resource and Energy Economics 35(3), pp. 217-234 (DOI: 10.1016/j.reseneeco.2013.01.002).

Kander, A., et al., 2015, 'National greenhouse-gas accounting for effective climate policy on international trade', Nature Climate Change 5(5), pp. 431-435 (DOI: 10.1038/nclimate2555).

Karlsson, M., et al., 2020, 'Climate policy co-benefits: a review', Climate Policy 20(3), pp. 292-316 (DOI: 10.1080/14693062.2020.1724070).

Kay, S., et al., 2019, 'Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe', Land Use Policy 83, pp. 581-593 (DOI: 10.1016/j.landusepol.2019.02.025).

Kehlbacher, A., et al., 2016, 'The distributional and nutritional impacts and mitigation potential of emission-based food taxes in the UK', Climatic Change 137(1), pp. 121-141 (DOI: 10.1007/s10584-016-1673-6).

Kemp, R., 2016, Scope for reduction in transport CO2 emissions by modal shift, Lancaster University - Energy Technologies Institute (https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2016/02/Scope-for-reduction-in-transport-CO2-emissions-by-modal-shift-ETI-Comms.pdf).

Kim, T. and Langpap, C., 2015, 'Incentives for Carbon Sequestration Using Forest Management', Environmental and Resource Economics 62(3), pp. 491-520 (DOI: 10.1007/s10640-014-9827-3).

Kirkegaard, J. K., et al., 2023, 'Tackling grand challenges in wind energy through a socio-technical perspective', Nature Energy (DOI: 10.1038/s41560-023-01266-z).

Kitzing, L., et al., 2021, Wind energy policy and economics, Danmarks Tekniske Universitet, Institut for Vindenergi, Risø Campus, 4000, Roskilde, Danmark (https://doi.org/10.11581/DTU.00000204).

Klenert, D., et al., 2023, 'Meat taxes in Europe can be designed to avoid overburdening low-income consumers', Nature Food 4(10), pp. 894-901 (DOI: 10.1038/s43016-023-00849-z).

Klimarådet, 2023, Landbrugets omstilling ved en drivhusgasafgift (https://klimaraadet.dk/da/analyse/landbrugets-omstilling-ved-en-drivhusgasafgift).

Koch, N., et al., 2022, 'Attributing agnostically detected large reductions in road CO2 emissions to policy mixes', Nature Energy 7(9), pp. 844-853 (DOI: 10.1038/s41560-022-01095-6).

Kölbel, J. F., et al., 2020, 'Can Sustainable Investing Save the World? Reviewing the Mechanisms of Investor Impact', Organization & Environment 33(4), pp. 554-574 (DOI: 10.1177/1086026620919202).

König, L. M. and Araújo‐Soares, V., 2021, 'Will the Farm to Fork strategy be effective in changing food consumption behavior? A health psychology perspective', Applied Economic Perspectives and Policy, p. aepp.13220 (DOI: 10.1002/aepp.13220).

Korosuo, A., et al., 2023, 'The role of forests in the EU climate policy: are we on the right track?', Carbon Balance and Management 18(1), p. 15 (DOI: 10.1186/s13021-023-00234-0).

Krause, A., et al., 2020, 'A regional assessment of land‐based carbon mitigation potentials: Bioenergy, BECCS, reforestation, and forest management', GCB Bioenergy 12(5), pp. 346-360 (DOI: 10.1111/gcbb.12675).

Kryszk, H., et al., 2023, 'Barriers and Prospects for the Development of Renewable Energy Sources in Poland during the Energy Crisis', Energies 16(4), p. 1724 (DOI: 10.3390/en16041724).

Kuh, K. F., 2020, 'The Legitimacy of Judicial Climate Engagement', (DOI: 10.15779/Z38M03XX8R).

Kulovesi, K. and Oberthür, S., 2020, 'Assessing the EU's 2030 Climate and Energy Policy Framework: Incremental change toward radical transformation?', Review of European, Comparative & International Environmental Law 29(2), pp. 151-166 (DOI: 10.1111/reel.12358).

Larcker, D. F. and Watts, E. M., 2020, 'Where's the greenium?', Journal of Accounting and Economics 69(2), p. 101312 (DOI: 10.1016/j.jacceco.2020.101312).

LeadIT, 'Green Steel Tracker' (https://www.industrytransition.org/green-steel-tracker/) accessed 27 July 2023.

Leahy, S., et al., 2020, 'Challenges and Prospects for Agricultural Greenhouse Gas Mitigation Pathways Consistent With the Paris Agreement', Frontiers in Sustainable Food Systems 4 (https://doi.org/10.3389/fsufs.2020.00069).

Lebastard, L., et al., 2023, GVC exporter performance during the COVID-19 pandemic: the role of supply bottlenecks Working Paper Series, No 2766, ECB, European Central Bank.

Lebedeva, N., et al., 2021, 'Batteries - Technology Development Report 2020', JRC Publications Repository (https://dx.doi.org/10.2760/24401).

Leip, A., et al., 2015, 'Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity', Environmental Research Letters 10(11), p. 115004 (DOI: 10.1088/1748-9326/10/11/115004).

Lenschow, A., et al., 2018, 'Understanding coherence between policy spheres', Environmental Policy and Governance 28(5), pp. 323-328 (DOI: 10.1002/eet.1818).

Linsenmeier, M., et al., 2023, 'Global benefits of the international diffusion of carbon pricing policies', Nature Climate Change 13(7), pp. 679-684 (DOI: 10.1038/s41558-023-01710-8).

Liu, L.-J., et al., 2023, 'Carbon emissions and economic impacts of an EU embargo on Russian fossil fuels', Nature Climate Change 13(3), pp. 290-296 (DOI: 10.1038/s41558-023-01606-7).

Löffler, K. U., et al., 2021, 'Drivers of green bond issuance and new evidence on the "greenium"', Eurasian Economic Review 11(1), pp. 1-24 (DOI: 10.1007/s40822-020-00165-y).

Lorek, S. and Spangenberg, J. H., 2019, 'Energy sufficiency through social innovation in housing', Energy Policy 126, pp. 287-294 (DOI: 10.1016/j.enpol.2018.11.026).

Lowe, R. J. and Drummond, P., 2022, 'Solar, wind and logistic substitution in global energy supply to 2050 – Barriers and implications', Renewable and Sustainable Energy Reviews 153, p. 111720 (DOI: 10.1016/j.rser.2021.111720).

Ludemann, C. I., et al., 2023, 'A global reference database in FAOSTAT of cropland nutrient budgets and nutrient use efficiency: nitrogen, phosphorus and potassium, 1961-2020', Earth System Science Data Discussions, pp. 1-24 (DOI: 10.5194/essd-2023-206).

Lund, J. F., et al., 2023, 'Net zero and the unexplored politics of residual emissions', Energy Research & Social Science 98, p. 103035 (DOI: 10.1016/j.erss.2023.103035).

Maestre-Andrés, S., et al., 2019, 'Perceived fairness and public acceptability of carbon pricing: a review of the literature', Climate Policy 19(9), pp. 1186-1204 (DOI: 10.1080/14693062.2019.1639490).

Magrini, A., et al., 2020, 'From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example', Developments in the Built Environment 3, p. 100019 (DOI: 10.1016/j.dibe.2020.100019).

Mai-Moulin, T., et al., 2021, 'Effective sustainability criteria for bioenergy: Towards the implementation of the european renewable directive II', Renewable and Sustainable Energy Reviews 138, p. 110645 (DOI: 10.1016/j.rser.2020.110645).

Maiti, M., 2021, 'Is ESG the succeeding risk factor?', Journal of Sustainable Finance & Investment 11(3), pp. 199-213 (DOI: 10.1080/20430795.2020.1723380).

Malico, I., et al., 2019, 'Current status and future perspectives for energy production from solid biomass in the European industry', Renewable and Sustainable Energy Reviews 112, pp. 960-977 (DOI: 10.1016/j.rser.2019.06.022).

Malins, C., 2023, The fat of the land. The impact of biofuel demand on the European market for rendered animal fats., Report for Transport & Environment (https://www.cerulogy.com/the-fat-of-the-land) accessed 29 October 2023.

Marin, G. and Vona, F., 2019, 'Climate policies and skill-biased employment dynamics: Evidence from EU countries', Journal of Environmental Economics and Management 98, p. 102253 (DOI: 10.1016/j.jeem.2019.102253).

Mata Pérez, M. D. L. E., et al., 2019, 'The multi-speed energy transition in Europe: Opportunities and challenges for EU energy security', Energy Strategy Reviews 26, p. 100415 (DOI: 10.1016/j.esr.2019.100415).

Material Economics, 2018, The Circular Economy - a Powerful Force for Climate Mitigation, Stockholm, Sweden (https://materialeconomics.com/s//s/s.com/s/s.com///s//s/s.com/s/s.com/s//s/s.com/s/s.com/s//s/s.com/s/s.com/publications/the-circular-economy-a-powerful-force-for-climate-mitigation-1).

Material Economics, 2019, Industrial Transformation 2050. Pathways to Net-Zerro Emissions from EU Heavy Industry (https://materialeconomics.com/latest-updates/industrial-transformation-2050).

Material Economics, 2021, EU biomass use in a net-zero economy, (https://materialeconomics.com/s//s/s.com/s/s.com///s//s/s.com/s/s.com/s//s/s.com/s/s.com/s//s/s.com/s/s.com/latest-updates/eu-biomass-use).

Material Economics, 2022, Scaling up Europe. Bringing Low-CO2 Materials from Demonstration to Industrial Scale. Report commissioned by Breakthrough Energy (https://materialeconomics.com/publications/scaling-up-europe).

Mather-Gratton, Z. J., et al., 2021, 'Understanding the sustainability debate on forest biomass for energy in Europe: A discourse analysis' Dwivedi, P. (ed.), PLOS ONE 16(2), p. e0246873 (DOI: 10.1371/journal.pone.0246873).

Matthes, F. and Graichen, J., 2022, Policy Brief: Emissions trading system for road transport and buildings in the policy mix for achieving climate neutrality in the EU. (https://www.oeko.de/fileadmin/oekodoc/Emissions-trading-system-for-transport-and-buildings-RefFix.pdf) accessed 5 November 2023.

Matthews, A., 2021, 'Can the new CAP help EU agriculture to meet the targets in the European Green Deal?', European Court of Auditors Journal (2/2021), pp. 13-29 (https://eca.europa.eu/da/Pages/news.aspx?nid=15671).

Mauler, L., et al., 2021, 'Battery cost forecasting: a review of methods and results with an outlook to 2050', Energy & Environmental Science 14(9), pp. 4712-4739 (DOI: 10.1039/D1EE01530C).

Mazzucato, M., 2018, 'Mission-oriented innovation policies: challenges and opportunities', Industrial and Corporate Change 27(5), pp. 803-815 (DOI: 10.1093/icc/dty034).

McDonald, H., et al., 2023, 'QU.A.L.ITY Soil Carbon Removals?', Ecologic Institute (https://www.ecologic.eu/19080) accessed 25 November 2023.

Meckling, J., et al., 2022, 'Energy innovation funding and institutions in major economies', Nature Energy 7(9), pp. 876-885 (DOI: 10.1038/s41560-022-01117-3).

Meeus, L., 2020, The evolution of electricity markets in Europe, Edward Elgar Publishing, Cheltenham, UK; Northampton, MA. ISBN: 978 1 78990 546 5.

Metternicht, G., 2018, Land Use and Spatial Planning, Springer International Publishing, Cham (https://doi.org/10.1007/978-3-319-71861-3).

Michalak, J. and Michałowski, B., 2022, 'Understanding Sustainability of Construction Products: Answers from Investors, Contractors, and Sellers of Building Materials', Sustainability 14(5), p. 3042 (DOI: 10.3390/su14053042).

Midler, E., et al., 2023, Environmental and climate assessments of CAP Strategic Plans. Summary of impact based on four key Member States, Institute for European Environmental Policy and Ecologic (https://ieep.eu/wp-content/uploads/2023/04/Environmental-and-climate-assessements-of-CAP-Strategic-Plans_IEEP-2023.pdf).

Ministers responsible for Spatial Planning and Territorial Development and/or Territorial Cohesion, 2021, Territorial Agenda 2030: A future for all places (https://ec.europa.eu/regional_policy/sources/brochure/territorial_agenda_2030_en.pdf).

Mišík, M. and Oravcová, V., 2022, 'Ex Ante Governance in the European Union: Energy and climate policy as a "test run" for the post-pandemic recovery', Energy Policy 167, p. 113076 (DOI: 10.1016/j.enpol.2022.113076).

Moaniba, I. M., et al., 2018, 'Does reverse causality explains the relationship between economic performance and technological diversity?', Technological and Economic Development of Economy 24(3), pp. 859-892 (DOI: 10.3846/tede.2018.1429).

Moesker, K. and Pesch, U., 2022, 'The just transition fund – Did the European Union learn from Europe's past transition experiences?', Energy Research & Social Science 91, p. 102750 (DOI: 10.1016/j.erss.2022.102750).

Mollière, M., 2023, Ready or not. Who are the frontrunners in the global race to clean up trucks and gain technology leadership, Transport & Environment (https://www.transportenvironment.org/wp-content/uploads/2023/06/202306_truckmakers_ZE_readiness_report.pdf).

Monti, A. and Martinez Romera, B., 2020, 'Fifty shades of binding: Appraising the enforcement toolkit for the EU's 2030 renewable energy targets', Review of European, Comparative & International Environmental Law 29(2), pp. 221-231 (DOI: 10.1111/reel.12330).

Moschitz, H., et al., 2021, 'How can the EU Farm to Fork strategy deliver on its organic promises? Some critical reflections', EuroChoices 20(1), pp. 30-36 (DOI: 10.1111/1746-692X.12294).

Moskowitz, E., et al., 2023, 'How biofuel scams have undermined a flagship EU climate policy' (https://www.occrp.org/en/investigations/how-biofuels-scams-have-undermined-a-flagship-eu-climate-policy) accessed 4 September 2023.

Mosquera-Losada, M. R., et al., 2023, 'Policy challenges for agroforestry implementation in Europe', Frontiers in Forests and Global Change 6, p. 1127601 (DOI: 10.3389/ffgc.2023.1127601).

Moura, R. and Brito, M. C., 2019, 'Prosumer aggregation policies, country experience and business models', Energy Policy 132, pp. 820-830 (DOI: 10.1016/j.enpol.2019.06.053).

Muellbauer, J., 2023, Why we need a green land value tax and how to design it. INET Oxford Working Paper No. 2023-12., (https://www.inet.ox.ac.uk/publications/why-we-need-a-green-land-value-tax-and-how-to-design-it/), Institute for New Economic Thinking at the Oxford Martin School.

Mulholland, E. and Rodriguez, F., 2023, Europe's proposed heavy-duty CO2 standards: room for improvement., Factsheet, The International Council on Clean Transportation (https://theicct.org/wp-content/uploads/2023/05/fs-europe-heavy-duty-vehicle-co2-standards-may23.pdf).

Murphy, A., 2022, Risk issues within the Agricultural sector on the island of Ireland: mapping for a sectoral Just Transition, NERI Report Series No 15, Nevin Economic Research Institute (https://www.nerinstitute.net/sites/default/files/research/2022/7811%20NERI%20Report%20Series%20no%2015.pdf).

Nadin, V. and Fernández-Maldonado, A. M., 2023, 'Spatial planning systems in Europe: multiple trajectories', Planning Practice & Research 38(5), pp. 625-638 (DOI: 10.1080/02697459.2023.2258568).

NECPlatform, 2023, Multi-Level Governance in EU Energy and Climate Policy – First findings from NECPlatform, (https://energy-cities.eu/project/necplatform-resources/) accessed 14 September 2023.

Nemet, G. and Greene, J., 2022, 'Innovation in low-energy demand and its implications for policy', Oxford Open Energy 1, p. oiac003 (DOI: 10.1093/ooenergy/oiac003).

NESC, 2023, Just Transition in Agriculture and Land Use, Council Report No 162, National Economic & Social Council (https://www.nesc.ie/app/uploads/2023/06/162_just_transition_in_ag_land_use-1.pdf).

Neuhoff, K., et al., 2019, Building blocks for a climate-neutral European industrial sector. Policies to create markets for climate-friendly materials to boost EU global competitiveness and jobs. (https://climatestrategies.org/wp-content/uploads/2019/10/Building-Blocks-for-a-Climate-Neutral-European-Industrial-Sector.pdf).

Neuhoff, K. and Ritz, R. A., 2019, Carbon cost pass-through in industrial sectors, Energy Policy Research Group, University of Cambridge (https://www.jstor.org/stable/resrep30282) accessed 22 November 2023.

New Zealand government, 2022, Pricing agricultural emissions: report under section 215 of the climate change response act 2002 (https://environment.govt.nz/publications/pricing-agricultural-emissions-report-under-section-215-of-the-climate-change-response-act-2002/) accessed 12 September 2023.

Niamir, L., et al., 2020, 'Demand-side solutions for climate mitigation: Bottom-up drivers of household energy behavior change in the Netherlands and Spain', Energy Research & Social Science 62, p. 101356 (DOI: 10.1016/j.erss.2019.101356).

Nilsson, L. J., et al., 2021, 'An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions', Climate Policy 21(8), pp. 1053-1065 (DOI: 10.1080/14693062.2021.1957665).

Noriega, J. A., et al., 2018, 'Research trends in ecosystem services provided by insects', Basic and Applied Ecology 26, pp. 8-23 (DOI: 10.1016/j.baae.2017.09.006).

Norton, M., et al., 2019, 'Serious mismatches continue between science and policy in forest bioenergy', GCB Bioenergy 11(11), pp. 1256-1263 (DOI: 10.1111/gcbb.12643).

Novotny, V., 2023, 'Blue hydrogen can be a source of green energy in the period of decarbonization', International Journal of Hydrogen Energy 48(20), pp. 7202-7218 (DOI: 10.1016/j.ijhydene.2022.11.095).

Nowag, J., et al., 2021, 'Phasing out fossil fuel subsidies in the EU? Exploring the role of state aid rules', Climate Policy 21(8), pp. 1037-1052 (DOI: 10.1080/14693062.2021.1965523).

Nowak, M. J., et al., 2022, 'The Role of Spatial Policy Tools in Renewable Energy Investment', Energies 15(7), p. 2393 (DOI: 10.3390/en15072393).

Nykvist, B. and Olsson, O., 2021, 'The feasibility of heavy battery electric trucks', Joule (DOI: 10.1016/j.joule.2021.03.007).

Oberthür, S., 2019, 'Hard or Soft Governance? The EU's Climate and Energy Policy Framework for 2030', Politics and Governance 7(1), pp. 17-27 (DOI: 10.17645/pag.v7i1.1796).

Oberthür, S., et al., 2023, Towards an EU Climate Governance Framework to Deliver on the European Green Deal (https://brussels-school.be/sites/default/files/Policy%20options%20paper%20EU%20Climate%20Governance%20Framework%202023-compressed.pdf) accessed 20 September 2023.

Ocean Energy Europe, 2023, Ocean Energy. Key trends and statistics 2022 (https://www.oceanenergy-europe.eu/wp-content/uploads/2023/03/Ocean-Energy-Key-Trends-and-Statistics-2022.pdf) accessed 02 September 2023.

O'Connor, D., 2023, New emissions reduction plan will future-proof NZ's largest export sector (https://www.beehive.govt.nz/release/new-emissions-reduction-plan-will-future-proof-nz%E2%80%99s-largest-export-sector) accessed 20 October 2023.

Odyssee-Mure project, 2023, Odyssee database (https://www.odyssee-mure.eu/private/) accessed 9 August 2023.

OECD, 2021, Pricing Greenhouse Gas Emissions: Turning Climate Targets into Climate Action - OECD, (https://doi.org/10.1787/e9778969-en).

OECD, 2022, Housing Taxation in OECD Countries, OECD (https://doi.org/10.1787/03dfe007-en).

OECD, 2023a, Effective Carbon Rates. Extracted from OECD.Stat database (https://stats.oecd.org) accessed 17 October 2023.

OECD, 2023b, Green Growth Indicators, (https://stats.oecd.org/Index.aspx?DataSetCode=green_growth) accessed 14 October 2023.

OECD, 2023c, Gross domestic spending on R&D (indicator), Main Science and Technology Indicators (https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm) accessed 12 October 2023.

OECD and IISD, 2023, 'Fossil Fuel Subsidy Tracker' (https://fossilfuelsubsidytracker.org/) accessed 14 November 2023.

Osieczko, K., et al., 2021, 'Factors that influence the expansion of electric delivery vehicles and trucks in EU countries', Journal of Environmental Management 296, p. 113177 (DOI: 10.1016/j.jenvman.2021.113177).

Pahle, M., 2023, 'Pricing carbon for a fair and effective low-carbon road transport transition in the EU', One Earth 6(1), pp. 7-10 (DOI: 10.1016/j.oneear.2022.12.005).

Pahle, M., et al., 2023, 'The Emerging Endgame: The EU ETS on the Road Towards Climate Neutrality', Rochester, NY (https://papers.ssrn.com/abstract=4373443).

Pantzar, M. and Suljada, T., 2020, Delivering a circular economy within the planet's boundaries - An analysis of the new EU Circular Economy Action Plan, Institute for European Enviornmental Policy and Stockholm Environment Institute (https://ieep.eu/publications/an-analysis-of-the-new-eu-circular-economy-action-plan/) accessed 29 July 2023.

Partridge, C. and Medda, F. R., 2020, 'Green Bond Pricing: The Search for Greenium', The Journal of Alternative Investments 23(1), pp. 49-56 (DOI: 10.3905/jai.2020.1.096).

Pasichnyi, O., et al., 2019, 'Data-driven strategic planning of building energy retrofitting: The case of Stockholm', Journal of Cleaner Production 233, pp. 546-560 (DOI: 10.1016/j.jclepro.2019.05.373).

Pastori, E., et al., 2018, Research for TRAN Committee — Modal shift in European transport: a way forward, European Union (https://www.europarl.europa.eu/RegData/etudes/STUD/2018/629182/IPOL_STU(2018)629182_EN.pdf) access 18 November 2023.

Patacca, M., et al., 2023, 'Significant increase in natural disturbance impacts on European forests since 1950', Global Change Biology 29(5), pp. 1359-1376 (DOI: 10.1111/gcb.16531).

Pe'er, G., et al., 2019, 'A greener path for the EU Common Agricultural Policy', Science 365(6452), pp. 449-451 (DOI: 10.1126/science.aax3146).

Pe'er, G., et al., 2022, 'How can the European Common Agricultural Policy help halt biodiversity loss? Recommendations by over 300 experts', Conservation Letters (DOI: 10.1111/conl.12901).

Peeters, M. and Athanasiadou, N., 2020, 'The continued effort sharing approach in EU climate law: Binding targets, challenging enforcement?', Review of European, Comparative & International Environmental Law 29(2), pp. 201-211 (DOI: 10.1111/reel.12356).

Peñasco, C., et al., 2017, 'Analysing the Role of International Drivers for Eco-innovators', Journal of International Management 23(1), pp. 56-71 (DOI: 10.1016/j.intman.2016.09.001).

Peñasco, C., et al., 2021, 'Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments', Nature Climate Change 11(3), pp. 257-265 (DOI: 10.1038/s41558-020-00971-x).

Pérez Dominguez, I., et al., 2020, 'Economic assessment of GHG mitigation policy options for EU agriculture: A closer look at mitigation options and regional mitigation costs (EcAMPA 3)', JRC Research Reports (https://data.europa.eu/doi/10.2760/4668).

Philippidis, G., et al., 2019, 'Waste not, want not: A bio-economic impact assessment of household food waste reductions in the EU', Resources, Conservation and Recycling 146, pp. 514-522 (DOI: 10.1016/j.resconrec.2019.04.016).

Pilli, R., et al., 2022, 'The European forest carbon budget under future climate conditions and current management practices', Biogeosciences 19(13), pp. 3263-3284 (DOI: 10.5194/bg-19-3263-2022).

Pomponi, F., et al., 2021, 'Decoupling density from tallness in analysing the life cycle greenhouse gas emissions of cities', npj Urban Sustainability 1(1), p. 33 (DOI: 10.1038/s42949-021-00034-w).

Poore, J. and Nemecek, T., 2018, 'Reducing food's environmental impacts through producers and consumers', Science 360(6392), pp. 987-992 (DOI: 10.1126/science.aaq0216).

Popp, D. and Newell, R., 2012, 'Where does energy R&D come from? Examining crowding out from energy R&D', Energy Economics 34(4), pp. 980-991 (DOI: 10.1016/j.eneco.2011.07.001).

Potoćnik, J. and Teixeira, I., 2022, Making climate targets achievable. Improving wellbeing through reduced absolute resource use, A think piece of the International Resource Panel Co-Chairs, International Resource Panel (https://www.resourcepanel.org/reports/making-climate-targets-achievable) accessed 14 December 2023.

PPCA, 2017, PPCA Declaration, (https://poweringpastcoal.org/wp-content/uploads/PPCA-Declaration_Text-1.pdf) accessed 19 October 2023.

Prettico, G., et al., 2021, Distribution System Operator Observatory 2020. An in-depth look on distribution grids in Europe, JRC Science for Policy Report, Publications Office of the European Union, Luxembourg (https://data.europa.eu/doi/10.2760/311966).

Probst, B., et al., 2021, 'Global trends in the invention and diffusion of climate change mitigation technologies', Nature Energy 6(11), pp. 1077-1086 (DOI: 10.1038/s41560-021-00931-5).

Puga, D., 2010, 'The magnitude and causes of agglomeration economies', Journal of Regional Science 50(1), pp. 203-219 (DOI: 10.1111/j.1467-9787.2009.00657.x).

Ramos, V., et al., 2021, 'Legal framework of marine renewable energy: A review for the Atlantic region of Europe', Renewable and Sustainable Energy Reviews 137, p. 110608 (DOI: 10.1016/j.rser.2020.110608).

Re Cecconi, F., et al., 2022, 'Data-driven decision support system for building stocks energy retrofit policy', Journal of Building Engineering 54, p. 104633 (DOI: 10.1016/j.jobe.2022.104633).

Reis, V., et al., 2013, 'Rail and multi-modal transport', Research in Transportation Economics 41(1), pp. 17-30 (DOI: 10.1016/j.retrec.2012.10.005).

Reisinger, A., et al., 2021, 'How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals?', Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 379(2210), p. 20200452 (DOI: 10.1098/rsta.2020.0452).

Renders, N., et al., 2021, 'Standardized savings calculations within Europe: exchanging practices to streamline theory and practice', ECEEE Summer study proceedings, 2021. ISBN: 978-91-983878-9-3 (https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2021/4-monitoring-and-evaluation-for-a-wise-just-and-inclusive-transition/standardized-savings-calculations-within-europe-exchanging-practices-to-streamline-theory-and-practice/).

RGI, 2023, 'Public Acceptance', Renewables Grid Initiative (https://renewables-grid.eu/topics/public-acceptance.html?L=) accessed 14 September 2023.

Rickels, W., et al., 2022, 'Procure, Bank, Release: Carbon Removal Certificate Reserves to Manage Carbon Prices on the Path to Net-Zero', Energy Research & Social Science 94, p. 102858 (DOI: 10.1016/j.erss.2022.102858).

Rickels, W., et al., 2023, Potential efficiency gains from the introduction of an emissions trading system for the buildings and road transport sectors in the European Union, Working Paper No 2249, Kiel Working Paper (https://www.econstor.eu/handle/10419/273080).

Rietig, K., 2019, 'The importance of compatible beliefs for effective climate policy integration', Environmental Politics 28(2), pp. 228-247 (DOI: 10.1080/09644016.2019.1549781).

Ritchie, H., 2020, The carbon footprint of foods: are differences explained by the impacts of methane? (https://ourworldindata.org/carbon-footprint-food-methane) accessed 10 November 2023.

Rivers, N. and Schaufele, B., 2015, 'Salience of carbon taxes in the gasoline market', Journal of Environmental Economics and Management 74, pp. 23-36 (DOI: 10.1016/j.jeem.2015.07.002).

Roberts, C. and Geels, F. W., 2019, 'Conditions and intervention strategies for the deliberate acceleration of socio-technical transitions: lessons from a comparative multi-level analysis of two historical case

studies in Dutch and Danish heating', Technology Analysis and Strategic Management, pp. 1-23 (DOI: 10.1080/09537325.2019.1584286).

Rogelj, J., et al., 2021, 'Net-zero emissions targets are vague: three ways to fix', Nature 591(7850), pp. 365-368 (DOI: 10.1038/d41586-021-00662-3).

Rogge, K. S. and Reichardt, K., 2016, 'Policy mixes for sustainability transitions: an extended concept and framework for analysis', Research Policy 45(8), pp. 1620-1635 (DOI: 10.1016/j.respol.2016.04.004).

Rosenbloom, D., et al., 2020, 'Why carbon pricing is not sufficient to mitigate climate change—and how "sustainability transition policy" can help', Proceedings of the National Academy of Sciences 117(16), pp. 8664-8668 (DOI: 10.1073/pnas.2004093117).

Rosenow, J., et al., 2023, 'Levelling the playing field: Aligning heating energy taxes and levies in Europe with climate goals', Regulatory Assistance Project (https://www.raponline.org/knowledge-center/aligning-heating-energy-taxes-levies-europe-climate-goals/) accessed 17 October 2023.

Rosenthal, S. and Strange, W., 2004, 'Evidence on the nature and sources of agglomeration economies', in: Henderson, J. V. and Thisse, J. F. (eds), Handbook of Regional and Urban Economics, , pp. 2120-2171.

Ruiz, M. A., et al., 2023, 'Regulatory Challenges for Energy Infrastructure—Do Electricity Distribution Remuneration Schemes in Europe Promote the Use of Flexibility from Connected Users?', Current Sustainable/Renewable Energy Reports (DOI: 10.1007/s40518-023-00214-5).

Ruiz, P., et al., 2019, 'ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials', Energy Strategy Reviews 26, p. 100379 (DOI: 10.1016/j.esr.2019.100379).

Runge-Metzger, A. and Van Ierland, T., 2019, 'The Effort Sharing Regulation', in: Towards a Climate-Neutral Europe, Delbeke J and Vis P, Routledge ISBN 9789276082613.

Salvia, M., et al., 2021, 'Improving policy making and strategic planning competencies of public authorities in the energy management of municipal public buildings: The PrioritEE toolbox and its application in five mediterranean areas', Renewable and Sustainable Energy Reviews 135, p. 110106 (DOI: 10.1016/j.rser.2020.110106).

SAPEA, 2020, 'A sustainable food system for the European Union', Science Advice Policy by European Academies, DOI: 10.2777/282386 (https://scientificadvice.eu/advice/a-sustainable-food-system-for-the-european-union/).

SAPEA, 2023, Towards sustainable food consumption: Evidence review report, Zenodo (https://zenodo.org/doi/10.5281/zenodo.8031938).

Sapir, A., et al., 2022, 'Green Public Procurement: A Neglected Tool in the European Green Deal Toolbox?', Intereconomics 57(3), pp. 175-178 (DOI: 10.1007/s10272-022-1044-7).

Schebesta, H. and Candel, J. J. L., 2020, 'Game-changing potential of the EU's Farm to Fork Strategy', Nature Food 1(10), pp. 586-588 (DOI: 10.1038/s43016-020-00166-9).

Schiavina, M., et al., 2022, 'Land use efficiency of functional urban areas: Global pattern and evolution of development trajectories', Habitat International 123, p. 102543 (DOI: 10.1016/j.habitatint.2022.102543).

Schlacke, S., et al., 2022, 'Implementing the EU Climate Law via the "Fit for 55" package', Oxford Open Energy 1, p. oiab002 (DOI: 10.1093/ooenergy/oiab002).

Schneider, E., 2023, 'Germany's Industrial strategy 2030, EU competition policy and the Crisis of New Constitutionalism. (Geo-)political economy of a contested paradigm shift', New Political Economy 28(2), pp. 241-258 (DOI: 10.1080/13563467.2022.2091535).

Schoenefeld, J. J. and Knodt, M., 2021, 'Softening the surface but hardening the core? Governing renewable energy in the EU', West European Politics 44(1), pp. 49-71 (DOI: 10.1080/01402382.2020.1761732).

Schumacher, K., 2019, 'Approval procedures for large-scale renewable energy installations: Comparison of national legal frameworks in Japan, New Zealand, the EU and the US', Energy Policy 129, pp. 139-152 (DOI: 10.1016/j.enpol.2019.02.013).

Schütze, F. and Stede, J., 2021, 'The EU sustainable finance taxonomy and its contribution to climate neutrality', Journal of Sustainable Finance & Investment, pp. 1-33 (DOI: 10.1080/20430795.2021.2006129).

Schwerhof, G., et al., 2022, Equity and efficiency effects of land value taxation. IMF Working Paper No. 2022/263, (https://www.imf.org/en/Publications/WP/Issues/2022/12/17/Equity-and-Efficiency-Effects-of-Land-Value-Taxation-527079), International Monetary Fund.

Searchinger, T., et al., 2022a, 'EU climate plan sacrifices carbon storage and biodiversity for bioenergy', Nature 612(7938), pp. 27-30 (DOI: 10.1038/d41586-022-04133-1).

Searchinger, T., et al., 2022b, Europe's land future? Opportunities to use Europe's land to fight climate change and improve biodiversity - and why proposed policies could undermine both, Princeton University (https://searchinger.princeton.edu/sites/g/files/toruqf4701/files/searchinger-james-dumas_europes_land_future_full_report_2022.pdf) accessed 26 November 2023.

Searle, S., 2021, Intermediate crops in the Renewable Energy Directive, ICCT Fact Sheet, The International Council on Clean Transportation (https://theicct.org/sites/default/files/publications/intermediate-crops-RED-II-eu-oct21.pdf).

Segreto, M., et al., 2020, 'Trends in Social Acceptance of Renewable Energy Across Europe—A Literature Review', International Journal of Environmental Research and Public Health 17(24), p. 9161 (DOI: 10.3390/ijerph17249161).

Seidl, R., et al., 2017, 'Forest disturbances under climate change', Nature Climate Change 7(6), pp. 395-402 (DOI: 10.1038/nclimate3303).

Semieniuk, G., et al., 2022, 'Stranded fossil-fuel assets translate to major losses for investors in advanced economies', Nature Climate Change 12(6), pp. 532-538 (DOI: 10.1038/s41558-022-01356-y).

Senf, C. and Seidl, R., 2020, 'Mapping the forest disturbance regimes of Europe', Nature Sustainability 4(1), pp. 63-70 (DOI: 10.1038/s41893-020-00609-y).

Serafimova, T., et al., 2022, Modal shift: the moment of truth. Main takeaways and lessons learnt from the European year of rail, (https://fsr.eui.eu/publications/?handle=1814/74040) accessed 17 October 2022.

Sesana, M. M., et al., 2020, 'Overview of the Available Knowledge for the Data Model Definition of a Building Renovation Passport for Non-Residential Buildings: The ALDREN Project Experience', Sustainability 12(2), p. 642 (DOI: 10.3390/su12020642).

Seto, K. C., et al., 2016, 'Carbon Lock-In: Types, Causes, and Policy Implications', Annual Review of Environment and Resources 41(1), pp. 425-452 (DOI: 10.1146/annurev-environ-110615-085934).

Shishlov, I. and Censkowsky, P., 2022, 'Definitions and accounting of climate finance: between divergence and constructive ambiguity', Climate Policy 22(6), pp. 798-816 (DOI: 10.1080/14693062.2022.2080634).

Shoman, W., et al., 2023, 'Battery electric long-haul trucks in Europe: Public charging, energy, and power requirements', Transportation Research Part D: Transport and Environment 121, p. 103825 (DOI: 10.1016/j.trd.2023.103825).

Sikkema, R., et al., 2021, 'How can solid biomass contribute to the EU's renewable energy targets in 2020, 2030 and what are the GHG drivers and safeguards in energy- and forestry sectors?', Renewable Energy 165, pp. 758-772 (DOI: 10.1016/j.renene.2020.11.047).

Simon, M., et al., 2022, 'What is missing for large scale deployment of CCS in Europe?', SSRN Electronic Journal (DOI: 10.2139/ssrn.4276193).

Skinner, C., et al., 2014, 'Greenhouse gas fluxes from agricultural soils under organic and non-organic management — A global meta-analysis', Science of The Total Environment 468-469, pp. 553-563 (DOI: 10.1016/j.scitotenv.2013.08.098).

Slominski, P., 2016, 'Energy and climate policy: does the competitiveness narrative prevail in times of crisis?', Journal of European Integration 38(3), pp. 343-357 (DOI: 10.1080/07036337.2016.1140759).

SolarPower Europe, 2022a, EU market outlook for solar power: 2022-2026 (https://www.solarpowereurope.org/insights/market-outlooks/eu-market-outlook-for-solar-power-2022-2026-2) accessed 19 October 2023.

SolarPower Europe, 2022b, EU Solar Jobs Report 2022 - Addressing the solar skills challenge (https://api.solarpowereurope.org/uploads/SPE_EU_Solar_Jobs_Report_September_2022_5925da42fc.pdf?updated_at=2022-09-20T14:05:03.808Z) accessed 6 October 2023.

Stepanyan, D., et al., 2023, 'Impacts of national vs European carbon pricing on agriculture', Environmental Research Letters 18(7), p. 074016 (DOI: 10.1088/1748-9326/acdcac).

Stephan, A., et al., 2017, 'The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan', Research Policy 46(4), pp. 709-723 (DOI: 10.1016/j.respol.2017.01.009).

Stiglitz, J. E., 2019, 'Addressing climate change through price and non-price interventions', European Economic Review 119, pp. 594-612 (DOI: 10.1016/j.euroecorev.2019.05.007).

Strefler, J., et al., 2021, 'Alternative carbon price trajectories can avoid excessive carbon removal', Nature Communications 12(1), p. 2264 (DOI: 10.1038/s41467-021-22211-2).

Sykes, A. J., et al., 2020, 'Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology', Global Change Biology 26(3), pp. 1085-1108 (DOI: 10.1111/gcb.14844).

Szabo, J., 2022, 'Energy transition or transformation? Power and politics in the European natural gas industry's trasformismo', Energy Research & Social Science 84, p. 102391 (DOI: 10.1016/j.erss.2021.102391).

Tagliapietra, S., et al., 2019, 'The European union energy transition: Key priorities for the next five years', Energy Policy 132, pp. 950-954 (DOI: 10.1016/j.enpol.2019.06.060).

Teixidó, J., et al., 2019, 'The impact of the EU Emissions Trading System on low-carbon technological change: The empirical evidence', Ecological Economics 164, p. 106347 (DOI: 10.1016/j.ecolecon.2019.06.002).

Temme, E. H. M., et al., 2020, 'Demand-Side Food Policies for Public and Planetary Health', Sustainability 12(15), p. 5924 (DOI: 10.3390/su12155924).

Thies, C., et al., 2022, 'Project portfolio planning under CO 2 fleet emission restrictions in the automotive industry', Journal of Industrial Ecology 26(3), pp. 937-951 (DOI: 10.1111/jiec.13228).

Thomas, S., et al., 2019, 'Energy sufficiency policy for residential electricity use and per-capita dwelling size', Energy Efficiency 12(5), pp. 1123-1149 (DOI: 10.1007/s12053-018-9727-4).

Thomson, H., et al., 2019, 'Energy poverty and indoor cooling: An overlooked issue in Europe', Energy and Buildings 196, pp. 21-29 (DOI: 10.1016/j.enbuild.2019.05.014).

Toreti, A., et al., 2022, Drought in Europe: July 2022 : GDO analytical report. Technical Report by the JRC., Publications Office, LU (https://dx.doi.org/10.2760/014884).

Trinomics, 2020, Final Report Energy Taxes. Energy costs, taxes and the impact of government interventions on investments (https://trinomics.eu/wp-content/uploads/2020/11/Final-Report-Energy-Taxes.pdf).

Trinomics, 2023a, Applying the polluter-pays principle to agricultural emissions, No DOI: 10.2834/200 (https://climate.ec.europa.eu/document/996c24d8-9004-4c4e-b637-60b384ae4814_en).

Trinomics, 2023b, Assessment of the potential of sustainable fuels in transport, Study requested by the TRAN Committee, European Parliament. DOI: 10.2833/36298 (https://www.europarl.europa.eu/RegData/etudes/STUD/2023/733103/IPOL_STU(2023)733103_EN.pdf).

Tsemekidi Tzeiranaki, S., et al., 2019, 'Analysis of the EU Residential Energy Consumption: Trends and Determinants', Energies 12(6), p. 1065 (DOI: 10.3390/en12061065).

Tuomisto, H. L., et al., 2012, 'Does organic farming reduce environmental impacts? – A meta-analysis of European research', Journal of Environmental Management 112, pp. 309-320 (DOI: 10.1016/j.jenvman.2012.08.018).

UK CCC, 2022, 'CCC Monitoring Framework: assessing UK progress in reducing emissions' (https://www.theccc.org.uk/publication/ccc-monitoring-framework/?chapter=3-buildings#3-buildings) accessed 24 June 2023.

UNFCCC, 2015, The Paris Agreement, United Nations Framework Convention on Climate Change, Paris (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement) accessed 7 March 2021.

UNFCCC, 2021, World Leaders Kick Start Accelerated Climate Action at COP26, (https://unfccc.int/news/world-leaders-kick-start-accelerated-climate-action-at-cop26) accessed 14 April 2023.

UNFCCC, 2023, Technical dialogue of the first global stocktake Synthesis report by the co-facilitators on the technical dialogue, United Nations Framework Convention on Climate Change (https://unfccc.int/documents/631600) accessed 20 October 2023.

UNEP and CCAC, 2021, Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions., Nairobi. ISBN: 978-92-807-3854-4 (https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions).

Unterreiner, L., et al., 2016, 'Recycling of Battery Technologies – Ecological Impact Analysis Using Life Cycle Assessment (LCA)', Energy Procedia 99, pp. 229-234 (DOI: 10.1016/j.egypro.2016.10.113).

URBACT, 2023, 'URBACT' (https://urbact.eu/taxonomy/term/1364) accessed 27 November 2023.

Urban Agenda for the EU, 2021, Mainstreaming functional urban areas cooperation as a tool to mitigate urban sprawl. Guidelines and recommendations. (https://futurium.ec.europa.eu/sites/default/files/2021-09/2.5.5-Action%205-%20Promoting%20FUA%20cooperation%20%20as%20a%20tool%20to%20mitigate%20sprawl-Guidebook.pdf) accessed 08 September 2023.

Valin, H., et al., 2015, The land use change impact of biofuels consumed in the EU. Quantification of area and greenhouse as impacts, Study by Ecofys, IIASA and E4Tech for the European Commission (https://energy.ec.europa.eu/publications/land-use-change-impact-biofuels-consumed-eu_en) accessed 12 October 2023.

Van Den Oever, A. E. M., et al., 2022, 'Systematic review on the energy conversion efficiency of biomass-based Fischer-Tropsch plants', Fuel 324, p. 124478 (DOI: 10.1016/j.fuel.2022.124478).

Van Der Linden, S., et al., 2021, 'Behavioural climate policy', Behavioural Public Policy 5(4), pp. 430-438 (DOI: 10.1017/bpp.2020.44).

van Grinsven, A., et al., 2020, Used Cooking Oil (UCO) as biofuel feedstock in the EU. CE Delft report for Transport & Environment, (https://www.regenwald-statt-palmoel.de/images/pdf/CE_Delft_UCO.pdf).

Velten, E. et al., 2021, 'Measuring progress towards climate neutrality. Part I: assessing structural change through net zero indicators', Ecologic and IDDRI, (https://www.ecologic.eu/sites/default/files/publication/2021/Net_Zero_Indicators_Part_1-Technical_Proposal.pdf)

Venmans, F. M. J., 2016, 'The effect of allocation above emissions and price uncertainty on abatement investments under the EU ETS', Journal of Cleaner Production 126, pp. 595-606 (DOI: 10.1016/j.jclepro.2016.02.108).

Verde, S. F., et al., 2019, 'Free allocation rules in the EU emissions trading system: what does the empirical literature show?', Climate Policy 19(4), pp. 439-452 (DOI: 10.1080/14693062.2018.1549969).

Villarejo, P., et al., 2021, 'Building Renovation Passports in Spain: Integrating exiting instruments for building conservation, renovation and heritage protection', Energy Policy 157, p. 112506 (DOI: 10.1016/j.enpol.2021.112506).

Vogl, V., et al., 2021, 'The making of green steel in the EU: a policy evaluation for the early commercialization phase', Climate Policy 21(1), pp. 78-92 (DOI: 10.1080/14693062.2020.1803040).

Von Malmborg, F., 2023, 'First and last and always: Politics of the "energy efficiency first" principle in EU energy and climate policy', Energy Research & Social Science 101, p. 103126 (DOI: 10.1016/j.erss.2023.103126).

Vonsée, B., et al., 2019, 'Energy technology dependence - A value chain analysis of geothermal power in the EU', Energy 178, pp. 419-435 (DOI: 10.1016/j.energy.2019.04.043).

Voulis, N., et al., 2019, 'Rethinking European energy taxation to incentivise consumer demand response participation', Energy Policy 124, pp. 156-168 (DOI: 10.1016/j.enpol.2018.09.018).

Wagner, C., et al., 2020, 'A methodology for the assessment of multiple benefits of industrial energy efficiency measures', SN Applied Sciences 2(2), p. 270 (DOI: 10.1007/s42452-020-2071-2).

Wallace, N., 2019, 'EU member states agree on €38B InvestEU loans programme', Science Business, 25 February 2019 (https://sciencebusiness.net/news/eu-member-states-agree-eu38b-investeu-loans-programme) accessed 28 October 2023.

Watkins, E. and Meysner, A., 2022, European Circular Economy policy landscape overview. A report for PBL Netherlands Environmental Assessment Agency, Institute for European Environmental Policy (https://ieep.eu/wp-content/uploads/2022/11/European-Circular-Economy-policy-landscape-overview.pdf).

WCRF, 'Red and processed meat and cancer risks' (https://www.wcrf-uk.org/preventing-cancer/what-can-increase-your-risk-of-cancer/red-and-processed-meat-and-cancer-risk/#:~:text=This%20includes%20foods%20like%20steak,750g%20raw%20weight)%20a%20week.) accessed 29 June 2023.

Weikmans, R. and Roberts, J. T., 2019, 'The international climate finance accounting muddle: is there hope on the horizon?', Climate and Development 11(2), pp. 97-111 (DOI: 10.1080/17565529.2017.1410087).

Weitzel, M., et al., 2023, 'A comprehensive socio-economic assessment of EU climate policy pathways', Ecological Economics 204, p. 107660 (DOI: 10.1016/j.ecolecon.2022.107660).

Wells, G., et al., 2023, 'Confronting deep uncertainty in the forest carbon industry', Science 382(6666), pp. 41-43 (DOI: 10.1126/science.adh8117).

Wendler, M. and Halkier, B., 2023, 'Dietary transition requires work: exploring the practice-transition processes of young Danish meat reducers', Food, Culture & Society 0(0), pp. 1-19 (DOI: 10.1080/15528014.2023.2193501).

Wiehe, J., et al., 2020, 'How to achieve the climate targets? Spatial planning in the context of the German energy transition', Energy, Sustainability and Society 10(1), p. 10 (DOI: 10.1186/s13705-020-0244-x).

Willett, W., et al., 2019, 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', The Lancet 393(10170), pp. 447-492 (DOI: 10.1016/S0140-6736(18)31788-4).

Willis, R., et al., 2022, 'Deliberative democracy and the climate crisis', WIREs Climate Change 13(2), p. e759 (DOI: 10.1002/wcc.759).

WindEurope, 2022, 'What is the wind industry doing on skills and education to deliver a fair transition?' (https://windeurope.org/newsroom/news/what-is-the-wind-industry-doing-on-skills-and-education-to-deliver-a-fair-transition/) accessed 6 October 2023.

WindEurope, 2023, 'Wind energy in Europe: 2022 statistics and the outlook for 2023-2027, (https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027/)

WindEurope and Eurofer, 2023, Ensuring access to critical materials for steel and wind sectors essential for EU clean-tech economy, (https://windeurope.org/newsroom/press-releases/ensuring-access-to-critical-materials-for-steel-and-wind-sectors-essential-for-eu-clean-tech-economy/) accessed 6 November 2023.

Winter, G., 2020, 'Armando Carvalho and Others v. EU: Invoking Human Rights and the Paris Agreement for Better Climate Protection Legislation', Transnational Environmental Law 9(1), pp. 137-164 (DOI: 10.1017/S2047102520000072).

World Bank, 2023, State and trends of carbon pricing, 2023 (https://blogs.worldbank.org/climatechange/state-and-trends-carbon-pricing-2023).

WPKS, 2022, Auf dem Weg zur Klimaneutralität: Umsetzung des European Green Deal und Reform der Klimapolitik in Deutschland. Jahresgutachten 2021, Wissenschaftsplattform Klimaschutz (https://www.wissenschaftsplattform-klimaschutz.de/de/Jahresgutachten2021.html).

Wyns, T. and Khandekar, G., 2019, 'Industrial Climate Neutrality in the EU: Outline of an Integrated Industrial Green Deal', Intereconomics 54(6), pp. 325-332 (DOI: 10.1007/s10272-019-0848-6).

Wyns, T. and Khandekar, G., 2020, Metals for a climate neutral Europe: A 2050 blueprint, Institute for European Studies (https://www.eurometaux.eu/media/2005/full-report-8-56-17.pdf) accessed 14 October 2020.

Yeo, S., 2019, 'Where climate cash is flowing and why it's not enough', Nature 573(7774), pp. 328-332.

Zakeri, B., et al., 2022, 'Pandemic, War, and Global Energy Transitions', Energies 15(17), p. 6114 (DOI: 10.3390/en15176114).

Zaklan, A., 2023, 'Coase and Cap-and-Trade: Evidence on the Independence Property from the European Carbon Market', American Economic Journal: Economic Policy 15(2), pp. 526-558 (DOI: 10.1257/pol.20210028).

Zangheri, P., et al., 2019, 'Progress in the Implementation of the EU Energy Efficiency Directive through the Lens of the National Annual Reports', Energies 12(6), p. 1107 (DOI: 10.3390/en12061107).

Zannakis, M., et al., 2019, 'On the Relationship between Pro-Environmental Behavior, Experienced Monetary Costs, and Psychological Gains', Sustainability 11(19), p. 5467 (DOI: 10.3390/su11195467).

Zech, K. M. and Schneider, U. A., 2019, 'Carbon leakage and limited efficiency of greenhouse gas taxes on food products', Journal of Cleaner Production 213, pp. 99-103 (DOI: 10.1016/j.jclepro.2018.12.139).

Zell-Ziegler, C., et al., 2021, 'Enough? The role of sufficiency in European energy and climate plans', Energy Policy 157, p. 112483 (DOI: 10.1016/j.enpol.2021.112483).

Zhang, J. and Asutosh, A. T., 2023, 'A Sustainability Analysis Based on the LCA–Emergy–Carbon Emission Approach in the Building System', Applied Sciences 13(17), p. 9707 (DOI: 10.3390/app13179707).

Annex I - Sources and details for the assessment of progress

Indicator	*Historic progress*	*2030 benchmark*		*2050 benchmark*	
	Source	*source*	*type*	*source*	*type*
O1: overall GHG emission reductions	EU GHG inventory, 2022 based on proxy data	European Climate Law	legal objective	European Climate Law	legal objective
O2: primary and final energy consumption	Eurostat (nrg_bal_c)	Energy Efficiency Directive	legal objective	CTP MIX scenario	EC scenario output
O3: % of fossils in EU gross inland energy consumption	Eurostat (nrg_bal_c)	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
E1: energy supply GHG emissions	EU GHG inventory, 2022 based on proxy data	FF55 MIX scenario	EC scenario output	ACP4A 1.5LIFE and 1.5 TECH scenario	EC scenario output
E2a: share of fossils in the electricity mix	Eurostat (nrg_bal_c)	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
E2b: share of fossils in the electricity mix	Eurostat (nrg_bal_c)	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
E3: average electricity GHG intensity	EEA data	FF55 MIX scenario	EC scenario output	ACP4A 1.5LIFE and 1.5TECH scenario	EC scenario output
E4a: solar PV deployment	Eurostat (nrg_inf_epcrw)	FF55 MIX scenario, REPowerEU	EC scenario output	CTP MIX scenario	EC scenario output
E4b: onshore wind energy deployment	Eurostat (nrg_inf_epcrw)	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
E4c: offshore wind energy deployment	Eurostat (nrg_inf_epcrw)	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
E5: electrification rate	Eurostat (nrg_bal_c)	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
E6: energy-related methane emissions	EU GHG inventory	FF55 MIX scenario	EC scenario output	ACP4A 1.5LIFE scenario	EC scenario output
I1: industry GHG emissions	EU GHG inventory, EU ETS data for cement	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output

Indicator	*Historic progress*	*2030 benchmark*		*2050 benchmark*	
	Source	*source*	*type*	*source*	*type*
I2a: steel use	Eurofer for production and use, Eurostat (DS-059268) for trade	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
I2b: cement use	Eurofer for production and use, Eurostat (DS-059268) for trade	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
I2c: chemicals use	Eurostat for production and trade, use estimated by the Advisory Board	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
I3: Circular Material Use Rate	EEA	8th EAP	policy objective	*no benchmark*	*no benchmark*
I4a: GHG intensity steel	Eurofer for production, EU GHG inventories for emissions	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
I4b: GHG intensity cement	Cembureau for production, EU ETS data for GHG emissions	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
I4c: GHG intensity chemicals	Eurostat for production, EU ETS data for GHG emissions	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
I5: final energy use	Eurostat (nrg_bal_c)	FF55 MIX scenario, REPowerEU	EC scenario output	CTP MIX scenario	EC scenario output
I6a: % of fossils in final energy consumption	Eurostat (nrg_bal_c)	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
I6b: % of renewables in final energy consumption	Eurostat (nrg_bal_c)	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
I6c: % of electricity in final energy consumption	Eurostat (nrg_bal_c)	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
I7a: low-carbon projects in steel	Green Steel Tracker	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
I7b: low-carbon projects in cement	Cembureau	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*

Indicator	*Historic progress*	*2030 benchmark*		*2050 benchmark*	
	Source	*source*	*type*	*source*	*type*
I7c: low-carbon projects in chemicals	CEFIC	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
T1: transport GHG emissions	EU GHG inventory, 2022 based on proxy data	FF55 MIX scenario	EC scenario output	Sustainable and smart mobility strategy	proposed objective
T2a: Passenger transport demand	Eurostat Statistical Pocketbook 2022	FF55 MIX scenario	EC scenario output	ACP4A 1.5TECH and 1.5LIFE scenario	EC scenario output
T2b: Freight transport demand	Eurostat Statistical Pocketbook 2022	FF55 MIX scenario	EC scenario output	ACP4A 1.5TECH and 1.5LIFE scenario	EC scenario output
T3a: % of cars in passenger transport	Eurostat Statistical Pocketbook 2022	FF55 MIX scenario	EC scenario output	ACP4A 1.5TECH and 1.5LIFE scenario	EC scenario output
T3b: % of lorries in freight transport	Eurostat Statistical Pocketbook 2022	FF55 MIX scenario	EC scenario output	ACP4A 1.5TECH and 1.5LIFE scenario	EC scenario output
T3c: aviation passenger transport	Eurostat Statistical Pocketbook 2022	FF55 MIX scenario	EC scenario output	ACP4A 1.5TECH and 1.5LIFE scenario	EC scenario output
T3d: high-speed rail passenger transport	Eurostat Statistical Pocketbook 2022	Sustainable and smart mobility strategy	proposed objective	Sustainable and smart mobility strategy	proposed objective
T3e: rail freight transport	Eurostat Statistical Pocketbook 2022	Sustainable and smart mobility strategy	proposed objective	Sustainable and smart mobility strategy	proposed objective
T3f: IWW freight transport	Eurostat Statistical Pocketbook 2022	Sustainable and smart mobility strategy	proposed objective	Sustainable and smart mobility strategy	proposed objective

Indicator	*Historic progress*	*2030 benchmark*		*2050 benchmark*	
	Source	*source*	*type*	*source*	*type*
T4a: CO_2 intensity new passenger cars	EEA	CO_2 performance standards cars and vans	Legal objective	CO_2 performance standards cars and vans	Legal objective
T4b: CO_2 intensity new vans	EEA	CO_2 performance standards cars and vans	Legal objective	CO_2 performance standards cars and vans	Legal objective
T5a: % of ZEVs in new cars	EEA	CO_2 performance standards cars and vans (2035 target)	Legal objective	CO_2 performance standards cars and vans (2035 target)	Legal objective
T5b: % of ZEVs in new vans	EEA	CO_2 performance standards cars and vans (2035 target)	Legal objective	CO_2 performance standards cars and vans (2035 target)	Legal objective
T5c: # of ZEVs in lorries fleet	Alternative Fuels Observatory	Sustainable and smart mobility strategy	proposed objective	*no benchmark*	*no benchmark*
T6a: % of fossil fuels in transport FEC	Eurostat (nrg_bal_c)	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
T6b: % of 1st gen biofuels in transport FEC	SHARES, Eurostat	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
B1: building GHG emissions	EU GHG inventory, 2022 based on proxy data	FF55 MIX scenario	EC scenario output	ACP4A 1.5LIFE	EC scenario output
B2a: residential buildings final energy use	Eurostat (nrg_bal_c)	FF55 scenarios/REPowerEU	EC scenario output	CTP MIX scenario	EC scenario output
B2b: tertiary buildings final energy use	Eurostat (nrg_bal_c)	FF55 scenarios/REPowerEU	EC scenario output	CTP MIX scenario	EC scenario output
B3a: Type 1 renovation rate residential	CTP impact assessment	CTP MIX scenario	EC scenario output	*no benchmark*	*no benchmark*
B3b: Type 1 renovation rate tertiary	CTP impact assessment	CTP MIX scenario	EC scenario output	*no benchmark*	*no benchmark*

Indicator	*Historic progress*	*2030 benchmark*		*2050 benchmark*	
	Source	*source*	*type*	*source*	*type*
B4a: residential built surface areas	European Building Stock Observatory, Odyssee database	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
B4b: tertiary built surface areas	European Building Stock Observatory, Odyssee database	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
B5a: % of fossils in residential energy use	Eurostat (nrg_bal_c)	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
B5b: % of fossils in tertiary energy use	Eurostat (nrg_bal_c)	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
B6: heat pump stock	EHPA	REPowerEU	proposed objective	*no benchmark*	*no benchmark*
A1: agriculture GHG emissions	EU GHG inventory, 2022 based on proxy data	FF55 MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
A2a: bovine meat GHG intensity	GHG emissions based on EU GHG inventories, production based on FAOSTAT	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
A2b: dairy GHG intensity	GHG emissions based on EU GHG inventories, production based on FAOSTAT	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
A2c: pig meat GHG intensity	GHG emissions based on EU GHG inventories, production based on FAOSTAT	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
A3a: total fertiliser use	EU GHG inventories	Farm to Fork Strategy	proposed objective	*no benchmark*	*no benchmark*
A3b: nitrogen use efficiency		Farm to Fork Strategy	proposed objective	*no benchmark*	*no benchmark*
A4a: total bovine meat production	FAOSTAT	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
A4b: total dairy production	FAOSTAT	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
A4c: total pig meat production	FAOSTAT	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*

Indicator	*Historic progress*	*2030 benchmark*		*2050 benchmark*	
	Source	*source*	*type*	*source*	*type*
A5a: bovine meat consumption	FAOSTAT	*no benchmark*	*no benchmark*	ACP4A 1.5 (diet 5)	EC scenario output
A5b: dairy consumption	FAOSTAT	*no benchmark*	*no benchmark*	ACP4A 1.5 (diet 5)	EC scenario output
A5c: pig meat consumption	FAOSTAT	*no benchmark*	*no benchmark*	ACP4A 1.5 (diet 5)	EC scenario output
A6: food waste	Eurostat (env_wasfw)	Farm to Fork Strategy	proposed objective	*no benchmark*	*no benchmark*
A7: agricultural feedstock use for biofuels	JRC MTO commodity flows	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
L1: overall net emissions	EU GHG inventory, 2022 based on proxy data	LULUCF Regulation	legal objective	LULUCF Regulation IA	EC scenario output
L2a: land-use change: forests	EU GHG inventory	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
L2b: land-use change: wetlands	EU GHG inventory	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
L3: gross deforestation	EU GHG inventory	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
L4: gross afforestation	EU GHG inventory	*no benchmark*	*no benchmark*	*no benchmark*	*no benchmark*
L5: net land take	EU GHG inventory	*no benchmark*	*no benchmark*	7th EAP	proposed objective
L6: forest carbon sink	EU GHG inventory	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
L7: emissions from non-forest lands	EU GHG inventory	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output
L8: bioenergy use	Eurostat (nrg_bal_c)	CTP MIX scenario	EC scenario output	CTP MIX scenario	EC scenario output

Annex II - Errata

Overview of corrections made since the first publication of the report (18 January 2024).

Last updated: 12 April 2024

Section	Correction
Overall	Minor changes to layout. Cross-references corrected throughout the report.
Recommendations and summary	Correction to numbering of headings.
Recommendations and summary, p. 24	Correction to the required reductions under the EU ETS by 2030 compared to 2005 (-62% instead of -43%, which is the former required reduction under the 2018 ETS Directive).
Table 4	Correction to historical progress (based on 2005-2022 instead of 2017-2021) and the corresponding progress category for indicator E1.
Figures 12, 22, 62, 78, 80, 85, 86	Minor corrections to formatting.
Chapter 5 – Key messages	Small edits on page 51 to clarify that fugitive CH_4 emissions from coal operations, fossil gas operations and biomass combustion are the three largest sources of energy-related CH_4 emissions.
4.3	Factual corrections made to the respective shares of solar PV and wind in the EU energy supply (pages 61 and 62).
Figure 17	Right graph (offshore): corrected alignment of data on the horizontal axis.
Chapter 5	Cross-reference to Chapter 13 and section 13.3 corrected on page 86.
Figure 24	Imports and exports removed from legend (no data provided).
Figure 25	Correction to the title of the vertical axis, and to the date range of the horizontal axis to 2010-2030.
Figures 35 to 38	Correction to the reference for the 2030 benchmarks in the underlying notes and sources (Fit for 55 MIX scenario instead of the MIX scenario of the Climate Target Plan).
6.3	Correction to the cross-reference to section 6.2 on page 112.
Figure 40	Correction to the underlying data for the right graph (vans).
Figure 41	Correction to the title of the vertical axis and correction to the 2010 marker on the horizontal axis of the right graph (vans).
Figure 44	Data converted from Mtoe to TWh. Data source for the 2050 benchmark is corrected to the MIX scenario of the Climate Target Plan.
Figure 52	Correction to the title of the vertical axis.
Figure 58	Correction to the title of the figure.
Figure 61	Correction to the title of the vertical axis.
12.2	Page 240: for REPowerEU, the required annual investments were estimated at EUR 1450 billion, which was calculated as EUR 1241 bn per year under (Fit for 55) + an additional EUR 210 bn annually under REPowerEU. This was incorrect, as the EUR 210 bn figure for REPowerEU are the cumulative additional required investments in 2022-2027. The figure is now corrected to EUR 1276 bn (= EUR 1241 bn under Fit for 55 + EUR 35 bn additional per year under REPowerEU, based on an additional EUR 300 bn for the entire period 2022 to 2030).
Figure 77	Correction to the underlying data: - The data for CTP '21-'30 and FF55 '21-'30 was switched (correct data: EUR 1205 bn for CTP '21-'30 and EUR 1241 bn for FF55 '21-'30).

	- The data for REPowerEU '21-'30 is corrected from EUR 1450 bn to EUR 1276 bn (see above).
Footnote (9)	Correction to the required additional annual investments under the Net-Zero Industry Act to EUR 12 bn per year (92 cummulatively to 2030).


European Scientific
Advisory Board on
Climate Change

INDICATOR SPECIFICATION

Ammonia (NH3) emissions

This indicator tracks trends since 1990 in anthropogenic emissions of sulphur dioxide. The indicator also provides information on emissions by sectors: energy production and distribution; energy use in industry; industrial processes; road transport; non-road transport; commercial, institutional and households; solvent and product use; agriculture; waste; other. Geographical coverage: EEA-32. The EEA-32 country grouping includes countries of the EU-27 (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom) EFTA-4 (Iceland, Liechtenstein, Switzerland and Norway) and Turkey. Temporal coverage: 1990-2010

This indicator is discontinued. No more assessments will be produced.

Assessment versions

Published (reviewed and quality assured)

No published assessments

Rationale

Justification for indicator selection

The agriculture sector is responsible for over 90% of NH_3 emissions across the EEA-32. NH_3 contributes to acid deposition and eutrophication, which in turn, can lead to potential changes occurring in soil and water quality. The subsequent impacts of acid deposition can be significant, including adverse effects on aquatic ecosystems in rivers and lakes, and damage to forests, crops and other vegetation. Eutrophication can lead to severe reductions in water quality with subsequent impacts including decreased biodiversity, changes in species composition and dominance, and toxicity effects. In many cases, the deposition of acidifying and eutrophying substances still exceeds the critical loads of the ecosystems (see EEA indicator CSI 005 'Exposure of ecosystems to acidification, eutrophication and ozone'). Further details concerning emissions of acidifying pollutants are provided in the EEA Core Set Indicator CSI 001 'Emissions of acidifying substances'.

As a secondary particulate precursor, NH_3 also contributes to the formation of particulate aerosols in the atmosphere. Particulate matter is an important air pollutant due to its adverse impact on human health and NH_3 is therefore also indirectly linked to effects on human health (see EEA Core Set Indicator CSI 003 'Emissions of primary particles and secondary particulate precursors' for further details concerning emissions of particulate matter.

Scientific references

No rationale references available

Indicator definition

This indicator tracks trends since 1990 in anthropogenic emissions of sulphur dioxide.

The indicator also provides information on emissions by sectors: energy production and distribution; energy use in industry; industrial processes; road transport; non-road transport; commercial, institutional and households; solvent and product use; agriculture; waste; other.

Geographical coverage: EEA-32. The EEA-32 country grouping includes countries of the EU-27 (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom) EFTA-4 (Iceland, Liechtenstein, Switzerland and Norway) and Turkey.

Temporal coverage: 1990-2010

Units

ktonnes (1000 tonnes)

Policy context and targets

Context description

A number of policies have been implemented within Europe that either directly or indirectly act to reduce emissions of NH_3. These include:

The National Emission Ceilings Directive 2001/81/EC (NECD) which entered into force in the European Community in 2001. The NECD sets emission ceilings for four important air pollutants (NH_3, sulphur dioxide (SO_2), nitrogen oxides (NO_X) and non-methane volatile organic compounds (NMVOCs)) to be achieved from 2010 onwards for each Member State. The ceilings are designed to improve the protection in the Community of the environment and human health against risks of adverse effects arising from acidification, eutrophication and ground level ozone. The NECD is presently under review, the European Commission may adopt a proposal for a revised Directive during 2010.

The Gothenburg Protocol (1999) to the United Nations Economic Commission for Europe's (UNECE) Convention on Long-Range Transboundary Air Pollution (LRTAP Convention) to abate acidification, eutrophication and ground-level ozone. A key objective of the protocol is to regulate emissions on a regional basis within Europe and to protect eco-systems from transboundary pollution by setting emission reduction ceilings to be reached by 2010 for the same four pollutants as addressed in the NECD (i.e. NH_3, SO_X, NO_X, and NMVOCs). Overall for the EU Member States, the ceilings set within the Gothenburg protocol are generally either slightly less strict or the same as the emission ceilings specified in the NECD.

The Directive on Integrated Pollution Prevention and Control (96/61/EC) entered into force in 1999. It aims to prevent or minimise pollution to air, water or land from various industrial sources throughout the European Union. Those installations covered by Annex I of the IPPC Directive are required to obtain authorisation from the authorities to operate. New installations and existing installations, which are subject to 'substantial changes' have been required to meet the requirements of the IPPC Directive since 30th October 1999. Other existing installations must have been brought into compliance by the 30 October 2007. The emission limit values outlined in the permit conditions must be based on best available techniques (BAT). The Commission has been undertaking a review of the IPPC Directive and related legislation on industrial emissions and on the 21 December 2007 adopted a proposal for a Directive on industrial emissions. The proposal recasts seven existing Directives relating to industrial emissions (including IPPC and the Large Combustion Plant Directive (2001/80/EC) into a single legislative instrument.

Apart from the NECD and Gothenburg Protocol and the IPPC Directive, there is currently no other EU legislation proposed or in force specifically aimed at reducing ammonia emissions. However, several regulatory instruments have influenced EU emissions of ammonia from the agriculture sector since 1990, such as:

the Common Agricultural Policy (CAP);

the Nitrate Directive (91/676/EEC);

the Water Framework Directive (2000/60/EC).

These measures have had the indirect effect of changing agricultural practices across the EU, and have, for instance, led to a reduced use of nitrogenous fertilisers and to an overall decrease in cattle numbers, both of which affect the levels of ammonia emissions. The reforms of CAP, and specifically the removal of the link between farm production and payments, has also resulted in reduced livestock numbers across the EU-15 and hence also will have indirectly contributed to the decrease in ammonia emissions observed.

Targets

Emissions of NH_3 are covered by the EU National Emission Ceilings Directive (NECD) (2001/81/EC) and the Gothenburg protocol under the United Nations Convention on Long-Range Transboundary Air Pollution (LRTAP Convention) (UNECE 1999). The NECD generally involves slightly stricter emission reduction targets than the Gothenburg Protocol for EU-15 countries for the period 1990-2010. The Gothenburg Protocol entered into force on 17 May 2005, after ratification by 16 countries early in 2005.The 2012 revision to the Gothenburg protocol proposed emission reduction targets for 2020 relative to 2005 reported emissions for all EU-27 member states, and some EEA-32 non-EU member states.

Table: 2010 NH_3 ceilings under the NEC Directive and the Gothenburg Protocol (kt)

Country	2010 NECD ceilings	2010 CLRTAP Gothenburg Protocol ceilings	2020 CLRTAP Gothenburg Protocol ceilings
Austria	66	66	62
Belgium	74	74	70
Bulgaria	108	108	56
Cyprus	9	N/A	5
Czech Republic	80	101	64

Denmark	69	69	63
Estonia	29	N/A	10
Finland	31	31	31
France	780	780	634
Germany	550	550	545
Greece	73	73	63
Hungary	90	90	72
Iceland*	N/A	N/A	N/A
Ireland	116	116	108
Italy	419	419	395
Latvia	44	44	15
Liechtenstein	N/A	0.15	N/A
Lithuania	84	84	35
Luxembourg	7	7	5
Malta	3	N/A	2
Netherlands	128	128	122
Norway	N/A	23	21
Poland	468	468	267
Portugal	90	108	47
Romania	210	210	173
Slovakia	39	39	24
Slovenia	20	20	17
Spain	353	353	357
Switzerland	N/A	63	59
Sweden	57	57	47
Turkey*	N/A	N/A	N/A
United Kingdom	297	297	283

* Iceland and Turkey do not have a ceiling under either the NEC Directive or the Gothenburg protocol.

Related policy documents

1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone

Convention on Long-range Transboundary Air Pollution 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, amended on 4 May 2012.

Council Directive (91/676/EEC) 12 December 1991

Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC).

Council Directive 96/61/EC (IPPC)

Council Directive 96/61/EC of 24 September 1996 concerning Integrated Pollution Prevention and Control (IPPC). Official Journal L 257.

UNECE Convention on Long-range Transboundary Air Pollution

UNECE Convention on Long-range Transboundary Air Pollution.

Water Framework Directive (WFD) 2000/60/EC

Water Framework Directive (WFD) 2000/60/EC: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.

Key policy question

What progress is being made in reducing emissions of NH3?

Specific policy question

How do different sectors and processes contribute to emissions of NH3?

Methodology

Methodology for indicator calculation

This indicator is based on officially reported national total and sectoral emissions to EEA and UNECE/EMEP (United Nations Economic Commission for Europe/Cooperative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe) Convention on Long-range Transboundary Air Pollution (LRTAP Convention), submission 2011. For the EU-27 Member States, the data used is consistent with the emissions data reported by the EU in its annual submission to the LRTAP Convention.

Recommended methodologies for emission inventory estimation are compiled in the EMEP/EEA Air Pollutant Emission Inventory Guidebook, (EMEP/EEA, 2009). Base data are available from the EEA Data Service (http://dataservice.eea.europa.eu/dataservice/metadetails.asp?id=1096) and the EMEP web site (http://www.ceip.at/). Where necessary, gaps in reported data are filled by the European Topic Centre/EEA using simple interpolation techniques (see below). The final gap-filled data used in this indicator is available from the EEA Data Service (http://dataservice.eea.europa.eu/PivotApp/pivot.aspx?pivotid=478)

Base data, reported in the UNECE/EMEP Nomenclature for Reporting (NFR) sector format, is aggregated into the following EEA sector codes to obtain a consistent reporting format across all countries and pollutants:

- *Energy production and distribution*: emissions from public heat and electricity generation, oil refining, production of solid fuels, extraction and distribution of solid fossil fuels and geothermal energy;
- *Energy use in industry*: emissions from combustion processes used in the manufacturing industry including boilers, gas turbines and stationary engines;
- *Industrial processes*: emissions derived from non-combustion related processes such as the production of minerals, chemicals and metal production;
- *Road transport*: light and heavy duty vehicles, passenger cars and motorcycles;
- *Non-road transport*: railways, domestic shipping, certain aircraft movements, and non-road mobile machinery used in agriculture & forestry;
- *Commercial, institutional and households*: emissions principally occurring from fuel combustion in the services and household sectors;
- *Solvent and product use*: non-combustion related emissions mainly in the services and households sectors including activities such as paint application, dry-cleaning and other use of solvents;
- *Agriculture*: manure management, fertiliser application, field-burning of agricultural wastes
- *Waste*: incineration, waste-water management;
- *Other*: emissions included in national total for entire territory not allocated to any other sector

The following table shows the conversion of Nomenclature for Reporting (NFR) sector codes used for reporting by countries into EEA sector codes:

EEA classification	Non-GHGs (NFR)
National totals	National total
Energy production and distribution	1A1, 1A3e, 1B
Energy use in industry	1A2
Road Transport	1A3b
Non-road transport (non-road mobile machinery)	1A3 (excl. 1A3b)
Industrial processes	2
Solvent and product use	3
Agriculture	4
Waste	6
Commercial, institutional and households	1A4ai, 1A4aii, 1A4bi, 1A4bii, 1A4ci, 1A4cii, 1A5a, 1A5b
Other	7

Methodology for gap filling

An improved gap-filling methodology was implemented in 2010 that enables a complete time series trend for the main air pollutants (eg NO_X, SO_X, NMVOC, NH_3 and CO) to be compiled. In cases where countries did not report emissions for any year, it meant that gap-filling could not be applied. For these pollutants, therefore, the aggregated data are not yet complete and are likely to underestimate true emissions. Further methodological details of the gap-filling procedure are provided in section 1.4.2 'Data gaps and gap-filling' of the European Union emission inventory report 1990–2009 under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP).

Methodology references

EEA (2011). European Union emission inventory report 1990 — 2009 under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP). EEA technical report No 9/2011. Copenhagen.

EMEP/EEA (2009). EMEP/EEA Air pollutant emission inventory guidebook - 2009 This 2009 update of the emission inventory guidebook prepared by the UNECE/EMEP Task Force on Emissions Inventories and Projections provides a comprehensive guide to state-of-the-art atmospheric emissions inventory methodology. Its intention is to support reporting under the UNECE Convention on Long-range Transboundary Air Pollution and the EU National Emission Ceilings Directive.

EMEP, 2009. Transboundary, acidification, eutrophication and ground level ozone in Europe in 2007 EMEP August 2009, ISSN 1504-6192

Data specifications

EEA data references

National Emission Ceilings (NEC) Directive Inventory provided by **Directorate-General for Environment (DG ENV)**

National emissions reported to the Convention on Long-range Transboundary Air Pollution (LRTAP Convention) provided by **United Nations Economic Commission for Europe (UNECE)**

Data sources in latest figures

Uncertainties

Methodology uncertainty

The use of gap-filling for when countries have not reported emissions for one of more years can potentially lead to artificial trends, but it is considered unavoidable if a comprehensive and comparable set of emissions data for European countries is required for policy analysis purposes.

Data sets uncertainty

NH_3 emission estimates in Europe are more uncertain than those for NO_X, SO_2 and NMVOCs due largely to the diverse nature of major agricultural sources. It is estimated that they are around ±30% (EMEP, 2009). The trend is likely to be more accurate than the individual absolute annual values - the annual values are not independent of each other.

Overall scoring: (1-3, 1=no major problems, 3=major reservations)

Relevancy: 1

Accuracy: 2

Comparability over time: 2

Comparability over space: 2

Rationale uncertainty

This indicator is regularly updated by EEA and is used in state of the environment assessments. The uncertainties related to methodology and data sets are therefore of importance. Any uncertainties involved in the calculation and in the data sets need to be accurately communicated in the assessment, to prevent erroneous messages influencing policy actions or processes.

Further work

Short term work

Work specified here requires to be completed within 1 year from now.

Long term work

Work specified here will require more than 1 year (from now) to be completed.

General metadata

Responsibility and ownership

EEA Contact Info

Martin Adams

Ownership

European Environment Agency (EEA)

Identification

Indicator code
APE 003
Specification
Link: eea-32-ammonia-nh3-emissions-1
Version id: 2
First draft created:
19 Aug 2010, 09:12 PM
Publish date:
15 Oct 2010, 12:00 AM
Last modified:
04 Sep 2015, 06:59 PM
Primary theme: Environment and health

Frequency of updates

This indicator is discontinued. No more assessments will be produced.

Classification

DPSIR: Pressure
Typology: Performance indicator (Type B - Does it matter?)

Related content

Policy Document

1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone

[https://www.eea.europa.eu/policy-documents/1999-protocol-to-abate-acidification]

Policy Document

Water Framework Directive (WFD) 2000/60/EC

[https://www.eea.europa.eu/policy-documents/water-framework-directive-wfd-2000]

Policy Document

Council Directive 96/61/EC (IPPC)

[https://www.eea.europa.eu/policy-documents/council-directive-96-61-ec-ippc]

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D8DCPSBVAR

Older versions

15 Feb 2010 - EEA-32 ammonia (NH3) emissions

Topics

Environment and health

Greenhouse gas emissions from ruminant supply chains

A global life cycle assessment



Greenhouse gas emissions from ruminant supply chains

A global life cycle assessment

A report prepared by:

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Animal Production and Health Division

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Greenhouse gas emissions from ruminant supply chains
A global life cycle assessment

This report presents results from a broad assessment carried out to improve the understanding of greenhouse gas (GHG) emissions along livestock supply chains. The analysis was conducted at the Animal Production and Health Division of FAO and co-financed by the Mitigation of Climate Change in Agriculture (MICCA) programme. The following persons and institutions contributed to this work:

Study team:

- Pierre Gerber (Team Leader – FAO)
- Carolyn Opio (Principal investigator – FAO)
- Theun Vellinga (Livestock modeller – Wageningen University)
- Alessandra Falcucci and Giuseppe Tempio (GIS Modeler – FAO)
- Guya Gianni, Benjamin Henderson, Michael MacLeod, Harinder Makkar, Anne Mottet , Tim Robinson and Viola Weiler (Data collection and analysis – FAO)

The following provided comments, views and information that contributed to the analysis:

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- Imke de Boer (Wageningen University)
- Christel Cederberg (Swedish Institute for Food and Biotechnology and Chalmers University of Technology, Göthenburg)
- Jeroen Dijkman (FAO)
- M.R. Garg (National Dairy Development Board, India)
- Vincent Gitz (FAO)
- Mario Herrero (Commonwealth Scientific and Industrial Research Organisation)
- Muhammad Ibrahim (Centro Agronómico Tropical de Investigación y Enseñanza, Costa Rica)
- Hsin Huang (for the International Meat Secretariat)
- Stewart Ledgard (AgResearch – New Zealand)
- Adrian Leip (Joint Research Centre of the European Commission – Ispra)
- Brian Lindsay (for the Sustainable Agriculture Initiative)
- Tim McAllister (Agriculture and Agri-Food – Canada)
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Abbreviations

ABP	animal products and by-products
AEZ	agro-ecological zone
BFM	bone-free meat
Bo	manure maximum CH_4 producing capacity
CF	carbon footprint
CGIAR	Consortium of International Agricultural Research Centers
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CW	carcass weight
DM	dry matter
DMI	dry matter intake
DOM	dead organic matter
FCR	feed conversion ratio
EF	emission factor
EI	emission intensity
FPCM	fat and protein corrected milk
GHG	greenhouse gas
GLEAM	Global Livestock Environmental Assessment Model
GIS	Geographical Information System
GPP	gross primary production
GWP	global warming potential
HCFC	hydrochlorofluoro carbon
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg CO_2-eq	kilograms of CO_2 equivalent
LAC	Latin America and the Caribbean
LCA	life cycle assessment
LCI	life cycle inventory
LPS	livestock production system
LUC	land-use change
LULUCF	land use, land-use change and forestry
LW	live weight
MC	Monte Carlo Simulation
MCF	methane conversion factor
MMS	manure management system
N	nitrogen
NENA	Near East & North Africa
NH_3	ammonia
NIR	national inventory report
NO_X	nitrogen oxide air pollutants NO and NO_2 (nitric oxide and nitro gen dioxide)

N_2O	nitrous oxide
OECD	Organisation for Economic Cooperation and Development
PDF	probability distribution frequency
RCC	Rank Correlation Coefficient
SD	standard deviation
SSA	Sub-Saharan Africa
SOC	soil organic carbon
SPAM	Spatial Production Allocation Model
SRM	specified risk material
t CO_2-eq	tonnes of CO_2 equivalent
UNFCCC	United Nations Framework Convention for Climate Change
USDA	United States Department of Agriculture

Definitions of commonly-used terms

Anaerobic	In the absence of oxygen, i.e. conditions conducive to the conversion of organic carbon into methane (CH_4) rather than carbon dioxide (CO_2).
Breeding overhead	Animals that are kept to maintain the herd/flock size, rather than to produce food.
By-product	Material produced during the processing including slaughtering of a crop or livestock product that is not the primary objective of production (e.g. meals and brans, offal or skins).
Carbon footprint	The total amount of GHG emissions associated with a product along its supply-chain, and sometimes includes emissions from consumption, end-of-life recovery and disposal. Usually expressed in kg or t of carbon dioxide equivalent (CO_2-eq).
CO_2-equivalent emission	The amount of CO_2 emissions that would cause the same time-integrated irradiative forcing, over a given time horizon, as an emitted amount of a mixture of GHGs. It is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for the given time horizon. The CO_2 equivalent emission is a standard metric for comparing emissions of different GHGs (IPCC, 4 AR 2007).
Coefficient of variation	The standard deviation expressed as a percentage of the mean.
Cohort	Class of animals within a herd defined by their age and sex (e.g. adult females, replacement females, males for fattening, etc.).
Co-product	Material generated by a production activity that generates more than one output (e.g. meat, eggs and manure are co-products of chicken production).
Crop residue	Materials left in an agricultural field after the crop has been harvested (e.g. straw or stover).

Dairy herd	For the purposes of this assessment, includes milking animals, replacement stock and surplus calves that are fattened for meat production.
Direct energy	Energy used on-farm for livestock production, e.g. for lighting, heating and cooling.
Embedded energy	Energy or emissions arising during the manufacture of farm inputs, such as fertiliser or steel.
Emission factor	Factor that defines that rate at which a greenhouse gas is emitted, e.g. kg CH_4 per animal per year or kg N_2O-N/kg manure N.
Emissions intensity	Mass of emissions per unit of product, e.g. kg CO_2/kg of meat/milk.
Fat and protein corrected milk (FPCM)	Milk corrected for its fat and protein content to a standard of 4.0 percent fat and 3.3 percent protein. This is a standard used for comparing milk with different fat and protein contents. It is a means of evaluating milk production of different dairy animals and breeds on a common basis.
Feed conversion ratio	Measure of the efficiency with which an animal converts feed into tissue, usually expressed in terms of kg of feed per kg of output (e.g. CW, milk or protein).
Feed material	Individual feed type (e.g. maize grain or wheat straw).
Fieldwork	General term for the field operations undertaken during crop cultivation, e.g. ploughing, drilling, spreading, etc.
Geographical Information System	A computerized system organizing data sets through the geographical referencing of all data included in its collections.
Globalwarming potential	Defined by the Intergovernmental Panel on Climate Change (IPCC) as an indicator that reflects the relative effect of a GHG in terms of climate change considering a fixed time period, such as 100 years, compared with the same mass of carbon dioxide.
Grassland-based livestock systems	Livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten livestock units per hectare of agricultural land (FAO, 1996).

Manure N	Nitrogen in manure.
Methane conversion factor	The percentage of the manure's maximum methane producing capacity (Bo) that is achieved during manure management
Mixed farming systems	Livestock production systems in which more than 10 percent of the dry matter fed to livestock comes from crop by-products and/or stubble or more than 10 percent of the value of production comes from non-livestock farming activities (FAO, 1996).
Monte Carlo analysis	Method that uses repeated random sampling for estimating uncertainty in results.
Pixel	The smallest unit of information in GIS raster data, usually square in shape. In GIS dataset, each pixel represents a portion of the earth, and usually has an attribute value associated with it, such as soil type or vegetation class. Pixel is often used synonymously with cell.
Ration	The combination of feed materials constituting the animal's diet.
Synthetic N	Nitrogen in the form of manufactured fertilisers, such as ammonium nitrate.
Tier levels	Defined in IPCC (2006), these correspond to a progression from the use of simple equations with default data (Tier 1 emission factors), to country-specific data in more complex national systems (Tier 2 & 3 emission factors). Tiers implicitly progress from least to greatest levels of certainty as a function of methodological complexity, regional specificity of model parameters, spatial resolution and the availability of activity data.

Executive summary

BACKGROUND AND PURPOSE

In decades to come, the global demand for livestock products will continue to increase driven by growing populations, incomes and urbanization. As a consequence the sector needs to produce more but in a context of increasing natural resource scarcity and challenges posed by climate change.

In 2010, the ruminant sector contributed about 29 percent to global meat production (equivalent to 81 million tonnes) of which 79 percent is from the cattle sector and the remaining from buffalo and small ruminants. Global milk production in 2010 was 717 million tonnes with milk production from the cattle sector contributing the bulk, about 83 percent of global production.

While ruminants play an important role in providing high quality protein essential for human diets, they are an important source of greenhouse gas (GHG) emissions. The demand for bovine meat, mutton and milk is forecasted to grow at a rate of 1.2 percent, 1.5 percent and 1.1 percent, respectively, during the period 2006-2050. To avoid significant increases in total GHG emissions from the sector, a reduction of the intensity of emissions is required.

This report presents a life cycle analysis of the GHG emissions arising from ruminant supply chains around the year 2005. This first comprehensive and disaggregated global assessment of emissions enables the understanding of emission pathways and hotspots. This is a fundamental and initial step to identify mitigation strategies and inform public debate.

Two similar reports on the emissions from pig and chicken supply chains and on the emissions from the dairy sector are also available. An overall report providing an overview of results and exploring mitigation potential and options is also available.[1]

METHODOLOGY

This assessment is based on a life cycle assessment (LCA) and includes all main sources of emissions along the supply chain starting from land use and the production of feed, through emissions from animal production to emissions related to processing and transportation of products to the retail distribution point.

GHG emissions arising from land-use change (LUC) associated with livestock production were also assessed. Land-use change emissions considered include the transformation of forest to cropland and of forest to pasture in Latin America and the Caribbean. Given the year of reference (2005), latest trends could not be fully reflected (e.g. reduction of deforestation rates in LUC). A sensitivity analysis was conducted, showing that the period of the analysis has an important influence on results.

[1] FAO. 2010. Greenhouse gas emissions from the dairy sector – A life cycle assessment. FAO, Rome.
FAO. 2013a. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. FAO, Rome.
FAO. 2013b. Greenhouse gas emissions from pig and chicken supply chains – A global life cycle assessment. FAO, Rome.

Due to the lack of globally validated model and databases, sequestration and losses of soil C arising from pasture management could not be included in the assessment but can be significant. The effect of this was tested in the case of Western Europe; carbon sequestration could mitigate about 5 percent of total ruminant emissions in the region, but with a high degree of uncertainty.

This analysis covers emissions from the three major GHGs in agriculture, namely methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), omitting gases of minor importance.

The analysis was undertaken using the Global Livestock Environmental Assessment Model (GLEAM). This model quantifies GHG emissions arising from production of the main livestock commodities: meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens.

The model calculates total emissions and (commodity) production for a given farming system within a defined area. The emissions per unit of product can be calculated for combinations of different commodities/farming systems/locations at different spatial scales.

In a complex analysis such as this, results are not definitive, but rather the best assessment that could be made and subject to improvement in subsequent revisions. Methodological developments are being developed within the context of the LEAP Partnership (Livestock Environmental Assessment and Performance),[2] to harmonize metrics and approaches used in the assessment of environmental performance of livestock supply chains, including future updates of this report.

KEY FINDINGS

Overall sectoral contribution to global GHG emissions

Globally, ruminant supply chains are estimated to produce 5.7 gigatonnes CO_2-eq *per annum* representing about 80 percent of the livestock sector emissions. Emissions from beef and milk production represent respectively 35 and 30 percent of the livestock sector emissions (equivalent to 4.6 gigatonnes CO_2-eq). Buffalos and small ruminants supply chains have a much lower contribution, representing respectively 8.7 percent and 6.7 percent of sector emissions.

Main emission sources

The largest source of GHG emissions in ruminant production is methane (CH_4) from enteric fermentation, which accounts for about 47 percent of the sector's emissions and more than 90 percent of the total CH_4 emissions. Nitrous oxide (N_2O) emissions originating mainly from feed production and N deposited during grazing represent 24 percent of the sector's GHG emissions.

Emissions from land-use change associated with the expansion of grassland into forest account for 14.8 percent of total emissions related to beef production.

While LUC contributes a significant amount to total emissions; and particularly so in certain regions, these estimates vary greatly depending on the assumptions made, data and approach applied.

[2] http://www.fao.org/ag/againfo/livestock-benchmarking/en/.

Emission intensities (emission of GHG per unit of product) per commodity

Average emission intensity for products from ruminants were estimated at 2.8, 3.4 and 6.5 kg CO_2-eq/kg fat and protein corrected milk (FPCM) for cow milk, buffalo and small ruminant milk, respectively, and 46.2, 53.4, and 23.8 kg CO_2-eq/kg carcass weight (CW) for beef, buffalo and small ruminant meat, respectively.

EMISSION INTENSITIES PER PRODUCTION SYSTEMS AND REGIONS

There are variations in emission intensities across regions and production systems for each commodity. These variations are largely driven by differences in production goals (specialized versus non-specialized production) and management practices, including animal husbandry methods, animal health and genetics which influence levels of productivity.

In addition, there is a wide divergence in emission intensity for different commodities produced within the same region under comparable conditions (production systems and climatic zones) pointing to the existence of a considerable emission intensity gap (Section 4.4).

Variation by production systems

Globally, mixed systems provide the bulk of the meat and milk output: about 79 percent of the beef, 85 percent of cow's milk and 70 and 68 percent of small ruminant milk and meat is produced in this system. In addition, mixed systems also supply about 97 and 96 percent of buffaloes' milk and meat, respectively.

On average, mixed systems have slightly lower emission intensities than grassland-based systems. This difference is explained by several factors such as reproductive efficiency (higher fertility rates, lower age at calving,) animal health (lower mortality rates), management (higher slaughter weights, reduced time to slaughter), and better feed quality in mixed farming systems. All these factors combine to result in higher productivity and lower emission intensity.

Variation by region

World regions show highly diverse emission intensities which are to large extent explained by their contribution to production, their production systems and management practices.

Cattle

Regional emission intensity of milk ranges from 1.6 kg CO_2-eq/kg FPCM to 9.0 kg CO_2-eq/kg FPCM. Generally, milk production in low productive systems has higher emission intensities than in high production systems of most affluent counties where better animal feeding and nutrition results in lower enteric and manure emissions and emission intensity at animal level. Improved genetics and animal health care and animal husbandry combine with better feeding to reduce the breeding overhead (i.e. animals kept to maintain the herd) thus further reducing emission intensity at herd level. In North America, manure management emissions are relatively high due to the use of liquid manure management systems that produce greater quantities of methane emissions.

Emission intensity of beef at regional level show a great deal of diversity; ranging from 14 kg CO_2-eq/kg CW in Eastern Europe and the Russian Federation to 76 kg CO_2-eq/kg CW in South Asia. Beef production has the highest emission intensi-

ties in South Asia, sub-Saharan Africa, Latin America and the Caribbean, and East and Southeast Asia. The quality and type of feed, low reproduction efficiency, poor herd management practices, genetics and animal health (high mortality) explain the higher emission intensities in these regions. In addition, in Latin America and the Caribbean, almost one third of the emissions from beef production are related to pasture expansion into forested areas. This figure is however associated with a high level of uncertainty as a result of methodological uncertainty and data gaps.

Regions with the lowest emission intensity such as Europe, North America and Oceania are not necessarily characterized by similar production systems. For example, in Europe about 80 percent of the beef is produced from dairy surplus calves and culled cows which explains the relatively low emission intensity of beef. In North America and Oceania, production is generally characterized by a high level of specialization and higher productivity, which results in lower emission intensities. However, in these two regions, beef cattle may be reared either intensively or extensively (on grain or grass).

Buffalos

Global buffalo milk and meat production is concentrated in three major world regions: South Asia, Near East & North Africa and East & Southeast Asia. South Asia alone produces as much as 90 percent and 70 percent of the global buffalo milk and meat, respectively. Milk produced in South Asia has lower emission intensity, explained by high milk yields compared to Near East & North Africa and East & Southeast Asia. Emission intensity of buffalo meat production is particularly high in East & Southeast Asia as productivity of the animals is low due to poor feed resources (largely based on low quality feed resources such as crop residues and pasture) and low reproductive efficiency. With the exception of a few countries in the Mediterranean region, buffalo production in industrialized world regions plays a very minor role.

Small ruminants

With the exception of small ruminant milk production in Western Europe and lamb and mutton production in Oceania and Western Europe, meat and milk from small ruminants is generally more important in developing world regions. Emission intensity for small ruminant milk is however highest in developing regions such as NENA and East & Southeast Asia, SSA and South Asia due to poorer production conditions in which animals are for the most part reared for subsistence purposes. In contrast, in industrialized countries where small ruminant milk production is important, emission intensity is low due to the specialization of production.

The contribution to global small ruminant meat production is characterized by a dichotomy between regions; global lamb and mutton production is largely concentrated in Western Europe and Oceania while production of meat from goats takes place in developing regions. Emission intensity for small ruminant meat is lowest in Oceania and Western Europe and highest in developing regions.

This difference in emission intensity of small ruminant meat and milk is due to variations in reproductive efficiency (resulting in a smaller "breeding overhead"), feed quality, and management practices that are generally poorer in developing regions.

FACTORS DRIVING EMISSION INTENSITY LEVELS

Differences in emission intensities are driven by a combination of factors.

- At animal level emission intensity is influenced by: (i) digestibility, quality and composition of the feed ration which influence the level of enteric methane emissions and manure emissions (lower release of nitrogen and volatile solids) per unit of product produced (milk or weight gain); and (ii) improved genetics and animal health contribute to better conversion of feed into animal products further reducing emission intensity at animal level.
- At animal level, emission intensity is influenced by feed quality combined with genetics, animal health, reproduction strategies (replacement, age at first calving) reducing the relative number of unproductive animals in the herd and thus emissions per unit of product generated at herd level.
- Land-use change, i.e. pasture and feed crop expansion, is a major driver of emissions. Feed originating from areas where LUC takes place has higher emission intensities.
- Manure management practices influence the release of methane and nitrous oxide.

CONCLUSIONS

The range of emission intensity within supply chains suggests that there is room for improvement. The areas with mitigation potential are the following:

- Improving feeding practices and digestibility of diets;
- Improving yields through genetics, feeding practices and animal health, and overall management;
- Reducing land-use change arising from feed crop cultivation and pasture expansion;
- Improving manure management – reducing the use of uncovered liquid manure management systems (MMSs), particularly in dairy systems;
- Improving the efficiency of feed crop production, particularly improving fertilization management.

This report focuses on one measure of environmental performance: kg CO_2-eq/kg commodity. When evaluating GHG mitigation measures, attention should also be paid to their potential impacts on other environmental dimensions, for example on water quality, as well as on broader development objectives, such as food security and poverty reduction.

1. Introduction

1.1 BACKGROUND

The global livestock sector is faced with a three-fold challenge: the need to increase production to meet demand, adapt to a changing and increasingly variable economic and natural environment and, at the same time, improve its environmental performance. While positive effects of grazing systems are locally verified on biodiversity and landscapes, major concerns have been raised about the potential consequences associated with livestock sector growth, including increasing natural resource use and degradation, contribution to global warming, water resource depletion, biodiversity erosion and habitat change. These concerns have resulted in a widespread interest from governments, consumers and industry in the assessment of the environmental performance of livestock production.

The evidence of human-induced climate change (IPCC, 2006) and the important contribution of the livestock sector to total anthropogenic emissions highlight the urgent need to better understand the sources of the livestock sector's greenhouse gas (GHG) emissions and related mitigation options. Starting in 2009, the Animal Production and Health Division of FAO has been engaged in a comprehensive assessment of livestock-related GHG emissions aimed at identifying low-emission development pathways for the livestock sector. The undertaking follows two broad objectives: first, to improve and break down the initial estimates of livestock sector's overall emissions provided in *Livestock's long shadow – Environmental issues and options* (FAO, 2006) and, second, to identify the major available mitigation options along livestock supply chains.

This report presents an update of the *Livestock's long shadow* assessment of GHG emissions from ruminant supply chains. It should be understood as a step in a series of assessments to measure and guide progress regarding the sector's GHG emissions.

1.2 SCOPE OF THIS REPORT

Livestock commodities differ in resource use and emission profile. These variations reflect fundamental differences in the underlying biology and modes of production. The reporting structure reflects this by bringing together species with important shared features concerning their emission profile. This report quantifies the main sources of GHG emissions, and estimates GHG emissions for major ruminant products, predominant ruminant production systems, main world regions and agro-ecological zones (AEZs), and major stages in the supply chains.

The assessment takes a supply chain approach in estimating emissions generated during: (a) the production of inputs for the production process; (b) crop and animal production; and (c) subsequent transport and processing of the outputs into basic products. Given the global scope of the assessment and the complexity of livestock supply chains, several hypotheses and generalizations had to be made to keep data requirements of the assessment manageable. They are documented in the report and their impact on results is analysed. Emissions related to the consumer (the purchase, storage and preparation of food) and food losses that take place at retail and consumer level are not included.

This report addresses a technical audience in private and public organizations, academia and LCA practitioners. Policy-makers and the informed general public will find a comprehensive review of results, methods and the mitigation potential in the livestock sector in an overview report published in parallel to this report (FAO, 2013a).

By providing the most accurate information available on a global scale, this assessment helps to identify priority areas for mitigation and technical options that can reduce GHG emissions from the ruminant sector. It also provides a benchmark against which future trends can be measured.

This report focuses on GHG emissions only; other environmental dimensions, such as water resources, land, biodiversity and nutrients, have not been considered. GHG emissions from the livestock sector cannot be taken as an indicator of environmental sustainability in general. There are important synergies and trade-offs among competing environmental criteria that require fuller assessment.

The base year selected for assessment is 2005. This year was chosen because at the start of the assessment, the available spatial data, and in particular information on the predicted livestock densities, were based on 2005 data.

1.3 THE GLOBAL LIVESTOCK ENVIRONMENTAL ASSESSMENT MODEL

This assessment is based on a newly-developed analytical framework: the Global Livestock Environmental Assessment Model (GLEAM). GLEAM intends to pull together the existing knowledge on production practices and emissions pathways and create a framework for disaggregation and comparison of emissions on a global scale. The model is developed for six animal species (cattle, buffalo, sheep, goats, pigs and chicken) and related edible products. It recognizes two farming systems for ruminant species (mixed and grazing), three for pigs (backyard, intermediate and industrial) and three for chicken (backyard, industrial egg and industrial meat). Overall, this amounts to over 14 000 theoretical supply chains, defined here as unique sets of commodity, farming system, country and climatic zone. The physical area corresponding to each of these sets is further decomposed in cells on a map.

Four publications present the results of this work:

- This technical report addressing the world's cattle, buffalo and small ruminant (sheep and goat) sectors.
- A report addressing the world's pig and chicken (meat and eggs) sectors, published in parallel to this report (FAO, 2013b).
- An earlier technical report published in 2010, addressing the world's dairy sector (FAO, 2010).
- An overview report, summarizing the above at the sector level and providing additional cross-cutting analysis of emissions and mitigation potential, published in parallel to this report (FAO, 2013a).

Since the publication of the FAO report on GHG emissions from the dairy sector (FAO, 2010), GLEAM has been improved to include additional GHG emissions sources such as direct on-farm energy use and indirect energy embodied in farm buildings and equipment. In addition, new data (herd parameters, feed rations) has also been made available, so this report presents an update of the results on dairy production presented in 2010.

1.4 OUTLINE OF THIS REPORT

This report consists of six sections (including this introductory section). Section two starts with a brief introduction to the global ruminant sector describing production systems and their contribution to global ruminant milk and meat production.

Section 3 gives an overview of the approach used in the estimation of GHG emissions in this assessment, providing basic information on the LCA approach. The section presents a description of the functional units used, system boundary, allocation to co-products and sources of GHG emissions. The section also provides an overview of ruminant production system typology applied, the tool (GLEAM) and methods as well as broad information on data sources and management. Detailed description of the approach and methods can be found in the appendices.

The results (total emissions and emission intensities) of this assessment are presented in Section 4 followed by a discussion on the main important sources and drivers of emissions from ruminant species as well as a discussion on uncertainty and assumptions likely to influence the results (Section 5). It also presents the results of a Monte Carlo uncertainty analysis performed in this study.

Section 6 presents the conclusions and recommendations that can be drawn from this work as well as provides direction on areas for improvement.

The appendices in this report provide a detailed description of the GLEAM model, methods applied (on quantifying carbon losses from land-use change, on-farm direct and indirect energy use and post farmgate emissions) and data. The appendices also explore different computation approaches (e.g. for estimating LUC emissions and allocation of emissions to slaughter by-products) presenting their impact on emission intensity.

2. Overview of the global ruminant sector

In this report, the ruminant sector comprises cattle, sheep and goat, and buffalo. The global ruminant population in 2010 was estimated to be 3 612 million (FAOSTAT, 2012), with cattle making up nearly 40 percent, sheep and goat 55 percent, and buffalo the remaining 5 percent. Within the ruminant sector, the cattle sector is by-far the most important: contributing about 64 and 600 million tonnes of meat and milk, respectively; about 79 and 83 percent of total meat and milk production from ruminants. Small ruminant products constitute a relatively small share of globally-produced ruminant meat and milk, about 17 percent and 4 percent, respectively.

Ruminants are mainly reared in either grazing or mixed systems and the relative global importance of mixed systems compared with grazing systems is reflected by the fact that about 73 percent of all ruminants are reared in mixed farming systems. This study estimates that globally about 79 percent of the beef and 85 percent of cattle milk and 70 percent and 68 percent of the small ruminant milk and meat, respectively, is produced in mixed systems. Mixed systems also supply the bulk of products from buffalo; about 97 and 96 percent of milk and meat, respectively. Within these two systems, there is a wide variation in farming practices of which is subject to several factors such as climatic conditions, availability of fodders, market demand, etc.

Agro-ecological conditions are important determinants of the characteristics of ruminant production and estimates of the relative importance of ruminant meat and milk production within the AEZs varies between cattle, buffalo, and small ruminants (see Maps 1, 2, 3, 4 and 5 in Appendix G). In cattle production, temperate zones contribute 50 percent and 38 percent of the milk and beef compared with 21 percent and 33 percent from humid zones and 29 percent and 29 percent from arid zones.

On the other hand, arid zones contribute the bulk of milk and meat production from small ruminants and buffalo; 69 percent and 52 percent of small ruminant milk and meat, and 84 percent and 70 percent of buffalo milk and meat. The humid and temperate zones contribute 12 percent and 18 percent of small ruminant milk and 18 and 29 percent of the meat.

The relative importance of the different species varies enormously – while economic conditions play a key role, factors such as biophysical conditions and cultural values are also important.

Beef production is the most diverse form of all ruminant meat production. It is produced in extremely diverse production systems, ranging from grazing to mixed livestock-crop systems. Beef is either produced in "dedicated" beef herds, where beef is the only main product, or as a co-product from dairy production, i.e. surplus calves from dairy herds are raised for beef and culled cows are used for meat.

Specialized beef production units may take many forms: breeding and growing beef enterprises, breeding and finishing, growing and finishing on pasture or in feedlots, etc. Such forms of production are usually located in the industrialized

world regions and Latin America. However, in many parts of the world, particularly in the developing regions, this distinction between dairy and specialized beef production is subtle especially where cattle are considered multifunctional producing both milk and meat as well as other valuable non-edible products and services such as manure, hides and skin, and are used for draught power.

Despite their small contribution to global milk and meat output, sheep and goat farming plays a larger role in some specific economies. In many marginal rural areas, it plays a significant socio-economic role. An important attribute of small ruminants is that they are able to thrive and produce on unfavourable land and are generally suited to harsh climatic conditions where cattle would perform poorly. Sheep and goats are better converters of low-quality fibrous feed into meat and milk due to their better digestive ability to utilize poor quality roughages. In this regard, about 56 percent of the world's small ruminants are located in arid zones and 27 percent and 21 percent in the temperate and humid zones, respectively. However, these animals also adapt very easily to intensive production systems and can produce meat and milk efficiently.

Milk and meat products from sheep and goats have two purposes: they are used for subsistence at household level or are sold as niche products. Meat and milk from sheep is usually obtained from high yielding animals kept under intensive conditions e.g. dairy intensive systems in the Mediterranean region, lamb production in New Zealand and Australia. In Northern Europe and Oceania (particularly New Zealand), sheep are kept mainly for meat production while in the Mediterranean region almost all sheep and goats belong to dairy breeds where milk is the main output of production and meat considered as a by-product.

Similar to other ruminant species, systems of buffalo production vary widely through the different regions of the world and are determined by several interacting factors that include climate (tropical or temperate, humid or arid), location (rural, peri-urban or urban), cropping systems (rain-fed or irrigated, annual or perennial crops), type of operation (small or large farm, subsistence or commercial), and primary purpose for buffalo production and/or management (milk, meat, draught power or mixed).

In South Asia, North Africa and the Near East, buffalo are mainly kept for milk and meat production. In East & Southeast Asia, draught power and meat are important, while in Europe, buffalo are kept on large commercial farms under modern intensive systems for milk and meat production (Perera, 2011).

Buffalo provide milk, meat, hides and draught power. Among the different products obtained from buffalo, meat and hides are more important, although buffalo play an important role in milk production in Asian countries and few countries in the Mediterranean region. Global milk production is concentrated in two countries, India and Pakistan, which together account for 92 percent of the world's total milk production. Buffalo have an inherent ability to produce milk of high fat contents (ranging from 6 to 8.5 percent) and, because of this, buffalo milk is preferred over cow milk in some regions of the world such as South Asia. In 2010, about 98 percent of the global buffalo meat production was produced in South, East and Southeast Asia with the bulk contributed by India and Pakistan. This is easily explained by the fact that the two countries have 73 percent of the global buffalo population. Besides edible products, ruminants also produce a host of non-edible products such

as manure, hides and skin, and natural fibre (wool, cashmere and mohair). While farm mechanization has resulted in significant reduction in the use of animals for draught power, farmers in many parts of the world still rely on cattle and buffalo as a source of draught power.

3. Methods

3.1 CHOICE OF LIFE CYCLE ASSESSMENT (LCA)

The use of Life Cycle Assessment (LCA) to assess food production is becoming increasingly common. This trend is driven by the need of policy-makers, producers and consumers for reliable and comprehensive environmental information to identify environmentally and economically sustainable agricultural products and practices.

The LCA approach, which is defined in ISO standards 14040 and 14044 (ISO, 2006), is now widely accepted in agriculture and other industries as a method for evaluating the environmental impact of production, and for identifying the resource and emission-intensive processes within a product's life cycle. The main strength of LCA lies in its ability to provide a holistic assessment of production processes in terms of resource use and environmental impacts, as well as to consider multiple parameters (ISO, 2006).

LCA also provides a framework to broadly identify effective approaches to reduce environmental burdens and is recognized for its capacity to evaluate the effect that changes within a production process may have on the overall life-cycle balance of environmental burdens. This enables the identification and exclusion of measures that simply shift environmental problems from one phase of the life cycle to another.

However, LCA also presents significant challenges, particularly when applied to agriculture. First, the data-intensive nature of the method places limitations on the comprehensive assessment of complex food chains and biological processes. Limited data availability can force the practitioner to make simplifications, which can lead to losses of accuracy.

A second difficulty lies in the fact that methodological choices and assumptions such as system boundary delineation, functional units, and allocation techniques may be subjective and affect the results. These complications call for a thorough sensitivity analysis.

3.2 GENERAL PRINCIPLES OF LCA

The LCA method was originally applied to analyse industrial process chains, but is increasingly being used to assess the environmental impacts of agriculture. It involves the systemic analysis of production systems to account for all inputs and outputs associated with a specific product within a defined system boundary. The system boundary largely depends on the goal of the study.

The reference unit that denotes the useful output of the production system is known as the functional unit, and it has a defined quantity and quality. The functional unit can be based on a defined quantity, such as 1 kg of product, or it may be based on an attribute of a product or process, such as 1 kg of fat and protein corrected milk (FPCM) or 1 kg of carcass weight (CW).

The application of LCA to agricultural systems is often complicated by the multiple-output nature of production, because major products are usually accompanied by the joint production of by-products. This requires appropriate partitioning of

environmental impacts to each product from the system according to an allocation rule, which may be based on different criteria such as economic value, mass balances, product properties, etc.

3.3 USE OF LCA IN THIS ASSESSMENT

In the last five years, an increasing number of LCA studies have been carried out for livestock production, mostly in Organisation for Economic Cooperation and Development (OECD) countries (Leip *et al*., 2010; Ledgard *et al.,* 2011; Beauchemin *et al*., 2010; de Vries and de Boer, 2010; Verge *et al*., 2008; Foley *et al*., 2011). Although LCA methods are well defined, the studies vary considerably in their level of detail, their definition of system boundaries, the emission factors (EFs) they use, and other technical aspects such as the allocation techniques and functional units they employ.

This assessment sets out to perform a complete LCA for the global livestock sector, using consistent calculation methods, modelling approaches, data and parameters for each production system within the sector. In contrast to previous LCA studies carried out for the livestock sector, which have primarily concentrated on either farm level or the national level emissions in OECD countries, this study is global in scope and includes both developed and developing countries.

As a consequence of its global scope, the approach developed for this study has had to overcome onerous data requirements by relying on some simplifications that result in a loss of accuracy, particularly for systems at lower levels of aggregation.

This assessment follows the attributional approach, which estimates the environmental burden of the existing situation under current production and market conditions, and allocates impacts to the various co-products of the production system. This differs from the consequential LCA approach, which considers potential consequences of changes in production, and relies on a system expansion analysis to allocate impacts of co-products (Thomassen *et al*., 2008).

The current assessment is based on the methodology for LCA, as specified in the following documents:

- ISO, 2006. *Environmental management – Life Cycle Assessment- Requirements and guidelines* - BS EN ISO 14044.
- British Standards Institute PAS 2050; 2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (BSI, 2008).

3.3.1 Functional unit

Ruminant production systems produce a mix of goods and services:

- Edible products: meat and milk.
- Non-edible products and services including natural fibre (wool, cashmere, mohair), draught power, hides and skin, manure and capital.

In this assessment, the functional units used to report GHG emissions for meat are expressed as a kg of carbon dioxide equivalents (CO_2-eq) per kg of carcass weight (CW) and emissions from milk are reported in CO_2-eq per kg of FPCM. FPCM is a method used to standardize milk produced in different systems with varying qualities. Appendix A provides details of the equations used in the standardization of milk from ruminants.

3.3.2 System boundary

The assessment encompassed the entire livestock production chain, from feed production through to the final processing of product, including transport to the retail distribution point (see Figure 1).

The cradle to retail system boundary is split into two subsystems:

- *Cradle to farmgate* includes all upstream processes in livestock production up to the farmgate where the animals or products leave the farm, i.e. production of farm inputs and on-farm production activities.
- *Farmgate to retail* includes transport of animals and product (milk) to processing plants (dairies and slaughter plants) or directly to market, processing into primary products, refrigeration during transport and processing, production of packaging material, and transport to the retail distributor.

All aspects related to the final consumption of milk and meat products (i.e. consumer transport to purchase product, food storage and preparation, food waste and waste handling of packaging) lie outside the defined system, and are thus excluded from this assessment.

To calculate GHG emissions from cradle to farmgate, a simplified description of livestock production systems (derived from Oenema *et al.*, 2005; Schils *et al.*, 2007; Del Prado and Scholefield, 2008) was developed (Figure 1).

Livestock production is complex, with a number of interacting processes that include crop and pasture production, manure handling, feed processing and transport, animal raising and management, etc. This requires modelling the flow of all

Figure 1.
System boundary as defined for this assessment

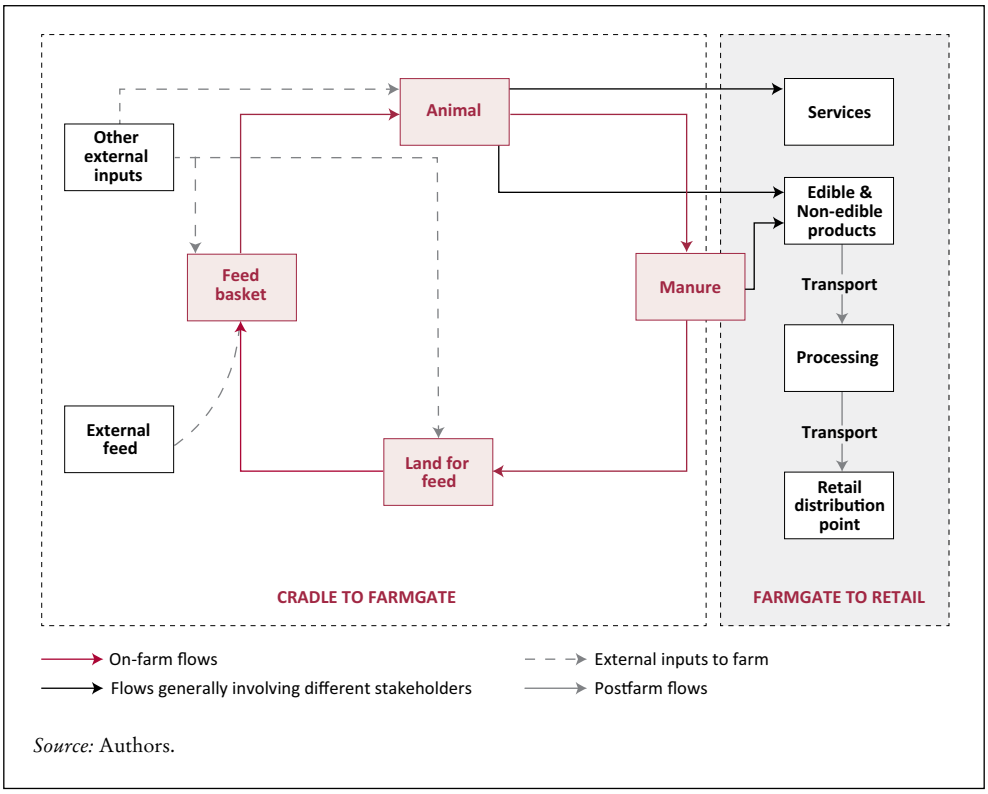

Source: Authors.

Table 1. Sources of GHG emissions included and excluded in this assessment

Food chain	Activity	GHG	Included	Excluded
Upstream	Feed production	N_2O	Direct and indirect N_2O from: • Application of synthetic N • Application of manure • Deposition of manure on pasture, ranges • Crop residue management	• N_2O losses related to changes in C stocks • Biomass burning • Biological fixation • Emissions from non-N fertilizers and lime
		CO_2	• Energy use in field operations • Energy use feed transport and processing • Fertilizer manufacture • Feed blending • Land-use change related to deforestation soybean and pasture expansion	• Changes in carbon stocks from land use under constant management practices
	Non-feed production	CO_2	• Indirect (embedded) energy related to the manufacture of on-farm buildings and equipment	• Production of cleaning agents, antibiotics and pharmaceuticals
Animal production unit	Livestock production	CH_4	• Enteric fermentation • Manure management	
		N_2O	• Direct and indirect N_2O from manure management	
		CO_2	• Direct on-farm energy use for milking, cooling, ventilation and heating	
Downstream	Post farmgate	CO_2; CH_4; HFCs	• Transport of live animals and product to slaughter and processing plant • Transport of processed product to retail point • Refrigeration during transport and processing • Primary processing of meat into carcasses or meat cuts and raw milk and dairy products • GHGs related to leakage of refrigerants during transportation • Manufacture of packaging	• On-site waste water treatment • Emissions from animal waste or avoided emissions from on-site energy generation from waste • Emissions related to slaughter by-products e.g. rendering material, offal, hides and skin • Retail and post-retail energy use • Waste disposal at retail and post-retail stages

Source: Authors.

products through internal chains on the farm and also allowing for imports and exports from the farm. The model therefore provides a means of integrating all these processes and linking all components in a manner that adequately captures major interactions among biological and physical processes. The flows are represented as directional lines between compartments in the system.

- "*Land for feed*" is the land used for feed production, on the farm itself or within the vicinity of production site (with negligible emissions related to the transport of feed to the animal rearing site).
- "*External feed*" originates from off-site production and includes by-products from the food industry and feed crops produced and transported over longer distances, e.g. soybeans; in most situations, the external feed is concentrate feed.
- "*Manure*" is shown partly outside the 'cradle-to-farmgate' system boundary in order to illustrate situations where manure is used as a fertilizer on food crops, either on- or off-farm, or where manure is used as fuel.
- "*Other external inputs*" refers to the inputs into production such as energy, fertilizer, pesticides, on-farm machinery, etc.

The connection of the four compartments shown in Figure 1 requires the devel-

opment of specific models (see Appendix A) and attribution techniques (see Section 3.6 and Appendix A) for the allocation of emissions among different processes, uses and outputs. These compartments not only represent different activities in the production process such as animal production, feed production, manure management, etc., but also define the inter-linkages among production processes such as the link between animal performance (genetics, management), animal feed requirements (energy and protein requirements) and the production of outputs such as edible and non-edible products and services, and emissions.

3.3.3 Sources of GHG emissions

This study focuses on emissions of the three major GHGs associated with animal food chains – methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) – as well as GHGs related to refrigerants. The following emission sources were included and further grouped into pre- and post farmgate sources, and a number of potential GHG emissions and sinks were excluded from the analysis (Table 1).

Table 1 also illustrates a number of processes and activities in the livestock food chain that have been excluded due to:

- lack of global databases, e.g. on the production of co-products at slaughterhouse, post retail emissions, etc.;
- lack of methodology or consensus on quantification approach, e.g. changes in soil carbon stocks from LU; and
- limited contribution of the processes to the carbon footprint, e.g. use of production of cleaning agents, antibiotics and pharmaceuticals.

Emission categories and a description of the emissions included in each category are presented in Table 2.

Table 2. Description of emission categories used in this assessment

Category		Description
Feed N_2O		Direct and indirect N_2O emissions from manure deposited on pasture Direct and indirect N_2O emissions from organic and synthetic N applied to crops and pasture
Feed CO_2	blending and transport	CO_2 arising from the production and transportation of compound feed
	fertilizer production	CO_2 from energy use during the manufacture of urea and ammonium nitrate (and small amounts of N_2O)
	processing and transport	CO_2 from energy use during crop processing (e.g. oil extraction) and transportation by land and (in some cases) sea
	field operations	CO_2 arising from the use of energy for field operations (tillage, fertilizer application). Includes emissions arising during both fuel production and use.
Feed LUC CO_2		CO_2 from LUC associated with soybean cultivation and pasture expansion
Indirect (embedded) energy CO_2		CO_2 arising from energy use during the production of the materials used to construct farm buildings and equipment
Manure N_2O		Direct and indirect N_2O emissions arising during manure storage prior to application to land
Manure CH_4		CH_4 emissions arising during manure storage prior to application to land
Enteric CH_4		CH_4 arising from enteric fermentation
Direct energy CO_2		CO_2 arising from energy use on-farm for heating, ventilation etc.
Post farmgate		Energy use in processing and transport

Source: Authors.

Figure 2.
Overview of the GLEAM modules and computation flows

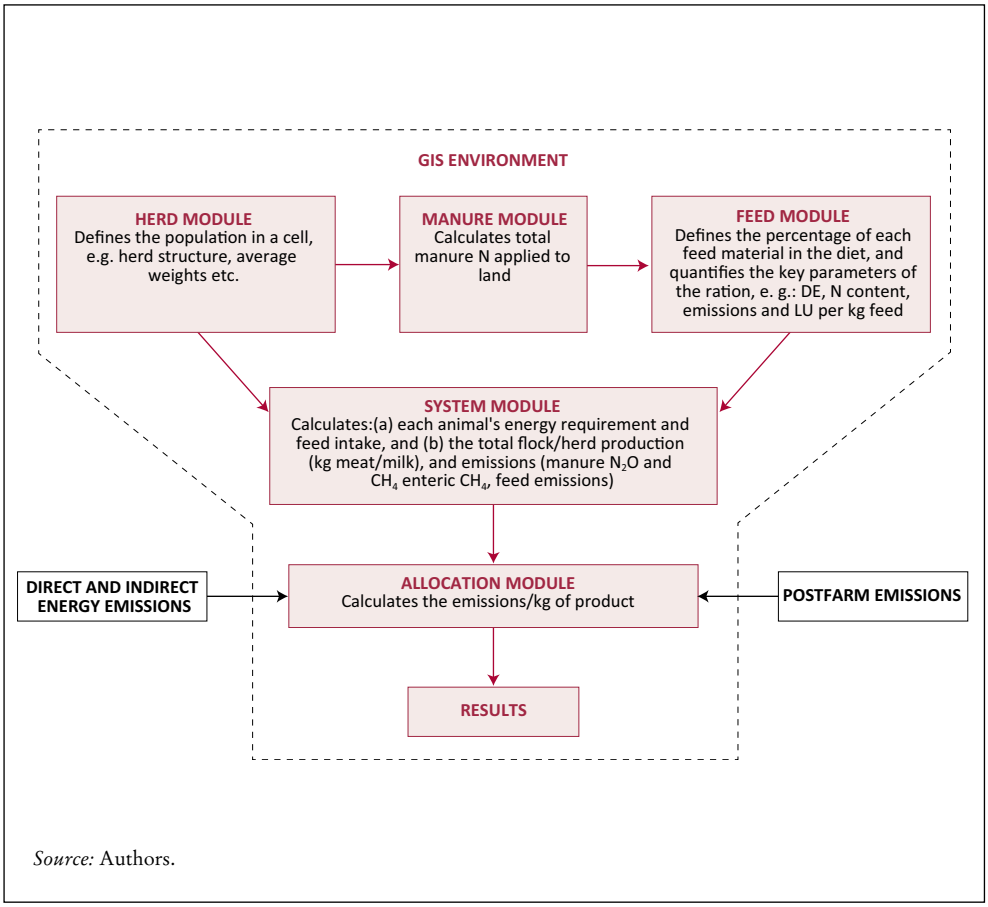

Source: Authors.

3.4 OVERVIEW OF CALCULATION METHOD

A specific model and related databases were developed to carry out this assessment. The Global Livestock Environmental Accounting model (GLEAM) was designed to represent processes and activities from the production of inputs into the production process to the farmgate, the point at which products and animals leave the farm. It consists of five main modules: *herd module, manure module, feed basket module, system module and allocation module* and two additional modules for the calculation of direct and indirect on-farm energy and post farmgate emissions (Figure 2). Appendix A provides a detailed explanation of GLEAM.

3.4.1 Spatial variation and the use of Geographic Information System

A challenge faced in conventional LCA modelling is the complexity and variation in biophysical characteristics (such as soil and climate) as well as production processes. Data on farming activities and farming system parameters were collected at different levels of aggregation: production system, country level, AEZs, or a combination thereof (e.g. information on manure storage in developing countries was available for a combination of production systems and AEZs). Additional data, such as livestock numbers, pasture and availability of feedstuff was available in the form of Geographical Information System (GIS) grids (raster layers), with a spatial resolution not coarser than 5 arc minutes (ca. 10 km x 10 km at the equator). For

the outputs of GLEAM, a spatial resolution of 3 arc minutes (ca. 5 km x 5 km at the equator) was used.

GIS can store observed data for specific locations (e.g. soil types, climate factors), can model new information from these data and can also calculate regional summaries such as total area, emissions, etc. GIS was used to analyse spatially varied data (such as crop yields, livestock species distribution), generate location-specific input data required for LCA modelling (e.g. define the typology of livestock production systems, and calculate location-specific feed-crop availability, classification of dominant soil types in forested areas and location-specific temperature to estimate EFs such as CH_4 conversion factors for MMS) and store numerical model input and output data in a GIS database.

The use of GIS allowed the incorporation of spatial heterogeneity into the modelling process which brought with it the benefit of enhancing the reliability of data used as well as results. Furthermore, it produced a more spatially accurate inventory of emissions, particularly CH_4 emissions which are modelled based on animal cohorts and feed intake. In this way, emissions were estimated at any location of the globe, based on available information, and then aggregated along the desired category, e.g. farming systems, country group, commodity and animal species. This assessment thus demonstrates the potential of coupling GIS technology with LCA for assessing GHG emissions from the livestock food chain.

3.4.2 Emission factors

The GHG EFs applied for the various emission sources in this study are specified in Appendix B of this report. A combination of IPCC (2006) Tier 1 and Tier 2 approaches and EFs were used in the estimation of emissions.

Despite the existence of country-specific EFs, the study applied the same approach to all countries. The use of a unified approach was preferred for the assessment, to ensure consistency and comparability of results across regions and farming systems.

IPCC Tier 2 approaches were used in the characterization of livestock population, to calculate emissions related to enteric fermentation as well as manure management and storage. The Tier 1 method was used where data was generally lacking, e.g. estimation of carbon stocks from LUC and N_2O emissions from feed production.

Global Warming Potentials (GWPs) with a time horizon of 100 years based on the 4th Assessment Report of the IPCC (IPCC, 2007) were used to convert N_2O and CH_4 to CO_2-eq terms. Consequently, GWP of 25 and 298 were used for CH_4 and N_2O, respectively.

3.4.3 Land use and land-use change

Assessment of changes in carbon stocks for agricultural land remaining in the same land use category requires dynamic process models and/or detailed inventory measurements. According to IPCC (2006), these models should be able to represent all relevant management practices and their driving variables compatible with available country data. Their validity should also be reported in empirical assessments. As no models satisfy these criteria and are validated on a global scale, this analysis doesn't incorporate C stock changes under constant land use. Nevertheless, a discussion on the effect of this simplification is provided in Appendix C, in particular about the role of grasslands in C sequestration.

Land-use change (LUC) is a highly complex process. It results from the interaction of drivers which may be direct or indirect[3] and which can involve numerous transitions, such as clearing, grazing, cultivation, abandonment and secondary forest re-growth. The debate surrounding the key drivers of deforestation is a continuing one and the causal links (direct and indirect) are both complex and unclear.

In this assessment, LUC considered are the transformation of forest to cropland and of forest to pasture. The former focuses on deforestation associated with soybean production in Brazil and Argentina. This choice results from the use of 2005 as year of reference and from the following observations of trends in LU transitions and crop expansions:

- In the period 1990-2006,[4] which is used as the reference time period in this study, the main global cropland expansions were for maize and soybean production;
- Maize and soybean expansion occurred in different regions of the world but only in Latin America can it be linked to a decrease in forest area during the same period; and
- Within Latin America, Brazil and Argentina account for 91 percent of the total soybean area. Over the period 1990–2006, 90 percent of the soybean area expansion in Latin America took place in these two countries.

LUC emissions were then attributed to only those countries supplied by Brazil and Argentina for soybean and soybean cake, proportionally to the share on imports from these two countries in their soybean supply. This study also provides an analysis of sensitivity to these assumptions, in particular on the reference time period, the expansion of soybean at the expense of other land types including forestland (arable and perennial cropland and grassland) and the assumption that all traded soybean and soybean cake is associated with LUC (see Appendix C).

The second LU transformation focuses on deforestation associated with pasture expansion in Latin America. This choice results from the observation that, during the period 1990-2006, significant pasture expansions and simultaneous forest area decrease occurred in Latin America and Africa. However, due to the lack of reliable data and information, it is difficult to draw conclusions on the land-use conversion trends in Africa.

LUC emissions associated with the expansion of pasture into forest areas in Latin America are attributed to beef production in those countries in which the conversion occurred. Appendix C provides an elaboration of the approach applied.

3.5 DATA SOURCES AND MANAGEMENT

The availability of data varies considerably within and among key parameters. In general, the OECD countries possess detailed statistics, supported by several scientific and technical publications. In contrast, there is a severe paucity of data in non-OECD countries. Where detailed and accurate data are available, they are often outdated and/or lack supporting metadata. Appendix B presents some of the data utilized in this assessment.

[3] Direct drivers include conversion of forest areas for plantation crops or cattle ranching, rural settlements, mining and logging. Indirect drivers include subsidies for agribusiness, investment in infrastructure, land tenure issues, absence of adequate surveillance by the government and demand for forest products, such as timber.

[4] 1990 is chosen as the initial year because it is the most recent available year with a consistent forest dataset from the FAOSTAT database. This practically discounts 4 years of LUC related emissions, compared to the 20-year timeframe recommended by IPCC (IPCC, 2006).

Table 3. Overview of the data sourced for the preparation of this assessment

Data groups	Data collection approach and sources
Herd (animal parameters)	Literature reviews, reports and surveys (see Appendix B)
Manure management	Literature reviews and reports (see Appendix B)
Feed basket	Literature reviews, reports; IFPRI (GIS based data)
LCI feed components	Literature reviews, reports; IFPRI (GIS based data), LCI databases Sweden and the Netherlands
Yield	Literature reviews and FAOSTAT
Non-edible products	Literature reviews and reports, FAOSTAT
Carbon stocks	Use of model based on Gross Primary Production (GPP)
Deforestation	FAO Forestry statistics, IPCC guidelines, literature and own calculations (see Appendix C)
Animal population characterization	Herd layer data, FAOSTAT and FAO Gridded Livestock of the World
Capital goods	Ecoinvent database and literature reviews

Source: Authors.

During the process of data collection, gaps initially encountered were addressed, to the extent possible, by extensive research of databases, literature sources and expert opinion. Assumptions were made when data could not be obtained. Data collection involved a combination of research, direct communication with experts, and access to public and commercially available life cycle inventory (LCI) packages such as Ecoinvent. The study's main data sources included:

- Gridded Livestock of the World (FAO, 2007).
- National Inventory Reports of Annex I countries (UNFCCC, 2009a).
- National Communications of non-Annex I countries (UNFCCC, 2009b).
- Geo-referenced databases on crop production from the International Food Policy Research Institute (You *et al.*, 2010).
- Above-ground net primary production (NPP) (Haberl *et al.*, 2007)
- Life Cycle Inventory (LCI) data from the Swedish Institute for Food and Biotechnology (Flysjö *et al.*, 2008), and Wageningen University, the Netherlands (I. de Boer, personal communication).
- Reports from the CGIAR research institutes.
- Statistics from FAO (FAOSTAT, 2009).
- Peer-reviewed journals.

The data have been organized into data groups or "basic data layers". Table 3 summarizes the data collection approach and sources for each main data group.

Further detail on data and data sources is given in Appendix B.

3.6 ALLOCATION OF EMISSIONS BETWEEN PRODUCTS, BY-PRODUCTS AND SERVICES

Livestock produce a mix of goods and services that cannot be disaggregated easily into individual processes. For example, a dairy cow produces milk, manure, draught power and capital services, and eventually meat when it is slaughtered. Given that multiple products are produced from each of the ruminant species, the environmental burden associated with production needs to be allocated for each of the products. In LCA, specific techniques are required to attribute relative shares of

Figure 3.
An illustration of production activities and partitioning of total emissions to products and services from cattle

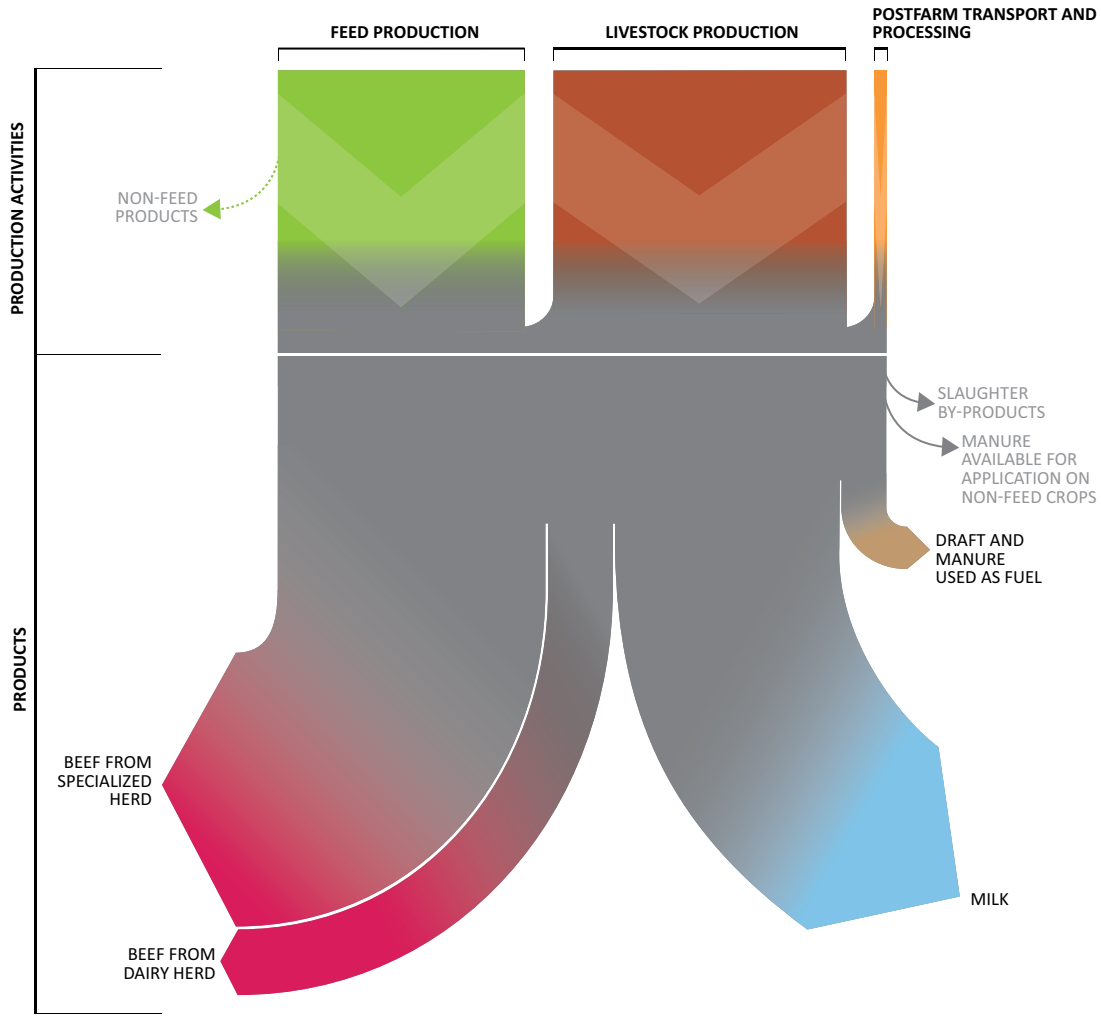

Source: Authors.

GHG emissions to each of these goods and services. The ISO recommends avoiding allocation by dividing the main process into sub-processes, or by expanding the product system to include additional functions related to the co-products (ISO, 2006). In situations where allocation cannot be avoided (as is often the case in biological processes such as livestock production), GHG emissions can be allocated on the basis of causal and physical relationships.

Where physical relationships alone cannot be established or used as a basis for allocation, emissions should be allocated in a way which reflects other fundamental relationships. In the latter case, the most commonly used approach is economic allocation which, in the context of jointly produced products, allocates emissions to each product according to its share of the products' combined economic value. Other indexes, such as weight or protein content, can also be used (Cederberg and

Figure 4.
Classification of ruminant production systems used in the assessment

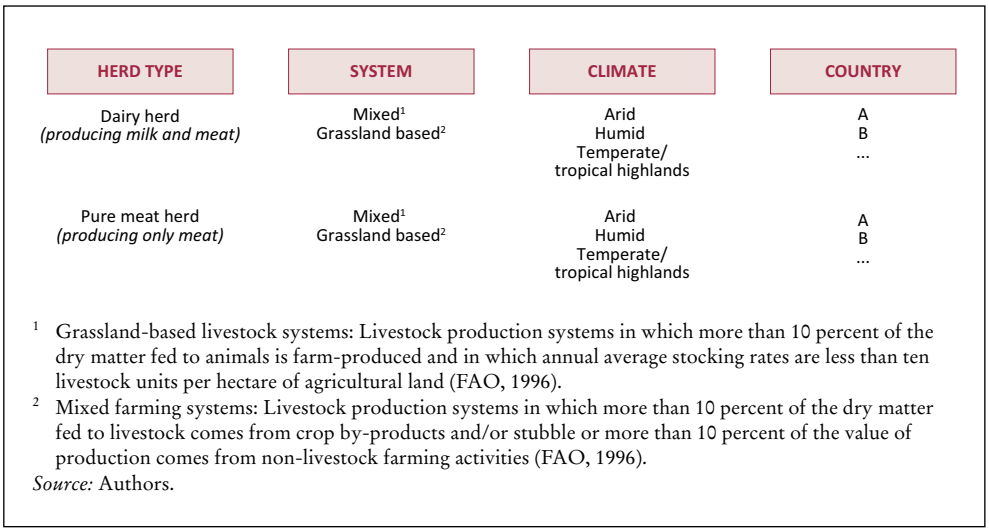

[1] Grassland-based livestock systems: Livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten livestock units per hectare of agricultural land (FAO, 1996).
[2] Mixed farming systems: Livestock production systems in which more than 10 percent of the dry matter fed to livestock comes from crop by-products and/or stubble or more than 10 percent of the value of production comes from non-livestock farming activities (FAO, 1996).
Source: Authors.

Stadig, 2003). The allocation techniques used in this assessment to apportion emissions to products and services produced by ruminant systems are summarized below:

- Edible products (e.g. meat and milk): allocation based on protein content.
- Edible and non-edible products (e.g. milk, meat and fibre): allocation based on economic value of outputs.
- Slaughter by-products: no allocation is performed in this assessment. Appendix F explores the impact of allocating emissions to slaughter by-products.
- Manure: allocation based on sub-division of production process.
  - manure storage: emissions from manure management systems (MMS) allocated to livestock sector;
  - manure applied to feed: emissions allocated to livestock sector based on mass harvested and relative economic value;
  - manure applied to non-feed: no allocation to livestock sector; and
  - manure used for fuel: Emissions are deducted from the overall emissions and therefore are not allocation to livestock sector.
- Capital function: no allocation is performed in this assessment.
- Services (e.g. animal draught power): biophysical allocation based on extra-life time gross energy requirements for labour and emissions are deducted from the overall livestock emissions.

A detailed account of the application of the allocation technique is provided in Appendix A. Figure 3 illustrates flows of outputs from the cattle sector.

3.7 PRODUCTION SYSTEM TYPOLOGY

This assessment estimates emissions at global, regional and farming system levels. A farming system typology was thus adapted to provide a framework for examining GHG emission from different dairy farming systems. This typology is based on the classification principles set out by FAO (1996), namely, the feed-base and the agro-ecological conditions of production systems (Figure 4).

The following three AEZs were used:

- *"temperate": temperate regions*, where for at least one or two months a year the temperature falls below 5 ºC; and *tropical highlands*, where the daily mean temperature in the growing season ranges from 5 to 20 ºC.;
- *"arid": arid and semi-arid tropics and subtropics*, with a growing period of less than 75 days and 75-180 days, respectively; and
- *"humid": humid tropics and sub-humid tropics* where the length of the growing period ranges from 181-270 days or exceeds 271 days, respectively.

The widely-used classification approach developed by FAO (1996) that was used here has a number of advantages: it allows researchers to use the multiple databases developed using this structure [e.g. geo-referenced data on animal numbers in each livestock production system (LPS)]; it provides a conceptual framework to make estimates where data are lacking; and it enhances the compatibility of this work with other analyses using similar classification schemes.

4. Results

4.1 CATTLE

This study estimates that in 2005, total emissions from cattle production amount to 4 623 million tonnes CO_2-eq. These emissions include emissions associated with the production of meat and milk, emissions related to land-use change, emissions associated with post farmgate activities, and emissions related to non-edible products and services, draught power and manure used for fuel.

The following sub-sections present the emissions associated with edible products (meat and milk) as well as a disaggregated overview of the contribution of production systems and regions to emissions.

4.1.1 Total production, absolute emissions and emission intensities

In 2005, the global cattle sector produced approximately 508.6 million tonnes of milk and 61.4 million tonnes of beef, of which 56 percent of beef was produced by the specialized beef sector and 44 percent by the dairy herd. Table 4 reports the volume of production, absolute emissions and average GHG emissions per kg of milk and meat for the dairy and beef subsectors.

Globally, about 4 255.9 million tonnes of CO_2-eq were emitted by the global cattle sector in 2005; of this 1 419.1 million tonnes were associated with milk production and 2 836.8 million tonnes with beef production.[5] This is equivalent to 2.8 kg CO_2-eq per kg of fat and protein corrected milk and 46.2 kg CO_2-eq per kg of carcass weight.[6]

Regarding beef production from the cattle sector, there is a distinct difference in emission intensity between beef produced by the dairy herd and the specialized beef herd; the carbon intensity of beef from the specialized beef herds is almost fourfold that produced from the dairy herd (67.8 vs. 18.4 kg CO_2-eq per kg CW) (Table 4). The low emission intensity for dairy meat is caused by the fact that both milk and meat are produced by the dairy herd. Because a large proportion of the

Table 4. Global production, absolute GHG emissions and emission intensities for milk and beef

Cattle herd	Production *(million tonnes)*		Absolute emissions[1] *(million tonnes CO_2-eq)*		Average emission intensity *(kg CO_2-eq/kg product)*	
	Milk[2]	**Meat[2]**	**Milk**	**Meat**	**Milk[2]**	**Meat[2]**
Dairy	508.6	26.8	1419.1	490.9	2.8	18.4
Beef	-	34.6	-	2345.9	-	67.8
Totals	**508.6**	**61.4**	**1419.1**	**2836.8**	**2.8**	**46.2**

[1] Absolute emissions include emissions from production, post farmgate processes and land-use change.

[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.

Source: GLEAM.

[5] Unless otherwise stated, the term "beef" refers to meat from dairy and specialized beef herds.

[6] Does not include emissions associated to slaughter by-products. See Appendix F for discussion of effects on results.

Figure 5.
Relative contribution of different processes to total GHG emissions from the global cattle sector

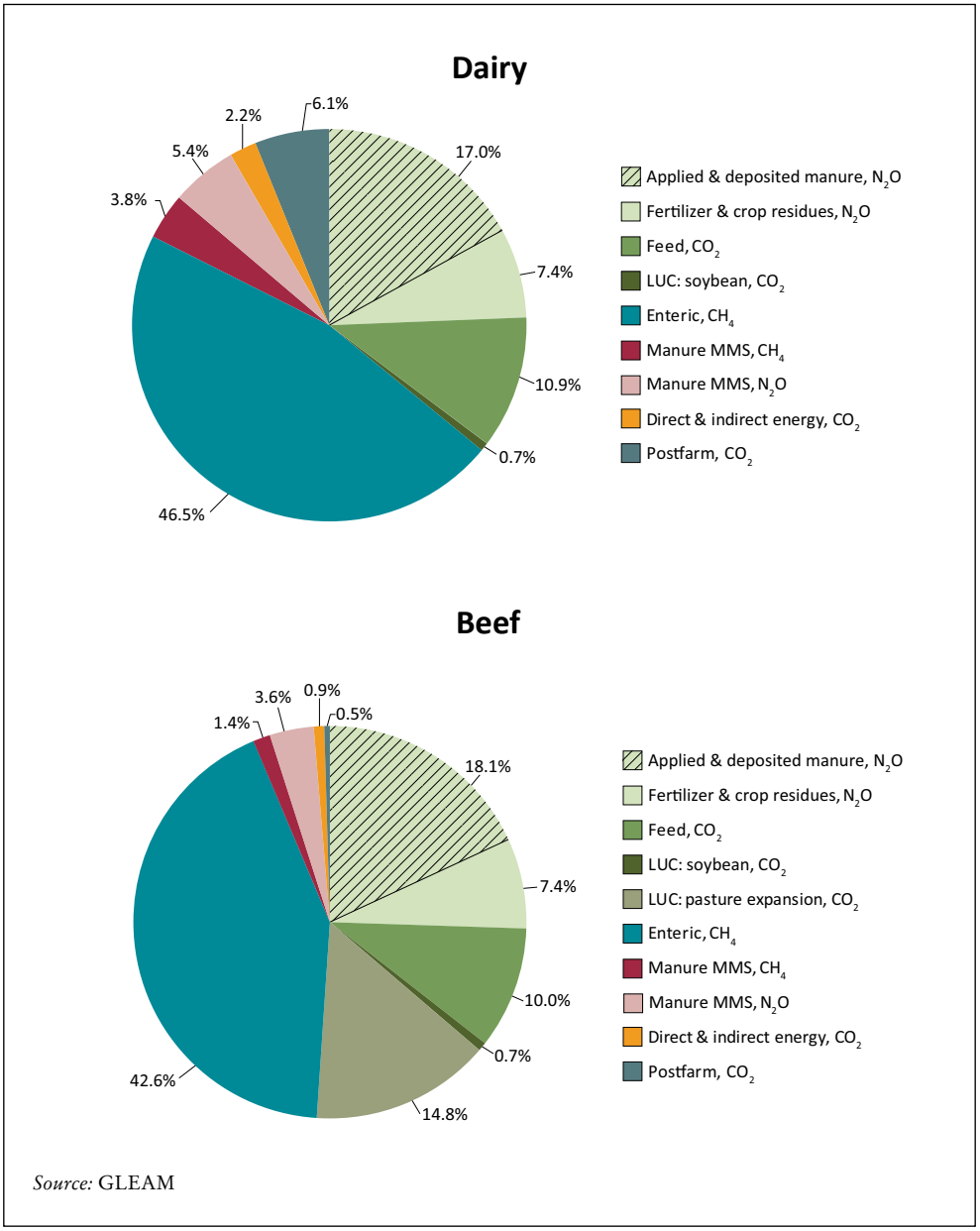

Source: GLEAM

total protein from the dairy herd originates from milk (see Map 6 in Appendix G), a greater proportion of the emissions from dairy herd is attributed to milk. Consequently, this reduces the GHG emissions attributed to meat from culled dairy cows and related meat production from surplus animals.

On the other hand, the specialized beef herd carries the entire burden of emissions because only one product is produced, while the reproductive overhead (cows, bulls and replacement animals) is almost the same. The overhead costs of the cow in dairy-based production systems are largely attributed to milk while in the specialized beef system the full costs are allocated to those animals destined for beef production.

Figure 6.
Contribution to total milk and beef production by production systems and agro-ecological zone[1]

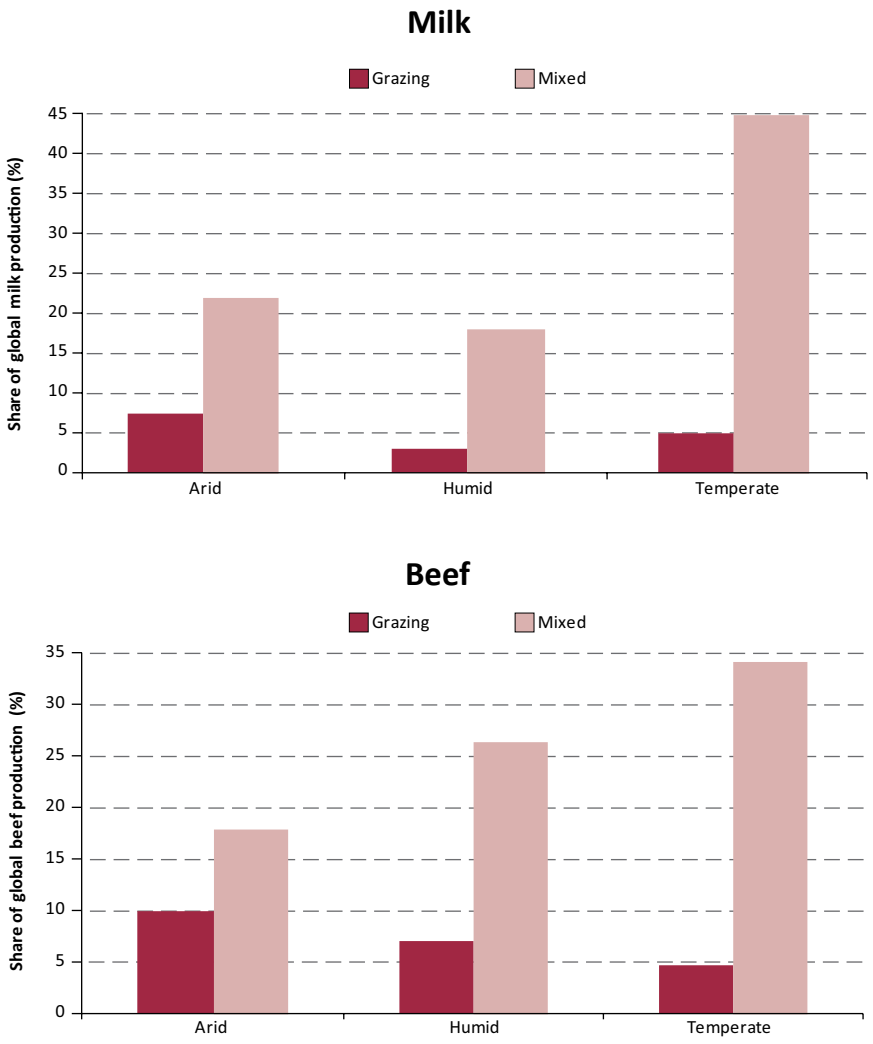

[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

The relative contribution of production processes and gases to the emissions profile for milk and beef at global level is illustrated in Figure 5. A significant share of total GHG emissions is from CH_4 which accounts for 50 percent and 44 percent of the total emissions, with enteric fermentation contributing more than 92 percent and 97 percent of the total CH_4 emissions in dairy and beef production.

In both dairy and beef herds, N_2O emissions amounted to relatively similar proportions of the total carbon footprint – approximately 29 percent of the emissions. Main sources of N_2O emissions include N_2O from manure deposited during grazing and feed production.

On a global scale, CO_2 emissions represent 20 percent and 27 percent of the dairy and beef emission profiles, respectively. The difference in CO_2 emissions between

dairy and beef herds is due to the CO_2 emissions from land-use change associated with the expansion of grassland into forest areas which accounts for 14.8 percent of the total emissions related to beef production and 55 percent of the CO_2 emission.

4.1.2 Emissions by production system and agro-ecological zone

Grass-based systems and mixed livestock production systems contribute 22 and 78 percent of global beef production, and 15 percent and 84 percent of global milk production, respectively (Figure 6).

Average emission intensities for milk and beef produced in grazing and mixed farming systems were estimated at 2.9 and 2.5 kg CO_2-eq/kg FPCM and 42.0 and 38.4 kg CO_2-eq/kg CW, respectively. The variation in emission intensity between the two systems is explained by several factors such as the generally higher slaughter weights, lower age at calving, reduced time to slaughter, and lower mortality rates and better feed quality in mixed farming systems.

Lowest emission intensity in milk and beef production corresponds to the temperate zones in both grassland-based and mixed farming systems (Figures 7 and 8), where productivity is rather high and CH_4 from enteric fermentation is low as a consequence of high digestibility of the feed in these zones. Concomitantly, temperate zones have slightly higher emissions associated with CO_2 feed compared with the humid and arid areas as a result of the high dependency on imported concentrate feed and synthetic fertilizer use in feed production. Lower emission intensity of beef produced in temperate zones is also related to the importance of dairy production in these areas; about 44 percent of the beef from the dairy sector is produced in temperate zones. Beef from the dairy sector as a consequence of the dairy system characteristics comes with discounted emissions because a large share of the emissions related to the meat from culled breeding animals is allocated to milk production.

Enteric CH_4 is the largest source of emissions in all systems; however it is highest in arid and humid zones of both grazing and mixed farming systems where feed, for the most part, is of low quality.

Nitrous oxide emissions from feed production are dominant in both grazing arid and humid zones resulting from manure deposited on pasture during grazing, while in the mixed systems high N_2O emissions are not only associated with manure deposition but also use of synthetic fertilizer in feed production (see Section 5.2).

On the other hand, CH_4 emissions from manure management in both systems are negligible and this is explained by the high proportion of manure that is managed in dry MMS such as drylots or solid systems. Nitrous oxide from manure management is generally low especially in grazing systems because animals are grazing most of the time and manure is mostly deposited on pasture.

4.1.3 Regional emissions, production and emission intensities

In terms of total production, approximately 67 percent of the total protein from the global cattle sector is from milk. However, this global estimate obscures variations at regional level, where large differences exist both in terms of production and emissions. With the exception of Latin America and the Caribbean, the contribution of milk protein to the total protein from the cattle sector on average ranges from 56 percent in sub-Saharan Africa to 81 percent in Western Europe (Figure 9; Map 6 in Appendix G). In Latin America, meat protein contributes about 54 percent of the

Figure 7.
Emission intensities for milk by production system and agro-ecological zone[1]

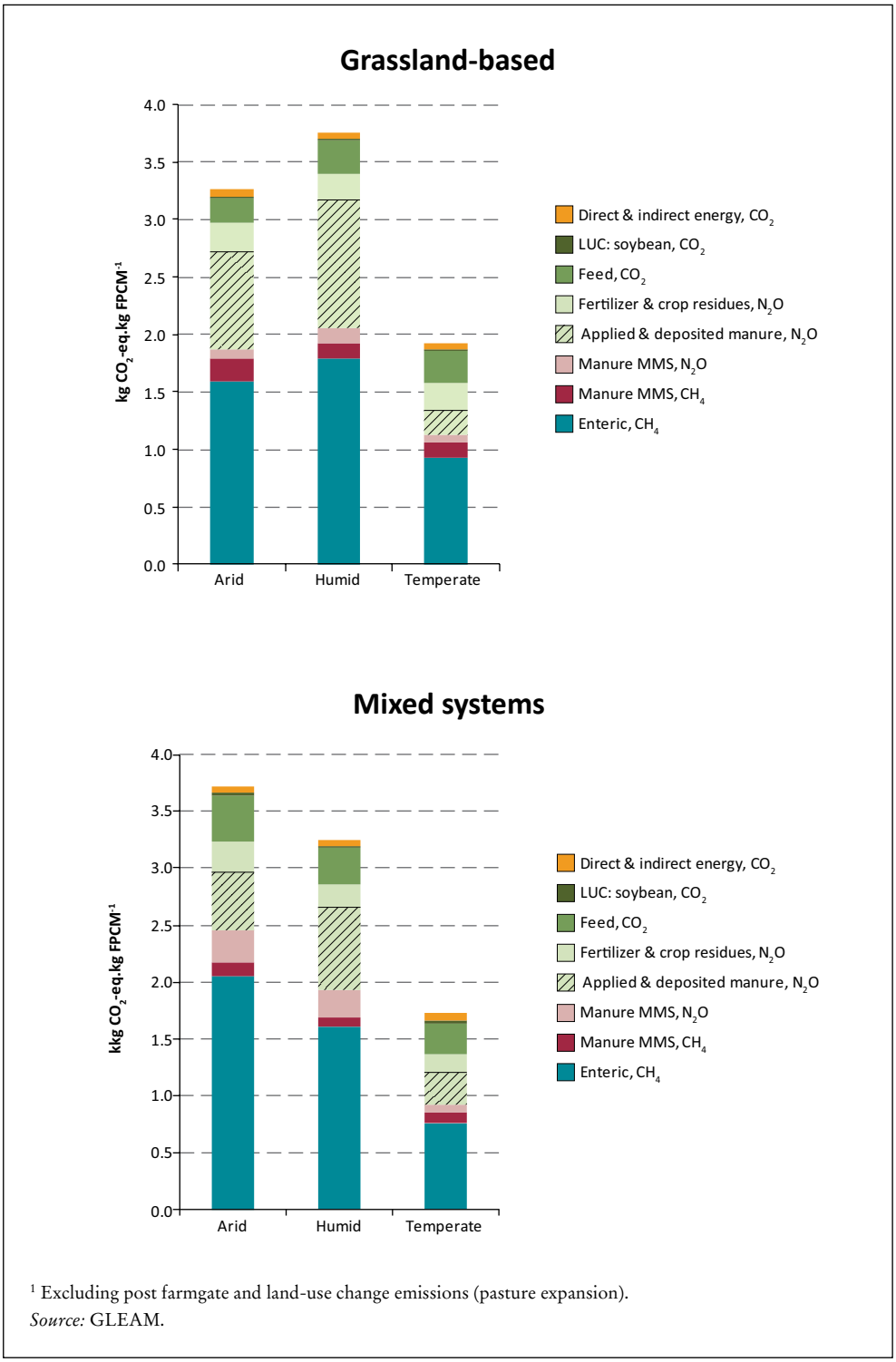

[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

Figure 8.
Emission intensities for beef by production system and agro-ecological zone[1]

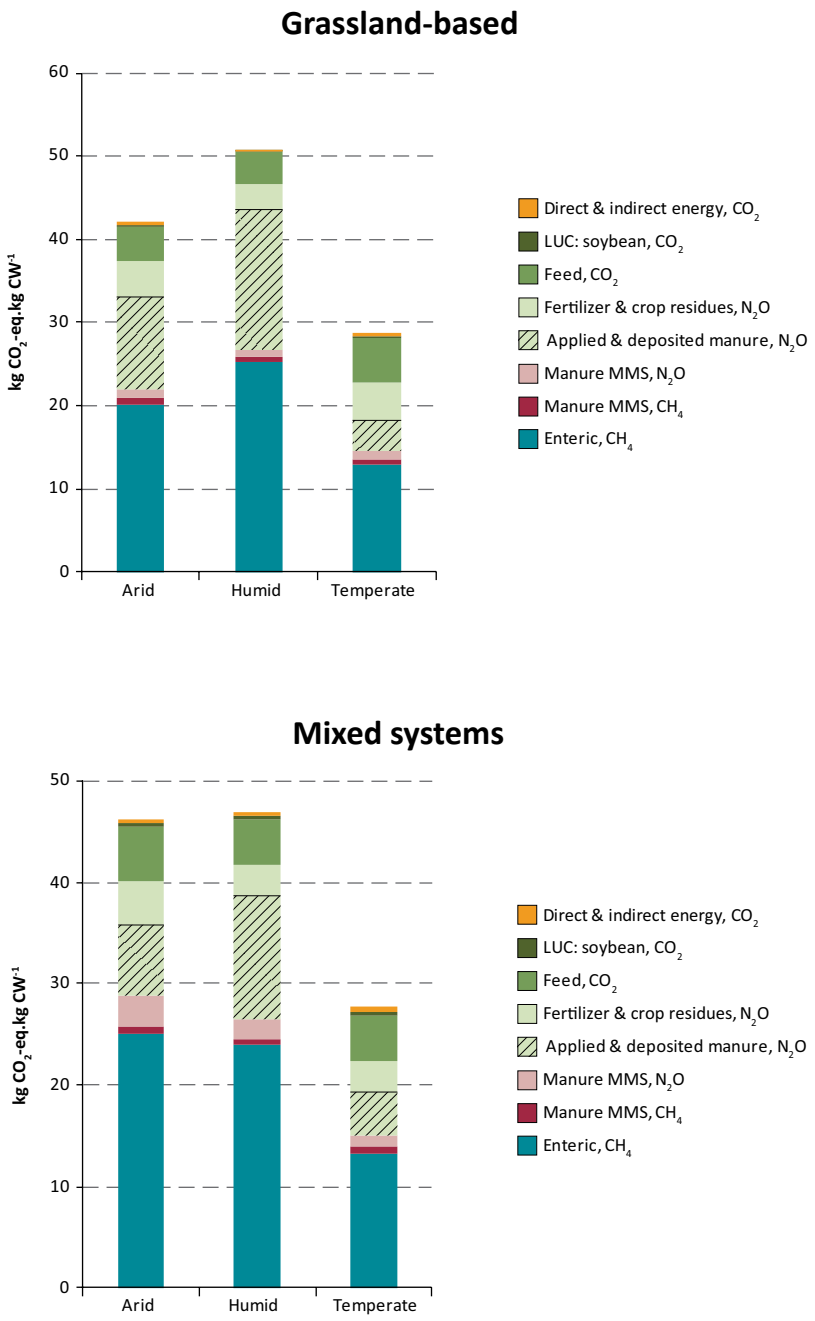

[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

Figure 9.
Regional contribution to milk and meat protein

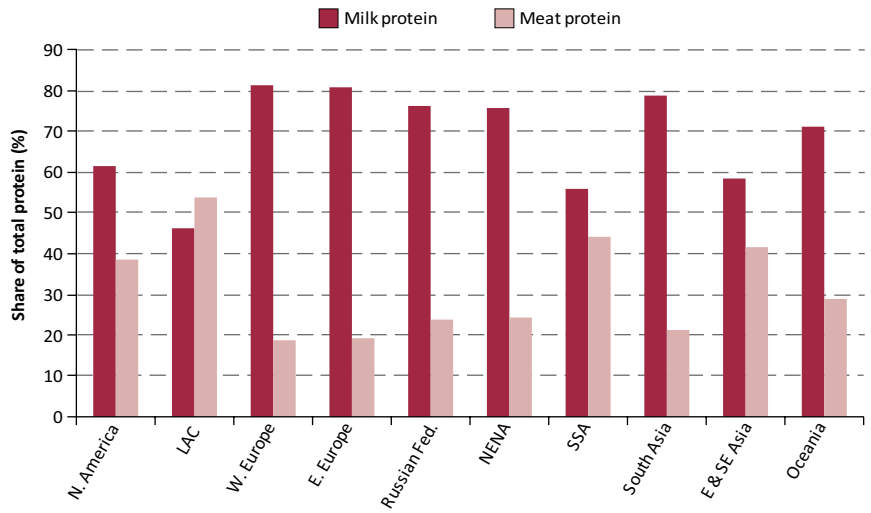

Source: GLEAM.

Figure 10.
Emissions per kg meat and milk protein, comparing allocation of emissions to different outputs

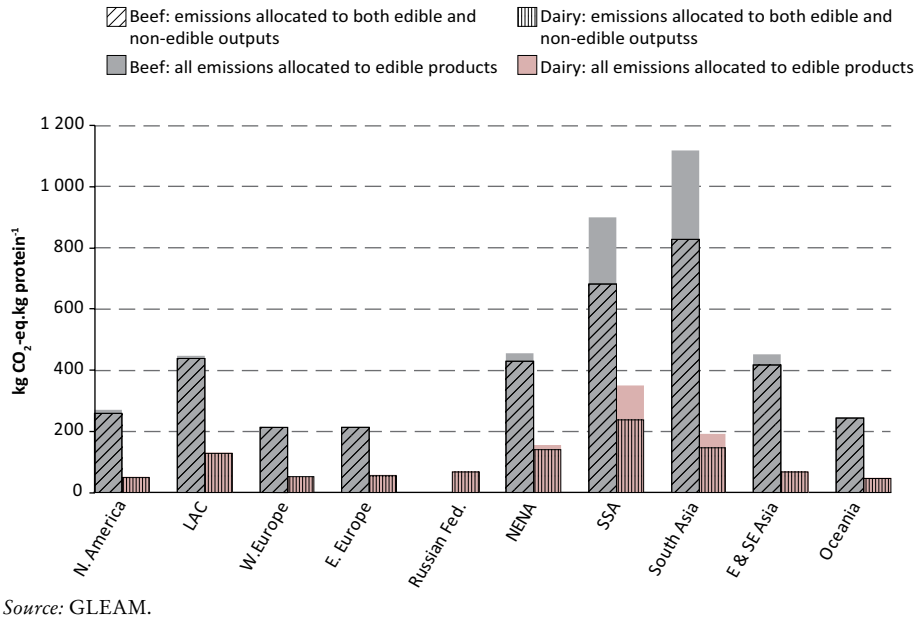

Source: GLEAM.

total protein from cattle, mainly because the emphasis is on beef production rather than dairy. In the other world regions, meat protein ranges between 18 percent in Europe to 44 percent in sub-Saharan Africa.

Figure 10 presents a regional comparison of emission intensities for two computation approaches where (i) all emissions from cattle production are allocated to the main edible outputs from the system, milk and meat; and (ii) emissions related to other functions and processes, e.g. draught power and those related to the use of manure as a source of fuel, are deducted from the overall system emissions.

Figure 10 illustrates the difference in carbon equivalent impact and the extent to which production is specialized, i.e. whether it is meant for milk and meat production or whether animals are kept for other purposes. The starkest difference in emission intensity is shown for sub-Saharan Africa and South Asia where cattle herds are multi-purpose, producing not only edible products but also non-edible products and services that are utilized in other production processes within or outside the livestock sector boundary. In these regions, use of draught power is important as well as the use of manure as a source of fuel, and allocation of emissions to these products and services significantly lowers the emission intensity of edible products in these regions. In contrast, in industrialized regions, production is more specialized with cattle being specifically reared to produce meat and milk products. In these regions, emission intensity is generally lower, because production is more

Figure 11a.
Regional variation in GHG emission intensities for cow milk

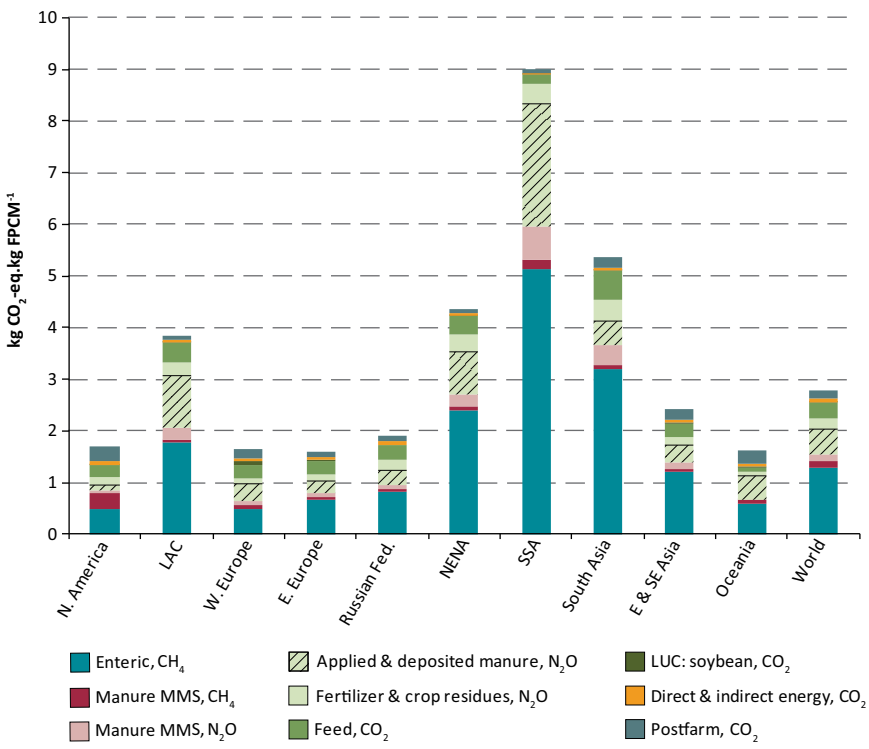

Source: GLEAM.

efficient, yields are higher, and animals are not kept for longer periods for other purposes such as draught power.

Figures 11a and 11b present regional variation in emission intensity for milk and meat (after allocation to draught and manure used for fuel) and the contribution of emission categories to the emission profile.

For milk, emission intensities vary from 1.6 kg CO_2-eq/kg FPCM in Eastern and Western Europe to 9 kg CO_2-eq/kg FPCM in sub-Saharan Africa (Figure 11a). Generally, industrialized regions of the world exhibit the lowest emission intensities per kg FPCM ranging between 1.6 and 1.7 kg CO_2-eq/kg FPCM, while in developing regions the range of emission intensity for milk is wider – 2.0 and 9.0 kg CO_2-eq/kg FPCM.

The main contribution to the GHG emission profile of milk in developing regions is enteric fermentation while in industrialized regions dominant emissions are largely related to feed production and processing. With regard to manure management, CH_4 emissions are highest in North America where on average 27 percent of manure from the dairy sector is managed in liquid systems that produce greater quantities of CH_4 emissions (see Section 5.3.1). In contrast, N_2O emissions from manure management are higher in developing regions as a result of the higher proportion of manure managed in dry systems.

Figure 11b.
Regional variation in GHG emission intensities for beef

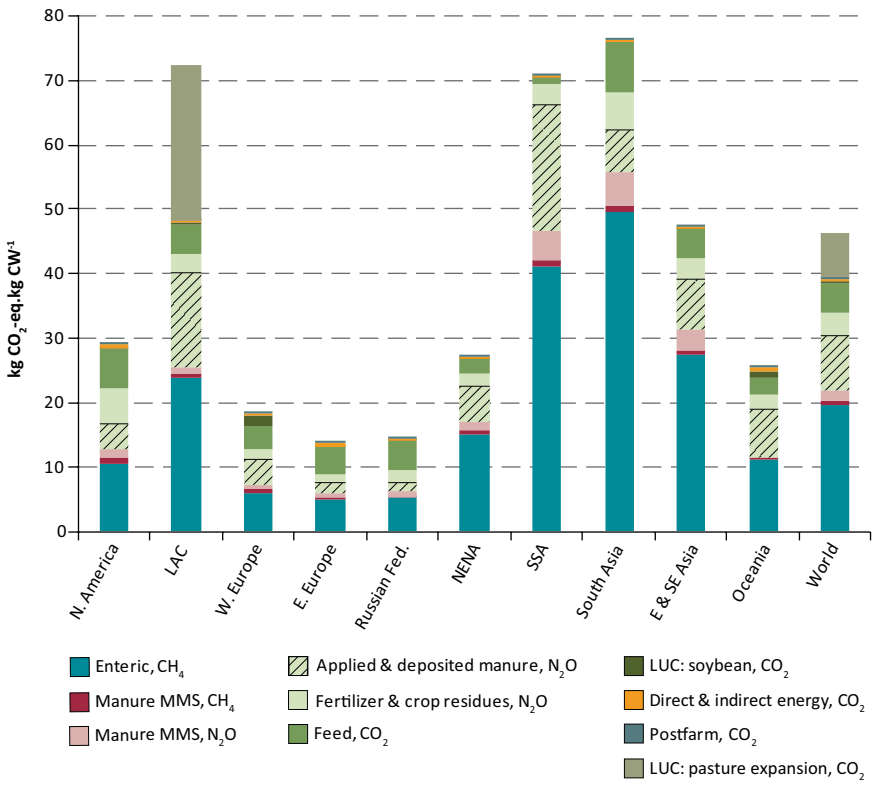

Source: GLEAM.

Figure 12.
Regional comparison of emission intensity per kilogram of carcass

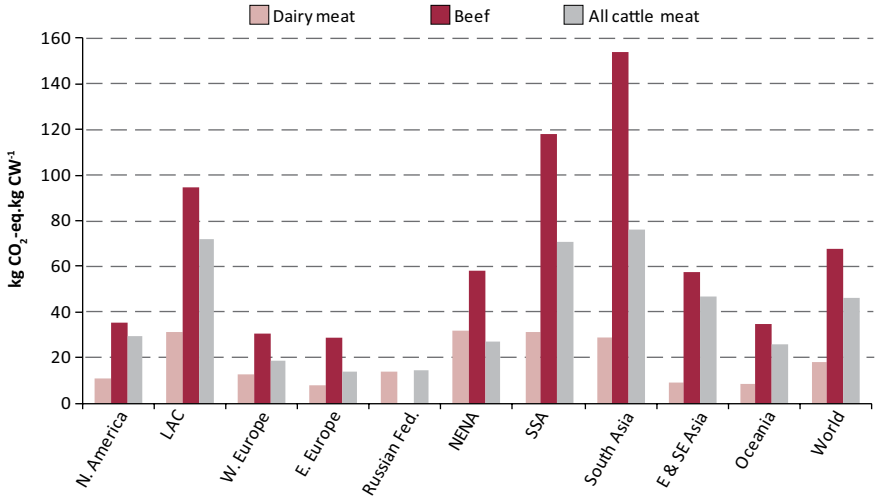

Source: GLEAM.

Regional variability in emission intensity for beef is presented in Figure 11b, with GHG emissions per kg carcass weight (CW) ranging from 14 kg CO_2-eq/kg CW in Eastern Europe and Russian Federation to 76 kg CO_2-eq/kg CW in South Asia. Highest emission intensities are found in developing regions: South Asia, sub-Saharan Africa, LAC and East and Southeast Asia. A key driver for the high emissions associated with beef is largely related to low feed digestibility, lower slaughter weights and higher age at slaughter. The carbon footprint of beef produced in Latin America comprises emissions related to land-use change from pasture expansion into forested areas. Consequently, land-use change is a major driver of emissions in the region, representing approximately one-third of the footprint (Figure 11b), equivalent to 24 kg CO_2-eq/kg CW. These LUC estimates are however associated with a high level of methodological uncertainty and do not capture recent deforestation trends (the period considered is 1990-2006).

The low emission intensities associated with beef in Europe (Western and Eastern Europe, and the Russian Federation) is explained by the large proportion of the beef produced from the dairy herd.[7] About 80 percent of the beef production in Europe is derived as a co-product from dairy production (from surplus calves and culled cows); in the Russian Federation, all beef is estimated to be produced by the dairy sector. The dairy sector therefore has a much higher impact on beef production in these regions and this is directly linked to the need for their dairy sectors to sustain milk production through production of calves in order to keep cows lactating. Figure 12 compares the regional emission intensity for beef produced by the dairy and beef herd and the average emission intensity of all beef produced by the cattle sector. The low emissions are also an artefact of the production characteristics of dairy herd (dual products) (see discussion on allocation techniques in Appendix A) and hence a large proportion of the emissions attribut-

[7] Table B22, Appendix B presents the contribution of dairy and beef herds to total beef production.

able to dairy cows is allocated to milk, resulting in a lower allocation to beef from the dairy herd.

The emission intensity for beef in Western Europe, North America and Oceania is lower than the global average mainly because these regions are key beef-producing regions characterized by high efficiency in production and high feed digestibility (Map 8 in Appendix G).

Table B13 in Appendix B illustrates average feed digestibility values for the average feed ration used in beef production in different regions. Highest feed digestility is found in industralized countries where feed rations are laregly composed of higher quality roughages and concentrates. The digestibility of average feed rations in developing regions is much lower, particulary in sub-Saharan Africa, South Asia and parts of East and Southeast Asia. Feed rations in this regions are laregly composed of roughages of low quality (grass, crop residues and leaves).

Regarding the contribution of different processes to the emission profile for beef, a distinct difference can be observed between the two broad regional groupings (developing and industrialized).

In developing regions, analogous to the dairy, the overall emission profile for beef is dominated by enteric CH_4 and N_2O emissions related to feed from manure deposited on pasture during grazing. The relatively higher N_2O emissions from manure management in sub-Saharan Africa, South Asia, and East and Southeast Asia reflects the higher share of manure managed in dry systems.

In contrast, enteric CH_4 emissions play a less important role in industrialized regions; however, this is compensated by high CO_2 and N_2O from feed emissions, reflecting a high dependence on feed imports, high fertilizer use in feed production and a higher level of mechanization (see Section 5.2).

4.2 BUFFALO

Milk and meat production from the global buffalo sector contributes an equivalent of 619 million tonnes CO_2-eq consisting of emissions from the production of meat and milk, emissions related to land-use change, emissions associated with post farmgate activities, and emission related to non-edible products and services, i.e. draught power and manure used for fuel.

4.2.1 Total production, absolute emissions, and emission intensities

In 2005, global buffalo milk and meat production amounted to 115.2 and 3.4 million tonnes, respectively, and associated with this, about 390 and 180.2 million tonnes CO_2-eq were emitted from the production of milk and meat from buffaloes, respectively (Table 5). On average, the emission intensity of buffalo milk and meat is estimated at 3.4 kg CO_2-eq/kg FPCM and 53.4 kg CO_2-eq/kg CW, respectively (Table 5). The emission intensity of meat produced by the dairy herd is significantly lower than that produced from the meat herd and the reasons are similar to those outlined in the previous sub-section on the cattle sector.

Enteric fermentation is by far the most important source of emissions, contributing over 60 percent of the emissions in both milk and meat production (Figure 13). Other important sources of emissions include emissions from feed production, particularly N_2O emissions from manure deposited largely determined by the long grazing period. Emissions from manure management (N_2O and CH_4 emissions) together contribute 6 percent and 7 percent of the total emissions from dairy and meat herds.

Table 5. Global production, emissions and emission intensity for buffalo milk and meat

Buffalo herd	Production *(million tonnes)*		Absolute emissions[1] *(million tonnes CO_2-eq)*		Average emission intensity *(kg CO_2-eq/kg product)*	
	Milk[2]	Meat[2]	Milk	Meat	Milk[2]	Meat[2]
Milk	115.2	2.4	389.9	40.4	3.4	16.6
Meat	-	0.95		139.9	-	143.9
Totals	**115.2**	**3.4**	**389.9**	**180.2**	**3.4**	**53.4**

[1] Absolute emissions include emissions from production and post farmgate emissions.
[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.
Source: GLEAM.

Figure 13.
Relative contribution of different processes to GHG emission profile of buffalo milk and meat

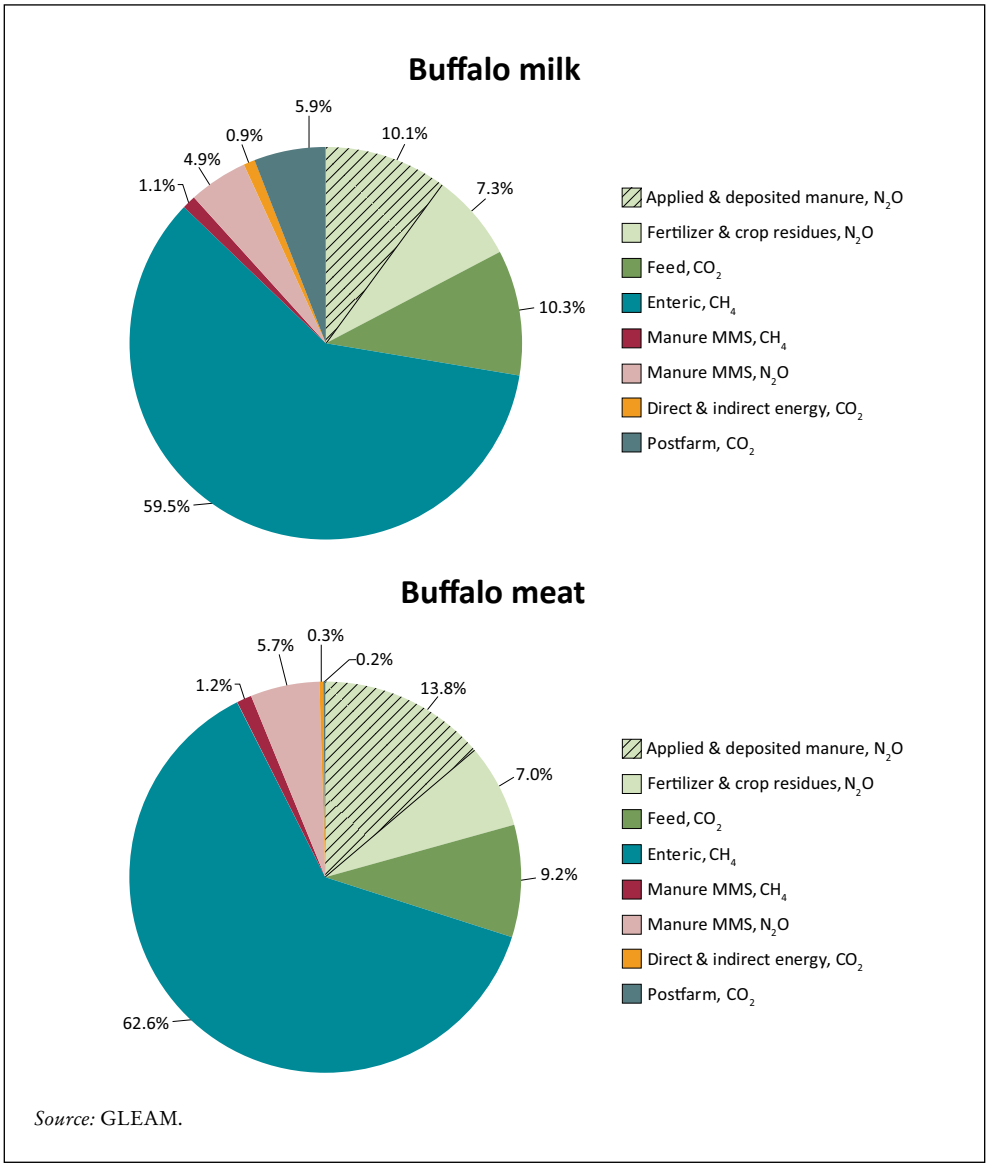

Source: GLEAM.

4.2.2 Emissions by production system and agro-ecological zone

Average emission intensity of buffalo milk from grazing and mixed farming systems is estimated at 3.4 and 3.2 kg CO_2-eq/kg FPCM, respectively. On the other hand, the emission intensity of buffalo meat from grazing and mixed farming systems is 36.7 and 54.0 kg CO_2-eq/kg CW, respectively. About 82 percent and 67 percent of milk and meat production from buffalo is produced in the mixed arid zones. Production in the other ecological zones is unimportant.

Lowest emission intensities for milk are found in the grazing temperate and mixed arid production systems (Figure 14).

Lowest emission intensities for buffalo meat are found in the arid zones in both grazing and mixed systems (Figure 15), which contribute 70 percent of all buffalo meat, while humid zones in both systems have highest emission intensities. Important sources of emissions include: enteric fermentation, N_2O from feed production and grazing; and CO_2 emissions from feed production and processing. N_2O from manure and feed is an important source of emissions in the humid zones; these emissions are largely driven by the predominance of dry manure management systems and emissions from the deposition of manure on pasture. The remaining emissions are insignificant in terms of their contribution towards the carbon profile.

4.2.3 Regional production emissions and emission intensities

Global buffalo milk and meat production is important in three main world regions: South Asia, NENA and East & Southeast Asia; South Asia contributes 90 percent and 70 percent of the global buffalo milk and meat, respectively, and average milk emission intensity ranges from 3.2 to 4.8 kg CO_2-eq/kg FPCM (Figure 16a); milk produced in South Asia has the lowest emission intensity, explained by high yields. Emission intensity in South Asia is similar to the global average, explained by the fact that the bulk of buffalo milk (90 percent) is produced in the region.

On the other hand, the emission intensity of buffalo meat production at regional level ranges from 21 kg CO_2-eq/kg CW in NENA to 70.2 kg CO_2-eq/kg CW in East & Southeast Asia (Figure 16b). Key buffalo meat producing regions include South Asia (producing 70 percent of the global production), East & Southeast Asia (20 percent) and NENA (5 percent).

Enteric CH_4 and feed N_2O emissions associated with feed production are the dominant sources of emissions. Key sources of emissions in the buffalo carbon profile comprise CH_4 from enteric fermentation (contributing more than half of the carbon footprint), and CO_2 and N_2O emissions associated with feed production. Nitrous oxide emissions from manure management are significant in East & Southeast Asia, where manure is managed in dry and solid systems.

Figure 14.
Emission intensities for buffalo milk by production system and agro-ecological zone[1]

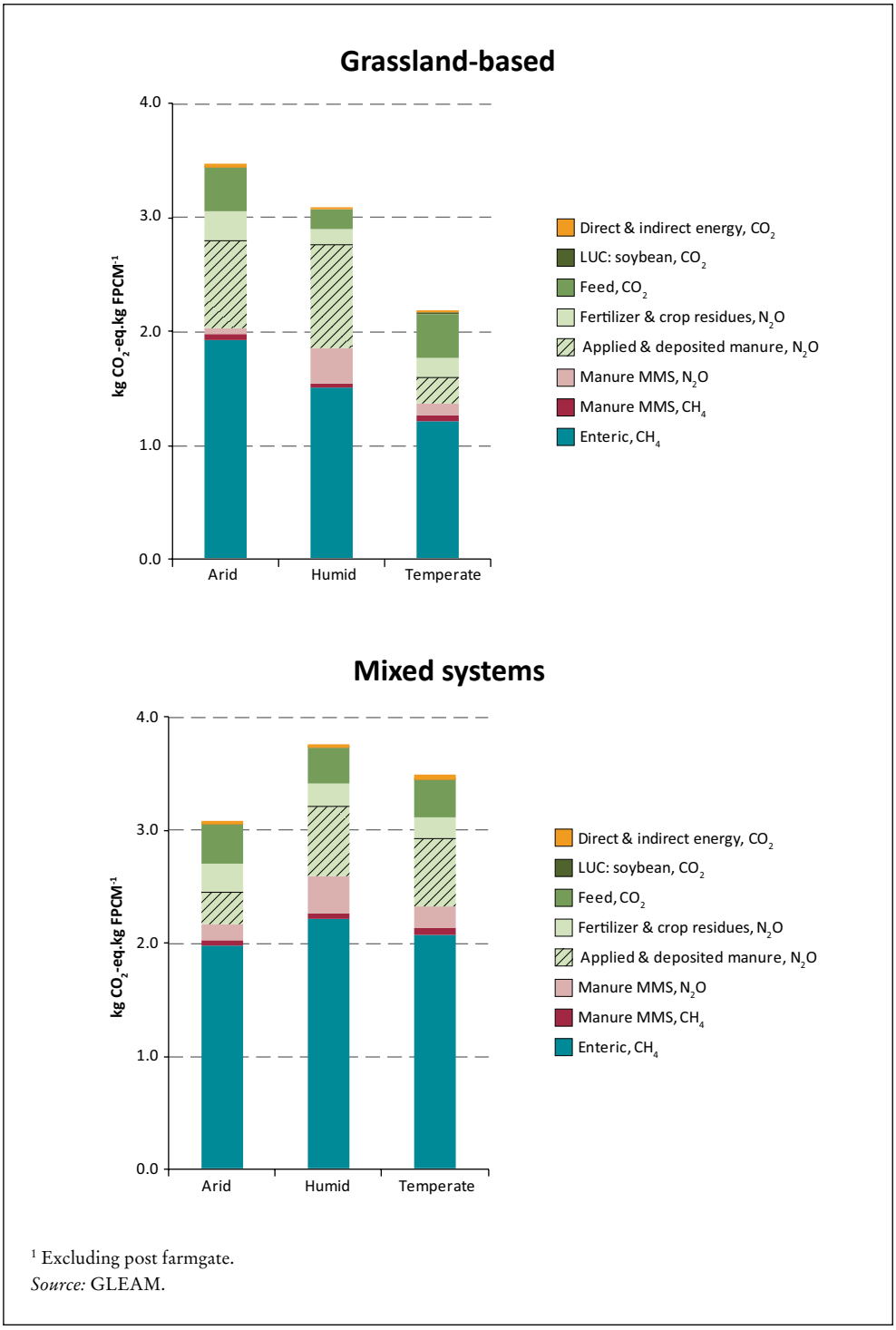

[1] Excluding post farmgate.
Source: GLEAM.

Figure 15.
Emission intensities for buffalo meat by production system and agro-ecological zone[1]

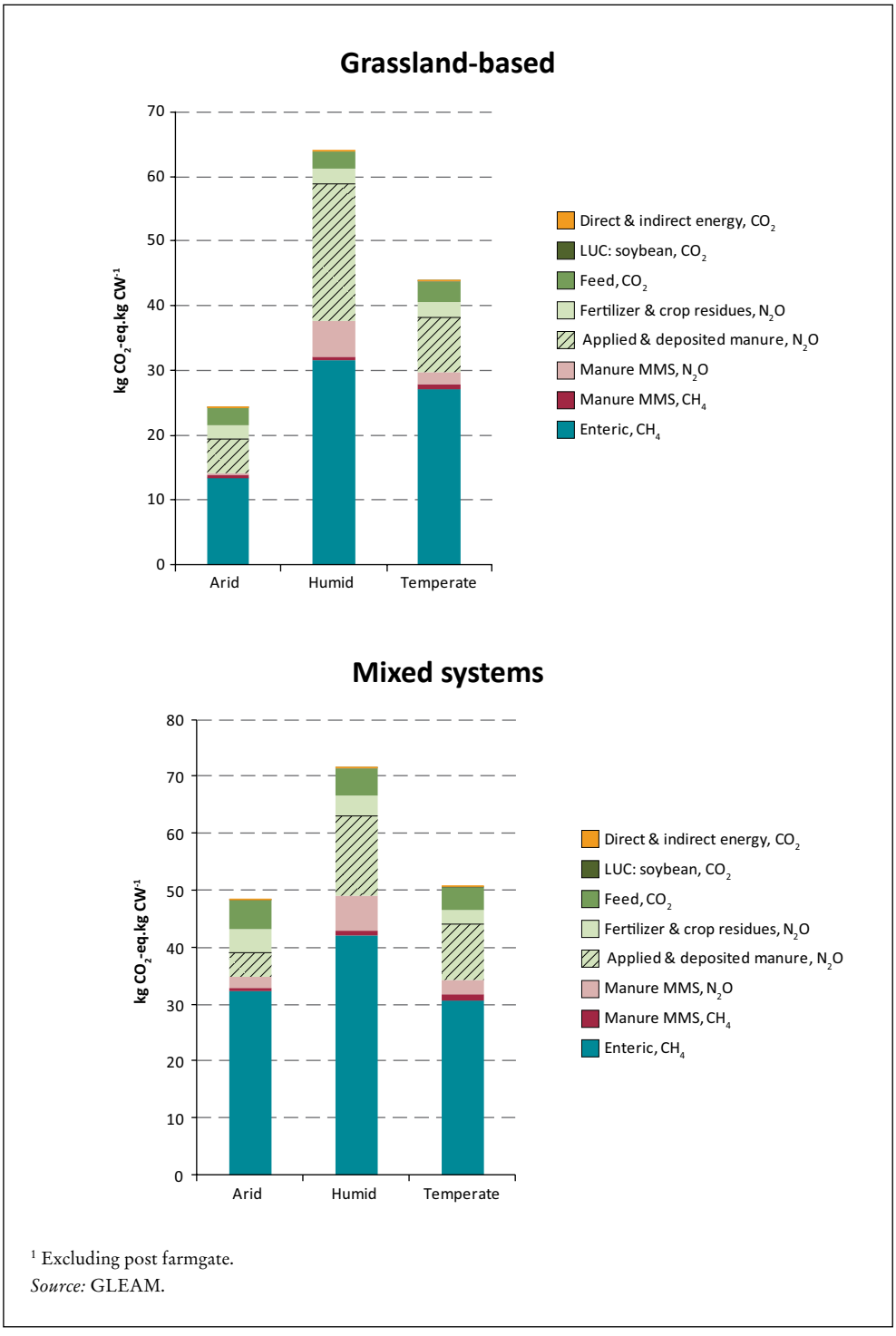

[1] Excluding post farmgate.
Source: GLEAM.

Figure 16a.
Regional variation in GHG emission intensities for buffalo milk[1]

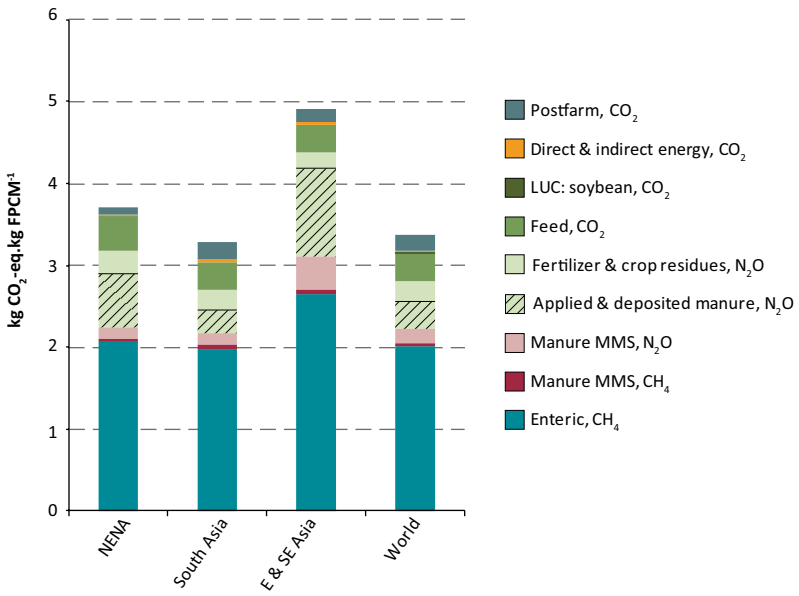

[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 16b.
Regional variation in GHG emission intensities for buffalo meat[1]

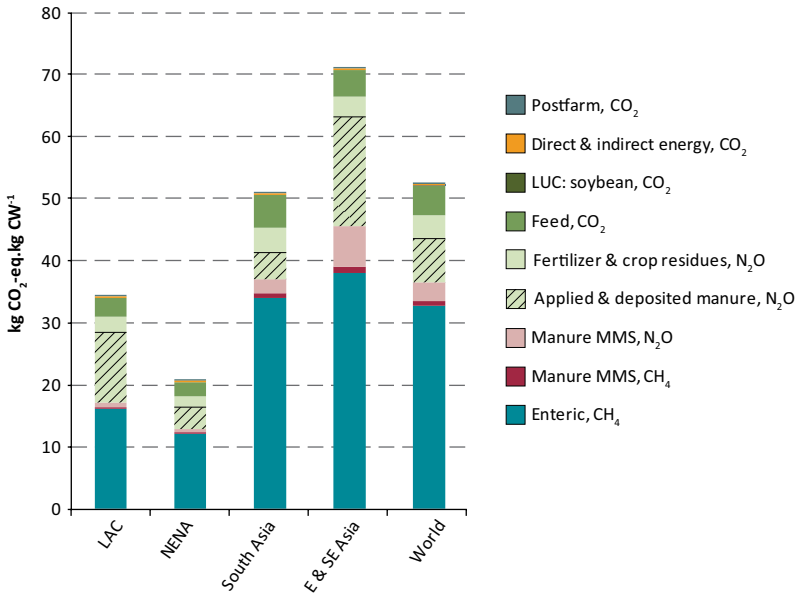

[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

4.3 SMALL RUMINANTS

The contribution of the small ruminant sector to GHG emissions is equivalent to 474 million tonnes CO_2-eq. These total emissions from the sheep and goat production comprise emissions from production of edible (meat and milk) and non-edible products (natural fibre) as well as emissions from post farmgate processes. The discussion in subsequent sections presents total emissions and emission intensities related to small ruminant production at global, farming system and regional grouping levels for edible products.

4.3.1 Total production, absolute emissions, and emission intensities

Globally, small ruminant production of meat and milk is responsible for 428.8 million tonnes CO_2-eq, of which 254.4 million tonnes CO_2-eq (59 percent) are associated with sheep production and 174.5 tonnes CO_2-eq (41 percent) are associated with goat production. Total production from the small ruminant sector amounts to 20.0 and 12.6 million tonnes of milk and meat, respectively. Goats contribute almost 60 percent of the milk produced by small ruminants, while sheep contribute 62 percent of the meat (Table 6).

On average, the emission intensity of small ruminant milk is 6.5 kg CO_2-eq/kg FPCM. In terms of emission intensity, goat's milk has lower emission intensity (5.2 kg CO_2-eq/kg FPCM compared with 8.4 kg CO_2-eq/kg FPCM for milk from sheep) due to higher yields compared with milk from sheep. Average emission intensity for small ruminant meat is 23.8 kg CO_2-eq/kg CW, while emission intensity for sheep and goats meat is quite similar – 24.0 and 23.5 kg CO_2-eq/kg CW, respectively (Table 6).

Similar to cattle and buffalo, CH_4 emissions are important, accounting for half of the total emissions associated with small ruminant production (Figure 17). Enteric fermentation is the single most important emission category in both milk and meat production, contributing 57 percent and 55 percent of the total GHG emissions from milk and meat production, respectively.

Nitrous oxide emissions amount to relatively similar proportions (27 percent and 28 percent) of the total carbon footprint for both milk and meat. Within this, N_2O emissions from manure storage and management are insignificant (4 percent and 2 percent for milk and meat, respectively), mainly because small ruminants are grazing most of the time and consequently a very small proportion of the manure is managed.

Table 6. Global production, emissions and emission intensity for small ruminants

Species	Production *(million tonnes)*		Absolute emissions[1] *(million tonnes CO_2-eq)*		Average emission intensity *(kg CO_2-eq/kg product)*	
	Milk[2]	Meat[2]	Milk	Meat	Milk[2]	Meat[2]
Sheep	8.0	7.8	67.4	186.9	8.4	24.0
Goats	12.0	4.8	62.4	112.5	5.2	23.5
Totals	**20.0**	**12.6**	**129.4**	**299.4**	**6.5**	**23.8**

[1] Absolute emissions include emissions from production and post farmgate emissions.

[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.

Source: GLEAM.

Figure 17.
Relative contribution of different processes to GHG emission profile of small ruminant milk and meat

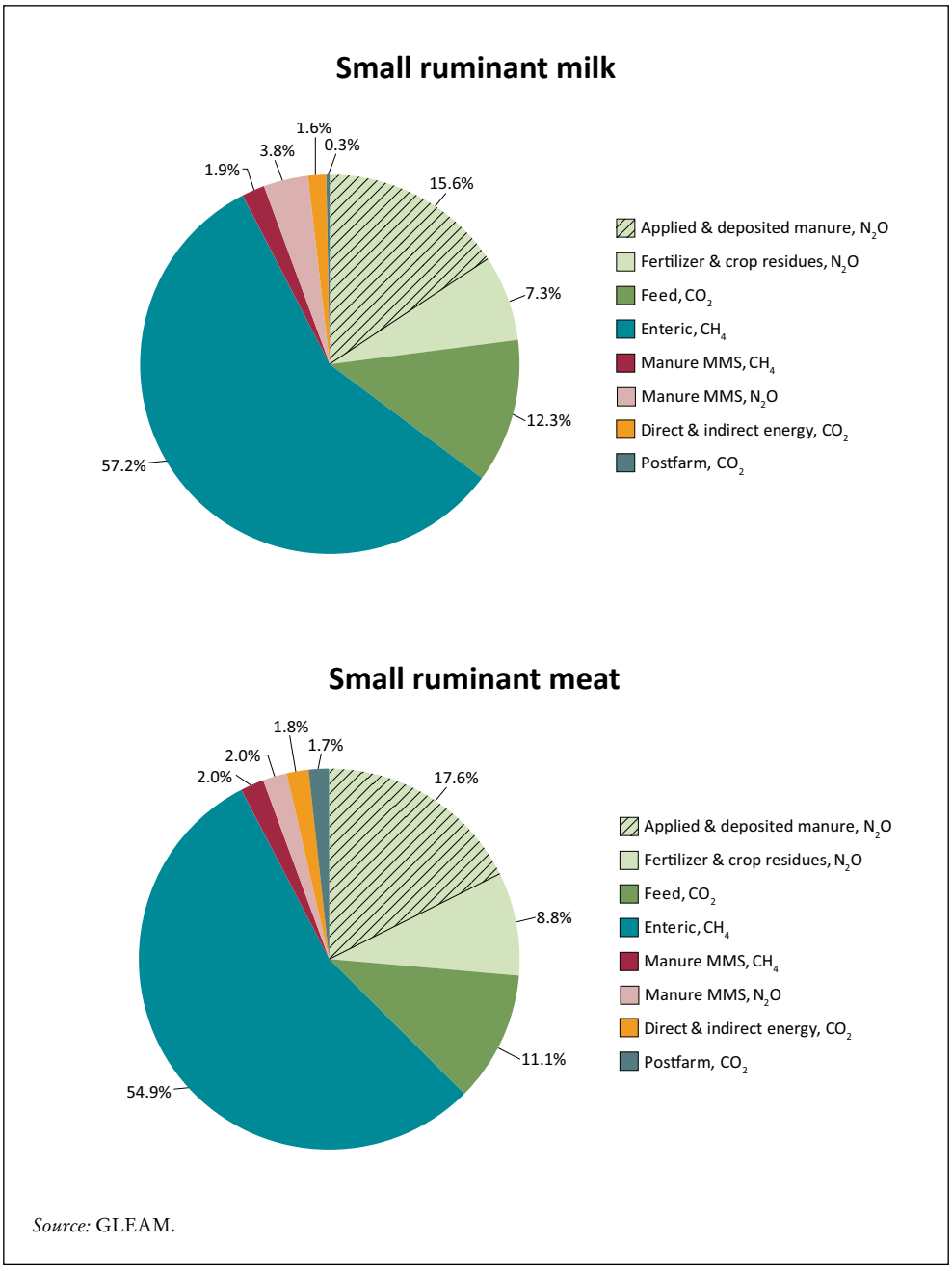

Source: GLEAM.

Within the emissions profile, CH_4 from manure management is unimportant because virtually all manure is either deposited on pasture or managed in dry systems such as drylots and solid storage systems (see Table B19, Appendix B). Emissions associated with feed production comprising both N_2O (mainly from manure) and CO_2 emissions amount to 35 percent of the total emissions. Carbon dioxide emissions from on-farm energy use and embedded energy as well as post farmgate activities make a relatively small contribution towards the overall carbon footprint.

4.3.2 Emissions by production system and agro-ecological zone

Emission intensity for milk is higher in grazing systems with an average of 7.6 kg CO_2-eq/kg FPCM compared with 6.6 kg CO_2-eq/kg FPCM in mixed farming systems (Figure 18). A similar trend is found for small ruminant meat; average emission intensity per kg CW is 24.0 and 23.2 kg CO_2-eq/kg CW in grazing and mixed systems, respectively (Figure 19).

In small ruminant milk production in grazing systems, emissions intensity is highest in temperate zones, a trend which contrasts with the emission intensity trends for dairy cattle (see Figure 7). The higher emission intensity for small ruminant milk in grazing temperate zones is explained by a combination of factors: (i) total emissions are dominated by emissions from the temperate areas in regions such as Asia and Africa, where production conditions are poor for the most part; (ii) sheep milk production dominates small ruminant milk in the temperate zones, however milk yields from sheep are much lower compared with goats; and (iii) goats milk, which is characterized by higher yields per animal, mainly occurs in the arid areas.

On the other hand, for small ruminant meat there is no systematic trend across production systems; in grazing systems, highest emission intensity is found in temperate zones, while in mixed systems, meat produced in the arid zones has the highest emission intensity.

The difference in emission intensity of small ruminant meat is explained by a combination of factors: (i) high emission intensity in grazing temperate areas is related to the fact that in temperate zones small ruminants, particularly sheep, are reared for mainly for meat and therefore the carcass bears the whole burden of emissions; (ii) temperate grazing areas are also characterized by low yields, which are closely related to poor production conditions and low feed digestibility, hence the high emission intensity.

Figure 19, however, masks much of the variation that can be found within similar production systems and climatic conditions. Disaggregated emission intensity at production system level show temperate zones in grassland-based systems with highest emission intensity, about 27.5 kg CO_2-eq/kg CW. However, regions such as Oceania and W. Europe show a contrasting trend, with lowest emission intensities within this production system and AEZ typology (13.7 and 19.8 kg CO_2-eq/kg CW, respectively) as a result of their efficient production systems. Within temperate grassland-based systems, the predominance of other regions such as East & Southeast Asia, NENA and Latin America & Caribbean drive the emission intensities of the system. These high emissions are largely related to poor quality feed, poor performance of animals, and slower growth rates.

Methane emissions from enteric fermentation dominate the emission profile in both systems and across all three AEZs. Nitrous oxide emissions associated with feed production are relatively higher for grassland-based systems and this arises from the deposition of manure on pasture.

The high CH_4 emissions from manure management in the mixed farming systems relative to grazing systems indicate the management of manure in systems other than pasture-based systems.

CO_2 emissions related to feed production, transport and processing are important in the temperate areas in both systems, accounting for 12 percent and 19 percent, respectively, and 12 percent and 14 percent, respectively, of the average carbon footprint of small ruminant milk and meat produced in grazing and mixed temperate zones.

Figure 18.
Emission intensities for small ruminant milk by production system and agro-ecological zone[1]

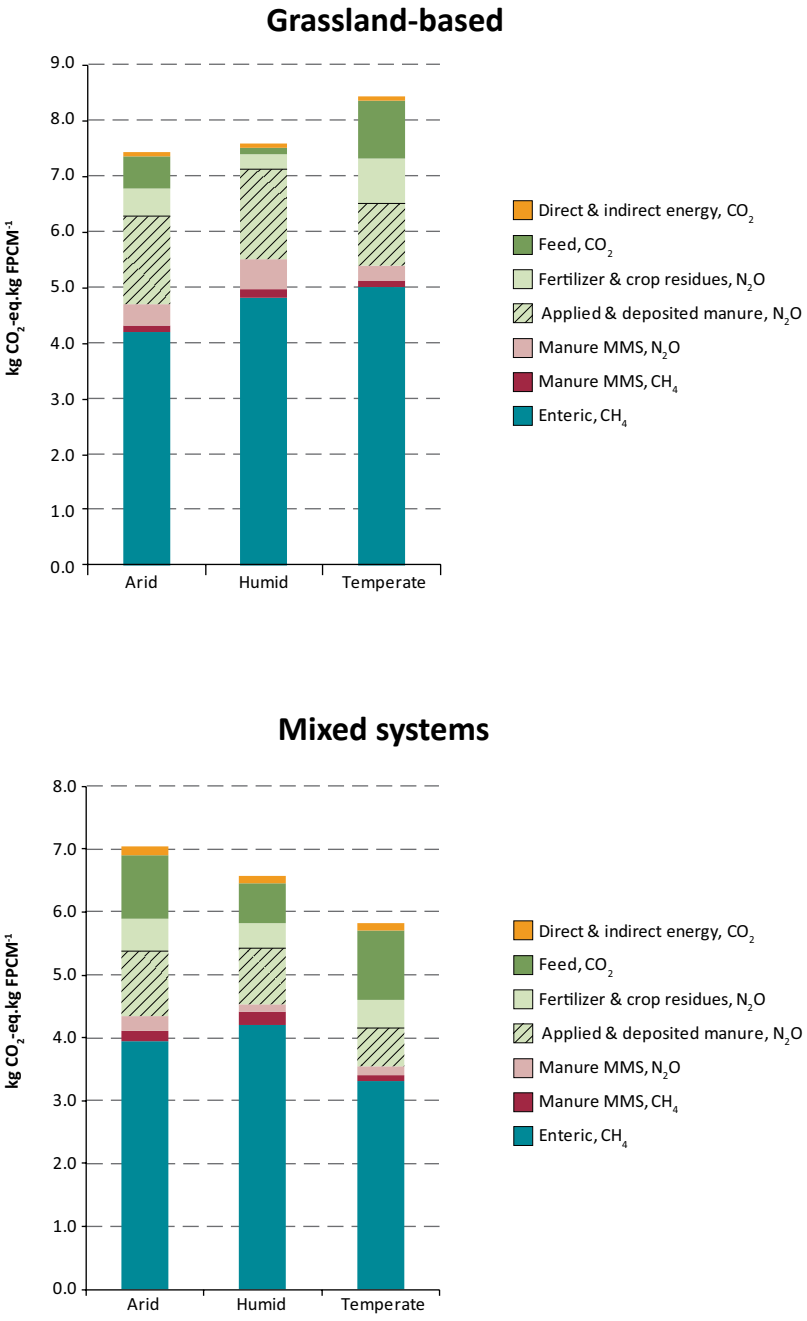

[1] Excluding post farmgate.
Source: GLEAM.

Figure 19.
Emission intensities for small ruminant meat by production system and agro-ecological zone[1]

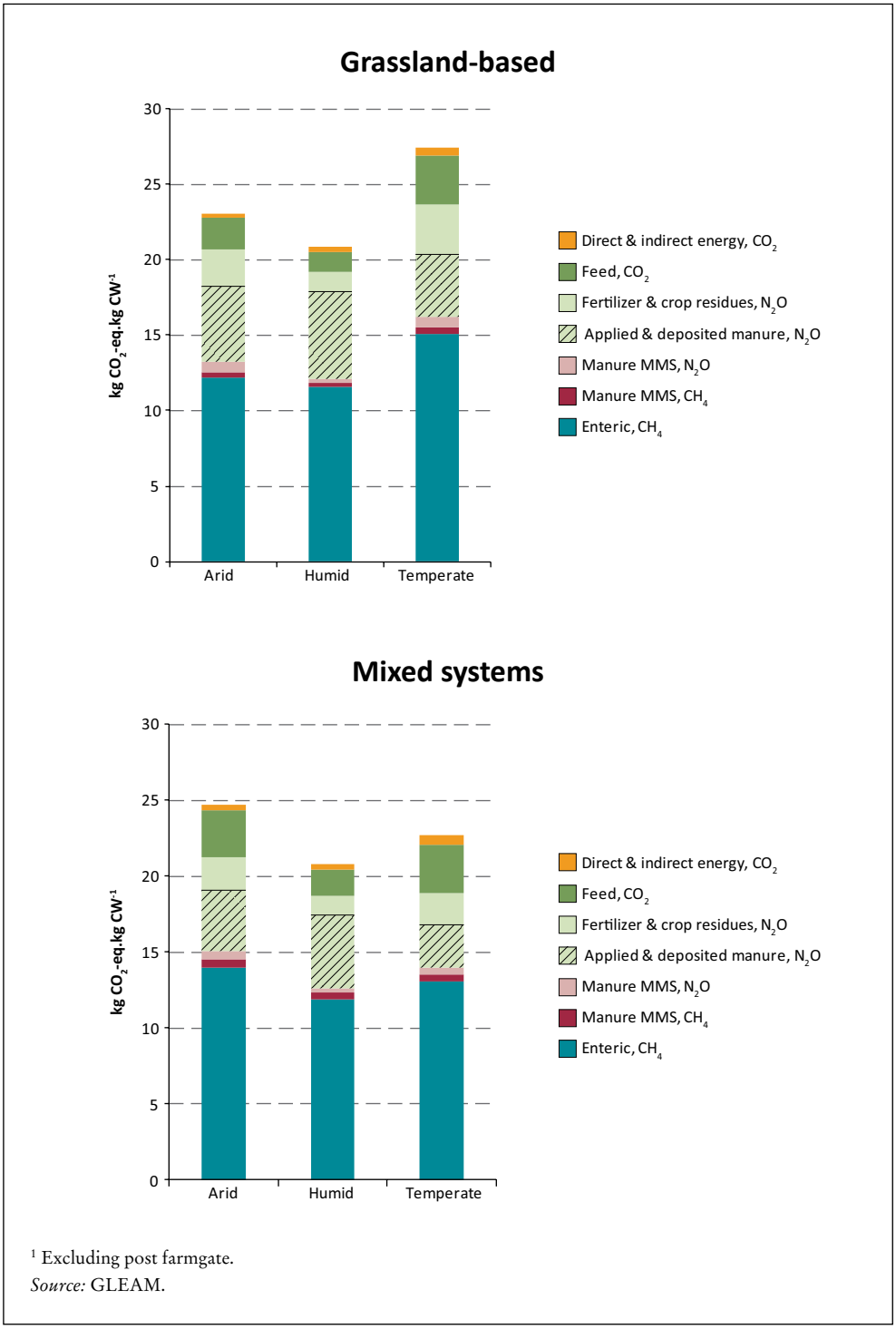

[1] Excluding post farmgate.
Source: GLEAM.

Figure 20a.
Regional contribution to global small ruminant milk production[1]

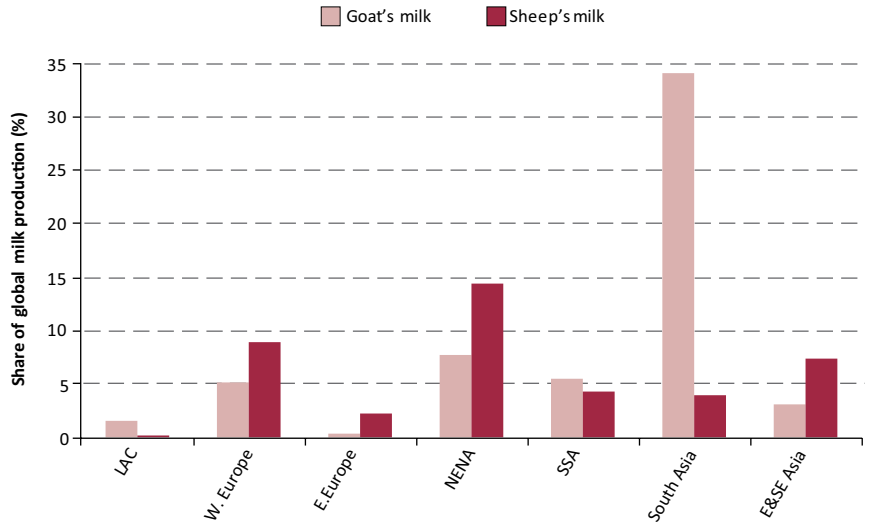

[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

4.3.3 Regional production, emissions and emission intensities

The production of small ruminant milk and meat is largely concentrated in developing regions. Figures 20a and 20b illustrate this trend; with the exception of small ruminant milk production in Western Europe and lamb and mutton production in Oceania and Western Europe, small ruminant production is generally more important in developing world regions.

Small ruminants produce not only edible products; other important co-products include natural fibre such as wool, cashmere and mohair. As mentioned in Section 3.6 of this report, we have applied an economic value allocation to partition total GHG emissions between the edible products (meat and milk) and non-edible products (natural fibre). Figure 21 illustrates the impact of allocation to co-products.

Figure 21 illustrates those regions where the natural fibre production is important and has a high economic value compared with edible products, such as North America, Latin America & Caribbean, Oceania, and East & Southeast Asia. In the other regions, natural fibre production is generally not profitable and of low economic value.

At a regional level, emission intensity for small ruminant milk ranges from 4.7 kg CO_2-eq/kg FPCM in Western and Eastern Europe to almost 8.9 kg CO_2-eq/kg FPCM in East & Southeast Asia. Emissions in NENA, sub-Saharan Africa and South Asia are 8.7, 6.9, and 4.9 kg CO_2-eq/kg FPCM, respectively (Figure 22a). Within the developing regions, South Asia has the lowest emissions explained by high milk productivity. Overall, across the regions, goats milk tends to have lower emission intensity mainly because of the higher productivity compared with sheep.

Methane from enteric fermentation is the dominant source of emissions in developing regions, ranging from 60 percent of the GHG emissions profile in South Asia to 69 percent in sub-Saharan Africa. For developing regions, N_2O emission related

Figure 20b.
Regional contribution to global small ruminant meat production[1]

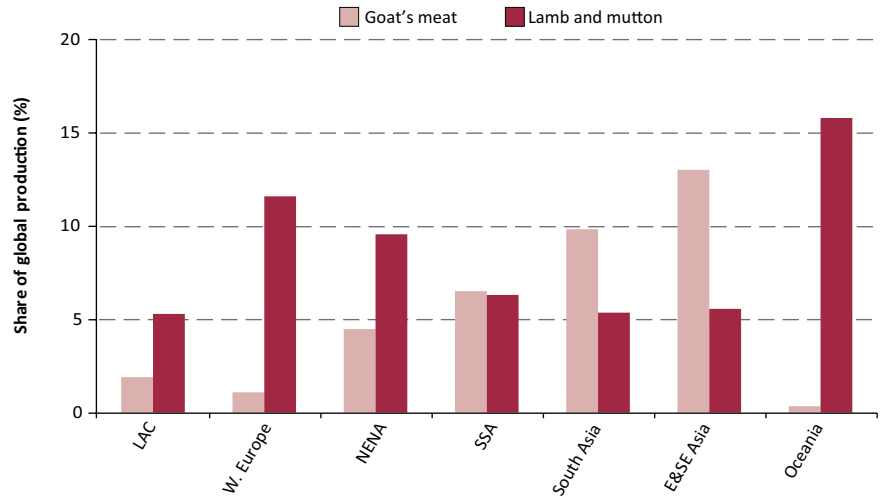

[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 21.
Emissions per kg meat and milk protein, comparing allocation of emissions to different outputs

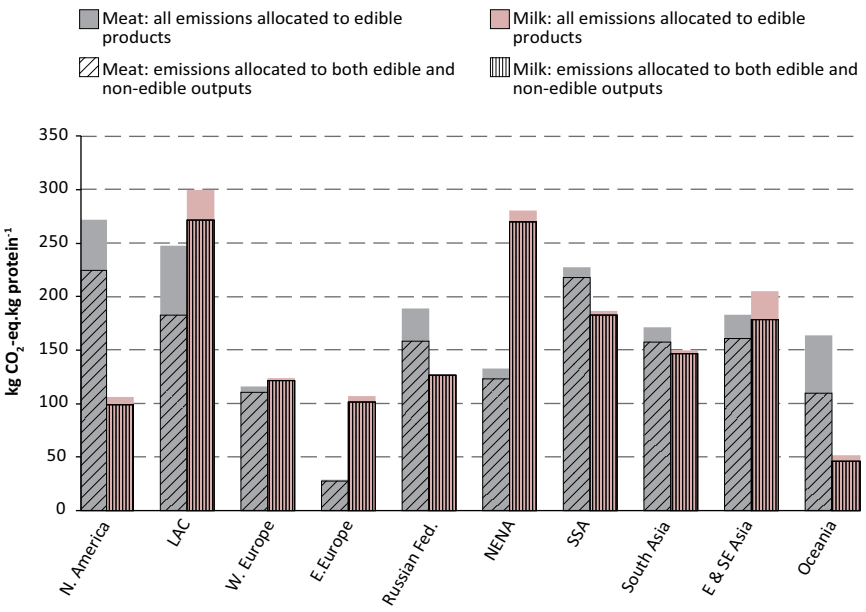

Source: GLEAM.

Figure 22a.
Regional variation in GHG emission intensities for small ruminant milk[1]

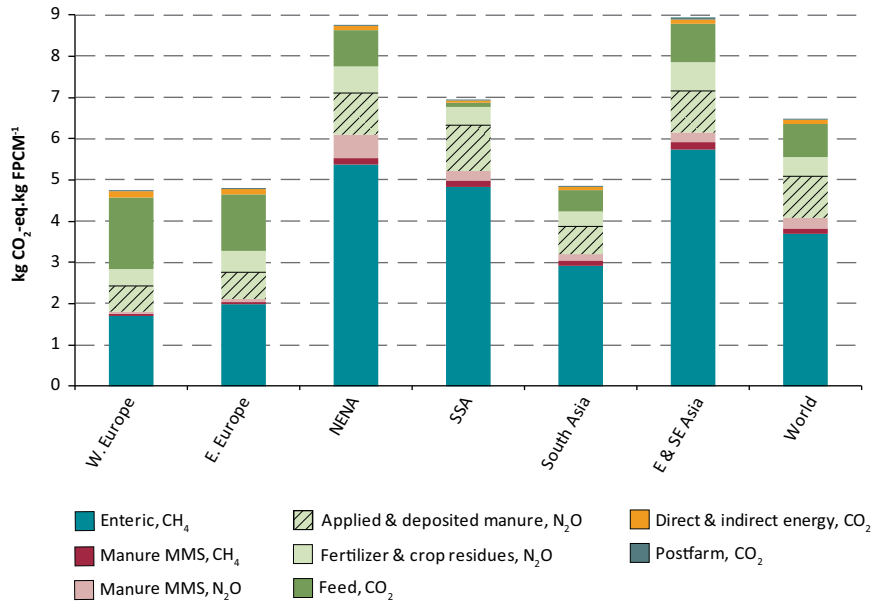

[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 22b.
Regional variation in GHG emission intensities for small ruminant meat[1]

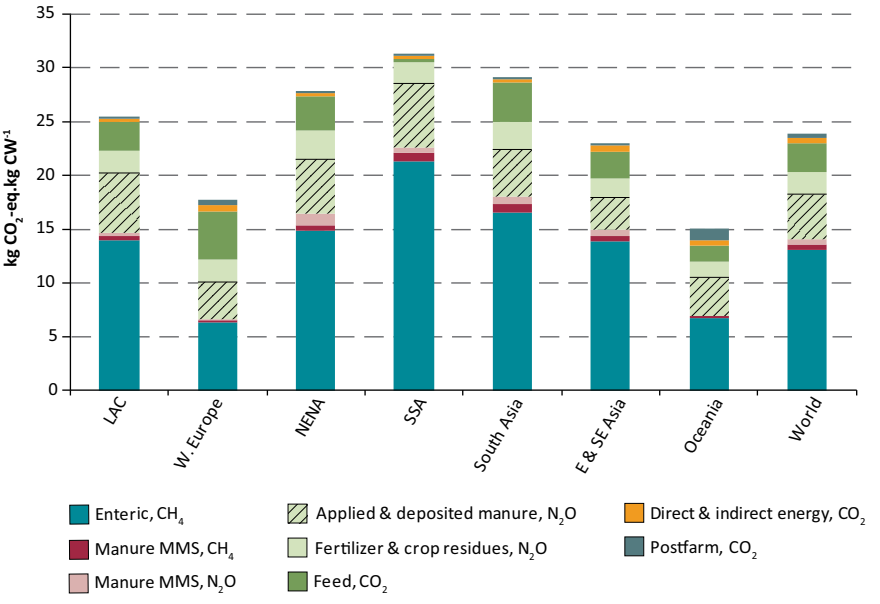

[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

to feed production is a significant source of emissions as a result of the deposition of manure during grazing (see Section 5.3 in Chapter 5). While CH_4 emissions from manure are negligible in most regions because manure is mainly managed in dry systems, in South Asia and East & Southeast Asia, CH_4 emissions from manure are slightly higher as a result of the higher temperatures in warmer climatic zones.

In most regions, N_2O from manure management is also negligible because a large proportion of the manure produced is deposited on pasture and these emissions are captured in feed production (in this analysis, manure deposited on pasture is considered as a fertilizer). However, NENA, sub-Saharan Africa, South Asia and East & Southeast Asia have relatively high N_2O emissions from manure because manure is not only deposited on pasture but also managed in other MMS such as drylot or solid systems which tend to have higher rates of conversion of N excreted to N_2O emissions.

Emissions of meat from small ruminants range from as low as 15 kg CO_2-eq/kg CW in Oceania to 31 kg CO_2-eq/kg CW in sub-Saharan Africa. Very little variation exists within the developing regions; emissions for East & Southeast Asia, Latin America, NENA and South Asia are 23.0, 25.5, 27.9 and 29 kg CO_2-eq/kg CW, respectively (Figure 22b). Contributions of different sources to emission intensity, differences among regions and the underlying reasons are very much the same as described above for milk.

Post farmgate emissions per kg carcass weight in Oceania are significant because of the importance of mutton and lamb exports from Australia and New Zealand. The two countries supply a major portion of global lamb and mutton exports, equivalent to 50 percent and 67 percent of their total production in 2005, respectively.

4.4 SUMMARY OF RESULTS

4.4.1 Comparison between ruminant species

Despite the similarities in emission profiles, there are differences among cattle, buffalo and small ruminant species. The carbon footprint for milk from small ruminants is more than double that of milk from dairy cattle and buffalo: 6.5 kg CO_2-eq/kg FPCM vs. 2.8 and 3.4 kg CO_2-eq/kg FPCM, respectively (Figure 23a). With regard to meat from ruminants, small ruminant meat has a smaller carbon footprint compared with that of beef; 23.8 kg CO_2-eq/kg CW vs. 46.2 and 53.4 kg CO_2-eq/kg CW for beef and buffalo meat, respectively (Figure 23b).

Among the edible commodities produced by ruminant systems, milk generally has the lowest emission intensity compared to meat suggesting that dairy systems are more efficient than pure meat systems. This is because dairy herds produce both milk and meat while beef systems are maintained mainly for calf production.

The difference in emission intensity among ruminant species can be attributed to a number of factors such as:

- Higher milk yields from dairy cattle and buffalo as opposed to small ruminants;
- Greater fecundity, and faster reproductive cycles and growth rates in small ruminants;
- Larger supporting breeding herds are required to sustain the production of beef; non-productive animals produce CH_4 and urinary-N without contributing to milk and meat production; and
- Whether LUC is associated with the production process.

Figure 23a.
Average emission intensity for milk from cattle, buffalo and small ruminants

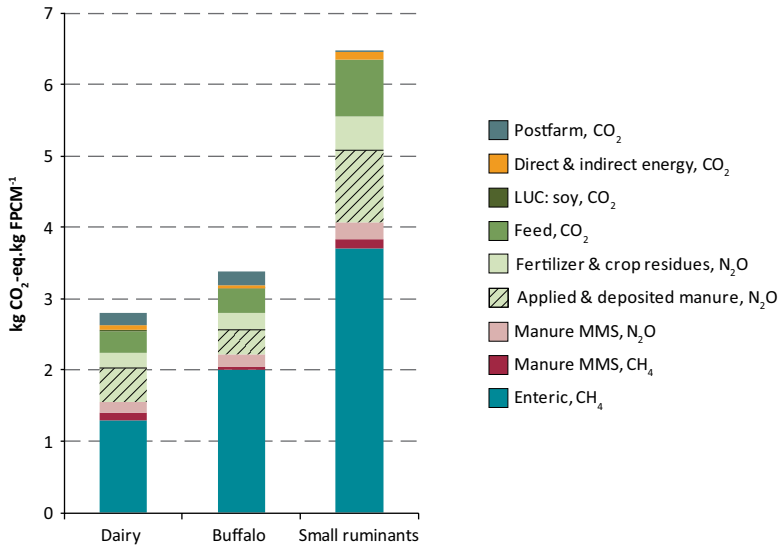

Source: GLEAM.

Figure 23b.
Average emission intensity for meat from cattle, buffalo and small ruminants

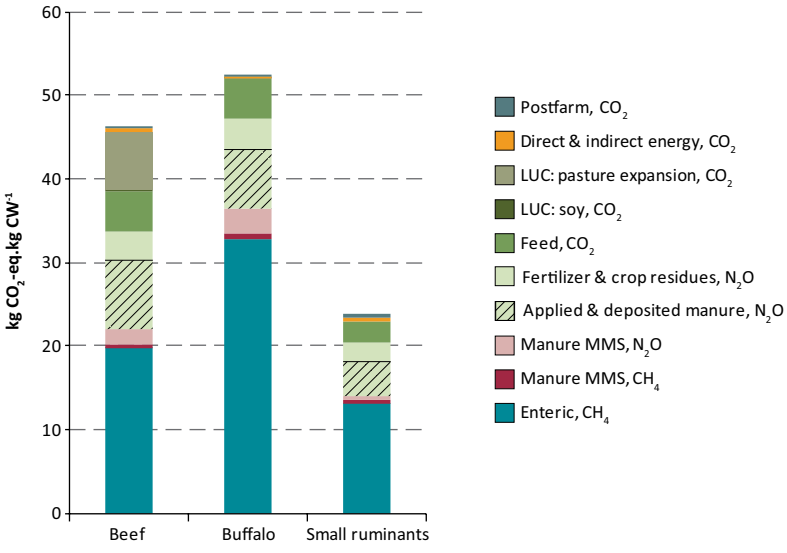

Source: GLEAM.

This assessment also found a wide diversity in emission intensity at regional and production system level. These variations are largely driven by differences in production goals (specialized versus non-specialized production) and management practices, including animal husbandry methods, animal health and genetics which influence levels of productivity.

4.4.2 Emission intensity gap within systems, climatic zones and regions

The comparison of emission intensity for ruminant commodities produced within the same region and comparable production conditions (production systems and agro-ecological zones) shows the existence of a considerable emission intensity gap. Average emission intesities within each region for each combination of production system and climatic zone as well as the lowest and highest emission intesity of pixels accounting for 10 percent of the production in the same system-region-AEZ were assessed. Figure 24 is a schematic representation of the analytical approach used to assess the emission intensity gap within regions, production systems and climatic zones.

Tables 7-9 provide an illustration of this variation in emission intensity for cattle (dairy and beef), buffalo milk and small ruminants (milk and meat). The emission intensity gap is particularly substantial in dairy and beef production. For example, in mixed temperate dairy systems in sub-Saharan Africa, the average emission intesity is 7.6 kg CO_2-eq/kg FPCM, compared to 1.6 and 13.3 kg CO_2-eq/kg FPCM in lowest and higher 10 percent, respectively (Table 7).

Within the dairy mixed and grassland-based systems in sub-Saharan Africa, Latin America and the Caribbean, and East and Southeast Asia, the emission intensity of the lowest 10 percent is comparable to other regions with similar production conditions. This is explained by the dominance of high productive countries within these systems and climatic zones. For example, in sub-Saharan Africa, within the dairy mixed and grassland-arid zones, South Africa alone accounts for almost 25 percent

Figure 24.
Schematic representation of emission intensity gap, for a given commodity, within a region, climate zone and farming system

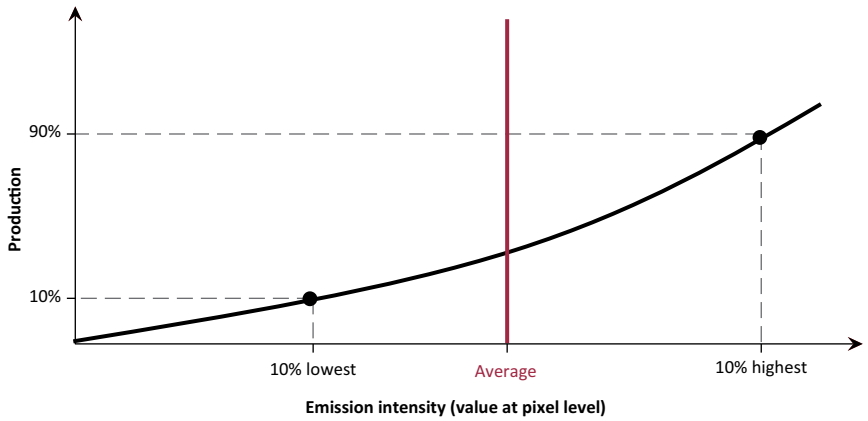

Source: Authors.

Table 7. Variation of cattle emission intensities within regions, systems and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Mixed dairy									
N. America	1.7	1.9	2.0	1.3	1.5	1.7	1.5	1.7	1.9
Russian Fed	1.7	1.8	1.9	1.8	1.9	2.0	1.7	1.8	2.0
W. Europe	1.5	1.6	1.8	1.5	1.6	1.7	1.5	1.7	1.8
E. Europe	1.8	1.8	2.0	1.4	1.6	1.8	1.8	1.9	1.9
NENA	1.9	4.3	9.7	2.6	3.7	5.3	2.3	3.5	9.4
E & SE Asia	2.1	2.7	3.7	1.4	2.3	2.9	1.5	2.6	3.4
Oceania	1.7	1.8	1.9	1.0	1.0	1.8	NA	NA	NA
South Asia	4.0	5.2	6.8	3.4	4.5	6.5	4.1	6.8	8.0
LAC	1.4	3.1	4.9	1.4	3.0	5.0	1.7	4.0	5.4
SSA	1.7	10.0	17.2	1.7	7.6	13.3	5.5	9.7	17.3
Grassland dairy									
N. America	1.7	1.9	1.9	1.3	1.7	1.8	1.7	1.9	2.0
Russian Fed	1.7	1.8	1.8	1.8	1.9	2.0	NA	NA	NA
W. Europe	1.5	1.6	1.8	1.5	1.7	1.8	1.7	1.7	1.9
E. Europe	1.7	1.9	2.0	1.5	1.6	1.7	NA	NA	NA
NENA	1.4	5.9	10.6	2.7	3.2	4.1	10.0	10.1	10.2
E & SE Asia	1.6	1.8	2.0	1.6	2.5	7.3	2.4	7.7	10.1
Oceania	1.7	1.8	1.9	1.5	1.5	1.5	1.5	1.6	1.8
South Asia	2.9	3.8	5.2	2.7	4.1	5.5	3.8	4.1	4.2
LAC	1.7	3.1	6.0	1.8	3.6	5.5	2.2	4.8	6.3
SSA	1.8	9.6	16.6	1.7	3.1	5.6	6.3	10.8	18.9
Mixed beef									
N. America	28.4	32.0	36.1	26.0	28.5	30.3	26.9	28.6	30.5
W. Europe	13.6	19.9	23.0	12.9	17.3	21.9	20.2	24.1	25.7
E. Europe	11.1	12.0	12.7	12.3	13.9	16.3	11.2	11.9	12.6
NENA	17.5	28.4	35.7	16.7	20.4	25.5	18.1	24.4	34.0
E & SE Asia	36.9	46.9	61.3	33.1	43.0	54.0	40.1	54.5	81.0
Oceania	29.1	31.1	33.8	11.7	20.5	31.6	11.0	18.9	31.9
South Asia	25.3	73.0	110.5	20.4	46.8	77.6	58.8	103.0	168.1
LAC	36.5	42.9	48.5	37.4	46.6	59.0	38.2	46.8	53.9
SSA	44.2	75.0	106.6	27.4	56.0	73.0	32.9	59.7	95.3
Grassland beef									
N. America	24.2	31.2	36.6	27.4	29.9	32.9	27.7	28.7	30.1
W. Europe	14.1	20.4	23.0	18.7	21.7	24.7	23.9	23.9	25.6
E. Europe	11.6	12.4	13.2	12.0	12.9	14.6	NA	NA	NA
NENA	19.5	36.6	38.5	15.9	18.6	21.5	35.0	35.3	35.6
E & SE Asia	47.3	55.0	66.7	26.4	47.5	57.5	53.3	62.4	70.1
Oceania	28.9	30.5	33.2	10.3	17.4	29.4	11.2	25.2	31.9
South Asia	22.6	31.6	33.6	21.3	26.9	26.5	71.4	76.9	80.6
LAC	42.8	48.9	57.2	40.8	52.4	72.7	43.8	53.9	64.9
SSA	41.1	76.9	102.6	38.3	43.2	58.8	49.9	93.4	118.8

[1] Regions representing less than 2% of global production within systems are not included.
Note: The 'average' is calculated at regional-climatic zone level. "10% lowest" is the upper bound of lowest emission intensities up to 10% of production.
"10% highest" is the lower bound of highest emission intensities down to 90% of production.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

Table 8. Variation of buffalo milk emission intensities within regions, systems and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Mixed dairy									
NENA	2.8	3.4	4.8	2.8	3.6	4.3	3.3	3.3	4.0
E & SE Asia	2.6	4.0	5.8	3.7	5.2	6.6	4.2	5.2	6.2
South Asia	2.7	3.3	4.1	2.4	3.0	4.2	2.6	3.5	4.5
Grassland dairy									
NENA	2.7	4.3	5.0	3.5	3.6	3.8	NA	NA	NA
E & SE Asia	2.6	2.7	2.8	2.5	3.0	4.0	3.0	3.3	3.5
South Asia	2.7	3.0	3.3	2.4	2.7	2.9	2.5	2.7	2.8

[1] Regions representing less than 2% of global production within systems are not included.
Note: The 'average' is calculated at regional-climatic zone level. "10% lowest" is the upper bound of lowest emission intensities up to 10% of production. "10% highest" is the lower bound of highest emission intensities down to 90% of production.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

of production in this regional-system-climatic zone with emission intensity ranging between 1.4 and 1.8 kg CO_2-eq/kg FPCM. Similarly, in mixed and grassland-based systems in temperate zones, South Africa contributes 20 and 70 percent of the regional production, respectively, with emission intensity ranging between 1.5 and 1.9 kg CO_2-eq/kg FPCM.

In Latin America and the Caribbean, milk production in Mexico in both grassland and mixed arid and temperate areas represents 30 percent of the production within these regional climatic zones and emission intensity ranges between 1.4 and 1.9 kg CO_2-eq/kg FPCM.

High milk productivity systems in countries such as Israel and Saudi Arabia within the arid zones result in low emission intensity (range between 1.2-1.5 kg CO_2-eq/kg FPCM for Israel and 1.1-2.0 kg CO_2-eq/kg FPCM for Saudi Arabia). About 23 percent of production within the mixed temperate dairy system in East and Southeast Asia occurs in Japan with a range of emission intensity 1.2 to 1.4 kg CO_2-eq/kg FPCM.

This variation highlights the heterogeneity within each production system and emphasizes the opportunities for reducing emission intensity particularly in low productive regions by bridging the gap in emission intensities between efficient producers and producers with a potential for improvement. This mitigation potential doesn't require changes in farming systems and can be based on already existing technologies and practices. It is estimated to 30% of the sector's total emissions and further explored in the overview report published in parallel to the current one (FAO, 2013a). This situation is completed by case study analysis to explore regional dimensions of mitigation in the sector.

Table 9. Variation of small ruminants emissions intensities within regions, system and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Grassland dairy									
W. Europe	2.8	4.9	6.4	2.5	5.1	6.5	1.6	2.9	4.4
E. Europe	4.2	4.7	5.1	2.6	3.6	5.0	NA	NA	NA
NENA	5.7	11.2	14.2	4.1	5.4	6.6	8.0	9.5	10.7
E & SE Asia	6.3	6.9	7.9	9.0	11.3	13.5	3.4	5.7	11.8
South Asia	3.3	6.0	8.1	3.8	6.5	8.8	2.5	2.6	2.7
LAC	3.0	8.0	11.7	3.2	8.1	11.6	3.2	9.6	11.4
SSA	5.1	6.6	9.4	6.1	7.0	8.3	7.2	8.7	10.6
Mixed dairy									
W. Europe	3.1	4.7	6.4	2.3	4.7	7.6	3.5	5.3	8.4
E. Europe	4.5	4.8	5.2	2.9	4.4	5.2	4.3	4.9	5.2
NENA	4.6	9.3	13.1	3.6	5.9	7.9	3.7	7.8	9.8
E & SE Asia	3.0	5.6	7.5	5.4	9.3	11.4	6.0	7.5	9.8
South Asia	2.9	4.2	6.3	3.0	5.1	7.7	3.0	5.9	7.9
LAC	2.7	5.9	10.2	2.9	4.8	10.4	1.9	5.5	11.1
SSA	5.3	7.4	10.2	6.5	7.5	8.6	5.7	7.3	8.9
Grassland meat									
W. Europe	7.8	12.7	20.2	9.6	20.4	23.8	19.2	19.9	21.5
NENA	11.4	24.7	42.2	18.2	42.9	57.5	15.3	16.1	16.8
E & SE Asia	19.1	24.6	32.0	18.3	25.8	32.4	9.4	13.2	19.0
Oceania	13.4	14.9	16.7	13.2	14.1	14.5	14.0	14.7	15.3
South Asia	9.3	26.7	35.4	8.5	16.6	24.5	20.8	22.1	23.7
LAC	18.6	24.6	29.9	17.4	29.0	38.5	18.3	24.9	33.8
SSA	16.8	26.2	37.4	20.3	22.4	30.0	21.7	33.8	46.3
Mixed meat									
W. Europe	7.4	15.2	21.6	9.7	18.8	22.6	18.0	25.4	26.7
NENA	12.9	23.4	41.1	14.8	32.6	51.7	14.3	16.1	17.9
E & SE Asia	13.9	20.4	29.9	18.0	22.2	26.5	9.3	15.5	23.7
Oceania	13.4	14.3	15.6	13.6	13.9	15.0	13.9	14.6	15.2
South Asia	17.2	32.8	44.5	9.9	29.5	45.8	14.7	20.0	35.5
LAC	17.2	22.7	27.5	22.1	30.4	38.5	16.4	23.5	30.4
SSA	18.0	34.0	49.7	19.3	28.2	34.7	25.4	35.6	43.3

[1] Regions representing less than 2% of global production within systems are not included.
Note: The 'average' is calculated at regional-climatic zone level. "10% lowest" is the upper bound of lowest emission intensities up to 10% of production. "10% highest" is the lower bound of highest emission intensities down to 90% of production.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

5. Discussion

This section discusses the key drivers of variation in emissions from major processes in the ruminant supply chain that contribute significantly to the carbon footprint of ruminant species, highlighting differences among species and world regions. The section also discusses some of the parameters and assumptions that could strongly influence the results.

5.1 METHANE EMISSIONS FROM ENTERIC FERMENTATION

Regardless of the species, the largest source of GHG emissions in ruminant production is CH_4, with more than 90 percent originating from enteric fermentation and the rest from manure. Globally, enteric fermentation from cattle, buffalo, and small ruminants contributes 2 448 million tonnes CO_2-eq, of which 76 percent is emitted by cattle and 14 percent and 10 percent by buffalo and small ruminants, respectively. The production of enteric CH_4 from ruminants is mainly affected by feed intake and feed quality which, in turn, defines the total energy and nutrient intake and consequently animal performance.

Many of these factors are interrelated, some of which affect net emissions and others emission intensity. At animal level, net emissions are influenced by feed intake and digestibility, while emission intensity is a function of net emissions, yield per animal, health and genetics. At herd level, factors affecting net emissions are similar to those cited above, while emission intensity is determined by issues such as reproductive and mortality rates, herd structure, management, etc. The following sections discuss some of the important factors that drive the variation in enteric CH_4.

Productivity. Productivity is an important factor in explaining the variation of emissions among different production typologies. Studies show a close correlation between carbon footprint and yield per animal (Capper *et al.*, 2008; Gerber *et al.*, 2011; Cederberg and Flysjo, 2004), highlighting the trend of decreasing emission intensity with increasing productivity. Regions and production systems with greater productivity have lower emission intensity partly because high yields shift the distribution of feed towards less feed for maintenance functions and more for production. As productivity per animal increases, CH_4 emissions per animal are typically higher because of higher feed intake. However, as the productivity of each animal increases, the farmer can reduce the herd size to produce the same amount of output.

Figure 25a illustrates the differences in emission efficiency among the regions; the main reason for the differences is to be found in low productivity of the herd, which is in turn caused by low fertility, high mortality rates, low growth rates and low feed digestibility (see Appendix B). Gerber *et al.* (2011) have demonstrated the relationship between the carbon footprint of dairy cattle milk and productivity, and a similar trend has been established for small ruminants (Figure 25b). Lower-producing dairy animals tend to lose more feed energy as CH_4 per unit of milk produced. The benefits of improving animal productivity on CH_4 emissions results from the *dilution effect* of fixed maintenance where increasing productivity

Figure 25a.
Regional variation in productivity and CH_4 emissions from enteric fermentation for beef herds

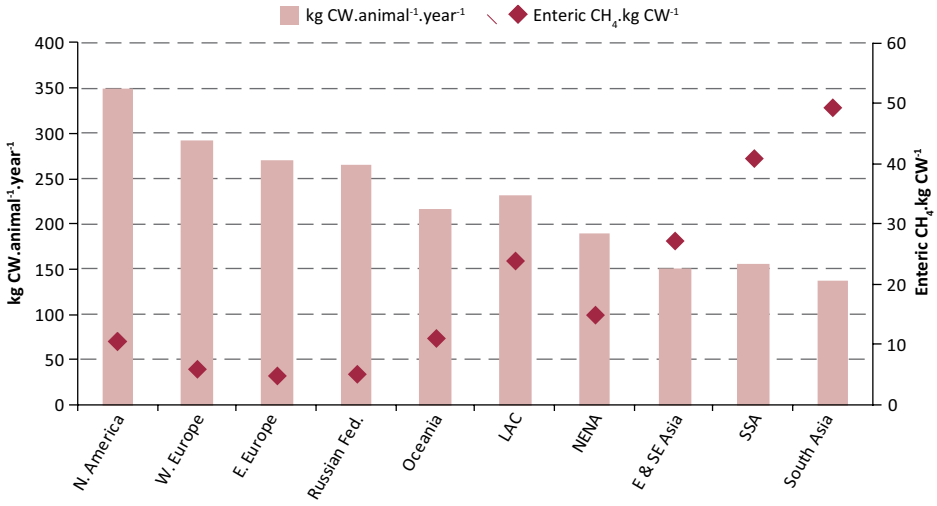

Source: GLEAM.

Figure 25b.
Regional variation in productivity and CH_4 emissions from enteric fermentation for dairy goats

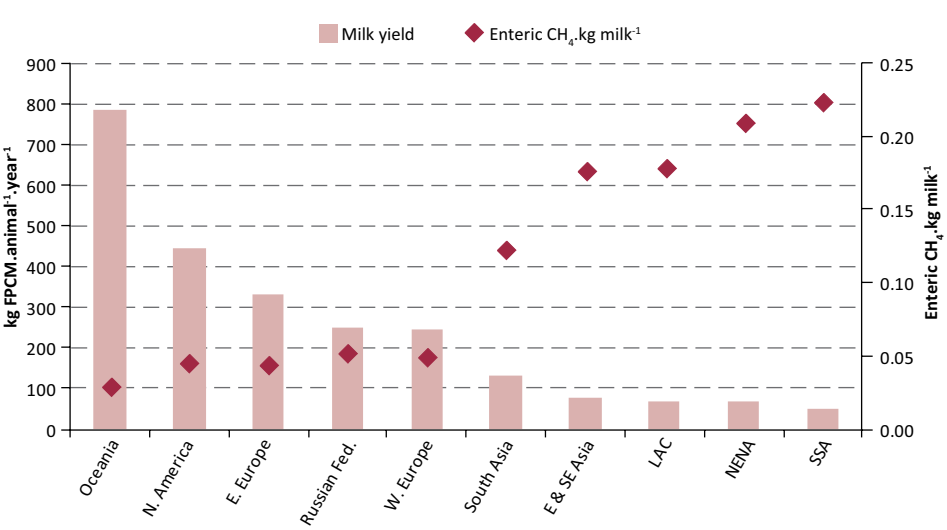

Source: GLEAM.

Figure 26.
Regional variation in digestibility of the feed ration and CH_4 emissions from enteric fermentation for beef cattle

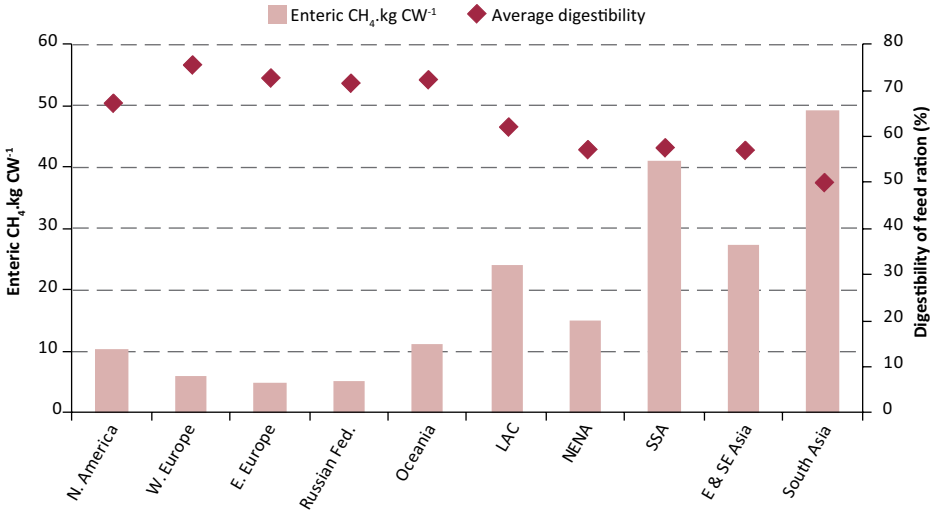

Source: GLEAM.

decreases the amount of CH_4 emitted per unit of product because emissions that arise from energy requirements for maintenance are spread over a larger output.

Feed digestibility. Enteric CH_4 emissions are also determined by feed properties, particularly the digestibility of the feed ration. The energy content of feed also affects the amount of CH_4 produced in enteric fermentation, with lower quality of feed causing greater CH_4 emissions (Figure 26). Regions with higher feed digestibility also often have higher proportion of high quality roughages, feed crops and concentrates in their diets, often an indication of higher quality ration (see Tables B7-B12 in Appendix B). As the digestibility of the feed ration increases, the amount of energy available to the animal also increases per kg of feed intake. With an increase in per kg of feed intake, more production can be realized and therefore CH_4 produced per kg of production decreases.

Herd structure. A key factor that explains the variations in emissions across regions is the structure of the herd. Breeding populations are required to maintain the herd and thus reproductive performance is important because the cost of maintaining and replacing breeding stock also affects feed efficiency. In regions where the composition of the herd is skewed towards higher number of animals in the breeding herd, overall CH_4 emissions and emission intensities are most likely high because demand is placed on feed (with a large share of feed energy used for maintenance requirements rather than production). Figures 27a and 27b present the percentage contribution of enteric fermentation to total CH_4 from beef and dairy cattle by cohort groups. A breakdown of enteric CH_4 emissions by source not only illus-

Figure 27a.
Regional variation in the relative contribution of animal cohorts to enteric CH_4 – dairy herds

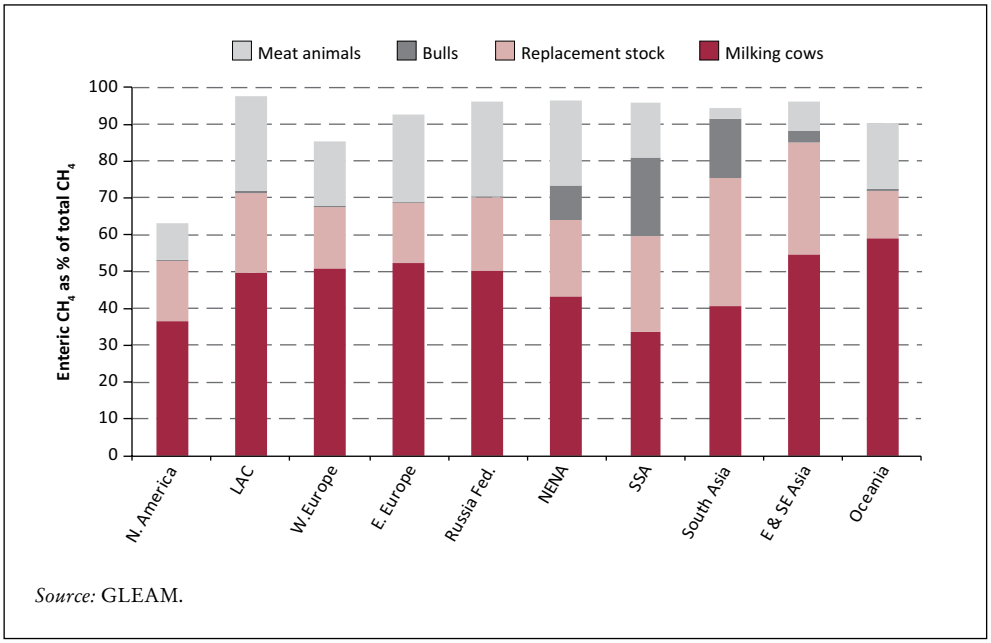

Source: GLEAM.

Figure 27b.
Regional variation in the relative contribution of animal cohorts to enteric CH_4 – beef herds

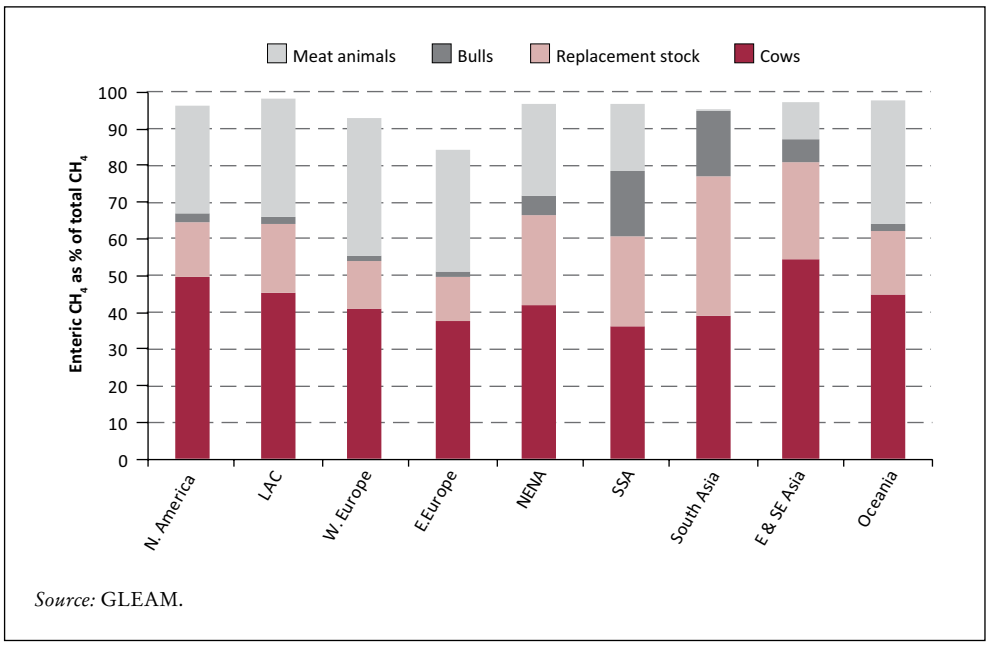

Source: GLEAM.

trates the key hotspots of CH_4 emissions but also explains the variation in emission intensity among regions.

Figure 27a illustrates regional differences in dairy herd structure. Non-milk producing animals in dairy herds typically include replacement animals and adult bulls; these categories of animals are significant contributors to the CH_4 costs of producing milk at the herd level. While CH_4 from enteric fermentation is the main contributor to GHG emissions in all regions, there are major differences in the sources of emissions. Generally, in regions such as sub-Saharan Africa and South Asia, a large proportion of enteric CH_4 (approximately 50 percent) originates from the breeding herd and replacement stock, in combination with a low milk production per cow; hence a large proportion of the resources are used for other purposes such as maintenance and draught power. In these regions, non-milk productive functions contribute substantially to the maintenance energy requirement of the herd because they represent a significant use of energy and resources with no production of usable edible product produced.

In contrast, in Western and Eastern Europe, Oceania, Russian Federation, and East & Southeast Asia, more than 50 percent of the enteric CH_4 is from milking cows, pointing to increased use of feed for productivity purposes and thus explaining the lower emission intensity in these regions.

In typical beef systems, mature cows are kept for only calf production and have to be maintained along with bulls and replacement stock, which increases emissions per unit of carcass produced. The breeding stock in beef production systems (cows, replacement stock and bulls) accounts for 55-99 percent of the total feed requirements of the beef herd, and 52-97 percent of total CH_4 emissions. A higher slaughter generation (meat animals for fattening) is an indication of higher reproductive performance of the breeding herd and specialization of production such as in Oceania, Europe, North America and Latin America.

For small ruminants, there is no systematic difference in herd structure among regions, largely attributable to the greater fecundity in small ruminants and faster growth rates compared with cattle. The absence of draught power also reduces the gap among regions.

Energy partitioning and utilization. Methane is produced in the process of feed energy utilization within the animal. Changes in the efficiency of feed energy utilization therefore influence CH_4 emissions of animals. The efficiency of feed energy utilization depends on the type of animal, the type or quality and quantity of feed, environmental conditions, etc.

The way energy is partitioned between the different body functions (maintenance and production) also helps explain the variation in emission intensity. All animals have a necessary maintenance requirement that must be met and results in no production, yet are still associated with CH_4 losses. Ruminants partition feed energy over the following functions: maintenance, growth, lactation and reproduction; and in all cases, maintenance has priority. In situations where feed quality is low, relatively less energy is left for (re)productive functions.

The proportion of feed energy expended on animal maintenance as opposed to productive purposes is higher in those regions with low production rates at both animal (Figures 28a, 28b and 28c) and herd (Figures 29a and 29b) level. Figures 28a, 28b and 28c present the partitioning of energy requirements across the world regions for

Figure 28a.
Regional comparison of energy partitioning across the different functions in milking cows

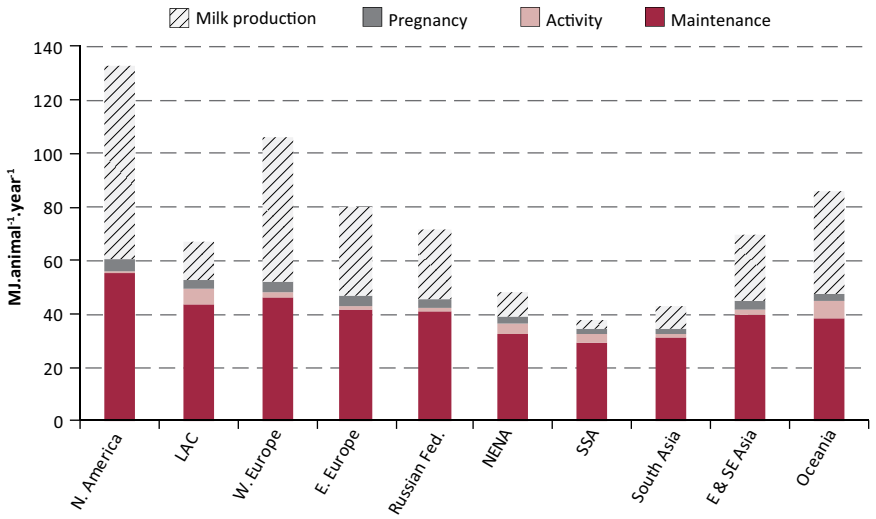

Source: GLEAM.

Figure 28b.
Regional comparison of energy partitioning across the different functions in milking ewes

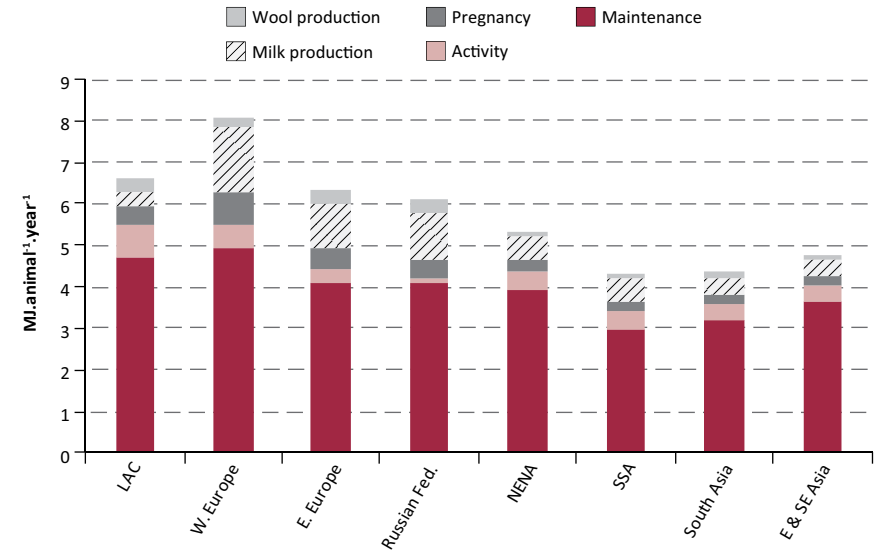

Source: GLEAM.

Figure 28c.
Regional comparison of energy partitioning across the different functions in adult female goats

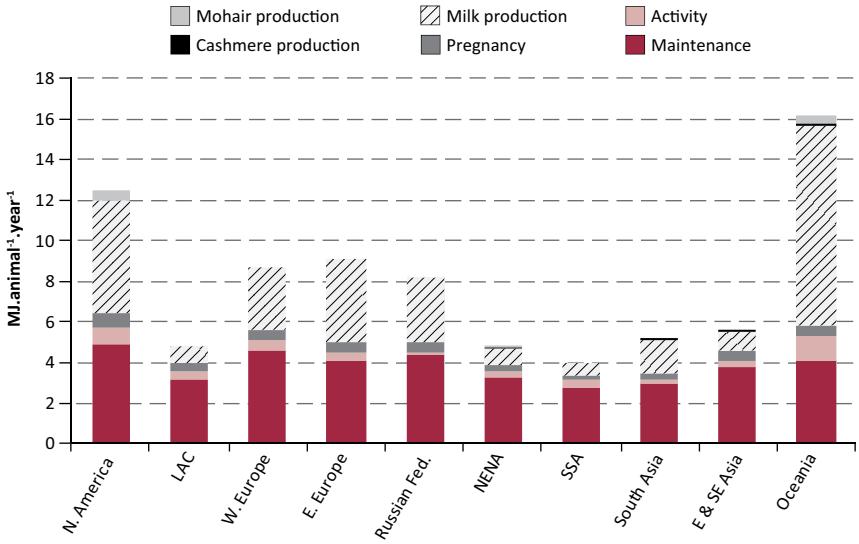

Source: GLEAM.

Figure 29a.
Regional comparison of energy partitioning across the different functions in dairy cattle herds

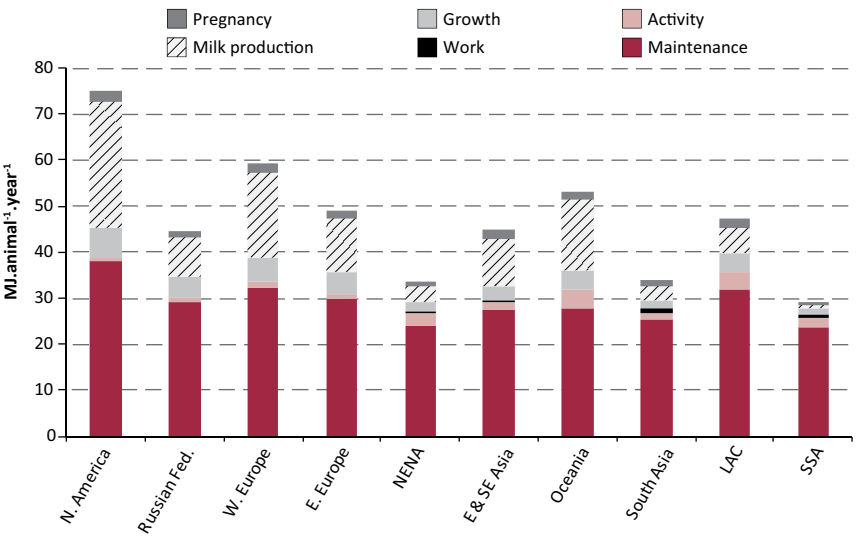

Source: GLEAM.

Figure 29b.
Regional comparison of energy partitioning across the different functions in beef cattle herds

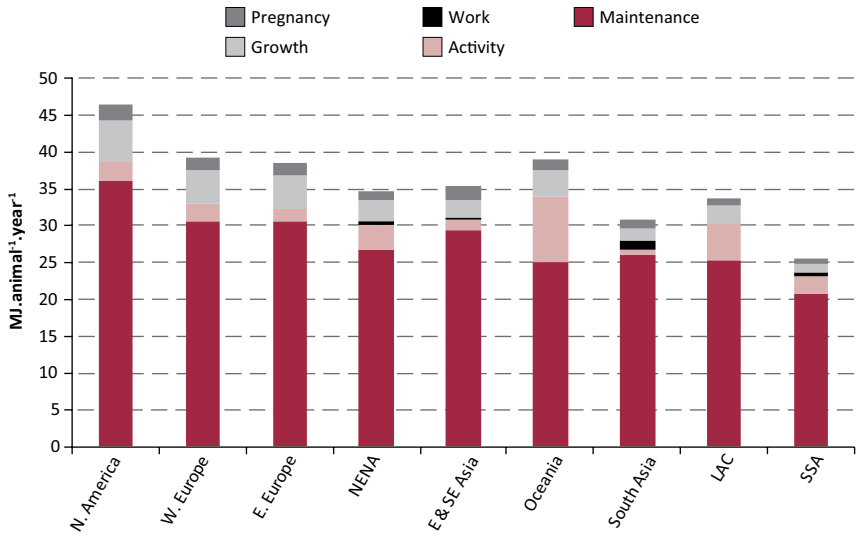

Source: GLEAM.

milk production from cattle and small ruminants. For example, in dairy cattle in sub-Saharan Africa, NENA, South Asia and Latin America & Caribbean, energy intake is low and, as a consequence, a large proportion of energy is used for maintenance (78 percent, 67 percent, 72 percent and 67 percent, respectively) while in industrialized regions a greater share is used for lactation as illustrated in Figure 28a.

Key assumptions and uncertainties. Given that enteric CH_4 is the single largest contributor to GHG emissions in ruminant production, the method and EFs used for calculating CH_4 from enteric fermentation are fundamental for assessing the carbon footprint of ruminant species. Enteric CH_4 emissions were calculated on the basis of the IPCC Tier 2 approach (IPCC, 2006 Volume 4, Chapter 10), where CH_4 emissions are estimated for different animal categories in the herd as a direct function of gross energy requirements and the CH_4 conversion rate (see Appendix A).

Uncertainties in Tier 2 estimates may be associated with population data, production practices and performance data, including feeding strategy. The use of Tier 2 methodology requires a detailed characterization of the livestock population. Uncertainty in livestock population depends on the extent and reliability of livestock population data. In addition, different accounting conventions for animals, particularly for those that do not live for a whole year such as small ruminants, also add to the uncertainty. Furthermore, total animal numbers are often reported as single values and composition of the different cohorts in herds is not reported separately, making it difficult to characterize these populations.

To overcome this problem in this study, the population was modelled on the basis of a number of herd parameters (see Tables B2-B6 in Appendix B) obtained through

data collection and literature reviews. In addition, there is a scarcity of published data on production practices, dietary information, dry matter intake (DMI) and animal performance, which may contribute to the uncertainty of model prediction. While the feed rations used in this assessment represent the general diet characteristics within each region/country, there may be some uncertainty associated with local variation in feed as well as management practices which may also affect the ultimate energy requirements of the animal and consequently CH_4 emissions.

5.2 EMISSIONS FROM FEED PRODUCTION

Feed production constitutes 36 percent, 36 percent and 28 percent of the total emissions for cattle, small ruminants and buffalo, respectively. Emissions related to feed are a function of several factors:

- *Feed ration* (i.e. specific feed materials in the ration). Feed materials have different emission intensities because they are produced in different modes. Generally, rations with higher proportions of by-products and concentrates tend to have higher emission intensities. The regional average feed composition for ruminant species is presented in Appendix B.
- *Mode of feed production:* whether feed production utilizes additional production inputs such as fertilizers, pesticides, etc.
- *Source of feed materials:* reliance on off-farm produced feed or imported feed also has an impact on the emission intensity of the feed-crop.
- *Feed associated with LUC adds additional emissions* (see Appendix C on land use and LUC).

Feed conversion is a measure of the efficiency with which animals convert feed into a gain in body weight or usable product. There are large differences in feed conversions among the various species. The feed conversion of ruminants is usually much lower than that of non-ruminants. High feed consumption per kilogram of protein is partly due to the biological time-lag that it takes for an animal to reach slaughter weight or to calve, and partly due to the amount of feed required by the breeding stock. For example, a suckler cow gives birth to one calf per year. This calf needs between one to four years to reach slaughter weight, depending on production conditions.

Feed conversion also varies among regions for the following reasons:

- animals need a certain amount of feed as their maintenance energy requirement;
- the proportion of breeding stock in the herd – these animals also need to be fed even though they are unproductive;
- regions that rely on dairy herds for their meat supply have a higher feed conversion ratio (FCR) because they produce two products; and
- the characteristics of the production system are also important; aspects such as mortality rates (when animals die or are culled before they reach slaughter weight or first lactation represents significant loss of feed resources), growth rates, age at first calving (lower age at first calving reduces feed requirements during the growth period), etc. influence feed requirements.

Figure 30 compares feed utilization efficiency for dairy and beef herds by region expressed as DMI per unit of protein produced. Increased animal performance due to improved genetics, nutrition and management results in improved feed use efficiency. This improvement is largely a function of dilution of the growing animal's

Figure 30.
Regional variation in feed conversion ratio for the cattle sector

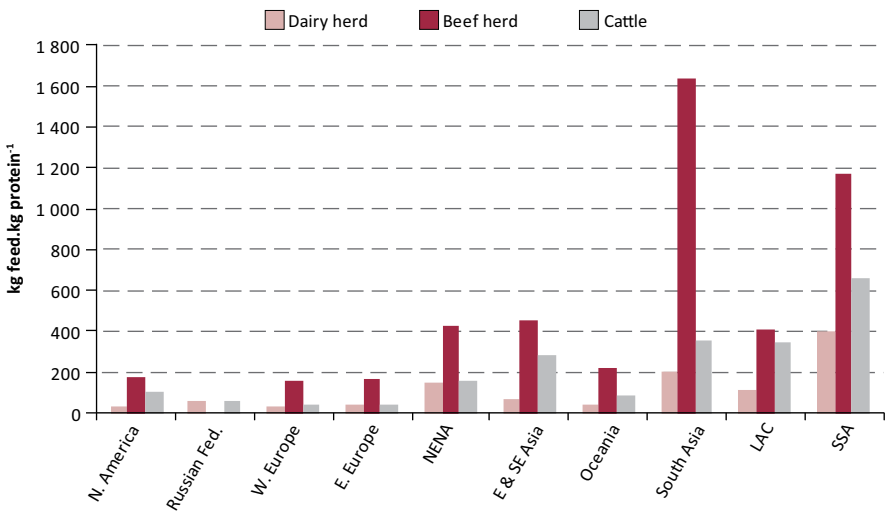

Source: GLEAM.

maintenance requirements in respect to their total feed requirements. A higher proportion of feed is used for growth and production while a lower proportion for maintenance.

In cattle production, emissions of N_2O are the predominant emissions in feed production in all regions (Figure 31a). This trend is similar for small ruminants, with the exception of North America and Western Europe where both N_2O and CO_2 emissions contribute equal shares of emissions, while in Eastern Europe CO_2 emissions per kg of feed intake are higher (Figure 31b). In cattle production, South Asia has the lowest emission intensity per kg of DMI, a consequence of the large proportion of crop residues used as feed material which make up more than 60 percent of the feed ration (see Tables B7 and B8, Appendix B).

5.2.1 Nitrous oxide from feed production

Nitrous oxide emissions associated with feed production are related to the use of N fertilizer in feed production, N_2O arising from the deposition of manure on grazing land, N from crop residues returned to soils, and N_2O emissions from the application of manure to land.

Manure is an important source of N_2O emissions, and in ruminant production systems manure N_2O emissions from feed production result from manure deposited directly by animals on pasture as well as the manure applied to crops. In the latter case, manure applied to land comprises of all manure that is handled in MMS and includes manure from other species.

N_2O emissions may arise directly as a result of application of the N sources mentioned above. In addition to the direct emissions, N inputs may also lead to indirect formation of N_2O after leaching or following gaseous losses and deposition of ammonia and nitric oxides. In ruminant production, the main source of N_2O

Figure 31a.
Regional difference in N_2O and CO_2 emission intensity of feed – cattle

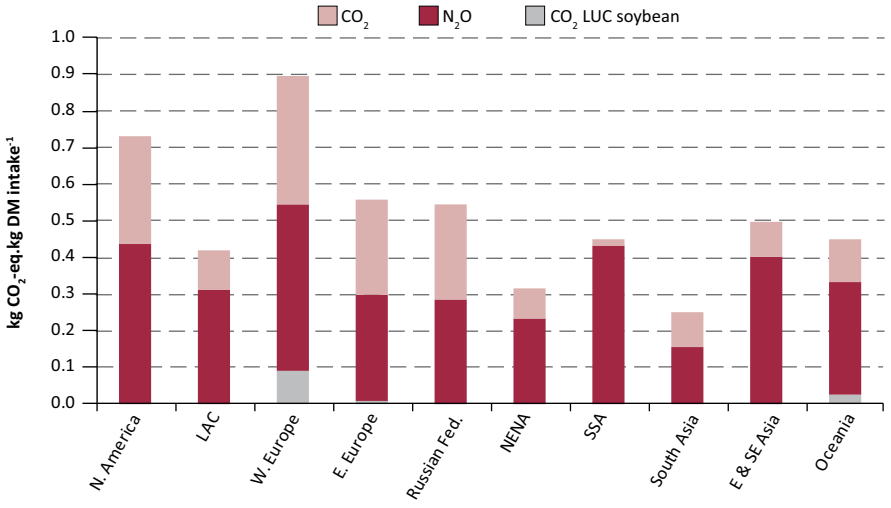

Source: GLEAM.

Figure 31b.
Regional difference in N_2O and CO_2 emission intensity of feed – small ruminants

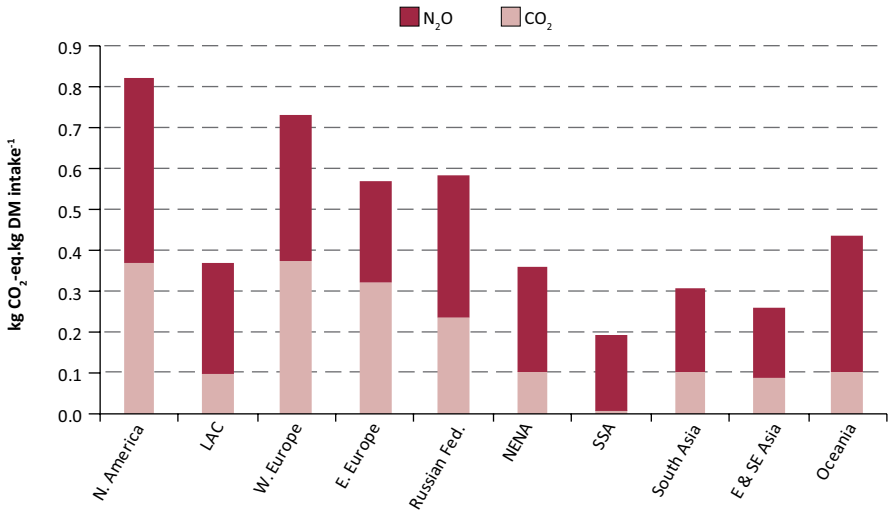

Source: GLEAM.

emissions is manure, with most of the N_2O losses originating from manure that has been deposited or applied.

Figures 32a and 32b present emission intensities for feed for cattle and small ruminants illustrated by region and source of N. In all developing regions, as well as in Oceania and Western Europe, the predominant source of N_2O emissions associated with both cattle and small ruminant species is manure deposited during grazing and applied manure. On the contrary, N_2O emissions from fertilizer application (N fertilizer) are important in North America and to a lesser extent in Europe.

The composition of the feed ration is a key factor in explaining the variation in N_2O emissions because of the vast differences in feed production (see Tables B7-B12, Appendix B, for detailed feed basket composition). For example, in regions where fresh grass is the dominant source of feed, N inputs within the system are more likely to come from manure. However, in intensive grazing systems, N_2O emissions are also likely to be important due to the use of N chemical fertilizer to maintain the productivity of pastures. High N_2O emissions from grazing in regions such as Latin America and the Caribbean and sub-Saharan Africa are mainly a consequence of the importance of pasture as a source of feed. For small ruminants, N_2O emissions from grazing are concentrated in Oceania, sub-Saharan Africa and Latin America.

Regions with a high proportion of concentrates in the feed basket (and to a certain extent hay produced off-farm and silage), are likely to have a larger proportion of N_2O emissions from nitrogen fertilizer. N_2O emissions from fertilizer use in feed production for cattle are significant in North America, and Europe due to the high N application rates on feed in these regions. In the rest of the world's regions, use of fertilizer is negligible; in these regions, N nutrients for feed crop production are largely met from manure. It is also important to note that fertilizer input for other crops can be high in these regions as a consequence of large differences in crop yield and N fertilizer use. N_2O emissions from feed production can be very different for the same feed crop in grown in different locations.

Assumptions and uncertainties. Determining N_2O emissions is often difficult due to the high spatial and temporal variability of N_2O fluxes. N_2O emissions related to feed are based on the IPCC guidelines (2006) following the Tier 1 protocol, and in the modelling of N_2O emissions we adopted a simplified approach that took into account only N additions from fertilizer, manure and biomass on pasture and feed crops. However, other factors also drive N_2O emissions, such as local climatic conditions and soil properties (including water and N dynamics, soil type and structure), and management practices (tillage, irrigation, N application techniques, etc.), thus rendering the quantification of N_2O emissions challenging, which also implies that the results may contain substantial uncertainty.

There are additional uncertainties related to N_2O emissions, such as those related to N application rates coupled with limited information on manure application techniques and timing; the fate of manure and the lack of detailed estimates of the proportion of manure excreted at pasture; and how residues are managed (whether burned or incorporated). In addition, the N content in pasture and manure can vary during the year due to climatic conditions and stages of grass growth. All these aspects are difficult to capture given the scale of the analysis.

In this study, it is also assumed that all managed manure is applied to crops pro-

Figure 32a.
Regional difference in N_2O emission intensity of feed – cattle

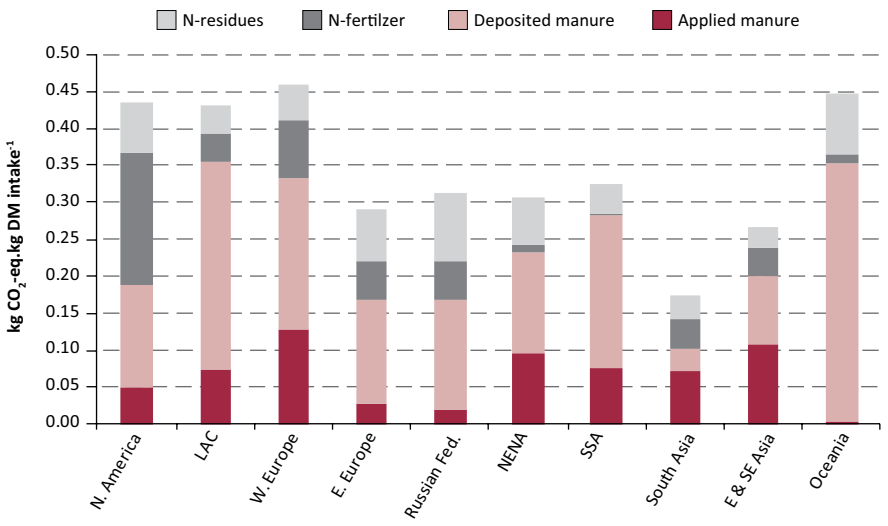

Source: GLEAM.

Figure 32b.
Regional difference in N_2O emission intensity of feed – small ruminants

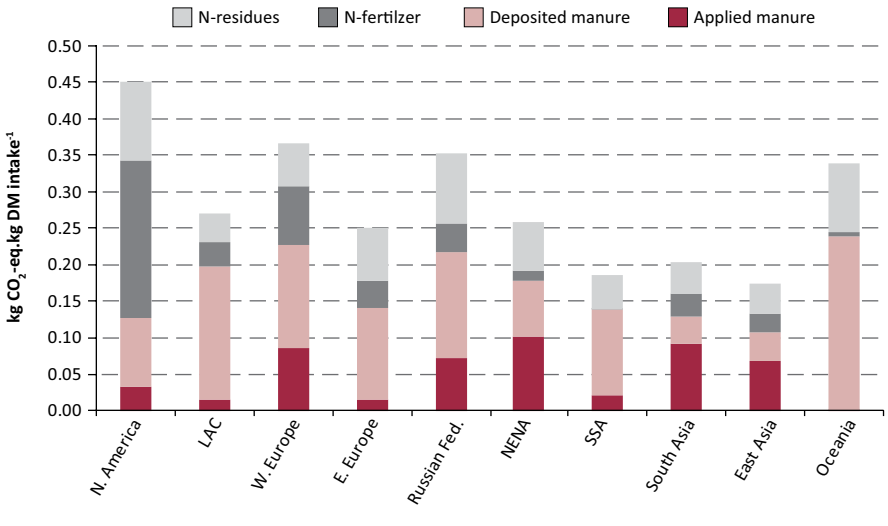

Source: GLEAM.

duced in the same location that production takes place. This may result in high N_2O emissions from applied manure particularly in areas where crop yields are low.

Another important aspect that influences the emissions from feed production is the choice of feed material; for example, in regions where the use of crop residues and by-products is important, there will be a tendency towards lower emission intensities per kg of DM because part of those emissions have been allocated to the main crop while regions that rely on concentrate feed, cultivated pasture, grains as a source of feed are likely have to have higher emissions intensities.

5.2.2 Carbon dioxide emissions from fossil fuel use in feed production

Carbon dioxide emissions from feed production are related to the use of fossil fuels, particularly diesel in tractors and harvesting machinery, oil in dryers, and natural gas in the manufacture and application of synthetic fertilizer and LUC. In the post-farm stages of feed production, CO_2 is emitted in conjunction with various feed processes (with drying being important) and transport.

In general, CO_2 emissions from energy use in feed production, processing and transport are strongly correlated to the feed ration. Other factors that also explain the variation in emission intensity among world regions include: the level of mechanization, the rate of fertilizer application, dependence on imported feed and source of feed (a key determinant of emissions related to transport of feed) and the extent to which the feed in question is associated with LUC.

Figures illustrate the emission intensity of feed by different processes in feed production and by region for both cattle (Figure 33a) and small ruminants (Figure 33b). In both cases, CO_2 emissions from fossil fuel use in feed production are important in industrialized regions. In these regions, two key factors explain the high emission intensities: (i) high fertilizer application rates; and (ii) transport of feed due to the higher proportion of by-products, feed crops or imported hay in the feed ration.

In other world regions, emission intensity is low and dominated by CO_2 emissions from energy use in field work. In both cattle and small ruminant production, sub-Saharan Africa has the lowest CO_2 feed emissions and there are several reasons for this: (i) reliance on natural pasture as a source of feed and low concentrate feed use; (ii) low use/negligible use of inputs such as fertilizer in the production of feed; and (iii) the low level of mechanization in the region.

Assumptions and uncertainties. The estimation of CO_2 emissions in this study are influenced by a number of assumptions and factors such as energy source and related emission coefficients used (see Table B14, Appendix B); level of mechanization (Table A1, Appendix A); and where feed is sourced and composition of the feed ration – both of which are variable.

5.2.3 Carbon dioxide emissions from land-use change

Emissions from LUC attributable to the ruminant sector amount to 450 million tonnes CO_2-eq, the bulk of these emissions (93 percent) are related to pasture expansion into forest areas for beef production in Latin America. The use of soybean produced on previously forested land as feed especially for dairy production contributes another 30 million tonnes CO_2-eq. The approach used in this assessment for estimating emissions from C stock changes associated with livestock induced LUC is further elaborated in Appendix C.

Figure 33a. Regional variation in CO_2 (fossil fuel-related) emission intensity of feed – cattle

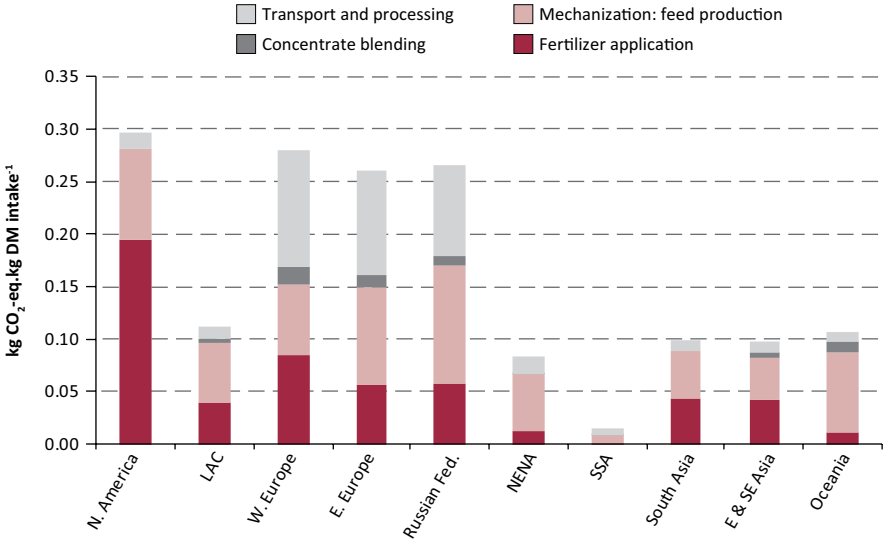

Source: GLEAM.

Figure 33b.
Regional variation in CO_2 (fossil fuel-related) emission intensity of feed – small ruminants

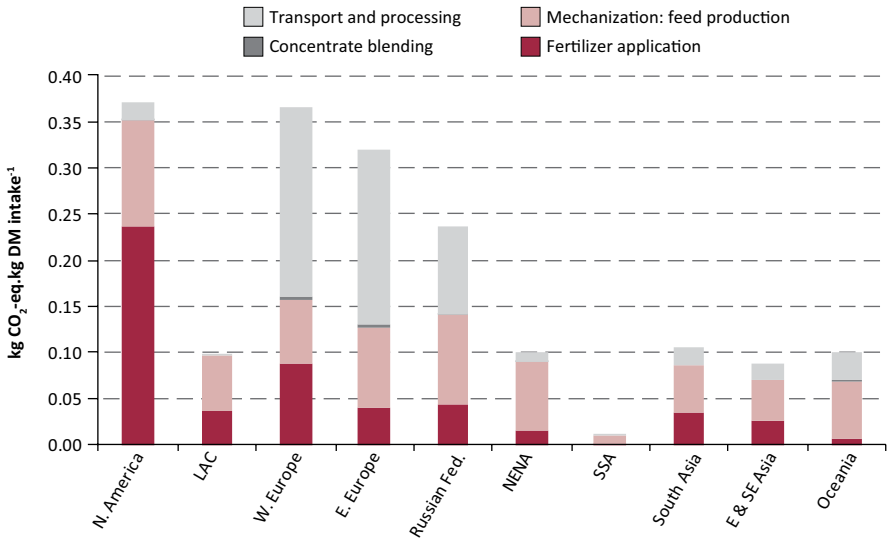

Source: GLEAM.

Table 10. Regional sources of soybean and soybean cakes in 2005

	Brazil		Argentina		Other	
	Soybean	Soybean Cake	Soybean	Soybean Cake	Soybean	Soybean Cake
	percentage					
LAC	42	49	41	15	17	36
E & SE Asia	17	7	14	10	68	83
E. Europe	0	9	0	27	100	63
N. America	0	0	0	0	100	100
Oceania	0	60	0	0	100	40
Russian Fed.	5	5	0	37	95	57
South Asia	6	2	1	0	93	98
SSA	0	0	1	60	99	39
NENA	12	7	19	23	69	69
W. Europe	61	34	0	38	38	28

Source: FAOSTAT (2013).

Table 11. Main exporters of soybean and soybean cakes in 2005

	Soybean		Soybean cake	
	Exports *(million tonnes)*	Share of global exports	Exports *(million tonnes)*	Share of global exports
Argentina	20.8	37%	10.0	15%
Brazil	14.4	26%	22.4	34%
United States of America	5.1	9%	25.7	39%
India	4.8	8%	0.0	0%
Paraguay	0.8	1%	3.0	5%

Source: FAOSTAT (2013).

Soybean expansion. In quantifying total emissions associated with the transformation of forest for soybean cultivation, LUC emissions are attributed to only those countries supplied by Brazil and Argentina with soybean and soybean cake. Tables 10 and 11 present the regional share of soybean and soybean cake sourced from Brazil and Argentina and main exporting countries, respectively.

This analysis shows that about 224 million tonnes CO_2-eq are emitted *per annum* from the expansion of soybean production in Brazil and Argentina to meet global demand for pigs, chickens and cattle feed. The bulk of these emissions arise in response to soybean demand in Europe, East Asia and LAC (Table 12) which source large quantities of their soybean feed from Argentina and Brazil. The emissions estimated for the livestock sector in Western Europe are particularly high, which not only indicates a high reliance on imported soybean and soybean cake for feed, but also use of soybean with a high emission intensity, particularly because a large share is sourced from Brazil (see Table 10).

On a species level, the largest share of these emissions is attributed to the non-ruminant sector, equivalent to 195 million tonnes CO_2-eq (87 percent). This is not

Table 12. Regional comparison of land-use change emissions associated with soybean production

Region	Cattle	Pigs	Chicken
	(million tonnes CO_2-eq)		
Latin America	5.2	19.3	47.9
East and Southeast Asia	0.9	25.3	25.1
East Europe	0.6	2.1	0.4
North America	0.5	0.0	0.1
Oceania	2.4	1.5	1.6
Russian Federation	0.1	0.1	0.1
South Asia	0.0	0.0	4.5
Sub-Saharan Africa	0.0	0.0	0.5
Near East and North Africa	0.2	0.0	5.6
Western Europe	19.6	36.7	23.9
World	**29.6**	**85.0**	**109.6**

Source: GLEAM.

surprising because of the high share of soybean in diets of non-ruminants. Regarding the cattle sector, LUC emissions from soybean are important in Europe where it is utilized in dairy production. The results suggest that emissions are largely influenced by: (i) the quantity of soybeans and soybean cake imported from the two countries; and (ii) the share of soybean in the ration of the diet.

Pasture expansion. According to our estimations, about 13 million hectares of forest land in Latin America were converted to pasture land between 1990 and 2006. Deforestation for pasture establishment in the region emitted about 420 million tonnes CO_2-eq per year, releasing on average 32 tonnes CO_2-eq ha^{-1} yr^{-1}. At country level, changes in C stocks range between 30 and 35 tonnes CO_2-eq ha^{-1} yr^{-1} (Table 13). The estimates of GHG emissions due to pasture-driven LUC presented here represent a first step towards an estimation of LUC emissions. The analysis is consistent with the Tier 1 methodology outlined in the IPCC guidelines (IPCC, 2006). In order to progress towards better methodologies, certain gaps in data, methods, and in scientific understanding need to be addressed.

These preliminary estimates indicate that the inclusion of CO_2 emissions from land-use change have a significant influence on the carbon footprint of livestock products. However, changes in soil carbon sequestration due to land use are important are important and need to be considered.

Assumptions and uncertainties. Due to the uncertainty in the methods and data for calculating the impacts of LUC, we recognize the high level of uncertainty associated with this estimation. There is much uncertainty regarding the magnitude of LUC emissions due to (a) uncertainty in the estimates of deforestation rates; (b) uncertainty in the carbon storage capacity of different forests, (c) the modes of C release, and (d) uncertainties in the dynamics of land use, thus limiting the accuracy of the estimated carbon loss (Houghton and Goodale, 2004; Ramankutty *et al.*, 2006).

Table 13. Annual carbon stock changes and emissions from pasture expansion in Latin America

Countries	Average emissions		Total carbon losses
	tonnes CO_2/ha	*tonnes CO_2/ha/yr*	*million tonnes CO_2-eq*
Brazil	- 509.7	- 31.9	-325.3
Chile	- 510.7	- 31.9	-36.7
Paraguay	- 488.1	- 30.5	-31.7
Nicaragua	- 485.3	- 30.3	-13.8

Source: Authors' calculations.

This analysis also relies on a Tier 1 approach and use of IPCC default values and is therefore subject to high levels of uncertainty. We test other existing methods and assumptions in Appendix C to illustrate the range of uncertainty that exists.

The way in which the LUC emissions should be allocated over beef production is a question for further research. Within this analysis, we allocate emissions to total beef produced within the country; however, not all beef production is carried out on deforested land. A related methodological issue is the debate on the allocation of emission related to LUC because of the complexity in ascertaining the key driver of land-use change. In addition, the calculated emission intensity is highly sensitive to the time period selected over which emissions from the initial deforestation are annualized. Appendix C explores alternative approaches to estimating emissions related to LUC, incorporating some of the issues discussed here.

5.3 EMISSIONS FROM MANURE MANAGEMENT

5.3.1 Methane from manure management

Animal manure emits CH_4 depending on the way it is produced and managed. Ruminants (cattle, buffalo and small ruminants) contribute 109 million tonnes of CH_4 from manure (2 percent of total emissions from ruminants), of which 86 percent is from cattle. Three primary factors affect the quantity of CH_4 emitted from manure management operations: type of treatment or storage facility, climate and composition of the manure.

Storage and treatment of manure in liquid systems such as lagoons or ponds leads to the development of anaerobic conditions which result in high CH_4 emissions. In addition, higher ambient temperature and moisture content also favour CH_4 production. The composition of manure is directly related to animal types and diets.

Manure CH_4 emissions are lower in regions where manure is handled in dry systems. In dairy and beef cattle production, where liquid MMS (lagoons, liquid/slurry systems) are common, the proportion of manure CH_4 emissions in total CH_4 emissions is considerable, and particularly in regions where animals are confined for a part of the year, such as Europe and North America. For dairy, this ranges from 5 percent in Eastern Europe to 35 percent in North America; on the other hand, in beef production the use of liquid systems is confined to Western Europe and Eastern Europe where 6 percent and 14 percent of CH_4 emissions originate from manure, respectively. The anaerobic nature of liquid manure systems increases the potential for CH_4 production and reduces N_2O production.

In the other world regions, a large fraction of the manure from cattle is handled in dry systems, while in small ruminant production manure is managed in dry systems, including drylots and solid systems, or deposited on pastures and ranges.

Maps 9 and 10 in Appendix G present the CH_4 conversion factor that defines the portion of CH_4 producing potential achieved by each manure management system. Methane conversion factor is higher in North America and Europe, which explains the higher CH_4 emissions. The high CH_4 conversion factor in North America and Europe is due to the use of liquid MMS.

Assumptions and uncertainties. In this study, CH_4 emissions from manure management are calculated using the IPCC Tier 2 approach. This approach uses country-specific inputs of volatile solids estimated from DMI, feed digestibility and ash content of manure, a CH_4 conversion factor based on climate and type of manure management and storage system, and the maximum CH_4 potential (Bo) of manure based on species and diet.

Uncertainties related to estimation of CH_4 from manure management derive from: limited activity data on manure management; differences in manure management practices; and the effect of time-related aspects such as storage periods, as well as seasonal temperature variations in emission rates which are not explicitly accounted for in the calculations.

5.3.2 Nitrous oxide from manure management

Nitrous oxide is produced directly and indirectly during storage and treatment of manure before it is applied to land. Indirect N_2O emissions result from volatile N losses that occur mainly from ammonia (NH_3) and NO_X and leaching of nitrate. Key important variables that influence N_2O emissions from manure management include the amount of N excreted and the way in which manure is managed. A considerable amount of N entering the livestock food chain through feed is wasted; ruminants excrete between 75 percent and 95 percent of the N they ingest (Castillo *et al*., 2000; Eckard *et al*., 2007). Maps 11 and 12 in Appendix G compare the proportion of feed nitrogen retained by dairy and beef herds.

Animal productivity is important for N excretion; as more milk or meat is produced per animal, the maintenance requirement of protein per unit of production is reduced. Thus, the animal product can be produced with less N consumed and excreted. Figure 34 illustrates the relationship between animal performance and N excretion per kg of milk protein; a comparison among regions reveals that, on average, high-producing animals excrete less N per unit of protein produced because more nutrients are directed towards production.

Manure handling and storage also influence N_2O emissions from manure. A large proportion of N_2O from manure management is released as direct N_2O, the bulk of which originates from dry systems (with approximately 60 percent and 65 percent from drylot systems in beef and dairy cattle production). All manure from small ruminants and buffalo is managed in dry systems (drylot and solid systems). Nitrous oxide emissions are most likely to occur in dry manure handling systems that have aerobic conditions (in the presence of oxygen), but that also contain pockets of anaerobic (in the absence of oxygen) conditions.

For dairy and beef cattle, most N_2O emissions from manure management are found in developing regions. Oceania is the only region without N_2O emissions

Figure 34.
Nitrogen excretion per kg milk protein versus average regional milk yield – dairy cattle



Source: GLEAM.

associated with manure management because all manure from beef and small ruminants in Oceania is assumed to be deposited on pasture. The proportion of N_2O from leaching is insignificant and has a limited impact on total N_2O from manure management because only a small proportion of leached N is converted to N_2O.

Assumptions and uncertainties. The basis for the estimation of N emissions is the total mass of N excreted. Excretion is determined as the difference between crude protein intake and retention within the animal. N_2O emissions associated with manure deposited on pasture, ranges and paddocks are not included in these estimates but considered as part of the feed production component (cf. Appendix A), because they are considered as a source of N fertilizer in feed production.

5.4 COMPARISON WITH OTHER STUDIES

A direct comparison with literature values from other LCAs is often complicated by the use of differing boundaries, functional units, disparate assumptions and algorithms in calculating emissions. Nevertheless, comparisons can be useful to provide an indication of the validity of results and contribute to drawing conclusions. Tables 14 and 15 compare existing studies for beef cattle and small ruminants with the current study. While several studies have focused on the cattle sector and to a limited extent small ruminants, many of these estimates are at a much smaller scale and are often specific to regions or production systems within countries (e.g. Verge *et al.*, 2008; Peters *et al.*, 2009; Biswas *et al.*, 2010; Beauchemin *et al.*, 2010; Pelletier *et al.*, 2010; Nguyen *et al.*, 2010; Kanyarushoki *et al.*, 2010; Zhou *et al.*, 2007, Zervas and Tsiplakou, 2012; Edwards-Jones *et al.*, 2009). For purposes of this comparison, only those studies with a national or regional scope were selected.

Table 14. Comparison of emission intensities for beef cattle

Study	Country	System	Scope							Emission Intensities/Emissions	
			Enteric CH_4	Manure CH_4	Manure N_2O	Feed N_2O	Feed CO_2	Energy	Post farmgate	Study	GLEAM
Foley *et al.* (2011)	Ireland	Pastoral suckler (National average farm scenario)	Y	Y	Y	Y	Y	N	N	23.1 kg CO_2-eq/kg CW	27.7 kg CO_2-eq/kg CW
Leip *et al.* (2010)	EU27	Beef	Y	Y	Y	Y	Y	Y	N	22.2 kg CO_2-eq/kg CW	24.1 kg CO_2-eq/kg CW
Cederberg *et al.* (2009)	Brazil		Y	Y	Y	Y	Y	Y	N	28 kg CO_2-eq/kg CW (without LUC)	32.4 kg CO_2-eq/kg CW (without LUC)
Williams *et al.* (2006)	Brazil		Y	Y	Y	Y	Y	Y	Y	32.2 kg CO_2-eq/kg CW (without LUC)	32.4 kg CO_2-eq/kg CW (without LUC)
Casey and Holden (2006)	Ireland	Typical Irish beef	Y	Y	Y	Y	Y	Y	N	11.26 kg CO_2-eq/kg LW	19.1 kg CO_2-eq/kg LW
Ogino *et al.* (2007)	Japan		Y	Y	Y	Y	Y	N	N	32.1 kg CO_2-eq/kg CW	39.0 kg CO_2-eq/kg CW
Ominski *et al.* (2003)	Canada		Y	N	N	N	N	N	N	16.1 million tonnes CO_2	17.5 million tonnes CO_2

Y: emission category included; N: emission category excluded.

Table 15. Comparison of emission intensities for small ruminants

Study	Country	Species	System	Scope							Emission Intensity	
				Enteric CH_4	Manure CH_4	Manure N_2O	Feed N_2O	Feed CO_2	Energy	Post farmgate	Study	GLEAM
Leip *et al.* (2010)	EU27	Small ruminant meat		Y	Y	Y	Y	Y	Y	N	20.3 kg CO_2-eq/kg CW	18.1 kg CO_2-eq/kg CW
Leip *et al.* (2010)	EU27	Small ruminant milk		Y	Y	Y	Y	Y	Y	N	2.9 kg CO_2-eq/kg milk	4.7 kg CO_2-eq/kg milk
Ledgard *et al.* (2011)	New Zealand	Lamb		Y	Y	Y	Y	Y	Y	Y	19 kg CO_2-eq/kg CW	14.8 kg CO_2-eq/kg CW (with allocation to wool) 19.0 kg CO_2-eq/kg CW (without allocation to wool)
Ripoli-Bosch *et al.* (2010)	Spain	Lamb	Grazing Mixed Zero-grazing	Y	Y	Y	Y	Y	Y	N	Grazing: 56.7 Mixed: 48.5 kg CO_2-eq/kg CW	25.9 kg CO_2-eq/kg CW
Yamaji *et al.* (2003)	China	Goats		Y	Y	N	N	N	N	N	869 gigagrams CH_4	641 gigagrams CH_4
Yamaji *et al.* (2003)	China	Sheep		Y	Y	N	N	N	N	N	760 gigagrams CH_4	925 gigagrams CH_4

Y: emission category included; N: emission category excluded.

The following factors have been identified as potential reasons for the deviation in results.

Scope. Studies can: (a) have different system boundaries; (b) include different emissions categories within the same system boundaries; (c) have different functional units; or (d) include different emission sources within an emission category.

Input data/assumptions. Quantifying emissions requires input data on key parameters such as livestock population numbers and distributions, herd structures and crop yields. Ideally, validated empirical data sets should be used, but there are often gaps in the data on key parameters, which necessitate assumptions. In many cases, key input data have been found to vary; for example a comparison of small ruminant population numbers in the 27 Member States of the European Union (EU27) revealed that the small ruminant population for these countries used in this current study are 30 percent higher than those used by Leip *et al*. (2010). The authors also noted that there was an observed difference between the small ruminant inventory that they utilized and national inventory reports. The animal inventory utilized in this study was, however, found to be consistent with those reported by the countries.

Calculation methods. A review of the studies revealed the major differences in methodology across all studies particularly in the use of different approaches such as use of Tier 1 vs. Tier 2 approaches, and differences in allocation technique applied. Generally, due to the importance of enteric fermentation, most recent studies apply a Tier 2 approach, particularly for cattle. While the approach may be similar, studies may obtain different results which may largely depend on data inputs such as animal weights, feed digestibility and feed composition, all of which are important in assessing emissions from enteric fermentation. On the other hand, the assessment of enteric fermentation in small ruminants in the few studies conducted (Leip *et al.,* 2010; Yamaiji *et al.*, 2003; Edward-Jones *et al.*, 2009) has largely been based on the Tier 1 approach using the IPCC default value of 8 kg CH_4 per head.

The allocation technique applied may also explain variations in emission intensity. Significant differences were found between this study and the EU27 study (Leip *et al*., 2010) for small ruminant milk production (cf. Table 14), which is also explained by the differences in allocation techniques. The authors allocate emissions between three outputs: milk, meat and lamb/kids based on the nitrogen content of the products, and emissions related to the raising of young animals during pregnancy are allocated to meat. In contrast, this study allocates emissions between milk, meat and wool based on economic value of the products and subsequently utilizes protein content of products to allocate emissions among the edible products (see allocation technique in Appendix A). A key explanation of the deviation between the current study and EU27 study is related to the fact that a large part of the total dairy herd emissions (i.e. emissions associated with the adult females and male animals and replacement animals) in our study are allocated to milk, while only emissions of the dairy activity (time from the first lactation to the slaughtering of the animal) are allocated to milk in the EU27 study (Weiss and Leip, 2012).

The overlying issues with comparison lie in the lack transparency of information and a standardized methodology or protocol for conducting LCAs and reporting results. The variability among studies in methods used places emphasis on the need to clearly define and agree on methodologies for estimating GHG emissions from the ruminant sector.

5.5 ANALYSIS OF UNCERTAINTY

Estimates of GHG emissions are subject to large uncertainties. Fundamentally, uncertainties are associated with the variables used in the calculation of EFs, in estimates of activity data (e.g. animal populations and herd parameters) and assumptions made. This section presents a partial analysis of uncertainty, based on the Monte Carlo (MC) Simulation approach.

In order to focus the analysis of uncertainty, parameters that had the greatest influence on emission intensity were identified. Key contributors to emissions were defined as those emissions categories contributing more than 10 percent of the emissions and with a high degree of uncertainty arising from either the lack of data or inherent

Table 16. Summary of parameters and uncertainty distributions used in the Monte Carlo simulation runs for dairy and beef in France

Parameters and emission factors	Distribution	CV[1]	Min	Max	Reference and basis for uncertainty estimates
Parameters					
Feed digestibility	Normal	0.10			Assuming IPCC uncertainty range of ±20% (IPCC, 2006 – Volume 4, Chapter 10, Section 10.2.3)
Dairy: Milk yield	Normal	0.2			Institut de l'Élevage, 2011
Dairy: Age at first calving	Normal	0.19			Institut de l'Élevage, 2011
Beef: Age at slaughter	Normal	0.23			Institut de l'Élevage, 2011
Beef: Age at first calving	Normal	0.17			Institut de l'Élevage, 2011
Emission factors					
Enteric CH_4 emission factor	Normal	0.10			Assuming IPCC (2006, Volume 4, Chapter 10, Section 10.3.4) uncertainty range of ±20%
EF1: N_2O emission factor, synthetic and organic N	Beta Pert		0.003	0.03	IPCC (2006, Table 11.1)
EF3: N_2O emission factor, pasture, rangeland and paddock	Beta Pert		0.007	0.06	IPCC (2006, Table 11.1)
EF4: Emission factor, N volatilization	Beta Pert		0.002	0.05	IPCC (2006, Table 11.3)
EF5: Emission factor, leaching	Beta Pert		0.0005	0.025	IPCC (2006, Table 11.3)
Fraction of applied synthetic N to volatilization NH_3, No_x	Beta Pert		0.03	0.3	IPCC (2006, Table 11.3)
Fraction of applied organic N to volatilization NH_3, No_x	Beta Pert		0.05	0.5	IPCC (2006, Table 11.3)
Ammonium Nitrate manufacture EF	Normal	0.27			Based on values for fertilizer CO_2 EFs in Wood and Cowie (2004)
Soybean scenario 1: GLEAM	Normal	0.08			See Appendix C on LULUC
Soybean scenario 2: PAS 2050-1:2012	Normal	0.15			See Appendix C on LULUC
Soybean scenario 3: One-Soy	Normal	-			See Appendix C on LULUC
Soybean scenario 4: Reduced time-frame	Normal	0.08			See Appendix C on LULUC

[1] CV – Coefficient of Variation is the ratio of the standard deviation to the mean. The 95 percent confidence interval is approximately equal to the standard deviation or coefficient multiplied by two.

variability or assumptions made. For the ruminant sector, emission categories that contribute more than 10 percent include CH_4 from enteric fermentation, CO_2 from land-use change, and N_2O from feed production (see Section 4). Section 5.4 highlighted some of the important factors that are likely to influence emissions. The MC simulation was applied to two countries, France and Paraguay. In France, uncertainties in both mixed dairy and beef production systems were assessed, while in Paraguay the focus was on grazing systems. The choice of countries was based on criteria such as the availability of statistics for inventory data [standard deviation (SD), confidence interval or ranges], and relative importance of production in these countries.

5.5.1 The approach

Choice of probabilistic distributions of input variables. Monte Carlo simulations enable an investigation into how input uncertainty propagates through the life-cycle emissions model. However, there is little data on probability distributions of the input data required to perform a MC simulation.

In this assessment, the probability distributions were defined using the SD from a number of sources and applying the coefficient of variation indicated in Tables 16 and 17, and normal distributions were assigned to technical parameters for which no choice of mode could be justified given available information.

Table 17. Summary of parameters and uncertainty distributions used in the Monte Carlo simulation runs for beef in Paraguay

Parameters and emission factors	Distribution	CV[1]	Min	Max	Reference and basis for uncertainty estimates
Parameters					
Feed digestibility	Normal	0.10			Assuming IPCC uncertainty range of ±20% (IPCC, 2006 – Volume 4, Chapter 10, Section 10.2.3)
Beef: Age at slaughter	Normal	0.24			Ferreira *et al.* (2007); Fréchou (2002)
Beef: Age at first calving	Normal	0.02			Ferreira *et al.* (2007); Fréchou (2002)
Emission factors					
Enteric CH_4 Emission factor	Normal	0.10			Assuming IPCC (2006, Volume 4, Chapter 10, Section 10.3.4) uncertainty range of ±20%
EF1: N_2O emission factor, synthetic and organic N	Beta Pert		0.003	0.03	IPCC (2006, Table 11.1)
EF3: N_2O emission factor, pasture, rangeland and paddock	Beta Pert		0.007	0.06	IPCC (2006, Table 11.1)
EF4: Emission factor, N volatilization	Beta Pert		0.002	0.05	IPCC (2006, Table 11.3)
EF5: Emission factor, leaching	Beta Pert		0.0005	0.025	IPCC (2006, Table 11.3)
Fraction of applied synthetic N to volatilization NH_3, No_x	Beta Pert		0.03	0.3	IPCC (2006, Table 11.3)
Fraction of applied organic N to volatilization NH_3, No_x	Beta Pert		0.05	0.5	IPCC (2006, Table 11.3)
Ammonium Nitrate manufacture EF	Normal	0.27			Based on values for fertilizer CO_2 EFs in Wood and Cowie (2004)
Land-use change: Pasture expansion (combined scenario)	Normal	0.28			Combined uncertainty range calculated based on IPCC default uncertainty values for carbon pools and uncertainty in land area estimates

[1] CV – Coefficient of Variation is the ratio of the standard deviation to the mean. The 95 percent confidence interval is approximately equal to the standard deviation or coefficient multiplied by two.

Table 18. Emission intensity for imported soybean and soybean cake used in France

Approach	Soybean Cake	Soybean
	kg CO_2-eq/kg product	
GLEAM	4.81	5.35
PAS 2050-1:2012	1.42	1.58
One-Soy	2.98	3.31
Reduced time-frame	2.31	2.56

Source: Authors' calculations.

Table 19. Default carbon stock values for Paraguay and uncertainty values of carbon pools

	Carbon stocks	Uncertainty of the carbon pool[1]
	tonnes C/ha	*percentage*
Previous land: Forest		
Biomass	260.4	±24%
Soil carbon	65	±95%
Dead organic matter (DOM)	2.8	±30%
Total carbon stocks	**328.2**	
Land-use after conversion: Grassland		
Biomass	0	0[2]
Soil carbon	63	±95%
Dead organic matter	0	0[3]
Total Carbon stocks	**63**	
Carbon stock change	**265.2**	

[1] Two standard deviation CI 95%.
[2] No uncertainty analysis is needed for Tier 1 since the default assumption is that all biomass is cleared and therefore the default biomass after conversion is zero.
[3] No uncertainty analysis is needed for Tier 1 since the default assumption is unchanging carbon stocks in DOM.
Source: Authors' calculations.

For the IPCC parameters, these are mainly provided with a potential range, often estimated by expert opinion or drawn from studies. The ranges for EF1, EF3, EF4, EF5 were taken from IPCC (2006) and beta-pert distributions were used to model parameters from IPCC based on the maximum and minimum value. These distributions and underlying data sources are also summarized in Tables 16 and 17.

We also employed MC simulation analysis to understand the uncertainty associated with LUC. The approaches described in Appendix C were used to generate parameter ranges used in the MC simulation. The three alternative soybean approaches were only applied to the French case study where imported soybean cake is used as feed. The soybean emission intensity calculated for the GLEAM and the three additional scenarios for soybean imported by France from Brazil and Argentina are presented in Table 18.

The approach for assessing the uncertainty related to changes in C stocks resulting from pasture expansion into forest areas takes into account the *uncertainty associated with carbon fluxes from carbon pools considered* and the *uncertainty as-*

sociated with the land area estimates. The two uncertainties were run separately and then combined. The IPCC guidelines (2006) indicate that, if using aggregate land use area statistics for activity data (e.g. FAO data on land area), as is the case in this study, a default level of uncertainty for the land area estimates of ±50 percent may be applied.

Estimates of the carbon loss on land conversion include uncertainties in several underlying quantities: the carbon in the above-ground biomass, the carbon in the below-ground biomass (generally estimated as a percentage of the above-ground biomass), the carbon in the soil, and the fraction of all carbon lost upon conversion. The uncertainty associated with carbon fluxes from three carbon pools considered in this study are taken from IPCC guidelines (2006, Volume 4) and the "Good Practices Guidelines" for national GHG inventories (IPCC, 2003) and are presented in Table 19.

Total uncertainty combining uncertainty in carbon stock changes per hectare with the uncertainty in land area converted was calculated using the *error propagation approach* outlined in Chapter 6, IPCC Good Practice Guidance (2000, Chapter 6 equations 6.3 and 6.4) that combines different uncertainties to provide an uncertainty estimate for an inventory. The result of the combined uncertainty used as input in the Monte Carlo simulation is presented in Table 17.

Uncertainty estimates and sensitivity analysis. In this assessment, the number of simulations run was 10 000. For any analysis of this type, it is important to determine the sources of uncertainty and the impact that parameters and their embedded assumptions have on the results. A sensitivity analysis was therefore used to identify parameters that have a significant effect on the uncertainty estimates. Sensitivity analysis also identifies the most influential parameters indicating emissions sources that offer the opportunity to decrease the overall uncertainty associated with life-cycle of milk and beef production emissions. The relative sensitivity of input variables was assessed by Monte Carlo using the *Rank Correlation Coefficient (RCC)*[8] calculated between all inputs variables and the emission intensity as their contribution to the overall uncertainty.[9]

5.5.2 Results from the uncertainty analysis

France

The mean emission intensity for milk production in mixed farming system in kg CO_2-eq calculated on the basis of kg milk was estimated to be 1.9 kg CO_2-eq/kg milk (±0.95 kg CO_2-eq/kg milk at the $CI_{95\%}$). The range of values around the mean obtained with the uncertainty analysis was 0.9-2.8 kg CO_2-eq/kg milk (Figure 35 and Table 20). The average emission intensity for beef is 15.6 kg CO_2-eq/kg CW (±8.0 kg CO_2-eq/kg CW) (Figure 36 and Table 20) The range of values was 7.5-23.6

[8] RCC is a measure of the strength and direction of association between input variables and output estimates. If an input parameter and an output estimate have a high correlation coefficient, it means that the input has a significant impact on the output; positive correlation coefficients indicate that an increase in the input is associated with an increase in the output estimate while negative coefficients indicate an inverse relationship. The larger the absolute value of the correlation coefficient, the stronger the relationship.

[9] Crystal ball computes the rank correlation between inputs and each output parameter then normalizes these to sum to 100 percent. This provides a measure of sensitivity, i.e. the contribution of each parameter to the overall uncertainty of emission intensity.

Table 20. Summary of results from Monte Carlo analysis for mixed dairy and beef production in France

	Mixed dairy production	Mixed beef production
Mean emission intensity	1.89 kg CO_2-eq/kg milk	15.6 kg CO_2-eq/kg CW
EI standard deviation	0.49	4.10
Coefficient of Variation	26%	26%

Source: Authors' calculations.

Figure 35.
Probability distribution for milk emission intensity in France

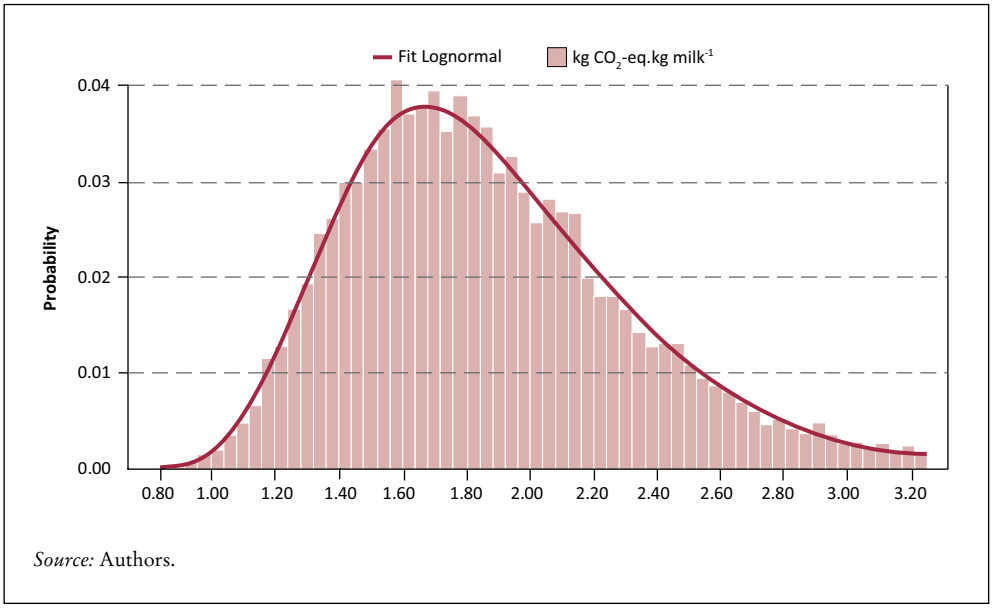

Source: Authors.

Figure 36.
Probability distribution for beef emission intensity in France

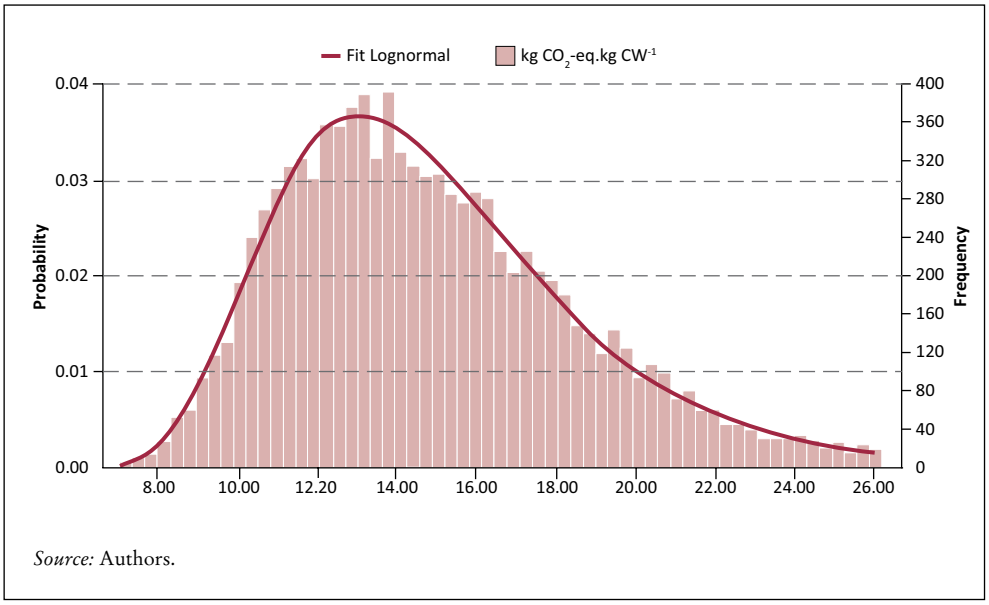

Source: Authors.

Table 21. Impact of alternative soybean scenarios on emission intensity for dairy and beef in France

	GLEAM	PAS 2050-1:2012	One-Soy	Reduced time-frame
Beef				
Mean Emission intensity *(kg CO_2-eq/kg CW)*	15.6	14.9	15.2	15.0
Contribution to variance	0%	0.1%	0%	0%
Dairy				
Mean Emission intensity *(kg CO_2-eq/kg milk)*	1.89	1.78	1.82	1.81
Contribution to variance	0%	0%	0%	0%

Source: Authors' calculations.

kg CO_2-eq/kg CW. Both probability distribution frequencies (PDFs) for France are positively skewed indicating that the distribution has a longer right tail (Figures 35 and 36).

The coefficient of variation defines the standard deviation as a percentage of the mean and can be used to compare SDs with different means. Despite the markedly different means and SD for milk and beef, the coefficient of variation for both milk and beef in France is 26 percent of the mean.

Impact of alternative soybean approaches on emission intensity. Different scenarios to assess the impact of soybean-related LUC were tested for both dairy and beef production systems in France and the results are presented in Table 21. Soybean cake accounts for a small proportion of the feed ration (between 2-6 percent of the feed ration for both dairy and beef) and hence has a negligible impact on emission intensity.

Paraguay

Figure 37 presents the results from the Monte Carlo simulation for Paraguay. The mean value for the emission intensity of beef produced in grazing systems in Paraguay (including carbon losses from deforestation for pasture) is 294.2 kg CO_2-eq/kg CW (±136.3 kg CO_2-eq/kg CW), with the 95 percent certainty interval around the mean ranging from 157.8-430.6 kg CO_2-eq/kg CW. The coefficient of variation (CV) is estimated at 24 percent of the mean.

Impact of LUC uncertainty on emission intensity of beef in Paraguay. Table 22 presents the results from the propagation of uncertainty associated with land area estimates, carbon stock losses per hectare as well as the combined scenario of the two uncertainties.

The assumptions and uncertainties in total land area converted and carbon stocks and their impact on the mean were about the same magnitude. The sensitivity analysis showed that uncertainty in the total land area converted is the single largest contributor to variance, accounting for 27 percent of the variance, while uncertainty in estimates of the carbon in soil and biomass accounts for nearly 9 percent of the variance.

Figure 37.
Probability distribution for beef emission intensity in Paraguay

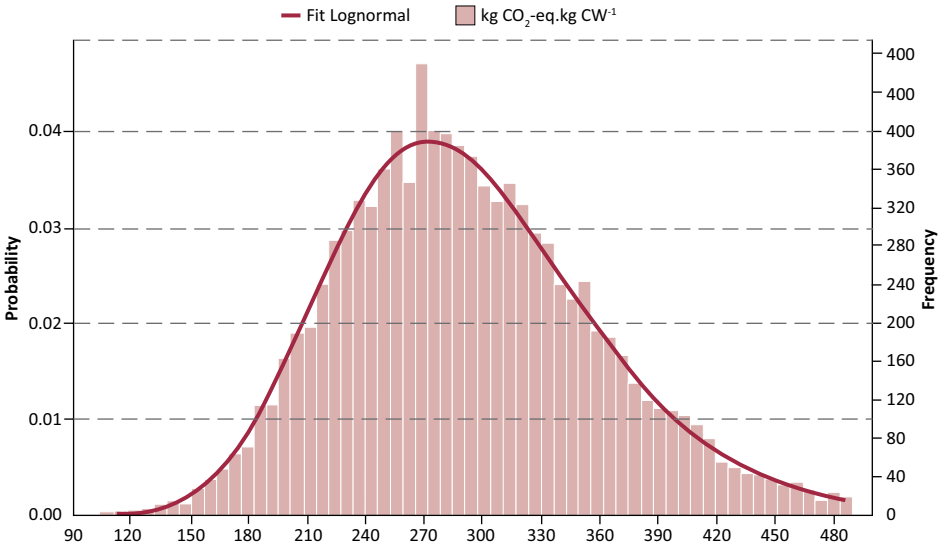

Source: Authors.

Table 22. Effects of alternative LUC uncertainty estimates on average emission intensity for beef production in Paraguay

	Emission intensity *(kg CO_2-eq/kg CW)*		
		95% probability range	
	Mean	**Low**	**High**
Land area	292.1 (22%)*	163.7	420.6
Carbon stocks	293.4 (21%)*	173.0	413.7
Baseline (combined scenario)	294.2 (24%)*	157.9	430.6

* Percentages in brackets relate to Coefficient of Variation (CV)
Source: Authors' calculations.

Analysis of sensitivity. Tables 23 and 24 illustrate the *contribution to variance* (CoV)[10] and the *RCC* for the uncertain input parameters (above a 1 percent threshold) and presents the most important factors affecting the total uncertainty measured by the absolute value of *RCC* between the parameters and the emission intensity. For milk production in mixed systems in France, three parameters contribute about 90 percent of the total variance in the emission intensity; feed digestibility is the largest contributor to variance, accounting for almost half of the total, and the uncertainty in N_2O EF3 and milk yield contributing another 22 and 20 percent of the variance, respectively. In beef production, the N_2O EF3 and feed digestibility parameters contribute 93 percent of the variance (Table 23).

[10] The contribution to variance (CoV) provides information on how much each variable contributed to the uncertainty of emission intensity relative to the contribution of other variables.

Table 23. Percent Contribution to Variance (CoV) and Rank Correlation Coefficient (RCC) in mixed dairy and beef systems in France

Parameter	Dairy		Beef	
	CoV	**RCC**	**CoV**	**RCC**
Feed digestibility	47%	-0.66	42.2%	-0.63
N_2O EF3 Pasture, ranging and paddock	22.2%	0.45	51.5%	0.69
Milk yield	20.4%	-0.43	NA	NA
Age at first calving	5.4%	0.22	NS	NS
EF for enteric fermentation	1.7%	0.12	NS	NS
EF 1 for synthetic and organic N	1.0%	0.09	2.5%	0.15
EF 4 for N volatilization	NS	NS	1.5%	0.12
EF 5 for N leaching	NS	NS	1.2%	0.1

NA: Not Applicable; NS: Not Significant.
Source: Authors' calculations.

Table 24. Percent Contribution to Variance (CoV) and Rank Correlation Coefficient (RCC) for grazing beef systems in Paraguay

Parameter	Beef	
	CoV	**RCC**
N_2O EF3 Pasture, ranging and paddock	44%	0.64
Land-use change pasture: combined scenario	34%	0.52
Feed digestibility	17%	-0.40
Age at slaughter	5%	0.21

Source: Authors' calculations.

The sensitivity analysis shows that the key parameters contributing to uncertainty for both the dairy and beef scenarios are:

- the feed digestibility variable plays a significant role in total emissions; 47 percent and 42 percent of the uncertainty in emission intensity of milk and beef is caused by the uncertainty in feed digestibility variable, respectively. Digestibility is a dominant factor in the calculations of a number of emission sources and hence its role in influencing the uncertainty in emission intensity.
- N_2O EF3 for manure deposited on pasture due to the high degree of uncertainty i.e., wide distribution (large natural variability) of possible values.
- In dairy production, milk yield has an impact on the uncertainty of milk emission intensity due to the high variability in milk production.

For Paraguay, the sensitivity analysis shows that 4 parameters: N_2O EF3 Pasture, ranging and paddock, feed digestibility and land-use change, and age at slaughter contribute 99 percent of the variance to the emission intesity of beef in Paraguay (Table 24).

The uncertainty in N_2O EF3 is the largest contributor to variance (44 percent); the rate of emissions of N_2O (per unit N applied/deposited) is perhaps the most uncertain effect in GHG emission profile. In addition to the wide distribution N_2O EF3 (the N_2O emissions factor for N deposited on pasture, range or paddock), it is assumed that 95 percent of the manure in this case is deposited directly on pasture

hence the high N_2O emissions. The uncertainty in the estimates of LUC combined scenario (carbon stock losses per hectare and in the land area estimates) account for 34 percent of the variance.

In conclusion, the uncertainty performed for the two case studies show that relatively few parameters (N_2O EF3 Pasture, ranging and paddock, feed digestibility and LUC) are responsible for most of the variance. Although the present analysis captures several important parameter uncertainties, significant model uncertainties still remain.

Point estimates from LCAs describe only an average situation and many scenarios may be equally plausible. Uncertainty analysis such as these offer the opportunity to understand and estimate the imprecision of the average result resulting from uncertainties in input data as well as deliver more meaningful results.

6. Conclusion

Globally, ruminant supply chains are estimated to produce 5.7 gigatonnes CO_2-eq *per annum* of which 81 percent, 11 percent and 8 percent is associated with cattle, buffalo and small ruminant production.

This report provides the first comprehensive and disaggregated global assessment of emissions from the ruminant sector, which enables the understanding of emission pathways and hotspots. This is a fundamental, initial step towards identification of mitigation strategies.

Average emission intensity for products from ruminants were estimated at 2.8, 3.4 and 6.5 kg CO_2-eq/kg FPCM for cow milk, buffalo and small ruminant milk, respectively, and 46.2, 53.4, and 23.8 kg CO_2-eq/kg CW for beef, buffalo and small ruminant meat, respectively. Although there is great heterogeneity among production systems, some commodities are associated with particularly high emission intensities. These emission profiles and the on-going growth in output call for the adoption of mitigation practices.

The ranges of emission intensity within supply chains suggest that there is room for improvement (Tables 7 to 9). This mitigation potential is further explored in an overview report published in parallel to this one (FAO, 2013a). It is estimated to reach 30% of the sector's global emissions. The overview report also explores regional mitigation potentials through case study analysis. When drawing any conclusions about scope for improvement, one must distinguish those production parameters that can be managed from those that are related to agro-ecological conditions and cannot be managed. This is particularly true for extensive production systems, where the environment cannot be controlled, or at prohibitive costs.

Regarding these systems, and those facing particularly harsh environments, mitigation practices should not be proposed at the cost of diminished resilience and food security. Bearing these caveats in mind, the results of this study indicate six areas of possible interventions to reduce the emission intensity from ruminant supply chains:

- Reducing LUCs arising from pasture expansion and feed crop cultivation;
- Improving feeding practices and digestibility of diets;
- Improving grazing and pasture management to increase soil organic carbon (SOC) stocks;
- Increasing yields, e.g. through genetics, feeding and animal health;
- Improving manure management – reducing the use of uncovered liquid MMS, particularly in dairy systems; and
- Increasing energy use efficiency, especially in postfarm part of the supply chain.

Comparison of this study with others shows that methods matter. Discrepancies in results are well explained by different system boundaries, allocation methods and computation of emissions, especially with regard to LUC, enteric CH_4 and feed N_2O. The many different methods that are being used to measure and assess the emissions of animal rearing make it difficult to compare results and set priori-

ties for the continuous improvement of environmental performance along supply chains. This calls for an effort to harmonize approaches and data used in this kind of analysis.

This report presents an update and refinement of the previous assessment in *Livestock's long shadow* (FAO, 2006). It should be understood as one step in a series of assessments, to measure and guide progress in the sector's environmental performance.

Numerous hypothesis and methodological choices were made, introducing a degree of uncertainty in the results. Furthermore, data gaps forced the research team to rely on generalizations and projections. A partial sensitivity analysis was conducted in order to illustrate the effect of these approximations. Results were tested for methodological choices regarding land-use change emissions and input data uncertainty. This partial analysis showed that the emission intensity at 95% confidence interval is ±50%

Priorities for refinement of GLEAM include:

- Information about the feed rations, particularly the amount of roughage, by-products and concentrates in the ration;
- Information on manure management;
- Methods for allocation of emissions, especially for slaughter by-products;
- Quantification of the emissions associated with land use and LUC;
- Quantification of feed N_2O that better reflect where and how manure N is applied to crops.

Methodological developments are been carried out by private and public sector organizations to improve the accuracy and comparability of results over time. LEAP – the Partnership on Livestock Environmental Assessment and Performance[11] will be instrumental to these developments; this multi-stakeholder initiative is facilitated by FAO and involves government representatives, private sector organizations and civil society in an effort to harmonize indicators and methods for the assessment of environmental performance in the livestock sector.

Although estimating GHG emissions from the sector provides an important starting point for understanding the sector's potential for mitigating emissions, identifying approaches to reduce emissions requires complementary analysis.

First, the private and public costs of mitigation, as well as the social dimensions associated with technology changes and the impact of mitigation efforts on food consumption trends, should be understood in order to identify viable and acceptable options. Several groups are addressing these questions, including FAO. There is also a need to broaden the scope of environmental performance assessment beyond GHG emissions, in order to avoid undesired policy outcomes. GLEAM will progressively be adapted to compute a wider set of metrics that enable several environmental parameters to be quantified. The model provides a consistent and transparent analytical framework within which to explore proposed mitigation methods, thereby providing an empirical basis for policy-making.

[11] http://www.fao.org/ag/againfo/livestock-benchmarking/en/

References

Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T.A. & McGinn, S.M. 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. *Agricultural Systems*, 103: 41–50.

Biswas, W.K., Graham, J., Kelly, K. & John, M.B. 2010. Global warming contributions from wheat, sheep meat and wool production in Victoria, Australia – A life cycle assessment. *Journal of Cleaner Production*, 18(14): 1386–1392.

BSI. 2008. PAS 2050:2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution. London.

BSI. 2012. PAS 2050-1:2012. Assessment of life cycle greenhouse gas emissions from horticultural products Supplementary requirements for the cradle to gate stages of GHG assessments of horticultural products undertaken in accordance with PAS 2050. British Standards Institution. London.

Capper, J., Cady, R.A. & Bauman, E.D. 2008. The relationship between cow production and environmental impact.

Casey, J.W. & Holden, N.M. 2006. Quantification of GHG emissions from suckler-beef production in Ireland. *Agricultural Systems*, 90: 79-98.

Castillo, A.R., Kebreab, E., Beever, D.E. & France, J. 2000. A review of efficiency of nitrogen utilization in dairy cows and its relationship with environmental pollution. *J. Anim. Feed Sci.* 9: 32.

Cederberg, C. & Flysjö, A. 2004. Environmental assessment of future pig farming systems - quantifications of three scenarios from the FOOD 21 synthesis work. *The Swedish Institute for Food and Biotechnology,* SIK Report No. 723: 1–54.

Cederberg, C. & Stadig, M. 2003. System expansion and allocation in life cycle assessment of milk and beef production. *Int. J. Life. Cycle Assess.*, 8(6): 350–356.

Cederberg, C., Meyer, D. & Flysjö, A. 2009. *Life cycle inventory of greenhouse gas emissions and use of land and energy in Brazilian beef production*. SIK Report No. 792.

de Vries, M. & de Boer, I.J.M. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science,* 128: 1-11.

Del Prado, A. & Scholefield, D. 2008. Use of SIMSDAIRY modelling framework system to compare the scope on the sustainability of a dairy farm of animal and plant genetic-based improvements with management-based changes. *Journal of Agricultural Science*, 146: 195-211.

Eckard, R.J., Chapman, D.F. & White, R.E. 2007. Nitrogen balances in temperate perennial grass and clover dairy pastures in south-eastern Australia. *Aust. J. Agric. Res*., 58: 1167–1173.

Ecoinvent. 2009. Swiss Centre for Life Cycle Inventories database. Available at http://www.ecoinvent.ch/

Edward-Jones, G., Plassmann, K. & Harris, I.M. 2009. Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK. *Journal of Agricultural Science*, 147: 707-719.

FAO. 1996. *World livestock production systems: current status, issues and trends*, by Seré, C. & Steinfeld, H. FAO Animal Production and Health Paper 127. FAO. Rome.

FAO. 2006. *Livestock's long shadow – Environmental issues and options,* by Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. & de Haan, C. FAO. Rome.

FAO. 2007. *Gridded livestock of the world 2007*, by Wint, W. & Robinson, T. FAO. Rome.

FAO. 2010. *Greenhouse gas emissions from the dairy sector – A life cycle assessment,* by Gerber, P., Opio, C., Vellinga, T., Herderson, B. & Steinfeld, H. FAO. Rome.

FAO. 2013a. *Tackling climate change through livestock*, by Gerber, P., Steinfeld, H., Henderson, B., Opio, C., Mottet, A., Dijkman, J., Falcucci, A. & Tempio, G. FAO. Rome.

FAO. 2013b. *Greenhouse gas emissions from pig and chicken supply chains – A life cycle assessment*, by MacLeod, M., Gerber, P., Mottet, A., Tempio, G., Falcucci, A., Opio, C., Henderson, B. & Steinfeld H. FAO. Rome.

FAOSTAT. 2009. FAO Statistical Database. Accessed 2009.

FAOSTAT. 2011. FAO Statistical Database. Accessed 2011.

FAOSTAT. 2012. FAO Statistical Database. Accessed 2012.

Ferreira, N., Cattoni, C.J., Caceres, S.C. & Frutos, J. 2007. An economic opportunity survey of small dairy farms in Paraguay. *Trop. Anim. Health Prod.*, 39: 603-610.

Flysjö, A., Cederberg, C. & Strid, I. 2008. LCA-databas för konventionella fodermedel - miljöpåverkan i samband med production. *SIK rapport No. 772*, Version 1.1.

Foley, P.A., Crosson, P., Lovett, D.K., Boland, T.M., O'Mara, F.P. & Kenny, D.A. 2011. Whole-farm systems modeling of greenhouse gas emissions from pastoral suckler beef cow production systems. *Agriculture, Ecosystems & Environment,* 142: 222-230.

Fréchou, R.V. 2002. Las actividades percuarias en el MERCOSUR.

Gerber, P., Vellinga, T., Opio, C. & Steinfeld, H. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science*, 139(1-2): 100–108.

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht W. & Fischer-Kowalski M. 2007. Quantifying and mapping the global human appropriation of net primary production in Earth's terrestrial ecosystem. *Proceedings of the National Academy of Sciences of the USA* 104: 12942-12947.

Houghton, R.A. & Goodale, C.L. 2004. Effects of LUC on the carbon balance of terrestrial ecosystems. *In* DeFries, R.S., Asner, G.P. & R.A. Houghton, eds. *Ecosystems and Land-use change*. Washington, D.C., American Geophysical Union.

IEA. 2009. International Energy Agency – Statistical database. http://www.iea.org.

Institut de l'Élevage. 2011. Institut de l'Élevage, France. http://www.inst-elevage.asso.fr/

IPCC. 2000. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., Enmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., Meijer, J., Miwa, K. and Tanabe, K. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA/IGES, Hayama, Japan.

IPCC. 2003. Good Practice Guidance for Land Use, land-Use Change and Forestry. Penman, J., Gytarsky, M., Hiraishi, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/IGES, Hayama, Japan.

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories prepared by the National Greenhause Gas Inventories Programme,* Eggleston, H.S., Buenida, L., Miwa, K., Nagara, T. & Tanabe, K. (eds). Published: IGES, Japan.

IPCC. 2007. *Climate change 2007: IPCC Fourth Assessment Report*. Cambridge University Press, UK.

ISO. 2006. *Environmental management – Life Cycle Assessment – Requirements and guidelines*. ISO 14044. Geneva.

Kanyarushoki, C., van der Werf, M.G.H. & Fuchs, F. 2010. Life cycle assessment of cow and goat milk chains in France. *Proceedings of LCA Food 2010*. Bari, Italy.

Ledgard, S.F., Lieffering, M., Coup, D. & O'Briens, B. 2011. Carbon footprinting of New Zealand lamb from the perspective of an exporting nation. *Animal Frontiers*, 1(1): 40–45.

Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S. & Biala, K. 2010. *Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS) - Final Report*, European Commission, Joint Research Centre.

Nguyen, T.L.T., Hermansen, J.E. & Mogensen, L. 2010. Environmental consequences of different beef production systems in the EU. *J. Clean. Prod*. 18: 756-766.

Oenema, O., Wrage, N., Velthof, G. L., van Groenigen, J. W., Dolfing, J. & Kuikman, P. J. 2005. Trends in global nitrous oxide emissions from animal production systems. *Nutrient Cycling in Agroecosystems,* 72(1): 51-65.

Ogino, A., Orito, H., Shimada, K. & Hirooka, H. 2007. Evaluating environmental impacts of the Japanese beef cow-calf system by the life cycle assessment method. *Animal Science Journal,* 78: 424–432.

Ominski, K.H., Boadi, D.A., Wittenberg, K.M., Fulawka, D.L. & Basarab, J.A. 2003. Estimates of enteric methane emissions from cattle in Canada using the IPCC Tier-2 methodology.

Pelletier, N., Pirog, R. & Rasmusssen, R. 2010. Comparative life cycle environmental impacts of three beef production strategies in the upper Midwestern United States. *Agricultural Systems*, 103: 41–50.

Perera, B.M.A.O. 2011. Reproductive cycles of buffalo. *Anim Reprod Sci*, 124(3-4): 194-99.

Peters, G.M., Rowley, H.V, Wiedemann, S., Tucker, R., Short, M.D. & Schulz, M. 2010. Red meat production in Australia: Life cycle assessment and comparison with overseas studies. *Environ. Sci. Technol.*, 44(4): 1327–1332.

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A. & Houghton, R. A. 2006. Challenges to estimating carbon emissions from tropical deforestation. *Global Change Biol*., 13: 51–66, 2007.

Ripoli-Bosch, R., de Boer, I.J.M., Bernues, A. & Vellinga, T. 2010. Greenhouse gas emissions throughout the life cycle of Spanish lamb-meat: a comparison of three production systems. In: *Economic, social and environmental sustainability in sheep and goat production systems*. 7th International Seminar of the FAO-CIHEAM Network on Sheep and Goats, Sub- Network on Production Systems, Zaragoza, Spain.

Schils, R.L.M., de Haan, M.H.A., Hemmer, J.G.A., van den Pol-van Dasselaar, A., de Boer, J.A., Evers, A.G., Holshof, G., van Middelkoop, J.C. & Zom, R.L.G. 2007. DairyWise, a whole-farm dairy model. *J. Dairy Sc.,* 90: 5334–5346.

Thomassen, M. A., Dalgaard, R., Heijungs, R. & de Boer, I. 2008. Attributional and consequential LCA of milk production. *International Journal of Life Cycle Assessment*, 13(4): 339–349.

UNFCCC. 2009a. 2009 Annex I Party GHG Inventory Submissions. from http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4771.php.

UNFCCC. 2009b. Non-Annex I National Communications. from http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php.

Verge, X.P.C., Dyers, J.A., Desjardins, R.L. & Worth, D. 2008. Greenhouse gas emissions from the Canadian beef industry. *Agricultural Systems*, 98(2): 126–134.

Weiss, F. & Liep, A. 2012. Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model. *Agriculture, Ecosystems & Environment*, 149: 124–134.

Williams, A., Audsley, E. & Sandars, D.L. 2006. *Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities.* DEFRA project report IS0205. Department for Environment, Food and Rural Affairs. London.

Wood, S. & Cowie, A. 2004. *A review of greenhouse gas emission factors for fertiliser production.* Research and Development Division, State Forests of New South Wales. Cooperative Research Centre for Greenhouse Accounting for IEA Bioenergy Task 38.

Yamaji, K., Ohara, T. & Akimoto, H. 2003. A country-specific, high resolution emission inventory for methane from livestock in Asia in 2000. *Atmospheric Environment*, 37: 4393–4406.

You, L., Crespo, S., Guo, Z. Koo, J., Ojo, W., Sebastian, K., Tenorio, T.N., Wood, S. & Wood-Sichra, U. 2010. Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2. Available at http://MapSPAM.info

Zervas, G. & Tsiplakou, E. 2012. An assessment of GHG emissions from small ruminants in comparison with GHG emissions from large ruminants and monogastric livestock. *Atmospheric Environment*, 49: 13–23.

Zhou, J.B., Jiang, M.M., & Chen, G.Q. 2007. Estimation of methane and nitrous oxide emission from livestock and poultry in China during 1949–2003. *Energy Policy,* 35: 3759–3767

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APPENDIX A

The Global livestock environmental assessment model (GLEAM)

1. INTRODUCTION

The Global Livestock Environmental Assessment Model (GLEAM) is a process-based static model that simulates the functioning of livestock production systems. The current version of the model (V1.0) focuses primarily on the quantification of GHG emissions, but future versions will include other processes and flows for the assessment of other environmental impacts, such as those related to water, nutrient and land use.

The model differentiates the 11 main livestock commodities, which are: meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens. It calculates the GHG emissions and production for a given production system within a defined spatial area, thereby enabling the calculation of the emission intensity for combinations of commodities, farming systems and locations.

The main purpose of this appendix is to explain the way in which GLEAM calculates the emission intensity of livestock products. The input data used in GLEAM (and associated issues of data quality and management) are addressed in Appendix B. The focus of this appendix is on:

- providing an overview of the main stages of the calculations;
- outlining the formulae used; and
- explaining some of the key assumptions and methodological choices made.

2. MODEL OVERVIEW

The model is GIS-based and consists of:

- input data layers;
- routines written in Python (http://www.python.org/) that calculate intermediate and output parameters; and
- procedures for running the model, checking calculations and extracting output.

The basic spatial unit used in the GIS is a cell of 3 arc minutes. The emissions and production are calculated for each cell using input data of varying levels of spatial resolution (see Appendix B). The overall structure of GLEAM is shown in Figure A1, and the purpose of each module summarized below.

- The **herd module** starts with the total number of animals of a given species and system within a cell (see Appendix B for a brief description of the way in which the total animal numbers are determined). The module also determines the herd structure (i.e. the number of animals in each cohort group, and the rate at which animals move between cohort groups) and the characteristics of the average animal in each cohort (e.g. weight and growth rate).
- The **manure module** calculates the rate at which excreted N is applied to pasture and crops.

- The **feed module** calculates key feed parameters, i.e. the nutritional content and emissions per kg of the feed ration.
- The **system module** calculates each animal's energy requirement, and the total amount of animal product (milk, meat and fibre) produced in the cell each year. It also calculates the total annual emissions arising from manure management, enteric fermentation and feed production.
- The **allocation** module combines the emissions from the system module with the emissions calculated outside GLEAM, i.e. emissions arising from (a) direct on-farm energy use; (b) the construction of farm buildings and manufacture of equipment; and (c) post-farm transport and processing. The total emissions are then allocated to output in the form of products and services (milk, meat and eggs, fibre and draught power) and the emission intensity per unit of commodity calculated. Each of the stages in the model is described in more detail below.

3 HERD MODULE

The functions of the herd module are to:

- Determinate the herd structure, i.e. the proportion of animals in each cohort, and the rate at which animals move between cohorts; and
- Calculate the characteristics of the animals in each cohort, i.e. the average weight and growth rate of adult females and adult males.

Emissions from livestock vary depending on animal type, weight, phase of production (e.g. whether lactating or pregnant) and feeding situation. Accounting for these variations in a population is important if emissions are to be accurately characterized. The use of the IPCC (2006) Tier 2 methodology requires the animal population to be categorized into distinct cohorts. Data on animal herd structure are generally not available at the national level. Consequently, a specific herd module was developed to decompose the herd into cohorts. The herd module characterizes the livestock population by cohort, defining the herd structure, dynamics and production.

Herd structure. The national herd is disaggregated into six cohorts of distinct animal classes: adult female and adult male, replacement female and replacement male, and male and female surplus or fattening animals which are not required for maintaining the herd. Figure A2 provides an example of a herd structure (in this case for cattle). In this assessment it is assumed that all surplus calves are fattened for meat.[12]

The key production parameters required for herd modeling include data on *mortality, fertility, growth and replacement rates,* also known as "rate parameters". In addition, other parameters are used to define the herd structure. They include:

- the age or weight at which animals transfer between categories e.g. the age at first parturition for replacement females or the weight at slaughter for fattening animals;
- duration of key periods i.e. gestation, lactation, time between servicing; and
- the ratio of breeding females to males.

[12] In some intensive dairy systems, surplus calves may be slaughtered within a few days after birth.

Figure A1.
Schematic representation of GLEAM

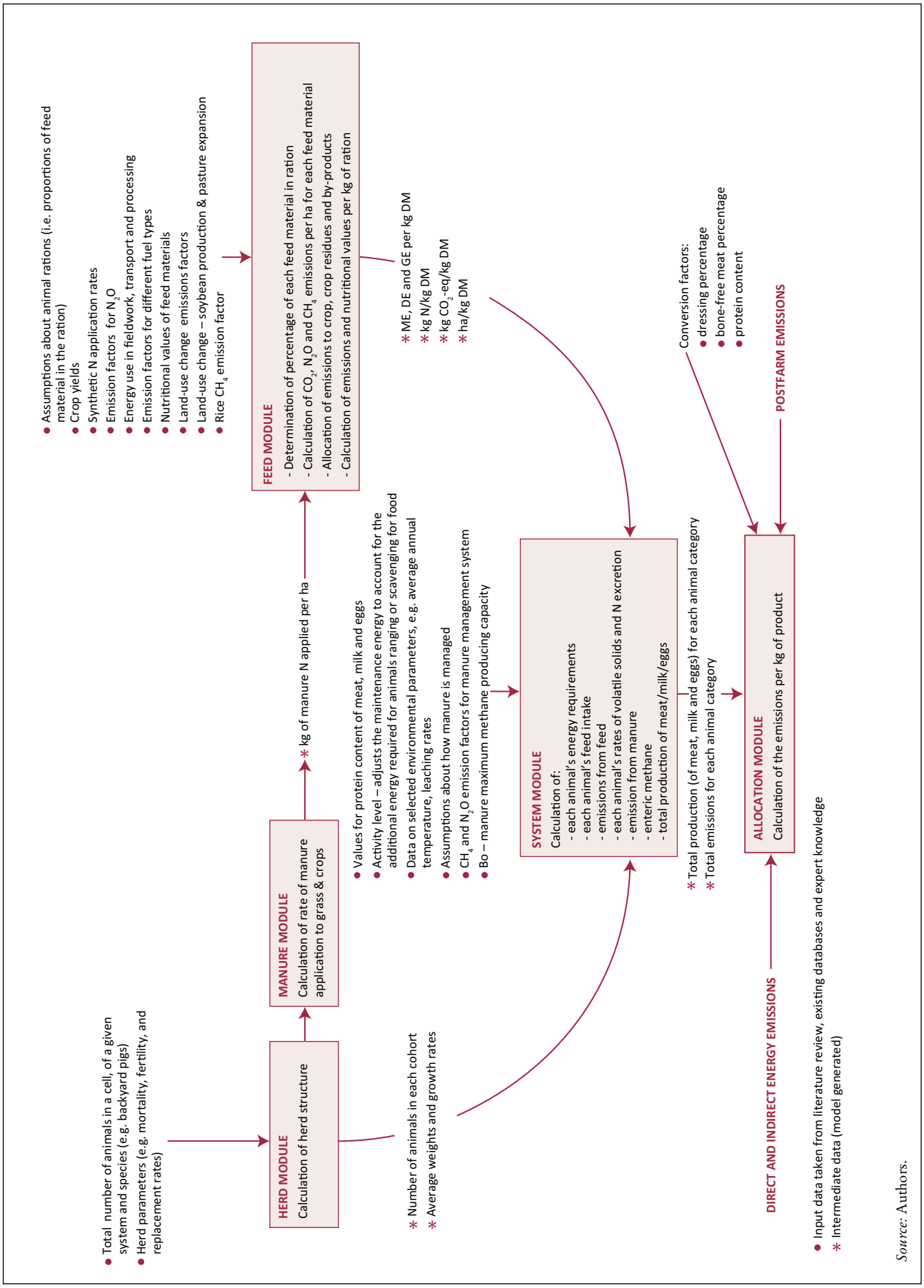

Source: Authors.

Figure A2.
Structure of herd dynamics for cattle

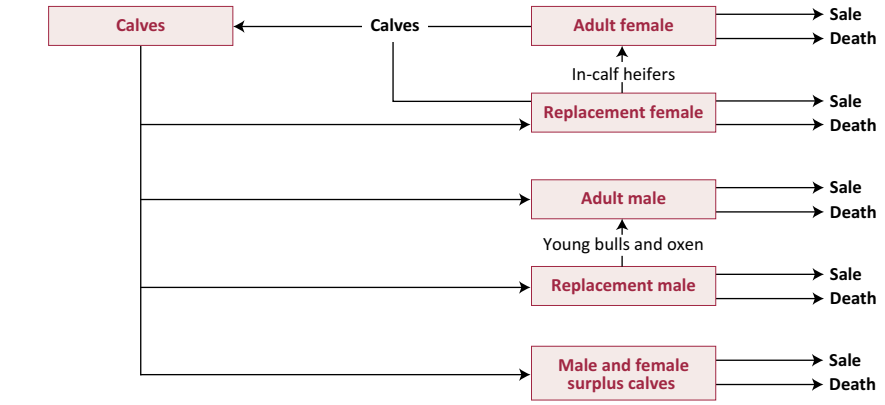

Source: Authors.

4. MANURE MODULE

The function of the manure module is to calculate the rate at which excreted N is applied to feed crops.

The manure module calculates the amount of manure N collected and applied to grass and cropland in each cell by:

- calculating the amount of N excreted in each cell by multiplying the number of each animal type in the cell by the average N excretion rates;
- calculating the proportion of the excreted N that is lost during manure management and subtracting it from the total N, to arrive at the net N available for application to land; and
- dividing the net N by the area of (arable and grass) land in the cell to determine the rate of N application per ha.

5. FEED MODULE

The functions of the feed module are to:

- Calculate the composition of the ration for each species, system and location;
- Calculate the nutritional values of the ration per kg of feed DM; and
- Calculate of GHG emissions and land use per kg of DM of ration.

The feed module determines the diet of the animal, i.e. the percentage of each feed material in the ration, and calculates the emissions (N_2O, CO_2 and CH_4) arising from the production, processing and transport of the feed. It allocates the emissions to crop co-products such as crop residues or meals) and calculates the emission intensity per kg of feed. It also calculates the nutritional value of the ration, in terms of its energy and N content.

5.1 Determination of the ration

Animal rations are generally a combination of different feed ingredients. For ruminants, three broad categories of feed are considered: roughages, by-products and concentrates. Typically, major feed ingredients include:

- Grass: ranges from natural pasture and roadsides to improved and cultivated grasslands and leys.
- Feed crops: crops specially grown to feed livestock, e.g. maize silage or grains.
- Tree leaves: browsed in forests or collected and carried to livestock.
- Crop residues: plant material left over from food or other crops, such as straw or stover, left over after harvesting.
- Agro-industrial by-products and wastes: by-products from the processing of non-feed crops such as oilseeds, cereals, sugarcane, and fruit. Examples include cottonseed cakes, rapeseed cakes and brans.
- Concentrates: high quality mixtures of by-products and feed that are processed at specialized feed mills into compound feed.

In all livestock production systems, the composition of the feed ration depends on the availability of pasture and fodder, the crops grown and their respective yields. The fraction of concentrates in the ration varies widely, according to the need to complement locally available feed, the purchasing power of farmers, and access to markets. While actual diets will vary depending on what crops are grown locally and the price of feed crops, the balance of forage, crops and by-products must be reasonable in order to match animal performance. The proportion of each feed component is determined differently for industrialized and developing country regions:

- for the industrialized regions, the composition (i.e. feed materials) and relative portions of the feed ration materials are taken from country national inventory reports, literature and targeted surveys.
- for developing countries, due to scanty information, a feed allocation scheme was devised based on literature and expert knowledge. This allocation scheme assumes that in developing regions there is a close relationship between land use and the feed ration.

Feed allocation scheme for developing countries. The feed allocation scheme is based on the availability of feed resources (crops and forage) and animal requirements. The determination of the feed ration is outlined stepwise below:

1. Define the proportion of by-products and concentrates in the ration (based on surveys, literature and expert knowledge) and the difference is considered roughages.
2. Calculate the total roughage availability in each pixel based on the dry matter yields per hectare of pasture, fodder and crop residues and the land area of the respective feeds. Data for this calculation was obtained from a number of sources: FAOSTAT for specific crops (e.g. fodder beet, soybean, rapeseed, cottonseed, sugar beet and palm fruit); You *et al.* (2010) from the Spatial Production Allocation Model (SPAM) for 20 crops; and Haberl *et al.* (2007) to estimate the above-ground net primary productivity for pasture.
3. Feed requirements for all ruminant species were then assessed. This was done by expressing the different ruminant species and categories of animals in cattle equivalent, to take into account the fact that these animals are competing for the same feed resource.
4. To assess the feed availability, a ratio between the total roughage availability (calculated in 2 above) and ruminant species biomass (in cow equivalent calculated in 3 above) was obtained.

5. Total ruminant annual feed requirements are then calculated for the total cow equivalent based on the assumption that an animal consumes about 2 to 3 percent of its bodyweight on a daily basis and hence, on an annual basis, DMI will range between 7.3 and 14 kg DM.
6. The total amount of roughage feed available is then compared with the animal feed requirements within each cell. Comparing the total feed availability with the animal requirements provides an indication of feed adequacy in terms of sufficiency, deficiency or surplus for any given location. An area can be classified based on the dry matter availability and generally a dry matter availability of less than 2 percent of the bodyweight can be considered as a deficit, dry matter availability between 2 and 3 percent can be considered as adequate, and above 3 percent can be considered as surplus. In situations where ample feed is not available to meet the requirements of the animals (i.e. less than 2 percent), the feed ration is supplemented with leaves and hay.
7. The proportion of each roughage material within the feed ration is then obtained by dividing the quantity available of each roughage material by the total available roughage.
8. The proportions of the roughage materials (calculated in 7 above) plus the by-products and concentrate proportions (defined in 1 above) form the total feed ration which sums to 100.

Tables B7 to B12 in Appendix B present the average feed rations and the proportions of the different feed materials within the feed ration for the world's main regions and species.

5.2 Determination of the ration's nutritional values

Nutritional values such as the digestibility and N-content of each individual feed material are used to calculate the nutritional value of animal feed rations. These nutritional values are multiplied by the percentage of each feed material in the ration to arrive at the average energy and N content per kg of DM for the ration as a whole. Table B13 in Appendix B compares regional variation in digestibility of feed rations for ruminant species.

5.3 Determination of the ration's GHG emissions and land use per kg of DM from feed

The categories of GHG emission included in the assessment of each feed material's emissions are:

- direct and indirect N_2O from grass and crop cultivation;
- CO_2 arising from loss of above and below ground carbon brought by land-use change;
- CO_2 from the on-farm energy use associated with field operations (tillage, manure application, etc.) and crop drying and storage;
- CO_2 arising from the manufacture of fertilizer;
- CO_2 arising from crop transport; and
- CO_2 arising from off-farm crop processing.

A brief outline of how the emissions were calculated is provided below.

Determination of feed emissions: N_2O from pasture and crop cultivation. Nitrous oxide emissions from cropping include direct N_2O, and indirect N_2O from leach-

ing and volatilization of ammonia. It was calculated using the IPCC (2006) Tier 1 methodology. Synthetic N application rates were defined for each crop at a national level, based on existing data sets (primarily FAO's fertilizer use statistics, http://www.fao.org/ag/agp/fertistat/index_en.htm) and adjusted down where yields were below certain thresholds. Manure N application rates were calculated in the manure module. Crop residue N was calculated using the crop yields and the IPCC (2006, Volume 4, Chapter 11, p. 11.17) crop residue formulae.

Determination of pasture and crop emissions: CO_2 from land-use change. The approach for estimating emissions from land-use change is presented in Appendix C.

Determination of feed emissions: CO_2 from fertilizer manufacture. The manufacture of synthetic fertilizer is an energy-intensive process, which can produce significant amounts of GHG emissions, primarily via the use of fossil fuels, or through electricity generated using fossil fuels. The emissions per kg of fertilizer N will vary depending on the factors such as the type of fertilizer, the efficiency of the production process, the way in which the electricity is generated, and the distance the fertilizer is transported. Due to the lack of reliable data on these parameters, and on fertilizer trade flow, the average European fertilizer emissions factor of 6.8 kg CO_2-eq per kg of ammonium nitrate N in all regions was used (Jenssen and Kongshaug, 2003), which includes N_2O emissions arising during manufacture.

Determination of feed emissions: CO_2 from field operations. Energy is used on-farm for a variety of field operations required for crop cultivation, such as tillage, preparation of the seed bed, sowing and application of synthetic and organic fertilizers, crop protection and harvesting. The type and amount of energy required per ha, or kg, of each feed material parent crop was estimated. In some countries, field operations are undertaken using non-mechanized power sources, i.e. human or animal labour. The energy consumption rates were adjusted to reflect the proportion of the field operations undertaken using non-mechanized power sources. Table A1 gives an indication of the average level of mechanization per region. From the level of mechanization, we also inferred reliance on animal draught power in the country, and therefore the bull to cow ratio in the herd. The emissions arising from fieldwork per ha of each crop were calculated by multiplying the amount of each energy type consumed per ha, by the emissions factor for that energy source.

Table A1. Estimated average level of mechanization by region

Continent	Estimated rate of mechanisation *(percentage)*
Africa	16
Asia	78
Central and South America	96
Europe	100
North America	100
Oceania	100

Source: FAOSTAT (2009).

Determination of feed emissions: CO_2 from transport and processing. Pasture and crop residues, by definition, are transported minimal distances and are allocated zero emissions for transport. Non-local feeds are assumed to be transported between 100 km and 700 km by road to their place of processing. In countries where more of the feed is consumed than is produced (i.e. net importers), feed that are known to be transported globally (e.g. soybean meal) also receive emissions that reflect typical sea transport distances. Emissions from processing arise from the energy consumed in activities such as milling, crushing and heating, which are used to process whole crop materials into specific products. Therefore, this category of emissions applies primarily to feeds in the by-product category.

Determination of feed emissions: CO_2 from blending and transport of compound feed. Energy is used in feed mills for blending non-local feed materials to produce compound feed and to transport it to its point of sale. It was assumed that 186 MJ of electricity and 188 MJ of gas were required to blend 1 000 kg of DM, and that the average transport distance was 200 km.

5.4 Allocation of emissions between crop and its by-products

In order to calculate the emission intensity of the feed materials, emissions need to be allocated between the crop and its by-products, i.e. the crop residue or by-products of crop processing used as feed. The general expression used is:

$$GHGkgDM = GHGha/(DMYGcrop \cdot FUEcrop + DMYGby \cdot FUEby) \cdot EFA/MFA$$

where:

GHGkgDM	=	emissions (of CO_2, N_2O, or CH_4) per kg of dry matter
GHGha	=	emissions per ha
DMYGcrop	=	gross crop yield (kgDM/ha)
DMYGby	=	gross crop residue or by-product yield (kgDM/ha)
FUEcrop	=	feed use efficiency, i.e. fraction of crop gross yield harvested
FUEby	=	feed use efficiency, i.e. fraction of crop residue or by-product gross yield harvested
EFA	=	economic fraction, crop or co-product value as a fraction of the total value (of the crop and co-product)
MFA	=	mass fraction, crop or co-product mass as a fraction of the total mass (of the crop and co-product)

Dry matter yields and estimated harvest fractions were used to determine the mass fractions. Where crop residues were not used for feed or bedding, they were assumed to have a value of zero, i.e. 100 percent of the emissions were allocated to the crop.

Allocation techniques of feed emissions is summarized in Table A2. Emissions from post-processing blending and transport are allocated entirely to feed. It should be highlighted that emissions that are not allocated to feed do not cease to exist. Rather, they are allocated to other commodities. Failure to follow this approach may lead to incorrect policy conclusions.

Table A2. Summary of the allocation techniques used in the calculation of plant-based feed emissions

Products	Source of emissions	Allocation technique
All feed crops and their by-products	N_2O from manure application N_2O from synthetic fertilizer CO_2 from fertilizer manufacture CO_2 from fieldwork	Allocation between the crop and co-product is based on the mass harvested, and the relative economic values (using digestibility as a proxy)
By-products only	CO_2 from processing CO_2 from LUC (for soybean)	Allocated to the processing by-products based on mass and economic value
Feed produced off-farm	CO_2 from transportation and blending	100 percent to feed material

Source: Authors.

6. SYSTEM MODULE

The functions of the system module are to:

- Calculate the average energy requirement (MJ) and feed intake (kg DM) of each animal cohort;
- Calculate the total feed emissions and land use arising from the production, processing and transport of the feed;
- Calculate the CH_4 and emissions arising during the management of manure;
- Calculate enteric CH_4 emissions.

6.1 Calculation of animal energy requirement

The system module calculates the energy requirements of each animal, which is then used to determine the feed intake (in kg of DM). The model uses the IPCC Tier 2 algorithms (IPCC, 2006 Volume 4, Chapter 10, Equations 10.3 to 10.13) to calculate energy requirements for each animal sub-category. The gross energy requirement is the sum of the requirements for maintenance, lactation and pregnancy, animal activity, weight gain and production.[13] The method estimates a maintenance requirement (as a function of live-weight and energy expended in feeding); a production energy requirement influenced by the level of productivity (e.g. milk yield, live-weight gain, wool production); physiological state (pregnancy and lactation); and the stage of maturity of the animal. Based on production and management practices, the net energy and feed requirements of all animals are first calculated, taking into account the following parameters:

- *Weight*. Larger animals need more energy for maintenance than smaller ones.
- *Production*. The output from animals can be milk and meat, but also non-edible products and services. Data on production of edible and non-edible products is taken from literature and statistical databases. In general terms, a higher production or more labour per day requires more energy and thus more feed per day.

[13] Total production is computed on the basis of herd parameters (reproduction, mortality, etc.) and productivity parameters (such as milk yield and weight gain) used in the analysis. Consequently, total production may not be consistent with total production in the FAOSTAT database.

- *Production/feeding environment (Grazing or stall feeding).* Animals in ranging systems that have to search for their feed (often over long distances) have higher energy requirements than those in grazing systems or stall-fed systems.

6.2 Calculating feed intake, total feed emissions and land use

The feed intake of each animal category (in kg DM/day) is calculated by dividing the animal's energy requirement by the average energy content of the ration from the feed module:

Feed intake (kgDM/animal/day) = total energy requirements (MJ/animal/day)/feed energy content (MJ/kgDM)

where: feed energy content = 18.45 (MJ/kgDM)

The feed intake of each cohort is multiplied by the number of animals in each group to obtain the total daily feed intake for the entire herd. The feed emissions and land use associated with the feed production are then calculated by multiplying the total feed intake for the herd by the emissions or land use per kg of DM taken from the feed module.

6.3 Calculation of CH_4 emissions arising enteric fermentation

Emissions from enteric fermentation (kg CH_4/head) are a function of feed digestibility (DE), i.e. the percentage of gross energy intake that is metabolized. An enteric methane conversion factor, Y_m (percentage of gross energy converted to methane) is used to calculate the methane emissions from enteric fermentation. A Tier 2 approach is applied for the calculation of enteric CH_4 emissions due to the sensitivity of emissions to diet composition and the relative importance of enteric CH_4 to the overall GHG emissions profile in ruminant production. The IPCC (2006) defines the CH_4 conversion factor (Y_m) as 6.5±1 percent, indicating that Y_m is at the high end of the range when digestibility of feed is low and vice versa. The Y_m value of 6.5 is realized at a digestibility of 65 percent. To better reflect the wide-ranging diet quality and feeding characteristics globally, this assessment developed specific Y_m values based on the following formula:

$$Y_{m\ Cattle} = 9.75 - 0.05 \cdot DE$$
$$Y_{m\ mature\ sheep} = 9.75 - 0.05 \cdot DE$$
$$Y_{m\ lamb<1\ year} = 9.75 - 0.05 \cdot DE$$

Y_m is subsequently used in the following formula to estimate the CH_4 emission factor

$$EFCH_4 = (365 \cdot GE \cdot (Y_m / 100) / 55.65)$$

where: $EFCH_4$ is the CH_4 emission factor (kg CH_4 head $^{-1}$ yr $^{-1}$); Y_m corresponds to CH_4 conversion factor; GE is the gross energy intake (MJ head^{-1} day^{-1}) and the factor 55.65 (MJ kg CH_4) represents the energy content of CH_4.

6.4 Calculation of CH_4 emissions arising during manure management

Calculating the CH_4 per head from manure using a Tier 2 approach requires (a) estimation of the rate of excretion of volatile solids per animal, and (b) estimation of the proportion of the volatile solids that are converted to CH_4. The volatile solids excretion rates are calculated using Equation 10.24 from IPCC (2006). Once the volatile solids excretion rate is known, the proportion of the volatile solids converted to CH_4 during manure management per animal per year can be calculated using Equation 10.23 from IPCC (2006).

The CH_4 conversion factor depends on how the manure is managed. In this study, the manure management categories and emission factors in IPCC (2006, Volume 4, Chapter 10, Table 10A-7) were used. The proportion of manure managed in each system is based on official statistics (such as the Annex I countries' National Inventory Reports to the UNFCCC), other literature sources and expert judgement.

6.5 Calculation of N_2O emissions arising during manure management

Calculating the N_2O per head from manure using a Tier 2 approach requires (a) estimation of the rate of N excretion per animal, and (b) estimation of the proportion of the excreted N that is converted to N_2O.

The N excretion rates are calculated using Equation 10.31 from IPCC (2006) as the difference between intake and retention. N-intake depends on the feed dry matter intake and the N content per kg of feed. The feed dry matter intake depends, in turn, on the animal's energy requirement (which is calculated in the system module, and varies depending on weight, growth rate, milk yield, pregnancy, weight gain and lactation rate and level of activity) and the feed energy content (calculated in the feed module). N retention is the amount of N retained in, either as growth, pregnancy live weight gain or milk.

The rate of conversion of excreted N to N_2O depends on the extent to which the conditions required for nitrification, denitrification, leaching and volatilization are present during manure management. The IPCC (2006) default emission factors for direct N_2O (IPCC, 2006 Volume 4, Chapter 10, Table 10.21) and indirect via volatilization (IPCC, 2006 Volume 4, Chapter 10, Table 10.22) are used in this study, along with variable leaching rates, depending on the AEZ.

7. ALLOCATION MODULE

The functions of allocation module are to:

- Sum up the total emissions for each animal cohort;
- Calculate the amount of each commodity (meat, milk, eggs, wool) produced;
- Allocate emissions to each commodity (meat and meat), non-edible outputs (fibre and manure used for fuel), draught and services; and
- Calculate total emissions and emission intensity of each commodity.

7.1 Calculation of the total emissions for each animal cohort

The system module calculates the total emissions arising from feed production, manure management and enteric fermentation. Post farmgate emissions (Appendix D) and direct and indirect on-farm energy use (Appendix E) are calculated separately and incorporated in the allocation module.

7.2 Calculation of the amount of each commodity (meat, milk, fibre) produced

Milk. Total milk production was calculated based on average milk production per animal and number of milking animals. Total milk is then converted to fat and protein milk. Using FPCM as the basis for comparison ensures a comparison between milk produced by different breeds and feeding regimes. All milk was converted to FPCM using the following equations:

Milk yield from cattle was corrected at 4.0 percent fat and 3.3 percent protein using the equation: FPCM (kg) = milk production, kg • [0.337+ 0.116 • fat, (percent) + 0.06 • protein, (percent)]

Milk yield from small ruminants was corrected at 6.5 percent fat and 5.8 percent protein according to Pulina, Macciotta and Nuda (2004) using the equation: FPCM (kg) = milk production, kg • [0.25+ 0.085 • fat, (percent) + 0.035 • protein, (percent)]

Buffalo milk production was expressed was corrected at 4 percent fat and 3.1 percent protein using the following equation (Di Palo, 1992): FPCM (kg) = milk production, kg • [1+ 0.011 • {(fat, (percent) • 10-40) + (10 • protein, (percent)-31)}]

Meat. Total meat production is calculated from the number of live animals (per cohort group) that leave the farm for slaughter and the live weight at which they are sold. Dressing percentages for the conversion of live weight to carcass weight are given in Appendix B, Tables B20 and B21. Conversion of carcass to bone-free meat is obtained by multiplying by 0.75 and 0.70 for large and small ruminants, respectively. The conversion of bone-free meat (BFM) to protein is based on the assumption that BFM is 18 percent protein by weight.

Natural fibre. Total fibre (wool, mohair and cashmere) is estimated by multiplying kg of fibre produced per animal by the number of fibre producing animals in the herd.

7.3 Allocation to co-products and calculation of emission intensity

For ruminant species, emissions are allocated between the edible commodities, i.e. meat and milk. In reality, there are usually significant amounts of other commodities produced during processing, such as skin, feathers and offal. However, the values of these can vary markedly between countries, depending on the market conditions, which, in turn, depend on factors such as food safety regulations and consumer preferences. Allocating no emissions to these can lead to an over-allocation to meat. The potential effect of this assumption is explored in Appendix F. Allocation techniques applied in this assessment are discussed below:

Meat and milk. Emissions related to goods and services other than meat and milk (e.g. fibre, manure used for fuel, draught power) were first calculated separately and deducted from the overall system emissions, before emissions were attributed to meat and milk.

Within the dairy herd, some animals only produce meat (fattened surplus calves), while others contribute to the combined production of meat and dairy products (milked cows, adult reproduction male animals and replacement stock). For the latter group, we chose to allocate GHG emissions on the basis of their protein con-

Table A3. Example of allocation between edible products from dairy production

	Part of herd producing milk and meat *(milking cows, adult male, replacement stock)*	**Part of herd producing meat only** *(surplus males and females)*
Total emissions *(kg CO_2-eq)*	1 700 000	350 000
Total protein *(kg)*	Milk: 18 000 Meat: 1 500	Meat: 2 500
Fraction of milk protein	0.92	NA
Fraction of meat protein	0.08	1
Emission intensity of milk	= (1 700 000 · 0.92)/18 000 **= 87 kg CO_2-eq/kg protein**	
Emission intensity of meat	= [(1 700 000 · 0.08) + 350 000]/(1 500+2 500) **122 kg CO_2-eq/kg protein**	

NA: Not Applicable.
Source: Authors' calculations.

tent. Table A3 provides an illustration of how the technique is applied. This method reflects the fact that a primary function of the livestock sector is to provide humans with edible protein. The advantages of using protein content are that it enables direct comparison with other food products and is also relatively stable in time (as opposed, for example, to the relative prices of meat and milk) and that it can be applied in situations where markets are absent or where they are highly localized and not comparable across regions. However, a disadvantage is that other nutritional properties, such as minerals, vitamins and energy, and essential fatty acids are not captured.

Emissions related to surplus calves fattened for meat production were entirely attributed to meat production. However, the emissions related to the production of calves, i.e. the pregnancy of the dairy cows and female replacement stocks, were allocated to milk because they are an essential input for milk production. No emissions were allocated to the other parts of the slaughtered animal (e.g. skin, horns), although these are utilized and represent an economic yield. This may result in a slight overestimation of the emissions per kg of carcass weight. In beef herds, all emissions were allocated to meat after the deduction of emissions related to draught power (in the case of cattle) and fibre (wool, cashmere and mohair) from small ruminants.

Manure. Manure is another by-product of livestock production. The emissions related to manure were allocated through the subdivision of the production processes:

- *Emissions related to manure storage* were fully allocated to the livestock system.
- *Emission from manure applied on the land used for feed, food and cash crop production* were allocated to livestock in situations where the crop as a whole or in part (e.g. silage, grain, oilseeds) was used for animal nutrition. In situations where manure was entirely deposited on grassland and feed crops, no allocation was required because the manure remained within the livestock system. On the other hand, where parts of the crop (e.g. crop residues) were used for feed, emissions were allocated according to the relative weight of harvested products used as feed, corrected for digestibility. Due to

the absence of an economic value for crop residues, digestibility was used as a proxy for economic value. In cases where the crop was not used for animal nutrition, emissions were not allocated to livestock.

- *Emissions from manure used for fuel at the household level* leave the livestock system and therefore emissions from burning were not allocated to the livestock system.
- *Emissions from manure discharged into the environment* were solely attributed to livestock activities.

Fibre (wool, cashmere and mohair). Fibre is a by-product of sheep and goat production; however in some countries these products can be considered as main products of production due to their price leverage and market value. In this study, the allocation of the carbon footprint to fibre was performed based on the market value of all system outputs – meat, milk, and fibre products. The fractions of the economic value of the co-product within the total economic value of all products produced by a given species were utilized as an allocation factor to partition GHG emissions between fibre and the edible products. This fraction was determined as:

$$F_w = (Wool_{kg} \cdot Price_{wool})/(Meat_{kg} \cdot Price_{meat} + Milk_{kg} \cdot Price_{milk} + Wool_{kg} \cdot Price_{wool})$$

where: F_w is the ratio of economic value of wool to the total economic value of all products produced. Similar calculations were performed for countries producing cashmere and mohair. Wool, meat and milk represent the mass of the product in kg. Table A4 provides an illustration of how the technique is applied. To implement the total economic value, producers prices averaged over five years were taken from the FAOSTAT price domain, reflecting prices that farmers receive at the farmgate. Subsequent to the deduction of emissions for fibre production from the overall emissions, protein content was then used to allocate emissions between meat and milk.

Table A4. Example of allocation between non-edible (wool) and edible products from sheep dairy production

	Part of herd producing milk, meat and wool			Part of herd producing meat and wool only
Total emissions *(kg CO_2-eq)*	80 000			20,000
Total protein *(kg)*	Milk: 500	Meat: 50		Meat: 200
Total economic value *($)*	Milk: 4 000		Meat: 9 000	Wool: 700
Fraction of milk protein	0.9			NA
Fraction of meat protein	0.1			1
Total emission allocated to wool	=80 000 · [700/(4 000+9 000+700)] **= 4 088 kg CO_2-eq**			=20 000 · [700/(4 000+9 000+700)] **= 1 022 kg CO_2-eq**
Total emissions allocated to milk and meat	= 80 000 – 4 088 **= 75 912 kg CO_2-eq**			= 20 000 – 1 022 **= 18 978 kg CO_2-eq**
Emission intensity of milk	= (75 912 · 0.9)/500 **= 138 kg CO_2-eq/kg protein**			
Emission intensity of meat	= [(75 912 · 0.1) + 18 978]/(50+200) **= 104 kg CO_2-eq/kg protein**			

NA: Not Applicable.
Source: Authors' calculations.

Animal draught power. Herd structure, and thus the emissions profile, is affected by the use of animals, usually oxen, for labour. The use of animals for draught power has an influence on the herd's sex and age structure which skews towards higher ratios of male and older animals. Oxen must grow to maturity before they can be used for traction, and this usually takes four years, and therefore they compete with other stock for feed and other resources. The animals are then generally used for a decade before they are slaughtered. The adult male to female ratio is substantially higher than normal when animals are used for draught power because males are slaughtered at a later age.

To allocate emissions to draught power services, we first calculated total emissions and meat output from draught animals alone. In a subsequent calculation step, emissions related to the meat produced from these animals were estimated as being identical to those of meat produced from non-draught animals, slaughtered at an earlier age. The difference (accruing from the extra lifetime and the energy requirements for the labour of draught animals) was then attributed to draught power services.

Capital functions of cattle. In any cattle production system, animals constitute a form of capital, and can be sold or bought according to investment and cash flow requirements. In many pastoral systems, the capital functions of cattle are a particularly important, because they enable the accrual of savings to manage cash needs, insure against risk, and manage crises in the absence of adequate financial institutions. Therefore, low replacement rates are often a feature in these systems, because cattle are often kept even after their productivity drops. While the provision of these capital functions affects the herd structure and emission profiles of these systems, no emissions were allocated to capital services, due to difficulties in obtaining relevant information.

Slaughter by-products. In addition to the production of carcasses, slaughtering processes also produce a whole package of by-products, organs, hide, blood, etc. that are utilized for other purposes, often outside the livestock food chain. Thus, the allocation of emissions to by-products produced at the slaughterhouse can have a major impact on the GHG emission intensity for meat products. This study did not explicitly take into account by-products from slaughter due to the lack of reliable information and data. However, we explored the impact of their inclusion on emission intensity of beef in a selected case study (see Appendix F).

In terms of edible product, ruminants produce both milk and meat. The emissions were allocated between these two commodities, using the following method:

- Quantify the total emissions from animals required for milk and meat production (adult female and adult male, replacement stock and surplus animals).
- Deduct emissions related to draft power (for large ruminants), and manure used for fuel based on the approaches outlines above.
- For the dairy sector, which produces both milk and meat, emissions are allocated on a protein basis (see Tables A3 and A4). For small ruminants, allocation is first performed between the edible and non-edible products based on economic value and subsequently protein content is used to allocate between milk and meat.

REFERENCES

Di Palo, R. 1992. Produzione lattea nella bufala con diete tradizionali e con impiego di acidi grassi. PhD thesis, Università di Napoli.

FAO. 2007. *Gridded livestock of the world 2007* by Wint, W. and Robinson, T. FAO. Rome.

FERTISTAT. 2009. Fertilizer use statistics, FAO. http://www.fao.org/ag/agp/fertistat/index_en.htm.

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht W. & Fischer-Kowalski M. 2007. Quantifying and mapping the global human appropriation of net primary production in Earth's terrestrial ecosystem. *Proceedings of the National Academy of Sciences of the USA* 104: 12942-12947.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, *Volume 4: Agriculture, Forestry and Other Land Use*. Intergovernmental Panel on Climate Change. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. & Tanabe K. eds. Published: IGES, Japan.

Jenssen, T.K. & Kongshaug, G. 2003. Energy consumption and greenhouse gas emissions in fertiliser production. IFS Proceedings No.509. International Fertiliser Society. York.

Pulina, G., Macciotta, N. & Nuda, A. 2004. Milk composition and feeding in the Italian dairy sheep. *Ital. J. Anim. Sci.*, 4(SUPPL. 1): 5-14.

You, L., Crespo, S., Guo, Z., Koo, J., Ojo, W., Sebastian, K., Tenorio, T.N., Wood, S. & Wood-Sichra, U. 2010. *Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2.* Available at http://MapSPAM.info.

APPENDIX B

Data and data sources

This appendix presents the main data utilized in this assessment. The data can be classified into *basic input data* and *intermediate data*. Basic input data can be defined as primary data such as animal numbers, herd parameters, mineral fertilizer application rates, temperature, crop yields, etc. and are data taken from other sources such as literature, databases, and surveys. Intermediate data are an output of the modelling procedure required in further calculation in GLEAM and may include data on growth rates, animal cohort groups, feed rations, animal energy requirements, feed intake, etc.

1. DATA RESOLUTION AND DISAGGREGATION

Data availability, quality and resolution vary according to the parameter and the country in question. In OECD countries, where farming tends to be more regulated, there are often comprehensive national or regional data sets, and in some cases sub-national data (e.g. for manure management in U.S. dairy). Conversely, in many non-OECD countries, data are unavailable, necessitating the use of regional default values (e.g. herd parameters). Examples of the spatial resolution of some key parameters are given in Table B1.

2. HERD

Livestock distributions. Maps of the spatial distribution of each animal species and production systems are one of the key inputs into the GLEAM model. Total ruminant numbers at a national level are reported in FAOSTAT. The spatial distributions used in this study were based on maps developed in the context of FAO's Gridded Livestock of the World (FAO, 2007).

Herd parameters. The national herd is disaggregated into cohorts according to six animal classes: adult female and male, replacement female and male, and male and female surplus or fattening animals that are not required for maintaining the herd and are kept for meat production only. The key biological parameters required for herd modelling incorporate data on mortality, fertility and growth rate, also known as "rate parameters".

- *Fertility parameters:* data on fertility are usually incorporated in the form of parturition rates (e.g. calving, kidding, lambing rates), and are normally defined as the number of births occurring in a specified female population in a year. For cattle, the number of births per year is assumed to be one. However, in the case of small ruminants, litter size is taken into account. The model utilizes age-specific fertility rates for adult and young replacement females. The proportion of breeding females that fail to conceive is also included.
- *Mortality rates:* data on mortality are incorporated in the form of death rates. In the modelling process, age specific death rates are used; mortality rate in calves and mortality rate in other animal categories. The death rate of

Table B1. Spatial resolution of the main input variables

Parameters	Cell[1]	Subnational	National	Regional[2]	Global
Herd					
Animal numbers	X				
Weights		X →		X	
Mortality, fertility and replacement data		X →		X	
Manure					
N losses rates					X
Management system		X →		X	
Leaching rates				X	
Feed					
Crop yields	X				
Harvested area	X				
Synthetic N fertilizer rate			X		
N residues	X[3]			X[4]	
Feed ration			X[5] →	X	
Digestibility and energy content			X →		X
N content				X →	X
Energy use in fieldwork, transport and processing					X
Transport distances					X
Land-use change					
Soybean (area and trade)			X		
Pasture (area and deforestation rate)			X		
Animal productivity					
Yield (milk, eggs, and fibers)			X →	X	
Dressing percentage			X →	X	
Fat and protein content			X →		X
Product farmgate prices[6]			X →	X	
Postfarm					
Transport distances of animals or products			X		
Energy (processing, cooling, packaging)			X		
Mean annual temperature	X				
Direct and indirect energy			X →	X	

→ The spatial resolution of the variable varies geographically and depends on the data availability. For each input variable, the spatial resolution of a given area is defined as the finest available.

[1] Animal numbers and mean annual temperature: ~ 5 km x 5 km at the equator; crop yields, harvested area and N residues: ~ 10 km x 10 km at the equator.

[2] Geographical regions or agro-ecological zones.

[3] For monogastrics.

[4] For ruminants.

[5] Ruminants: rations in the industrialized countries; Monogastrics: rations of swill and concentrates.

[6] Only for allocation in small ruminants.

calves reflects the percentage of pregnancies that end with a dead calf. This may occur by abortion, still birth or death in the first 30 days after birth.

- *Growth rates:* the growth rate of animals is based on the age at which they attain adult weight. For females, this depends on the age at first parturition, although some growth takes place after this. The age at which animals are sold for slaughter is based on the defined slaughter weight and the calculated growth rate.
- *Replacement rates:* these represent the number of adult animals replaced by younger adult animals per year. The replacement rate of female animals is taken from the literature. Literature reviews did not reveal any data on the replacement rate of male animals, so the replacement rate was defined as the reciprocal value of the age at first parturition, on the assumption that farmers will prevent in-breeding by applying this rule. For small ruminants, adult males are usually exchanged twice by farmers and therefore have three service periods.

Tables B2-B6 present input herd parameter data used in this analysis.

Table B2. Herd parameters for dairy cattle, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult cow	747	500	593	518	371	486	463	346	551	325
Adult bull	892	653	771	673	477	326	601	502	717	454
Calves at birth	41	33	38	36	20	28	31	23	38	20
Slaughter female	564	530	534	530	329	256	410	87	540	274
Slaughter male	605	530	540	530	367	243	410	141	540	278
	Rate *(percentage)*									
Replacement adult cow	35	31	31	27	15	28	22	21	21	10
Fertility	77	83	83	84	73	80	80	75	80	72
Death rate female calves	8	8	8	8	20	15	10	22	9	20
Death rate male calves	8	8	8	8	20	15	10	50	9	20
Death rate other animals	3	4	4	4	6	6	4	8	9	6
Age at first calving (years)	2.1	2.3	2.3	2.2	3.4	2.5	2.1	3.1	2.6	4.0

Source: Input data based on literature, surveys and expert knowledge.

Table B3. Herd parameters for beef cattle, regional averages

Parameters	N. America	Russian Fed.[1]	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult cow	649	0	529	530	431	501	403	350	419	271
Adult bull	843	0	688	689	563	542	524	505	545	347
Calves at birth	40	0	35	35	29	33	27	23	28	20
Slaughter female	606	0	529	530	445	223	403	73	392	349
Slaughter male	565	0	529	530	478	218	403	68	400	288
	Rate *(percentage)*									
Replacement adult cow	14	0	15	15	21	16	22	21	14	11
Fertility	93	0	93	93	75	90	93	75	73	59
Death rate female calves	11	0	10	10	18	15	10	22	14	19
Death rate male calves	11	0	10	10	18	15	10	50	14	19
Death rate other animals	4	0	3	3	7	7	3	8	6	7
Age at first calving (years)	2.0	0	2.3	2.3	2.8	2.5	2.1	3.1	3.4	3.9

[1] Based on our estimates, the Russian Federation has no specialized beef herd.

Source: Input data based on literature, surveys and expert knowledge.

Table B4. Herd parameters for goats, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult female	64	55	59(61)	50	37(40)	44(34)	50	32(31)	35(37)	29(31)
Adult male	83	100	88(91)	100	53(56)	60(43)	81	42(39)	50(60)	36(40)
Kids at birth	6.4	2.2	4.0(4.6)	5.0	2.7(3.2)	3.9(2.1)	3.6	2.7(2.4)	3.5(3.7)	2.2(2.3)
Slaughter female	36	30	26	30	32	27	38	25	27	19
Slaughter male	36	30	26	30	32	27	38	25	28	19
	Rate *(percentage)*									
Replacement female	30	18	17	18	19	24	21	19	24	16
Fertility	85	90	87	90	87	88	87	81	80	87
Death rate kids	18	5	4	5	31	37	12	15	14	27
Death rate other	9	2	2	2	7	16	6	5	5	7
Age at first kidding (years)	1.4	1.3	1.3	1.3	1.6	1.1	1.4	1.8	1.5	2.0

Note: Numbers in brackets refer to parameters for meat animals.

Source: Input data based on literature, surveys and expert knowledge.

Table B5. Herd parameters for sheep, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult female	80	49	62	44	41	47	70	35	59	38
Adult male	108	101	82	85	55	65	98	45	81	51
Lambs at birth	4	3	4	3	3	4	4	3	3	3
Slaughter female	27	21	29	21	26	26	35	24	29	24
Slaughter male	27	21	29	21	26	26	35	24	29	24
	Rate *(percentage)*									
Replacement female	21	23	29	22	21	16	24	18	20	17
Fertility	92	95	91	90	83	77	100	81	91	76
Death rate lambs	19	17	18	18	25	31	9	24	18	33
Death rate other	8	2	3	5	12	14	4	12	12	13
Age at first lambing (years)	2.1	1.9	1.6	1.8	1.4	1.6	1.8	1.6	2.0	1.5

Source: Input data based on literature, surveys and expert knowledge.

Table B6. Herd parameters for buffalo, regional averages

Parameters	LAC	E & SE Asia	E. Europe	N. America	Russian Fed.	South Asia	NENA	W. Europe
	Weights *(kg)*							
Adult female	650	380	559	650	650	485	500	648
Adult male	900	398	700	800	800	532	610	800
Calves at birth	38	24	38	38	38	31	32	38
Slaughter female	400	190	481	350	440	215	310	352
Slaughter male	475	190	380	350	440	135	309	352
	Rate *(percentage)*							
Replacement female	10	20	20	10	20	20	16	10
Fertility	75	57	68	76	68	53	69	76
Death rate female calves	7	29	8	8	8	24	18	8
Death rate male calves	7	28	8	8	8	44	18	8
Death rate others	2	6	4	4	4	9	6	4
Age at first calving (years)	3.0	4.0	3.2	2.5	3.6	4.0	3.1	2.5

Note: Based on this analysis, SSA and Oceania have no buffalo herd.
Source: Input data based on literature, surveys and expert knowledge.

3. FEED

Animal rations are generally a combination of different feed ingredients. For ruminants, three broad categories of feed are considered: roughages, by-products and concentrates. Feed is defined by a feed ration which differs among animal categories as defined in the herd module. Three separate feed rations are formulated for the following categories: adult females; replacement males and females and adult males; and surplus (meat) animals for fattening. Tables B7 to B12 present the average feed rations and proportions of different feed materials within the feed basket by region and ruminant species.

In this assessment, all plant-based feed materials are identified by three key parameters: dry-matter yield per hectare; net energy content (or digestibility); and nitrogen content. These three parameters are data input in the calculation of the feed ration and its nutritive value. The dry matter yield determines the type of feed ingredients that make up the feed ration as well as the potentially available feed in a region. The digestibility and N-content of feed define the quality properties of feed and determine the efficiency with which feed is digested and eventual GHG emissions. Table B13 presents regional average feed ration digestibility values.

Emission factors for key data inputs into feed production. Emissions of fossil CO_2 from feed production, transport and processing are dependent on the amounts and types of fuels used. Table B14 presents emission factor data used in the calculation of the feed emission intensity.

Emissions of CO_2 and N_2O occurring during the production of nitrogenous fertilizers. The most commonly occurring mineral fertilizer, ammonium nitrate, which consists of equal parts of ammonium- and nitrate-nitrogen, currently releases ~6.8 kg CO_2-equivalents in production (Jenssen and Kongshaug , 2003). Due to the lack of reliable data on these parameters, and on fertilizer trade flow, the average European fertilizer emissions factor of 6.8 kg CO_2-eq per kg of ammonium nitrate N in all regions was used.

4. MANURE

There are considerable differences in emissions from MMS. Data requirements for the estimation of GHG emissions from MMS include: information on how manure is managed, the types of MMS, and the proportion of manure managed in these systems. Additionally, climatic information (e.g. temperature) is important because emission factors are climate dependent. It was thus necessary to consider the climate under which livestock is managed in each country.

On a global scale, there is limited data available on how manure is managed and the proportion of the manure managed in each system. Consequently, this study relied on various data sources such as national inventory reports, literature and expert knowledge to define the proportions of manure management systems. It uses the IPCC (2006) classification of MMSs (definition in Table 10.18, IPPC guidelines). Regional variations manure management practices are presented in Tables B15 to B19.

Table B7. Dairy cattle feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	14.4	23.8	33.2	22.5	41.4	22.4	68.3	10.7	54.9	56.8
Hay	17.0	23.8	16.6	22.8	17.8	19.2	5.6	14.2	15.4	18.1
Legumes and silage	30.6	34.3	22.6	33.2	0.3	2.7	10.4	-	-	-
Crop residues	-	1.8	2.5	1.8	31.7	38.4	-	60.1	8.7	17.0
Sugarcane tops	-	-	-	-	1.6	0.6	-	3.5	2.6	1.9
Leaves	-	-	-	-	3.6	2.3	-	6.1	6.5	3.0
By-products and concentrates										
Bran	4.4	2.9	2.0	3.0	0.6	0.5	2.5	0.2	0.4	0.1
Oilseed meals	6.4	4.6	8.5	5.7	2.3	6.7	1.3	5.2	6.4	3.1
Wet distillers grain	4.3	-	-	-	-	-	-	-	-	-
Grains	22.8	7.2	13.2	9.1	0.2	7.2	11.8	-	4.9	0.1
Molasses	-	-	0.1	-	0.5	-	-	-	0.1	0.1
Pulp	-	1.8	1.3	1.8	-	-	-	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B8. Beef cattle feed ration, regional averages

	N. America	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage								
Roughage									
Fresh grass	35.2	36.0	21.0	24.9	23.6	63.5	8.0	65.1	61.1
Hay	39.4	14.8	21.9	36.7	18.7	6.8	12.5	9.4	12.6
Legumes and silage	7.8	23.1	32.3	2.1	0.7	10.7	-	-	-
Crop residues	-	3.8	2.1	24.2	46.2	-	68.0	10.2	19.4
Sugarcane tops	-	-	-	0.1	0.8	-	3.6	2.5	3.7
Leaves	-	-	-	9.2	2.8	-	5.9	4.1	1.6
By-products and concentrates									
Bran	0.9	1.7	3.5	0.3	0.2	3.8	0.1	0.1	-
Oilseed meals	0.6	7.6	6.6	1.9	2.7	1.5	1.9	3.9	1.4
Wet distillers grain	1.0	-	-	0.0	-	-	-	-	-
Grains	15.1	10.6	10.5	0.6	4.2	13.7	-	4.7	0.1
Molasses	-	0.7	-	-	-	-	-	-	-
Pulp	-	1.7	2.1	-	-	-	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B9. Dairy buffalo feed ration, regional averages

	N. America	W. Europe	E. Europe	NENA	E & SE Asia	South Asia	LAC
	percentage						
Roughage							
Fresh grass	-	1.7	38.9	3.4	35.7	5.2	65.3
Hay	15.6	16.1	25.9	10.7	13.7	20.1	12.2
Legumes and silage	34.4	33.7	17.3	-	-	-	-
Crop residues	5.2	5.0	-	72.8	39.5	54.8	8.4
Sugarcane tops	-	-	-	5.8	2.2	4.7	2.2
Leaves	-	-	-	4.0	2.3	8.1	5.2
By-products and concentrates							
Bran	4.7	0.8	4.6	1.6	3.3	3.6	3.4
Oilseed meals	10.9	11.5	5.2	1.6	3.3	3.6	3.4
Wet distillers grain	7.3	7.0	-	-	-	-	-
Grains	15.6	18.2	8.1	-	-	-	-
Molasses	-	-	-	-	-	-	-
Pulp	6.2	6.0	-	-	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B10. Buffalo meat feed ration, regional averages

	Russian Fed.	NENA	E & SE Asia	South Asia	LAC
	percentage				
Roughage					
Fresh grass	41.1	38.9	37.8	5.9	68.0
Hay	27.4	27.7	12.0	19.8	13.2
Legumes and silage	18.3	-	-	-	-
Crop residues	-	29.8	43.5	60.1	8.9
Sugarcane tops	-	-	2.1	4.7	2.3
Leaves	-	2.2	2.5	7.5	5.3
By-products and concentrates					
Bran	4.7	0.7	1.1	1.0	1.1
Oilseed meals	3.3	0.7	1.1	1.0	1.1
Wet distillers grain	-	-	-	-	-
Grains	5.2	-	-	-	-
Molasses	-	-	-	-	-
Pulp	-	-	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B11. Small ruminant milk feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	29.7	32.0	24.9	32.5	46.4	23.0	62.2	23.9	74.9	58.8
Hay	37.5	24.6	19.3	25.0	7.0	33.8	6.9	6.3	11.9	4.9
Legumes and silage	2.6	9.8	6.6	10.0	0.7	-	7.8	-	-	-
Crop residues	-	11.5	16.4	11.8	38.4	26.9	1.1	53.9	8.7	31.1
Sugarcane tops	-	-	-	-	2.2	0.3	-	2.3	2.1	3.9
Leaves	-	-	-	-	0.9	2.1	-	1.6	0.3	0.2
By-products and concentrates										
Bran	5.8	8.6	11.3	8.2	2.1	6.9	9.8	6.0	1.0	0.6
Oilseed meals	2.1	2.3	4.3	2.1	1.7	6.9	0.6	6.0	1.0	0.6
Wet distillers grain	-	-	-	-	-	-	-	-	-	-
Grains	17.2	3.6	5.4	3.3	0.2	-	5.5	-	-	-
Molasses	0.2	-	0.7	-	-	-	-	-	-	-
Pulp	4.9	7.6	11.1	7.2	0.3	-	6.1	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B12. Small ruminant meat feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	34.8	38.2	45.4	37.0	34.9	19.7	75.4	25.7	68.9	57.9
Hay	44.0	29.4	21.6	29.0	22.2	32.6	7.5	6.6	18.8	8.8
Legumes and silage	3.0	11.8	9.7	12.0	0.6	-	9.3	-	-	-
Crop residues	-	13.7	13.0	13.9	37.4	39.2	1.2	55.9	9.9	27.9
Sugarcane tops	-	-	-	-	1.8	0.3	-	4.2	1.4	5.2
Leaves	-	-	-	-	2.2	1.5	-	1.7	0.2	0.2
By-products and concentrates										
Bran	0.2	3.6	2.8	4.3	0.5	3.3	4.7	3.0	0.4	-
Oilseed meals	0.5	0.2	2.2	0.3	0.3	3.3	0.1	3.0	0.4	-
Wet distillers grain	-	-	-	-	-	-	-	-	-	-
Grains	17.3	0.4	0.7	0.5	-	-	0.9	-	-	-
Molasses	0.2	-	1.3	-	-	-	-	-	-	-
Pulp	-	2.6	3.4	3.1	-	-	1.0	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B13. Calculated feed digestibility, regional averages

Region	Dairy	Beef	Small Ruminants	Buffalo
	percentage			
N. America	71.8	68.3	66.2	73.4
Russian Fed.	72.6	-	65.4	70.7
W. Europe	77.0	76.1	69.7	75.5
E. Europe	73.5	73.8	67.4	72.8
NENA	56.1	57.7	55.5	52.0
E & SE Asia	59.0	57.4	56.3	56.0
Oceania	72.9	72.9	69.8	-
South Asia	52.6	50.7	54.1	52.1
LAC	62.2	62.7	58.9	60.5
SSA	57.3	57.2	55.5	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B14. Emissions factors for fuel consumption

Fuel	Emission factor	Source
Diesel	3.2 kg CO_2-eq/litre diesel	Berglund *et al.* (2009)
Oil	5.7 kg CO_2-eq/kg oil	de Boer (2009)
Coal	17.8 kg CO_2-eq/kg coal	de Boer (2009)
Gas	7.6 kg CO_2-eq/m^3 gas	de Boer (2009)

Table B15. Dairy cattle manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Uncovered anaerobic Lagoon	Liquid slurry	Pasture, range, pad-dock	Solid storage
			percentage				
N. America	-	9.5	-	27.2	26.3	11.8	25.2
Russian Fed.	-	-	-	-	-	22.5	77.5
W. Europe	-	2.3	-	0.1	41.6	26.6	29.5
E. Europe	-	1.4	-	-	10.2	17.0	71.3
NENA	3.6	-	39.4	-	-	46.1	10.9
E & SE Asia	1.5	-	29.1	-	3.1	30.7	35.7
Oceania	-	1.2	-	4.6	0.1	94.2	-
South Asia	20.0	-	54.4	-	-	23.5	2.0
LAC	0.4	-	41.5	-	-	53.5	4.7
SSA	6.9	-	34.8	-	-	39.7	18.5

Source: Input data from literature, national inventory reports and expert knowledge.

Table B16. Beef cattle manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Uncovered anaerobic Lagoon	Liquid slurry	Pasture, range, paddock	Solid storage
				percentage			
N. America	-	-	12.8	-	0.7	43.4	43.2
Russian Fed.	-	-	-	-	-	-	-
W. Europe	-	4.2	0.1	-	22.1	47.6	25.9
E. Europe	-	-	-	-	65.0	33.0	2.0
NENA	9.3	-	34.9	-	-	42.8	12.9
E & SE Asia	0.6	-	33.9	-	-	27.7	37.8
Oceania	-	-	-	-	-	100.0	-
South Asia	20.0	-	58.2	-	-	20.3	1.4
LAC	0.2	-	4.8	-	-	91.8	3.2
SSA	6.2	-	34.3	-	-	46.5	13.0

Source: Input data from literature, national inventory reports and expert knowledge.

Table B17. Buffalo milk production manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Liquid slurry	Pasture, range, paddock	Solid storage
			percentage			
N. America	17.4	40.2	42.4	-	-	-
W. Europe	3.4	61.9	34.7	-	-	-
E. Europe	13.0	67.8	18.2	-	1.0	-
NENA	50.8	9.2	-	38.9	-	1.1
E & SE Asia	31.0	13.3	-	53.6	-	2.0
South Asia	37.8	1.3	-	40.4	-	19.9
LAC	50.7	1.2	-	48.0	-	-

Source: Input data from literature, national inventory reports and expert knowledge.

Table B18. Buffalo meat production manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Liquid slurry	Solid storage
			percentage		
Russian Fed.	27.8	66.6	5.6	-	-
NENA	48.7	22.9	-	13.4	14.5
E & SE Asia	28.6	9.1	-	61.2	0.8
South Asia	38.6	1.5	-	39.7	2-
LAC	93.8	1.2	-	4.9	-

Source: Input data from literature, national inventory reports and expert knowledge.

Table B19. Small ruminant manure management systems, regional averages

MMS	Drylot	Pasture, range, paddock	Solid storage
	percentage		
N. America	-	47.4	53.0
Russian Fed.	-	18.0	82.0
W. Europe	-	83.8	16.2
E. Europe	-	64.6	35.2
NENA	37.5	57.2	5.2
E & SE Asia	0.8	56.7	42.3
Oceania	-	100.0	-
South Asia	12.8	85.0	2.0
LAC	3.7	83.3	12.7
SSA	9.3	84.4	6.2

Source: Input data from literature, national inventory reports and expert knowledge.

Table B20. Dressing percentages for large ruminants

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Dairy cattle										
Adult and replacement females	50	50	50	50	48	50	50	50	50	47
Adult and replacement male	50	50	50	50	48	50	50	50	50	47
Surplus female and male	52	52	52	52	50	55	52	55	52	47
Beef cattle										
Adult and replacement females	55	55	55	55	50	50	50	50	50	47
Adult and replacement male	55	55	55	55	50	50	50	50	50	47
Surplus female and male	60	60	60	60	55	55	55	55	55	47
Buffalo										
Adult and replacement females	49	49	49	49	49	49	49	49	49	49
Adult and replacement male	50	50	50	50	50	50	50	50	50	50
Surplus female and male	55	55	55	55	55	55	55	55	55	55

Source: Input data from literature, surveys and expert knowledge.

Table B21. Dressing percentages for small ruminants

Region	Goats	Sheep
	percentage	
N. America	52	52
Russian Fed.	43	45
W. Europe	43	48
E. Europe	43	45
NENA	44	45
E & SE Asia	48	49
Oceania	45	50
South Asia	43	48
LAC	44	49
SSA	48	45

Source: Input data from literature, surveys and expert knowledge.

5. PRODUCTION AND ALLOCATION

Dressing percentage. Dressing percentage can be defined as the percent of the live animal that ends up in the carcass. The LW:CW ratio varies substantially depending on a range of factor including breed, gender, diet, age, diet, cold versus warm carcass weight, and distance trucked. Tables B20 and B21 present the dressing percentages used for large and small ruminants.

Emission allocation factors. Table B22 presents a comparison of dairy and beef herds in total cattle population across world regions, their contribution to total beef production and the allocation factors used in this assessment for the allocation of emissions between milk and meat from the dairy herd. Emission allocation factor for wool, yield and total economic value (for meat, milk and wool produced by sheep) are presented in Table B23. See Appendix A for more details on allocation techniques applied.

Table B22. Percentage of dairy and beef herds, ratio of beef production from cattle herds and emission allocation factor for milk and meat from the dairy herd

	Percentage of cattle		Ratio of beef production from dairy and specialized beef herd		Allocation factor between milk and meat from the dairy herd
Region	Dairy herd	Beef herd	Dairy herd	Beef herd	Fraction
LAC	24.8	75.2	0.31	0.69	0.92
E & SE Asia	20.9	79.1	0.23	0.77	0.93
E. Europe	99.2	0.80	0.99	0.01	0.94
N. America	23.8	76.2	0.24	0.76	0.94
Oceania	38.1	61.9	0.38	0.62	0.96
Russian Federation	100.0	-	1.00	-	0.91
South Asia	56.9	43.1	0.60	0.40	0.90
SSA	57.5	42.5	0.59	0.41	0.90
NENA	98.9	1.1	0.98	0.02	0.92
W. Europe	70.5	29.5	0.70	0.30	0.95

Source: GLEAM.

Table B23. Emission allocation factors for sheep

Country*	Total economic value *('000 US$)*	Wool allocation factor	Wool *(kg/animal)*
Afghanistan	78 513	0.14	2.6
Albania	169 530	0.03	3.1
Algeria	519 567	0.08	2.4
Argentina	980 205	0.28	6.2
Armenia	18 138	0.09	2.1
Australia	4 967 220	0.38	6.4
Austria	31 346	0.02	3.5
Azerbaijan	79 042	0.13	2.1
Bangladesh	16 262	0.16	2.6
Belarus	1 797	0.06	5.0
Belgium	8 128	0.21	3.5
Bhutan	292	0.50	2.6
Bolivia	137 832	0.32	5.3
Bosnia and Herzegovina	41 272	0.09	3.1
Brazil	278 548	0.30	6.1
Bulgaria	44 497	0.09	5.0
Canada	24 881	0.11	5.5
Chile	88 762	0.26	6.0
China	1 797 202	0.17	2.1
Colombia	38 411	0.80	6.0
Croatia	91 675	0.01	3.1
Cyprus	26 049	0.01	2.1
Czech Republic	10 792	0.23	5.0
Denmark	9 372	0.26	5.0
Ecuador	45 468	0.51	4.3
Egypt	190 515	0.08	2.4
Eritrea	53 231	0.05	2.0
Estonia	1 554	0.08	2.8
Ethiopia	62 025	0.42	2.0
Finland	3 064	0.15	2.8
France	792 773	0.04	3.5
Georgia	28 259	0.20	2.1
Germany	144 509	0.04	3.5
Greece	1 368 750	0.01	3.1
Hungary	84 145	0.04	5.0
India	875 770	0.16	2.6
Indonesia	181 290	0.11	1.0
Iran (Islamic Republic of)	1 099 145	0.05	2.6
Iraq	149 159	0.19	2.1
Ireland	243 544	0.20	2.0
Israel	31 197	0.02	2.1

(Continued)

Table B23. *(Continued)*

Country*	Total economic value *('000 US$)*	Wool allocation factor	Wool *(kg/animal)*
Italy	1 022 570	0.02	3.1
Jordan	83 719	0.03	2.1
Kazakhstan	149 923	0.09	2.1
Kenya	103 366	0.11	2.0
Kuwait	24 814	0.21	2.1
Kyrgyzstan	46 492	0.06	2.1
Latvia	914	0.15	2.8
Lebanon	18 130	0.12	2.1
Lesotho	20 706	0.49	3.8
Lithuania	863	0.08	2.8
Luxembourg	911	0.09	3.5
Macedonia	62 263	0.02	3.1
Malaysia	1 475	0.15	1.0
Mali	158 637	0.13	2.0
Malta	1 382	0.04	3.1
Mexico	342 445	0.02	2.0
Moldova, Republic of	15 252	0.10	5.0
Mongolia	79 706	0.06	2.1
Montenegro	8 935	0.02	3.1
Morocco	674 549	0.12	2.4
Myanmar	14 162	0.03	1.0
Namibia	36 361	0.07	3.8
Nepal	15 740	0.12	2.6
Netherlands	74 491	0.03	3.5
New Zealand	1 699 390	0.23	5.5
Norway	143 600	0.18	2.8
Pakistan	250 607	0.14	2.6
Paraguay	12 046	0.29	5.3
Peru	305 378	0.26	6.0
Poland	13 963	0.07	5.0
Portugal	315 014	0.02	3.1
Republic of Serbia	58 074	0.02	3.1
Romania	370 170	0.05	5.0
Russian Federation	321 514	0.18	5.0
Saudi Arabia	412 672	0.13	2.1
Slovakia	9 059	0.09	5.0
Slovenia	8 112	0.02	3.1
South Africa	1 048 040	0.23	3.8
Spain	1 659 448	0.02	4.5
State of Libya	196 954	0.09	2.4
Sudan	1 310 660	0.03	2.4

(Continued)

Table B23. *(Continued)*

Country*	Total economic value *('000 US$)*	Wool allocation factor	Wool *(kg/animal)*
Sweden	20 060	0.09	2.8
Switzerland	42 600	0.02	3.5
Syrian Arab Republic	2 711 860	0.02	2.1
Tajikistan	26 784	0.24	2.1
Tunisia	277 587	0.11	2.4
Turkey	1 792 952	0.04	2.1
Turkmenistan	171 606	0.77	2.1
Ukraine	24 660	0.10	5.0
United Arab Emirates	28 401	0.13	2.1
U.K. of Great Britain and Northern Ireland	1 110 150	0.05	2.8
United Republic of Tanzania	49 968	0.09	2.0
United States of America	174 326	0.22	4.8
Uruguay	258 626	0.41	6.2
Uzbekistan	130 762	0.51	2.1
Yemen	268 873	0.09	2.1

* Represents 95 percent of the global sheep population.

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (FAOSTAT).

REFERENCES

Berglund, M., Cederberg, C., Clason, C. & och Lars Törner, M.H. 2009. Jordbrukets klimatpåverkan – underlag för att beräkna växthusgasutsläpp på gårdsnivå och nulägesanalyser av exempelgårdar. *Delrapport i JoKer-proJeKtet, Hushållningssällskapet Halland.*

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories prepared by the National Greenhause Gas Inventories Programme,* Eggleston, H.S., Buenida, L., Miwa, K., Nagara, T. & Tanabe, K. (eds). Published: IGES, Japan.

You, L., Crespo, S., Guo, Z., Koo, J., Ojo, W., Sebastian, K., Tenorio, T.N., Wood, S. & Wood-Sichra, U. 2010. *Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2.* Available at http://MapSPAM.info.

Jenssen, T.K. & Kongshaug, G. 2003. Energy consumption and greenhouse gas emissions in fertiliser production. *The International Fertiliser Society*, York, U.K. Proceedings No. 509.

APPENDIX C

Changes in carbon stocks related to land use and land-use change

1. INTRODUCTION

This appendix discusses GHG emissions and changes in carbon stocks that result from land use and LUC. Land uses and LUCs are defined; the relevant carbon pools and emission sources are discussed in the context of these categories; the approaches to estimating emissions and changes in carbon stocks are outlined; and finally, justification for and an explanation of the selected estimation methods used in this study is also provided.

Land use, LUC and forestry (LULUCF) is defined by the United Climate Change Secretariat as: *a greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities*. Six land use categories are defined in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: 1. Forest Land; 2. Cropland; 3. Grassland; 4. Wetlands; 5. Settlements; and 6. Other Land.

Land may remain in any of these categories or, in the case of LUC, its use may change to another category (e.g. from forest to grassland). Thus, each land use category can be further subdivided into land that is converted from one land use category to another, and land that remains in the same category. While this study focuses on the emissions from LUC, emissions from land use are also discussed.

1.1 GHG emissions from land-use change

Most LUCs alter the soil and vegetation of the land, thus changing the amount of carbon stored per unit area. These changes may be positive or negative, and may occur in each carbon pool: biomass (above- and below-ground); dead organic matter (dead wood and litter); and soil (soil organic matter).

LUC can significantly alter the carbon stored in biomass, by replacing the vegetation of the existing land use category with the vegetation of another land use category. Conversion of forest land to either grassland or cropland can lead to large and rapid losses of the typically large stores of carbon in forest vegetation, when this vegetation is replaced with herbaceous grasses or annual crops.

While most of the carbon stored in forest biomass is lost following conversion, some carbon will be transferred from one pool to another; e.g. when trees are felled, a portion of the above-ground biomass is transferred to the dead organic matter pool, and a portion of the below-ground biomass is transferred to the soil organic matter pool.

The drainage and cultivation or grazing of organic soils is also an important cause of the oxidation and loss of SOC for both croplands and grasslands (Armentano and Menges, 1986). While the most important GHG emission flux is CO_2, the oxidization of the various organic carbon pools as a consequence of LUC can also release N_2O.

Land conversion often results in an abrupt change where most biomass is lost, followed by a longer period where biomass is oxidized at a much slower pace. The IPCC (2006) assumes a default 20-year transition period following conversion over which all losses are accounted for.

The conversion of forest land to agricultural land may also lead to losses from the SOC pool. When forest land is converted to cropland, there is an average reduction in soil carbon of between 25 and 30 percent in the upper metre of soil (Houghton and Goodale, 2004).[14] These soil carbon losses are due, in part, to a lower fraction of non-soluble material in the more easily decomposed crop residues, and to the breaking up of aggregates and subsequent exposure of organo-mineral surfaces to decomposers following tillage (Post and Kwon, 2000). On the other hand, because grasslands, unlike crops, are not ploughed (temporary cultivated pastures are classified to be crops), little change in soil carbon is expected following the conversion of forests to grasslands (Houghton and Goodale, 2004).

When either cropland or grasslands are abandoned, there is a re-accumulation of carbon in vegetation as the land returns to its natural state, and the greater the biomass of the returning vegetation the larger is the long-term carbon sink due to the recovery. Post and Kwon (2000) note relatively low rates of accumulation in mineral soil following the abandonment of cropland. Considering all LUCs during the 1990s, Houghton & Goodale (2004) estimate that the average annual emissions from LUC were estimated to be 2.2 petagram C yr^{-1}, with almost all of this emanating from deforestation in the tropics.

1.2 Land use and its effects on emissions and carbon stocks

Agricultural lands hold substantial carbon stocks, mostly in soil organic matter. Carbon stock changes in agricultural lands are closely tied to management practices, which can either enhance or erode carbon stocks. Practices which raise (lower) the photosynthetic input of carbon and/or slow (accelerate) the release of stored carbon through respiration, erosion or fire will increase (decrease) carbon stocks (Smith *et al*., 2007). While it is possible for substantial biomass carbon to be stored through perennial plantings on agricultural lands (e.g. silvopastoral systems), carbon accumulation and losses occur mostly in the SOC pool. This below-ground carbon pool also has slower rates of turnover than above-ground pools, because most of the organic carbon in soils comes from the conversion of plant litter into more persistent organic compounds (Jones and Donnelly, 2004).

Smith *et al.* (2007) estimated that 89 percent of the agriculture sector's total mitigation potential is from SOC sequestration. For grasslands, practices such as the optimization of grazing intensities to maximize grass production, moderate intensification of nutrient-poor grasslands, and the restoration of degraded pastures are known to improve sequestration rates (Conant and Paustian, 2002; Sousanna *et al.*, 2010). Conversely, the overgrazing of grasslands reduces vegetation and the amount of litter returned to soils, and it leads to erosion and degradation contributing to CO_2 losses from the SOC pool. For croplands, significant changes in SOC stocks are associated with management practices including tillage, residue management, nutrient management and the use of organic amendments (Smith *et al.*, 2007).

[14] While there is some variation around this range, it has been documented in numerous studies, and has been found to be broadly robust across all ecosystems (Houghton and Goodale, 2004).

Historically, while agricultural management practices can result in either reductions or accumulations in the SOC pool, agricultural lands are estimated to have released more than 50 petagram C (Paustian *et al*., 1998; Lal, 1999, 2004), some of which can be restored via better management. Currently, however, the net flux of CO_2 between the atmosphere and agricultural lands is estimated to be approximately balanced (Smith *et al*., 2007). For the estimation of net livestock sector GHG emissions, which is the main purpose of this report, measures of net CO_2 current fluxes by region are of greater interest than the sequestration/mitigation potential.

The lack of a globally consistent and regionally detailed set of net CO_2 flux estimates make it difficult to quantify these potential emission sources and sinks by region in this study, although there are some relevant studies that provide useful estimates of these net fluxes for specific regions and agricultural land use categories. For example, based on literature observations for temperate grasslands mainly from Western Europe, Soussana *et al*. (2010) estimate that grasslands SOC sequestration rates averaged 5 ± 30 gC/m^2 per year. Nevertheless, Soussana *et al*. (2010) concede that the uncertainties associated with SOC stock changes following changes in management are very high. Further, stocks of SOC are very vulnerable to disturbances, including tillage, fire, erosion, and droughts that can lead to rapid reversals of accumulated stocks. Moreover, the authors recommend that further research is needed to separate the influence of management factors from other climate-related factors such as average temperature increase and CO_2 fertilization, in order to be able to attribute sequestration to direct anthropogenic causes.

There is also considerable potential to sequester carbon in croplands through a range of options available that include reduced and zero tillage, set-aside, perennial crops, deep rooting crops, more efficient use of organic amendments, improved rotations, irrigation, etc. In Brazil, for example, long-term field experiments (Costa de Campos *et al*., 2011; Dieckow *et al*., 2010; Vieira *et al*., 2009; Sisti *et al*., 2004) have evaluated the impact of conservation tillage and crop rotations on SOC. The results from these studies confirm that non-tillage and crop rotations can enhance the conservation of SOM and increase C accumulation. For example, Dieckow *et al*. (2010) who assessed the 17-year contribution of no-tillage crop rotations to C accumulation in subtropical Ferralsol of Brazil concluded that crop-forage systems and crop-based systems with legume represent viable strategies to increase soil organic C stocks. They found that the alfalfa system with maize at each three years showed the highest C accumulation (0.44 tonnes C/ha/yr). The bi-annual rotation of ryegrass (hay)-maize-ryegrass-soybean sequestered 0.32 tonnes C/ha/yr. However, an assessment of realistically achievable potentials for carbon sequestration in croplands needs to take into account economic, political and cultural constraints and other environmental impacts (such as non-CO_2 GHG emissions) also need to be accounted for.

2. QUANTIFICATION OF CARBON EMISSIONS AND SEQUESTRATION

2.1 Changes of carbon stocks related to land-use change

The most fundamental step in assessing emissions from LUC is the tracking of changes in areas of land use and conversions from one land use category to the next. This requires a time series of data, or at least two points in time, to capture changes in the area of land for each category.

Comprehensive guidance on methodological approaches for estimating LUCs as well as emissions and removals from LULUCF is provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Three different approaches are suggested with differing degrees of accuracy to best ensure the consistent representation of LUCs for given data quality and availability. The most accurate of these, Approach 3, requires the use of spatially-explicit data for land use categories and conversions, and includes the use of gridded map products derived from remote sensing imagery. At the other extreme is Approach 1, which relies on non-spatially explicit data from census and survey data, often reported at country or province level, and which only permits net changes in land use categories over time, and cannot specify inter-category conversions. Finally, Approach 2 enables the tracking of conversions between land use categories without the spatially-explicit location data. Naturally, the choice among the simple and more sophisticated approaches involve big trade-offs between the data and analytical resource requirements, and the accuracy with which LUCs and their attendant emissions and carbon removals are estimated.

For grassland remaining grassland, cropland remaining cropland, and conversion from forestland to either of these land use categories, the 2006 IPCC Guidelines require that changes in carbon stocks from each carbon pool (i.e. above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter), as well as emissions of non-CO_2 gases, are estimated. The guidelines do, however, provide flexibility in the use of methods that range from very simple approaches that rely on default emission factors to more sophisticated approaches that use detailed location-specific data and process models that fully characterize the fluxes between carbon pools.

2.1.1 Biomass and dead organic matter (DOM) pools

As mentioned, land-use conversions are often associated with an initial abrupt change and subsequent transition period following conversion. The 2006 IPCC Guidelines provide separate equations for these two phases when using Tier 2 and 3 approaches. Where country-specific emission factors are available and comprehensive national data are available, country-defined Tier 3 methodologies based on either process models or detailed inventories, stratified by climate and management regime can be recommended. These methods can also use non-linear loss and accumulation response curves during the transition phase.

At the other extreme, Tier 1 methods assume that both biomass and DOM pools are lost immediately after conversion from forestland to agricultural land, and that agricultural land reaches its steady-state equilibrium in the first year following conversion. While the IPCC provides default values to quantify biomass levels prior to and after conversion, there is assumed to be no accumulation in the DOM pool in the transition phase on agricultural land following conversion from forestland.

The Tier 2 methods represent a compromise, better capturing the dynamics of land-use conversion, by specifying separate equations for the abrupt change and transition phases, accounting for biomass accumulation during the latter phase. They also rely on some country-specific estimates of initial and final biomass stocks, instead of relying solely on default values.

Further, both Tier 2 and Tier 3 methods account for transfers between carbon pools and can estimate carbon pool changes using either the gain-loss or stock-

difference methods**.** The former method includes all processes that cause changes in a carbon pool, including biomass growth and the transfer of carbon from one pool to another. Alternatively, the stock-difference method can be used where carbon stocks are measured at two points in time. Both methods are valid, providing they can represent disturbances and continuously varying trends, and can be verified with actual measurements (IPCC, 2006).

2.1.2 Soil organic carbon (SOC) stocks

Changes in the SOC pools in both mineral and organic soils should be taken into account when estimating emissions and carbon accumulation resulting from LUC (IPCC, 2006). This requires that the areas of converted land be stratified by climate region, management and major soil type. Simple Tier 1 methods, which rely on default reference SOC stock change factors, can be used, or more country- or region-specific reference C stocks and stock change factors can be combined with more disaggregated land use activity data to use either Tier 2 or Tier 3 methods. Some of the process models suited to Tier 3 methods are discussed in the following section.

In this study, LUC emissions are estimated for each major carbon pool, including the biomass, DOM and SOC pools are estimated using Tier 1 methods. While Tier 2 and Tier 3 methods are recommended, the Tier 1 approach was deemed to be appropriate given the global nature of the assessment combined with the absence of country-specific emission factors, inventory data and/or a suitable global process model.

2.2 Changes in carbon stocks for agricultural land remaining in the same land use category

As with LUCs, the estimation of emissions and carbon accumulation from management practices on land that remains in the same land use category requires that changes in carbon stocks from each major carbon pool (i.e., above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter), as well as emissions of non-CO_2 gases, are estimated.

For agricultural lands, changes in these carbon pools and non-CO_2 emission fluxes depend on management practices such as grazing, burning, pasture management, tillage and residue management. Tier 2 and Tier 3 methods are able to estimate changes in each carbon pool and in emissions resulting from management practices, while Tier 1 methods can only be used to estimate these changes for the SOC pool (and non-CO_2 emissions from burning), but not for the other carbon pools. As with the measurement of emissions and carbon storage under LUC, the same gain-loss and/or stock-difference methods can be employed.

As discussed, Tier 3 methods can be used to more accurately assess changes in these carbon pools and non-CO_2 emission sources, using dynamic process models and/or detailed inventory measurements to estimate carbon stock changes. Process model-based approaches simultaneously solve multiple equations to estimate net changes in carbon stocks. These models can incorporate management effects such as grazing intensity, fire, fertilization, tillage and residue management, and they can be combined with regionally representative sampling-based estimates to validate and extrapolate to other agricultural lands. According to IPCC (2006), important criteria for selecting these models include: their ability to represent all relevant management practices and production systems, the compatibility of model's driving variables (inputs) with available country data, and validity gauged by the model's ability

to represent stock change dynamics reported in empirical assessments. Well-known biogeochemical models that can satisfy these criteria include the Century model (and the daily time-step version, Daycent), DNDC and RothC.

The RothC (Hart, 1984; Jenkinson *et al.,* 1987; Coleman *et al*., 1997; Smith *et al.,* 2006) and Century (Parton *et al.*, 1987; Falloon and Smith, 2002; Kirschbaum and Paul, 2002) models can be used to simulate GHG gas exchange and carbon cycling dynamics of cropland, grassland and forestland land use categories, and both operate on monthly time-steps. Soil texture and weather data are the major input variables. While the Century model can simulate the dynamics of carbon in biomass, DOM and SOC pools, as well as nitrogen, phosphorous, and sulphur dynamics, RothC only estimates SOC stocks and CO_2 losses from decomposition of SOC.

The Daycent model is the daily time-step version of the Century model (Del Grosso *et al.*, 2001; Parton *et al.*, 1998), which is well suited to capturing N mineralization and N gas production in non-waterlogged soils, along with the same carbon pool dynamics modelled in Century. As with Daycent, the denitrification-decomposition (DNDC) model (Li, 1996; Li *et al.*, 1992 and 1994) simulates soil carbon and nitrogen fluxes using a daily time-step but, unlike Daycent, it is also able to represent N gas and CH_4 fluxes from waterlogged soils, such as found in rice paddies. Both Daycent and DNDC have higher data demands than either Century or RothC, due their short time-steps and wider range of biogeochemical dynamics. Since none of these models has been validated on a global scale, they have not been applied in this analysis.

3. QUANTIFICATION OF CARBON STOCK CHANGES FROM LAND USE AND LAND-USE CHANGE IN THIS REPORT

In this study, LUC emissions are estimated for three major carbon pools, including the biomass, DOM and SOC pools. It could be argued that Tier 2 and Tier 3 methods, including process-based modelling approaches, should have been used to capture variability and possibly to reduce uncertainty in the emission and carbon accumulation estimates. However, given the global nature of the assessment, and the absence of country-specific EFs, carbon stock/flux inventory data and/or a suitable global process model (cf. previous section), the Tier 1 approach was deemed a suitable option to develop preliminary estimates and shed light on the potential magnitude of the LUC emissions for the sector.

For the reasons outlined above, this assessment does not cover changes in C stocks occurring under constant land use management. This may be done in future updates once global datasets are available and/or models have been calibrated for global studies.

This section presents the approach applied in this study to quantify LUC emissions, discussing the rationale for the approach chosen, and the results from the analysis. It also explores the implications of alternative approaches to quantifying LUC emission.

3.1 Approach for feed crops

The analysis focuses on one specific feed product – soybean – in specific countries in Latin America. This assessment is based on observed land use trends, feed crop expansion trends and trade flow patterns as well as findings from previous studies such as Wassenaar *et al.* (2007) and Cederberg *et al.* (2011).

Figure C1.
Net land conversion between 1990 and 2006, by region

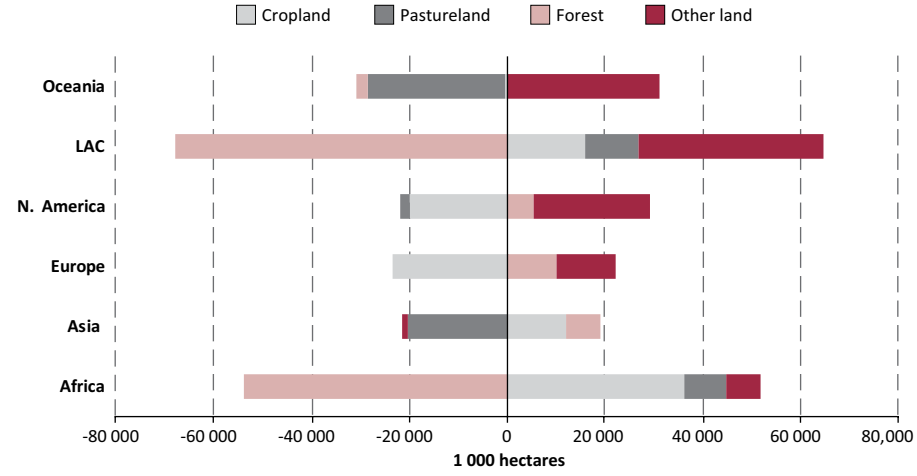

Source: FAOSTAT (2012).

This study uses IPCC guidelines as a basis for the quantification of LUC emissions. This choice is largely based on the fact that the IPCC approach meets the UNFCCC requirements for calculating and reporting of GHG emissions from LUC. The cropland part of this assessment also relies on other guidelines such as the PAS 2050 (also based on IPCC guidelines) for input data. According to IPCC guidelines, emissions arising from LUC are allocated over a 20-year period (the "amortization" period). Because of data availability (forestry inventories are only available from 1990),[15] in this assessment, the rates of LUC are taken as the average over the 16-year period (1990–2006). This practically discounts four years of emissions.

Agriculture has been a major driving force behind land transformation; globally, the area of land used for agriculture increased by 83 million ha over the period 1990–2006. In most regions, cropland has increased whereas pasture and forest land decreased (Figure C1). The most affected regions in terms of crop expansion are Latin America, Asia and Africa. Declining agricultural land (i.e. cropland and pastureland) is observable in Europe and North America where agricultural land abandonment has resulted in reforestation. During the period considered (1990-2006), deforestation occurred mainly in Africa and Latin America. More recent trends in deforestation, in particular in Asia, and their association with feed production are therefore not considered in this study.

Between 1990 and 2006, crop expansion was mainly driven by major oil crops (e.g. soybeans, rapeseed, sunflower and oil palm) the demand for which was fuelled by demand for vegetable oil, feed and, more recently, biofuel policies. The expansion of soybean production is argued to be one of the major drivers of LUC, par-

[15] The FAOSTAT forest area dataset (based on the Global Forest Resource Assessment) used in this study is only available from 1990 and in order to align the C stocks assessment with the livestock input data which is based on 2005 statistics, land use conversion trends were assessed for the period 1990 to 2006.

Table C1. Global area expansion for selected crops with highest area expansion (1990-2006)

Crop	Area expansion *(1 000 ha)*	Share of global gross crop expansion *(percentage)*
Soybeans	38 110	22.6
Maize	15 620	9.2
Rapeseed	9 815	5.8
Rice, paddy	8 650	5.1
Sunflower seed	7 237	4.3
Oil palm fruit	7 205	4.3

Source: FAOSTAT (2012).

ticularly deforestation (Pacheco, 2012; Nepstad *et al.*, 2006; Fearnside, 2005; Bickel and Dros, 2003; Carvalho *et al.*, 2002). The global area under cultivation of soybean has increased rapidly in recent decades; between 1990 and 2006, the global soybean area increased faster than any other crop (Table C1). Maize expansion is also important, representing 9.2 percent of global crop expansion. At the same time, crops such as wheat, barley and oats, have strongly declined, which explains the apparent discrepancies with the net land conversion trends in Figure C1.

A comparison of the two major crops driving agricultural expansion reveals key regional differences with regard to their importance (Figure C2). The expansion of soybean area has been significant in North and South America, while maize expansion is more important in Africa and Asia.

Deforestation for crop expansion has been an important LUC process in Africa, however crop expansion in the region has been mainly driven by sorghum and millet, with maize and soybeans only accounting for 5 percent and 0.5 percent of total gross cropland expansion respectively. In Africa, pasture expansion has also occurred largely at the expense of forest area. However, due to lack of reliable data and information it is difficult to draw conclusions on the land-use conversion trends in this region.

Figure C2.
Maize and soybean area expansion between 1990 and 2006, by region

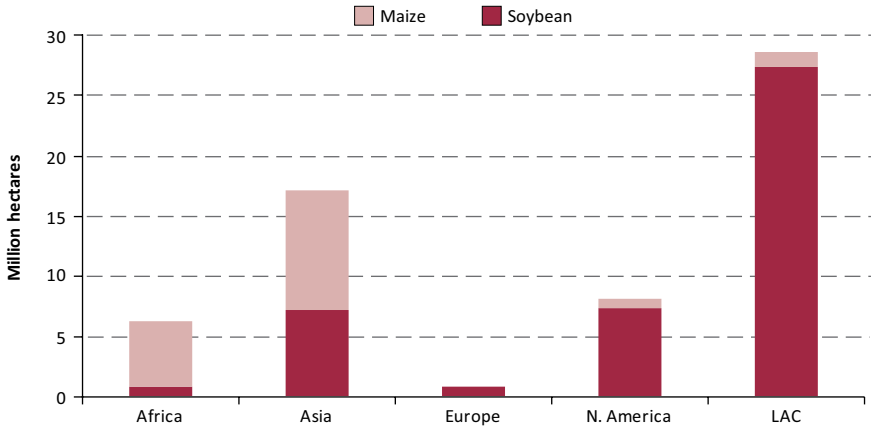

Source: FAOSTAT (2012).

Table C2. Average annual land-use change rates in Argentina and Brazil (1990-2006)

Land-use type	Argentina	Brazil
	(1 000 ha)	
Agricultural area	+351	+1 288
Grasslands	-7	+753
Arable land & permanent crops	+358	+535
Soybean area	+648	+534
Forest area	-149	-2 855
Other land	-201	+1 567

Source: FAOSTAT (2009).

In North America, soybean expansion is responsible for 37 percent of total crop expansion and maize 7 percent. However in this region the overall trend has been a decrease of total cropland (due to sharp decreases in wheat and barley areas) and pastures and an increase of forest area.

In Asia, soybean expansion is responsible for 7 percent of total crop expansion and maize 8 percent. At the same time, forest land has increased overall in Asia and pastureland has decreased. But the two trends occurred in different subregions within Asia. Pasture decrease mainly occurred in Mongolia and Iran, where maize and soybean expansion were null or limited. On the contrary, expansion of soybean and maize area has largely occurred in India and China (77 percent of gross maize expansion and 96 percent of gross soybean expansion), however, forest area increased in these two countries. Pastures decreased in India but to a limited extent of 1.2 million ha, compared to the 5.8 and 3.0 million ha of soybean and maize expansion in the country, respectively.

In Latin America, most of the decrease in forest area occurred in countries with soybean expansion. Trends in land conversion, particularly deforestation, are therefore closely linked to the expansion of soybean.

Based on these observations the scope of our assessment was narrowed to the soybean expansion in Latin America. Within Latin America, Brazil and Argentina account for 91 percent of the total soybean area. In the period 1990–2006, 90 percent of the soybean area expansion in Latin America took place there, further narrowing the scope to these two countries. An assessment of land use trends in these key producing countries shows that the expansion in soybean area has been largely gained at the expense of forest area (Table C2).

In Argentina, the annual increase of area dedicated to soybean is much larger than the increase of total arable land (Table C2), indicating that there has been a shift in land use from other crops to soybean. According to FAOSTAT statistics, 44 percent of the new soybean area was gained against other crops, while the rest was gained against forest (22 percent) and other land (31 percent). The latter category covers natural vegetation that does not include forest and grazed natural grasslands.

The reported annual increase of soybean area in Brazil is 534 000 ha (Table C2). We assumed a simplified pattern of deforestation in the Amazon, in which cleared land is first used as pasture and/or crop land, and then left as fallow land. The latter, classified as "other land" in FAOSTAT, is occupied by weeds, grasses, shrubs and,

Table C3. Net changes in area for main land-use categories (1990–2006)

Region	Arable land & permanent crops	Pasture	Forest area	Other land
		(1 000 ha)		
Africa	36 025	8 863	-53 700	7 001
Asia* (*South, East and SE Asia*)	12 149	-20 506	6 855	-1 068
Europe	-55 646	-152 441	261	-96 796
North America	-20 073	-1 954	5 387	23 811
Latin America and the Caribbean	15 753	11 069	-67 870	37 973
Oceania	-263	-28 408	-2 112	30 926

* Central Asia excluded due to incomplete dataset.
Source: FAOSTAT (2012).

partly, by secondary forest. Under this assumption, every year roughly 2.9 million ha are converted to arable land and grassland. At the same time, agricultural land is abandoned at a rate of 1.6 million ha per year. The annual net increase of arable land and grassland is 0.53 and 0.75 million ha, respectively. We thus assume that all incremental soybean area is gained at the expense of forest area.

Rates of C loss/gain arising from specific land-use transitions were taken from PAS 2050 guidelines (BSI, 2008), which are based on IPCC (2006). The PAS 2050 guidelines estimate deforestation (conversion of forest to annual cropland) releases in Brazil at an average 37 tonnes CO_2-eq/ha, and conversion of forest and shrub land to annual crop in Argentina at 17 and 2.2 tonnes CO_2-eq per ha, respectively. GHG emissions from soybean-driven LUC were calculated as the accumulated emissions for one year resulting from the total area deforested during the period 1990–2006 divided by the total soybean production in 2006. Based on this data, two LUC emission intensities were estimated for soybean cake produced in Brazil and Argentina, respectively: **7.69 and 0.93 kg CO_2-eq/kg soybean cake**. Soybeans and soybean cake produced elsewhere were assumed not to be associated with LUC.

3.2 Pasture expansion and land-use change

It has been argued that while forest conversion to soybean cultivation is occurring, the majority of deforested area is destined to pasture formation (Morton *et al*., 2006; Brown *et al.*, 2005). Wassenaar *et al.* (2007) developed a spatial and temporal model framework to analyse the expansion of pasture into forest in Latin America. The analysis predicted that, on average, 76 percent of deforested land would become pasture. Table C3 presents the net changes for different land use categories across regions; pasture expansion has been notable in Latin America and Africa while, at the same time, forest area in Latin America and Africa during the same period declined substantially.

3.2.1 Approach

The approach is based on the IPCC stock-based approach termed the *Stock-Difference Method*, which can be applied where carbon stocks are measured at two points in time to assess carbon stock changes (IPCC, 2006). The following emissions from deforestation were considered:

- CO_2 emissions from changes in biomass stocks (above-and below-ground biomass);
- CO_2 emissions from changes in dead organic matter (litter and deadwood);
- CO_2 emissions from changes in soil carbon stocks.

For each of the carbon pools mentioned above, several factors such as land use (forest, croplands, pasture), climatic zone, ecotype (tropical moist or tropical dry forest), soil type (mineral or organic soils), forest type, etc., were taken into consideration. Since data from forestry inventories are only available from 1990, the changes in carbon stocks due to deforestation could only be calculated for the period 1990-2006.

The calculations of land-use change were accomplished in two steps: first, the assessment of land use dynamics; and second, the carbon emissions based on land use dynamics and biophysical conditions. A complete assessment of carbon emissions from LUC involves the quantification of several key elements including deforestation rates, land use dynamics, and initial carbon stocks in biomass and soil. Two types of information are fundamental to enable emissions to be calculated: rates of deforestation and per hectare changes in carbon stocks in the different carbon pools. The following sections provide a detailed description of the applied methodology and assumptions made.

Determining total land area converted from forest to grassland. To accurately estimate carbon fluxes from LUC, it is critical to understand LUC dynamics following deforestation. With regard to land-use transition matrices, a simplified approach was adopted. Changes in land use area were estimated on the basis of the Tier 1 approach outlined in Chapter 3 of the IPCC guidelines, which estimates the total change in area for each individual land use category in each country.

FAOSTAT statistics on total land area (classified by land use category) were used to calculate the annual net change in the area of each land use category.

Table C4 presents the countries in which the increase in pasture area was largely facilitated by a decrease in forest area, and our estimates show that about 13 million hectares were deforested for pasture establishment.

Table C4. Pasture expansion against forestland in Latin America (1990-2006)

Countries	Pasture area change *(1 000 ha)*	Share of regional expansion *(percentage)*
Brazil	10 212.3	77.2
Chile	1 150.0	8.7
Paraguay	1 040.0	7.9
Nicaragua	454.3	3.4
Other*	365.0	2.8
Total	**13 221.6**	100

* 'Other' category includes: Honduras, Ecuador, Panama, El Salvador and Belize.
Source: Authors' calculations based on FAOSTAT data.

Table C5. Country specific estimates of above-and below-ground biomass

Countries	Above-ground biomass[1] *(tonnes DM/ha)*	Ratio of below- to above- ground biomass[2]	Below-ground biomass *(tonnes DM/ha)*	Total biomass[3] *(tonnes DM/ha)*
Brazil	220	0.24	52.8	272.8
Chile	220	0.24	52.8	272.8
Paraguay	210	0.24	50.4	260.4
Nicaragua	210	0.24	50.4	260.4
Ecuador	300	0.37	111	411.0
Other*	220	0.24	52.8	272.8

[1] Derived from IPCC, Volume 4, Chapter 4, Table 4.4.

[2] Ratio of above-below ground factors are derived from IPCC guidelines, Table 4.7.

[3] Total biomass is the sum of above-and below-ground biomass.

* 'Other' category includes: Honduras, Ecuador, Panama, El Salvador and Belize.

Changes in carbon stocks from above- and below-ground biomass. The method applied here focuses on stock changes in biomass associated with woody vegetation which are capable of accumulating large quantities of carbon over a long period of time. The Tier 1 method necessitates the estimation of biomass before and after conversion using IPCC equation 2.16 (Volume 4, Chapter 2).

Biomass in forests is determined by ecological zone, type of native vegetation and geographical location of forests. Based on the IPCC Tier 1 approach, in the conversion of forest to grassland it is assumed that all biomass is cleared and therefore the default biomass after conversion is 0 tonnes DM ha^{-1}. The IPCC guidelines (Chapter 4, Volume 4, Table 4.7) provide average default values for above-ground biomass in forests. Due to the lack of data on below-ground biomass, the ratio of below-to-above ground biomass (root-to-shoot ratio) was used to estimate the below-ground component of biomass and the total biomass (tonnes DM/ha) given in Table C5. A default factor of 0.50 tonnes C per tonnes DM (carbon fraction for woody biomass was used to convert biomass into carbon stocks per hectare.

Changes in carbon stocks from dead organic matter (DOM) pools. The conceptual approach to estimating changes in C stocks in dead wood and litter pools is to estimate the C stocks in the old and new land use categories and apply this change in the year of conversion. Equation 2.23 (IPCC, 2006, Volume 4, Chapter 2) was used to estimate changes in C stocks from DOM.

According to the IPCC Tier 1 approach, DOM pools in non-forest land categories after the conversion are zero and this is based on the assumption that all DOM carbon losses occur entirely in the year of land-use conversion. Tier 1 also assumes that carbon contained in biomass killed during the conversion of land is emitted to the atmosphere and none is added to the dead wood and litter pools. Tier 1 default factors for dead wood and litter were taken from IPCC (2006, Volume 4, Chapter 2, Table 2.2).

Changes in soil carbon stocks. SOC stock changes do not occur instantaneously but over a period of years to decades. The current IPCC good practice guidance for GHG inventories assumes a period of 20 years for a new equilibrium to occur after conversion (IPCC, 2006). The change in the amount of SOC depends on factors such as climate region, native soil type, management system after conversion

Figure C3.
Main soil classes in Latin American forested areas based on the World Reference Base for Soil Resources classification

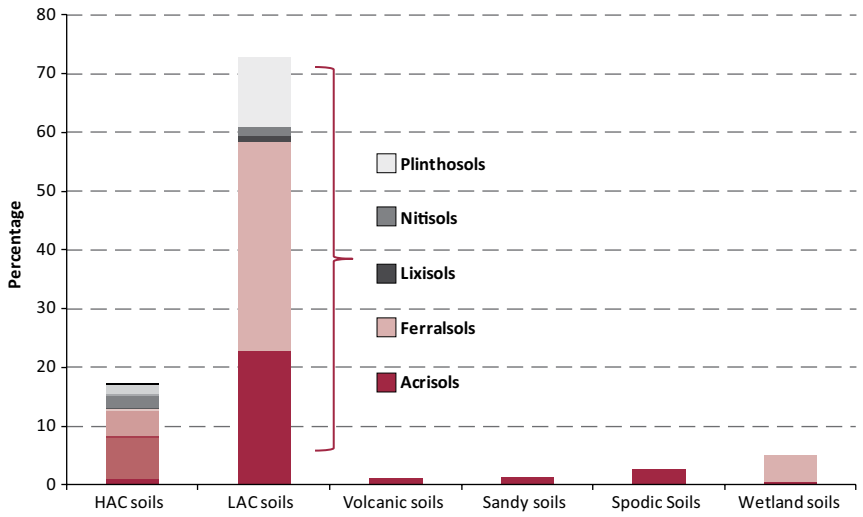

LAC: low activity clay; HAC: high activity clay.
Source: Authors.

and input use. The calculation of SOC losses per hectare of area transformed from forest to grassland is based on equation 2.25 in IPCC (2006, Volume 4, Chapter 2), which takes into account changes in soil carbon stocks associated with type of land use, management practices and input of organic matter (fertilization, irrigation, liming and grazing intensity) in the soil.

The approach makes a distinction between organic and mineral soil carbon pools, and the focus is on the impacts of LUC on the organic pool, because inorganic soil carbon is assumed to be insensitive to land-use change and management. Land converted to grassland was stratified according to climatic region, management and major soil types based on country specific classifications. The starting point was to derive a soil type classification of areas under forest in the selected countries in order to determine SOCs. This was accomplished with overlays of suitable climatic and soil maps coupled with spatial data on forest land area[16,17]. Figure C3 presents the mapping results of country-specific soil types on forested land and provides information on the dominant soil groups in forested areas in Latin America.

To establish SOC stocks, the soil divisions were further aggregated into dominant soil type classes (Figure C3) defined in IPCC guidelines based on the World Reference Base (WRB) for Soil Resources classification. Based on this aggregation, at a regional level, soils with low activity clay cover nearly 73 percent of the forested area in the nine countries. The remaining forested area is made up of the other five dominant soil types of which the high activity clay soil types cover 17 percent of the area (Figure C3).

[16] FAO/IIASA/ISRIC/ISS-CAS/JRC. 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

[17] Arino, O., Ramos, J., Kalogirou, V., Defourny, P. & Achard, F. 2010. "GlobCover 2009", Proceedings of the Living Planet Symposium, SP-686, June 2010. Data downloaded from http://ionia1.esrin.esa.int/ in August 2011.

Table C6. Default soil organic C stocks for mineral soils

Climate region	High activity clay soils	Low activity clay soils
	(tonnes C.ha^{-1} in 0-30 cm depth)	
Boreal	68	NA
Cold temperate, dry	50	33
Cold temperate, moist	95	85
Warm temperate, dry	38	24
Warm temperate, moist	88	63
Tropical, dry	38	35
Tropical, moist	65	47
Tropical, wet	44	60
Tropical, montane	88	63

NA: Not Applicable because these soils do not normally occur in some climatic zones.
Source: IPCC (2006).

Table C7. Soil organic carbon pool at 0-30 cm depth

Countries	Soil C stocks under forest	Soil C stocks under grassland	Net change in carbon stocks	Net annual change
	tonnes C.ha^{-1}		*tonnes C.ha^{-1}*	*tonnes C.ha^{-1} yr^{-1}*
Brazil	60	58.20	-1.8	- 0.11
Chile	44	42.68	-1.3	- 0.08
Paraguay	65	63.05	-2.0	- 0.12
Nicaragua	35	33.95	-1.1	- 0.07
Honduras	56	54.32	-1.7	- 0.11
Ecuador	78	75.66	-2.3	- 0.15
Panama	65	63.05	-2.0	- 0.12
El Salvador	50	48.50	-1.5	- 0.09
Belize	65	63.05	-2.0	- 0.12

Source: Authors' calculations based on IPCC (2006).

The 2006 IPCC guidelines provide average default SOC stocks for the dominant soil classes clustered by eco-region reproduced in Table C6. The default reference soil organic C stocks are for the top 30 cm of the soil profile because different land use management methods mostly affect soil carbon in the surface layer.

For Tier 1, all stock change factors (F_{lu}, F_{mg}, F_I) were assumed to be equal to 1 for forest land, corresponding to the default values in IPCC guidelines. For grasslands, stock change factors used for land use and input (G_{lu}, *and* F_I) were assigned a value of 1.

The quality of management of tropical pastures after conversion is critical in understanding whether the soils under this land use represent a source or a sink of atmospheric carbon. Differences in management practices could significantly affect subsequent trends in soil carbon. Due to the limited data on management and input, default values were used.

It was assumed that pastures are moderately degraded and therefore a coefficient of 0.97 (IPCC, 2006 Volume 4 , Chapter 6, Table 6.2) for F_{mg} stock factor was applied, which represents overgrazed or moderately degraded grasslands with reduced productivity and receiving no management inputs. This assumption is based

on the findings of studies (Hernandez *et al*., 1995; Murty *et al*., 2002; De Oliveira *et al*., 2006; Cerri *et al*., 2005;) which inferred that most of the pastures in LAC are in some process of degradation caused by poor management methods, low input fertilization and no maintenance. The results (Table C7) show a net decrease in SOC with losses ranging between 1.1 to 2.3 tonnes C ha^{-1}.

3.3 Sensitivity analysis and the influence of LUC method

Modelling of land use and LUC emissions is subject to great uncertainties mainly because of the complexity of LULUCF processes, the challenges of obtaining reliable global data and the absence of validated approaches to estimate carbon stock changes. In particular, uncertainty regarding the magnitude of LUC emissions arises due to uncertainties in: (a) the rates of land use; (b) the carbon storage capacity of different forests, initial carbon stocks and the modes of C release; and (c) the dynamics of land use not normally tracked. In addition, a value judgment has to be made regarding what drives LUC and, consequently, how the emissions should be allocated. In order to explore the potential effect that different methodologies can have, the results obtained with the GLEAM approach are compared to three alternative approaches: (a) PAS 2050-1:2012; (b) One-Soy; and (c) reduced time-frame approach. These approaches are summarized in Table C8.

3.3.1 Alternative approaches

PAS 2050-1: 2012 approach. Several studies suggest that deforestation is related to the expanding soybean sector (Fearnside, 2005; Bickel and Dros 2003; Carvalho *et al.*, 2002), but others dispute this claim, and argue that soybean is expanding into land previously under pasture, and is not causing new deforestation (Mueller, 2003; Brandao *et al.*, 2005). Due to the lack of knowledge of the origin of the converted

Table C8. Alternative approaches for soybean LUC emissions calculations

Method	Spatial allocation	Temporal allocation of LUC emissions	Quantification of rates of LUC	Quantification of rates of C loss/gain
GLEAM approach (current study)	To all soybean produced within the country	20 years	FAOSTAT average LUC rates 1990-2006 Brazil: forest→crops (100%) Argentina: other crops (44%), forest (22%) and other land (31%)→soybean	IPCC (2006) Tier 1
PAS 2050-1:2012	To all soybean produced within the country	20 years	Average rates over 20 years. LUC rates based on (a) or (b) - whichever results in the highest emission factor. (a) from grassland forest and perennial arable in equal proportion (b) from grassland, forest and perennial arable in proportion to their rates of change	IPCC (2006) Tier 1
One-Soy	To traded soybean	20 years	FAOSTAT average LUC rates 1990-2006 Brazil: forest→crops (100%) Argentina: other crops (44%), forest (22%) and other land (31%)→soybean	IPCC (2006) Tier 1
Reduced time-frame	To all soybean produced within the country	20 years	FAOSTAT average LUC rates 2002-2007 Brazil: forest→crops Argentina: other crops (44%), forest (22%) and other land (31%)→soybean	IPCC (2006) Tier 1

Source: Authors.

land, the GLEAM results were compared with PAS 2050-1:2012 (BSI, 2012), which provides a way of quantifying LUC emissions when previous land use is not known and only the crop and country are known. The PAS 2050-1:2012 calculations of emissions related to land-use change are accomplished in two steps.

First, rates of land-use change need to be calculated based on the PAS 2050-1: 2012. To calculate these, four categories of land are considered: forest, pasture, annual cropland and perennial cropland. Time series data on land area for forest, pasture, annual and perennial crops taken from FAOSTAT were used to: (i) determine whether the crop in question was associated with LUC by quantifying the rate of expansion over a 20-year period; and (ii) determine the share of LUC associated with each land category. In a second step, carbon losses based on land dynamics and biophysical conditions (climate, soil type, forest type, crop management, etc.) were computed based on the IPCC (2006) Tier 1 approach. The two sources of carbon taken into account in this approach are vegetation and soil. Two LUC EFs were calculated, based on different assumptions regarding where land for soybean expansion is derived from: (i) assuming that land for soybean production is gained in equal proportions from grassland, forest and perennial cropland; (ii) assuming that land for soybean is gained from other land use categories in proportion to their relative rates of change. The highest of the two EF's was then selected, in accordance with the guidelines. BSI (2012) present a detailed account of methodology and data sources.

One-Soy approach. In this approach it is assumed that all soybeans, irrespective of where they have been produced, are associated with LUC. The central argument for this scenario is that the global demand for soybeans is largely interconnected and is a key driver of LUC. An average LUC emission factor associated with soybean was estimated by calculating the total LUC emissions attributable to globally-traded soybean and soybean cake and then dividing this by total global soybean cake exports. Because the emission intensity was applied to all traded soybean and soybean cake, the approach equally distributes the LUC emissions across all importing countries irrespective of where the soybean is produced.

Reduced time-frame approach. Annual deforestation rates are highly variable, so the period over which the rates of LUC are estimated can therefore have a significant influence on results. Since data from forestry inventories are only available from 1990, this assessment was based on the average rates of LUC over the period 1990-2006. This not only coincides with a period of high rates of deforestation but also high soybean area expansion. In the reduced time frame approach, the LUC emissions are calculated based on the average rates of LUC over the period from 2002-07, while maintaining the underlying assumptions in the study.

3.3.2 Results

Effect of LUC approach on soybean LUC emission factor. Table C9 reports the LUC factors for soybean cake (kg CO_2-eq per kg soybean cake) calculated using each of the approaches. The choice of method for estimating LUC EFs can strongly influence the emission intensity of livestock products and illustrates the complexity of analysing LUC processes.

Table C9. Summary of soybean LUC emission intensity for the four approaches

Scenario	Argentina	Brazil
	(kg CO_2-eq per kg soybean cake)	
GLEAM approach (current study)	0.93	7.69
PAS 2050-1:2012	4.23	3.21
One-Soy	2.98	2.98
Reduced time-frame	0.34	3.70

Source: Authors' calculations.

The *PAS 2050-1: 2012* approach produces markedly different LUC emission factors due to the assumptions made regarding the land use category against which additional land for soybean production was gained and the relative share of this gain (Table C10). Unlike Brazil, Argentina has a higher EF using the default assumption (that expanded crop areas are derived from forest, grassland and perennial crops in equal proportion) than using the relative rates of change. The higher proportion of soybean cultivated on expanded areas in Argentina (76 percent) compared to Brazil (55 percent), combines with the default LUC assumptions, to give Argentina a higher soybean EF than Brazil under PAS 2050-1:2012.

The strength of the *One-Soy* approach is that it recognizes that global demand is a key driver of LUC. However, it penalizes those countries whose production is not directly associated with LUC and may not provide the right signals to producers and consumers of soybean.

In the *reduced time-frame approach*, the emission intensity of soybean cake from Argentina and Brazil reduces by more than half. Average annual deforestation rates appear to be close over the two periods 1990-2006 and 2002-2007 (1.76 and 1.98 million ha respectively, Figure C4), but the average annual rates of soybean expansion differ and they are higher for 2002-2007: between 1990 and 2006, the soybean area in Brazil increased by 534 000 ha/year whereas the increase for the period 2002-2007 was 840 000 ha/year. The lower emission intensity for 2002-2007 therefore results from the rate of deforestation relative to the rate of soybean expansion, not from the absolute change in deforestation rate.

Table C10. Proportion of expanded soybean area derived from each land-use category

Land-use category	GLEAM approach		PAS 2050-1:2012 approach	
	Brazil	Argentina	Brazil	Argentina
	percentage			
Forest	100	22	51 (33)	23 (33)
Grassland	0	0	0 (33)	0 (33)
Shrubland	0	31	0 (0)	0 (0)
Annual cropland	0	44	46 (0)	61 (0)
Perennial cropland	0	0	3 (33)	16 (33)

Note: Figures in brackets are the PAS 2050-1 default land use transformations.
Sources: Based on FAOSTAT (2012).

Figure C4.
Annual forest loss in Brazil

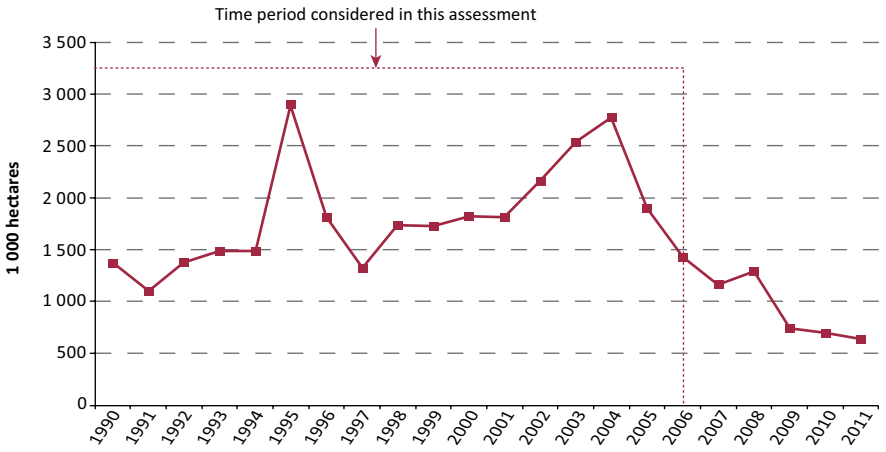

Source: INPE, 2012.

Table C11. Estimated changes in pasture area and annual carbon losses for the reduced time-frame approach

Country	Change in pasture area *(1 000 ha)*	Carbon losses *(tonnes CO_2/ha/year)*
Brazil	3 563.6	- 51.0
Chile	1 079.3	- 51.1
Paraguay	1 464.6	- 48.8
Nicaragua	311.6	- 48.5
Honduras	170.0	- 50.8
Ecuador	No gain in pasture	-
Panama	60.3	- 50.8
El Salvador	45.3	- 50.8
Belize	0.3	- 51.1
Total/average	**6 695.3**	**- 50.4**

Source: Authors' calculations.

For pasture expansion, emissions are highly sensitive to the time period chosen; using a ten-year time-frame scenario, annual carbon losses are 50.4 tonnes CO_2 ha^{-1} yr^{-1} (Table C11) while in the current study annual carbon losses were estimated at 32 tonnes CO_2 ha^{-1} yr^{-1}. Shorter periods, however, place emphasis on deforestation resulting in higher annual carbon losses per hectare placing higher relative weighting of near-term emissions.

4. COMPARISON WITH OTHER STUDIES

The emissions intensity for LUC per kg of soybean and soybean cake calculated in this study are compared with other studies in Table C12. The emissions intensity used in this study is higher than some other studies, but within the overall range.

The emissions intensity of soybean is highly dependent on the calculation method and assumptions (Flysjo *et al.*, 2012). Variation arises from differences in:

- Calculation of C losses in soil and vegetation (above- and below-ground).
- Quantification of land-use transitions – i.e. how much of the LUC can be attributed to cropping.
- Allocation of LUC arising from cropping to specific crops, e.g. emissions are usually allocated to one of the following: (a) soybean grown in country/region; (b) all expanding crops grown in country region; (c) all crops grown globally. This leads to huge variations in the emissions per kg of crop.
- The time period over which emission are allocated.

Table C12. Soybean LUC emissions per unit of output and hectare

Study	Area covered by study	Emissions	*Converted/all soybean /all crops
FAO (2010)	Argentina	1.04 kg CO_2-eq/kg soybean	All soybean
FAO (2010)	Brazil	7.69 kg CO_2-eq/kg soybean cake	All soybean
FAO (2010)	Brazil	8.54 kg CO_2-eq/kg soybean cake	All soybean
FAO (2010)	Brazil	12.81 kg CO_2-eq/kg soybean cake	Converted
FAO (2010)	Brazil	14.23 kg CO_2-eq/kg soybean	Converted
Leip *et al.* (2010) grass>soybean	South America	1.50 kg CO_2-eq/kg soybean cake	All soybean Cited in Flysjo *et al.* (2012)
Leip *et al.* (2010) mix>soybean	South America	3.10 kg CO_2-eq/kg soybean cake	All soybean Cited in Flysjo *et al.* (2012)
Leip *et al.* (2010) forest>soybean	South America	10.00 kg CO_2-eq/kg soybean cake	All soybean Cited in Flysjo *et al.* (2012)
Sonesson *et al.* (2009, p13)	Brazil	1.50 kg CO_2-eq/kg soybean	All soybean ~0.6 of this is due to LUC
Audsley *et al.* (2010, p.59)	Brazil	5.30 kg CO_2-eq/kg soybean	All soybean
Audsley *et al.* (2010, p.59)	Argentina	1.60 kg CO_2-eq/kg soybean	All soybean
Castanheira & Freire (2011)	Low (Argentina)	~0.5 kg CO_2-eq/kg soybean	Converted
Castanheira & Freire (2011)	High (Brazil)	~15 kg CO_2-eq/kg soybean	Converted
Nemecek *et al.* (2012)	Brazil	1.47 kg CO_2-eq/kg soybean	All soybean Brazil, LUC, Ecoinvent v2.2
Nemecek *et al.* (2012)	Brazil	5.21 kg CO_2-eq/kg soybean	All soybean Brazil, LUC, Ecoinvent v3.0
Reijnders & Huijbregts (2008)	Brazil – cerrado	1 to 2.7 kg CO_2-eq/kg soybean	Converted
Reijnders & Huijbregts (2008)	Brazil – forest	5 to 13.9 kg CO_2-eq/kg soybean	Converted
FAO (2010)	Brazil – deforestation	37.00 kg CO_2-eq/ha	Converted
FAO (2010)	Brazil – deforestation	22.20 kg CO_2-eq/ha	All soybean
Audsley *et al.* (2009)	All LUC	1.43 kg CO_2-eq/ha	Allocates LUC to all crops globally
Audsley *et al.* (2010, p.59)	Brazil – deforestation	37.00 kg CO_2-eq/ha	Converted
Audsley *et al.* (2010, p.59)	Brazil – grassland	11.00 kg CO_2-eq/ha	Converted
Reijnders & Huijbregts (2008)	Brazil – forest	14 to 39 kg CO_2-eq/ha	Converted
Schmidt *et al.* (2011)	All LUC	8.42 kg CO_2-eq/ha	Allocates LUC to all crops globally

**EF* for (a) converted land; (b) average over all soybean grown in country/region; or (c) all crops grown globally.

Table C13. Comparison of studies on LUC associated with pasture expansion in Brazil

Study and area	Approach	Scope	Carbon losses *(tonnes CO_2-eq /ha)*
Current study (Brazil)	IPCC stock-based approach (stock difference method) Period: 1990-2006	Biomass Soil carbon Dead organic matter	506.7
Cederberg *et al.*, 2011 (Brazil -Legal Amazon Area)	Net committed emissions approach Period: 1986-2006	Biomass Soil carbon CH_4 and N_2O	572
Leip *et al.*, 2010 (Beef imported into EU from Brazil)	Net committed emissions approach Period: 1986-2006	Biomass Soil carbon CH_4 and N_2O	568.7

For pasture expansion, with the exception of Brazil where impacts of deforestation have been analysed to a greater degree, there are relatively few estimates of the impact of carbon losses the due to deforestation. We therefore compared the results obtained for Brazil with estimates from other studies (Table C13).

Despite the difference in calculation approach, our estimates are very similar to those found in the literature. This may be partly coincidental because the approaches differed in many respects; for example, the period assessed, the calculation method and assumptions and well as emission factors. Cederberg *et al.* (2011) apply different carbon stock losses for the different pools and take into account the impacts on fire used in forest clearing on CO_2 emissions.

The estimates of LUC emissions presented in this report are still very preliminary and need to be interpreted with caution. This is an important area for improvement of GLEAM and it is planned that future developments of the model will include a more detailed and complete assessment of LUC emissions.

5. LAND USE

For the reasons explained above, this analysis could not incorporate C stock changes under constant land use. This section attempts to evaluate the effect of this simplification on results. Given the importance of grasslands as a potential as a C sink (Soussana *et al.*, 2010), we focus our case study on this land use rather than on feed-crops.

Furthermore, we selected the European Union for this evaluation in view of data availability in this region. National inventories in the European Union are indeed increasingly accurate because Member States are requested to maintain and monitor the area of permanent grassland by the Common Agricultural Policy. Member States are required to report annual estimates of their total area of permanent grassland.

Soussana *et al.* (2010) estimate an average grassland C sequestration rate of 5 ± 30 g C/m^2/year for temperate grasslands under baseline, constant land use. This estimate is derived from an exhaustive literature review, and inventories of SOC stocks at regional or local level, mainly from Western Europe.

Using this estimate, we computed that permanent grasslands in the European Union (estimated at 62.7 million ha) represent a sink of 3.1 ± 18.8 million tonnes C per year, equivalent to 11.5 ± 69.0 million tonnes CO_2-eq per year. This estimate

Table C14. Total GHG emissions from the ruminant sector in the European Union and changes in C stocks in permanent pasture

Systems	Total emissions based on a LCA approach and excluding land use[1]	C sequestration in permanent grassland under baseline constant management[2]
	(million tonnes CO_2-eq/year)	
Total ruminant sector	**390.5**	**11.5 ± 69.0**
Cattle, grazing	25.6	
Cattle, mixed	322.8	
Small ruminants, grazing	4.6	
Small ruminants, mixed	37.4	

[1] Based on GLEAM.

[2] Based on Soussana *et al.* (2010).

is compared with the 390.5 million tonnes CO_2-eq emitted yearly by the ruminant sector in the European Union (Table C14).

Taking into account C stock changes in permanent pastures, net emissions from the EU ruminant sector are therefore estimated between 310 and 448 million tonnes CO_2-eq/year.

Net sequestration/emission of C in permanent pasture under stable management practices may thus be significant in the European Union, and should be included in the assessment of GHG emissions of the sector. The estimate computed here is however one order of magnitude smaller than the sum of all other emissions along the supply chain. Furthermore, even in a region where data availability is comparatively high, the uncertainty about C fluxes is such that it cannot be ascertained if permanent grasslands are net sequesters or emitters of carbon.

The European Union only accounts for a limited share of total grassland area (about 2 percent according to FAOSTAT, 2013), so including land use sequestration/emissions could have even greater effects on net emissions of the sector in other regions. For example, Cerri *et al.* (2004) measured that brasilian pastures established in the early 90's could store up to 330 $g.m^{-2}$ of carbon in the 20 first centimeters of soil. This would however require a better understanding SOC dynamics in grasslands and the development of models and databases to monitoring and predicting changes in C stocks.

REFERENCES

Armentano, T.V. & Menges, E.S. 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology*, 74: 755–774.

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C. & Williams, A. 2009. *How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050.* Food Climate Research Network and WWF. UK.

Audsley, E., Angus, A., Chatterton, J., Graves, A., Morris, J., Murphy-Bokern, D., Pearn, K., Sandars, D. & Williams, A. 2010. *Food, land and greenhouse gases. The effect of changes in UK food consumption on land requirements and greenhouse gas emissions.* London: The Committee on Climate Change.

Bickel, U. & Dros, J. M. 2003. *The impacts of soybean cultivation on Brazilian ecosystems.* Bonn, AIDEnvironment-WWF): p 33. (available at http://assets.panda.org/downloads/impactsofsoybean.pdf).

BSI. 2008. PAS 2050:2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. UK: British Standards Institution (BSI).

BSI. 2012. PAS 2050-1:2012. Assessment of life cycle greenhouse gas emissions from horticultural products Supplementary requirements for the cradle to gate stages of GHG assessments of horticultural products undertaken in accordance with PAS 2050. British Standards Institution. London.

Brandao, A.S.P., Castro de Rezende, G. & Da Costa Marques, R.W. 2005. Agricultural growth in the period 1999–2004, outburst in soybeans area and environmental impacts in Brazil. IPEA Discussion Paper No. 1062. Instituto de Pesquisa Econômica Aplicada. Brasilia.

Brown, J.C., Koeppe, M., Coles, B. & Price, K.P. 2005. Soybean production and conversion of tropical forest in the Brazilian Amazon: the case of Vilhena, Rondônia. *Ambio,* 34: 462–9.

Carvalho, G.O., Nepstad, D., McGrath, D., Vera Diaz. M. del C. & Barros, A.C. 2002. Frontier expansion in the Amazon. Balancing development and sustainability. *Environment Sci. Policy Sustainable Dev.*, 44: 32–42.

Castanheira, E. & Freire, F. 2011. *Life-cycle greenhouse gas assessment of soybeans.* Paper presented at Life-Cycle Management Conference, 2011. Berlin.

Cederberg, C., Persson, M.U., Neovius, K., Molander, S. & Clift, R. 2011. Including Carbon Emissions from Deforestation in the Carbon Footprint of Brazilian Beef. *Environmental Science & Technology*, 45 (5): 1773–1779.

Cerri, C.C., Melillo, J.M., Feigl, B.J., Piccolo, M.C., Neill, C., Steudler, P.A., Carvalho, M.S., Godinho, V.P., Cerri, C.E.P. & Bernoux, M. 2005. Recent history of the agriculture of the Brazilian Amazon Basin. *Outlook on Agriculture*, 34(4): 215–223.

Cerri, C.E.P., Paustian, K, Bernoux, M., Victoria, R.L., Melillo, J.M. & Cerri, C.C. 2004. Modelling changes in soil organic matter in Amazon forest to pasture conversion with the Century model. *Global Change Biology*, 10(5):815-832.

Coleman, K., Jenkinson, D.S., Crocker, G.J., Grace, P.R., Klir, J., Korschens, M., Poulton, P.R. & Richter, D.D. 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma* 81: 29–44.

Conant, R.T. & Paustian, K. 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochemical Cycles*, 16(4): 1143. doi:10.1029/2001GB001661.

Costa de Campos, B., Carneiro Amado, T. J., Bayer, C., Nicoloso, Rodrigo da Silveira, & Fiorin, J.E. 2011. Carbon stock and its compartments in a subtropical oxisol under long-term tillage and crop rotation systems. *Rev. Bras. Ciênc. Solo* 35(3): 805-817.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, L., Ojima, D.S. & Schimel, D.S. 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In Shaffer, J., Liwang Ma & S. Hansen, eds. *Modelling carbon and nitrogen dynamics for soil management*, pp. 303-332. Boca Raton, Florida, USA, CRC Press.

Dieckow, J., Zendonadi dos Santos, N., Bayer, C., Molin, R., Favaretto, N. & Pauletti, V. 2010. No-tillage crop rotations, C sequestration and aspects of C saturation in a subtropical Ferralsol. 19th World Congress of Soil Science, Soil Solutions for a Changing World. Brisbane, Australia.

FAO. 2009. *State of the World's Forests 2009*. FAO publication, ISBN 978-92-5-106057-5. Rome, Italy.

FAO-FRA. 2010. *Global Forestry Resource Assessment 2010*. United Nations Food and Agriculture Organization: Rome, 2010.

FAO. 2010. *Greenhouse gas emissions from the dairy sector – A life cycle assessment*, by Gerber, P., Opio, C., Vellinga, T., Herderson, B. & Steinfeld, H. FAO. Rome.

FAOSTAT. 2011. *FAO Statistical Database*. Accessed 2011.

Falloon, P. & Smith, P. 2002. Simulating SOC changes in long-term experiments with RothC and CENTURY: Model evaluation for a regional scale experiment. *Soil Use and Management*, 18: 101–111.

Fearnside, P.M. 2005. Deforestation in Brazilian Amazonia: history, rates and consequences. *Conservation Biology*, 19(3): 680–688.

Flysjö, A., Cederberg, C., Henriksson, M. & Ledgard, S. 2012. The interaction between milk and beef production and emissions from LUC - critical considerations in life cycle assessment and carbon footprint studies of milk. *Journal of Cleaner Production*, 28: 134–142.

Hart, P.B.S. 1984. *Effects of soil type and past cropping on the nitrogen supplying ability of arable soils*. University of Reading, UK.

Hernandez, M., Argel, P.J., Ibrahim, M.A. & Mannetje, L. 1995. Pasture production, diet selection and liveweight gains of cattle grazing *Brachiaria brizantha* with or without *Arachis pintoi* at two stocking rates in the Atlantic zone of Costa Rica. *Trop. Grassl*., 29 (3): 134-141

Houghton, R.A. & Goodale, C.L. 2004. Effects of LUC on the carbon balance of terrestrial ecosystems. In DeFries, R.S., Asner, G.P. & R.A. Houghton, eds. *Ecosystems and Land-use Change*. Washington, D.C., American Geophysical Union.

IPCC. 2000. *Land Use, Land-Use Change, and Forestry*. Cambridge, UK, Cambridge University Press.

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories prepared by the National Greenhause Gas Inventories Programme,* Eggleston, H.S., Buenida, L., Miwa, K., Nagara, T. & Tanabe, K. (eds). Published: IGES, Japan.

Jenkinson, D.S., Hart, P.B.S., Rayner, J.H. & Parry, L.C. 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. *INTECOL Bulletin* 15: 1-8.

Jones, M.B. & Donnelly, A. 2004. Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO_2. *New Phytologist*, 164: 423–439.

Kirschbaum, M.U.F. & Paul, K.I. 2002. Modelling C and N dynamics in forest soils with a modified version of the CENTURY model. *Soil Biology and Biochemistry*, 34: 341–354.

Lal, R. 1999. Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Progress in Environmental Science*, 1: 307–326.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304: 1623–1627.

Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S. & Biala, K. 2010. *Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS) - Final Report*, European Commission, Joint Research Centre.

Li, C., Frolking, S. & Frolking, T.A. 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *Journal of Geophysical Research*, 97(D9): 9759–9776.

Li, C., Frolking, S. & Harriss, R. 1994. Modeling carbon biogeochemistry in agricultural soils. *Global Biogeochem Cycles*, 8: 237–254.

Li, C. 1996. The DNDC model. In D.S. Powlson, P. Smith & J.U. Smith, eds. *Evaluation of Soil Organic Matter Models Using Existing, Long-Term Datasets*, pp. 263–267. NATO ASI Series I, Vol. 38. Heidelberg,Springer-Verlag.

Morton, D.C., DeFries, R.S., Shimabukuro, Y.E., Anderson, L.O., Arai, E., Espiritu-Santo, F. del B., Freitas, R. & Morisette, J. 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *PNAS USA*, 103(39): 14637–41.

Mueller, C.C. 2003. Expansion and Modernization of Agriculture in the Cerrado – The Case of Soybeans in Brazil's Center-West, p. 28.

Murty, D, Kirschbaum, M.U.F, McMurtrie, R.E & McGilvray, H. 2002. Does forest conversion to agricultural land change soil organic carbon and nitrogen? A review of the literature. *Global Change Biology*, 8: 105–123.

Nemecek, T., Weiler, K., Plassmann, K., Schnetzer, J., Gaillard, G., Jefferies, D., Garcia-Suarez, T., King, H. & Milà I Canals L. 2012. Estimation of the variability in global warming potential of worldwide crop production using a modular extrapolation approach. *Journal of Clean Production*, 31: 106–17.

Nepstad, D., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Sschlesinger, P., Lefebvre, P., Alencar, A., Prinz, E., Fiske, G. & Rolla, A. 2006. Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conservation Biology*, 20: 65–73.

Pacheco, P. 2012. Soybean and oil palm expansion in South America: A review of main trends and implications. CIFOR Working Paper 90. Center for International Forestry Research. Bogor, Indonesia.

Parton, W.J., Schimel, D.S., Cole, C.V. & Ojima D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal*, 51: 1173–1179.

Parton,W.J., Hartman, M.D., Ojima, D.S. & Schimel, D.S. 1998. DAYCENT: its land surface submodel: description and testing. *Global Planet Change*, 19: 35–48.

Paustian, K., Cole, C.V., Sauerbeck, D. & Sampson, N. 1998. CO_2 mitigation by agriculture: An overview. *Climatic Change*, 40: 135–162.

Post, W.M. & Kwon, K.C. 2000. Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology*, 6(3): 317–327.

Reijnders, L. & Huijbregts, M.A.J. 2008. Biogenic greenhouse gases linked to the life cycles of biodiesel derived from European rapeseed and Brazilian soybeans. *Journal of Cleaner Production,* 16: 1943-1948.

Schmidt, G.A., Jungclaus, J.H., Ammann, C.M., Bard, E., Braconnot, P., Crowley, T.J., Delaygue, G., Joos, F., Krivova, N.A., Muscheler, R., Otto-Bliesner, B.L., Pongratz, J., Shindell, D.T., Solanki, S.K., Steinhilber, F. & Vieira, L.E.A. 2011. Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0). *Geoscientific Model Development*, 4: 33-45.

Sisti, C.P.J. , dos Santos, H.P., Kohhann, R., Alves, B.J.R., Urquiaga, S. & Boddey R.M. 2004. Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. *Soil & Tillage Research*, 76: 39–58.

Soussana, J.F., Tallec, T. & Blanfort, V. 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal*, 4(3): 334–350.

Smith, P., Smith, J., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M., Reginster, I. & Kankaanpää, S. 2006. Projected changes in mineral soil carbon of European forests, 1990–2100. *Canadian Journal of Soil Science*, 86: 159–169.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. & Sirotenko, O. 2007. Agriculture. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave & L.A. Meyer, eds. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC*). New York, Cambridge University Press.

Sonesson, U., Cederberg, C. & Berglund, M. 2009. *Greenhouse gas emissions in animal feed production decision support for climate certification*. Uppsala, Sweden. Available online: http://www.klimatmarkningen.se/wp-content/uploads/2009/12/2009-2-feed.pdf

Vieira, F. C. B., Bayer, C., Zanatta, J.A., Mielniczuk, J. & Six, J. 2009. Building Up Organic Matter in a Subtropical Paleudult under Legume Cover-Crop-Based Rotations. *Soil Science Society of America Journal*, 73(5): 1699-1706.

Wassenaar, T., Gerber, P., Verburg, M., Rosales, M., Ibrahim, M. & Steinfeld, H. 2007. Projecting land-use changes in the Neotropics: The Geography of Pasture Expansion into Forest. *Global Environmental Change*, 17: 86–104.

APPENDIX D

Postfarm emissions

GHG emissions accounted for in the post farmgate part of the supply chain include emissions related to fuel combustion and energy use in the transport, processing and refrigeration of products. The system boundary is from the farmgate up to the retail point. During this phase of the life cycle, three distinct emission streams were studied: emissions from the transport and distribution of live animals, milk and meat (domestic and international); GHG emissions from processing and refrigeration; and emissions related to the production of packaging material.

The system boundary for this part of the food chain included emissions from the farmgate to the retail distribution centre. Excluded from the analysis were estimates of GHG emissions from on-site waste-water treatment facilities, emissions from animal waste[18] at the slaughter site, the retail and consumption part of the food chain (household transport and preparation) and disposal of packaging and waste, which fall outside the scope of the system boundary studied but may warrant further research. Due to the lack of data, emissions related to by-products (rendering material, offal, etc.) are therefore currently excluded. However, we investigated the impact of allocating emissions to slaughter by-products (Appendix F).

1. APPROACH AND ASSUMPTIONS

1.1 Milk from ruminant species

The quantification of post farmgate emissions for milk produced by cattle, small ruminants and buffalo was based on a similar approach. The approach (and level of complexity) was largely influenced by two factors: the importance of the subsectors contribution to global milk production and the availability of data. Consequently, a more comprehensive approach was applied to the milk from the global cattle dairy sector, as outlined in FAO's report on GHG emissions in the dairy sector published in 2010.[19]

In the estimation of post farmgate emissions for small ruminant and buffalo milk, a similar but simplified approach was adopted; for small ruminants, it was assumed that all milk that left the farm was processed into cheese. FAOSTAT production statistics on goat and sheep cheese production were used to identify countries where cheese production is important. In producing countries with no cheese production, the sheep and goat milk was assumed to be consumed on farm and hence no post farmgate emissions were estimated for these countries. In addition, since not all milk is processed and traded, the proportion of small ruminant milk leaving the farm was estimated from the cheese production and total milk production within the country.

[18] In some countries, manure/slurry from the slaughterhouse is anaerobically digested and the biogas is used for heating and electricity. The challenge is that there insufficient information available on on-site energy generation from animal waste; thus, the resulting substituted energy and avoided GHG emissions are not considered in the calculations.

[19] FAO. 2010. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf

The difference in calculation approach between cow's milk and buffalo milk is that for dairy cattle milk six products were considered (processed milk, cheese, whey, yoghurt, skimmed milk powder and whole milk powder), while post farmgate emissions for buffalo milk comprised emissions related to transport and processing of raw milk into processed milk. Emissions related to international trade of dairy products was only considered for the cattle dairy sector.

1.2 Meat from ruminant species

GHG emissions reported for this part of the food chain are based on the finished product leaving the facility and do not account for meat co-products and rendering products; however, in a life cycle assessment, when a system produces multiple products each of which have economic value, it is standard practice to assign some of the emissions from that process to each of the co-products.

In this analysis, all emissions were allocated to the carcass and therefore meat carries the whole burden. Post farmgate emissions for meat include: emissions associated with the transport of live animals to slaughterhouses, emissions related to slaughter and primary processing of carcasses, refrigeration of carcasses at processing plant and transport and refrigeration of product. Emissions related to international trade of meat products (carcasses and boneless meat) are taken into account. Due to the complexity of tracking trade flows of live animals the related emissions are excluded from this analysis.

2. ENERGY CONSUMPTION

Energy consumption is the most important source of GHG emissions from the post farmgate supply food chain. Table D1 presents average regional and country CO_2 emission coefficients applied in this analysis. The CO_2 intensities are determined by the composition of the energy sources employed and average GHG emissions from electricity consumption was modelled as a mix of existing electricity sources (e.g. coal, hydro, nuclear, oil, etc.) in different countries and regions taken from the International Energy Agency (IEA, 2009).

Table D1. Average regional specific CO_2 emissions per MJ from electricity and heat generation

Region/country	CO_2 emissions *(g CO_2/MJ)*
Europe 27	99
North America	142
Australia	254
New Zealand	84
Japan	120
Other Pacific	139
Russian Federation	90
Latin America	54
Asia (excluding China)	202
China	216
Africa	175

Source: IEA (2009).

The variation in CO_2 intensity is explained by the different energy sources and energy mixes utilized in different regions and countries. For example, regions such as Asia and Africa, and countries like Australia that rely on coal as their dominant source of energy for electricity production, have on average higher CO_2 emissions compared with Latin America and New Zealand with lower CO_2 emissions per MJ produced owing to the higher proportion of electricity that is based on renewable resources like hydroelectric power which are recognized to be carbon neutral.

3. EMISSIONS RELATED TO TRANSPORT

The food sector is transport-intensive – large quantities of food are transported in large volumes and over long distances. This can sometimes be of significance but, in terms of the overall contribution to the life cycle carbon footprint of a product, most LCA studies have found that the contribution of transport is relatively small. The carbon implications of food transport is not only a question of distance; a number of other variables, such as transport mode, efficiency of transport loads and the condition of infrastructure (road quality), fuel type, etc., are important determinants of the carbon intensity of products.

The efficiency of different transport modes varies considerably. Transport modes differ significantly in energy intensity and hence GHG emissions. Air transport has a very high climate change impact per tonne transported, whereas sea transport is relatively efficient. Long-distance transport by ship is very energy efficient, with estimates between 10 and 70 g CO_2 per tonnes-km, compared with estimates of 20-120 and 80-250 g CO_2 per tonnes-km for rail and road, respectively (Marintek, 2008). Poor road infrastructure has an impact on the emission per unit product transported because it increases fuel consumption. Cederberg *et al.* (2009) found that, in Brazil, due to generally poor road conditions, the consumption of diesel was estimated to be 25 percent higher than under normal road conditions. Different loads also affect the efficiency of utilization of transport per unit of product. Larger loads transported for longer distances are more efficient than lighter loads transported over shorter distances.

During transportation, food also often requires refrigeration which increases the use of energy and also introduces leakage of refrigerants into the GHG emissions equation (refrigerants are often high in climate impact).

Emissions related to transport were estimated for the different phases, that is, transportation of live animals from the farm to the slaughter plant and transportation of the processed product from plant to retail centre for distribution. In the case of international trade, emissions were calculated for transport from slaughter plant to the port of export to the retail point for distribution. In an effort to estimate the contribution of international freight transport to GHG emissions, we combined data on trade flows, transportation mode, transport EFs and distances.

The following sections provide a detailed description of the methodology and the assumptions used in the estimation of emissions associated with the transport of live animals and meat. For the approach on milk, a detailed description is provided in FAO's report on GHG emissions in the dairy sector published in 2010.[20]

[20] FAO. 2010. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf

3.1 Transport of live animals from the farm to slaughter plant

Due to the complexity of live animal movements and data limitations, several simplifications and assumptions were made:

- *Share of animals transported to slaughter plants*: Not all animals produced are slaughtered in slaughter plants/abattoirs; slaughtering may also take place on-farm or may be carried out by local butchers within the vicinity of production and thus may not involve the transportation of live animals. For industrialized countries, it was assumed that about 98 percent of the animals are slaughtered in slaughterhouses. In developing countries, the share of animals transported to slaughter plants varied between 15 and 75 percent. A lower share was assumed for developing countries based on the assumption that slaughtering infrastructure is generally lacking and that animals are often slaughtered in closer proximity to where they are raised, with slaughter being carried out by local butchers or the household itself. Other factors taken into consideration include the importance of exports within the economy, where we assumed that key exporting developing countries such as Brazil, Argentina, Paraguay, Botswana and Namibia (due to phytosanitary requirements of importing countries) would have a higher share of animals slaughtered in slaughter plants.
- *Average distance between farm and slaughter plant*: Data on distances between the farm and slaughter plants was taken from literature for industrialized regions: an average distance of 80 km for Europe and 200 km for North America. In developing countries, due to poor infrastructure, slaughter is assumed to take place near the point of sale: an average distance of 50 km was assumed.
- *Mode of transport:* We assumed that a greater proportion of live animals was transported by road.
- *Emission intensity per kg of carcass transported*: Based on secondary data, two average coefficients were utilized in this study for two groupings of countries: 0.21 and 0.38 kg CO_2-eq per tonnes CW-km for industrialized and developing countries, respectively.

Transport emissions of livestock between the farm and the slaughter plant were calculated using the equation below:

$$GHG_{transport}^{farm\text{-}slaughterplant} = D_{farm\text{-}plant} \cdot ef_{transport} \cdot sh_{live\ animal}^{farm\text{-}plant}$$

where:

$GHG_{transport}^{farm\text{-}slaughterplant}$ = GHG emission intensity, kg CO_2-eq/kg CW-km

$D_{farm\text{-}plant}$ = average distance between farm and slaughter plant, km

$ef_{transport}$ = average EF for transport, kg CO_2-eq/kg CW-km

$sh_{live\ animal}^{farm\text{-}plant}$ = share of animals transported from farm to slaughter plant, percentage

Table D2. Emission intensity for road transport

	Winther *et al*. 2009, *(100 percent)**	Winther *et al*. 2009, *(100 percent)**	Ecoinvent, *(100 percent)**	Ecoinvent, *(70 percent)**	Ecoinvent, *(90 percent)**	AEA 2008	Cederberg *et al*. 2009
	(kg CO_2-eq/tonnes CW-km)						
Articulated lorry, max load 32 tonne							0.11
Lorry, chilled, max load 20 tonne	0.085	0.102	0.18	0.16	0.14	0.08-0.25	
Lorry, frozen, max load 20 tonne	0.073	0.099	0.19	0.17	0.15	0.08-0.25	0.145

Note: Emission intensities also include emissions related to leakage of cooling agents.

* The EFs represent the percentage of the vehicle utilized and accounts for the fact that vehicles will not be fully utilized at all times.

Source: SIK (2010).

3.2 Transport and distribution of meat from processing plant to retail point

The calculation of GHG emissions associated with meat transport included the transport of meat from slaughter plant to a retail distribution point. Transport and distribution emissions sources comprise emissions from fuel combustion during transport, as well as emissions from energy consumption for refrigeration and refrigerant leakage from chilled vehicles or container ships. Two modes of transport were considered in this phase: refrigerated road transport and marine transport.

Road transport. Refrigerated road transport covered here refers to transport between the processing plant and the domestic market and, in the case of international trade, transport from plant to port and entry port to retail distribution centre in importing country. Table D2 presents emission intensities for different modes of road transport taken from peer-reviewed studies and databases such as Ecoinvent. Average emission intensities were found to vary depending on the transport load (tonnage), transport utilization and type of product transported (chilled or frozen).

In this study, the following average emission intensity values presented in Table D3 below were used. Regarding the transport of meat from processing plant directly to the domestic retail, we assumed that the product is transported as chilled carcass by a small vehicle with a maximum load of 20 tonnes within a minimum retail distance of 50 km.

Ocean transport. In 2005, about 6.5 and 0.97 million tonnes of beef and lamb were traded globally (FAOSTAT, 2012). Emissions from the international trade of meat were calculated on the basis of the amount and type of product traded, distances

Table D3. Average emissions intensities associated with road transport from plant to retail

	Chilled	Frozen
	(kg CO_2-eq/tonnes CW-km)	
Carcass	0.18	0.20
Boneless	0.117	0.130

Source: SIK (2010).

between the slaughterhouse and retail centre, and the average GHG emission per kg of product transported.

- *Trade:* A trade matrix was developed based on FAOSTAT trade flow data in order to determine key exporters (Table D4 as an example), destinations and quantities traded. This analysis covers almost 85 percent of the total amount of beef and lamb traded globally. A distinction is made between the type of meat traded (whether carcass or boneless) because it has implications for the amount of energy used for refrigeration during transportation and consequently CO_2 emissions.
- *Distance:* Distances were estimated between the major exporting and importing ports and it was assumed that the traded product was destined to major cities which are key population and consumption hubs. Emissions were calculated for the average distance for transport between the exporting country and importing country (port to port) and the transit distance inside the importing country to main retail centre. Distance matrices were estimated from http://sea-distances.com/index.htm and http://www.distances.com/.
- *Vessel size:* It was assumed that smaller ships are utilized for shorter distances (e.g. transport of products within regions) and larger ships for longer distances such as inter-continental trade. Table D5 presents emission intensities for ocean transport taken from secondary sources and demonstrates the variation in emission intensity for different vessel sizes.

Table D4. International trade in beef, 2005

Key exporters	tonnes
Brazil	1 285 805
Australia	991 945
USA	439 862
Ireland	363 372
Netherlands	351 757
New Zealand	344 289
Germany	335 044
Canada	323 729
Argentina	297 091
Uruguay	249 609
Total	**6 316 672**

Source: FAOSTAT (2011).

Table D5. Emission intensity for ocean transport

Container ship	Winther *et al.* (2009)	AEA (2008)	Cederberg *et al.* (2009)	Ecoinvent
	(kg CO_2-eq/tonnes CW-km)			
Large, chilled/frozen	0.037	0.018	0.014	0.011
Small, chilled/frozen	0.056		0.061	0.043

Note: Emission intensities also include emissions include related to leakage of cooling agents.
Source: SIK (2010).

Based on secondary data, the average emission intensities applied were 0.025 and 0.05 kg CO_2-eq per tonne product (CW) transported per km for large and small container ships transporting carcasses, respectively and 0.014 and 0.029 kg CO_2-eq per tonne CW per km for large and small container ships transporting bone-free meat.

To manage the versatile nature and complexity of trade flows, we only accounted for trade from and to the most significant trading partners.

4. EMISSIONS RELATED TO SLAUGHTER AND PRIMARY PROCESSING OF MEAT

GHG emissions assessed here include emissions from the direct inputs of energy in the slaughter and primary processing of meat and milk, as well as the GHG emissions related to use and leakage of refrigerants. The meat sector also produces a range of co-products including by-products such as bones, blood, fat, offal, feather, etc. Due to the lack of data on the total amount of raw material rendered, this analysis does not take into account emissions associated with the co-products.

Average energy use per kg of carcass weight during slaughter was based on studies from Sweden (Anon, 2002), Denmark, Finland and Spain (Lafargue, 2007) and the European Union (Ramirez *et al*., 2006). Due to the limited data on energy use during this phase, in this study we assumed an average value of 1.4 MJ/kg CW and 4.5 MJ/kg CW for beef and lamb, respectively. Slaughterhouse emissions were calculated by combining this average value with the average regional specific CO_2 emissions per MJ of energy (taking into account regional/country electricity generating mixes) given in Table D1 to obtain the average GHG emissions per kg of carcass processed. Table D6 presents regional average emission factors for processed beef and lamb and mutton and illustrates the importance of energy source as well as the energy intensity associated with the processing of different meat. Compared with beef, processing of lamb and mutton on average has higher emission intensity per kg product processed because of the high energy intensity of the process (4.5 MJ/kg CW) and, when combined with high emitting energy sources such as coal, the emission intensity is high as is the case in Australia (Table D6).

Table D6. Regional emission factors for processing of beef and lamb

Region	Beef	Lamb and mutton
	(kg CO_2-eq/tonnes CW-km)	
EU27	0.14	0.45
North America	0.20	0.64
Australia	0.40	1.14
New Zealand	0.12	0.38
Japan	0.17	0.54
Other Pacific	0.20	0.63
Russian Federation	0.13	0.41
Latin America	0.07	0.24
Asia (excluding China)	0.30	0.91
China	0.30	0.97
Africa	0.25	0.78

Source: Authors' calculations.

5. EMISSIONS RELATED TO PRODUCTION OF PACKAGING MATERIALS

Packaging is a fundamental element of almost every food product and a vital source of environmental burden and waste. The type of packaging used also influences transport efficiency because it has its own weight but also because it affects the weight/volume ratio of the product. Two types of packaging can be distinguished: primary packaging and secondary packaging. Primary packaging is packaging closest to the product and often follows the product all the way to the consumer. Secondary packaging is used to assemble together primary packaging to shelter the product during transport and make it possible to transport more of the product at a time. The climate impact of packaging is one of the least studied aspects within the food chain. Due to the lack of data on the global variations in packaging of meat, this study applied 0.05 kg CO_2-eq per kg CW for both primary and secondary packaging from slaughter-plant to retail.

REFERENCES

AEA. 2008. *Comparative Life Cycle Assessment of Food Commodities Produced for UK Consumption through a Diversity of Supply Chains.* Appendix 3 – Post Farm Gate Activity Data. Cranfield University. Report to Defra 2008.

Anon. 2002. *Maten och miljön Livscykelanalys av sju livsmedel,* (Food and the environment Life Cycle Assessment of seven food items). LRF, Sweden.

Cederberg, C., Meyer, D. & Flysjö, A. 2009. *Life cycle inventory of greenhouse gas emissions and use of land and energy in Brazilian beef production.* SIK Report No 792.

Ecoinvent. 2009. Swiss Centre for Life Cycle Inventories database. Available at http://www.ecoinvent.ch/.

FAO. 2010. *Greenhouse gas emissions from the dairy sector – A life cycle assessment*, by Gerber, P., Opio, C., Vellinga, T., Herderson, B. & Steinfeld, H. FAO. Rome.

FAOSTAT. 2011. FAO Statistical Database. Accessed 2011.

FAOSTAT. 2012. FAO Statistical Database. Accessed 2012.

IEA. 2009. CO_2 emissions from fuel combustion. IEA Statistics. International Energy Agency. Paris.

Lafargue, P.L. 2007. *LCA of Spanish meals with different protein sources.* Master's thesis, Dept. of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden.

MARINTEK. 2008. Updated Study on Greenhouse Gas Emissions from Ships Phase 1 – Preliminary results Presented to First Inter-sessional Meeting of the Working Group on GHG Emissions from Ships, June 24, 2008.

Ramírez, C.A., Patel, M. & Blok, K. 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. *Energy,* 31(12): 2047–2063.

Winther, U., Ziegler, F., Hognes, E.S., Emanuelsson, A., Sund, V. & Ellingsen, H. 2009. *Carbon footprint and energy use of Norwegian seafood products.* Sintef Report SFH80 AH096068.

APPENDIX E

Emissions related to energy use

This appendix presents the approach and coefficients applied in this study for estimating GHG emissions from direct on-farm energy use (non-feed related) and embedded energy in farm buildings and equipment. Direct and indirect emissions were estimated for all ruminant species; a general approach is used for all species with a few modifications taking into account differences between production typologies and species, but also between herd (dairy and beef).

1. INDIRECT (EMBEDDED ENERGY): EMISSIONS RELATED TO CAPITAL GOODS

Capital goods including machinery, tools and equipment, buildings such animal housing, forage and manure storage are a means of production. Though not often considered in LCAs, capital goods carry with them embodied emissions associated with manufacture and maintenance. These emissions are primarily caused by the energy used to extract and process typical materials that make up capital goods such as steel, concrete or wood. This assessment focuses on the quantification of embedded energy in capital goods including farm buildings (animal housing, feed and manure storage facilities) and farm equipment such as milking and cooling equipment, tractors and irrigation systems.

To determine the effective annual energy requirement, the total embodied energy of the capital energy inputs was discounted and we assumed a straight-line depreciation of 20 years for buildings, 10 years for machinery and equipment and 30 years for irrigation systems. A simplified approach was adopted in the calculations; emission coefficients were defined for the dairy cattle sector and these were then extrapolated to the beef cattle, buffalo and small ruminant sector.

1.1 Farm infrastructure

Emissions of a representative set of farm buildings were calculated from typical material of building components, including steel, concrete and wood used in the construction of animal housing, manure storage and feed storage facilities. Data related to the density of the building material was taken from various sources and literature.

- *Animal housing*: Five different levels of housing were defined with varying degrees of quality and emissions related to these were calculated (Table E1). These five housing types were then distributed across the different production systems (grassland and mixed), AEZs (arid, humid and temperate), and country grouping [OECD, least developed countries (LDCs) and other developing countries] based on the level of economic development. The percentage allocated for the different values of housing was based on two criteria: (i) livestock density in the two production systems and three AEZs based on number of adult females; and (ii) the average milk yield per cow per year. Tables E2 and E3 illustrate the allocation of embedded energy in small ruminant housing in arid zones in OECD countries and the average emission factor (accounting for depreciation).

Table E1. Typology of animal housing considered in this assessment

Level of investment and definition	Characteristics			Production system
	Floor, foundation, walls	**Roof, roof-frame**	**Supports**	
High: *high technology and use of high quality materials*	Material: concrete	Material: steel	- Stanchions - Columns - Rafters	- Industrial units - Peri-urban - Fattening units
Average: *intermediate level of technology and use of good quality materials*	Without walls; or ½ walls (concrete)		- Stanchions - Columns - Rafters	- Peri-urban - Fattening units - Mixed systems
Low	No walls, floor not paved	Material: steel	Material: Steel	Mixed systems
Very low	Cement floor or unpaved floor (dirt) No walls	Material: steel for roof	Local/hand-made material e.g. wood for columns/ rafters	- Mixed systems - Peri-urban
Nil: *situation with no housing or existing shelter such as kraals made from local materials (wood, manure) and no embedded energy involved.*				

Source: Authors.

Table E2. An example of a life cycle inventory for a high investment structure for small ruminants

Material	Structure	GWP_{100} *(kg CO_2-eq[1])*	Quantity of material per unit *(kg of material/25 kg LW - AFSR[2])*	Emission intensity *(kg CO_2-eq/25 kg LW AFSR[2])*
		A	B	C= A/B
Concrete	Floor	262.61	0.10	26.3
Concrete	Support – foundation	262.61	0.03	6.8
Steel – structural	Support – stanchions	1.79	0.52	21.0
Steel – structural	Roof frame – rafters	1.79	0.89	9.6
Steel – structural	Roof frame – purlins	1.79	1.04	3.1
Bricks – concrete	Walls	262.61	0.03	4.7
Galvanized metal – shed	Roof	1.79	1.07	4.1
Total				**83.7**

[1] Data taken from Ecoinvent database.
[2] AFSR: Adult Female Small Ruminant.
Source: Authors' calculations.

Table E3. Allocation of embedded energy in housing – an example for small ruminants in arid zones in OECD countries

Country grouping	Level of investment	Emission intensity *(kg CO_2-eq/25 kg LW AFSR[1])*	Allocation *(percentage)*	Emission factor *(kg CO_2-eq/25 kg LW AFSR[1])*
OECD	High	83.7	20	16.7
	Average	76.7	20	15.3
	Low	47.0	50	23.5
	Very low	10.5	-	0.0
	Nil	0.00	10	0.0
Total			100	**55.6**
Depreciation (20 years)				**2.8**

[1] AFSR: Adult Female Small Ruminant.

- *Manure storage:* The calculation for energy embodied in manure storage facilities was based on a similar methodology and allocation technique outlined above. As capital investment, only a platform of concrete was considered and calculated as a percentage of the floor-surface of the standard shelter (25 percent on 90 days and 50 percent on 180 days of manure storage). The period of manure storage considered includes 90 days in arid and humid areas and 180 days in temperate days in both grassland and mixed systems. Although liquid manure storage plays an important role in industrialized regions particularly for dairy, only solid manure storage was considered for this assessment.
- *Feed storage:* The calculation for energy embodied in feed storage facilities was based on a similar methodology and allocation technique outlined for housing and manure storage. The period of feed storage considered includes 90 days in arid and humid areas and 180 days in temperate days in both grassland and mixed systems. Due to their importance in a majority of countries, only hay and straw were used as the basis for feed density. The required volume of storage capacity was calculated on the basis of roughage requirements (based on 2 percent intake of DM) and the Bulk Specific Weight and Density[21] for hay and straw. The quality of the feed storage was assumed to be similar to the animal housing infrastructure.

1.2 Farm equipment

Emissions embodied in farm equipment were calculated on the basis of the five levels of farm infrastructure (ranging from nil to high), with allocation criteria similar to those outlined for farm infrastructure. For these calculations, farm equipment was divided into three categories: tractors, tractor implements and hand tools; milking and milk storage equipment; and irrigation facilities. Emissions related to steel were derived from the Ecoinvent database.

- *Tractors, implements and hand tools*: The calculation for energy used in the manufacture of tractors and tractor implements and tools is related to the number of tractors used per hectare; an average weight of steel per hectare based on Dyer and Desjardins (2005); and the stocking rate of adult females per hectare. It is assumed that in areas with over 1 000 ha per tractor, the use of hand tools is prevalent and for these situations we estimated 5kg of hand tools.
- *Milking and storage/cooling equipment*: Equipment taken into account includes bulk tanks and cans, post bars, vacuum pump, pipelines, plate cooler units. Table E4 presents the milking and storage/cooling equipment considered in this study.
- *Irrigation systems*: Two basic types of irrigation systems were considered: border strip and spray irrigation and were applicable only to the high and average level of investment farm. Due to the lack of more recent data, the calculation for energy embodied in irrigation systems is based on the approach used by Wells (1998).

[21] This is a measurement of a feed's mass (weight) per unit volume of space the feed occupies; the standard unit is kg/m^3.

Table E4. Milking, cooling and storage equipment considered in this assessment

Equipment	Description
Coolers	Medium-scale herd composed of 40 cows producing 20 l/day (milked twice a day); using a tank of 1600 litres Small-scale herd composed of 14 cows producing 20 l/day (milked twice a day); using 10 cans of 60 litres each
Post bars	Medium-scale herd – 4+4 posts steel made Medium-scale herd – 2 posts wood made
Pipeline	Medium-scale herd – double pipeline set suspended over the central corridor
Milking vacuum pump	Medium-scale herd – consider an average typology: 2 mobile and 1 fixed floor
Cooling system	Medium-scale herd – consider an average value among low, medium, high

Source: Authors.

Table E5 presents average emission factors for embedded energy for on-farm capital goods in dairy cattle production. For beef cattle and buffalo, we took a simplified approach by applying 50 percent of the EF coefficient calculated for dairy cattle. Emission factors used for small ruminant dairy are presented in Table E6 and a similar approach of applying 50 percent of the EFs to small ruminant meat herds was adopted.

2. DIRECT ENERGY: EMISSIONS RELATED TO ON-FARM ENERGY USE

On-farm energy in ruminant production relates to the use of energy for milking, milk pumping, on-farm cooling of milk, ventilation, heating and lighting, water heating, watering and feeding of animals.

Various studies have estimated the amount of direct energy used on farm (Barrington *et al*., 1999; Dalgaard *et al*., 2000; Cederberg and Mattsson, 2000; ADAS, 2000; Haas *et al*., 2001; Wells, 2001; Ludington and Johnston, 2003; Barber and Pellow, 2005; Casey and Holden, 2005; Dyer and Desjardins, 2006; Saunders and Barber, 2007; DEFRA, 2007a, 2007b; Schils *et al.*, 2007; FEC, 2008; Horndahl, 2008; DairyCo, 2009; Thomassen *et al*., 2008; CAFRE, 2009; Bestfootforward (personal communication, 2010); ATTRA, 2010; Williams *et al*., 2010; Rotz *et al.*, 2010). Based on these studies, it is estimated that the average energy use is 0.219 kWh/kg raw milk.

It is however difficult to make an accurate estimate of the average energy use for these individual farm processes as well as the type of energy used because of the lack of disaggregated data. However, four studies (Bestfootforward (personal communication, 2010); Ludington and Johnston, 2003; DEFRA, 2007b); and Thomassen *et al*., 2009) provide a breakdown by source, which indicates that 38 percent of total direct energy consumed on-farm is electricity and 62 percent non-electricity. Using the results above (i.e. total direct energy use is 0.219 kWh/kg raw milk, which is split 38:62 electricity: non-electricity) and assuming that the main non-electricity use is diesel, the emissions can be calculated, see Table E7. The two coefficients (0.083 and 0.135 kWh/kg milk) are used in the calculation of the EFs for on-farm direct energy use.

Countries were ranked by milk yield, then categorized into five groups (representing the five categories of dairy farm mechanisation: High, Average, Low, Very low, Nil). Energy use will vary between these five levels. It was assumed that the

Table E5. Average emission factors for embedded energy for dairy cattle

Grouping	System	Capital goods	Arid (kg CO_2-eq/ 100 kg LW)	Humid (kg CO_2-eq/ 100 kg LW)	Temperate (kg CO_2-eq/ 100 kg LW)
OECD	Grassland based	Buildings	4.42	4.72	9.03
		Machinery & Implements	13.78	16.22	28.16
	Mixed based[1]	Buildings	4.89	5.08	9.55
		Machinery & Implements	16.22	19.03	30.23
LDC countries	Grassland based	Buildings	0.68	0.68	0.83
		Machinery & Implements	1.35	1.35	1.35
	Mixed based[1]	Buildings	1.33	1.33	1.89
		Machinery & Implements	1.98	1.98	1.98
Non-OECD	Grassland based	Buildings	1.71	2.31	3.32
		Machinery & Implements	2.94	5.85	4.04
	Mixed based[1]	Buildings	2.38	3.04	6.64
		Machinery & Implements	3.56	6.62	18.55

[1] Includes landless systems
Source: Authors' calculations.

Table E6. Average emission factors for embedded energy for dairy sheep and goats

Grouping	Production system	kg CO_2-eq/25 kg LW	kg CO_2-eq/100 kg LW
LDC	Arid	1.00	0.04
	Humid	0.82	0.03
	Temperate	0.73	0.03
OECD	Arid	5.65	0.23
	Humid	5.05	0.20
	Temperate	6.76	0.27
Other developing	Arid	2.01	0.08
	Humid	2.62	0.11
	Temperate	6.01	0.24

Source: Authors' calculations.

Table E7. Total on-farm direct energy use and associated emissions for high level dairy farms

Category	Rate of energy use (kWh/kg milk)	Emissions (kg CO_2-eq/kWh)	Emissions (kg CO_2-eq/kg milk)
Electricity	0.08	0.54	0.05
Non-electricity	0.14	0.27	0.04
Total			**0.08**

Source: Authors' calculations.

Table E8. Emissions from direct energy for different levels of mechanization

Category	Rate of electricity use	Rate of non-electricity	Emissions from electricity	Emissions from non-electricity	Total emissions from direct energy
	(kWh/kg milk)		*(kg CO_2-eq/kg milk)*		
High	0.08	0.14	0.05	0.04	**0.08**
Average	0.08	0.07	0.05	0.02	**0.06**
Low	0.08	0.03	0.05	0.01	**0.05**
Very low	0.00	0.01	0.00	0.00	**0.00**
Nil	0.00	0.00	0.00	0.00	**0.00**

Source: Authors' calculations.

Table E9. Emission factors for direct on-farm energy use for dairy cow milk production in OECD and non-OECD countries

Region	Electricity EF[1]	Default global EF	Grassland			Mixed		
	($kgCO_2$/kWh)							
Unadjusted EF			**Arid**	**Humid**	**Temperate**	**Arid**	**Humid**	**Temperate**
Europe (Unadjusted EF)			0.071	0.072	0.074	0.072	0.074	0.074
Developing countries			0.020	0.020	0.020	0.027	0.027	0.027
Non-OECD			0.038	0.044	0.05	0.045	0.054	0.062
Adjusted emission factors								
EU-27	0.36	0.54	0.059	0.060	0.061	0.060	0.061	0.061
OECD-Europe	0.34	0.54	0.058	0.059	0.060	0.059	0.060	0.060
USA	0.54	0.54	0.071	0.072	0.074	0.072	0.074	0.074
Canada	0.19	0.54	0.048	0.049	0.050	0.049	0.050	0.050
OECD North America	0.50	0.54	0.068	0.069	0.071	0.069	0.071	0.071
Australia	0.90	0.54	0.094	0.095	0.098	0.095	0.098	0.098
Japan	0.44	0.54	0.064	0.065	0.067	0.065	0.067	0.067
South Korea	0.46	0.54	0.066	0.067	0.068	0.067	0.068	0.068
New Zealand	0.21	0.54	0.049	0.050	0.051	0.050	0.051	0.051

[1] IEA (2010).

Source: Authors' calculations.

rate of electricity use would be the same for high, average and low systems, where milking activities are largely mechanized. It was further assumed that no electricity is used in very low and nil level systems. For the allocation across the five categories, the median adult female (ADF) weight and milk yield were used and the milk yield per kg of ADF calculated for each category. Table E8 presents the emission intensity of milk from direct on-farm energy use for the different levels of mechanization.

On-farm energy use was then adjusted to reflect the variations across farming systems in terms of level of mechanisation and energy use efficiency. It was assumed that 50 percent of OECD emissions are from electricity. The EFs for OECD countries were adjusted to take into account variations in the amount of CO_2 emitted per kWh electricity. It was assumed that non-OECD countries do not use mains electricity, and standard emission factors are used for diesel/petrol (which means

Table E10. Regional emission factors for direct on-farm energy use

Region	Beef: grassland based	Beef: mixed	Sheep and goats: meat
	kg CO_2-eq/kg LW		
Europe			
EU27	0.18	0.21	0.33
OECD-Europe	0.17	0.21	0.33
Non-OECD Europe	0.07	0.09	0.19
North America			
USA	0.24	0.29	0.34
Canada	0.12	0.15	0.31
Other	0.22	0.27	0.34
Pacific			
Australia	0.36	0.42	0.38
Japan	0.20	0.24	0.33
South Korea	0.21	0.25	0.34
New Zealand	0.12	0.16	0.31
OECD Pacific	0.22	0.27	0.34
Pacific average	0.00	0.00	0.34
Non-OECD Pacific	0.00	0.00	0.17
Former Soviet Union	0.07	0.09	0.16
Latin America			
Brazil	0.07	0.09	0.15
Other	0.07	0.09	0.16
Asia			
India	0.07	0.09	0.19
China	0.07	0.09	0.18
Thailand	0.07	0.09	0.17
Other	0.07	0.09	0.18
Africa	0.07	0.09	0.18
Middle East	0.07	0.09	0.18

Source: Authors' calculations.

that emissions in some countries, e.g. Brazil, will be overestimated). Table E9 presents the adjusted EFs for direct on-farm energy use for milk production in OECD countries and EFs for non-OECD countries.

Direct on-farm energy for non-dairy herd (beef cattle, buffalo, small ruminant meat herd/flock): Direct energy use is associated primarily with the handling of manure, bedding and feed, which are dependent on the system (i.e. grass or mixed) and the level of mechanization, rather than the climate. Therefore it was assumed that the energy use for a given mechanization level and system is independent of climate. We assumed that minimal direct energy use is associated with meat production was assumed –in developing regions - low levels housing and mechanized feed, bedding manure handling. Table E10 presents regional EFs for direct on-farm energy use for ruminant meat production used in this assessment.

REFERENCES

ADAS. 2000. Energy use in organic farming systems OF0182. ADAS Consulting Ltd. Terrington, UK. Available at http://orgprints.org/8169/

ATTRA. 2010. Dairy Farm Energy Efficiency. Available at www.attra.ncat.org/attra-pub/PDF/dairyenergy.pdf

Barber, A. & Pellow, G. 2005. Energy Use and Efficiency Measures For the New Zealand Dairy Farming Industry. AgriLINK New Zealand Ltd.

Barrington, S., Choiniere, D. & Clarke, S. 1999. COWPOWER, a computer system to optimize standby power units for dairy operations. ASAE/CSAE Meeting Presentation—Paper No. 99–3014.

CAFRE. 2009. Report of Pilot Energy Benchmarking Project 2007/2008.

Casey, J.W. & Holden, N.M. 2005 Analysis of greenhouse gas emissions from the average Irish milk production system, *Agricultural Systems*, 86(1): 97-114.

Cederberg, C. & Mattsson, B. 2000. Life cycle assessment of milk production — a comparison of conventional and organic farming. *Journal of Cleaner Production*, 8(1): 49–60.

DairyCo. 2009. Energy efficiency on farm – a practical guide. Agriculture and Horticulture Development Board. Kenilworth, UK.

Dalgaard, T., Niels Halberg, N. & Porter John, R. 2001. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture, Ecosystems & Environment*, 87(1): 51–65.

DEFRA. 2007a. The Environmental, Social and Economic Impacts Associated with Liquid Milk Consumption in the UK and its Production. A Review of Literature and Evidence. DEFRA Project Code EVO 2067. Department for Environment, Food and Rural Affairs. London.

DEFRA. 2007b. Direct energy use in agriculture: opportunities for reducing fossil fuel inputs.DEFRA Project Code AC0401. Department for Environment, Food and Rural Affairs. London.

Dyer, J.A. & Desjardins, R.L. 2006. An integrated index of electrical energy use in Canadian agriculture with implications for greenhouse gas emissions. *Biosystems Engineering*, 95(3): 449–460.

Ecoinvent. 2009. Swiss Centre for Life Cycle Inventories database. Available at http://www.ecoinvent.ch/

FEC Service. 2008. Dairy Technology Powerpoint Presentation. FEC Services Ltd. Available http://www.dardni.gov.uk/ruralni/energy_efficiency_dairy.pdf

Haas, G., Wetterich, F. & Köpke, U. 2001 Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Agriculture, Ecosystems & Environment,* 83(1-2): 43–53.

Horndahl, T. 2008. Energy Use in Farm Buildings Swedish University of Agricultural Sciences Report 2008:8.

IEA. 2009. CO_2 emissions from fuel combustion. IEA Statistics. International Energy Agency. Paris.

IEA. 2010. CO_2 emissions from fuel combustion Highlights, p. 107. International Energy Agency. Paris.

Ludington, D. & Johnson, E.L. 2003 Dairy farm energy audit summary report. Nyserda, Albany.

Rotz, C.A., Montes, F. & Chianese, D.S. 2010. The carbon footprint of dairy production systems through partial life cycle assessment. *J. Dairy Sci.*, 93: 1266–1282.

Saunders, C. & Barber, A. 2007. Comparative energy and greenhouse gas emissions of New Zealand's and the UK's dairy industry. Research Report No. 297 Lincoln University. Christchurch, New Zeeland.

Schils, R.L.M., de Haan, M.H.A., Hemmer, J.G.A., van den Pol-van Dasselaar, A., de Boer, J.A., Evers, A.G., Holshof, G., van Middelkoop, J.C. & Zom, R.L.G. 2007. DairyWise, a whole-farm dairy model. *J. Dairy Sci*., 90: 5334–5346.

Thomassen, M.A., Dalgaard, R., Heijungs, R. & de Boer, I. 2008. Attributional and consequential LCA of milk production, *Int. J. Life Cycle Assess.*, 13: 339–349.

Wells, C. 2001. Total energy indicators of agricultural sustainability: dairy farming case study. Technical Paper 2001/3. Ministry of Agriculture and Forestry. Wellington, New Zealand.

Williams, A., Pearn, K., Sandars, D.L., Audsley, E., Parsons, D. & Chatterton, J. 2010. Analysis of the 2007/8 DEFRA Farm Business Survey Energy Module DEFRA Project Code RMP 5465 Natural Resources Management Centre, Cranfield University. 106 pp.

APPENDIX F

Relative value of slaughter by-products and effect on allocation of emissions

The main edible product from slaughtered animals is meat, but slaughterhouses also produce a whole range of by-products (organs, hide, blood, etc.). Between 30 and 60 percent of animal weight, depending on the species, does not end up as meat for human consumption.

Little documented information is usually available on the marketing of by-products from abattoirs but it is generally considered that they constitute a crucial part of profitability, with a more than significant share of the margin. They are subdivided into edible and non-edible materials.

1. EDIBLE BY-PRODUCTS

The main edible by-products of a slaughtered animal are offal, also known as variety meat or organ meat. Offal is divided into red (heart, livers, kidneys, lungs, tongue, cheek meat and deboned head trimmings) and white (intestine, stomachs, sweetbread [thymus and pancreas] and brain). Edible by-products can also be blood and fats that are fit for human consumption, and used in further processed products such as sausages.

According to a survey in the French meat industry, all edible materials from the carcass, including meat and offal, account for 45 percent of the live weight of an adult cattle (see Table F1). By-products are therefore 55 percent of the animal live weight. This is consistent with the results of a study on yields of by-products in various breeds of cattle slaughtered in Texas in 1989 (Terry *et al.*, 1990). It is also

Table F1. Beef cattle products and by-products, by type of use

Use of animal products and by-products (ABP)	Beef *(percentage of LW)*
EDIBLE	
Meat, offal, blood and fats for human consumption	45
INEDIBLE	
ABP withdrawn for sanitary reasons, SRM*, wastes	10
Protein, blood and fats (pet food, animal feed, drug industry)	20
Bones (feed industry, glue, gelatine)	8
Skins & hides (leather)	6
Digestive tract content (compost/fertilizers)	10
Lost due to carcass chilling and drying	1

* Specified risk material with regard to BSE (brain, eye, medulla, etc.).

Source: FranceAgriMer. 2012. *Observatoire des coproduits* (based on a survey of 40 meat plants in France).

consistent with the results of a more recent USDA study (Marti *et al.*, 2011), that estimated total by-products at 44 percent of total live weight, but did not include the digestive tract content (approximately 10 percent).

Edible by-products, mainly offal, account for around 12 percent of adult cattle live weight (Ockerman and Hansen, 2000). Human consumption of offal varies by culture and region, but can be found almost everywhere, in developed as well as in developing countries. Following animal health crises, such as the outbreak of *bovine spongiform encephalopathy* (BSE) in 1996, and the ban on the use of these products by a number of countries, the global offal market accounts for 15 to 20 percent of production.

World trade of bovine offal is estimated at one million tonnes per year. Asia (in particular China and Japan) is the main outlet for bovine offal, and is far from being self-sufficient, with 40 percent of global imports. Russian Federation doubled its imports in the past ten years, importing more than 100 000 tonnes of beef offal today, despite the ban on U.S. beef in 2004 due to BSE. Other significant importers include Egypt and Central Africa.

Offal exporters are the main beef exporters: United States (27 percent), Australia (14 percent), Argentina (12 percent) and Brazil (9 percent). In other countries, offal is often sold locally.

2. NON-EDIBLE BY-PRODUCTS

For adult cattle, non-edible by-products represent on average 55 percent of the total live weight. Material to be eliminated, such as by-products withdrawn for sanitary reasons (e.g. liver with flukes), specified risks materials and wastes from the first water treatment, account for 10 percent of the animal weight and are a cost for the meat plant.

Hides and skin constitute the most profitable non-edible by-products of the meat industry, with about 6 percent of the animal weight and sometimes up to 75 percent of the by-products value (Marti *et al.*, 2011). They are also the most internationally traded by-products, with Italy and Turkey as major outlets for many exporters.

In terms of weight, the most important group of non-edible by-products (accounting for 20 percent of total live weight) is constituted by floor trimmings, blood and fats used mostly for pet food but also for animal feed (processed animal protein, like meat and bone meal), or in the drug or cosmetic industry. Bones (8 percent of the weight) often go through rendering with this category to produce processed animal protein. They can also be used to produce glue or gelatine that go back into the human consumption chain.

Digestive tract content is usually about 10 percent of the animal weight and is used as fertilizer or as biogas material on the meat plant to produce energy.

3. VALUE OF BY-PRODUCTS

Edible and non-edible by-products accounted for 11 percent of the total value of the carcass sold by slaughterhouses in 2011, according to a survey of 10 cattle slaughterhouses in France (Observatoire des prix et des marges, 2012). The share of by-products in the total value tends to increase over time (it was only 6 percent in 2005).

This result is consistent with a study by Terry *et al.* (1990) that estimates the value of edible and inedible by-products from cattle at 9 to 12 percent of the total live

Table F2. Total revenue from one adult cattle sold by the slaughterhouse and share of by-products

Year	Total revenue *(€/kg)*	All by-products value *(€/kg)*	All by-products *(percentage)*	Edible by-products value *(€/kg)*	Edible by-products *(percentage)*	Non-edible by-products *(percentage)*
2005	4.19	0.28	6	0.14	3	3
2006	4.39	0.29	6	0.15	3	3
2007	4.39	0.38	9	0.15	4	5
2008	4.5	0.26	6	0.16	4	2
2009	NA	NA	NA	0.17	NA	NA
2010	4.69	0.4	9	0.16	4	5
2011	4.96	0.53	11	0.16	3	8

NA: Not Applicable.

Source: Observatoire des prix et des marges, 2012; Service de Nouvelles des Marchés.

Table F3. Emissions intensity of beef with and without allocation to slaughter by-products in Western Europe

	kg CO_2-eq/kg LW
No allocation to by-products	18.8
With allocation to by-products	17.7

Source: Authors' calculations.

value. It is also consistent with Marti *et al.* (2011), who estimated that by-products added value to one steer at 10 percent in average over the period 2000 to 2011.

Nevertheless, because of consumption habits, value for edible by-products can be very different from one country to another. For example, offal like hearts or stomach has greater value on the Chinese market than on any other market.

According to data from the Rungis Wholesale Market in France, total value of offal for one adult cattle was € 52.2 in 2011, that is to say 0.16 cents per kg of total products for one animal. Offal market prices were lower in 2005, and the market is very sensitive to sanitary crises, but the contribution of edible by-products in the total revenue from slaughtered adult cattle is generally stable at about 3 to 4 percent. We estimate that the value of other edible by-products is not significant compared with edible offal.

Non-edible by-products therefore account for the rest of the revenue from by-products; about 8 percent of the total revenue in 2011, a share that has increased by 5 percent since 2005.

The global value of non-edible by-products is quite volatile and this is mainly driven by the value of hides and skins. The world skin markets drop of 2008 and 2009 is reflected in Table F2 with a decrease of non-edible by-products in 2008.

This case study in France is one of the few examples available. Results appear to be consistent with a similar study by USDA but they cannot be seen as representative on a global scale since the categories and actual uses of slaughter by-products varies greatly from region to region and in time. Furthermore, alternative types of allocation (e.g. dry mass) could be used however these require further developments.

Nevertheless, because of the similarities among Western European breeds and among European markets of animal products, we can extrapolate the results of the French case study to Western Europe. Table F3 presents the effect of allocation

emissions to by-products using 6 percent as the allocation value of emissions to slaughter by-products in Western Europe.

Due to the lack of a comprehensive global data on by-products in the meat sector, the allocation of emissions to slaughter by-products could not be performed in this assessment. This may be improved in a future assessment depending on information shared by the industry and the development of harmonized methods to allocate by-products at slaughterhouses.

REFERENCES

Lapasin, C., Gac, A., Scislowski, V., Chevillon, P., & Guardia, S. 2012. Recherche de méthode d'évaluation de l'expression de l'empreinte carbone des produits viande. France Agrimer, Paris. http://idele.fr/domaines-techniques/elevage-environnement-et-territoires/evaluation-environnementale/publication/idelesolr/recommends/recherche-de-methodes-devaluation-de-lexpression-de-lempreinte-carbone-des-produits-viande.html

Marti, D.L., Johnson, R.J. & Mathews, K.H. 2011. Where's the (Not) Meat? By-products From Beef and Pork Production. A Report from the Economic Research Service, USDA. http://www.ers.usda.gov/media/147867/ldpm20901.pdf

Observatoire des prix et des marges. 2012. http://agriculture.gouv.fr/IMG/pdf/Rapport_parlement_2012_v8_cle01dc4d.pdf.

Ockerman, H.W. & Hansen, C.L. 2000. *Animal By-product Processing and Utilization,* First edition, Lancaster, PA. Technomic.

Terry, C.A., Knapp, R.H., Edwards, J.W., Mies, W.L., Savell, J.W. & Cross, H.R. 1990. Yields of by-products from different cattle types. *Journal of Animal Sciences*, 68: 4200–4205.

APPENDIX G

Maps

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Map 1
Distribution of dairy cattle populations

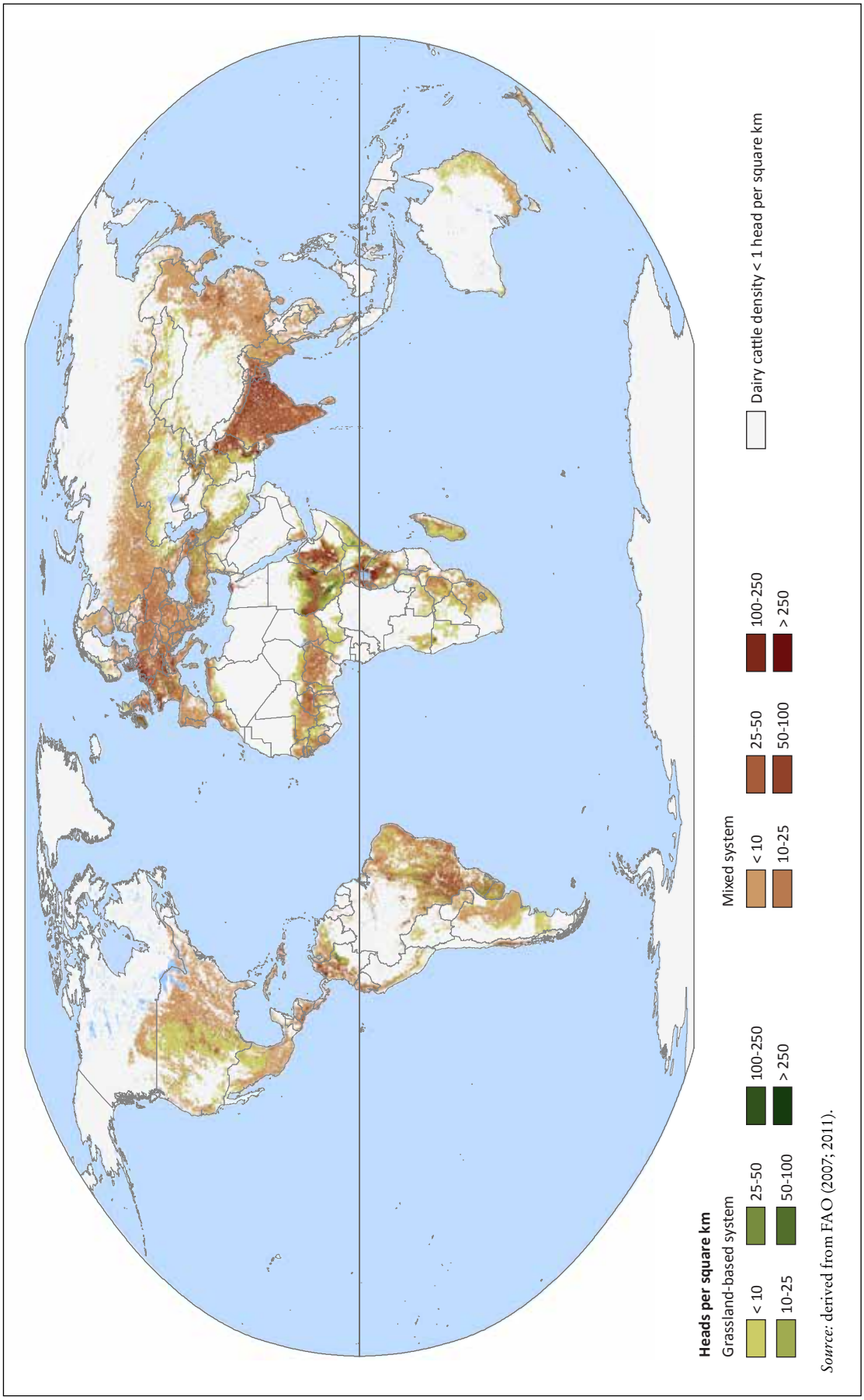

Source: derived from FAO (2007; 2011).

Map 2
Distribution of beef cattle populations

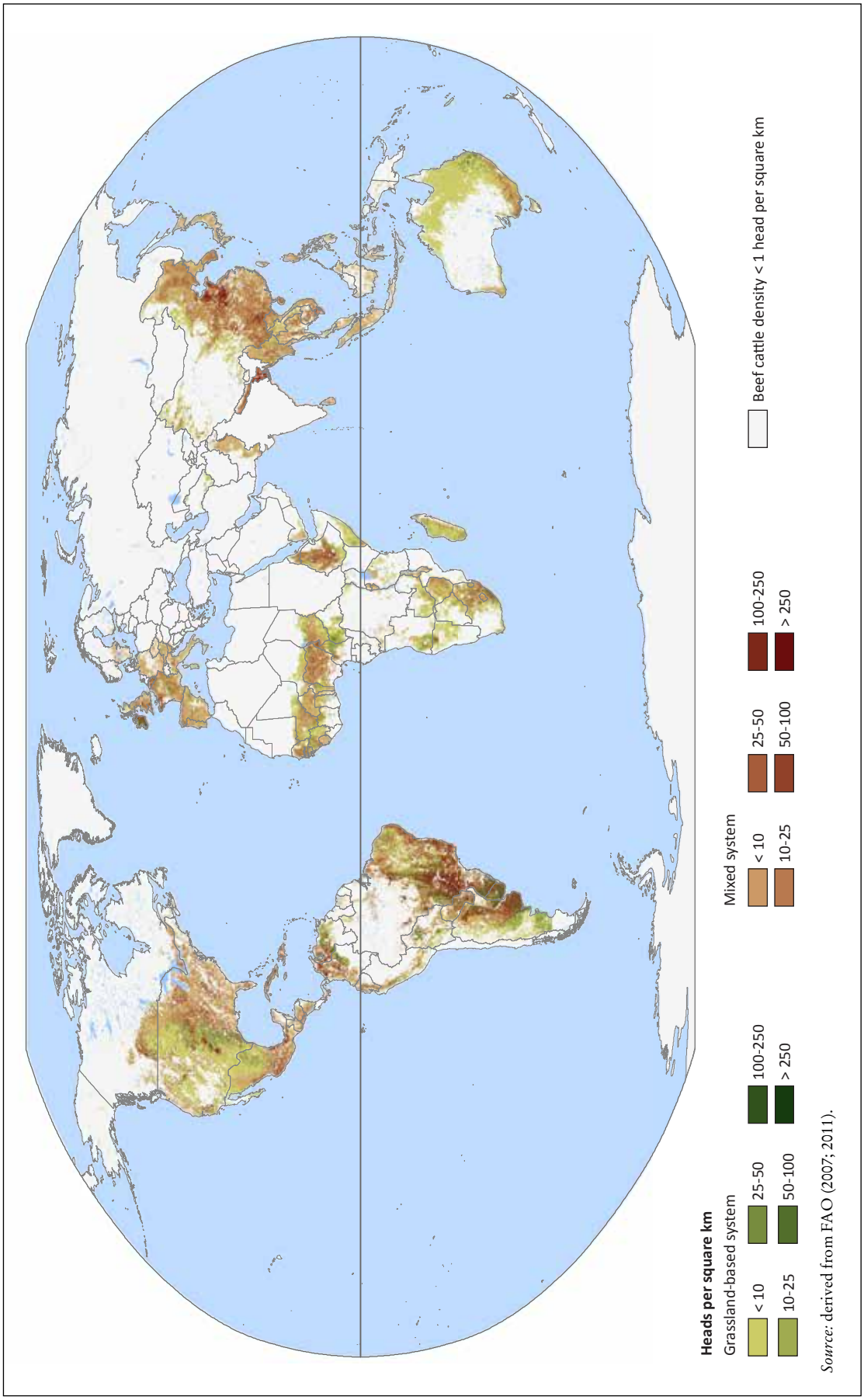

Source: derived from FAO (2007; 2011).

Map 3
Distribution of buffalo populations

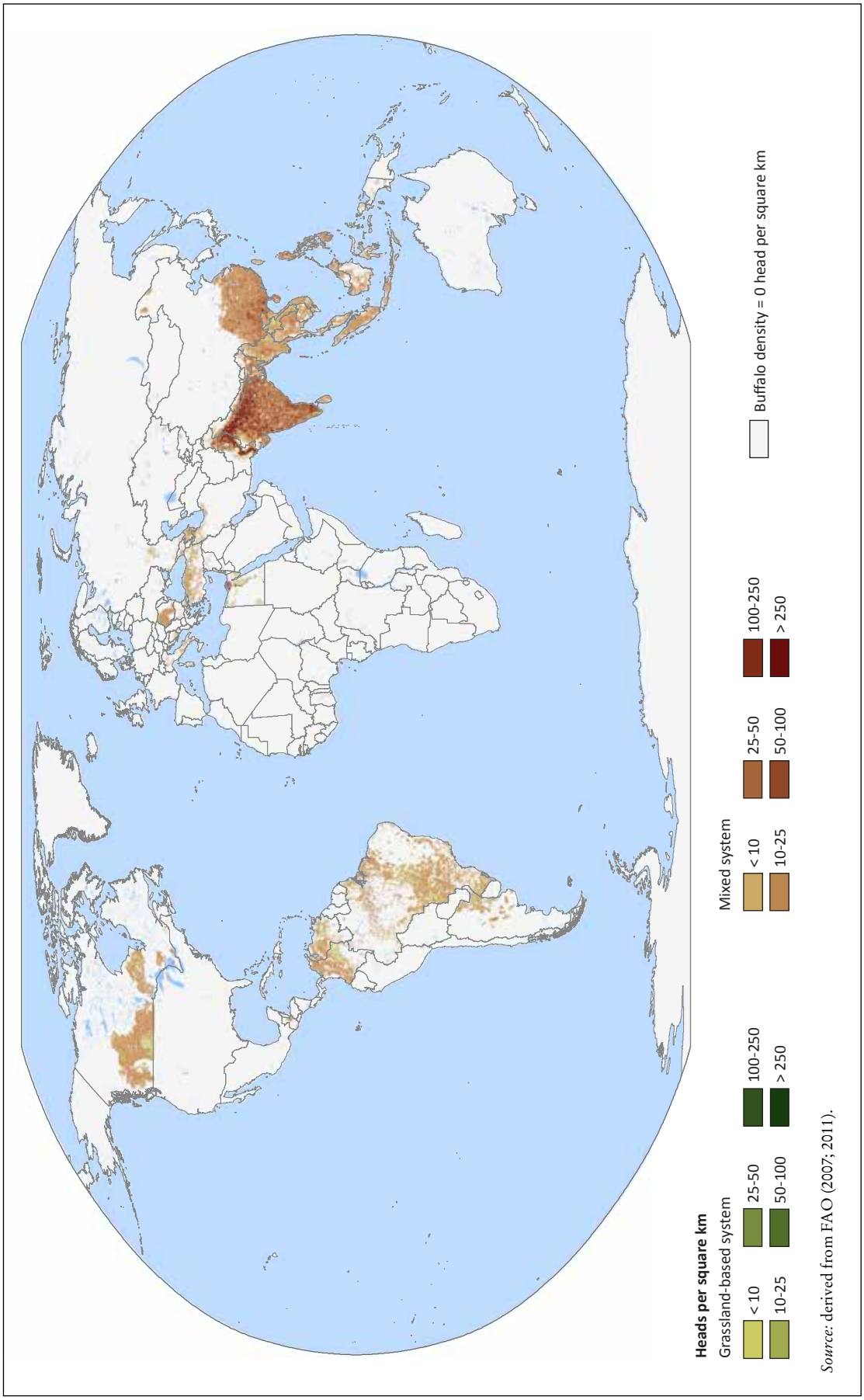

Source: derived from FAO (2007; 2011).

Map 4
Distribution of goat populations

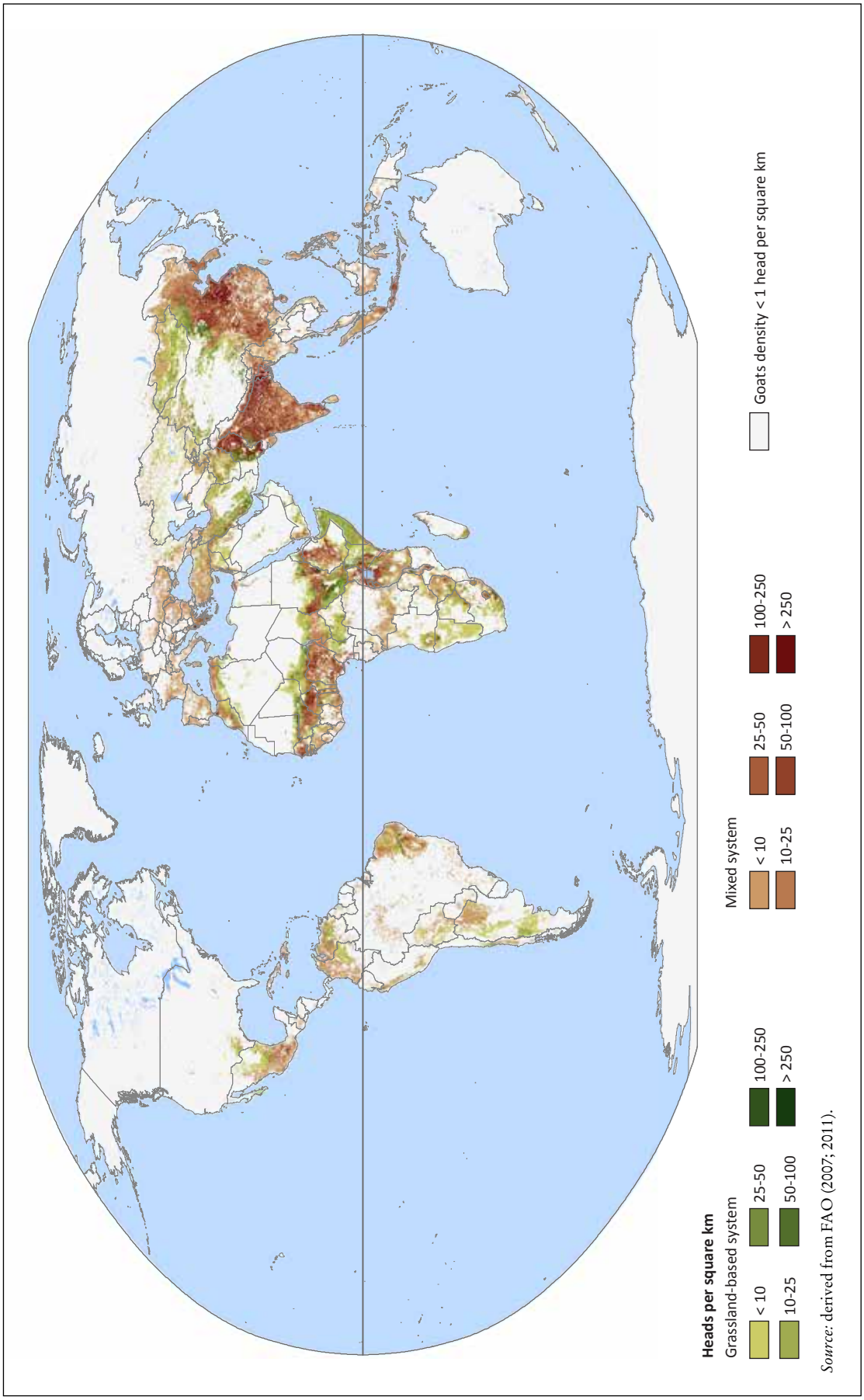

Source: derived from FAO (2007; 2011).

Map 5
Distribution of sheep populations

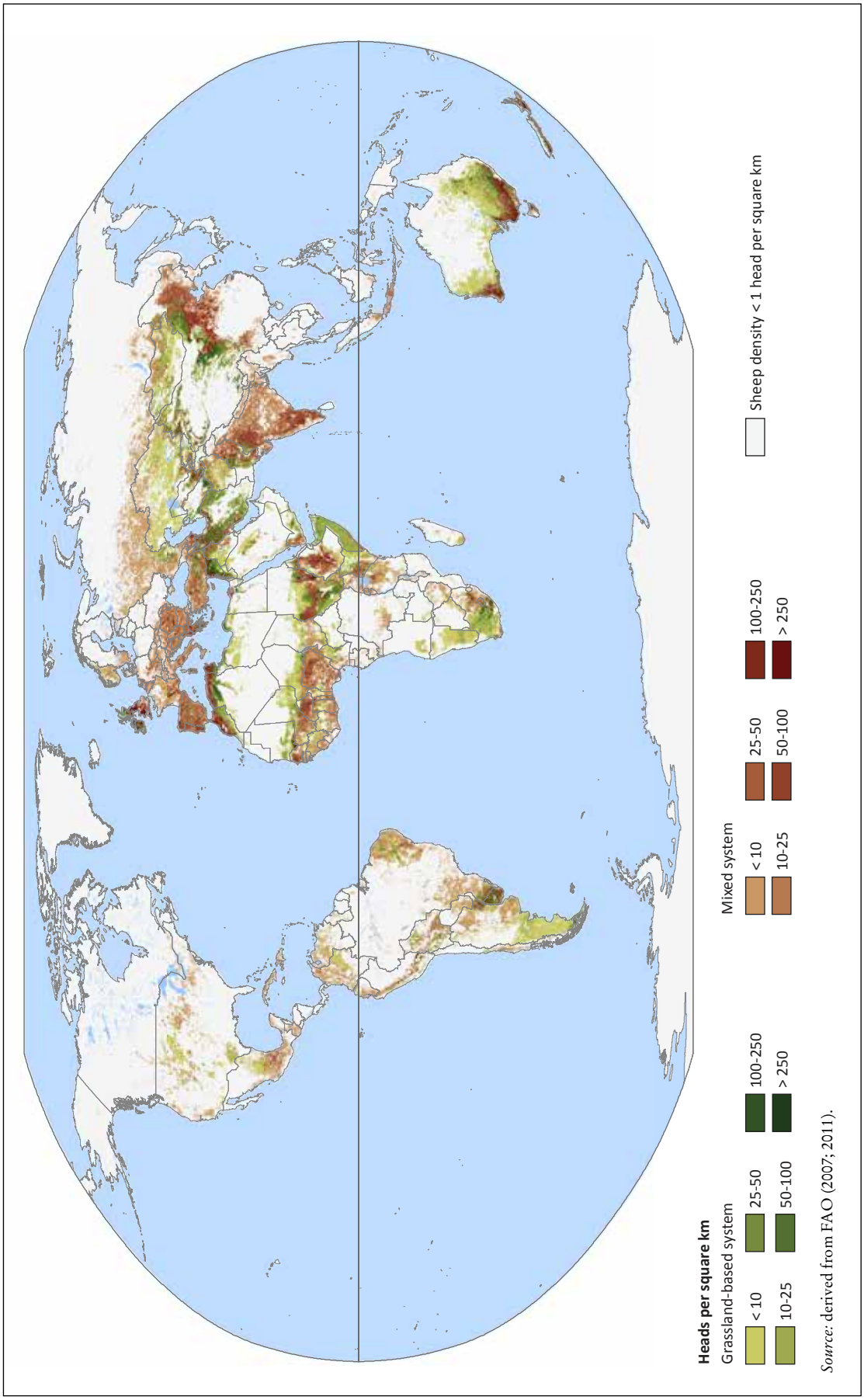

Source: derived from FAO (2007; 2011).

Map 6
Proportion of milk protein in total protein from cattle dairy herds

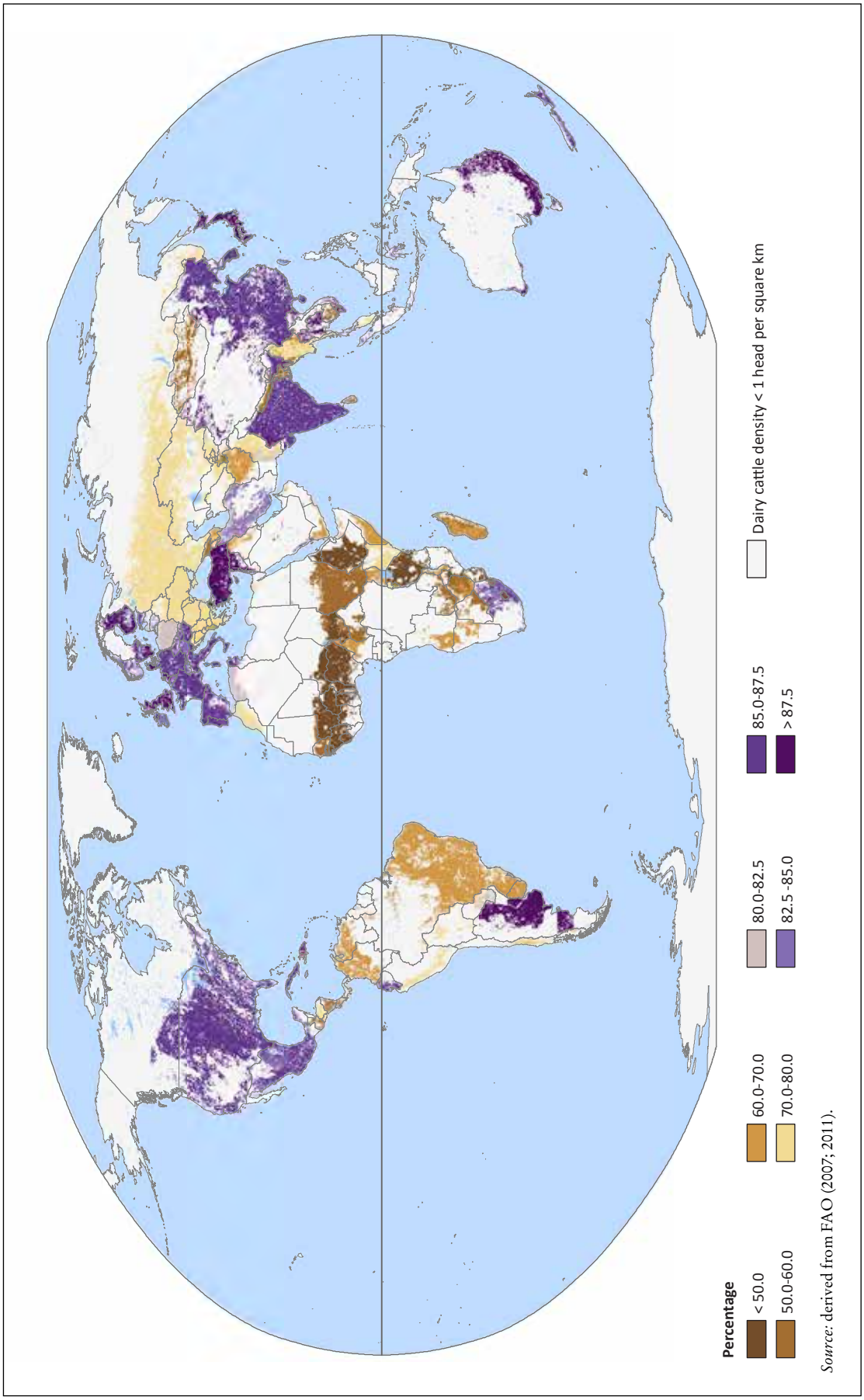

Source: derived from FAO (2007; 2011).

Map 7
Average feed digestibility for dairy cattle

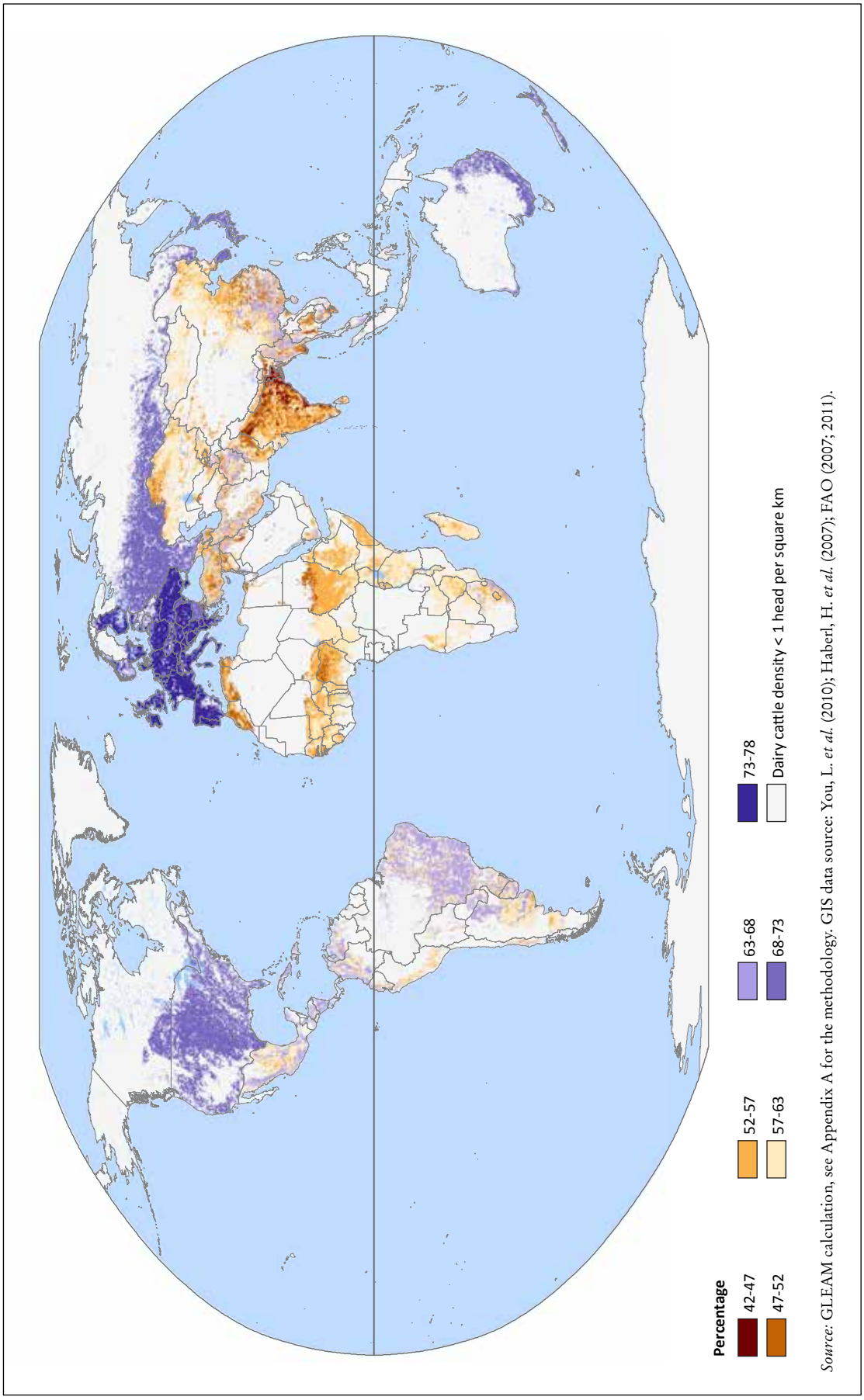

Source: GLEAM calculation, see Appendix A for the methodology. GIS data source: You, L. *et al.* (2010); Haberl, H. *et al.* (2007); FAO (2007; 2011).

Map 8
Average feed digestibility for beef cattle

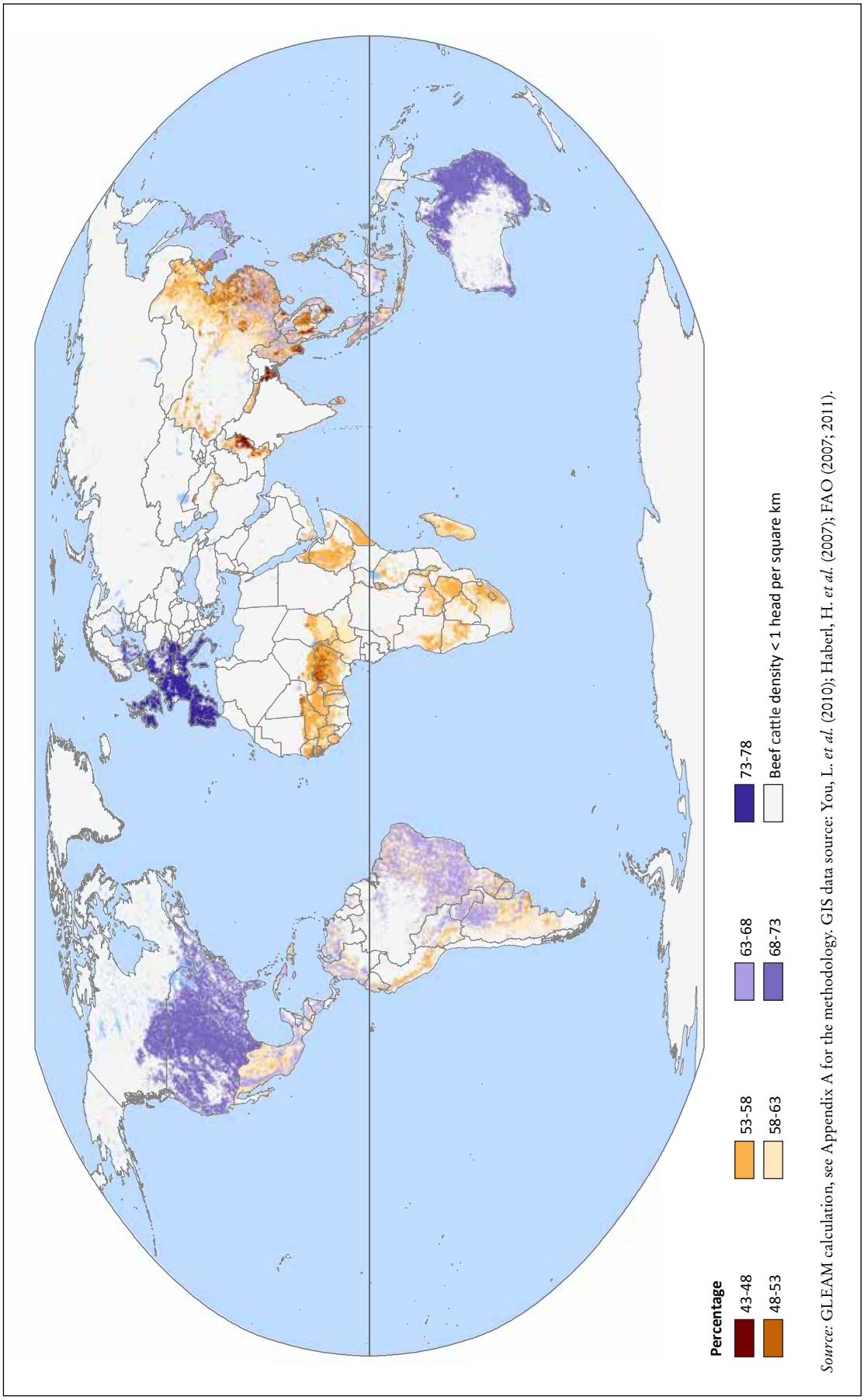

Source: GLEAM calculation, see Appendix A for the methodology. GIS data source: You, L. *et al.* (2010); Haberl, H. *et al.* (2007); FAO (2007; 2011).

Map 9
Manure methane conversion factor for dairy cattle

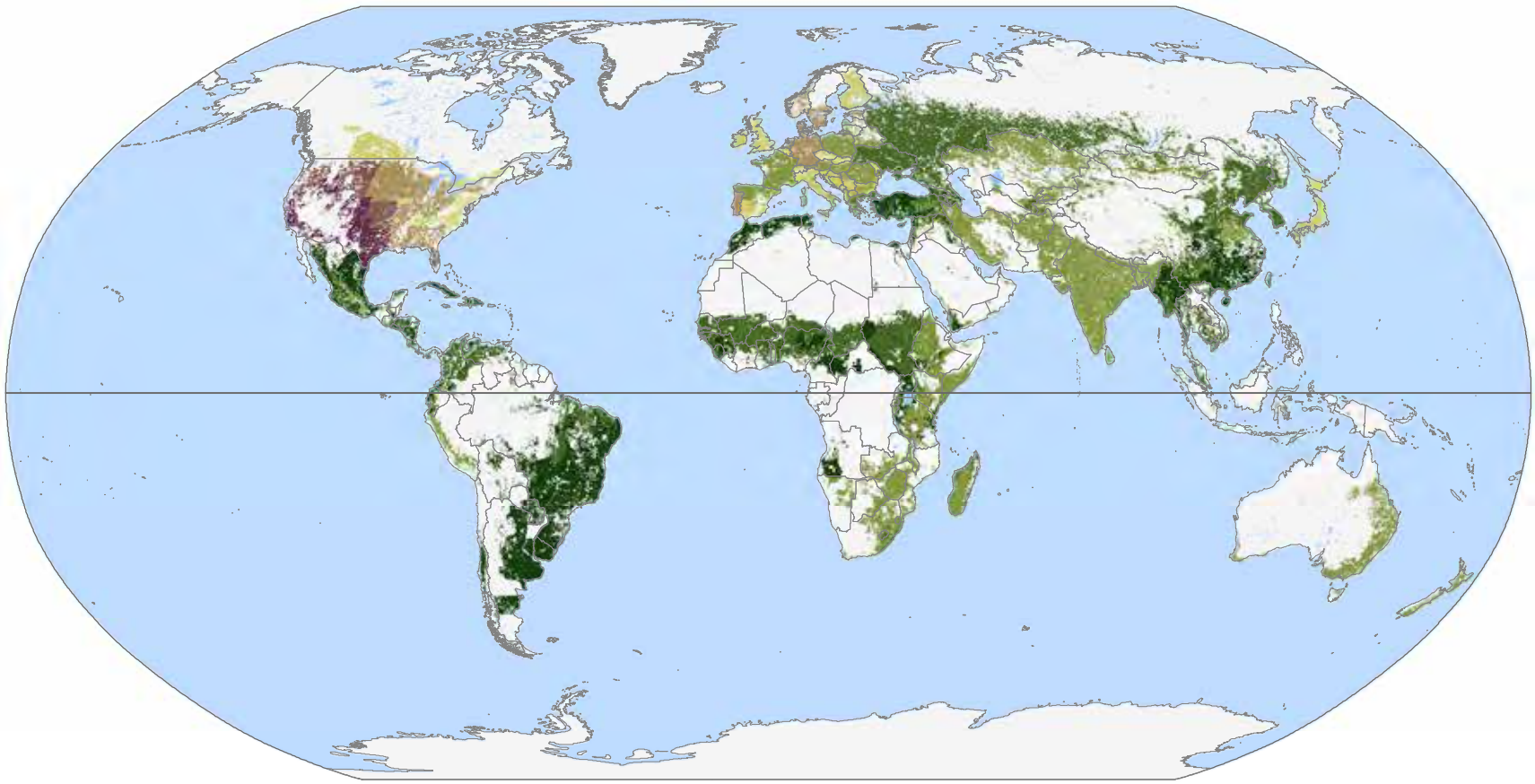

Source: GLEAM calculation, see Appendix A for the methodology. Main input data: IPCC (2006); Hijmans, R.J. *et al.* (2005); FAO (2011).

Map 10
Manure methane conversion factor for beef cattle

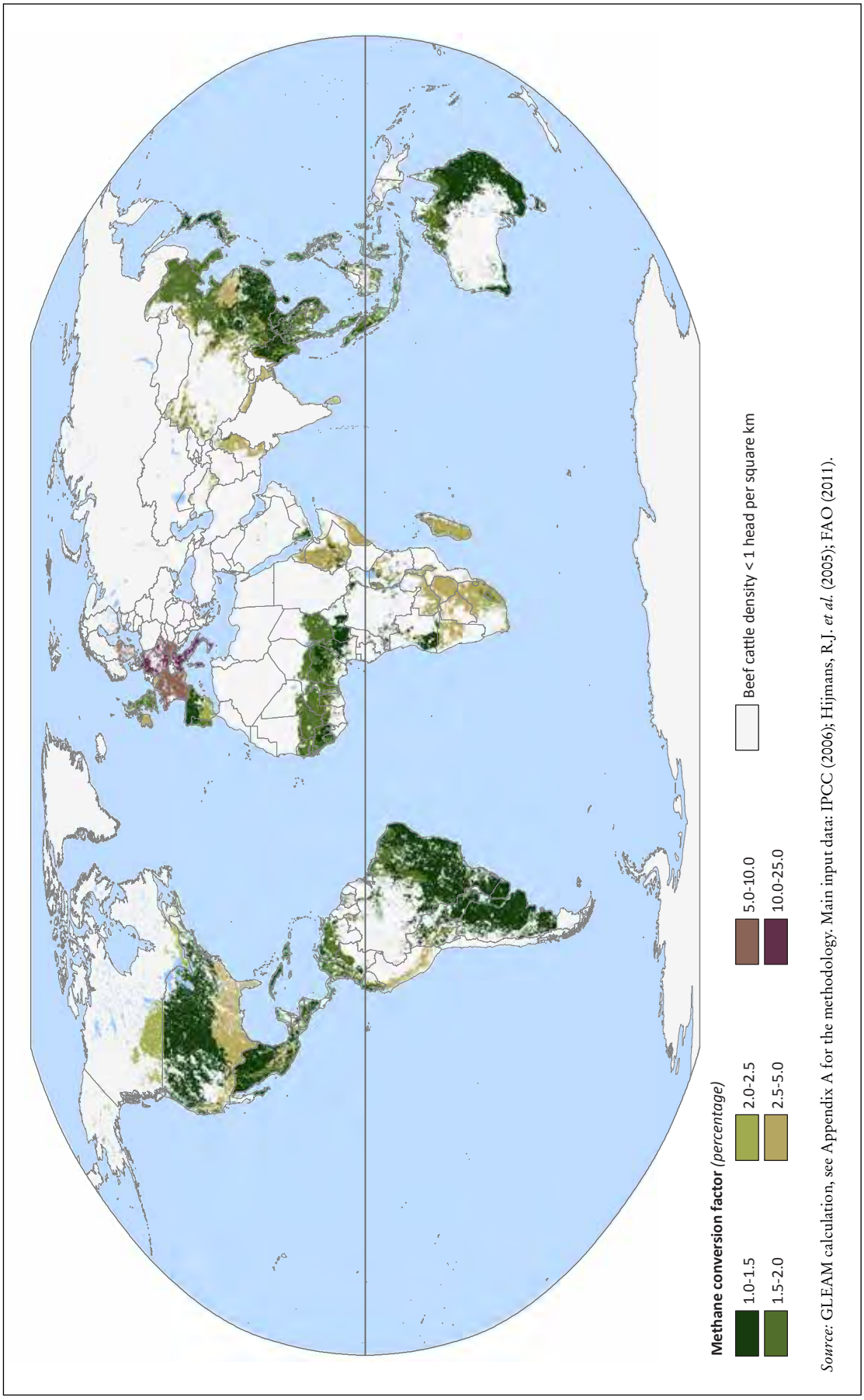

Source: GLEAM calculation, see Appendix A for the methodology. Main input data: IPCC (2006); Hijmans, R.J. *et al.* (2005); FAO (2011).

Map 11
Proportion of feed N retained in product – dairy cattle herds

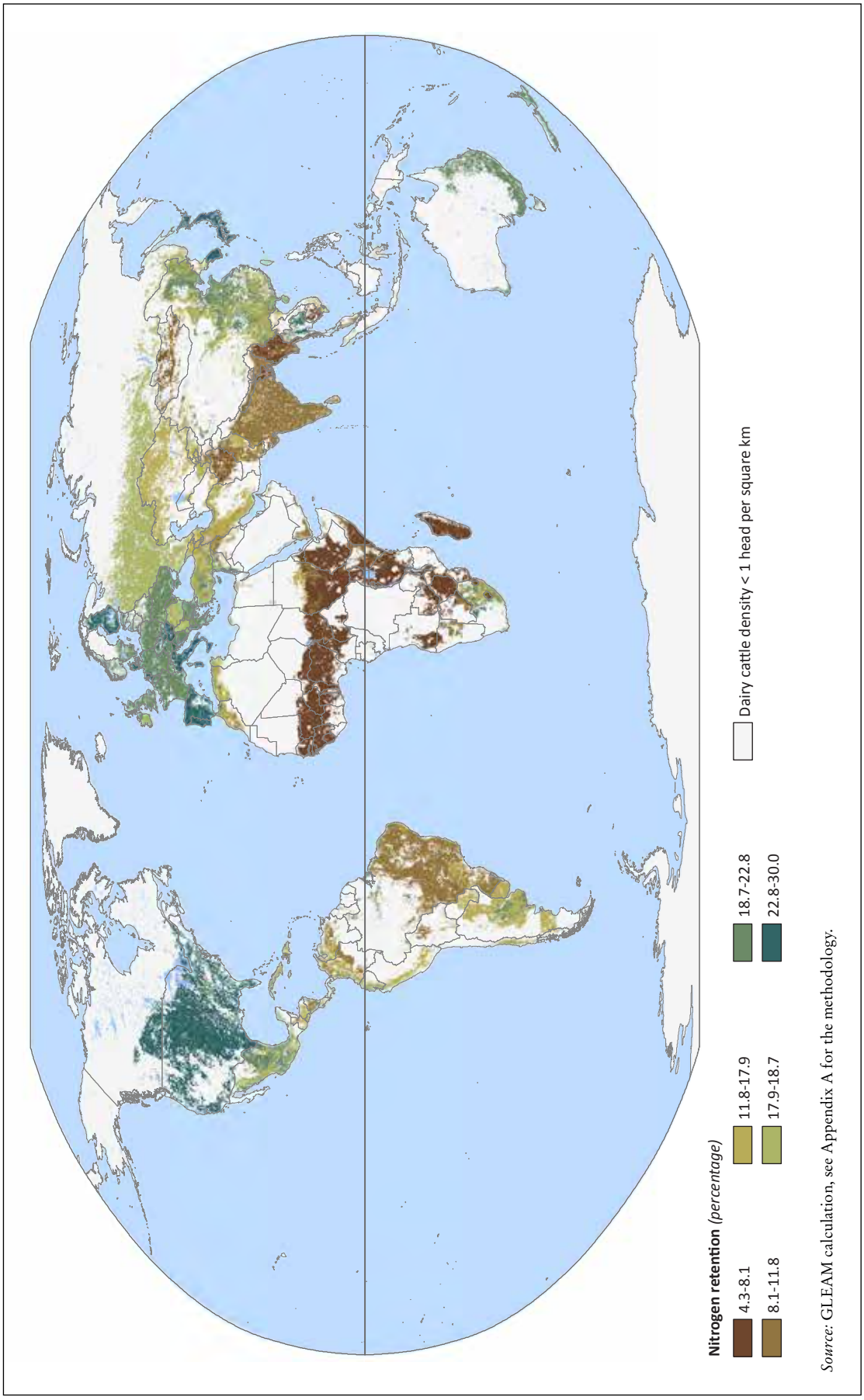

Source: GLEAM calculation, see Appendix A for the methodology.

Map 12
Proportion of feed N retained in product – beef cattle herds

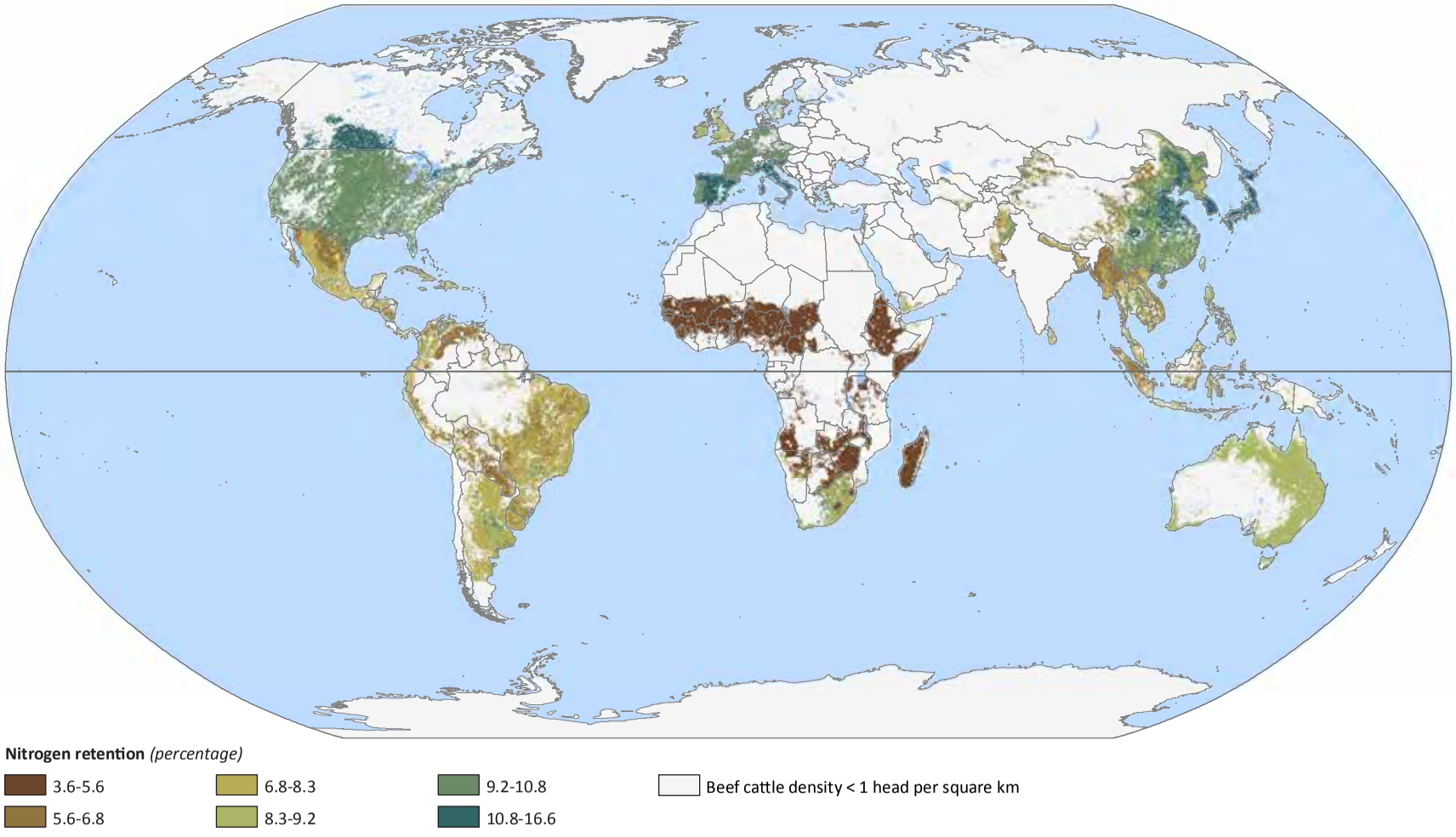

Source: GLEAM calculation, see Appendix A for the methodology.

REFERENCES

FAO. 2007. *Gridded livestock of the world 2007* by Wint, W. & Robinson, T.P. FAO. Rome.

FAO. 2011. *Global livestock production systems*, by Robinson, T.P., Thornton, P.K., Franceschini, G., Kruska, R.L., Chiozza, F., Notenbaert, A., Cecchi, G., Herrero, M., Epprecht, M., Fritz, S., You, L., Conchedda,G., & See, L. FAO. Rome.

Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht W. & Fischer-Kowalski M. 2007. Quantifying and mapping the global human appropriation of net primary production in Earth's terrestrial ecosystem. *Proceedings of the National Academy of Sciences of the USA.* 104: 12942-12947.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones P.G. & Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology,* 25: 1965-1978.

IPCC. 2006. IPCC guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme, H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe K. eds. IPCC. Kanagawa.

You, L., Crespo, S., Guo, Z. Koo, J., Ojo, W., Sebastian, K., Tenorio, T.N., Wood, S. & Wood-Sichra, U. 2010. Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2. Available at http://MapSPAM.info.

APPENDIX H

Country list

The country grouping used in this assessment is based on the FAO Global Administrative Unit Layers (GAUL). The GAUL aims at compiling and disseminating the most reliable spatial information on administrative units for all the countries in the world providing a contribution to the standardization of the spatial dataset representing administrative units. Country classification is done on a purely geographic basis. For further information: http://www.fews.net/docs/special/GAUL_Disclaimer.pdf

LATIN AMERICA AND THE CARIBBEAN (LAC)

Anguilla
Antigua and Barbuda
Argentina
Aruba
Bahamas
Barbados
Belize
Bolivia
Brazil
British Virgin Islands
Cayman Islands
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
Falkland Islands (Malvinas)
French Guiana
Grenada
Guadeloupe
Guatemala
Guyana
Haiti
Honduras
Jamaica
Martinique
Mexico
Montserrat
Netherlands Antilles
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
Saint Kitts and Nevis
Saint Lucia
Saint Vincent and the Grenadines
Suriname
Trinidad and Tobago
Turks and Caicos Islands
United States Virgin Islands
Uruguay
Venezuela

SUB-SAHARAN AFRICA (SSA)

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Benin
Botswana
Burkina Faso
Burundi
Cote d'Ivoire
Cameroon
Cape Verde
Central African Republic
Chad
Comoros
Congo
Democratic Republic of the Congo
Djibouti
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia
Ghana
Guinea
Guinea-Bissau
Kenya
Lesotho
Liberia
Madagascar
Malawi
Mali
Mauritania

Mauritius
Mayotte
Mozambique
Namibia
Niger
Nigeria
Rwanda
Reunion
Saint Helena
Sao Tome and Principe
Senegal
Seychelles
Sierra Leone
Somalia
South Africa
Swaziland
Togo
Uganda
United Republic of Tanzania
Zambia
Zimbabwe

NEAR EAST AND NORTH AFRICA (NENA)
Algeria
Armenia
Azerbaijan
Bahrain
Cyprus
Egypt
Gaza Strip
Georgia
Iraq
Israel
Jordan
Kazakhstan
Kuwait
Kyrgyzstan
Lebanon
Morocco
Oman
Qatar
Republic of Sudan
Saudi Arabia
South Sudan
State of Libya
Syrian Arab Republic
Tajikistan
Tunisia
Turkey
Turkmenistan
United Arab Emirates
Uzbekistan
West Bank
Western Sahara
Yemen

SOUTH ASIA
Afghanistan
Bangladesh
Bhutan
British Indian Ocean Territory
India
Iran (Islamic Republic of)
Maldives
Nepal
Pakistan
Sri Lanka

EASTERN EUROPE
Belarus
Bulgaria
Czech Republic
Hungary
Moldova, Republic of
Poland
Romania
Slovakia
Ukraine

RUSSIAN FEDERATION
Russian Federation

EAST ASIA AND SOUTHEAST ASIA
Brunei Darussalam
Cambodia
China
Christmas Island
Democratic People's Republic of Korea
Hong Kong
Indonesia
Japan
Lao People's Democratic Republic
Macau
Malaysia
Mongolia
Myanmar
Philippines
Republic of Korea
Singapore
Thailand
Timor-Leste
Viet Nam

OCEANIA
American Samoa
Australia
Cook Islands
Fiji
French Polynesia
Guam
Kiribati

Marshall Islands
Micronesia (Federated States of)
Nauru
New Caledonia
New Zealand
Niue
Norfolk Island
Northern Mariana Islands
Palau
Papua New Guinea
Pitcairn
Saint Pierre et Miquelon
Samoa
Solomon Islands
Tokelau
Tonga
Tuvalu
Vanuatu
Wake Island
Wallis and Futuna

WESTERN EUROPE

Albania
Andorra
Austria
Belgium
Bosnia and Herzegovina
Croatia
Denmark
Estonia
Faroe Islands
Finland
France
Germany
Greece
Guernsey
Iceland
Ireland
Isle of Man
Italy
Jersey
Latvia
Liechtenstein
Lithuania
Luxembourg
Madeira Islands
Malta
Monaco
Montenegro
Netherlands
Norway
Portugal
Republic of Serbia
San Marino
Slovenia
Spain
Svalbard and Jan Mayen Islands
Sweden
Switzerland
The former Yugoslav Republic of Macedonia
United Kingdom of Great Britain and Northern Ireland

NORTH AMERICA

Bermuda
Canada
Greenland
United States of America

Food and Agriculture Organization of the United Nations

Pathways towards lower emissions

A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems

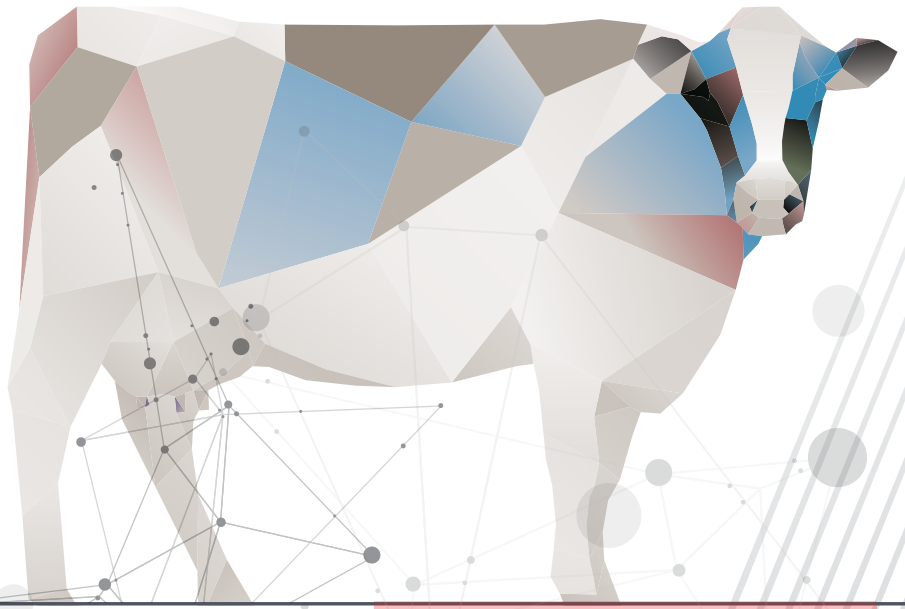

Pathways towards lower emissions

A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems



Food and Agriculture Organization of the United Nations
Rome, 2023

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Foreword

Livestock play a vital role in providing essential nutrition and supporting the livelihoods and resilience of countless families and communities worldwide. However, if not managed properly, livestock systems can have negative impacts on the environment, with greenhouse gas emissions generated throughout the production chain contributing to global warming.

In conjunction with the imperative reductions in fossil fuel consumption, the livestock sector should actively participate in climate action while concurrently addressing the growing demand for animal products driven by a rising global population and diet changes. The reduction of greenhouse gas emissions is an important component of the FAO Strategy on Climate Change and its plan of action and is firmly embedded in the Organization's Strategic Framework. We are unwavering in our commitment to provide data and knowledge, foster capacity building, and facilitate greenhouse gas assessments and mitigation interventions within livestock systems.

Achieving a transformation towards lower emissions necessitates collaborative efforts from all stakeholders, underscoring the indispensability of investments to implement ambitious climate action targets that position the livestock sector as a key contributor to emission reduction. The formulation and prioritization of effective mitigation strategies requires comprehensive assessments of baseline emissions, bearing a high degree of specificity for different species, production systems, and countries.

This report builds upon prior FAO assessments and presents an updated, comprehensive overview of emissions originating from livestock systems globally. It accomplishes this by meticulously quantifying emission sources, different greenhouse gases, and making all findings publicly accessible through a user-friendly web application for in-depth analysis of emissions data at a high level of details.

Beyond evaluating baseline emissions, this report offers estimations of future emissions under scenarios of increased production and outlines pathways to reduce emissions through the application of well-established best practices in animal management. It clearly demonstrates that ambitious programs and wide-ranging interventions have the potential to bend the curve of increasing emissions with growing production.

These measures include improving animal health, enhancing feed quality, adopting circular economy approaches, reducing food loss and waste, among others. However, these enhancements do not come at zero cost but require investments in the sector to narrow efficiency gaps, while ensuring an increased global supply of animal products from meat, milk, and eggs. Although interventions must be tailored to specific sites and designed at the local level, the pathways elaborated in this report serve as a clear illustration that producing more with less is possible if the technical potential of mitigation is harnessed.

By working together, we can drive the transformation of livestock systems and achieve our ambitious goals of improved production, a healthier environment, enhanced nutrition, and a better quality of life for all, leaving no one behind.



Maria Helena Semedo

Deputy Director-General, FAO

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Abbreviations and acronyms

AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
BAU	business-as-usual
COAG	Committee on Agriculture
COP	Conference of the Parties
CO_2eq	carbon dioxide equivalent
DM	dry matter
DMI	dry matter intake
EDGAR	Emissions Database for Global Atmospheric Research
EEA	European Environment Agency
FAO	Food and Agriculture Organization of the United Nations
GHG	greenhouse gas
GLEAM	Global Livestock Environmental Assessment Model
GLEAM-*i*	Global Livestock Environmental Assessment Model-interactive
GLW	Gridded Livestock of the World
GPS	Global Perspectives Studies
GWP	global warming potential
HFCs	hydrofluorocarbons
HICs	high-income countries
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessment
LEAP	FAO Livestock Environmental Assessment and Performance Partnership
LMICs	low- to middle-income countries
LUC	land-use change
LULUCF	land use, land-use change and forestry
NDC	Nationally Determined Contributions
NDDB	National Dairy Development Board
NRD	national recommended diets
PFCs	perfluorocarbons
RBP	Ration Balancing Programme
RRPCP	Regional Resilient Pastoral Communities Project
SLCP	short-lived climate pollutant
SCL	Sub-Committee on Livestock
TASF	terrestrial animal source food
UNFCCC	United Nations Framework Convention on Climate Change

Chemical elements

CH_4	methane
CO_2	carbon dioxide
N	nitrogen
NF_3	nitrogen trifluoride
NH_3	ammonia
N_2O	nitrous oxide
SF_6	sulphur hexafluoride

Units

Gt	gigatonne, metric unit equivalent to 1 billion (10^9) tonnes
Mt	million tonne, metric unit equivalent to 1 million (10^6) tonnes
Kt	kilotonne, metric unit equivalent to 1 thousand (10^3) tonnes

Key messages

This report provides a comprehensive assessment of greenhouse gas (GHG) emissions from livestock agrifood systems, comprising farm gate, land-use change (LUC) and supply chain processes. The assessment employs the Food and Agriculture Organization (FAO) of the United Nations's latest Global Livestock Environmental Assessment Model (GLEAM), a geospatial framework that simulates the environmental impact of livestock systems. Through GLEAM, users can analyse activity data from different livestock production systems and calculate the carbon footprint of livestock projects at various scales, supporting an in-depth analysis of emission inventories and national and international climate commitments.

The findings from GLEAM reveal that livestock agrifood systems – which include cattle, buffaloes, sheep, goats, pigs and chickens – are responsible for 6.2 gigatonnes (Gt) of carbon dioxide equivalent (CO_2eq) emissions. This accounts for approximately 12 percent of all anthropogenic GHG emissions based on the reference year 2015. We show that these estimates are consistent with published FAO data and literature at the global level, and add significant value to the existing approaches, particularly in supporting more robust analyses for mitigation strategies.

The emission intensity, or carbon footprint, of livestock production varies significantly across countries, species and production systems due to differences in breeds, management practices, feed quality and environmental conditions.

Some of the major highlights of the results for the share of emissions can be summarized by species, products and sources. Of all the six animal species considered, cattle contribute to over 60 percent of global livestock emissions. Of the edible animal products – meat, milk and eggs – two-thirds of the emissions are linked to meat production across all species. Finally, about one-third of emissions emanates from the production, processing and transport of feed inputs when considering the global emissions by source.

By 2050, the growing and more affluent global population is anticipated to drive a 20 percent increase in animal product demand for animal produts compared to 2020 levels. Without intervention, this upward trend could result in increased emissions from livestock systems, potentially undermining efforts to reduce GHG emissions and exacerbating global temperature rises.

The adoption of sustainable practices is crucial in attaining lower emissions and mitigating the environmental impact of livestock systems. There are several pathways towards lower emissions, encompassing interventions on the supply side and reductions in the demand for animal products. They include improvements of animal health, the reduction of food loss and waste, enhancements in breeding practices, and the implementation of measures directly targeting GHG emissions.

By collectively implementing these enhancements, the livestock sector has the potential to achieve significant emission reductions while still meeting the anticipated increase in the demand for animal products by 2050.

Enhancing productivity and products efficiency across the entire production chain is the most promising way to reducing emissions, promoting sustainability, and mitigating the environmental impact of the livestock sector.

There is no universal solution to lowering emissions from livestock. More work is needed to understand the barriers hindering the implementation and scaling up of interventions. Continuing investments in the livestock sector remains vital to effectively address the unique challenges encountered in various production systems, with different animal species and across diverse locations.

Executive summary

This report presents a comprehensive global assessment of GHG emissions from livestock systems, utilizing the FAO's GLEAM based on the most recent available data. GLEAM employs a life cycle assessment (LCA) approach, quantifying emissions associated with raising animals, including enteric fermentation. It also considers indirect emissions from upstream activities, such as feed and other inputs, and part of the downstream processes including post-farm transport, processing and packaging of raw products. For the reference year of 2015, livestock systems with cattle, buffaloes, sheep, goats, pigs and chickens collectively contribute to 6.2 Gt CO_2eq emissions, constituting approximately 12 percent of all anthropogenic GHG emissions. It is important to note that this figure is lower than previous GLEAM estimates, but direct comparisons are not feasible due to differences in methodology, input data and global warming potential (GWP) values. The predominant contributor, accounting for 62 percent of emissions, is the farming of cattle. In terms of products, about two-thirds of the emissions are allocated to the meat production across all species. Additionally, about one-third of global emissions are related to the production of feed inputs, including fertilizer and pesticide use.

This report identifies significant disparities in the relative emissions associated with the production of one unit of milk, meat or eggs – commonly referred to as "emission intensity" or "carbon footprint" – across countries, species and production systems. These discrepancies result from differences in breeds, management practices, feed quality and environmental conditions, and underscore the potential for reducing the carbon footprint by addressing these factors. It is important to note that the method employed has a limitation: the allocation of emissions exclusively to edible products. This approach does not account for the multifunctionality of livestock in many regions of the world where livestock is kept not only for its product but also for its role to provide draft power, financial asset, savings and social status.

Drawing from an extensive literature review, this report illustrates pathways toward lower emissions through a set of interventions on both the supply and the demand sides of animal production. These interventions include improvements in animal health and welfare, the reduction of food loss and waste throughout the production chain, enhancements in breeding practices, elevated feed quality, and targeted measures to mitigate GHG emissions, such as rumen manipulation and the use of feed additives. The most significant reductions in both absolute and relative emissions can be achieved by prioritizing improvements in productivity, not only per animal but also by optimising efficiency at each stage of the production chain.

This report estimates that, if implemented collectively, these improvements have the potential to reduce emissions from the livestock sector significantly, while still meeting the additional 20 percent animal protein demand projected by 2050. The most significant relative increase in total demand is anticipated in Africa, whereas the demand for animal products in Europe is expected to remain stagnant or even decrease. Asia would witness the most substantial increase in absolute demand to cater for the needs of its growing population. In a business-as-usual (BAU) scenario, this rising demand would lead to a commensurate increase in emissions from livestock systems, contravening commitments for GHG reduction and contributing to further global temperature increases.

While the scenarios offer an overview of what can be achieved based on the potential percentage reduction of each intervention strategy, it is important to recognize that the actual impact on GHG emissions may vary. The effectiveness of intervention options depends on factors such as access to services, farmers' willingness to implement interventions, economic considerations and uncertainties surrounding the efficacy of certain measures. The presented impact might be less than expected if these factors impede implementation, and some of the interventions could even result in higher emissions reduction, given the relatively moderate percentage reductions considered in the scenarios.

It is also crucial to emphasize that there is no one-size-fits-all approach to reducing emissions from livestock. Each production system, species and location possess unique characteristics, costs, benefits, interactions and trade-offs. Therefore, careful consideration is necessary when prioritising measures along the pathway. Nevertheless, this report unequivocally demonstrates that the livestock sector can play a pivotal role in reducing GHG emissions. However, it is essential to acknowledge that production might be affected by changing climate and environmental conditions. Continuing investments in the livestock sector will be paramount to advance our understanding of the barriers to implementation and the scaling up of interventions.


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1.Introduction

In 2015, the global livestock agrifood systems, comprising farm gate, LUC and supply chain processes (FAO, 2022a), produced about 810 million tonnes (Mt) of milk, 78 Mt of eggs and 330 Mt of meat annually, equivalent to about 85 Mt of high-quality protein.[1] Terrestrial animal source food (TASF) currently contributes 21 percent to the total caloric supply, equating to about 383 gram (g) of daily TASF per capita (FAO, 2023a). Livestock play a vital role in providing essential nutrition and supporting the livelihoods of families and communities, especially in rural areas of low- to middle-income countries (LMICs). The demand for animal products is anticipated to rise due to the global population growth, increasing income levels and urbanization. In particular, the demand for TASF in LMICs quadrupled between 1970 and 2020, with this upward trend expected to continue (FAO, 2018a).

Despite ongoing improvements in production efficiency, the GHG emissions from livestock systems remain a significant challenge. The Intergovernmental Panel on Climate Change (IPCC) highlighted the substantial contribution of fossil fuel use and agriculture, predominantly by livestock, to the increase in atmospheric methane (CH_4) emissions (IPCC, 2021). Given the urgency to meeting the objectives of the Paris Agreement (United Nations, 2015), it is crucial to complement the necessary and immediate drastic reductions in carbon dioxide (CO_2) emissions from the fossil fuel combustion with effective strategies for reducing emissions of non-CO_2 gases, also in livestock agrifood systems.

This report presents a comprehensive global assessment of GHG emissions from diverse livestock systems with a base year of 2015, employing the latest version of GLEAM (GLEAM 3). The history of GLEAM dates back to 2010 (see Figure 1) when it was first developed following the 2006 guidelines of IPCC (2006), with the first global assessment published in Gerber *et al.* (2013) for the reference year 2005.

In response to the need for conducting scenario assessments, an online, interactive version of GLEAM (GLEAM-*i*)[2] was developed, based on GLEAM 2 data. The GLEAM-*i* has been

[1] High-quality protein contains all the essential amino acids in right proportion, and can easily be digested. (FAO, 2023a)

[2] https://gleami.apps.fao.org/

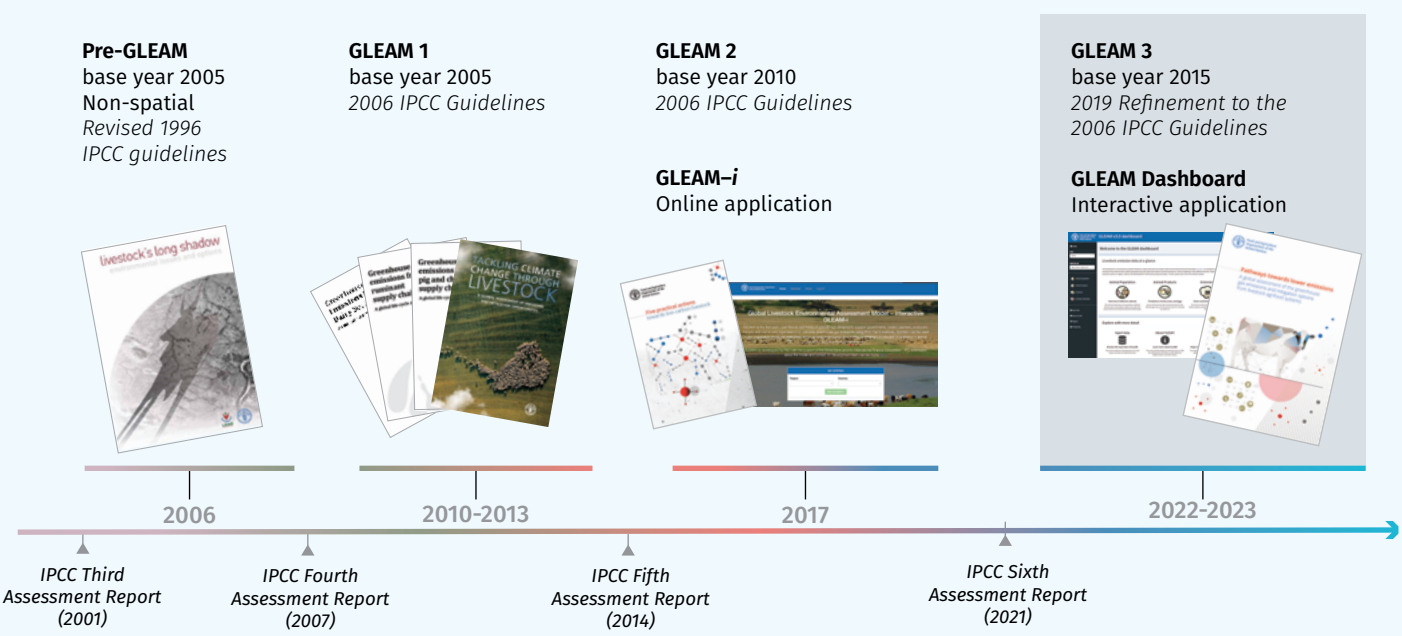

Figure 1.
Historical development phases of GLEAM with different versions, reference years and related key publications

utilized in a number of GHG emission assessments and scenario analyses by a variety of stakeholders to facilitate capacity development for international finance institutes and governments, and to incorporate GHG accounting to their livestock investment projects at the national level, as seen in IFAD and FAO (2021).

The results discussed in this report are based on the latest version of the model (GLEAM 3) and calculated for the reference year 2015, incorporating refinements made to the 2006 guidelines of IPCC in 2019 (IPCC, 2019a). The GLEAM model continues to evolve, with future versions slated to include additional environmental externalities and an open-access platform to enable users to compare mitigation actions.

GLEAM, a spatially explicit model (see Appendix for further information), adopts an LCA approach, considering both direct farm emissions and indirect emissions throughout the production chain from the production of inputs to the primary processing of products, including transport to primary processing facilities, but excluding the retail and household stage (see Figure 2). The types of GHG covered in GLEAM are CH_4, N_2O and CO_2, the three major GHGs associated with livestock supply chains (Gerber *et al.*, 2013).[3]

Moreover, GLEAM builds on FAO's Gridded Livestock of the World (GLW) (FAO, 2015), a model that allows to develop spatial distribution of livestock species globally at a high resolution based on national or international statistics. Currently, GLEAM employs GLW data as inputs to calculate GHG emissions related to cattle, buffaloes, sheep, goats, pigs and chickens.

To facilitate the visualization of the outputs of GLEAM analysis, FAO released in 2022 the GLEAM dashboard, an interactive web application enabling on-the-fly analysis and visualization of data related to GHG emissions from livestock systems (FAO, 2022b). This web application provides easy access to most of the input and output data underpinning this report.

In addition to complementing the previous assessments by updating emissions for the base year 2015, this report also draws from a comprehensive literature review and offers

[3] Emissions from other gases, such as those generated from the leakages of cooling devices, could be allocated to livestock systems. But they represent a small fraction of all emissions. For instance, combined emissions from fluorinated gasses, i.e. hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3), were less than 1.2 percent of total emissions in 2022 (https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/summary-by-gas/). The fraction associated with the global livestock sector is likely to be very small.

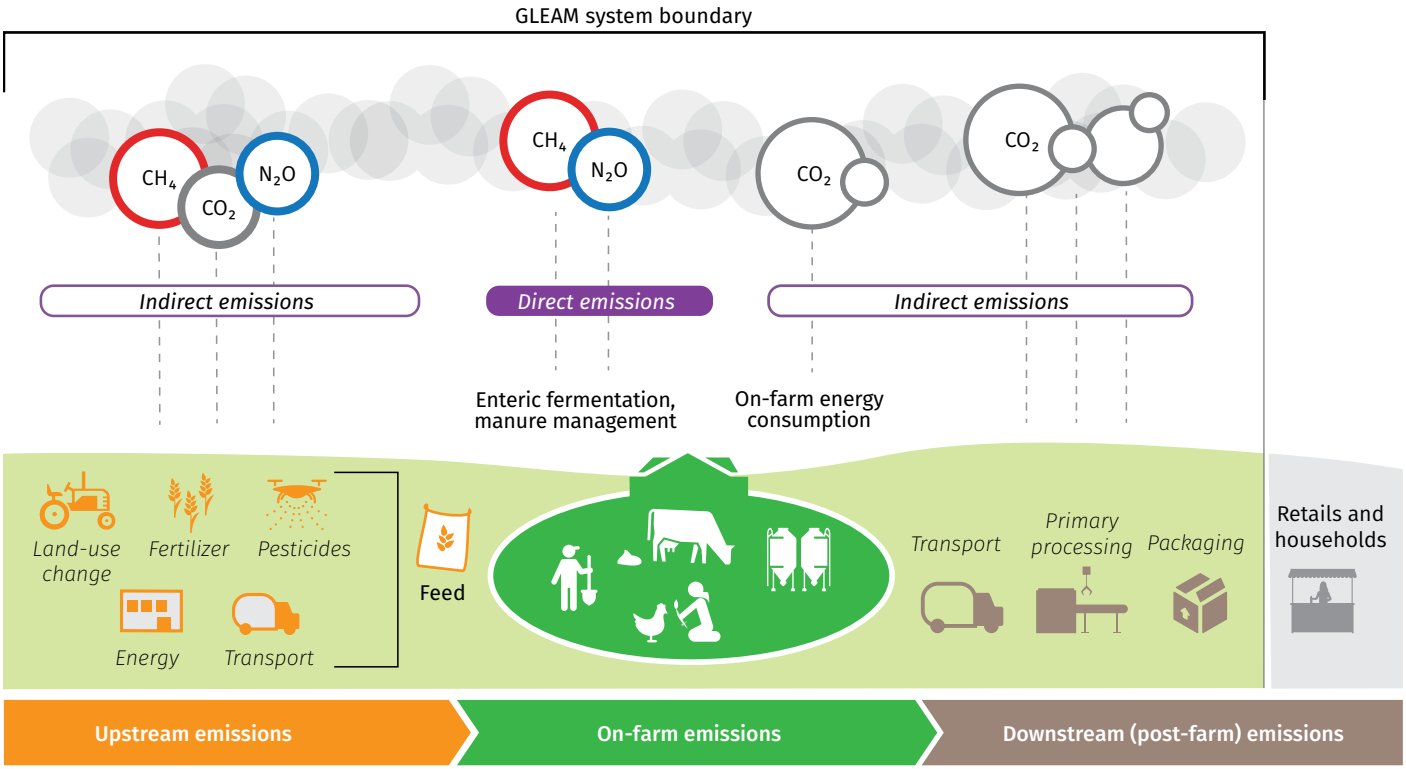

global assessments of potential reductions in emissions achievable through interventions in animal production, animal health, feeding, breeding and consumer behaviour. These interventions present pathways for reducing emissions from livestock compared to the projected demand under BAU conditions. However, the proposed reduction magnitude should be interpreted with consideration for factors such as relevance, adoption rates and the efficacy of the proposed mitigation options.

While this report and the earlier assessments all rely on GLEAM, it is important to note that assessments for different time periods should not be interpreted as a time series. Instead, they represent different snapshots that utilize slightly different methodologies and rely on different models.

Evaluating the trajectory of emissions from livestock over time and interpreting trends would require not only different animal numbers for different periods but also time-varying and spatially explicit input data for various factors such as productivity, feed intake, herd composition and others. These aspects will be addressed in future releases.

Figure 2.
Overview of livestock production chain and different sources of emissions and gases, and the system boundary in GLEAM 3

Note: In the context of this assessment, emissions from the livestock sector are defined as direct when originating from the animals, either through enteric fermentation or during manure management, while indirect emissions are those associated with other processes within the supply chain, such as energy consumption, feed production and the manufacturing of inputs and equipment. This distinction facilitates the analysis and discussion of emissions and mitigation options under a life cycle approach. However, this use of terminology differs from the definitions in IPCC (2019a), where the terms refer to the physical pathways of N_2O emissions from nitrogen all of which are included in the estimates generated by GLEAM.



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2. Baseline protein production and related greenhouse gas emissions

Global animal protein production

The spatial distribution and concentration (tonne protein/km^2) of meat, milk and egg production from cattle, buffaloes, goats, sheep, pigs and chickens in GLEAM broadly aligns with the distribution of animals with some regional and local differences that reflect cultural, historical and environmental conditions (see Figure 3). Regions with high milk production include most of Europe, south Asia and north America, whereas meat production is concentrated in east Asia, Europe, and north and south Americas. Egg production is less dependent on environmental conditions and is therefore distributed following the demand for egg protein.

The production of TASF is linked to GHG emissions along the supply chain, which can be reported either in terms of total emissions (absolute) or emission intensity (emissions produced per unit of product) as explained in the following subsection.

Absolute greenhouse gas emissions

Since national targets set by countries mostly aim to reduce total GHG emissions as part of their commitments and reporting to the Paris Agreement and to the United Nations Framework Convention on Climate Change (UNFCCC), it is crucial to focus on total emissions.

Globally, the production of the animal protein, as presented in the previous subsection "Global animal protein production", is associated with a total of 6.2 Gt CO_2eq of emissions, constituting approximately 12 percent of the estimated 50 to 52 Gt CO_2eq total anthropogenic emissions in 2015 (FAO, 2022a). Among the livestock species, cattle are the primary contributors to GHG emissions, producing around 3.8 Gt CO_2eq per year and accounting for approximately 62 percent of all livestock emissions. Pigs, chickens, buffaloes and small ruminants contribute to 14, 9, 8 and 7 percent, respectively, of livestock's overall emissions. In terms of commodities, meat production claims the largest share of emissions at 67 percent, followed by milk at 30 percent and eggs 3 percent (see Figure 4).

Direct emissions from the livestock sector globally, encompassing CH_4 from enteric fermentation, and CH_4 and N_2O from manure management, amount to 3.7 Gt CO_2eq which is equivalent to approximately 60 percent of the total livestock emissions.

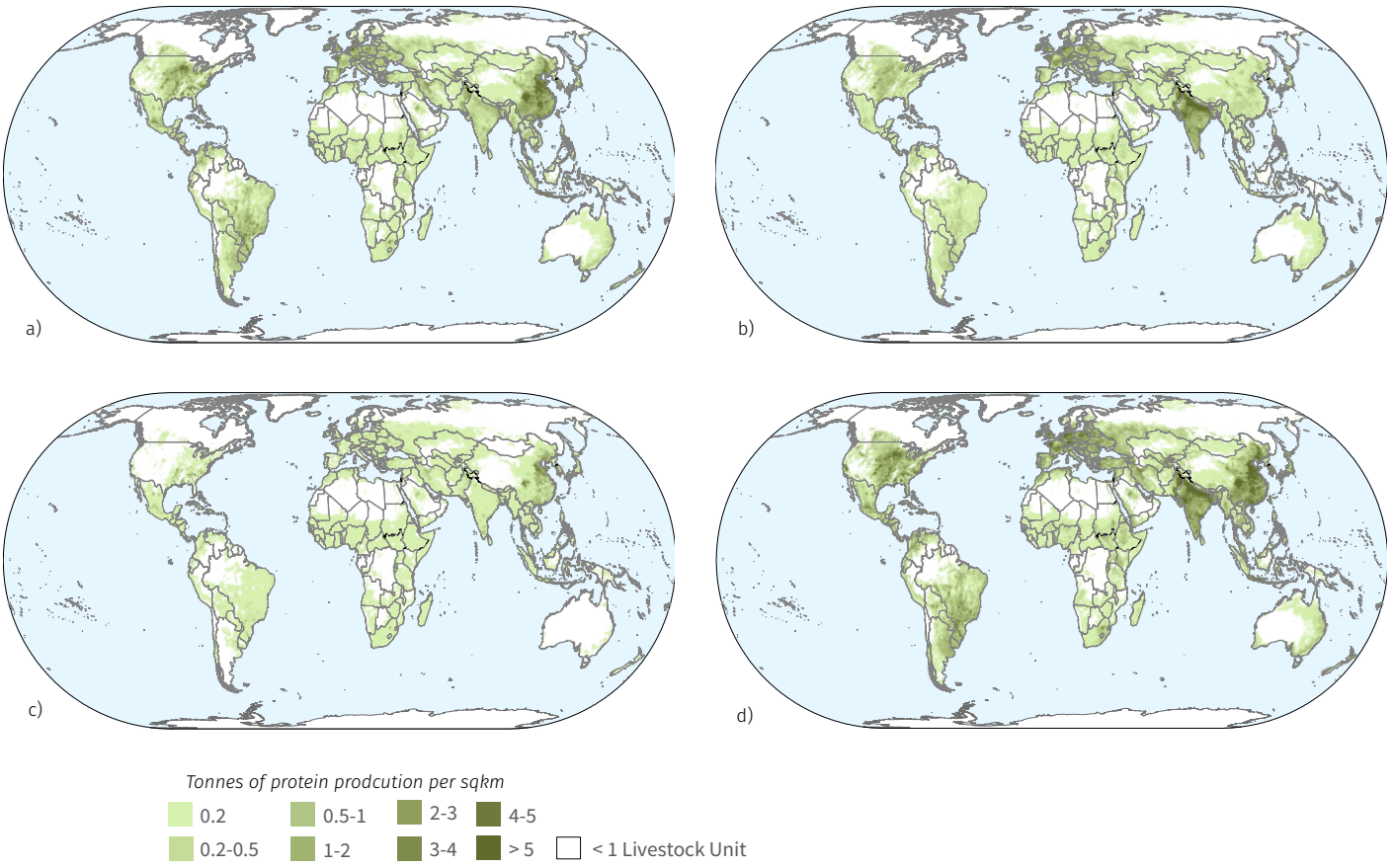

Indirect emissions account for the remaining 40 percent (2.6 Gt CO_2eq) and stem from various sources. These include the manufacture of fertilizers and pesticides for feed production and field operations in the form of CO_2, feed production itself involving CO_2 from blending and pelleting of concentrate, feed N_2O from applied synthetic fertilizer, and crop residues decomposition, as well as CH_4 from rice cultivation, manure deposition and application resulting in N_2O and CH_4 emissions, and processing and transportation of feed, live animals and livestock products which emit CO_2. Indirect emissions also include CO_2 associated with LUC, particularly forest conversion to pastureland, and expansion of palm oil and soybean plantations for feed production.[4]

When considering emission sources, CH_4 from enteric fermentation, manure management and rice production for feed contribute to the largest share of total emissions. The relative importance of these sources makes CH_4 emission the most important GHG within the livestock sector. In aggregate, 54 percent of all livestock emissions are attributed to CH_4, while CO_2 and N_2O represent smaller proportions, accounting for 31 and 15 percent, respectively (see Figure 5).

Emission sources and the specific gases involved vary considerably across locations, livestock species and production systems, emphasizing that highly aggregated views may conceal important details. A comparison of emission sources in Figure 4 between ruminant species (cattle, buffaloes, goats and sheep) and monogastric species (pigs and chickens) reveals significant differences. In ruminant systems, enteric CH_4 accounts for a far greater proportion of total emissions, whereas in monogastric systems, feed production, LUC and manure management are the main contributors. Given the relative importance of CH_4 from enteric fermentation, the spatial distribution of emissions generally aligns with the distribution of bovine animals (see Figure 6). However, areas with high absolute

Figure 3.
Production of animal protein from meat (a), milk (b), eggs(c),a dn total protain (d).

Note: Detailed results are available on the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/).

Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.
Final boundary between the Sudan and South Sudan has not yet been determined.

Source: **United Nations Geospatial.** 2020. Map of the World. United Nations. Cited 22 August 2022. www.un.org/geospatial/file/3420/download?token=TUP4yDmF modified with GLEAM 3 data.

[4] Details are given in the Appendix.

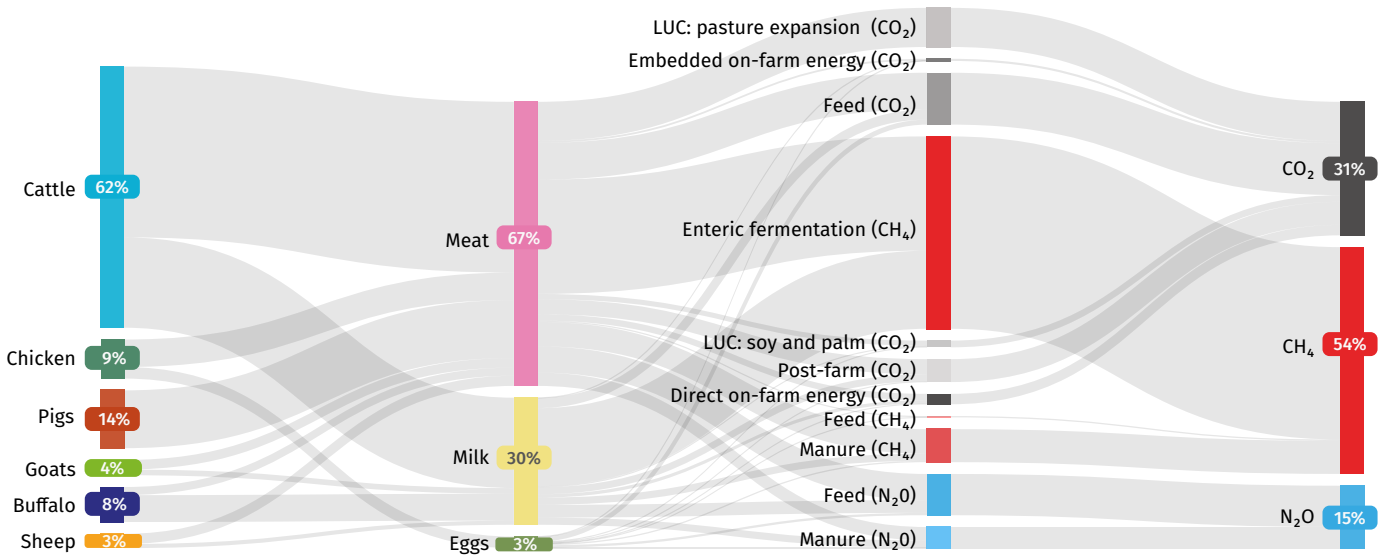

emissions are also observed in parts of Asia, attributed to highly concentrated pig and chicken population. For example, in eastern Asia, the main source of emissions for chickens is feed production (comprising 47 percent of the total), while for pigs, manure management is the main source, followed by feed.

Globally, emissions hotspots from livestock systems are prevalent in south Asia, Europe, and north and south Americas, where significant concentration of ruminant livestock are found, and emissions are dominated by CH_4 from enteric fermentation (see Figure 6). When analysed by economic region, it is observed that 42 percent of all livestock emissions originate in upper-middle-income economies, 29 percent in the lower-middle-income economies, 21 percent in high-income economies, and 7 percent in low-income economies.

For livestock agrifood systems, GLEAM considers key activities across farm gate, LUC and supply chain processes (see Figure 2). These activities represent a subsection of what FAO defines and estimates as the total GHG emissions from agrifood systems (FAO, 2022a). Therefore, it is possible to map GLEAM activities and emission estimates to the larger FAO categories, and assess consistency of the relevant emissions estimates (see Table 1).

Figure 4.
Sankey diagram of emission sources in 2015 by species, products, sources of emissions and gasses

Note: Based on GLEAM 3. More detailed regional views are available from the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/). Total of 6.2 Gt CO_2eq.
CH_4 = methane (red), N_2O = nitrous oxide (blue), CO_2 = carbon dioxide (grey), GHG = greenhouse gas.

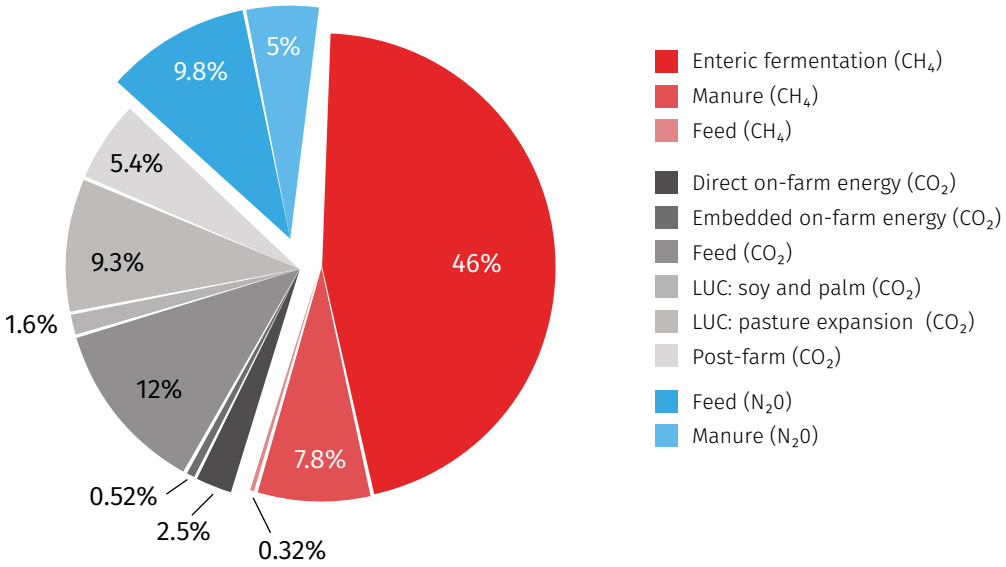

Figure 5.
Total emissions by sources calculated with GLEAM 3

Note: Percentages are rounded to two significant digits.
CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide, LUC = land-use change.

TABLE 1. Comparison of world total emission estimates for livestock agrifood systems between GLEAM, FAOSTAT and other studies by component and in total, for the year 2015

GLEAM Livestock agrifood system category		GLEAM	FAOSTAT	Xu *et al.* (2021)[i]	Poore and Nemecek (2018)[ii]	FAO agrifood systems category
		Gt CO2eq[iii]				
Enteric fermentation (CH_4)	46%	2.9	2.6[iv]	2.5	2.1	Farm gate
Manure (CH_4)	7.8%	0.5	0.3[iv]	0.25	0.29	
Feed (CH_4)	0.3%	0.02	0.02[iv,v]	0.08		
Manure (N_2O)	5.0%	0.3	0.1[iv]	0.12		
Feed (N_2O)	9.8%	0.6	1.1[iv,vi]	0.95	2.19	
Direct on-farm energy (CO_2)	2.5%	0.2	0.4[vi]			
Embedded on-farm energy (CO_2)	0.5%	0.03	-			
LUC: soy and palm (CO_2)	1.6%	0.1	1.3[vii]	2.1	1.6	Land-use change (LUC)
LUC pasture expansion (CO_2)	9.3%	0.6				
Post-farm (CO_2)	5.4%	0.3	2.1[vi,viii]	0.20[ix]		Pre- and post-production
Feed (CO_2)	12%	0.7		2.85[x]		
Livestock agrifood systems	100%	6.2	7.9	9.1		
World total agrifood			16.3	16.2[ix]	13.7	
World total GHG with LULUCF			51.0			
World total GHG without LULUCF			50.1		52.3	
Share agrifood			32%	32%	26%	
Share livestock agrifood/Total GHG without LULUCF		12%	16%			

[i] Based on a global gridded model that partitions estimated crop and grazing into food and feed use, taking into account the trade for the year 2010. Values for enteric fermentation and manure management were taken from FAOSTAT.

[ii] Global total GHG emissions are taken from the Emissions Database for Global Atmospheric Research, with values for emissions from organic soils, savannah burning, land use change, enteric fermentation, methane emissions from rice, and methane from manure management replaced by data from this study. Values are for the year 2010. The total for the food system is based on IPCC AR5 GWP values.

[iii] Converted using GWP values from IPCC AR6.

[iv] Taken directly from the corresponding FAOSTAT livestock category. Feed N2O includes manure left on the pasture.

[v] Taken from the corresponding FAOSTAT agrifood systems category and converted to its livestock feed component, using 3 percent crop/livestock split based on the food/feed ratio of the world total rice production in 2015.

[vi] Taken from the corresponding FAOSTAT agrifood systems category and converted to its livestock feed component, assuming 45 percent crop/livestock split based on the food/feed ratio of the world total crop production in 2015. Feed N2O includes splits for both synthetic and manure fertilizers.

[vii] Deforestation emissions from south America only. It is likely an underestimate of the total world livestock-related LUC.

[viii] Includes the agrifood systems processes not covered in GLEAM, such as retail, household consumption and food waste disposal.

[ix] Excluding emissions from transportation, trade and stock variation.

[x] It combines CO_2 emissions for feed production including mining, manufacturing, and transporting of fertilizer and pesticides; CO_2 emissions from the on-farm fuel and energy use; soil carbon losses from cropping activities; autotrophic and heterotrophic respiration.

Note: Figures for GLEAM are direct output from simulations, while FAOSTAT figures are sourced from the agrifood systems database either directly or modified for their livestock component (FAO, 2022a).
CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide, CO_2eq = carbon dioxide equivalent, LUC = land-use change, LULUCF = land use, land-use change and forestry.

At the outset, current FAO data indicate that global total agrifood systems emissions were 16.3 Gt CO_2eq in 2015, accounting for approximately 30 percent of the anthropogenic total (FAO, 2022a) as also reported widely, with FAO input, in recent IPCC reports such as the

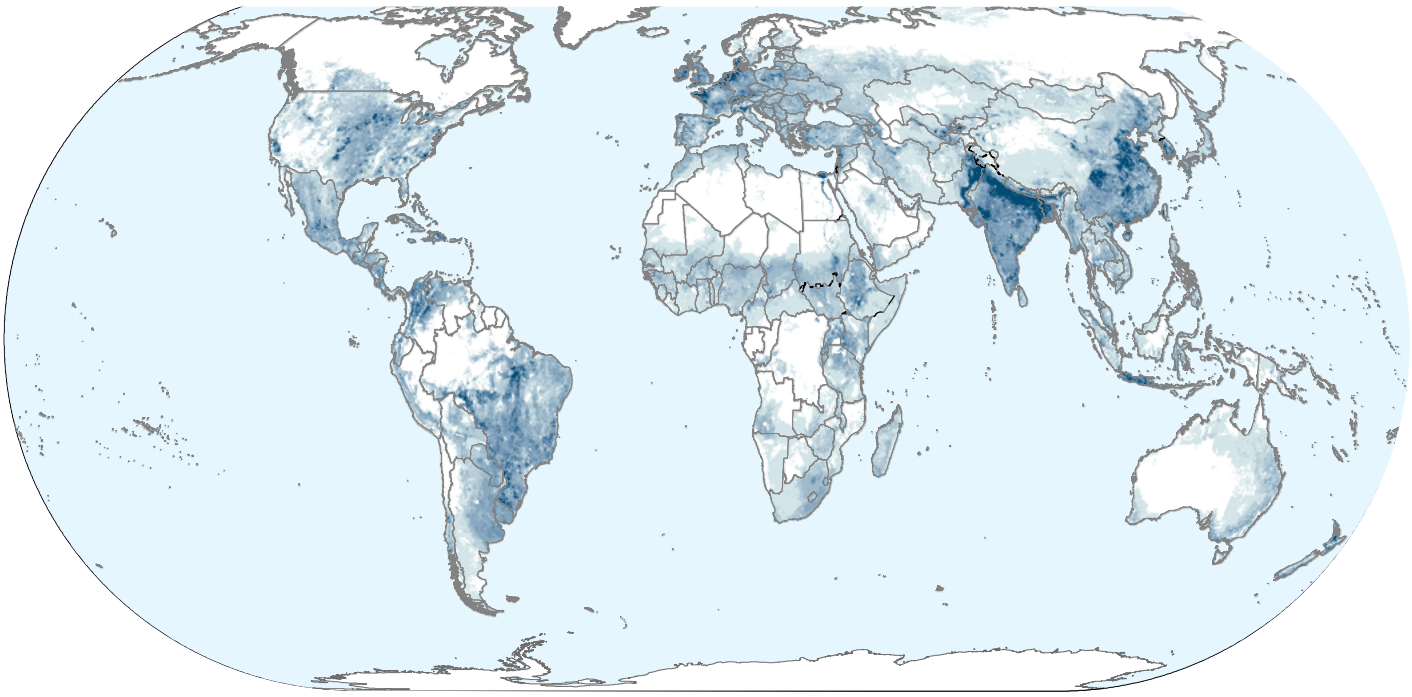

Figure 6.
Total greenhouse gas emissions from all livestock systems
Note: In tonnes of CO_2eq per square kilometre.

Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.
Final boundary between the Sudan and South Sudan has not yet been determined.

Source: **United Nations Geospatial.** 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/file/3420/download?token=TUP4yDmF modified with GLEAM 3 data.

IPCC's Special Report on Climate Change and Land (IPCC, 2019b) and the Sixth Assessment Report (AR6) of IPCC (IPCC, 2022). The GLEAM analysis reported here adds an estimate of the portion of total agrifood systems emissions due to livestock.

While the GLEAM approach is different from the models underlying current global estimates across the agrifood systems continuum, the results in Table 1 show that most single component estimates are quite consistent with those published in current literature and disseminated in FAOSTAT (FAO, 2022a), leading to the total livestock agrifood systems estimates that are fairly similar. They range from 6 to 8 Gt CO_2eq in 2015, well within the underlying uncertainties of 30 percent and above, characterizing most sub-components (Tubiello *et al.*, 2021). Both approaches combined further suggest that the contribution of livestock to total anthropogenic emissions is 12 to 16 percent. Differences, where they arise, are due mainly to two factors. First, GLEAM and FAOSTAT differ in terms of the level of complexity in describing livestock systems. Second, they differ in the set of agrifood systems processes considered. In the first case, GLEAM models livestock production within the farm gate using an IPCC Tier 2 approach, which is richer in terms of process granularity. This enables a richer analysis of mitigation options but requires more data and modelling. In contrast, FAOSTAT adopts a simpler Tier 1 approach, allowing for estimating emissions over longer time series based on a simpler set of input data which are more easily available through national statistics. In the second case, when compared to a full agrifood systems continuum, GLEAM does not cover emissions generated during retail, household consumption or waste disposal, and does not include all the LUC processes covered in FAOSTAT. These different approaches lead to the use of different equations and adoption of different coefficients across specific processes, often generating numerical differences, mostly at the country or regional level.

Box 1: What do animals eat?

Food and feed compete for land, but 1.3 billion hectares (ha) of the 2.5 billion ha land used to fulfil global feed demand cannot be cultivated (Mottet *et al.*, 2017a). Investigating whether the convertible area would yield more benefits if used as cropland is an area that warrants further research.

GLEAM estimates the DMI for each animal at the pixel, starting from the energy requirements of the animal based on its physiological state and taking into account the quality of the available feed at a particular location.

The model calculates that around 6.2 Gt of DM are needed annually to meet the needs of the global livestock population. Approximately 60 percent of this DM is derived from grass and leaves that are inedible for humans. Other important categories include crop residues, as well as oil seeds and by-products from various industries and processing. Overall, only 15 percent of the DMI could be consumed as food from edible commodities such as maize or soybean.

The largest share of the DMI is allocated to feed for cattle, followed by chickens, pigs and other ruminant animals (see Figure B1).

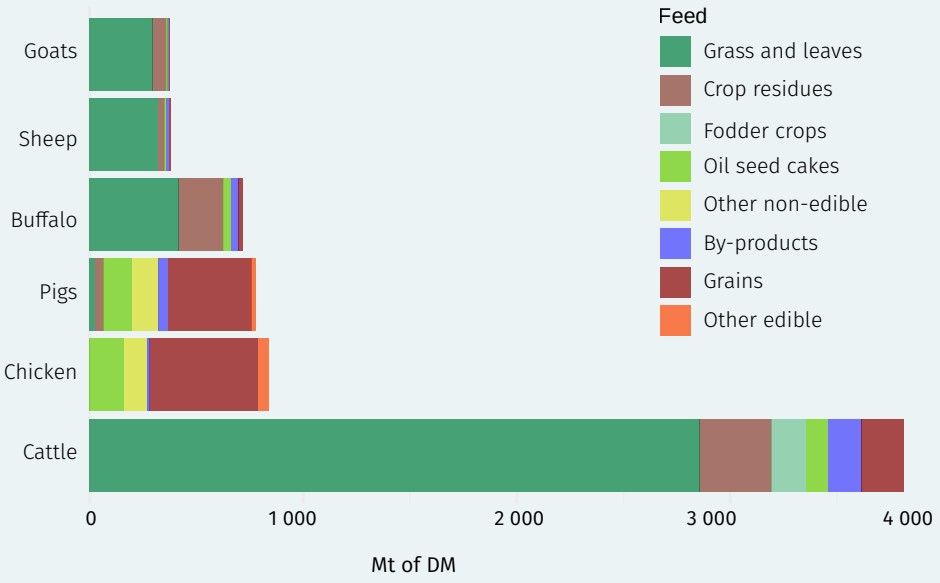

Figure B1.
Dry matter intake by species and feed category

Note: Estimated from GLEAM 3.

Emission intensities

The reduction in emission intensity, signifying emissions per unit of product, serves as an indicator of improved production efficiency – essentially producing the same amount of output using fewer inputs or generating higher amounts of outputs with the same inputs. Emission intensities vary greatly among and within various production systems, reflecting agroecological conditions, farm management practices, and interactions within the value chain components. The variability between high- and low-emission-intensity systems, even within the same production system, presents opportunities for emission mitigation (Gerber *et al.*, 2013).

Historically, emission intensities were calculated for the amount of product or kilogram (kg) of protein contained. However, over the past decade, research has shifted its focus on efficiency, defining it from diverse perspectives and paying more attention to the metrics. The choice of metrics influences the relative results and comparisons between species.

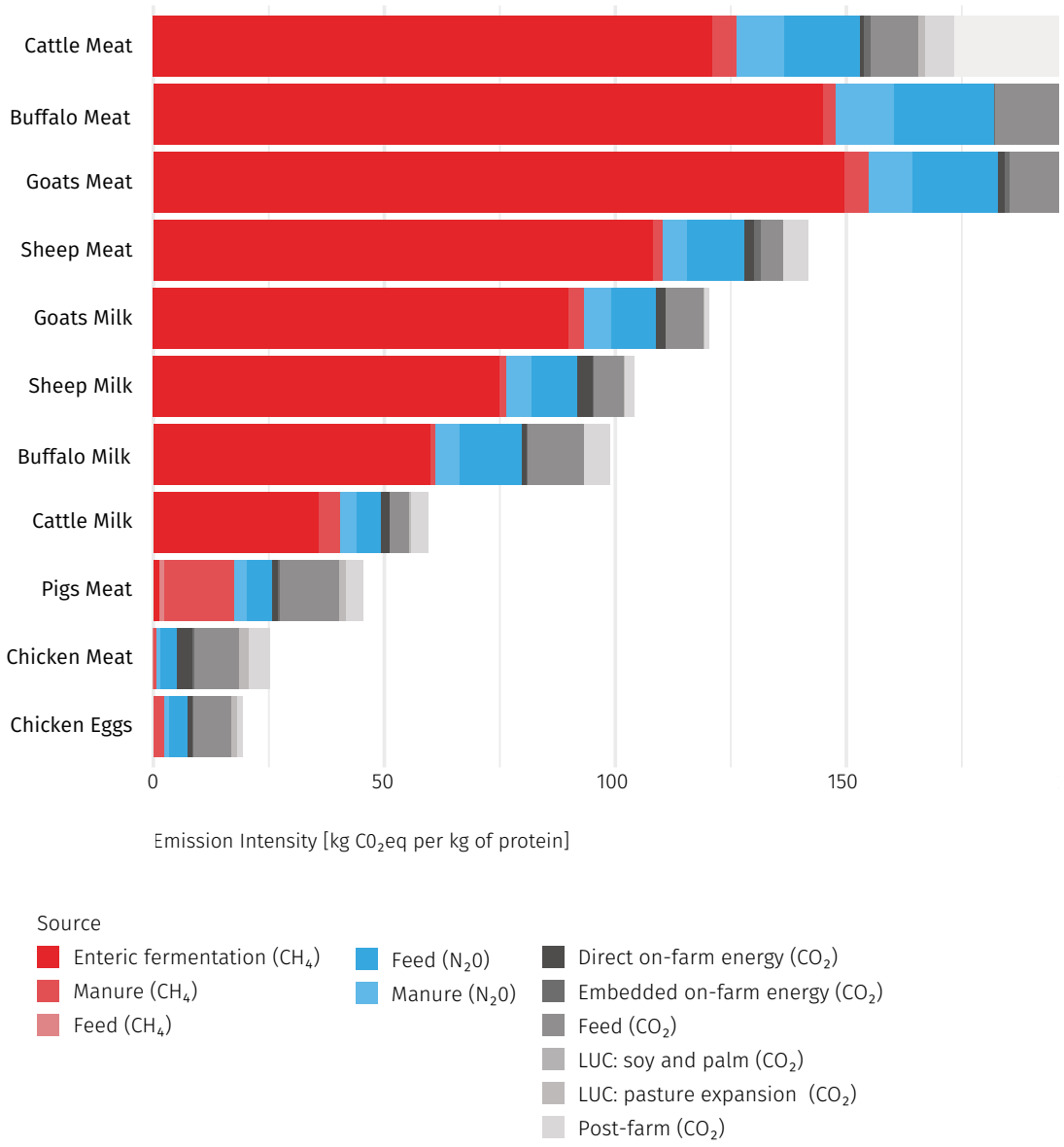

Figure 7.
Emission intensities showing the source of emissions by species and commodity

Note: More granular and regional views are available from the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/). CH_4 = methane (red), N_2O = nitrous oxide (blue), CO_2 = carbon dioxide (grey), LUC = land-use change.

Figure 7 provides a summary of global emission intensities, measured per kg of protein,[5] for various products across different species, and highlights the relative contribution of different sources of emissions to the emissions associated with the production of different animal products.

While global average values provide an overview of the environmental performance, they hide important variations in the efficiency of TASF, reflecting differences in products, species, production systems and management practices. In general, emission intensity tends to be lower in regions with higher absolute emissions, such as north America (see Figure 8), and higher in regions with lower absolute emissions, such as in sub-Saharan Africa. The obvious target regions for improving the efficiency of livestock production, measured by emissions generated per unit of product, tend to be in LMICs in Africa, south America and Asia (see Figure 8). This is not to promote intensification in these regions at all costs, but rather to advocate learning from systems with relatively lower emission intensities in order to optimize others within the same system. While mitigation efforts in these areas can reduce local emission intensity, their current contribution to global emissions is relatively low, resulting in a limited impact on global emissions.

[5] To facilitate the comparability of different product quantities, protein content was used as a common denominator, although alternative conversion factors could also be used.

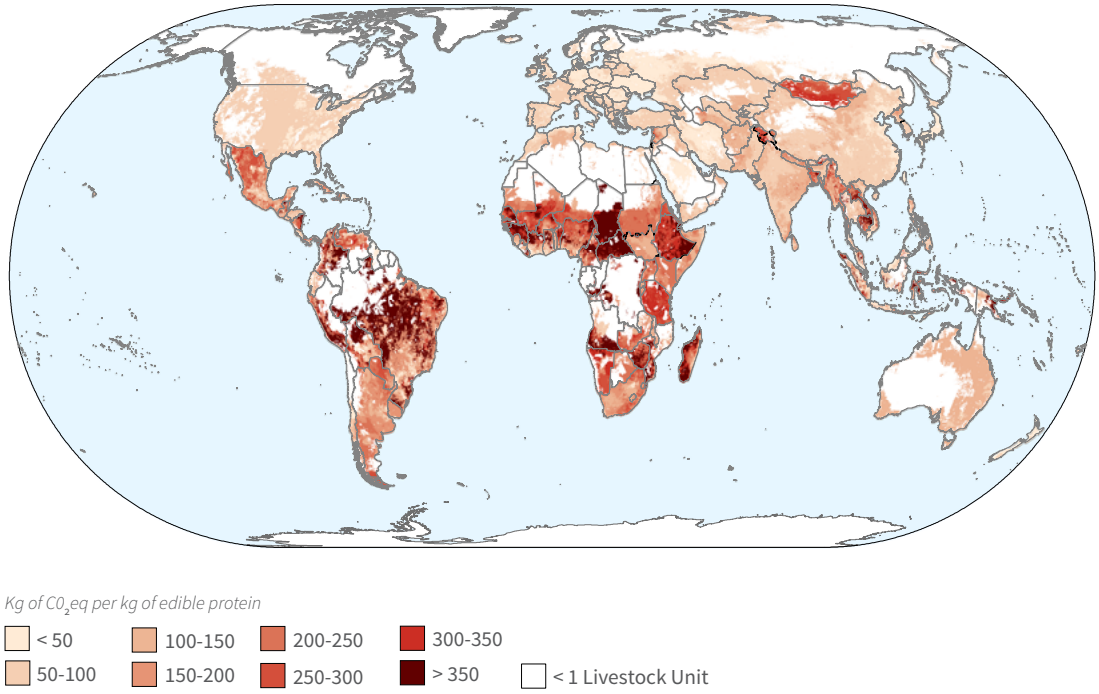

Figure 8.
Emission intensities from all livestock systems

Note: Detailed results are available on the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/).

Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties. Final boundary between the Sudan and South Sudan has not yet been determined.

Source: **United Nations Geospatial.** 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/file/3420/download?token=TUP4yDmF modified with GLEAM 3 data.

Increasing emission intensity may not necessarily lead to a decrease in absolute emissions. If the relative increase in production outweighs the reduction in emission intensity, emissions may rise with any increase in production. If the efficiency gains translate into higher profits, this may lead to further growth and depletion of natural resources in the livestock sector, necessitating the (re)design and implementation of new policies or adaptation of existing ones. Here, herd sizes play a key role in this context. Focusing solely on improving emission intensity may also come at the expense of other goals, such as animal welfare. Efforts to improve emission intensity must, therefore, analyse these trade-offs and interactions.

The spatial variation of GHG emission intensities within a production system depends on different sources of feed materials, management practices, animal breeds and environmental conditions. For example, in grassland systems, the average emission intensity of cattle milk is 56 kg of CO_2eq per kg of milk protein, but this figure ranges from 21 kg to more than 400 kg of CO_2eq per kg of milk protein (see Figure 9). The significant variability between systems offers valuable insights into reducing emission intensities by improving existing systems without transitioning to entirely new ones, and by leveraging existing technologies and strategies.

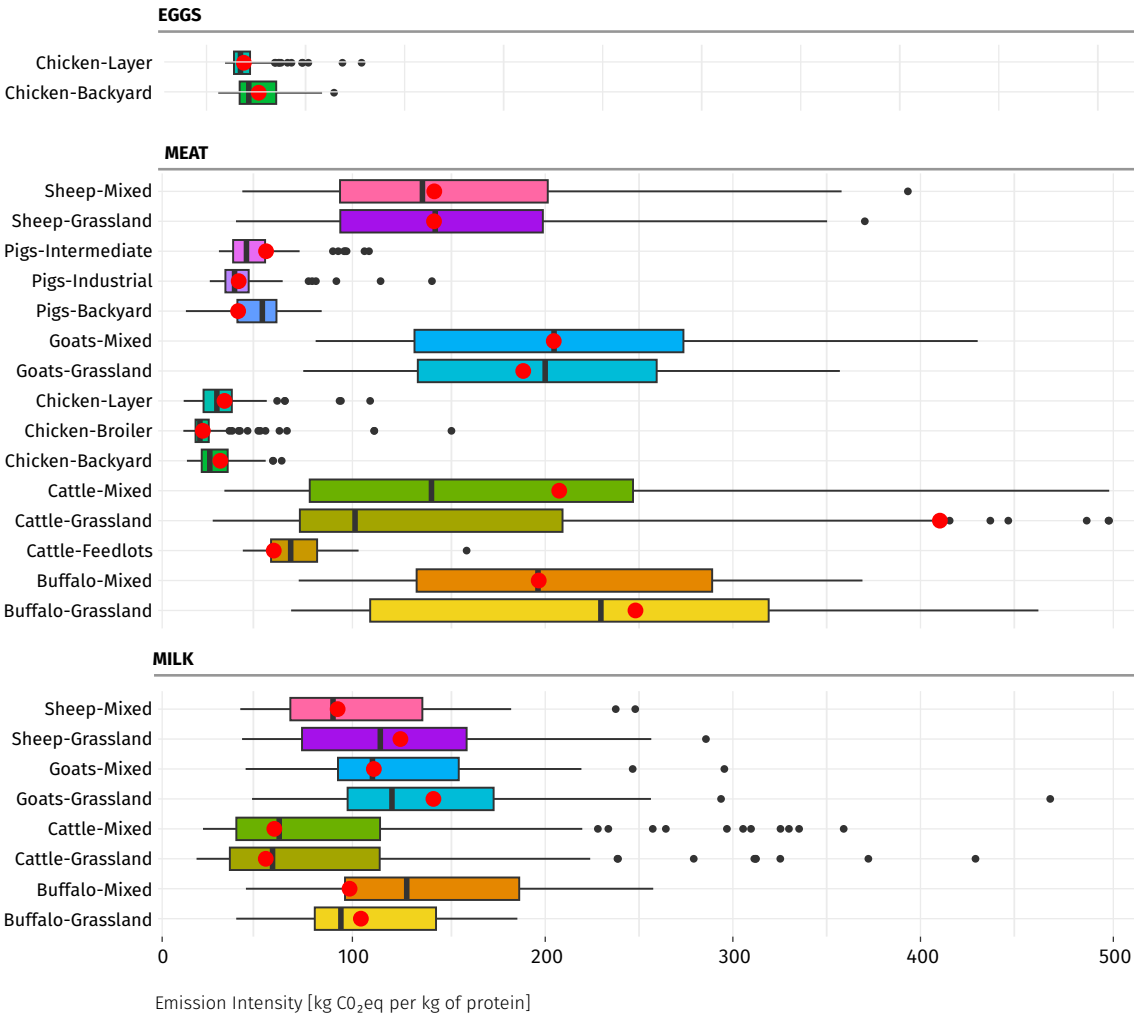

Figure 9.
Box-Whisker plots of the emission intensity for different production systems, species and commodity, aggregated by countries

Note: for countries with production > 1000 tonnes. The red dot indicates the global average value, and the box indicates the lower and upper quantiles, the vertical bar the median value.

Business-as-usual production and emissions to 2050

Many factors affect dietary preferences, resulting in a great diversity of dietary patterns worldwide. These patterns reflect historical, cultural, social and economic influences. Moreover, diets are not static and evolve in line with changes in wealth, urbanisation and globalisation. Increasing wealth and urbanisation often lead to higher levels of TASF consumption in many societies, whilst concerns over the climate change, animal welfare and health are driving a reduction in TASF consumption in other regions. Figure 10 provides a summary of the projected per capita demand for different animal products and anticipated increase in total population by continent.

While most of the projected increase from 2012 has already occurred, the most significant change is expected in Africa. As the population in east Asia nears its peak and global per capita consumption level remains relatively high, Africa is poised for substantial growth. In almost all African regions, the per capita demand for meat is projected to increase by nearly 20 percent per capita from 2020, and the population by 80 percent. However, the demand for animal products per capita in Africa is still very low, and the projected demand by 2050 represents less than 10 percent of the total demand for animal protein.

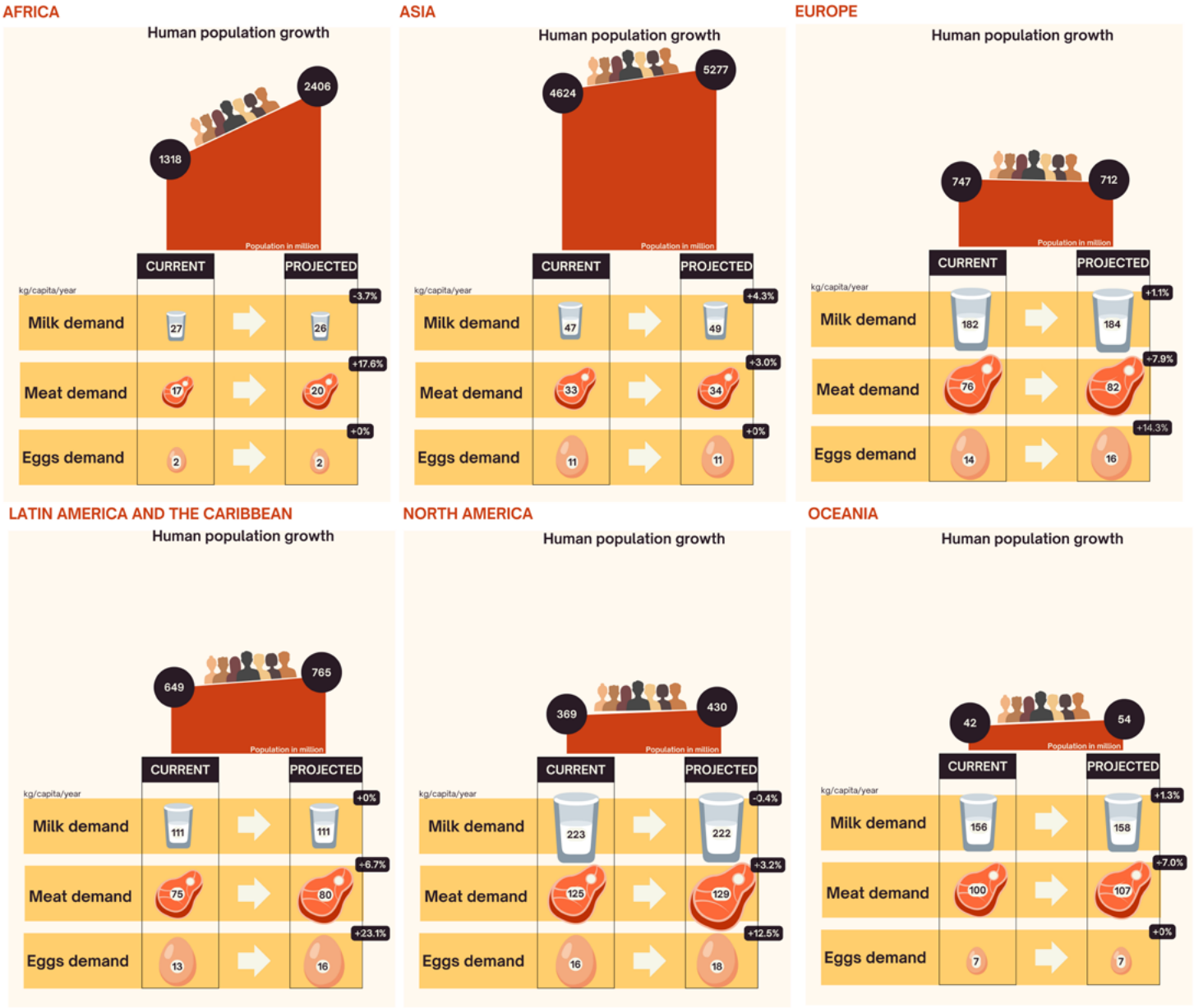

TABLE 2. Demand for the animal protein by continent in 2020, projected demand for 2050 and the relative change

Continent	2020 (Mt)	2050 (Mt)	Relative change (%)
Americas	18.69	22.88	22
Asia	36.20	42.57	18
Africa	4.71	9.49	102
Europe	14.09	14.23	1
Oceania	0.71	0.97	37
World	74.39	89.81	21

Note: Mt = million tonne.

Source: Based on FAO. 2018b. The future of food and agriculture: Alternative pathways to 2050. Rome. https://www.fao.org/global-perspectives-studies/resources/detail/en/c/1157074/projections.

Figure 10.
Current and projected per capita demand for the animal products

Note: In kg/capita/year.

Source: Based on FAO. 2018a. Nutrient flows and associated environmental impacts in livestock supply chains: Guidelines for assessment (Version 1). Livestock Environmental Assessment and Performance (LEAP) Partnership. Rome. 196 pp. Licence: CC BY-NC-SA 3.0 IGO. https://www.fao.org/3/ca1328en/CA1328EN.pdf, and population growth (million people) based on **United Nations, Department of Economic and Social Affairs, Population Division (UNDESA).** 2022. World Population Prospects 2022, Data Sources. UN DESA/POP/2022/DC/NO. 9. https://population.un.org/wpp/Publications/Files/WPP2022_Data_Sources.pdf.

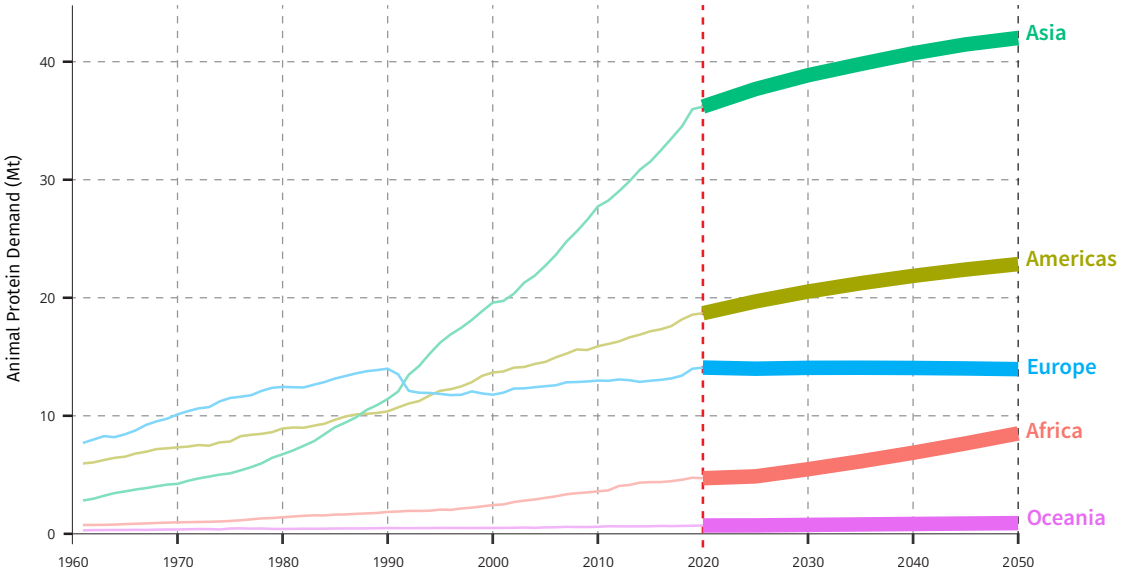

Figure 11.
Historical and projected demand for animal products

Source: Based on FAOSTAT food balance sheets and the projected demand from FAO. 2018b. The future of food and agriculture: Alternative pathways to 2050. Rome. https://www.fao.org/global-perspectives-studies/resources/detail/en/c/1157074/. To harmonize the two dataset, future projections from FAO's Global Perspectives Studies (GPS) team were calculated as relative change from 2020 and applied to the estimates from FAOSTAT for the same year: FAO. 2022a. Greenhouse gas emissions from agrifood systems. Global, regional and country trends, 2000-2020. FAOSTAT Analytical Brief Series No. 50. Rome. https://www.fao.org/3/cc2672en/cc2672en.pdf.

Taken together, the population growth and the changes in per capita demand will lead to an additional demand in animal protein of 21 percent by 2050 globally (see Figure 10 and Table 2).

Combining the projected increase in demand with historical data from FAOSTAT food balance sheets (FAO, 2010a) puts this increase in perspective (see Figure 11). The global increase in demand for animal products since the 1990s was largely driven by population growth in eastern Asia. However, this growth is expected to decelerate after the first quarter of the century due to reduced population growth. The most substantial relative change in future demand is projected for countries in Africa, where the demand for animal protein is projected to double for most countries by 2050, mostly driven by strong population growth. In contrast, demand in Europe and Oceania is projected to stagnate or even decline.

These projected changes in demand for various commodities necessitate a corresponding increase in production for different species. Meeting this demand can be achieved through either increasing production per animal or expanding the herd size. With no intervention or improvements in productivity, the sector will have to respond to this heightened demand by increasing the size of herds and flocks. This, in turn, would lead to a commensurate increase in GHG emissions, pushing global livestock emissions to nearly 9.1 Gt CO_2eq by 2050.[6] This scenario would also bring about some shifts in the composition of total emissions by gas, with approximately 54 percent in the form of CH_4, 15 percent as N_2O, and 31 percent as CO_2.

[6] To project future emissions, productivity yields and emission factors from GLEAM were combined with GPS projections for domestic production of animal commodities from 2020 to 2050, in a BAU scenario. To do so, the GPS projections in 5-year steps were rebased to the respective values for 2020 available in FAO (2023b). The projected values of production for each animal commodity were then converted to proteins and aggregated to calculate the total protein production for each animal species included in GLEAM. Such values were then divided by the respective productivity yields from the model to estimate associated projections for herd and flock sizes. The projected stock numbers were then multiplied by the respective average emission factors per stock head for each species and country to estimate the corresponding GHG emissions. It is important to note, however, that such estimates assume no changes in productivity and emission intensities compared to 2015.


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3. Scaling-up mitigation options

Reducing GHG emissions from the livestock sector is needed to limit the rise of the global average temperatures. Particularly, the reduction of enteric CH_4 emissions, a short-lived climate pollutant (SLCP), is essential to limit the global warming to less than 2 degrees Celsius, preferably less than 1.5 degrees Celsius. Overall, the mitigation options should focus on cutting absolute GHG emissions, and the impact of such reductions on global warming depends on the type of GHG reduced. With at least 27 percent of global anthropogenic CH_4 emissions taking place in the livestock sector in 2020 (FAO, 2023b), there is a significant opportunity for the sector to contribute to the objectives of the Paris Agreement. Mitigation options can target either the demand or the supply side by increasing productivity or reducing emissions per unit of product. Demand-side interventions include managing the overall demand for TASF, influencing the nature of demand, and addressing food loss and waste. On the supply side, options include on-farm reductions, upstream and downstream measures (such as improving the production of raw materials, feed production and processing, and enhancing the collection, transport and processing of animal products), improved recycling of biomass and manure, carbon sequestration and on-farm renewable energy production, in particular, through biogas or solar energy (FAO, 2019a).

Box 2: Methane

Methane is a SLCP with a lifetime of about 12 years in the atmosphere. Biogenically produced CH_4 has a GWP of 27 over a 100-year period, meaning that 1 kg of CH_4 is 27 times more potent than 1 kg of CO_2 at trapping heat in the atmosphere (Forster *et al.*, 2021). Over a shorter 20-year span, its warming effect is over 80 times greater than that of CO_2 (Forster *et al.*, 2021). Methane emissions have nearly doubled in the past 200 years. This increase has been mainly anthropogenic-driven and predominantly located in the Northern Hemisphere (Canadell *et al.*, 2021).

However, considering its short lifespan in the atmosphere and high GWP when compared to CO_2, it has been responsible for approximately 20 percent of the direct radiative forcing since 1750 (Forster *et al.*, 2021). Radiative forcing quantifies the impact of certain factors on Earth's energy balance and, consequently, global temperatures.

To limit the current pace of global warming to below 2 °C and preferably to 1.5 °C, 196 countries adopted the Paris Agreement, a legally binding international treaty under UNFCCC in 2015 (United Nations, 2015).

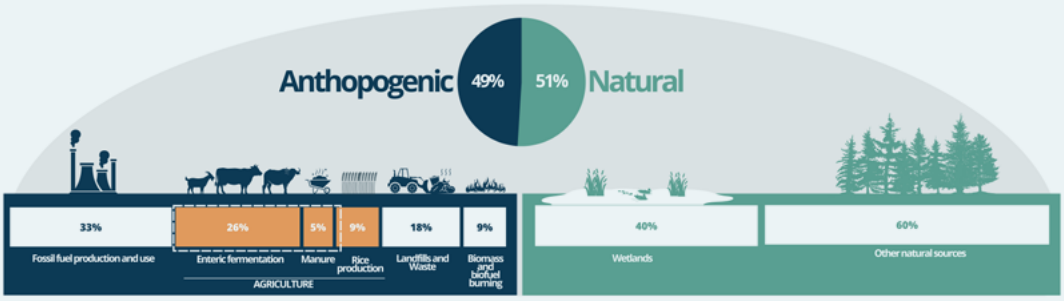

Figure B2.1.

Anthropogenic and natural sources of methane emissions

Note: Figures refer to the estimates from **Canadell, J.G., Monteiro, P.M.S., Costa, M.H., Cotrim da Cunha, L., Cox, P.M., Eliseev, A.V., Henson, S. *et al.*** 2021. Global Carbon and other biogeochemical cycles and feedbacks. In: *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* First edition. Cambridge University Press. https://doi.org/10.1017/9781009157896. The dashed box indicates the share of the agricultural emissions associated with the livestock sector from GLEAM 3. This portion accounts for the emissions from the enteric fermentation, manure management and for a small share of emissions associated with the rice production used as feed ingredient for poultry and pigs.

To meet this target, CH_4 from ruminants must be reduced by 11 to 30 percent by 2030, and 24 to 47 percent by 2050, compared to 2010 levels (Arndt *et al.*, 2022). Since the twenty-sixth session of the Conference of the Parties (COP26) in November 2021, more than 150 countries have joined a voluntary initiative of the Global Methane Pledge, committing to collectively reduce CH_4 emissions by 30 percent before 2030 (https://www.globalmethanepledge.org/). This reduction, if achieved, could lead to a temperature decrease of approximately 0.2 °C by 2050.

A recent study by Arndt *et al.* (2022) reported that the full global adoption of highly effective methane mitigation strategies could achieve a 30 percent reduction in CH_4 emissions by 2030. However, meeting the targeted reduction by 2050 may face challenges due to potential increases in CH_4 emissions associated with increased demand for milk and meat. Achieving 100 percent adoption of these mitigation options is unlikely in practice, reflecting the need for additional and more effective strategies. Methane emissions can result from both anthropogenic and natural processes.

Enteric fermentation (CH_4) - *Relative contibution and absolute values (Mt)*

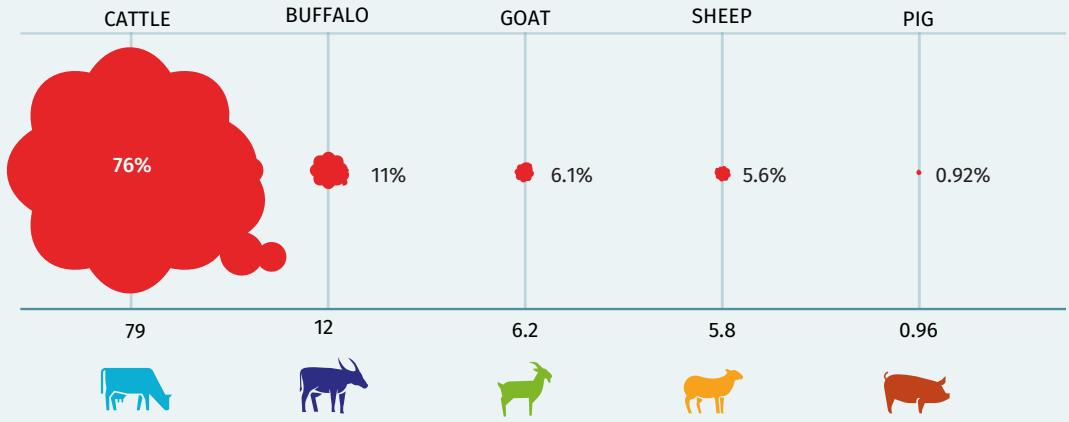

Manure Management (CH_4) - *Relative contibution and absolute values (Mt)*

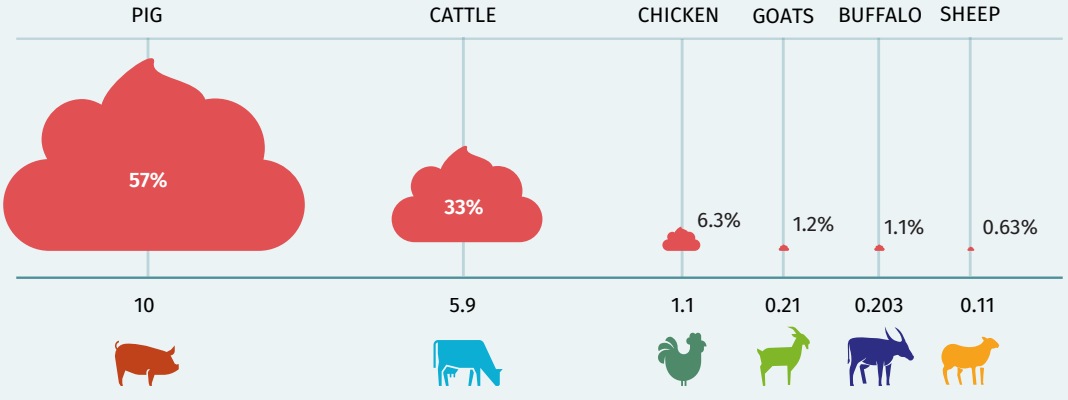

Figure B2.2.

Global animal population and methane emitted by enteric fermentation and manure management

Note: Methane (CH_4) emissions by species from GLEAM 3.

Anthropogenic CH_4 emissions constitute 50 to 60 percent of global CH_4 emissions, varying with estimation methods (Canadell *et al.*, 2021).

Within anthropogenic emissions, agriculture accounts for 40 percent, fossil fuel production and use for 33 percent, landfills and waste management for 18 percent, and biomass burning and biofuels for 9 percent. Agricultural CH_4 emissions predominately stem from livestock (78 percent), followed by rice production systems (22 percent). Methane emissions from enteric fermentation and manure management estimated by GLEAM 3 for 2015 amount to 122 Mt per year, closely aligned with IPCC estimate of 109 Mt per year, within a 10 percent margin (see Figure B2.1).

Livestock emissions primarily arise from the enteric fermentation of ruminants and, to a lesser extent, manure management. Enteric fermentation is a physiological digestive process involving the microbial breakdown of complex carbohydrates, primarily the cellulose, into simpler compounds such as volatile fatty acids, CO_2 and CH_4. Methane is also released during the storage and treatment of manure and from the deposition of manure on pastures (IPCC, 2019a).

Of the six livestock species assessed with GLEAM 3, ruminants are responsible for 89 percent of the total CH_4 emissions, while monogastric animals contribute 11 percent. Among the ruminant, cattle contribute to the majority of CH_4 production at 69 percent of the total. In comparison, other ruminant species contribute to a lesser extent, with 10 percent from buffaloes, 5 percent from goats, and 5 percent from sheep. Non-ruminant species, including pigs and poultry, contribute 10 percent and 1 percent, respectively.

The distribution of CH_4 emissions among different sources also varies across livestock species. Ruminants, such as cattle, buffaloes, goat and sheep, emit a large amount of CH_4 through enteric fermentation, ranging from 56 to 75 percent, and a smaller amount through manure management, ranging from 1 to 4 percent. In contrast, monogastric animals such as pigs and chickens emit more CH_4 through manure management, ranging from 5 to 33 percent, and less through enteric fermentation, from 0 to 3 percent. These variations are mostly attributed to physiological and anatomical differences between ruminants and non-ruminants, as well as differences in manure storage practices across farming systems. For instance, in cattle, emissions primarily originate from mixed systems (63 percent), where manure is managed mostly in dry lot or at the pasture, while emissions from grassland and feedlot systems account for 25 and 2 percent of CH_4 emissions, respectively. In the case of monogastric animals, pigs produce more CH_4 emissions (9 percent of the total) than chickens (1 percent). Industrial pig systems, with the highest share of manure managed in liquid form, contribute more to CH_4 emissions (51 percent) than intermediate (31 percent) and backyard systems (18 percent). The storage of manure in liquid forms, such as in lagoons, ponds, tanks or pits, can generate considerable CH_4 emissions due to anaerobic decomposition, whereas the decomposition occurs under more aerobic conditions when manure is deposited on pastures, rangelands, or stored in solid form (e.g. stacks or piles), leading to lower CH_4 production from the manure (IPCC, 2019a) (see Figure B2.2).

Changes in consumption of terrestrial animal source food

A reduction in TASF consumption may intrinsically be assumed to be associated with lower GHG emissions. However, it is important to consider the complex interplay of historical, cultural and location-specific factors influencing the dietary habits. Some studies may oversimplify by assuming an immediate, universal dietary shift, neglecting the nutritional challenges and the financial constraints that may render such changes unfeasible particularly for the world's poorest (Hirvonen *et al.*, 2019).

Box 3: Can alternative animal products help reduce emissions?

Emerging alternative sources of protein that largely eliminate animals from the production chain are increasingly being considered as potential replacements for TASF, and to reduce the environmental impact associated with the livestock production. Among those are plant-based meat products that use plant-based proteins, nutrients and other ingredients to produce the products similar to the animal products in texture and taste (plant-based analogues). The second group of emerging products involves the *in vitro* cultivation of animal cells or microbial cells to produce meat analogues (cultured meat) (FAO, 2023a).

Since their initial development in the early 2000s, both types of products have garnered considerable attention. Presently, over 100 companies worldwide are engaged in cultivated meat research, but large-scale production is not yet a reality. Concerns related to food safety and nutritional value exist throughout the entire production chain for these products (FAO and WHO, 2023).

Only a few countries so far have approved the sale of cultivated meat, but widespread commercialization of these products faces challenges due to technical, ethical and policy considerations (Wood *et al.*, 2023).

The environmental impact of both plant-based and the cultivated meat is highly debated. However, cell-based meats cannot be considered identical to the animal source food they aim to eventually replace, mainly due to differences in nutritional quality. Equally important is the fact that animal's roles in providing financial security, status and social value beyond its food value may be jeopardised, further causing inequalities between high- and low-income countries (Wood *et al.*, 2023).

For cultivated meat, a LCA of full-scale and lab-scale production companies suggests that the carbon footprint of these products is highly dependent on the energy mix used for production (Sinke *et al.*, 2023). However, such assessment has not been conducted for production at scale (Van Eenennaam and Werth, 2021).

The actual reduction of GHG emissions resulting from dietary changes depends on how the animal protein is substituted and how these substitutes are produced. For instance, replacing meat with calorically equivalent greenhouse vegetables or out-of-season fruits flown from afar could potentially reverse many GHG emissions offsets (Fresán and Sabaté, 2019).

Dietary changes that consider nutritional, health and environmental concerns about food consumption[7] often derive from the national recommended diets (NRD). Typically, NRDs recommend reduced intake of sugars, dairy products, meat and oils, with large variations across individual countries. In HICs, adhering to NRDs would generally lead to an overall decrease in consumption, shifting towards less TASF and more fruits and vegetables (Behrens *et al.*, 2017).

In LMICs, the average diet often falls below recommended calorie levels and lacks sufficient proteins, fruits, vegetables and nuts. In those regions, a dietary shift is generally associated with increased overall consumption and a higher quantity of both plant- and animal-based foods. Behrens *et al.* (2017) have analysed the potential impact of large-scale adoption of NRDs on GHG emissions. In HICs, such shift could translate to a reduction in GHG emissions of between 13 and 17 percent. However, the expected reduction in the middle-income countries is marginal (4.4 percent) with increasing emissions in some countries due to increased consumption of nuts, fruits and vegetables, partly grown in

[7] FAO defines healthy diets as sustainable healthy diets which are dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable (FAO, 2019a).

greenhouses. Taken together, these GHG reductions could amount to a decrease of 0.19 to 0.53 Gt CO_2eq per year for the 37 countries considered,[8] representing a 2 to 5 percent reduction in emissions associated with the entire global food system.

In most countries, the demand-side efforts to promote sustainable and healthy diets need to be complemented by improvements in production efficiency to achieve more substantial mitigation effects (Chang *et al.*, 2021).

Reducing food loss and waste

Reducing food loss and waste[9] is an option to reduce GHG emissions through a reduction of demand. Food that is not lost negate the need for production, minimizing emissions. The amount of food loss globally is estimated at 14 percent,[10] with large regional variations and differences among food groups (FAO, 2019b). The loss and waste rates for TASF are generally considered to be lower than these average value. Food waste can be environmentally managed through composting or utilized in biogas generation (FAO, 2023a).

Milk, meat and eggs tend to be wasted at the consumption stage (including the retail, households, restaurants and canteens, for example) and is generally higher in HICs. It is often linked to poor planning, impulse shopping, inadequate stock management, insufficient knowledge about food labels, inappropriate package sizes, and various socioeconomic, cultural and demographic factors within households (FAO, 2019b). A study in Europe (Karwowska , Łaba and Szczepański, 2021) identified that up to 23 percent of meat product losses and wastes occur, with nearly two-thirds at the consumer level.

In LMICs, losses are caused partly by inadequate slaughtering and cooling facilities, as well as improper handling and sanitation. An FAO study (Tatlıdil, Dellal and Bayramoğlu, 2013) found that approximately 6 percent of milk production in Turkey is lost during distribution, mostly due to the problems with the compliance of the cold chain requirements. In the case of meat, 5 percent is lost during processing and packaging, resulting from the discarding of the out-of-standard items. Considerable benefits can be achieved by promoting a circular bioeconomy in many places along livestock supply chains.

Increases in productivity

Productivity gains in the sector have been substantial over the last decades, and are well documented for many regions and systems. These gains result from enhanced efficiency at every production stage along the supply chain and, in many cases, can be achieved by the adoption of best practices. Improving production efficiency is reported to have a greater impact in mitigating emissions from the livestock sector than the demand-side efforts (Chang *et al.*, 2021).

Earlier simulations using GLEAM data suggest that emissions from livestock can potentially be reduced by up to 30 percent through the enhancement of productivity and resource use efficiency employing existing methods (Gerber *et al.*, 2013). There is a large potential to improve management practices, especially in LMICs (Ndung'u et *al.*, 2022).

[8] These countries represent 64 percent of the global population. Prorating the emissions from the food system globally (~16.5 Gt CO2eq), Tubiello et al. (2021) translates to savings of 2 to 5 percent.

[9] FAO refers to the decreases in the amount of produce occurring at the supplier side (up to, but excluding the retail) as *food loss*, whereas the uneaten food at the retail and the consumer side is referred to as *food waste*.

[10] Food Loss Index, Sustainable Development Goal Indicator 12.3.1a.

At the individual animal level, efficiency gains in dairy farming can contribute up to 38 to 46 percent of the total emission reduction by 2050 (Chang *et al.*, 2021). Significant reduction can also be achieved through improvement of management practices such as reducing the age of slaughter (Herrero *et al.*, 2016).

Further evidence for the productivity gains has been documented for the global dairy systems (FAO and GDP, 2019) and shows that from 2005 to 2015, milk production increased by 30 percent, while the global dairy herd expanded by only 11 percent during the same period. This resulted in an 11 percent decrease in emission intensity and a more modest rise in GHG emissions compared to what would be expected without efficiency gains.

To estimate the impact of these improvements on future emissions, historical trends in annual productivity of edible proteins were analysed using data from FAO (2023b).[11] The scope of the analysis was to estimate the annual relative changes in productivity to be combined with GLEAM productivity data and projected emissions, while considering the regional differences for each modelled species.[12] For example, while the annual productivity increase for poultry could be negligible in western Europe, it could almost reach 2.6 percent in northern and southern Africa. If ongoing productivity improvements continue, 24 percent of the BAU emission from the livestock sector could potentially be mitigated by 2050 on a global scale.[13]

Selective breeding

Genetic selection is one of the methods to mitigate enteric CH_4 emissions, given that both CH_4 emissions and production (g/day) exhibit heritability and repeatability. Although CH_4 yield (g CH_4/kg DMI) demonstrates less genetic variation than CH_4 emissions when measured over the medium term, it remains a heritable and repeatable trait (Pickering *et al.*, 2015). Selection for the low CH_4 production can be direct or indirect. Direct selection refers to selecting based on a CH_4 trait, for example, through the CH_4 measurements in respiration chambers while indirect selection would mean the breeding based on the traits that are correlated with CH_4, e.g. residual feed intake (Fouts *et al.*, 2022). By selecting for the animals with low residual feed intake, de Haas *et al.* (2011) report that the CH_4 production can be decreased by 11 to 26 percent in 10 years. It is, however, important to make sure that feed intake remains unchanged to be able to attribute the change to the selection. Otherwise, the increased feed intake may lead to the increases in enteric CH_4 emissions (Pickering *et al.*, 2015).

Currently, CH_4 trait is not included in the national breeding goals. If the current genetic trends continue, CH_4 production (g/day) can increase by 13 percent by 2050 due to the traits considered in the current breeding schemes. Including CH_4 in the national breeding programmes together with other breeding goal traits such as fertility and health has the potential to reduce the CH_4 production (g/day), but this may come at the expense of a drop in genetic trend for milk production (de Haas *et al.*, 2021). Introducing high-yielding exotic

[11] For each species and year, protein productivity was estimated by converting the total production of edible commodities in protein and dividing it by the respective number of heads in the stock.

[12] To this purpose, the annual relative changes in productivity by each species and region were estimated and averaged for the last 10 years available in FAOSTAT, from 2011 to 2021. In this context, only relative increases were considered, assuming no changes for species and regions presenting an average decrease in productivity, potentially related to episodic crisis. Moreover, to reduce the impact of outliers while also producing a conservative estimate, average regional increases by species were set to a maximum value corresponding to the sum of the global average plus one standard deviation for the last 15 years available.

[13] Such mitigation potential was estimated under the assumption that the productivity improvements would not lead to an increase in emissions per stock head, thus assuming a corresponding decrease in the emission intensities of animal commodities.

breeds to improve the productivity may come at the expense of elevated susceptibility to pathogens (Khasapane *et al.*, 2023; Vordermeier *et al.*, 2012). Breeding improvements may not be possible in all production systems and all parts of the world, and often, when it is available, may be constrained by the lack of quality and available feed especially in LMICs.

Further research is still needed to assess the impacts of direct selection on the downstream and upstream net GHG emissions (Fouts *et al.*, 2022). Similarly, the selection using fixed intake values in respiration chambers is unlikely to reflect the actual CH_4 yield for grazing animals for which the intake varies depending on the quality and the quantity of herbage mass. Therefore, the relationship between CH_4 emissions, feed intake and production traits should be investigated further (Hickey *et al.*, 2022). In this regard, the portable accumulation chambers are a spot-sampling method that could be used to investigate the correlated traits (Jonker *et al.*, 2023).

Rumen manipulation

CH_4 inhibitors

The two most commonly used CH_4 inhibitors are 3-Nitrooxypropanol (3-NOP) and Bromoform-containing seaweed species. It should be noted that these inhibitors may be suitable for zero-grazing systems and grazing systems with supplementation, but not practical for grazing systems without feed supplementation, such as pastoral systems. This limitation, coupled with potential affordability and acceptability challenges, restricts their application primarily to intensive beef production systems (Mukherji *et al.*, 2023).

3- Nitrooxypropanol (3-NOP)

Recently, 3-NOP has been reported to inhibit CH_4 emissions without affecting the feed intake or productivity (Arndt *et al.*, 2022; Beauchemin *et al.*, 2022; FAO, 2023c). A recent meta-analysis of the models by Kebreab *et al.* (2023) reported that the impact of 3-NOP dose of 70.5 mg/kg DM results in the reductions of CH_4 production (g/day), CH_4 yield (g/kg DMI) and CH_4 emission intensity (g/kg energy-corrected milk) of 32.7 percent, 30.9 percent and 32.6 percent, respectively.

Bromoform-containing seaweed

The use of macroalgae (seaweeds) such as *Asparagopsis taxiformis* and *A. armata* to inhibit CH_4 production depends on their chemical composition, time of collection and growth environment. The main bioactive compound is in the form of bromoform which inhibits methanogenesis in the rumen. Supplementation of *Asparagopsis taxiformis* in the diets of the dairy cows and steers can lead to an inhibition of CH_4 production from 9 to 98 percent (Beauchemin *et al.*, 2022; Fouts *et al.*, 2022). Recent research demonstrated that the bromoform in *Asparagopsis taxiformis* can be excreted in milk and urine, and cause inflammation in the rumen wall, posing concerns for its use. Bromoforms and other halogenated compounds can also leak into the environment during the processing because they are highly volatile, furthering debates around their safety for humans and the environment (Muizelaar *et al.*, 2021).

Vaccines

Through vaccination, antibodies in the saliva reach the rumen and target methanogens. Subharat *et al.* (2015) reported that immunoglobulin A and G levels in the cattle saliva were reduced by 40 percent and 80 percent, respectively, after an eight-hour exposure to rumen

contents, indicating the stability of antibodies in the rumen. Despite promising *in vitro* results, research demonstrating the effect of vaccination *in vivo* on CH_4 production is still in its early stages. The efficacy of methanogen vaccine and their impact on food quality and safety require further exploration as well (FAO, 2023c). Despite the efforts in the past two decades, the between-animal variability and interregional differences in the rumen microbiome pose concerns around the development and application of a vaccine at global scale (Beauchemin *et al.*, 2022). Further efforts to understand rumen ecology, such as the Hungate 1000 (Seshadri *et al.*, 2018) and Global Rumen Census (2023), are likely to enrich the current knowledge (Beauchemin *et al.*, 2022).

Feeding and nutrition of animals

The impact of the strategies presented below on the proportional change of GHG emissions will be based on the adoption at scale and what is possible to implement at a particular production system. Here, the efficacy depends on various factors such as farmer's willingness to adopt and pay for the intervention, the consumer behaviour, and not the least the farm conditions and its long-term impact on the production. Any use of the feed additives often faces regulatory requirements in several countries, and it is important to better evaluate the food quality and safety issues associated with its wider use.

Dietary strategy

The production of various feed ingredients contributes to embedded GHG emissions, either through inputs like synthetic fertilizer production or direct emissions during feed production, harvesting and processing. To reduce the carbon footprint of livestock production, it is important to formulate rations with feed ingredients that can ideally enhance productivity while reducing net emissions, without compromising profitability. It is important to pay attention to the fact that the ration balancing strategy does not lead to increased upstream or manure emissions that could offset reductions in the enteric CH_4 emissions. This can happen, for example, if high protein feeds are fed in excess (Mohankumar Sajeev, Winiwarter and Amon, 2018).

Dietary strategy can favour the short retention time of the feed in the rumen, which declines the microbial access to the organic matter (Beauchemin *et al.*, 2022), for example, by increasing concentrate level in ruminant diets (Arndt *et al.*, 2022). However, implementing this approach must consider the availability of concentrates, often limited in LMICs due to high commodity prices and food-feed competition (Mottet *et al.*, 2017a). Conversely, feeding ruminants high levels of cereals may adversely impact animal health and welfare, leading to issues like acidosis (Jaramillo-Lopez *et al.*, 2017). In addition, relying on high-quality grain and soybean in livestock diets can drive LUC and deforestation. In general, it is important to adhere to feeding recommendations for each feed item to avoid potential trade-offs in animal welfare.

Lipids and essential oils

Supplementing ruminants with dietary lipids can act as a toxic agent against methanogens and protozoa, leading to a shift in the rumen environment, increasing propionate production, and reducing enteric CH_4 emissions (Beauchemin *et al.*, 2022). The addition of lipids to the diet can reduce absolute CH_4 emissions by 19 percent. Combining lipids with CH_4 inhibitors or electron sinks may have additive effects, although their impact on manure emissions needs to be investigated further (Arndt *et al.*, 2022).

Box 4: Ration balancing

The Ration Balancing Programme (RBP) in India was initiated by India's National Dairy Development Board (NDDB) to improve milk production and reduce feeding costs among smallholder dairy farmers. Given the reliance on low- and medium-productivity animals, their feeding is composed mainly of locally available crop residues like straws and stovers along with seasonal grasses and agro-industrial by-products and concentrates such as oilseed cakes, chunnies and brans with very low or negligible minerals. Such type of feeding often leads to nutrient imbalances in protein, minerals and vitamins. To create awareness about the evidence-based feeding among dairy farmers, NDDB has developed a software package for personal computers and smartphones. The software optimizes rations for individual dairy animals using locally available feed resource. Chemical composition of the feed and fodders available in the country was analysed to prepare the feed data library for the software.

The RBP was implemented for 2.86 million milking animals owned by 2.15 million farmers in 33 374 villages across 18 states in India.

The effect of the RBP on enteric CH_4 emissions was assessed using GLEAM with the nutritional content and digestibility (taken from the literature) of the feed items for a subset of some 30 000 cattle and buffaloes in five provinces based on the crop-specific dry matter intake (DMI) for each animal before and after the intervention.

Feeding of nutritionally balanced rations in smallholder dairy settings resulted in a substantial decrease in DMI, and a reduction in enteric CH_4 emissions by more than 13 percent. At the same time, feeding costs were reduced by almost 9 percent, and milk yield increased by an average of 3 percent. Further improvements to the intervention could address trade-offs between different GHGs, improve digestibility of locally available crop residues, and introduce new feed ingredients. Given the importance of CH_4 emissions from enteric fermentation in the overall livestock emissions in India, this intervention holds promise for reducing the country's overall livestock GHG emissions (see Figure B3).

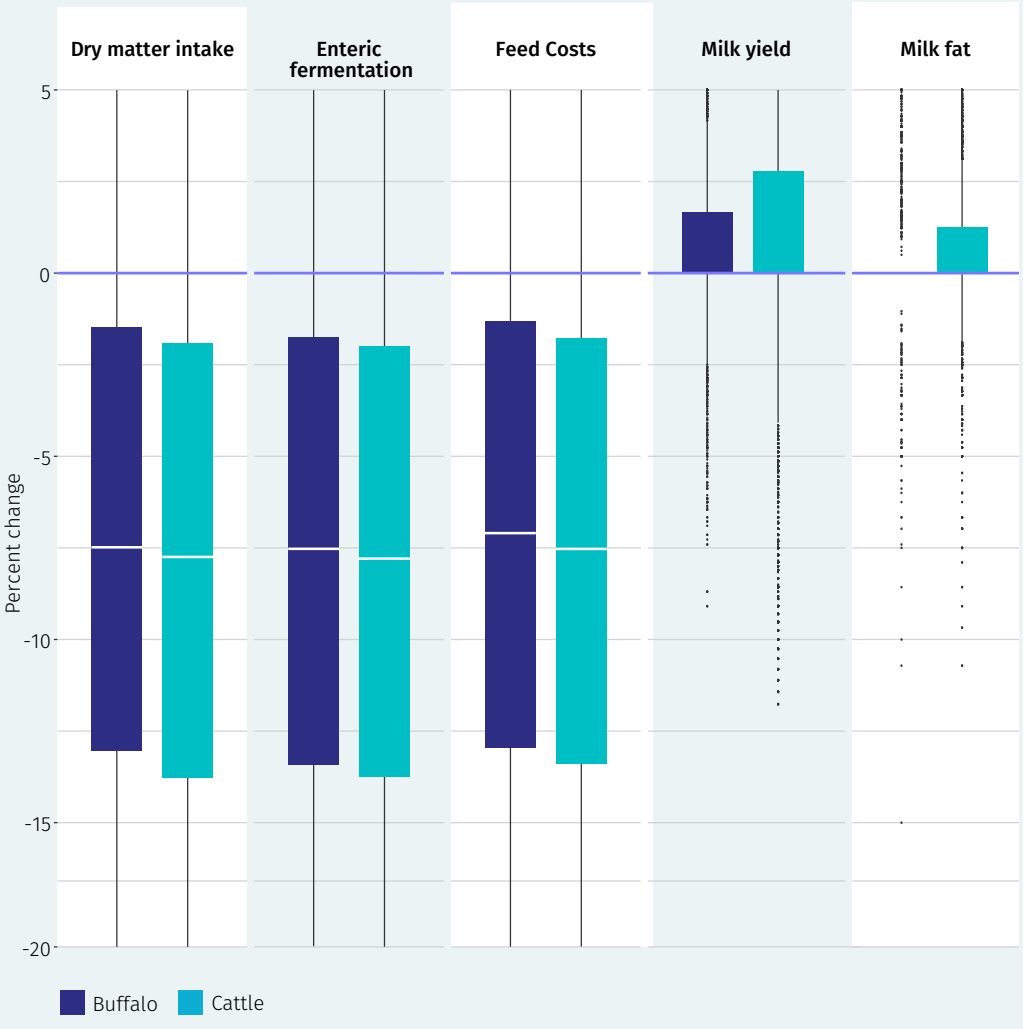

Figure B3.
Impact of Ration Balancing Programme on dry matter intake, methane from enteric fermentation, feed costs, milk yield, milk fat in India

Note: DMI = dry matter intake, CH4 = methane
Source: NDDB (https://www.nddb.coop) and GLEAM (https://www.fao.org/gleam/en/).

Essential oils have been shown to have bioactive compounds to reduce CH_4 emissions through antimicrobial activity *in vitro*. Rofiq *et al.* (2021) evaluated the effect of six essential oils (garlic, clove, thyme, cinnamon, mint and orange peel) on *in vitro* rumen CH_4 production, and found that all six essential oils could reduce CH_4 production at six-hour incubation. An essential oil blend decreased CH_4 emissions by 10 percent (Belanche *et al.*, 2020). The use of lipids to mitigate CH_4 emissions is more suitable for zero-grazing systems and grazing systems with supplementation (Mukherji *et al.*, 2023).

Tanniferous forages

Using high-quality fodders such as legumes and high-starch forages has been shown to promote low-emission ruminant systems (Beauchemin *et al.*, 2022). Tannin extracts are naturally available in the tropical and temperate plants, and the consumption of condensed and hydrolysable tannins by ruminants is shown to reduce nitrogen (N) excretion while not hampering the productivity. Tannins by modifying methanogenesis (Aboagye and Beauchemin, 2019) can decrease CH_4 emissions by 6 to 45 percent (FAO, 2023c). Tanniferous forages can be a mitigation strategy for most existing systems, including zero-grazing, grazing with supplementation or without supplementation (Mukherji *et al.*, 2023).

Saponin-containing plants or extracts also possess the ability to regulate protozoa populations in the rumen. They achieve this by increasing propionate production and reducing hydrogen availability (FAO, 2023c). These compounds show promise in mitigating CH_4 emissions, provided their inclusion remains below 0.5 percent DM (Ridla *et al.*, 2021).

Improved animal health and welfare

There is growing evidence that addressing specific diseases and health conditions in livestock can play a crucial role in reducing GHG emissions. Improving animal health not only contributes to general productivity gains,[14] but also results in lower emissions per unit of output. Enhanced animal health, characterized by reduced mortality rates and healthier animals, leads to improved productivity, growth rates of animals and thus lower emissions. Improving animal health can also increase production efficiency by reducing the need to discard products due to food safety concerns (Özkan *et al.*, 2022).

Parasites, by compromising feed efficiency and productivity, may increase CH_4 yields per kg of DMI by 33 percent (Fox *et al.*, 2018). Including the increased feed intake due to delayed weaning and compensation for maternal body loss, parasitism can lead to 11 percent, 32 percent and 30 percent increases in enteric CH_4, manure CH_4 and manure N_2O emissions, respectively, per kg of lamb weight gain (Houdijk *et al.*, 2017).

Animal welfare should also be considered when designing mitigation strategies to ensure that improvements do not come at the expense of the animal welfare (Lanzoni *et al.*, 2023a). Llonch *et al.* (2017) reported that steers with high cortisol levels, subjected to stressful conditions, had lower DMI, which resulted in a higher feed efficiency (i.e. lower feed conversion rate and residual feed intake) and a greater CH_4 yields (g/kg DMI). The rise in the CH_4 yields (g/kg DMI) was mostly associated with the prolonged retention of feedstuff in the rumen, intensifying fermentation. In addition, stressors encountered by animals at various stages of their lives are frequently linked to increased mortality rates (Velarde *et al.*, 2015) and reduced fertility (da Silva *et al.*, 2023), both of which can indirectly increase GHG emissions. When examining the entire production chain, suboptimal welfare conditions

[14] Improved animal health as part of a *One Health* approach delivers additional benefits through minimizing the risk of emerging zoonotic diseases, antimicrobial resistance, and the improvements in food safety (World Bank, 2021a).

and the presence of acute and chronic stress may lead to higher levels of discards and a lack of willingness for the consumer to consume the product due to alterations in carcass quality, e.g. texture and colour (Alcalde *et al.*, 2017; Gonzalez-Rivas *et al.*, 2020). However, standardized approaches are needed to promote objective assessment of animal welfare and environmental impacts (Lanzoni *et al.*, 2023b).

The reduction in absolute emissions resulting from improvements in animal health is contingent upon various factors such as the type of pathogen, interactions between pathogens and vectors, environmental conditions and the health status of the animals (e.g. genetics, nutrition and management) (Özkan *et al.*, 2016). Besides, some diseases are more amenable to intervention than others (Skuce *et al.*, 2016). The impact of such interventions can also differ when implemented in isolation or as part of a comprehensive package. For example, interventions that include improved animal health (e.g. vaccination and heat stress reduction through providing shade and water) have been shown to significantly reduce absolute emissions from 10 percent in mixed dairy systems in east Africa, and up to 41% in small ruminants in west Africa (Mottet *et al.*, 2017b).

A conservative estimate of likely savings from the improvement of animal health in a UK context is around 10 percent reduction in GHG emissions (Skuce, 2022), with a global potential estimated at 0.2 Gt CO_2eq per year (Herero *et al.*, 2016). However, the potential for productivity improvements through animal health interventions is generally higher in LMICs where disease occurrence is currently high and institutional capacity and resources for disease prevention or treatment are limited (Özkan *et al.*, 2022). While absolute emissions at the animal level may increase due to healthier animals having higher feed intake and longer lifespans, supply-chain level emissions could decrease because fewer replacement animals would be needed (Özkan *et al.*, 2022).

Carbon sequestration in grasslands

Agricultural systems not only emit GHGs but also hold the potential to sequester carbon in grazing systems, by enhancing the above- and below-ground carbon capture through improved pasture management and treeplanting. The integration of trees in the silvopastoral systems, where trees are introduced into grazed pastures, can be very effective in capturing and temporarily storing carbon. It also enhances productivity and protects against the extreme weather conditions (Agethen, Mauricio and Deblitz, 2021). The impact of grazing on soil carbon sequestration is contingent upon agroecological conditions and management practices (World Bank, 2021c). Furthermore, the potential for carbon sequestration is influenced by existing carbon stocks, making global quantification challenging and subject to change over time. Consequently, estimates of sequestration potential varies widely, further complicated by concerns over the reversibility of sequestration efforts (Godde *et al.*, 2020) and variations in soil carbon estimation methodologies. The lack of representative evidence from different parts of the world underscores the need for long-term experiments to validate assumptions. The maintenance of grazing land is deemed more crucial than restoring degraded land, as the absence of former is likely to cause significant losses in soil carbon stocks.

The peer-reviewed literature on carbon sequestration in grassland reports values between 37 Mt CO_2 and 2 090 Mt CO_2/year, depending on the approaches considered (Godde *et al.*, 2020). Henderson *et al.* (2015) estimated that improved grazing management could achieve 148 Mt CO_2/year. Using a soil carbon model, Dondini *et al.* (2023) estimated that adopting best practices in grassland management – such as reducing grazing intensity, implementing agroforestry and using organic fertilizers – could sequester an average of 0.29 t C/ha/year over 20 years, equivalent to 1.06 t CO_2/ha/year, with large regional

variations based on soil characteristics. If these rates were applied to all grasslands globally (1.81 billion ha), it could result in the removal of 1 933 Mt CO_2 from the atmosphere each year, representing nearly one-third of the sector's current annual emissions.

Clearly, achieving such rates of carbon sequestration in grasslands would require a large-scale adoption across all grazing areas, accompanied by investment costs that may not be feasible in the short term. The actual potential for carbon sequestration in grasslands is much smaller and depends partly on potential economic returns. Large-scale national projects may provide entry points for sequestering carbon in grasslands by restoring degraded pastures, but soil carbon sequestration does not occur indefinitely. Soil carbon reaches an equilibrium after a certain period. Depending on carbon prices, the economic potential of carbon sequestration has been estimated in the range of 37 Mt CO_2 to 800 Mt CO_2 per year (Godde *et al.*, 2020). Given the large range of reported values and the economic constrains, we optimistically estimate the global potential for carbon sequestration in livestock to be 600 Mt CO_2 per year.

It is important, however, to note that equating carbon in emissions to carbon removals by sinks are reversible and that may undermine efforts to reduce GHG emissions, reflecting the need for establishing distinct targets for removals and emission reductions (Carton, Lund and Dooley, 2021). Although this strategy is incorporated as a mitigation option in this section, in principle, it should be regarded as an offset mechanism rather than a strategy directly reducing emissions.

Circular bioeconomies

Circular bioeconomy involves the meticulous recycling, reusing and refurbishing of natural resources at every stage of the food system, while preserving these resources and nutrients, and preventing new resource extractions (Oosting *et al.*, 2022; FAO, 2023d). Livestock systems have the potential in advancing circular bioeconomies, serving as both recipients and as contributors. They act as recipients by utilizing waste streams from other activities (such as industry by-products as feed), and as contributors by providing valuable co-products for other activities (e.g. using manure for crop fertilization). Livestock transform feed, much of which is not suitable for direct human consumption, into valuable proteins such as meat and milk.

Incorporating industrial by-products into animal diets emerges as an effective strategy to enhance circularity of the system and unlock significant biomass potential (Oosting *et al.*, 2022; Wilkinson and Lee, 2018). Some of these by-products can potentially reduce CH_4 emissions through interaction with ruminal microbiota and animal's physiological process (Jalal *et al.*, 2023). For instance, the use of grape marc, a by-product of the wine industry rich in condensed tannins and crude fat, was associated with a 20 percent decrease in CH_4 production (g CH_4/day) and CH_4 yield (g/kg DMI) (Moate *et al.*, 2014). Giller *et al.* (2022) also showed that supplementing 500 g/kg DM of pomegranate pomace significantly decreased CH_4 yield *in vitro* (ml CH_4/g DMI) by about 28 percent, owing to its high hydrolysable tannin contents.

In addition, incorporating industrial by-products in animal feed can help mitigate waste-related emissions from other production cycle, serving as an indirect mitigation practice. For example, substituting at least 39 percent of the pig diet by swill (household waste and organic material used as feed, mainly composed of food losses and waste) resulted in decreased N losses by 11 to 53 percent, an increase of N use efficiency from 6 to 30 percent, and reduced demand for soybeans by 31 Mt per year and grains by 20 Mt per year (Uwizeye *et al.*, 2019). However, the recent outbreak of African swine fever in Asia and Africa highlights the need for specific investments in infrastructure, policies

and regulations to ensure the safety of swill as feed. Moreover, utilizing feed derived from the recycling of waste streams in the production of novel protein sources, such as insects, macro- and micro-algae, can augment the supply of TASF and present opportunities for mitigating GHG emissions (Oosting *et al.*, 2022). Frehner *et al.* (2020) suggest that, when looking at cropland use alone, scenarios with TASF from low-cost option livestock (i.e. livestock fed on by-products, food waste and grass sources) perform best.

Livestock can act as direct contributor to the circular bioeconomy by considering manure as a co-product of livestock systems (Leip, Bodirsky and Kugelberg, 2021). Maximizing the use of manure to improve soil fertility is integral to effective mitigation practices, valorising biomass and potentially improving crop production while reducing energy consumption associated with synthetic fertilizer production and use (He *et al.*, 2023). Currently, manure supplies only around 12 percent of the gross N input for cropping (Liu *et al.*, 2010), but potentially it could cover more than 80 percent of the N and phosphorus requirements for agricultural plants globally (Bouwman *et al.*, 2013). To avoid overfertilization and mitigate detrimental environmental effects, measures should be implemented to improve manure spreading also in areas beyond those in close proximity to barns, enhancing integrated crop-livestock systems (Kleinpeter *et al.*, 2023; de Vries *et al.*, 2020). These systems can also contribute to reducing the need for inputs such as land, water and nutrients, thereby enhancing overall efficiency (Beal *et al.*, 2023). Pastoral and silvopastoral systems exemplify circular bioeconomies, with animals grazing on land that would otherwise not be used for other purposes due to biophysical reasons. In these systems, animals provide manure and nutrients to the land where they graze on biomass residuals, effectively avoiding wastage (Montagnini, Ibrahim and Murgueitio, 2018; FAO, 2022d; Oosting *et al.*, 2022).

Energy use

Even though the contribution of energy use to global livestock emissions is considerably low, there exists significant untapped potential for creating offsets – reducing the overall GHG balance of livestock systems – by focusing on the generation of renewable energy along the entire supply chain. The production of inputs, such as synthetic fertilizers, is an energy-intensive process, estimated to account for 2 percent of global energy consumption (Walling and Vaneeckhaute, 2020). Moreover, it is responsible for 1.3 percent of all global CO_2 emissions and 10 percent of total emissions associated with fertilizer application (IFA, 2022). On a global scale, energy consumption for manufacturing synthetic fertilizers and pesticides was responsible for 381 and 67 Mt of CO_2 emissions, respectively, in 2020 (FAO, 2023b). These figures represent about 2.3 and 0.4 percent of the entire emissions associated with agrifood systems.

Expanding the utilization of land and buildings linked to livestock farms for the installation of solar and wind power facilities presents an additional opportunity for offsetting emissions. Solar panels can also provide shade to grazing livestock. Realizing the potential of such offsets, sometimes referred to as insets when achieved through on-farm interventions, hinges on the establishment of appropriate carbon-accounting mechanisms in place. These mechanisms are crucial for credibly offsetting the emission savings generated by these renewable energy initiatives against the emissions produced by livestock, contributing to a net reduction in emissions within a specific farming unit. There may be additional ways to offset emissions from outside the farm unit, including carbon trading.

Manure

Various technical options exist to mitigate emissions of CH_4 and N_2O from manure, including aspects such as feeding, animal housing, handling and storage, grazing and application as a fertilizer to agricultural soils. It is important to note that these options may not precisely align with the emission sources from the livestock in IPCC, and there could be interconnected relationships with some of the sections above. For example, the animal diet significantly influence both enteric CH_4 emissions and manure emissions. Dietary manipulation through reduced crude protein compared to high protein feeds, can reduce overall ammonia (NH_3) volatilization emissions by 42 percent, while increasing the CH_4 emissions by 71 percent. Additionally, it can reduce N_2O emissions from manure by 30 percent (Mohankumar Sajeev, Winiwarter and Amon, 2018).

Implementing practices such as daily or weekly removal of manure from animal housing systems can be a beneficial strategy. This approach results in a 22 percent reduction in NH_3 volatilization and substantial decreases in emissions of methane (CH_4) by 55 percent and N_2O by 41 percent. The key mechanism here is the reduction of manure accumulation, mitigating the release of these gases (Mohankumar Sajeev, Winiwarter, and Amon, 2018).

Chemical and biological scrubbers[15] in animal housing have a history of being used to limit NH_3 volatilization from pig and poultry housing achieving a reduction of 59 percent. However, biological scrubbers may increase N_2O emissions by 164 percent due to extended bed residence times. Daily or weekly removal of manure from animal housing systems can reduce NH_3 volatilization by 22 percent, CH_4 emissions by 55 percent and N_2O by 41 percent through the reduction of manure accumulation (Mohankumar Sajeev, Winiwarter and Amon, 2018). Biofilters are suitable when manure is stored in wet form or slurry (Mukherji *et al*., 2023).

Manure treatment options can be employed to handle manure and reduce emissions, including anaerobic digestion, acidification and composting. Organic matter degradation in anaerobic digestion results in the formation of CH_4 and CO_2, with CH_4 utilized as a renewable energy source. It leads to a 3 percent reduction in NH_3 volatilization, a 29 percent reduction in CH_4 emissions, and a 23 percent reduction in N_2O emissions (Mohankumar Sajeev, Winiwarter and Amon, 2018). Anaerobic digesters are effective to reduce CH_4 emissions in systems where manure is stored in solid and liquid form, but are not suitable for grazing systems (Mukherji *et al*., 2023). Barriers to implementation include installation costs, liquid slurry transport and labour requirements. In small-scale dairy systems with four to five cows in east Africa, biogas implementation may reduce total emissions from manure by 60 to 80 percent (Ericksen and Crane, 2018). The large-scale implementation of biogas, especially in grazing systems, requires an in-depth analysis due to the need of stalling more animals to ensure a constant supply of manure to the digesters.

The acidification of manure also holds potential for reducing CH_4 emissions during storage by lowering pH and inhibiting methanogenesis (74 percent), along with a decrease in N_2O emissions due to reduced bacterial activity of nitrifiers (17 percent). However, this method is suitable only when the manure is in a wet form or slurry (Mukherji *et al*., 2023). Conversely, using covers during storage can yield varied results: a 65 percent reduction in NH_3, a 12 percent decrease in CH_4, but an increase in N_2O emissions by more than 500 percent due to the formation of aerobic and anaerobic zones facilitating nitrification and denitrification processes (Mohankumar Sajeev, Winiwarter and Amon, 2018).

[15] Air scrubbers are one of the end-of-pipe solutions where the exhaust air is led through a wet packed bed to remove water soluble components (Van Der Heyden, Demeyer and Volcke, 2015).

Impermeable covers are more suitable for systems where the manure is stored in a wet form or slurry (Mukherji *et al*., 2023). Additional strategies include decreasing the manure storage temperature, leading to a 5 percent reduction in CH_4 emissions per 1 °C reduction below 20 °C (FAO, 2023c). Similarly, decreasing the manure storage time is helpful when the manure is stored in wet and solid forms (Mukherji *et al*., 2023). Kreidenweis *et al*. (2021) compared GHG emissions from four manure treatment options for broilers, including storage before distribution, composting, anaerobic digestion in a biogas plant and production of biochar. The authors reported that biogas production from broilers result in the lowest GHG emissions. This was mainly due to emission savings from avoiding synthetic fertilizers and energy production. Composting was found to generate the highest emissions, attributed to increased N_2O emissions from NH_3 volatilization (Kreidenweis *et al*., 2021). Notably, composting is a strategy viable only when the manure is stored in solid form (Mukherji *et al*., 2023).

Methane emissions from manure application tends to be low, mainly because of aerobic conditions. However, research indicates that shallow injection has been shown to reduce NH_3 volatilization by 71 percent compared to surface spreading. On the other hand, this method has also been associated with an increase in N_2O by 259 percent, likely attributed to the creation of high-moisture anaerobic zones that increase the denitrification (Mohankumar Sajeev, Winiwarter and Amon, 2018).

The most substantial emissions from manure occur in confined management options where the manure is handled in liquid form (IPCC, 2019a). The adoption potential of a strategy depends on regulations in a particular country or region, as well as the availability of technical and economic resources for its implementation. Grazing systems require different strategies compared to housed systems. For instance, short-rotation pasture management and short-rotation corrals and bomas are two manure management systems that can reduce CH_4 emissions in grazing systems (Mukherji *et al*., 2023). In grazing systems, the implementation of silvopastoral systems, which inhibit nitrification, and use of N fixing plants, such as legumes, as an alternative to N fertilizer, has considerable potential to reduce both CH_4 and N_2O emissions (up to 50 percent) while enhancing carbon capturing in soils (Rivera and Chará, 2021).


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4. Low-emission pathways to 2050

With no change in productivity, the increase in demand for TASF by over 20 percent compared to 2020 would have to be met by an equivalent rise in the overall number of animals. This would result in a proportional increase in both upstream and downstream emissions, elevating baseline livestock emissions from 6.2 Gt CO_2 eq in 2015 to 9.1 Gt CO_2 eq by 2050. This BAU scenario outlined here assumes no efficiency improvements throughout the production chain.[16] Consequently, it explores the extent of the absolute emissions change associated with a specific intervention.

The low-emission pathways depicted in Figure 12 are a product of a comprehensive literature review detailed in section 3. Table 3 presents a summary of assumptions regarding the anticipated impact of each intervention on absolute emissions and their respective sources. Recognising the vast diversity of livestock systems worldwide, it is important to note that this global analysis of pathways may not cater to the specificities of individual production systems. Nevertheless, it serves to illustrate the concept and offers order-of-magnitude assessments, aiding in the design and implementation of sector-wide actions to mitigate GHG emissions.

Many of the barriers to adoption are poorly understood. For illustrative purposes, the assumed impact of interventions discussed above is considered cumulative, with no overlaps. These first order approximations suggest that by 2050, emissions from livestock systems could be significantly reduced while achieving a 20 percent increase in animal protein production to meet the need of a growing population and increasing per capita demand.

It is crucial to acknowledge the limitations inherent in this global pathway illustration. Some of the proposed interventions involve intricate interactions and interdependencies, posing challenges for clear delineation. Practices may not be mutually exclusive, and both synergies and conflicts may arise (Hristov *et al.*, 2013). Therefore, in some cases, the pathway could double-count mitigation potentials. For instance, increasing productivity has the potential to reduce projected sector emissions by 20 percent by 2050.

[16] This BAU scenario assumes no change in productivity as most of these changes will not happen automatically but require investments and interventions.

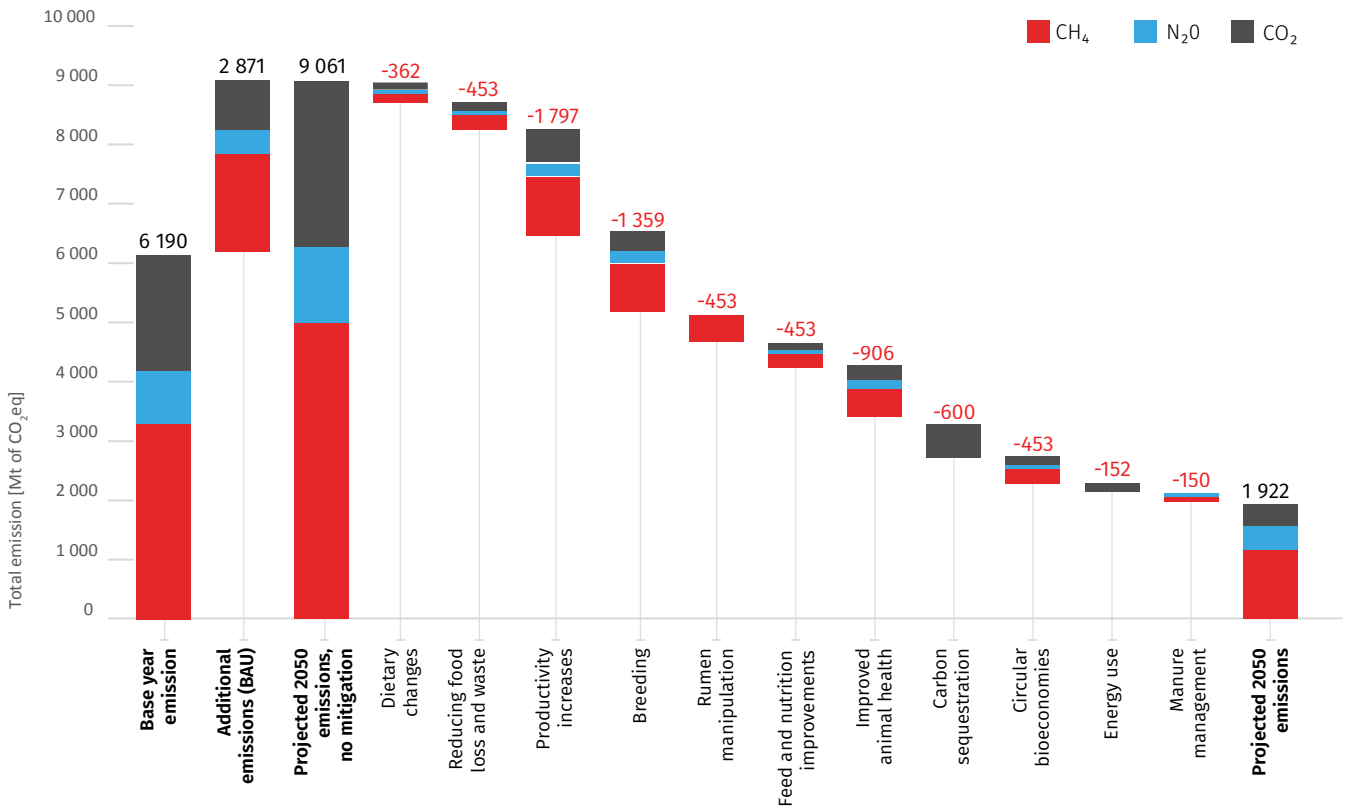

Figure 12.
Base year and projected emissions from livestock systems shown as a waterfall chart with a range of mitigation measures applied to 2050 with their technical potential

Note: 100 percent adoption is assumed. Interventions are assumed to have cumulative impacts and the order of interventions is thematically structured, without the intention to rank them for their importance. The percentage reduction used for each intervention are explained in the summary Table 3.

However, livestock productivity can be enhanced from various strategies related to other mitigation pathways, including feeding interventions (Deen *et al.*, 2019), selective breeding for high-yielding animals (Brito *et al.*, 2021) and improvement in animal health and welfare (Özkan *et al.*, 2022).

Future objectives should prioritize the adaptation of existing systems for higher efficiency gains, rather than pursuing herd expansion and productivity increase at all costs (Adesogan *et al.*, 2020). However, improved efficiency should not compromise other aspects, such as animal health and welfare (Fraser, 2008; Broom, 2019), rural populations, biodiversity, soil fertility and other environmental impact categories (Del Pardo *et al.*, 2013: Garcia, 2020; Clay *et al.*, 2020), as well as human health (Magouras *et al.*, 2020). The process of intensification carries risks to food and nutrition security, emphasizing the need for efforts directed at optimization through identifying best practices and their effective implementation. This approach is likely to foster a more favourable market environment, especially for smallholder farmers.

A comparable example related to animal health improvements may provide insights into the expected mechanisms of emission reductions. Consider a scenario where a healthier animal is likely to consume more feed, increasing emissions at the individual animal level, assuming diet quality and herd size remain constant. However, emissions at the herd or value chain level may decrease due to a reduced need for replacement animals that do not contribute to milk production but still contribute to life cycle emissions (Özkan *et al.*, 2022). Actions to enhance animal health, including improved prevention and treatment plans, can also aim at lowering the burden of antimicrobial resistance (Mutua *et al.*, 2020), with subsequent implications for biodiversity and human health (Ferri *et al.*, 2017). While improvements in feed and nutrition show promise as mitigation strategies, they should also be approached cautiously due to inherent trade-offs with various other aspects, including animal health and welfare. For instance, increasing the proportion of concentrate feed in the diet to reduce enteric CH_4 emissions may have detrimental effects on animal welfare due to the high levels of fermentable carbohydrates (Llonch *et al.*, 2017). However, when offered at recommended amounts, they can be very effective.

TABLE 3. Overview of the estimated global reduction potential for the different interventions and the main assumptions

Theme	Interventions	Reduction potential (%)	Assumptions and sources
Demand	Changes in consumption of TASF	4	Prorating the emissions reductions of 0.19–0.53 Gt CO_2eq per year estimated by Behrend (2017) for the global food systems.
	Reducing food loss and waste	5	Impact through reducing TASF food waste by 70 percent; Assumption based on a calculation from FAO (2019), Lipinski (2020) and Bajzelj (2014), but applied to supply chains.
Animal and feed management	Productivity increases	20	Based on an analysis of FAOSTAT production data at regional level.
	Breeding	8	Assumes that selective breeding improves herd structure through reduced age at first calving, and considers 11-26 percent reductions in CH_4 emissions (g/day) in 10 years through selection (Haas *et al.*, 2011); however, a lower rate was used to consider that breed improvements may not be possible in all parts of the world; when available, there may be constraints regarding feed that inhibit its full potential.
	Rumen manipulation	5	A moderate 5 percent assumed because the CH_4 inhibitors are not available or are unlikely to be adopted in LMICs in the short-term.
	Feed and nutrition improvements	12	Assuming some feed improvements also applicable to extensive systems.
	Improved animal health	10	Skuce (2022) based on expert judgements.
Soils	Carbon sequestration	7	Dondini *et al.* (2023) and considering the economic factors.
Supply chain	Circular bioeconomies	5	A moderate 5 percent assumed to account for the potential increase in supply chain emissions in some regions with increased use of low digestible feed sources in spite of more significant impact reported in the literature for certain feed supplements (Moate *et al.*, 2014; Giller *et al.*, 2022).
	Energy use	2	A moderate 2 percent reduction due to low share of energy use in the entire supply chain emissions; Assuming replacement of fossil fuel and general energy efficiency improvements along the value chain.
Manure	Manure management	2	A moderate 2 percent reduction due to low share of manure emissions in the entire supply chain, considering, e.g. 50 percent reduction of CH_4 and N_2O from manure following implementation of silvopastoral systems (Rivera and Chará, 2021), and the trade-offs between CH_4 and N_2O emissions (Mohankumar Sajeev, Winiwarter and Amon, 2018) and the differences in production systems (Mukherji *et al.*, 2023).

Note: Gt = gigatonne, CO_2eq = carbon dioxide equivalent, TASF = terrestrial animal source food, CH_4 = methane, N_2O = nitrous oxide, LMICs = low- to middle-income countries, HICs = high-income countries.

The implementation of selective breeding may encounter limitations in certain regions, particularly in LMICs, where challenges related to feed availability may hinder its full potential. Besides, genetic selection is a long-term process, and its impacts are not expected to be immediate (Króliczewska *et al.*, 2023). Despite these challenges, selective breeding can synergize with various strategies, such as circular bioeconomies. Breeding programmes focusing on indigenous breeds, particularly in LMICs, can lead to increased resilience, reduce vulnerability to specific diseases (Kim *et al.*, 2020), and optimize the utilization of low-quality biomass (Habib, Pollott and Leaver, 2011, Mwai *et al.*, 2015), as native breeds are better converters of the fibre with low digestibility in their local conditions.

Crop residues and by-products from the grain industries can therefore play a key role in animal nutrition, but their low-quality properties may lead to increases in emissions depending on the feed ingredient they substitute. Reducing food loss and waste by 5 percent and improving integration of circular bioeconomies are outlined as two distinct practices here. However, they exhibit partial overlap by promoting circular bioeconomic practices, as the integration of by-products as inputs for the livestock system automatically avoid some waste. Assessing the effectiveness of waste reduction and/or the adoption of a circular bioeconomic model as a mitigation strategy hinges on how these practices compare to using resources efficiently to increase productivity. Complex economic mechanisms, such as the *rebound effect,* might counteract the positive effects of the adoption of the practice (Castro *et al.*, 2022). For this reason, when the effect of food loss and waste is assessed with

economic modelling, a very limited GHG reduction is observed, (0.07 percent on total GHG emissions with a 25 percent reduction in food waste) (FAO, 2019b). Furthermore, achieving large-scale implementation of these practices necessitates governance, with public, private and social actors collaborating to promote multidisciplinary programmes (Mak *et al.*, 2020; Paltaki *et al.*, 2021; Oosting *et al.*, 2022).

The preceding discussion underscores the need to differentiate achievable interventions in various production systems. In east African mixed dairy systems, potential reduction in absolute emissions ranges from 10 to 24 percent through improvements in feed quality, animal health and husbandry (Mottet *et al.*, 2017b). However, approaches to reduce enteric CH_4 emissions will vary across systems. While CH_4 inhibitors, tanniferous forages and lipids are suitable for zero-grazing systems exclusively, herd management and breeding (including artificial insemination and selective breeding) offer benefits across all existing systems (Mukherji *et al.*, 2023) (see Table 4).

TABLE 4. Applicability of mitigation interventions to reduce methane emissions from different ruminant production systems

Intervention	Zero-grazing	Grazing with feed supplementation	Grazing without feed supplementation
CH_4 inhibitors	+++	++	-
Tanniferous forages	+++	+++	+++
Electron sinks	+++	+++	-
Dietary lipids and oils	+++	++	-
Concentrates	+++	++	-
Herd management	+++	+++	+++
Pasture and forage management	+	+++	+++
Low CH_4 emitting animals	+++	+++	+

Note: Applicability interpretation is of author's own (- none, + low, ++ medium, +++ high). CH_4 = methane.

Source: Adapted from *Mukherji et al. 2023.*

Likewise, strategies to curtail CH_4 emissions from manure management will depend on the manner of manure storage. For instance, anaerobic digesters, daily cleaning, collection and land spread, decreasing storage time and composting are applicable when manure is stored in both liquid and solid forms. On the other hand, the use of biofilters and covers, acidification, solid-liquid separation, and complete removal of manure residues between storage period are viable only when the manure is stored in wet form or slurry. Grazing systems benefit from strategies such as short rotation pasture management, short-rotation corrals and bomas (see Table 5).

The reported impact of these interventions should be interpreted with caution, as it heavily relies on the characteristics of the production system. Factors such as local production conditions, the sources and relative importance of different inputs (land, labour and capital), prevailing agroecological conditions, and socioeconomic context (Sova *et al.*, 2018), cultural values, farmers' willingness to implement and associated costs all play pivotal roles.

Given the diversity and complex nature of livestock systems worldwide, mitigation interventions should be tailored to each specific context. At the local level, a nuanced understanding of the underlying dynamics that contribute to a farm's success is likely to provide valuable insights for other farms on their journey to optimization.

To address this, GLEAM conducts sub-national and livestock system-specific data collection and analysis, primarily relying on national statistics, FAOSTAT, and national inventories (see case studies). This approach enables the identification of mitigation priorities that align with national policies and regulations.

TABLE 5. Applicability of manure management strategies to reduce methane emissions

Manure management strategy	Manure in wet form/slurry	Manure in solid form	Grazing systems
Anaerobic digesters	+	+	-
Impermeable covers	+	-	-
Daily cleaning, collection and land spread	+	+	-
Decreasing storage time	+	+	-
Acidification	+	-	-
Biofilter/air scrubbers	+	-	-
Solid-liquid separation and/or composting (aeration)	+	+ (Composting/aeration with biochar)	-
Complete removal of manure residues between storage periods	+	-	-
Short rotation pasture management	-	-	+
Short rotation corrals/bomas	-	-	+

Note: (- not applicable, + applicable). CH_4= methane.

Source: Adapted from *Mukherji et al. 2023.*


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5. Climate change impacts on livestock and adaptation

It is important to recognize that the projected increases in production and productivity from livestock systems are based on the assumption of no change in environmental and climate conditions in the future. However, potential changes in climate variability, extreme events and mean climate trends could impact various stages of the supply chain. The complex interactions of these changes are illustrated in Figure 13 (Godde *et al.*, 2021).

Climate change exerts both direct and indirect effects on livestock. Direct impacts include reduced animal productivity, and compromised health and welfare. Livestock health may suffer from changes in behaviour, alterations in physiology and immune system depression, and shifts in other variables like pathogen ecology and spread, feed quality, availability and affordability, water quality and availability. Additionally, climate change can influence management strategies (Lacetera, 2018; Özkan *et al.*, 2016).

The greatest indirect impact on the livestock supply chain can be expected through changes in feed resources due to shifts in temperature, precipitation, and atmospheric CO_2 levels. These changes will affect both the availability and nutritional quality of feed, exhibiting large regional variations in the magnitude and direction of impacts. On a global scale, increased climate variability is likely to yield overall negative impacts on feed quantity and quality (Godde *et al.*, 2021), driven by alterations in water availability and demand, as well as the frequency of floods and droughts. For instance, prolonged dry seasons may reduce forage quality, growth and biodiversity, while floods could alter root structure and leaf growth rate (Rojas-Downing *et al.*, 2017). Pasture composition may be affected by shifted seasonal patterns, changes in optimal growth rate, and water availability. Elevated CO_2 levels might diminish forage quality, but reduce transpiration, improving water-use efficiency of forages (Rojas-Downing *et al.*, 2017).

Climate changes could also impact post-farm processing, storage and packaging through additional demands for storage and food safety measures. Moreover, changes in availability and quality of labour may affect production, particularly due to factors such as heat stress (see Figure 13).

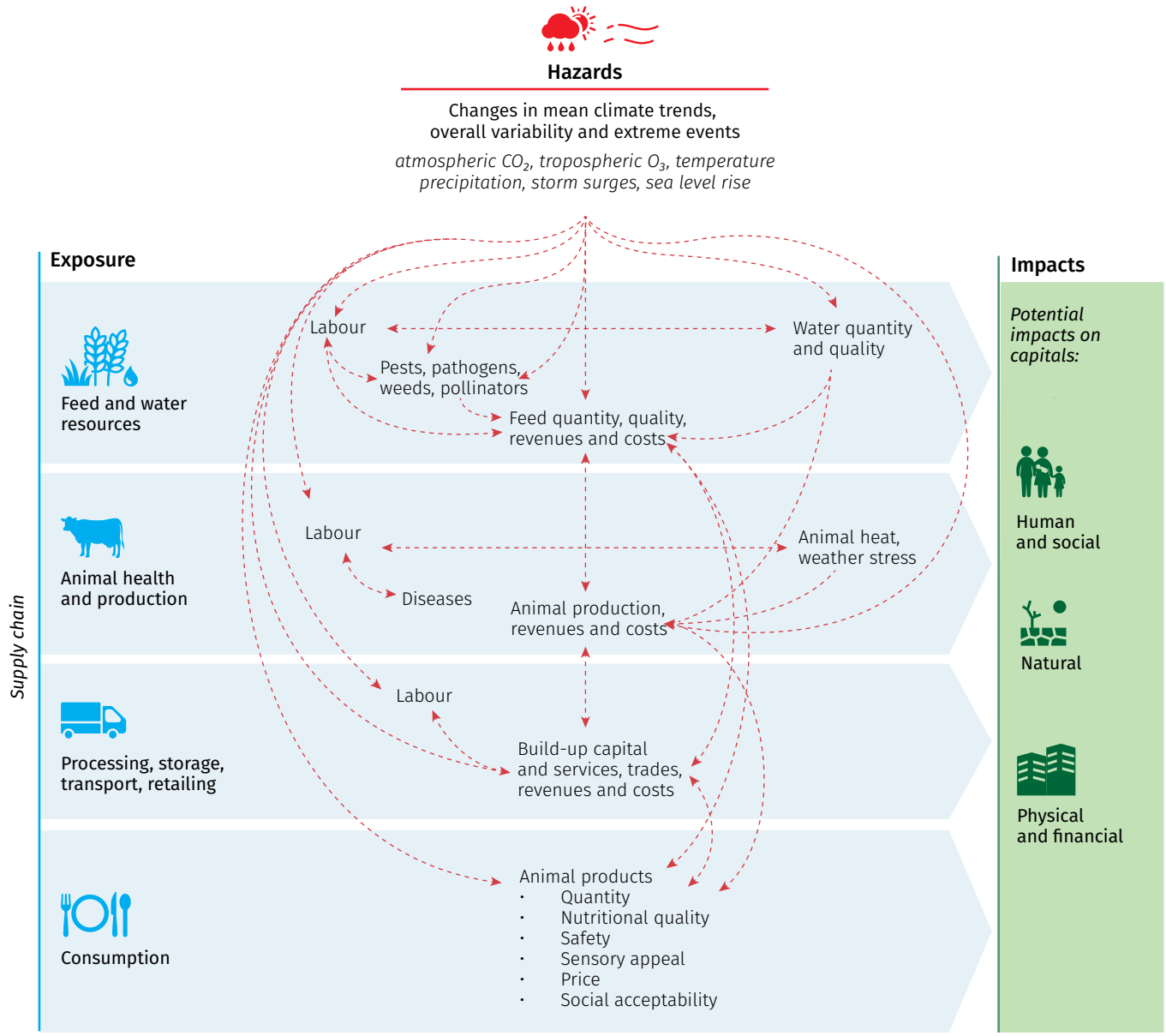

Addressing these changes necessitates site-specific considerations, as they are challenging to project and involve intricate interactions with potential trade-offs affecting input and product prices. Designing efforts to reduce the vulnerability of livestock systems to climate changes should consider these complex conditions. Livestock systems generally exhibit a higher adaptive capacity than other systems, such as crops. Adaptation measures may involve interventions in animal management, infrastructure and resource use to address heat stress. Additionally, income-related and policy changes are essential, requiring careful consideration of tradeoffs and risks at various spatial and temporal scales. For example, Africa's cattle, bred from zebu (humped) and taurine (unhumped) that formed the genome of the cattle in the Horn of Africa 1000 years ago, possess genes conferring tolerant to heat, drought, resistance to diseases like *Trypanosomiases*, and the capacity to combat inflammation and tick infestations (Kim *et al.*, 2020).

Figure 13.
Potential impact of climate change on the livestock supply chains

Source: Adapted from **Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K. & Herrero, M.** 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Global Food Security, 28: 100488. https://doi.org/10.1016/j.gfs.2020.100488.


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6. Remaining gaps and future directions

System boundaries

Greenhouse gas assessments typically focus on emissions within a country's boundaries. While GLEAM traces emissions linked to inputs like feed back to the producing country and allocates them to the consuming country, it does not consider the trade of products, as this lies beyond GLEAM's system boundary (see Figure 2). All upstream emissions are allocated to the location where primary animal production takes place, aligning with international LCA reporting that assess emissions at the national level. However, a considerable amount of primary animal products and derived commodities are traded globally, with trade volume steadily increasing over the last two decades due to production growth (FAO, 2022c).

For the trade of dairy products, the GHG emissions embedded in the trade of animal products can be allocated to the consuming country using bilateral trade statistics from FAOSTAT (expressed in milk equivalents)[17] and applying the emission intensity for raw milk in the producing country. Converting all dairy products to milk equivalents suggests that approximately 140 Mt (18 percent) out of the 750 Mt of raw milk produced in 2020 were exported, mostly as cheese, skim milk or whole milk powder or whey. Applying the emission intensity calculated by GLEAM for raw milk, this corresponds to 200 Mt of CO_2eq (15 percent) embedded in the trade of dairy products (excluding emissions associated with transport, further processing and packaging). Figure 14 illustrates the emissions embedded in traded dairy products and the embodied emissions in imports and exports between FAO subregions. Such analysis can inform trade-adjusted emission estimates and highlight the role of consumers and producers in emission flows across the globe through trade (Foong *et al.*, 2022).

Variability in the emission intensities

The intensity of GHG emissions generally decreases dramatically as production increases, highlighting the fact that increases in production offer co-benefits to improve food security,

[17] Bilateral trade data from FAOSTAT was used for milk and derived products. All products were converted to raw milk equivalents using the conversion factors from https://www.fao.org/3/cc3418en/cc3418en.pdf. Emission factors are taken from the 2015 reference year.

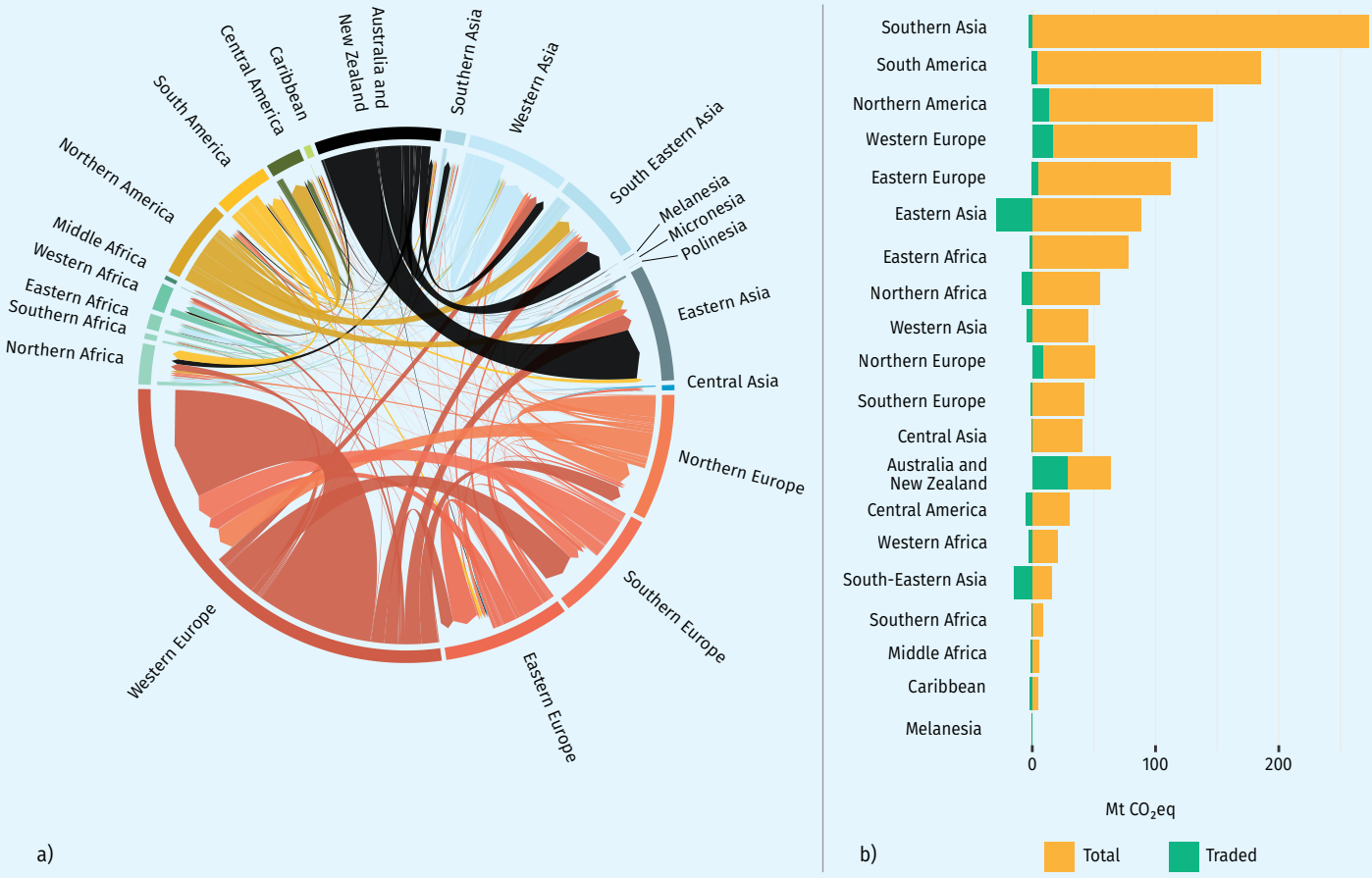

Figure 14.
Trade flows of milk and dairy products within and between regions (a), and corresponding embedded emissions in those products (b)

Note: Based on FAO regions (FAOSTAT country list) showing small differences in relative trade volumes and emissions in the size of the arrows between regions (three-year average values between 2019 and 2021).

especially in the countries where the annual milk production of a cow is less than 2 000 kg (see Figure 15). The figure reveals a pattern: countries with low productivity and high emission intensities have a larger proportion of emissions stemming from enteric CH_4 compared to countries with lower emission intensities and higher productivity. Prioritizing countries or systems where CH_4 is the dominant emission could lead to faster impacts on the global warming, while targeting those where emissions are mainly composed of N_2O and CO_2 could slow down the accumulation of the long-lasting GHGs in the atmosphere.

Yet, this figure does not recognize the uniqueness of different production systems in different countries. There is a large variability in the emission intensity between and within systems. It is possible that modelling studies using spatially explicit data may not reveal the individuality of production systems or the influence of management features on emission intensities at the farm level. For example, Ndung'u *et al.* (2022) collected farm-level data from 313 smallholder farming systems in western Kenya and reported that emission intensities ranged from 20 to >1000 kg CO_2eq/kg crude protein. Acknowledging the high level of variation in farm emissions and emission intensities within and across regions, they also reported that some of the low-input farms produced considerably lower emission intensities, reflecting the potential for others to adapt the management practices and lower emissions.

The contribution of LMICs to the total amount of emissions is not significant, emphasizing the potential to improve efficiencies and reduce emission intensity instead of focusing on the reduction of absolute emissions. Besides, cattle may be kept for other purposes in these countries and have roles other than producing food only, thus improving milk yield may not be the primary goal of the production system, for example, mixed smallholder systems with side activities. It is also important to note that this figure does

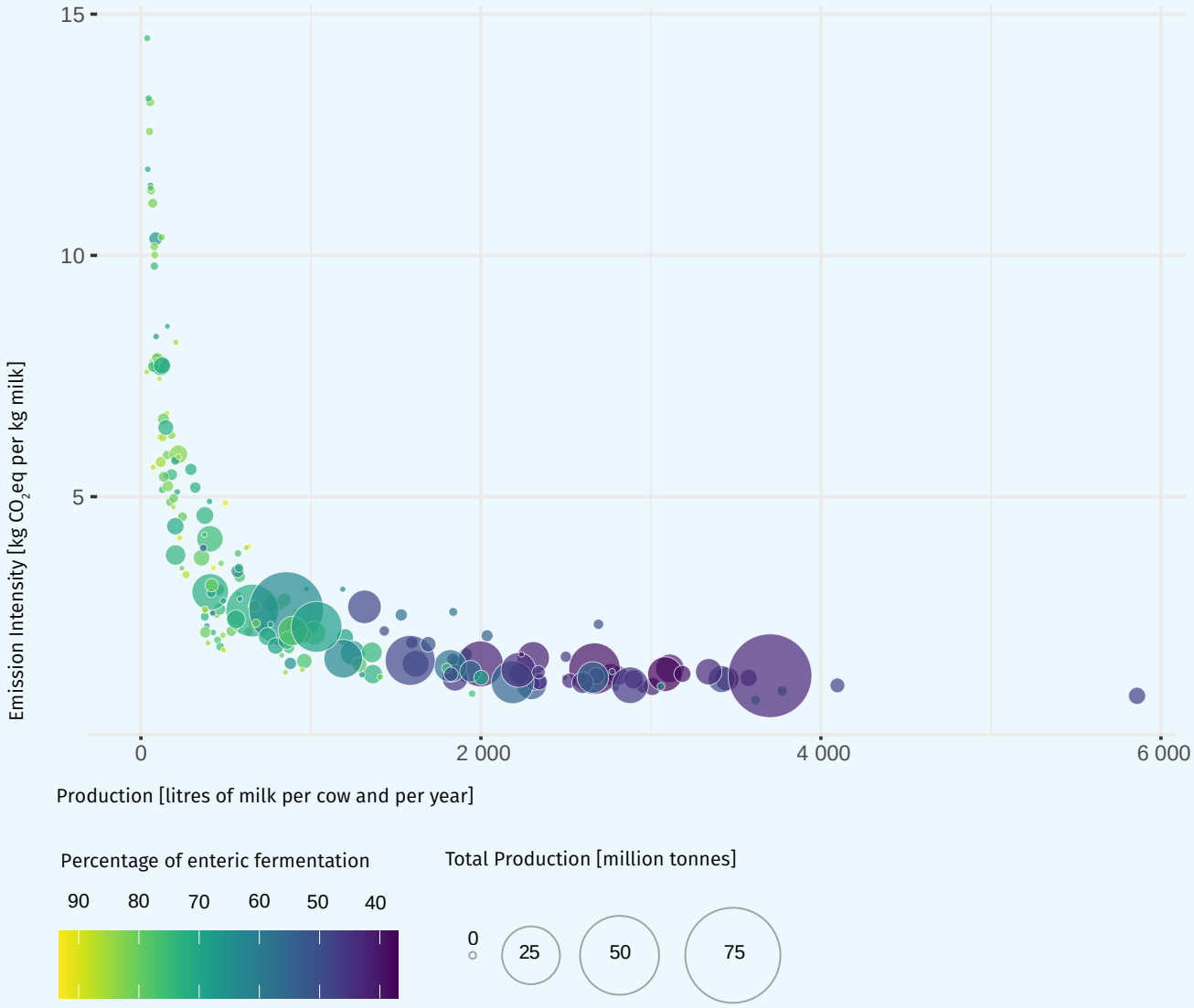

not aim to advocate for intensification at all costs. Aggressive increases in milk yields may accompany welfare issues. Similarly, expanding herds with more exotic breeds may not achieve the proposed yields and may leave the systems vulnerable to the effects of the climate change (Oltenacu and Broom, 2010). Adapting exotic breeds will require a monitoring system for any potential impact on the animal health and whether the animals are fed according to their requirements of quality and affordable feed, if the feed is available in the first place.

Figure 15.
Relationship between average emission intensities of greenhouse gases from the national dairy systems (cattle and buffalo) and average productivity of those dairy systems

Note: Each point represents a country the size of which is proportional to the total dairy emissions for that country. The colour of the spot indicates the percentage of emissions coming from enteric fermentation.

Source: GLEAM 3

Comparisons to previous estimates

The most recent estimate of livestock emissions using GLEAM 3, 6.2 Gt CO_2eq, is based on the reference year 2015. This estimate constitutes approximately 38 percent of the total emissions from agrifood systems, which FAO estimates at 16.3 Gt CO_2eq for 2015 (FAO, 2022a; Tubiello *et al.*, 2021) (see Table 1). At the same time, it is lower than the previous global assessment of 7.5 Gt CO_2eq for 2010, produced using GLEAM 2 (FAO, 2019a), or 7.1 Gt CO2eq estimated in Gerber *et al.* (2013) for 2005. The main difference is linked to the updated methodologies for estimating direct and indirect GHG emissions, as well as emissions associated with the LUC, including deforestation and pasture expansion. These

results are based on the recent IPCC methodology refinement (IPCC, 2019a), FAO Livestock Environmental Assessment and Performance (LEAP) Partnership guidelines (FAO, 2016a, 2016b, 2016c, 2016d, 2018a, 2020), and the global N assessment by Uwizeye *et al.* (2020). The new estimates of N_2O emissions are half of those estimated previously using GLEAM, owing to improvement in N_2O estimates based on the IPCC refinement and Uwizeye *et al.* (2020), which reduced uncertainties identified in the 2006 IPCC methodology (Groen *et al.*, 2016; Groen and Heijungs, 2017; Uwizeye *et al.*, 2017).

The three pertinent gases from livestock systems (CH_4, N_2O and CO_2) exert varying impacts on global warming and temperature increase. To consolidate these different gasses, climate metrics, often expressed in CO_2eq, have been defined. Among these, the 100-year GWP (GWP100) is the metric endorsed by COP27, as recommended by IPCC and UNFCCC for the reporting of GHG inventories (UNFCCC, 2023). The conversion factors for non-CO_2 gases have evolved over time and for different IPCC reports (see Table 6), significantly influencing both the absolute and relative emissions from the sector.

TABLE 6. Effect of using different GWP100 conversion factors on GHG emissions from the livestock sector

			GWP100			Emissions by gas (Mtonnes)					
IPCC AR version	**GLEAM version**	**GLEAM ref year**	**Methane (CH_4)**	**Nitrous oxide (N_2O)**	**Carbon dioxide (CO_2)**	**CH_4**	**N_2O**	**CO_2**	**Total emissions from livestock (Gtonnes of CO_2 eq)**	**Total anthropogenic emissions (Gtonnes of CO_2 eq)**	**Livestock contribution (%)**
AR4 (2007)	1	2005	25	298	1	124	6.71	2000	7.1	49.0	14.5
AR5 (2015) with cc fb	2	2010	34	298	1	118	6.38	2100	8.0	54.1	14.8
AR5 (2015) no cc fb	2	2010	28	265	1	118	6.38	2100	7.1	51.8	13.7
AR6 (2021)	3	2015	27	273	1	123	3.35	1960	6.2	51.0	12.0

Note: GWP100 = global warming potential over a 100-year period, cc fb = climate-carbon feedback, ARs = Assessment Reports.
Source: GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/) and IPCC Assessment Reports (AR4, AR5 and AR6).

Limitations of life cycle assessment methodology

The life cycle assessment (LCA) as a method, is useful in identifying opportunities within a system but lacks the ability in attributing differences between HICs and LMICs. This limitation is primarily due to the multifunctionality of livestock production systems in LMICs, where the livestock is kept not only for its product but also for its role to provide draft power, financial asset and savings and social status, none of which is accounted for in the traditional allocation methods. While an LCA can offer the carbon footprint of livestock products at a given time, it cannot fully account for the diverse purposes of keeping livestock, especially as many LCAs lack data with spatial and temporal resolution. The constraints of LCA studies and allocation methods may obscure the role of livestock in smallholder farming systems, where emissions per unit of product may be considerably lower if the multifunctionality of livestock keeping were considered in emission allocation (Gerber *et al.*, 2013).

Emissions from ruminants are allocated to both edible (e.g. meat and milk) and non-edible (e.g. manure used for fuel and draught power from large ruminants and fibres from small ruminants) commodities. Emissions from non-edible commodities are deducted from the total emissions before attributing them to meat and milk. In monogastric animals, emissions are allocated among edible products (e.g. meat and eggs for layers and backyard animals, and meat for pigs and broilers) (FAO, 2022c).

Future improvements of GLEAM

While GLEAM has been instrumental in understanding the nature of emissions from livestock systems, its current capability to quantify the impact of discussed mitigation options is limited. The next release will therefore incorporate modules that can simulate the impact of various mitigation options over time. The envisioned new platform, GLEAM-X, will offer on-demand simulations online, allowing users to immediately assess the impact of implementing different interventions under different scenarios on certain environmental indicators. This enhancement will make the simulations more relevant for countries and projects and will also generate consistent GHG inventories for the sector.

Moreover, the current modelling system and input data are not accessible to a broad user base due to data and software limitations. Future releases will adopt open data policies, and make the data available to all users to the extent possible. They will serve as a hub for livestock emissions and related datasets.

The high uncertainty and heterogeneity in input data quality and reference periods make it challenging to simulate trajectories from livestock systems globally (beyond updating the animal numbers). A more systematic data collection will facilitate attributing changes in total emissions to changes in the animal herd, shifts in animal production parameters, or in inputs such as feed and others.



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7. Examples of FAO support

FAO provides its Members with technical assistance for the sustainable and low-emission development of the livestock sector. Specifically addressing climate change, FAO helps Members in quantifying baseline GHG emissions and identifying tailored mitigation options for the sector. Furthermore, FAO facilitates collaboration among national and international stakeholders through national and regional dialogues, with a simultaneous emphasis on capacity development. The examples provided below illustrate some of these efforts, although the list is not exhaustive.

Support the update of Nationally Determined Contributions

Nationally Determined Contributions (NDC) are countries' commitments to reducing GHG emissions and adapting to the impacts of climate change. Under the Paris Agreement (Article 4, Paragraph 2), each party is mandated to prepare, communicate and maintain its NDC every five years, with each submission expected to be more ambitious than the previous one. NDCs delineate country-specific mitigation and adaptation commitments and targets, encompassing aspects such as capacity-building, innovation, technology development, and domestic and international climate finance. The conditional emission reduction targets reported in the NDCs of most LMICs can serve as a crucial entry point for supporting actions in priority-listed countries.

NDCs are country-driven, allowing for self-determined scope. Countries have the flexibility to choose the approach for reporting the expected mitigation potential of targeted interventions, such as using GHG models or adhering to IPCC Tier levels. Additionally, the leading agency responsible for NDCs is determined by the individual countries. However, industrialized countries (Annex I of the Kyoto Protocol) submit economy-wide absolute emission reduction targets, while LMICs (non-Annex I) can work towards such targets over time, with or without international support. Furthermore, countries reporting NDCs with GHG mitigation targets often include only direct emissions at the sector level, as required by the Paris Agreement. This typically covers CH_4 from enteric fermentation, and CH_4 and N_2O from manure management systems. Emissions from feed production, processing, transport and energy use are reported separately. Therefore, efforts targeting supply chain emissions beyond the farm gate need to be analysed using LCA, which considers upstream and downstream emissions.

Livestock mitigation and adaptation measures outlined in the NDCs encompass a spectrum of aspects related to animal health, feed management, breeds, manure, herd, pasture and rangeland, silvopastoralism and biogas production (Rose *et al*., 2021a, 2021b). These commitments vary from qualitative measures, including policies, actions and programmes, to specific and quantifiable targets, such as CH_4 emissions reduction and other productivity, diversification and improvement targets. Among the new and updated NDCs (as of July 2021), 55 percent of agricultural adaptation and 36 percent of mitigation components specifically address livestock and grassland even though there are significant gaps in the quantified results (Crumpler *et al*., 2021).

To address the need to raise ambitions, FAO supports countries in identifying livestock mitigation and adaptation interventions and integrating them into national climate actions, as recommended by the first session of the Livestock Sub-Committee of FAO's Committee on Agriculture (COAG SCL). FAO employs the multistakeholder consultation approaches to facilitate communication and coordination with sectoral ministries and agencies, aiding the integration of sectoral targets and measures into updated NDCs. To date, FAO has supported approximately 12 countries in aligning their national policies with NDC commitments in the livestock sector. This ensures the development of lowemission and climateresilient objectives that align with socioeconomic goals, such as increasing production and productivity, poverty reduction, food security and income generation.

At the same time, the livestock sector is highly vulnerable to climate change, making adaptation a priority over mitigation. A crucial step is, therefore, to identify synergies and trade-offs between mitigation and adaptation interventions. Many adaptation measures have mitigation co-benefits which are rarely quantified in the NDCs (Rose *et al*., 2021a, 2021b). Quantification of the mitigation potential in the livestock sector requires the use of at least the Tier 2 GHG assessment methods. Most countries only use Tier 1 methods (FAO and GRA, 2020). While a Tier 1 approach may be the only available option in many countries, it is well recognized that Tier 2 and Tier 3 approaches allow for more nuanced analyses of mitigation options based on more detailed data.

FAO Strategy on Climate Change

Capacity building support for livestock-related climate actions is closely aligned with the recently released FAO Strategy on Climate Change 2022-2031 (FAO, 2022e). The strategy is founded on the four betters: better production, better nutrition, a better environment and a better life. Directly contributing to the second pillar of the FAO Climate Change Strategy, this support aligns with outcomes 2.1 (implementation, monitoring, and reporting of climate commitments) and 2.2 (mainstreaming climate resilience, adaptation, and mitigation). The data and information provided in this report aim to support the implementation and scaling up of climate action under the third pillar of the strategy, focusing on the local level and scaling up climate action.

Committee on Agriculture, Sub-Committee on Livestock

FAO's initiatives on livestock climate actions are a response to the Members' request made during the first session of FAO's COAG SCL. In this session, Members urged FAO to assist them in incorporating effective and actionable mitigation and adaptation targets related to livestock into their national climate actions and policies. Additionally, they sought support for capacity-building programmes and enhancements in GHG emissions reporting and assessments.

FAO's work on methane

Collaborating closely with Members in Africa, Asia and Latin America, FAO works to assess CH_4 emissions and identify climate-smart mitigation actions within the livestock sector. Through national and regional dialogues, it also facilitates collaboration among national and international stakeholders, providing capacity development and supporting the development of national roadmaps via the establishment of national methane hubs. In support of countries committed to the Paris Agreement, the organization further offers policy support, assisting in the integration of livestock-specific interventions into their NDCs, working with countries in understanding the impact of implementing market-based policy instruments to reduce enteric CH_4 emissions in the dairy sector (Acosta *et al.*, 2023). Furthermore, the organization is actively involved in collaborative initiatives with various partners such as the Green Climate Fund, International Fund for Agricultural Development and others, to develop projects which aim to promote a low-carbon and climate-resilient livestock sector. In addition, FAO's Statistics Division also fully contributes to the Global Carbon Budget, a large-scale international research effort. This division provides data, statistics and knowledge to support policy debates (Sanois *et al.*, 2020).

Livestock Environmental Assessment and Performance Partnership (LEAP)

The technical advisory group of FAO's LEAP Partnership, in collaboration with over 54 international scientists, has produced a comprehensive report titled "Methane emissions in livestock and rice systems: Sources, sinks, quantification, mitigation, and metrics" (FAO, 2023c). This report analyses the sources and sinks of CH_4, quantifies CH_4 emissions, evaluates different metrics to quantify the impact of CH_4 emissions on global warming, and provides a summary of existing CH_4 mitigation solutions. Moreover, FAO LEAP Partnership has developed sectorial guidelines for evaluating the environmental performance of the livestock sector concerning feed, feed additives and livestock species.

Global Agenda for Sustainable Livestock (GASL)[18]

This is a partnership of livestock stakeholders with a mutual objective of sustainable development of the sector. The partnership brings together diverse entities, including governments, the private sector, producers, research and academic institutions, and non-governmental organizations. Together, these stakeholders work collectively to address interconnected challenges related to global food security and health, equity and growth, as well as resources and climate change.

Sustainable Livestock Transformation Initiative

FAO has recently launched the Sustainable Livestock Transformation Initiative (FAO, 2023e), which is designed to assist its Members in realizing the transformative potential of the livestock sector, with a focus on achieving increased productivity with fewer resources. The initiative aims to promote the widespread adoption of best practices across the entire livestock value chain. This encompasses various stakeholders, including farmers, pastoralists, traders, processors, wholesalers, retailers and other actors.

[18] https://www.livestockdialogue.org/.

Case studies

The following case studies provide a glimpse of FAO's efforts in the livestock sector to mitigate GHG emissions. Case study 1 illustrates the organization's role in equipping countries with tools and methods to update their baseline emissions, facilitating the development of mitigation strategies to further strengthen their NDC commitments. Case study 2 delves into a project-level assessment, comparing scenarios involving the implementation of various mitigation packages as part of a nationwide project.

Case study 1
Estimation of Rwanda's methane emissions using GLEAM

The GLEAM model is currently utilized as a tool to assist countries in enhancing their climate ambitions, particularly in their future NDCs. This is accomplished through the integration of livestock-specific interventions in the initiative known as "Policy analysis to support NDC for climate action in livestock systems" developed by FAO. Rwanda is actively participating in this initiative, focusing on updating the assessment of baseline GHG emissions from cattle; in particular, CH_4 based on IPCC Tier 2 methodology and to formulate specific mitigation measures. The tool was applied to nine different production systems in Rwanda, considering types of breeds and feeding strategies.

The analysis revealed that dairy cattle production in Rwanda emitted about 3.6 Mt CO_2eq in 2020. The primary sources of emissions include enteric fermentation (CH_4: 74 percent) and manure management systems (CH_4: 15 percent, N_2O: 11 percent). Annual emissions per animal vary from 55 kg CH_4 for other dairy cattle to 81 kg CH_4 for dairy cows. CH_4 emissions represent 89 percent of the total GHG emissions from dairy cattle systems in Rwanda (see Figure 16). CH_4 emissions from enteric fermentation are evenly distributed across all the production systems.

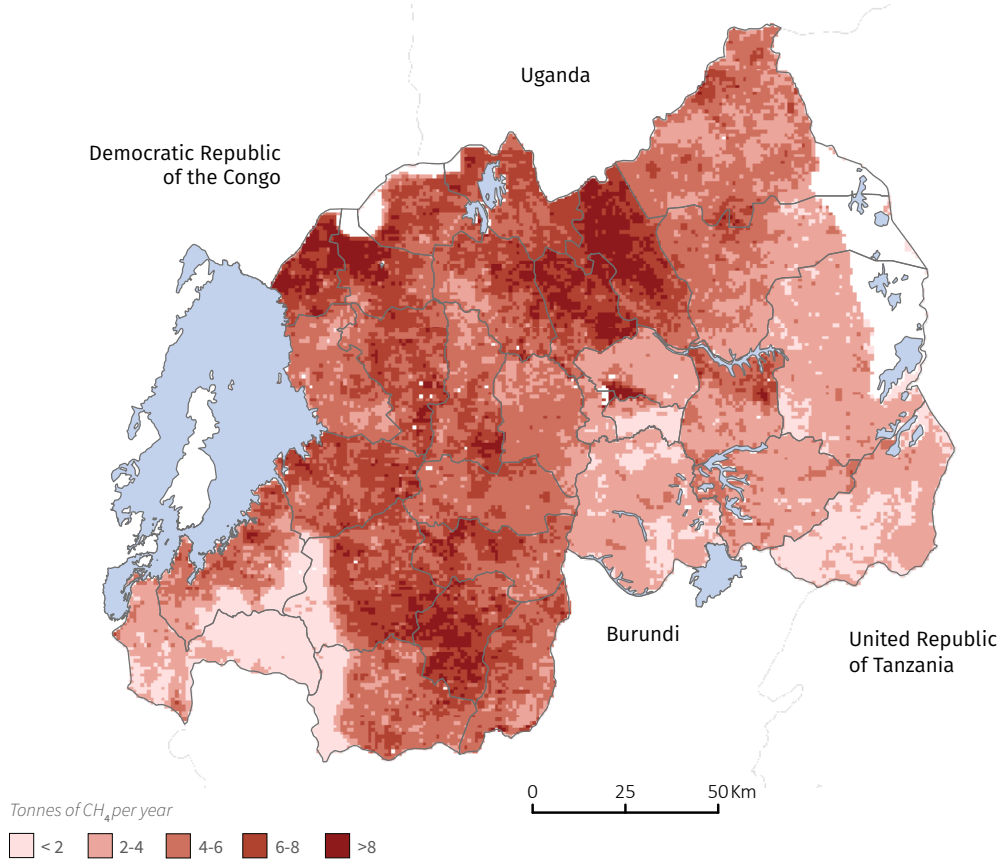

Figure 16.
Total methane emissions from cattle in Rwanda

Note: CH_4 = methane.

Source: **FAO**. 2023f. Livestock Climate Actions in Rwanda. *Enhancing nationally determined contributions for a better future.* Draft report. Rome.

Source:
United Nations Geospatial. 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/ file/3420/download?token=TUP4yDmF modified with GLEAM 3 data.

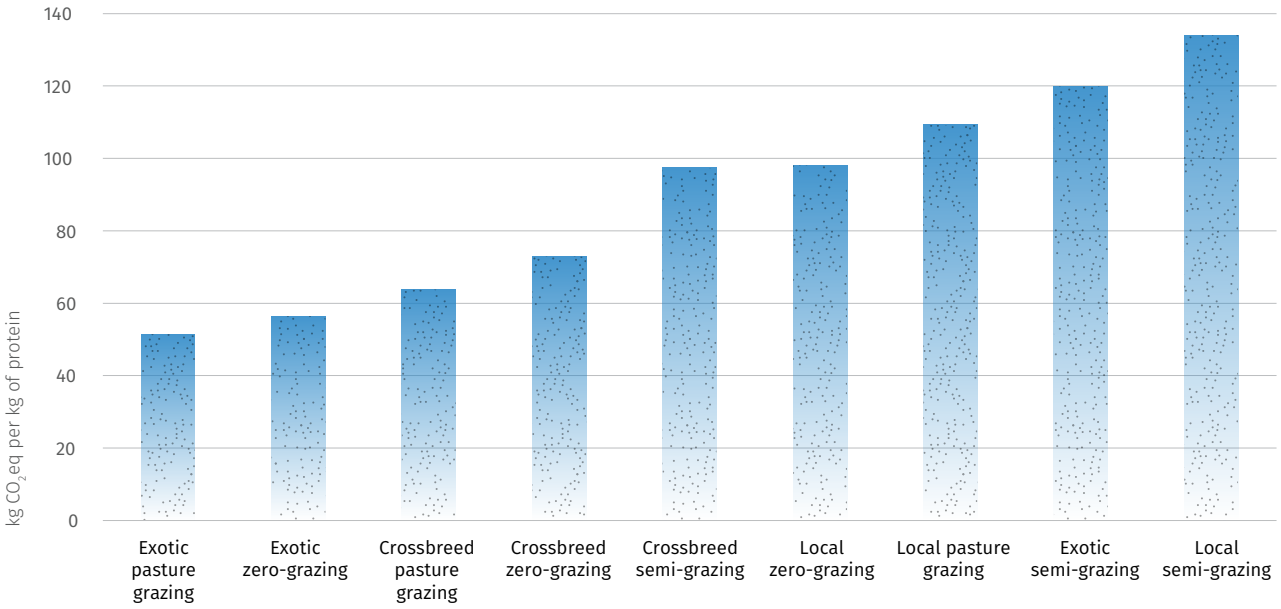

Figure 17.
Enteric methane emission intensity

Note: CH_4 = methane

Source: **FAO**. 2023f. Livestock Climate Actions in Rwanda. *Enhancing nationally determined contributions for a better future.* Draft report. Rome.

Considering that the dairy cattle systems in Rwanda contribute to both meat and milk production for local and international markets, the enteric CH_4 emission intensity, expressed per unit of animal proteins, showed variability in environmental performance across different systems and breeds. Notably, there are relatively low emissions for exotic and crossbreeds in both zero-grazing and pasture grazing systems, as depicted in Figure 17.

The GLEAM analysis also considered the calculation of additional indicators, including enteric CH_4 production (daily CH_4/head) and CH_4 yield (amount of enteric CH_4 emissions per unit of feed consumption), categorized by breeds and animal groups. These findings offer insights into identifying the most suitable production systems, animal categories and geographical areas for implementing interventions. The next phase of this study aims to pursue objectives focused on reducing CH_4 emissions from enteric fermentation through the implementation of best management practices that enhance dairy cattle productivity and health.

Case study 2
Project level assessment of GHG emissions using GLEAM-*i*

GLEAM-*i*[19] was used to quantify the GHG emissions associated with the implementation of the IFAD-funded Regional Resilient Pastoral Communities Project (RRPCP) that aims to reduce poverty in rural areas through improving pasture productivity and enhancing climate resilience of the pastoral communities in Kyrgyzstan[20] (IFAD and FAO, 2021). The project targeted a 20 percent improvement in the productivity of dairy cattle, sheep, and goats through vaccination, a breeding program (specifically for dairy cattle), and enhancements to the feed base. The analysis focused on herd, feed and manure levels to compare the project's impact to a scenario without the project, projecting results over 20 years from the project's initiation (2022 versus 2042 during the capitalization phase). Improvements in health and reproduction resulted in a more optimal herd structure. For instance, adjusting the age at first parturition reduced the number of female calves needed for replacement, subsequently decreasing the number of meat animals in the herd, resulting in a smaller overall herd size in the model.

[19] https://gleami.apps.fao.org/

[20] https://www.ifad.org/en/web/operations/-/project/2000001978

This reduction in animal numbers contributed to lower total emissions and emission intensity. Healthy animals contribute to the herd structure by reduced mortality rates and improved production output. The project's feed improvements involved increased use of higher-quality feeds, such as replacing low-quality hay with more nutritious options like sugar beet residues and maize silage. Cultivating fodder crops also alleviated grazing pressure on nearby pastures which are often degraded.

According to the modelling results, the targeted interventions resulted in a 17 percent reduction in total emissions and a 20 percent reduction in emission intensity. Simultaneously, protein production increased by 4 percent, and feed intake decreased by approximately 15 percent (see Figure 18).

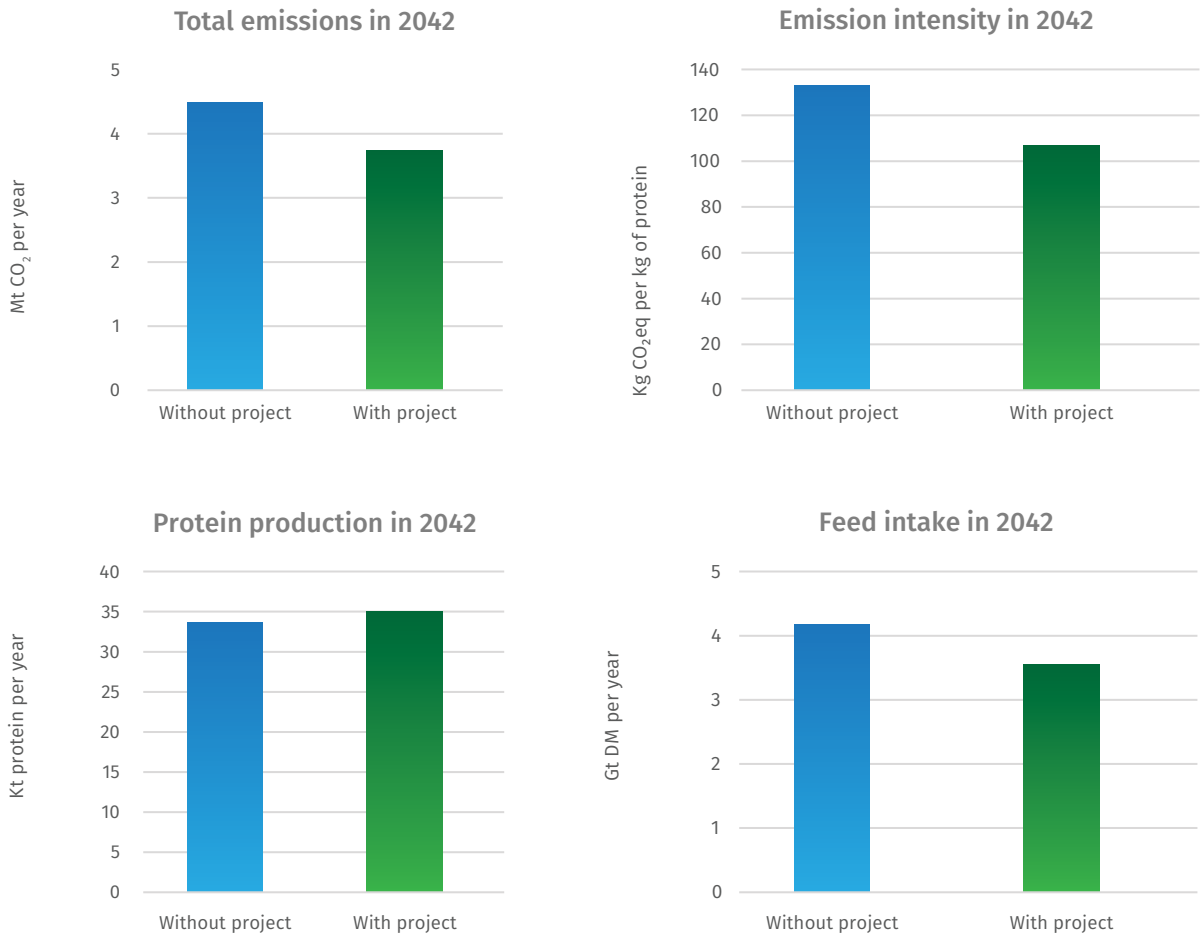

This assessment was conducted as part of the Low carbon and Resilient Livestock Development project,[21] which encompasses eight country-level projects. These projects are: The Rwanda Dairy Development Project, The Restoration of Landscapes and Livelihoods Project in Lesotho, The Dairy Modernization and Market Access Project in Georgia, The RRPCP in Kyrgyzstan, The Community-based Agricultural Support Project Plus in Tajikistan, The Rural Development – Rural Sustainable Development Project in the Semi-arid Region of Bahia in Brazil, The Dairy Value Chains Development Project II in Uzbekistan, and finally, The Transforming Agriculture through Diversification and Entrepreneurship Programme in Malawi. Conducted in collaboration with IFAD, the project aims to enhance the capacities of governments and other stakeholders across the entire sector to understand and implement low carbon livestock options.

Figure 18.
Results showing the impact of the Regional Resilient Pastoral Communities Project on the total emissions, emission intensity, protein production and feed intake using GLEAM-*i*

[21] https://www.fao.org/climate-change/projects-and-programmes/project-detail/low-carbon-and-resilient-livestock-dßevelopment-strategies-for-climate-informed-investments/en



8. Conclusions

Considering the growing demand for TASF predicted by 2050, a rise in the world animal population is expected, resulting in the increased GHG emissions from the livestock sector. Emissions have been predicted to rise from 6.2 Gt CO_2eq in 2015 to 9.1 Gt CO2eq by 2050. In this report, the mitigation potential of several interventions for the livestock sector was modelled to evaluate their potential effect against a BAU scenario, which assumes no change in the emissions per unit of output and no efficiency improvements along the production chain.

Simultaneous adoption of all these measures could not only limit but also reduce the projected emissions of 9.1 Gt CO_2eq that would be generated with no interventions by 2050. The most promising interventions in terms of GHG reduction include enhancing the livestock productivity, implementing feed and nutrition practices, and improving animal health and welfare. Other practices such as breeding, changes in consumption of TASF, reducing food loss and waste, and rumen manipulation also contribute to lower but still not negligible mitigation potentials.

However, it is important to stress that some of the proposed interventions exhibit intricate interactions and interdependencies, often posing challenges for their disentanglement and leading to partial double-counting of mitigation potential. Additionally, efforts to reduce GHGs must not compromise progress toward other sustainability goals. In the context of the livestock, sustainable development goals can be conveniently grouped into four interconnected domains: 1) food and nutrition security; 2) livelihoods and economic growth; 3) animal health and welfare; and 4) climate and natural resource use (FAO, 2018c).

To realize the modelled pathways and effectively reduce emissions by 2050, the adoption of proposed practices at the local level is essential. Given the complexity and diversity of farming systems, mitigation interventions should be customized to suit specific local contexts. Institutions play a pivotal role in setting priorities and facilitating the adoption of ambitious climate action through incentives, legislation, guidelines, education, extension services, awareness campaigns and market access. In conclusion, collaborative efforts from all industry stakeholders are critical to successfully mitigate the anticipated increase in sectoral GHG emissions. Based on the presently available data, this path appears both viable and effective.

References

Aboagye, I.A. & Beauchemin, K.A. 2019. Potential of molecular weight and structure of tannins to reduce methane emissions from ruminants: A review. *Animals*, 9(11): 856. https://doi.org/10.3390/ani9110856

Adesogan, A.T., Havelaar, A.H., McKune, S.L., Eilittä, M. & Dahl, G.E. 2020. Animal source foods: Sustainability problem or malnutrition and sustainability solution? Perspective matters. *Global Food Security*, 25: 100325. https://doi.org/10.1016/j.gfs.2019.100325

Agethen, K., Mauricio, R.M. & Deblitz, C. 2021. Economics of greenhouse gas mitigation strategies in a north- eastern brazilian beef production system. *Proceedings of the XXIV International Grassland Congress / XI International Rangeland Congress (Sustainable Use of Grassland and Rangeland Resources for Improved Livelihoods), 25-29 October 2021.* https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=4750&context=igc

Alcalde, M.J., Suárez, M.D., Rodero, E., Álvarez, R., Sáez, M.I. & Martínez, T.F. 2017. Effects of farm management practices and transport duration on stress response and meat quality traits of suckling goat kids. *Animal*, 11(9): 1626–1635. https://doi.org/10.1017/S1751731116002858

Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D. & Rounsevell, M.D.A. 2017. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Global Food Security*, 15: 22–32. https://doi.org/10.1016/j.gfs.2017.04.001

Arndt, C., Hristov, A.N., Price, W.J., McClelland, S.C., Pelaez, A.M., Cueva, S.F., Oh, J. *et al.* 2022. Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050. *Proceedings of the National Academy of Sciences*, 119(20): e2111294119. https://doi.org/10.1073/pnas.2111294119

Beal, T., Gardner, C.D., Herrero, M., Iannotti, L.L., Merbold, L., Nordhagen, S. & Mottet, A. 2023. Friend or foe? The role of animal-source foods in healthy and environmentally sustainable diets. *The Journal of Nutrition*, 153(2): 409–425. https://doi.org/10.1016/j.tjnut.2022.10.016

Beauchemin, K.A., Ungerfeld, E.M., Abdalla, A.L., Alvarez, C., Arndt, C., Becquet, P., Benchaar, C. *et al.* 2022. Invited review: Current enteric methane mitigation options. *Journal of Dairy Science*, 105(12): 9297–9326. https://doi.org/10.3168/jds.2022-22091

Behrens, P., Kiefte-de Jong, J.C., Bosker, T., Rodrigues, J.F.D., De Koning, A. & Tukker, A. 2017. Evaluating the environmental impacts of dietary recommendations. *Proceedings of the National Academy of Sciences*, 114(51): 13412–13417. https://doi.org/10.1073/pnas.1711889114

Belanche, A., Newbold, C., Morgavi, D., Bach, A., Zweifel, B. & Yáñez-Ruiz, D. 2020. A meta-analysis describing the effects of the essential oils blend agolin ruminant on performance, rumen fermentation and methane emissions in dairy cows. *Animals*, 10(4): 620. https://doi.org/10.3390/ani10040620

Bertoli, S., Goujon, M. & Santoni, O. 2016. The CERDI-seadistance database. https://zenodo.org/records/46822

Bouwman, L., Goldewijk, K.K., Van Der Hoek, K.W., Beusen, A.H.W., Van Vuuren, D.P., Willems, J., Rufino, M.C. & Stehfest, E. 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proceedings of the National Academy of Sciences*, 110(52): 20882–20887. https://doi.org/10.1073/pnas.1012878108

Brito, L.F., Bedere, N., Douhard, F., Oliveira, H.R., Arnal, M., Peñagaricano, F., Schinckel, A.P., Baes, C.F. & Miglior, F. 2021. Review: Genetic selection of high-yielding dairy cattle toward sustainable farming systems in a rapidly changing world. *Animal*, 15: 100292. https://doi.org/10.1016/j.animal.2021.100292

Canadell, J.G., Monteiro, P.M.S., Costa, M.H., Cotrim da Cunha, L., Cox, P.M., Eliseev, A.V., Henson, S. *et al.* 2021. Global Carbon and other biogeochemical cycles and feedbacks. In: *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. First edition. Cambridge University Press. https://doi.org/10.1017/9781009157896

Carton, W., Lund, J.F. & Dooley, K. 2021. Undoing equivalence: Rethinking carbon accounting for just carbon removal. *Frontiers in Climate*, 3: 664130. https://doi.org/10.3389/fclim.2021.664130

Castro, C.G., Trevisan, A.H., Pigosso, D.C.A. & Mascarenhas, J. 2022. The rebound effect of circular economy: Definitions, mechanisms and a research agenda. *Journal of Cleaner Production*, 345: 131136. https://doi.org/10.1016/j.jclepro.2022.131136

Chang, J., Peng, S., Yin, Y., Ciais, P., Havlik, P. & Herrero, M. 2021. Reply to comment by Rigolot on "Narratives behind livestock methane mitigation studies matter". *AGU Advances*, 2(4): e2021AV000549. https://doi.org/10.1029/2021AV000549

Copernicus Global Land Service. 2021. Providing bio-geophysical products of global land surface. *Copernicus – Europe's eyes on Earth.* [Cited 3 November 2023]. https://land.copernicus.eu/global/products/dmp

Crumpler, K., Abi Khalil, R., Tanganelli, E., Rai, N., Roffredi, L., Meybeck, A., Umulisa, V., Wolf, J. and Bernoux, M. 2021. *2021 (Interim) Global update report: Agriculture, Forestry and Fisheries in the Nationally Determined Contributions.* Environment and Natural Resources Management Working Paper No. 91. Rome, FAO. https://doi.org/10.4060/cb7442en

da Silva, W.C., Silva, J.A.R.D., Camargo-Júnior, R.N.C., Silva, É.B.R.D., Santos, M.R.P.D., Viana, R.B., Silva, A.G.M.E., Silva, C.M.G.D. & Lourenço-Júnior, J.D.B. 2023. Animal welfare and effects of per-female stress on male and cattle reproduction—A review. *Frontiers in Veterinary Science*, 10: 1083469. https://doi.org/10.3389/fvets.2023.1083469

Deen, A.U., Tyagi, N., Yadav, R.D., Kumar, S., Tyagi, A.K. & Singh, S.K. 2019. Feeding balanced ration can improve the productivity and economics of milk production in dairy cattle: a comprehensive field study. *Tropical Animal Health and Production*, 51(4): 737–744. https://doi.org/10.1007/s11250-018-1747-8

de Haas, Y., Windig, J.J., Calus, M.P.L., Dijkstra, J., De Haan, M., Bannink, A. & Veerkamp, R.F. 2011. Genetic parameters for predicted methane production and potential for reducing enteric emissions through genomic selection. *Journal of Dairy Science*, 94(12): 6122–6134. https://doi.org/10.3168/jds.2011-4439

de Haas, Y., Veerkamp, R.F., De Jong, G. & Aldridge, M.N. 2021. Selective breeding as a mitigation tool for methane emissions from dairy cattle. *Animal*, 15: 100294. https://doi.org/10.1016/j.animal.2021.100294

de Vries, M., Wouters, B., Suharyono, D., Sutiarto, A., & Berasa, S. E. 2020. Effects of feeding and manure management interventions on technical and environmental performance of Indonesian dairy farms: Results of a pilot study in Lembang Sub-District, West Java. Wageningen Livestock Research. https://edepot.wur.nl/515314

Dondini, M., Martin, M., De Camillis, C., Uwizeye, A., Soussana, J.-F., Robinson, T. & Steinfeld, H. 2023. *Global assessment of soil carbon in grasslands – From current stock estimates to sequestration potential*. FAO Animal Production and Health Paper No. 187. Rome, FAO. https://doi.org/10.4060/cc3981en

Ericksen, P. & Crane, T. 2018. The feasibility of low emissions development interventions for the East African livestock sector: Lessons from Kenya and Ethiopia. ILRI Research Report 46. Nairobi, Kenya. https://cgspace.cgiar.org/bitstream/handle/10568/91527/RR46.pdf

European Environment Agency (EEA). 2016. *EMEP/EEA air pollutant emission inventory guidebook 2016: technical guidance to prepare national emission inventories.* LU, Publications Office. https://data.europa.eu/doi/10.2800/247535

FAO. 2010a. FAOSTAT: Food Balances (2010-). In: *FAO.* Rome. https://www.fao.org/faostat/en/#data/FBS

FAO. 2010b. Greenhouse gas emissions from the dairy sector – A life cycle assessment. Rome. https://www.fao.org/3/k7930e/k7930e00.pdf

FAO. 2015. Livestock systems, available online at https://www.fao.org/livestock-systems/global-distributions/en/

FAO. 2016a. *Environmental performance of large ruminant supply chains: Guidelines for assessment.* Livestock Environmental Assessment and Performance Partnership. Rome. https://www.fao.org/documents/card/en?details=cd7ec1b8-7801-4ce1-87ed-0bdb575672a5%2f

FAO. 2016b. *Environmental performance of animal feeds supply chains: Guidelines for assessment.* Livestock Environmental Assessment and Performance Partnership. Rome. https://www.fao.org/feed-safety/resources/resources-details/en/c/1062409/

FAO. 2016c. *Greenhouse gas emissions and fossil energy demand from small ruminant supply chains.* Guidelines for assessment.Livestock Environmental Assessment and Performance Partnership. Rome. https://www.fao.org/3/i6434e/i6434e.pdf

FAO, 2016d. *Greenhouse gas emissions and fossil energy demand from poultry supply chains. Guidelines for assessment.* Livestock Environmental Assessment and Performance (LEAP) Partnership. Rome. https://www.fao.org/documents/card/en?details=01cf7106-bb20-4150-b4f8-1e1ab4a7f069

FAO. 2018a. *Nutrient flows and associated environmental impacts in livestock supply chains: Guidelines for assessment (Version 1).* Livestock Environmental Assessment and Performance (LEAP) Partnership. Rome. 196 pp. Licence: CC BY-NC-SA 3.0 IGO. https://www.fao.org/3/ca1328en/CA1328EN.pdf

FAO. 2018b. The future of food and agriculture: Alternative pathways to 2050. Rome. https://www.fao.org/global-perspectives-studies/resources/detail/en/c/1157074/

FAO. 2018c. Shaping the future of livestock – sustainably, responsibly, efficiently. The 10th Global Forum for Food and Agriculture. Rome. https://www.fao.org/3/I8384EN/i8384en.pdf

FAO. 2019a. *Five practical actions towards low-carbon livestock.* Rome. https://www.fao.org/3/ca7089en/CA7089EN.pdf

FAO. 2019b. *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*. Rome. https://www.fao.org/documents/card/en?details=ca6030en

FAO. 2020. *Environmental performance of feed additives in livestock supply chains – Guidelines for assessment – Version 1.* Livestock Environmental Assessment and Performance Partnership (FAO LEAP). Rome. ttps://doi.org/10.4060/ca9744en

FAO. 2022a. *Greenhouse gas emissions from agrifood systems. Global, regional and country trends, 2000-2020*. FAOSTAT Analytical Brief Series No. 50. Rome. https://www.fao.org/3/cc2672en/cc2672en.pdf

FAO. 2022b. GLEAM v3 Dashboard. In: *Shiny Apps.* [Cited Oct. 2020]. https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public/

FAO. 2022c. *Dairy Market Review: Emerging trends and outlook 2022*, Rome. https://www.fao.org/3/cc3418en/cc3418en.pdf

FAO. 2022d. *Grazing with trees – A silvopastoral approach to managing and restoring trees*. FAO Forestry Paper, No. 187. Rome. https://doi.org/10.4060/cc2280en

FAO. 2022e. *FAO Strategy on Climate Change 2022–2031*. Rome. https://www.fao.org/3/cc2274en/cc2274en.pdf,

FAO. 2023a. *Contribution of terrestrial animal source food to healthy diets for improved nutrition and health outcomes – An evidence and policy overview on the state of knowledge and gaps.* Rome. https://doi.org/10.4060/cc3912en

FAO. 2023b. FAOSTAT Emissions totals, Rome. https://www.fao.org/faostat/en/#data/GT

FAO. 2023c. *Methane emissions in livestock and rice systems – Sources, quantification, mitigation and metrics*. Rome. https://doi.org/10.4060/cc7607en

FAO. 2023d. *Bioeconomy for sustainable food and agriculture.* Rome. https://www.fao.org/3/cc6905en/cc6905en.pdf

FAO. 2023e. *Sustainable livestock transformation – A vision for FAO's work on animal production and health.* Rome. https://doi.org/10.4060/cc7474en

FAO. 2023f. *Livestock Climate Actions in Rwanda. Enhancing nationally determined contributions for a better future.* Draft report. Rome.

FAO & GDP. 2019. *Climate change and the global dairy cattle sector – The role of the dairy sector in a low-carbon future*. Rome. 36 pp. Licence: CC BY-NC-SA- 3.0 IGO. https://www.fao.org/documents/card/en?details=CA2929EN

FAO & GRA. 2020. *Livestock Activity Data Guidance (L-ADG).* FAO and Global Research Alliance on Agricultural Greenhouse Gases. https://doi.org/10.4060/ca7510en

FAO & WHO. 2023. *Food safety aspects of cell-based food*. Rome. https://doi.org/10.4060/cc4855en

Ferri, M., Ranucci, E., Romagnoli, P. & Giaccone, V. 2017. Antimicrobial resistance: A global emerging threat to public health systems. *Critical Reviews in Food Science and Nutrition*, 57(13): 2857–2876. https://doi.org/10.1080/10408398.2015.1077192

Foong, A., Pradhan, P., Frör, O. & Kropp, J.P. 2022. Adjusting agricultural emissions for trade matters for climate change mitigation. *Nature Communications*, 13(1): 3024. https://doi.org/10.1038/s41467-022-30607-x

Forster, P., Storelvmo T., Armour K., Collins W., Dufresne J.-L., Frame D., Lunt D.J. *et al.* 2021. The earth's energy budget, climate feedbacks, and climate sensitivity. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi:10.1017/9781009157896.009

Fouts, J.Q., Honan, M.C., Roque, B.M., Tricarico, J.M. & Kebreab, E. 2022. Enteric methane mitigation interventions. *Translational Animal Science*, 6(2): txac041. https://doi.org/10.1093/tas/txac041

Fox, N.J., Smith, L.A., Houdijk, J.G.M., Athanasiadou, S. & Hutchings, M.R. 2018. Ubiquitous parasites drive a 33% increase in methane yield from livestock. *International Journal for Parasitology*, 48(13): 1017–1021. https://doi.org/10.1016/j.ijpara.2018.06.001

Frehner, A., Muller, A., Schader, C., De Boer, I.J.M. & Van Zanten, H.H.E. 2020. Methodological choices drive differences in environmentally-friendly dietary solutions. *Global Food Security*, 24: 100333. https://doi.org/10.1016/j.gfs.2019.100333

Fresán, U. & Sabaté, J. 2019. Vegetarian diets: planetary health and its alignment with human health. *Advances in Nutrition*, 10: S380–S388. https://doi.org/10.1093/advances/nmz019

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S. *et al.* 2005. The ecoinvent database: Overview and methodological framework (7 pp). *The International Journal of Life Cycle Assessment*, 10(1): 3–9. https://doi.org/10.1065/lca2004.10.181.1

Frolking, S., Wisser, D., Grogan, D., Proussevitch, A. & Glidden, S. 2020. GAEZ+_2015 Crop Harvest Area. Harvard Dataverse. https://dataverse.harvard.edu/citation?persistentId=doi:10.7910/DVN/KAGRFI

Gerber, P., Vellinga, T., Opio, C. & Steinfeld, H. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science*, 139(1–2): 100–108. https://doi.org/10.1016/j.livsci.2011.03.012

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities.* Rome, FAO. https://www.fao.org/3/i3437e/i3437e.pdf

Gilbert, M., Conchedda, G., Van Boeckel, T.P., Cinardi, G., Linard, C., Nicolas, G., Thanapongtharm, W. *et al.* 2015. Income disparities and the global distribution of intensively farmed chicken and pigs. *PLOS ONE*, 10(7): e0133381. https://doi.org/10.1371/journal.pone.0133381

Gilbert, M., Nicolas, G., Cinardi, G., Van Boeckel, T.P., Vanwambeke, S.O., Wint, G.R.W. & Robinson, T.P. 2018. Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Scientific Data*, 5(1): 180227. https://doi.org/10.1038/sdata.2018.227

Giller, K., Bossut, L., Eggerschwiler, L. & Terranova, M. 2022. In vitro ruminal fermentation, methane production and nutrient degradability as affected by fruit and vegetable pomaces in differing concentrations. *Journal of Animal Physiology and Animal Nutrition*, 106(5): 957–967. https://doi.org/10.1111/jpn.13656

Global Rumen Census. 2023. *Global Rumen Census. In: Global Research Alliance on Agricultural Greenhouse Gases*. https://globalresearchalliance.org/research/livestock/collaborative-activities/global-rumen-census/

Godde, C.M., De Boer, I.J.M., Ermgassen, E.Z., Herrero, M., Van Middelaar, C.E., Muller, A., Röös, E. *et al.* 2020. Soil carbon sequestration in grazing systems: managing expectations. *Climatic Change*, 161(3): 385–391. https://doi.org/10.1007/s10584-020-02673-x

Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K. & Herrero, M. 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, 28: 100488. https://doi.org/10.1016/j.gfs.2020.100488

Gonzalez-Rivas, P.A., Chauhan, S.S., Ha, M., Fegan, N., Dunshea, F.R. & Warner, R.D. 2020. Effects of heat stress on animal physiology, metabolism, and meat quality: A review. *Meat Science*, 162: 108025. https://doi.org/10.1016/j.meatsci.2019.108025

Groen, E.A., Van Zanten, H.H.E., Heijungs, R., Bokkers, E.A.M. & De Boer, I.J.M. 2016. Sensitivity analysis of greenhouse gas emissions from a pork production chain. *Journal of Cleaner Production*, 129: 202–211. https://doi.org/10.1016/j.jclepro.2016.04.081

Groen, E.A. & Heijungs, R. 2017. Ignoring correlation in uncertainty and sensitivity analysis in life cycle assessment: what is the risk? *Environmental Impact Assessment Review*, 62: 98–109. https://doi.org/10.1016/j.eiar.2016.10.006

Habib, M., Pollott, G. & Leaver, D. 2011. Digestibility and nitrogen balance of high- and low-quality forages supplemented with high- and low-protein concentrates fed to two breeds of cattle. *Journal of Applied Animal Research*, 39(4): 303–310. https://doi.org/10.1080/09712119.2011.607891

He, Z., Zhang, Y., Liu, X., De Vries, W., Ros, G.H., Oenema, O., Xu, W. *et al.* 2023. Mitigation of nitrogen losses and greenhouse gas emissions in a more circular cropping-poultry production system. *Resources, Conservation and Recycling*, 189: 106739. https://doi.org/10.1016/j.resconrec.2022.106739

Heffer, P., Gruère, A. & Roberts, T. 2017. Assessment of fertilizer use by crop at the global level, International Fertilizer Association (IFA) and International Plan Nutrition Institute (IPNI). https://www.ifastat.org/consumption/fertilizer-use-by-crop

Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., Wirsenius, S. *et al.* 2016. Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, 6(5): 452–461. https://doi.org/10.1038/nclimate2925

Henderson, B.B., Gerber, P.J., Hilinski, T.E., Falcucci, A., Ojima, D.S., Salvatore, M. & Conant, R.T. 2015. Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. *Agriculture, Ecosystems & Environment*, 207: 91–100. https://doi.org/10.1016/j.agee.2015.03.029

Hickey, S.M., Bain, W.E., Bilton, T.P., Greer, G.J., Elmes, S., Bryson, B., Pinares-Patiño, C.S. *et al.* 2022. Impact of breeding for reduced methane emissions in New Zealand sheep on maternal and health traits. *Frontiers in Genetics*, 13: 910413. https://doi.org/10.3389/fgene.2022.910413

Hirvonen, K., Bai, Y., Headey, D. & Masters, W.A. 2020. Affordability of the EAT–Lancet reference diet: a global analysis. *The Lancet Global Health*, 8(1): e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4

Houdijk, J.G.M., Tolkamp, B.J., Rooke, J.A. & Hutchings, M.R. 2017. Animal health and greenhouse gas intensity: the paradox of periparturient parasitism. *International Journal for Parasitology*, 47(10–11): 633–641. https://doi.org/10.1016/j.ijpara.2017.03.006

Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J. & Oosting, S. 2013. *Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO2 emissions.* Edited by Pierre J. Gerber, Benjamin Henderson and Harinder P.S. Makkar. FAO Animal Production and Health Paper No. 177. FAO, Rome, Italy. https://www.uncclearn.org/wp-content/uploads/library/fao180.pdf

IFA. 2022. *Reducing emissions from fertilizer use*. International Fertilizer Association and Systemiq. https://www.fertilizer.org/wp-content/uploads/2022/09/2022_IFA_Systemiq_Reducing_Emissions_from_Fertilizer_Use_Report_Jan_12_2023.pdf

IFAD & FAO. 2021. Low carbon livestock development in Kyrgyzstan. Quantifying the future impact of the Regional Resilient Pastoral Communities Project on greenhouse gas emissions. Rome. https://www.fao.org/3/cb7221en/cb7221en.pdf

IPCC. 2006. *2006 IPCC guidelines for national greenhouse gas inventories - Volume 4: Agriculture, Forestry and Other Land Use*. [Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K., eds.] Hayama, Japan, Institute for Global Environmental Strategies. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_00_Cover.pdf

IPCC. 2019a. 2019 *Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories*, [Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. & Federici, S., eds.]. Published: IPCC, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

IPCC. 2019b. *Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* [Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. & Malley, J., eds.]. World Meteorological Organization, Geneva, Switzerland. https://www.ipcc.ch/srccl/

IPCC. 2021. *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. First edition. Cambridge University Press. https://doi.org/10.1017/9781009157896

IPCC. 2022. *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. First edition. Cambridge University Press. https://doi.org/10.1017/9781009157926

Jalal, H., Giammarco, M., Lanzoni, L., Akram, M.Z., Mammi, L.M.E., Vignola, G., Chincarini, M., Formigoni, A. & Fusaro, I. 2023. Potential of fruits and vegetable by-products as an alternative feed source for sustainable ruminant nutrition and production: A review. *Agriculture*, 13(2): 286. https://doi.org/10.3390/agriculture13020286

Jaramillo-López, E., Itza-Ortiz, M.F., Peraza-Mercado, G. & Carrera-Chávez, J.M. 2017. Ruminal acidosis: strategies for its control. *Austral journal of veterinary sciences*, 49(3): 139–148. https://doi.org/10.4067/S0719-81322017000300139

Jonker, A., Hickey, S.M., Rowe, S.J., Janssen, P.H., Shackell, G.H., Elmes, S., Bain, W.E. *et al.* 2018. Genetic parameters of methane emissions determined using portable accumulation chambers in lambs and ewes grazing pasture and genetic correlations with emissions determined in respiration chambers1. *Journal of Animal Science*, 96(8): 3031–3042. https://doi.org/10.1093/jas/sky187

Karwowska, M., Łaba**, S. & Szczepański, K.** 2021. Food loss and waste in meat sector—Why the consumption stage generates the most losses? *Sustainability*, 13(11): 6227. https://doi.org/10.3390/su13116227

Khasapane, N.G., Byaruhanga, C., Thekisoe, O., Nkhebenyane, S.J. & Khumalo, Z.T.H. 2023. Prevalence of subclinical mastitis, its associated bacterial isolates and risk factors among cattle in Africa: a systematic review and meta-analysis. *BMC Veterinary Research*, 19(1): 123. https://doi.org/10.1186/s12917-023-03673-6

Kastner, T., Kastner, M. & Nonhebel, S. 2011. Tracing distant environmental impacts of agricultural products from a consumer perspective. *Ecological Economics*, 70(6): 1032–1040. https://doi.org/10.1016/j.ecolecon.2011.01.012

Kebreab, E., Bannink, A., Pressman, E.M., Walker, N., Karagiannis, A., Van Gastelen, S. & Dijkstra, J. 2023. A meta-analysis of effects of 3-nitrooxypropanol on methane production, yield, and intensity in dairy cattle. *Journal of Dairy Science*, 106(2): 927–936. https://doi.org/10.3168/jds.2022-22211

Kim, K., Kwon, T., Dessie, T., Yoo, D., Mwai, O.A., Jang, J., Sung, S. *et al.* 2020. The mosaic genome of indigenous African cattle as a unique genetic resource for African pastoralism. *Nature Genetics*, 52(10): 1099–1110. https://doi.org/10.1038/s41588-020-0694-2

Kleinpeter, V., Alvanitakis, M., Vigne, M., Wassenaar, T., Lo Seen, D. & Vayssières, J. 2023. Assessing the roles of crops and livestock in nutrient circularity and use efficiency in the agri-food-waste system: A set of indicators applied to an isolated tropical island. *Resources, Conservation and Recycling*, 188: 106663. https://doi.org/10.1016/j.resconrec.2022.106663

Kreidenweis, U., Breier, J., Herrmann, C., Libra, J. & Prochnow, A. 2021. Greenhouse gas emissions from broiler manure treatment options are lowest in well-managed biogas production. *Journal of Cleaner Production*, 280: 124969. https://doi.org/10.1016/j.jclepro.2020.124969

Króliczewska, B., Pecka-Kiełb, E. & Bujok, J. 2023. Strategies used to reduce methane emissions from ruminants: controversies and issues. *Agriculture*, 13(3): 602. https://doi.org/10.3390/agriculture13030602

Lacetera, N. 2019. Impact of climate change on animal health and welfare. *Animal Frontiers*, 9(1): 26–31. https://doi.org/10.1093/af/vfy030

Lanzoni, L., Waxenberg, K., Ramsey, R., Rees, R.M., Bell, J., Vignola, G. & Atzori, A.S. 2023a. The potential of improved animal welfare as an environmental impact mitigation strategy in dairy sheep farming. *Animal - science proceedings*, 14(2): 370. https://doi.org/10.1016/j.anscip.2023.01.492

Lanzoni, L., Whatford, L., Atzori, A.S., Chincarini, M., Giammarco, M., Fusaro, I. & Vignola, G. 2023b. Review: The challenge to integrate animal welfare indicators into the Life Cycle Assessment. *animal*, 17(5): 100794. https://doi.org/10.1016/j.animal.2023.100794

Lassaletta, L., Billen, G., Grizzetti, B., Garnier, J., Leach, A.M. & Galloway, J.N. 2014. Food and feed trade as a driver in the global nitrogen cycle: 50-year trends. *Biogeochemistry*, 118(1–3): 225–241. https://doi.org/10.1007/s10533-013-9923-4

Leip, A., Britz, W., Weiss, F. & De Vries, W. 2011. Farm, land, and soil nitrogen budgets for agriculture in Europe calculated with CAPRI. *Environmental Pollution*, 159(11): 3243–3253. https://doi.org/10.1016/j.envpol.2011.01.040

Leip, A., Bodirsky, B.L. & Kugelberg, S. 2021. The role of nitrogen in achieving sustainable food systems for healthy diets. *Global Food Security*, 28: 100408. https://doi.org/10.1016/j.gfs.2020.100408

Livestock Environmental Assessment and Performance (LEAP) Partnership. 2015. Global database of GHG emissions related to feed crops. http://www.fao.org/partnerships/leap/database/ghg-crops/en/

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J.B. & Yang, H. 2010. A high-resolution assessment on global nitrogen flows in cropland. *Proceedings of the National Academy of Sciences*, 107(17): 8035–8040. https://doi.org/10.1073/pnas.0913658107

Llonch, P., Haskell, M.J., Dewhurst, R.J. & Turner, S.P. 2017. Current available strategies to mitigate greenhouse gas emissions in livestock systems: an animal welfare perspective. *Animal*, 11(2): 274–284. https://doi.org/10.1017/S1751731116001440

MacLeod, M., Gerber, P., Mottet, A., Tempio, G., Falcucci, A., Opio, C., Vellinga, T., Henderson, B. & Steinfeld, H. 2013. *Greenhouse gas emissions from pig and chicken supply chains – A global life cycle assessment.* Rome, FAO. https://www.fao.org/3/i3460e/i3460e00.htm

MacLeod, M.J., Vellinga, T., Opio, C., Falcucci, A., Tempio, G., Henderson, B., Makkar, H. *et al.* 2018. Invited review: A position on the Global Livestock Environmental Assessment Model (GLEAM). *Animal*, 12(2): 383–397. https://doi.org/10.1017/S1751731117001847

Mak, T.M.W., Xiong, X., Tsang, D.C.W., Yu, I.K.M. & Poon, C.S. 2020. Sustainable food waste management towards circular bioeconomy: Policy review, limitations and opportunities. *Bioresource Technology*, 297: 122497. https://doi.org/10.1016/j.biortech.2019.122497

Moate, P.J., Williams, S.R.O., Torok, V.A., Hannah, M.C., Ribaux, B.E., Tavendale, M.H., Eckard, R.J. *et al.* 2014. Grape marc reduces methane emissions when fed to dairy cows. *Journal of Dairy Science*, 97(8): 5073–5087. https://doi.org/10.3168/jds.2013-7588

Mohankumar Sajeev, E.P., Winiwarter, W. & Amon, B. 2018. Greenhouse gas and ammonia emissions from different stages of liquid manure management chains: Abatement options and emission interactions. *Journal of Environmental Quality*, 47(1): 30–41. https://doi.org/10.2134/jeq2017.05.0199

Montagnini, F., Ibrahim, M., & Murgueitio, E. 2013. Silvopastoral systems and climate change mitigation in Latin America. Bois et Forêts Des Tropiques, 316(2), 3–16. https://drflorenciamontagnini.files.wordpress.com/2015/03/montagnini-et-al-2013-sps-climate-mitigation.pdf

Mottet, A., De Haan, C., Falcucci, A., Tempio, G., Opio, C. & Gerber, P. 2017a. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security*, 14: 1–8. https://doi.org/10.1016/j.gfs.2017.01.001

Mottet, A., Henderson, B., Opio, C., Falcucci, A., Tempio, G., Silvestri, S., Chesterman, S. & Gerber, P.J. 2017b. Climate change mitigation and productivity gains in livestock supply chains: insights from regional case studies. *Regional Environmental Change*, 17(1): 129–141. https://doi.org/10.1007/s10113-016-0986-3

Muizelaar, W., Groot, M., Van Duinkerken, G., Peters, R. & Dijkstra, J. 2021. Safety and Transfer Study: Transfer of Bromoform Present in *Asparagopsis taxiformis* to Milk and Urine of Lactating Dairy Cows. *Foods*, 10(3): 584. https://doi.org/10.3390/foods10030584

Mukherji, A., Arndt, C., Arango, J., Flintan, F., Derera, J., Francesconi, W., Jones, S, Loboguerrero, A.M., Merrey, D., Mockshell, J., Quintero, M., Mulat, D.G., Ringler, C., Ronchi, L., Sanchez, M, Sapkota, T. and Thilsted, S. 2023. *Achieving agricultural breakthrough: A deep dive into seven technological areas*. Montpelier, France: CGIAR System Organization. https://cgspace.cgiar.org/handle/10568/131852

Mutua, F., Sharma, G., Grace, D., Bandyopadhyay, S., Shome, B. & Lindahl, J. 2020. A review of animal health and drug use practices in India, and their possible link to antimicrobial resistance. *Antimicrobial Resistance & Infection Control*, 9(1): 103. https://doi.org/10.1186/s13756-020-00760-3

Mwai, O., Hanotte, O., Kwon, Y.-J. & Cho, S. 2015. - Invited Review - African Indigenous Cattle: Unique Genetic Resources in a Rapidly Changing World. *Asian-Australasian Journal of Animal Sciences*, 28(7): 911–921. https://doi.org/10.5713/ajas.15.0002R

National Research Council. 1994. *Nutrient Requirements of Poultry: Ninth Revised Edition, 1994*. Washington, D.C., National Academies Press. https://doi.org/10.17226/2114

National Research Council. 1998. *Nutrient Requirements of Swine: 10th Revised Edition*. Washington, D.C., National Academies Press. https://doi.org/10.17226/6016

Navarro, J., Bryan, B.A., Marinoni, O., Eady, S. & Halog, A. 2016. Mapping agriculture's impact by combining farm management handbooks, life-cycle assessment and search engine science. *Environmental Modelling & Software*, 80: 54–65. https://doi.org/10.1016/j.envsoft.2016.02.020

Ndung'u, P.W., Takahashi, T., Du Toit, C.J.L., Robertson-Dean, M., Butterbach-Bahl, K., McAuliffe, G.A., Merbold, L. & Goopy, J.P. 2022. Farm-level emission intensities of smallholder cattle (Bos indicus; B. indicus–B. taurus crosses) production systems in highlands and semi-arid regions. *Animal*, 16(1): 100445. https://doi.org/10.1016/j.animal.2021.100445

Oltenacu, P. & Broom, D. 2010. The impact of genetic selection for increased milk yield on the welfare of dairy cows. *Animal Welfare*, 19(S1): 39–49. https://doi.org/10.1017/S0962728600002220

Oosting, S., Van Der Lee, J., Verdegem, M., De Vries, M., Vernooij, A., Bonilla-Cedrez, C. & Kabir, K. 2022. Farmed animal production in tropical circular food systems. *Food Security*, 14(1): 273–292. https://doi.org/10.1007/s12571-021-01205-4

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T., Henderson, B. & Steinfeld, H. 2013. *Greenhouse gas emissions from ruminant supply chains – A global life cycle assessment.* Rome, FAO. https://www.fao.org/3/i3461e/i3461e00.htm

Özkan, Ş., Vitali, A., Lacetera, N., Amon, B., Bannink, A., Bartley, D.J., Blanco-Penedo, I. *et al.* 2016. Challenges and priorities for modelling livestock health and pathogens in the context of climate change. *Environmental Research*, 151: 130–144. https://doi.org/10.1016/j.envres.2016.07.033

Özkan, Ş., Teillard, F., Lindsay, B., Montgomery, H., Rota, A., Gerber P., Dhingra M. & Mottet, A. 2022. The role of animal health in national climate commitments. Rome, FAO. https://doi.org/10.4060/cc0431en

Paltaki, A., Michailidis, A., Chatzitheodoridis, F., Zaralis, K. & Loizou, E. 2021. Bioeconomy and Livestock Production Nexus: A Bibliometric Network Analysis. *Sustainability*, 13(22): 12350. https://doi.org/10.3390/su132212350

Pendrill, F., Persson, U.M. & Kastner, T. 2020. Deforestation risk embodied in production and consumption of agricultural and forestry commodities 2005-2017. Zenodo. Cited 3 November 2023. https://zenodo.org/record/4250532

Pickering, N.K., Oddy, V.H., Basarab, J., Cammack, K., Hayes, B., Hegarty, R.S., Lassen, J. *et al.* 2015. Animal board invited review: genetic possibilities to reduce enteric methane emissions from ruminants. *Animal*, 9(9): 1431–1440. https://doi.org/10.1017/S1751731115000968

Poore, J. & Nemecek, T. 2018. Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392): 987–992. https://doi.org/10.1126/science.aaq0216

Rivera, J.E. & Chará, J. 2021. CH_4 and N_2O emissions from cattle excreta: A review of main drivers and mitigation strategies in grazing systems. *Frontiers in Sustainable Food Systems*, 5: 657936. https://doi.org/10.3389/fsufs.2021.657936

Robinson, T.P., Thornton, P., Franceschini, G., Kruska, R., Chiozza, F., Notenbaert, A., Cecchi, G. *et al.* 2018. Global distribution of ruminant livestock production systems V5 (5 minutes of arc). Harvard Dataverse, V1. https://doi.org/10.7910/DVN/WPDSZE

Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T. & Woznicki, S.A. 2017. Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, 16: 145–163. https://doi.org/10.1016/j.crm.2017.02.001

Rose, S., Khatri-Chhetri, A., Stier, M., Vu, T., Nelson, K. & Dittmer, K. 2021a. Agricultural sub-sectors in new and updated NDCs: 2020-2021 dataset. CCAFS dataset version 2.1., updated October 2022. Wageningen, Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). https://hdl.handle.net/10568/115962

Rose, S., Khatri-Chhetri, A., Dittmer, K., Stier, M., Wilkes, A., Shelton, S., Arndt, C. & Wollenberg, E. 2020. Livestock management ambition in the new and updated nationally determined contributions: 2020-September 2022: Analysis of agricultural sub-sectors in countries' climate change strategies. Updated October 2022. CCAFS Info Note. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). https://cgspace.cgiar.org/bitstream/handle/10568/115885/CCAFS%20Info%20Note%20Livestock%202021%20NDCs.pdf

Sakomura, N. 2004. Modeling energy utilization in broiler breeders, laying hens and broilers. *Revista Brasileira de Ciência Avícola*, 6(1): 1–11. https://doi.org/10.1590/S1516-635X2004000100001

Seshadri, R., Leahy, S.C., Attwood, G.T., Teh, K.H., Lambie, S.C., Cookson, A.L. *et al.* 2018. Cultivation and sequencing of rumen microbiome members from the Hungate1000 Collection. *Nature Biotechnology*, 36(4): 359–367. https://doi.org/10.1038/nbt.4110

Sinke, P., Swartz, E., Sanctorum, H., Van Der Giesen, C. & Odegard, I. 2023. Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030. *The International Journal of Life Cycle Assessment*, 28(3): 234–254. https://doi.org/10.1007/s11367-022-02128-8

Skuce, P.J., Bartley, D.J., Zadoks, R.N. & Macleod, M. 2016. Livestock health and greenhouse gas emissions. Edinburgh, UK. https://sefari.scot/sites/default/files/documents/Skuce%2CP.%20et%20al%20%282016%29.%20Livestock%20health%20and%20greenhouse%20gas%20emissions.%20ClimateXchange%2C%20Scotland's%20Centre%20of%20Expertise%20on%20Climate%20.pdf

Skuce, P. 2022. Acting on methane: opportunities for the UK cattle and sheep sectors. Ruminant Health & Welfare. https://ruminanthw.org.uk/wp-content/uploads/2022/04/SO-634-Ruminant-Report-Methane-April-2022-web.pdf

Sova, C.A., Grosjean, G., Baedeker, T., Nguyen, T.N., Wallner, M., Jarvis, A., Nowak, A., Corner-Dolloff, C., Girvetz, E., Laderach, P. & Lizarazo. M. 2018. Bringing the concept of climate-smart agriculture to life: Insights from csa country profiles across africa, asia, and latin america. World Bank, and the International Centre for Tropical Agriculture, Washington, DC. http://hdl.handle.net/10986/31064

Subharat, S., Shu, D., Zheng, T., Buddle, B.M., Janssen, P.H., Luo, D. & Wedlock, D.N. 2015. Vaccination of cattle with a methanogen protein produces specific antibodies in the saliva which are stable in the rumen. *Veterinary Immunology and Immunopathology*, 164(3–4): 201–207. https://doi.org/10.1016/j.vetimm.2015.02.008

Swaney, D.P., Howarth, R.W. & Hong, B. 2018. Nitrogen use efficiency and crop production: Patterns of regional variation in the United States, 1987–2012. *Science of The Total Environment*, 635: 498–511. https://doi.org/10.1016/j.scitotenv.2018.04.027

Tatlıdil, F.F., Dellal, I. & Bayramoğlu, Z. 2013. Food losses and waste in Turkey, Country Report, Rome, FAO. https://www.fao.org/publications/card/en/c/274dfc13-7c02-428c-9ae7-e81724dfbfcc

Trase. 2020. How Trase assesses 'commodity deforestation' and 'commodity deforestation risk'. https://policycommons.net/artifacts/2485181/how-trase-assesses-commodity-deforestation-and-commodity-deforestation-risk/3507609/.

Tubiello, F.N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., Obli-Laryea, G. *et al.* 2021. Greenhouse gas emissions from food systems: building the evidence base. *Environmental Research Letters*, 16(6): 065007. https://doi.org/10.1088/1748-9326/ac018e

UNFCCC. 2023. Decision 6/CP.27, Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex 1 to the Convention, Report of the Conference of the Parties on its twenty-seventh session. https://unfccc.int/sites/default/files/resource/cp2022_10a01_adv.pdf

United Nations. 2015. Paris agreement In: Report of the Conference of the Parties to the UNFCCC (21st Session, 2015). Paris. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations, Department of Economic and Social Affairs, Population Division (UNDESA). 2022. *World Population Prospects 2022, Data Sources.* UN DESA/POP/2022/DC/NO. 9. https://population.un.org/wpp/Publications/Files/WPP2022_Data_Sources.pdf

Uwizeye, A., Gerber, P.J., Groen, E.A., Dolman, M.A., Schulte, R.P.O. & De Boer, I.J.M. 2017. Selective improvement of global datasets for the computation of locally relevant environmental indicators: A method based on global sensitivity analysis. *Environmental Modelling & Software*, 96: 58–67. https://doi.org/10.1016/j.envsoft.2017.06.041

Uwizeye, A., Gerber, P.J., Opio, C.I., Tempio, G., Mottet, A., Makkar, H.P.S., Falcucci, A., Steinfeld, H. & De Boer, I.J.M. 2019. Nitrogen flows in global pork supply chains and potential improvement from feeding swill to pigs. *Resources, Conservation and Recycling*, 146: 168–179. https://doi.org/10.1016/j.resconrec.2019.03.032

Uwizeye, A., De Boer, I.J.M., Opio, C.I., Schulte, R.P.O., Falcucci, A., Tempio, G., Teillard, F. *et al.* 2020. Nitrogen emissions along global livestock supply chains. *Nature Food*, 1(7): 437–446. https://doi.org/10.1038/s43016-020-0113-y

Van Der Heyden, C., Demeyer, P. & Volcke, E.I.P. 2015. Mitigating emissions from pig and poultry housing facilities through air scrubbers and biofilters: State-of-the-art and perspectives. *Biosystems Engineering*, 134: 74–93. https://doi.org/10.1016/j.biosystemseng.2015.04.002

Van Eenennaam, A.L. & Werth, S.J. 2021. Animal board invited review: Animal agriculture and alternative meats – learning from past science communication failures. *Animal*, 15(10): 100360. https://doi.org/10.1016/j.animal.2021.100360

Velarde, A., Fàbrega, E., Blanco-Penedo, I. & Dalmau, A. 2015. Animal welfare towards sustainability in pork meat production. *Meat Science*, 109: 13–17. https://doi.org/10.1016/j.meatsci.2015.05.010

Vordermeier, M., Ameni, G., Berg, S., Bishop, R., Robertson, B.D., Aseffa, A., Hewinson, R.G. & Young, D.B. 2012. The influence of cattle breed on susceptibility to bovine tuberculosis in Ethiopia. *Comparative Immunology, Microbiology and Infectious Diseases*, 35(3): 227–232. https://doi.org/10.1016/j.cimid.2012.01.003

Walling, E. & Vaneeckhaute, C. 2020. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. *Journal of Environmental Management*, 276: 111211. https://doi.org/10.1016/j.jenvman.2020.111211

Wilkes, A. & van Dijk, S. 2018. Tier 2 inventory approaches in the livestock sector: A collection of agricultural greenhouse gas inventory practices. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). https://hdl.handle.net/10568/109610

Wilkinson, J.M. & Lee, M.R.F. 2018. Review: Use of human-edible animal feeds by ruminant livestock. *Animal*, 12(8): 1735–1743. https://doi.org/10.1017/S175173111700218X

Wood, P., Thorrez, L., Hocquette, J.-F., Troy, D. & Gagaoua, M. 2023. "Cellular agriculture": current gaps between facts and claims regarding "cell-based meat". *Animal Frontiers*, 13(2): 68–74. https://doi.org/10.1093/af/vfac092

World Bank. 2009. *Minding the stock: bringing public policy to bear on livestock sector development*. Washington, D.C. World Bank Group. http://documents.worldbank.org/curated/en/573701468329065723/Minding-the-stock-bringing-public-policy-to-bear-on-livestock-sector-development

World Bank. 2021a. Moving towards sustainability: The livestock sector and the world bank. In: *World Bank*. https://www.worldbank.org/en/topic/agriculture/brief/moving-towards-sustainability-the-livestock-sector-and-the-world-bank

World Bank. 2021b. Opportunities for climate finance in the livestock sector: Removing obstacles and realizing potential. World Bank, Washington, DC. http://hdl.handle.net/10986/35495

World Bank. 2021c. Soil organic carbon MRV sourcebook for agricultural landscapes. World Bank, Washington, DC. http://hdl.handle.net/10986/35923

World Bank. 2021d. Investing in sustainable livestock (ISL) guide. In: World Bank Group. [Cited 3 November 2023]. https://www.sustainablelivestockguide.org/

Appendix: Description of GLEAM

Overview

GLEAM adopts a Tier 2 methodology to estimate emissions from livestock systems for a specified base year. The model follows a LCA approach, meaning that it includes emissions both on the farm and throughout the upstream and downstream phases of production. It focuses on six animal species: cattle, buffaloes, sheep, goats, pigs and chickens.

The system boundary is defined from the cradle (production of inputs) to the primary processing stage (see Figure 2). This approach differentiates key stages within the livestock agrifood systems, such as LUC, feed production (including fertilizer production and use), processing and transport, animal production, manure management, and the processing and transportation of the products. The model captures specific emissions at each step, offering a comprehensive and nuanced picture of the livestock systems and how the sector draws on the natural resources.

TABLE A.1. Overview of GHG emission sources in livestock production systems considered in GLEAM 3

Source of emissions		Description
Feed CO_2	Field operations	CO_2 emissions arising from the use of fossil fuels during field operations
	Fertilizer production	CO_2 emissions from the manufacture and transport of synthetic nitrogenous, phosphate and potash fertilizers
	Pesticide production	CO_2 emissions from the manufacture, transport and application of pesticides
	Processing and transportation	CO_2 generated during the processing of crops for feed and transportation by land and sea
	Blending and pelleting	CO_2 arising from the blending and preparation of concentrate feed
LUC CO_2 (feed)	Soybean cultivation	CO_2 emission due to LUC associated with the expansion of soybean
	Palm kernel plantation	CO_2 emission due to LUC associated with the expansion of palm oil plantations
Pasture expansion CO_2 (feed)		CO_2 emission due to LUC associated with the expansion of pastures
Feed N_2O	Applied and deposited manure	Direct and indirect N2O emissions from manure deposited on the fields and used as organic fertilizer
	Synthetic fertilizer and crop residues	Direct and indirect N2O emissions from applied synthetic nitrogenous fertilizer and crop residues decomposition
Feed CH_4	Rice production	CH_4 emissions arising from the cultivation of rice used as feed
Energy CO_2	Direct energy use on-farm	CO_2 emissions arising from energy use on-farm for ventilation, heating, etc.
	Embedded energy use	CO_2 emissions arising from energy use during the construction of farm buildings and equipment
Post-farm CO_2		CO_2 emissions from the processing and transportation of livestock products to the primary processing but excluding retail and consumers
Enteric fermentation CH_4		CH_4 emissions caused by enteric fermentation
Manure management CH_4		CH_4 emissions arising from manure storage and management
Manure management N_2O		N_2O emissions arising from manure storage and management

Note: CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide, LUC = land-use change.

It also uses detailed geographic information on the agroecological conditions, livestock distributions and production systems, as well as on the feed-crop and fodder production, which allows spatial variability to be accounted for in an analysis of the livestock GHG emissions at different scales. GLEAM was developed with the objective of providing a global inventory of livestock emissions but has since been adapted in partnership with countries

to generate the national inventories and analyse different mitigation scenarios to help countries chart the pathways towards low-emission livestock systems.

Earlier versions of the GLEAM data and methodology are reported in various documentation (FAO, 2010b; Opio *et al.*, 2013; MacLeod *et al.*, 2013; Gerber *et al.*, 2013; MacLeod *et al.*, 2018). This Appendix provides a summary of the key features of GLEAM 3. More detailed information on the model can be found at GLEAM website: https://www.fao.org/gleam/en/. Table A.1 provides a summary of the sources of emissions and the respective gases considered in GLEAM 3.

With the update to version 3, there was a change in the values of the GWP over a 100-year period (GWP100), following the guidelines in the most recent (IPCC) AR6 (IPCC, 2022). This update significantly changes the relative values of the non-CO_2 gases when expressed in CO_2eq. GWP100 values associated with different IPCC reports are summarized in Table A.2.

TABLE A.2. GWP100 values used in different GLEAM versions and respective IPCC Assessment Reports

	Base year	IPCC AR version	Carbon dioxide (CO_2)	Methane (CH_4)	Nitrous oxide (N_2O)
GLEAM 1	2005	AR4 (2007)	1	25	298
GLEAM 2	2010	AR5 (2015)	1	34	298
GLEAM 3	2015	AR6 (2022)	1	27*	273

Note: *CH4 from the non-fossil sources, GWP100: global warming potential over a 100-year period, ARs: Assessment Reports, AR5: carbon-climate feedbacks included, CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide.

A Tier 2 approach is used in GLEAM 3, which is recommended in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019a). For the direct and indirect emissions of N_2O, the model uses European Environmental Agency guidelines (EEA, 2016) and Uwizeye *et al.* (2020). These methods are aligned with the guidelines produced by LEAP Partnership (2015).

The GLEAM model currently simulates emissions globally, at a spatial (pixel) resolution of 5 arc minutes (about 10 kilometres at the equator). It starts with modelled livestock numbers in each pixel, sourced from the GLW (Gilbert *et al.*, 2018) and updated to the base year 2015 (version 4). Livestock data are categorized by production system, with ruminant livestock assigned to systems based on land cover (mixed crop-livestock or livestock only) and climate conditions (arid and semi-arid, humid and sub-humid, or temperate and tropical highlands), following an updated methodology described in Robinson *et al.* (2018). Data on animals raised in feedlots are also included where available. Monogastric species (pigs and chickens) are assigned to systems based on the level of intensification, using the methodology described in Gilbert *et al.* (2015) with updated data. Within each system, herds and flocks are further disaggregated into cohorts, for example, ruminant herds are broken down into adult females, adult males, replacement females, replacement males, and male and female fattening animals (or surplus animals).

Feed intake

In GLEAM, for each species, production system and cohort, the DMI is calculated based on various energy requirements for maintenance, activity, growth, gestation, milk production (for ruminants only), drought power (for large ruminants) and fibre production (for small ruminants). For ruminants, the energy requirements of each animal are calculated following the IPCC (2019a) Tier 2 approach. For pigs and chickens, energy calculations are based on the methods described in National Research Council (1994, 1998) and Sakomura (2004).

The spatial distribution of feed rations by species, production system and cohort is simulated through a multi-step process. The share and composition of different feed categories, including forages, crop residues, by-products and concentrate feeds, in the ration of each animal category are initially defined at the national or regional level through literature review and expert opinion. The composition of locally sourced feed categories, such as forages, crop residues and secondgrade crops, is estimated based on local availability. The availability is determined from the DM yields of different feed products, which are calculated using spatially explicit crop data provided by Frolking *et al*. (2020). Dry matter productivity for grasslands is taken from Copernicus Global Land Service (2021).

Nutritional values of feed are taken from several sources including Feedipedia[22] and the National Research Council (1994, 1998) guidelines for pigs and poultry. These data are used to calculate average values of digestibility, gross and metabolizable energy, and nitrogen content are calculated for each species, production system and feed item.

Enteric fermentation

Enteric CH_4 emissions from ruminants and pigs are calculated using equations from IPCC (2019a) that relate the amount of feed gross energy consumed by the animal to the proportion of the feed converted to CH_4, taken from (IPCC, 2019a) and (FAO, 2010b).

Manure management

Manure management and application are the key components of crop and livestock production systems. Manure contributes to soil fertility and the nutrient and energy cycles. It also contributes to the emissions of N_2O and CH_4. GLEAM estimates GHG emissions from manure storage and management. CH_4 emissions from manure management are calculated following the IPCC (2019a) Tier 2 methodology. Manure management emission factors vary by climatic zone, as determined using a map provided in IPCC (2019a). N_2O emissions are based on methodology presented in EEA (2016) and Uwizeye *et al*. (2020), that maintains a N mass balance along livestock supply chains. The spatial distribution of manure managed in each system is based on official statistics, such as National Inventory Reports of Annex I countries submitted to UNFCCC, literature reviews and expert opinion.

Emissions associated with feed production, processing and transport

Emissions associated with feed production include CO_2 emissions from the production of synthetic fertilizers and pesticides, energy consumption for tillage, crop management, processing and transport. For some crops, emissions include transportation and energy used in blending and pelleting. There are also emissions associated with LUC to produce specific feed items.

Data on the type and amount of energy used for field operations during the crop cultivation, for feed processing and for the associated emissions were taken from the literature review, existing databases such as Livestock Environmental Assessment and Performance Partnership (LEAP, 2015) and expert knowledge. N_2O emissions related to feed

[22] https://www.feedipedia.org/

production arise from fertilizer application, manure application and deposition, and N from the crop residues. These emissions may be direct or indirect, such as those from volatilization and leaching of N compounds. Emissions of N_2O from feed production are estimated based on the methodologies presented in EEA (2016) and Uwizeye *et al*. (2020).

Crop-specific data on N synthetic fertilizer applications at the national level were obtained by combining the data from Swaney *et al*. (2018), the International Fertilizer Association (Heffer, Gruère and Roberts, 2017), Navarro *et al*. (2016), Lassaletta *et al*. (2014), Leip *et al*. (2011) and FAOSTAT. Synthetic phosphorus and potassium fertilizer, as well as pesticides application rates, were defined at a national level, based on the LEAP database (LEAP, 2015).

Nitrogen from the manure application rates on crops used as feed and deposition on pastures were estimated by the model. To this end, the N losses due to emissions during manure management and storage, prior to the application, are removed from the total N excreted by animals to estimate the amount of N available for the recycling in agriculture and its associated N_2O emissions. For rice cultivation, additional emissions occur in the form of CH_4. These emissions vary depending on the water regime during and prior to cultivation, and the nature of the organic amendments. The average CH_4 flux per hectare of rice was calculated for each country using the IPCC (2019a) Tier 1 methodology as described in Volume 4, Chapter 5.5.

Most emission factors used to estimate diverse emissions from feed production are expressed per unit of harvested area of crop. To calculate emission intensity per kg of feed material consumed by animals, these emissions are divided by the DM yield of each respective crop, provided by Frolking *et al*. (2020). To account for the part of the crop that is consumed by animals, emissions are also allocated between the crop and its co-products, such as crop residues and agroindustrial by-products, based on a combination of weight and economic value.

All emissions related to feed are traced from the place of production to the place of on-farm consumption using bilateral trade data from FAOSTAT and a tracing algorithm (Kastner, Kastner and Nonhebel, 2011). These data were also combined with the sea distance dataset from Bertoli, Goujon and Santoni (2016), to estimate CO_2 emissions arising from transport of feed.

Finally, emission intensities per kilogram of each feed material are combined with estimated feed ration composition and feed intake requirements to calculate the total emissions associated with the feed consumption by animals.

Emissions related to deforestation and the expansion of cropland and pastures for livestock production are estimated using a modified version of data by Pendrill *et al*. (2020) and Trase (2020). For cropland expansion, only soy and oil palm crops are considered, as these are major feed crops that are related to the expansion of the cropland.

Direct on-farm energy use

Direct on-farm energy use includes CO_2 emissions arising from energy usage on the farm required for livestock production including, for example, lighting, ventilation, washing and milking. Emission factors for direct energy use are based on a literature review, expert opinion and existing databases.

Embedded energy use

Following GLEAM's LCA, emissions that are related to the construction of buildings and farm equipment required to produce animal products are included. The distribution of housing types and equipment differs by production system, agroecological zone and the income group of the country. CO_2 emissions related to each type were estimated using embodied energy use values from Frischknecht *et al*. (2005).

Post-farm emissions

Emissions from post-farm activities include transportation to a processing centre, cooling, processing and packaging. The emission factors to estimate emissions related to the processing and packaging of animal products are taken from a meta-analysis by Poore and Nemecek (2018).

Allocation of emissions to animal products

Emissions are allocated along the production chain to different animal products and services. The first step in this process is the allocation of emissions between edible (meat, milk and eggs) and nonedible products (draught power, fibres and manure burned as fuel), which is based on the energy requirements by animals, with the exception of manure burned as fuel, of which the emissions are allocated based on the manure N mass balance. Finally, the emissions allocated to the edible products are assigned to meat, milk and eggs based on their protein content.

For more detailed information on the key datasets used in various stages of the modelling process, refer to Table A.3 which provides an overview along with associated references.

TABLE A.3. Overview of key data sources used in GLEAM 3

Name	Description	Base year	Reference	Remarks
GLW	A spatial explicit global model of livestock species distribution	2015	Updated version (v4) from Gilbert *et al.* (2018)	
Global agroecological zones	Modelled spatial distribution of the major crops and their yields for rainfed and irrigated systems	2015	Frolking *et al.* (2020)	
FAOSTAT bilateral trade	Trade data for individual commodities between individual countries	2015	FAOSTAT and tracing algorithm from Kastner, Kastner and Nonhebel (2011)	
Ruminant production systems	Ruminant production systems as determined by climate and land-cover	2015	Updated version from Robinson *et al.* (2018)	
Chicken and pig production systems	Classified as extensive (for home-consumption) and intensive (market-oriented); pigs also include an intermediate system	2015	Updated from Gilbert *et al.* (2015)	
Embedded energy use	LCA datasets for building materials and equipment	2000	Frischknecht *et al.* (2005)	
LUC	Estimates of tropical deforestation embodied in the production and trade of the agricultural commodities by country and year, for the period 2005–2017	2015	Pendrill *et al.* (2020)	Only soy, oil palm and pasture expansion are included
LCA	Trade flows to identify sourcing regions, profile supply chain risks, and assess opportunities for sustainable production	2015	Trase (2020)	Used for Brazilian soy and pasture expansion for beef production
Climate zone map	Climate regions classification (corrected version)	1985–2015	IPCC (2019)	
DM productivity	Represents the dry biomass increase of the vegetation, and used as a proxy for the grassland productivity	2015	Copernicus Global Land Service (2021)	

Note: GLW= Gridded Livestock of the World, LUC = land-use change, LCA = life cycle assessment, DM = dry matter.

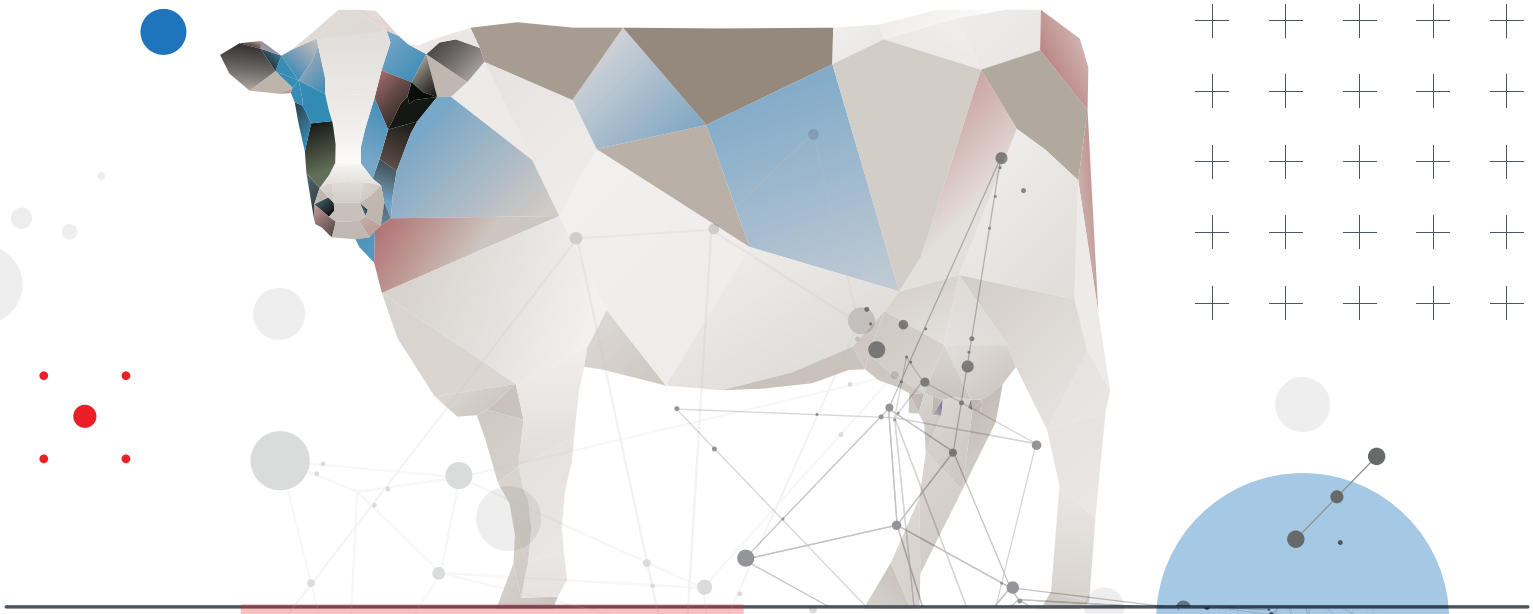

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Beef Cattle Spacing Requirements

Overcrowding can have negative effects on animal performance and efficiency. To maximize growth performance, producers should ensure the pen and bunk space are adequate.

Updated: March 7, 2023



Cattle with correct bunk spacing. Image courtesy of Pedro Carvalho, Penn State

Introduction

Have you ever wondered if you could fit a few more head of feedlot cattle in your barn? If so, there are some things that should be considered first. Overcrowding can have negative effects on animal performance and efficiency. Cattle function in a social order. More dominant animals will get to eat first, for example. If cattle are overcrowded, this hierarchy may impact growth performance, because the lower the animal is in the social order, the less likely that animal will get access to the bunk and grow as well as the more dominant animals. To maximize growth performance, producers should ensure the pen and bunk space are adequate.

The requirements for animal housing, both bunk and pen size, are published for all animals in the FASS Guidelines for Animal Care and Use (FASS) and are summarized below for growing beef cattle.

Space Requirements

Space requirements for calves and finishing cattle change depending on the type of housing, weight of cattle, and feed management (Table 1). Often times, when designing a lot/barn or addition, it is advisable to use the maximum space within a given range. Calculating on the higher side allows for room to grow the business, either by number or size of individual cattle, without compromising performance.

Floor or ground area and feeder space recommendations for beef cattle		
	Calves, 400 to 800 lb	Finishing cattle, 800 to 1,200lb
Area or space	ft^2	ft^2
Barns (unheated cold housing)		
Open front with dirt lot	15 to 20	20 to 25
Enclosed, bedded pack	20 to 25	30 to 35
Enclosed, slotted floor	12 to 18	18 to 25
Feeder space when fed:		
	in	in
Once daily	18 to 22	22 to 26
Twice daily	9 to 11	11 to 13
Free choice grain	3 to 4	4 to 6
Self-fed roughage	9 to 10	10 to 11

Example

Review this example (Figure 1) to aid understanding: Imagine you want to construct an enclosed, unheated barn with a bedded pack to house 500 finishing cattle. Cattle will have free choice access to grain on one designated side of the barn. The space required for an enclosed bedded pack barn for finishing cattle is 35 ft^2/head. In total, the barn would need to be 17,500 ft^2 (35 ft^2/hd x 500 hd = 17,500 ft^2). The bunk space requirement for finishing cattle with free choice grain access or a grain-based finishing TMR is 6 in. In total, the bunk space would need to be 3,000 in or 250 ft (6 in/hd x 500 hd = 3,000 in). Knowing the amount of housing and bunk space required, a barn layout could be designed. In this case, because animals are only fed on one side of the barn, the length of the barn needs to be at least 250 ft. The other side should be 70 ft (17,500 ft^2 / 250 ft = 70 ft).

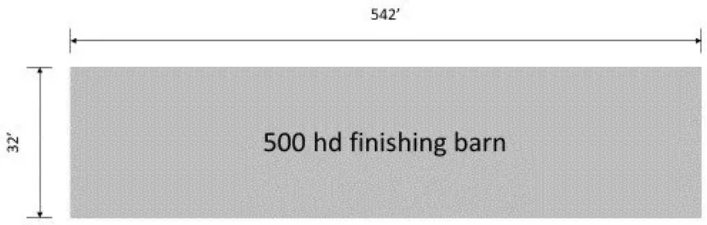

These spacing considerations should be afforded even to refurbished barns used for cattle. In many cases, with older building in particular, bunk space is the first limitation to the number of animals that can housed in a facility. As stated earlier, shortchanging the bunk space allotment will potentially result in reduced growth performance of cattle and could even result in injuries if competition is extreme. Thus, if placing cattle in existing facilities, check these space requirements carefully.

Conclusion

To maximize growth performance, make sure there is adequate pen and bunk space for growing and finishing cattle. If space per animal is limited, then consider decreasing animal numbers or making barn renovations to increase space. Limited pen or bunk space will reduce the feed intake of less dominant animals compared to more dominant animals, because cattle function in a social order. Thus, overcrowding feedlots has negative effects on animal performance.

References

FASS. 2010. Guide for the Care and Use of Agricultural Animals in Research and Teaching. FASS Champaign, IL.

Ingvartsen, K. L., and H. R. Andersen. 1993. Space Allowance and Type of Housing for Growing Cattle: A Review of Performance and Possible Relation to Neuroendocrine Function. Acta Agriculturae Scandinavica, Section A — Animal Science 43(2):65-80. doi: 10.1080/09064709309410147

Stricklin, W. R., and C. C. Kautz-Scanavy. 1984. The role of behavior in cattle production: A review of research (https://doi.org/10.1016/0304-3762(84)90043-9). Applied Animal Ethology 11(4):359-390.

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Fugitive methane emissions from an agricultural biodigester

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ABSTRACT

The use of agricultural biodigesters provides a strategy for reducing greenhouse gas (GHG) emissions while generating energy. The GHG reduction associated with a biodigester will be affected by fugitive emissions from the facility. The objective of this study was to measure fugitive methane (CH_4) emissions from a Canadian biodigester. The facility uses anaerobic digestion to produce biogas from cattle manure and other organic feedstock, which is burnt to generate electricity (1 MW capacity) and heat. An inverse dispersion technique was used to calculate emissions. Fugitive emissions were related to the operating state of the biodigester, and over four seasonal campaigns the emission rate averaged 3.2, 0.8, and 26.6 kg CH_4 hr^{-1} for normal operations, maintenance, and flaring periods, respectively. During normal operations the average fugitive emission rate corresponded to 3.1% of the CH_4 gas production rate.

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1. Introduction

Agricultural biodigesters are seen as a viable means to reduce greenhouse gas (GHG) emissions while generating clean energy for on-farm consumption and to sell to power companies. Through anaerobic digestion, biodigesters reduce organic compounds in waste material to methane (CH_4) and carbon dioxide (CO_2). The subsequent capture and combustion of CH_4 can result in a reduction in GHG emissions compared to traditional waste management.

The net GHG reduction associated with a biodigester will be affected by fugitive (unintended) CH_4 emissions from the facility. Accounting for these emissions is an important part of the calculation of carbon credits for biodigestion offset protocols, such as the Organic Waste Digestion Project Protocol [1] in the United States and the Quantification protocol for the anaerobic decomposition of agricultural materials [2] in Alberta, Canada. However, measurements of the magnitude of fugitive emissions from biodigester facilities are lacking.

A draft report to U.S. Environmental Protection Agency on anaerobic digestion systems [3] recommended adoption of the 2008 California Climate Action Registry default value, where the fugitive emission rate is taken as 15% of the total CH_4 production rate, unless a lower value can be justified by supporting documentation. Methodologies developed under the Clean Development Mechanism [4] assume a fugitive emission rate of 15% for anaerobic digesters when calculating GHG reductions. The Intergovernmental Panel on Climate Change [5] assumes a default value of 10% for digesters. In a report on offset methodologies [6] it was recommended that one assume 0–5% fugitive emissions from covered anaerobic lagoons.

The objective of this project was to measure fugitive CH_4 emissions from a biodigester facility. The first portion of the

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paper describes the application of an inverse dispersion technique to measure emissions. We then present the results of four seasonal measurement campaigns at a modern biodigester in Alberta, Canada. This includes a brief discussion of how our measurements could affect GHG offset calculations.

2. IMUS Biodigester

The Integrated Manure Utilization System (IMUS) biodigester was developed by Highmark Renewables Inc. and the Alberta Research Council. Located near Vegreville, Alberta, it is one of the largest and most technologically advanced of its kind, and may become the model for additional biodigesters in Canada. It operates adjacent to a beef cattle feedlot (capacity of 36,000 head) and uses anaerobic digestion to produce biogas from the cattle manure, as well as other organic feedstock delivered to the site. The biogas is made up of about 55% CH_4, and is used to generate electricity and heat.

The electrical generating capacity of the facility is approximately 1 MW (future expansion will boost capacity to 5 MW). It consumes about 100 tonnes of manure daily, or about 20% of the feedlot output. The main steps in the IMUS operation are:

1. Dry manure is collected from feedlot pens and transported to a storage pad at the facility.
2. Manure (and other organic material) is loaded from the storage pad to a feedstock "hopper" by bucket loading tractor. Here the feedstock is mixed with warm water and recycled effluent (heated by waste heat) and pumped to one of two digester tanks.
3. Anaerobic digestion takes place in two insulated concrete tanks: 15 m in diameter and 11 m high, capped with a heavy rubberized cover. Internal temperature is maintained at

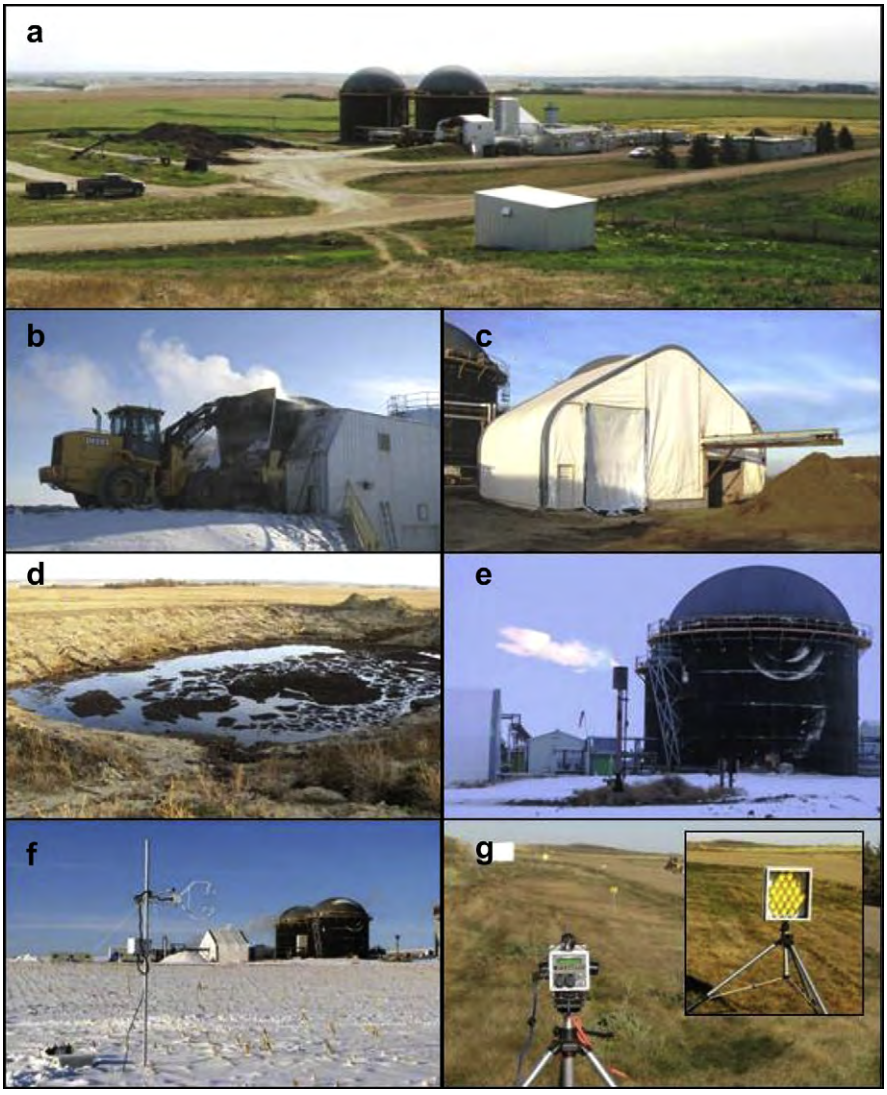

Fig. 1 – Photographs from the IMUS facility: a) distant view showing black digester tanks; b) feedstock hopper where feedstock enters the facility; c) fertilizer tent where solids are separated from the digestate; d) runoff pond; e) gas flare; f) sonic anemometer east of the facility; and g) methane laser and reflector.

55 °C to promote bacterial growth. Approximately 5% new manure is added to the tanks each day, and 5% of the digestate (slurry left after digestion) is removed.

4. Biogas is collected under the rubber cover of the digester tanks and is treated to reduce moisture and hydrogen sulfide before the gas is fed to the generator.
5. Digestate leaving the tanks flows through a separation process where solids are removed. The liquid is pumped to a lagoon at the feedlot (which also collects feedlot runoff). The lagoon water is re-used at the hopper stage, and to irrigate nearby fields. Separated solids are stockpiled and sold as fertilizer.

Photographs of the IMUS facility are shown in Fig. 1, and a map of the facility is given in Fig. 2.

3. Emission measurement technique

Measuring fugitive gas emissions from a biodigester facility is a challenge. There are many possible emission sites, such as flares, leaky pipes, ponds, open loading hoppers, etc. A measurement survey of all of these potential sites would be a time consuming task. In this study we use an alternative "inverse-dispersion" technique for measuring the totality of emissions, which promises economy and simplicity.

The inverse dispersion technique is a micrometeorological method that uses a downwind concentration measurement C to deduce the gas emission rate Q. The relationship between C and Q depends on the size and shape of the emission source, wind conditions, and the C sensor location. In principle, the relationship can be quantified by an atmospheric dispersion model. The model predicts the ratio of the downwind concentration (above the background level) to the emission rate, $(C/Q)_{sim}$, so that

$$Q = \frac{(C - C_b)}{(C/Q)_{sim}} \quad (1)$$

where C_b is the background gas concentration. The advantage of the technique is the limited measurement requirements: only a single concentration sensor and basic wind information, with flexibility in the measurement location. The technique is well suited to situations where the wind can be described by simple statistical relationships (e.g., flat and homogeneous terrain), and where emission sources are spatially well defined [7].

The IMUS facility presents complications for an inverse dispersion calculation. Buildings and structures create wind

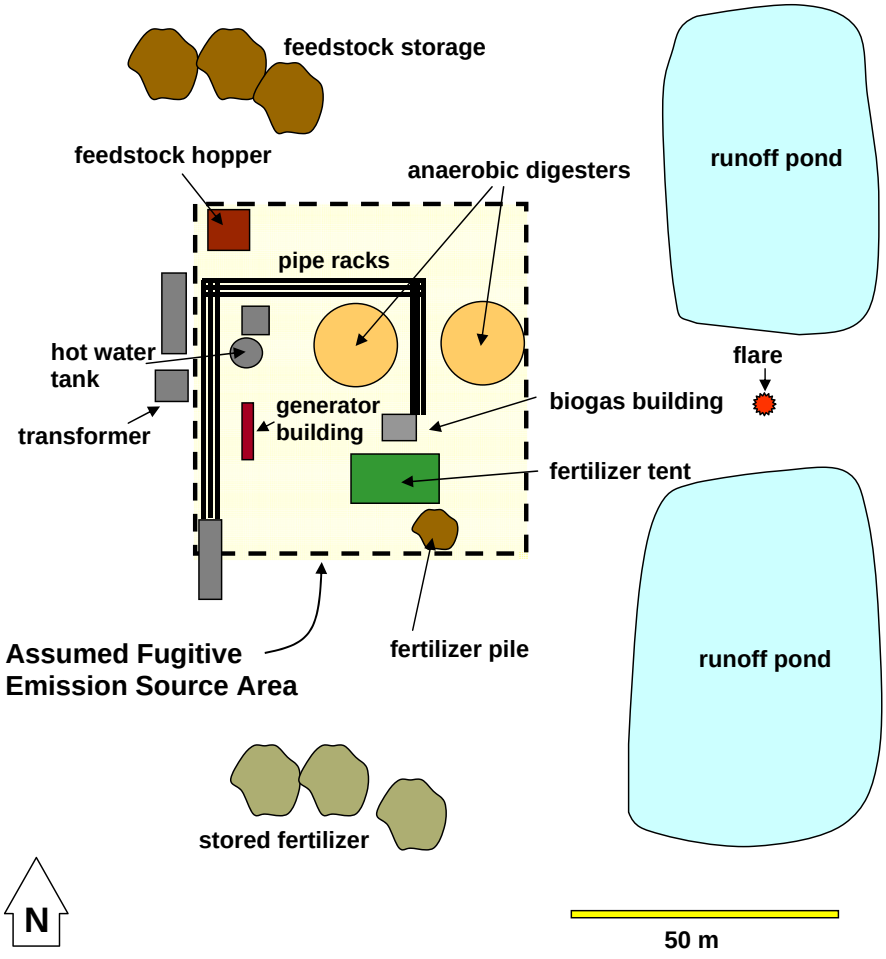

Fig. 2 – Map of the IMUS facility. The dashed square is the assumed source area for fugitive emissions (excluding the flare). The size of the runoff ponds, feedstock storage pile, and the fertilizer piles varied during the study.

complexity, and the actual location(s) of fugitive emissions is unknown. However, several studies have shown that if C is measured far enough downwind of the emission site there is insensitivity to these complications [8–10]. In these cases one can assume simplified wind conditions (i.e., an ambient wind measurement) and an imprecise designation of the source area when calculating $(C/Q)_{sim}$. How far downwind is sufficient? Flesch et al. [8] argue that one should be more than ten times the height of the largest wind obstacle h (in this study the digester tanks, $h = 11$ m) and roughly two times the maximum distance between potential sources x_s (in this study the distance between the feedstock hopper and the fertilizer pile exiting the separator tent, $x_s \approx 70$ m).

We use a backward Lagrangian stochastic (bLS) dispersion model [11] to calculate $(C/Q)_{sim}$ (this is described in more detail below). The "bLS technique" has been used to measure gas emissions from farms [12], fields [13], feedlots [14], ponds [15], and pastures [16]. Harper et al. [17] summarized several verification studies, conducted in a variety of settings, and concluded that with careful use the bLS technique has an expected accuracy of ± 10%.

3.1. Concentration and wind observations

Emissions were measured during autumn, winter, spring, and summer seasonal campaigns in 2008–2009, with each campaign lasting 6–7 days. Methane concentrations were measured with open-path lasers (GasFinder 2.0, Boreal Laser Inc., Edmonton, Canada; Spectra-1, PKL Lasers Inc., Edmonton, Canada). These sensors give the line-average concentration between the laser unit and a distant retroreflector (see picture in Fig. 1g).

Fig. 3 shows the laser lines used in winter and summer. Our main focus was on emissions within the facility boundary (identified in Fig. 2). The winter diagram in Fig. 3 illustrates the primary configuration, with laser lines positioned to give concentrations upwind and downwind of the facility. At any time the lines being used depended on the wind direction, and lines were switched manually as the wind direction changed. The primary lines were far enough from the facility to satisfy the placement criteria described above: more than 10 times the digester tank height, and about two hopper-to-fertilizer-pile distances downwind. At certain times we were concerned with emissions from secondary sources (e.g., the runoff ponds), and then we would temporarily position lasers downwind of these sources in order to estimate their emissions.

A 3-D sonic anemometer (CSAT-3, Campbell Sci., Logan, Utah) provided the wind measurements for our calculations, as described in Flesch et al. [7]. The anemometer was positioned to measure ambient winds in an open field approximately 200 m east of the facility (surface of corn stubble, snow, bare soil, or young corn plants depending on the season). The anemometer was placed at height $z_{son} = 1.85$ m (see Fig. 1f) to evaluate key wind parameters needed for the dispersion model: friction velocity u^*, Obukhov stability length L, surface roughness length z_0, and wind direction β.

3.2. bLS Application details

Field observations were prepared in time series of 15-min average CH_4 concentrations and wind parameters. The bLS software WindTrax (available at www.thunderbeach-scientific.com) was used to calculate $(C/Q)_{sim}$ for each 15-min period, with the total fugitive emission rate Q then given from Eqn (1). WindTrax is based on the bLS dispersion model described in Flesch et al. [7].

The IMUS facility is represented as a spatially uniform surface area source (Fig. 2) in the bLS calculation. The area includes what we believe are the potential emission sites. This treatment is undoubtedly wrong, as fugitive emissions will not occur uniformly over the designated ground area, and may occur at heights above ground. However, with C measured sufficiently far downwind of the facility, the (C/Q) ratio is assumed to be insensitive to these simplifications (as discussed in Flesch et al. [8]). We anticipate two complications. During gas flaring CH_4 can originate outside the designated source area. Flaring is not part of normal operations and

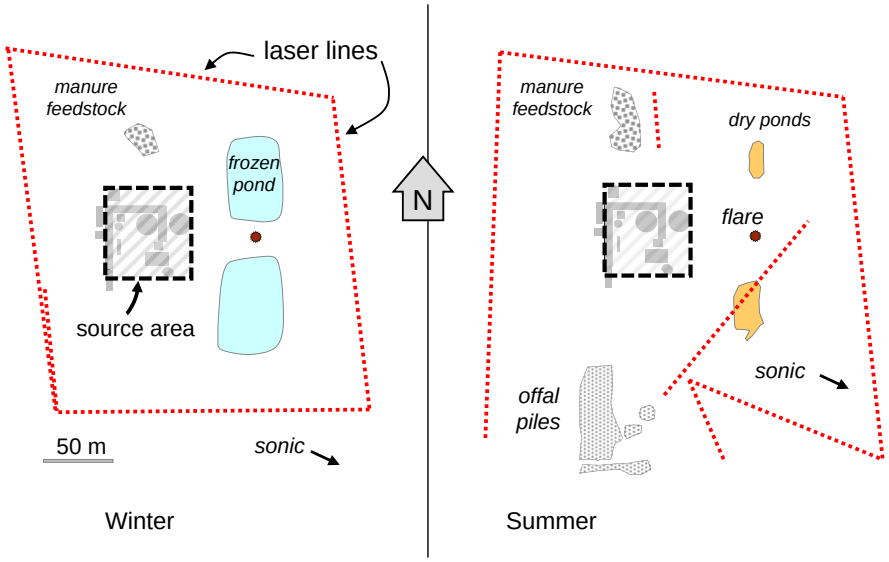

Fig. 3 – Location of the laser lines used in the winter and summer measurement campaigns.

when it occurs (known by the IMUS management) we redo our analysis and include the flare as an emission source, assuming the main facility continues to emit gas at the rate calculated during non-flaring periods. Another complication is the potential for CH_4 emissions from nearby secondary sources (e.g., runoff ponds, manure feedstock, etc.) to be falsely attributed to emissions from the IMUS facility. Our approach was to independently calculate these secondary emissions and include them in our dispersion analysis as known CH_4 sources, i.e., subtracting their calculated contribution to downwind concentration before calculating facility emissions.

Not all observation periods allow for good emission measurements. Dispersion models are known to be inaccurate in some conditions. Three criteria were used to remove periods of potential inaccuracy [8]:

1. low winds (when the friction velocity $u^* \leq 0.15$ m s^{-1});
2. strongly stable/unstable atmospheric stratification (the Obukhov length $|L| \leq 10$ m);
3. unrealistic wind parameters (surface roughness length $z_0 \geq 0.3$ m).

For some wind directions the fugitive emission plume only "glances" the path of the lasers, leading to uncertain Q estimates. To avoid these problems we:

4. removed periods when the laser measurement footprint (an output variable in WindTrax) does not cover 50% or more of the designated IMUS source area.

4. Results

4.1. Autumn measurements

Autumn measurements took place from 27 October to 1 November 2008. The average on-site air temperature during the period was 4.2 °C, with temperatures ranging from 16 °C to −2 °C. No significant precipitation was observed. In addition to periods of normal facility operations, there were periods of gas flaring and facility maintenance.

The potential for CH_4 emissions from secondary sources complicates our analysis. We judged the south runoff pond to be an emission source. This pond alone received runoff from the facility, and bubbles were observed rising to the surface at this pond. A laser line was positioned approximately 20 m north of the south pond and the bLS technique was used to estimate pond emissions during one afternoon having southerly winds. The calculated pond emission rate was 0.18 kg CH_4 hr^{-1} (this proves to be less than 5% of the emission rate from the IMUS facility). This pond was added as a known source in the analysis. We believe the north runoff pond was an insignificant CH_4 source. No measurable concentration rise was observed downwind of the feedstock or fertilizer piles, and we assume zero emissions from these areas.

Fig. 4 shows the time series of IMUS fugitive emissions during the autumn campaign (data gaps are due to winds not meeting the measurement criteria, or temporary laser misalignment). Measured emission rates range from near zero to just over 60 kg CH_4 hr^{-1}. There are two important features in the emission data. One is the high emission rates on 29 October. Management confirmed this was a day with biogas flaring, and some gas venting due to a malfunction of the flare igniter. The second feature is the low emission rates between 30 October and 1 November, a period of plant maintenance.

We define "normal" operations as periods without flaring or maintenance (i.e., the facility operates as intended). During normal operations the average autumn fugitive emission rate was 3.9 kg CH_4 hr^{-1} ($\sigma = 1.4$ kg hr^{-1}, $n = 109$ observations). There was substantial period-to-period variability in emissions, but no clear relationship with air temperature, windspeed, or time-of-day. During facility maintenance from 30 October to 1 November the emission rate fell to 0.5 kg CH_4 hr^{-1} ($\sigma = 0.9$ kg hr^{-1}, $n = 95$).

4.2. Winter measurements

Winter measurements were made from 11 to 16 December 2008. The average on-site air temperature during the period was −21 °C, with temperatures ranging from −1 °C to −38 °C. No significant precipitation was noticed during the observations. An advantage of the winter period was that secondary CH_4 sources were insignificant (e.g., the ponds were completely frozen and we observed no downwind concentration rise).

Fig. 4 shows winter emissions ranging from 0.9 to over 70 kg CH_4 hr^{-1}. The larger emission rates correspond to gas flaring. Roughly half of our good winter observations correspond to flaring periods. The emission rate averaged over all periods was 15.8 kg CH_4 hr^{-1} ($\sigma = 17.8$ kg hr^{-1}, $n = 158$ observations). This includes "normal" operations when emissions averaged 3.4 kg CH_4 hr^{-1} ($\sigma = 1.7$ kg hr^{-1}, $n = 91$), and flaring periods where emissions averaged 32.7 kg CH_4 hr^{-1} ($\sigma = 15.7$ kg hr^{-1}, $n = 67$). Period-to-period variability in emissions was poorly correlated with air temperature, windspeed, or time-of-day.

4.3. Spring measurements

Spring measurements were made from 11 to 17 May 2009. The average air temperature during the period was 7.2 °C, with temperatures ranging from −4 to 20 °C. There was light snow and rain during the period, but this did not impact our measurements. There were no reported flaring events, although there was a period of maintenance when the feedstock hopper was serviced.

We anticipated the south runoff pond would again be a CH_4 source, and on several days a laser was positioned to measure pond emissions. Over 33 observation periods the average pond emission rate was 0.24 kg CH_4 hr^{-1} (similar to the autumn value). A laser was also positioned downwind of the feedstock pile. From 40 observations the average feedstock emission rate was 0.20 kg CH_4 hr^{-1}. The pond and feedstock piles were included as known sources in our analysis.

Fig. 4 shows the emission time series during the spring. Emission rates range from near zero to almost 7 kg CH_4 hr^{-1}. The maximum spring emission rates are significantly smaller than the autumn or winter maxima due to the lack of flaring. Emissions were low during facility maintenance on 13–14 May. An interesting feature is the appearance of a strong diurnal emission cycle on 16 May (and suggested on 17 May),

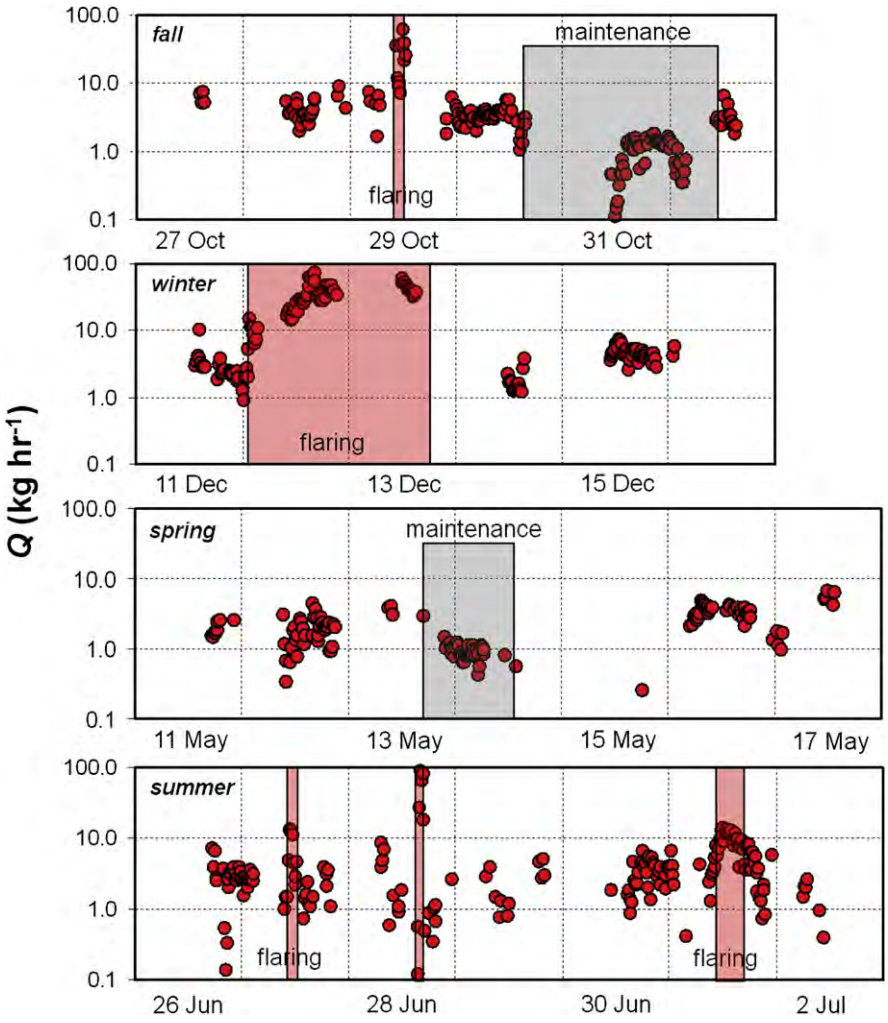

Fig. 4 – Timeseries of fugitive emissions (Q) from the biogas facility for the four seasonal campaigns. Periods of flaring and maintenance are identified. Each data point represents emissions over a 15-min observation period. Emission rates are plotted on a log scale (to de-emphasis the high rates during flaring).

with maximum emissions during the day and minimums at night. We hypothesize that this is due the daytime schedule of feedstock loading into the hopper. Why this is not seen on other days (or in other seasons) is unclear.

The overall fugitive emission rate during the spring was 2.1 kg CH_4 hr^{-1} ($\sigma = 1.3$ kg hr^{-1}, $n = 149$ observations), including "normal" operations where emissions averaged 2.5 kg CH_4 hr^{-1} ($\sigma = 1.3$ kg hr^{-1}, $n = 108$), and maintenance periods where emissions averaged 0.9 kg CH_4 hr^{-1} ($\sigma = 0.2$ kg hr^{-1}, $n = 41$). The lower spring emission rate during normal operations, compared with autumn or winter, may be related to the lower spring biogas production rate at the facility.

4.4. *Summer emissions*

Summer measurements took place from 26 June to 2 July 2009. The average on-site air temperature during the period was 14.4° C, with temperatures ranging from 3 to 21° C. The regional weather station reported 17 mm of rain during the period. There was flaring during our measurements, but no prolonged maintenance periods.

The runoff ponds were almost dry during summer, and we assume they were emission sources. A laser was positioned downwind of the feedstock pile, and from nine observations we estimate the feedstock emission rate was 0.4 kg CH_4 hr^{-1}. During the summer there was a large stockpile of "fresh" organic feedstock south of the facility (offal from a poultry rendering plant). For much of the measurement period a laser was positioned downwind of this stockpile (see Fig. 3), and from 72 observation periods we calculate an average emission rate of 5.2 kg CH_4 hr^{-1}. The feedstock and offal piles were included as known sources in the analysis.

Fig. 4 shows the time series of summer emissions. Values range from near zero to over 80 kg CH_4 hr^{-1}. The largest emissions occurred during three reported flaring events. The average summer emission rate was 4.7 kg CH_4 hr^{-1} ($\sigma = 9.3$ kg hr^{-1}, $n = 223$ observations), which includes "normal" operations where emissions average 2.9 kg CH_4 hr^{-1} ($\sigma = 2.1$ kg hr^{-1}, $n = 199$), and flaring/venting periods of 20.2 kg CH_4 hr^{-1} ($\sigma = 22.6$ kg hr^{-1}, $n = 24$). As in the previous seasons, the variability in emissions appeared uncorrelated with temperature, windspeed, or time-of-day.

5. Discussion

5.1. Emission summary

Table 1 summarizes the seasonal fugitive emission rates, categorized into periods of normal operations (when the IMUS facility operated as designed), flaring, and maintenance. Note the seasonal consistency in emissions during normal operations, with average rates ranging between 2.7 and 4.0 kg CH_4 hr^{-1}. There is also consistency during flaring and maintenance. Compared to normal operations, fugitive emissions increased by roughly a factor of 10 when flaring occurred, and fell to roughly 1/5 during maintenance.

Biodigester GHG offset protocols assume fugitive emissions are a percentage of the CH_4 production rate [4–6]. According to the IMUS management, the seasonal gas production at the facility was 131 (autumn and winter), 50 (spring), and 161 kg CH_4 hr^{-1} (summer). The low spring production was due to non-ideal feedstock material (protein content was too high for optimum decomposition). In Table 2 we express fugitive emissions as a percentage of these CH_4 production rates. During normal operations the emissions ranged from 1.7% in the summer to 5.2% in the spring. Over all four seasons the average is 3.1% of gas production. It is interesting that the seasonal range in absolute emissions (2.7–4.0 kg CH_4 hr^{-1}) is proportionally smaller than the range in percentage emissions (1.7–5.2% of gas production). This indicates that emissions were not highly dependent on the gas production rate, e.g., low spring production did not result in a proportional reduction in fugitive emissions.

Our observations show a clear pattern of reduced emissions when facility maintenance halted feedstock loading. During these periods gas was still produced and burnt to generate electricity, albeit at a slowly decreasing rate. For some initial short period of time, the only substantive difference between maintenance and normal periods was feedstock loading. Thus the drop in maintenance-period emissions is evidence that the loading hopper was the main source of fugitive CH_4 emissions. This is not surprising. The hopper is where feedstock is handled and mixed with warm water, and this process is open to the atmosphere (see Fig. 1). Further evidence for the hopper as the dominant source was the observed reduction in summer emissions. Prior to the summer the hopper was modified to create a negative pressure environment in the hopper interior (with air pulled into the biodigester). This should reduce the "escape" of gas to the atmosphere. The fact that we indeed saw lower summer emissions – lower than autumn or winter in absolute terms, and lower than all seasons in terms of gas production rates – is evidence that the hopper was the main source of fugitive emissions, and that hopper modifications were effective.

5.2. Implications for carbon credit calculations

Common biodigester GHG protocols assume fugitive emissions rates are 5–15% of the total CH_4 gas production rate [4–6]. We found that during normal operations the fugitive emissions were only 3.1% of the gas production rate. The choice of a 15% rate of emissions, as opposed to the observed 3.1%, would have a profound impact on the calculation of carbon credits for the IMUS biodigester (t CO_2e, tonnes of carbon dioxide equivalents). For a CH_4 production rate of 1030 t y^{-1} (118 kg hr^{-1}), a 15% rate of fugitive emissions would result in calculated CH_4 losses of 155 t CH_4 y^{-1}, or 3250 t CO_2e y^{-1} assuming a 100-year global warming potential for CH_4 of 21. Compared to the measured fugitive emission rate of 3.1%, this represents an overestimation of 2580 t CO_2e, and a potential financial loss of $30,960 to $64,500 per year, assuming the introductory floor and ceiling carbon prices proposed in the 'American Power Act' of $12 and $25 per t CO_2e. The financial implications of this calculation become even greater as this facility expands and increases electrical generating capacity from 1 to 5 MW.

Our measurements suggest that modifications to the feedstock hopper may have resulted in even lower fugitive emission rates. Our summer measurements, made after hopper modifications, found fugitive emissions during normal operations had dropped to 1.7% of gas production. However, because the fugitive emission rate depended dramatically on the operating state of the biodigester, the actual emission rate over a prolonged period would depend on the frequency of flaring and maintenance.

5.3. Flare efficiency

Periods of gas flaring led to large increases in fugitive emissions. Flaring occurs when gas cannot be used for electrical generation (e.g., due to generator servicing, H_2S scrubber malfunction, etc.). With limited storage capacity, the buildup of unused gas must be released and burnt in the flare. Flare efficiency (η) is a measure of the efficiency of converting CH_4 in the vented gas stream to CO_2 during burning. This can be calculated from the CH_4 content of the vented biogas stream and the CH_4 content of the flare exhaust:

Table 1 – Average fugitive emission rates (kg CH_4 hr^{-1}) from the IMUS biogas facility for the four seasonal measurement campaigns. The standard deviation of the emission rates is given in parenthesis, along with the number of 15-min observation periods (n).

Operating State	Autumn	Winter	Spring	Summer	Average
Normal	3.8 (1.4) $n = 83$	3.5 (1.7) $n = 86$	2.6 (1.3) $n = 99$	2.8 (2.1) $n = 176$	3.2
Flaring/Venting	26.6 (16.8) $n = 11$	32.7 (15.7) $n = 67$	–	20.4 (22.5) $n = 24$	26.6
Maintenance	0.7 (0.7) $n = 74$	–	0.9 (0.2) $n = 37$	–	0.8
All periods	*3.8 (7.0) $n = 197$*	*16.3 (17.9) $n = 153$*	*2.2 (1.4) $n = 136$*	*4.9 (9.8) $n = 200$*	

Table 2 – Average seasonal fugitive emission rates from the IMUS biodigester as a percentage of seasonal biogas production rates. Emissions are categorized into periods of normal operations, flaring/venting, and maintenance.

		Autumn	Winter	Spring	Summer	Average
IMUS Gas Production kg CH_4 hr^{-1}		131	131	50	161	118
Fugitive emissions (% of gas production)	Normal	2.9%	2.7%	5.2%	1.7%	3.1%
	Flaring/Venting	20%	25%	–	13%	19%
	Maintenance	0.5%	–	1.8%	–	1.2%

$$\eta = 1 - \frac{\text{CH}_4 \text{ flowrate in exhaust}}{\text{CH}_4 \text{ flowrate in vented biogas}} \quad (2)$$

For periods of flaring we estimate efficiency using the measured CH_4 flare emission rates (Q_{flare}) and the seasonal CH_4 production rates (GP_{season}) for the facility:

$$\eta = 1 - \frac{Q_{flare}}{GP_{season}} \quad (3)$$

This assumes the CH_4 flow rate in the vented gas stream equals GP_{season}. In our analysis we assume that flared CH_4 is dispersed as a non-buoyant tracer from the stack (height $z = 5$ m). However, if partially burnt CH_4 is warm it can rise upon emission, and lead to errors in our Q_{flare} calculation. However, Johnson et al. [18] showed that "fuel stripping" occurs in flares, with unburnt fuel ejected on the underside of the plume, countering the effect of a rising plume. In view of these complications, one must consider our estimates of η to have large uncertainty.

For all of our observations (all seasons) η ranges from 0.48 to 0.99, with an average of 0.81 ($\sigma = 0.14$, $n = 99$). This is a lower figure than found in several studies (e.g., [19]). RIRDC [20] reports that flaring efficiencies for unshrouded biogas flames (such as used here) should be in the range of $\eta = 0.90$ to 0.95. However, a field study of flares [21] found η as low as 0.62. And for diluted biogas (55% CH_4), low flare exit velocities, and high wind conditions, the data of Johnson and Kostiuk [22] suggest η could fall well below 0.90.

5.4. *Secondary CH_4 sources*

The objective of this study was to determine fugitive emissions from the biodigester, which we defined as the engineered facility that includes the feedstock hopper, the biodigester, effluent separator, fertilizer output tent, generator, flare, and the piping that ties these components together. This is the area within the 60 × 60 m square identified in Fig. 2 (and including the flare). We were not directly interested in CH_4 sources outside this area, which included the feedstock piles, the runoff ponds, and the offal storage area. However, we did estimate emissions from these "secondary" sources in order to more accurately calculate emissions from the IMUS facility. These secondary emission rates may also be of interest when considering the total GHG implications of a biodigester system.

The secondary emissions were generally small compared to emissions from the IMUS facility (Fig. 5). The pond and feedstock pile each emit less than 10% of that from the IMUS facility during normal operations. The offal storage pile in summer was an exception in being a large source of CH_4. Emissions from the offal were almost twice that from the IMUS facility: 5.1 kg CH_4 hr^{-1} versus 2.8 kg CH_4 hr^{-1} (normal operations). This illustrates the potential for on-site storage of fresh organic material to be a large emission source. But this is unlikely to represent an increased GHG emission component of biodigester systems, as traditional waste management will have a similar period of waste storage prior to land application. For this reason emissions during waste storage are generally excluded in carbon credit offset protocols for biodigesters [1,2]. It is possible that the duration of waste storage is actually reduced in a biodigester system – as feedstock energetic value decreases over time, there is incentive to minimize storage.

The IMUS biodigester is integrated into a beef feedlot production system. As a part of this system, feedlot runoff is collected in a retention lagoon and is then pumped and mixed with manure at the IMUS hopper. Effluent from the digester is returned to the feedlot lagoon following solid/liquid separation. In this study we did not measure the emission contribution associated with effluent return to the lagoon. Such a transfer may alter the CH_4 emissions compared to an exclusive runoff lagoon. Adding biodigester effluent may increase lagoon emissions by introducing additional organic matter to the lagoon. However this may be offset by the reduction in organic matter in the feedlot runoff as a result of the removal of manure from the feedlot for biodigester feedstock. Additionally, Harper et al. [17] found a 50% decrease in CH_4 emissions from swine waste effluent after processing in anaerobic digester. So the returned effluent may be a weaker emission source than the original lagoon water.

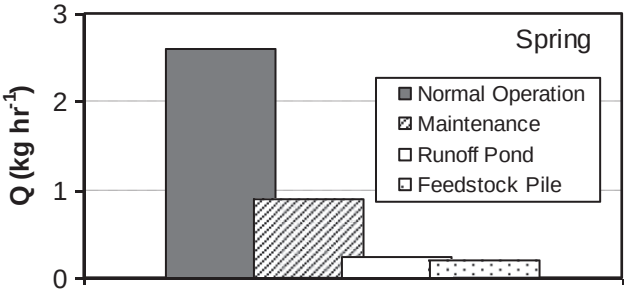

Fig. 5 – Spring fugitive emission rates (Q) from the biogas facility (during "Normal Operation" and "Maintenance") and from secondary sources (the "Runoff Pond" and the "Feedstock Pile").

6. Conclusions

Fugitive emissions of CH_4 from the IMUS biodigester facility were related to its operating state. Over four seasonal measurement campaigns the average emission rates were 0.8, 26.6, and 3.2 kg CH_4 hr^{-1} for maintenance, flaring, and normal operating periods, respectively. During normal operations the feedstock hopper appears to be the main source of emissions, although when flaring occurs the flare is an order-of-magnitude larger source.

Fugitive emissions were relatively small when expressed as a percentage of biogas production. During normal operations the fugitive emission rate was 3.1% of the CH_4 gas production rate. This is much lower than the default values of 5–15% assumed in GHG offset protocols [4–6], and this has large financial implications when calculating GHG offsets and carbon credits. However, the emission rate over any prolonged period will ultimately depend on the frequency of flaring and maintenance.

The bLS inverse dispersion technique proved well-suited to our study. With modest equipment and labor resources (one person) we were able to quickly setup and monitor emissions. Monitoring occurred continuously, with equipment left unattended except to swap batteries, move lasers to address wind changes, or focus on different sources (laser reconfiguration took only a few minutes). And because of the modest resource requirements it was possible to monitor emissions for prolonged periods, and capture the characteristics of a highly variable source.

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REFERENCES

[1] Climate Action Reserve. Organic waste digestion project protocol: avoiding methane emissions from anaerobic digestion of food waste and/or agro-industrial wastewater. Version 1.0. Climate Action Reserve. Available online at, http://www.climateactionreserve.org/how/protocols/adopted/organic-waste-digestion/current/; 2009 [accessed 22.06.11].

[2] Alberta Environment. Quantification protocol for the anaerobic decomposition of agricultural materials. Edmonton, Alberta: Alberta Environment. Available online at, http://environment.alberta.ca/02301.html; 2007 [accessed 22.06.11].

[3] Martin JH. Methane to markets: international guidance for quantifying and reporting the performance of anaerobic digestion systems for livestock Manures. EPA; 2008. Contract No. EP-W-07–067.

[4] CDM. Forced methane extraction from organic waste-water treatment plants for grid-connected electricity supply and/or heat production. Draft revision to approved baseline methodology 2005, AM0013 (AM0013 / Version 02, Sectoral Scope: 1, 15 April 2005), United Nations Framework Convention on Climate Change.

[5] IPCC. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme. Japan: IGES; 2006. Published:.

[6] EPA. Climate leaders greenhouse gas inventory protocol offset project methodology for project type: managing manure with biogas recovery systems (Version 1.3)Clim Prot Partnerships Division/Climate Change Division. Office of Atmospheric Programs, U.S. Environmental Protection Agency; 2008.

[7] Flesch TK, Wilson JD, Harper LA, Crenna BP, Sharpe RR. Deducing ground-air emissions from observed trace gas concentrations: a field trial. J Appl Meteorol 2004;43:487–502.

[8] Flesch TK, Wilson JD, Harper LA, Crenna BP. Estimating gas emission from a farm using an inverse-dispersion technique. Atmos Environ 2005;39:4863–74.

[9] McGinn SM, Flesch TK, Harper LA, Beauchemin KA. An approach for measuring methane emissions from whole farms. J Environ Qual 2006;35:14–20.

[10] Gao Z, Desjardins RL, Flesch TK. Assessment of the uncertainty of using an inverse dispersion technique to measure methane emissions from animals in a barn and in a small pen. Atmos Environ 2010;44:3128–34.

[11] Wilson JD, Sawford BL. Review of Lagrangian stochastic models for trajectories in the turbulent atmosphere. Bound Layer Meteor 1996;78:191–210.

[12] Harper LA, Flesch TK, Powell JM, Coblentz WK, Jokela WE, Martin NP. Ammonia emissions from dairy production in Wisconsin. J Dairy Sci 2009;92:2326–37.

[13] Sanz A, Misselbrook T, Sanz MJ, Vallejo A. Use of an inverse dispersion technique for estimating ammonia emission from surface-applied slurry in Central Spain. Atmos Environ 2010;44:999–1002.

[14] van Haarlem RP, Desjardins RL, Gao Z, Flesch TK, Li X. Methane and ammonia emissions from a beef feedlot in western Canada. Can J Anim Sci 2008;88:641–9.

[15] McGinn SM, Coates T, Flesch TK, Crenna BP. Ammonia emissions from dairy cow manure stored in a lagoon over summer. Can J Soil Sci 2008;88:611–5.

[16] Laubach J, Kelliher FM. Methane emissions from dairy cows: comparing open-path laser measurements to profile-based techniques. Agric For Meteorol 2005;135:340–5.

[17] Harper LA, Flesch TK, Weaver KH, Wilson JD. The effect of biofuel production on swine farm ammonia and methane emissions. J Environ Qual 2010;39:1984–92.

[18] Johnson MR, Wilson DJ, Kostiuk LW. A fuel stripping mechanism for wake stabilized jet diffusion flames in a crossflow. Combust Sci. Tech 2001;169:155–74.

[19] Pohl JH, Lee J, Payne R, Tichenor BA. Combustion efficiency of flares. Combust Sci Tech 1986;50:217–31.

[20] RIRDC. Assessment of Australian biogas flaring standards. Rural Industries Research and Development Corporation. Australia: Barton, ACT; 2008.

[21] Strosher M. Investigation of flare gas emissions in Alberta. Alberta Research Council Report to Environment Canada, Alberta Energy and Utilities Board, and Canadian Association of Petroleum Engineers, 1996.

[22] Johnson MR, Kostiuk LW. Efficiencies of low-momentum jet diffusion flames in crosswinds. Combust Flame 2000;123:189–200.

The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity

7

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gases can be estimated. Using either these new approaches, or treating short- and long-lived GHG emissions pathways separately, can improve the quantification of the contribution of emissions to global warming within a cumulative emissions framework, compared to approaches that aggregate emissions of GHGs using standard CO_2 equivalent emissions metrics. As discussed in Box 7.3, there is *high confidence* that multi-gas emissions pathways with the same time-dependence of aggregated CO_2 equivalent emissions estimated from standard approaches, such as weighting emissions by their GWP-100 values, rarely lead to the same estimated temperature outcomes.

7.6.1.5 Emissions Metrics by Compounds

Emissions metrics for selected compounds are presented in Table 7.15, with further compounds presented in the Supplementary Material, Table 7.SM.7. The evolution of the CO_2 concentrations in response to a pulse emission is as in AR5 (Joos et al., 2013; Myhre et al., 2013b), the perturbation lifetimes for CH_4 and N_2O are from Section 7.6.1.1. The lifetimes and radiative efficiencies for halogenated compounds are taken from Hodnebrog et al. (2020a). Combined metrics (CGTPs) are presented for compounds with lifetimes less than 20 years. Note that CGTP has units of years and is applied to a change in emissions rate rather than a change in emissions amount. Changes since AR5 are due to changes in radiative properties and lifetimes (Section 7.6.1.1), and indirect contributions (Section 7.6.1.3). Table 7.15 also gives overall emissions uncertainties in the emissions metrics due to uncertainties in radiative efficiencies, lifetimes and the climate response function (Supplementary Material, Tables 7.SM.8 to 7.SM.13).

Following their introduction in AR5 the assessed metrics now routinely include the carbon cycle response for non-CO_2 gases (Section 7.6.1.3). As assessed in this earlier section, the carbon cycle contribution is lower than in AR5. Contributions to CO_2 formation are included for methane depending on whether or not the source originates from fossil carbon, thus methane from fossil fuel sources has slightly higher emissions metric values than that from non-fossil sources.

Table 7.15 | Emissions metrics for selected species: global warming potential (GWP), global temperature-change potential (GTP). All values include carbon cycle responses as described in Section 7.6.1.3. Combined GTPs (CGTPs) are shown only for species with a lifetime less than 20 years (Section 7.6.1.4). Note CGTP has units of years and is applied to a change in emissions rate rather than a change in emissions amount. The radiative efficiencies are as described in Section 7.3.2 and include tropospheric adjustments where assessed to be non-zero in Section 7.6.1.1. The climate response function is from Supplementary Material 7.SM.5.2. Uncertainty calculations are presented in Supplementary Tables 7.SM.8 to 7.SM.13. Chemical effects of CH_4 and N_2O are included (Section 7.6.1.3). Contributions from stratospheric ozone depletion to halogenated species metrics are not included. Supplementary Table 7.SM.7 presents the full table.

Species	Lifetime (Years)	Radiative Efficiency (W m^{-2} ppb^{-1})	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100	CGTP-50 (years)	CGTP-100 (years)
CO_2	Multiple	$1.33 \pm 0.16 \times 10^{-5}$	1.	1.000	1.000	1.000	1.000		
CH_4-fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8	13.2 ± 6.1	7.5 ± 2.9	2823 ± 1060	3531 ± 1385
CH_4-non fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8	10.4 ± 6.1	4.7 ± 2.9	2675 ± 1057	3228 ± 1364
N_2O	109 ± 10	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 118	273 ± 130	130 ± 64	290 ± 140	233 ± 110		
HFC-32	5.4 ± 1.1	$1.1 \pm 0.2 \times 10^{-1}$	2693 ± 842	771 ± 292	220 ± 87	181 ± 83	142 ± 51	78,175 ± 29,402	92,888 ± 36,534
HFC-134a	14.0 ± 2.8	$1.67 \pm 0.32 \times 10^{-1}$	4144 ± 1160	1526 ± 577	436 ± 173	733 ± 410	306 ± 119	146,670 ± 53,318	181,408 ± 71,365
CFC-11	52.0 ± 10.4	$2.91 \pm 0.65 \times 10^{-1}$	8321 ± 2419	6226 ± 2297	2093 ± 865	6351 ± 2342	3536 ± 1511		
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5301 ± 1395	7380 ± 2430	10,587 ± 3692	7660 ± 2464	9055 ± 3128		

Box 7.3 | Physical Considerations in Emissions Metric Choice

Following AR5, this Report does not recommend an emissions metric because the appropriateness of the choice depends on the purposes for which gases or forcing agents are being compared. Emissions metrics can facilitate the comparison of effects of emissions in support of policy goals. They do not define policy goals or targets but can support the evaluation and implementation of choices within multi-component policies (e.g., they can help prioritize which emissions to abate). The choice of metric will depend on which aspects of climate change are most important to a particular application or stakeholder and over which time horizons. Different international and national climate policy goals may lead to different conclusions about what is the most suitable emissions metric (Myhre et al., 2013b).

Global warming potentials (GWP) and global temperature-change potentials (GTP) give the relative effect of pulse emissions, that is, how much more energy is trapped (GWP) or how much warmer (GTP) the climate would be when unit emissions of different compounds are compared (Section 7.6.1.2). Consequently, these metrics provide information on how much energy accumulation (GWP) or how much global warming (GTP) could be avoided (over a given time period, or at a given future point in time) by avoiding the emission of a unit of a short-lived greenhouse gas compared to avoiding a unit of CO_2. By contrast, the new metric approaches of combined GTP (CGTP) and GWP* closely approximate the additional effect on climate from a time series of short-lived GHG emissions, and can be used to compare this to the effect on temperature from the emission or removal of a unit of CO_2 (Section 7.6.1.4; Allen et al., 2018b; Collins et al., 2020).

Box 7.3 (continued)

If global surface temperature stabilization goals are considered, cumulative CO_2 equivalent emissions computed with the GWP-100 emissions metric would continue to rise when short-lived GHG emissions are reduced but remain above zero (Figure 7.22b). Such a rise would not match the expected global surface temperature stabilization or potential decline in warming that comes from a reduction in emissions of short-lived greenhouse gases (Pierrehumbert, 2014; Allen et al., 2018b; Cain et al., 2019; Collins et al., 2020; Lynch et al., 2020, 2021). This is relevant to net zero GHG emissions goals (Section 7.6.2 and Box 1.4).

When individual gases are treated separately in climate model emulators (Cross-Chapter Box 7.1), or weighted and aggregated using an emissions metric approach (such as CGTP or GWP*) which translate the distinct behaviour from cumulative emissions of short-lived gases, ambiguity in the future warming trajectory of a given emissions scenario can be substantially reduced (Cain et al., 2019; Denison et al., 2019; Collins et al., 2020; Lynch et al., 2021). The degree of ambiguity varies with the emissions scenario. For mitigation pathways that limit warming to 2°C with an even chance, the ambiguity arising from using GWP-100 as sole constraint on emissions of a mix of greenhouse gases (without considering their economic implications or feasibility) could be as much as 0.17°C, which represents about one-fifth of the remaining global warming in those pathways (Denison et al., 2019). If the evolution of the individual GHGs is not known, this can make it difficult to evaluate how a given global multi-gas emissions pathway specified only in CO_2 equivalent emissions would achieve (or not) global surface temperature goals. This is potentially an issue as Nationally Determined Contributions frequently make commitments in terms of GWP-100-based CO_2 equivalent emissions at 2030 without specifying individual gases (Denison et al., 2019). Clear and transparent representation of the global warming implications of future emissions pathways including Nationally Determined Contributions could be achieved either by their detailing pathways for multiple gases or by detailing a pathway of cumulative carbon dioxide equivalent emissions approach aggregated across GHGs evaluated by either GWP* or CGTP metric approaches (Cain et al., 2019; Collins et al., 2020; Lynch et al., 2021). It should be noted that although the Paris Agreement Rulebook asks countries to report emissions of individual GHGs separately for the global stocktake (Decision 18/CMA.1, annex, paragraph 38), which can allow the current effects of their emissions on global surface temperature to be accurately estimated, estimates of future warming are potentially ambiguous where emissions are aggregated using GWP-100 or other pulse metrics.

Although there is significant history of using single-basket approaches, supported by emissions metrics such as GWP-100, in climate policies such as the Kyoto Protocol, multi-basket approaches also have many precedents in environmental management, including the Montreal Protocol (Daniel et al., 2012). Further assessment of the performance of physical and economics-based metrics in the context of climate change mitigation is provided in the contribution of Working Group III to AR6.

7.6.2 Applications of Emissions Metrics

One prominent use of emissions metrics is for comparison of efforts measured against climate change goals or targets. One of the most commonly discussed goals is in Article 2 of the Paris Agreement which aims to limit the risks and impacts of climate change by setting temperature goals. In addition, the Paris Agreement has important provisions which relate to how the goals are to be achieved, including making emissions reductions in a manner that does not threaten food production (Article 2), an early emissions peaking target, and the aim to 'achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century' (Article 4). Article 4 also contains important context regarding international equity, sustainable development, and poverty reduction. Furthermore, the United Nations Framework Convention on Climate Change (UNFCCC) sets out as its ultimate objective, the 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.'

How the interpretation of the Paris Agreement and the meaning of 'net zero' emissions, reflects on the appropriate choice of metric is an active area of research (Schleussner et al., 2016, 2019; Fuglestvedt et al., 2018; Collins et al., 2020). Several possible scientific interpretations of the Article 2 and 4 goals can be devised, and these, along with emissions metric choice, have implications both for when a balance in GHG emissions, net zero CO_2 emissions or net zero GHG emissions are achieved, and for their meaning in terms of temperature outcome (Fuglestvedt et al., 2018; Rogelj et al., 2018; Wigley, 2018). In AR6 net zero GHG emissions is defined as the condition in which metric-weighted anthropogenic GHG emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period (see Box 1.4 and Appendix VII: Glossary). The quantification of net zero GHG emissions depends on the GHG emissions metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric. As the choice of emissions metric affects the quantification of net zero GHG emissions, it therefore affects the resulting temperature outcome after net zero emissions are achieved (Lauder et al., 2013; Rogelj et al., 2015; Fuglestvedt et al., 2018; Schleussner et al., 2019). Schleussner et al. (2019) note that declining temperatures may be a desirable outcome of net zero. Rogelj and Schleussner (2019) also point out that the use of physical metrics raises questions of equity and fairness between developed and developing countries.

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The Intersectionality of Environmental Injustice, Other Societal Harms, and Farmed Animal Welfare

Laura Fox

ABSTRACT

How we treat nonhuman animals (''animals'') not only reflects the morals and values of society, but our treatment also has enormous effects on society. Our actions toward farmed animals, in particular, cause immense suffering and devastating impact. Building upon a concurring opinion drafted by Judge J. Harvie Wilkinson III of the Fourth Circuit, this article discusses the myriad environmental, animal welfare, and societal harms of factory farming. Addressing the underlying animal-rearing practices that breed these harms will abate many of them. Such practices include caging animals in spaces so small they cannot turn around, warehousing animals in structures with no outdoor access, collecting tons of gallons of animal waste and disposing of it in the surrounding environment, and slaughtering animals at such high rates and line speeds that food and worker safety are put on the line. These actions disregard animal welfare and have enormously harmful external environmental and societal consequences. Black, Indigenous, People of Color (BIPOC) and people experiencing poverty are affected the most by each of the associated harms. These intersectional injuries demonstrate that farmed animal welfare is an integral component of environmental justice.

Keywords: animal welfare, climate change, environmental justice, public health, worker safety

INTRODUCTION

''It is past time to acknowledge the full harms that the unreformed practices of [animal] farming are inflicting.''[1] With these words, penned by Judge J. Harvie Wilkinson III, the Fourth Circuit acknowledged that industrialized animal agriculture inflicts injuries that are intersectional and require extensive and expeditious repair. Factory farming is not just an issue of animal welfare or rights; it is also an issue of environmental justice, workers' rights, and public health. In his brilliant concurrence in *McKiver v. Murphy-Brown*, Judge Wilkinson skillfully weaves the myriad environmental, animal welfare, and societal harms of factory farming into a cohesive narrative. The relationship of these harms to our treatment of animals makes clear that farmed animal welfare is critical to counter many of the environmental injustices disproportionately impacting marginalized communities.

This article proceeds as follows. It begins with an overview of the groundbreaking nuisance lawsuit brought by disenfranchised neighbors against one of the world's largest meat producers. It then examines how the intensive animal confinement practices common within the industry harms animals, imperils public health, and increases zoonotic risk, which prompts practices that again perpetuate harms to animals, the environment, and the

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[1] *McKiver v. Murphy-Brown, LLC*, 980 F.3d 937, 977 (4th Cir. 2020) (Wilkinson, J., concurring).

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community. Next, how this industrialized system exploits workers, undermines worker safety, and pollutes the environment is discussed, including how each of these harms, worsened by extreme animal confinement practices, excessively injure people of color and low-income communities. Many legislative bodies are only furthering this systemic injustice by passing laws that protect the powerful and burden the vulnerable. Those actions are mentioned followed by a discussion of how an unlikely player—the insurance industry—can positively effect change in this space for people, the environment, and farmed animals.

MCKIVER V. MURPHY-BROWN

> Many plaintiffs in this suit have tended their hearths for generations—one family for almost 100 years. They are exactly whom the venerable tort of nuisance ought to protect. Murphy-Brown's interference with their quiet enjoyment of their properties was unreasonable. It was willful, and it was wanton.—J. Wilkinson

The Mc*Kiver* matter involved Kinlaw Farms, a nearly 15,000-pig Concentrated Animal Feeding Operation (CAFO) in North Carolina. Kinlaw was run by a contract farmer of Murphy-Brown, LLC, d/b/a Smithfield Hog Production Division, a subsidiary of Smithfield Foods, LLC, the world's largest pig processor and pork producer. Smithfield Foods, in turn, is a wholly owned subsidiary of WH Group, a Chinese company. The over 150,000 pounds of waste the pigs at this CAFO generated every day was stored in open-air ''lagoons'' (which Judge Wilkinson describes as ''essentially three uncovered, 8 million-gallon cesspools''). These cesspools were emptied by spraying the waste material into the air over the surrounding land.[2]

This lagoon-and-sprayfield system causes many problems for surrounding neighbors, from wretched stench to fly infestations to water and air contamination. Consequently, Kinlaw's neighbors sued the company for nuisance—a tort action used to address injuries caused by unreasonable interference with the use and enjoyment of one's property. This lawsuit was just one in a series of nuisance suits brought by more than 500 neighbors of various Smithfield-affiliated operations. Smithfield's subsidiary lost several of these cases at trial to the tune of millions in compensatory and punitive damages.[3] It appealed the *McKiver* verdict, resulting in the remarkable concurrence by Judge Wilkinson, in which he recognizes that ''treating animals better will benefit humans'' and that our collective welfare is ''integrally connected.''

INTENSIVE CONFINEMENT HARMS ANIMALS

> The warp in the human-hog relationship, and the root of the nuisance in this suit, lay in the deplorable conditions of confinement prevailing at Kinlaw, conditions that there is no reason to suppose were unique to that facility.—J. Wilkinson

The industrialized CAFO system used to produce billions of animals each year to feed America's meat appetite causes harm to animals on a massive scale. The intensive confinement practices and overcrowded conditions that are commonplace in CAFOs frustrate, distress, and cause suffering to animals.[4] Many animals even die due to complications from their congested environment. At Kinlaw, ''the mortality rate was around seven percent,'' and the piled-up carcasses in dumpsters were an eyesore to neighbors.[5] The natural mortality rate is much lower in animals raised outside of extreme confinement.[6]

Extensive scientific evidence shows that intensively confined animals suffer because they cannot exercise, fully extend their limbs, or engage in many important natural behaviors.[7] A federal advisory board noted, and commonsense tells us, that good animal welfare requires that animals be able to perform species-specific behaviors.[8] Naturally, since intensive confinement interferes with these behaviors, it is detrimental to the animals' well-being. The harms to animals in this industrialized system are vast and overwhelming. Still, farmed animals are not the only ones that suffer from the consequences of

[2]*McKiver* at 979.

[3]Smithfield Foods ordered to pay $473.5M for pig stench. *CBS News* (Aug. 3, 2018) <https://www.cbsnews.com/news/smithfield-foods-ordered-to-pay-473-5m-for-pig-stench/>. (Last accessed on July 16, 2022).

[4]Mingyue Zhang, Xiang Li, Jianhong Li, Hanqing Sun, Xiaohui Zhang, and Jun Bao. ''Effects of Confinement on Physiological and Psychological Responses and Expression of Interleukin 6 and Brain Derived Neurotrophic Factor mRNA in Primiparous and Multiparous Weaning Sows.'' *Asian-Australasian Journal of Animal Sciences* 30 (2017): 1350–1357; H.R. Whay, D.C.J. Main, Laura Elizabeth Green, G. Heaven, H. Howell, M. Morgan, A. Pearson, and A.J.F. Webster. ''Assessment of the Behaviour and Welfare of Laying Hens on Free-Range Units.'' *The Veterinary Record* 161 (2007): 119–128.

[5]*McKiver* at 980–981.

[6]See, for example, The Humane Society of the United States (HSUS), Understanding Mortality Rates of Laying Hens in Cage-Free Egg Production Systems. (2010) <https://www.humanesociety.org/sites/default/files/docs/mortality-cage-free-egg-production-system.pdf>. (Last accessed on July 16, 2022); Maria Camila Ceballos, Karen Camille Rocha Góis, Thomas D. Parsons, and Meghann Pierdon. ''Impact of Duration of Farrowing Crate Closure on Physical Indicators of Sow Welfare and Piglet Mortality.'' *Animals* 11 (2021): 969.

[7]HSUS. An HSUS Report: The welfare of intensively confined animals in battery cages, gestation crates, and veal crates. (July 2012). <https://www.humanesociety.org/sites/default/files/docs/hsus-report-animal-welfare-of-intensively-confined-animals.pdf>. (Last accessed on July 16, 2022).

[8]Agricultural Marketing Service (AMS). National Organic Standards Board Livestock Committee Animal Welfare Discussion Document Stocking Density. (Sept. 9, 2010). <https://www.ams.usda.gov/sites/default/files/media/LSDDStockingRatesOct2010.pdf>. (Last accessed on July 16, 2022).

the industry's inhumane practices. Wildlife and even companion animals are harmed by the industry's contribution to climate change, habitat loss, rising seas, wildfires, and the spread of parasites and pathogens.[9]

PUBLIC HEALTH IMPLICATIONS OF EXTREME CONFINEMENT PRACTICES

> This triangular rotation among animals, workers, and homeowners is no fluke. It repeats again and again. Consider another similarly structured example: the problem of viral disease. It is well-established that close confinement leads to the ''increased risk of the spread of disease'' between hogs.—J. Wilkinson

Animals concentrated in large numbers and tight environments at CAFOs create a breeding ground for disease. Packing animals into cages or side by side in crates provides limited movement and no opportunity for animals to move away from one another. This overcrowding is a serious issue because maintaining distance works for animals as it does for humans in slowing the spread of infectious diseases.[10] Keeping animals in crates or cages intensifies this problem because they are harder to disinfect.[11] Cleaning every joint or nook of cages is not always possible, so, if the infectious agents are persistent outside the host, the infection can begin again when new animals are put into those cages.[12]

Even without cages, high stocking densities amplify pandemic risk.[13] Stocking density refers to the number of animals kept on a given unit of area. For example, it is common industry practice to provide broiler chickens (those raised for their meat) less than one square foot of space per bird, which gives each bird about the size of a typical sheet of paper.[14] Like cage systems, this limited space provides little to no opportunity for animals to spread out and keep their distance.

As Judge Wilkinson noted, ''it is well established that close confinement of animals leads to the increased risk of disease'' transmission.[15] If one animal becomes infected, her close proximity to other animals can intensify the virus's rapid spread from one animal to another. And with each transfer, the virus has the potential to mutate into something novel and even more deadly. Thus, our factory farm system, which depends on large numbers and tight confinement, plays a Russian roulette game with viruses.[16]

Those working in or living near factory farms are at the highest risk of exposure to potential zoonotic diseases (those transmitted from animal to human), but as experience with the COVID-19 pandemic has shown, viruses that are highly virulent have the potential to spread rapidly and create a global problem.[17] Most new diseases affecting humans are of animal origin.[18] These zoonotic diseases are usually directly related to the human

[9]Jonathan Lovvorn. ''Climate Change Beyond Environmentalism Part I: Intersectional Threats and the Case for Collective Action.'' *29 Geo Envtl L Rev* 1 (2017): 40. <https://gielr.files.wordpress.com/2017/04/zsk00117000001.pdf>. (Last accessed on July 16, 2022); Jonathan Lovvorn. ''Climate Change Beyond Environmentalism Part II: Near-Term Climate Mitigation in a Post-Regulatory Era.'' *30 Geo Envtl L Rev* (2018): 224. <https://gielr.files.wordpress.com/2018/06/gt-gelr180001.pdf>. (Last accessed on July 16, 2022).

[10]United Nations Environment Programme. Preventing the Next Pandemic: Zoonotic Diseases and How to Break the Chain of Transmission 15. (2021). <https://www.cbd.int/doc/c/084c/e8fd/84ca7fe0e19e69967bb9fb73/unep-sa-sbstta-sbi-02-en.pdf>. (Last accessed on July 16, 2022) (noting ''Factory farming of pigs, for example, promoted transmission of swine flu due to a lack of physical distancing between the animals''); Centers for Disease Control and Prevention (CDC). How to Protect Yourself & Others. (Nov. 29, 2021). <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/prevention.html#stay6ft%20>. (Last accessed on July 16, 2022) (instructing people to ''Stay 6 feet away from others'').

[11]European Food Safety Authority. ''Report of the Task Force on Zoonoses Data Collection on the Analysis of the Baseline Study on the Prevalence of Salmonella in Holdings of Laying Hen Flocks of Gallus gallus.'' *The EFSA Journal* 97 (2007). <https://www.efsa.europa.eu/en/efsajournal/pub/rn-97>. (Last accessed on July 16, 2022).

[12]See, for example, Hayatuddeen Bako Aliyu, L. Sa'idu, A. Jamilu, A.D. Andamin, and S.O. Akpavie. ''Outbreaks of Virulent Infectious Bursal Disease in Flocks of Battery Cage Brooding System of Commercial Chickens.'' *Journal of Veterinary Medicine* 4 (2016): 1–7.

[13]US Department of Agriculture (USDA), Animal Plant Health Inspection Service (APHIS). High Pathogenicity Avian Influenza Control in Commercial Poultry Operations—A National Approach: Final Environmental Assessment 77. (Dec. 2015) (''APHIS and the poultry industry agree that the impact of an HPAI outbreak is amplified where poultry production is highly concentrated or networked.''); Roberto A. Saenz, H.W. Hethcote, and G.C. Gray ''Confined Animal Feeding Operations as Amplifiers of Influenza.'' *Vector-Borne & Zoonotic Diseases* 6 (2006): 338, 339 (''The crowding of swine and poultry in CAFOs increases the transmission of influenza viruses.'').

[14]National Chicken Council. National Chicken Council Animal Welfare Guidelines and Audit Checklist For Broilers 12. (Sept. 2020). <https://www.nationalchickencouncil.org/wp-content/uploads/2021/02/NCC-Animal-Welfare-Guidelines_Broilers_Sept2020.pdf>. (Last accessed on July 16, 2022) (standard D5 on ''Flock Husbandry'' allows for up to 9 lbs. [of live chickens] per square foot).

[15]*McKiver* at 980 (internal quotations omitted); see also Humane Society International (HSI). An HSI report: The connection between animal agriculture, viral zoonoses, and global pandemics. (Sept. 2020). <https://blog.humanesociety.org/wp-content/uploads/2020/10/Animal-agriculture-viral-disease-and-pandemics-FINAL-4.pdf>. (Last accessed on July 16, 2022).

[16]Rhea Hirshman. ''Rigging the roulette wheel to slow the spread of viruses.'' Yale Medicine (2006). <https://tinyurl.com/mrxnsayz>. (Last accessed on July 16, 2022).

[17]Sarah Goldman, Anna Aspenson, Prashasti Bhatnagar, and Robert Martin ''Essential and in Crisis: A Review of the Public Health Threats Facing Farmworkers in the US.'' *Johns Hopkins Center for a Livable Future* (May 4, 2021). <https://clf.jhsph.edu/publications/essential-and-crisis-review-public-health-threats-facing-farmworkers-us>. (Last accessed on July 16, 2022).

[18]Kate E. Jones, Nikkita G. Patel, Marc A. Levy, Adam Storeygard, Deborah Balk, John L. Gittleman, and Peter Daszak. ''Global Trends in Emerging Infectious Diseases.'' *Nature* 451 (2008): 990–994.

consumption of animal-sourced food—be it from wildlife (as suspected in the case of COVID-19) or farmed animals (as in many avian and swine flu outbreaks), both of which facilitates direct contact with animals.[19]

INTENSIVE CONFINEMENT INCREASES ZOONOTIC RISK

> Pathogens like H1-N1 ''swine flu,'' which incubate and mutate in pigs, can sometimes jump to human hosts. The swine flu outbreak of 2009, which led to almost 275,000 hospitalizations and 12,500 deaths in the United States, put the country on notice of that fact.—J. Wilkinson

According to the United Nations, the worldwide growth in industrialized farming of animals means that there have never before been as many opportunities for pathogens to pass through animals and the environment to affect humans.[20] The risk of viral disease from intensively confined farmed animals is an existential threat.

For instance, avian influenza (bird flu) is currently spreading throughout parts of Europe and Asia and has the potential to cause severe harm.[21] Bird flu is a viral respiratory disease that infects all avian species and can also infect pigs and humans—so it has zoonotic potential. It is categorized based on its virulence to chickens as either low- (LPAI) or high-pathogenic avian influenza (HPAI). It is a common disease in birds, but it frequently mutates, making it very dangerous. With each mutation, the virus may become more severe. Additionally, virus mutations make diseases harder to target by immune systems and with vaccines or therapeutics. HPAI is a potentially fatal virus to humans and has a mortality rate much higher than many other infectious diseases, including COVID-19. When people have become infected with certain strains of bird flu, the mortality rate is about 60%.[22]

Given the nature of the threat, activities known to increase public risk, such as confinement practices at CAFOs, ought to be strictly regulated. However, no federal laws regulate the treatment of animals on the farm (as distinct from during transport or at slaughter facilities).[23] Still, the federal government could take action to incentivize safer and more humane practices. As it stands, the government's HPAI control plan does nothing to disincentivize dangerous, high-density animal operations.[24]

In fact, when an outbreak occurs and the U.S. Department of Agriculture (USDA) assists in killing the farmed animals to control the spread, the federal government pays producers to restock their cages or refill their warehouses at the same density, even in large facilities that use dangerous and extreme confinement practices.[25] This approach makes about as much sense as being encouraged to build a hotel on a cliff above a very populated area in a hurricane belt, and each time it is damaged or collapses, the government gives the homeowner money to rebuild in the same spot.

USDA could instead condition indemnification on placing animals in cage-free low-density environments.[26] Not only would this improve conditions for the millions of animals currently raised in extreme confinement, but raising animals in a safer more diffuse environment would also slow the mutation and spread of disease.[27] Disincentivizing extreme confinement practices through indemnification procedures is a viable reasonable alternative that would diminish much of the industry's environmental impact, reduce animal suffering, and help prevent future outbreaks. As the UN recognizes, outbreak prevention is cheaper, safer, and more humane than waiting to respond to an outbreak.[28] USDA recently settled a lawsuit related to these practices by agreeing to thoroughly evaluate the environmental impacts of killing and burying or burning millions of animals and the discriminatory effect of those impacts.[29]

[19]Congressional Research Service. Wildlife Trade, COVID-19, and Other Zoonotic Diseases. (Feb. 19, 2021). <https://crsreports.congress.gov/product/pdf/IF/IF11494>. (Last accessed on July 16, 2022); CDC. United States Health Security National Action Plan: Strengthening Implementation of the International Health Regulations based on the 2016 Joint External Evaluation. <https://www.cdc.gov/onehealth/pdfs/us-ohzdp-report-508.pdf>. (Last accessed on July 16, 2022).

[20]United Nations Environment Programme. UNEP Frontiers 2016 Report: Emerging Issues of Environmental Concern 18. (2016). <https://environmentlive.unep.org/media/docs/assessments/UNEP_Frontiers_2016_report_emerging_issues_of_environmental_concern.pdf>. (Last accessed on July 16, 2022).

[21]World Organisation for Animal Health. High Pathogenicity Avian Influenza (HPAI)—Situation Report (Dec. 13, 2021). <https://www.oie.int/app/uploads/2021/12/hpai-situation-report-20211213.pdf>. (Last accessed on July 16, 2022).

[22]Yong Poovorawan, Sunchai Pyungporn, Slinporn Prachayangprecha, and Jarika Makkoch. ''Global Alert to Avian Influenza Virus Infection: From H5N1 to H7N9.'' *Pathogens and Global Health* 107 (2013): 217–223.

[23]Humane Methods of Livestock Slaughter Act, 7 U.S.C. § 1901 *et seq.*; Poultry and Poultry Products Inspection Act, 21 U.S.C. § 451 *et seq.*; Twenty-Eight Hour Law, 49 U.S.C. § 80502.

[24]*Humane Soc'y of the U.S., et al. v. U.S. Department of Agriculture, et al.*, No. 2:20-CV-03258-AB-GJS (C.D. Cal. 2020).

[25]USDA. Conditions for Payment of HPAI Indemnity Claims. 83 Fed. Reg. 40,433. (Aug. 15, 2018).

[26]*Supra* note 24.

[27]Temple Grandin. ''Methods to Prevent Future Severe Animal Welfare Problems Caused by COVID-19 in the Pork Industry.'' *Animals* 11 (2021): 830.

[28]See *supra* note 8 at 24; see also The World Organisation for Animal Health. ''Prevention and control of animal diseases worldwide, economic analysis—Prevention versus outbreak costs.'' *Agra CEAS Consulting* (Sept. 2007): 12–14. <https://www.oie.int/fileadmin/Home/eng/Support_to_OIE_Members/docs/ppt/OIE_-_Cost-Benefit_Analysis__Part_I_.pdf>. (Last accessed on July 16, 2022).

[29]*HSUS, et al. v. USDA*, No. 2:20-cv-03258 (CDCA 2020); Brain Collins and Lauri Torgenson-White. ''Why are we accepting the mass slaughter of animals through heatstroke?'' *Washington Post* (July 6, 2022). <https://www.washingtonpost.com/opinions/2022/07/06/avian-flu-chickens-birds-why-are-we-accepting-mass-slaughter-animals-through-heatstroke/>. (Last accessed on July 16, 2022).

INHUMANE MASS-KILLING METHODS

> Dying hogs imperil human well-being in other ways. … [T]he problem lies in Kinlaw's method of storing and disposing of the numerous dead hogs. Kinlaw piled carcasses into uncovered storage containers that plaintiffs call ''dead boxes.''—J. Wilkinson

For now, however, USDA's strategy does not focus on mitigation efforts but instead aims to contain viruses as they emerge. When an infected flock or herd is detected, USDA's reactionary plan requires animals to be killed *en masse* (or, as the government euphemistically calls it, ''depopulated'').[30] The approved methods of killing represent additional concerns for animal welfare, the environment, and public health.

Ventilation shutdown (VSD), for instance, involves shutting down a facility's entire ventilation system—the huge fans on the warehouse-like structures used to regulate temperature and filter debris. Turning them off causes a buildup of carbon dioxide and heat that suffocates the birds or pigs in the facility—essentially cooking conscious animals to death. Another method involves applying water-based foam over birds, which slowly expands to suffocate the birds while conscious, causing an agonizing slow death.[31] There are other methods of killing, such as poisoning, decapitation, and captive bolt gun, but since these require individual handling, they are not seen as practical for use on large flocks or herds in an emergency.

Fast-expanding nitrogen-filled foam is a more humane method that could be deployed quickly in an emergency.[32] Unlike water-based foam, the gases in this foam render birds unconscious before they suffocate. If USDA stopped subsidizing dangerous practices, the risk of infection would be lower and thus reduce the need for such destructive measures. But, if extreme measures such as depopulation are in consideration, we should insist upon a standard of humaneness.

These depopulation methods were contemplated for use during emergencies (i.e., when there is a real and serious threat to public health and safety). But the industry has deployed them to kill animals for non-emergencies. For instance, backups at slaughterhouses due to COVID outbreaks among workers prompted farmers to kill healthy animals using VSD.[33]

WORKER EXPLOITATION AND SAFETY HAZARDS

> Viewing the sheds' diminished air quality solely as a ''hog problem'' misses the very real hazard it represented for workers.—J. Wilkinson

While these brutal killing methods manifest first in animal suffering, they also impose harm upon farmworkers who carry them out. The act of brutally killing animals takes a major toll on farmworkers' mental health.[34] And it was the physical health of slaughterhouse workers that led to the unnecessary and cruel use of emergency depopulation methods on healthy animals.[35] Coronavirus outbreaks at meatpacking plants nationwide have resulted in the deaths of more than 260 employees.[36]

Big animal agriculture's systemic worker safety issues extend beyond the recent COVID-19 outbreaks. Slaughterhouse workers have historically had one of the most dangerous jobs with high rates of injury, dismemberment, and death—and the current crisis has exacerbated the dangers of these jobs.[37] Yet, worker safety is being jeopardized even more by increased line speeds at slaughterhouses. The slaughter line is the conveyor belt-like system on which animals are hung to move through the slaughter process. Workers manually shackle chickens upside down by their legs to these lines. At 140 birds per minute, the line speed at poultry plants already caused injuries and inhumane handling problems. But at many plants, the speed was increased to 175 birds per minute.[38]

For pigs, the increase went from 1106 pigs per hour to being limitless at pork processing plants, even though faster lines result in increased food safety hazards,

[30]USDA. Highly pathogenic avian influenza response plan: The Red Book. (May 2017). <https://www.aphis.usda.gov/animal_health/emergency_management/downloads/hpai_response_plan.pdf>. (Last accessed on July 16, 2022).

[31]Ibid. at 5–44.

[32]Dorothy McKeegan. ''The Use of Foam for Depopulation of Poultry.'' *University of Glasgow.* (2018).

[33]Michael Corkery and David Yaffe-Bellamy. ''Meat Plant Closures Mean Pigs Are Gassed or Shot Instead.'' *New York Times* (May 14, 2020). <https://www.nytimes.com/2020/05/14/business/coronavirus-farmers-killing-pigs.html>. (Last accessed on July 16, 2022).

[34]Mathew Scully. ''The Human Cost of 'Culling' Livestock and 'Depopulating' Farms.'' *National Review*. (May 7, 2020). <https://www.nationalreview.com/2020/05/coronavirus-pandemic-human-cost-of-culling-livestock-depopulating-farms/>. (Last accessed on July 16, 2022).

[35]Sophie Kevany. ''Millions of Farm Animals Culled as US Food Supply Chain Chokes Up.'' *The Guardian*. (Apr. 29, 2020). <https://www.theguardian.com/environment/2020/apr/29/millions-of-farm-animals-culled-as-us-food-supply-chain-chokes-up-coronavirus>. (Last accessed on July 16, 2022).

[36]US House of Representatives. Coronavirus Infections and Deaths Among Meatpacking Workers at Top Five Companies Were Nearly Three Times Higher than Previous Estimates. (Oct. 27, 2021). <https://coronavirus.house.gov/sites/democrats.coronavirus.house.gov/files/2021.10.27%20Meatpacking%20Report.Final_.pdf>. (Last accessed on July 16, 2022).

[37]Occupational Safety and Health Administration (OSHA). Agricultural Operations. <https://www.osha.gov/agricultural-operations/hazards>. (Last accessed on July 16, 2022); Bureau of Labor Statistics, U.S. Department of Labor. ''A Look at Workplace Safety in Agriculture.'' *The Economics Daily.* <https://www.bls.gov/opub/ted/2020/a-look-at-workplace-safety-in-agriculture.htm>. (Last accessed on July 16, 2022); Penn State. ''Study Reveals Agriculture-Related Injuries More Numerous Than Previously Known.'' *Science Daily* (June 23, 2021). https://www.sciencedaily.com/releases/2021/06/210623113910.htm>. (Last accessed on July 16, 2022).

[38]Food Safety and Inspection Service (FSIS). ''FSIS' Criteria for Consideration of Waiver Requests from Young Chicken Slaughter Establishments to Operate at Line Speeds Up to 175 Birds Per Minute.'' *FSIS Constituent Update* (Feb. 23, 2018).

humane handling violations, and worker safety issues.[39] Workers struggling to keep up with fast-moving lines are at heightened risk of work-related injuries such as wrist and finger sprains or breaks and carpal tunnel. In turn, keeping up with humane handling standards becomes increasingly difficult. Also, increasing line speeds means more workers on the lines or workers moving more rapidly, which reduces their ability to distance themselves, putting them at greater risk of becoming infected, and making slaughterhouses hot spots for COVID-19.[40]

While USDA subsequently withdrew its plan to increase line speeds at poultry plants by regulation, dozens of plants still operate under waivers, allowing them to process 175 birds per minute.[41] A federal court recently invalidated the part of the agency action increasing pig line speeds.[42] While a request to stay the invalidation pending appeal was denied (even though USDA did not oppose the stay),[43] the USDA is now attempting to sidestep the rulemaking process by creating a so-called trial program that will allow up to nine facilities to apply to operate at faster processing-line speeds.[44]

Increases in line speeds cause negative downstream effects. To fulfill a steady supply of animals to meet these high rates of slaughter, production too must increase.[45] As such, the unsafe conditions during slaughtering and processing are sustained by the unsustainable scale of industrial animal agriculture in CAFOs. For the sake of the animals, workers, and food safety, USDA should revoke the waivers for poultry plants and reverse course on eliminating maximum line speeds for pigs.

ENVIRONMENTAL AND SOCIAL JUSTICE ISSUES

> At the end of all this wreckage lies an uncomfortable truth: these nuisance conditions were unlikely to have persisted for long—or even to have arisen at all—had the neighbors of Kinlaw Farms been wealthier or more politically powerful.—J. Wilkinson

Slaughterhouse and farmworkers risk their lives to keep up with the public demand for meat. These workers are often from disenfranchised groups—many are immigrants, Black, Indigenous, People of Color (BIPOC), living on low incomes, or otherwise marginalized.[46] Similarly, those who live in the communities surrounding these operations are also often oppressed or disadvantaged.[47] These community members suffer many discrete and pervasive harms from health problems and reduced life spans to air and water pollution to noise, odor, and aesthetic harms to decreased property values and diminished ability to use outdoor space or recreate safely.[48] In Judge Wilkinson's view, these ''harms are well established, almost to the point of judicial notice, to be visited disproportionately upon the dispossessed—[in the *McKiver* case] on minority populations and poor communities.''[49] The unacceptable truth that Judge Wilkinson pointed to is that these harms would not have been tolerated for as long as they have been had the surrounding community been ''wealthier or more politically powerful.''[50]

Fortunately for the plaintiffs in the *McKiver* matter, the court understood that our long-standing tort traditions are designed to protect not just the rich but everyone, especially from unreasonable, willful, and wanton conduct like that of Smithfield. But this result has been a long time coming, built upon many other disenfranchised communities that have suffered and continue to disproportionately bear the harms of big agribusinesses that have for too long acted with impunity.[51]

President Biden has committed to addressing issues of inequality in the environmental sector and bringing higher visibility to those who environmental injustices

[39]See FAC, *Farm Sanctuary et al., v. USDA et al.*, Dkt. 22, 2020 WL 5604236 (W.D.N.Y.) <https://law.lclark.edu/live/files/30373-farm-sanctuary-v-usda>. (Last accessed on July 16, 2022); see also FSIS. Modernization of Swine Slaughter Inspection. 84 Fed. Reg. 52,300 (Oct. 1, 2019).

[40]Matt McConnell. ''As line speeds increase, meatpacking workers are in ever more danger.'' *Human Rights Watch* (2018). <https://www.hrw.org/news/2019/09/18/line-speeds-increase-meatpacking-workers-are-ever-more-danger>. (Last accessed on July 16, 2022).

[41]HSUS. Biden Administration withdraws Trump-Era Plan for higher line speeds at chicken slaughterhouses (Jan 25, 2021). <https://blog.humanesociety.org/2021/01/biden-administration-withdraws-trump-era-plan-for-higher-line-speeds-at-chicken-slaughterhouses.html>. (Last accessed on July 16, 2022).

[42]*United Food and Commercial Workers Union, Local No. 663 v. U.S. Dep't of Agric.*, 2021 WL 1215865 (D.Minn., 2021).

[43]Order, *United Food and Commercial Workers Union, et al. v. Quality Pork Processors, Inc., et al.*, No. 21-2220 (8th Cir. July 15, 2021); USDA's Response with No Opposition to Motion for Stay, *United Food and Commercial Workers Union, et al. v. Quality Pork Processors, Inc., et al.*, No. 21-2220 (8th Cir. June 23, 2021).

[44]Tom Polansek. ''U.S. to allow pork plants to operate faster in trial program.'' *Reuters* (Nov. 10, 2021). <https://www.reuters.com/world/us/us-allow-pork-plants-operate-faster-trial-program-2021-11-10/>. (Last accessed on July 16, 2022).

[45]84 Fed. Reg. at 52,335.

[46]Nathan T. Dollar. ''Who are America's Meat and Poultry Workers?'' *Economic Policy Institute* (Sept. 24, 2020). https://www.epi.org/blog/meat-and-poultry-worker-demographics/>. (Last accessed on July 16, 2022).

[47]Kelley J. Donham, Steven Wing, David Osterberg, Jan L. Flora, Carol Hodne, Kendall M. Thu, and Peter S. Thorne. ''Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations.'' *Environmental Health Perspectives* 115 (2007): 317–320; Wendee Nicole. ''CAFOs and Environmental Justice: The Case of North Carolina.'' *Environmental Health Perspectives* 121 (2013): A182–A189.

[48]Nina G.G. Domingo, Srinidhi Balasubramanian, Sumil K. Thakrar, Michael A. Clark, Peter J. Adams, Julian D. Marshall, Nicholas Z. Muller, Spyros N. Pandis, Stephen Polasky, Allen L. Robinson, Christopher W. Tessum, David Tilman, Peter Tschofen, and Jason D. Hill. ''Air Quality–Related Health Damages of Food.'' *Proceedings of the National Academy of Sciences* 118 (May 2021): e2013637118.

[49]*McKiver* at 982.

[50]Ibid.

[51]Christine Ball-Blakely. ''CAFOs: Plaguing North Carolina Communities of Color.'' *Sustainable Development Law & Policy* 18 (2017): 1.3.

have negatively impacted.[52] Environmental justice should be top of mind when reviewing for deficiencies in federal rulemakings. A standing executive order requires agencies that choose to raise environmental justice when assessing an action to examine whether there are ''disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations.''[53] But agencies have not often lived up to that obligation.

When developing its HPAI response plan, USDA failed to evaluate its environmental justice impacts. First, the agency claimed that there was ''no way of determining'' the effects in advance but then concluded that its plan ''poses no disproportionate adverse effects to minority and low-income populations.''[54] This statement is entirely contradictory and legally inadequate, especially when the agency knows that there is a correlation between race, income, and exposure to hazardous waste disposal (animal carcasses included). As Judge Wilkinson put it, this connection is ''well-established—almost to the point of judicial notice.''

LEGISLATIVE BACKLASH AND RIGHT TO FARM ACTS

> The scale of industrial hog farming is no warrant to ride roughshod over the property rights of neighbors, the health of workers and community members, and the lives of the hogs themselves.—J. Wilkinson

Disappointingly, not everyone has the same sensibilities as Judge Wilkinson. While the Smithfield nuisance cases were being litigated in the Eastern District of North Carolina, the North Carolina legislature amended the State's Right to Farm Act (RTFA), limiting what remedies are available for nuisance actions to lost property value—meaning that those who experience similar harms to the plaintiffs in *McKiver* could no longer recover for damages relating to their suffering, annoyance, and loss of enjoyment.[55] This change heavily stymies restorative action and strips away long-standing property rights and protections of many already disenfranchised people. A legal challenge to North Carolina's RTFA was recently dismissed on appeal.[56]

However, all is not lost. Following the successful series of nuisance cases against Smithfield, aggrieved neighbors of similar CAFOs filed a new suit, bringing additional causes of action, including trespass, negligence, and unjust enrichment.[57] Unsurprisingly, Smithfield argued that North Carolina's newly amended RTFA bars each of these actions. Fortunately, the district court recognized that negligence, trespass, and nuisance are distinct causes of action that should be considered on their own merits and so declined to dismiss the case.[58] (Unfortunately, we have seen this approach go sideways in other jurisdictions. Courts in Indiana have found contrarily that its RTFA, which only references nuisance, also protects against negligence and trespass claims perceived to be ''repackaged'' nuisance claims).[59]

Legislative backlash is always a possible unintended consequence of pursuing any lawsuit, especially against parties associated with politically powerful industries.[60] Newly enacted legislation extends Florida's RTFA to protect CAFO operators against not only nuisance, negligence, and trespass but also claims of personal injury, strict liability, and other torts.[61] This law aims to shield farms, including large CAFOs, from multiple tort actions unless the challenged activity arises from the operation's noncompliance with state or federal environmental laws, regulations, or best management practices or is located within half a mile from the complainant's property. The law defines ''Nuisance'' as ''any interference with reasonable use and enjoyment of land, including, but not limited to, noise, smoke, odors, dust, fumes, particle emissions, or vibration. The term also includes all claims that meet the requirements of this definition, regardless of whether the plaintiff designates those claims as brought in nuisance, negligence, trespass, personal injury, strict liability, or other tort.''

The Florida Right to Farm law contains caveats that, at first glance, appear to provide some balance, such as excluding conduct that does not comply with state and federal environmental laws. But to a striking degree, federal environmental laws have insufficiently regulated harmful agricultural practices that contaminate the air, water, and soil and generate large amounts of greenhouse gas emissions.[62] Lately, these laws have been weakened even further. For instance, under recent Environmental Protection Agency (EPA) guidance (although allegedly unlawful guidance), CAFOs are no longer required to report harmful emissions under The Emergency Planning

[52]White House. Executive Order on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis. (Jan. 20, 2021). <https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-protecting-public-health-and-environment-and-restoring-science-to-tackle-climate-crisis/>. (Last accessed July 16, 2022).

[53]Exec. Order No. 12898, § 1–101 (Feb. 11, 1994).

[54]*Supra* note 10 (USDA) at 38.

[55]Robert Branan. ''North Carolina's Right to Farm Law After Smithfield Litigation.'' *NC State Extension*. <https://farmlaw.ces.ncsu.edu/land-use-and-zoning/land-ownership-and-liability/north-carolinas-right-to-farm-law-after-smithfield-litigation/>. (Last accessed on July 16, 2022).

[56]*Rural Empowerment Assoc. for Community Help, et al. v. State of North Carolina*, No. COA21-175 (N.C. Ct. App. 2021).

[57]*Barden, et al., v. Murphy-Brown, et al.*, 7:20-cv-00085 (EDNC, 2020).

[58]*Barden v. Murphy-Brown, LLC*, No. 7:20-CV-85-BR, 2021 WL 965915, at *4 (E.D.N.C. Mar. 15, 2021).

[59]*Himsel, et al., v. 4/9 Livestock, LLC, et al.*, No. 18A-PL-645 (Ind. Ct. of App. 2019).

[60]Nancy Fink Huehnergarth. ''Big Agriculture Bullies and Lobbies to Keep Americans in the Dark.'' *Forbes* (May 5, 2016). <https://www.forbes.com/sites/nancyhuehnergarth/2016/05/05/big-ag-bullies-and-lobbies-to-keep-americans-in-the-dark/?sh=688388c7502c>. (Last accessed on July 16, 2022).

[61]2021 Fla. Sess. Law Serv. Ch. 2021-7 (amending FL ST § 823.14). <https://www.flsenate.gov/Session/Bill/2021/88/ByCategory>. (Last accessed on July 16, 2022).

[62]Megan Stubbs. ''Environmental Regulation and Agriculture.'' *Congressional Research Service*. (June 16, 2014). <https://sgp.fas.org/crs/misc/R41622.pdf>. (Last accessed on July 16, 2022).

and Community Right-to-Know Act (EPCRA), 42 U.S.C. §§ 13101 *et seq*., a law designed to help warn community members of possible hazards such as dangerously high levels of ammonia or hydrogen sulfide in their area.[63]

Even if laws such as EPCRA were applied to industrial agribusiness operations to their fullest extent, many operations would still be below the thresholds that trigger these laws, yet nonetheless, create substantial nuisances for neighbors.[64] State environmental laws do very little to fill in the gaps.[65] Still, these environmental laws were not meant to address the same harms as the centuries-old tort claims of nuisance, trespass, or negligence. Lawyers and advocates should be on the lookout as other jurisdictions move to introduce similar RTFA amendments.

INSURANCE PRACTICES CAN LEAD CHANGE

> [P]laintiffs' suffering—stemming from Murphy-Brown's mistreatment of its hogs—was avoidable. … In fact, not one of the above problems is insuperable. Many can be mitigated [by, f]or example, … decreas[ing] the number of hogs penned in each shed. …—J. Wilkinson

Lawsuits do have unintended positive consequences from time to time as well. Following the successful nuisance cases in North Carolina, a growing number of insurers have been unwilling to cover many of the harmful activities of industrialized farming. Building upon the finding that Smithfield's nuisance-causing behavior was willful and wanton, its insurers argue that Smithfield was fully aware of the harms its practices would cause and therefore is not entitled to insurance benefits.[66] Indeed, these nuisance lawsuits show that there was nothing accidental about the injury to neighbors caused by the CAFO and that Smithfield knew about the harmful effects of its farming practices.[67]

Still, Smithfield sued its insurers to force coverage for similar dangerous deeds.[68] Astonishingly, Smithfield is arguing that its ACE Auto Policy requires the insurer to cover costs associated with ''Smithfield's. … operation of large trucks carrying live and dead hogs,'' which ''caused noise, dust, lights, and odors that reached and disturbed nearby landowners.''[69] Since such injuries cannot reasonably be characterized as arising from ''an 'accident' involving an automobile,'' the insurance company is contesting its supposed duty to cover the damage Smithfield's actives caused.[70]

Insurers are increasingly refusing to pay for industrialized agriculture's known harmful and dangerous practices. Heightened awareness of the clear public health risks related to extreme animal confinement and related harmful practices of Big Ag may reinforce the tendency of insurers to decline coverage or increase premiums. The risk of zoonoses from factory farms is like the risk of forest fires from power lines.[71] As the stakes become more apparent and substantiated, insurers may have an incentive to condition coverage on less risky practices—such as lower stocking density and cage and crate-free operations.

TRANSFORMATIONAL CHANGE IS NEEDED

> Finally there is Wilbur, the pig who was friends with a spider, a rat, geese, sheep, cows, and a little girl. Charlotte's Web reminds us that all life is interconnected. And while not all pigs will be pardoned like Wilbur, it is fitting that the creatures who give their very lives for us, receive in return our efforts to make their brief stay on earth less intolerable. For their sake and for ours. Such is the web of life.—J. Wilkinson

It is certainly tempting to view the recent actions by insurers, along with Judge Wilkinson's remarkable concurring opinion, as an indication of an emerging shift in public attitudes and public policy concerning industrialized animal agriculture and its deplorable treatment of farmed animals. In addition to animal welfare, society will need to take greater account of the many burdens industrialized animal agriculture disproportionately places on marginalized communities and the harms it causes our environment and climate. Transformational change in this sector will depend on stronger alliances between environmental, animal, social justice, workers' rights, public health, and other interests. Consistent with Judge Wilkinson's resonant observation: ''[F]or the animals' sake and for ours, we should take efforts to make farmed animals lives less intolerable.''[72]

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[63]EPA. CERCLA and EPCRA Reporting Requirements for Air Releases of Hazardous Substances from Animal Waste at Farms. (Apr. 30, 2018); *Rural Empowerment Assoc. for Comm. Help, et al., v. EPA, et al*., No. 18-cv-02260-TJK (D.D.C. 2018).

[64]Jon Elliott. ''Reporting EHS Releases—Responsibilities Continue Except For Some Farm Emissions. Audit.'' *Compliance and Risk Blog* (July 16, 2019). <http://blog.stpub.com/reporting-ehs-releases-responsibilities-continue-except-for-some-farm-emissions>. (Last accessed on July 16, 2022).

[65]See, for example, Lisa Sorg. ''The Plot Thickens on SBI Investigation of Duplin County Employee Over Hog Lagoon Tests.'' *NC Policy Watch* (June 6, 2018). <https://tinyurl.com/y48flst8>. (Last accessed on July 16, 2022).

[66]*Old Republic Insurance Co. v. Murphy-Brown, et al.*, 7:20-cv-00205 (EDNC, 2020).

[67]*McKiver* at 969–972, 983.

[68]*Murphy-Brown, LLC v. ACE Am. Ins. Co*., No. 19-cvs-793, 2019 WL 6878942 (N.C. Super. Dec. 16, 2019).

[69]*Murphy-Brown, LLC and Smithfield Foods, Inc. v. ACE American Insurance Company et al.*, 2021 WL 4552116 (N.C.), 2–3.

[70]Ibid.

[71]Noor Zainab Hussain. ''PG&E in California Will Pay to Bury Power Lines to Prevent Wildfires.'' *Insurance Journal* (Aug. 2, 2021). <https://www.insurancejournal.com/magazines/mag-features/2021/08/02/625030.htm>. (Last accessed on July 16, 2022).

[72]*McKiver* at 984.

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Cows swept away by flash flooding in southeastern Minnesota

fox5ny.com/news/cows-swept-away-by-flash-flooding-in-southeastern-minnesota

FOX 5 New York June 30, 2019



BYRON, Minn. (FOX 9) - Flash flooding in southeastern Minnesota swept away a herd of cows Friday morning. A video taken by Don Ehlenfeldt in Oxbow Park near Byron at 6:45 a.m. shows the cows floating downstream.

The owner of the cows, Bob Eustice, said 57 cows from his farm near the Zumbro River were swept away.

Heavy rain overnight likely caused the water to rise in a creek that runs through the pastures, and the cows were swept downstream into the river, according to Capt. Mike Bromberg, director of emergency management for Olmsted County.

Several of the cows have been located on a bank downriver, but the water remains high, and crews have no way to get to them until it recedes, he said. He estimated the cows were swept about one and a half to two miles downstream.

Officials said 35-40 of the cows have been recovered, and they are still searching.

Around 10 a.m., Olmsted County Emergency Management reported water covering the roadway on County Road 103 east of the park. According to the Facebook page, Oxbow Park and Zollman Zoo are currently closed due to flooding from the recent rain.

Bromberg said three or four roads remain closed in the county for water on the roadway.

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June 13, 2025

Paul Shriner
U.S. Environmental Protection Agency
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Re: Detailed Study of Concentrated Animal Feeding Operations Point Source Category

Paul,

On November 26, 2024, via a Dropbox link provided by the agency, Food & Water Watch provided the Environmental Protection Agency (EPA or Agency) with numerous peer-reviewed scientific studies, water quality data, and other materials to inform the Agency's ongoing study of the Concentrated Animal Feeding Operations (CAFOs) point source category. Shortly thereafter, in December 2024, EPA released its Preliminary Effluent Guidelines Program Plan 16 which, among other things, set forth the Agency's intention to complete the CAFO study by late 2025. With this target in mind, Food & Water Watch hereby submits this memorandum describing how the materials we submitted, as well as additional forthcoming materials, should inform EPA's study.

The information submitted and cited throughout this memo demonstrates that EPA must update the CAFO effluent limitations guidelines (ELGs) to account for significant new technological advancements and environmental data. EPA's hands-off approach to CAFO regulation following the *Waterkeeper*[1] and *Pork Producers Council*[2] judicial decisions has left the nation's approximately 6,174 permitted CAFOs[3] to operate with outdated and substandard pollution control technologies and practices. Meanwhile, unchecked consolidation continues to radically transform the animal agriculture industry to the detriment of consumers, family farms, and the environment.[4] Despite rampant National Pollutant Discharge Elimination System (NPDES) permit evasion—an issue that we urge

[1] *Waterkeeper Alliance v. EPA*, 399 F.3d 486 (2d Cir. 2005).
[2] *Nat'l Pork Prods. Council v. EPA*, 635 F. 3d 738 (5th Cir. 2011).
[3] EPA, NPDES PERMITTING STATUS REPORT: NATIONAL SUMMARY, ENDYEAR 2023 (May 14, 2024) https://www.epa.gov/system/files/documents/2024-06/cafo-status-report-2023.pdf [hereinafter CAFO PERMITTING INVENTORY].
[4] FOOD & WATER WATCH, FACTORY FARM NATION 2024 EDITION, https://www.foodandwaterwatch.org/2024/09/21/factory-farm-nation-2024-edition/.

EPA to address[5]—strengthening the ELGs for those facilities that are permitted would result in major water quality improvements and go a long way toward ensuring polluters are held accountable for damage to our nation's waters.

This memo first briefly outlines evidence demonstrating the undeniable and adverse water quality impacts attributable to CAFOs and their contributions to harmful health outcomes, particularly in frontline communities. Next, we set forth the legal standards that must guide EPA's review and revisions to the CAFO ELGs as provided by the Clean Water Act (CWA) and relevant case law. We then describe how the existing regulatory scheme fails to control CAFO water pollution to such an extent that updating the ELGs is the only logical course of action. Finally, we provide EPA with evidence-backed recommendations for new regulations, including technologies and practices that must be considered as the bases for updated ELGs.

An update to the CAFO ELGs is long overdue. Upon conclusion of this detailed study, EPA will be more than justified in requiring CAFO operators to comply with standards rigorous enough to protect water quality for all communities.

[5] *See* FOOD & WATER WATCH ET AL., PETITION TO REVISE THE CLEAN WATER ACT REGULATIONS FOR CONCENTRATED ANIMAL FEEDING OPERATIONS 15–22 (2017), https://www.foodandwaterwatch.org/wp-content/uploads/2021/06/citizens_cafo_cwa_petition.pdf [hereinafter 2017 PETITION] (describing the under-permitting issue and proposing a regulatory solution).

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I. CAFOs Are Discharging Pollutants to Waters of the United States

CAFOs operating under the existing ELGs are contributing to the degradation of U.S. waters. CAFOs generate, handle, and dispose of numerous harmful pollutants. These pollutants threaten public health, wildlife, and water quality as they make their way into public and private waters both above and below ground.[6] CAFOs discharge pollutants to water through various pathways, including seepage through corrals, waste storage structures, and below land application areas; overflows from waste storage structures; air deposition of volatilized pollutants; and runoff from land application fields and production areas.[7] CAFOs and their pollution are often concentrated in certain regions and watersheds, disproportionately harming environmental justice communities.[8] Additional regulatory controls are plainly necessary to remedy environmental injustice, protect the public from future harms, and comply with the CWA.[9]

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[6] EPA, LITERATURE REVIEW OF CONTAMINANTS IN LIVESTOCK AND POULTRY MANURE AND IMPLICATIONS FOR WATER QUALITY 2 (July 2013) [hereinafter EPA LITERATURE REVIEW].

[7] SCOTT BRADFORD, U.S. ENV'T PROT. AGENCY, TRANSPORT AND FATE OF NUTRIENTS AND INDICATOR MICROORGANISMS AT A DAIRY LAGOON WATER APPLICATION SITE: AN ASSESSMENT OF NUTRIENT MANAGEMENT PLANS 66 (2011); Michael A. Mallin & & Lawrence B. Cahoon, *Industrialized Animal Production—A Major Source of Nutrient and Microbial Pollution to Aquatic Ecosystems*, 24 POPULATION AND ENV'T 369, 377 (2003); EPA, DRAFT INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2022 5–12, https://perma.cc/UX33-BZLQ (discussing deposition of volatilized nitrous oxide); *see also* THOMAS HARTER ET AL., NICHOLAS INSTITUTE FOR ENVIRONMENTAL POLICY SOLUTIONS, ASSESSING POTENTIAL IMPACTS OF LIVESTOCK MANAGEMENT ON GROUNDWATER 4–7 (2014) (charting studies that documented leaching from CAFO corrals and feedlot surfaces, manure lagoons, and land application areas).

[8] *See generally* Linda Lobao & Curtis W. Stofferahn, *The Community Effects of Industrialized Farming: Social Science Research and Challenges to Corporate Farming Laws*, 25 AG. & HUMAN VALUES 219 (2007). Because industrial livestock operations necessarily entail large amounts of noxious waste and hazardous working conditions, the CAFO industry is concentrated in under-resourced areas with cheap labor and little political power to oppose them. Wendee Nicole, *CAFOs and Environmental Justice: The Case of North Carolina*, 121 ENV'T HEALTH PERSPECTIVES A183, A183 (2013). Due to institutional racism, the communities suffering the worst impacts from CAFOs are often disproportionately comprised of immigrant, Black, Hispanic, Indigenous, and low-income residents. Letter of Concern from Lilian S. Dorka, External Civil Right Compliance Office, EPA Office of General Counsel, to William G. Ross, N.C. Dep't Env't Quality (Jan. 12, 2007), https://www.epa.gov/sites/default/files/2018-05/documents/letter_of_concern_to_william_g_ross_nc_deq_re_admin_complaint_11r-14-r4_.pdf ("NC Title VI Letter"); Julia Kravchenko et al., *Mortality and Health Outcomes in North Carolina Communities Located in Close Proximity to Hog Concentrated Animal Feeding Operations*, 79 N.C. MED. J 278, 281 (2018); Julia Lenhardt & Yelena Ogneva-Himmelberger, *Environmental Injustice in the Spatial Distribution of Concentrated Animal Feeding Operations in Ohio*, 6 ENVT'L JUSTICE 133, 137 (2013); Sacoby M. Wilson et al., *Environmental Injustice and the Mississippi Hog Industry*, 110 ENV'T HEALTH PERSPECTIVES 195, 200 (2002); Phoebe Gittelson et al., *The False Promises of Biogas: Why Biogas Is an Environmental Justice Issue*, 15 ENV'T JUSTICE 352, 352–54 (2022); Ji-Young Son et al., *Disparities in Exposure to Concentrated Animal Feeding Operations (CAFOs) and Other Animal Feeding Operations Across Multiple States in USA*, J. EXPOSURE SCI. ENV'T EPIDEMIOLOGY 1, 5–7 (2025) (pagination in accordance with submitted copy).

[9] The CWA specifically authorizes EPA to consider relevant factors like public health and environmental justice when establishing ELGs. 33 U.S.C. § 1314(b)(1)(B), (b)(4)(B). EPA has considered environmental justice in establishing other ELGs. Further, EPA has already found that strengthening CAFO ELGs by "requiring specific mandatory BMPs that include treatment requirements as appropriate for both production areas and land application areas" could advance environmental justice. EPA, EPA LEGAL TOOLS TO ADVANCE ENVIRONMENTAL JUSTICE 75 (May 2022),

Nutrient pollution is one of the primary mechanisms by which CAFOs are contributing to widespread water quality issues and impairments.[10] Manure from the billions of animals currently confined in U.S. CAFOs is high in nitrogen and phosphorus. When an excess of these pollutants enter waterways via runoff, seepage, deposition, or leachate, the resulting eutrophication chokes surface waters and causes harmful algal blooms to proliferate, posing severe threats to aquatic ecosystems, drinking water sources, and recreation.[11] Eutrophication also increases methane emissions from water bodies, with the potential to significantly amplify climate impacts over the next century.[12] Even though EPA has not effectively monitored CAFO water pollution, waters in areas with dense concentrations of CAFOs have been found to contain higher nutrient pollution than areas with crop agriculture alone.[13]

Land application of CAFO waste is also a major contributor to the nitrate crises plaguing groundwater in rural communities across the country.[14] In fact, California's State Water Resources Control Board recently acknowledged that land application of dairy waste "is responsible for the vast

https://www.epa.gov/system/files/documents/2022-05/EJ%20Legal%20Tools%20May%202022%20FINAL.pdf [hereinafter EPA ENVIRONMENTAL JUSTICE REPORT].

[10] *See* GOV'T ACCOUNTABILITY OFFICE, CONCENTRATED ANIMAL FEEDING OPERATIONS: EPA NEEDS MORE INFORMATION AND A CLEARLY DEFINED STRATEGY TO PROTECT AIR AND WATER QUALITY FROM POLLUTANTS OF CONCERN 24–27 (2008) (describing several studies that found degradation caused by CAFO nutrient pollution).

[11] David Osterberg & David Wallinga, *Addressing Externalities from Swine Production to Reduce Public Health and Environmental Impacts*, 94 AM. J. OF PUB. HEALTH 1703, 1705 (2004); Julia Lenhardt & Yelena Ogneva-Himmelberger, *supra* n.8 at 134; Zach Raff & Andrew Meyer, *CAFOs and Surface Water Quality: Evidence from Wisconsin*, 104 AM. J. AGRIC. ECON. 161, 161, 163 (2022); Lorrayne Miralha et al., *The Spatial Organization of CAFOs and Its Relationship to Water Quality in the United States*, 613 J. OF HYDROLOGY 1, 1–2, 5, 7–9 (2022); Letter from Robert S. Lawrence, M.D., M.A.C.P., et al., to Illinois Department of Agriculture & Members of The Fulton County Board 4 (Mar. 2, 2017), https://www.sraproject.org/wp-content/uploads/2017/03/CLF-letter-for-Fulton-County-IL_two-swine-breeding-operations.pdf; *see generally* Apurva Lad et al., *As We Drink and Breathe: Adverse Health Effects of Microcystins and Other Harmful Algal Bloom Toxins in the Liver, Gut, Lungs, and Beyond*, 12 LIFE 1 (2022).

[12] Jake J. Beaulieu et al., *Eutrophication will increase methane emissions from lakes and impoundments during the 21st century*, 10 NATURE COMMC'NS 1, 1 (2019).

[13] STEPHEN J. KALKOFF, ET AL., U.S. GEOLOGICAL SURVEY, U.S. DEP'T. OF INTERIOR, WATER QUALITY IN THE EASTERN IOWA BASINS, IOWA AND MINNESOTA, 1996–98 13 (2000).

[14] MINNESOTA CENTER FOR ENVIRONMENTAL ADVOCACY ET AL., PETITION FOR EMERGENCY ACTION PURSUANT TO THE SAFE DRINKING WATER ACT, 42 U.S.C. § 300I, TO PROTECT THE CITIZENS OF THE KARST REGION OF MINNESOTA, 18-20 (2023); IOWA ENVIRONMENTAL COUNCIL ET AL., PETITION FOR EMERGENCY ACTION PURSUANT TO THE SAFE DRINKING WATER ACT, 42 U.S.C. § 300I, TO PROTECT THE CITIZENS OF THE KARST REGION OF IOWA, 21-26 (2024); MIDWEST ENVIRONMENTAL DEFENSE CENTER ET AL., PETITION FOR EMERGENCY ACTION PURSUANT TO THE SAFE DRINKING WATER ACT, 42 U.S.C. § 300I, TO PROTECT THE CITIZENS OF KEWAUNEE COUNTY, WISCONSIN (2014); FOOD & WATER WATCH ET AL., PETITION FOR EMERGENCY ACTION PURSUANT TO THE SAFE DRINKING WATER ACT § 1431, 42 U.S.C. § 300I, TO PROTECT CITIZENS OF THE LOWER UMATILLA BASIN IN OREGON, 15-20 (2020); CENTER FOR FOOD SAFETY ET AL., PETITION FOR EMERGENCY ACTION UNDER SECTION 1431 OF THE SAFE DRINKING WATER ACT TO PROTECT RESIDENTS OF THE LOWER YAKIMA VALLEY, WASHINGTON, 16-23 (2021) [hereinafter SDWA Petitions, collectively].

majority of dairies' nitrogen impacts to groundwater quality."[15] Ingesting water contaminated with nitrates is associated with dangerous health conditions like colorectal cancer, thyroid disease, birth defects, premature births, and methemoglobinemia (a potentially fatal condition commonly known as "blue baby syndrome").[16] EPA has received at least five petitions for emergency action under the Safe Drinking Water Act from citizens living in hotbeds of CAFO activity, detailing how high concentrations of industrial livestock facilities are driving pervasive high groundwater nitrate concentrations.[17] Water quality testing cited in these petitions and elsewhere reveals elevated nitrate levels in groundwater beneath and downstream from CAFOs that jeopardize the health of nearby residents.[18]

Seepage from liquid waste storage structures (often called "lagoons" or "ponds") is another notable source of nitrate pollution.[19] While some states have independently required that unlined lagoons meet minimum permeability standards like the 1 x 10^{-6} cm/s standard in Appendix 10D to the United States Department of Agriculture's (USDA) Agricultural Waste Management Field Handbook, even storage structures built to this standard are "designed to leak."[20] To this point, EPA recently had to file a second enforcement action against several dairy CAFOs in Washington's Lower Yakima Valley due to the CAFOs' failure to comply with a consent decree intended to remedy nitrate contamination leaching from their facilities.[21] Despite provisions in the Washington NPDES General Permits that require CAFO lagoons to meet the minimum permeability standards outlined in

[15] STATE OF CALIFORNIA STATE WATER RESOURCES CONTROL BOARD, DRAFT ORDER 2024-00XX, IN THE MATTER OF REVIEW OF WASTE DISCHARGE REQUIREMENTS GENERAL ORDER NO 05-2013-0122 FOR MILK COW DAIRIES IN THE CENTRAL VALLEY REGION at 6 (Oct. 1, 2024) [hereinafter CA DAIRY ORDER].
[16] Mary H. Ward et al., *Drinking Water Nitrate and Human Health: An Updated Review*, 15 Int. J. Res. Public Health 1, 22 (2018) (pagination in accordance with submitted copy); JoAnn Burkholder, et al., *Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality*, 115 ENV'T HEALTH PERSPECTIVES 308, 310 (2007); *see generally* Roberto Picetti et al., *Nitrate and Nitrite Contamination in Drinking Water and Cancer Risk: A Systematic Review with Meta-Analysis*, 210 ENV'T RSCH. 1 (July 2022) (metastudy of health risks associated with nitrate pollution) (pagination in accordance with submitted copy).
[17] *See* SDWA Petitions, *supra* n.14.
[18] *Id.*; *see also* DAVID J. ERICKSON, WATER & ENVIRONMENTAL TECHNOLOGIES, EXPERT OPINION ON THE IDAHO CAFO GENERAL PERMIT 7, Attachment 1 (Aug. 23, 2023), [hereinafter Erickson Report] (describing nitrate plumes encountered during CAFO investigations).
[19] MELANIE REDDING, WASH. STATE DEP'T OF ECOLOGY, MANURE & GROUNDWATER QUALITY: LITERATURE REVIEW 63 (June 2016), [hereinafter WA LITERATURE REVIEW].
[20] *Food & Water Watch v. EPA*, 20 F.4th 506, 509 (2021) (quoting *Cmty. Ass'n for Restoration of the Env't, Inc. v. Cow Palace, LLC*, 80 F. Supp. 3d 1180, 1223 (E.D. Wash. 2015)).
[21] U.S. Department of Justice, *Department of Justice and EPA File Complaint Against Lower Yakima Dairies for Failing to Control Nitrate Contamination in Drinking Water* (June 26, 2024), https://www.justice.gov/usao-edwa/pr/department-justice-and-epa-file-complaint-against-lower-yakima-valley-dairies-failing.

Appendix 10D,[22] EPA's allegations indicate the dairies' lagoons are still contributing to dangerously high nitrate levels in groundwater.[23]

CAFOs also degrade waters by emitting ammonia from ventilation systems that subsequently deposits on land and surface waters.[24] CAFOs emit ammonia at much higher rates than pasture-raised operations due to greater reliance on silage and manure storage as well as high pressure spray irrigation of wastes.[25] Volatilized ammonia can account for up to 70 percent of nitrogen excreted by confined livestock.[26] Modeling suggests that over 500 tons of ammonia from poultry CAFOs are deposited into the Chesapeake Bay every year in this manner.[27] The adverse impacts of air deposition from CAFOs in the Delmarva Peninsula has led Maryland's Department of Environment to include best management practices (BMPs) targeting air deposition of ammonia in the state's NPDES general permit for CAFOs.[28] EPA must follow suit and amend the CAFO ELGs to safeguard waters across the country from this currently overlooked water pollution pathway.

In addition to exacerbating nutrient pollution, CAFOs also contribute to the spread of dangerous pathogens.[29] CAFO waste that reaches surface waters or groundwater increases the risk of pathogen transmission to animals and humans in the surrounding environment.[30] Researchers have

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[22] *Wash. State Dairy Fed'n v. Dep't of Ecology*, 18 Wn. App. 2d 259, 271 (Wash. Ct. App. 2021); *Friends of Toppenish Creek v. Wash. Dep't of Ecology*, PCHB No. 23-002, Order on Summary Judgment 9–10 (Feb. 6, 2025).
[23] U.S. Dep't of Justice, *supra* n.23 at 21–31, 33–34.
[24] Jordan Baker et al., *Modeling and Measurements of Ammonia from Poultry Operations: Their Emissions, Transport, and Deposition in the Chesapeake Bay*, 706 SCI. TOTAL ENV'T 1, 28 (2020), https://www.sciencedirect.com/science/article/abs/pii/S0048969719352829?via%3Dihub (pagination in accordance with submitted copy); Burkholder, *supra* n.16 at 308–312.
[25] Alyssa M. Burns, et al., *Data Gap: Air Quality Networks Miss Air Pollution from Concentrated Animal Feeding Operations*, 57 ENV'T SCI. & TECH. 20718, 20720 (2023).
[26] Horacio A. Aguirre-Villegas & Rebecca A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, 143 J. CLEANER PRODUCTION 169, 169 (2017); *see also* EPA, DEVELOPMENT DOCUMENT FOR THE FINAL REVISIONS TO THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM REGULATION AND THE EFFLUENT GUIDELINES FOR CONCENTRATED ANIMAL FEEDING OPERATIONS 6-30 (Dec. 2002), [hereinafter 2003 TDD] (estimating that a quarter of total nitrogen deposition onto beef feedlot surfaces is lost to volatilization).
[27] *Id.*
[28] *See Md. Dep't of the Env't v. Assateague Coastal Trust*, 484 Md. 399, 484 (2023) (recognizing state and federal authority to regulate air deposition to surface waters through NPDES permits and citing evidence that air deposition of ammonia from CAFOs is a significant source of nitrogen to Maryland's waters); Baker, *supra* n.**Error! Bookmark not defined.** at 3.
[29] GOV'T ACCOUNTABILITY OFFICE, *supra* n.10 at 24–28 (describing studies establishing links between CAFOs and exposure to hazardous bacteria and bacterial components such as *E. coli*, *campylobacter*, and endotoxin); EPA LITERATURE REVIEW, *supra* n.6 at 58–63 (listing confirmed and suspected outbreaks associated with manure and describing contamination pathways).
[30] Lawrence, *supra* n.11 at 2–4; Letter from James D. Yager, Ph.D, et al., Johns Hopkins Center for a Livable Future, to Michael Rife et al., Montgomery Township Supervisors 2–3 (Jun. 1, 2017); Letter from Robert Martin et al., Johns

documented fecal bacteria from swine in surface waters downstream from CAFO hotspots at levels that exceed state and federal water quality standards.[31] Fecal material can also be dispersed through air. A recent study conducted by Johns Hopkins Bloomberg School of Public Health found that "fecal matter from swine CAFOs is contributing to the contamination of indoor and outdoor household surfaces of nearby community residents," with 44 percent of neighboring residences and 38 percent of CAFO worker residences testing positive for swine microbes.[32]

Further, CAFOs routinely administer antibiotics for non-therapeutic purposes, thereby contributing to the discharge and proliferation of pharmaceuticals and antibiotic-resistant bacteria that threaten aquatic life and human health.[33] Bacteria can survive in untreated farm animal waste for up to 12 months, while up to 75 percent of administered antibiotics are not metabolized by animals and so persist in waste and in soil after land application.[34] Even when waste is treated by anaerobic digesters, digestate can maintain favorable conditions for antibiotic-resistant genes to develop and spread to the bacteria in surrounding water, soil, and air.[35] Infections caused by antibiotic-resistant

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Hopkins Center for a Livable Future, to State of Hawai'i Department of Health and Office of Environmental Quality Control 2 (Feb. 5, 2018); Xunde Li, et al., *Fecal Indicator and Pathogenic Bacteria and Their Antibiotic Resistance in Alluvial Groundwater of an Irrigated Agricultural Region with Dairies*, 44 J. OF ENV'T QUALITY 1435, 1435 (2015); CARRIE HRIBAR, NAT'L ASSOC. OF LOC. BDS. OF HEALTH, UNDERSTANDING CONCENTRATED ANIMAL FEEDING OPERATIONS AND THEIR IMPACT ON COMMUNITIES, 10–11 (Mark Schultz, 2010); Burkholder, *supra* n.16 at 308; Tucker R. Burch et al., *Quantitative Microbial Risk Assessment for Contaminated Private Wells in the Fractured Dolomite Aquifer of Kewaunee County, Wisconsin*, 129 ENV'T HEALTH PERSPECTIVES 067003-1, 067003-1 (2021); *See* Timothy P. Neher et al., *Catchment-Scale Export of Antibiotic Resistance Genes and Bacteria from an Agricultural Watershed in Central Iowa*, 15 PLOS One 1, 12 (Jan. 2020) (field experiment in Iowa demonstrating elevated fecal bacteria and antibiotic resistance indicators in catchments downstream from CAFOs) (pagination in accordance with submitted copy); *see also* WORLD ANIMAL PROTECTION, SILENT SUPERBUG KILLERS IN A RIVER NEAR YOU: HOW FACTORY FARMS CONTAMINATE PUBLIC WATER COURSES ON THREE CONTINENTS 19 (2021); Martin, *supra* n.30.

[31] Christopher D. Heaney et al., *Source Tracking Swine Fecal Waste in Surface Water Proximal to Swine Concentrated Animal Feeding Operations*, 511 SCI. TOTAL ENV'T 1, 8 (2015) (pagination in accordance with submitted copy).

[32] Kathleen M. Kurowski et al., *Swine Production Intensity and Swine-Specific Fecal Contamination of Household Surfaces at Residences of Industrial Livestock Operation Workers and Community Residents, North Carolina, USA*, 985 SCI. TOTAL ENV'T 1, 7 (2025).

[33] EPA LITERATURE REVIEW, supra n.6 at 49–56; Martin, *supra* n.30; Yager, et al., *supra* n.30 at 2; S. Koike, et al., *Monitoring and Source Tracking of Tetracycline Resistance Genes in Lagoons and Groundwater Adjacent to Swine Production Facilities Over a 3-Year Period*, 73 APPLIED AND ENV'T MICROBIOLOGY 4813, 4822 (2007); Mao et al., *Distribution and Antibiotic Resistance Profiles of Salmonella enterica in Rural Areas of North Carolina After Hurricane Florence in 2018*, 5 GEOHEALTH 1, 12 (2020); Burkholder, *supra* n.16 at 309; *see generally* Randhir P. Deo, *Pharmaceuticals in the Surface Water of the USA: A Review*, 1 CURR. ENV'T HEALTH REPORT 113, 114 (2014) (identifying CAFOs as a source of pharmaceutical pollution in surface waters and calling for monitoring and increased source controls); Airu Huang et al., *A Review of Processes for Removing Antibiotics from Breeding Wastewater*, 18 INT'L J. ENV'T. RSCH. PUBLIC HEALTH 1, 2 (2021) ("With the development of the breeding industry and the widespread application of antibiotics, a large amount of wastewater containing antibiotics is produced. If this is discharged into the environment without effective treatment, it will cause serious pollution, altering the ecological balance and endangering human health.").

[34] WORLD ANIMAL PROTECTION, *supra* n.30; J.C. Chee-Sanford et al., *Occurrence and Diversity of Tetracycline Resistance Genes in Lagoons and Groundwater Underlying Two Swine Production Facilities*, 67 APPLIED ENV'T MICROBIOLOGY 1494, 1494 (2001).

[35] WORLD ANIMAL PROTECTION, *supra* n.30; Chee-Sanford, *supra* n.34 at 1501; Mao, *supra* n.33 at 12.

bacteria are more difficult and expensive to treat, and more likely to be fatal than non-resistant strains.[36] Residents unlucky enough to live near CAFOs are at heightened risk of contracting a waterborne illness generally[37] in addition to facing uniquely high risks from antibiotic-resistant bacteria.[38]

Hormones and other pharmaceuticals present in CAFO waste pose additional threats to humans and wildlife.[39] Heightened levels of hormones naturally present in animal waste as well as synthetic pharmaceutical-grade growth hormones commonly administered to livestock have consistently been found in surface waters, groundwater, and spring water surrounding CAFOs.[40] These hormones, especially synthetic hormones with longer half-lives,[41] alter the reproductive biology and development of aquatic species in waters near CAFOs. Changes observed include demasculinization and defeminization of fish, decreased fertility in female fish, and abnormal reproductive proteins in turtles.[42] Other veterinary pharmaceuticals can remain in manure and leachates even during prolonged storage, and have been documented in water resources surrounding CAFOs.[43] For instance, livestock fed ractopamine—a beta-agonist used to artificially hasten animal growth—excrete 95 percent of the administered dose within 3 days of consumption.[44] When waste containing ractopamine is discharged to waters, the pollution induces harmful behavioral changes and oxidative stress in fish.[45]

Exposure to these pharmaceuticals in drinking water raises risks stemming from "cumulative effects of long-term low-dose exposure," as well as unintentionally ingesting pharmaceuticals that are

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[36] Martin, *supra* n.30.
[37] Martin, *supra* n.30.
[38] Lawrence, *supra* n.11; Yager, *supra* n.30; Martin, *supra* n.30; WORLD ANIMAL PROTECTION, *supra* n.30; Koike, *supra* n.33; Mao, *supra* n.33; Chee-Sanford, *supra* n.34; Xunde Li, *supra* n.30 at 1435, 1441, 1443, 1445; Burkholder, *supra* n.16 at 310.
[39] EPA LITERATURE REVIEW, *supra* n.6 at 56–57; GOV'T ACCOUNTABILITY OFFICE, CONCENTRATED ANIMAL FEEDING OPERATIONS: EPA NEEDS MORE INFORMATION AND A CLEARLY DEFINED STRATEGY TO PROTECT AIR AND WATER QUALITY FROM POLLUTANTS OF CONCERN 24 (2008); HRIBAR, *supra* n.30 at 5; Edward F. Orlando, et al., *Endocrine-Disrupting Effects of Cattle Feedlot Effluent on an Aquatic Sentinel Species, the Fathead Minnow*, 112 ENV'T HEALTH PERSPECTIVES 353, 356–357 (2004); Burkholder, *supra* n.16 at 308; BRADFORD, *supra* n.7 at 1, 12, 66.
[40] Orlando, et al., *supra* n.39 at 353–354; HRIBAR, *supra* n.30 at 5.
[41] Orlando, et al., *supra* n.39 at 357.
[42] *Id.* at 353, 356–357; HRIBAR, *supra* n.30 at 5.
[43] Burkholder, *supra* n.16 at 308–9; S. Bartelt-Hunt et al., *Occurrence of Steroid Hormones and Antibiotics in Groundwater Impacted by Livestock Waste Control Facilities*, 123 J. CONTAM. HYDROL. 94 (April 2011).
[44] Georges Bories et al., European Food & Safety Authority, *Scientific Opinion of the Panel on Additives and Products or Substances Used in Animal Feed: Safety Evaluation of Ractopamine*, 1041 THE EUROPEAN FOOD SAFETY AUTHORITY J. 1-52, 8-52 (2009).
[45] *See generally* A. Sachett et al., *Ractopamine Hydrochloride Induces Behavioral Alterations and Oxidative Status Inbalance in Zebrafish*, 81 J. TOXICOLOGY & ENV'T HEALTH, Pt. A (Feb. 2018).

incompatible with an individual's prescribed medication.[46] These observations led researchers to the conclusion that "generally accepted livestock waste management practices do not adequately or effectively protect water resources from contamination with excessive nutrients, microbial pathogens, and pharmaceuticals present in the waste."[47]

Salts, heavy metals, semimetals, and other trace elements added to feed and eventually expelled by livestock also impact water quality.[48] CAFO waste is known to contain many of the same elements found in sewage sludge, including "arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, and zinc."[49] Following a 2009 petition for rulemaking that chronicled reports of residual arsenic in meat and poultry food products,[50] the Food and Drug Administration withdrew its approvals of feed additives with arsenic. However, other elements that are not agronomically useful or taken up by crops remain in feed and wastes, resulting in accumulation and metal-contaminated runoff.[51] In North Carolina, for example, excessive accumulations of zinc and copper in areas with high concentrations of industrial animal agriculture have degraded soil quality to toxic levels.[52] Excessive salt in CAFO waste also impacts soil quality and can actually restrict crop establishment and growth.[53] In this manner, allowing land application of CAFO waste that has not been treated or even tested for metals and other trace elements directly undermines plant growth and contributes to overapplication of manure, fertilizer, and soil amendments that further reduce water quality.

II. EPA Must Adhere to CWA Requirements When Evaluating the CAFO ELGs

In setting the CAFO ELGs, EPA must "identify, in terms of amounts and constituents and chemical, physical, and biological characteristics of pollutants, the degree of effluent reduction attainable through the application of [the applicable technological standard]."[54] Pollutant reductions mandated by the ELGs will vary based on whether the facility is new or existing. Because new sources

[46] Burkholder, *supra* n.16 at 310.
[47] *Id.* at 308.
[48] *Id.*; BRADFORD, *supra* n.7 at 1, 12, 66; EPA LITERATURE REVIEW, *supra* n.6 at 43–47.
[49] National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitations Guidelines and Standards for Concentrated Animal Feeding Operations, 66 Fed. Reg. 2960, 2978 (Jan. 12, 2001).; Burkholder, *supra* n.16 at 308.
[50] *See generally* CENTER FOR FOOD SAFETY & INSTITUTE FOR AGRICULTURE AND TRADE POLICY, CITIZEN PETITION TO THE FOOD AND DRUG ADMINISTRATION (Dec. 8, 2009), https://www.centerforfoodsafety.org/files/arsenic-petition-12-8-09-final_67875.pdf.
[51] 66 Fed. Reg. at 2978.
[52] Steph Kulesza et al., *Mitigating Zinc and Copper Toxicity in North Carolina Soils* (March 27, 2024), https://content.ces.ncsu.edu/mitigating-zinc-and-copper-toxicity-in-north-carolina-soils.
[53] BRADFORD, *supra* n.7 at 14–15.
[54] 33 U.S.C. §§ 1314(b)(1)(A), 1316(a)(1).

can install cutting edge pollution reduction technologies and practices without the added cost of retrofitting, the CWA imposes stricter limitations on those facilities. In this manner, the Act is "technology forcing."[55]

Under the Act, the relevant technological standards are: (1) best practicable technology currently available (BPT), (2) best available technology economically achievable (BAT), (3) best conventional pollutant control technology (BCT), and best available demonstrated control technology (BADT). In addition to establishing technological bases for effluent limitations, CWA Section 304 also authorizes EPA to promulgate rules establishing BMPs to control toxic and hazardous pollutants, runoff, spillage and leaks, sludge or waste disposal, and drainage from materials storage that may contribute significant amounts of pollutants to jurisdictional waterways.[56]

The BAT standard represents the CWA's current[57] level of pollution reduction stringency required to control the discharge of toxic and nonconventional pollutants (including nutrients) from existing sources.[58] In general, EPA must set BAT based upon the best available technology EPA determines to be economically achievable across the category or subcategory as a whole.[59] Availability for BAT purposes is not dependent on temporal availability of the requisite technology to any one plant.[60] Rather, "BAT limitations must be based on the performance of the best-performing plant in an industrial field."[61] Importantly, the "industrial field" is not limited to CAFOs. It also includes other point source categories employing pollution control practices that could be transferred to achieve

[55] *See NRDC v. EPA*, 822 F.2d 104, 123–24 (D.C. Cir. 1987) ("Thus, the most salient characteristic of this statutory scheme, articulated time and again by its architects and embedded in the statutory language, is that it is technology-forcing . . . . This policy is expressed as a statutory mandate, not simply as a goal."); *Sw. Elec. Power Co. v. U.S. EPA*, 920 F.3d 999, 1003, 1005 (5th Cir. 2019) (contrasting the technology-based ELG system with a system based on water quality and citing cases).
[56] 33 U.S.C. § 1314(e).
[57] Point sources were first required to achieve the level of pollution reduction attainable by technologies and practices determined to be BPT by 1989. Since 1989, BAT has replaced this lesser standard.
[58] *Id.* at §§ 1311(b)(2)(A), 1314(b)(2)(B).
[59] *Sw. Elec.*, 920 F.3d at 1006.
[60] *Chem. Mfrs. Ass'n v. EPA*, 870 F.2d 177, 243 (5th Cir. 1989); *see also NRDC v. EPA*, 808 F.3d 556, 576–77 (2d Cir. 2015) (emphasizing that lack of supply was not a legitimate reason to exempt a subcategory from installing BAT because "the purpose of BAT is to force technology to keep pace with need").
[61] *Sw. Elec.*, 920 F.3d at 1006, 1018; *Chem. Mfrs. I*, 870 F.2d at 226; *see also Kennecott v. EPA*, 780 F.2d 445, 448 (4th Cir. 1985) ("In setting BAT, EPA uses not the average plant, but the optimally operating plant, the pilot plant which acts as a beacon to show what is possible.")

similar effluent treatment in the CAFO context.[62] Thus EPA must consider transferrable technologies when updating the CAFO ELGs.

BAT must "represent a commitment of the maximum resources economically possible to the ultimate goal of eliminating all polluting discharges."[63] As such, courts have referred to this as the CWA's "gold standard" for controlling discharges from existing sources.[64] The factors that control EPA's designation of BAT are: (1) the age of equipment and facilities involved, (2) the processes employed, (3) the engineering aspects of the application of various types of control technologies, (4) process changes, (5) the cost of achieving such effluent reduction, (6) non-water quality impacts (including energy requirements), and (7) any other factors EPA deems appropriate.[65] The Supreme Court has stated that BAT must be set in a manner that reflects "reasonable further progress" beyond BPT toward the CWA's ultimate goal of eliminating pollutant discharges.[66] Setting BAT beyond previous ELG iterations is critical to achieving the CWA's mandate that pollution control requirements become more stringent over time.[67] For this reason, courts reviewing ELGs reject reliance on an expansive view of "other factors" to block adoption of stronger effluent limits.[68]

BCT represents the current level of stringency for controlling discharge of conventional pollutants from existing sources.[69] "BCT is not an additional level of control, but replaces BAT for conventional pollutants."[70] Per the CWA, EPA must choose BCT based on "consideration of the reasonableness of the relationship between the costs of attaining a reduction in effluents and effluent reduction benefits derived, and the comparison of the cost and level of reduction of such pollutants from the discharge from publicly owned treatment works to the cost and level of reduction of such pollutants from a class or category of industrial sources."[71] The two parts of the BCT cost assessment

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[62] *Cal. & Haw. Sugar Co. v. EPA*, 553 F.2d 280, 287–88 (2d Cir. 1977); *see also NRDC*, 808 F.3d at 564, 572–573 ("EPA can mandate that BAT requires use of a technology that is not currently available within a particular industry when (1) the technology is available in another industry, (2) EPA finds that the technology is transferrable from that other industry, and (3) EPA can reasonably predict that such technology will adequately treat the effluent.").
[63] *NRDC v. EPA*, 863 F.2d 1420, 1426 (9th Cir. 1988).
[64] *Sw. Elec.*, 920 F.3d at 1003.
[65] 33 U.S.C. § 1314(b)(2)(B).
[66] *EPA v. Nat'l Crushed Stone*, 449 U.S. 64, 74 (1980) (quoting 33 U.S.C. § 1311(b)(2)(A)); *see also NRDC*, 808 F.3d at 576 ("[A]gain, the purpose of BAT is to force technology to keep pace with need.").
[67] *See NRDC*, 822 F.2d at 123–24 ("Thus, the most salient characteristic of this statutory scheme, articulated time and again by its architects and embedded in the statutory language, is that it is technology-forcing . . . . This policy is expressed as a statutory mandate, not simply as a goal.").
[68] *Sw. Elec.*, 920 F.3d at 1016–20.
[69] 33 U.S.C. §§ 1311(b)(2)(E), 1314(b)(4).
[70] *BP Exploration v. EPA*, 66 F.3d 784, 790 (6th Cir. 1995).
[71] 33 U.S.C. § 1314(b)(4)(B).

have come to be known as the "industry cost-effectiveness test" and the "POTW test."[72] Beyond these tests, the CWA further compels EPA to "take into account" the familiar BAT consideration factors: age, processes used, engineering factors, process changes, environmental impacts, and other factors as EPA deems appropriate.[73]

The last of the technological controls, BADT, must be set at the most stringent treatment level attainable by a CAFO.[74] As new sources are uniquely capable of installing the most effective and efficient production processes and wastewater treatment technologies up front, without the added costs of retrofitting, "EPA is statutorily required to give serious consideration to a standard permitting *no* discharge of pollutants."[75] However, as the name indicates, any zero-discharge standard for new sources must be demonstrably attainable, e.g. proven with monitoring data. A technology may qualify as "demonstrated" when even one facility employs that technology to achieve a greater degree of effluent reduction than it could achieve using a less effective technology or practice.[76]

In setting new source performance standards (NSPS), EPA must consider two factors: "the cost of achieving such effluent reduction, and any non-water quality environmental impact and energy requirements."[77] In determining whether the cost of a candidate BADT can be reasonably borne by a subcategory, the relevant consideration is the incremental cost of compliance relative to the cost of the new facility as a whole.[78] Accordingly, even technologies that may impose a reasonable measure of financial burden on CAFO owners are appropriate to use as a basis for NSPS.

Finally, EPA must consider additional BMPs to control CAFO pollutants. BMPs can serve as technology-derived standards in EPA's guidelines where numeric effluent limits are "infeasible."[79] EPA's authority to mandate the use of BMPs does not detract from its obligation to issue technology-based standards where feasible. Moreover, when resorting to BMPs in place of numeric technology-

[72] *Am. Paper Inst. v. EPA*, 660 F.2d 954, 960–61 (4th Cir. 1981).
[73] 33 U.S.C. § 1314(b)(4)(b).
[74] *Chem. Mfrs.*, 870 F.2d at 261 ("Congress also recognized that new sources are uniquely situated to push toward the outer envelope of pollution control technology in a way that will further progress toward the national goal of eliminating the discharge of all pollutants.").
[75] *NRDC*, 822 F.2d at 123 (citing 33 U.S.C. § 1316(b)(1)(B)).
[76] *Chem. Mfrs.*, 870 F.2d at 263–64 (citing *Am. Iron & Steel Inst. v. EPA*, 526 F.2d 1027, 1058 (1975)).
[77] 33 U.S.C. 1316(b)(1)(B). Though this test mirrors the BAT methodology, BADT must advance the CWA's goal of achieving further pollution reductions. *Chem. Mfrs.*, 870 F.2d at 263 (calling it "intuitive" that Congress would not create separate schemes for new and existing sources if it intended the standards to be identical).
[78] *Nat'l Wildlife v. EPA*, 286 F.3d 554, 571 (D.C. Cir. 2002).
[79] *NRDC v. Costle*, 568 F.2d 1369, 1380 (D.C. Cir. 1977); 40 C.F.R. § 122.44(k).

based standards, EPA must still demonstrate that the pollutant reductions required by the standard can be achieved by those BMPs.[80]

III. The Current CAFO ELGs Are Inadequate and a Failure to Revise Them Following the Detailed Study Would Be Arbitrary and Capricious

The current CAFO ELGs impose several BMP requirements on Large CAFOs confining poultry, swine, dairy and beef cattle.[81] To meet the production area prohibition against any discharge except some precipitation-induced overflows, EPA has established as BPT, BCT, BAT, and BADT requirements for CAFOs to design, construct, operate, and maintain the production area to contain CAFO waste and precipitation runoff from a 25-year, 24-hour rainfall event; conduct certain routine visual inspections of the production area; install depth markers in waste impoundment structures; handle animal mortalities to prevent discharges; and maintain relevant records.[82]

To meet the land application effluent limitation that requires CAFOs to minimize the transport of nutrients to surface waters, EPA has established as BPT, BCT, BAT, and BADT requirements for CAFOs to develop and implement a nutrient management plan (NMP) that includes application rates to achieve realistic crop production goals, infrequent manure and soil sampling provisions, inspection of land application equipment for leaks, minimum setback distances, and recordkeeping.[83]

A wealth of evidence demonstrates that these CAFO ELGs are not adequate to protect waters of the U.S. from pollutant discharges or achieve applicable effluent limits. As explained more fully below, not only do the current production area requirements fail to achieve the zero-discharge effluent limit, but the land application BMPs currently in place likewise fail to minimize nutrient transport to surface waters. Because EPA has a statutory obligation to ensure that the CAFO ELGs are actually achieving the effluent limits the Agency has set, it must update these deficient ELGs accordingly.

Not only have these deficient ELGs resulted in ineffective permits, they are also at the crux of the widespread failure to permit discharging CAFOs in the first place.[84] The current regulations' primary limitation on discharging CAFOs is a narrative standard requiring these operations to implement NMPs that will "minimize phosphorous and nitrogen transport" from land application

[80] *Citizens Coal v. EPA*, 447 F.3d 879, 899–900 (6th Cir. 2006).
[81] *See* 40 C.F.R. §§ 412.30 and 412.40 (limiting ELG applicability to operations exceeding Large CAFO size thresholds). *See also id.* at § 122.23(b)(4).
[82] *See id.* at §§ 412.31(a), 412.32(a), 412.33(a), 412.35(a), 412.37(a)–(b), 412.43(a), 412.44(a), 412.45(a), 412.46(a).
[83] *See id.* at §§ 412.4, 412.31(b), 412.32(b), 412.33(b), 412.35(b), 412.37(c), 412.43(b), 412.44(b), 412.45(b), 412.46(b).
[84] Though EPA has estimated that 75 percent of CAFOs discharge and thus need NPDES permits, *see* Revised National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines for Concentrated Animal Feeding Operations in Response to the Waterkeeper Decision, 73 Fed. Reg. at 70418, 70469 (Nov. 20, 2008), less than 30 percent of CAFOs are currently permitted. *See* CAFO PERMITTING INVENTORY, *supra* n.3.

fields to surface waters.[85] Thus, the regulations effectively acknowledge that at absolute best, NMPs are only expected to *minimize* dry weather discharges from land applying CAFOs.[86] At the same time, the regulations allow CAFOs to implement the very same NMPs to escape permitting altogether, paradoxically assuming that an unpermitted CAFO with a NMP can somehow *eliminate* dry weather discharges such that they don't need a permit at all.[87] This circular logic and fundamental misunderstanding of what nutrient management planning is capable of has led to an under-permitting crisis. By EPA's own estimate, nearly 10,000 CAFOs discharge point source pollution yet unlawfully evade permitting.[88]

EPA must update the CAFO ELGs to ensure that all discharging CAFOs are subject to strong pollution control standards that protect water quality. The CAFO ELGs are critically flawed for numerous reasons, including: (1) NMPs—the primary BMP prescribed by EPA regulations—are not effective at even minimizing nutrient loss (much less eliminating it); (2) the ELGs ignore numerous other pollutants of concern; (3) the ELGs do not prohibit myriad practices known to harm water quality; (4) the ELGs entirely overlook subsurface discharges that reach jurisdictional waters; (5) the ELGs fail to address aerial deposition of pollutants to waterways; and (6) the ELGs are not based on representative effluent monitoring.

A. NMPs Are Not as Effective at "Minimizing" Nutrient Loss as Current Guidelines Assume

As EPA has already concluded, NMPs—the primary BMP required by current CAFO ELGs—are not sufficiently protective of water quality for the simple reason that they are not designed to minimize nutrient runoff to waterways (nor do they to any significant degree). Rather, the primary goal of nutrient management planning is to maximize crop yields. Even while acknowledging that NMP application rates are "agronomic rather than water-quality based,"[89] EPA has long relied on the faulty assumption that applying manure at recommended application rates will prevent excessive pollution runoff from CAFO land application fields.[90] Yet the Agency recently found the opposite to

[85] 40 C.F.R. § 412.4(c)(2).
[86] *See id.* at § 122.23(e) ("EPA entirely exempts from regulation all precipitation-related discharges from CAFO fields covered by NMPs as "agricultural stormwater.").
[87] *Id.*
[88] EPA estimates there are approximately 21,179 CAFOs nationwide, 6,174 of which have NPDES permits. *See* CAFO PERMITTING INVENTORY, *supra* n.3. If 75 percent (15,884) of CAFOs discharge, an additional 9,710 unpermitted CAFOs should be covered under the NPDES program.
[89] EPA, Confined Animal Feeding Operations: An Overview of the NPDES CAFO Program Mostly by the Numbers 28 (June 2019) (EPA presentation on the CAFO industry and the NPDES regulatory program for CAFOs).
[90] National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations (CAFOs), 68 Fed. Reg. 7176, 7197 (Feb. 12, 2003) (finding that land application "in accordance with practices designed to ensure appropriate agricultural utilization of nutrients" will "minimize[] the potential for subsequent discharge of pollutants to waters of the United States").

be true, concluding that agronomic rates are in fact *not* achieving effluent limitations that require CAFOs to minimize transport of nutrients to surface waters. In 2021, EPA conceded that "[e]ven if CAFOs were to comply with their NMPs, *their standards are insufficient*. NMP standards are set by each state, and states typically rely on USDA standards, which focus on maximizing crop growth, *rather than on preventing excess nutrient runoff.*"[91] In other words, the dual goals, expressed in EPA's regulations and state technical standards, of maximizing production and minimizing pollution are simply incompatible.[92]

State regulators have made similar findings. For instance, in reviewing its waste discharge requirements for dairy CAFOs, the California State Water Resources Control Board recently concluded that land application at agronomic rates "is responsible for the vast majority of dairies' nitrogen impacts to groundwater"—often a pollution pathway to hydrologically connected jurisdictional surface waters—"forc[ing] [the State] to take a hard look at what [it] now recognizes has been an inadequate approach for regulating dairy waste discharges."[93] The Board further determined that, going forward, more stringent regulation is necessary to account for the reality that existing land application practices are "primarily [] a method of disposing of dairy waste that has secondary benefits of fertilizing crops, rather than a method of crop fertilization that may have incidental impacts to groundwater."[94]

These federal and state findings are supported by substantial scientific evidence demonstrating that NMPs are an ineffective pollution control practice for several reasons. *First*, technical standards typically authorize the overapplication of animal wastes to ensure that crops have sufficient nutrients for optimal growth. This prioritization of crop growth over all else undermines the ability of NMPs to minimize nutrient runoff. *Second*, inherent complexities involved in designing and executing NMPs significantly limit their efficacy, even when operators comply with them. *Third*, NMP standards fail to

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[91] EPA, Confined Animal Feeding Operations: A Primer On The Federal Program 18 (Dec. 2021) (emphasis added) [hereinafter EPA CAFO Primer] (presentation on EPA regulation of CAFOs). Evidence also suggests that CAFOs are regularly out of compliance with their NMPs. *See, e.g.*, BEN CHUGG ET AL., STANFORD UNIV., DETECTING ENVIRONMENTAL VIOLATIONS WITH SATELLITE IMAGERY IN NEAR REAL TIME: LAND APPLICATION UNDER THE CLEAN WATER ACT (2022), https://dho.stanford.edu/wp-content/uploads/LandApp.pdf (finding substantial infractions of the prohibition on winter manure applications and repeated applications in excess of reporting); Environmental Integrity Project, *84% of MD Poultry Operations Failed Water Pollution Control Inspections from 2017-2020* (Oct. 28, 2021), https://environmentalintegrity.org/news/md-poultry-operations-fail-water-pollution-control-inspections/ ("[M]ore than half of the poultry farms for which records were available in 2019 reported to the state that they spread manure on their crops in amounts greater than allowed under their nutrient management plans.").

[92] 40 C.F.R. § 412.4(c)(1) (directing CAFOs to "achieve realistic production goals, while [also] minimizing nitrogen and phosphorous movement to surface waters,"); *see also* Andrew Sharpley, *Agricultural Phosphorous Water Quality and Poultry Production: Are They Compatible?*, 78 POULTRY SCI. 660, 668 (1999) ("It cannot be assumed that there is a direct relationship between soil test calibration for crop response to [nutrients] and surface runoff enrichment potential . . . .").

[93] CA DAIRY ORDER, *supra* n.15 at 6.

[94] *Id.* at 6.

distinguish between distinct forms of CAFO waste or provide for any heightened restrictions on anaerobically digested waste, which carries increased water quality risks.

Researchers have known for decades that "[e]ven under ideal conditions, with a well-planned system, there is still a significant risk of losses to the environment"[95] because land application of animal waste at so-called recommended rates frequently overloads fields with far more nutrients than plants can uptake or soil can retain, creating serious water pollution risks.[96] This is particularly the case for phosphorous. Because most crops require more nitrogen than phosphorous, nitrogen-based approaches to manure application are more common than phosphorous-based plans. This "presents a special problem because the N-to-P ratio in manures is lower than that needed by crops . . . [causing] excess P [to] build[] up to environmentally harmful levels in fields that received repeated applications."[97] This nutrient mismatch "invariably means [phosphorous] is overapplied relative to needs," and has led some researchers to conclude that nitrogen-based application rates "are much higher than agronomic requirements."[98]

For example, researchers analyzing recommended application rates for bermudagrass, a crop commonly grown on CAFO waste application fields, found that "[a]pplying poultry litter to meet the N requirements of bermudagrass resulted in 356 kg P/ha being applied that was not removed by the bermudagrass. Clearly this results in an accumulation of soil P and increase in P loss in surface runoff and subsurface flow occurs."[99] Land application of dairy and swine CAFO waste is no better.[100] Once excess phosphorous in soil reaches a particular saturation point, it begins to leach into surface and

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[95] L.M. Risse, et al., *Land Application of Manure for Beneficial Reuse*, *in* NATIONAL CENTER FOR MANURE AND ANIMAL WASTE MGMT. WHITE PAPERS 17 (J.M. White et al., eds. 2001).

[96] *See e.g.*, Kimberly A Rosov, et al., *Waste Nutrients from U.S. Animal Feeding Operations: Regulations are Inconsistent Across States and Inadequately Assess Nutrient Export Risk*, 269 J. ENV'T MGMT. l, 8 (2020) (finding "standing operating procedures for land application of swine wastes create significant potential for nutrient overloads of soils and potential export of excess nutrients from CAFOs to surrounding environment; Burkholder, *supra* n.16 at 308 (surveying literature that found high concentrations of nitrogen in surface waters adjacent to spray fields where animal waste was applied at recommended rates).

[97] Risse, *supra* n.95 at ii.

[98] UNIVERSITY OF KENTUCKY RESEARCH FOUNDATION, DEMONSTRATION OF ENHANCED TECHNOLOGIES FOR LAND APPLICATION OF ANIMAL NUTRIENT SOURCES IN SENSITIVE WATERSHEDS: FINAL PROGRESS REPORT 2 (2008); E. Osei et al., *Environmental Benefits and Economic Costs of Manure Incorporation on Dairy Waste Application Fields*, 68 J. ENV'T MGMT. 1, 6 (2003).

[99] Sharpley, *supra* n.92 at 667.

[100] BRADFORD, *supra* n.7 at 8 ("[A] potential problem arises when the relative content of nitrogen and phosphorous in lagoon water differs from that in the crop. In this case, NMPs that are designed to meet the nitrogen requirement for crops may result in the over-application of phosphorous."); Lawrence Cahoon & Scott H. Ensign, *Spatial and Temporal Variability in Excess Soil Phosphorus Levels in Eastern North Carolina*, 69 NUTRIENT CYCLING IN AGROECOSYS. 111, 112, 122–23 (2004); *see also* UNIV. OF GEORGIA COOP. EXTENSION, SMALL FARM NUTRIENT MANAGEMENT PRIMER: FOR UN-PERMITTED ANIMAL FEEDING OPERATIONS 4-6 (Thomas M. Bass & L. Mark Risse, eds. 2015); Risse, *supra* n.95 at 18 ("Nutrients applied from animal manure should match the needs of the crop, but the ratios of N, P, K and various micro nutrients excreted by animals are generally different from crop requirements.").

groundwater.[101] Some states do require NMPs to include phosphorus-based plans under certain circumstances.[102] However, these approaches remain highly variable, and studies demonstrate that phosphorous is nevertheless routinely overapplied even in states with phosphorous-based planning requirements.[103] Complicating matters further, recent studies show that applying waste at agronomic rates for phosphorous can cause excessive nitrogen releases to groundwater and surface water as well.[104] Because the current regulatory landscape explicitly allows CAFO operators to apply both nitrogen and phosphorous in excess of crop needs, downstream water quality impacts inevitably result.[105]

Difficulties inherent to accurately estimating water delivery and utilization by crops and differential nutrient uptake rates further undermine the effectiveness of nutrient planning. From the outset, EPA has acknowledged that "crafting proper waste application rates is a complicated task" requiring technical expertise in "soil science and soil fertility, nutrient application and management, crop production, soil and manure testing and results interpretation, fertilizer materials and their characteristics, BMPs for the management of nutrients and water, and applicable laws and regulations."[106]

Indeed, an EPA study "designed to test the assumption that a well-designed and executed NMP is protective" of waters identified myriad obstacles to developing effective NMPs.[107] For example, difficulties in accounting for the precise water demands of crops, other sources of plant available water beyond irrigation, and preferential flow paths in soil that allow CAFO wastewater to bypass the root zone all impede the ability of NMPs to minimize surface and groundwater

[101] CHESAPEAKE BAY FOUNDATION, MANURE'S IMPACTS ON RIVERS, STREAMS, AND THE CHESAPEAKE BAY 8 (July 28, 2004).
[102] *Id.* at 8–9 (noting that Virginia, Delaware, Pennsylvania, and Maryland all require that NMPs account for crop phosphorous needs to some extent).
[103] ENVIRONMENTAL INTEGRITY PROJECT, MANURE OVERLOAD ON MARYLAND'S EASTERN SHORE 8 (Dec. 8, 2014), http://dcpgonline.org/uploads/EIP_POULTRY-REPORT_-_Manure_Overload.pdf (finding 75 percent of phosphorous from poultry operations on Maryland's Eastern Shore was applied in excess of crop needs despite the state's phosphorous-based planning requirements).
[104] Matthew T. Streeter, et al., *Effects of Cattle Manure and Soil Parent Material on Shallow Groundwater Quality*, 6 AGROSYS. GEOSCIS. & ENV'T 1, 6 (2023) (explaining "if cattle manure (and any other nutrient input) is applied at agronomic rates for [phosphorous] while not accounting for manure [nitrogen] in the total budget for that nutrient, the potential to degrade groundwater resources with No3-N is high.") (pagination in accordance with submitted copy); *cf.* Coleen N. Brown, et al., *Tracing Nutrient Pollution from Industrialized Animal Production in Large Coastal Watershed*, 192 ENV'T MONITORING ASSESSMENT 1, 15–16 (2020) (detecting CAFO-derived nutrients and high nitrate concentrations in surface waters many kilometers downstream from CAFOs).
[105] Burkholder, *supra* n.16 at 308 (2007) (surveying literature that found high concentrations of nitrogen in surface waters adjacent to spray fields where animal waste was applied at recommended rates); Chris Jones, et al., *Livestock manure driving stream nitrate*, 48 AMBIO 1143, 1151–52 (2019); Zihao Bian, *Production and Application of Manure Nitrogen and Phosphorus in the United States Since 1860*, 13 EARTH SYST. SCI. DATA 515, 515–16 (2021).
[106] *Waterkeeper Alliance*, 399 F.3d at 501 n.19 (quoting 68 Fed. Reg. at 7213).
[107] BRADFORD, *supra* n.7 at xi.

contamination.[108] Additionally, predicting accurate nutrient budgets is further complicated by the fact that other contaminants in CAFO waste actually restrict plant growth and hinder a crop's ability to uptake nutrients.[109] In light of these factors, the Agency found that only a highly conservative plan that treated wastewater prior to application to remove most of the suspended solid content and "depleted the soil organic reservoir . . . by applying only a fraction of" plant nutrient needs (neither of which are required by current CAFO ELGs) actually minimized pollution.[110] In contrast, a "more aggressive" plan—like those actually advised by USDA and state conservation standards—led to increased "leaching and contaminant migration."[111]

Finally, the failure of NMP standards to account for different, more water pollution-prone types of CAFO waste streams further underscores their inadequacy. In the decades since EPA updated the CAFO ELGs, CAFOs have increasingly implemented anaerobic digester systems to ostensibly limit the climate impact of their waste and capitalize on lucrative state and federal incentive programs.[112] Though USDA has readily acknowledged that the waste product resulting from the digestion process (digestate) alters a CAFO waste stream's chemistry in ways that directly bear on nutrient management, presenting additional and more serious risks to water quality than undigested manure,[113] neither EPA nor USDA standards for land application (upon which most state technical standards are based) establish digestate-specific requirements to mitigate its heightened risk.

As recognized by USDA's Natural Resource Conservation Service ("NRCS"), "[d]igestate has increased potential for some air and nutrient emissions compared to raw manure" because "[c]ompounds such as nitrogen, phosphorous, and other elements become more soluble due to anaerobic digestion and therefore have higher potential to move with water."[114] Recent studies confirm that digested CAFO waste behaves much differently on the landscape than undigested manure due to its altered chemical composition, increasing short-term nitrogen loss, and contributing to metals and antibiotic-resistant pathogen accumulation.[115]

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[108] *Id.* at 66.
[109] *Id.* at 67; Ishmail Sheriff *et al., Microplastics in Manure: Sources, Analytical Methods, Toxicodynamic, and Toxicokinetic Endpoints in Livestock and Poultry*, 12 ENV'T ADVANCES 1, 2 (2023) (pagination in accordance with submitted copy).
[110] BRADFORD, *supra* n.7 at 67.
[111] *Id.*
[112] *See infra* at Section IV.A.3.
[113] *See* USDA-NRCS, CONSERVATION PRACTICE STANDARD CODE 366, ANAEROBIC DIGESTER 8–9 (Aug. 2023), https://www.nrcs.usda.gov/sites/default/files/2023-08/366_NHCP_CPS_Anaerobic_Digester_2023.pdf (recommending that "additional equipment, processes and technologies may be necessary or useful to treat digestate to reduce emissions and the potential for groundwater and surface water contamination during digestate storage and land application based on its intended use.").
[114] *Id.*
[115] *See* Roger Nkoa, *Agricultural Benefits and Environmental Risks of Soil Fertilization with Anaerobic Digestates: A Review.* 34 AGRONOMY FOR SUSTAINABLE DEVELOPMENT 473, 482–84 (2014); Chengjun Pu, et al., *Impact of Direct Application of*

In sum, the Agency itself has acknowledged many times over that its previous assumptions about NMPs and their ability to simultaneously "achieve realistic production goals, while minimizing nitrogen and phosphorous movement to surface waters"[116] are unfounded. Maximizing agricultural production and minimizing pollution are fundamentally contradictory concepts that cannot be – and have not been – squared by EPA's ineffective nutrient management requirements. This critical flaw in the CAFO ELGs has far-reaching ramifications beyond even the universe of permitted CAFOs. Not only are these insufficient nutrient management practices required in CAFO permits, but EPA further compounds its error by allowing *unpermitted* CAFOs that follow these same faulty requirements to exempt their land application discharges from regulation as agricultural stormwater.[117]

The CWA requires EPA to "prescribe conditions for [NPDES] permits to *assure compliance* with" all applicable requirements, including effluent limitations.[118] In order to effectuate this mandate, EPA must align its CAFO ELGs with the scientific reality, stop pretending that NMPs accomplish pollution reduction to a degree that they do not, and promulgate revised technology-based requirements that are actually protective of water quality. Failure to do so despite the scientific evidence EPA has before it, and its own changed understanding of the problem, would be arbitrary and capricious.

B. The CAFO ELGs Ignore Pollutants of Concern

Pursuant to the CWA and EPA's implementing regulations, NPDES permits must establish technology-based effluent limitations for *all* pollutants present in a discharge.[119] However, the CAFO effluent guidelines fail to do so. Instead, EPA's long-standing approach to regulating CAFO discharges is reliant on the fundamental misconception that CAFO waste is comprised solely of manure, leading the Agency to regulate only certain pollutants that naturally occur in manure (i.e. fecal coliform and nutrients) and disregard numerous other contaminants in CAFO waste streams—including salts, heavy metals, pharmaceuticals, cleaning products, and synthetic hormones—all of which meet the CWA's broad definition of "pollutant."[120]

Biogas Slurry and Residue in Fields: In Situ Analysis of Antibiotic Resistance Genes from Pig Manure to Fields. 344 J. HAZARDOUS MATERIALS 441, 443, 446–47 (2018).

[116] 40 C.F.R. § 412.4(c)(1).

[117] *Id.* at § 122.23(e).

[118] 33 U.S.C. § 1342(a)(2) (emphasis added).

[119] *See* 40 C.F.R. § 125.3(a)(2) (requiring permits to contain technology-based limits for "conventional pollutants," "all toxic pollutants," and "all pollutants which are neither toxic or conventional pollutants."); *see also* 33 U.S.C. 1362(6) (broadly defining "pollutant" to include "dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt and industrial, municipal, and agricultural waste discharged into water").

[120] EPA regulates the various heavy metals used by CAFOs as feed additives as priority pollutants in other contexts. *See* 400 C.F.R. § 423, App. A. Additionally, pharmaceuticals and synthetic hormones added to livestock feed and excreted in

As EPA has acknowledged, the current regulatory framework either entirely ignores certain pollutants found in CAFO waste,[121] or "implicitly assume[s]" that nutrient management requirements focused on the agronomically valuable constituents of animal manure may have some incidental impact on reducing other contaminants, even though they have no accepted agronomic use.[122] But the Agency has never "thoroughly tested these hypotheses,"[123] nor made an affirmative finding that current CAFO ELGs do in fact constitute the best pollution control technologies and BMPs for reducing other pollutants of concern. To the contrary, the little data EPA has gathered on this front suggest otherwise. For instance, when EPA promulgated its 2003 CAFO rule, which incorrectly assumed that all Large CAFOs would obtain NPDES permits, it estimated that the rule would only reduce metal pollution by five percent.[124] Given the exceedingly low rates of permitting since,[125] it follows that any reductions in metal pollution in the intervening decades have been negligible.

Moreover, courts have soundly rejected EPA's past attempts to shirk its CWA duty to under-regulate CAFO pollutants in this way, finding that EPA violates the statute when it fails to "impose ELGs specifically designed to reduce [certain pollutants of concern] in CAFO discharges" or otherwise make an "affirmative finding that [current ELGs] do *in fact* represent" the appropriate level of pollution control technology for reducing such pollutants.[126] EPA's continued failure to promulgate CAFO ELGs that address all pollutants of concern is thus unlawful.

C. The CAFO ELGs Allow Practices Known to Harm Water Quality

As written, EPA's ELGs for Large CAFOs allow CAFO operators to engage in several production and land application area practices known to cause discharges and harm water quality, undermining the permits' narrative requirements to eliminate or minimize discharges, respectively.[127] EPA's failure to promulgate CAFO technical standards that prohibit harmful practices is arbitrary,

livestock waste are clearly "biological materials" and "chemical wastes." 33 U.S.C. § 1362(6); *see also Nat'l Cotton Council of Am. v. EPA*, 553 F.3d 927, 935–938 (6th Cir. 2009) (explicating the broad scope of the terms "biological materials" and "chemical wastes.").

[121] For instance, EPA has noted that the current ELGs do not address "plate chiller waste, filter backwash water, chemicals used in the production area (for disinfection) or pollutants that have fallen to the ground immediately downward from confinement building exhaust ducts and ventilation fans and are carried by precipitation-related runoff to waters of the US." EPA, NPDES PERMIT WRITERS' MANUAL FOR CONCENTRATED ANIMAL FEEDING OPERATIONS 4-18 (Feb. 2012) [hereinafter CAFO NPDES PERMIT WRITERS' MANUAL].

[122] BRADFORD, *supra* n.7 at 66 ("The current regulatory framework is based on nutrient management plans (NMPs) to ensure that lagoon water is applied to agricultural lands at agronomic rates to meet the nutrient demands of crops. Other lagoon water contaminants are implicitly assumed to be retained, inactivated, or degraded in the root zone. Additional studies are needed to thoroughly test these hypotheses.").

[123] *Id.*

[124] 68 Fed. Reg. at 7239.

[125] CAFO PERMITTING INVENTORY, *supra* n.3 (showing less than 30 percent of Large CAFOs have NPDES permits).

[126] *See Waterkeeper Alliance*, 399 F.3d at 519 (the need to establish ELGs for other pollutants beyond pathogens was not before the court).

[127] Small and Medium CAFOs are also permitted to engage in these practices, as the CAFO ELGs do not apply to these operations.

capricious, and contrary to EPA's obligations to develop guidelines sufficient to protect water quality and make progress towards the Act's goal of eliminating pollution.

EPA concedes that its current pollution control standards fail to effectively "limit the discharge of pollutants under certain circumstances."[128] Food & Water Watch alerted the Agency to those circumstances more than eight years ago in a Petition to revise CAFO CWA regulations, discussing at length numerous high-risk practices currently allowed by EPA's CAFO ELGs that are contributing to water quality degradation.[129] These practices include:

1) Manure storage in unlined and inadequately lined lagoons and impoundments;
2) Ventilation of pollutants near waters or conduits to waters of the U.S.;
3) Application of CAFO waste on frozen, saturated, or snow-covered ground;
4) Application of CAFO waste via spray irrigation equipment;
5) Application of CAFO waste on steep slopes;
6) Manure storage in exposed stockpiles; and
7) Lagoon design standards based on outdated weather and storm frequency data.

Though the Agency recognizes these practices to be high-risk, rather than prohibiting them by regulation, it instead has urged states to do so themselves, with little success.[130] For one thing, the Agency knows many state permitting agencies are themselves prohibited from exceeding EPA's minimum BMP requirements, including major livestock-producing states like Iowa, North Carolina, and Wisconsin.[131] A 2013 study conducted by the Environmental Law Institute found that a total of 13 states had enacted such "no more stringent than" laws, and an additional 23 states have adopted laws that make it more difficult to establish state standards that surpass these minimum federal requirements.[132]

Moreover, even when states have not expressly passed legislation to hamstring their permitting agencies from implementing more protective technical standards, the reality is state regulators often

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[128] EPA ENVIRONMENTAL JUSTICE REPORT, *supra* n.8 at 75.
[129] 2017 PETITION, *supra* n.5 at 46–55.
[130] *See* CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.121 at 4-36, 5-29–5-30, 6-15–6-16.
[131] *See e.g.*, Iowa Code § 459.311(2) ("any rules adopted pursuant to this [minimum requirements for manure control] subsection shall be no more stringent than requirements under the federal Water Pollution Control Act . . . ."); N.C. Gen. Stat. § 150B-19.3 ("An agency authorized to implement and enforce State and federal environmental laws may not adopt a rule for the protection of the environment or natural resources that imposes a more restrictive standard, limitation, or requirement than those imposed by federal law or rule"); Wis. Stat. § 283.11(2) ("all rules promulgated by the department under this chapter [pollution discharge elimination] . . . shall comply with and not exceed the requirements of the federal water pollution control act . . . .").
[132] ENV'T LAW INST., STATE CONSTRAINTS: STATE-IMPOSED LIMITATIONS ON THE AUTHORITY OF AGENCIES TO REGULATE WATERS BEYOND THE SCOPE OF THE FEDERAL CLEAN WATER ACT 1 (2013), https://www.eli.org/sites/default/files/eli-pubs/d23-04.pdf.

lack adequate resources to fully implement permitting programs.[133] Even EPA has noted that states have not prioritized regulation of feedlot wastes, and that budgetary constraints make it unlikely that states will meet—much less exceed—program and permitting responsibilities under the current rules.[134]

Faced with this lack of resources and in some cases limited permitting authority, most states default to the USDA technical standards outlined in NRCS Code 590, which EPA has already determined are insufficient.[135] Indeed, the Agency has found that "USDA's [NMP] guidance lacks many of the details EPA believes are necessary to ensure discharges of manure and other process wastewater are adequately controlled" because they contain "no avenue for ensuring that [C]AFOs implement any management practices or achieve a particular performance standard."[136] Despite EPA's finding that "consistency with NRCS Code 590 may not by itself ensure compliance with the regulatory requirements for technical standards of nutrient management"[137] it has allowed a patchwork of state technical standards that in many cases rely solely on NRCS Code 590 guidance to serve as the main vehicle for CAFO regulation, which in turn has allowed the harmful practices identified above to proliferate.

D. The CAFO ELGs Ignore Hydrologic Discharges

Another critical flaw in the current CAFO ELGs is that they fail to ensure CAFOs are not violating production area or land application effluent limitations due to discharges to jurisdictional surface waters via hydrologically connected groundwater. Under the CWA, a CAFO is liable for discharges of "pollutants that reach navigable waters after traveling through groundwater if [those] discharge[s] [are] the functional equivalent of a direct discharge from the point source into navigable waters."[138] Thus, if a CAFO has subsurface discharges into a jurisdictional water from its lagoons, it violates the zero-discharge effluent limitation for production areas.[139] Likewise, if CAFO waste applied

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[133] EPA ENVIRONMENTAL JUSTICE REPORT, *supra* n.8 at75 (finding that "state permitting agencies lack the resources to regularly inspect [CAFO] facilities"); CLAUDIA COPELAND, CONGRESSIONAL RESEARCH SERVICE, ANIMAL WASTE AND WATER QUALITY: EPA REGULATION OF CONCENTRATED ANIMAL FEEDING OPERATIONS (CAFOS) 18 (Feb. 16, 2010) ("[I]t is unclear how state agencies will find the resources needed to carry out their responsibilities under the revised rules without reducing resources for other important activities."); Terence J. Centner, *Regulating the Land Application of Manure from Animal Production Facilities in the USA*, 14 WATER POLICY 319, 329 (2012) (noting that "state regulatory agencies do not have the resources to penalize producers who fail to follow BMPs").

[134] Copeland, *supra* n.133 at 24; Jillian P. Fry, et al., *Investigating the Role of State Permitting and Agriculture Agencies in Addressing Public Health Concerns Related to Industrial Food Animal Production*, 9 PLOS 1, 4 (2014) (discussing how state agencies "don't have staff or money" to effectively implement CAFO programs).

[135] EPA CAFO Primer, *supra* n.91 at 8.

[136] 66 Fed. Reg. at 3033.

[137] EPA, MANAGING MANURE NUTRIENTS AT CONCENTRATED ANIMAL FEEDING OPERATIONS 6-1 (Dec. 2004).

[138] *Cnty. of Maui v. Hawaii Wildlife Fund*, 590 U.S. 165, 185 (2020).

[139] 40 C.F.R. § 412.31(a).

to fields excessively leaches into hydrologically connected groundwaters, the CAFO violates the minimize standard for land application areas.[140]

Over twenty years ago, EPA acknowledged groundwater contaminated by CAFO pollutants is a "significant transport mechanism" for surface water discharges due to the prevalence of hydrologic connections.[141] CAFO pollutants that seep into groundwater have been shown to migrate to surface waters. Investigations in Washington and California have shown nitrate pollution that seeps into groundwater from CAFOs can travel over two miles downgradient from the source. [142] In many scenarios, such seepage will clearly lead to hydrologic discharges that are functionally equivalent to direct discharges.

Nationally, 40 percent of average annual stream flow originates from groundwater,[143] and these connections are even more pervasive in certain regions where CAFOs are concentrated. For instance, in the Chesapeake Bay watershed, the U.S. Geological Survey estimates about half of the nitrogen loads from all sources to nontidal streams and rivers originate from groundwater.[144] Groundwater feeds half of all stream flow in North Carolina.[145] In Idaho's Magic Valley, where the majority of the state's dairy industry is located, agricultural irrigation is the largest contributor to recharging the Snake River Plain aquifer—an essential drinking water source.[146] As pollution from the CAFO industry seeps into groundwater, some of these contaminants are discharged directly into the Snake River at distinct points along its route.[147]

In Wisconsin, where groundwater is particularly vulnerable to contamination due to the region's karst geology,[148] CAFOs have contaminated ground and surface water to such an extent that regulators have created a factual presumption of discharge requiring all CAFOs that land apply waste

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[140] *Id.* at § 412.4(c)(1).
[141] 66 Fed. Reg. at 2980; EPA, RISK ASSESSMENT EVALUATION FOR CONCENTRATED ANIMAL FEEDING OPERATIONS 52–53 (May 2004) [hereinafter EPA RISK ASSESSMENT].
[142] Erickson Report, *supra* n.18 at 7.
[143] 66 Fed. Reg. at 2980.
[144] *Id.*
[145] *See* NORTH CAROLINA DIVISION OF WATER RESOURCES, THE WATER CONNECTION: WATER RESOURCES, DROUGHT, AND THE HYDROLOGIC CYCLE IN NORTH CAROLINA 5 (Sep. 2009) (estimating most streams and rivers in the state receive approximately half their volume from groundwater).
[146] UNIVERSITY OF IDAHO, EASTERN SNAKE RIVER PLAIN SURFACE AND GROUND WATER INTERACTION at 2–3, https://idwr.idaho.gov/wp-content/uploads/sites/2/legal/american-falls/AF-20020118-ESPA-Surface-Water-and-Groundwater-Interaction.pdf.
[147] *Id.* at 3–5; *see also* IDAHO CONSERVATION LEAGUE, THE 2021 GROUNDWATER REPORT: GROUNDWATER QUALITY IN THE MAGIC VALLEY 3–7 (2021).
[148] WISCONSIN DEP'T OF NATURAL RESOURCES, GROUNDWATER COLLABORATION WORKGROUP FINAL REPORT, 11 (June 2016), https://www.kewauneeco.org/i/f/files/Land%20%26%20Water%20Conservation/Groundwater%20Collaboration%20Workgroup%20Final%20Report.pdf.

to obtain NPDES permits and implement groundwater controls.[149] These same karst conditions are found throughout much of the Midwest where industrial agriculture is clustered, creating significant pollution problems in both ground and surface waters.[150]

Though EPA must "prescribe conditions for [NPDES] permits to *assure compliance* with" effluent limitations,[151] the CAFO ELGs fail to do so for the subsurface discharge pathway. For instance, the BMPs EPA prescribes for CAFO production areas all focus on waste *overflows*,[152] despite the well-established fact that lagoons can and do leak into groundwater. As EPA well knows, "[e]ven assuming [] lagoons were constructed pursuant to NRCS standards, these standards specifically allow for permeability, and thus, the lagoons are designed to leak."[153] NRCS guidance allows a seepage rate of 5,000 gallons per acre per day for compacted clay lined lagoons,[154] translating into an astronomical 1.825 *million* gallons per acre annually. Accordingly, EPA determined in 2001 that imposing groundwater-focused production area requirements on CAFOs would significantly reduce nitrogen loading to surface waters, with an estimated annual 3 million pounds reduction from the dairy and beef subcategories alone.[155] Yet the current CAFO ELGs are completely silent on this discharge pathway.

The same is true for the land application requirements EPA prescribes. Though it is well-documented that land application at agronomic rates "is responsible for the vast majority of [] nitrogen impacts to groundwater,"[156] and at the epicenter of many serious groundwater contamination crises across the country,[157] EPA's current CAFO ELGs entirely fail to address land application impacts to hydrologically connected groundwater.

For decades, EPA has relied on states to address the pervasive problem of subsurface CAFO discharges polluting jurisdictional waters, claiming that a national technology-based standard is

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[149] *See* Wis. Admin. Code § N.R. 243.11(3); Wisconsin NRCS Standard 590 (Dec 2015), https://datcp.wi.gov/Documents/NM590Standard2015.pdf.
[150] *See generally* SDWA Petitions, *supra* n.14.
[151] 33 U.S.C. § 1342(a)(2).
[152] 40 C.F.R. §§ 412.31(a), 412.37.
[153] *Food & Water Watch*, 20 F.4th at 509.
[154] NRCS, AGRICULTURAL WASTE MANAGEMENT FIELD HANDBOOK, CHAPTER 10: AGRICULTURAL WASTE MANAGEMENT SYSTEM COMPONENT DESIGN, Appendix 10D (July 2024), https://directives.nrcs.usda.gov//sites/default/files2/1720533311/Chapter%2010%20-%20Agricultural%20Waste%20Management%20System%20Component%20Design.pdf.
[155] 66 Fed. Reg. at 3062.
[156] CA DAIRY ORDER, *supra* n.15 at 6.
[157] *See* Letter from Allamakee County Protectors – Education Campaign et al., to Bruno Pigott, EPA Office of Water (Oct. 29, 2024), https://www.foodandwaterwatch.org/wp-content/uploads/2024/10/EPA-Letter-Requesting-SDWA-Meeting-Oct-29-2024.pdf (summarizing the status of five emergency petitions pleading with EPA to address the severe nitrate contamination of groundwater and drinking water resources caused by CAFOs in Wisconsin, Oregon, Washington, Minnesota, and Iowa).

inappropriate given the "site-specific variables" that factor into such discharges.[158] But this hands-off approach has largely failed—particularly given the inability of many states to impose requirements more stringent than those established by EPA[159]—and has consequently created stark pollution disparities and an anti-regulatory race to the bottom further driving industry consolidation.

Moreover, EPA's position simply doesn't square with its broad authority and obligation to conduct site-specific analysis and create industry subcategories when necessary. EPA regularly makes estimates about difficult to discern site-specific factors when setting ELGs, and the Ninth Circuit has rejected the Agency's attempts to shirk site-specific analysis in the past.[160] If EPA finds that specific topographies or other geologic factors render certain regions fundamentally different and more vulnerable to surface water discharges via groundwater, the Agency is well within its authority to subcategorize the industry based on geographic location and impose targeted groundwater requirements where necessary.[161] EPA's decades-long failure to do so is arbitrary and capricious.

E. The CAFO ELGs Ignore Aerial Discharges

The CAFO ELGs also arbitrarily ignore discharges via aerial deposition of pollutants. As with hydrological discharges, EPA has long recognized that aerial deposition is a significant source of pollution to surface waters, that CAFOs discharge pollutants through aerial deposition, and that such discharges are subject to NPDES permitting requirements.[162] Practices that pose particularly high aerial discharge risks include storing CAFO waste in liquid form, operating industrial ventilation systems in confinement pens, and spraying liquid manure onto land application areas.[163] Despite acknowledging aerial deposition as an issue in past CAFO ELG rulemakings, EPA has yet to address this pathway through either technology-based effluent guidelines or BMPs. This oversight has had measurable consequences. Economic data from 2008 to 2012 show that even as gross economic

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158 68 Fed. Reg. at 7216.

159 *See supra* Section III.C.

160 *See Ass'n of Pac. Fisheries v. EPA*, 615 F.2d 794, 819–20 (9th Cir. 2007) (rejecting EPA's failure to consider full spectrum of costs when setting BAT where the Agency claimed certain costs were too site-specific to merit consideration).

161 *See Chem. Mfrs.*, 870 F.2d at 214–15 (finding EPA must create subcategories where a group of operations is "so fundamentally different from other plants on which the limitations are based that they cannot practicably achieve the effluent limitations achieved by the average of the best plants in the industry."); *Citizens Coal*, 447 F.3d at 904 (affirming subcategorization based on site-specific factors of geographic location).

162 66 Fed. Reg. at 2980 (acknowledging that "atmospheric deposition is the third leading cause of water quality impairment for estuaries, and the fifth leading cause of water quality impairment for lakes, ponds, and reservoirs," and identifying land application as a source of aerial deposition); *see also id.* at 3104 ("A fraction of the air emissions from AFOs [including those from manure management systems and animal housing] are subsequently redeposited on land or in surface waters."); 68 Fed. Reg. at 7236, 7240 (listing volatilization and subsequent redeposition along with direct discharge and leaching to groundwater as primary pathways by which CAFO pollutants reach surface waters); 2003 TDD, *supra* n.26 at 8-153–8-154 (similar); *see also Nat'l Pork Prods. Council*, 635 F.3d at 754–56 (describing EPA's position that aerial deposition of dust from poultry CAFO ventilation systems are discharges that must be permitted).

163 *Id.*; *see also* 2003 TDD, *supra* n.26 at 8-156 ("Field estimates of volatilization loss from surface-applied manure range from about 10 to 70 percent of NH3-N applied.").

damage from particulate matter in other sectors fell, damage caused by the livestock industry grew.[164] This is unacceptable, as EPA's role in establishing ELGs is to pursue the "ultimate goal of eliminating *all* pollutant discharges."[165] Given the wealth of evidence demonstrating that aerial depositions from CAFOs are causing surface water discharges and contributing to water quality impairments,[166] EPA must use this opportunity to regulate this significant pollution pathway.

The CWA grants EPA clear authorization to regulate air deposition to surface waters through the ELGs.[167] As the Supreme Court recently recognized, discharges that travel through media to reach navigable waters are discharges within the meaning of the CWA, so long as they "reach the same result [as a direct discharge] through roughly similar means."[168] The same reasoning applies to the discharge of gaseous ammonia, particulate matter, and other pollutants that reach surface waters through the air, particularly if the pollution reaches a nearby waterway relatively quickly.[169] In fact, treating aerially deposited discharges as non-jurisdictional would allow CAFOs to avoid regulation by simply spraying their waste into the air—a loophole the Supreme Court deemed impermissible in the groundwater context.[170] As the Sixth Circuit Court of Appeals held while determining pesticide applications were discernible, confined, and discrete conveyances within the meaning of the CWA's definition of point source, "there is no requirement that the discharged [pollutant] immediately cause harm to be considered coming from a point source."[171] Rather, when determining whether a discharge is subject to NPDES permitting requirements, "the relevant inquiry is whether—but for the point source—the pollutants would have been added to the receiving body of water."[172] Plainly, but for the CAFOs, aerial deposition of volatilized CAFO pollutants to surface waters would not be occurring. Moreover, given the significant amounts of pollution CAFOs aerially discharge to surface waters, failure to

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[164] Peter Tschofen et al., *Fine Particulate Matter Damages and Value Added in the US Economy*, 116 PNAS 19857, 19858 (2019).
[165] *NRDC*, 863 F.2d at 1426 (emphasis added).
[166] *Supra* nn.25–**Error! Bookmark not defined.** and accompanying text.
[167] *See* 33 U.S.C. §§ 1311(a), 1342(a)(1) (precluding the discharge of any pollutant to waters of the United States, except in compliance with a NPDES permit); *id.* § 1362(12) (defining "discharge of a pollutant" as "*any* addition of any pollutant to navigable waters from any point source) (emphasis added), 1362(14) (defining CAFOs as point sources without exception).
[168] *Cnty. of Maui*, 590 U.S. at 183–84 (acknowledging jurisdiction over "functionally equivalent" discharges to surface water through groundwater).
[169] *Id.* at 185 (explaining that time and distance are usually, but not always, the most important factors in determining whether a functionally equivalent discharge exists).
[170] *Id.* at 178 ("If that is the correct interpretation of the statute, then why could not the pipe's owner, seeking to avoid the permit requirement, simply move the pipe back, perhaps only a few yards, so that the pollution must travel through at least some groundwater before reaching [a jurisdictional water]? We do not see how Congress could have intended to create such a large and obvious loophole.").
[171] *Nat'l Cotton Council*, 553 F.3d at 939.
[172] *Id.* at 940 (citing *S. Fla. Water Mgmt. Dist. v. Miccosukee Tribe of Indians*, 541 US 95, 103 (2004)*; see also League of Wilderness Defs. / Blue Mountain Diversity Project v. Forsgren*, 309 F.3d 1181, 1183 (9th Cir. 2002) (finding aerial spraying of pollutants over forestland that then discharged to waterways required NPDES permit).

account for aerial deposition prevents EPA and other permitting authorities from attaining the Act's mandate to ensure permitted discharges do not cause or contribute to exceedances of water quality standards.[173]

Again, while site-specific factors like temperature, pH, humidity, precipitation, and distance to surface waters impact aerial deposition of CAFO pollutants, leaving regulation of these discharges completely up to the states has not been a successful strategy. Rather than filling the gap left by EPA, even states with the worst documented impacts from aerially deposited CAFO pollution refuse to include specific and legally binding requirements in NPDES permits to control aerial depositions.[174] To date, reviewing courts have largely deferred to agencies in these determinations.[175] And as detailed above, several states have statutory provisions that prohibit any regulation of CAFOs beyond what EPA includes in the federal regulations.[176] The remedy to uncontrolled aerial deposition of pollutants from CAFOs is obvious—EPA must impose specific and mandatory BMPs that are demonstrated to reduce aerial deposition.[177]

F. The CAFO ELGs Are Not Based on Representative Monitoring Data

A significant part of the challenge in establishing evidence-based CAFO ELGs is EPA's and other permitting authorities' failure to require collection and reporting of representative effluent monitoring data from CAFOs.[178] The CWA specifically mandates inclusion of monitoring requirements sufficient to produce representative data that demonstrate whether a CAFO is complying with the effluent limits in its NPDES permit.[179] The unwillingness to impose upon CAFOs the same monitoring requirements that all other point sources are required to undertake and report to permitting agencies in periodic discharge monitoring reports has left EPA and the public in the dark about the precise extent to which various CAFO practices are discharging pollutants to jurisdictional waters. Indeed, in announcing this very CAFO study, EPA acknowledged this dearth of monitoring, admitting that data on CAFOs are so "sparse" that the Agency "was only able to analyze monitoring data from sixteen reporting CAFOs" across the entire country—a paltry 0.2 percent of permitted

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[173] *See* 33 U.S.C. § 1342(a).
[174] *See e.g.*, *Assateague Coastal Trust*, 484 Md. at 442 (reprinting Maryland Department of Environment's response to comments requesting aerial deposition controls, in which the Department characterizes aerial discharges as an air quality issue and declining to include the remedial measures requested by commenters).
[175] *Id.* at 486 ("We see no reason to require the [Maryland Department of Environment] to precisely identify the BMPs that are required for ammonia emissions.").
[176] *See, e.g.*, Iowa Code § 459.311; Colo. Rev. Stat. § 25-8-504; Miss. Code Ann. § 49-17-34; § 75-5-203, MCA.
[177] *Citizens Coal*, 447 F.3d at 899.
[178] *See* 2017 PETITION, *supra* n.5 at 34–37.
[179] 33 U.S.C. §§ 1318(a), 1342(a)(2); 40 C.F.R. § 122.44(i).

CAFOs.[180] This black box in which CAFOs have been allowed to operate has led to chronic under-permitting, insufficiently protective ELGs and permits, and severe environmental consequences that threaten public health across the country.

Multiple adjudicatory bodies have now agreed that regulators' failure to include representative monitoring requirements in CAFO permits runs afoul of the CWA.[181] In particular, the Ninth Circuit Court of Appeals held that the Act "requires every NPDES permittee to monitor its discharges . . . in a manner sufficient to determine whether it is in compliance with the relevant NPDES permit."[182] The Court further held that EPA's 2020 NPDES general permit for CAFOs in Idaho violated the CWA because it did not include production area monitoring to ensure compliance with the permit's zero-discharge effluent limit and did not include land application area monitoring to ensure compliance with the permit's zero dry weather discharge effluent limit.[183] The Court also noted that "[e]ffective self-monitoring reveals permit violations, thereby promoting enforcement of the CWA."[184]

To remedy the legal and practical deficiencies created by inadequate monitoring, EPA must incorporate monitoring technologies and practices into the CAFO ELGs. "The NPDES program fundamentally relies on self-monitoring."[185] Continued exclusion of monitoring from EPA's CAFO regulations will not only hamstring enforcement efforts, but also keep EPA in the dark about opportunities to reduce and ultimately eliminate CAFO pollution through additional amendments to the ELGs. If CAFOs were required to submit representative discharge monitoring reports like other point source categories, EPA could identify the facilities achieving the best pollution reductions, making this entire detailed study process much more straightforward and enabling EPA to better comply with its mandatory duty to regularly review, and if necessary revise, the CAFO ELGs.[186] A

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[180] EPA, EFFLUENT GUIDELINES PROGRAM PLAN 15, App. A at A-2 (Jan. 2023); *see also* FOOD & WATER WATCH, COMMENTS OF FOOD & WATER WATCH ON PRELIMINARY EFFLUENT GUIDELINES PROGRAM PLAN 15 3–4 (Oct. 14, 2021) (casting doubt on the legitimacy and accuracy of what little CAFO monitoring data EPA has collected).
[181] *Food & Water Watch*, 20 F.4th at 517–18; *Wash. State Dairy Fed'n*, 18 Wn. App. 2d at 299–303; *Friends of Toppenish Creek*, Washington Pollution Control Hearing Board, PCHB No. 23-002. Other cases involving the same legal question are currently pending before state tribunals in Montana, Colorado, and Michigan. *Upper Missouri Waterkeeper v. Mont. Dep't of Env't Quality*, Case No. DV-16-2023-0001249; *Center for Biological Diversity v. Colorado Dep't of Public Health & Env't*, Case No. 2024-CV-30436; *In re Michigan Farm Bureau*, Dkt. No. 20-009773.
[182] *Food & Water Watch*, 20 F.4th at 516.
[183] *Id.* at 517–18.
[184] *Id.* at 516.
[185] *Id.* (quoting *Sierra Club v. Union Oil Co. of Cal.*, 813 F.2d 1480, 1491 (9th Cir. 1987), *vacated and remanded on other grounds*, 485 U.S. 931, 108 S. Ct. 1102, 99 L. Ed. 2d 264 (1988), *and reinstated and amended by* 853 F.2d 667 (9th Cir. 1988)).
[186] *See* 33 U.S.C. § 1314(b) (requiring EPA to conduct an annual review of ELGs and revise them as appropriate).

failure to impose mandatory representative monitoring of all known CAFO discharge points and reporting of monitoring data would be arbitrary and capricious.

IV. EPA Must Update the CAFO ELGs with New Technologies and Practices Available to Control CAFO Pollution

EPA must take action to correct the critical flaws in the CAFO ELGs identified above and strengthen the regulations consistent with its statutory duty.[187] Bringing the CAFO ELGs into compliance with the CWA will require the Agency to prohibit technologies and practices that exacerbate surface water pollution and to impose additional production area and land application requirements based on new and/or readily available technologies and practices.

A. The CAFO ELGs Must Mitigate the Water Quality Impacts of Outdated Technologies and Practices That Exacerbate CAFO Pollution

The CWA was designed to impose increasingly stringent pollutant reduction requirements on industrial point sources over time.[188] Certain pollutant control technologies and practices have been proven ineffective or discovered to have adverse impacts that outweigh any benefits. Thus, the only reasonable result of EPA's study of the CAFO category and its ELGs is to remove or substantially limit regulatory reliance on these outdated methods. EPA must therefore revise 40 C.F.R. § 412.4 to either prohibit outright or adopt more stringent waste management controls for spray irrigation, other high-risk land application practices, and anaerobic digesters. These technologies and practices are not acceptable BMPs, nor should they serve as the bases for any technology-based effluent limitation in the CAFO ELGs.

1. Center Pivots, Guns, and Other High-Pressure Broadcast Irrigation Technologies

Under the existing ELGs, CAFOs are permitted to land apply manure and other wastes using any equipment so long as they comply with setback, vegetated buffer, or compliance alternative requirements.[189] This flexibility has resulted in the proliferation of irrigation guns, center pivots, and other broadcast irrigation technologies that spray liquid waste onto land application fields.[190] These technologies are generally employed by and primarily benefit large CAFOs as opposed to smaller scale

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[187] *Id.*

[188] *Id.* (requiring EPA to review and appropriately revise ELGs annually); *see also id.* § 1311(b) (setting ultimate goal of eliminating all point source discharges).

[189] 40 C.F.R. § 412.4(c).

[190] WIS. MANURE IRRIGATION WORKGROUP, CONSIDERATIONS FOR THE USE OF MANURE IRRIGATION PRACTICES App'x B (Apr. 2016), https://fyi.uwex.edu/manureirrigation/files/2016/04/Manure-Irrigation-Workgroup-Report-2016.pdf; *see also* Katie M. Englin, *Efficient Irrigation Starts with the Flow Meter*, SEAMETRICS, https://www.seametrics.com/blog/efficient-irrigation-starts-with-the-flow-meter/ (visited June 12, 2025) ("Today over 70% of irrigation systems in the U.S. are pressurized.").
CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.121 at 6-48; HRIBAR, *supra* n.28 at 3; Michelle B. Nowlin, *Sustainable Production of Swine: Putting Lipstick on a Pig?*, 37 VT. LAW REV. 1079, 1087–88 (2013).

livestock operations that do not generate enough waste to necessitate long-term manure storage.[191] In addition to contributing to increased concentration and consolidation of the livestock industry, high-pressure spray irrigation methods have been proven to exacerbate water pollution. Moreover, spraying liquid manure causes pollutants in the waste to volatilize, leading to air pollution that adversely impacts the health and quality of life of communities living downwind from these facilities. To remedy these impacts, EPA must amend the CAFO ELGs to prohibit the use of irrigation guns and center pivots for land application of manure and other waste products.

Performance[192]

High-pressure spray equipment like irrigation guns and center pivots are not appropriate for land application of CAFO waste because of the likelihood of discharge to surface waters.[193] As EPA is aware, spray irrigation equipment is known to discharge directly into ditches and other drainage systems that abut land application fields.[194] Even when the expelled waste is aimed at a field rather than a waterway, spray technologies create volatilized pollutant particles that drift and discharge into surface waters.[195] Ultimately, high-pressure spray irrigation poses unnecessary discharge risks and contributes to elevated levels of nutrients and other pollutants in waterways near sprayfields.[196]

Existing BMPs in the CAFO ELGs are insufficient to prevent spray irrigation equipment from discharging to surface waters. The default setback for CAFOs spraying waste onto land application fields is 100 feet from "any down-gradient surface waters, open tile line intake structures, sinkholes, agricultural well heads, or other conduits to surface waters."[197] However, the ELGs also permit CAFOs to spray waste within 35 feet of a surface water or conduit if they have installed a vegetated

[191] Tucker R. Burch et al., *Quantitative Microbial Risk Assessment for Spray Irrigation of Dairy Manure Based on an Empirical Fate and Transport Model*, 125 ENV'T HEALTH PERSPECTIVES 067003-1, 067003-1 (2017) (pagination in accordance with submitted copy).
[192] This and subsequent evaluations of technology "performance" includes analysis of the following BAT factors: (1) the age of equipment and facilities involved, (2) the process employed, and (3) engineering aspects of the application of the application of various types of control technologies.
[193] *See* WIS. MANURE IRRIGATION WORKGROUP, *supra* n.190 at 3, 39–42 (discussing potential for surface water discharge); *Parris v. 3M Co.*, 595 F. Supp. 3d 1288, 1322 (N.D. Ga. 2022) (collecting cases in which "land application systems, spray head sprinklers, and trucks constitute point sources when used to spread treated wastewater and manure on land").
[194] *See* EPA, IMPLEMENTATION GUIDANCE ON CAFO REGULATIONS—CAFOS THAT DISCHARGE OR ARE PROPOSING TO DISCHARGE 9 (May 28, 2010), https://19january2021snapshot.epa.gov/sites/static/files/2015-08/documents/cafo_implementation_guidance.pdf (photograph of spray irrigation equipment causing dry weather discharge at CAFO); *see also Cmty. Ass'n for Restoration of the Env't v. Henry Bosma Dairy*, 65 F. Supp. 2d 1129, 1147 (E.D. Wash. 1999) (noting a "verified discharge of animal wastes from a spray gun").
[195] Burkholder, *supra* n.16 at 309; 2017 PETITION, *supra* n.5 at 52–53; Horacio A. Aguirre-Villegas & Rebecca A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, 143 J. CLEANER PRODUCTION 169, 169 (2017).
[196] Burkholder, *supra* n.16 at 308.
[197] 40 C.F.R. § 412.4(c)(5).

buffer.[198] Neither of these setbacks is sufficient to prevent volatized pollutants from discharging to surface waters or conduits when spray irrigation equipment is known to jettison these pollutants up to 10 kilometers away from the source.[199] While a vegetated buffer may mitigate against discharges from runoff or contaminated groundwater, they are plainly insufficient to prevent discharges from spray irrigation.

Non-Water Quality Impacts

Pollutants expelled by spray irrigation technologies include aerosolized bacterial and viral pathogens that create serious health risks when inhaled by neighboring residents or deposited on food crops.[200] Indeed, multiple studies have confirmed that communities situated near CAFOs suffer higher infection rates.[201] Farmworkers and CAFO employees bear the brunt of these unnecessary hazards,[202] all while safer and more precise land application methods are widely available and in use.[203] Irrigation guns and center pivots also allow CAFOs to land apply waste more frequently,[204] leading to cumulative exposure risks that are often not accounted for in the scientific literature.[205] CAFOs commonly employ these technologies at night, elevating the likelihood of pathogen transmission due to the lack of ultraviolet radiation from the sun.[206] Because sunlight helps to neutralize pathogens—including antibiotic-resistant bacteria[207]—EPA must prohibit the use of spray irrigation at night. This BMP

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198 *Id.*
199 *See* ROBERT L. KELLOGG ET AL., USDA, MANURE NUTRIENTS RELATIVE TO THE CAPACITY OF CROPLAND AND PASTURELAND TO ASSIMILATE NUTRIENTS: SPATIAL AND TEMPORAL TRENDS FOR THE UNITED STATES 69 (2000) ("Deposition (both wet and dry) of ammonia and ammonium has been shown in some studies to occur in close proximity to the source of emission, sometimes within 100 meters and often within 10,000 meters."); R.S. Dungan, *Fate and Transport of Bioaerosols Associated with Livestock Operations and Manures*, 88 J. ANIMAL SCI. 3693, 3699 (2010) (table of studies, including one showing elevated bacteria levels 200 meters downwind of a land application site); WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.190 at C-14 (reprinting Mark A. Borchardt & Tucker R. Burch, *Airborne Pathogens from Dairy Manure Aerial Irrigation and the Human Health Risk*, which found risk of contracting *Salmonella* from aerosolized manure-borne pathogens exceeded EPA's drinking water risk threshold at distances below 1,000 feet).
200 Dungan, *supra* n.199 at 3693–96; Steve Wing et al., *Environmental Injustice in North Carolina's Hog Industry* 108 ENV'T HEALTH PERSPECTIVES 225, 225 (2000); Risse et al., *supra* n.95 at 298; Burkholder, *supra* n.16 at 309.
201 *See generally* Joan A. Casey et al., *Industrial Food Animal Production and Community Health*, 2 CURRENT ENV'T HEALTH REPORTS 259 (2015) (literature review concluding that communities living near industrial food animal production suffered heightened risk of respiratory illness, MRSA, Q fever, and adverse stress and mood conditions); Kravchenko, *supra* n.8 at 284 (describing a variety of adverse health impacts in communities near CAFOs even when controlling for confounding variables).
202 SARAH GOLDMAN ET AL., JOHNS HOPKINS CENTER FOR A LIVABLE FUTURE, ESSENTIAL AND IN CRISIS: A REVIEW OF THE PUBLIC HEALTH THREATS FACING FARMWORKERS IN THE US 44 (2021); Wing, *supra* n.200.
203 Dungan, *supra* n.199 at 3698 (acknowledging that tank spreading lowers pathogen transport risk); *see also infra* Section IV.B.4.d (waste incorporation).
204 Burch, *supra* n.191 at 087009-1.
205 WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.190 at 53, C-14.
206 Andrew D. McEachran et al., *Antibiotics, Bacteria, and Antibiotic Resistance Genes from Cattle Feed Yards via Particulate Matter*, 122 ENV'T HEALTH PERSPECTIVES 337, 341 (April 2015); Risse, *supra* n.95 at 298.
207 Risse, *supra* n.95 at 298.

would also help improve permit enforcement, as unsupervised nighttime spray irrigation throws yet another wrench into the already exceedingly difficult process of evaluating NMP compliance.[208]

Crucially, health harms attributable to spray irrigation technologies include significant mental and physical health impacts from unbearable odor.[209] Residents who work and live near CAFOs report experiencing stenches so foul that they "interfere with daily activities, preventing neighbors from opening windows, drying clothes, gardening, and hosting family and friends."[210] State regulators recognize that pressurized spray irrigation in particular exacerbates odors, but have largely failed to adopt mandatory BMPs to alleviate burdens on surrounding communities.[211] If EPA does not prohibit the use of these technologies outright, it must at least consider BMPs to reduce adverse impacts including mandatory nozzle settings that ensure waste droplets meet minimum size thresholds, foregoing spray application when winds are above 5 mph, and limiting spray irrigation to the late morning and early afternoons to reduce odor and pathogen transmission.[212] However, as applied to the criteria for technology-based effluent limits, evidence of water quality harm and air quality related health hazards supports a full ban on pressurized spray application of CAFO waste.

2. Other High-Risk Land Application Practices

EPA and other agencies recognize that certain spreading practices, including spreading CAFO waste on steep slopes, bare soils, and frozen, snow-covered, or saturated ground, elevate the risk of runoff and pollutant transport. Nonetheless, EPA and NRCS currently leave it up to the states to determine what conditions are acceptable for manure spreading and what precautions, if any, CAFO owners and operators must take when spreading on sloped land or during winter months.[213] This has resulted in a patchwork of state-based requirements,[214] and many states with both numerous CAFOs

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[208] *See infra* Section III.F (discussing barriers to NPDES permit enforcement).
[209] Casey, *supra* n.201; NC Title VI Letter, *supra* n.8 at 4–7, Kaitlin Kelly-Reif & Steve Wing, *Urban-Rural Exploitation: An Underappreciated Dimension of Environmental Injustice*, 47 J. RURAL STUDIES 350, 355 (2016).
[210] Title VI Letter, *supra* n.8 at 4–7; Kelly-Reif & Wing, *supra* n.209; WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.199 at 35.
[211] WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.199 at 35, 37; Donald L. Pfost et al., *Odors from Livestock Operations: Causes and Possible Cures*, https://extension.missouri.edu/publications/g1884 (Nov. 2018) (noting that low-pressure, low trajectory irrigation reduces odor and merely recommending consideration of measures to reduce odors from center pivots); WILLIAM L. KRANZ ET AL., U. NEBRASKA-LINCOLN, APPLICATION OF LIQUID ANIMAL MANURES USING CENTER PIVOT IRRIGATION SYSTEMS 3 (2007).
[212] WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.190 at 37 (recommending droplet sizes greater than 150 micrograms to reduce odors), 36 (recommending avoiding application when air is warming or windy).
[213] *See* USDA-NRCS, CONSERVATION PRACTICE STANDARD 590, NUTRIENT MANAGEMENT 4 (May 2019), https://www.nrcs.usda.gov/sites/default/files/2022-09/Nutrient_Management_590_NHCP_CPS_2017.pdf, which only mentions slope as a consideration factor when allowing nutrient application despite a likelihood of runoff, such as on frozen, snow-covered, or saturated soils.
[214] *See, e.g.*, JESSICA DEXTER, ENV'T LAW & POLICY CTR., CULTIVATING CLEAN WATER: STATE-BASED REGULATION OF AGRICULTURAL RUNOFF POLLUTION 47-51 (2010), https://www.iaenvironment.org/webres/File/News%20%26%20Resources/Publications/Cultivating_Clean_Water_Report.pdf.

and high-risk conditions that wholly fail to prohibit such practices in their NPDES implementing regulations.[215] Absent a national prohibition on these reckless application practices, operators will continue to land apply waste under high-risk conditions, fail to maintain adequate storage to avoid winter application, and adversely impact surface water quality through preventable land application discharges.

EPA must strengthen the CAFO ELGs to prohibit the spreading of manure on steep slopes, frozen, saturated, or snow–covered ground, or during periods of crop dormancy when such conditions are expected to occur before crop nutrient uptake occurs, because manure application under these conditions is known to lead to surface water discharges, and is therefore inconsistent with the requirement that land application be conducted in such a way that minimizes the risk of nutrient loss. In conjunction with this requirement, EPA must require adequate storage to ensure that operators may not simply dump excess stored manure on fields each spring, as that would also lead to unacceptable risk of pollution runoff.

Performance

In the NPDES Permit Writers' Manual for CAFOs, EPA cautions against, but fails to prohibit spreading of manure—even liquid manure—on steep slopes.[216] Steeply sloped areas often lack soil properties that foster normal plant growth, meaning that it is less likely that nutrients from manure will be fully assimilated by plants, and more likely that these excess nutrients will be transported to surface and ground waters.[217] In EPA's own literature review of academic research relating to livestock and poultry manure impacts, the Agency found land slope to be a key determinant of runoff and of the likelihood of pathogen transport.[218]

In light of "considerable research [that] has demonstrated that runoff from manure application on frozen or snow-covered ground has a high risk of water quality impact," [219] the Permit Writers' Manual also says that state programs "should either prohibit application of manure and process wastewater on snow, ice, and frozen ground, or include specific protocols that CAFO owners or operators . . . will use to conclude whether application to a frozen or snow–or ice–covered field (or a

[215] *See, e.g.,* WIS. DEP'T OF NAT. RES., WPDES PERMIT NO. WI-0063274-01: LARGE DAIRY CAFO GENERAL PERMIT 3.7.4-3.7.7 (Apr. 4, 2011) (allowing for liquid and solid manure application on frozen and snow-covered ground under various circumstances); Ill. Admin. Code § 560.206 (noting that "[w]aste application on frozen or snow-covered land should be avoided," yet providing for legal application to frozen and snow-covered ground); Sierra Club Michigan Chapter, *Why are CAFOs Bad?*, http://www.sierraclub.org/michigan/why-are-cafos-bad (visited June 11, 2025) (noting that Michigan CAFOs may be permitted, either through their NMP or under an order from the state with specifications for winter application, to apply waste to snow or frozen ground).
[216] CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.121 at 5-30.
[217] *Id.* at A-8.
[218] EPA LITERATURE REVIEW, *supra* n.6 at 23, 25.
[219] CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.121 at G-14.

portion thereof) poses a reasonable risk of runoff,"[220] Similarly, NRCS, EPA's primary resource for developing technical standards,[221] advises that "[n]utrients must not be surface–applied if nutrient losses offsite are likely" and warns against spreading on "frozen and/or snow-covered soils, and when the top 2 inches of soil are saturated from rainfall or snow melt."[222] But rather than prohibiting these dangerous practices, EPA merely "strongly encourages" states to adopt such prohibitions themselves.[223] This recommendation has proven inadequate.

The increased likelihood of runoff associated with application of manure to frozen, saturated, or snow-covered ground is widely recognized by agricultural experts, including agricultural extension program technical staff, state agencies, and EPA itself. Liquid or semi–liquid manure cannot easily permeate ground that is already saturated or that is frozen, and thus is much more likely to run off into nearby waterways, particularly when snow or frozen ground begins to melt.[224] EPA has collected considerable research documenting "extremely high concentrations of nitrogen and phosphorous in runoff" due to winter application of waste. [225] Per this research, winter application of dairy manure can result in a 1,480 percent increase in soluble phosphorus concentrations found in nearby surface waters, and up to 576 percent increases in ammonia-nitrogen concentrations. [226] One study of Vermont streams and lakes concluded that 40 percent of studied waterbodies experienced significant water quality impairments from the addition of just two winter-spread fields in their watersheds.[227] A Wisconsin study similarly estimated that 25 percent of annual phosphorous loading was directly attributable to winter spreading of animal wastes.[228]

Moreover, in areas where soils reach freezing temperatures, there are generally no winter crops available to uptake the nutrients in manure, meaning there is little to no agronomic benefit to winter applications and nutrients are susceptible to loss before any spring crop has been planted.[229] Indeed,

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[220] *Id.* at 6-15.
[221] USDA & EPA, UNIFIED NATIONAL STRATEGY FOR ANIMAL FEEDING OPERATIONS Sec. 3.2 (March 9, 1990), https://www3.epa.gov/npdes/pubs/finafost.pdf.
[222] NRCS STANDARD 590 at 4.
[223] CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.121 at 6-16; *see also id.* at 5-30 (listing standards, including prohibiting application of manure to frozen or snow-covered ground, which permit authorities "may include" as technology-based standards).
[224] INT'L JOINT COMM'N, A BALANCED DIET FOR LAKE ERIE: REDUCING PHOSPHOROUS LOADINGS AND HARMFUL ALGAL BLOOMS 75 (2014), https://ijc.org/sites/default/files/2014%20IJC%20LEEP%20REPORT.pdf; EPA RISK ASSESSMENT, *supra* n.141 at 23, 71.
[225] CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.121 at G-14. (citing research finding a 1,480 percent increase in soluble P concentrations and 576 percent increases in ammonia-nitrogen concentrations following winter application of dairy manure).
[226] *Id.* (citing 1990 and 1991 Clausen studies).
[227] *Id* (citing 1989 Clausen and Meals study).
[228] *Id.* (citing 1985 Moore and Madison study).
[229] B. HINDMARSH, ONTARIO MINISTRY OF AGRICULTURE, FOOD, AND RURAL AFFAIRS, WINTER APPLICATION OF MANURE AND OTHER AGRICULTURAL SOURCE MATERIAL 1 (Aug. 2021). Similarly, in a PowerPoint presentation

"the absence, or poor growth of crops (limiting uptake of manure nutrients and water), winter weather, and winter soil conditions generally exacerbate off-site losses of manure-derived pollutants."[230] EPA's own peer-reviewed technical guidance similarly concludes that "[f]rom the dual perspectives of nutrient utilization and pollution prevention, [] winter is the least desirable time for land application."[231] According to Michigan regulators, that is because "[b]ased on the frozen and/or snow-covered conditions, the minimal settling and breaking down of the waste during these conditions, and the inability to predict or control snowmelt and rainfall, *there are no practices* that can ensure the runoff from fields with surface-applied waste on frozen or snow-covered ground will not be polluted."[232]

Other authorities, ranging from the state level to international, have also recognized the harms likely to result from land application in winter months and on frozen ground. The International Joint Commission, an international organization created by the Boundary Waters Treaty (ratified by the United States and Canada in 1909), recommends that to protect Lake Erie, all adjacent states should ban the spreading of manure on frozen or snow-covered ground because of the likelihood of those practices polluting surface waters.[233] The Iowa State University Extension acknowledges that "[b]roadcasting manure onto frozen, snow-covered, water-saturated soils increases the potential for nutrient losses with rainfall or snowmelt runoff to surface water systems."[234] Similarly, the Penn State Extension warns that "[s]preading manure in the winter is discouraged because it is a high-risk time period for nutrient losses and contamination of surface water,"[235] and the Ohio State University

derived from a white paper prepared for EPA by contract company Tetra Tech, Tetra Tech noted that a "comprehensive literature review found no published research to support agronomic factors as a basis for recommending winter manure application." TETRA TECH, *Winter Manure Application and Water Quality: Overview of the Literature* 4 (Oct. 30, 2014), http://bloximages.chicago2.vip.townnews.com/auburnpub.com/content/tncms/assets/v3/editorial/f/ef/fef9f5a8-8a50-53b9-a377-eaf2a11a9362/5483213e3e237.pdf.pdf.

[230] Jian Liu, et al., *A review of regulations and guidelines related to winter manure application*, 47 AMBIO 657, 657, 670 (Feb. 3, 2018).

[231] CAFO NPDES PERMIT WRITERS' MANUAL, *supra* n.121 at G-1–2 (noting that "[w]here there is a reasonable risk [of runoff from application on snow, ice, and frozen soil], EPA strongly prefers that technical standards prohibit application on the field or the pertinent portion thereof during times that the risk exists or may arise").

[232] MICHIGAN DEP'T ENV'T, GREAT LAKES, AND ENERGY, PERMIT NO. MIG010000 44 (March 27, 2020), https://www.michigan.gov/-/media/Project/Websites/egle/Documents/Programs/WRD/CAFO/MIG010000-General-Permit-2025.pdf.

[233] INT'L JOINT COMM'N, *supra* n.224 at 9.

[234] IOWA STATE UNIV. EXTENSION & OUTREACH, USING MANURE NUTRIENTS FOR CROP PRODUCTION 6 (May 2016), http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1089&context=extension_pubs.

[235] Charles White & Robert Meinen, PENN STATE EXTENSION, *The Do's and Don'ts of Winter Manure Spreading* (Dec. 13, 2022), https://extension.psu.edu/the-dos-and-donts-of-winter-manure-spreading.

Extension advises that "[w]inter application should not be part of a manure management plan and it should only be viewed as a last resort."[236]

Cost and Availability[237]

Regulating these spreading activities is clearly practicable, as evidenced by the fact that several states with numerous CAFOs do restrict the spreading of manure under high-risk conditions. For example, Maryland and Delaware have both implemented an outright ban on manure spreading during winter months, with additional restrictions in place outside the closed period for spreading on frozen, snow-covered or saturated fields.[238] Other States have limited application to sloped land in certain conditions.[239] Moreover, international examples of winter and high-risk spreading restrictions abound, including across European countries and certain Canadian and New Zealand provinces.[240]

Non-Water Quality Impacts

Beyond surface water degradation, these high-risk application practices also increase the risk of polluted runoff infiltrating wells and contaminating underground sources of drinking water. The Minnesota Department of Public Health has identified that applying waste to frozen ground heightens the risk of drinking water and public water supply contamination.[241] In Wisconsin, there have been documented instances of land application to snow-covered fields—performed in full compliance with state winter spreading regulations—that have poisoned nearby drinking water wells with astronomically high levels of *E. coli* and other dangerous pollutants and resulted in life-threatening illnesses.[242] Given the substantial and unwarranted risk these spreading practices pose to surface water,

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[236] Amanda Meddles, OHIO STATE UNIV. EXTENSION, *Properly Applying Manure on Frozen Ground*, OHIO'S COUNTRY JOURNAL (Jan. 24, 2012), http://ocj.com/2012/01/properly-applying-manure-on-frozen-ground/; *see also* UTAH FARMSTEAD ASSESSMENT FOR GROUND WATER AND SURFACE WATER PROTECTION, HOW TO MANAGE STORED MANURE AND PROTECT YOUR WATER 7 (Mar. 2012), http://extension.usu.edu/files/publications/factsheet/WQFA-13.pdf (advising on proper manure handling and storage for water protection, and directing that "[m]anure should not be applied to frozen or snow-covered ground unless all runoff can be controlled."); OHIO DEP'T AGRIC. ET AL., OHIO LAKE ERIE PHOSPHORUS TASK FORCE II FINAL REPORT 51 (Nov. 2013), https://www.motherjones.com/wp-content/uploads/task_force_report_october_2013.pdf.

[237] This and subsequent evaluations of technology "cost and availability" includes analysis of the following BAT factors: (1) the age of equipment and facilities involved, (4) process changes, and (5) the cost of achieving effluent reduction.

[238] *See* MD. DEP'T AGRIC., NUTRIENT APPLICATION REQUIREMENTS, Ch. IV.C.2–3, E.3, F.2 (July 2024), https://mda.maryland.gov/resource_conservation/Documents/nm_manual/1-D1-1-1D1-6.pdf; 3 Del. Admin. Code 1201-6.2.

[239] *See* Tenn. Comp. R. & Regs. 1200-4-5.14 app. A (prohibiting application to steep slopes); 327 Ind. Admin Code § 16-10-3(f)(1) (prohibiting application to frozen ground with slopes greater than 2 percent grade); 510 Ill. Admin. Code tit. 8 § 900.803(s) (prohibiting application to frozen or snow-covered land with slopes greater than 5 percent).

[240] *See* Liu, *supra* n.230, at 660–662, 665 (discussing implementation of winter spreading ban throughout European Union, in Manitoba and Quebec, and Canterbury.)

[241] MINN. DEP'T HEALTH, WELLHEAD PROTECTION ISSUES RELATED TO FEEDLOT OPERATIONS 2 (Sep. 11, 2012), https://www.health.state.mn.us/communities/environment/water/docs/swp/feedlot.pdf.

[242] *See e.g.*, Jim Lundstrom, *Brown Water*, DOOR COUNTY PULSE (Sep. 17, 2014), https://doorcountypulse.com/brown-water/ (detailing how a CAFO operator's application of 18,000 gallons of waste to a field covered with 18 inches of

combined with their potentially severe public health consequences, EPA should prohibit land application under these high-risk circumstances.

3. Anaerobic Digesters

Anaerobic digesters are systems that produce "biogas" from feedstocks like plant materials and animal waste.[243] They accomplish this by containing feedstock in an oxygen-deprived environment, introducing and cultivating methanogenic bacteria, and collecting the resulting biogas emissions comprised of methane and other gases. In addition to biogas, operators must manage "digestate" or the remaining solid and liquid waste leftover after gas production.[244] Using anaerobic digesters to generate biogas from animal waste from CAFOs has become increasingly common over the past decade, thanks in large part to state and federal programs incentivizing biogas projects.[245] With the rising prevalence of anaerobic digesters on CAFOs and claims that digesters can reduce nutrient and pathogen runoff, this technology may seem like a viable candidate for inclusion in the ELGs as a basis for an effluent limitation on pathogens.[246] In reality, however, anaerobic digestion increases the risk that a CAFO will discharge pollution to waterways. Further, digesters are not affordable without uncertain government funding and cause adverse non-water quality impacts that outweigh any methane emission reduction benefits. While the immediate decommissioning of existing CAFO digesters may be beyond the scope of EPA's ELG revision, the ELGs should prohibit the construction and operation of new digesters and ensure facilities with existing digesters handle and dispose of digestate in a manner that reduces water quality risks.

Performance

Allowing the use of anaerobic digesters in the CAFO ELGs is not consistent with the CWA because digesters do not reduce water pollution. In fact, anaerobic digestion creates water pollution risks above and beyond those posed by CAFOs without anaerobic digesters. Digestate contains the

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snow, in compliance with state regulations, contaminated the residential drinking well of a nearby family with over 10,000 parts per mL of *E. coli* and 100,000 parts per ML of coliform); Declaration of Nancy Utesch, Dkt. No. 26.17, *Food & Water Watch v. EPA* (9th Cir. 23-2146), ¶ 10 (describing knowledge of same incident as "nearly killing [the family's] infant child who had to be treated in intensive care.").

[243] EPA, *How Does Anaerobic Digestion Work?*, https://www.epa.gov/agstar/how-does-anaerobic-digestion-work (accessed March 28, 2025).

[244] *Id.*

[245] Credit for Production of Clean Hydrogen and Energy Credit, 90 Fed. Reg. 2224, 2289 (Jan. 10, 2025); *see also* EPA, Livestock Anaerobic Digester Database, https://www.epa.gov/agstar/livestock-anaerobic-digester-database (accessed March 28, 2025) (listing anaerobic digester projects by year and noting which received federal funding).

[246] *See* EPA, *The Benefits of Anaerobic Digestion*, https://www.epa.gov/agstar/benefits-anaerobic-digestion (accessed April 25, 2025). Notably, EPA considered and rejected anaerobic digesters as a basis for large dairy and swine CAFO ELGs in 2002. 68 Fed. Reg. at 7216–17.

same pollutants of concern as undigested waste, including nutrients, salts, pesticides, pharmaceuticals, heavy metals like lead, copper, and mercury, and carcinogens like hexavalent chromium.[247] Most of these pollutants are not destroyed during digestion, but rather consolidated in the digestate as a portion of the feedstock is transformed into methane gas.[248] [249] Nutrients in digestate are particularly detrimental to water quality because anaerobic digestion increases the proportion of inorganic nitrogen and phosphorus in CAFO waste. Inorganic nutrients are more water soluble, elevating the likelihood that these pollutants will reach ground and surface waters when land applied or spilled during an accident.[250] Digestion also increases cumulative ammonia emissions by as much as 81 percent compared to storage and land application of undigested waste,[251] increasing risks associated with aerial pollution deposition.

The little evidence that does suggest anaerobic digestion can reduce CAFO water pollution is largely based on pathogen destruction data generated in laboratory settings. Studies of digesters operating in the field show they attain far lower and more variable pathogen reductions than digesters in laboratory settings.[252] For instance, one study of anaerobic digesters processing manure in Wisconsin found that pathogen deactivation rates were two times lower than the removal rates suggested in past literature.[253] To ensure a realistic analysis of possible amendments to the CAFO ELGs, EPA should assign more weight to research based on CAFOs operating under real-world conditions than it does to research conducted in a controlled laboratory setting.

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[247] Alberto Pivato et al., *Use of Digestate from a Decentralized On-Farm Biogas Plant as Fertilizer in Soils: An Ecotoxicolofical Study for Future Indicators in Risk and Life Cycle Assessment*, 49 WASTE MGMT. 1, 28 (2016) (pagination in accordance with copy submitted).

[248] *See* 68 Fed. Reg. at 7216–17 (explaining that digesters "would not necessarily lead to significant reductions for many of the pollutants discharged to surface waters from CAFOs"); 2003 TDD, *supra* n.26 at 8-69 ("The reductions of P, K, or other nonvolatile elements reported in the literature for covered lagoons are not really reductions at all. The material settles and accumulates in the lagoon, awaiting later management."). FRIENDS OF THE EARTH, A BROWN CLOUD OVER THE GOLDEN STATE: HOW DAIRY DIGESTERS ARE DRIVING CAFO EXPANSION AND ENVIRONMENTAL INJUSTICE IN CALIFORNIA 28 (2024), https://foe.org/wp-content/uploads/2024/10/BrownCloud-ENGLISH-Final-1.pdf; CARLIN MOLANDER & MOLLY ARMUS, MAKING A BAD SITUATION WORSE: MANURE DIGESTERS AT MEGA DAIRIES IN WISCONSIN 16 (2024), https://foe.org/wp-content/uploads/2024/06/WI-Case-Study_v2.pdf.

[249] The exception to this rule is active pathogens, which can be reduced under optimal conditions—but not eliminated—by digestion as discussed *infra* at nn.252–262 and accompanying text.

[250] NRCS STANDARD 366 at 8–9; FOOD & WATER WATCH, HARD TO DIGEST: GREENWASHING MANURE INTO RENEWABLE ENERGY 2 (Nov. 2016).

[251] Michael Holly et al., *Greenhouse Gas and Ammonia Emissions from Digested and Separated Dairy Manure During Storage and After Land Application*, 239 AG. ECOSYSTEMS, AND THE ENV'T 410, 413 (2017).

[252] *See* Tucker R. Burch et al., *Fate of Manure-Borne Pathogens during Anaerobic Digestion and Solids Separation*, 47 J. ENV'T QUALITY 336, 341 (2018), https://doi.org/10.2134/jeq2017.07.0285 ("In our own study, microbe inactivation was poor when initially compared with expectations from the literature.").

[253] *Id.*

EPA must also consider field data that show digesters create additional water pollution risks rather than improperly focusing on purported pathogen reduction benefits. Catastrophic spills, excessive land application, and even explosions[254] are issues at CAFOs that use anaerobic digesters to process their waste. In 2022, an on-farm digester built to receive waste from three dairies in northwest Iowa leaked approximately 376,000 gallons of manure into the surrounding environment, discharging bacteria and ammonia into a nearby creek.[255] Despite a 10,000 dollar fine, the digester operator was unable to prevent at least two additional discharges over the ensuing year.[256] The same year, a hog CAFO in North Carolina reported that its digester collapsed, spilling tens of thousands of gallons of manure, mortalities, and food waste onto surrounding fields and into neighboring wetlands.[257] In Minnesota, a digester owned by a major corporation in the biogas industry spilled untold quantities of waste after the facility's tank failed in March 2025.[258] A survey of large Wisconsin dairy CAFOs employing digesters also found that all five had experienced spills *and* been fined for improper land application of waste.[259] In Oregon, a Tillamook CAFO digester spilled an estimated 300,000 gallons of digestate, some of which discharged to a storm water pipe that emptied into a nearby creek.[260] Even CAFOs that land apply digested waste according to rates set forth in an NMP are likely contributing to water pollution because current NMP guidance (which does not even adequately prevent risks from ordinary manure) does not properly account for digestate's elevated soluble pollutant levels.[261]

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[254] Steve Verberg, *Blast Destroys Roof of Troubled Biodigester Near Waunakee*, WISCONSIN STATE J. (August 6, 2014), https://agupdate.com/news/local/environment/blast-destroys-roof-of-troubled-biodigester-near-waunakee/article_56b6030d-5b7c-54a9-8f3e-2adb0a93b4ed.html.

[255] Jared Strong, *Company Filled Massive Manure Container Despite Signs of a Leak, DNR says*, IOWA CAPITAL DISPATCH (July 6, 2022), https://iowacapitaldispatch.com/2022/07/06/company-filled-massive-manure-container-despite-signs-of-a-leak-dnr-says.

[256] Erin Jordan, *'More Manure Means More Energy' Iowa Dairies with Biogas Digesters are Growing Their Herds, Which Concerns Water Quality Advocates*, The Gazette (Nov. 3, 2024), https://www.thegazette.com/agriculture/moremanure-means-more-energy-iowa-dairies-with-biogas-digesters-are-growing-their-herds-which-c/ (finding "manure leaking from a tile line" in April 2022 and "500 gallons of manure 'foam'" released into the environment in January 2023).

[257] Will Atwater, *Wayne County Wetland Continues to Suffer: Farm with Massive Hog Waste Spill Nets New Violation Amid Bacteria Concerns*, NORTH CAROLINA NEWS (July 28, 2023), https://www.northcarolinahealthnews.org/2023/07/28/wayne-county/.

[258] *LSP Demands Answers Surrounding Recent Manure Spill in Kandiyohi County* (March 7, 2025), https://landstewardshipproject.org/lsp-demands-answers-surrounding-recent-manure-spill-in-kandiyohi-county/.

[259] *See* MOLANDER & ARMUS, *supra* n.248 at 6.

[260] George Plaven, *Cleanup Underway After Manure Digester Spill Near Tillamook* (July 25, 2019), https://capitalpress.com/2019/07/25/cleanup-underway-after-manure-digester-spill-near-tillamook/

[261] *See supra* Section III.A.

Digesters are also a false solution to water pollution because they incentivize CAFOs to grow their herds, leading to further concentration of pollutants in already overwhelmed watersheds.[262] Digester operations require large amounts of CAFO waste to function[263] and optimize biogas production infrastructure, incentivizing CAFOs to grow their herds to take advantage of economies of scale by maximizing biogas production.[264] USDA's most recent Census of Agriculture data show that herd size on California dairies with more than 2,500 milk cows increased by a whopping 26.8 percent over 5 years, boosting total milk cows in that size category from 808,503 in 2017 to approximately 1,025,716 in 2022.[265] Research investigating factory farm digesters in 8 states shows that "herd sizes at dairy CAFOs with digesters grew 3.7 percent year-over-year, which is *24 times* the growth rate for overall dairy herd sizes."[266] In some CAFO-intensive counties, herd sizes are growing even faster despite local opposition efforts.[267] The additional manure and other wastes from these operations pose water quality threats above and beyond business as usual, further exacerbating water quality risks.[268]

Finally, anaerobic digestion will not reduce water pollution from CAFOs because digestion incentivizes excessive, hazardous, and avoidable liquid manure storage at the expense of less harmful management strategies. When it comes to manure management, livestock operations have a variety of options for storage and treatment.[269] The rise in manure liquification, slurry storage in lagoons, land application of liquid waste, and the concomitant water quality impacts of these practices is a direct result of industry consolidation toward fewer and larger operations.[270] Digesters are only compatible with large-scale, centralized storage of liquid and slurry wastes, further entrenching livestock production in an overly consolidated system that inherently endangers water quality with the risk of

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[262] LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY ET AL., COMMENTS ON PROPOSED AMENDMENTS TO THE LOW CARBON FUEL STANDARD 2 (Feb. 20, 2023).
[263] EPA only recommends anaerobic digestion for CAFOs with at least 500 cattle or 2,000 hogs. *Is Anaerobic Digestion Right for Your Farm?*, https://www.epa.gov/agstar/anaerobic-digestion-right-your-farm#q2 (visited April 7, 2025).
[264] The U.S. Department of Treasury recently agreed that tax credits for biogas production from manure run the risk of incentivizing CAFOs to generate pollutants they would not otherwise produce. 90 Fed. Reg. at 2285. *See also* FOOD & WATER WATCH, THE BIG OIL AND BIG AG PONZI SCHEME: FACTORY FARM GAS 4–5 (Jan. 2024), https://www.foodandwaterwatch.org/wp-content/uploads/2024/01/RPT2_2401_GreenwashingBiogas-WEB3.pdf.
[265] LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY, *supra* n.262 at 2.
[266] CHLOË WATERMAN & MOLLY ARMUS, BIOGAS OR BULL****: THE DECEPTIVE PROMISE OF MANURE BIOGAS AS A METHANE SOLUTION 59 (2024), https://foe.org/wp-content/uploads/2024/03/Factory-Farm-Gas-Brief_final.pdf (emphasis added).
[267] MOLANDER & ARMUS, *supra* n.248 at 17.
[268] *Id.* at 25.
[269] *See, e.g.*, *infra* Section IV.B.4.a (SLS), IV.B.3.a.iii (dry manure handling).
[270] LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY, *supra* n.262 at 19–20.

catastrophic spills and mismanagement of huge quantities of waste. For all of these reasons, the use of digesters on CAFOs does not reduce—and likely increases—water pollution.

Cost and Availability

Digesters are prohibitively expensive for all but the largest CAFOs.[271] Not only are the digesters themselves expensive, operations looking to invest in digestion must also purchase, install, and maintain various pumps, tanks, pipes, monitors, and electrical equipment.[272] Total project costs to install a functional on-farm digester system vary widely, but average over 1 million dollars and can exceed 16 million dollars,[273] making the technology unaffordable for most facilities.[274] As the largest, wealthiest livestock operations scale up to take advantage of policies incentivizing digesters, smaller farms inevitably get pushed out, further exacerbating rampant consolidation within the industry.[275] This trend is already well underway in California, where the state's favorable treatment of biogas in its Low Carbon Fuel Standard (LCFS) program is transforming its animal agriculture sector to the detriment of smaller operations.[276] In this manner, incentivizing digesters poses an existential threat to family farms that raise livestock on the land instead of in confinement operations.

The costs of anaerobic digestion are so large that CAFOs could not install and operate these technologies without the constant stream of government support programs that are currently propping up the biogas industry.[277] These taxpayer-funded subsidies—which include government

[271] Gittelson, *supra* n.8 at 358; Food & Water Watch, *supra* n.4 at 10; Hyunok Lee & Daniel A. Sumner, *Dependence on Policy Revenue Poses Risks for Investments in Dairy Digesters*, 72 CALIFORNIA AGRIC. 226, 231 (Dec. 2018); *see also* ASSEMBLY NO. 3 ON RES. & TRANSP., AGENDA 14–16 (Apr. 19, 2017), https://abgt.assembly.ca.gov/sites/abgt.assembly.ca.gov/files/April%2019%20-%20Toxics%20Recycling%20Ag.pdf (providing detailed digester cost analysis demonstrating how "costs skyrocket for small dairies" and further noting how cost contributes to a "high rate of project failure").

[272] Gittelson, *supra* n.8 at 358.

[273] *See* DAIRY DIGESTER RESEARCH AND DEVELOPMENT PROGRAM, CAL. DEP'T OF FOOD & AGRIC., REPORT OF FUNDED PROJECTS (2015–2022) 21–28, https://www.cdfa.ca.gov/oefi/ddrdp/docs/2022_DDRDP_Legislative_Report.pdf (listing total costs for 117 biogas projects, including one covered lagoon digester project that cost $16,642,393); *see also* 2002 CAFO ELG Cost Methodology at 5-119–5-125, A-105 (EPA's evaluation of the costs of anaerobic digester installation undertaken to inform the 2003 CAFO ELG rulemaking).

[274] EPA, *supra* n.263 (EPA only recommends digestion for CAFOs with a minimum of 500 cattle or 2,000 hogs); *see also* Gittelson, *supra* n.8 at 358; FOOD & WATER WATCH, *supra* n.264 at 9–10.

[275] For example, in Oregon, the number of cows at the state's mega-dairies increased by 60 percent from 2002 to 2022 while half of the state's small dairies disappeared. Juliet Grable, *Mega-Dairy CAFOs Tout Methane Digesters to Green Their Image*, SIERRA (Mar. 7, 2024), https://www.sierraclub.org/sierra/mega-dairy-cafos-tout-methane-digesters-green-their-image. *See also supra* nn.262–268 and accompanying text.

[276] LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY, *supra* n.262 at 8–10.

[277] Markus Lauer et al., *Making Money From Waste: The Economic Viability of Producing Biogas and Biomethane in the Idaho Dairy Industry*, 222 APPLIED ENERGY 621, 622 (2018); FOOD & WATER WATCH, *supra* n.264 at 3–4.

grants, tax incentives, and pollution trading schemes like California's LCFS[278]—make the production of biogas profitable. For example, analysis of one digester receiving LCFS credits showed that 93 percent of revenue was from state-issued energy credits, while only 7 percent—approximately a quarter of the digester's annual operating costs—was from selling biogas on the market.[279] Representatives from the biogas industry readily admit that government incentives and pollution credit markets are the drivers of digester profits and the reason the decades-old technology has only recently taken off.[280] While the entities trying to entice CAFOs into digester investment project profitability within a few years, "changes in state or federal policies on energy or environmental issues . . . could substantially alter economic calculations pertaining to digester investment."[281]

Indeed, influential policy shifts have already occurred, and more are on the horizon. Under the LCFS, pollution credit prices have fluctuated between 20 dollars and 200 dollars, due in part to changing federal attitudes on biofuels.[282] At present, the federal government seems poised to eliminate a critical revenue stream for digester projects alleging climate benefits.[283] Moreover, programs like the LCFS are mired in litigation and political controversy spearheaded by environmental justice advocates who argue California's methane accounting is a scam and view the program's incentives for factory farms as a direct threat to their communities.[284] If any one of these forces is successful in toppling extra-market supports for biogas, CAFO owners with new digesters could be left holding considerable loan obligations and stranded assets.[285] EPA must take the mercurial nature of these government

[278] Gittelson, *supra* n.8 at 358 (listing examples of grants and cost-sharing agreements); FOOD & WATER WATCH, *supra* n.264 at 3–4; CHLOË WATERMAN & MOLLY ARMUS, *supra* n.266; Friends of the Earth, *supra* n.**Error! Bookmark not defined.** at. 35–40.
[279] Lee & Sumner, *supra* n.271 at 231–32.
[280] Kari Lydersen, *Biogas Expansion May Compound Worker Risks* (Nov. 16, 2022), https://www.canarymedia.com/articles/enn/biogas-expansion-may-compound-worker-risks.
[281] Lee & Sumner, *supra* n.271 at 233.
[282] *Id.*; see also FRANZISKA FÖRD, WHAT CAN CANADIANS LEARN FROM THE CALIFORNIA LCFS? (December 2024), https://www.naviusresearch.com/wp-content/uploads/2025/01/Blog-December-2024-California-price-trends.pdf.
[283] *See* Unleashing American Energy, Exec. Order No. 14154, 90 Fed. Reg. 8353 (2025) (pausing Inflation Reduction Act funding and revoking executive orders related to clean energy and climate); Karl Plume & Ed White, *North American Biofuels Sector Contracts Amid Trade and Policy Uncertainty* (March 20, 2025), https://www.reuters.com/business/energy/north-american-biofuels-sector-contracts-amid-trade-policy-uncertainty-2025-03-20.
[284] *See* FOOD & WATER WATCH, *Groups Sue CARB Over Environmental Impacts of Flagship Climate Program* (Dec. 19, 2024), https://www.foodandwaterwatch.org/2024/12/19/groups-sue-carb-over-environmental-impacts-of-flagship-climate-program/ (announcing litigation against the California Air Resources Board).
[285] *See* Ashita Gona & Mike Henchen, *US Can't Meet Climate Goals While Spending Billions on Gas Infrastructure* (Aug. 2, 2021), https://rmi.org/us-cant-meet-climate-goals-while-spending-billions-on-gas-infrastructure/.

supports into account when evaluating digester costs. In sum, digesters are not available or affordable to the industry, and the ELGs should prohibit CAFOs from installing them.

Non-Water Quality Impacts

Finally, in addition to the negative water quality impacts discussed above, any benefits that may be attainable through use of anaerobic digesters on CAFOs are outweighed by harmful non-water quality impacts. Proponents allege digesters are necessary to reduce greenhouse gas emissions from livestock operations, thereby reducing the livestock industry's climate footprint. But the greenhouse gas reduction capabilities of anaerobic digesters have been overstated. Moreover, any purported greenhouse gas emissions reductions occur at the expense of other considerations, including air quality, land use, water use, and worker safety.[286]

Processing manure in anaerobic digesters will not achieve the level of greenhouse gas reductions promised by digester proponents. Digesters that use internal combustion engines to generate electricity or power electrolysis emit large amounts of toxic nitrous oxide, a potent greenhouse gas that also contributes to the formation of particulate matter.[287] Beyond the digesters themselves, digestate also emits more nitrous oxide than undigested waste.[288] Further, as discussed above, incentives for biogas drive CAFOs to increase the number of animals in confinement to maximize profits from pollution credit trading schemes.[289] Needlessly increasing herd sizes will increase emissions from enteric fermentation, the primary source of methane emissions from the livestock industry.[290] Feeding larger herds also requires more crops, incentivizing conversion of the nation's remaining grasslands and wetlands to cropland, a land use change that eats away at carbon sinks and further undermines any methane reductions attributable to digesters.[291] Similarly, increased herd size can dramatically increase a CAFO's water use.[292]

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[286] Harish K. Jeswani et al., *Environmental Sustainability of Biofuels: A Review*, 476 PROCS. ROYAL SOC'Y A. 1, 1–2 (2020), https://doi.org/10.1098/rspa.2020.0351.
[287] LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY, *supra* n.262 at 3.
[288] Gittelson et al., *supra* n.8, at 356–57.
[289] 90 Fed. Reg. at 2285.
[290] FOOD & WATER WATCH, *supra* n.264 at 5 (estimating that 27 percent of the U.S.'s annual methane emissions come from enteric fermentation while only 9 percent come from manure management).
[291] *See generally* Seth A. Spawn et al., *Carbon Emissions from Cropland Expansion in the United States*, 14 ENV'T RSCH. LETTERS 1, 7–9 (2019) (discussing the role of land use change from grassland to cropland as a major source of greenhouse gas emissions).
[292] LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY, *supra* n.262 at 6–7.

Digesters also boost methane emissions from lagoon storage and land application of liquid waste as CAFOs grow their herds and transition away from other common manure management practices.[293] The conclusion that digesters reduce overall greenhouse gas emissions from CAFOs is derived from the assumption that uncovered lagoons are the baseline from which emission reduction benefits must be measured. This is a faulty premise because many facilities utilize—and EPA recognizes[294]—viable alternatives to lagoons that already achieve lower greenhouse gas emissions.[295] Research suggests that farms that transition from anaerobic digesters to other waste management methods, such as cleaner aerobic technologies, can reduce greenhouse gas emissions from manure management by 98.9 percent.[296] For example, as discussed below, separating CAFO waste into solids and liquids reduces organic pollutants in the liquid portion, reducing the risk of pollution impacts from land application of the liquids and allowing the solids to be composted for beneficial reuse.[297] However, CAFOs making money from generating and selling biogas have an incentive to retain volatile organics in slurries because the high organic content maximizes biogas output.[298] In fact, poultry CAFOs that primarily handle dry wastes are increasingly looking to liquify their litter just so they can generate biogas.[299] Such examples make clear that, while digesters may reduce methane emissions from storage on CAFOs already storing large amounts of liquid waste in uncovered lagoons,

[293] *Id.* at 19–20 (explaining that methane emissions potential from liquid manure storage is higher than dry manure management systems).
[294] EPA, AGSTAR PROJECT DEVELOPMENT HANDBOOK: A HANDBOOK FOR DEVELOPING ANAEROBIC DIGESTION/BIOGAS SYSTEMS ON FARMS IN THE UNITED STATES 1-8–1-9 (3d ed.), https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf.
[295] *See generally* USDA, PART 651 AGRICULTURAL WASTE MANAGEMENT FIELD HANDBOOK, CH. 9 AGRICULTURAL WASTE MANAGEMENT SYSTEMS (Dec. 2011), https://directives.nrcs.usda.gov/sites/default/files2/1712930953/17184.pdf; *see also infra* Sections IV.B.2.a (treatment), IV.B.3.a.iii (dry manure handling), and IV.B.4.a (SLS).
[296] MATIAS B. VANOTTI ET AL., U.S. DEP'T OF AGRIC., GREENHOUSE GAS EMISSION REDUCTIONS AND CARBON CREDITS FROM IMPLEMENTATION OF AEROBIC MANURE TREATMENT SYSTEMS IN SWINE FARMS (2006), https://www.ars.usda.gov/ARSUserFiles/60820000/Manuscripts/2006/Man720.pdf.
[297] *See* CAL. DEP'T FOOD & AGRIC., RECOMMENDATIONS FOR SHORT-LIVED CLIMATE POLLUTANTS: AN AGRICULTURAL WORKGROUP REPORT FOR THE CALIFORNIA AIR RESOURCES BOARD AND CALIFORNIA DEPARTMENT OF FOOD AND AGRICULTURE 12–13 (June 2015), https://perma.cc/9CEA-U4NX ("[W]hen dry systems are used . . . emissions can be dramatically reduced – perhaps by more than 90 percent."); *see also infra* Section IV.B.4.a (SLS).
[298] *See* LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY, *supra* n.262 at 9 (discussing example of a dairy that shifted away from a system that produced less emissions after installing a digester).
[299] *See generally* UNIVERSITY OF MARYLAND, CASE STUDY: ANAEROBIC DIGESTION AND CAPTURE FROM POULTRY LITTER ON THE MARYLAND EASTERN SHORE, https://mda.maryland.gov/resource_conservation/counties/UMD%20Factsheet%20PFED%20Poultry%20Litter%20Digester.pdf (visited April 30, 2025).

such lagoons are neither the norm nor the baseline from which reasonable CAFO emission controls should be measured.[300]

Even assuming EPA is able to put safeguards in place to prevent digester incentives from increasing CAFO herd sizes or liquid waste storage, and assuming a baseline of liquid waste in uncovered lagoons, digesters increase emissions of non-greenhouse gas air pollutants such as ammonia.[301] Digestate also has higher potential to emit hydrogen sulfide and gaseous ammonia, dangerous air pollutants that contribute to respiratory illness and react with ozone to create nitrous oxide—yet another greenhouse gas.[302] EPA must consider these emissions risks, not just the claimed benefits from captured methane.

Producing and transporting biogas generated by anaerobic digesters also makes CAFOs reliant on pipelines and trucks, further harming local air quality and entrenching dangerous fossil fuel infrastructure in our agricultural system.[303] Transport trucks often run on diesel fuel, while gas pipelines notoriously leak tremendous amounts of methane, further negating any alleged greenhouse gas savings.[304] Reliable claims about emissions impacts attributable to anaerobic digestion must be based on analyses that quantify and include these emissions.

Finally, EPA should consider that digesters pose serious threats to worker safety. Between heavy machinery, toxic fumes, and pollutant-induced illnesses, CAFOs are already dangerous places to work.[305] Introducing digesters and additional liquid waste storage to supply those digesters is a recipe for disaster. Diagnostics and repairs to digester and lagoon infrastructure sometimes requires workers to submerge themselves into manure-filled cesspools—a situation that has already caused multiple deaths.[306] Additionally, the pressurized environment inside an anerobic digester creates

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[300] LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY, *supra* n.262 at 18–20.
[301] Holly, *supra* n.251 at 413 ("Digestion [] resulted in an 81% increase in cumulative emissions compared to [storage and land application of undigested waste] over the entire study period similar to previous studies."); MOLANDER & ARMUS, *supra* n.248 at 14.
[302] Gittelson, *supra* n.8 at 356–57; Mallin & Cahoon, *supra* n.7 at 377–78 (explaining that digestion results in wastewater that increases emissions of volatilized ammonia when land-applied).
[303] Evan Halper & Samuel Oakford, *California Draws Ire as Out-of-State Factory Farms Turn Pig Poop into Cash* (April 19, 2025), https://www.washingtonpost.com/business/2025/04/19/climate-factory-farms-carbon-credit-california/; Gittelson, *supra* n.8, at 355.
[304] *Id;* MOLANDER & ARMUS, *supra* n.248; FOOD & WATER WATCH, *supra* n.264 at 5.
[305] *See generally* F.M. Mitloehner & M.S. Calvo, *Worker Health and Safety in Concentrated Animal Feeding Operations*, 14 J. AGRICULTURAL SAFETY AND HEALTH 163, 178 (Mar. 2008); *see also* David I. Douphrate, *Work Related Injuries and Fatalities on Dairy Farm Operations – A Global Perspective*, 18 J. AGROMEDICINE 256, 259 (2013) (chronicling injuries and fatalities on dairy farms in the U.S.); Lisa Foust Prater, *Manure Pit Accidents More Deadly Than Not* (March 20, 2024), https://www.agriculture.com/manure-pit-accidents-are-more-deadly-than-not-7853529 (similar).
[306] Lyderson, *supra* n.280.

explosion risks that generally do not exist at CAFOs without digesters.[307] To protect workers, nearby communities, and animals, EPA must ensure the CAFO ELGs do not inadvertently contribute to increased health and safety hazards.

In sum, anaerobic digesters threaten water quality, do not live up to their climate or pathogen reduction claims, incentivize CAFO expansion, and increase air pollution and safety risks. The ELGs should prohibit the installation and operation of new digesters on CAFOs and update the ELGs to regulate existing digesters and digestate management more stringently.

B. EPA Must Base the CAFO ELGs on Available Technologies and Practices that Reduce CAFO Pollution

As a first step toward updating the ELGs and regulating the CAFO industry in accordance with the CWA, EPA must consider how it currently regulates analogous point source categories to control similar waste streams. The CWA obligates EPA to consider whether pollution control practices used by these categories could be transferred to achieve similar effluent treatment in the CAFO context.[308] Here, EPA must consider practices used by sewage treatment plants as well as meat and poultry product (MPP) facilities.

Next, the Agency must consider various new, improved, and more readily available pollution reduction technologies and BMPs, many of which are already in use at CAFOs across the country. The weight of the evidence available to EPA leaves no doubt that NMPs have failed to achieve either zero discharge from production areas or minimized nutrient transport from land application areas to jurisdictional waters. Unsurprisingly, NMPs are also ineffective at preventing non-nutrient pollutants from entering waterways. Because storing and land applying waste in accordance with an NMP is not an effective approach, the time has come for EPA to consider an alternative tool for regulating CAFO management practices. As such, EPA must consider requiring CAFOs to develop and implement a planning document detailing the requirements and prohibitions applicable to a facility's production area and land application practices that improves on an NMP in four primary ways. First, the plan must include management practices designed to control the discharge of all pollutants of concern in

[307] *See* FOOD & WATER WATCH, *supra* n.264 at 9 (describing study documenting explosions at biogas plants).
[308] *Cal. & Haw. Sugar*, 553 F.2d at 287–88 (affirming EPA's use of a technology transferred from another point source category's ELGs where the agency adequately justified transferability); *see also NRDC*, 808 F.3d at 564, 572–573 ("EPA can mandate that BAT requires use of a technology that is not currently available within a particular industry when (1) the technology is available in another industry, (2) EPA finds that the technology is transferrable from that other industry, and (3) EPA can reasonably predict that such technology will adequately treat the effluent.").

CAFO waste as opposed to nutrients alone (i.e., a pollutant management plan (PMP) rather than an NMP). Second, the plan must incorporate into existing production area requirements widely available technologies that come closer to achieving the zero-discharge effluent limit. Third, the plan's land application requirements must be tailored to achieve pollution reduction goals as opposed to maximizing crop yields.[309] Fourth, PMPs must require representative monitoring and reporting to ensure compliance with ELG requirements and inform future ELG revisions. As described below, the studies and other materials submitted by Food & Water Watch support the codification of the following technologies and practices into the ELGs.

1. BMPs and Treatment Systems Used to Regulate Similar Waste Streams

In setting the CAFO ELGs, EPA must consider its treatment of other point source categories with similar waste streams.[310] Two categories in particular produce similar waste streams with overlapping contaminants of concern: publicly owned treatment works that handle sewage and MPPs. Accordingly, EPA must consider the technologies and practices used as the basis for these ELGs when assessing whether and how to update the CAFO ELGs.

a. Sewage Treatment Plants

California regulators recently concluded that "[i]n many respects, the application of dairy waste to dairy cropland is more akin to the land application of waste produced by domestic sewage treatment plants than to the application of nitrogen fertilizer for the business enterprise of growing crops in traditional agricultural fields."[311] The same can be said of other land-applied CAFO wastes, particularly liquified wastes, because of the application method and because sewage and CAFO waste share many of the same pollutants of concern.[312] Due to these similarities, EPA has acknowledged that "[m]any municipal wastewater treatment techniques may be applied to CAFO wastewater."[313] Logically, then, EPA must consider whether CAFOs can use the same or similar technologies and BMPs used by sewage treatment plants to achieve similar pollution reductions.

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[309] EPA should also consider prohibiting land application of untreated waste altogether to comply with the statutory requirement "to give serious consideration to a [NSPS] standard permitting *no* discharge of pollutants," since achieving zero discharge is not possible with land application of CAFO waste. *NRDC*, 822 F.2d at 123.
[310] *Cal. & Haw. Sugar*, 553 F.2d at 287–88; *NRDC*, 808 F.3d at 564, 572–573.
[311] CA DAIRY ORDER, *supra* n.15 at 53.
[312] Standards for the Use and Disposal of Sewage Sludge, 58 Fed. Reg. 9248, 9249 (Feb. 19, 1993) (listing "volatile organics, organic solids, nutrients, disease-causing pathogenic organisms (e.g. bacteria, viruses, and others), heavy metals and inorganic ions, and toxic organic chemicals from industrial wastes, household chemicals, and pesticides").
[313] BRADFORD, *supra* n.7 at 14; *see also* EPA LITERATURE REVIEW, *supra* n.6 at 66–69 (discussing applicability of techniques used at drinking water treatment plants to treat CAFO pollution).

Section 405 of the CWA prescribes specific processes EPA must follow in regulating the use and disposal of sewage sludge.[314] Specifically, Section 405 requires EPA to promulgate regulations that set forth BMPs "adequate to protect public health and the environment from any reasonably anticipated adverse effects" of toxic pollutants in sewage sludge.[315] While the requirements of Section 405 are separate from and in addition to EPA's obligation to establish ELGs under Section 304, Section 304 grants EPA discretion to impose similar BMPs for CAFO waste.[316] Moreover, EPA's insistence that BMPs are "particularly suited" to regulating land application of CAFO waste makes the sewage sludge regulations—and especially the regulations for land application of sewage sludge—uniquely relevant to the CAFO ELGs.[317]

EPA should consider imposing three key requirements from the sewage sludge land application regulations to CAFO land application activities. First, EPA should consider promulgating cumulative pollutant-specific limits for land application areas. Like the existing CAFO ELGs, the sewage sludge regulations permit application of sewage sludge to agricultural land so long as application does not exceed agronomic rates.[318] Unlike the CAFO regulations, however, EPA's sewage sludge regulations forbid land application in excess of cumulative pollutant limits established for arsenic, cadmium, copper, lead, mercury, molybdenum, nickel, selenium, and zinc.[319] EPA deemed these limits necessary to protect human and environmental health from harm attributable to land application of sewage sludge. Given the similar risks presented by sewage sludge and CAFO waste, EPA must either regulate land application of these substances congruently or provide a non-arbitrary reason for treating them differently.

Second, EPA should consider requiring that land-applied CAFO waste not exceed pathogen levels designated to protect human health and the environment, just as it does for sewage sludge.[320] As exemplified by recent review of the impacts of livestock waste on *E. coli* contamination of leafy greens,[321] pathogens in CAFO waste threaten public health as well as the economic wellbeing of

[314] 33 U.S.C. § 1345.
[315] *Id.* at § 1345(d)(2)(D).
[316] *Id.* at § 1345(e); *see also id.* § 1345(b) (authorizing EPA to consider non-water quality environmental impacts and any other factors the agency deems relevant when establishing ELGs).
[317] *See* 68 Fed. Reg. at 7227 (explaining EPA's position that numeric effluent limitations are infeasible for CAFOs).
[318] 40 C.F.R. § 503.14(d).
[319] *Id.* at § 503.12(b), (e), (g)–(j); *see also id.* § 503.13 (chart of cumulative limits).
[320] *Id.* at § 503.15(a) (citing 40 C.F.R. § 503.32(a).
[321] Stelio Viazis et al., *An Overview of Farm Investigation Findings Associated with Outbreaks of Shiga Toxin-Producing Escherichia Coli Infections Linked to Leafy Greens: 2009–2021*, 88 J. FOOD PROD. 1, 4–7 (2025) (pagination in accordance with submitted copy).

farmers. More than a decade ago, EPA even acknowledged the need to "[i]mplement control technologies for treatment of animal waste to reduce pathogen loads prior to land application or off-site transfer."[322] The Agency should therefore assess which pathogens commonly found in CAFO waste pose unacceptable risks, mandate testing of waste prior to land application, and prohibit land application of waste that exceeds pathogen limits sufficient to safeguard public health. At a minimum, CAFO waste should be subject to the same pathogen standards EPA requires for sewage sludge transferred to third parties for land application.[323] However, EPA should also consider new evidence suggesting these standards are out-of-date and insufficiently protective. For instance, some sewage sludge criteria give producers the option to choose between meeting a general fecal coliform standard or a standard based on specific pathogens like *Salmonella*.[324] Though EPA has previously used fecal coliform as an indicator for other harmful pathogens, "[t]ransport properties and the virulence of various pathogens vary to a wide degree, and may be poorly represented by the bacterial indicators *E. coli* and *enterococci*."[325] Where scientific evidence indicates updated pathogen standards are necessary, EPA should introduce revised standards as part of its revision to the CAFO ELGs.

Third, EPA should consider requiring CAFOs that land apply to comply with the same vector attraction reduction requirements that facilities land applying sewage sludge must meet.[326] Vector attraction reduction is necessary for CAFO waste just as it is for sewage sludge due to the tendency of animal waste to attract birds, insects, and other animals that may contribute to the spread of pathogens.[327] Requiring those land applying CAFO waste to manage vector attraction in the manner prescribed by the sewage sludge regulations would provide flexibility as those regulations offer a menu of pollution control options to choose from based on the understanding that cost-effectiveness of any given method will vary depending on site-specific characteristics of the facility. For instance, the regulatory menu specifies compliance pathways for waste treated aerobically or anaerobically.[328]

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322 EPA RISK ASSESSMENT, *supra* n.141 at 97.
323 40 C.F.R. § 503.32(a) (setting forth standards for Class A sewage sludge).
324 *Id.* at § 503.32(a).
325 DR. SHANE ROGERS & DR. JOHN HAINES, EPA, DETECTING AND MITIGATING THE ENVIRONMENTAL IMPACT OF FECAL PATHOGENS ORIGINATING FROM CONFINED ANIMAL FEEDING OPERATIONS: A REVIEW 53 (2005).
326 40 C.F.R. §§ 503.15(c), 503.33(a)(1) & (5).
327 *See* 58 Fed. Reg. at 9254 (describing the need for vector control in the sewage sludge regulations); Casey, *supra* n.201 at 260 ("Studies have identified bacterial pathogens, such as antibiotic-resistant strains of *Staphylococcus* and *Enterococcus*, in and around [CAFOs], including colonizing animals and surfaces, in manure, and carried by flies and rats near operations.").
328 40 C.F.R. § 503.33(b).

Notably, the vector control regulations also endorse measures recommended by these comments, including solid liquid separation ("SLS"), injection, and incorporation.[329]

EPA should also consider using the maximum pollutant limits for land-applied sewage sludge to inform similar limits for land-applied CAFO waste. EPA acknowledges that CAFO waste contains many of the same pollutants that the Agency regulates in sewage sludge through enforceable concentration limits.[330] Land-applied waste threatens human health and the environment, regardless of whether it originates from humans or livestock. EPA must either evaluate and regulate these risks similarly[331] or provide a logical justification for treating like risks differently. And either way, the ELGs may not continue to ignore known pollutants of concern.

b. Meat and Poultry Products

The second regulated industry EPA must consider in developing the CAFO ELGs is the MPP category. As part of the ongoing process of updating the MPP ELGs, EPA has proposed specific effluent limits for nitrogen, phosphorus, and conventional pollutants[332]—primary pollutants of concern in CAFO waste.[333] As discussed below, several of the technologies and practices determined to be BAT for MPP facilities are already in use at CAFOs.[334] Given the similarities between the waste streams and the apparent availability of these technologies for use at CAFOs, any study of the CAFO ELGs that fails to consider technologies delineated as BAT, BCT, or NSPS for removing nutrients and conventional pollutants from MPP waste would be arbitrary and capricious.

EPA's proposed rule for the MPP regulations begins by discussing screens and dissolved air floatation as technologies widely used by MPP facilities to remove conventional pollutants.[335] As

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[329] *Id.*
[330] *See* 68 Fed. Reg. at 7235–36 (discussing "arsenic, copper, selenium, zinc, cadmium, molybdenum, nickel, lead, iron, manganese, aluminum, and boron" as elements of environmental concern in manure, as well as pathogenic bacteria such as *Salmonella*, *E. coli*, *Cryptosporidium parvum*, and *Giardia* in CAFO waste); 40 C.F.R. §§ 503.13 (limits for arsenic, cadmium, copper, lead, mercury, molybdenum, nickel, selenium, and zinc in land-applied sewage sludge), 503.32 (limits for fecal coliform and *Salmonella* in land-applied sewage sludge).
[331] *See* EPA, TECHNICAL SUPPORT DOCUMENT FOR LAND APPLICATION OF SEWAGE SLUDGE, VOLUME I 5-20–5-299 (Nov. 1992), https://19january2021snapshot.epa.gov/sites/static/files/2018-11/documents/tsd-land-application-volume1.pdf (evaluating pollutant pathways for land-applied sewage sludge).
[332] EPA, TECHNICAL DEVELOPMENT DOCUMENT FOR PROPOSED EFFLUENT LIMITATIONS GUIDELINES AND STANDARDS FOR THE MEAT AND POULTRY PRODUCTS POINT SOURCE CATEGORY 131 (Dec. 2023) [hereinafter MPP TDD].
[333] BRADFORD, *supra* n.7 at 3–4.
[334] *See infra* n.**Error! Bookmark not defined.** and accompanying text.
[335] Clean Water Act Effluent Limitations Guidelines and Standards for the Meat and Poultry Products Point Source Category, 89 Fed. Reg. at 4474, 4482 (Jan. 23, 2024); *see also* MPP TDD, *supra* n.332 at 61–63 (discussing various forms of SLS as "primary treatment" for MPP facilities).

discussed in Section IV.B.4.a, these SLS methods should be considered to treat conventional pollutants in CAFO waste as well.

All options EPA is considering for the final MPP regulations include biological treatment to achieve full denitrification. During full denitrification (also sometimes referred to as nitrification/denitrification), "[n]itrogen removal is carried out through a three-step biological process: (1) The conversion of ammonia from organic nitrogen by hydrolysis and microbial activities, called ammonification; (2) the aerobic conversion of ammonia to nitrate by reacting the ammonia with oxygen in a process called nitrification; and (3) the conversion of nitrate to nitrogen gas by reacting the nitrate with organic carbon under anoxic conditions in a process called denitrification."[336] Activated sludge can be added to the process to achieve up to "95 percent reductions in BOD, suspended solids, and reductions in ammonia nitrogen."[337] A variety of biological treatment systems are capable of achieving full denitrification, allowing operations to determine which system is most efficient and cost effective for their site-specific characteristics.[338] Several of these systems have been proven effective in treating swine wastewater for not only nutrients and conventional pollutants, but for antibiotics as well.[339] EPA should consider establishing effluent limits based on the removal capacity of biological treatment options, as the Agency has done for MPP waste.[340]

Each of EPA's three proposals for the MPP rules also includes chemical precipitation. Chemical precipitation is an advanced form of SLS during which chemicals that encourage coagulation and promote particle adhesion are added to wastewater to cause pollutants to settle to the bottom of a basin where the pollutant-laden sludge can be collected for further treatment.[341] "MPP facilities use

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[336] 89 Fed. Reg. at 4487.
[337] *Id.* at 4482–83.
[338] MPP TDD, *supra* n.332 at 63–68 (discussing various series of aerobic/anoxic tanks, sequencing batch reactors, moving bed biofilm reactors, and membrane bioreactors); *see also* M.B. Vanotti et al., *Removing and Recovering Nitrogen and Phosphorus from Animal Manure, in* 67 ANIMAL MANURE PRODUCTION, CHARACTERISTICS, ENVIRONMENTAL CONCERNS, AND MANAGEMENT 299 (H.M. Waldrip et al. eds. 2020) (discussing use of high-performance nitrifying sludge to improve pollution treatment efficiency in cold weather); Huang, *supra* n.33 at 3–5 (discussing various biological treatments—including biological aerated filters, sequencing batch reactors, and membrane bioreactors—and their capacities to remove commonly used antibiotics).
[339] Vanotti, *supra* n.338 at 299–307; *see also* David Townsend et al., *The Premium Standard Farms Nitrification and Denitrification Experience* (June 6, 2006), https://porkgateway.org/resource/the-premium-standard-farms-nitrification-and-denitrification-experience/ (describing an advanced nitrification and denitrification system consisting of multiple basins installed in a pig CAFO to treat waste from 52,800 animals).
[340] While many MPP facilities are discharge directly to waterways and do not claim their waste has any agronomically beneficial use, application of MPP nutrient controls to CAFOs is still warranted because both categories are responsible for widespread nutrient pollution.
[341] MPP TDD, *supra* n.332 at 68.

chemical precipitation for phosphorus removal through the addition of metal salts, most commonly alum or ferric chloride."[342] Chemical additives proven to remove phosphorus from CAFO wastewater include magnesium phosphate (struvite) in combination with ethylenediaminetetraacetic acid (70 to 80 percent effective at removing phosphorus from swine and dairy wastewater, 90 to 98 percent effective at removing phosphorus from poultry manure); lime (79.8 to 94.7 percent effective in removing phosphorus from pig waste); a combination of acid, hydrated lime, and organic polyelectrolytes (80 to 90 percent effective in removing phosphorus from poultry litter and swine waste); and metal salts like alum, aluminum chloride, ferric sulfate, and ferric chloride, alone or in combination with polymers (variety of phosphorus removal efficacies depending on the dose applied).[343]

Chemical additives can also assist in the removal of conventional pollutants like total suspended solids. Noting the potential transferability of chemical treatment to the CAFO category, EPA previously estimated the cost of using chemical treatment to remove 90 to 95 percent of total suspended solids from swine CAFO wastewater to be between 1.27 and 2.79 dollars per hog.[344] Plainly, chemical precipitation is worthy of full consideration in EPA's detailed study of the CAFO industry.

2. Controlling All Pollutants of Concern

Consistent with EPA's statutory obligation to create CAFO ELGs specifically designed to address all pollutants of concern present in the waste stream,[345] the PMP approach EPA should adopt must require practices and technologies to treat, remove, or prevent discharge of all such pollutants. Various treatment technologies are available for removing nutrients, pathogens, conventional pollutants, certain metals, pharmaceuticals, and microplastics from waste streams, which could be adopted at CAFOs. EPA must consider establishing effluent limitations based on the pollution reduction capabilities of these technologies. Additionally, EPA should consider addressing pollutants at the source by limiting or prohibiting the use of inputs like feed additives that end up in the waste stream.

[342] *Id.* at 68.
[343] Vanotti, *supra* n.338, at 285–92; EPA LITERATURE REVIEW, *supra* n.6 at 67.
[344] BRADFORD, *supra* n.7 at 14.
[345] *Waterkeeper Alliance*, 399 F.3d at 519.

a. Terra Blue Treatment System for CAFOs Using Liquid Waste Management[346]

One of the most detailed studies to date examining systems to control water pollutants from CAFOs was completed after at least 46 lagoons on North Carolina hog CAFOs owned and operated by subsidiaries of Smithfield Foods, Inc. breached during Hurricane Floyd, causing widespread environmental harm that disproportionately impacted Black communities, low-income communities, and households that rely on groundwater for drinking.[347] Following the disaster, North Carolina's Attorney General negotiated a consent decree in which the corporate CAFO owners agreed to "commit $15 million for the development of Environmentally Superior Technologies[348] for the management of swine waste and to facilitate the development, testing, and evaluation of potential technologies on Company-owned Farms."[349] Although the vast majority of North Carolina's CAFOs are still operating without anything close to adequate pollution controls, the Environmentally Superior Technologies that emerged from the consent decree—a system known as Terra Blue[350] (formerly Super Soils)—could form the basis for effective and legally compliant CAFO ELGs. In particular, EPA should consider using Terra Blue's system of technologies as the basis for NSPS applicable to CAFOs that manage liquid waste, as the system has reliably achieved demonstrable reductions of multiple pollutants at the CAFOs where Terra Blue is in use.

[346] Because Terra Blue was developed in North Carolina where hog CAFOs predominate, research on the system's efficacy was conducted using pig waste. However, due to similarities in waste streams and management issues, EPA should consider Terra Blue as a treatment option for other CAFOs such as dairies that also manage liquid waste.
[347] Don Carrington, *Lawsuit Challenges A.G.'s Hog Waste 'Slush Fund'* (Oct. 27, 2016), https://www.carolinajournal.com/lawsuit-challenges-ags-slush-fund/; Steve Wing et al., *The Potential Impact of Flooding on Confined Animal Feeding Operations in Eastern North Carolina*, 110 ENV'T HEALTH PERSPECTIVES 387, 390–91 (2002).
[348] North Carolina law defines "Environmentally Superior Technologies" as "any technology, or combination of technologies that (1) is permittable by the appropriate government authority; (2) is determined to be technically, operationally, and economically feasible and (3) meets the following environmental performance standards: 1. Eliminate the discharge of animal waste to surface and groundwater through direct discharge seepage or runoff; 2. Substantially eliminate atmospheric emissions of ammonia; 3. Substantially eliminate the emission of odor that is detectable beyond the boundaries of the farm; 4. Substantially eliminate the release of disease-transmitting vectors and airborne pathogens; and 5. Substantially eliminate nutrient and heavy metal contamination of soil and groundwater." M.B. VANOTTI ET AL., DEVELOPMENT OF ENVIRONMENTALLY SUPERIOR TECHNOLOGY IN NORTH CAROLINA: THE SUPER SOIL PROJECT 2 (2005), https://www.ars.usda.gov/ARSUserFiles/60820000/Manuscripts/2005/Man707.pdf.
[349] Agreement between the Attorney General Of North Carolina; Smithfield Foods, Inc.; Brown's Of Carolina, Inc.; Carroll's Foods, Inc.; Murphy Farms, Inc.; Carroll's Foods Of Virginia, Inc.; And Quarter M Farms, Inc. 3, https://www.northcarolinahealthnews.org/wp-content/uploads/2022/12/3.-Smithfield-Agreement.pdf.
[350] The system was formerly called "Super Soils." Viney P. Aneja et al., *From Pollution to Resource: Advancing Swine Waste Treatment in the USA*, 8 FRONTIERS SUSTAINABLE FOOD SYS. 1, 6 (2024), https://scholarship.law.duke.edu/cgi/viewcontent.cgi?article=7037&context=faculty_scholarship.

Performance

Terra Blue is a three-step system that processes liquid CAFO waste through (1) SLS enhanced by a polymer (polyacrylamide, or "PAM") to encourage flocculation; (2) biological treatment to enhance nitrification (the chemical process by which ammonia is transformed into nitrite and nitrate); and (3) alkali chemical precipitation to remove phosphorus and destroy pathogens.[351] A 4,400-animal swine CAFO in North Carolina that installed and operated the system for a full year shortly after the consent decree was reached was able to remove 97.6 percent of suspended solids, 99.7 percent of biological oxygen demand, 98.5 percent of total Kjeldahl nitrogen, 98.7 percent of ammonia, 95 percent of total phosphorus, 98.7 percent of copper, 99 percent of zinc.[352] Notably, a majority of suspended solids, zinc, copper, and phosphorus were removed during the polymer-assisted solids separation portion of the process.[353] The researchers working on the demonstration project concluded that "the technology was technically and operationally feasible," and met the technical performance standards that define an Environmentally Superior Technology.[354] Since these initial tests, additional data have been collected from other CAFOs that have installed versions of the Super Soils/Terra Blue system, verifying its capacity for significant pollution reductions that align with the CWA's ultimate goal of eliminating water pollution from CAFOs.[355]

Cost and Availability

At its inception, the system now known as Terra Blue was determined to be prohibitively costly.[356] However, over the past 25 years, researchers have developed second and third generations of the system to improve cost-effectiveness. Total capital costs of the second-generation system assessed for a 6,000-pig CAFO in North Carolina came to $556,000 for installation and $58,000 for annual operation and maintenance.[357] While these costs are significant, large operations (like those on which the Terra Blue system has been installed and tested so far) can likely recover these costs in the form of benefits resulting from improved pollution control. For instance, flushing confinement pits with recycled wastewater that has undergone ammonia removal has been shown to improve animal

[351] *Id.*; Vanotti, *supra* n.348 at 4; *see also* Vanotti, *supra* n.338 at 281.
[352] Vanotti, *supra* n.348 at 4–5.
[353] *Id.* at 4; Vanotti, *supra* n.338 at 281–82.
[354] Vanotti, *supra* n.348 at 5.
[355] Aneja, *supra* n.350 at 9.
[356] Nicole, *supra* n.8 at A188.
[357] Aneja, *supra* n.350 at 8.

health and productivity, netting the studied CAFO economic benefits valued at $91,920 annually.[358] CAFOs can also compost the solid waste fraction after SLS to produce fertilizer that can be sold.[359] EPA must consider these and other benefits that offset installation and operational costs as part of its analysis.

Given its proven efficacy, the Terra Blue system would also result in huge savings for community members suffering from heightened healthcare costs, reduced property values, and lost recreational profits currently attributable to CAFOs. Requiring swine CAFOs to install, operate, and maintain the Terra Blue system would be a step toward more equitable allocation of the costs of industrial livestock production.

EPA must also consider the availability of state and federal funds to assist CAFOs with installation costs of innovative pollution treatment technologies like Terra Blue.[360]

Non-Water Quality Impacts

The Terra Blue system also redresses adverse non-water quality environmental impacts. Field studies of facilities employing the system have seen up to 100 percent removal of odorous compounds in liquid waste thanks in large part to denitrifying bacteria in the system's second step.[361] This means that Terra Blue has the capacity to significantly abate odor nuisances caused by swine CAFOs (and likely other CAFOs using liquid manure management) across the country.

Further, emissions reductions that would result from broad implementation of Terra Blue could significantly reduce the swine industry's climate footprint and local air quality impacts. Between reductions in ammonia (a precursor to nitrous oxide formation) and methane emissions, researchers estimate that facilities using Terra Blue can expect approximately 96.9 percent reductions in greenhouse gas emissions from manure management. These emissions reductions are critical to combatting the existential threats posed by climate change, as well as improving local air quality to benefit frontline communities.

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[358] *Id.* at 10–11.
[359] *Id.* at 6.
[360] *See id.* at 12 (mentioning the availability of funds through the Environmental Quality Incentives Program (EQIP) and Conservation Innovation Grants (CIG)). These longstanding federal support programs are stable funding sources, unlike the more volatile supports available for digesters. *See supra* Section IV.A.3.
[361] *Id.* at 9.

b. Other Available Treatment Options

EPA should also investigate other treatment options that may be effective in treating additional pollutants of concern, including pollutants like pharmaceuticals, PFAS, and microplastics that the current ELGs ignore. While we do not endeavor to provide a comprehensive list of all such treatment options, vermiculture and advanced oxidation processes are examples of technologies worthy of further analysis. These and other technologies and practices may be available to help CAFOs control discharges of emerging pollutants of concern. Without targeted treatment, CAFOs will continue to discharge these pollutants to waters, contributing to health and environmental harms.

Vermiculture, vermicomposting, and vermifiltration all refer to the use of earthworms to convert waste into compost. EPA briefly mentioned vermicomposting in the technical development document created to inform the 2003 CAFO ELGs. However, the Agency has not undertaken a full analysis of whether vermiculture may be an appropriate basis for the ELGs despite its acknowledgement that farm-scale systems for vermicomposting had been developed.[362] Since the 2003 rule, field studies have been conducted that indicate vermiculture can be effective in treating multiple CAFO pollutants of concern. One study of a vermifilter system installed on a 1500-head dairy CAFO in California found that the treatment reduced wastewater ammonia concentrations by 97 percent, total nitrogen by 84 percent, phosphorus by 84 percent, and total suspended solids by 95 percent.[363] The system was also effective in reducing salts, metals, and other trace elements in effluent.[364] Other studies have documented pathogen removal as well.[365]

Vermiculture systems can be scaled to meet the wastewater treatment needs of a variety of CAFO sizes, with some projects treating up to 750,000 gallons per day.[366] Vermiculture also has the potential to produce significant non-water quality benefits. Monitoring results show vermifilter systems can emit up to 99 percent less methane than a CAFO's lagoon system, while also cutting power usage.[367] Further, vermifilter systems produce compost instead of sludge, allowing CAFOs to offset installation and operating costs by eliminating the need for sludge management and creating a

[362] 2003 TDD, *supra* n.26 at 8-117–18.
[363] Sabina Dore et al., *A Vermifiltration System for Low Methane Emissions and High Nutrient Removal at a California Dairy*, 18 BIORESOURCE TECH. REPORTS 1, 7 (2022) (pagination in accordance with submitted copy).
[364] *Id.*
[365] *Id.* at 2.
[366] *See Projects*, https://biofiltro.com/projects/ (video testimonials by CAFOs that have installed biofiltro vermifilter systems of various specifications).
[367] Dore, *supra* n.363 at 2, 6.

separate compost revenue stream. California's State Water Resources Control Board recently acknowledged that expanded markets for vermicompost could make the technology cost-effective for more CAFOs going forward.[368] EPA's detailed study would benefit from additional analysis of vermiculture and similar emerging technologies to control the full suite of CAFO pollutants.

Advanced oxidation processes are other emerging treatment options that show promise at addressing a spectrum of CAFO pollutants, including pharmaceuticals. Although a growing body of evidence demonstrates that pharmaceuticals in CAFO waste threaten aquatic life and human health,[369] existing ELGs do not include treatment or practices that control these hazardous pollutants. Several studies now indicate that oxidization using hydroxyl radicals to decompose and mineralize organic pollutants can also substantially reduce the antibiotic content of CAFO waste.[370] Again, EPA briefly mentioned advanced oxidation processes during its rulemaking for the 2003 rule, but the Agency did not conduct a detailed assessment of the treatment options at that time.[371] Since 2003, further research on additional advanced oxidation processes has been published, indicating emerging methods like Fenton's process may be capable of achieving high antibiotic removal rates cost effectively while also removing heavy metals, fecal coliform, and phosphorus.[372] In light of this new information, we ask EPA to revisit advanced oxidation processes as a basis for ELGs targeting pharmaceuticals and other CAFO pollutants.

In surveying other emerging technologies, EPA should pay special attention to options capable of controlling emerging pollutants of concern, including PFAS and microplastics. Like humans, livestock are exposed to carcinogenic PFAS, commonly known as "forever chemicals," in their feed and drinking water.[373] PFAS ingested by livestock in CAFOs either accumulate within the animals or are excreted in their waste.[374] Thus, significant amounts of PFAS may be building up on land application areas, running off into waters, and contaminating soil and groundwater beneath land application areas, waste storage areas, and mortality management areas. EPA recognizes these risks

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368 CA DAIRY ORDER, *supra* n.15 at 57.
369 *Supra* nn.33–47 and accompanying text.
370 Huang, *supra* n.33 at 5–8; Eva Domingues et al., *Advanced Oxidation Processes Perspective Regarding Swine Wastewater Treatment*, 776 SCI. TOTAL ENV'T 1, 4–14 (2021).
371 *See* 2003 TDD, *supra* n.26 at 8-117 (briefly discussing disinfection via ozonation and UV radiation).
372 *See* Domingues, *supra* n.370 at 12 (summarizing studies evaluating pollution removal capacities of advanced oxidation processes); Huang, *supra* n.33**Error! Bookmark not defined.** at (similar).
373 Clare Death et al., *Per- and Polyfluoroalkyl Substances (PFAS) in Livestock and Game Species: A Review*, 774 Sci. Total Env't 1, 3–4 (2021); *see also* Jared Jaborek & Jeannine Schweihofer, *How will PFAS impact the Michigan cattle industry?*, MICH. STATE U. (Oct. 14, 2022), https://www.canr.msu.edu/news/how-will-pfas-impact-the-michigan-cattle-industry.
374 Death, *supra* n.373 at 3–8.

and has acknowledged its authority to address them through the CWA.[375] We therefore request that EPA assess pollution control options for PFAS in its detailed study.

Similarly, EPA should consider options for controlling microplastic pollution from CAFOs. As EPA is aware, "microplastics are harmful and pervasive emerging contaminants" that pose myriad threats to human health when ingested through drinking water.[376] Like PFAS, microplastics ingested by livestock accumulate in animal tissues and are excreted in waste. Emerging research indicates that "animal manure is a source of microplastics entering the environment owing to its wide use as fertilizer on farmlands."[377] Accordingly, EPA must consider practices and technologies to control microplastics from CAFOs as part of its detailed study.

c. Restrictions on Feed Additives

EPA should also consider implementing feed restrictions to minimize or eliminate the presence of pollutants in excreted waste, particularly where treatment cannot adequately remove certain heavy metals or pharmaceuticals from the waste stream or reduce nutrients and pathogens to the extent necessary to meet pollution reduction goals. EPA has already considered requiring CAFOs to adopt certain dietary restrictions and feeding strategies in the context of reducing nutrient pollution,[378] and has imposed similar "stock limitations" on other point source categories that restrict the pollutant content of process inputs.[379] In the decades following EPA's 2002 evaluation of such limitations for CAFOs, new studies have emerged demonstrating how feed restrictions can be an effective pollution reduction tool.

For instance, researchers have found that "limiting the use and types of antibiotics, particularly 'critically important antimicrobials,' in animal production is the most direct route of controlling agricultural antibiotic release into the environment."[380] The European Union has adopted maximum

[375] EPA, PFAS STRATEGIC ROADMAP: EPA'S COMMITMENTS TO ACTION 2021-2024 16, https://www.epa.gov/system/files/documents/2021-10/pfas-roadmap_final-508.pdf.
[376] FOOD & WATER WATCH ET AL., PETITION TO INCLUDE MICROPLASTICS ON THE SIXTH UNREGULATED CONTAMINANT MONITORING RULE UNDER THE SAFE DRINKING WATER ACT 1 (2024), https://www.foodandwaterwatch.org/wp-content/uploads/2024/11/Microplastics-Petition-to-EPA.pdf.
[377] Sheriff, *supra* n.109 at 13.
[378] *See e.g.*, 2003 TDD, *supra* n.26 at 4-28–4-31, 4-44 (considering dietary restrictions for swine and poultry as a nutrient pollution reduction practice).
[379] *See e.g.*, Effluent Limitations Guidelines and New Source Performance Standards for the Oil and Gas Extraction Point Source Category, 66 Fed. Reg. 6850, 6864 (Jan. 22, 2001) (establishing BAT and NSPS imposing "stock limitations" on PAH content, sediment toxicity, and biodegradation of the synthetic materials which form the base fluid of synthetic-based drilling fluids (SBFs), or product substitution in the alternative, in addition to setting discharge limitations in a two part approach to controlling SBF-cuttings discharges).
[380] Amy Pruden et al., *Management Options for Reducing the Release of Antibiotics and Antibiotic Resistance Genes to the Environment*, 121 ENV'T HEALTH PERSPECTIVES878–885, 879 (2013).

limits on heavy metals in animal feed additives, which has proven to be an effective strategy for reducing the overall spread of heavy metals and resulting environmental pollution.[381]

Feed restrictions can also demonstrably reduce nutrient and pathogen presence in CAFO waste. One study found that eliminating wet distillers grains with solubles from cattle finishing diets can reduce *E. coli* levels in excreted waste by nearly 40 percent.[382] Formulating diets to ensure optimal levels of protein reduces nitrogen excretion by as much as 62 percent depending on animal type, not only limiting the amount of nitrogen eventually land applied to fields, but also reducing ammonia emissions and the deposition of nitrogen to surface waters.[383] EPA must consider setting these types of common sense feeding requirements to effect pollution reduction for the full spectrum of CAFO pollutants.

3. Updating Production Area Requirements

EPA must revise production area requirements to cover all discharge pathways and ensure that CAFOs are in fact achieving the zero-discharge effluent limitation. In addition to existing requirements geared towards preventing waste overflow, the regulations must incorporate technologies and practices that will prevent discharges to surface water via groundwater and air pathways. This can be achieved through stronger requirements for liquid manure storage systems that include impermeable liners and adequate leak detection technologies to control seepage, lagoon covers, proper containment of solid wastes, and ventilation system filtration to limit air pollutants from depositing to surface waters.

a. Liquid Manure Storage Requirements

Uncovered and unlined anaerobic lagoons pollute waterways, emit significant air pollution, and create unbearable burdens on communities near CAFOs. Numerous examples demonstrate that storing and treating CAFO waste in these structures—even those that comply with NRCS practice standards—has not prevented the discharge of pollutants to jurisdictional waters.[384] Moreover, lagoon specifications allowed under the current ELGs beleaguer neighboring communities with severe non-

[381] M. Hejna et al., *Review: Nutritional Ecology of Heavy Metals*, 12 ANIMAL 2156, 2157 (2018).
[382] J.E. Wells et. al., *Impact of Reducing the Level of Wet Distillers Grains Fed to Cattle Prior to Harvest on Prevalence and Levels of Escherichia coli 0157:H7 in Feces and on Hides*, 74 J. FOOD PROT., 1611, 1613 (May 2011).
[383] C.A. Rotz, *Management to Reduce Nitrogen Losses in Animal Production*, 82 J. ANIM. SCI., E119, E122 (2004); *see also* Adeline Bouguoin et al., *Nitrogen excretion from beef cattle fed a wide range of diets compiled in an intercontinental dataset: a meta-analysis*, 100 J. ANIM. SCI. 1, 10–11 (2022); F.M. Mitloehner & M.S. Calvo, *supra* n.305 at 178.
[384] STEPHEN R. HUTCHINS ET AL., EPA, CASE STUDIES ON THE IMPACT OF CONCENTRATED ANIMAL FEEDING OPERATIONS (CAFOS) ON GROUND WATER QUALITY 15, 26, 38, (Sept. 2012); Harter, *supra* n.7 at 5–6 (noting that "significant leaching can occur through sink-swell fractures in [] sidewalls" of lagoons designed to NRCS guidelines).

water quality impacts, primarily in the form of noxious odors.[385] To better control pollution discharges from liquid manure storage structures, EPA must consider requiring composite synthetic liner systems and lagoon covers. Alternatively, EPA could require or incentivize the dry handling of manure in place of liquid handling systems.

i. *Require Liners for Subsurface Lagoons*

Unlike other point source categories that use liquid waste storage structures, the CAFO ELGs do not provide detailed lagoon liner specifications.[386] EPA previously stated that accumulation of solids and compacted soil at the bottom of lagoons would adequately mitigate the risk of pollutants seeping into groundwater and being transported to surface waters and drinking water sources. However, recent research indicates this assumption is incorrect.[387] Multiple studies have confirmed that, as a result of natural wear and tear as well as improper lagoon upkeep, pollutants such as ammonia-N and antibiotic-resistant bacteria seep from unlined lagoons into groundwater where they are then transported downstream.[388] Nitrate plumes underlying CAFOs have been observed to travel through groundwater to nearby surface waters, threatening water quality.[389] According to recent Supreme Court precedent, EPA has a legal duty to regulate these hydrologic discharges.[390] Scientific evidence and information from state permitting authorities now suggest that composite liners with double synthetic layers and leak detection are BAT for liquid manure storage structures. Imposing a requirement that CAFOs install liners that conform to this design standard would correct the ELGs' failure to address subsurface discharges, ensuring the ELGs are based on technology that is actually capable of meeting the zero-discharge from production areas standard.[391]

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[385] Aneja, *supra* n.350 at 2 (describing odorous compounds emitted by lagoons); *supra* nn.209–211 and accompanying text (describing impacts on communities).

[386] *Compare, e.g.*, 40 C.F.R. § 257.70 (design criteria for coal combustion residual landfill liners) *with* 40 C.F.R. § 122.42(e) (requiring only "proper operation and maintenance of the storage facilities").

[387] *See* Noah Rudko et al., *Development of a Point-Source Model to Improve Simulations of Manure Lagoon Interactions with the Environment*, 325 J. ENV'T MGMT. 1, 2 (2023) (sealing likely not adequate to prevent groundwater contamination in "lagoons constructed on sandy soils with high permeability or with shallow groundwater tables"), 9 ("The effects of manure sealing that might reduce leakage rates as earthen structures age are offset by processes such as freezing and thawing cycles, or wetting and drying.") (pagination in accordance with submitted copy).

[388] Chee-Sanford, *supra* n.34 at 1499 (detecting tetracycline-resistant bacteria from lagoons at swine CAFOs in groundwater); S. Koike et al., *supra* n.33 at 4822 ("[A]nimal waste seeping from unlined lagoons at two swine confinement facilities had an impact on the dissemination of tetracycline resistance genes in groundwater near the facilities."); Rudko et al., *supra* n.387, at 5 ("The groundwater monitoring wells downgradient of the lagoon had elevated concentrations of each of the sampled water quality parameters, indicating that the lagoon was the only factor driving elevated ammonia-N concentrations in the downgradient wells.").

[389] Erickson Report, *supra* n.18 at 1–2, 7.

[390] *Cnty. of Maui*, 590 U.S. at 186.

[391] *Nat'l Crushed Stone*, 449 U.S. at 74 (quoting 33 U.S.C. 1311(b)(2)(A)). As explained in Section III.D, the current ELGs are not actually designed to achieve the zero-discharge production area effluent limit because EPA has ignored hydrological discharges. Thus, additional progress toward that goal is still necessary.

Performance

The best performing subsurface waste storage structure liners include three key elements: (1) synthetic liner(s) (sometimes referred to as geomembranes or geotextiles); (2) a composite design; and (3) built-in leak detection.[392] Synthetic liners are generally made of plastics like high-density polyethylene, polyvinyl chloride, or low linear density polyethylene processed to certain specifications.[393] "Composite liner" is an umbrella term that refers to layers of various materials designed to slow the movement of pollutants to the subsurface outside the liner. Composite liner designs—and the efficacy of those designs in controlling CAFO pollution—vary widely.

Liquid waste storage structures with at least one synthetic liner layer outperform lagoons that rely solely on compacted soil and manure sealing (i.e. "earthen-lined" lagoons).[394] Synthetic liners are particularly effective in vulnerable areas with permeable (non-clay) soils, high water tables, karst topography, shallow aquifers, high hydrological connectivity, or nearby drinking water wells.[395] Composite liners provide even more protection. A study that examined the efficacy of various landfill liners in controlling seepage of many of the same pollutants of concern in CAFO waste found that "composite liners are substantially better than single liners in terms of controlling leakage."[396] However, simple composite designs limited to a single geomembrane over soil attenuation layer are less reliable in the CAFO context. While these designs may suffice to control groundwater pollution from landfills, they "should not be used as primary (single) liners in lagoons" where frequent filling and emptying disrupt tensile stress on the geomembrane.[397] A study conducted by the Minnesota Pollution Control Agency shows that adding a clay layer and ballasting the geomembrane (i.e. using a weight such as a layer of soil to hold the liner in place) can improve the performance of a composite design with a single synthetic layer, helping to reduce the nitrogen content of downgradient groundwater by 55 percent and measurably decrease phosphorus and organic carbon as well.[398] However, states like Washington still recommend groundwater monitoring at facilities that rely on a composite design with only a single synthetic liner due to the elevated leakage potential.[399]

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[392] R.K. Rowe, *Long-term Performance of Containment Barrier Systems*, 55 GEOTECHNIQUE 631, 652 (2005) ("[A]ll of the leakages reported for composite liners are small and, correspondingly, the contaminant transport by advection will be very small.").
[393] MINN. POLLUTION CONTROL AGENCY, LIQUID MANURE STORAGE AREA HANDBOOK App'x F (Feb. 2017).
[394] *See* WA LITERATURE REVIEW, *supra* n.19 at 27, 28, 67 (June 2016), (collecting studies).
[395] *See also* MINN. POLLUTION CONTROL AGENCY, *supra* n.393 at 7–13 (discussing locational risks that merit additional precautions).
[396] *Rowe, supra* n.392 at 672.
[397] WASH. STATE DEP'T OF ECOLOGY, LAGOON AND LINER DESIGN GUIDELINES T7-9 (April 2023) [hereinafter WA LAGOON DESIGN GUIDELINES].
[398] WA LITERATURE REVIEW, *supra* n.19 at 67; *see also* Rowe, *supra* n.392 at 651 (recording average and peak flows through composite geomembrane/geosynthetic clay liners and composite geomembrane/composite clay liners).
[399] WA LAGOON DESIGN GUIDELINES, *supra* n.397 at T7-12.

Double synthetic lined lagoons are currently the most effective practice advised for use at CAFOs.[400] Double lined lagoons are composed of two geomembranes and often include leak detection and collection systems between the synthetic layers.[401] This is the design EPA imposed on a Yakima Valley dairy subjected to an enforcement action after Agency officials noted the facility's leaky lagoons were contributing to widespread groundwater pollution that endangered nearby communities.[402] Double liners are also currently in use at MPP facility evaporation ponds to control chlorides—a pollutant also of concern in CAFO waste.[403] EPA's understanding that composite liners with double synthetic layers are available to reduce pollution discharges from individual CAFOs and MPP facilities should also guide the Agency in its revision of the CAFO ELGs.

Merely recommending (or even requiring) that CAFO operators meet a specified lagoon permeability standard has not adequately protected groundwater because wear, tear, and improper installation or upkeep are often not apparent to the naked eye.[404] To overcome this challenge, engineers recommend that liquid manure storage structures include leak detection devices, particularly where representative groundwater monitoring is not occurring.[405] Leak detection allows CAFO operators to take immediate remedial action that can prevent discharges entirely. Without leak detection or groundwater quality monitoring, enforcing a lagoon permeability standard is impossible, illegally undermining one of the pillars of the CWA.[406] Simply requiring double-lined synthetic composite liners with leak detection mechanisms would facilitate straightforward enforcement and provide a better safeguard against pollution that threatens drinking water and surface waters.

Cost and Availability

Lagoon liner costs vary according to design.[407] While more protective designs like double synthetic liners are generally more expensive to install, their current use at CAFOs, including in

[400] *Id.* at T7-10, T7-12–T7-13.
[401] *Id.*
[402] Letter from Eric Winiecki, EPA Region 10, to David Erickson (March 29, 2017), at 4; *see also* WESTERN ENVIRONMENTAL LAW CENTER, *WA Industrial Dairy Installs Court-Ordered Manure Lagoon Liners to Protect Groundwater* (Dec. 12, 2016), https://westernlaw.org/wa-industrial-dairy-installs-court-ordered-manure-lagoon-liners-protect-groundwater-news-rel/ (opining that, with the installation of the new lagoon design, "Cow Palace has set the standard that the rest of the CAFO industry must now follow in order to protect people's health.").
[403] EPA, Response to FOIA 2025-EPA-04763 at 10.
[404] *See infra* nn.20–23 and accompanying text; *see also* WA LITERATURE REVIEW, *supra* n.19 at 69 (". . . it has been determined that design permeability data do not adequately predict actual seepage rates."); Erickson Report, *supra* n.18 at 5.
[405] Erickson Report, *supra* n.18 at 5, 9.
[406] *See* 33 U.S.C. § 1251(e) ("Public participation in the development, revision, and enforcement of any regulation, standard, effluent limitation, plan, or program established [under the CWA] shall be provided for, encouraged, and assisted by [EPA].").
[407] Dairyland Initiative, University of Wisconsin, *Manure Management*, https://thedairylandinitiative.vetmed.wisc.edu/home/housing-module/adult-cow-housing/manure-management/ (accessed April 24, 2025).

response to enforcement actions, demonstrates that they are available and affordable. Moreover, allowing CAFOs to cut costs by relying on compacted soil-lined lagoons and manure sealing falls short of BAT and burdens the public with the costs of dealing with excessive pollution. EPA has broad authority to consider these relevant costs when evaluating additional ELGs to control production area pollution.[408]

The costs for CAFOs to install commonsense pollution controls like synthetic liners, clay attenuation layers, and leak detection are justified because the alternative is saddling the public—and particularly frontline, rural communities—with higher healthcare, home maintenance, and utility bills. For instance, while retrofitting lagoons with double synthetic liners on a large CAFO can cost upwards of a million dollars,[409] reducing nitrate levels in drinking water wells impacted by CAFOs to below the Safe Drinking Water Act threshold can cost up to one million dollars *per well*.[410] Similarly, the Northeast Wisconsin Karst Task Force recounts "millions of dollars spent helping municipalities, farmers, and rural homeowners address [pervasive nitrate and bacteria contamination issues]," without any meaningful progress toward reducing the number of contaminated wells or the severity of the contamination.[411]

Municipal ratepayers also pay for externalities created by CAFOs. In Des Moines where factory farms and row crop agriculture are responsible for a whopping 65 percent of nitrogen loading to the two rivers that source the city's drinking water, ratepayers have been forced to cover the costs of a 4 million dollar reverse osmosis treatment system.[412] The need for advanced treatment has caused water bills to double over the past decade, and rates are expected to continue to increase up to 10 percent each year.[413] Further, upfront costs for sturdier liners and leak detection systems are offset by lower repair costs in the long run and lower likelihood that a CAFO will be saddled with litigation and remediation costs from an enforcement action.[414]

To reduce costs without sacrificing water quality, EPA could even permit CAFOs to make "alternate liner demonstrations," as the Agency does for coal ash impoundments. Such a provision

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[408] 33 U.S.C. § 1314(b)(2)(B) (authorizing EPA to consider the cost of effluent reductions, non-water quality impacts, and any other factors EPA deems appropriate); *see also Weyerhaeuser v. Costle*, 590 F.2d 1011, 1045 (D.C. Cir. 1978) (affirming EPA's discretion in deciding "how to account for the consideration factors, and how much weight to give each factor).

[409] *See* EPA, Public Comments on Proposed Modification of NPDES Permit # IDG010000 (compiled Nov. 13, 2024), at 4 (comment from industry group estimating that installation of a double synthetic lagoon liner costs $4 per square foot, or approximately $1.7 million for a 2,400-cow dairy).

[410] Minnesota Center for Environmental Advocacy et al., *supra* n.14 at 18.

[411] Midwest Environmental Defense Center et al., *supra* n.14 at 26.

[412] Kat Ruane et al., *The Devastating Toll of Factory Farm Pollution in Iowa* (Jan. 29, 2025), https://www.foodandwaterwatch.org/2025/01/29/iowa-factory-farm-water-pollution/.

[413] *Id.*

[414] WA LAGOON DESIGN GUIDELINES, *supra* n.397 at T7-14.

would exempt liquid manure storage structures from synthetic liner requirements if the CAFO could demonstrate through hydrogeologic and monitoring data that the "effective hydraulic conductivity of the engineered liner and/or naturally occurring soil is so low that, even if leachate migrates from the unit, the volume of leachate that can be released to the underlying aquifer over the active life of the impoundment is so small that these releases will not result in adverse effects at any point in the future."[415] Of course, such demonstrations would need to consider the cumulative impacts of all waste impoundments in the relevant watershed. If EPA chooses to regulate the storage of polluting materials on CAFOs differently than it regulates the storage of polluting materials in other point source categories, it must provide a rational explanation for doing so.

ii. *Require Covers for Liquid Manure Storage Structures*

Allowing CAFOs to store waste in uncovered lagoons is an outdated practice that is not representative of the best performing facilities in the industry. Uncovered lagoons are more susceptible to overflows and contribute to excessive amounts of land-applied waste that increase the risk of pollution discharge. Moreover, lagoon covers have the capacity to reduce emissions of odors and airborne pollutants, particularly ammonia that can aerially deposit on surrounding land and surface waters. EPA must consider requiring CAFOs that store liquid waste to do so in affordable covered structures that also minimize adverse non-water quality impacts.

Performance

Despite BMPs in the existing ELGs that require CAFOs to maintain minimum capacity necessary to contain precipitation from 25-year, 24-hour rainfall events,[416] uncovered lagoons continue to overflow due to human error and severe storms.[417] Lagoon covers can prevent rainfall from overwhelming storage capacity and causing catastrophic overflows that contaminate waterways.[418] This feature is increasingly important for pollution control as rainfall events become heavier and more unpredictable due to anthropogenic climate change. As EPA is aware, covers are already in use at many CAFOs. A 2001 consent decree reached in a CAFO enforcement case, in which EPA was a party, required permeable covers on all anaerobic lagoons to reduce odors as well as ammonia and

[415] EPA, Hazardous and Solid Waste Management System: Disposal of CCR, 85 Fed. Reg. 72,506, 72,408 (Nov. 12, 2020).
[416] As discussed in Food & Water Watch's 2017 Petition, this standard is itself outdated, as it relies on weather data from 1961. *See* 40 C.F.R. § 412.2(i); 2017 PETITION, *supra* n.5 at 56–58.
[417] *See, e.g.*, Greg Stanley, *Seventeen Manure Pits Reportedly Overflow at Large Feedlots in Southern Minnesota* (June 26, 2024), https://www.startribune.com/manure-pits-reportedly-overflow-at-16-large-feedlots-in-southern-minnesota/600376074 (quoting Minnesota feedlot operator who stated "we get 100-year floods every other year it seems"); Kendra Pierre-Louis, *Lagoons of Pig Waste Are Overflowing After Florence*, https://www.nytimes.com/2018/09/19/climate/florence-hog-farms.html (Sept. 19, 2018); *see also* Rudko, *supra* n.387 at 5–6 (finding the primary causes of lagoon overflows at Washington dairies are mismanagement and extreme rainfall).
[418] 2003 TDD, *supra* n.26 at 4-21.

hydrogen sulfide emissions.[419] Because lagoon covers help to control ammonia emissions, they are likely to assist in reducing aerial deposition of ammonia into waterways. Gas permeable liners can even be paired with subsequent acid stripping to convert ammonia into nonvolatile ammonium ions that can be made into fertilizer.[420]

Cost and Availability

As indicated by their prevalence on existing CAFOs, lagoon covers are affordable. Covers are widely available for less than 16 dollars per yard and, depending on the material, can last for up to 20 years.[421] Given the variety of options at different price points, most facilities should have no trouble finding a cover that fits the engineering specifications, processes, and site-specific considerations of their individual operations.

In assessing the cost of a cover requirement, EPA must also consider that covering lagoons may reduce disposal costs for CAFO operators by decreasing the overall volume of liquid waste.[422] In EPA's 2002 CAFO rulemaking, the Agency recognized that lagoons at swine facilities fill to capacity within just a few years of beginning operation due in part to precipitation.[423] This has led to the need for increased lagoon construction, created incentives to overapply waste when lagoons are full, and contributed to lagoon failures that cause catastrophic waste spills. Thus, requiring CAFOs to install lagoon covers could have the added benefits of slowing the need for additional lagoon construction and decreasing the frequency of land application by allowing CAFOs to more efficiently store waste. By giving CAFO operators more certainty about the volume of waste in their lagoons, lagoon covers would also help address inadequate maintenance of treatment volume, a factor that EPA previously identified as "the single most common reason for the failure of lagoon systems.[424]

EPA's cost analysis of a BMP mandating lagoon covers must also include costs currently externalized onto neighboring residents, including in the form of healthcare bills. Odorous irritants, particulate matter, and pathogens from inadequately contained CAFO waste contribute to disproportionate rates of respiratory illness and antibiotic-resistant infections in nearby

[419] Consent Decree Between United States of America and Citizens Legal Environmental Action Network, Inc. and Premium Standard Farms, Inc. and Continental Grain Company, Inc. at App'x A, Citizens Legal Action Network, Inc. v. Continental Grain Company, Inc., No. 98-6099-CV-W-6.
[420] Vanotti, *supra* n.338 at 295.
[421] University of Minnesota Extension, *Covers for Manure Storage* (2024), https://extension.umn.edu/manure-management/covers-manure-storage (citing Rose M. Steinglein et al., Covers for Mitigating Odor and Gas Emissions in Animal Agriculture: An Overview (2011)).
[422] 2003 TDD, *supra* n.26 at 4-21.
[423] *Id.* at 4-18.
[424] *Id.* at 4-21.; *see also id.* at 4-82 (describing anaerobic lagoons' "sensitivity to sudden changes in temperature and loading rates).

communities.[425] In this manner, overly lenient ELGs unfairly foist the costs of irresponsible CAFO operation onto vulnerable populations.[426]

Non-Water Quality Impacts

EPA has recognized that covers also help control odors and volatilized pollutants.[427] While the scope of emission reductions depends on the material used, covers can reduce odor emission by 40 to 99 percent.[428] Covers are also effective at reducing gaseous pollutants like ammonia, hydrogen sulfide, and methane.[429] According to the University of Colorado, manure slurry stored in covered lagoons can retain 3.5 times more nitrogen than slurries stored in open lagoons where nitrogen freely volatilizes.[430] Monitoring from two swine facilities in Utah using Bio-Cap™ Multi-layer covers showed evaporation rates were 45 percent less for covered lagoons than uncovered lagoons, evincing a decrease in overall pollutant volatilization.[431] Monitoring data provided by the manufacturer that compared uncovered lagoons to lagoons capped with Bio-Cap™ Multi-layer covers showed the covered facilities reduced odors by 83.7 percent, hydrogen sulfide emissions by 94.7 percent, and ammonia emissions by 65.78 percent.[432] The manufacturer claims a Colorado swine facility that installed the cover technology in 1999 achieved similar results.[433]

Controls for odor and other air pollutants from CAFOs are desperately needed to mitigate harmful impacts to nearby residents who experience disproportionately high rates of respiratory illness, high blood pressure, and psychological distress.[434] Moreover, lagoon covers provide more reliable methane emissions reductions compared to manure crusts, helping to mitigate the livestock industry's contribution to climate change.[435]

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[425] Casey, *supra* n.201 at 259–60, 265.
[426] *Id.*; *see also* Kelly-Reif & Wing, *supra* n.209 at 2, 5 ("The costs of the injuries, illnesses, and deaths caused by dangerous CAFO work are not borne by the pork industry. Rather, occupational injuries and accidents are primarily paid for by workers, their families, and taxpayers.").
[427] 2003 TDD, *supra* n.26 at 4-18.
[428] University of Minnesota Extension, *supra* n.421.
[429] *Id.*
[430] S.G. Lupis et al., *Best Management Practices for Reducing Ammonia Emissions: Lagoon Covers*, U. COLO. (Dec. 2012), https://extension.colostate.edu/topic-areas/agriculture/best-management-practices-for-reducing-ammonia-emissions-lagoon-covers-1-631b/.
[431] BEI AG ENVIRONMENTAL SOLUTIONS, UTAH BIO-CAP ML FINAL REPORT 5 (Jan. 21, 2003), https://epiair.com/wp-content/uploads/2012/01/Case-Study-BioCap-ML-Final-Report-1-21-03.pdf.
[432] *Id.*
[433] EMISSION SOLUTIONS, INC. & BAUMGARTNER ENVIRONICS, INC., EMISSION TESTS OF THE BIOCAP™ BIOCOVER INSTALLED ON A COLORADO SWINE LAGOON 2, https://epiair.com/wp-content/uploads/2012/04/COReport.pdf.
[434] Casey et al., *supra* n.201 at 262–265; Kelly-Reif & Wing, *supra* n.209 at 5); Steve Wing, *Air Pollution from Industrial Swine Operations and Blood Pressure of Neighboring Residents*, 121 ENV'T HEALTH PERSPECTIVES 92, 94–95 (2013).
[435] Jonah M. Greene et al., *National Greenhouse Gas Emission Reduction Potential from Adopting Anaerobic Digestion on Large-Scale Dairy Farms in the United States*, 58 ENV'T SCI. & TECH. 12409, 12412– 13 (2024) (explaining that the assumption that natural crusts will reduce lagoon methane emissions by up to 40 percent is rarely justified).

iii. *Require or Incentivize Dry Manure Handling*

In addition to considering technologies that can mitigate the substantial water quality impacts of liquid manure handling systems, EPA should alternatively consider NSPS and/or BAT requirements that prohibit new CAFOs from using liquid manure handling and transition existing CAFO operators away from liquid manure handling. As EPA has long found, "[r]educed water use or handling of wastes in a dry or drier form lowers the risk of pollutants entering surface waters."[436] Therefore, surface quality benefits can be achieved by requiring new operations to employ dry scrape systems for the removal of manure from livestock housing structures, and requiring or incentivizing existing operations to retrofit wet flush systems with a dry scrape system.

Performance

According to the Agency, "[r]eplacing a flush system with a dry scrape system," or for that matter, requiring dry scrape systems from the outset, "dramatically reduces the amount of water used in manure handling and also reduces the tonnage of manure by decreasing dilution with water."[437] Not only does this technology eliminate reliance on large lagoon systems in favor of storage options like prefabricated or formed storage tanks, "from which contaminants are less likely to seep,"[438] but compared with a wet flush system, the resulting manure product is more readily transported to areas where there is an increase in available land base where fertilizer is actually needed.[439] In other words, a CAFO operator using a dry scrape system would be less likely to overapply waste to cropland immediately surrounding the production area due to the practical difficulty and high cost associated with hauling the waste elsewhere.

Cost and Availability

Though EPA previously found the use of dry scrape systems to be uncommon outside of poultry operations when it last reviewed the technology in 2002,[440] the Agency soon thereafter reported otherwise. Since at least 2003, EPA acknowledged dry scrape systems as the primary manure removal practice for beef cattle raised on open lots, and the typical method of manure removal for dry lot dairy operations.[441] The Agency has also noted the impracticality of flush systems in colder climates where flush water is more likely to freeze.[442] Moreover, CAFOs have continued to adopt the practice in the intervening decades. For instance, California dairy operations have increasingly

[436] 2003 TDD, *supra* n.26 at 8-1.
[437] *Id.* at 8-16.
[438] *Id.*
[439] *Id.* at 8-17.
[440] *Id.*
[441] EPA, *NPDES Permit Writers' Guidance Manual and Example NPDES Permit For Concentrated Animal Feeding Operations*, App. B at B-11, B-12, B-14 (Dec. 31, 2003), https://www3.epa.gov/npdes/pubs/cafo_permit_guidance_entirepub.pdf.
[442] *Id.*

completed flush-to-scrape conversions in recent years, aided in part by state incentive programs for alternative manure management systems.[443] California regulators have found scrape system retrofits to be a relatively "low cost option" as compared with liquid waste management systems involving lagoons and anaerobic digestion,[444] with costs presumably reducing further for new construction.

Non-Water Quality Impacts

Beyond the clear water quality benefits of dry manure handling systems, they also provide other important non-water quality benefits, particularly as it relates to water conservation and the reduction of climate-altering methane emissions. Because wet manure handling creates the anaerobic conditions that lead to methane production, dry manure handling that pairs scrape systems with other practices like composting or solar drying of waste have been shown to substantially reduce greenhouse gas emissions. For instance, California researchers have concluded that converting one 4,250-head dairy to primarily dry handling practices will result in emissions reductions of up to 17,174 $MTCO_2e$ per year,[445] the equivalent climate impact of 1,932,486 gallons of gasoline consumed.[446]

b. Solid Waste Storage Requirements

In addition to manure, CAFOs also store large amounts of other solid wastes, including silage, compost,[447] and mortalities. When stockpiled, these organic wastes release significant amounts of nitrate through ammonia volatilization and pollutant-laden leachate that can infiltrate groundwater or contaminate stormwater runoff.[448] Controlling leachate is critical, as researchers estimate the liquid can be "40 times stronger than dairy parlor wastewater and up to 200 times stronger than raw sewage."[449]

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[443] *See* CAL. DEPT. OF FOOD AND AGRIC., ALTERNATIVE MANURE MANAGEMENT PROGRAM – INCENTIVE PROJECT-LEVEL DATA (Jan. 8, 2025), https://www.cdfa.ca.gov/oefi/AMMP/docs/AMMP_Project_Level_Data.pdf (documenting 17 flush-to-scrape conversions at Dairy CAFOs since 2018).

[444] CALIFORNIA AIR RES. BOARD, SHORT-LIVED CLIMATE POLLUTANT REDUCTION STRATEGY 122 (Mar. 14, 2017); *see also id.* at 123 (estimating capital costs of flush-to-scrape conversion at a 2,000-milking cow dairy to be $1.6 million over a ten-year period, and continued operating and maintenance costs over same time frame to be $0.4 million).

[445] CALIFORNIA DAIRY RESEARCH FOUNDATION, Small Dairy Climate Change Research: An Economic Evaluation Of Strategies For Methane Emission Reduction Effectiveness And Appropriateness In Small And Large California Diaries 35 (Mar. 31, 2020), https://www.cdfa.ca.gov/oefi/research/docs/CDFA_SmallDairyResearch_FINAL_Report.pdf.

[446] *See* EPA, *Greenhouse Gas Equivalencies Calculator* (Nov. 2024), https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results.

[447] While "composting is a well-suited technology for on-farm management of agricultural residues, [] it is not an environmentally sustainable technology for treating manure alone. Certain chemical and physical characteristics of animal manures are not adequate for composting and could limit the efficiency of the process . . . ." Vanotti, *supra* n.338 at 283.

[448] *See* M.M. Gebrehanna et al., *Silage Effluent Management: An Overview*, 143 SOIL, WATER, & CLIMATE 113, 113 (Oct. 2014) ("Silage effluent is a potent wastewater that can be produced when ensiling crops that have a high moisture content. Silage effluent can cause fish-kills and eutrophication."); Vanotti, *supra* n.338 at 283.

[449] JOSEPH P. HARNER, KANSAS ST. UNIV., SILAGE LEACHATE: A PROBLEM WITH POTENTIAL BENEFITS (May 2006), https://bookstore.ksre.ksu.edu/download/silage-leachate-a-problem-with-potential-benefits_MF2728; *see also* Dr. Rebecca Larson, U. WISC., *Silage Runoff Characterization* 6 (Apr. 3, 2013), https://www.slideshare.net/slideshow/silage-runoff-characterization-mah/19908018 (chart comparing concentrations of pollutants typical of silage leachate to pollutant concentrations of residential wastewater).

Because leachate contains such high nutrient concentrations, even seemingly negligible amounts can signify major nutrient losses that reduce the nutritional value of feed and contribute to water quality impairments.[450] In fact, "silage bunkers [are] one of the highest concentrated runoff nutrient loss areas on a farm in terms of loading per unit area."[451] Leachate from compost, which often includes mortalities on CAFOs, contains similar pollutants of concern as well as elevated pathogen risks.[452]

Existing guidelines require that production areas be "designed, constructed, operated, and maintained to contain all manure, litter, and process wastewater."[453] Regulations also require CAFO operators to divert clean water and properly manage mortalities.[454] In practice, these vague mandates have not resulted in production area practices that prevent the discharge of leachate or runoff. Many states allow "temporary" uncovered solids stockpiling on bare ground despite the fact that leachate release generally peaks within a few days.[455] To stem the flow of production area pollution, EPA must consider requiring liners and covers for all waste stockpiles.

Performance

The most effective methods for controlling leachate pollution generally consist of a liner and leachate collection system paired with covers and stormwater diversions to prevent contaminated runoff. Pollution reduction rates attributable to such a system depend on the material being stored and the composition of the liner. Silage leachate, for example, is extremely corrosive and can damage both concrete and steel.[456] Thus, while merely prohibiting the practice of stockpiling on bare ground would be an improvement to the ELGs, EPA should also consider establishing minimum standards for liner composition.

In the United Kingdom, farmers are required to seal baled silage in an impermeable membrane such as high-density plastic.[457] Bagging silage is an effective method of preventing leachate from reaching waters because it prevents both rainwater contamination and seepage into groundwater. In

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[450] PETER WRIGHT ET AL., EFFECTIVENESS OF SILAGE LEACHATE TREATMENT WITH VEGETATIVE FILTER AREAS (Aug. 2004), https://socwisconsin.org/wp-content/uploads/2016/05/Wrightetal_2004_SilageLeachateTrtmtVTA.pdf (noting that leachate losses from silo storage can equate to 15 percent of total feed nutrients or 7 pounds of phosphorus per cow per year).

[451] Michael A. Holly et al., *Silage Storage Runoff Characterization: Annual Nutrient Loading Rate and First Flush Analysis of Bunker Silos*, 264 AG. ECOSYSTEMS & ENV'T 85, 90 (2018).

[452] BRADLEY A. CLEARY, ASSESSMENT OF THE TRANSPORT OF BURIED LIVESTOCK LEACHATE THROUGH A SYNTHETIC CLAY LINER 35 (July 2009), https://central.bac-lac.gc.ca/.item?id=MR55444&op=pdf&app=Library&is_thesis=1&oclc_number=745898967.

[453] 40 C.F.R. § 412.31(a)(1)(i).

[454] *Id.* § 122.42(e)(1).

[455] *See* WRIGHT, *supra* n.450 at 2 ("The amount of juice from silage peaks quickly after harvest and then decreases to a trickle over time.").

[456] Harner, *supra* n.449; Gebrehanna, *supra* n.448 at 114.

[457] DEP'T FOR ENV'T, FOOD & RURAL AFFAIRS, *Storing Silage, Slurry, and Agricultural Fuel Oil* (Oct. 12, 2023), https://www.gov.uk/guidance/storing-silage-slurry-and-agricultural-fuel-oil.

this manner, bagging silage allows farmers to collect the low flow, high pollutant concentration leachate and divert it to further treatment before it enters the environment.[458] Similar "ag-bag" services are available in the U.S. and serve the dual purpose of reducing leaching to groundwater and reducing runoff caused by precipitation comingling with the stockpile.[459] EPA should therefore consider BMPs requiring that silage be bagged in a low permeability geomembrane.

Research also indicates geosynthetic clay liners can reduce permeability to protect groundwater quality and prevent leachate transport to surface waters. Field testing conducted in Canada shows the addition of a geosynthetic clay liner reduced hydraulic conductivity in a mortality pile by three orders of magnitude as compared to a soil liner alone.[460] Modeling conducted pursuant to the same study indicated that using a geosynthetic clay liner "could reduce the maximum contaminate concentration at the top of the aquifer by 38 percent for sandy soils and by 32 percent for clayey soils."[461]

While site-specific considerations may impact the specifications for storage areas, EPA must set baseline requirements and can distinguish between regional differences in the generally applicable ELGs. For instance, EPA can require locations that experience freezing temperatures have concrete barriers with air content and water/cement ratios sufficient to withstand freeze and thaw cycles without cracking, consistent with industry best practices outlined in American Concrete Institute guidance.[462] National standards establishing more specific regulatory minimums are necessary because, contrary to the expectation set forth in past rulemakings,[463] states have largely failed to promulgate additional regulations necessary to account for site-specific conditions. To prevent patchwork regulatory coverage that does not adequately protect national water quality, EPA should consider a BMP that uniformly requires solid waste storage area liners.

Cost and Availability

In evaluating affordability, EPA must consider that minimizing effluent loss from silage storage by adequately drying material prior to storage maximizes the value of the feed, partially offsetting costs associated with drying and installing concrete barriers.[464] According to one

[458] *See* Wright, supra n.450 at 12–13 (describing variable efficacy in vegetated buffers intended to treat leachate).
[459] *See e.g.*, Ag-bag, https://ag-bag.com/ (visited June 9, 2025).
[460] CLEARY, *supra* n.452 at 48. Laboratory modeling confirmed the benefits of a geosynthetic liner. *Id.* at 74.
[461] *Id.* at 94.
[462] *See generally* AMERICAN CONCRETE INSTITUTE, BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE (ACI 318-19) (2022), available at https://www.concrete.org/store/productdetail.aspx?ItemID=318U19&Language=English&Units=US_Units.
[463] *See, e.g.*, 68 Fed. Reg. at 7211 (anticipating that states would establish site-specific land application limits sufficient to prevent excessive phosphorus application).
[464] *See* Gebrehanna et al., *supra* n.448 at 113 ("Effluent release during silage making represents a loss of silage dry matter (DM), and a reduction in the value of the silage as feed.").

manufacturer, bagged silage can greatly reduce loss of matter, allowing operators to feed more cows with the same amount of feed at a reduced fermentation time.[465]

c. Outlet Filters for CAFOs with Ventilation Systems

As described in Sections I and III.E, air deposition is a significant source of jurisdictional water pollution from CAFOs. Pollutants of concern for this pathway include ammonia, pathogens, dust, and particulate matter.[466] While liquid manure storage structures are a major source of ammonia emissions from CAFOs, confinement pens where animals are held also contribute ammonia to surface waters, as do other parts of the CAFO where deposited nitrogen is then prone to wash into waters as runoff. Both courts and EPA have previously acknowledged EPA's authority to regulate water pollution transmitted through aerial pathways.[467] Further, ammonia deposition from a CAFO into surface waters constitutes a jurisdictional discharge from that CAFO if it is the functional equivalent of a direct discharge.[468] Accordingly, EPA must consider technologies and BMPs to control pollutants from these pathways. To combat nitrogen pollution from ammonia deposition, as well as the deposition of pathogens, dust, and other particulate matter, commenters urge EPA to consider requiring the use of filters and scrubbers in confinement ventilation systems.

Performance

A variety of filters and scrubbers are available and effective in reducing ammonia emissions and other air pollutants from CAFO housing. Much like the composite liners recommended for use with liquid manure storage structures, the most effective air deposition reduction systems have multiple components designed to provide extra layers of protection. Filters and scrubbers use physical, biological, and chemical processes to trap or neutralize pollutants.[469] Removal efficiencies depend on the type of filter used, but data are available for a variety of designs and pollutants at various livestock confinements.[470] Notably, ventilation outlets with acid scrubbers can remove up to 99 percent of ammonia before air leaves a CAFO, while biofilters can remove up to 67 percent of ammonia while

[465] AgBag, https://www.agbag.co.uk/ (visited June 9, 2025).
[466] Li Guo, *Mitigation Strategies of Air Pollutants for Mechanical Ventilated Livestock and Poultry Housing – A Review*, 13 ATMOSPHERE 1, 9 (2022).
[467] *See Nat'l Pork Prods. Council*, 635 F.3d at 754–56 (describing EPA's position that aerial deposition of dust from poultry CAFO ventilation systems are discharges that must be permitted); *Nat'l Cotton Council*, 553 F3d at 940 (recognizing that pesticides sprayed from point sources that deposit in waterways are jurisdictional discharges under the CWA).
[468] *Cnty. of Maui v. Hawaii Wildlife Fund*, 590 U.S. at 185.
[469] Guo, *supra* n.466 at 9–11.
[470] *Id.* at 12–13 (providing ammonia, particulate matter, and bacteria removal efficiencies for various filter types at swine and poultry CAFOs); *see also* Vanotti, *supra* n.338 at 293 (listing studies).

also providing significant odor mitigation.[471] Multistage scrubbers, such as those that use a combination of water, acid, and a biofilter, have been shown to achieve 90 percent reductions in particulate matter while also significantly cutting emissions of airborne bacteria.[472] Filters with gas permeable membranes or electrostatic spinning technologies have also been proven effective in removing particulate matter, bacteria, and viruses.[473] EPA can and should use these removal efficiencies and available data on per-animal emissions to set specific emission reduction standards for air-deposited water pollutants like ammonia.[474]

Cost and Availability

The availability of outlet filters to control air deposition of pollutants from CAFOs is supported by their widespread use in other countries. In the Netherlands, for instance, pig and poultry operations have been employing acid scrubbers and trickling biofilters to address soil acidification and eutrophication for decades.[475] The rollout of these technologies for animal feeding operations has been so successful that they are now considered commercially available, "off-the-shelf techniques."[476]

Site-specific considerations such as facility design, climate, and top pollutants of concern will impact which filtration system makes sense for a given facility.[477] However, the availability of multiple, tailorable filter options ensures that the majority of CAFOs with housing ventilation systems could find workable options to significantly reduce air-deposited water pollutants such as ammonia, particulate matter, and pathogens.

Costs of installing outlet filters in CAFOs vary widely depending on whether the operation is new or existing, the size of the confinement, and the configuration of the filter or scrubbing system. Estimated investment and operational costs are available, though likely out of date.[478] EPA should

[471] Guo, supra n.466 at 12; *see also* R. W. Melse & N.W.M. Ogink, *Air Scrubbing Techniques for Ammonia and Odor Reduction at Livestock Operations: Review of On-Farm Research in the Netherlands*, 48 TRANSACTIONS AM. SOC'Y AG. ENG'RS 2303, 2306, 2308 (2005), https://edepot.wur.nl/31455 (noting that scrubbers are capable of attaining up to 99 percent ammonia removal and describing a long term farm study that showed an average of 90 percent removal).
[472] Guo, *supra* n.466 at 13–14.
[473] *Id.* at 15–16.
[474] Melse & Ogink, *supra* n.471 at 2304.
[475] *Id.* at 2303.
[476] *Id.* at 2303.
[477] Guo, *supra* n.466 at 16.
[478] Roland W. Melse et al., *Multi-Pollutant Scrubbers for Removal of Ammonia, Odor, and Particulate Matter from Animal House Exhaust Air* (2008), https://lpelc.org/multi-pollutant-scrubbers-for-removal-of-ammonia-odor-and-particulate-matter-from-animal-house-exhaust-air/.

update these cost estimates, require filtration systems at new sources, and evaluate the feasibility of retrofitting existing sources.

Non-Water Quality Impacts

Installing filters and scrubbers in CAFO ventilation systems will provide important environmental benefits in addition to improving water quality. Most obviously, filters installed to reduce aerial deposition of pollution will also reduce air pollution. Filters that reduce ammonia and particulate matter emissions are especially beneficial as exposure to high levels of these pollutants is associated with adverse cardiac, respiratory, and mental health outcomes.[479] In fact, a recent study of a spatially explicit pollution inventory estimated that fine particulate matter ($PM_{2.5}$) from animal-based food production in the United States is responsible for at least 12,700 premature deaths every year, and that this is largely driven by ammonia.[480] Many filters that target odorous ammonia and particulate matter also reduce emissions of hydrogen sulfide, an odorous and toxic gas that is responsible for many human and animal deaths in livestock facilities.[481] Due in part to this ability to trap hydrogen sulfide, many filters are effective in reducing odor impacts on surrounding communities.[482]

Using ventilation filters to reduce the dispersal of particulate matter can also reduce the spread of pathogens and antibiotic-resistant genes. Clouds of particulate matter generated by CAFOs across the country are vectors for pathogenic microorganisms, including antibiotic-resistant bacteria.[483] Antibiotic and antiviral drugs themselves may also be distributed as particulate matter, unintentionally exposing the non-livestock animals (including humans) to drugs intended for livestock alone.[484] Filters and scrubbers installed at ventilation outlets in animal housing have the capacity to capture and neutralize pathogens and antibiotic-resistant genes that could otherwise wreak havoc on other animal feeding operations, wildlife populations, and even global human health.[485]

When evaluating the non-water quality impacts of including ventilation outlet filters and scrubbers in the ELGs, EPA should also consider the costs that are currently being borne by

[479] Mitloehner & Calvo, *supra* n.305 at 174–75; Casey, *supra* n.201 at 263, 264; Tschofen, *supra* n.164 at 19857.
[480] Nina G. G. Domingo et al., *Air Quality-Related Health Damages of Food*, 118 PNAS 1, 1–2 (2021) (pagination in accordance with submitted copy).
[481] Guo, *supra* n.466 at 12–13; Ji-Qin Ni et al., *Emission Factors and Characteristics of Ammonia, Hydrogen Sulfide, Carbon Dioxide, and Particulate Matter at Two High-Rise Layer Hen Houses*, 154 ATMOSPHERE 260, 261 (2017).
[482] Melse & Ogink, *supra* n.471 at 2310–11.
[483] McEachran, *supra* n.206 at 337–38, 340–41.
[484] *Id.* at 340–42.
[485] Guo, *supra* n.466 at 9.

communities forced to endure poor air and water quality attributable to existing CAFOs. Economic data from 2008 to 2012 show that even as gross economic damage from particulate matter in other sectors fell, damage caused by the livestock industry grew.[486] Homes lose value when CAFOs move within their vicinity and rural economies wither as residents are forced out to avoid odors and pests.[487] A variety of studies have determined the public is willing to pay for reduced environmental hazards associated with CAFOs, including improved recreation, property values, health impacts, drinking water, and climate outcomes.[488] Requiring even a subset of CAFOs, such as those with jurisdictional discharges based on the *Maui* factors,[489] to install and operate ventilation outlet filters or scrubbers would benefit CAFO workers and frontline communities, helping to alleviate the environmental injustices currently perpetrated by CAFOs against their neighbors, including noxious odors, pests, and the resulting reduced property values.[490]

4. Tailoring Land Application Requirements for Pollution Reduction

As EPA well knows, current land application requirements have utterly failed to "minimize" transport of nutrients to surface waters, much less other pollutants of concern. Significant revisions to the CAFO ELGs are necessary to ensure that CAFO land application practices reflect BAT. Not only must EPA consider technologies capable of reducing the nutrient content of waste prior to application so that land application areas have a chance of assimilating the amount of nutrients applied, but the Agency must heed its own findings that the agronomic approach to land application does not adequately reduce excess nutrient runoff, and align application rates, technologies, and practices with pollution reduction goals instead of maximum crop yields.

a. Solid Liquid Separation

EPA must consider requiring CAFOs that generate waste in slurry form to employ SLS. SLS is an affordable and, when paired with additional practices, effective pollution control technology that is already widely used in diverse CAFO settings.

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[486] Tschofen, *supra* n.164 at 19858.
[487] *See generally* DR. WILLIAM J. WEIDA, COLORADO COLLEGE, A SUMMARY OF THE REGIONAL ECONOMIC EFFECTS OF CAFOS (July 21, 2001).
[488] Gemma Del Rossi et al., *The Economics of Nutrient Pollution from Agriculture*, 15 ANN. REV. RES. ECON. 105, 117–118 (2023).
[489] *Cnty. of Maui*, 590 U.S. at 184–85.
[490] *See generally* WEIDA, *supra* n.487.

Performance

There are a variety of SLS methods, each of which has benefits and drawbacks that may make one system better suited for a particular CAFO.[491] This variety of options makes SLS a flexible requirement. Overall, SLS reduces the organic load in CAFO wastewater, thereby decreasing nutrient and pathogen concentrations in liquid containment structures and land-applied liquid waste and reducing water quality risks.[492] The solids can then be composted either on or offsite to create valuable fertilizer without the heightened leaching risks associated with higher inorganic nutrient concentrations.[493] Meanwhile, SLS improves the liquid fraction's nutrient ratio, total suspended solids concentration, and pathogen content for plant growth compared to unseparated slurry.[494] SLS is also a critical first step to many more advanced pollutant treatment methods.[495]

With the understanding that a portion of land-applied waste will be discharged to waters, EPA should consider imposing maximum pollutant concentrations for land-applied waste based on demonstrated reductions attained by SLS. For many SLS methods, estimated dry matter, total nitrogen, total phosphorus, volatile solids, and pathogen indicators removal efficiencies have already been documented.[496] EPA must also consider establishing differentiated minimum removal requirements based on CAFO size, as larger CAFOs will be able to—and should be required to—attain greater overall pollutant reductions and achieve greater cost efficiency by investing in more advanced SLS methods like centrifuges with polymer additives or dissolved air floatation tanks.[497] As the 2017 rulemaking petition described, establishing ELGs for additional CAFO size categories is

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[491] *See*, *e.g.*, Vanotti, *supra* n.338 at 280 (comparing a screw press separator to a rotating drum screen separator).
[492] BRADFORD, *supra* n.7 at 13.
[493] *Id.*; Vanotti, *supra* n.338 at 277; *see also* M. Hjorth et al., *Solid-liquid Separation of Animal Slurry in Theory and Practice: A Review*, 30 AGRONOMY SUSTAINABLE DEVEL. 153, 155 (2010) (contrasting manure management in Asia with management in North America); MINN. POLLUTION CONTROL AGENCY, RESPONSE TO COMMENTS ON THE GENERAL NPDES AND SDS FEEDLOT PERMITS 7–9 (2025), https://www.pca.state.mn.us/sites/default/files/wq-f3-64.pdf.
[494] *Id.*
[495] *See* Vanotti, *supra* n.338 at 289 (describing use of calcium hydroxide to remove and recover phosphorus from liquid wastewater after SLS), 300 (describing biological nitrification/denitrification process for separated waste).
[496] *See* Giorgia Cocolo, Assessment of Different Solid-Liquid Separation Techniques for Livestock Slurry 12–20, 36, 49–50, 62 (2013) (PhD thesis, Scuola di Dottorato), https://air.unimi.it/retrieve/dfa8b990-f12e-748b-e053-3a05fe0a3a96/phd_unimi_R09277.pdf; Vanotti, *supra* n.338 at 279–82; Hjorth, *supra* n.493 at 160–176; Rotz, *supra* n.383 at E128 (estimating 25 percent N reduction in liquid portion); Liang Wang, *Nutrient Reduction of Dairy Manure through Solid-Liquid Separation with Flocculation and Subsequent Microalgal Treatment*, 190 APPLIED BIOCHEM. & BIOTECH. 1425, 1429–36 (2020); BRADFORD, *supra* n.7 at 43 (estimating that the combination of inclined screen separator, sedimentation tank, and sand filter removed over 90 percent of pathogen indicator microorganisms); Greene, *supra* n.435 at 12415 (estimating 15 percent N removal and up to 30 percent removal of volatile solids attributable to SLS); Lide Chen & Hernan Tejeda, *Estimating the Efficiency and Cost of an On-Farm Centrifuge Separator* (Dec. 2020), https://www.uidaho.edu/extension/publications/bul/bul991#Study (providing tons of nutrients removed by screen separators on their own and in combination with centrifuge separators).
[497] Notably, EPA's recent proposal to update the MPP regulations begins by describing screens, dissolved air floatation, and chemical additives as technologies used by MPP facilities to remove conventional pollutants. 89 Fed. Reg. at 4482.

necessary to account for the tendency of CAFOs to cluster just beneath the Large CAFO threshold to avoid regulation.[498]

Cost and Availability

Many CAFOs already employ some form of SLS to help mitigate water and air pollution.[499] In fact, SLS was already considered a common practice when EPA studied the CAFO category ELGs in 2002.[500] Since then, SLS has only increased in popularity. For instance, a 2024 survey of Wisconsin dairies found that 80 percent employed some sort of SLS.[501] Driven by the "need to improve animal manure management systems to protect water and air quality and comply with [] regulations," advances in SLS over the past two decades have resulted in numerous SLS technologies that can be tailored to work for CAFOs with a variety of characteristics. Consequently, many researchers and regulators have recognized the benefits of SLS already in use on CAFOs.[502] In fact, an EPA study on NMP implementation determined an SLS system consisting of an inclined screen, sedimentation tank, and sand filtration was "necessary for efficient management of the NMP."[503] Similarly, the USDA's NRCS concluded that SLS is often "a necessary component to achieve manure treatment goals for a farm."[504]

One of the primary benefits of SLS is the flexibility attributable to the diversity of available SLS technologies and methods. For instance, CAFOs may employ mechanical separation methods such as filtration screens, and presses, or harness natural forces through the use of centrifuges, settling basins, or Dorr separators.[505] SLS can also be accomplished or assisted by chemical means through the addition of coagulants and flocculants.[506] This diversity increases opportunities for treatment at all kinds of CAFO facilities, but also means there are a range of pollution reduction capabilities, costs,

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[498] *See* 2017 PETITION, *supra* n.5 at 31–32 (requesting that EPA shrink or eliminate the Medium CAFO category).
[499] Rotz, *supra* n.383 at E128 ("Some type of liquid and solid separation is often used to reduce the solids content of manure entering the lagoon.").
[500] 2003 TDD, *supra* n.26 at 4-82 ("One common practice for the treatment of waste at dairies is solids separation."), 8-17–23 (describing prevalence of gravity and mechanical separation at dairy and hog CAFOs).
[501] RUTHIE LAZENBY, UCLA, MITIGATING EMISSIONS FROM CALIFORNIA'S DAIRIES 8 (Jan. 2024).
[502] *See, e.g.*, NY STATE DEP'T OF AGRIC. & MARKETS, RFP0326 - REQUEST FOR PROPOSALS, CAFO ENHANCED NUTRIENT AND METHANE MANAGEMENT PROGRAM 5 (2024), https://agriculture.ny.gov/system/files/documents/2024/06/requestforproposals_rfp0326_cafo_enmp.pdf (listing SLS among a menu of BMPs that control nutrient and greenhouse gas pollution); Yijia Zhang et al., *Solid-Liquid Separation and its Environmental Impact on Manure Treatment in Scaled Pig Farms—Evidence Based on Lifecycle Assessment*, 13 Agric. 1, 16 (2023) (pagination in accordance with submitted copy); WISCONSIN MANURE IRRIGATION WORKGROUP, *supra* n.199 at 14.
[503] BRADFORD, *supra* n.7 at 40.
[504] USDA-NRCS, ENVIRONMENTAL ENGINEERING NATIONAL ENGINEERING HANDBOOK, PT. 637, CH. 4, SOLID-LIQUID SEPARATION ALTERNATIVES FOR MANURE TREATMENT AND HANDLING 4-145 (2019).
[505] Cocolo, *supra* n.496 at 13–22.
[506] *Id.*

and benefits associated with SLS implementation on CAFOs.[507] USDA's Economic Research Service has noted that many simple mechanical SLS technologies are "generally affordable at approximately $40,000 for a 120-head dairy farm."[508] According to a study of a 4,000-cow dairy CAFO in Idaho, the combined capital and operation costs of a centrifuge system for a large CAFO are approximately $90,100,[509] indicating significant savings are attainable through economies of scale. The study also noted that large facilities already using inclined screen separators can save on operating costs by incorporating a centrifuge into their SLS system.[510]

In addition to the cost per unit of pollutant removed, EPA's affordability analyses should also consider financial benefits that will flow to CAFOs employing SLS. For example, lower solids content in wastewater reduces equipment maintenance and buildout costs by preventing clogged irrigation systems and limiting the need for additional liquid storage structure capacity; recycled solids can replace bedding, cutting down on operational costs; and composted solids can be sold as fertilizer, adding another source of income to CAFO revenue streams.[511] The already widespread use of this technology further underscores its availability and affordability to the industry.

Non-Water Quality Impacts

In addition to helping CAFOs achieve water pollution reductions, SLS has many non-water quality benefits that EPA must consider. For instance, removing volatile solids prior to long-term liquid waste storage reduces greenhouse gas emissions.[512] In fact, a 2017 study of dairy CAFOs concluded that SLS reduced methane emissions by 46 percent and overall greenhouse gas emissions by 44 percent, indicating it was more effective than anaerobic digestion in combatting emissions from manure storage.[513] Relatedly, solids suspended in liquid waste are a primary source of odors that plague residents near CAFO lagoons.[514] Removal of these solids can help reduce odors.[515] Finally, CAFOs that rely on flushing systems to remove manure from production areas can reuse SLS liquids, reducing dewatering of aquifers and waterways.[516]

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[507] Vanotti, *supra* n.338**Error! Bookmark not defined.** at 277; USDA-NRCS, *supra* n.504 at 4-145–4-14; TENG LIM ET AL., USDA-ERS, INCREASING THE VALUE OF ANIMAL MANURE FOR FARMERS 40–43, 64–65 (March 2023).
[508] Lim, *supra* n.507 at 40.
[509] *See* Chen & Tejeda, *supra* n.496 ($48,151.91 in capital costs + $41,949 in operating costs).
[510] *Id.*
[511] Lazenby, supra n.501 at 10; USDA-NRCS, *supra* n.504 at 4-30, 4-98; LIM, *supra* n.507 at 40, 71 (March 2023).
[512] Lazenby, supra n.501 at 10.
[513] Holly, *supra* n.251 at 416.
[514] USDA-NRCS, *supra* n.504 at 4-22.
[515] *Id.* at 4-45, 4-129, 4-133; Hjorth, *supra* n.493 at 154, 165; IOWA STATE U. EXTENSION, *Solids Separation*, https://www.extension.iastate.edu/ampat/solids-separation (visited March 3, 2025).
[516] *See* Vanotti, *supra* n.338351 at 277 (describing availability of separated liquids for water reuse).

Given the promising implementation of SLS technologies by CAFOs and the abundance of information on the efficacy of those technologies in removing pollutants, EPA must consider requiring SLS as a BMP and/or designating SLS as BAT.

b. Abandoning the Agronomic Approach to Application Rates

Maximizing crop yields is outside the scope of EPA's authority under the CWA and is therefore not an appropriate goal for the CAFO guidelines. As such, the Agency must re-orient its view of land application as a pollutant disposal practice to be closely regulated and monitored, rather than a crop production tool limited only by optimal yield recommendations. Waste application can only function as a nutrient pollution prevention practice when such application is limited to the land's assimilative capacity under real world conditions—not ideal crop production conditions.[517] Thus, application standards must be set based on their ability to achieve environmental—and not agricultural—targets, considering not only the assimilative capacity of available cropland, but also all discharge pathways and known water quality risks.

Several examples of developing and implementing this kind of nutrient planning within the United States and abroad can serve as instructive models to guide CAFO ELG updates. For instance, the California State Water Resources Control Board is currently updating its land application requirements for dairy CAFOs to shift away from an agronomic approach in favor of application rates that more directly relate to groundwater protection outcomes.[518] The State is developing a groundwater loading limit expressed as the maximum annual pounds of nitrogen allowed to leach below the root zone per acre per acre foot of water, calculated to ensure groundwater does not exceed maximum contaminant levels.[519] Regulators will then derive a multi-year land application rate formula that determines how much nitrogen can be applied to dairy cropland consistent with the groundwater loading limit.[520] EPA could take a similar approach to setting application rates for achieving surface water quality protection.

Alternatively, EPA could consider adopting protective application rates like those used throughout the European Union to reduce manure nutrient losses to surface waters for the past three decades. The EU's Nitrate Directive sets a 170 kg/ha (151.67 lbs/acre) annual farm-level limit on N application from manure while giving member states the flexibility to set more specific soil and crop

[517] *See* Kellogg, *supra* n.199 at 1 ("When manure application rates exceed the capacity of the land to assimilate nutrients, repeated applications can lead to a buildup of nutrients in the soil. This increases the potential for nutrients to move from the field through leaching and runoff to pollute ground and surface water."); Qiuchun Yang et al., *Spatiotemporal Patterns of Livestock Manure Nutrient Production in the Conterminous United States from 1930 to 2012*, 541 SCI. TOTAL ENV'T 1592, 1597–98 (2016) (using assimilative capacity of land as a benchmark for assessing negative environmental impacts).
[518] *See* CA DAIRY ORDER, *supra* n.15 at 54.
[519] *Id.* at 55.
[520] *Id.*

rates consistent with this limit.[521] A Dutch law implementing this directive known as the Manure and Fertilisers Act set initial soil and crop specific standards for N and P, and then periodically lowers those rates to meet environmental targets.[522]

EPA could also consider creating a nationally applicable tool to ensure PMPs include land application requirements that will achieve water quality protection. For example, New Zealand has created a computer software model called Overseer to estimate nutrient use and losses within a farm system, a tool that has undergone rigorous scientific review and redevelopment in recent years, and which is used by regulators to set allowable "Nitrogen Loss Limits" for livestock operations.[523]

c. Flow Meters in Land Application Equipment

While replacing NMPs with PMPs as described above is crucial, the change is unlikely to significantly reduce pollution from land application of CAFO waste unless EPA simultaneously addresses plan noncompliance. Monitoring results prove not only that NMPs are inadequate, but that many CAFOs are land applying waste at rates and under conditions that violate those NMPs.[524] To ensure permitted CAFOs land apply waste at rates calculated to reduce discharges of all pollutants, EPA must mandate the use of flow meters for any CAFO that land applies liquid waste.

Performance

Flow meters are devices that measure the amount of liquid that passes through a piece of irrigation equipment.[525] Flow meters provide precise data about how much liquid has been applied to a particular field and the rate at which application occurred.[526] Many modern flow meters also include automated leak detection.[527] Flow meters are flexible tools that are compatible with many types of irrigation equipment, including those commonly used by CAFOs.[528] By requiring CAFOs to submit

[521] European Union, Council Directive of 12 December 1991 Concerning The Protection Of Waters Against Pollution Caused By Nitrates From Agricultural Sources 1 (1991), https://eur-lex.europa.eu/eli/dir/1991/676/oj/eng.
[522] *See* Hans J.M. Van Grinsven et al., *Evaluation of the Dutch Implementation of the Nitrates Directive, the Water Framework Directive and the National Emission Ceilings Directive*, 78 WAGENINGEN J. LIFE SCI. 69, 72–74 (2016).
[523] NEW ZEALAND MINISTRY FOR PRIMARY INDUS., *Overseer: A Nutrient Management Tool For Farmers And Growers* (visited April 8, 2025), https://www.mpi.govt.nz/agriculture/farm-management-the-environment-and-land-use/overseer-a-nutrient-management-tool-for-farmers-and-growers; ENV'T CANTERBURY REG'L COUNCIL, *Using Overseer* (visited Apr. 8, 2025), https://www.ecan.govt.nz/your-region/farmers-hub/farming-plans-and-consenting/overseer/.
[524] CA DAIRY ORDER, *supra* n.15 at 60; BRADFORD, *supra* n.7 at 8.
[525] MCCROMETER, *Flow Meters for Agricultural Applications: An Overview* (June 25, 2020), https://blog.mccrometer.com/flow-meters-for-agriculture-applications-an-overview/.
[526] Englin, *supra* n.190.
[527] *Id.*
[528] *Id.* (mentioning center pivot, drip, and sprinkler irrigation and concluding that "[n]o matter your method of irrigation, an efficient irrigation system should include a working flow meter"); MCCROMETER, *supra* n.525 (discussing flow meters for use with dairy lagoons); UTAH ST. UNIV., *Accurate Irrigation Water Flow Measurement in Pipes*, https://extension.usu.edu/irrigation/research/accurate-irrigation-water-flow-pipes (listing various types of flow meters and assessing pros and cons of each).

regular flow metering reports that include the time and date of readings and waste nutrient concentration data, EPA would gain valuable insight about whether facilities are complying with their NMPs/PMPs by land applying in accordance with specified rates, avoiding application during wet weather, and more.[529] This information is essential to identify and remedy NPDES permit noncompliance that is contributing to widespread water quality problems.[530]

Cost and Availability

Flow meters are available and cost effective.[531] Some states and localities already have laws that require the use of flow meters, including for entities who appropriate water from surface sources and groundwater aquifers.[532] Flow metering is so prevalent in agriculture that NRCS includes them in its Conservation Practice Standard for Irrigation Water Management.[533] Indeed, the Central Valley Dairy Representative Monitoring Program, a non-profit group of dairy owners and operators, reported in 2019 that flow meters were "at hand" and "could be implemented in relatively short order" in California at a cost of $300 to $1,000 per dairy.[534] Flow meters will also save CAFOs money that they otherwise would have spent on water and electricity bills.[535]

Non-Water Quality Impacts

The primary non-water quality impact that would result from a BMP mandating the use of flow metering at CAFOs is water conservation. Industrial animal agriculture uses huge quantities of water.[536] Flow meters allow irrigators to limit liquid application to only what is necessary for plant growth, maximizing efficiency in one aspect of CAFO water use. With rising instances of severe

[529] Some flow meters even come with built-in datalogging that includes weather data at the time of application, eliminating the need for EPA, state regulators, and the public to chase down weather reports. UTAH ST. UNIV., *supra* n.528.
[530] National Pollutant Discharge Elimination System (NPDES) Concentrated Animal Feeding Operation (CAFO) Reporting Rule, 76 Fed. Reg. 65,432 (Oct. 21, 2011).
[531] *See* UTAH ST. UNIV., *supra* n.528 (Table 5, providing an overview of flow meter equipment costs).
[532] *See, e.g.*, Minn. Stat. § 103G.281(2); 23 Cal. Code Reg. § 993(b)(4) (requiring submission of telemetered data to a public website).
[533] USDA-NRCS, CONSERVATION PRACTICE STANDARD 449, IRRIGATION WATER MANAGEMENT (Jan. 2024), https://www.nrcs.usda.gov/sites/default/files/2024-09/449_NHCP_CPS_Irrigation_Water_Management_2023.pdf.
[534] CENTRAL VALLEY DAIRY REPRESENTATIVE MONITORING PROGRAM, SUMMARY REPRESENTATIVE MONITORING REPORT v (April 1, 2019), https://leadershipcounsel.org/wp-content/uploads/2019/10/Dairy-report.pdf.
[535] MCCROMETER, *supra* n.525 (discussing the use of flow meters for expense management).
[536] *See* Dara Meredith Fedrow, Water Use in Confined Animal Feeding Operations (CAFOs) in Minnesota: Who's Keeping Track? 44 (Graduate thesis, 2019), https://scholarworks.umt.edu/cgi/viewcontent.cgi?article=12430&context=etd (estimating that large hog and dairy CAFOs in Minnesota alone used 4.2 billion gallons of water in 2017).

drought and rampant aquifer depletion in farm country,[537] water conservation is an enormous benefit that EPA must consider in evaluating whether to include a flow metering BMP in the CAFO ELGs.

d. Manure Incorporation

Manure incorporation is a land application practice commonly used by CAFOs and farms that land apply CAFO waste.[538] During incorporation, CAFO waste is mixed into the top layer of soil by tilling or aerating[539] the soil directly after application. Incorporation of liquid wastes can also be achieved by injecting waste deeper into the soil using a shallow disc injector, spoke wheel injector, chisel injector or other injection technology.[540] Many states already require some level of incorporation because mixing waste into the soil immediately after application reduces the likelihood that pollutants will pool and run off into ditches, tile drains, or nearby surface waters.[541] There is also evidence indicating that incorporation may reduce odor and air pollution.[542] Given the prevalence of incorporation and injection in the industry already, EPA should consider including this available practice as a BMP for all CAFOs that land apply waste.

Performance

Numerous studies show that incorporating manure likely helps to conserve nutrients in soil and reduce nutrient runoff. During EPA's consideration of the CAFO ELGs in 2002, the Agency recognized that incorporation and injection can reduce erosion and runoff, keeping nutrients and

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[537] *See* U.S. GLOBAL CHANGE RES. PROGRAM, IMPACTS, RISKS AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II, CH. 10 AGRICULTURE AND RUAL COMMUNITIES (2018), https://nca2018.globalchange.gov/chapter/10/ (predicting agricultural production in the U.S. will decline in response to increasing drought conditions and extreme heat); *see generally* Taro Mieno et al., *Aquifer Depletion Exacerbates Agricultural Drought Losses in the US High Plains*, 2 NATURE WATER 1 (2024) (pagination in accordance with submitted copy).

[538] According to USDA, surface application with incorporation is the second most common land application method after application without incorporation, and was used on 5.5 million acres of cropland from 2013 through 2019. Nigel Key & Laura Dodson, *Farmers Spread Most Manure through Surface Applications* (July 3, 2023), https://ers.usda.gov/data-products/charts-of-note/chart-detail?chartId=106802; *see also* MARCEL AILLERY ET AL., USDA-ERS, MANAGING MANURE TO IMPROVE AIR AND WATER QUALITY 12 (2005), https://ers.usda.gov/sites/default/files/_laserfiche/publications/46336/29004_err9.pdf (estimating approximately 40 percent of cropland in the Chesapeake Bay watershed benefitted from manure incorporation).

[539] *See* CORNELL U. COOPERATIVE EXT., SUBSURFACE (TILE) DRAINAGE BEST MANAGEMENT PRACTICES (2011), http://nmsp.cals.cornell.edu/publications/factsheets/factsheet58.pdf (calling aerators a promising approach for shallow incorporation that minimizes soil disturbance).

[540] CORNELL U. COOP. EXTENSION, LIQUID MANURE INJECTION (2015) http://nmsp.cals.cornell.edu/publications/factsheets/factsheet87.pdf.

[541] John E. Gilley & L. Mark Risse, *Runoff and Soil Loss as Affected by the Application of Manure*, 43 BIO. SYS. ENG'G 1583, 1587 (2000); *see e.g.*, Minn. R. § 7020.2225 (requiring injection or incorporation within 24 hours and prior to rainfall in sensitive areas); Wis. Admin. Code § 243.14 (mandating injection or incorporation in surface water quality management areas); 510 ILCS § 77/20 (requiring injection or incorporation for land application in a 10-year floodplain); *see also* E. Osei, *supra* n.98 at 5 (discussing prevalence of incorporation among Texas dairies that also employ SLS).

[542] CORNELL U. COOP. EXTENSION, *supra* n.540.

other pollutants on land application sites.[543] Since then, additional research has quantified nutrient and hormone discharge reductions attributable to incorporation.

Incorporation has proven particularly effective at reducing off-field transport of phosphorus. Practices that reduce phosphorus pollution should be a priority for the CAFO ELGs as existing regulations allow CAFOs to use nitrogen-based application rates that result in excess phosphorus on fields.[544] For instance, modeling based on dairy CAFOs in Texas indicated that incorporation of land-applied waste could achieve up to 45 percent reductions in soluble phosphorus losses to edge-of-field runoff.[545] Field studies confirm the phosphorus reduction potential of incorporation as a BMP. In a study of swine manure applied to Iowa cropland, total phosphorus concentrations in runoff from unincorporated fields were more than two times higher than concentrations in runoff from fields that incorporated manure after application.[546]

Incorporation can also significantly reduce nitrogen pollution. Mixing promotes conversion of organic nitrogen to plant-available inorganic nitrogen, increasing the percentage of nitrogen that is taken up by crops and reducing the nitrogen content of runoff.[547] According to a 2005 literature review conducted by USDA, incorporation significantly reduces nitrogen losses from land application fields for hog, dairy, poultry, and beef operations.[548] Part of this reduction in nitrogen water pollution is due to incorporation's ability to control nitrogen volatilization.[549] As discussed in Sections I and III.E, deposition of aerosolized pollutants—and particularly ammonia—is a major pathway by which CAFOs discharge pollutants to surface waters. Because incorporation has been shown to dramatically

[543] 2003 TDD, *supra* n.26 at 8-179.
[544] *See supra* Section III.A.
[545] Osei, *supra* n.98 at 1.
[546] Brett L. Allen et al., *Effect of Liquid Swine Manure Rate, Incorporation, and Timing of Rainfall on Phosphorus Loss with Surface Runoff*, 37 J. ENV'T QUALITY 125, 135–36 (2008).
[547] U. MINN., *Manure Application Methods and Nitrogen Losses*, https://extension.umn.edu/manure-management/manure-application-methods-and-nitrogen-losses. Of course, this assumption will not hold if EPA does not enforce against manure applications to unplanted fields. *See* MARCEL AILLERY ET AL., *supra* n.538 at 4, 7 (warning of the need to account for increased soil retention of nitrogen when injecting manure).
[548] MARCEL AILLERY ET AL., *supra* n.538 at 12.
[549] CORNELL U. COOP. EXTENSION, *supra* n.540 ("Liquid manure injection in the spring or into a growing crop reduces N volatilization loss, resulting in much greater retention of plant-available N."); Gabriella Burkett et al., *Influence of Manure Injection Versus Surface Application on Corn for Silage and Winter Rye Yield, Quality, Phosphorus Balance and Soil Test Phosphorus*, 16 J. AG. & FOOD RES. 1, 1 (2024) ("[S]urface application of manure often results in loss of ammonium-N (NH_4-N) fraction through ammonia volatilization.") (pagination in accordance with submitted copy).

reduce ammonia emissions,[550] CAFOs that incorporate their manure can be expected to contribute far less ammonia to waters.

Incorporation has also been shown to reduce hormone transport to surface waters and overall runoff volume, indicating incorporation may be effective in reducing the off-field movement of other CAFO pollutants.[551] Cumulatively, these results suggest that EPA should consider amending the ELGs to require incorporation or injection of land-applied CAFO waste as soon as possible after application, but at least within 24 hours.

Replacing broadcast spray irrigation with injection of liquid waste may produce even greater pollution reductions than incorporation of solid waste.[552] One study examining land application activities in the Mid-Atlantic region found that replacing broadcast irrigation with low-disturbance injection reduced total nitrogen in the watershed by 19 percent and total phosphorus by 44 percent.[553] Similarly, experiments conducted in Pennsylvania showed phosphorus lost to runoff was reduced by 68 percent on fields that injected dairy waste in place of broadcast irrigation.[554]

Cost and Availability

As indicated by the widespread use of incorporation and injection at existing land application sites,[555] these practices are available and affordable. While initial investments in tank and injector technologies can be expensive, many states offer grants to help cover the costs of incorporation

[550] MARCEL AILLERY ET AL., *supra* n.538 at 54 (estimating that injecting manure resulted in just 12 percent of ammonia emissions attributable to surface application); Holly, *supra* n.513 at 414 ("There is abundant literature on reductions of NH_3 when manure is rapidly incorporated (40–90%)."); UNION OF CONCERNED SCIENTISTS, CAFOS UNCOVERED: THE UNTOLD COSTS OF CONFINED ANIMAL FEEDING OPERATIONS 59 (2008) (estimating that injection can reduce ammonia emissions by 50 to 100 percent depending on the method used).
[551] Odette Mina et al., *Estrogen Transport in Surface Runoff from Agricultural Fields Treated with Two Application Methods of Dairy Manure*, 45 J. ENV'T. QUALITY 2007, 2013 (2016) (finding shallow disc injection reduced estrogen transport to runoff by two orders of magnitude compared to broadcast irrigation); MINNESOTA POLLUTION CONTROL AGENCY, RUNOFF REDUCTIONS WITH INCORPORATED MANURE 2 (May 2018), https://www.pca.state.mn.us/sites/default/files/wq-f1-08.pdf.
[552] *See* I.J. ROSS ET AL., U. KENTUCKY WATER RES. RSCH. INST., EFFECTS OF SOIL INJECTION OF LIQUID DAIRY MANURE ON THE QUALITY OF SURFACE RUNOFF 63 (1978) ("Injection of the manure into the soil essentially eliminated any pollutant yield in the runoff from the test plots as compared to surface application.").
[553] Arghajeet Saha et al., *Water Quality Benefits of Weather-Based Manure Application Timing and Manure Placement Strategies*, 333 J. ENV'T. MGMT. 1, 2 (2023) (pagination in accordance with submitted copy).
[554] Emad Jahanzad et al., *Varying Influent of Dairy Manure Injection on Phosphorus Loss in Runoff over Four Years*, 48 J. ENV'T. QUALITY 450, 450, 454 (2019).
[555] *See infra* n.541 and accompanying text; *see also* Aguirre-Villegas, *supra* n.26 at 174, fig.4 (conveying survey results showing prevalence of injection on Wisconsin livestock operations).

equipment.[556] And many CAFOs already own or have access to incorporation tools or have equipment that is compatible with low-cost incorporation accessories. Even for CAFOs that must purchase, maintain, and operate an additional piece of machinery, incorporation is likely to pay for itself over time as incorporation reduces the need for additional applications of nitrogen fertilizer.[557] Research conducted on a dairy in Illinois concluded that switching from surface application to injection saved the operator 150 dollars per hectare, more than enough to cover the additional cost of injection.[558] Modeling based on Texas dairies indicates that "the cost of incorporating solid manure on waste application fields is small for all dairy sizes," amounting to just 3 percent of net returns at most.[559]

Non-Water Quality Impacts

Requiring incorporation of land-applied CAFO waste is likely to result in beneficial non-water quality impacts as well. As discussed, incorporation can reduce air emissions from CAFOs, alleviating health impacts and improving quality of life for farm workers and surrounding communities. Reductions in ammonia emissions are likely to improve respiratory health and pulmonary function.[560] Assuming manure is applied at appropriate rates, incorporation can also be effective in reducing odors.[561] Further, some injection methods are compatible with no-till strategies intended to bolster soil health and promote long-term sustainability of farmland.[562] These benefits would help to offset the already minimal costs of mandating incorporation as a BMP and help ensure CAFOs are not unfairly offloading externalities onto nearby communities.

5. Monitoring

All NPDES permits must include representative monitoring and reporting provisions sufficient to ensure compliance with the permit's effluent limits.[563] "Effective self-monitoring reveals

[556] *See, e.g.*, NY DEP'T OF AGRIC. & MARKETS, CAFO ENHANCED NUTRIENT AND METHANE MANAGEMENT PROGRAM (ENMP) PROJECT DESCRIPTIONS (2025) (describing state funds awarded to CAFOs for upgrades, including injection systems, to mitigate environmental impacts), https://agriculture.ny.gov/system/files/documents/2025/02/round1awarddescriptions_cafo_enmp.pdf.
[557] Osei, *supra* n.98 at 9.
[558] Gabriella Burkett et al., *supra* n.549 at 9.
[559] Osei, *supra* n.98 at 9.
[560] Mitloehner & Carvo, *supra* n.305 at 171, 174.
[561] CORNELL U. COOP. EXTENSION, *supra* n.539; MARCEL AILLERY ET AL., *supra* n.538 at 7.
[562] CORNELL U. COOP. EXTENSION, *supra* n.539; 2003 TDD, *supra* n.26 at 8-179.
[563] 33 U.S.C. § 1318(a)(2)(A)(iii); 40 C.F.R. §§ 122.44(i)(1), 122.41(j)(1), 122.48(b); *see also Food & Water Watch,* 20 F.4th at 518; *Wash. State Dairy Fed.*, 18 Wn. App. 2d at 300–03; *see also NRDC*, 808 F.3d at 580–84; *NRDC v. Cnty. of Los Angeles*, 725 F.3d 1194, 1203–10 (9th Cir. 2013).

permit violations, thereby promoting enforcement of the [law]."[564] Accordingly, EPA's NPDES permit writers' manual makes clear that "[m]onitoring is performed to determine compliance with effluent limitations established in NPDES permits."[565] Once collected, monitoring data must be reported to the permitting entity, making the information publicly available via a records request or government website.[566] Without representative monitoring and reporting requirements, regulators and the public are left in the dark as to whether permitted CAFOs are actually complying with applicable effluent limitations and whether particular CAFOs are causing or contributing to exceedances of water quality standards. Mere assumptions that implementing technologies and practices will result in permit compliance are impermissible under the CWA.[567] Nevertheless, the CAFO ELGs do not include specific requirements instructing permittees on how to conduct representative monitoring to determine compliance. EPA should correct this deficiency by incorporating specific monitoring requirements for production areas and land application areas into the CAFO ELGs.

a. Production Areas

As discussed in Sections I and III.D, the current ELGs do not prevent seepage and leachate from lagoons and solid storage areas from infiltrating groundwater, where pollutants may then discharge to surface waters or drinking water sources. Following the Ninth Circuit's opinion on this issue in *Food & Water Watch v. EPA*, EPA revised the NPDES General Permit for CAFOs in Idaho to include a provision requiring that permittees develop a subsurface discharge monitoring plan as part of their NMP.[568] Alternatively, permittees will be excused from the subsurface discharge monitoring plan requirement if (1) they submit documentation from a professional engineer or similarly qualified expert certifying none of the facility's lagoons has any subsurface connection to any water of the U.S., or (2) the CAFO has documentation that each lagoon is constructed of concrete,

[564] *Food & Water Watch*, 20 F.4th at 516 (citing *Sierra Club v. Union Oil Co. of Cal.*, 813 F.2d 1480, 1491 (9th Cir. 1987), *vacated and remanded on other grounds*, 485 U.S. 931 (1988), *and reinstated and amended by* 853 F.2d 667 (9th Cir. 1988)).
[565] CAFO NPDES Permit Writers' Manual, *supra* n.121 at 5-1, 8-2; *see also Food & Water Watch*, 20 F.4th at 516 (explaining that CAFO NPDES permits "fundamentally rel[y] on self-monitoring" because "[e]ffective self-monitoring reveals permit violations, thereby promoting enforcement of the [law].").
[566] 33 U.S.C. § 1318(b).
[567] *NRDC,* 808 F.3d at 565, 583 (striking down a NPDES permit for ballast water from vessels because compliance with that permit's water quality-based effluent limitations was merely assumed from compliance with other permit terms and rejecting U.S. EPA's argument that if a vessel was in compliance with the permit's other effluent limitations, the permittee was "generally expected to already be controlling [its] vessel discharges to a degree that is protective of water quality.").
[568] EPA, PERMIT NO. IDG010000 11–12 (2024).

steel, or has a double synthetic liner with leak detection.[569] In revising the ELGs, EPA must consider including and expanding this requirement to cover solid storage areas such as compost and mortality piles and leachate lagoons in addition to manure storage structures.

CAFOs have many options for subsurface discharge monitoring that could be included as examples of how to develop a satisfactory subsurface discharge monitoring plan. One option is to require a series of groundwater monitoring wells. Monitoring wells are frequently used in other NPDES permits for other categories. Siting one well up-gradient from the production area and other wells down-gradient from the production allows CAFOs, regulatory authorities, and the public to compare data and determine whether the production area is contributing to elevated pollutant levels down-gradient. Another option is to require regular monitoring using lysimeters or interstitial devices.[570] Regardless of the method chosen, monitoring requirements must be accompanied by clear standards for controlling placement of monitoring devices (considering proximity to potential contamination sources and the hydrogeological characteristics of the site), frequency of testing, and stringent reporting requirements, including reporting results through Discharge Monitoring Reports (DMRs) and notices of non-compliance.

b. Land Application Areas

EPA must also consider options to ensure CAFOs monitor discharges from land application areas. In the Idaho permit, EPA required "visual inspection of the downgradient edge of the field and any other potential discharge locations (e.g., tile drains, ditches, or other conveyances) must be conducted during the land application event and after the land application event to check for field runoff and discharges."[571] While this is a step in the right direction that should be incorporated into the ELGs to ensure uniform requirements for CAFOs across the country, flow metering requirements discussed above must also be included to ensure NMP compliance.[572] Additionally, EPA must make clear that the results of visual inspections and flow metering data must be regularly submitted to regulatory authorities as part of a CAFO's discharge monitoring reports.

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[569] *Id.*
[570] EPA, *Release Detection for Underground Storage Tanks (USTs) – Interstitial Method* (April 22, 2025), https://www.epa.gov/ust/release-detection-underground-storage-tanks-usts-interstitial-method.
[571] EPA, PERMIT NO. IDG010000 10.
[572] *See supra* Section IV.B.4.c.

Further, EPA must require monitoring to detect subsurface discharges from land application areas. Even assuming EPA does not correct the agricultural stormwater loophole,[573] EPA's regulations require that a CAFO's NMP "ensure appropriate agricultural utilization of the nutrients in [land-applied] manure, litter, or process wastewater."[574] Nutrients from land-applied waste that seep below a crop's root zone cannot be appropriately utilized,[575] indicating the CAFO applying the waste is either not following its NMP—a permit violation meriting enforcement action—or that the CAFO must revise its NMP (such as by lowering application rates or specifying operational practices to avoid cracks or other preferential flow paths) in order to comply with federal law. Under the existing regulatory regime, permitting authorities have no way of knowing whether subsurface land application area discharges are occurring. Thus, this regulatory structure does not "assure compliance with permit limitations," as required by law.[576] To correct this deficiency, EPA should consider requiring CAFOs to conduct representative subsurface monitoring of land application areas using readily available soil moisture probes or lysimeters installed to measure moisture below crop roots.[577] Monitoring and reporting soil moisture below the root zone would help safeguard water quality by providing regulatory agencies and the public with data necessary for EPA to effectively review and revise the ELGs going forward, as well as to facilitate enforcement against CAFOs that over- or mis-apply waste.

V. Conclusion

The evidence is clear: EPA's existing regulatory regime has utterly failed to control water pollution from CAFOs. This decades long failure has led to devastating impacts for frontline communities, agricultural workers, and the environment. But even as EPA has allowed CAFO pollution discharges to proliferate, technologies and practices capable of controlling those discharges have emerged. With information and data supporting the efficacy of these methods now squarely before the Agency, EPA must act. It is time for EPA's regulation of the CAFO industry to finally catch up to its statutory obligations under the CWA.

As demonstrated by many of the studies described in this memo and provided to the Agency, many CAFOs are already achieving pollutant reductions using widely available technologies. EPA

[573] *See* 2017 PETITION, *supra* n.5 at 22–25 (describing how the agriculture stormwater exemption has severely undercut EPA's ability to adequately regulate CAFOs).
[574] 40 C.F.R. § 122.42(e)(1)(viii).
[575] As discussed elsewhere in this memo, CAFO waste contains numerous pollutants that provide no benefit to crops at any application rate. Waste must be treated to reduce or remove these pollutants prior to land application.
[576] *Id.* §§ 122.44(i)(1), 122.41(j)(1).
[577] Erickson Report, *supra* n.18 at 10–11.

must use this information to create ELGs that prohibit practices known to cause discharges and control all pollutants and pathways of concern. Further, EPA must maximize pollution controls by subcategorizing the CAFO industry such that facilities generating and handling the largest amounts of dangerous waste and those sited in geographically vulnerable locations are subjected to the most stringent controls. Anything less is contrary to the CWA and undermines EPA's mission to protect human health and the environment.

Respectfully submitted,

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The EPA's Failure to Track Factory Farms

Issue Brief • August 2013

Executive Summary

Concentrated animal feeding operations (CAFOs) are facilities that raise large numbers of livestock in confined conditions, leading to high concentrations of manure and water pollution. In the spring of 2013, the U.S. Environmental Protection Agency (EPA) released documents in response to a Freedom of Information Act (FOIA) request that detailed the EPA's internal process for proposing a CAFO reporting rule, known as the "308 Rule" under Section 308 of the Clean Water Act (CWA).

The 308 Rule would have required all CAFOs nationwide to submit basic information to the EPA, including: the owner name and contact information, the location as defined by latitude and longitude or street address, the National Pollutant Discharge Elimination System (NPDES) permit coverage, the maximum number and type of each animal in confinement, and the acres of land available for land application of manure. The EPA proposed the rule in October 2011 and withdrew it under industry pressure in July 2012.

The documents provided through the FOIA request reveal the EPA's failure to collect data about CAFOs across the nation as well as critical weaknesses in the CAFO permitting process.

Permitting Is Incomplete: As of 2011, the EPA estimated that only 41 percent of NPDES-defined CAFOs actually had NPDES permits.

Records Are Scattered and Incomplete:

- 22 states submitted CAFO records to the EPA's internal Integrated Compliance Information System database. Nine of those states had significant records shortfalls.
- 15 states had no CAFO data available in any EPA system or via other electronic public access.

State Permitting Regulations Are Outdated: As of the EPA's reporting in 2011, only 32 percent of the 38 states that granted permits for CAFOs had up-to-date regulations. Nearly half of permitting states met only a decade-old standard, and 16 percent did not even meet that standard.

Neither the EPA nor any other federal agency collects comprehensive data on the number of CAFOs or their size or location. This lack of data impairs the EPA's ability to enforce permitting requirements, identify sources of severe water quality problems, and evaluate CAFOs' overall impact on water quality. The EPA has facility-specific information for other point source polluting industries and shares that information in public databases, such as the Toxics Release Inventory, but the agency has not achieved the same level of transparency for CAFOs.

The proposed 308 Rule would have required all CAFOs nationwide to submit basic information to the EPA, such as the location, contact information, number and type of animals, permit status, and land available for waste application. The EPA inexplicably withdrew the 308 Rule, claiming that the agency would rely on existing data sources, but this analysis demonstrates that those sources are weak and incomplete.

The EPA's own findings contradict its rationale for withdrawing the 308 Rule, and the EPA does not otherwise justify its change in position. That's why Food & Water Watch, Iowa Citizens for Community Improvement, the Environmental Integrity Project, the Center for Food Safety and the Humane Society of the United States are suing the EPA to force it to do what it should have done in the first place: create an accurate, publicly available database of all CAFOs in the United States.



Introduction

In the spring of 2013, three environmental organizations obtained documents from the U.S. Environmental Protection Agency (EPA) through the Freedom of Information Act (FOIA). The documents related to the EPA's process of gathering data about concentrated animal feeding operations (CAFOs). Those documents were shared with several organizations, including Food & Water Watch. On April 4, 2013, the EPA took the uncharacteristic move of asking for the original set of documents back due to pressure from the livestock industry and Congress, offering a limited subset of the documents as a replacement.[1] Food & Water Watch declined to return the original documents to the EPA.

CAFOs are facilities that raise large numbers of livestock in confined conditions, leading to high concentrations of waste and water pollution.[2] The documents obtained from the FOIA request detailed the EPA's recent rulemaking process, known as the "308 Rule," that would have required basic data collection about CAFOs under Section 308 of the Clean Water Act (CWA). These hundreds of documents provided from the FOIA request reveal the EPA's failure to collect data about these large industrial livestock facilities across the nation as well as weaknesses in the CAFO permitting process.

The release of documents was met with outraged responses from meat industry and livestock organizations, which claimed violations of privacy.[3] These organizations have missed the point: CAFOs discharge pollutants into national waters, and they should be treated like any other polluting facility under the CWA. Federal regulation should include National Pollution Discharge Elimination System (NPDES) permits for all CAFOs and create a public national database with basic information about the ownership, operation and location of these facilities and their scale. Releasing this data should not be controversial. But to make matters worse, the EPA has failed for decades to even collect it, under pressure from the livestock and poultry industry to hide their facilities from public view.

Food & Water Watch, Iowa Citizens for Community Improvement, the Environmental Integrity Project, the Center for Food Safety and the Humane Society of the United States are suing the EPA to force it to do what it should have done in the first place: create an accurate, publicly available database of all CAFOs in the United States. It is impossible to regulate CAFO facilities effectively without even compiling a list of how many exist. The EPA should reissue the 308 Rule as a critical step in reducing pollution from CAFOs.

CAFOs Are a Major Source of Water Pollution

According to the EPA, agriculture remains a major source of water pollution.[4] States have identified animal feeding operations specifically as the polluters of almost 20,000 miles of rivers and streams and over 250,000 acres of lakes, reservoirs and ponds.[5] While livestock waste in appropriate quantities can serve a useful purpose as fertilizer for crops, the huge concentration of animals in CAFOs leads to excessive concentrations of waste.[6] Large-scale commercial livestock and poultry operations produce an estimated 500 million tons of manure each year, more than three times the sewage produced by the entire U.S. human population.[7] Yet, unlike human waste, livestock waste from CAFOs is untreated and is usually applied directly to fields as fertilizer, often at rates that exceed those necessary to fertilize crops.[8]

Many studies have found that CAFO waste contaminates nearby bodies of water with numerous pollutants, including nitrogen, phosphorus, hormones, antibiotics and pathogens.[9] According to the Government Accountability Office (GAO), "manure and wastewater from animal feeding operations can adversely impact water quality through surface runoff and erosion, direct discharges to surface water, spills and other dry-weather discharges, and leaching into the soil and groundwater."[10]

History of Weak Regulations and Poor Tracking

The CWA, passed in 1972, gave the EPA the authority to regulate any entity discharging pollution into national waterways, including CAFOs. The EPA has considered CAFOs a "point source" of water pollution since the 1970s.[11] The EPA initially focused its efforts on industrial sites and sewage treatment plants, leaving CAFOs virtually unregulated for years.[12] The EPA began requiring National Pollutant Discharge Elimination System (NPDES) permits for some CAFOs in 2003, with revisions made to the regulations in 2008.[13]

The permits, issued by the EPA or a state agency under the EPA's authority, set "specific limits and conditions" on how CAFOs discharge waste into local bodies of water.[14] The 2008 CAFO regulations include significant weaknesses, foremost among them relying on individual CAFO operators to determine if they discharge or intend to discharge and thus whether they should apply for a permit.[15] According to a 2003 GAO report, however, "EPA officials believe that most large operations either discharge or have a potential to discharge animal waste to surface waters and should have discharge permits."[16]

Just as worrisome as the inconsistent permitting is the lack of information the EPA possesses about CAFOs. Neither the EPA nor any other federal agency collects comprehensive data on the number of CAFOs or their size or location. Without that information, the EPA simply cannot regulate CAFOs effectively.[17] The lack of data affects the EPA's ability to enforce permitting requirements, identify sources of severe water quality problems, evaluate CAFOs' overall impact on water quality and promote best management practices on CAFOs.[18] Attempts by the EPA to mitigate this situation, such as compiling estimates based on NPDES permits issued to CAFOs, have



not been successful.[19] The GAO recommended in 2008 that the EPA "complete its efforts to develop a comprehensive national inventory of permitted CAFOs and incorporate appropriate internal controls to ensure the quality of the data."[20]

Counting CAFOs: The Proposed CAFO Reporting Rule (308 Rule)

The 2008 CAFO permitting rules changed the legal threshold for when a CAFO must apply for an NPDES permit. The EPA left it up to CAFO operators to determine, and thereby limited the number of CAFOs likely to obtain NPDES permits.[21] As a result, those CAFOs not seeking permits would not have to provide basic information to their state permitting authority or the EPA through the permitting process.

Several environmental organizations filed a lawsuit against the EPA to challenge the 2008 CAFO rule. As part of the Settlement Agreement, the EPA agreed to propose a CAFO information collection rule under Section 308 of the CWA.[22] The Proposed CAFO Reporting Rule ("308 Rule") acknowledged the shortcomings of the EPA's data collection, including the impossibility of ensuring compliance with the law without that data.[23] The EPA also notes, "*unlike many other point source industries*, EPA does not have facility-specific information for all CAFOs in the United States" (emphasis added).[24] In other words, it is possible for the agency to collect such information for polluting facilities. It simply hasn't been done for CAFOs.

On October 21, 2011, the EPA published the 308 Rule, which included two potential EPA actions to collect information from CAFOs. The first proposal would have required all CAFOs nationwide to submit basic information to the EPA; the second proposal would have required the EPA to select focus watersheds and then request basic information from CAFOs located in those watersheds. The EPA also solicited comments on alternative ways for the agency to obtain the necessary information about CAFOs and meet the objectives of the 308 Rule.[25] The Settlement Agreement required data to be collected on up to14 areas of interest, but the rule covered only five because the EPA considered the other information to be obtainable from other sources.[26] The EPA estimated that approximately 20,000 facilities would have had to report information under the 308 Rule.[27]

Withdrawal of the Rule

Instead of following through and finalizing the rule, however, the EPA punted by withdrawing the rule in July 2012. In the official withdrawal notice, the EPA claims that the agency will use "existing sources of information, including state NPDES programs, other regulations, and other programs at the federal, state, and local level," [28] but as our analysis of EPA

documents obtained through the FOIA request demonstrates (and the EPA already stated in the original 308 Rule), those sources are woefully inadequate. By bailing on the 308 Rule, the EPA maintains the status quo of not even knowing how many CAFOs there are in the United States.

CAFO Data: Incomplete and Disorganized

NPDES Permit Shortfalls

The EPA is supposed to regulate CAFOs under the CWA. The EPA delegates its authority to the states, which are supposed to issue permits to CAFOs. The resultant patchwork system is ineffective at best, with most CAFOs operating without permits. According to an EPA file dated the end of 2011, an estimated 41 percent (approximately 7,600 out of 18,500) of NPDES-defined CAFOs actually had NPDES permits. At the state level, the estimated number of permitted CAFOs ranges from 0 to 100 percent. Thirteen states reported permitting fewer than 10 percent of estimated CAFOs, including states with large numbers of CAFOs such as Iowa, Illinois, North Carolina, Arkansas and Oklahoma.[29]

But it appears that the problem is even more fundamental than failure to regulate these facilities. Food & Water Watch's analysis of the FOIA documents reveals broad gaps in the EPA's knowledge of even the most basic information about CAFOs. According to EPA estimates from 2011, there are just over 18,500 "facilities defined as CAFOs under NPDES." Yet, another document with estimates from the U.S. Department of Agriculture (USDA) indicates the number of large and medium-sized CAFOs to be much higher, just over 47,000 facilities.[30]

An internal EPA draft, "Charting the CAFO Universe," indicates that current sources of data about CAFOs are incomplete. The USDA Census of Agriculture, for instance, collects cumulative data by county, but it does not provide site-specific information.[31] States that implement NPDES permits must provide that information to the EPA, but only eight states were known for certain to collect all the information covered in the 308 Rule.[32] Not all states submitted data into the Integrated Compliance Information System (ICIS), the EPA's electronic database of NPDES-permitted CAFOs, or even maintain records in an electronic form at all.[33] And while data on NPDES-permitted CAFOs is useful, it does not address the problem of identifying and permitting unpermitted CAFOs.

CAFO Records by Source

The EPA analyzed CAFO records from various sources as part of the preparation for the 308 Rule. The agency found that only 22 states submitted files for the EPA's ICIS database. The ICIS data is available only to the EPA and other government officials.[34] In the public domain, 11 states submitted files to the EPA's Enforcement and Compliance History Online (ECHO) system, and 21 states have CAFO records available on the Internet on sites other than ECHO. The EPA reports that 15 states have no CAFO data available in ICIS, ECHO or via other electronic public access.[35] (See Figure 1.)

ICIS: The EPA's Internal Database

Twenty-two states have CAFO records in the EPA's ICIS database. These records contain information about NPDES-permitted CAFOs, not unpermitted CAFOs. According to ICIS data from May 2010, 40 percent of states with CAFO records in ICIS had fewer files in the system than their total number of NPDES-permitted CAFOs. The total estimated shortfall is nearly 2,500 CAFO records.[36] (See Figure 2.)

Figure 1: Data Sources for CAFO Records

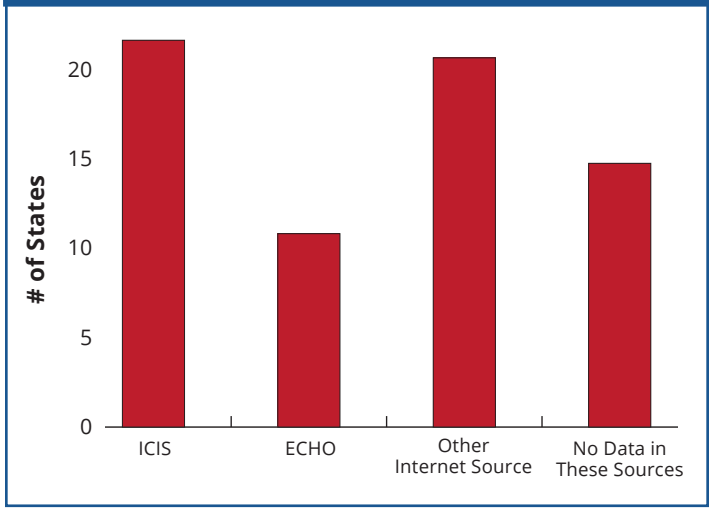

Because some states are in more than one system, the total number of states is greater than 50.

Figure 2: CAFO Records Shortfalls in ICIS

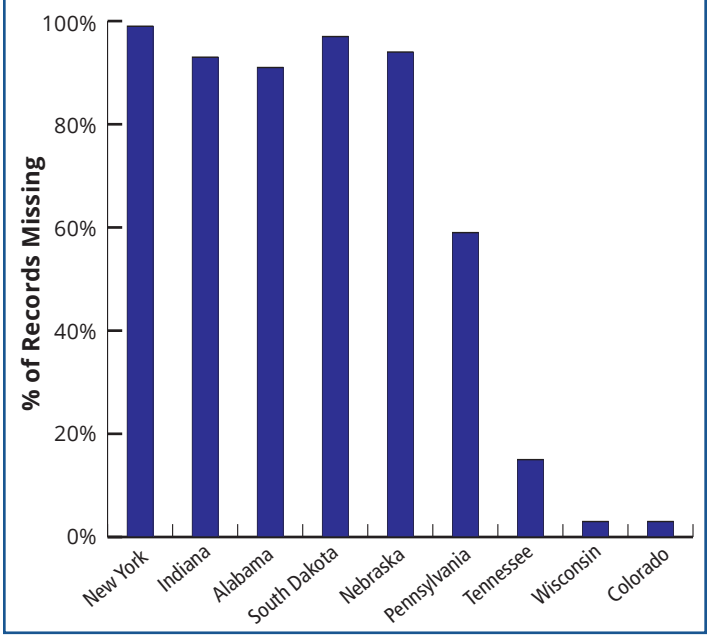

The number of NPDES-permitted CAFOs per state is as reported by EPA Regional Offices.

Data Source, Fig. 1 and 2: Food & Water Watch analysis of data in documents released through Freedom of Information Act, on file at Food & Water Watch.

ECHO and Other Public Sources

The FOIA records included a separate analysis by the EPA of the CAFO records available in the public domain, including ECHO and other Internet sources. Thirty-two states had CAFO records publicly available. The EPA did not compare the number of CAFO records in these sources against the estimated universe of CAFOs or total NPDES-permitted CAFOs from these states, so it is unclear if the number of CAFO records in each file is complete. No set of records contained all five areas of interest listed in the 308 Rule.[37] Those include: owner name and contact information, location as defined by latitude and longitude or street address, NPDES permit coverage, maximum number and type of each animal in confinement, and acres of land available for land application of manure.[38] (See Figure 3.)

Food & Water Watch's analysis of files of records contained in the FOIA documents found inconsistencies with the EPA's analysis, which reinforces the need for a centralized set of records.[39]

The EPA's Reliance on States Is Insufficient

When withdrawing the proposed 308 Rule, the EPA stated that it could gather data necessary to regulate CAFOs from existing state records. Relying on states for accurate data presents challenges not only because of inconsistent permitting and data collection, but also because the states' NPDES permitting requirements are in most cases not up to date. Of the 38 states that permit CAFOs, their regulations vary in what set of federal CAFO permitting rules they meet. As of the EPA's reporting in 2011, just under a third of permitting states have up-to-date NPDES permitting regulations. Nearly half of permitting states meet only a decade-old standard, and 16 percent do not even meet that standard.[40] (See Figure 4 on page 6.)

States' comments on the 308 Rule reveal conflicting approaches to collecting CAFO data, and even hostility on the part of some states to sharing information with the federal government. On one hand, as the EPA reported, "Generally, state and state association commenters questioned the need for new regulations in light of states already having the information the EPA was seeking by virtue of existing CAFO programs at the state and local level."[41] These claims of having complete information are patently false given that state NPDES-permitting programs lack information for *unpermitted* CAFOs.

The completeness of the data notwithstanding, states expressed a variety of other concerns should the rule be finalized. Comments from states included concerns about the burden of implementing the rule, about data collection serving as a distraction from permitting tasks, about the EPA's authority to require information sharing from the states, and about CAFO operators' privacy.[42] In comments from the South Dakota Secretaries of Environment and Natural Resources and Agriculture, the state officials bold-

Figure 3: CAFO Record Details in Publicly Available Sources

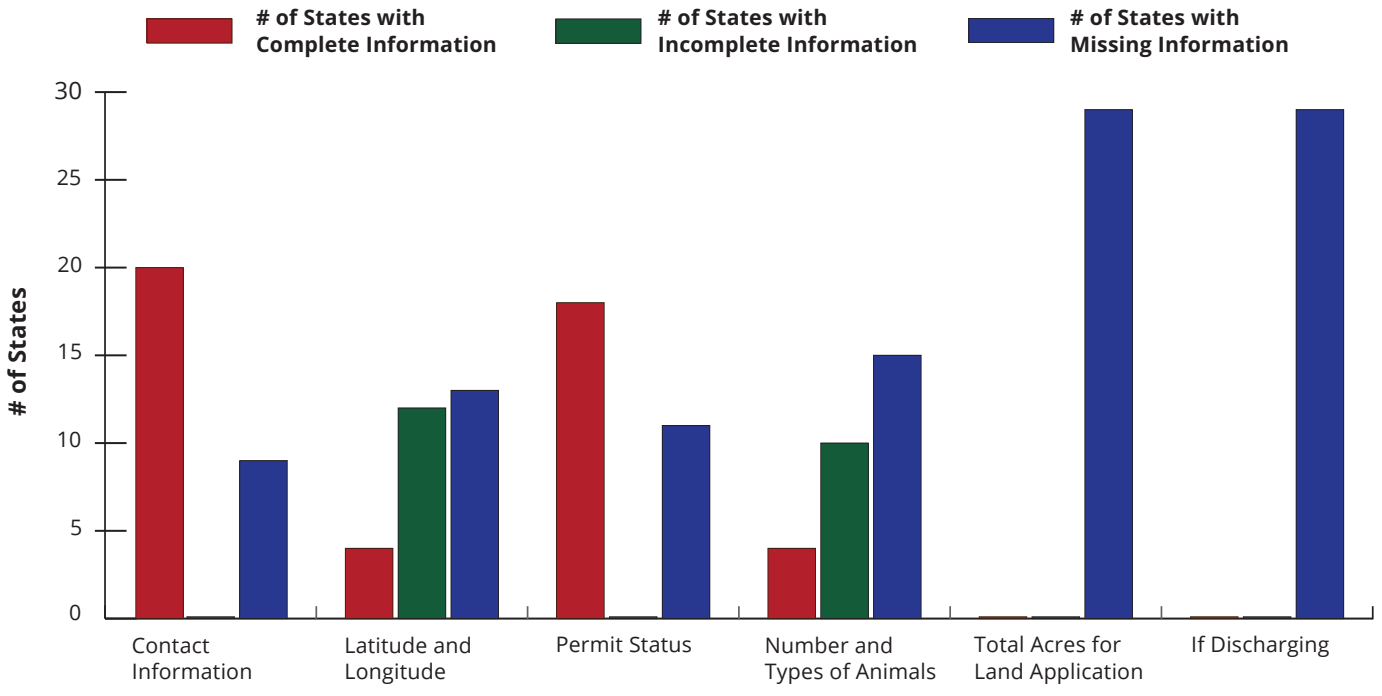

Three states did not provide information on what data their records contained.
Data Source: Food & Water Watch analysis of data in documents released through Freedom of Information Act, on file at Food & Water Watch.

Figure 4: Status of State Permitting Regulations

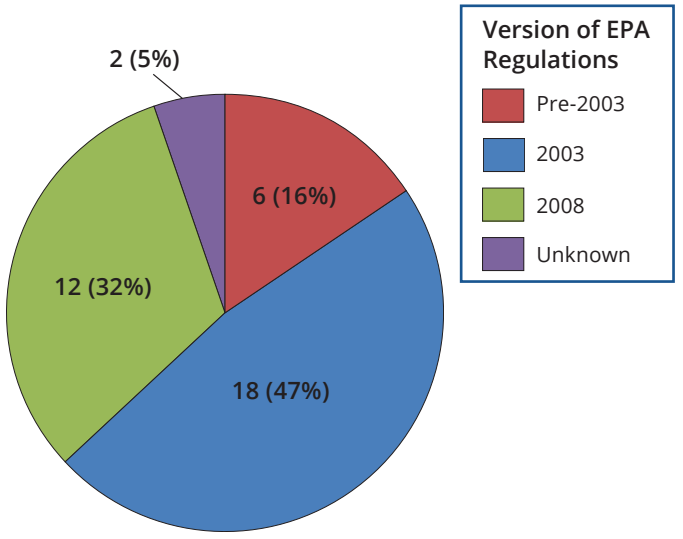

Data Source: Food & Water Watch analysis of data in documents released through Freedom of Information Act, on file at Food & Water Watch.

ly declare, "we will not provide this information to EPA unless South Dakota producers request us to do this for them," but they indicate that anyone can come in person to the Department of Environment and Natural Resources office during regular business hours to see the paper files should they be so motivated.[43]

The 308 Rule withdrawal notice indicates that the EPA signed a Memorandum of Understanding (MOU) with the Association of Clean Water Administrators (ACWA) to facilitate collection of existing CAFO data from the states.[44] Notably, the ACWA "urged EPA not to finalize the rule."[45] According to the final MOU, the ACWA will "foster a dialogue between the EPA and ACWA members to facilitate the exchange of information."[46] It is unclear how such an effort is any more likely to yield a comprehensive database of CAFOs than a finalized rule. The MOU neither meets the terms of the Settlement Agreement nor furthers the collection and publication of CAFO records.

In July 2013, the EPA proposed a new rule that would require that all reports from NPDES-permitted CAFOs be submitted electronically with the goal of greater transparency as well as cost savings for state governments.[47] While a useful step, this new proposed rule does not adequately replace the provisions of the withdrawn 308 Rule.

Privacy Concerns and CAFO Data in the Public Domain

Livestock and poultry organizations and some members of Congress have raised concerns about releasing the business locations of CAFOs to the public.[48] Eight industry trade groups, including the American Farm Bureau, National Cattlemen's Beef Association and National Pork Producers, wrote to the EPA to express "deep concern" and "outrage" over perceived violations of personal privacy due to the FOIA release.[49] The industry groups assert that releasing data about CAFOs threatens farm families and increases the risk of bioterrorism against the food supply.[50] A letter from the Republican senators on the Environment and Public Works Committee shares similar rhetoric about the FOIA release, claiming that the EPA "has shown no regard for the privacy and safety of private citizens, and businesses" (sic).[51]

These claims simply do not bear out in real life, as information about individual CAFOs, including location, already exists in the public domain. In a written response to Congressional questions at an oversight hearing, the EPA noted that: "[T]here is an extensive amount of CAFO facility-specific location information already available on the Internet from certain State permitting programs that provide the facility's name, city, and animal numbers, as well as maps with location data on individual CAFOs. EPA is not aware of instances where such publicly available information has put CAFO owners and operators at risk."[52]

Iowa offers one example of a state with many CAFOs that provides public information about them on the Internet. The Iowa Department of Natural Resources Animal Feeding Operations database contains many of the areas of interest from the 308 Rule, including owner name, facility location, number and type of animals, and whether or not the facility has an NPDES permit.[53] The database includes the NPDES permit number and expiration date for those that have permits.

Additionally, Iowa reports compliance information in this database, allowing community members to examine any violations attributed to nearby facilities.[54] While Iowa faces problems with its CAFO regulation system,[55] Iowa's database demonstrates a significant level of transparency that already exists in a state with a large number of CAFOs. North Carolina, another state with high numbers of CAFOs, offers a map of its livestock facilities along with permitting information.[56]

Livestock and poultry organizations claim that CAFO locations should not be released because the operators and their families often live at or near the facilities.[57] In effect, the industry is asking for special treatment, but having any home-based business can come at some cost to family privacy.[58] Other home-based businesses are not hidden from public scrutiny. For instance, in nearly all states, in-home child-care providers must obtain a license and be inspected regularly.[59]

CAFOs have the potential to discharge large volumes of waste into local bodies of water. Any facility with the potential for such pollution deserves public scrutiny. Consider the case of Freedman Farms in Columbus County, North Carolina. Its operator intentionally released over 324,000 gallons of untreated hog waste into a stream over the course of a few days, an action so egregious it yielded over a million dollars in fines and a jail sentence.[60]

In northwest Iowa in 2010, the EPA took legal action against several medium-sized, unpermitted beef CAFOs that discharged manure into impaired creeks in violation of the CWA. The EPA required that these facilities obtain NPDES permits and improve their facilities to manage wastewater.[61]

Without permits, these CAFOs fell through the regulatory cracks until their polluting activities were so egregious as to attract notice. Claims of personal privacy ring hollow against the potential for and actual ecological damage that occurs through CAFO discharges.

EPA Provides Complete, Public Information for Other Polluting Industries

Toxics Release Inventory Program

In order to understand just how unregulated CAFOs are, it is useful to consider how other industries that generate pollutants are regulated. The EPA's Toxics Release Inventory Program (TRI) monitors the release of toxic industrial chemicals through annual self-reporting of the amount of chemicals released into the air, water or land, including off-site pollution. The TRI monitors over 650 of the toxic industrial chemicals with negative health or environmental impacts used in the United States.[62] These chemicals include those found in CAFO waste, including nitrogen compounds that lead to nitrate in water and phosphorous.[63]

A wide range of manufacturing facilities must report their use of toxic chemicals, but not CAFOs, where the pollutants occur in livestock waste.[64] The TRI Program monitors pollutant releases from animal slaughtering and meat processing facilities,[65] but not pollutants generated throughout the animals' lives in CAFOs. It monitors dairy product manufacturing,[66] but not raising dairy cattle in confinement and managing the resulting waste. It monitors fertilizer manufacturing,[67] but not CAFOs, whose livestock generate gallons upon gallons of animal waste used as fertilizer.

The nearly 21,000 TRI facilities reported 4.09 billion pounds of industrial chemicals released in 2011. Sixty percent was disposed of on land on-site; 5 percent was disposed of in on-site surface water discharges.[68] Most CAFO waste is applied to land as fertilizer, yet the EPA does not track applications directly.

The TRI makes polluting industries' data publicly available.[69] The average citizen can locate polluting industries in their state, county or zip code with an interactive map and information about the types and quantities of toxic chemicals released. Individuals can search by geographic location, by chemical or by industry.[70] Fact sheets include the top polluters, the most common pollutants, amounts of pollutants and how the pollutants are disposed of.[71] The maps include direct links to profiles of each facility including name, TRI identification number,



address, latitude and longitude, phone number and toxic release data submitted to the EPA[72] — in other words, the very type of data that the EPA does not have in complete form for CAFOs, let alone in a publicly available electronic database.

Efforts to Reinstate the 308 Rule

When the EPA proposed the 308 Rule, the agency lacked basic information about the number and scale of CAFOs across the United States. Since the EPA abandoned its rule-making process, the agency remains in the exact same position.

While proposing a rule does not obligate the EPA to adopt it, the law states that the EPA may not withdraw the rule without reasoned justification.[73] The EPA's own findings contradict its rationale for withdrawing the 308 Rule, and the EPA does not otherwise justify its change in position. That's why Food & Water Watch, in partnership with Iowa Citizens for Community Improvement, the Environmental Integrity Project, the Center for Food Safety and the Humane Society of the United States, are suing the EPA to force it to do what it should have done in the first place: create an accurate, publicly available database of all CAFOs in the United States. It is long past time that CAFOs be treated like any other polluting industry and be held fully accountable for their discharges. Reinstating the 308 Rule is an important step toward that goal.

Endnotes

1 Stoner, Nancy. Acting Assistant Administrator, U.S. Environmental Protection Agency (EPA). "Amended Freedom of Information Act Response #2012-1337 and 2012-1516." April 4, 2013; Peterka, Amanda. "EPA: Enviro groups return CAFO data at heart of Hill probes." *E&E Daily*. April 11, 2013.

2 EPA, Office of Water, Office of Wastewater Management. "NPDES Permit Writer's Manual for Concentrated Animal Feeding Operations." (EPA 833-F-12-001.) February 2012 at 2-1; Government Accountability Office (GAO). "Concentrated Animal Feeding Operations: EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern." (GAO-08-944.) September 2008 at 5 to 6.

3 Peterka. April 11, 2013.

4 EPA. "Protecting Water Quality from Agricultural Runoff." March 2005. Available at http://www.epa.gov/owow/nps/Ag_Runoff_Fact_Sheet.pdf. Accessed August 19, 2013.

5 EPA. Water Quality Assessment and Total Maximum Daily Loads Information. Available at http://www.epa.gov/waters/ir/. Accessed July 2013.

6 GAO. 2008 at 5.

7 Pew Commission on Industrial Farm Animal Production. "Putting meat on the table: industrial farm animal production in America." April 2008 at 23.

8 Seely, Ron. "Who's watching the farm?" *Wisconsin State Journal*. February 28, 2010; GAO. 2008 at 1 to 2.

9 GAO. 2008 at 6, 10, 20, 70 to 73.

10 *Ibid.* at 9.

11 EPA. February 2012 at 2-1.

12 GAO. "Increased EPA Oversight Will Improve Environmental Program for Concentrated Animal Feeding Operations." (GAO-03-285.) January 2003 at 2, 9 to 10.

13 EPA. "Concentrated Animal Feeding Operations Final Rule Making – Fact Sheet." October 2008. Available at http://www.epa.gov/npdes/pubs/cafo_final_rule2008_fs.pdf. Accessed August 14, 2013.

14 GAO. 2008 at 9.

15 EPA. October 2008.

16 GAO. 2003 at 7.

17 GAO. 2008 at 4 to 5.

18 EPA. "Proposed National Pollutant Discharge Elimination System Concentrated Animal Feeding Operation Reporting Rule." Questions and Answers. October 2011. Available at http://www.epa.gov/npdes/pubs/2011_npdes_cafo_qa.pdf. Accessed August 21, 2013.

19 GAO. 2008 at 8.

20 *Ibid.* at 48.

21 EPA. October 2008.

22 76 Fed. Reg. 65435. (October 21, 2011).

23 *Ibid.* at 65431.

24 *Ibid.* at 65436.

25 *Ibid.* at 65431.

26 *Ibid.* at 65435 to 65437, 65439.

27 EPA. "Hearing Questions for the Record (QFR) Prepared for the Environmental Protection Agency, Administrator Lisa Jackson from Chairman Simpson." EPA FY 13 Budget Oversight. February 29, 2013. Documents released through Freedom of Information Act, on file at Food & Water Watch.

28 77 Fed. Reg. 42679. (July 20, 2012).

29 Food & Water Watch analysis of data in documents released through Freedom of Information Act, on file at Food & Water Watch.

30 *Ibid.*

31 EPA. "Characterizing the CAFO Universe – Strategy to Obtain CAFO Information." (Draft). March 1, 2013 at 6 to 7. Documents released through Freedom of Information Act, on file at Food & Water Watch.

32 *Ibid.* at 8 to 9.

33 *Ibid.* at 9, 13 to 14.

34 EPA. "The Integrated Compliance Information System (ICIS)." Available at www.epa.gov/compliance/data/systems/icis. Accessed July 10, 2013.

35 Food & Water Watch analysis of data in documents released through Freedom of Information Act, on file at Food & Water Watch.

36 *Ibid.*

37 *Ibid.*; 76 Fed. Reg. 65437. (October 21, 2011).

38 76 Fed. Reg. 65437. (October 21, 2011).

39 Food & Water Watch analysis of data in documents released through Freedom of Information Act, on file at Food & Water Watch.

40 *Ibid.*

41 77 Fed. Reg. 42681. (July 20, 2012).

42 EPA. "Detailed Significant State Comments." Undated; EPA. "Summary of Major Comments on the proposed NPDES CAFO Reporting Rule." February 3, 2012. Documents released through Freedom of Information Act, on file at Food & Water Watch.

43 Pirner, Steven and Walt Bones. South Dakota Departments of Environment and Natural Resources and Agriculture. Comment on proposed National Pollutant Discharge Elimination System Concentrated Animal Feeding Operation Reporting Rule. December 22, 2011. Documents released through Freedom of Information Act, on file at Food & Water Watch.

44 77 Fed. Reg. 42681. (July 20, 2012).

45 EPA and Association of Clean Water Administrators (ACWA). "Memorandum of Understanding Between the U.S. Environmental Protection Agency and Association of Clean Water Administrators: Collaborative Efforts to Collect and Exchange Information about Confined Animal Feeding Operations." July 7, 2012. Documents released through Freedom of Information Act, on file at Food & Water Watch.

46 Dunn, Alexandra Dapolito, and Sean Rolland. E-mail to ACWA Members. Subject: "High Priority: ACWA MOU with EPA on CAFO Inventory & Data." July 19, 2012. Documents released through Freedom of Information Act, on file at Food & Water Watch.

47 78 Fed. Reg. 46007-8. (July 30, 2013).

48 American Farm Bureau Federation et al. Letter to Acting EPA Administrator Bob Perciasepe. Undated. Available at http://www.nationalchickencouncil.org/wp-content/uploads/2013/03/cwa-foia13.0222.pdf. Accessed August 19, 2013; Vitter, David et al. Letter to EPA Acting Administrator Bob Perciasepe. April 4, 2013. Available at http://www.epw.senate.gov/public/index.cfm?FuseAction=Files.View&FileStore_id=29622852-f843-4442-8e07-10c291c9889a. Accessed August 19, 2013.

49 American Farm Bureau Federation et al.

50 *Ibid.*; Peterka. April 11, 2013.

51 Vitter, David et al.

52 EPA. February 29, 2013.

53 76 Fed. Reg. 65437. (October 21, 2011); Iowa Department of Natural Resources. Animal Feeding Operations Database. Available at https://programs.iowadnr.gov/animalfeedingoperations. Accessed August 21, 2013.

54 Iowa Department of Natural Resources. Animal Feeding Operations Database.

55 Iowa Department of Natural Resources. "Response to U.S. EPA Region 7." September 2012. Available at http://www.iowadnr.gov/Portals/idnr/uploads/afo/files/dnrresponse-cafo0912.pdf. Accessed August 21, 2013.

56 *See:* North Carolina Department of Natural Resources. Animal Feeding Operations Unit: Facility Map. http://portal.ncdenr.org/web/wq/animal-facility-map. Accessed August 23, 2013.

57 American Farm Bureau Federation et al.

58 McConnon, Jim. "Bulletin #4190, Starting a Business in Your Home: Weighing the Pros and Cons." University of Maine Cooperative Extension. 2000. Available at http://extension.umaine.edu/publications/4190e. Accessed August 20, 2013.

59 Beale, Henry B.R. "Home-Based Business and Government Regulations." Small Business Administration. February 2004 at 63 to 65.

60 Blythe, Anne. "$1 million from hog farm case to help Waccamaw River." *News Observer*. July 25, 2012.

61 EPA. [Press release]. "Eight Beef Feedlots in Northwest Iowa Face Enforcement Actions as EPA Emphasizes Compliance with Clean Water Act." August 12, 2010.

62 EPA. "2011 Toxics Release Inventory: National Analysis Overview." January 2013 at 3 to 4.

63 EPA. "Toxic Chemical Release Inventory Reporting Forms and Instructions (Revised 2012 Version): Section 313 of the Emergency Planning and Community Right-to-Know Act." (EPA 260-R-13-001.) February 2013 at II-2, II-3, and II-9; GAO. 2008 at 6, 10, 20, 70 to 73.

64 EPA. February 2013 at I-1 to II-20.

65 *Ibid.* at I-2.

66 *Ibid.* at I-1.

67 *Ibid.* at I-7.

68 EPA. January 2013 at 4.

69 EPA. February 2013 at 6.

70 EPA. TRI Explorer. Available at http://iaspub.epa.gov/triexplorer/tri_release.chemical. Accessed July 30, 2013.

71 EPA. "2011 Summary of TRI Information for Marion County, IN." Available at http://iaspub.epa.gov/triexplorer/tri_release.chemical. Accessed August 1, 2013.

72 EPA. "Facility Profile Report: Best-Ever Dairy Products." Available at http://iaspub.epa.gov/triexplorer/tri_release.chemical. Accessed August 1, 2013; EPA. "2011 Summary of TRI Information for Marion County, IN." Available at http://iaspub.epa.gov/triexplorer/tri_release.chemical, accessed August 1, 2013.

73 See *Int'l Union, United Mine Workers of America v. U.S. Dept. of Labor,* 358 F.3d at 44 (citing *Williams Natural Gas Co. v. FERC,* 872 F.2d 438, 443-44 (D.C. Cir. 1989), addressing an agency withdrawal of a proposed regulation and holding that the Mine Safety and Health Administration could not terminate a proposed rulemaking with no justification.

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TACKLING CLIMATE CHANGE THROUGH LIVESTOCK

A GLOBAL ASSESSMENT OF EMISSIONS AND MITIGATION OPPORTUNITIES

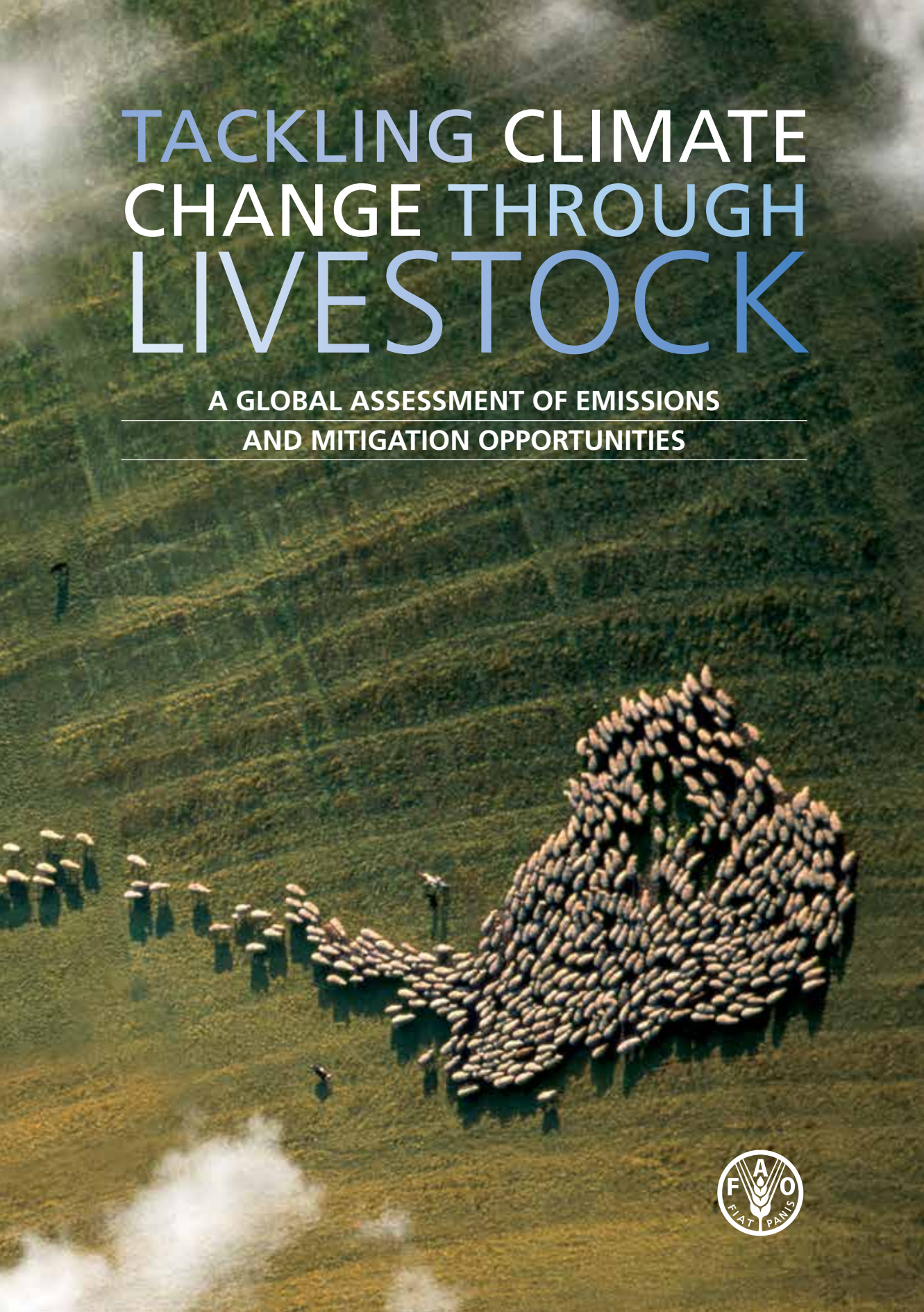

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A GLOBAL ASSESSMENT OF EMISSIONS AND MITIGATION OPPORTUNITIES

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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THE AGGREGATE PICTURE

3.1 OVERALL EMISSIONS

Important contribution to total human-induced emissions

Total GHG emissions from livestock supply chains are estimated at 7.1 gigatonnes CO_2-eq per annum for the 2005 reference period. They represent 14.5 percent of all human-induced emissions using the most recent IPCC estimates for total anthropogenic emissions (49 gigatonnes CO_2-eq for the year 2004; IPCC, 2007).

This absolute figure is in line with FAO's previous assessment, *Livestock's long shadow*, published in 2006 (FAO, 2006), although it is based on a much more detailed analysis involving major methodological refinements and improved data sets (Chapter 2). Relative contributions cannot be compared because reference periods differ. The 2006 assessment compared its estimate (based on a 2001 to 2004 reference period) with the total CH_4, N_2O and CO_2 anthropogenic emissions estimate provided by the World Resource Institute (WRI) for the year 2000.

Methane: the most emitted gas

About 44 percent of the sector's emissions are in the form of CH_4. The remaining part is almost equally shared between N_2O (29 percent) and CO_2 (27 percent). Livestock supply chains emit:[9]

- 2 gigatonnes CO_2-eq of CO_2 per annum, or 5 percent of anthropogenic CO_2 emissions (IPCC, 2007)
- 3.1 gigatonnes CO_2-eq of CH_4 per annum, or 44 percent of anthropogenic CH_4 emissions (IPCC, 2007)
- 2 gigatonnes CO_2-eq of N_2O per annum, or 53 percent of anthropogenic N_2O emissions (IPCC, 2007)

Emissions of hydrofluorocarbons (HFCs) are marginal on a global scale.

3.2 EMISSIONS BY SPECIES AND COMMODITIES

Cattle contribute most to emissions

Cattle are the main contributor to the sector's emissions with about 4.6 gigatonnes CO_2-eq, representing 65 percent of sector emissions. Beef cattle (producing meat and non-edible outputs) and dairy cattle (producing both meat and milk, in addition to non-edible outputs) generate similar amounts of GHG emissions.

Pigs, poultry, buffaloes and small ruminants have much lower emission levels, with each representing between 7 and 10 percent of sector emissions (see Figure 2).

[9] GHG emission values are computed in GLEAM for 2005, while IPCC estimates of total anthropogenic emissions are for 2004.

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The False Promises of Biogas: Why Biogas Is an Environmental Justice Issue

Phoebe Gittelson, Danielle Diamond, Lynn Henning, Maria Payan, Lynn Utesch, and Nancy Utesch

ABSTRACT

Years of community-driven research and participatory action have shed an important light on the copious negative health issues burdening communities adjacent to industrial agriculture. Rural communities in Wisconsin and Delaware have helped us in establishing an emerging source of pollution toward environmental justice communities—biogas. Biogas is being falsely marketed as a renewable energy solution to solve the problems of an already polluting industry, Concentrated Animal Feeding Operations (''CAFOs''). This greenwashing is problematic for many reasons and is in itself an environmental justice issue. The production of biomethane from manure-to-energy projects, such as manure digesters, is hazardous to local communities, locks farmers into more debt, and perpetuates the expansion of our current harmful agriculture practices, while increasing fossil fuel infrastructure by entrenching CAFOs with pipelines for the gas that is produced. In this article, we breakdown why biogas is not sustainable, how manure-to-energy projects perpetuate environmental injustices, examine current state policies on manure-to-energy projects, and how policy can be improved to protect frontline communities and farmers.

Keywords: CAFO, biogas, manure digesters, biomethane, environmental justice, factory farm

INTRODUCTION

There is a suite of social science and public health studies that have documented environmental injustices in rural areas stemming from industrialized agriculture and other extractive industries.[1] A pattern of negative pollution and public health consequences of industrial animal agriculture facilities threatening environmental justice communities in rural areas has been established.[2]

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[1] Kendall Thu and E. Paul Durrenberger. *Pigs, Profit, and Rural Communities.* (State Albany, NY: University of New York Press, 1998); John Gaventa. *Power and Powerlessness: Quiescence and Rebellion in an Appalachian Valley*. (Urbana, IL: University of Illinois Press, 1980); Pew Commission on Industrial Farm Animal Production. *Putting Meat on the Table: Industrial Farm Animal Production*. (A Project of the Pew Charitable Trusts and Johns Hopkins Bloomberg School of Public Health, 2008).

[2] Kelley J. Donham, Steven Wing, David Osterberg, Jan L. Flora, Carol Hodne, Kendall M. Thu, and Peter S. Thorne. ''Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations.'' *Environmental Health Perspectives* 15 (2007): 317–320; Sacoby M. Wilson, Frank Howell, Steve Wing, and Mark Sobsey. ''Environmental Injustice and the Mississippi Hog Industry.'' *Environmental Health Perspectives* 110 (suppl 2) (2002): 195–201; Steve Wing. ''Social Responsibility and Research Ethics in Community-Driven Studies of Industrialized Hog Production.'' *Environmental Health Perspectives* 110 (2002): 437–444; S. Wing and S. Wolf. ''Intensive Livestock Operations, Health, and Quality of Life Among Eastern North Carolina Residents.'' *Environmental Health Perspectives* 108 (2000): 233–238; S. Wing, D. Cole, and G. Grant. ''Environmental Injustice in North Carolina's Hog Industry.'' *Environmental Health Perspectives* 108 (2000): 225–231.

Research has shown that improving sustainable healthy rural communities is found to be dependent on integrating socioeconomic development and environmental protection.[3] The concentration and industrialization of agriculture are associated with economic and community decline locally and regionally,[4] and one of the most significant social impacts of Concentrated Animal Feeding Operations (''CAFOs'') is found to be the disruption of quality of life for neighboring residents.[5] Furthermore, it has been established that CAFOs are disproportionally located in communities of color and, or low income communities—a form of environmental injustice that has negative impacts on community health.[6]

We identify a growing problem in this realm that is disguised as a solution to the waste problems caused by CAFOs—biogas or manure-to-energy projects. Although the agribusiness industry, government, and even public interest environmental organizations have touted this technology as beneficial to the environment, farmers, and rural communities, we find the opposite to be true. We bring to light government regulatory failures, failures in environmental justice initiatives, and the reality of environmental harms that are exacerbated by biogas systems.

Our research seeks to bridge the divide between social science and public health research with laws and policies that perpetuate the problem, as opposed to address it. We offer policy solutions to address some of the problems rural communities are experiencing as a result of the false promises of biogas technology.

BACKGROUND

Dr. Sacoby Wilson's groundbreaking research in ''Environmental Injustice and the Mississippi Hog Industry'' revealed that living near industrial hog operations is a major public health concern for disproportionately burdened communities.[7] This study and others also referenced herein indicate that emissions from swine confinement houses are associated with adverse respiratory problems and a decline in quality of life for communities in their proximity.[8] The high density of hogs grown in confinement houses produce vast amounts of waste,[9] and community members who live close to these operations may have adverse health effects such as irritation to their eyes, noses, and throats; decline in quality of life; and possible mental health disorders. There are also water quality problems associated with leakage from the manure lagoons, and runoff from the spray fields that can contaminate surface and groundwater.[10] Some of the environmental contaminants emitted into the atmosphere include ammonia, hydrogen sulfide, volatile organic compounds, particulates, and other pollutants.[11] Wilson's research reveals the disproportionate amount of CAFOs in Black communities and how these hazardous operations adversely impact the physical, mental, and economic health of rural communities.

Dr. Wilson continued to expand on this research in ''An Ecologic Framework to Study and Address Environmental Justice and Community Health Issues'' (2009).[12] In this study, Wilson discusses the history of environmental justice and expands the vocabulary needed to accurately describe the many layers of intersecting structural oppression. He states as follows:

> I introduce the terms ''environmental slavery'' and ''environmental servitude'' as interchangeable conceptualizations that capture the experience of disadvantaged and vulnerable communities who are differentially exposed to unhealthy environmental conditions and resource-poor settings. Vulnerable communities are used (directly or indirectly) to host social and environmental disamenities and externalities through planning, zoning, industrial siting, infrastructure and development inequities; while communities consisting of dominant racial and class populations benefit from the inequities, access to more amenities, and the ecological goods and services of host communities. There is an underdevelopment and/or destabilization in the growth, health, and quality of life of host communities overburdened by environmental and social externalities and spatially and socially bounded by limited access to environmental amenities. Moreover, the footprints (ecological, economic, and social) of dominant racial and class populations lead not only to the use of host communities as sinks, but also the use of individual community members as sinks for environmental and psychosocial stressors.[13]

In Paul Mohai and Robin Saha's ''Reassessing Racial and Socioeconomic Disparities in Environmental Justice

[3]Kelley J. Donham, Steven Wing, David Osterberg, Jan L. Flora, Carol Hodne, Kendall M. Thu, and Peter S. Thorne. ''Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations.'' *Environmental Health Perspectives* 115 (2007): 318.

[4]Ibid at 317.

[5]Ibid at 318.

[6]Ibid. See also S. Wing and S. Wolf. ''Intensive Livestock Operations, Health, and Quality of Life Among Eastern North Carolina Residents.'' *Environmental Health Perspectives* 108 (2000): 233–238; S. Wing, D. Cole, and G. Grant. ''Environmental Injustice in North Carolina's Hog Industry.'' *Environmental Health Perspectives* 108 (2000): 225–231.

[7]Sacoby M. Wilson, Frank Howell, Steve Wing, and Mark Sobsey. ''Environmental Injustice and the Mississippi Hog Industry.'' *Environmental Health Perspectives* 110 Supplement 2 (2002): 199.

[8]Ibid.

[9]The new trend of large-scale production involves a high density of hogs grown in confinement houses and producing vast amounts of waste. The hog waste is collected and stored through different systems, including below-floor slurry storage (deep pit), underground slurry storage, anaerobic lagoons, and oxidation pits. One of the most popular methods is the storage of the waste in anaerobic cesspools, commonly called ''lagoons,'' where it undergoes microbial digestion. The hog waste effluent is later sprayed onto fields. Ibid at 195.

[10]Ibid at 195–196.

[11]Ibid.

[12]Sacoby M. Wilson. ''An Ecologic Framework to Study and Address Environmental Justice and Community Health Issues.'' *Environmental Justice* 2 (2009): 16.

[13]Ibid.

Research'' (2006), the authors examine the significant racial and socioeconomic disparities associated with hazardous sites, and the variation within the disparities found.[14] Their study addresses the failures of current methods used to assess environmental disparities adequately in accounting for the proximity between the hazard under investigation and nearby residential populations.[15]

Christopher W. Tessum expands on these inequities in ''Inequity in Consumption of Goods and Services Adds to Racial–Ethnic Disparities in Air Pollution Exposure'' (2019). This seminal study found that Black and Hispanic communities on average bear a ''pollution burden'' of 56% and 63% excess exposure, respectively, relative to the exposure caused by their consumption.[16] $PM_{2.5}$ air pollution is disproportionately induced by the racial–ethnic majority and disproportionately inhaled by racial–ethnic minorities.[17]

Dr. Wilson lays out a holistic framework to address environmental justice and health issues by reiterating that we must take an ''ecological systems approach to community health, [which] incorporates spatial and temporal concepts on the social organization of our living environments, considers ecologic features of the built and social environments that influence health, and utilizes contextual expertise to address environmental justice and health issues at the community level.''[18]

Although social and public health scientists have identified rural areas as a geo-special dimension of environmental justice research,[19] rural environmental injustices have lacked proper attention by the environmental justice movement as a whole. Notably there is a void of adequate legal and policy solutions available to rural people.[20] Correspondingly, research is revealing how government-driven agricultural policies legalize pollution and the differential treatment of rural people. The greenwashing of biogas as a solution to the environmental hazards associated with CAFOs is an example of this kind of legalized pollution.

METHODS

Our research is community driven in nature—in that questions about whether farmers should invest in manure-to-energy projects, and how and why governments are supporting them, were questions that needed immediate answers in communities already burdened by manure-to-energy projects. In collaboration with our community partners significant data was collected through publicly available government records, or records obtained from various governmental agencies through the Freedom of Information Act. We also researched government laws and regulations; scientific and other kinds of peer-reviewed journals, biogas industry trade magazines and other types of publications. In addition, we incorporate both participant observation and participatory action research conducted via community engagement with the Socially Responsible Agriculture Project (''SRAP''), and the rural communities in which SRAP works. We participated with our community partners in the engagement of public officials and regulatory entities to try to address problems or anticipated problems from CAFO biogas facilities. For example, we explored how California's cap-and-trade program generates carbon-offset credits for factory farms with biogas digesters in Wisconsin. From this background research,[21] we were able to better understand the motivation for the expansion of biogas infrastructure to factory farms. Through these methods we observed how harmful biogas projects were being perpetuated in part through government action, despite the sunlight being shown on their false promises.

FINDINGS

One of our major findings that became apparent throughout our engagement was the government's lack of understanding and lack of transparency regarding how industrial agriculture facilities, and their waste streams, directly harm rural communities that are fenceline to CAFOs. In this article, we shine a light on the budding issue of manure-to-energy projects because rural communities are alarmed by the transformation of CAFOs into combined factory farms and biogas facilities under the guise of ''green energy'' or ''compost projects.'' In this study, we explain how a lack of oversight, regulation, and transparency perpetuates the expansion of industrial agriculture in already burdened environmental justice communities. We argue that biogas is not a solution and

[14]P. Mohai and R. Saha. ''Reassessing Racial and Socioeconomic Disparities in Environmental Justice Research.'' *Demography* 43 (2006): 383–399.

[15]Ibid.

[16]Christopher W. Tessum, Joshua S. Apte, Andrew L. Goodkind, Nicholas Z. Muller, Kimberley A. Mullins, David A. Paolella, Stephen Polaskyf, Nathaniel P. Springer, Sumil K. Thakrar, Julian D. Marshall, and Jason D. Hill. ''Inequity in Consumption of Goods and Services Adds to Racial–Ethnic Disparities in Air Pollution Exposure.'' *PNAS* 116 (2019): 6001–6006.

[17]Ibid at 6003.

[18]Sacoby M. Wilson. ''An Ecologic Framework to Study and Address Environmental Justice and Community Health Issues.'' *Environmental Justice* 2 (2009): 18.

[19]David Pellow. ''Environmental Justice and Rural Studies: A Critical Conversation and Invitation to Collaboration.'' *Journal of Rural Studies* 47 (2016): 381–386; Loka Ashwood and Kate MacTavish. ''Introduction: Tyranny of the Majority and Rural Environmental Injustice.'' *Journal of Rural Studies* 47(A) (2016): 271–277.

[20]Lisa R. Pruitt. ''The Rural Lawscape: Space Tames Law Tames Space.'' In: I. Braverman, N. Blomley, D. Delaney, and A. Kedar (eds.) *The Expanding Spaces of Law: A Timely Legal Geography*. (Stanford University Press, 2013); Lisa R. Pruitt, Amanda L. Kool, Lauren Sudeall, Michele Statz, Danielle M. Conway, and Hannah Haksgaard. ''Legal Deserts: A Multi-State Perspective on Rural Access to Justice.'' *Harvard Law & Policy Review* (2018): 15–156; Ann M. Eisenberg. *Distributive Justice and Rural America*. 61 B.C. L. Rev. 189 (2020): 223. <https://lawdigitalcommons.bc.edu/bclr/vol61/iss1/5>. (Last accessed on March 10, 2021).

[21]Socially Responsible Agriculture Project. ''Trading Pollution: Wisconsin Industrial Dairies with Documented Regulatory Compliance Problems Benefit from California Greenhouse Gas Cap-and-Trade Program.'' August 2020. <https://sraproject.org/2020/08/2016/>. (Last accessed on March 10, 2021).

examine current policy while also suggesting policy recommendations that shift away from this polluting industry and instead invest back into communities.

Biogas is an environmental justice issue

Biogas is not sustainable. Although biogas comes from organic materials such as animal waste or food waste, it is hardly ''clean'' or ''green'' in the way most people understand those concepts.[22] Biogas is flammable, highly toxic, and potentially explosive.[23] Harmful compounds and air contaminants are introduced into the environment during biogas production and use through both combustion processes and diffusive emissions.[24] Burning manure-produced gas emits the same air contaminants as the combustion of fossil fuels. To make matters worse, the factory farms that produce the biomethane can emit harmful pollutants into the air and discharge nitrates into groundwater.[25]

Manure-to-energy projects, specifically manure digesters,[26] are sold as a solution to farmers to help them mitigate the costs of production by turning excess animal waste into energy through biogas. The installation of a manure digester on a factory farm is the first step for farmers in the process of turning their manure into a revenue stream, but it is also the first step in entrenching factory farms in more fossil fuel infrastructure, as producing and transporting biogas requires pipelines, fleets of trucks, and interconnection with the local power grid.[27] Furthermore, gas pipelines and other infrastructure leak tremendous volumes of methane that contribute to climate change, negating any alleged ''renewable natural gas'' savings.[28] Annual methane emissions have increased by about 50 million tonnes from the 2000–2006 average, mainly driven by agriculture and the natural gas industry,[29] and atmospheric concentrations of methane are now >2.5 times above preindustrial levels.[30] Although methane is only one component of total factory farm greenhouse gas emissions, these also include enteric methane, nitrous oxide (NOx) from fertilizer and manure application, and carbon dioxide from fuel combustion and input manufacture.[31]

Studies show that even if manure digesters were installed on every single dairy farm across the country and worked at optimal efficiency, this would still fall short of the industry's goal of reducing its total greenhouse gas emissions by 25%.[32] Similar to biogas, natural gas has been falsely marketed as a renewable and clean energy source, whereas in reality it destroys communities and has been proven to be a radioactive and hazardous energy source.[33] Biogas is the industry's next attempt at greenwashing another polluting fuel to save their industry. Fossil fuels, including natural gas fields and leaking pipelines, contributed 108 million tonnes of methane emissions in 2017, a rise of 17%.[34] Ultimately, biomethane is a false solution that perpetuates the expansion of big ag monopolies, the toxic, hazardous, and destructive practices of CAFOs and fossil fuel infrastructure.

Manure-to-energy projects perpetuate environmental injustices. Factory farms are inherently polluting entities that poison adjacent rural communities with toxic chemicals that eventually cause local public health disasters, economic hardship, and generational trauma.

[22]Jessica McKenzie. ''The Misbegotten Promise of Anaerobic Digesters.'' *The Counter*, 3 December 2019. <https://thecounter.org/misbegotten-promise-anaerobic-digesters-cafo/>. (Last accessed on March 10, 2021).

[23]U.S. Department of Agriculture. ''Conservation Practice Overview: CPS Anaerobic Digester (Code 366).'' October 2017. <https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_026500.pdf>. (Last accessed on March 10, 2021).

[24]Valerio Paolini, Francesco Petracchini, Marco Segreto, Laura Tomassetti, Nour Naja, and Angelo Cecinato. ''Environmental Impact of Biogas: A Short Review of Current Knowledge.'' *Journal of Environmental Science and Health Part A* 53 (2018): 899–906.

[25]Center for Food Safety. ''Stop the Dairy Digester Scam.'' 23 April 2019. <https://www.centerforfoodsafety.org/issues/305/food-and-climate/blog/5580/take-action-stop-the-dairy-digester-scam>. (Last accessed on March 10, 2021).

[26]Manure digesters use anaerobic digestion to convert organic material into biogas, which can then be refined into biomethane and used to produce electricity. Three main substances come out of the process of manure digestion, methane gas, also known as biomethane, that can be used as an energy source; liquid manure that can be used for fertilizer; and solid manure that can be used for composting and animal bedding. (Scott Gordon. ''What Manure Digesters Can and Can't Do.'' *WisContext*, 30 November 2016. <https://www.wiscontext.org/what-manure-digesters-can-and-cant-do>. (Last accessed on March 10, 2021).

[27]Daniel P. Duffy. ''The Costs and Benefits of Anaerobic Digesters.'' *MSW Management*, 4 June 2017. <https://www.mswmanagement.com/landfills/article/13030153/the-costs-and-benefits-of-anaerobic-digesters>. (Last accessed on March 10, 2021) (to be referred to as ''*The Costs and Benefits of Anaerobic Digesters*'' throughout the rest of the document).

[28]Robert W. Howarth, *et al.* ''Methane and the Greenhouse-Gas Footprint of Natural Gas from Shale Formations.'' *Climatic Change* (April 2011): 679, 687, 688; Robert W. Howarth. ''A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas.'' *Energy Science & Engineering* 2 (2014): 1, 2; Robert B. Jackson, *et al.* ''Natural Gas Pipeline Leaks Across Washington, DC.'' *Environmental Science & Technology* 48 (2014): 2051; Lavoie. *Environmental Science & Technology* 52 (2017): 3373.

[29]Quirin Schiermeier. ''Global Methane Levels Soar to Record High.'' *Nature*, July 14, 2020. <https://www.nature.com/articles/d41586-020-02116-8?utm_source=Nature±Briefing&utm_campaign=8a93e2b69c-briefing-dy-20200715&utm_medium=email&utm_term=0_c9dfd39373-8a93e2b69c-44035969>. (Last accessed on March 10, 2021).

[30]Ibid.

[31]Jude L. Capper, Roger A. Cady, and Dale E. Bauman. ''The Relationship Between Cow Production and Environmental Impact.'' 2011: 10. <https://wcds.ualberta.ca/wcds/wp-content/uploads/sites/57/wcds_archive/Archive/2011/Manuscripts/Capper.pdf>. (Last accessed on March 10, 2021).

[32]Ibid.

[33]Justin Nobel. ''America's Radioactive Secret.'' *Rolling Stone*, 21 January 2020. <https://www.rollingstone.com/politics/politics-features/oil-gas-fracking-radioactive-investigation-937389/>. (Last accessed on March 10, 2021).

[34]Quirin Schiermeier. ''Global Methane Levels Soar to Record High.'' *Nature*, 14 July 2020. <https://www.nature.com/articles/d41586-020-02116-8?utm_source=Nature±Briefing&utm_campaign=8a93e2b69c-briefing-dy-20200715&utm_medium=email&utm_term=0_c9dfd39373-8a93e2b69c-44035969>. (Last accessed on March 10, 2021).

Several studies have shown that a disproportionate number of CAFOs are located in low-income and nonwhite areas and near low-income and nonwhite schools.[35] These facilities and the hazardous agents associated with them are generally unwanted in local communities and are often thrust upon those sectors with the lowest levels of political influence.[36]

CAFOs can house anywhere from hundreds to millions of animals—the quantity of urine and feces from even the smallest CAFO is equivalent to the urine and feces produced by 16,000 humans.[37] The waste produced at factory farms contains antibiotics, hormones, pathogens, heavy metals, and other animal drugs and chemicals that contaminate significant ground and surface water across the country. Noxious gases are also released through ventilation systems from the CAFO confinement houses, and environmental contaminants are also released through volatilization from the waste decomposing in lagoons, spray fields, and other waste collection sites.[38] Furthermore, studies show that manure management activities are the third major category of U.S. agricultural emissions, releasing NOx and methane in quantities that total 16% of total U.S. agricultural emissions.[39]

Manure-to-energy projects have a direct negative impact on frontline communities. In a recent study, ''the Composition and Toxicity of Biogas Produced from Different Feedstocks in California,'' scientists found that the concentrations of minor chemical and biological components in biogas have ''the potential to be toxic to human health and the environment, to form toxic substances during the combustion process, or to form toxic substances after photochemical aging in the atmosphere.''[40] Furthermore, The California Air Resources Board (CA-ARB) and the Office of Environmental Health Hazzard Assessment compiled a list of 12 trace components potentially present in biogas at levels significantly above traditional fossil natural gas, including carcinogens (arsenic, p-dichlorobenzene, ethylbenzene, n-nitroso-di-n-propylamine, and vinyl chloride) and noncarcinogens (antimony, copper, hydrogen sulfide, lead, methacrolein, mercaptans, and toluene).[41] Because the composition of biogas varies so greatly between feedstocks, and being that there are so few studies on the differences in trace contaminates, it is irresponsible to invest in anaerobic digestion until the public health consequences are determined.

Although manure digesters might have the potential to reduce methane emissions, emissions of other air pollutants, such as NOx may increase to unacceptable levels.[42] Breathing air with a high concentration of NO_x can cause breathing problems, headaches, chronically reduced lung function, eye irritation, loss of appetite, and corroded teeth.[43] Community environmental air quality assessments have shown concentrations of hydrogen sulfide and gaseous ammonia that exceed U.S. Environmental Protection Agency (''EPA'') and Agency for Toxic Substances and Disease Registry recommendations.[44] Studies have reported that neighbors of confinement facilities experienced increased levels of mood disorders, including anxiety, depression, and sleep disturbances attributable to exposures to malodorous compounds.[45] Research has also found that lower concentration and secretion of salivary immunoglobulin among swine CAFO neighbors during times of moderate to high odor compared with times of low or no odor, suggesting a stress-mediated physiological response to malodor.[46] Such stressors, coupled with inadequate health-promoting infrastructure (e.g., supermarkets, parks, open spaces, and medical facilities), reduce the community's ability to defend against the adverse health consequences of their differential burden and exposure.[47]

One recent study, ''Mortality and Health Outcomes in North Carolina Communities Located in Close Proximity to Hog Concentrated Animal Feeding Operations'' (2018), explains that residents living in proximity to hog CAFOs are chronically exposed to contaminants from land-applied wastes and their overland flows, leaking lagoons, and pit-buried carcasses, as well as airborne

[35]Kelley J. Donham, Steven Wing, David Osterberg, Jan L. Flora, Carol Hodne, Kendall M. Thu, and Peter S. Thorne. ''Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations.'' *Environmental Health Perspectives* 115 (2007): 318.

[36]Ibid.

[37]Sierra Club. ''Why Are CAFOs Bad.'' <https://www.sierraclub.org/michigan/why-are-cafos-bad>. (Last accessed on March 10, 2021).

[38]Sacoby M. Wilson, Frank Howell, Steve Wing, and Mark Sobsey. ''Environmental Injustice and the Mississippi Hog Industry.'' *Environmental Health Perspectives* 110, Supplement 2 (2002): 195.

[39]Peter Lehner and Nathan A. Rosenberg. *Legal Pathways To Carbon-Neutral Agriculture* 47 Envtl. L. Rep. News & Analysis 10845, 10847. <https://earthjustice.org/sites/default/files/files/Legal-Pathways-Carbon-Neutral-Agriculture.pdf>. (Last accessed on March 10, 2021).

[40]Yin Li, Christopher P. Alaimo, Minji Kim, Norman Y. Kado, Joshua Peppers, Jian Xue, Chao Wan, Peter G. Green, Ruihong Zhang, Bryan M. Jenkins, Christoph F.A. Vogel, Stefan Wuertz, Thomas M. Young, and Michael J. Kleeman. ''Composition and Toxicity of Biogas Produced from Different Feedstocks in California.'' *Environmental Science & Technology* 53 (2019): 11569–11579.

[41]Ibid at 11569.

[42]Jude L. Capper, Roger A. Cady, and Dale E. Bauman. ''The Relationship Between Cow Production and Environmental Impact.'' 2011: 10. <https://wcds.ualberta.ca/wcds/wpcontent/uploads/sites/57/wcds_archive/Archive/2011/Manuscripts/Capper.pdf>. (Last accessed on March 10, 2021).

[43]''NOx Gases in Diesel Car Fumes: Why Are They so Dangerous?'' *Phys.org*, September 2015. <https://phys.org/news/2015-09-nox-gases-diesel-carfumes.html#:~:text=NOx%20has%20direct%20and%20indirect,land%E2%80%94harming%20animals%20and%20plants>. (Last accessed on March 10, 2021).

[44]Kelley J. Donham, Steven Wing, David Osterberg, Jan L. Flora, Carol Hodne, Kendall M. Thu, and Peter S. Thorne. ''Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations.'' *Environmental Health Perspectives* 115 (2007): 318.

[45]Ibid.

[46]Ibid.

[47]Sacoby M. Wilson, Herb Fraser-Rahim, Edith Williams, Hongmei Zhang, LaShanta Rice, Erik Svendsen, and Winston Abara. ''Assessment of the Distribution of Toxic Release Inventory Facilities in Metropolitan Charleston: An Environmental Justice Case Study.'' *American Journal of Public Health* 102 (2012): 1974.

emissions, resulting in higher risks of certain diseases.[48] In fact, a previous survey based on studies of residential communities reported significant health risks for residents, including higher risks of bacterial infections, higher frequencies of symptoms of respiratory and neurological disorders, and depression.[49] This exposed that people living in southeastern North Carolina communities located near hog CAFOs had poorer outcomes for a variety of health conditions in different age groups than the residents of North Carolina communities located in zip codes without hog CAFOs; they had higher mortality due to infections, anemia,[50] kidney disease, and perinatal conditions, and higher rates of hospital admissions and emergency department visits for low birth weight infants.[51] The authors conclude that people who live in these types of rural fenceline communities may simultaneously be affected by multiple risk factors, including low income and education, higher smoking prevalence, and lower access to medical care.

In addition, manure digesters installed at CAFOs require supplementary fossil fuel infrastructure, such as miles of pipelines stretching from the CAFO to the refinement facility. This funnels more pollution into and through already burdened local communities. Odor abatement, noise mitigation, truck queuing, effluent discharge, gas pipeline usage, and interconnection with the local power grid requires both physical hookups, and net metering agreements that can impact the health and wellness of neighboring families.[52]

Incentivizing farmers to install manure-to-energy projects instead of encouraging farmers to shift to sustainable farming practices solely profits developers, while locking communities into a cycle of sickness, loss, injury, and destruction. For example, from 2010 through 2019 fifteen Wisconsin dairy CAFOs received 1,317,236 carbon credits for their manure digesters,[53] despite the fact that in May of 2017 the CA-ARB's Environmental Justice Advisory Committee (EJAC)[54] made a priority recommendation to the Board to: ''[S]top investing in dirty energy [and] [e]liminate subsidies and financing for fossil fuels and in technologies such as corn-based biofuels, agricultural methane, biomass burning, waste-to-energy, or other unsustainable technologies that result in negative impacts on environmental justice communities.''[55] In addition, the EJAC advised against committing California ''Cap-and-Trade through the Clean Power Plan,'' since ''carbon trading cannot be verified…''[56] Furthermore, these funds are supposed to be aimed at ''Improving public health, quality of life and economic opportunity in California's most burdened communities at the same time they're reducing pollution that causes climate change.[57]'' Expanding any polluting industry in areas already burdened by factory farms perpetuates the systemic oppression of environmental justice communities.

Manure-to-energy projects are rarely beneficial for farmers. Manure-to-energy projects are expensive, temperamental, and require farmers to produce more waste to

[48]Julia Kravchenko, Sung Han Rhew, Igor Akushevich, Pankaj Agarwal, and H. Kim Lyerly. ''Mortality and Health Outcomes in North Carolina Communities Located in Close Proximity to Hog Concentrated Animal Feeding Operations.'' *NCMJ* 79 (2018): 277–288.

[49]Ibid.

[50]Studies have suggested that exposure to ammonia, hydrogen sulfide, methane, and particulate matters near the CAFOs, contamination of water and soil with zinc, exposure to the antibiotic chloramphenicol previously widely used to treat infections in hogs, and inappropriate human use of veterinary medications (certain NSAIDs or antibiotics) cause anemia. Ibid at 284.

[51]Ibid at 284.

[52]''The Costs and Benefits of Anaerobic Digesters.'' <https://www.mswmanagement.com/landfills/article/13030153/the-costs-and-benefits-of-anaerobic-digesters>. (Last accessed on March 10, 2021).

[53]California Air Resources Board [hereinafter CA-ARB], Offset Credit Issuance Table. <https://ww3.arb.ca.gov/cc/capandtrade/offsets/issuance/issuance.htm>. (Last accessed on May 22, 2020).

[54]The California Environmental Protection Agency (Cal/EPA) Advisory Committee on Environmental Justice was formed in 2001 to help Cal/EPA incorporate environmental justice into all of its programs and policies. Three key recommendations called for Cal/EPA to recognize the significant burden of toxics and pollution on impacted communities. The advisory committee recommended that Cal/EPA: (1) Use a precautionary approach: A precautionary approach to decision making means that regulations should prevent harm when there is credible evidence that harm is occurring, or is likely to occur—even when complete scientific evidence or proof is not available—in drafting and enforcing regulations. (2) Prioritize pollution prevention over pollution control: All too often communities of color have been left feeling sorry by pollution control—sorry for their lost health and quality of life. (3) Evaluate the cumulative impacts of toxics in an impacted community when making regulatory decisions. This process requires that the health effects of all sources of pollution be taken into consideration when determining the impact of pollution in individuals, communities, and the environment. The landmark environmental justice policies were adopted by Cal/EPA. <https://www.environmentalhealth.org/index.php/en/where-we-work/state-of-california/california-environmental-justice>. (Last accessed on March 10, 2021).

[55]CA-ARB, 2017 Scoping Plan, Appendix A, AB 32 Environmental Justice Advisory Committee Recommendations. November 2017: 14. <https://ww3.arb.ca.gov/cc/scopingplan/2030sp_appa_ejac_final.pdf>. (Last accessed on May 22, 2020).

[56]CA-ARB, 2017 Scoping Plan, Appendix A, AB 32 Environmental Justice Advisory Committee Recommendations. November 2017: 6. <https://ww3.arb.ca.gov/cc/scopingplan/2030sp_appa_ejac_final.pdf>. (Last accessed on May 22, 2020).

[57]California Environmental Protection Agency. ''California Climate Investments to Benefit Disadvantaged Communities.'' <https://calepa.ca.gov/envjustice/ghginvest/#:~:text=Known%20as%20California%20Climate%20Investments,pollution%20that%20causes%20climate%20change>. (Last accessed on January 21, 2021).

meet the needs of the digester.[58] The costs to build and run a manure digester are rarely recovered, especially when taking into consideration both the construction and operating costs. One study revealed that the economic concentration of agricultural operations tend to remove a higher percentage of money from rural communities than when the industry is dominated by smaller farm operations, which tend to circulate money within the community.[59]

Without outside funding from a designee, operator, or developer, it simply does not make financial sense for most farms to build or operate a digester.[60] The capital costs for a digester include lift station pumps, mixing tanks, the digester tank itself, piping for gas and hot water, gas pumps, flow meters, safety features, generators, electrical wiring and controls as well as power transmission lines, design engineering, and on-site buildings for generators, maintenance, and operations.[61] In addition to direct financial considerations, there is considerable overhead generated by legal and management issues, such as insurance premiums, building permits, design and consulting fees, licensing and zoning, sales agreements with utilities to buy back electricity, and more.[62] With capital costs often exceeding $1 million, anaerobic or manure digesters are beyond the price range of most farmers in the United States.[63] The payback period (capital costs divided by annual net benefits) of this capital investment can be between 5 and 6 years.[64]

Grants and cost-share agreements from states, federal programs, and utility companies help fund the cost of manure digesters.[65] For example, in just under a 4-year period beginning in 2010, 12 Wisconsin dairy CAFOs received >13 million dollars in grants from the U.S. Department of Agriculture's Rural Energy for America Program.[66] Additional financial incentives have also been provided to these projects through the U.S. Department of Treasury's administrative of Section 1603 of the American Recovery and Reinvestment Tax Act of 2009,[67] among other programs.[68] California alone has funded >100 digester projects, spending nearly $200 million of its ambitious California Climate Investments dollars on digesters instead of using the money to help fund farmers through its Smart Agriculture Programs.[69] According to the California Climate Investments Annual Report (2020), $69.1 million dollars has been assigned for future dairy digester development and research.[70] Tax payer dollars should be used to fund sustainable farming practices that go directly to farmers instead of to major developers. Unfortunately, these digester projects are also helping to fund gas infrastructure and development, rather than sustainable farming practices, which would create jobs,

[58]The size of a conventional digester is equal to 15–20 times the daily waste volume produced, or more if the waste is diluted before digestion (Don D. Jones, John C. Nye, and Alvin C. Dale. ''Methane Generation from Livestock Waste.'' *Energy Management in Agriculture*. Department of Agricultural Engineering, Purdue University. <https://www.extension.purdue.edu/extmedia/AE/AE-105.html>. (Last accessed on March 10, 2021). The volume of waste that must be disposed of increases accordingly if dilution water is used. The EPA's ''minimum'' requirements reveal what large investment manure digesters are and how they do not reduce the waste on CAFOs, but instead incentivize the farmer to produce even more to *potentially* be successful in making any profit or breaking even from the digester. The U.S. EPA states that for farms to be potentially successful with anaerobic digestion, a minimum of 500 head of cattle, 2000 hogs with anaerobic lagoons or liquid slurry manure management systems, or 5000 hogs with deep pit manure management systems are suggested. (U.S. Environmental Protection Agency. ''Is Anaerobic Digestion Right for Your Farm?'' <https://www.epa.gov/agstar/anaerobic-digestion-right-your-farm>). This significantly limits their use, as more than 90% of dairy farms in the United States have fewer than 500 cows, accounting for 40% of all dairy cows in the country (Peter Lehner and Nathan A. Rosenberg. *Legal Pathways to Carbon-Neutral Agriculture*, 47 Envtl. L. Rep. News & Analysis 10845: 10865. <https://earthjustice.org/sites/default/files/files/Legal-Pathways-Carbon-Neutral-Agriculture.pdf>. (Last accessed on March 10, 2021).

[59]Kelley J. Donham, Steven Wing, David Osterberg, Jan L. Flora, Carol Hodne, Kendall M. Thu, and Peter S. Thorne. ''Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations.'' *Environmental Health Perspectives* 115 (2007): 317.

[60]''The Misbegotten Promise of Anaerobic Digesters.'' <https://thecounter.org/misbegotten-promise-anaerobic-digesters-cafo/>. (Last accessed on March 10, 2021).

[61]''The Costs and Benefits of Anaerobic Digesters.'' <https://www.mswmanagement.com/landfills/article/13030153/the-costs-and-benefits-of-anaerobic-digesters>. (Last accessed on March 10, 2021).

[62]Ibid.

[63]''Legal Pathways To Carbon-Neutral Agriculture.'' 10865. <https://earthjustice.org/sites/default/files/files/Legal-Pathways-Carbon-Neutral-Agriculture.pdf>. (Last accessed on March 10, 2021).

[64]''The Costs and Benefits of Anaerobic Digesters.'' <https://www.mswmanagement.com/landfills/article/13030153/the-costs-and-benefits-of-anaerobic-digesters>. (Last accessed on March 10, 2021).

[65]A reference document by the U.S. EPA and Aster regarding digester funding showed case studies in which operators paid between 0% and 30% of the capital cost of the manure digester, with the remaining costs subsidized through grants and cost-share agreements from states, federal programs, and utility companies. See Aster, U.S. EPA. *Funding On- Farm Anaerobic Digestion* (September 2012).

[66]USDA, Rural Development, Rural Business-Cooperative Service, Wisconsin Recipients Renewable Energy Systems/Energy Efficiency Loan and Grant Program, see ''List of REAP Recipients in Wisconsin.'' <https://www.rd.usda.gov/programs-services/rural-energy-america- program-renewable-energy-systems-energy-efficiency/wi>/. (Last accessed on May 22, 2020); see also List of REAP Recipients in Wisconsin. <https://www.rd.usda.gov/files/WI_REAP_Awards.pdf>. (Last accessed on May 22, 2020).

[67]U.S. Department of the Treasury, American Recovery and Reinvestment Act of 2009 1603 Program (providing payments for specified energy property in lieu of tax credits). <https://home.treasury.gov/policy-issues/financial-markets-financial-institutions-and-fiscal-service/1603- program-payments-for> (see List of Awards). (Last accessed on May 22, 2020).

[68]See Good Jobs First, Tracking Subsidies, Promoting Accountability in Economic Development, Subsidy Tracker. <https://www.goodjobsfirst.org/subsidy-tracker>. (Last accessed on May 22, 2020).

[69]<https://civileats.com/2020/04/24/are-dairy-digesters-the-renewable-energy-answer-or-a-false-solution- to-climate-change/>. See also State of California, California Climate Investments website. <www.caclimateinvestments.ca.gov>. (Last accessed on July 31, 2020).

[70]California Climate Investments 2020 Annual Report. <https://ww2.arb.ca.gov/sites/default/files/classic/cc/capandtrade/auctionproceeds/2020_cci_annual_report.pdf>. (Last accessed on March 10, 2021).

facilitate carbon sequestering, and empower and rehabilitate rural and frontline communities.

The gas industry has an inherent incentive to convince farmers to invest in manure digesters. From their perspective, it is easier to transform an existing factory to produce and process biogas than to build a new one. Developers and energy executives have been selling the production of biogas as a solution to problems already existing on factory farms (too much manure, open lagoons, etc.), falsely motivating farmers to invest in ''composting[71]'' infrastructure that in actuality is much more complex and extensive, and is built to produce, process, and transport biogas, allowing the gas industry to profit from the dividends of the farmers' practically unpaid labor.

Unfortunately, some states are buying the industry's sales pitch about renewable natural gas and are allowing factory farms to receive carbon offset credits or compliance credits for installing manure-to-energy projects on farms. Carbon cap-and-trade programs allow industrial polluters to pay other pollution sources for their claimed pollution reductions.[72] For example, manure-to-energy projects that meet California's carbon offset protocols can be traded through its cap-and-trade program by approved national registries or through private contractors, or designees, who are registered with the state.[73] The polluting entity can then use the credits obtained from the trade to meet states' air pollution control standards. Negotiated agreements for the exchange of carbon credits are generally done in a private market, so it is difficult to know exactly how much money or other benefits manure digester projects receive.[74] Also, many factory farms that are receiving these credits are not in compliance with environmental and health regulations.[75] Critics such as the Institute for Agriculture and Trade Policy and the National Family Farm Coalition have argued that carbon markets are inherently inequitable, lock out most farmers, and could lead to more pollution, particularly in disadvantaged communities.[76] In short, the public is footing the bill for manure digesters,[77] whereas the CAFO industry profits by offsetting operation costs, selling the energy to utilities, and selling their claimed air pollution reductions to other polluters. Taxpayer dollars should be used to fund sustainable farming practices that go directly to farmers and environmental justice communities instead of to the pockets of major developers.[78]

[71]Glenn Rolfe. ''Environmental Groups: Seaford Poultry Digester Project Needs Public Input.'' *Delaware State News*, December 17, 2020. <https://delawarestatenews.net/business/environmental-groups-seaford-poultry-digester-project-needs-public-input/>. (Last accessed on March 10, 2021).

[72]''California Cap-and-Trade Program Summary.'' *Socially Responsible Agriculture Project*. August 2020. <https://sraproject.org/2020/09/california-cap-and-trade-program-summary/>. (Last accessed on March 10, 2021).

[73]Ibid.

[74]Ibid, see also SRAP. ''Trading Pollution: Wisconsin Industrial Dairies with Documented Regulatory Compliance Problems Benefit from California Greenhouse Gas Cap-and-Trade Program.'' Press Release, August 2020. <https://sraproject.org/2020/08/2016/>. (Last accessed on January 31, 2021).

[75]SRAP. ''Trading Pollution: Wisconsin Industrial Dairies with Documented Regulatory Compliance Problems Benefit from California Greenhouse Gas Cap-and-Trade Program.'' Press Release, August 2020. <https://sraproject.org/2020/08/2016/>. (Last accessed on January 31, 2021). Even if compliance issues at these CAFOs result in an invalidation of credits, the CA-ARB's regulations only call for invalidations for the number of days a facility is out of compliance. Seventy-five percent of the examples of invalidation on CA-ARB's website are of dairy operations (California Air Resources Board. ''California Air Resources Board Offset Credit Regulatory Conformance and Invalidation Guidance.'' February 2015. <https://ww2.arb.ca.gov/sites/default/files/classic//cc/capandtrade/offsets/arboc_guide_regul_conform_invalidation.pdf>; California Air Resources Board. ''Offset Credit Invalidation.'' <https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/offset-credit-invalidation>).

[76]Gosia Wozniacka. ''Are Carbon Markets for Farmers Worth the Hype?'' *Civil Eats*, 24 September 2020. <https://civileats.com/2020/09/24/are-carbon-markets-for-farmers-worth-the-hype/>. (Last accessed on March 10, 2021).

[77]Gosia Wozniacka. ''Are Dairy Digesters the Renewable Energy Answer or a 'False Solution' to Climate Change?'' *Civil Eats*, 24 April 2020. <https://civileats.com/2020/04/24/are-dairy-digesters-the-renewable-energy-answer-or-a-false-solution-to-climate-change/>. (Last accessed on March 10, 2021).

[78]Manure to energy projects that meet California's carbon offset protocols can be traded by approved registries or through private contractors, or designees, that are registered in the state's Compliance Instrument Tracking System Service before these manure-to-energy projects are submitted. The California-based polluting entity can then use the credits obtained from the trade to meet the state's air pollution control standards. Negotiated agreements for the exchange of carbon credits are generally done in a private market. Thus, it is difficult to know exactly how much money or other benefits manure digester projects receive. However, the private company 3Degrees Group explains that digester projects are very expensive and carbon credits provide a very important stream of revenue to help make the projects economically viable <https://3degreesinc.com/resources/sunny-knoll-farm-digester/>. (Last accessed on March 10, 2021).What's important to understand, is that this program only benefits those that are able to comply with the rigorous guidelines of the California Air Resource Board's (''ARB'') Offset Protocols. Those that abide by these standards can generate offset credits that are facilitated by Offset Project Registries (''Registries'') <https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/offset-project-registries>. These Registries help facilitate the listing, reporting, and verification of offset projects developed, and issue Registry offset credits (''ROCs''). Id. But these ROCs cannot be used for compliance with the Cap-and-Trade Program, they need to be converted to ARB offset credits to be eligible for use in the Cap-and-Trade Program. After the issuance of ROCs, the ARB determines whether ARB offset credits should be issued for each offset project. If a project wants to deliver voluntary offsets, they may monitor, report, and verify greenhouse gas emission reductions under the Livestock Offset Protocol, but elect not to transition the resulting ROCs issued by the Registries to ARB offset credits, and are free to deliver the ROCs on the voluntary market. <https://ww2.arb.ca.gov/sites/default/files/classic/cc/capandtrade/protocols/livestock/livestock.2014.faq.pdf>. (Last accessed on March 10, 2021): 5. This complex system of compliance to even be eligible to receive carbon credits or participate in the carbon market is just another example of the powerful agriculture industry consolidating and dominating against those that are not part of the system. Funding and developing manure-to-energy projects does not benefit your average farmer because to actually profit from the project, you need to spend copious amounts of time and money toward being recognized by the ARB as an offset project, and even so, might not be granted the credits by the Registries to participate in the market. Those that opt in to allowing ARB recognized developers to front and fund the projects do not benefit from the cap-and-trade revenue and are stuck with operating costs.

Current national and state policies perpetuate environmental injustices and fail to support rural communities and sustainable farming practices

As of now, our national agriculture policies do not protect or incentivize sustainable farming practices that are necessary to build back national soil health and sequester carbon. Instead of subsidizing false solutions such as manure-to-energy projects, we must organize to reform our national and local-level farm bills and other government programs to invest and insure renewable, just, and equitable farming practices.

Some states are already taking the initiative to fight against the expansion of biogas. New York State just recently passed one of the country's most progressive climate-forward policies in its Climate Leadership and Community Protection Act (''CLCPA'').[79] The CLCPA ''prohibits waste-to-energy projects'' and ''biofuels used for energy or transportation purposes.[80],'' In essence, the state has banned the future development of manure-to-energy projects from its renewable energy platform. This kind of innovative lawmaking protects and prioritizes environmental justice communities, ensuring disadvantaged communities are not disproportionally burdened with more polluting infrastructure.

As we explained earlier, unlike New York, other states are propping up manure-to-energy projects as a gateway to regulatory ''compliance'' and profit through carbon cap-and-trade markets. For example, SRAP found Wisconsin CAFOs, which already struggle with pollution and other compliance issues, participate in and, therefore, benefit from the CA-ARB carbon trading program.[81] Regardless of the claimed air pollution reductions by CAFO manure digesters, we found numerous types of pollution events and regulatory problems caused by CAFOs participating in the program.[82] The CA-ARB carbon trading program does not take into account the severity of the environmental or health consequences of the regulatory violation.[83] CA-ARB invalidation verifiers should be checking for all violations of local, state, and federal laws that occur between initial waste collection and final disposal—not just specific dates of air-related noncompliance issues.[84] Strengthening regulations for factory farm operations and manure-to-energy projects is essential in protecting local communities from unnecessary health and economic burdens.

There are many ways that we can expand the programs currently in place to benefit struggling farmers and fenceline communities. Ensuring funding from existing federal conservation programs such as the Conservation Stewardship Program and Environmental Quality Incentives Program are directed toward truly sustainable farming practices, as well as expanding and creating local programs such as California's Healthy Soils Program Incentives, will help farmers and communities in numerous ways.[85] It is also imperative that we create new agriculture programs that lead with Indigenous knowledge, while creating equity and economic opportunities for Tribes and Indigenous communities. Shifting away from factory farming will create more jobs while bringing integrity, joy, and community back to farming.

The agribusiness industry's position that manure-to-energy projects help address climate change and CAFO waste problems needs to be more thoroughly studied and scrutinized. The reality experienced by those living in surrounding communities is that CAFOs rarely, if ever, actually deal with the pollution problems they create.[86] If nothing else, manure-to-energy projects have served as a facade to further a failed system that benefits the few at the expense of the public and the environment. Policymakers should be effectively enforcing existing environmental and public health regulations, as well as supporting and promoting more sustainable forms of livestock production and legitimate renewable energy programs.

RECOMMENDATIONS

Other policy suggestions include the following:

- There needs to be more openness and government transparency in permitting and other regulatory issues related to manure-to-energy projects.
- Governmental bodies need to stop providing financial incentives for the development of CAFO manure-to-energy technologies and instead focus funding on the promotion of sustainable agricultural practices.
- Subsidies that go to CAFOs must be eliminated so that traditional pasture-based animal agriculture and regenerative agriculture has a fair opportunity to compete and succeed in a free market.
- The federal government and states should establish, strengthen, and effectively enforce existing air and water pollution laws against CAFOs and stop subsidizing these facilities, particularly those that have caused pollution.
- States and local governments should provide citizens with more robust citizen suit provisions for enforcing environment regulations (similar to those provided under the federal Clean Water Act and Michigan's Environmental Protection Act). This way, the public would have greater ability to enforce environmental regulations when responsible agencies fail to act.

[79]Senate Bill S6599 (New York state climate leadership and community protection act). *The New York State Senate* 2019–2020. <https://www.nysenate.gov/legislation/bills/2019/s6599>.
[80]Ibid at page 13, line 6.
[81]SRAP. ''Trading Pollution: Wisconsin Industrial Dairies with Documented Regulatory Compliance Problems Benefit from California Greenhouse Gas Cap-and-Trade Program.'' Press Release, August 2020. <https://sraproject.org/2020/08/2016/>. (Last accessed on January 31, 2021).
[82]Ibid.
[83]Ibid.
[84]Ibid.
[85]''Are Carbon Markets for Farmers Worth the Hype?'' <https://civileats.com/2020/09/24/are-carbon-markets-for-farmers-worth-the-hype/>. (Last accessed on March 10, 2021).
[86]SRAP. ''Trading Pollution: Wisconsin Industrial Dairies with Documented Regulatory Compliance Problems Benefit from California Greenhouse Gas Cap-and-Trade program,'' Press Release, August 2020. <https://sraproject.org/2020/08/2016/>. (Last accessed on January 31, 2021).

- Environmental protection and enforcement measures should be strengthened to reduce pollution, as opposed to using pay-to-pollute schemes.
- Congress could condition the receipt of federal subsidy funds in the agricultural sector on the implementation of truly sustainable farming and feedstock practices, and federal government should rescind support for manure biogas projects. Companies participating in the carbon market should have to demonstrate certification of sustainable operations before receiving any federal permits or other government approvals.[87]
- States should adopt or expand programs aimed at greenhouse gas emissions mitigation or sequestration from the forestry or agricultural sectors, such as[88] the following:
  - Create more local subsidy programs, such as California's Smart Agriculture Programs, that create value in land's carbon sink potential and shape cultivation techniques consistent with decarbonization objectives.
  - State governments should consider requiring farm owners to comply with basic climate-friendly practices, such as installing buffer strips next to streams, to receive tax benefits for agricultural activities or easements.[89]
    - The CA-ARB's program should take into consideration the type and magnitude of regulatory violations in addition to total periods of noncompliance when invalidating carbon credits. The current program that invalidates credits only for the time period in which the violation occurred is an inadequate deterrence for poor management.
    - The CA-ARB should meaningfully address input provided by its EJAC to ''[s]top investing in dirty energy'' and to eliminate subsidies and financing for ''waste-to-energy and other unsustainable technologies'' that impose negative impacts on environmental justice communities.
- The carbon credit market should be nationalized, instead of privatized, and credits should only be traded locally.
  - The CA-ARB should place geographic restrictions on trading and limit the amount of pollution ''offset'' credits that companies can use to comply with the program. This will help incentivize local emissions reductions and the annual statewide reduction of GHGs.
- Congress should require the Farm Service Agency and the Farm Credit System lending institutions to offer programs providing favorable credit to farmers and ranchers using truly sustainable and climate-friendly practices relating to all loans.
- States should look to New York State and its climate-forward policy in its Climate Leadership and Community Protection Act (''CLCPA'') and create more innovative laws that protect and prioritize environmental justice communities, ensuring disadvantaged communities are not disproportionately burdened with more polluting infrastructure.
- All states should look to New York's policy that disallows manure-to-energy projects in its renewable energy portfolio and follow suit.

CONCLUSION

Overall, manure-to-energy projects have the potential to be helpful for small farms (not CAFOs) if the biogas produced on the farm is reused only at that farm. When manure-to-energy projects are installed on factory farms, the processing of the methane produced for the power grid or for the transportation sector releases CO_2 and hazardous air pollutants, and requires the installation of gas pipelines and other infrastructure that leak tremendous volumes of methane. Biomethane production burdens and poisons local communities while degrading our planet's health and sustainability. Manure-to-energy projects are not a sustainable solution to the problems caused by CAFOs because they entrench an already polluting facility with more contamination mechanisms. Local, state, and national governmental entities need to stop promoting and incentivizing CAFO manure-to-energy projects at the expense of the environment and rural communities.

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[87]Blake Hudson and Uma Outka. ''Chapter 25: Bioenergy Feedstocks,'' *Legal Pathways to Deep Carbonization in the United States Summary and Key Recommendations,* November 2018: 65. <https://biotech.law.lsu.edu/blog/deep_decarb_summary_booklet_online.pdf>. (Last accessed on March 10, 2021).

[88]Ibid.

[89]Peter H. Lehner and Nathan A. Rosenberg. ''Chapter 30: Agriculture.'' *Legal Pathways to Deep Carbonization in the United States Summary and Key Recommendations*, November 2018: 77–78. <https://biotech.law.lsu.edu/blog/deep_decarb_summary_booklet_online.pdf>. (Last accessed on March 10, 2021).

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Treating cattle with antibiotics affects greenhouse gas emissions, and microbiota in dung and dung beetles

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Antibiotics are routinely used to improve livestock health and growth. However, this practice may have unintended environmental impacts mediated by interactions among the wide range of micro- and macroorganisms found in agroecosystems. For example, antibiotics may alter microbial emissions of greenhouse gases by affecting livestock gut microbiota. Furthermore, antibiotics may affect the microbiota of non-target animals that rely on dung, such as dung beetles, and the ecosystem services they provide. To examine these interactions, we treated cattle with a commonly used broad-spectrum antibiotic and assessed downstream effects on microbiota in dung and dung beetles, greenhouse gas fluxes from dung, and beetle size, survival and reproduction. We found that antibiotic treatment restructured microbiota in dung beetles, which harboured a microbial community distinct from those in the dung they were consuming. The antibiotic effect on beetle microbiota was not associated with smaller size or lower numbers. Unexpectedly, antibiotic treatment raised methane fluxes from dung, possibly by altering the interactions between methanogenic archaea and bacteria in rumen and dung environments. Our findings that antibiotics restructure dung beetle microbiota and modify greenhouse gas emissions from dung indicate that antibiotic treatment may have unintended, cascading ecological effects that extend beyond the target animal.

1. Introduction

Antibiotics are extensively used in agriculture to promote growth and to treat or prevent livestock disease [1–7]; yet they may have major consequences for human and environmental health [4,8,9]. For example, the use of antibiotics in agriculture can favour the evolution of antibiotic resistance among pathogens and the spread of antibiotic resistance genes to surrounding environments (e.g. [10–12]). In addition, this practice can have other ecosystem-level ramifications that are likely to be important, but less appreciated. In particular, antibiotic treatment could affect two distinct, but potentially interacting ecological processes: the removal and recycling of livestock dung by decomposer organisms, and the release of greenhouse gases from dung.

Livestock dung provides a source of nutrients, organic matter and microbes to pasture ecosystems [13–15]. Dung can also act as a source of pathogens [16] and emit significant quantities of greenhouse gases, including methane [17,18]. However, these effects can be modified by the diverse communities that inhabit,

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consume and/or interact with dung, of which dung beetles have been particularly well studied [19–23]. In general, dung beetles play a critical role in carbon and nitrogen cycling, and the maintenance of soil fertility in both natural and agricultural pasture ecosystems [24,25]. Veterinary pharmaceuticals can harm beetles and other downstream consumers of livestock dung, which may depress dung decomposition and reduce the diversity of dung-based communities. But while the effects of antiparasiticides have been relatively well studied in this context (e.g. [26–29]), the effects of antibiotics on dung beetles remain poorly known [30].

In contrast to antiparasiticides, which may directly act on the physiology of dung consumers (e.g. [31]), broad-spectrum antimicrobial compounds could have far-reaching, microbially mediated ecological effects. For example, as microbial symbionts (microbiota) are often critical to insect health and reproduction [32,33], antibiotics retained in dung could affect beetle performance by altering beetle microbiota. Furthermore, antibiotic-induced restructuring of livestock gut microbiota could change the nutritional, chemical and microbiological properties of dung, the diet of dung beetles.

Antibiotics could also directly or indirectly modulate greenhouse gas emissions from livestock dung. Antibiotics have been shown to alter the structure and activity of mammalian gut and faecal microbiota [34–36]. In livestock such as cattle, certain members of the gut microbiota are responsible for producing key greenhouse gases such as methane, nitrous oxide and carbon dioxide [37–39]. Despite interest in reducing emissions of these microbially mediated greenhouse gases, and the frequent use of antimicrobial compounds in agriculture, the relationship between the two remains unclear. Furthermore, the effects of antibiotics on greenhouse gas fluxes and on dung beetles could be linked. For example, dung beetles can reduce methane production from dung to an extent that could have impacts in some agricultural systems [40]. As methanogenesis is thought to be inhibited by oxygen entering the dung pat through beetle tunnels [20], it could be sensitive to the size and number of dung beetles. In turn, if beetle performance and fitness are influenced by antibiotic-sensitive microbiota, the effect of dung beetles on greenhouse gas emissions could depend upon the antibiotic treatment.

We hypothesized that antibiotics administered to cattle alter dung beetle microbiota and, as a consequence, depress beetle fitness. In addition, we hypothesized that antibiotics modulate gas emissions from dung and the extent to which beetles influence emissions. To experimentally test these hypotheses, we treated cattle with and without a broad-spectrum antibiotic, and assayed microbial communities in cow dung and in field-collected dung beetles (*Aphodius fossor* L.). We also tested the effect of antibiotics on beetle size and numbers, and on fluxes of multiple greenhouse gases (carbon dioxide, nitrous oxide and methane) from dung. Our findings demonstrate that the common practice of administering antibiotics to livestock [1–7] can have important, unintended impacts on dung biota and the biogeochemical processes they mediate in agroecosystems.

2. Material and methods

(a) Experimental set-up

Ten cows were randomly assigned to two treatments: five were given a standard 3-day course of tetracycline and five were left as controls. None of the cows had undergone antibiotic treatment within the previous six months, except for one cow in the antibiotic group, which had received a course of penicillin six weeks prior to the experiment (for the full history of each cow, see the electronic supplementary material, Methods). From each cow, we collected fresh dung on a single day, beginning 1 h after the last administration of antibiotics. That afternoon, we separated the dung from each cow into six 1 l pats and placed each pat in a mescosm (an open-bottom, mesh-covered plastic bucket) in the field. We also included four control mesocosms without dung to measure background fluxes of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from the soil. More detail on experimental design is given in the electronic supplementary material, Methods.

To examine the effects of antibiotics on dung beetle microbiota, on the performance of beetles and on beetle-mediated effects on gas fluxes from cow pats, we focused on the dung beetle *Aphodius fossor* (L.). *Aphodius fossor* is a regionally widespread and locally common species [41], and its ecology and interactions with dung have been extensively studied (e.g. [20,21,42]). The beetles were collected in the field in early June from different localities and stored at 4°C until they were added to dung pats.

Dung beetles were added to four of the six dung pats produced by each cow (randomly chosen). Gas measurements and dung samples for microbial analysis were taken from two intact pats with beetles and two without beetles. The two additional pats with beetles were used for more invasive sampling of beetles for microbial characterization and to measure beetle reproduction and development. Based on beetle densities recorded in the field and on a previous study [42], we added 12 beetles to each pat, maintaining a sex ratio of 1 : 1.

(b) Gas flux measurements

Gas fluxes of CO_2, N_2O and CH_4 were measured from dung mesocosms in the field at five time points over the course of the experiment (more information given in the electronic supplementary material). Net gas fluxes emitted from each dung pat were calculated as in Penttilä *et al*. [20].

(c) Dung and beetle sampling

All dung and beetle samples were preserved for subsequent characterization of microbiota using 95% ethanol, which is an effective storage medium for microbial community analysis [43]. On days 2, 11 and 23 of the experiment, dung samples of approx. 1 ml were taken and stored in ethanol (see the electronic supplementary material, Methods).

To test whether antibiotic treatment affected beetle microbiota, two parent beetles from each pat were preserved in ethanol on day 7 of the experiment. To measure antibiotic effects on beetle size, reproduction and survival, we sampled pats on day 43 (for half-grown larvae) and days 71 and 73 (for the next generation of adult beetles). Larvae recovered were weighed while fresh and the width of their head capsule was measured. Total offspring counts by the end of the experiment were used as an integrated measure of both adult reproduction and offspring survival.

(d) Molecular protocol and sequence data processing

To characterize the overall beetle-associated microbial community, whole adults were homogenized and DNA was extracted from approximately 100 mg of homogenate with the MoBio PowerSoil kit, following similar studies [43,44]. Approximately 100 mg subsamples of dung were used for DNA extraction with the same kit. Using barcoded primers, we PCR-amplified the V4 region of the bacterial and archaeal 16S rRNA gene, with the amplicons sequenced on an Illumina MiSeq platform

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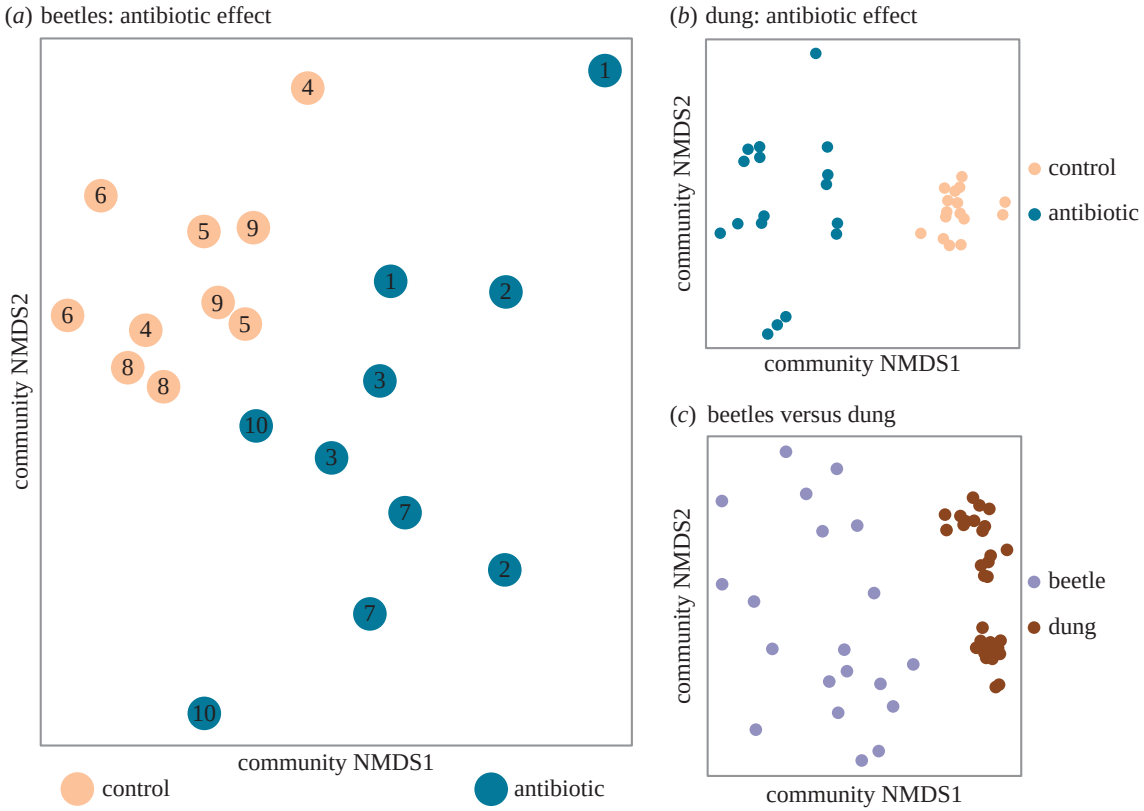

Figure 1. Microbial communities diverge upon antibiotic treatment and cluster according to sample habitat (beetle versus dung). Non-metric multidimensional scaling ordinations of microbiota in (*a*) parental dung beetles, where cow individual is indicated by numbers and treatment by colour, (*b*) dung samples only and (*c*) beetles versus dung. The ordinations visually represent Bray–Curtis dissimilarities among samples in two dimensions. (Online version in colour.)

as previously described [43,45]. Detail regarding sequence data processing and taxonomic identification is given in the electronic supplementary material, Methods.

(e) Statistical analysis

All statistical analyses were performed in R v. 3.2.2 [46], and plots were constructed with the ggplot2 package [47]. The vegan package [48] was used to analyse microbial community data. Following previous work (e.g. [43–45]), we used the Bray–Curtis dissimilarity metric to quantify variation in overall microbial community structure among samples. Non-metric multidimensional scaling plots were constructed to visualize Bray–Curtis dissimilarity in two dimensions. To avoid pseudoreplication of beetle data, dissimilarities (multivariate analyses) or performance variables (univariate analyses) were averaged between the beetles in each mesocosm; thus, multilevel statistical tests were conducted on the effects of antibiotic treatment and cow individual.

The effects of antibiotic treatment and cow individual on beetle and dung microbiota were tested using nested permutational multivariate ANOVA in the BiodiversityR package [49], with cow nested within treatment (999 permutations). Unless noted otherwise, below we report results from dung sampled on day 2 of the experiment, which we expected to most closely represent microbiota in the cow gut, but analyses of dung sampled on days 11 and 23 are shown in the electronic supplementary material. With each of the gases measured, we used ANOVA to assess effects of antibiotics and beetle presence on cumulative gas fluxes over the course of the experiment, as well as the interaction of the two factors. We analysed the proportion of methanogens in dung microbiota (all time points) with the same procedure, but with prior log transformation to meet the assumption of normality.

To assess antibiotic effects on the performance of larval offspring, we chose to focus on weight, which was highly correlated with head size (Spearman's rank correlation, $\rho = 0.68$, $p = 0.005$). Weight can be considered as a proxy for performance as it is correlated with adult fecundity in both *Aphodius* [50] and other insects (e.g. [51,52]). A nested ANOVA (cow individual within antibiotic treatment) was used to test for effects on larval weight; normality of model residuals was confirmed visually. The effect of antibiotic treatment on total counts of beetle offspring recovered from each dung pat was analysed by fitting a generalized linear mixed model with cow individual as a random effect, Poisson-distributed errors and a log link function.

3. Results and discussion

(a) Microbial community structure in beetles

Dung beetles are extraordinarily diverse [53], and both scientifically [54] and ecologically important [25]; yet only one previous study has used DNA sequence-based methods to characterize their microbiota (*Onthophagus taurus* [55]). Despite feeding on a microbe-rich substrate, we found that *A. fossor* adults transform dung microbiota during digestion or host symbionts not present in their diet. Overall, beetles and dung had compositionally distinct microbiota ($F_{1,51} = 17.32$, $p = 0.001$; figures 1*c* and 2), regardless of the dung sampling time point (electronic supplementary material, figures S1*a*,*b*), and beetles contained lower microbial diversity than their diet ($F_{1,51} = 45.12$, $p < 0.0001$; electronic supplementary material, figure S2). While the dung communities were dominated by Bacteroidia, Clostridia and Spirochaetes, the dung beetle microbiota were dominated by Gammaproteobacteria and Bacilli. Less than 25% of the operational taxonomic units (OTUs) that were relatively abundant in beetle communities (overall proportion greater than or equal to 1%) were

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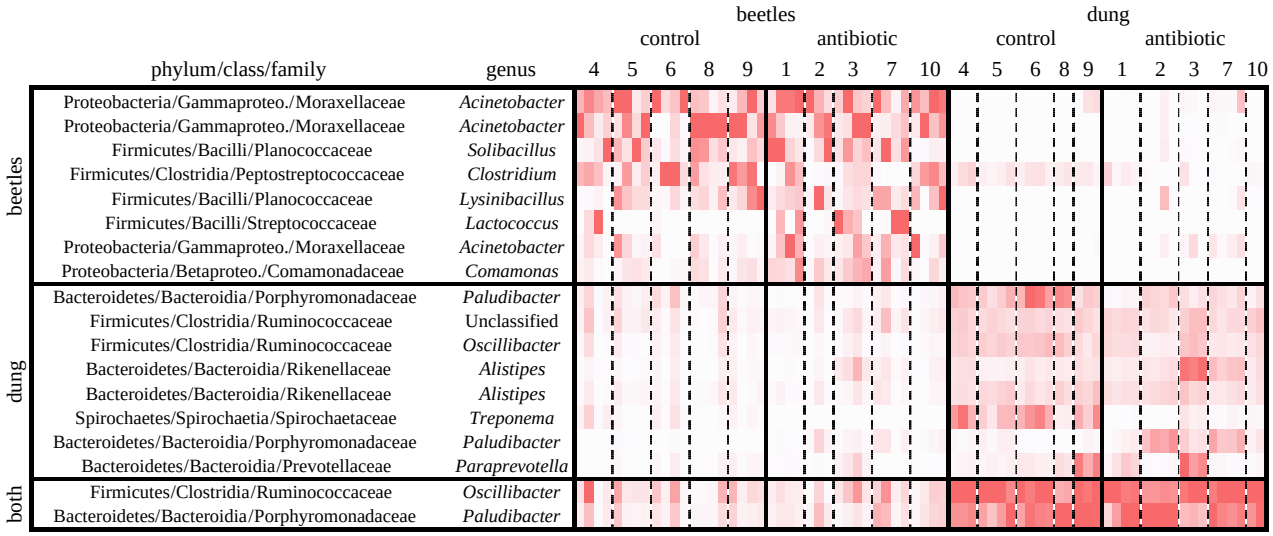

Figure 2. Variability in dominant microbial OTUs between individuals, sample habitats and treatments. The heatmap shows OTU relative abundance in each sample (columns) where darker shading indicates a higher proportion; the range of values is scaled separately for each sample. Numbers above columns denote cow individuals. For clarity, only the top 10 OTUs for each sample type are shown (two OTUs were in the top 10 of both beetles and dung). All OTUs shown are bacteria, as archaea were less abundant overall. (Online version in colour.)

also abundant in dung, implying that the dominant beetle microbes are either vertically transmitted or rare in dung. Indeed, the genus *Acinetobacter* was highly abundant in *A. fossor* (figure 2) and also found in *O. taurus* fed sterilized dung [55], suggesting that *Acinetobacter* could be vertically transmitted symbionts common among dung beetles.

(b) Effects of antibiotics on dung and dung beetle microbiota

As expected from previous work [34–36,56], we found a clear effect of antibiotic treatment on dung microbiota ($F_{1,23} = 4.84$, $p = 0.01$; figure 1*b*; electronic supplementary material, figure S2), and this effect persisted even 23 days after defecation and sample collection (electronic supplementary material, figure S1*c*,*d*). As in other animal taxa that maintain individual-specific microbiota (e.g. [56,57]), we also found that dung microbial communities clustered by cow individual ($F_{8,23} = 4.87$, $p = 0.001$; figure 2). Antibiotic treatment administered to cattle also affected dung beetle microbiota ($F_{1,10} = 2.39$, $p = 0.007$; figure 1*a*; electronic supplementary material, figure S2), and mirroring the patterns found for dung, the microbial communities in beetles also clustered by cow individual ($F_{8,10} = 1.38$, $p = 0.001$; figure 1*a*).

Antibiotics could alter beetle microbiota by multiple mechanisms. For example, antibiotic-induced changes in dung microbiota (figure 1*b*) could change the nutritional quality of the beetles' diet, or provide an altered inoculum to the beetle community. Alternatively, antibiotic residues present in dung and consumed by beetles may act on beetle gut microbiota. Concern has been raised over the persistence of antiparasiticides in the environment, where—as eukaryote-specific pharmaceuticals—they are directly toxic to animals [30,31,58]. Our data suggest that even antibacterials such as tetracycline may have similar far-reaching effects, by altering the microbiota of non-target animals.

(c) Beetle size and numbers

Despite clear antibiotic effects on beetle microbiota (figure 1*a*), and the often critical role of microbiota in insect biology [32,33], antibiotics did not influence dung beetle size, reproduction or survival. Larval weight was unaffected by antibiotic treatment ($F_{1,13} = 0.018$, $p = 0.90$), and the total number of beetle offspring recovered from dung pats by the end of the experiment was similar between treatments (Poisson GLMM, $z = -0.35$, $p = 0.73$). An average of 4.2 ± 1.5 versus 3.0 ± 0.71 offspring were collected from dung pats of control and antibiotic treatments, respectively (mean $\pm$ s.e.m., $n = 10$ per treatment). As not all members of the beetle microbiota responded to antibiotics (figure 2), one possible explanation is that the antibiotic effect on overall microbiota was driven by commensal and not mutualistic species. For example, *Acinetobacter* abundance was not sensitive to antibiotic treatment ($F_{1,10} = 0.35$, $p = 0.57$; figure 2), and tetracycline resistance has been documented among *Acinetobacter* in other environments [59,60]. Alternatively, microbial symbionts may simply not be important to the nutrition or development of dung beetles [61]. However, given the wide variety of processes that can be influenced by microbiota (e.g. [62–64]), the antibiotic-induced microbial restructuring we observed could affect unmeasured aspects of dung beetle biology.

(d) Greenhouse gas emissions from dung

The presence of beetles decreased methane fluxes from dung ($F_{1,36} = 7.49$, $p < 0.01$; figure 3*a*), an effect reported previously and probably due to oxygenation of the pat caused by beetle tunnels [20,40]. By contrast, antibiotic treatment consistently increased methane emissions ($F_{1,36} = 22.21$, $p < 0.0001$; figure 3*a*), which are probably related to changes in dung microbiota (figure 1*b*). Contrary to our expectations, the two effects were unrelated (interaction $F_{1,36} = 0.004$, $p = 0.95$), suggesting that beetle tunnelling activity is not affected by antibiotic modification of dung (and its impact on the beetle microbiome).

Carbon dioxide emissions were similar between treatments ($F_{1,36} = 0.001$, $p = 0.98$), and there was no effect of beetle presence ($F_{1,36} = 0.02$, $p = 0.88$) nor an interaction between the two factors ($F_{1,36} = 0.22$, $p = 0.64$), suggesting that antibiotics do not affect overall microbial decomposition rates. This result indicates that the antibiotic effect on methane production is not simply due to an increase in overall microbial

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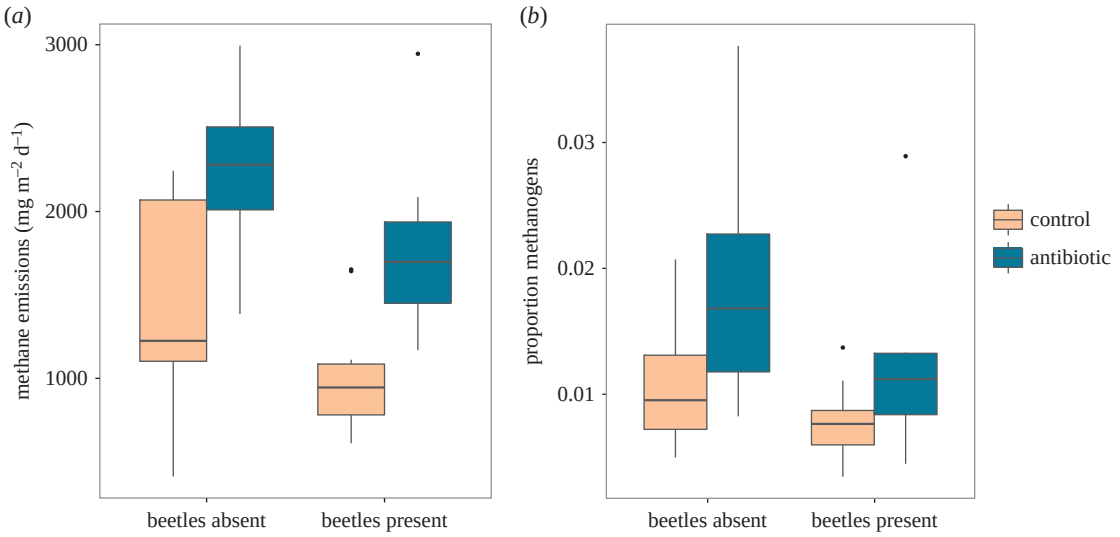

Figure 3. Dung methanogenesis is raised by antibiotic treatment and lowered by the presence of dung beetles, a pattern matched by methanogen abundance in dung microbiota. (*a*) Boxplot showing the factors affecting total methane emissions quantified from dung pats. (*b*) Boxplot showing the proportion of methanogenic archaea in DNA sequence libraries from the same dung samples. Bold horizontal lines indicate medians, box limits show first and third quartiles, whiskers extend to the most extreme values within 1.5× the inter-quartile range, and dots show outlying data points. (Online version in colour.)

activity. By contrast, fluxes of nitrous oxide, another potent greenhouse gas, were influenced by beetles in an antibiotic-dependent manner (electronic supplementary material, figure S3). Specifically, the presence of beetles raised nitrous oxide emissions ($F_{1,36} = 17.31$, $p < 0.001$), in agreement with a previous report [20] (but see [40]). In support of our original hypothesis, antibiotic treatment appeared to weaken this beetle-mediated increase (interaction $F_{1,36} = 5.85$, $p = 0.02$). There was no main effect of antibiotics alone ($F_{1,36} = 1.99$, $p = 0.17$), despite clear antibiotic-induced changes to dung microbiota (figure 1*b*). It remains to be determined whether antibiotics modulate the effect of beetle presence on nitrous oxide specifically through their impact on beetle microbiota (figure 1*a*).

(e) Implications and potential mechanism of methane effect

The large (1.8-fold) increase in methane emissions from the dung of cattle treated with antibiotics (figure 3*a*) has not been documented, despite the considerable literature on methane production from agricultural systems (e.g. [17,37–39,65,66]), and the long-standing and increasing administration of antibiotics to livestock. Previous studies have found either a short-lived decrease [65], or no effect following antibiotic treatment [66,67]; to the best of our knowledge, this is the first report of antibiotics increasing methane emissions. While dung emissions of methane are typically lower than those released from belching [68], they still comprise a substantial proportion of total agricultural methanogenesis in pasture systems [40]. Moreover, as the effects of antibiotics apparently derive from microbial interactions within the gut (explained below), they probably extend to gas emissions from enteric fermentation as well. Hence, we suggest that future research should be focused on antibiotic effects on methane emissions from belching.

The pattern of methane emissions (figure 3*a*) was qualitatively similar to that of the relative abundance of methanogens in the same dung pats (figure 3*b*). As with gas fluxes, antibiotics raised the proportional abundance of methanogens ($F_{1,35} = 8.72$, $p = 0.006$), and there was no interaction of antibiotics with beetle presence ($F_{1,35} = 0.26$, $p = 0.62$). We suggest that these patterns may be explained by competitive dynamics among gut microbiota. In the gut of ruminants and other mammals, methanogenic archaea may compete with bacteria for hydrogen, which is often scarce [69,70]. Tetracycline and some other broad-spectrum antibiotics are generally less effective against archaea, including methanogens isolated from mammalian digestive tracts [71,72]. Therefore, we propose that by specifically suppressing bacteria in the gut and subsequently in dung, antibiotic treatment enables methanogens to outcompete bacteria for hydrogen, increasing their concomitant methane output.

4. Conclusion

The routine practice of administering antibiotics to livestock [1–7] can have unexpected consequences for dung biota and greenhouse gas emissions from agriculture. First, antibiotics altered the composition of microbial communities associated with dung beetles, an ecologically important group of insects in many environments. This finding highlights a unique feature of antibacterial pharmaceuticals: even if not directly toxic to non-target animals, they may have a range of unanticipated effects by altering the microbiota of both livestock and wildlife. Second, we provide the first demonstration that antibiotics can increase dung emissions of methane, a potent greenhouse gas. Our findings call for analyses at larger scales (e.g. [40]) that take other factors into account, such as the relative importance of dung versus belching in gas emissions, and the global extent and purpose of antibiotic use in livestock production. Improved monitoring and estimates of agricultural antibiotic use will be necessary to identify whether antibiotics may impact the overall contribution of livestock production to global warming. Finally, further research into this effect will require unravelling the ecological interactions between microbes in the gut of livestock and their susceptibilities to antibiotic disturbance.

Ethics. In accordance with the Finnish Act on Animal Experimentation (62/2006), the Animal Experiment Board in Finland (ELLA) approved the procedures used in this study.

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Data accessibility. DNA sequences and all metadata are available from the Dryad Digital Repository: http://dx.doi.org/10.5061/dryad.6bs01.

Authors' contributions. T.J.H., N.F., T.R. and E.S. conceived the original idea. T.J.H. helped design the study, conducted molecular laboratory work, analysed data, and drafted the manuscript with additional input from N.F. and T.R. N.F. participated in study design and data analysis, and provided equipment and facilities for sequencing. B.H., T.R., H.V., J.T. and E.S. helped design the experiment, and J.T. administered the antibiotic treatments and handled the cows. B.H. and H.V. implemented all phases of the field experiment, including response measurements and beetle sampling. A.S. directed gas flux measurements and their interpretation. All authors contributed to the final version of the manuscript and gave approval for publication.

Competing interests. We have no competing interests.

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References

1. Mellon MG, Benbrook C, Benbrook KL. 2001 *Hogging it: estimates of antimicrobial abuse in livestock*. Cambridge, MA: Union of Concerned Scientists Publications.
2. McEwen SA, Fedorka-Cray PJ. 2002 Antimicrobial use and resistance in animals. *Clin. Infect. Dis.* **34**, S93–106. (doi:10.1086/340246)
3. Sarmah AK, Meyer MT, Boxall AB. 2006 A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (VAs) in the environment. *Chemosphere* **65**, 725–759. (doi:10.1016/j.chemosphere.2006.03.026)
4. Van Boeckel TP, Brower C, Gilbert M, Grenfell BT, Levin SA, Robinson TP, Teillant A, Laxminarayan R. 2015 Global trends in antimicrobial use in food animals. *Proc. Natl Acad. Sci. USA* **112**, 5649–5654. (doi:10.1073/pnas.1503141112)
5. U.S. Food and Drug Administration. 2015 Summary report on antimicrobials sold or distributed for use in food-producing animals. See http://www.fda.gov/downloads/ForIndustry/UserFees/AnimalDrugUserFeeActADUFA/UCM476258.pdf.
6. European Medicines Agency, European Surveillance of Veterinary Antimicrobial Consumption. 2015 Sales of veterinary antimicrobial agents in 26 EU/EEA countries in 2013. See http://www.ema.europa.eu/docs/en_GB/document_library/Report/2015/10/WC500195687.pdf.
7. Krishnasamy V, Otte J, Silbergeld E. 2015 Antimicrobial use in Chinese swine and broiler poultry production. *Antimicrob. Resist. Infect. Control*. **4**, 17. (doi:10.1186/s13756-015-0050-y)
8. Gustafson RH, Bowen RE. 1997 Antibiotic use in animal agriculture. *J. Appl. Microbiol.* **83**, 531–541. (doi:10.1046/j.1365-2672.1997.00280.x)
9. Kumar K, Gupta SC, Chander Y, Singh AK. 2005 Antibiotic use in agriculture and its impact on the terrestrial environment. *Adv. Agron.* **87**, 1–54. (doi:10.1016/S0065-2113(05)87001-4)
10. Schwarz S, Kehrenberg C, Walsh TR. 2001 Use of antimicrobial agents in veterinary medicine and food animal production. *Int. J. Antimicrob. Agents* **17**, 431–437. (doi:10.1016/S0924-8579(01)00297-7)
11. Teuber M. 2001 Veterinary use and antibiotic resistance. *Curr. Opin. Microbiol.* **4**, 493–499. (doi:10.1016/S1369-5274(00)00241-1)
12. Aarestrup FM. 2005 Veterinary drug usage and antimicrobial resistance in bacteria of animal origin. *Basic Clin. Pharmacol. Toxicol.* **96**, 271–281. (doi:10.1111/j.1742-7843.2005.pto960401.x)
13. Eghball B, Wienhold BJ, Gilley JE, Eigenberg RA. 2002 Mineralization of manure nutrients. *J. Soil Water Conserv.* **57**, 470–473.
14. Aarons SR, O'Connor CR, Hosseini HM, Gourley CJP. 2009 Dung pads increase pasture production, soil nutrients and microbial biomass carbon in grazed dairy systems. *Nutr. Cycl. Agroecosystems* **84**, 81–92. (doi:10.1007/s10705-008-9228-5)
15. Yoshitake S, Soutome H, Koizumi H. 2014 Deposition and decomposition of cattle dung and its impact on soil properties and plant growth in a cool-temperate pasture. *Ecol. Res.* **29**, 673–684. (doi:10.1007/s11284-014-1153-2)
16. Mawdsley JL, Bardgett RD, Merry RJ, Pain BF, Theodorou MK. 1995 Pathogens in livestock waste, their potential for movement through soil and environmental pollution. *Appl. Soil Ecol.* **2**, 1–15. (doi:10.1016/0929-1393(94)00039-A)
17. Jarvis SC, Lovell RD, Panayides R. 1995 Patterns of methane emission from excreta of grazing animals. *Soil Biol. Biochem.* **27**, 1581–1588. (doi:10.1016/0038-0717(95)00092-S)
18. Saggar S, Bolan NS, Bhandral R, Hedley CB, Luo J. 2004 A review of emissions of methane, ammonia, and nitrous oxide from animal excreta deposition and farm effluent application in grazed pastures. *New Zeal. J. Agric. Res.* **47**, 513–544. (doi:10.1080/00288233.2004.9513618)
19. Yokoyama K, Kai H, Koga T, Aibe T. 1991 Nitrogen mineralization and microbial populations in cow dung, dung balls and underlying soil affected by paracoprid dung beetles. *Soil Biol. Biochem.* **23**, 649–653. (doi:10.1016/0038-0717(91)90078-X)
20. Penttilä A, Slade EM, Simojoki A, Riutta T, Minkkinen K, Roslin T. 2013 Quantifying beetle-mediated effects on gas fluxes from dung pats. *PLoS ONE* **8**, e71454. (doi:10.1371/journal.pone.0071454)
21. Slade EM, Roslin T, Santalahti M, Bell T. 2015 Disentangling the 'brown world' faecal–detritus interaction web: dung beetle effects on soil microbial properties. *Oikos* **125**, 629–635. (doi:10.1111/oik.02640)
22. Nichols E, Gomez A. 2014 Dung beetles and fecal helminth transmission: patterns, mechanisms and questions. *Parasitology* **141**, 614–623. (doi:10.1017/S0031182013002011)
23. Manning P, Slade EM, Beynon SA, Lewis OT. 2016 Functionally rich dung beetle assemblages are required to provide multiple ecosystem services. *Agric. Ecosyst. Environ.* **218**, 87–94. (doi:10.1016/j.agee.2015.11.007)
24. Bang HS, Lee JH, Kwon OS, Na YE, Jang YS, Kim WH. 2005 Effects of paracoprid dung beetles (Coleoptera: Scarabaeidae) on the growth of pasture herbage and on the underlying soil. *Appl. Soil Ecol.* **29**, 165–171. (doi:10.1016/j.apsoil.2004.11.001)
25. Nichols E, Spector S, Louzada J, Larsen T, Amezquita S, Favila ME. 2008 Ecological functions and ecosystem services provided by Scarabaeinae dung beetles. *Biol. Conserv.* **141**, 1461–1474. (doi:10.1016/j.biocon.2008.04.011)
26. Wall R, Strong L. 1987 Environmental consequences of treating cattle with the antiparasitic drug ivermectin. *Nature* **327**, 418–421. (doi:10.1038/327418a0)
27. Madsen M, Nielsen BO, Holter P, Pedersen OC, Jespersen JB, Jensen K-MV, Nansen P, Gronvold J. 1990 Treating cattle with ivermectin: effects on the fauna and decomposition of dung pats. *J. Appl. Ecol.* **27**, 1–15. (doi:10.2307/2403564)
28. Floate KD, Wardhaugh KG, Boxall ABA, Sherratt TN. 2005 Fecal residues of veterinary parasiticides: nontarget effects in the pasture environment. *Annu. Rev. Entomol.* **50**, 153–179. (doi:10.1146/annurev.ento.50.071803.130341)
29. Pérez-Cogollo LC, Rodríguez-Vivas RI, Delfín-González H, Reyes-Novelo E, Ojeda-Chi MM. 2015 Lethal and sublethal effects of ivermectin on *Onthophagus landolti* (Coleoptera: Scarabaeidae). *Environ. Entomol.* **44**, 1634–1640. (doi:10.1093/ee/nvv139)
30. Schmitt H, Römbke J. 2008 The ecotoxicological effects of pharmaceuticals (antibiotics and antiparasiticides) in the terrestrial environment: a review. In *Pharmaceuticals in the environment* (ed.

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K Kümmerer), pp. 285–303. Berlin, Germany: Springer.

31. Verdú JR, Cortez V, Ortiz AJ, González-Rodríguez E, Martinez-Pinna J, Lumaret J-P, Lobo JM, Numa C, Sánchez-Piñero F. 2015 Low doses of ivermectin cause sensory and locomotor disorders in dung beetles. *Sci. Rep*. **5**, 13912. (doi:10.1038/srep13912)
32. Engel P, Moran NA. 2013 The gut microbiota of insects: diversity in structure and function. *FEMS Microbiol. Rev*. **37**, 699–735. (doi:10.1111/1574-6976.12025)
33. Douglas AE. 2015 Multiorganismal insects: diversity and function of resident microorganisms. *Annu. Rev. Entomol*. **60**, 17–34. (doi:10.1146/annurev-ento-010814-020822)
34. Looft T *et al.* 2012 In-feed antibiotic effects on the swine intestinal microbiome. *Proc. Natl Acad. Sci. USA* **109**, 1691–1696. (doi:10.1073/pnas.1120238109)
35. Looft T, Allen HK. 2012 Collateral effects of antibiotics on mammalian gut microbiomes. *Gut Microbes* **3**, 463–467. (doi:10.4161/gmic.21288)
36. Maurice CF, Haiser HJ, Turnbaugh PJ. 2013 Xenobiotics shape the physiology and gene expression of the active human gut microbiome. *Cell* **152**, 39–50. (doi:10.1016/j.cell.2012.10.052)
37. Moss AR, Jouany J, Newbold J. 2000 Methane production by ruminants: its contribution to global warming. *Ann. Zootech.* **49**, 231–253. (doi:10.1051/animres:2000119)
38. Kebreab E, Clark K, Wagner-Riddle C, France J. 2006 Methane and nitrous oxide emissions from Canadian animal agriculture: a review. *Can. J. Anim. Sci*. **86**, 135–158. (doi:10.4141/A05-010)
39. Martin C, Morgavi DP, Doreau M. 2010 Methane mitigation in ruminants: from microbe to the farm scale. *Animal* **4**, 351–365. (doi:10.1017/S1751731109990620)
40. Slade EM, Riutta T, Roslin T, Tuomisto HL. 2016 The role of dung beetles in reducing greenhouse gas emissions from cattle farming. *Sci. Rep*. **6**, 18140. (doi:10.1038/srep18140)
41. Roslin T. 2001 Spatial population structure in a patchily distributed beetle. *Mol. Ecol*. **10**, 823–837. (doi:10.1046/j.1365-294X.2001.01235.x)
42. Vessby K. 2001 Habitat and weather affect reproduction and size of the dung beetle *Aphodius fossor*. *Ecol. Entomol*. **26**, 430–435. (doi:10.1046/j.1365-2311.2001.00331.x)
43. Hammer TJ, Dickerson JC, Fierer N. 2015 Evidence-based recommendations on storing and handling specimens for analyses of insect microbiota. *PeerJ* **3**, e1190. (doi:10.7717/peerj.1190)
44. Hammer TJ, McMillan WO, Fierer N. 2014 Metamorphosis of a butterfly-associated bacterial community. *PLoS ONE* **9**, e86995. (doi:10.1371/journal.pone.0086995)
45. Ramirez KS *et al.* 2014 Biogeographic patterns in below-ground diversity in New York City's Central Park are similar to those observed globally. *Proc. R. Soc. B* **281**, 20141988. (doi:10.1098/rspb.2014.1988)
46. R Development Core Team. 2015 *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
47. Wickham H. 2009 *ggplot2: elegant graphics for data analysis*. New York, NY: Springer.
48. Oksanen J *et al.* 2015 vegan: Community Ecology Package. R package version 2.3-0. See http://CRAN.R-project.org/package=vegan.
49. Kindt R, Coe R. 1995 *Tree diversity analysis: a manual and software for common statistical methods for ecological and biodiversity studies*. Nairobi, Kenya: World Agroforestry Centre.
50. Hirschberger P. 1999 Larval population density affects female weight and fecundity in the dung beetle *Aphodius ater*. *Ecol. Entomol*. **24**, 316–322. (doi:10.1046/j.1365-2311.1999.00205.x)
51. Tammaru T, Kaitaniemi P, Ruohomäki K. 1996 Realized fecundity in *Epirrita autumnata* (Lepidoptera: Geometridae): relation to body size and consequences to population dynamics. *Oikos* **77**, 407–416. (doi:10.2307/3545931)
52. Honek A. 1993 Intraspecific variation in body size and fecundity in insects: a general relationship. *Oikos* **66**, 483–492. (doi:10.2307/3544943)
53. Hanski I, Cambefort Y (eds). 1991 *Dung beetle ecology*. Princeton, NJ: Princeton University Press.
54. Simmons LW, Ridsdill-Smith TJ (eds). 2011 *Ecology and evolution of dung beetles*. New York, NY: Wiley-Blackwell.
55. Estes AM, Hearn DJ, Snell-Rood EC, Feindler M, Feeser K, Abebe T, Dunning Hotopp JC, Moczek AP. 2013 Brood ball-mediated transmission of microbiome members in the dung beetle, *Onthophagus taurus* (Coleoptera: Scarabaeidae). *PLoS ONE* **8**, e79061. (doi:10.1371/journal.pone.0079061)
56. Grønvold A-MR, Mao Y, L'Abée-Lund TM, Sørum H, Sivertsen T, Yannarell AC, Mackie RI. 2011 Fecal microbiota of calves in the clinical setting: effect of penicillin treatment. *Vet. Microbiol*. **153**, 354–360. (doi:10.1016/j.vetmic.2011.05.040)
57. Costello EK, Lauber CL, Hamady M, Fierer N, Gordon JI, Knight R. 2009 Bacterial community variation in human body habitats across space and time. *Science* **326**, 1694–1697. (doi:10.1126/science.1177486)
58. Puniamoorthy N, Schäfer MA, Römbke J, Meier R, Blanckenhorn WU. 2014 Ivermectin sensitivity is an ancient trait affecting all ecdysozoa but shows phylogenetic clustering among sepsid flies. *Evol. Appl*. **7**, 548–554. (doi:10.1111/eva.12152)
59. Henwood CJ, Gatward T, Warner M, James D, Stockdale MW, Spence RP, Towner KJ, Livermore DM, Woodford N. 2002 Antibiotic resistance among clinical isolates of *Acinetobacter* in the UK, and in vitro evaluation of tigecycline (GAR-936). *J. Antimicrob. Chemother*. **49**, 479–487. (doi:10.1093/jac/49.3.479)
60. Coyne S, Courvalin P, Perichon B. 2011 Efflux-mediated antibiotic resistance in *Acinetobacter* spp. *Antimicrob. Agents Chemother*. **55**, 947–953. (doi:10.1128/AAC.01388-10)
61. Byrne MJ, Watkins B, Bouwer G. 2013 Do dung beetle larvae need microbial symbionts from their parents to feed on dung? *Ecol. Entomol*. **38**, 250–257. (doi:10.1111/een.12011)
62. Brownlie JC, Johnson KN. 2009 Symbiont-mediated protection in insect hosts. *Trends Microbiol*. **17**, 348–354. (doi:10.1016/j.tim.2009.05.005)
63. Feldhaar H. 2011 Bacterial symbionts as mediators of ecologically important traits of insect hosts. *Ecol. Entomol*. **36**, 533–543. (doi:10.1111/j.1365-2311.2011.01318.x)
64. Lizé A, McKay R, Lewis Z. 2013 Gut microbiota and kin recognition. *Trends Ecol. Evol*. **28**, 325–326. (doi:10.1016/j.tree.2012.10.013)
65. Johnson KA, Johnson DE. 1995 Methane emissions from cattle. *J. Anim. Sci*. **73**, 2483–2492.
66. Shibata M, Terada F. 2010 Factors affecting methane production and mitigation in ruminants. *Anim. Sci. J*. **81**, 2–10. (doi:10.1111/j.1740-0929.2009.00687.x)
67. Hashimoto AG, Varel VH, Chen YR. 1981 Ultimate methane yield from beef cattle manure: effect of temperature, ration constituents, antibiotics and manure age. *Agric. Wastes* **3**, 241–256. (doi:10.1016/0141-4607(81)90011-1)
68. Tubiello FN, Salvatore M, Rossi S, Ferrara A, Fitton N, Smith P. 2013 The FAOSTAT database of greenhouse gas emissions from agriculture. *Environ. Res. Lett*. **8**, 015009. (doi:10.1088/1748-9326/8/1/015009)
69. Strocchi A, Furne J, Ellis C, Levitt MD. 1994 Methanogens outcompete sulphate reducing bacteria for H_2 in the human colon. *Gut* **35**, 1098–1101. (doi:10.1136/gut.35.8.1098)
70. Morvan B, Bonnemoy F, Fonty G, Gouet P. 1996 Quantitative determination of H_2-utilizing acetogenic and sulfate-reducing bacteria and methanogenic archaea from digestive tract of different mammals. *Curr. Microbiol*. **32**, 129–133. (doi:10.1007/s002849900023)
71. Dridi B, Fardeau M-L, Ollivier B, Raoult D, Drancourt M. 2011 The antimicrobial resistance pattern of cultured human methanogens reflects the unique phylogenetic position of archaea. *J. Antimicrob. Chemother*. **66**, 2038–2044. (doi:10.1093/jac/dkr251)
72. Khelaifia S, Drancourt M. 2012 Susceptibility of archaea to antimicrobial agents: applications to clinical microbiology. *Clin. Microbiol. Infect*. **18**, 841–848. (doi:10.1111/j.1469-0691.2012.03913.x)

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Deep learning to map concentrated animal feeding operations

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Enforcement of environmental law depends critically on permitting and monitoring intensive animal agricultural facilities, known in the United States as 'concentrated animal feeding operations' (CAFOs). The current legal landscape in the United States has made it difficult for government agencies, environmental groups and the public to know where such facilities are located. Numerous groups have, as a result, conducted manual, resource-intensive enumerations based on maps or ground investigation to identify facilities. Here we show that applying a deep convolutional neural network to high-resolution satellite images offers an effective, highly accurate and lower cost approach to detecting CAFO locations. In North Carolina, the algorithm is able to detect 589 additional poultry CAFOs, representing an increase of 15% from the baseline that was detected through manual enumeration. We show how the approach scales over geography and time, and can inform compliance and monitoring priorities.

As US agriculture has grown and industrialized, livestock production has shifted to operations that exclusively raise large numbers of animals in confinement[1]. These CAFOs are estimated to produce more than 40% of US livestock[2], with large facilities each raising over 2,500 pigs or 125,000 broiler chickens[3]. Such specialization not only increases productivity, but also raises important questions about environmental impact. For recent reviews on the evidence of health and environmental effects of CAFOs, see previously published studies[4,5]. As the Environmental Protection Agency (EPA) noted, agriculture is "the leading contributor of pollutants to identified water quality impairments in the Nation's rivers and streams, lakes, ponds, and reservoirs"[6]. Livestock generate 13 to 25 times the amount of manure that humans produce; however, animal waste, in contrast to human waste, is not required to be treated[7]. CAFOs generate about 335 million tons of waste per year, with excess nutrients posing considerable ecological and human health risks[8,9].

Yet litigation over the past few decades has hindered regulatory efforts and environmental monitoring of CAFOs. Under the US Clean Water Act, CAFOs that 'discharge' pollutants into national waters are required to apply for and abide by the terms of a federal permit, known as the National Pollutant Discharge Elimination System (NPDES). NPDES permits require discharge reporting and violations of permit effluent limitations can trigger substantial fines. Federal courts have rejected the EPA's proposals to cover CAFOs that had the potential to discharge, holding that the EPA could only require permits for CAFOs that actually discharge pollutants (see *Waterkeeper v. EPA*[10] and *Nat'l Pork Producers Council v. EPA*[11]). Under-permitting—the failure to apply for a permit when required—is known to be a serious issue, as the EPA estimates that nearly 60% of CAFOs do not hold permits[12]. In 2008, the Government Accountability Office lamented the lack of basic information about CAFOs: "no federal agency collects accurate and consistent data on the number, size, and location of CAFOs"[13]. In 2011, the EPA proposed running a survey to collect such information, including global positioning system (GPS) location and size. The EPA sought comments on existing data sources, including the possibility of "augment[ing] information from satellite images and aerial photography location information to obtain a comprehensive, consistent national inventory of CAFOs"[12]. The proposal was withdrawn in 2012, with the EPA highlighting the possibility of obtaining such information from existing data sources[14]. In 2016, after the EPA requested the return of data it had released, a federal court concluded that the EPA could not release available GPS coordinates as a dataset, even in instances where individual locations were publicly available (*American Farm Bureau Fed. v. EPA*[15]). Owing to these developments, scholars have criticized the lack of basic information about CAFOs[16–18].

In response to the lack of information about CAFOs, a wide range of environmental and public interest groups—including Pew Charitable Trusts[19,20], the National Resources Defense Council[20], the Environmental Working Group[21], Food and Water Watch[22], Waterkeeper Alliance[21], the Sierra Club[23] and EarthJustice[20,24]—has engaged in extensive and resource-intensive efforts to improve monitoring of CAFOs. Because location information is critical for monitoring discharges and other forms of environmental noncompliance, numerous groups have attempted to collect more-comprehensive information about CAFO coordinates. Two groups, for instance, hired contractors to manually scan through satellite images in select states to identify CAFOs[21], including over three years of data for each state (S. Rundquist, personal communication). In other instances, contractors physically identified facilities by plane or car (J. Quinlivan, personal communication). After environmental interest groups (EIGs) petitioned to remove Iowa's authority to permit CAFOs, the EPA and Iowa's Department of Natural Resources entered into an agreement requiring Iowa to conduct a comprehensive census of CAFOs. To comply with the agreement, Iowa employed individuals to manually label satellite images, a process that took roughly 3.5 years to complete[25]. Although valuable, such efforts are resource-intensive and do not easily scale over time and geography.

We contribute to this important issue of public health and environmental law, science and sustainability by demonstrating how recent advances in image-learning, or 'deep-learning', techniques

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Fig. 1 | Examples of image occlusion. a–d, Examples of occluded (**a**,**c**) and non-occluded (**b**,**d**) images of poultry (**a**,**b**) and pig (**c**,**d**) CAFOs.

can considerably lower the cost of environmental monitoring and regulatory enforcement. Applications of deep learning to agricultural data have been reviewed previously[26]; however, the previous study does not include a case for environmental regulation of CAFOs. Although locating facilities alone does not measure discharges, it is a necessary, and time-consuming, step for any form of monitoring. We construct a dataset of pig and poultry CAFOs in North Carolina, by manually validating the data from a manual census conducted by two leading EIGs against publicly available, high-resolution satellite images from the US Department of Agriculture's National Agricultural Imagery Program (NAIP). Acquired annually during the growing season on a three-year cycle staggered across states, these images are easily downloadable through an online service at resolutions up to 1 m per pixel (Supplementary Notes). We downloaded all imagery for the state of North Carolina in the format of 299 × 299 image tiles at a resolution of 1 m per pixel and manually tagged 24,440 images. We trained two convolutional neural networks (CNNs) to detect the presence of pig and poultry CAFOs individually and demonstrate high-classification accuracy on the 25% of image tiles reserved for testing.

Although a necessary first step, determining whether an image tile contains a CAFO (henceforth referred to as 'image-level' predictions) is less useful for the regulatory context, as a single CAFO facility can be split across multiple image tiles. To consolidate image scores into actual facility locations for regulators (henceforth referred to as 'facility-level' predictions), we focused on poultry operations, which can contribute as much nutrient run-off to watersheds as pig operations[27,28], but are largely unpermitted in North Carolina and are therefore substantially harder to detect. We developed an algorithm to transform scores for image tiles into latitude and longitude point locations for individual poultry facilities. We show with manually validated results that we can detect 15% more poultry CAFOs than previously known. We further illustrate the utility of our approach by showing how it scales geographically and longitudinally and provides legally important estimates of facility size and other compliance priorities. Given the global growth in intensive livestock farming[29], our methods have potential for other jurisdictions.

Results

First, we demonstrate the accuracy of the model at the image level on the 25% of manually validated images that was reserved for test-

Table 1 | Image accuracy statistics

	Area under the curve			CAFO	Control
	Image	ROC	PR		
Poultry	All images	0.972	0.917	833	4,871
	Non-occluded	0.998	0.980	262	4,871
Pigs	All images	0.986	0.923	399	4,871
	Non-occluded	1.000	0.991	124	4,871

Statistics are presented for all test images (all images) and test images without occluded CAFO images (non-occluded). PR, precision-recall curve; ROC, receiver-operating characteristic curve.

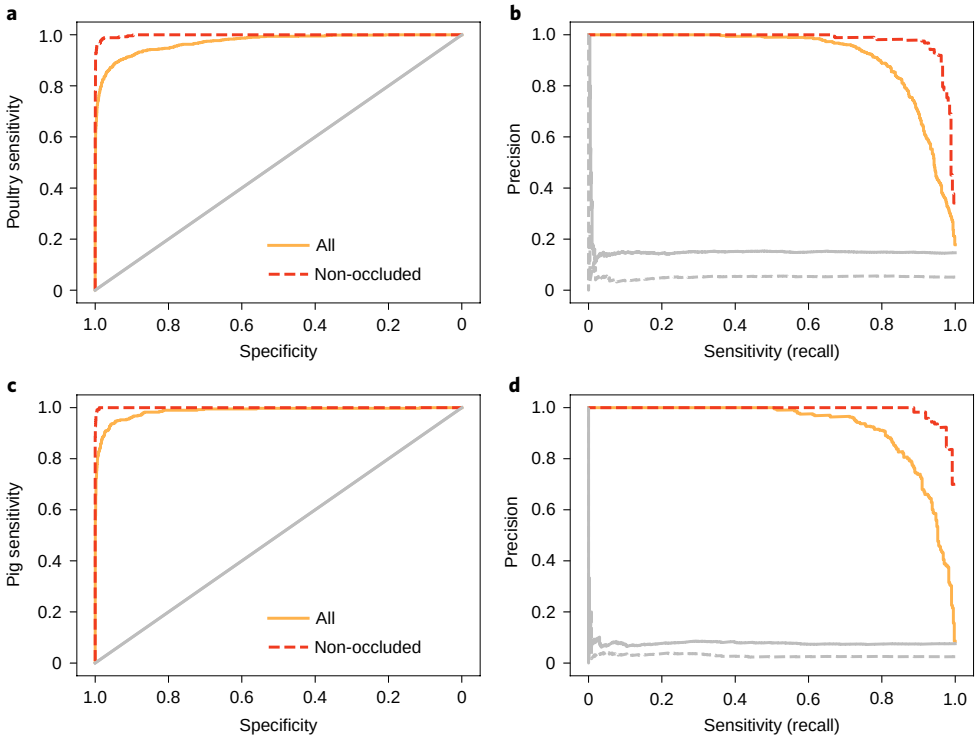

Fig. 2 | Classification performance. a–d, ROC curves (**a**,**c**) and precision-recall curves (**b**,**d**) for the poultry (**a**,**b**) and pig (**c**,**d**) models on the test set of images, split by whether the test sample included occluded CAFO images. The grey lines in each panel represent the performance of a random classifier predicting the presence of a poultry (**a**,**b**) or a pig (**c**,**d**) CAFO (dashed grey lines are associated with non-occluded images, solid grey lines with all images).

ing. Image tiles present a convenient unit of analysis but are limited in their ability to depict entire facilities due to the fact that facilities can span multiple images. Because tiles at times occluded substantial parts of the CAFO, we report accuracy metrics using (1) all CAFO and control images and (2) non-occluded CAFO images and all control images. We define 'non-occluded' as pig CAFO images with at least 25% of the image taken up by the CAFO facility or lagoon and, because poultry CAFOs tend to lack lagoons, poultry images with at least 10% of the image taken up by the CAFO facility (Fig. 1). Second, we report results from our facility identification, which addresses occlusion (when the facility is only partially in the image) by recentring images after an initial round of scoring and assigning latitude and longitude locations for poultry facilities within the images.

Image level. Because the optimal classification threshold (the probability level at which to classify an image as containing a CAFO) will vary on the basis of the end-user's tolerance for false-positive and false-negative images, we assessed performance at all classification thresholds between 0 and 1 for a holistic view of model performance. We first generated three standard classification accuracy metrics:

$$\text{Sensitivity} = \frac{\text{No. correct CAFO predictions}}{\text{No. CAFO images}}$$

$$\text{Specificity} = \frac{\text{No. correct control predictions}}{\text{No. control images}}$$

$$\text{Precision} = \frac{\text{No. correct CAFO predictions}}{\text{No. all CAFO predictions}}$$

where a CAFO prediction is correct if a CAFO image receives a CAFO probability score above a certain threshold, a control prediction is correct if a control image receives a CAFO score below that same threshold. Sensitivity (also known as recall) captures the proportion of correct predictions among CAFO images; specificity captures the proportion of correct predictions among control images; and precision, a measure of search relevance, captures the proportion of CAFO predictions that are truly CAFOs. The summary statistics that we present incorporate these metrics at all possible classification thresholds between 0 and 1.

With these metrics calculated at every classification threshold, we computed the area under the curve for the receiver-operating characteristic (ROC) curve, which plots specificity against sensitivity at each threshold and the precision-recall curve, which plots precision against sensitivity at each threshold. The area under the ROC curve provides a sense of average sensitivity across all possible values of specificity, whereas the area under the precision-recall curve provides a sense of average precision at all possible values of sensitivity. We report both sets of statistics because the precision-recall curve is recommended with class imbalance[30]. Relative to all of North Carolina, CAFOs are rare. On the basis of the EIG data, CAFO images constitute about 0.37% of the 1,684,879 images in North Carolina. Imbalance is more exaggerated statewide than in the test set owing to our attempt to manually validate as many CAFO images as possible. To provide a sense of performance on all images statewide, Supplementary Fig. 8 presents a weighted version of these metrics, using the weighting procedure described in the Supplementary Notes. For all metrics, values close to 1 indicate higher accuracy.

Table 1 presents the area under the curve values for the pig and poultry models, and Fig. 2 plots the corresponding ROC and precision-recall curves for all images (solid) and images without occlusion (dashed). Among all test images, the area under the curve for the poultry ROC curve is 0.97, which rises to over 0.99 for poultry and pig when excluding occluded CAFO images. We see comparable improvement in precision-recall curves when excluding occluded CAFO images. Table 1, however, shows that non-occluded



Fig. 3 | Illustration of class activation map algorithm for image-level classification. a, The algorithm first performs class activation mapping on the original image. **b**, Subsequently, the algorithm identifies the centroid of the activated clusters found by *k*-means clustering. **c**, The image is then recentred. **d**, Finally, the algorithm performs class activation mapping on the recentred image with both the pig and poultry models to identify the final class and size of the CAFO object. The poultry and pig scores in the top right corners of **b** and **d** indicate the predicted probability of the image containing a poultry or pig CAFO, respectively, obtained from the models.

CAFO images comprise only about 30% of all CAFO images, suggesting that more work is needed to transform image predictions into a useful format.

Facility level. As a substantive matter, environmental groups and regulators are more concerned with the locations of individual facilities than with the images. As is evident from Table 1, image occlusion stemming from the tile system may hinder detection of facilities. Figure 3 shows that when lagoons are occluded, a pig CAFO may appear close to a poultry CAFO, because the tile obscured the liquid manure storage system that is prototypical of pig CAFOs.

We therefore developed an approach to consolidate image-level predictions into latitude and longitude coordinates of unique facilities. We utilized 'class activation maps,' which depict which pixels activate the predicted class[31]. After classifying poultry CAFOs at the image level by taking the maximum score across the pig and poultry models, we used these activation maps to recentre the image on the CAFO. We then rescored the recentred images with both CNN models, and discarded any facilities for which the maximum score was no longer the poultry score or did not meet the poultry classification threshold. Finally, we clustered the activated pixels in the recentred image and represented the facility as a polygon shape, using the polygon centre as the point location. The end result is a list of latitudes and longitudes for (predicted) poultry facilities. Figure 3 depicts this process for a CAFO initially classified as poultry due to occlusion, but that was (correctly) reclassified as pig after recentring revealed the manure lagoon (see Supplementary Methods for details).

To provide a sense of performance, we manually validated the point locations for 4,659 predicted poultry facilities using a score threshold of 0.5 for the initial image-level predictions. We chose this threshold for demonstration purposes because it maintained a high harmonic mean of sensitivity and precision in both the weighted and unweighted test image samples (Supplementary Fig. 7). In practice, however, researchers may use different classification thresholds to meet their tolerance for false-positive and false-negative images. We also matched each confirmed poultry facility location to the nearest EIG location to determine the overlap between our results and the manual census. We considered model-identified CAFO locations to be the same as EIG locations when they were within 250 m of each other. Supplementary Figure 11 shows that this distance threshold correctly matched EIG locations to modelled locations in 99% of cases in a validation sample.

Through our earlier manual-validation efforts, we discovered that roughly 1.4% of EIG facility locations did not locate an existing poultry CAFO in reference to our NAIP imagery. Adjusting for this source of noise, we found that 73% of our predicted poultry facility locations were truly poultry CAFOs (analogous to precision),

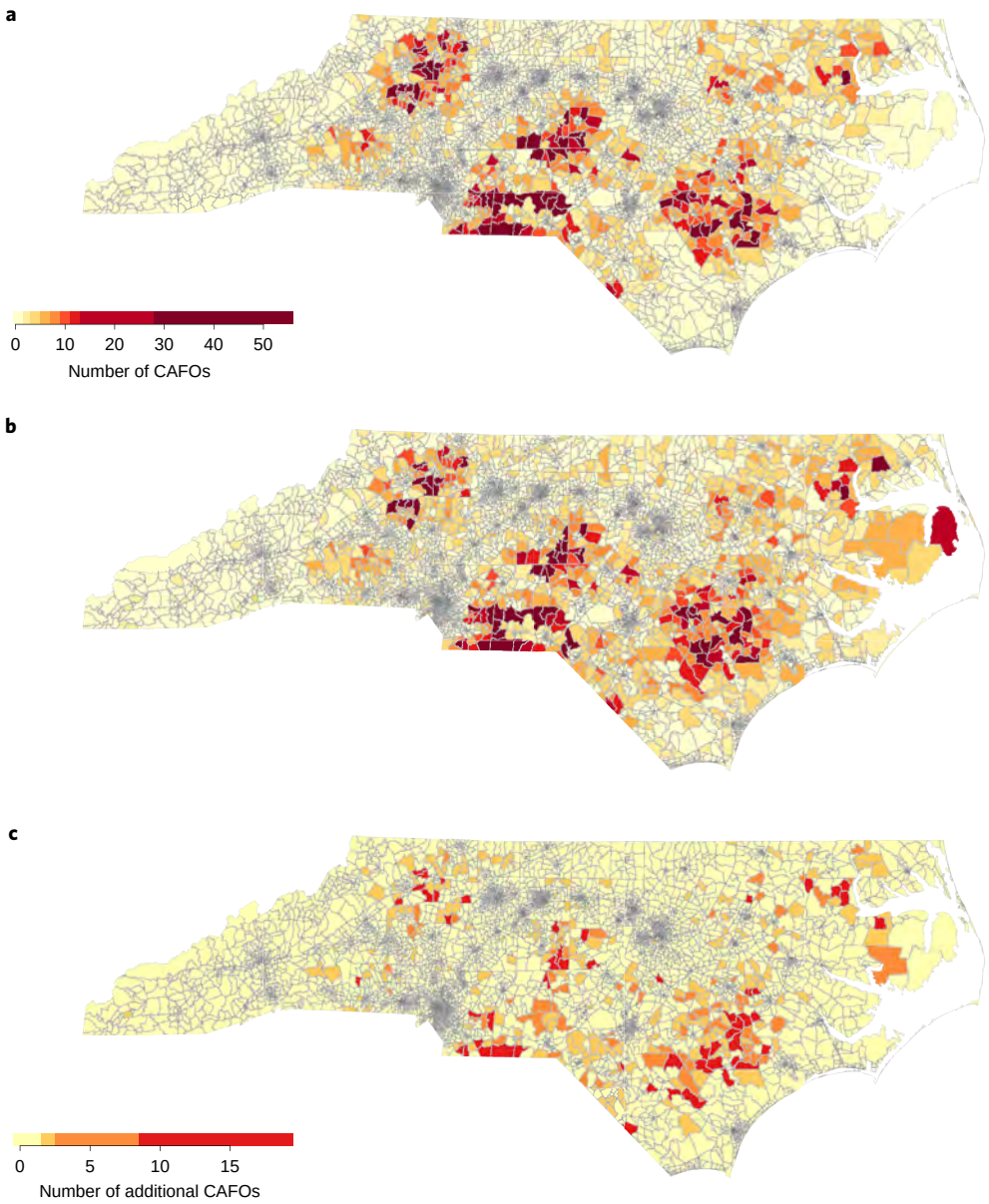

Fig. 4 | Heat map of manually identified and modelled poultry locations. a,**b**, The locations across North Carolina obtained by manual tagging efforts (**a**) and the fully automated machine-learning solution (**b**), including false-positive images. **c**, The 589 confirmed additional poultry facility locations.

whereas our predicted facility locations included 70% of EIG identified locations (analogous to sensitivity). It is worth noting that such precision is quite high given that CAFOs comprise only 0.4% of the raw image data. On average, modelled point locations were 60 m from the manually coded location provided by EIGs, when the length of a conventional CAFO barn can easily exceed 100 m.

Our model results and validation supplement EIG data in important ways. The validation efforts helped to identify difficult-to-classify facilities. Among the 1.4% of EIG locations that did not locate a poultry CAFO, for example, was a facility that visually appeared to be a CAFO, but was in fact a warehouse (Supplementary Fig. 13). Most importantly, although the model missed CAFOs that were manually detected by EIGs at a threshold of 0.5, it also detected an additional 589 CAFOs that EIGs were unable to detect. This is perhaps because the timing of the NAIP imagery (2014–2016) did not line up with the timing of the EIG manual census (2013–2014) or because, even to the human eye, poultry facilities can appear similar to other objects, such as airplane hangars and greenhouses, in aerial imagery because they lack outdoor lagoons. The newly detected facility locations represent a 15% gain from the manual census. Similar to capture–recapture methods[32], the model can help to identify facilities that may have been missed with the manual census of CAFOs.

One limitation to this facility-level analysis is that it is computationally intensive. That said, it is considerably less computationally demanding than image classification methods that use overlapping strides to ensure that CAFOs are centred in at least one image. Consolidating images into facility locations additionally reduces the burden on manual reviewers: at a threshold of 0.5, consolidation into facility locations reduces the number of items for review by nearly half (from 8,165 images to 4,659 facility locations).

Discussion

Having demonstrated the accuracy of a deep-learning approach, we illustrate some potential benefits and applications and conclude with future directions.

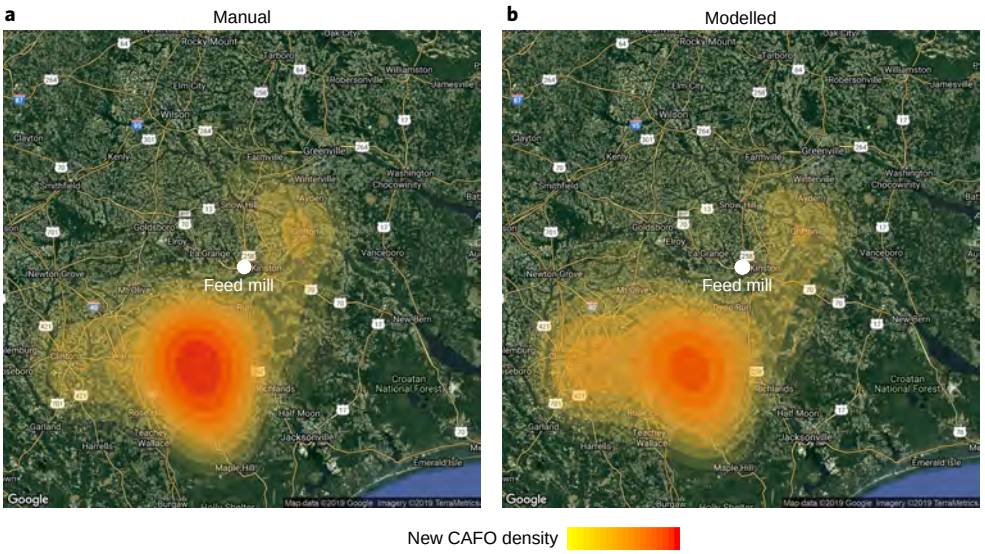

Fig. 5 | Longitudinal detection of CAFO growth. The density of poultry CAFO locations constructed after a feed mill opened in 2011 was quantified. **a**, Manually tagged density of CAFOs constructed after the feed mill opened. **b**, Modelled density.

Compared to the existing manual census, our approach promises to save considerable resources. For instance, the Environmental Working Group employs individuals to manually scan across a territory of satellite images on Google Maps, averaging 1.5 h per 1,000 km^2. To classify the entire state of North Carolina by manual tagging would require nearly 6 weeks of full-time work; to classify the entire United States would require over 7 years for a single imagery set. This manual census becomes infeasible as satellite coverage expands, for example, when including daily captures of the full globe[33]. By contrast, the automated approach can score North Carolina in fewer than 2 days with a standard workstation. The model may also be used as a complement to pinpoint where resources to validate images should be deployed. On the basis of the precision-recall curves weighted at the expected state-level distribution of images (269 control images for every CAFO image), we estimate that one could capture 75% of poultry CAFOs using less than 2% of manual resources or 95% of poultry CAFOs using less than 10% of manual resources (Supplementary Fig. 9). The facility consolidation approach reduces the use of manual resources even further—one can capture 70% of manually tagged poultry CAFOs using 0.28% of manual resources, while identifying an additional 15% of previously unknown facilities. Figure 4 provides a heat map of the distribution of poultry locations, comparing the manually identified locations with model-based locations. These maps show that our model is able to recover the geographical distribution of CAFOs extremely well.

Our approach also scales over time. This is important because the Government Accountability Office has expressly noted that the lack of consistent and reliable data has impeded the ability to understand changes in agricultural practices over time[13]. NAIP imagery data, however, were available at the same resolution in North Carolina from 2008 to 2016 (Supplementary Notes). Using these longitudinal data, we examined whether the construction of large industrial feed mills was associated with growth in poultry CAFOs[34]. We used public materials to identify the construction of feed mills in North Carolina and focused on one constructed in 2011. We applied our model to a 80-km radius around the feed mill, because this radius has been described to be the threshold for transportation costs[35], and manually tag historical NAIP images for validation. Figure 5 plots the area around the feed mill along with the density of poultry CAFOs that opened after the feed mill was constructed. The model detected 93% of all poultry CAFOs in the area and was 97% accurate in determining which ones appeared after the feed mill had opened.

Our approach may also help to determine NPDES compliance priorities. The class activation map can provide a meaningful measure for size, which is a critical dimension under federal law. The EPA has lamented the lack of information on size, as decentralized enforcement has resulted in missing, outdated or biased data, impeding prioritization across jurisdictions. We estimate the square footage of poultry CAFOs based on the activation maps (see Supplementary Methods for details). To assess the quality of estimates, we manually coded the number of barns for all model-detected facilities in Duplin and Cumberland counties. The Spearman rank correlation coefficient between the manually coded number of barns and the model size estimates is 0.46 ($P < 0.001$), showing that these estimates may be a meaningful way to enable environmental groups and regulators to prioritize resources.

In addition, our approach can facilitate the identification of facilities that pose particular risk due to proximity to water sources or abandonment. Supplementary Figures 14 and 15 provide specific examples. Abandoned CAFO sites may be cross-referenced with expired permit data to determine which facilities have undergone the appropriate clean-up procedures. Facilities operating under a Clean Water Act permit are required to remove waste and facilities from the site upon closure. Without such clean-up, the abandonment of all sites, permitted or not, can have considerable ecological consequences and should be prioritized for environmental compliance.

We conclude with some thoughts on future directions. First, although computer vision has been most rapidly adopted in the private sector, the public sector has been late to adopt artificial intelligence, creating a substantial 'technology gap'[36]. Our case study suggests that smart compliance, rather than displacing conventional enforcement[37], may free up the resources of nonprofit organizations and government agencies to focus efforts on facilities that pose the greatest risk of environmental harm. Partnerships between groups with the technical capacity and regulators are crucial to bridging the technology gap. Second, the challenge that we faced when trying to reconcile the EIG and NAIP data illustrates the importance of replicability. When nonprofit organizations or governments conduct exhaustive manual surveys, storing the underlying data (that is, image files or date stamps) should greatly facilitate the application of computer vision. Third, more work remains to be done to enable the efficient search

for, and detection and localization of, facilities. Last, although we demonstrated that our approach yields accurate predictions, prediction errors are of course still expected. Given that regulation demands high accuracy, a more appropriate solution may be a hybrid one, in which humans can iteratively refine model predictions[38].

We believe much work can be done to facilitate environmental monitoring, as satellite imagery data are available at continuously increasing resolution and frequency. One company, for instance, captures the globe's landmass on a daily basis[39] and another company captures images at 15 cm per pixel[40]. These improved data and the methods described herein may ultimately enable not only the identification of CAFOs, but also more genuine discharge measurements of CAFOs. Such applications may be useful not only in the context of the United States, but also in many other countries that have seen rapid growth in industrial agriculture[29].

Methods

Data. We started with two raw data sources. First, we obtained the most recent release of NAIP satellite images for North Carolina (2014–2016). We took advantage of the research platform from Descartes Labs, a geospatial analytics company, to download 299 × 299 image tiles, at 1 m per pixel, using the universal transverse mercator grid for North Carolina (Supplementary Notes). For the entire state, these raw NAIP data comprised 1,684,879 images (~32 gigabytes). Second, we obtained data from two environmental groups that contained point locations (latitude and longitude) of pig and poultry CAFOs from the manual census of North Carolina conducted between 2013 and 2014. The Environmental Working Group collected information on pigs and Waterkeeper Alliance collected information on poultry, which we call the EIG data. EIG point locations are based on permit data for pigs and a combination of ground monitoring and manual tagging of Google Earth satellite images for poultry. Owing to time differences in imagery data and imprecision in latitude and/or longitude (for example, referring to mailing address not agricultural facility), EIG point locations did not always resolve to a CAFO image in the NAIP data.

To resolve these differences in EIG and NAIP data for ground-truth data, we trained a team of student researchers to validate and tag NAIP images using a web application (Supplementary Fig. 1). For each image, coders were instructed to compare NAIP images against Google Maps and historical imagery on Google Earth where necessary, and to code animal type (pig, cattle, poultry or other) and facility features (building, manure storage type or feedlot). We validated our protocol for distinguishing CAFO types against the protocol independently derived by EIGs. Coders also indicated the proportion of the image depicting the CAFO and the proportion of the CAFO depicted in the image (see Supplementary Fig. 2 for examples). During the initial training of research assistants, we double-coded all images to ensure inter-coder reliability. Subsequently, the team met weekly to review and resolve classification conflicts on a randomly sampled subset of images.

We assigned the team (1) all NAIP images with an EIG (suspected CAFO) point location, (2) all images neighbouring an EIG point location on the universal transverse mercator grid (to match topology), and (3) randomly sampled control images, which were suspected not to contain a CAFO from the EIG census. Owing to resource constraints and the sheer number of control images, we developed a prototype model (98% accuracy) to help us to focus our efforts on more difficult control images to classify. Using scores from this model, we excluded control images with very low probabilities (below 0.007) of containing a CAFO from manual validation. We arrived at this score threshold through manual inspection of a random sample of results. Supplementary Figure 3 shows a representative set of excluded images, which tended to consist of trees and empty landscapes. The threshold excluded a total of 339,020 images out of 1,684,879 (about 20%) from eligibility to be sampled for manual validation. Supplementary Figure 4 confirms that these excluded images also had scores concentrated below 0.01 in the final poultry and pig models. We also oversampled difficult-to-classify images for manual validation by identifying Google's place categories that were associated with false-positive images in prototype models (see Supplementary Methods for details).

In total, the research team validated 24,440 images, with 3,385 and 1,599 images substantially depicting poultry and pig CAFOs, respectively. Interrater reliability for classification decisions was high (96% agreement).

Image modelling. We leveraged recent advances in image processing that have rapidly improved classification performance by CNNs, often dubbed 'deep learning'[41,42]. We applied transfer learning with Google's Inception V3 in the TensorFlow framework[43], which uses features learned on much larger image datasets, to retrain the final CNN layer for our classification problem[44].

Our classification problem involved three classes: poultry CAFOs, pig CAFOs and no CAFOs (control). There are several approaches to this type of multi-class problem. One approach would be to develop a single CNN to issue scores for all three classes at once. Another approach would be to develop one CNN to classify poultry CAFOs and another to classify pig CAFOs, with classification based on the higher of the two scores. Supplementary Figure 5 shows that the separate model approach outperformed the single model approach when it came to distinguishing poultry from pig images. Accordingly, we trained two separate CNNs to obtain probability scores for pig and poultry CAFOs independently.

We applied techniques common to CNNs to reduce overfitting on our training dataset[45,46]. In particular, we switched the left–right orientation of the images at random intervals, and randomly permuted the saturation (colour intensity) and brightness (contrast) of the RGB channels in the images. We also applied dropout to the input layer of our neural network, for which input units are randomly dropped during training with fixed probability to pare down the network[47]. Our classification problem involves substantial class imbalance: manual EIG coding produced 3,969 poultry locations and 2,291 pig locations out of 1,684,879 images of the entire state. Such class imbalance has been shown to negatively impact classification performance[48,49]. Accordingly, we naively oversampled images of CAFOs to match the number of images without CAFOs in the training set to enhance learning on the minority (CAFO) class. Supplementary Table 1 shows that naive oversampling outperformed other class-balancing techniques on prototype models. In addition, we oversampled difficult control images for manual validation. We randomly sampled high-scoring false-positive images from early rounds of model training and categorized them according to Google's place categories (see Supplementary Methods for details). These images were added to subsequent training rounds as control images. To optimize the learning rate (that is, the rate at which parameters of the loss function are updated in gradient descent), we used a triangular learning rate policy with an exponential decay parameter[50]. Supplementary Figure 6 provides a visualization of this procedure.

We randomly split our manually validated data into 60% for training, 15% for validation and 25% for testing. Because an image may only partially depict a CAFO (see Fig. 1 for examples of image occlusion), we experimented with limiting the CAFO images in the training set based on the fraction of the image depicting a CAFO and the fraction of the CAFO depicted in the image. Because pig CAFOs generally contain outdoor lagoons (manure storage pits), model performance improved when more of the image depicted the CAFO, increasing the chances that both facility and lagoon would be visible. Because poultry CAFOs tend to lack outdoor lagoons, more of the facility tended to fit within the image and performance improved when more of the CAFO was depicted in the image. Supplementary Table 2 describes the criteria that we used to limit CAFO images in the training set.

Facility detection. Because the image probability scores do not represent the proportion of a CAFO displayed in the image, image predictions do not provide the required facility locations (see the top panel of Supplementary Fig. 10 for an example). We required a localization approach to consolidate image-level predictions to a unique list of facilities with latitude and longitude point locations. The global average pooling layer of a CNN with Inception V3's architecture can perform localization tasks through a technique called class activation mapping[31]. This technique computes the dot product of the final softmax weights for a particular class and the feature map at the final global average pooling layer of the network to obtain a spatial representation of features that have activated the class.

By identifying the areas of the image that the model used to obtain the CAFO classification, class activation maps provide two additional pieces of information: where the activated pixels occur within the image, and a rough estimate of the object's size within the image. To provide the additional benefit of adding context to the object, we attempted to centre the CAFO within the image before using the class activation to estimate its size. By inspecting initial class activation maps, we saw that there may be many choices for the optimal centre of the facility. In addition, there may be several objects of interest within a single image. To be sure that we were exploring all the best possible centres identified by the model, we configured an algorithm to localize and compute the area of all possible CAFO objects within each image. The Supplementary Methods provide a detailed description of the procedure, and the bottom panel of Supplementary Fig. 10 provides a visual representation.

After running the algorithm described above on our true-positive poultry images, we scored all centred images once more with the pig and poultry models. This gave us the benefit of using newfound context after recentring to discard images that appeared to depict poultry facilities only because the liquid manure storage lagoon was occluded in the first instance (Fig. 3). Once the objects were confirmed as poultry by the second round of scoring, we developed a method to combine objects that represented the same CAFO within different images. First, we calculated the distances between all CAFO object centroids in metres on the universal transverse mercator grid. Next, we iteratively combined each object into a pair with its closest neighbouring object(s) if the neighbouring object's centroid was within 250 m of its centroid. The 250-m threshold was obtained by testing a range of thresholds and manually validating the accuracy of the resulting facility locations. We define the centroid for the newly paired set of objects as the average of all objects' centroids. As a size estimate, we keep the maximum square footage among all objects as the facility size, after prioritizing higher scoring objects and objects that are fully contained within the image. We repeated this process until the minimum distance between all CAFO objects was at least 250 m. In this way, we

reduced 9,601 possible CAFO objects statewide to 4,659 unique facilities. A detailed description on how we validated this approach can be found in the Supplementary Methods.

Data availability

The replication code and datasets generated during the current study are available in the GitHub repository github.com/slnader/cafo_public.

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References

1. Dimitri, C., Effland, A. & Conklin, N. *The 20th Century Transformation of U.S. Agriculture and Farm Policy* Economic Information Bulletin 3 (USDA, 2005).
2. Copeland, C. *Animal Waste and Water Quality: EPA Regulation of Concentrated Animal Feeding Operations (CAFOs)* Technical Report No. CRS-RL31851 (Congressional Research Service, 2010).
3. *40 C.F.R. 122.23 - Concentrated Animal Feeding Operations (Applicable to State NPDES Programs)* (Environmental Protection Agency, 2011); https://www.govinfo.gov/app/details/CFR-2011-title40-vol22/CFR-2011-title40-vol22-sec122-23
4. Casey, J. A., Kim, B. F., Larsen, J., Price, L. B. & Nachman, K. E. Industrial food animal production and community health. *Curr. Environ. Health Rep.* **2**, 259–271 (2015).
5. Hribar, C. *Understanding Concentrated Animal Feeding Operations and Their Impact on Communities* (National Association of Local Boards of Health, 2010).
6. Environmental Protection Agency National pollutant discharge elimination system permit regulation and effluent limitation guidelines and standards for concentrated animal feeding operations (CAFOs). *Fed. Regist.* **68**, 7176–7274 (2003).
7. Rogers, S. & Haines, J. *Detecting and Mitigating the Environmental Impact of Fecal Pathogens Originating from Confined Animal Feeding Operations* (EPA, 2005).
8. Graham, J. P. & Nachman, K. E. Managing waste from confined animal feeding operations in the United States: the need for sanitary reform. *J. Water Health* **8**, 646–670 (2010).
9. Conerly, O. & Vazquez Coriano, L. *Literature Review of Contaminants in Livestock and Poultry Manure and Implications for Water Quality* Report No. EPA 820-R-13-002 (EPA, 2013).
10. *Waterkeeper v. EPA* [2005] 399 F.3d 486 (2d Cir. 2005).
11. *Nat'l Pork Producers Council v. EPA* [2011] 635 F.3d 738 (5th Cir. 2011).
12. Environmental Protection Agency National pollutant discharge elimination system (NPDES) concentrated animal feeding operation (CAFO) reporting rule. *Fed. Regist.* **76**, 65431–65458 (2011).
13. *Concentrated Animal Feeding Operations: EPA Needs More Information and A Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern* Technical Report No. GAO-08-944 (US Government Accountability Office, 2008).
14. Environmental Protection Agency National pollutant discharge elimination system (NPDES) concentrated animal feeding operation (CAFO) reporting rule. *Fed. Regist.* **77**, 42679–42682 (2012).
15. *American Farm Bureau Fed. v. EPA* [2016] 836 F.3d 963 (8th Cir. 2016).
16. Brown, C. R. Uncooperative federalism, misguided textualism: the federal courts' mistaken hostility toward pre-discharge regulation of confined animal feeding operations under the clean water act. *Temple J. Sci. Technol. Environ. Law* **30**, 175–219 (2011).
17. Jerger, S. EPA's new CAFO land application requirements: an exercise in unsupervised self-monitoring. *Stanf. Environ. Law J.* **23**, 91–130 (2004).
18. Moses, A. & Tomaselli, P. in *International Farm Animal, Wildlife and Food Safety Law* (eds Steier, G. & Patel, K.) 185–214 (Springer, 2017).
19. Pew Commission on Industrial Farm Animal Production *Putting Meat on the Table: Industrial Farm Animal Production in America* (Pew Charitable Trusts and Johns Hopkins Bloomberg School of Public Health, 2007).
20. Peterka, A. Enviro groups return CAFO data at heart of Hill probes. *E&E Daily* https://www.eenews.net/stories/1059979265/print (11 April 2013).
21. Formuzis, A. Fields of filth: landmark report maps feces-laden hog and chicken operations in North Carolina. *Environmental Working Group* https://www.ewg.org/release/fields-filth-landmark-report-maps-feces-laden-hog-and-chicken-operations-north-carolina (22 June 2016).
22. *Factory Farm Nation 2015 Edition* (Food & Water Watch, 2015); https://www.factoryfarmmap.org/wp-content/uploads/2015/05/FoodandWaterWatchFactoryFarmFinalReportNationMay2015.pdf
23. *Stopping CAFO Pollution* (Michigan Chapter, Sierra Club, 2018); https://www.sierraclub.org/michigan/stopping-cafo-pollution
24. *Complaint Under Title VI of the Civil Rights Act of 1964* (EarthJustice, 2014); https://go.nature.com/2VRyw15
25. *2017 Annual Report for Work Plan Agreement Between the Iowa Department of Natural Resources and the Environmental Protection Agency Region 7* (Iowa Department of Natural Resources, 2017).
26. Kamilaris, A. & Prenafeta-Boldú, F. X. Deep learning in agriculture: a survey. *Comput. Electron. Agric.* **147**, 70–90 (2018).
27. Osburn, C. L., Handsel, L. T., Peirels, B. L. & Paerl, H. W. Predicting source of dissolved organic nitrogen to an estuary from an agro-urban coastal watershed. *Environ. Sci. Technol.* **50**, 8473–8484 (2016).
28. Patt, H. *A Comparison of PAN and P_2O_5 Produced from Poultry, Swine and Cattle Operations in North Carolina* (Division of Water Resources, North Carolina Department of Environmental Quality, 2017); https://go.nature.com/2NWY3Df
29. Ilea, R. C. Intensive livestock farming: global trends, increased environmental concerns, and ethical solutions. *J. Agric. Environ. Ethics* **22**, 153–167 (2009).
30. Saito, T. & Rehmsmeier, M. The precision-recall plot is more informative than the ROC plot when evaluating binary classifiers on imbalanced datasets. *PLoS ONE* **10**, e0118432 (2015).
31. Zhou, B., Khosla, A., Lapedriza, A., Oliva, A. & Torralba, A. Learning deep features for discriminative localization. In *IEEE Conference on Computer Vision and Pattern Recognition* 2921–2929 (IEEE, 2016).
32. Amstrup, S. C., McDonald, T. L. & Manly, B. F. *Handbook of Capture–Recapture Analysis* (Princeton Univ. Press, 2010).
33. Hurst, N. How daily images of the entire Earth will change the way we look at it. *Smithsonian* https://www.smithsonianmag.com/innovation/how-daily-images-entire-earth-will-change-way-we-look-it-180962467/ (13 March 2017).
34. MacDonald, J. M. et al. *Contracts, Markets, and Prices: Organizing the Production and Use of Agricultural Commodities* Agricultural Economic Report No. aer-837 (US Department of Agriculture, 2004).
35. McVey, M. J. et al. Identifying an efficient feed distribution system in the Midwest. In *SAEA 2003 Annual Meeting* https://go.nature.com/2Cece28 (Southern Agricultural Economics Association, 2003).
36. Newcombe, T. Is government ready for AI? *Government Technology* http://www.govtech.com/products/Is-Government-Ready-for-AI.html (1 July 2018).
37. Walton, B. EPA turns away from CAFO water pollution. *Circle of Blue* https://www.circleofblue.org/2016/water-policy-politics/epa-turns-away-cafo-water-pollution/ (2016).
38. Branson, S. et al. Visual recognition with humans in the loop. In *European Conference on Computer Vision* Vol. 6314 (eds Daniilidis, K. et al.) 438–451 (Springer, 2010).
39. Scoles, S. 88 new satellites will watch Earth, all the time, all the places. *Wired* https://www.wired.com/2017/02/88-tiny-satellites-will-watch-time-everywhere/ (14 February 2017).
40. *What are the technical specifications for Google Imagery?* (Google, 2018); https://support.google.com/mapsdata/answer/6261838?hl=en
41. Russakovsky, O. et al. ImageNet large scale visual recognition challenge. *Int. J. Comput. Vision* **115**, 211–252 (2014).
42. Simonyan, K. & Zisserman, A. Very deep convolutional networks for large-scale image recognition. In *3rd International Conference on Learning Representations* https://go.nature.com/2TwYLwN (Computational and Biological Learning Society, 2014).
43. Szegedy, C., Vanhoucke, V., Ioffe, S., Shlens, J. & Wojna, Z. Rethinking the inception architecture for computer vision. In *IEEE Conference on Computer Vision and Pattern Recognition* 2818–2826 (IEEE, 2016).
44. Oquab, M., Bottou, L., Laptev, I. & Sivic, J. Learning and transferring mid-level image representations using convolutional neural networks. In *IEEE Conference on Computer Vision and Pattern Recognition* 1717–1724 (IEEE, 2014).
45. Simard, P. Y., Steinkraus, D. & Platt, J. C. Best practices for convolutional neural networks applied to visual document analysis. 7th International Conference on Document Analysis and Recognition. Institute of Electrical and Electronics Engineers. 958-962 (2003).
46. Krizhevsky, A., Sutskever, I. & Hinton, G. E. ImageNet classification with deep convolutional neural networks. In *Advances in Neural Information Processing Systems* Vol. 25 (eds Pereira, F. et al.) 1097–1105 (ACM, 2012).
47. Srivastava, N., Hinton, G., Krizhevsky, A., Sutskever, I. & Salakhutdinov, R. Dropout: a simple way to prevent neural networks from overfitting. *J. Mach. Learn. Res.* **15**, 1929–1958 (2014).
48. Buda, M., Maki, A. & Mazurowski, M. A. A systematic study of the class imbalance problem in convolutional neural networks. *Neural Netw.* **106**, 249–259 (2018).
49. Mazurowski, M. A. et al. Training neural network classifiers for medical decision making: the effects of imbalanced datasets on classification performance. *Neural Netw.* **21**, 427–436 (2008).
50. Smith, L. N. Cyclical learning rates for training neural networks. 2017 IEEE Winter Conference on Applications of Computer Vision. Institute of Electrical and Electronics Engineers. 464-472 (2017).

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Author contributions
C.H.-N. and D.E.H. jointly designed the study, collected data, developed the methods, performed the analysis and wrote the manuscript.

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The authors declare no competing interests.

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Assessing Potential Impacts of Livestock Management on Groundwater

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ABSTRACT

This supplemental paper provides a brief review of the potential for groundwater pollution from animal feeding operations (AFOs). Management activities that address surface water quality may reduce nutrient loads, but they may also lead to a deterioration of groundwater quality as well as additional methane emissions. Groundwater pollutants may eventually compromise surface water quality when a portion of the groundwater returns to the stream as baseflow. These cross-media effects are important to consider within a holistic review of the sustainability of AFO measures. We outline the potential risk of groundwater quality degradation from proposals to improve surface water quality.

A review of methods to quantify the potential damage to groundwater from surface water programs indicates such research would require significant groundwater monitoring and a coupling of the findings with integrated assessment and models. We discuss methods of monitoring groundwater discharge from AFOs, including discharge from associated croplands receiving manure applications. We also summarize modeling tools used to assess the impact of management measures on groundwater quality. Our findings indicate that appropriate models exist to simulate the pollutant source, to simulate processes within the root zone and in the unsaturated zone below the root zone, and to assess transport in groundwater discharging into wells, streams, and springs. Research on the integration of these models—coupling source systems with root zone/unsaturated zone pollutant fate and transport models, with groundwater models, and with surface water models—is not as well defined.

This report shows an overwhelming lack of groundwater-related data on the effects of management practices in animal operations, including nutrient management practices in crops involving manure applications. Significant additional regulatory, funding, programmatic, and research resources are needed at the federal level to address groundwater-quality concerns.

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UNDERSTANDING GROUNDWATER POLLUTION IN ANIMAL FEEDING OPERATIONS

Animal feeding operations (AFOs) can impact groundwater quality by many contaminants. Salinity, nitrate, and pathogens are of primary concern (Harter, Davis, Mathews, and Meyer 2002; Harter et al., 2008; Park et al., 2012; Unc et al., 2012); others include pesticides (Hailberg 1989; Kolpin, Jake, and Robert 1998), antibiotics and other pharmaceuticals (Watanabe, Harter, and Bergamaschi 2008), steroid hormones (Kolodziej, Harter, and Sedlak 2004; Mansell et al. 2011), and dissolved organic carbon associated with total and carbon-specific trihalomethane forming potential (Chomycia, Hernes, Harter, and Bergamaschi 2008). AFOs' sources of groundwater pollution include animal holding areas, manure storage lagoons, and cropland receiving manure (Harter, Davis, Mathews, and Meyer 2002).

Animal Holding Areas

Animal holding areas include enclosed housing units, exercise corrals, and freestalls used to shelter, contain, exercise, and feed animals. Many forms of housing have an unlined, compacted soil floor susceptible to leaching losses to groundwater. Unlined areas tend to have a dense, low permeable compacted layer immediately below unconsolidated manure materials (Mielke, Norris, and McCalla 1974; Miller et al. 2008) that can slow water infiltration. Some areas have concrete floors that contain wastes and minimize leaching. Table 1 summarizes studies of leaching past the root zone or N loading rates to groundwater from AFO corrals and feedlots.

Leaching and N loading from corrals and feedlots are highly variable and depend on many factors including dairy age, unsaturated zone thickness, stocking rate, and rainfall and evapo-transpiration rates. California dairies are required to combat these problems by avoiding standing water in corrals and collecting runoff. There is little research to assess the impact of corral designs on groundwater (Hunter 2013). Most studies are more general, and they concentrate on the magnitude of, and processes controlling, leaching losses, often without measuring impact on groundwater quality.

Table 1. Leaching from CAFO Corral and Feedlot Surfaces

Citation	Leaching Indicator/ Study Design	Results	Estimated Leaching Depth/Rate	Notes
Miller et al. 2008	Soil chloride profile from 3 feedlot pens aged 4, 5, and 53 years; Southern Alberta, Canada	Elevated chloride (4,000 ppm) only to 0.7 m (2.3 ft) depth with chloride levels of 200 below 0.7 m	0.7 m (2.3 ft)	Corral surface: 4 to 93 x 10^{-7} m/s (0.1–2.6 ft/d). Low average annual rainfall of 378 mm (15 in)
Vaillant, Pierzynski, Ham, and DeRouchey 2009	Soil chloride, nitrogen, ammonium, and nitrate profiles from 4 established feedlots in Kansas	Total N in soil profile only 1/5 of leachable N available (1,000 kg N/ha/yr [900 lbs/ac/yr] or about 3% of the excreted N). Elevated ammonium, nitrate, and chloride at surface, but background levels reached at 1 m to 2 m (3–7 ft)	Less than 3 m (10 ft). Nitrogen loading rate of 1,000 kg N/ha/yr (900 lbs/ac/yr)	21 to 50 years of continuous operation
Harter, Davis, Mathews, and Meyer 2002	Nitrate and salinity measured in a monitoring well network on 5 CA dairies	Significant increase in the groundwater salinity between upgradient and downgradient corral monitoring wells	Some leaching implied	Shallow groundwater (depth to water table less than 4.5 m or 15 ft) with well-drained, coarse soils

Drommerhausen, Radcliffe, Brune, and Gunter 1995	Nitrate in groundwater	Impacted groundwater nitrate ranged from 212 to 608 mg/L	Some leaching implied	
VanderSchans et **al.** 2009	Mass balance and groundwater modeling, California	Groundwater models are insensitive to leaching from corrals, but study estimates that urine and manure add approximately 500 mm/yr (20 in/yr) of equivalent water to the corral surface, much of which evaporates	290 mm/yr (11 in/yr) to 580 mm/yr (23 in/yr) for a sloped and unsloped corral, respectively. Nitrogen loading rate of 872 kg N/ha (778 lbs/acre)	Nitrogen loading rate consistent with Vaillant, Pierzynski, Ham, and DeRouchey 2009
Harter et al. unpublished data	Soil cores to water table (30 m or 98 ft) from corrals near Bakersfield, California	Elevated nitrate concentrations in the upper unsaturated zone are typically above 200 mg/kg (dry soil) near the surface and gradually decrease to 20–50 mg/kg at 10 m to 15 m (35 to 50 ft)		Recharge rate of 40–60 mm/yr (about 2 in/yr). Dairies were in operation for over 50 years.

Table 2. Leaching from AFO Manure Lagoons

Citation	Leaching Indicator/ Study Design	Estimated Leaching Rate	Estimated Loading Rate	Notes
Ham 2002	Water balance study of 20 lagoons in Kansas	0.07 to 0.88 m/yr (0.23–2.9 ft/yr), and averaged 0.4 m/yr (1.3 ft/yr)	Nitrogen loading rate of 400 kg N/ha/yr to 5,000 kg N/ha/yr (360–4,500 lbs N/ac/yr)	14 swine sites, 5 cattle feedlots, and 1 dairy. Effective hydraulic conductivity of the sealing layer: 1.8 x 10^{-7} cm/s (2.2 in/yr)
Harter, Davis, Mathews, and Meyer 2002	Nitrogen, nitrate, and ammonium, measured in a monitoring well network from 5 dairies, California	N/A	Total nitrogen concentration in monitoring wells with a lagoon source area varied significantly, ranging from less than 10 mg N/L to more than 100 mg N/L (45 mg/L–450 mg/L nitrate equivalent). Often, most dissolved N is in ammonium form	Dissolved ammonium-N is typically converted to nitrate-N (at a one-to-one ratio in terms of nitrogen mass) as ammonium-laden groundwater moves into more oxic zones
VanderSchans et al. 2009	Groundwater modeling based on Harter, Davis, Mathews, and Meyer 2002data from California	0.8 m/yr (2.7 ft/yr)	Nitrate concentrations on the order of 100 mg N/L (450 mg/L as nitrate) and a loading rate of 807 kg N/ha/yr (720 lbs N/ac/yr)	Similar findings in Ham's (2002) Kansas study
Brown, Vence & Associates 2004	Monitoring wells on 10 dairies (6 with lagoon monitoring wells in the CA's Tulare Lake Basin)	N/A	Lagoon monitoring well average nitrate concentrations of 3 to 45 mg N/L (15 mg/L to 205 mg/L as nitrate)	Long-term averages of one to several years

Liquid Manure Storage Lagoons

Liquid manure stored in lagoons varies widely in composition and contains dissolved and sediment-bound organic and ammonium N. Dairy lagoons can have a great impact on groundwater quality (Ham 2002; VanderSchans et al. 2009). Nitrogen loading rates to groundwater from dairy lagoons is highly variable, and much of the N leached from the lagoon is, at least temporarily, stored in the unsaturated zone (Ham 2002; Harter University of California, unpublished data).

Research on the impact of specific manure storage lagoon management practices on groundwater quality is very limited. Unrelated research has been performed on synthetic liners used for industrial wastes and landfill leachate. Properly constructed and maintained, synthetic liner systems provide excellent protection from groundwater degradation (USEPA 2001). However, the use of synthetic liners in AFOs has been limited by their cost, although some jurisdictions now require them on new lagoons. Some lagoon leaching studies have considered various liners and subsurface materials (e.g., Ham 2002) and found high leaching rates when unlined lagoons are built into sandy or gravelly subsurface materials. Soil liners containing at least 10% clay can comply with Natural Resources Conservation Service (NRCS) guidelines (NRCS 2009), but significant leaching can occur through shrink-swell fractures in lagoon sidewalls (Baram et al. 2012). Hence, synthetic liners can protect groundwater quality, while other liners require substantial post-construction monitoring.

Table 3. Leaching from Manured Fields

Citation	Leaching Indicator/ Study Design	Estimated Loading Rate	Notes
Harter, Davis, Mathews, and Meyer 2002	Review (Table 1 in article)	Nitrate concentration in leachate below the root zone and in domestic wells nearby varied widely at five to eight times above the limit for safe drinking water	None
VanderSchans et al. 2009	Groundwater modeling on two Central Valley, California, dairies	211 kg N/ha/yr (188 lbs/ac/yr) to over 700 kg N/ha/yr (630 lbs/ac/yr) with an average of 486 kg N/ha/yr (434 lbs/ac/yr)	Values near the lower end of the above range were generally achieved under relatively strict nutrient management practices whereas the average and higher values for nitrate-N losses to groundwater represent traditional manure management practices

Table 4. Manure BMPs Implemented to Reduce Salt Leaching from Fields/Corrals/Lagoons

Citation	Management Unit	Management Practice	Observed Effect on Salt Loading/Accumulation	Comments/Effectiveness
ASCE 1990	Fields, row crops, low to medium infiltration rate soils	Irrigation: Furrow[a]	Pattern of salt accumulation is high in ridges between furrows, may increase in direction of slope if irrigations are nonuniform	Effective leaching beneath furrow channels, salt left in ridges. Leaching requires more water than irrigation methods with lighter, intermittent applications

Citation	Management Unit	Management Practice	Observed Effect on Salt Loading/Accumulation	Comments/Effectiveness
ASCE 1990	Fields, close-growing crops	Irrigation: Corrugation[a]	Leaves saltier strops between corrugation channels unless entire field surface inundated	Results similar to those created by furrow methods
ASCE 1990	Fields, most crops	Irrigation: Mobile Sprinkler[a]	No salt concentrations in root zone if system designed and managed well	Uniform leaching
ASCE 1990	Fields, mostly high value crops (due to high initial cost)	Irrigation: Micro irrigation (drip, trickle, sub-irrigation)[a]	Salt concentrates at outer fringes of soil mass wetted by each emitter	Soil mass wetted by each emitter is well-leached. Difficult to leach all soil to depth of root zone
Sutton and Humenik 2003	Lagoons	Gravity settling tanks and mechanical separation systems	Commonly removes 15–25% of the solids and some of the salts from the liquid manure	None
Sutton and Humenik 2003	Manure Storage/ manure composting	After separation from the waste stream, manure solids stored/composted	During composting, volume of solids is reduced by 40–50%, and concentrated nutrients become a stable form that can be easily stored and transported to application sites	None
SJV DMTFP 2005	General Manure Treatment	Related to technology associated with manure management	Although some technologies used to treat manure can produce a solid organic fraction of with relatively low salt levels, most technologies have no effect on the quantity of salt in various manure fractions.	Addressing manure treatment technology in general
SJV DMTFP 2005	General Manure Treatment	Thermal conversion	Ash byproduct of thermal conversion concentrates phosphorus and salts so that they can be appropriately disposed or utilized for industrial processes	Thermal conversion is classified as a technology that burns waste to produce energy or treats waste to produce fuels (i.e., direct combustion, pyrolysis, gasification, and hydrothermal liquefaction). Most of these technologies are not suitable for dairy manure due to high moisture levels
SJV DMTFP 2005	Lagoon	Aeration of dairy wastewater	Unlikely to have much effect on salts or other nutrients	None

[a] Not specific to manured fields, rather irrigation method for saline conditions.

Manure Treated Cropland

N loading rates from manured fields (Table 3) are lower than those from lagoons (Table 2), but can still be several times greater than safe drinking water limits allow (Harter, Davis, Mathews, and Meyer 2002). Thus, field N mass balance estimates are key in selecting appropriate manure management practices (Harter, Davis, Mathews, and Meyer 2002; VanderSchans et al. 2009). The National Dairy Environmental Stewardship Council has recommended synchronizing crop nutrient demand with manure application and rotating vegetable and forage crops as practices to improve the N mass balance on farms by reducing or eliminating the need for commercial fertilizer (NDESC 2005).

MANAGING GROUNDWATER POLLUTION IN ANIMAL FEEDING OPERATIONS

Point source discharges in animal holding areas commonly affect groundwater over a limited area (one to a few hectares). The release of contaminants is incidental, sporadic or accidental, and of limited duration (hours to months). Point sources do not contribute significantly to basin recharge (Freeze and Cherry 1979; Bower 2000; Domenico and Schwartz 2008], but the concentration of pollutants in point source discharge and affected groundwater is extremely high. Point sources have been regulated for nearly four decades. Science has made tremendous advances to support the cleanup of existing point source pollution in ground and surface waters.

In contrast, nonpoint source pollution typically occurs repeatedly, often as part of intentional land use management practices (e.g., irrigation) over long time periods across substantial surficial areas. Nonpoint source pollution is intrinsically linked to natural, intentional, or induced recharge, particularly in agricultural regions (UN/WWAP 2006; Burow, Nolan, Rupert, and Dubrovsky 2010; Siebert 2005). For salts and N, polluted waters are typically less than one order of magnitude above regulatory limits (relatively low intensity), while background concentration levels are often less than one order of magnitude below regulatory limits. In the United States, nonpoint sources are commonly controlled through voluntary efforts, education and outreach, or economic incentives. Regulatory efforts are now increasing, but often lacking in science.

Due to their diffuse nature, the control of surface water and groundwater discharge from nonpoint sources is significantly hampered by the difficulties in capturing and monitoring the water quality during events, which are spatially widespread, highly non-uniform, and often sporadic (high spatial and temporal variability). Representative water samples from such nonpoint source discharge events are exceedingly difficult to obtain and often require a significant investment in infrastructure and sample analysis. Few scientific tools for point sources are effective for nonpoint sources. Many nonpoint tools are conceptual and lack the physico-chemical rigor of point source contaminant hydrology, particularly for groundwater.

Also, there are critical differences between surface and groundwater discharges, which are important to consider when designing management options.

First, surface water discharge is rapid, while groundwater flow is much slower. Streamflow velocities are on the order of 0.1 to 10 meters per second (0.3 to 30 feet per second). Natural groundwater velocity in production aquifers is generally on the order of a few meters to hundreds of meters per year.

Second, surface water is organized in a reverse tree branch network: discharges from many smaller streams combine and mix into a larger stream. Hence, each watershed, regardless of scale, has a single outlet that can be monitored for cumulative water quality effects. Surface streamflows that merge at a confluence generally mix within a short distance downstream. In contrast, groundwater is organized as an unstructured three-dimensional flow system, constrained by geologic settings. An aquifer has many flow entry (recharge) locations, often distributed across the landscape, and many exit (discharge) locations, such as domestic, irrigation, and municipal wells, streams, and rivers. Recharge and discharge are key

drivers of the structure and dynamics of groundwater flow patterns. Mixing of groundwater from multiple sources is limited to dispersion processes. Mixing occurs predominantly at the fringes of individual plumes, but plumes of high pollutant concentration generally do not "dissolve" into the larger groundwater body by mixing. Plumes persist for decades to centuries. For nonpoint source processes, mixing and dispersion play a limited role in the distribution of groundwater contamination due to the wide spatial extent of pollution. The dominant mixing typically happens when groundwater is discharged into a well by pumping: the groundwater is instantaneously mixed with older, typically deeper water and younger, typically shallower water entering the well screen. Similarly, groundwater discharge to streams is subject to stream mixing.

Third, the cumulative impact of nonpoint (and point) source pollution on surface water is measured at the outlet of the watershed (USGS 2013). The cumulative impact of nonpoint (and point) source pollution on groundwater is measured by statistical evaluation of distributed multi-depth monitoring network data (e.g., Harter, Davis, Mathews, and Meyer 2002; Nolan, and Hitt 2006; Visser, Broers, Heerdink, and Bierkens 2009; Lockhart, King, and Harter 2013).

Fourth, waste discharges into surface water are regulated under the Clean Water Act and subject to NPDES permits and TMDL implementation plans. Waste discharges to groundwater are not regulated under federal legislation. The registration, management, and waste disposal practices of some toxic chemicals are regulated under various federal regulations (Federal Insecticide Fungicide and Rodenticide Act [FIFRA], 7 U.S.C. 136-136y, 1972; Toxic Substances Control Act [TSCA], 15 U.S.C. (C. 53) 2601-2692, 1976; Resources Conservation and Recovery Act [RCRA], 42 U.S.C. § 6901, 1976). However, federal regulation does not prohibit or regulate the discharge of nutrients and salts into potable groundwater resources unless it is by direct injection (Safe Drinking Water Act [SDWA], 42 U.S.C. § 300f, 1974).

The characteristics of the impact on groundwater of nonpoint source pollution (as opposed to point source pollution) pose some key challenges.

First, research on the effect of specific AFO management practices on groundwater quality across the spectrum of key crops, nutrient and water management practices, and hydrogeologic conditions in the United States is lacking. Most research has focused on the effects on surface water quality.

Second, effective monitoring schemes of groundwater quality associated with AFOs are only beginning—predominantly in Europe and in some states with regulations for groundwater discharge (e.g., California).

Third, coupling of root zone modeling tools with nonpoint groundwater contamination models is in its infancy. The integration of such models with surface water models and/or land-atmosphere-climate models is almost non-existent, but is a critical research mission for USDA.

Third, given the previous points, the evaluation, assessment, and monitoring of AFO management effects on groundwater is challenging.

Fourth, manure contains potential pollutants—(pathogens, antibiotics, pesticides, other endocrine disrupting chemicals in addition to nitrogen and salts, which may be of interest to WQT—that can affect the quality of surfacewater or groundwater. Runoff into surface water provides little attenuation of these pollutants. But transport in soils and aquifers leads to significant retardation in their environmental dissemination due to sorption processes; and many pollutants are subject to significantly increased degradation (microbial or otherwise), chemical transformations, and filtration (e.g., pathogens, pollutants sorbed to colloidal matter). In those cases, decreasing pollutant runoff while increasing pollutant infiltration into soils has some potentially beneficial attenuating consequences (Kolodziej, Harter, and

Sedlak 2004; Watanabe, Harter, and Bergamaschi 2008; Koehne, Koehne, and Simunek 2009). In sandy soils or soils with significant macropore structure (e.g., cracked clay soils overlying tile drains), attenuation processes prior to recharging groundwater or discharging into tile drains may be very limited.

Fifth, organic nitrogen and ammonia nitrogen are also much less mobile in the subsurface environment than in surface runoff. However, under aerobic conditions, nitrogen ultimately is transformed to nitrate, which is highly mobile and not subject to retardation or degradation. Any dissolved salts are similarly mobile in the subsurface environment. Most groundwater underlying agricultural basins is used for drinking water, discharged to nearby (or even distant) streams, or used for irrigation. Hence, for nitrate (except where significant denitrification is known to occur) and for salinity, the transfer of surface water discharges into groundwater discharges is not desirable.

For nitrate (but not for salts) increasing leaching to groundwater by reducing runoff is beneficial where subsurface conditions favor denitrification, thus ideally reducing nitrate to harmless N_2 gas. Some strongly reducing aquifer regions have been mapped by state and local agencies or by the U.S. Geological Survey, but in many locations, the rate of denitrification will be unknown or highly uncertain. An assessment would require (extensive) in situ groundwater monitoring. Denitrification may also produce N_2O, a potent greenhouse gas (Schlesinger 2009), an undesirable and poorly understood cross-media impact of denitrification.

Nutrient management practices exist to reduce nitrate both in runoff and groundwater (Dzurella et al. 2012), but little monitoring data exist that quantifiably link management practices to groundwater nitrate leaching.

MONITORING GROUNDWATER POLLUTION IN ANIMAL FEEDING OPERATIONS

Groundwater monitoring is accomplished with typically one to two monitoring wells upgradient of the targeted facility to determine background or ambient concentration, and two and or more wells immediately downgradient of the facility. However, linking groundwater pollution in monitoring wells to specific activities or sources within or near an AFO often yields ambiguous results. This is due to the ubiquitous release of two key groundwater pollutants of concern, nitrate and salinity, across an AFO's various management units (lagoons, corrals, manured fields), as well as surrounding farmland, which may receive applications of fertilizer or manure.

There are alternative monitoring approaches to address this dilemma. The Netherlands maintains an extensive three-tiered national water quality monitoring program encompassing soils, shallow groundwater, and deep groundwater. The Dutch program is designed as a national monitoring network, with sampling locations distributed in a randomized network stratified by major soil and aquifer types, and by major farm types. Results are evaluated statistically, similar to Harter, Davis, Mathews, and Meyer (2002). In New Mexico, all dairy farms must construct groundwater monitoring networks such that an assessment can be made of the farm's impact on groundwater quality. California, with more than 1,500 dairy farms, most of them classified as AFOs, initially required all facilities with significant management practice violations or suspected groundwater contamination to install monitoring networks, typically with 4–12 monitoring wells. New groundwater quality protection rules for dairies, however, put more emphasis on monitoring source management (CVRWB 2007).

Monitoring source management practices allows for an indirect assessment of actual pollutant discharges to groundwater, which are subject to uncertainties due to the complexity of potentially attenuating processes such as denitrification, ammonia volatilization, and crop uptake of significant amounts of salt. The advantage of monitoring source management practices as a regulatory control tool is that this provides the operator with a more tangible framework for managing potential pollutant sources.

A combination of source management practice monitoring with broader, regional groundwater monitoring (e.g., The Netherlands, California's Dairy Order) addresses the weaknesses of each approach when used alone.

MODELING GROUNDWATER POLLUTION FROM ANIMAL FEEDING OPERATIONS

Soil water and solute flux models such as GLEAMS, SWAT, and HYDRUS can simulate changes in long-term average pollutant leaching to groundwater, but field data for a range of management practices and crops are needed for model calibration. Unsaturated zone and groundwater quality are tightly linked, but contaminant fluxes below the root zone or in groundwater are very rarely monitored in field research projects. This increases uncertainty in unsaturated zone and groundwater model predictions.

An assessment of the impact on water quality due to animal farming management practices involves three integrated systems: nitrate or salt source system (corral construction, lagoon design, crop management system), the root zone and underlying unsaturated zone, and the groundwater system. Due to the size of many animal farming systems, especially when including pasture or cropland affected by manure applications, the assessment of groundwater pollution is akin to a nonpoint source pollution assessment, as opposed to a point-source assessment, where groundwater pollution is the result of a single, highly localized source.

Groundwater nonpoint-source assessment tools are grouped into three categories (NRC 1993):

(1) Overlay and index methods for maps of qualitative indices of groundwater vulnerability to pollution (Aller et al. 1987; National Research Council 1993; Civita and De Maio 2004; Pavlis, Cummins, and Donnell 2010).
(2) Statistical approaches for the likelihood of pollution from existing water-quality datasets and associated explanatory variables, using regression (Nolan, Hitt, and Ruddy 2002), fuzzy logic (Uricchio, Giordano, and Lopez 2004), artificial neural networks (Khalil, Almasri, McKee, and Kaluarachchi 2005), etc.
(3) Process-based methods that explicitly simulate the physics of soil and groundwater flow and transport. These approaches include zero-order mixing models (Mercado 1976; Lee 2007) or one-dimensional plug-flow models that assume vertical advective flux of contaminants into the aquifer (Refsgaard et al. 1999; Cho and Mostaghimi 2009). More complex approaches include coupled one-, two-, or three-dimensional numerical flow and transport models. Three-dimensional models of soil and groundwater transport are computationally demanding (Harter and Morel-Seytoux 2013). At sufficiently high resolution (centimeter to meter scale), their application is limited to small sites. Alternatively, when simulating entire groundwater basins, these models are operated under relatively coarse resolution (hundreds of meters to kilometers) and make significant assumptions about the physics of effective flow and transport processes at the scale of resolution.

An illustrative example of a process-based method is the streamline transport method (Ginn 2001; Weissmann, Zhang, LaBolle, and Fogg 2002; McMahon et al. 2008; Herrera 2010; Kourakos, Klein, Cortis, and Harter 2012). The method focuses on the affected recipients of groundwater pollution—a river receiving groundwater discharge, water supply wells, or springs used for water supply. The streamline method uses a backward tracing approach to connect these so-called "receptors" (wells, streams, springs) with their recharge sources, which may include pollutant sources (e.g., cropland, lagoons, corrals, etc.). The streamline method is based on a solid understanding of groundwater flow dynamics in an aquifer, usually obtained by computer modeling (Harter and Morel-Seytoux 2013). In the streamline method, groundwater flow is visualized using many individual streamline traces, or streamtubes. The streamtubes also carry pollutants, and computer models can be used to compute the travel time of pollutants between pollutant source and receptor. Computer models also account for the fate of pollutants (e.g., any sorption or degradation that may occur along the streamtube). The streamline method provides a visual illustration

of groundwater flow and transport dynamics, and thus some understanding of how groundwater obtained from a supply well or flowing into a stream may be linked to various pollution sources that recharge into an aquifer (Figure 1).

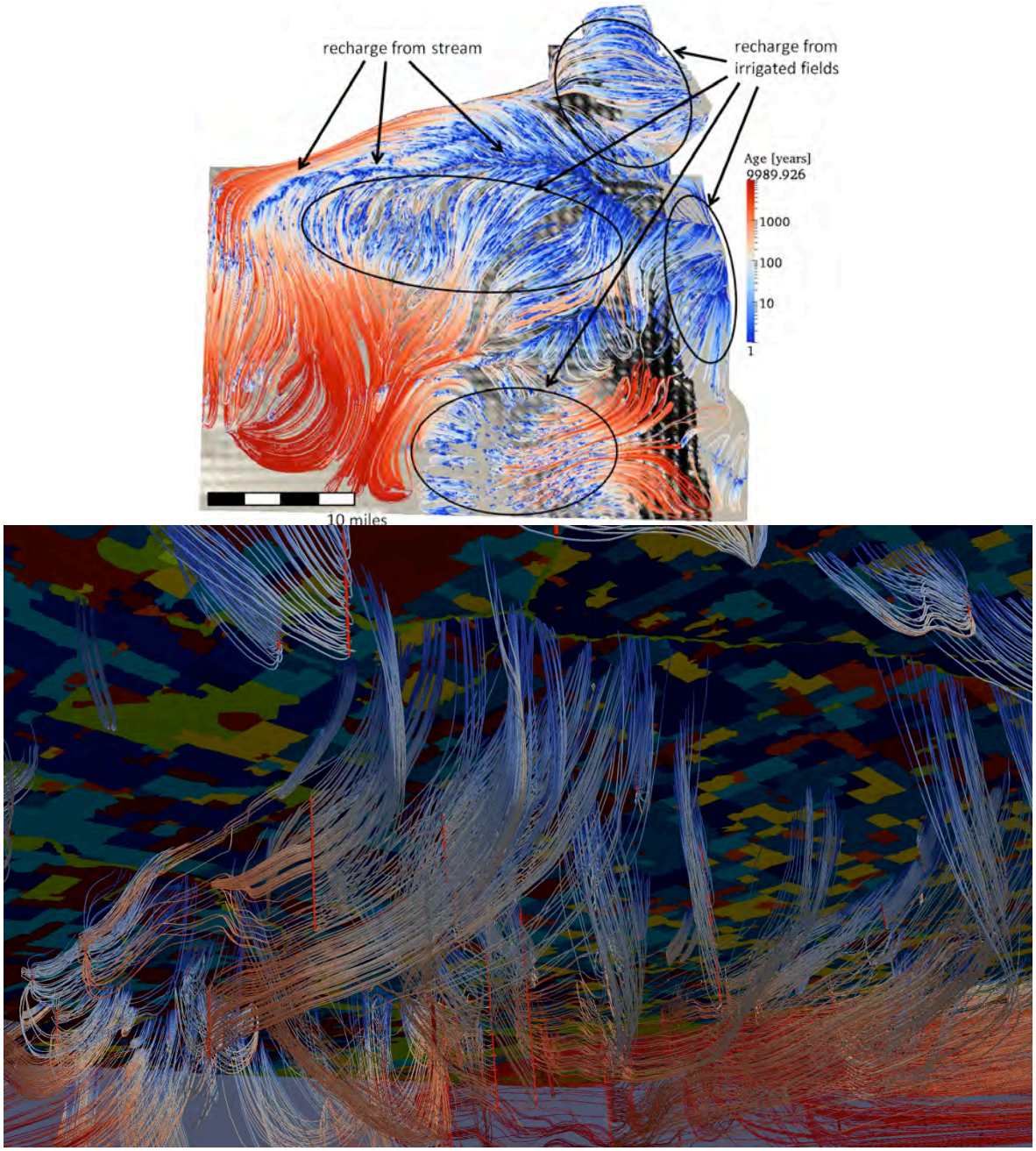

Figure 1. Streamline transport modeling concept illustrates the fate of nonpoint source pollutants in groundwater aquifers. The top panel shows a map view of groundwater streamlines across the groundwater basin delineated by the gray area; the bottom panel shows a three-dimensional view of streamlines from within the aquifer, looking upward against the land surface. The land surface is characterized by different land uses (various colors). The bluish/reddish streamlines (top) or streamtubes (bottom) represent streamlines of groundwater flow. The color shading of the streamlines indicates the groundwater age. Groundwater age begins with zero years at the point of recharge (dark blue). The longer the travel time, the older the groundwater. Only streamlines that converge on local water supply wells are shown. In the map view, the dark blue end of a streamline represents the recharge point, the lighter blue or reddish end point of a streamline represents the water supply well. In this example from south-central

California, recharge is mostly from two streams in the northern and central-eastern area, and from excess irrigation. Areas with little groundwater recharge (e.g., the southwestern part of this basin), pump very old groundwater that is transported there from far away (top). Water supply wells are the main "receptor" of groundwater. In the three-dimensional aquifer view (bottom), the intake screen (the portion of the well receiving groundwater) is represented as a red vertical tube. Individual well screens receive a mix of groundwater—younger groundwater enters near the top of the well screen, older groundwater enters near the bottom of the well screen. Within the same well, older groundwater may be from much further away than younger groundwater (bottom).

Figure 1 illustrates the streamlines obtained as part of a nonpoint source nitrate transport model for the Tule River aquifer in southern Central Valley, California (Kourakos and Harter 2013). In this illustration, groundwater age is indicated by the color along the streamline. The longer groundwater travels, the older it is. The youngest groundwater is dark blue; the oldest groundwater is dark red. The map view of groundwater streamlines in this basin indicates that the northern and central regions of the aquifer (Figure 1, top panel) receive most groundwater recharge via irrigation return and stream discharge. The streamtubes of wells located in those areas are relatively short and consist of only young water. On the other hand, there is little recharge in the southwestern and southeastern areas of this region. Wells in those regions tend to be very deep and they have sources located tens of miles away leading to long travel times, measured in centuries or even millenia. At any given time, water pumped from a water supply well (Figure 1, bottom panel) is actually a mix of ages. Typically the water near the top of the screen is relatively young (<10 years old). More recently recharged groundwater is likely to have a higher nitrate concentration due to the intensification of agriculture and animal farming during the past half century. The deeper parts of well screens often receive very old water (>100 years old) that would be relatively free of nonpoint source pollutants from animal farming. Depending on the depth of the wells and water availability (landscape recharge, stream recharge), recharge sources may only be a few tens of meters away or several miles to tens of miles upstream.

UNCERTAINTY IN ASSESSING RELATIVE CHANGES IN GROUNDWATER QUALITY DUE TO CHANGES IN MANAGEMENT PRACTICES

Groundwater flow (the shape, arrangement, and age of the streamlines shown in Figure 1) is influenced by the spatial distribution of recharge sources, wells, streams, and springs as much as it is influenced by the internal geologic structure of a groundwater basin. For example, hydraulic conductivity of the aquifer is highly variable but only measured in a few locations. In addition, preferential flow may occur in fractured rock aquifers or Karst aquifers, which may offer very limited capacity to naturally attenuate pollutants such as nitrate. This leads to uncertainty about the fate of pollutants in the subsurface. Uncertainty also arises from the complexity of land use decisions that cannot be accurately captured at a regional scale. These land use decisions translate into boundary conditions and stresses that critically drive assessment models. The complexity of these factors make it difficult to assess which source will have a direct impact on which receptor (well, stream section) and to precisely predict the extent of impact on wells or streams over time.

Methods outlined in the previous section can be used to assess the impact of policy or management decisions in AFO management for WQT for groundwater. Using sensitivity analysis and statistical methods, these tools also provide an opportunity to assess the degree of uncertainty associated with limited knowledge about sources or groundwater aquifer complexity. Figure 2 shows an example of the uncertainty due to different aquifer porosity values and different dispersivity. Porosity is an important factor that affects the speed at which pollutants may travel through the subsurface. Dispersivity refers to the tendency to disperse pollutants while they are transported through the aquifer. In Figure 2, each panel corresponds to a well at a different depth. Concentration as a function of time (so-called breakthrough curves) are shown. Different breakthrough curves are obtained depending on the choice of porosity or dispersivity, both of which are highly uncertain. In this example, dispersivity—within the range of

uncertainty—does not contribute to overall uncertainty about making pollutant concentration predictions: different colored curves (for the same porosity) are very similar. But porosity is an important factor. In this example, travel time can be significantly longer or shorter, depending on porosity: dashed, dotted, and solid lines are far apart from each other. Stochastic or other statistical modeling frameworks are promising tools to quantify some of the uncertainty, but they come at significantly higher expert and computational costs.

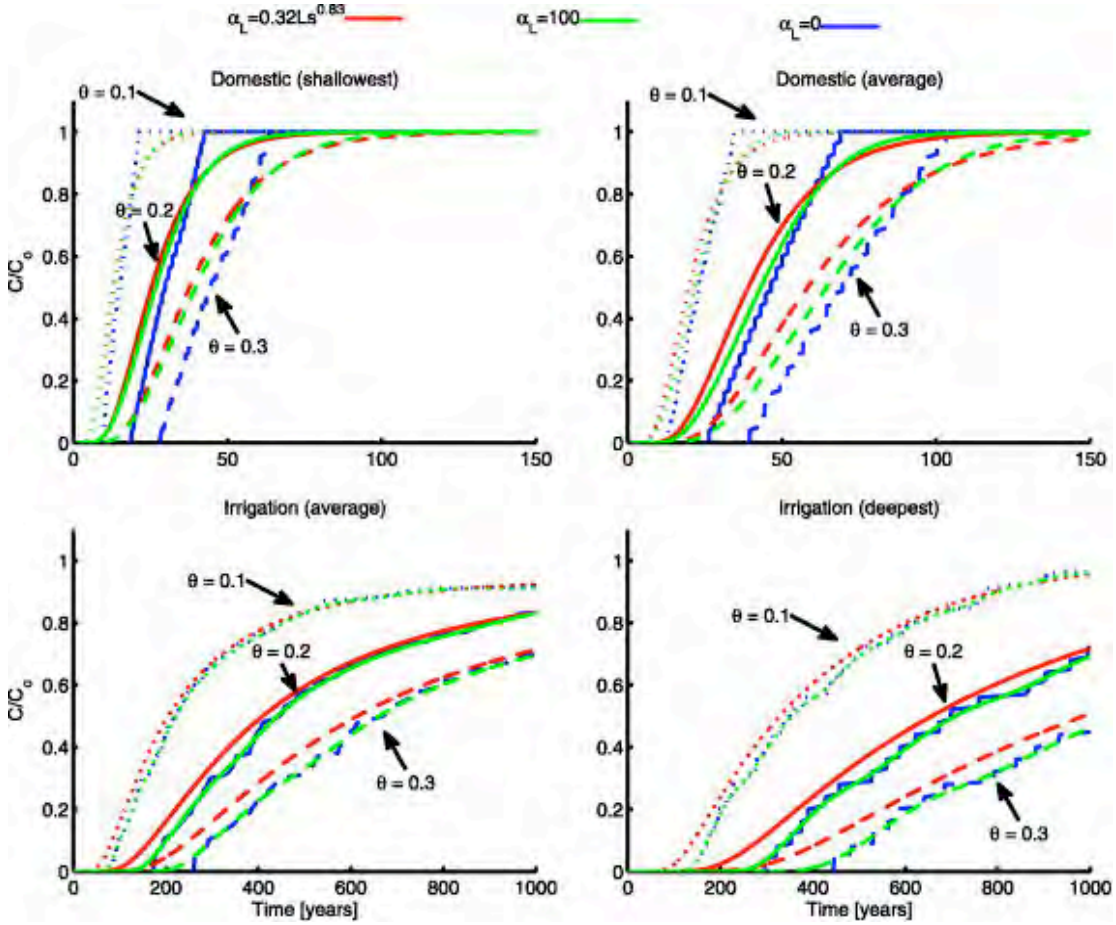

Figure 2. Hypothetical increase in relative concentration due to spatially extensive pollutant loading beginning at time 0. The upper panels show the concentration history for the shallowest domestic well (left) and for the average of all domestic wells (right). The lower panel shows the concentration history for average irrigation wells (deeper than domestic wells with longer screens, left) and for the deepest irrigation well (right). Colors indicate three different dispersion rates, α_L, blue being the case of zero dispersivity (plug flow). Line types indicate different porosities, θ. The sensitivity analysis provides a measure of uncertainty about future concentration predictions due to unknown aquifer conditions (uncertain dispersion, uncertain porosity). The sensitivity analysis shown here indicates that additional measurements of porosity could greatly reduce such uncertainty, while dispersivity is known with sufficient accuracy for purposes of this application. Any of the three dispersivity models could be used without significantly affecting results.

CONCLUSION

This supplemental paper briefly summarizes our current knowledge of how animal farming management practices affect groundwater, available monitoring tools, and an outline of assessment methods used to evaluate the impact on groundwater from changes in animal farming management arising from water quality trading to protect surface water resources.

We identify three main components of animal farms that affect groundwater: animal holding areas (animal yard, corrals, exercise yard), manure storage areas (lagoons), and manure application areas (fields). A large variety of management practices are associated with each of these potential groundwater pollution sources.

Animal farming is known to pose significant risks to groundwater pollution, primarily from microbial pollutants and due to nutrient losses, but also due to the elevated salinity of animal waste. Our current knowledge of the impact on groundwater from animal farming is largely based on studies that consider animal farming operations within a larger regional landscape or specific components of animal farms (e.g., animal yards, lagoons). Very few studies evaluate or compare specific management practices in regards to their impact on groundwater, largely due to the significant cost of groundwater monitoring.

Research is needed to better understand relative differences in groundwater quality and their relationship to current or alternative management practices for each of the three major components in animal farming (animal holding areas, manure storage areas, and manure application areas). Additional research should include comparative long-term groundwater quality monitoring, more extensive application of existing assessment methods, and development of new tools geared toward groundwater quality evaluation and measuring prediction uncertainty. Research on the integration of groundwater models with other models—coupling source systems with root zone/unsaturated zone pollutant fate and transport models, with groundwater models, and with surface water models is currently an emerging field in hydrologic simulation. These tools will be critical in the context of assessing the environmental effects of AFO management that also include the impact on air emissions and groundwater, which are often outside the expertise of watershed managers. Significant additional regulatory, funding, programmatic, and research resources are needed at the federal level to address groundwater quality concerns.

REFERENCES

Aller, L., T. Bennett, J.H. Lehr, R.J. Petty, and G. Hackett. 1987. *DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential using Hydrogeologic Settings*. Ada, Okla.: U.S. Environmental Protection Agency. http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20007KU4.txt.

ASCE (American Society of Civil Engineers). 1990. *Agricultural Salinity Assessment and Management.* ASCE Manuals and Reports on Engineering Practice 71, New York: ASCE.

Baram, S., S. Arnon, Z. Ronen, D. Kurtzman, and O. Dahan. 2012. "Infiltration Mechanisms Controls Nitrification and Denitrification Processes under Dairy Waste Lagoon." *Journal of Environmental Quality* 41(5): 1623–1632.

Bouwer, H. 2000. "Integrated Water Management: Emerging Issues and Challenges." *Agricultural Water Management* 45(3): 217–228.

Brown, Vence, and Associates. 2004. *Review of Animal Waste Management Regulations, Task 2 Report: Title 27 Effectiveness to Protect Groundwater Quality*. Central Valley Regional Water Quality Control Board. http://www.waterboards.ca.gov/centralvalley/water_issues/dairies/historical_dairy_program_info/index.shtml.

Burow, K.R., B.T. Nolan, M.G. Rupert, and N.M. Dubrovsky. 2010. "Nitrate in Groundwater of the United States, 1991−2003." *Environmental Science & Technology* 44(13): 4988–4997.

Central Valley Regional Water Board. 2007. "Waste Discharge Requirements General Order for Existing Milk Cow Dairies." Order No. R5-2007-0035. http://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/general_orders/r5-2007-0035.pdf.

Cho, J., and S. Mostaghimi. 2009. "Dynamic Agricultural Non-point Source Assessment Tool (DANSAT): Model Development." *Biosystems Engineering* 102(4): 486–499 .

Chomycia, J.C., P.J. Hernes, T. Harter, and B.A. Bergamaschi. 2008. "Land Management Impacts on Dairy-Derived Dissolved Organic Carbon in Groundwater." *Journal of Environmental Quality* 37(2): 333–343.

Civita, M., and M. De Maio. 2004. "Assessing and Mapping Groundwater Vulnerability to Contamination: The Italian 'Combined' Approach." *Geofisica International* 43(4): 513–532.

Domenico, P.A., and J.A. Schwartz. 2008. *Physical and Chemical Hydrogeology.* New York: John Wiley.

Drommerhausen, D.J., D.E. Radcliffe, D.E. Brune, and H.D. Gunter. 1995. "Electromagnetic Conductivity Surveys of Dairies for Groundwater Nitrate." *Journal of Environmental Quality* 24(6): 1083–1091.

Dzurella, K.N., J. Medellin-Azuara, V.B. Jensen, A.M. King, N. De La Mora, A. Fryjoff-Hung, T.S. Rosenstock, T. Harter, R. Howitt, A.D. Hollander, J. Darby, K. Jessoe, J.R. Lund, and G.S. Pettygrove. 2012. *Addressing Nitrate in California's Drinking Water, Technical Report 3: Nitrogen Source Reduction*

to Protect Groundwater Quality with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature. Davis, Calif.: Center for Watershed Sciences, University of California, Davis.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Englewood Cliffs, N.J.: Hemel Hempstead, Prentice-Hall International.

Ginn, T. 2001. "Stochastic-Convective Transport with Nonlinear Reactions and Mixing: Finite Streamtube Ensemble Formulation for Multicomponent Reaction Systems with Intra-Streamtube Dispersion." *Journal of Contaminant Hydrology* 47(1): 1-28.

Ginn, T. 2002. "Streamtube-Ensemble Techniques for Nonlinear Multicomponent Reactive Transport in Heterogeneous Media." In *Stochastic Methods in Subsurface Contaminant Hydrology*, edited by R. Govindaraju, 169–238 Hoboken, N.J.: ASCE Press.

Ham, J.M. 2002. "Seepage Losses from Animal Waste Lagoons: A Summary of a Four-Year Investigation in Kansas." *Transactions of the ASAE* 45(4): 983–992.

Harter, T., H. Davis, M.C. Mathews, and R.D. Meyer. 2002. "Shallow Groundwater Quality on Dairy Farms with Irrigated Forage Crops." *Journal of Contaminant Hydrology* 55(3–4): 287–315.

Harter, T., E.R. Atwill, L.L. Hou, B.M. Karle, and K.W. Tate. 2008. "Developing Risk Models of Cryptosporidium Transport in Soils from Vegetated, Tilted Soilbox Experiments." *Journal of Environmental Quality* 37(1): 245–258.

Harter T., and H. Morel-Seytoux. 2013. *Peer Review of the IWFM, MODFLOW and HGS Model Codes: Potential for Water Management Applications in California's Central Valley and Other Irrigated Groundwater Basins*. Final Report, California Water and Environmental Modeling Forum, Sacramento, July 2013. http://www.cwemf.org.

Harter, T. Unpublished data. "Deep Soil Cores underneath California Dairy Sites: Nitrate and Salt Dynamics." Davis, Calif.: University of California, Davis.

Herrera, P.A., A.J. Valocchi, and R.D. Beckie. 2010. "A Multidimensional Streamline-based Method to Simulate Reactive Solute Transport in Heterogeneous Porous Media." *Advanced Water Resources* 33(7): 711–727.

Hunter, W.J. 2013. "Pilot-Scale Vadose Zone Biobarriers Removed Nitrate Leaching from a Cattle Corral." *Journal of Soil and Water Conservation* 68(1): 52–59.

Khalil, A., M.N. Almasri, M. McKee, and J.J. Kaluarachchi. 2005. "Applicability of Statistical Learning Algorithms in Groundwater Quality Modeling." *Water Resources Research.* doi:10.1029/2004WR003608.

Koehne, J.M., S. Koehne, and J. Simunek. 2009. "A Review of Model Applications for Structured Soils: b) Pesticide Transport." *Journal of Contaminant Hydrology* 104(1–4): 36–60.

Kolpin, D., B. Jake, and G. Robert. 1998. "Occurrence of Pesticides in Shallow Groundwater of the United States: Initial Results from the National Water-Quality Assessment Program." USGS Staff Published Research. Paper 70. http://digitalcommons.unl.edu/usgsstaffpub/70.

Kolodziej, E.P., T. Harter, and D.L. Sedlak. 2004. “Dairy Wastewater, Aquaculture, and Spawning Fish as Sources of Steroid Hormones in the Aquatic Environment.” *Environmental Science and Technology* 38(23): 6377–6384.

Kourakos, G., F. Klein, A. Cortis, and T. Harter. 2012. “A Groundwater Nonpoint Source Pollution Modeling Framework to Evaluate Long-Term Dynamics of Pollutant Exceedance Probabilities in Wells and Other Discharge Locations.” *Water Resources Research*. doi:10.1029/2011WR010813.

Kourakos, G., and T. Harter, 2013. “Vectorized Simulation of Groundwater Flow and Streamline Transport.” *Environmental Modelling & Software* 52: 207–221.

Lee, S.S. 2007. “Unsaturated-Zone Leaching and Saturated-Zone Mixing Model in Heterogeneous Layers.” In *Springer Proceedings in Physics, Volume 112, part VI,* edited by T. Schanz, 387–399. Berlin, Germany: Springer.

Lockhart, K.M., A.M. King, and T. Harter. 2013. “Identifying Sources of Groundwater Nitrate Contamination in a Large Alluvial Groundwater Basin with Highly Diversified Intensive Agricultural Production.” *Journal of Contaminant Hydrology* 151: 140–154.

Mansell, D.S., R.J. Bryson, T. Harter, J.P. Webster, E.P. Kolodziej, and D. Sedlak. 2011. “Fate of Endogenous Steroid Hormones in Steer Feedlots under Simulated Rainfall-Induced Runoff.” *Environmental Science and Technology* 45(20): 8811–8818.

McMahon, P.B., K.R. Burow, L.J. Kauffman, S.M. Eberts, J.K. Böhlke, and J.J. Gurdak. 2008. “Simulated Response of Water Quality in Public Supply Wells to Land Use Change.” *Water Resources Research.* doi:10.1029/2007WR006731.

Mercado, A. 1976. “Nitrate and Chloride Pollution of Aquifers: A Regional Study with the Aid of a Single-Cell Model.” *Water Resources Research* 12(4): 731–747.

Mielke, L.N., P. Norris, and T.M. McCalla. 1974. “Soil Profile Conditions of Cattle Feedlots.” *Journal of Environmental Quality* 3(1): 14–17.

Miller, J.J., T. Curtis, F.J. Larney, T.A. McAllister, and B.M. Olson. 2008. “Physical and Chemical Properties of Feedlot Pen Surfaces Located on Moderately Coarse- and Moderately Fine-Textured Soils in Southern Alberta.” *Journal of Environmental Quality* 37(4): 1589–1598.

National Dairy Environmental Stewardship Council. 2005. “Cost-Effective and Environmentally Beneficial Dairy Manure Management Practices.” San Francisco: Sustainable Conservation. http://www.suscon.org/dairies/pdfs/NDESCreportCostEffective.pdf.

National Research Council. 1993. *Groundwater Vulnerability Assessment: Predicting Relative Contamination Potential Under Conditions of Uncertainty*. Washington, D.C.: National Academy Press.

NRCS (Natural Resources Conservation Service). 2009. *Natural Resources Conservation Service, Conservation Practice Standard, Waste Treatment Lagoon No. Code 359.* http://efotg.sc.egov.usda.gov/references/public/SD/359.pdf.

Nolan, B.T., K.J. Hitt, and B.C. Ruddy. 2002. “Probability of Nitrate Contamination in Recently Recharged Groundwaters in the Conterminous United States.” *Environmental Science and Technology* 36(10): 2138–2145.

Nolan, B.T., and K.J. Hitt. 2006. “Vulnerability of Shallow Groundwater and Drinking-Water Wells to Nitrate in the United States.” *Environmental Science and Technology* 40: 7834–7840.

Park, Y., E.R. Atwill, L.L. Hou, A.I. Packman, and T. Harter. 2012. “Deposition of Cryptosporidium Parvum Oocysts in Porous Media: A Synthesis of Attachment Efficiencies Measured under Varying Environmental Conditions.” *Environmental Science and Technology* 46(17): 9491–9500.

Pavlis, P., E. Cummins, and K. Mc Donnell. 2010. “Groundwater Vulnerability Assessment of Plant Protection Products.” *Human and Ecological Risk Assessment* 16(3): 621–650.

Refsgaard, J.C., M. Thorsen, J.B. Jensen, S. Kleeschulte, and S. Hansen. 1999. “Large-Scale Modeling of Groundwater Contamination from Nitrate Leaching.” *Journal of Hydrology* 221(3–4): 117–140.

San Joaquin Valley Dairy Manure Technology Feasibility Panel. 2005. *An Assessment of Technologies for Management and Treatment of Dairy Manure in California’s Central Valley*. Sacramento, Calif.: California Environmental Protection Agency, Air Resources Board. Available from http://www.arb.ca.gov/ag/caf/dairypnl/dmtfaprprt.pdf.

Schlesinger, W.H. 2009. “On the Fate of Anthropogenic Nitrogen.” *Proceedings of the National Academy of Sciences of the United States of America* 106(1): 203–208.

Siebert, S. 2005. “Global-Scale Modeling of Nitrogen Balances at the Soil Surface.” Frankfurt Hydrology Papers 02. Frankfurt am Main, Germany: Institute of Phyiscal Geography, Frankfurt University. https://www2.uni-frankfurt.de/45217765/FHP_02_Siebert_2005.pdf.

SJV DMTFP (San Joaquin Valley Dairy Manure Technology Feasibility Panel). 2005. *An Assessment of Technologies for Management and Treatment of Dairy Manure in California’s Central Valley.* December, 2005.

Sutton, A., and F. Humenik. 2003. “CAFO Fact Sheet#24: Technology Options to Comply with Land Application Rules.” Ames, Iowa: Midwest Plan Service, Iowa State University. http://www.heartlandwq.iastate.edu/ManureManagement/Regulations/cafosheets/fact24.htm.

Tanji, Kenneth K. (ed.). 1990. *Agricultural Salinity Assessment and Management.* Manual 71. New York: American Society of Civil Engineers.

Unc, A., M.J. Goss, S. Cook, X. Li, E.R. Atwill, and T. Harter. 2012. “Analysis of Matrix Effects Critical to Microbial Transport in Organic Waste-Affected Soils across Laboratory and Field Scales.” *Water Resources Research* 48(6): W00L12.

United Nations World Water Assessment Programme. 2006. “United Nations World Water Development Report 2: Water, a Shared Responsibility.” http://unesdoc.unesco.org/images/0014/001444/144409e.pdf. Paris, France: UNESCO.

Uricchio V.F., R. Giordano, and N. Lopez. 2004. “A Fuzzy Knowledge-based Decision Support System for Groundwater Pollution Risk Evaluation.” *Journal of Environmental Management* 73(3): 189–197.

U.S. Environmental Protection Agency. 2001. “United States Environmental Protection Agency, Solid Waste and Emergency Response (5306W), Geosynthetic Clay Liners Used in Municipal Solid Waste Landfills.” http://www.epa.gov/osw/nonhaz/municipal/landfill/geosyn.pdf.

U.S. Geological Survey. Various dates. *National Field Manual for the Collection of Water-Quality Data. Techniques of Water-Resources Investigations*. http://water.usgs.gov/owq/FieldManual. For a summary of revisions since 1999 go to http://water.usgs.gov/owq/FieldManual/mastererrata.html.

Watanabe, N., T. Harter, and B.A. Bergamaschi. 2008. "Environmental Occurrence and Shallow Groundwater Detection of the Antibiotic Monensin from Dairy Farms." *Journal of Environmental Quality* 37(supplement): S78–S85.

Weissmann, G.S., and G.E. Fogg. 1999. "Multi-Scale Alluvial Fan Heterogeneity Modeled with Transition Probability Geostatistics in a Sequence Stratigraphic Framework." *Journal of Hydrology* 226(1–2): 48–65.

Weissmann, G.S., Y. Zhang, E.M. LaBolle, and G.E. Fogg. 2002. "Dispersion of Groundwater Age in an Alluvial Aquifer System." *Water Resources Research* 38(10): 1198–1211..

Vaillant, G.C., G.M. Pierzynski, J.M. Ham, and J. DeRouchey. 2009. "Nutrient Accumulation Below Cattle Feedlot Pens in Kansas." *Journal of Environmental Quality* 38(3): 909–918.

Van der Schans, M.L., T. Harter, A. Leijnse, M.C. Mathews, and R.D. Meyer. 2009. "Characterizing Sources of Nitrate Leaching from an Irrigated Dairy Farm in Merced County, California." *Journal of Contaminant Hydrology* 110(1–2): 9–21.

Visser, A., H.P. Broers, R. Heerdink, and M.F.P. Bierkens. 2009. "Trends in Pollutant Concentrations in Relation to Time of Recharge and Reactive Transport at the Groundwater Body Scale." *Journal of Hydrology* 369(3): 427–439.

Reduce methane or face climate catastrophe, scientists warn

theguardian.com/environment/2021/aug/06/reduce-methane-or-face-climate-catastrophe-scientists-warn

https://www.theguardian.com/profile/fiona-harvey August 6, 2021



Animal farming is one of the activities producing methane, which has a warming potential more that 80 times that of CO2. Photograph: Yves Herman/Reuters

Cutting carbon dioxide is not enough to solve the climate crisis – the world must act swiftly on another powerful greenhouse gas, methane, to halt the rise in global temperatures, experts have warned.

Leading climate scientists will give their starkest warning yet – that we are rushing to the brink of climate catastrophe – in a landmark report on Monday. The Intergovernmental Panel on Climate Change will publish its sixth assessment report, a comprehensive review of the world's knowledge of the climate crisis and how human actions are altering the planet. It will show in detail how close the world is to irreversible change.

One of the key action points for policymakers is likely to be a warning that methane is playing an ever greater role in overheating the planet. The carbon-rich gas, produced from animal farming, shale gas wells and poorly managed conventional oil and gas extraction, heats the world far more effectively than carbon dioxide – it has a "warming potential" more than 80 times that of CO2 – but has a shorter life in the atmosphere, persisting for about a decade before it degrades into CO2.

Durwood Zaelke, president of the Institute for Governance and Sustainable Development and a lead reviewer for the IPCC, said methane reductions were probably the only way of staving off temperature rises of 1.5C above pre-industrial levels, beyond which extreme weather will increase and "tipping points" could be reached. "Cutting methane is the biggest opportunity to slow warming between now and 2040," he said. "We need to face this emergency."

Zaelke said policymakers must heed the IPCC findings on methane before the UN climate talks, Cop26, in Glasgow in November. "We need to see at Cop26 a recognition of this problem, that we need to do something on this."

Cutting methane could balance the impact of phasing out coal, a key goal at Cop26 because it is the dirtiest fossil fuel and has caused sharp rises in emissions in recent years. However, coal use has a perverse climate effect: the particles of sulphur it produces shield the Earth from some warming by deflecting some sunlight.

That means the immediate effect of cutting coal use could be to increase warming, although protecting the Earth in the medium and long term. Zaelke said cutting methane could offset that. "Defossilisation will not lead to cooling until about 2050. Sulphur falling out of the atmosphere will unmask warming that is already in the system," he said.

"Climate change is like a marathon – we need to stay in the race. Cutting carbon dioxide will not lead to cooling in the next 10 years, and beyond that our ability to tackle climate change will be so severely compromised that we will not be able to run on. Cutting methane gives us time."

Levels of methane have risen sharply in recent years, caused by shale gas, poorly managed conventional gas, oil drilling and meat production. Last year, methane emissions rose by a record amount, according to the UN environment programme.

Satellite data shows that some of the key sources of methane are poorly managed Russian oil and gas wells. Gas can be extracted from conventional drilling using modern techniques that all but eliminate "fugitive" or accidental methane emissions. But while countries such as Qatar take care over methane, Russia, which is a party to the 2015 Paris climate agreement but has made little effort to cut its emissions, has some of the leakiest infrastructure.

"Today more than 40% of EU gas is methane heavy gas from Russia, which is worse than coal for the climate," said Paul Bledsoe, a former Clinton White House climate adviser now with the Progressive Policy Institute in Washington. "The EU should begin to measure and then regulate methane emissions from all its natural gas imports to begin a cleanup of global natural gas."

Reducing methane emissions can save money. The UN's assessment found that about half of the reductions in methane needed could be achieved with a quick payback.

Zaelke urged governments to consider crafting a new deal, alongside the Paris agreement, that would cover methane and require countries to sharply reduce their gas. “I predict we will have to have a global methane agreement,” he said.

Methane is also produced by melting permafrost, and there have been indications that the Siberian heatwave could increase emissions of the gas. However, large-scale emissions from permafrost melting are thought to be still some way off, while emissions of methane from agriculture and industry can be tackled today.

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TOPICAL REVIEW

Underestimates of methane from intensively raised animals could undermine goals of sustainable development

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Abstract

Greenhouse gas emissions from meat and dairy production are often highly uncertain; these emissions are typically estimated using inventory-based, 'bottom-up' models, which contain uncertainties that are difficult to quantify. Modeled emissions estimates can be corroborated using atmospheric measurements—taken above and downwind of animal production regions—to produce 'top-down' emissions estimates. Top-down and bottom-up estimates of animal methane show good agreement when considering global emissions. However, in the US, where animal production is predominantly highly intensified with confined feeding operations, animal methane emissions may be 39%–90% higher than bottom-up models predict (expressed as mean differences across studies). Animal emissions may grow in the future as meat and dairy demand increases in developing countries. We examine East and Southeast Asia as a test case, where emissions from increased meat and dairy production are expected to be offset by improved efficiency from intensive methods. We adjust the share of direct emissions projected to come from intensive systems by the intensities derived from US top-down estimates. We find that region-wide emissions from meat and milk production could reach 1.52 (1.41–1.62) $GtCO_2eq$ by 2050, an amount 21% (13%–29%) higher than previously predicted. Therefore, intensification may not be as effective in mitigating emissions in developing countries as is commonly assumed.

1. Introduction: the role of intensification in sustainable development

Global meat consumption is expected to increase by 50% in the coming decades (FAO 2018a). This increase is primarily driven by rising affluence in developing low- and middle-income countries. Animal agriculture has been reported to represent 15.6% of total annual greenhouse gas (GHG) emissions globally (FAO 2017 using a 100 year global warming potential (GWP_{100}) for non-CO_2 GHGs), with emissions expected to increase in the coming decades.

Limiting GHGs from agriculture is urgent because business-as-usual agricultural growth is likely incompatible with limiting warming below 1.5 °C (Clark *et al* 2020). Reducing emissions from food systems is therefore urgent, even in scenarios in which fossil fuel usage is rapidly phased out. Sustainable intensification offers a possible solution; it is defined as the production of more meat and dairy with fewer resources, like land and feed, and lower emissions per animal (Godfray *et al* 2010).

The majority of global agricultural emissions are estimated to come from lower efficiency, pastoral systems (Steinfeld *et al* 2006). These systems include long-range grazing, backyard, and mixed crop-livestock systems, although the latter category has wide variation, and could count as intensive or semi-intensive depending on the specifics of the system (Robinson *et al* 2011). These forms of animal agriculture are referred to as extensive production systems because of their larger land footprint, and they are becoming less common globally (Gerber *et al* 2013).

Conversely, intensive production systems, like those in North America and the EU, are likely

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responsible for fewer direct and indirect emissions, in total and per unit of meat or dairy produced (Gerber *et al* 2013). Intensively managed animals in these regions are often raised in 'landless' systems (as defined by the UN Food and Agriculture Organization, FAO), where feed inputs are traded commodities and are largely detached from the immediate local resource base (Robinson *et al* 2011). Animals like pigs and chickens are highly confined for all of their lives, while beef cattle spend the latter part of their lives being 'finished' on enriched feeds in feedlots. These systems in the US are also referred to as concentrated animal feeding operations (CAFOs). However, this term is a more stringent categorization—as CAFOs may not include a number of smaller-scale facilities that are nonetheless highly industrialized and entail confinement.

Animal feeding in intensive, landless systems is oriented toward rapid weight gain and productivity (Robinson *et al* 2011). Animals live shorter lives relative to extensively-raised animals to optimize feed requirements and other input resources (Herrero *et al* 2013). Intensive systems for raising chickens, pigs, and dairy cows, and facilities for fattening or 'finishing' mature beef cattle to reach market weight in the North America restrict animal movement. Intensive landless systems typically do not allow for the expression of natural behaviors, access to pasture, or the ability to graze or forage for food. This type of animal agricultural production, often referred to as 'industrialized production', is now proliferating globally through developing low- and middle-income countries.

Intensively-raised animal-sourced foods have lower land and feed requirements, relative to extensively-raised animal-sourced foods (Swain *et al* 2018). The benefits of improved feed requirements are commonly assumed to include fewer GHG emissions: both lower indirect emissions from feed production and grazing, and fewer direct emissions from wastes like manure, urine, and belches, per unit of food produced. However, the aggregate air and water pollution from landless facilities, along with resource depletion of fresh water, can create local problems and contribute to environmental degradation (Carrel *et al* 2016, Richter *et al* 2020).

Researchers have therefore recommended intensifying existing extensive and pastoral systems to reduce GHG emissions (e.g. Steinfeld *et al* 2006, Thornton and Herrero 2010, Swain *et al* 2018). North American meat and dairy companies frequently claim that their emissions are improving, directly attributing this trend toward more intensive management practices (Cattlemen's Beef Board 2018, McDonald's Canada 2018, National Pork Board 2020). In unity with these messages, governments and nongovernmental organizations alike have promoted intensification for food security, environmental improvements, and GHG mitigation in low and middle-income countries (De Oliveira Silva *et al* 2018, FAO 2018b, Enahoro *et al* 2019, ILRI 2019). International development banks further incentivize intensive methods through conditional lending and low-interest loans for confined production infrastructure (Wasley and Heal 2020, World Bank International Finance Corporation 2020).

Extensive production methods currently predominate in low- and middle-income regions. Animal-sourced food consumption is also likely to grow as these countries develop economically (Alexandratos and Bruinsma 2012), with rising population and rising income-related dietary shifts. However, there is an ongoing shift toward intensification in these countries, both as an economic response to rising meat and dairy production and government agendas to develop economies through 'green revolution' type programs of achieving efficiency through intensification.

This shift toward intensification is expected to offset a substantial fraction of GHG emissions. In the greater East and Southeast Asia (ESA) region, an area of both rapid consumption growth and industrialization, these two trends are expected to approximately counter-balance one another, with 39% more meat consumption in 2050 relative to present day, but little net change in total emissions (FAO 2018a), credited to the efficiency of intensification.

However, the hypothesis that intensification leads to GHG emissions mitigation, in particular that this mitigation is large enough to offset projected increases in production and consumption, has not been corroborated through independent assessments. The following review describes the model-based methods in which GHGs from animal-sourced food production are typically assessed and forecasted. We then contrast this approach with recent atmospheric measurement-based methods, along with a discussion of both methods' inherent uncertainties. Lastly, we conclude with a test case analyzing commonly-accepted emissions projections, adjusting the projection from ESA intensive systems by the same degree to which present-day emissions from North American intensive systems are possibly biased. These prospective results imply that emissions may increase in the region through 2050, contrary to existing predictions that they will plateau or decrease after 2030. This case study has important implications for the standard paradigm of agricultural development in low- and middle-income countries, as it implies that the GHG mitigation benefits of intensification may be overestimated.

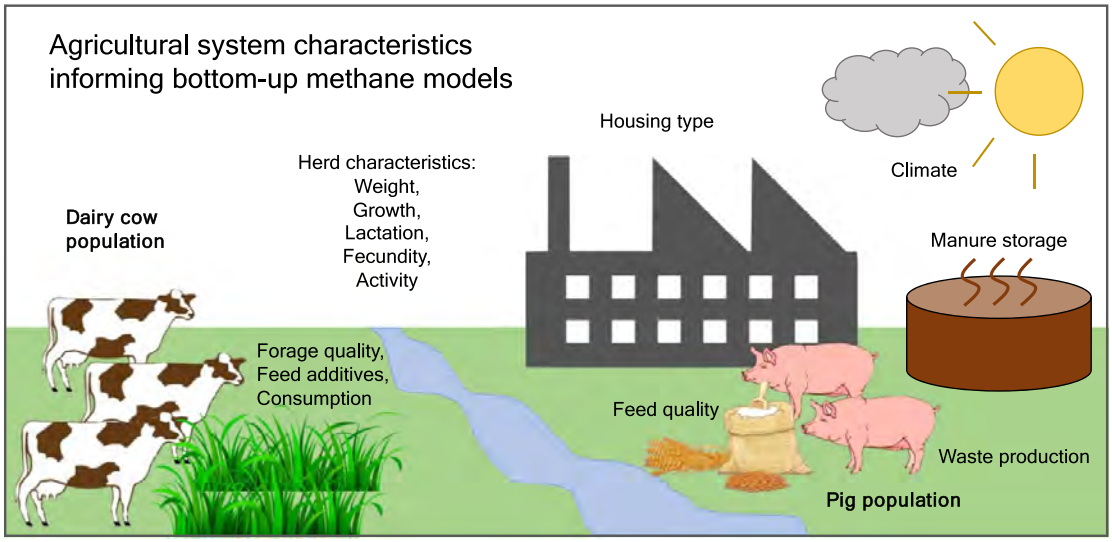

Figure 1. Characteristics of dairy cow and pig herds accounted for in bottom-up methane emissions models. Models use input variables, which are listed within this diagram and contain uncertainties, to calculate total enteric fermentation and manure management methane emissions. Models relate input variables to methane emissions using parameters (not shown), which also contain uncertainties.

2. Quantifying progress toward sustainable emissions

2.1. Bottom-up estimates of animal emissions

Present-day estimates of total GHG emissions in a given region are rarely measured directly. Rather, emissions estimates are based on animal emission models. Such models collect and integrate detailed information from multiple animals and production regions through counting, interviewing, and census-taking. Emissions models are referred to as 'bottom-up' estimates, because detailed information is collected at the ground-level, then multiplied and added up to calculate total emissions.

The predominant GHG from animal agriculture is methane. Methane is produced by enteric fermentation and manure management. Methane represents 50% of all animal emissions (direct + indirect) and 92% of direct animal emissions (FAO 2017).

Bottom-up estimates of methane are created by tallying up populations of each type of animal, known as activity data. These data are then multiplied by emissions factors—estimates of gas emitted by each animal daily or each operation annually. Separate emission factors are generally used for (a) enteric fermentation (belches) and the (b) handling and storage of their manure. Animal populations are subsequently multiplied by animal- and region-specific emissions factors, yielding an estimate of direct emissions produced. Bottom-up models are often also used to estimate indirect emissions from feed production and manure application to fields. However, this review mostly concerns direct emissions of animal agriculture, with some exceptions.

Emissions factors are calculated using detailed equations, provided in the IPCC guidelines of the Fourth Global Assessment Report (Dong *et al* 2006) and its 2019 refinement report (Gavrilova *et al* 2019). Multiple levels of detail or 'tiers' of estimates are provided, corresponding to different levels of aggregation and coarseness. Emissions factors are calculated at Tier 1 with fixed tabular values, Tier 2 with the more detailed equations that are standardized by the IPCC, or Tier 3 which are considered rigorous and detailed methods that are country-specific but nonetheless subjected to international peer review (Dong *et al* 2006). Each level reflects processed-based detailed input information on how animals are raised in each region, differing mainly in what level of detail is included by the modeler. The resulting emissions factors describe how much methane and nitrous oxide an average animal from each herd directly emits per day or year.

The development of these emissions factors requires information on how animals are raised in each region, including feed, physical activity, manure disposal, and local climate, along with their productivity, such as weight gain, lactation amount, and breeding rate (figure 1). Most of these local production and environmental characteristics are required inputs for all tiers of IPCC methods—including Tier 1 methods that rely on IPCC emissions factors and Tier 2 and 3 methods that provide detailed models that allow users to calculate their own emission factors. The remainder of this discussion will focus predominantly on Tier 2 emissions to provide a standard, if simplified framework for understanding, but there are commonalities among all three tiers.

The details used to develop methane emission factors can be incredibly fine-grained and include information on how much an average animal moves during a day, whether or not a dried crust is allowed

to form on top of the slurry tanks that handle liquid manure, the temperatures of a given animal operation and the seasonal cycle of weather conditions, and other highly specific details. This detailed information can be challenging to collect, even for countries with detailed agricultural censuses (Hristov *et al* 2017).

Detailed input information in bottom up emissions estimates contributes to their precision—the degree to which estimates can detect changes between one system or another. However, this detail does not guarantee estimates that are accurate—close to the true, real-world value. As more details are added and multiplied within the models, the model errors tend to increase. The errors in totaled emissions estimates are therefore considerably more uncertain than any single input. Ultimately, bottom-up estimates require simplifying assumptions and extrapolation from representative systems. They therefore may contain large uncertainties and compounding errors (Miller *et al* 2014, Miller and Michalak 2017) that make emissions difficult to accurately quantify, including estimates contained in national inventory reports.

The uncertainty envelopes in bottom-up emissions inventories may be underestimated, and are difficult to compare and scrutinize in existing sources. Uncertainties are required in the reporting from all UNFCCC annex-1 countries, including the United States. However, uncertainty ranges are not easily discoverable, are missing from a number of UNFCC reports and web portals, and do not clearly identify which types of the multiple types of model uncertainty they consider. The United States' inventory includes mention of uncertainty analysis performed on 185 input variables and categories, and reports resulting errors for enteric fermentation methane of approximately ±15% (US EPA O 2021). The details of the assessment are vague, stating that uncertainties for input variables 'were collected from published documents and other public sources; others were based on expert opinion and best estimates'. Conversely, the IPCC methodology states that Tier 1 and 2 uncertainty estimates for enteric fermentation may be on the order of 50% (Dong *et al* 2006), a substantially larger range than the US EPA and most other bottom up emissions inventories report. The 2019 update states that uncertainty estimates for enteric fermentation contains 'no refinement' (Gavrilova *et al* 2019). Uncertainty ranges in bottom-up estimates are possibly too small, even though they are intended to be fully comprehensive.

Furthermore, bottom-up inventories uncertainties often do not reflect uncertainties arriving from model structure and parameter selection, referred to as epistemic uncertainty (Sykes *et al* 2019), instead reflecting uncertainties arriving from input data. Bottom-up models structurally contain dozens of parameters that describe how inputs and outputs relate to one another. For instance, one commonly-used equation in Tier 1 and 2 methods for estimating the food consumption of cows uses multiple constant coefficients to relate live dairy cow body weight to quantity of dry matter ingested per day (equaions (10.18) in Dong *et al* 2006, Gavrilova *et al* 2019). These and other parameters are gleaned from small-scale studies, dating back to the early 1980s and 1990s (NRC 1989, 2001, references therein). Analyses of epistemic uncertainties studies have been done at the farm level (Sykes *et al* 2019) but are not explicitly utilized in the development of national inventories.

While these uncertainties have been detected across models may be common to all bottom-up estimates as they rely on similar assumptions and model parameters, introducing systematic biases that elude uncertainty analysis. The multiple sources of uncertainties in bottom-up estimates (input data, geographic distribution and allocation, model and parameter selection) are rarely analyzed holistically by existing studies. A recent analysis discovered that, while three different total US inventories of methane agree within 20%, their spatial discrepancies exceed 100% across certain US states (Hristov *et al* 2017). Altogether, the information used to develop bottom-up models, including input data and model parameters, may therefore lead to biases in reported estimates outcomes, due to their outdated nature, or due to a lack of representative information from the wide national and global variation in contemporary production systems (Wolf *et al* 2017).

In summary, bottom-up methods allow researchers to estimate animal emissions with a high level of precision, or fine-grained resolution, parsing out how GHG emissions differ between animal species, geographic regions, production systems, and food products, but not necessarily an accordingly high level of accuracy. The accuracy of these methods in different global regions remains poorly characterized, requiring independent methods to verify emissions estimates from animal agriculture.

2.2. Top-down estimates: evaluating animal emissions from the atmosphere

The GHG emissions estimates produced by bottom-up models can be compared against measurements taken from the air above animal operations, using sensors on tall towers, airplanes, and satellites.

Researchers use meteorological models and observations of wind direction, speed, and turbulence to link the measured GHG concentrations in the air back to their sources on the ground. These methods can be used to gauge the quantity of emissions from sources in the upwind footprint of the measurements over months or years—by measuring for prolonged periods of time and from multiple wind directions. Atmospheric estimates start by measuring GHGs in the sky, then trace those GHGs back to their source regions on the ground; these methods are referred to as 'top-down' estimates.

One limitation of top-down estimates is that these methods can only broadly distinguish among emission sources. The partitioning of sources typically depends upon differences in the spatial distribution of different source types, requiring accurate information regarding where these sources are distributed in geospatially gridded bottom-up data (e.g. Miller and Michalak 2017). For example, a top-down approach would struggle with this source partitioning if cattle are grazed amidst natural gas wells, or pig manure lagoons and natural wetlands are located in the same region.

The level of disaggregation or detail in emissions inventories also determines how finely top-down emissions estimates can be used to distinguish among source types. For example, top-down studies often employ a 'scaling factor inversion' to statistically partition sources—by scaling each emissions sector in a bottom-up inventory to match atmospheric observations. The number of these scaling factors is limited by the number of emissions categories present in the bottom-up gridded inventory and by the information content of the atmospheric observations used in the inverse model. The geospatially gridded inventories of animal emissions from EDGAR or the US EPA that are publicly available and used in the top-down analyses reviewed here are not disaggregated by type of animal or production type. Such disaggregated gridded bottom-up products would be useful for examining potential errors and biases, but could introduce further partitioning errors as the number of scaling factor coefficients would increase.

Another limitation is that top-down atmospheric estimates rely on wind observations and models with their own errors. Importantly, these atmospheric transport errors are different from the errors in bottom-up models (Pandey *et al* 2019). These errors are commonly reported in the literature and are non-compounding.

An additional challenge of top-down modeling is that these models are often under-constrained or under-determined by atmospheric observations. The number of atmospheric observation sites may be limited, while the spatial and temporal patterns of emissions can show complexity that exceeds the detection abilities of existing atmospheric observations. As a result, multiple configurations of the emissions or multiple solutions to a top-down estimation problem can reproduce the atmospheric observations within a specified error tolerance. Existing top-down models therefore have finite utility in constraining emissions at fine spatial scales. With that said, the uncertainties in top-down emissions estimate typically decrease at regional and national spatial scales (e.g. Miller *et al* 2013, 2019). The reported uncertainties at these scales are often smaller than the differences between bottom-up and top-down estimates, implying that top-down methane estimates are sufficiently robust to compare and contrast with bottom-up models at regional to continental scales (e.g. Turner *et al* 2015, Saunois *et al* 2020).

Top-down atmospheric estimates are therefore an independent way of testing the accuracy of the estimates produced by bottom-up emissions models across both small and large spatial scales, albeit with their own inherent uncertainties and limitations. To date, however, they cannot reliably distinguish between various sources that are co-located.

3. Comparing bottom-up and top-down estimates of US animal methane emissions

3.1. Quantifying differences between emissions estimates

We synthesized reports in the literature regarding top-down methane emissions estimates in regions of predominantly intensive production. We conducted literature searches on ISI Web of Science and Google Scholar for terms pertaining to top-down atmospheric estimates of methane, and filtered search results by spatial domain (state/province or larger) and whether they statistically partitioned livestock sector emissions from the total estimate. We present the results in table 1, alongside comparisons with bottom-up estimates.

Estimates from atmospheric measurements indicate that global animal methane emissions may be only slightly higher than the bottom-up models predict—about 5% higher—and within the margin of error (e.g. Turner *et al* 2015). A more recent comparison of methane estimates from total agricultural and waste sources from 2000 to 2017, which included all direct livestock emissions but also include rice crops and landfills, also found that bottom-up and top-down emissions estimates agree well within statistical uncertainty (Saunois *et al* 2020).

The difference is much greater in the United States; at least four top-down estimates of the contiguous US, representative of emissions occurring over at least one full year, indicate that direct animal methane emissions are 39%–90% higher than bottom-up models predict (Miller *et al* 2013, Wecht *et al* 2014, Turner *et al* 2015). Such comparisons are currently lacking for other predominantly intensified production regions, e.g. Europe.

This tendency is mirrored in smaller geographic regions within North America. Of five regional top-down studies, four found significantly higher methane emissions from areas of confined animal production than the bottom-up models suggest (Jeong *et al* 2016, Chen *et al* 2018, Desjardins *et al* 2018, Yu *et al* 2021). The exception is the Southeastern US, where there was close agreement between aircraft measurements and a short-term campaign (Sheng *et al* 2018). This and the Ontario Desjardins *et al* (2018) study were both conducted over an aircraft campaign lasting less than 2 months, meaning that these results may not be representative of the full annual

Table 1. Direct methane emissions from farmed animals in Tg CH_4. Scale factor refers to the relative magnitude of the top-down emissions estimate relative to the respective bottom-up estimate (e.g. 200% means top-down estimate is two times higher than bottom-up estimate). Emissions model abbreviations are EDGAR—Emissions Database for Global Atmospheric Research; EPA—Environmental Protection Agency; CALGEM—California GHG emissions measurement project. Bottom-up models reflect the models used to develop geospatially gridded datasets for comparison in the respective top-down analyses.

Region	Year	Bottom-up model	Bottom-up estimate	Top-down estimate	Scale factor	Reference
Globe USA	2009–2011	EDGAR	111 8.9	116 ± 10 14.8 ± 2.2	105% 166%	Turner *et al* (2015)
USA	2004	US EPA EDGAR	8.8 8.5	12.2 ± 1.3	139% 144%	Wecht *et al* (2014)
USA	2007–2008	US EPA EDGAR	9.3 8.9	17.0 ± 6.7	181% 190%	Miller *et al* (2013)
US Midwest	2016–2017	US EPA EDGAR	2.6 2.7	4.8 ± 1.5	185% 178%	Chen *et al* (2018)
US Upper Midwest	2017–2018	US EPA	3.3	4.11 ± 0.54	124%	Yu *et al* (2021)
California, USA	2013–2014	CALGEM	0.90	1.33 ± 0.40	149%	Jeong *et al* (2016)
E. Ontario, Canada	April–May 2011	IPCC Tier 2	0.013 ± 0.002	0.027 ± 0.006	217%	Desjardins *et al* (2018)
US Southeast	August–September 2013	US EPA	3 ± 0.5	2.9 ± 0.3	97%	Sheng *et al* (2018)

cycle. The Southeastern US is also an area of abundant wetland emissions (8–16 Tg CH_4 yr^{-1}), with close proximity to animal production areas, making accurate source partitioning challenging (Miller *et al* 2015).

The bottom-up models included in these sources use agricultural survey and census data on farmed animal populations, and use IPCC standards (predominantly Tier 2) to calculate their emissions factors. The bottom-up estimates (table 1, column 4) correspond to various base years and bottom-up models (table 1, columns 2 and 3 respectively) and model versions. Future work is therefore needed to compare bottom-up and top-down emissions estimates using the most recent bottom-up model versions across their respective regions and base years. While the models differ in assumptions made to calculate emissions factors, i.e. assumptions reflecting how animals are fed, housed, and raised, feeds tend to be energy-rich and animal production methods are intensive and confined throughout the US and Canada.

The discrepancies between bottom-up and top-down estimates in the US and Canada imply that models may under-predict the emissions intensity of animals raised in intensive, predominantly confined systems. This pattern furthermore suggests that a greater proportion of total global methane emissions from animals is coming from intensive systems than is routinely reported.

3.2. Why North American emissions may be underestimated by models

It is unclear why the modeled methane emissions from farmed animals in the US are often lower than emissions inferred from atmospheric measurements. Discrepancies do not seem specific to one animal or system. For example, Jeong *et al* (2016) analyzed airborne measurements from California and were able to partition emissions between dairy cattle and other animals. They found dairy cattle and other non-dairy animals' emissions were 45% and 69% higher, respectively, than the bottom-up model predicted. Therefore, emissions from multiple animal species may be underestimated by the bottom-up emissions models.

Bottom-up models also appear to routinely underpredict emissions from manure. Models of manure emissions are based on laboratory experiments within controlled test chambers. When methane is measured outside of the lab, in the air directly above manure tanks, pits, and piles, emissions tend to be greater than models predict, sometimes by more than 300% (Owen and Silver 2015). However, because manure represents approximately 11% of animal methane emissions, this difference is still not large enough to explain the gap in US animal methane emissions (Wolf *et al* 2017).

High methane emissions may also stem from animal disease. Infections in animals are widespread in intensive production systems; approximately one

quarter of US dairy cows have mastitis—a swelling and infection of udders accompanied by secretion of somatic cells into the milk (USDA 2016). Among beef cattle, nearly all feedlots have at least some cattle affected by bovine respiratory disease complex (BRDC or 'shipping fever') or lameness; BRDC has been detected in 16%, digestive disorders in 4%, and lameness in 2% of the entire US feedlot beef cattle population (USDA 2013). Digestive disorders and infectious parasites have multiple adverse effects on enteric fermentation emissions; they (a) decrease digestion efficiency, hence increasing overall feed requirements and methane output per unit of production (Houdijk *et al* 2017, Fox *et al* 2018) and (b) increase methane yield per unit of feed. The former tendency may be missed by bottom-up models if entirely healthy cattle are being taken as representative of the entire herd. The latter tendency cannot be represented at all by Tier 2 emissions methods models (Dong *et al* 2006, Gavrilova *et al* 2019), and would require new methods that could account for unhealthy/infected proportions of the herd. A full accounting for animal diseases, which are prevalent in modernized intensive systems, may result in bottom-up emissions that are higher than commonly reported.

The current body of top-down estimates is insufficient to understand precisely why bottom-up models may underpredict animal emissions. The metabolic processes that generate emissions (e.g. manure and belches) are highly co-located relative to the large and distant spatial scales at which atmospheric measurements for top-down estimates occur. Multiple inputs and metabolic processes contribute to the rate of methane conversion in an individual animal or manure storage system. In the future, a greater number of atmospheric measurements performed at smaller spatial scales, located in closer proximity to facilities where manure storage is separated animals enteric fermentation, could be utilized to better partition which types of animals, processes, and production systems are most responsible for driving the discrepancies.

4. Animal emissions in an international development context

4.1. Case study: intensification in East and Southeast Asia

Intensification in ESA, which includes mainland China, is expected to reduce marginal emissions substantially (Wang *et al* 2017, Yu *et al* 2018, FAO 2018a). A recent analysis of animal emissions in China recommends increasing per-capita production of animal products (Yu *et al* 2018), finding that improved efficiency will offset the increase in production and provide net methane emission reductions overall. The benefits of intensification, however, vary case by case, and by the proportions of direct and indirect GHG emissions, which can vary widely geographically (Poore and Nemecek 2018).

The following synthesis aims to approximately correct or scale future GHG emissions projections in the ESA region for direct animal emissions. We adjust the proportion of direct emissions in bottom-up emissions estimates by a mean and range of scaling factors derived from the USA top-down emissions scaling factors. This analysis serves as a prospective correction, outlining a possible consequence of business-as-usual development, but it is not a definitive prediction. The specific metabolic processes and source categories that can fully explain the discrepancy in North American emissions (table 1) are still unknown, including but not limited to manure methane fluxes influenced by climate and geography (Dong *et al* 2006). However, we expect that this analysis will approximately account for changes in the increased use of landless, intensive systems in the region, with common industrial production characteristics that are increasingly deployed in the ESA region and throughout the developing world (Wasley and Heal 2020).

The 2050 projections were taken from FAO, using regionally appropriate emissions factors from IPCC (FAO 2018a). The data are available on the online FAO data portal 'Food and Agriculture Projections through 2050 (www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en/). We used agricultural emissions and livestock herd size data from the 'business-as-usual' projection (FAO 2018a) and disaggregated further where necessary by supplementing this data with public data from FAO GLEAM, which further partitions emissions into production categories GHGs, and lifecycle processes (FAO 2017).

Total demand for animal-sourced foods is increasing in ESA concurrently with intensification. Emissions of each unit of production are assumed to decrease in the near future according to prospective bottom-up estimates (figure 2(A)). As a result of these two counterbalancing forces, animal emissions are expected to increase by 2030, then gradually go down until they return to early 2000s levels by 2050 (figure 2(B)). However, these bottom-up emission projections may overestimate the benefit of intensification.

If the share of direct GHG emissions projected to come from intensive systems is scaled in proportion with top-down US estimates (scaled up by 65%, the average inferred from top-down estimates, provided in table 1), future emissions per unit of meat and dairy will not decrease as much as FAO bottom-up estimates predict (figure 2(C)). Multiplying this emission intensity by total consumption, we find that the ESA region could reach 1.52 (1.41–1.62 total range) $GtCO_2eq$ by 2050, an amount 21% (13%–29%) higher than previously predicted (figure 2(D)).

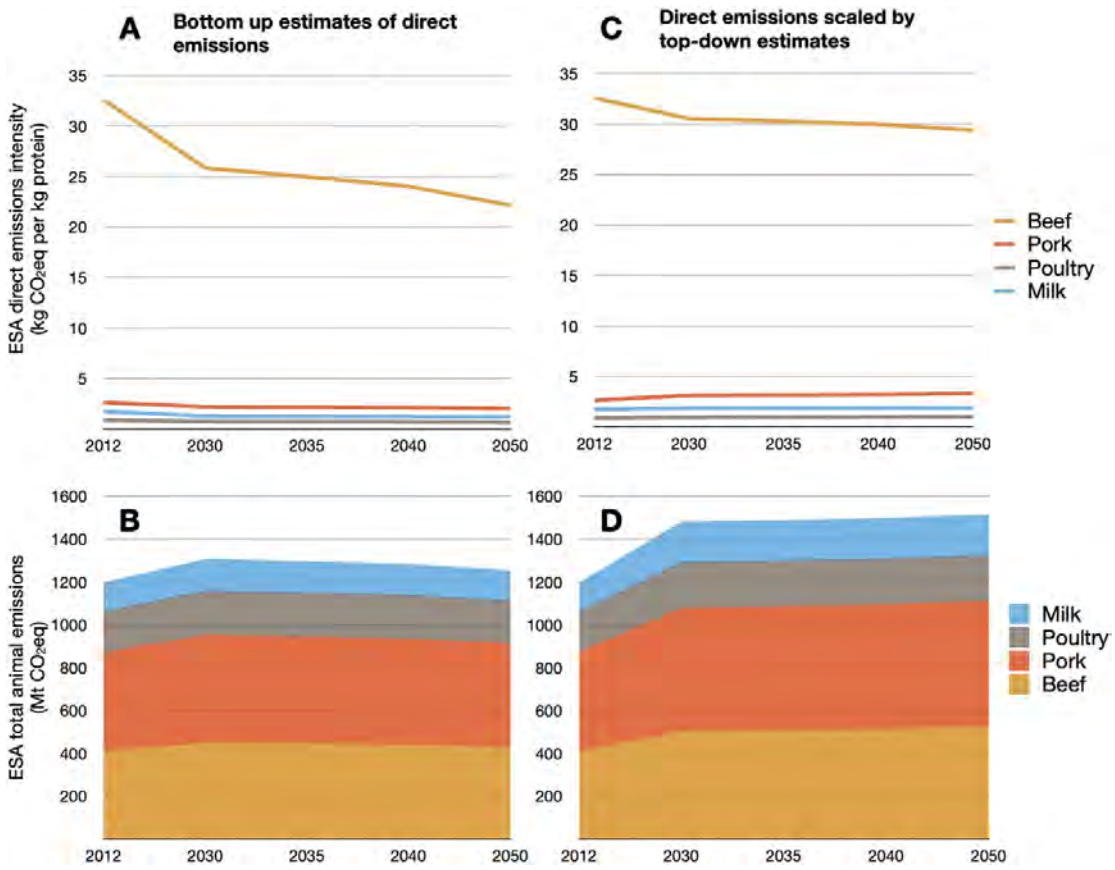

Figure 2. Present and future emissions intensities and total emissions from animal production in ESA, as estimated by bottom-up emissions models (A)–(B) and direct emissions from intensive production adjusted by a scale factor (1.65) derived from the average of top-down emissions estimates in the US (C)–(D).

Indirect emissions account for approximately 40%–50% of animal agriculture's emissions. This prospective analysis leaves indirect emissions unaltered (e.g. nitrous oxide from fertilizer applied to animal feeds and CO_2 emissions from land use change) while adjusting direct CH_4 emissions and also N_2O emissions from manure management; N_2O emissions appear to be similarly or more dramatically higher than bottom-up estimates when assessed using top-down methods (Owen and Silver 2015). Estimates of CO_2 from fossil fuel and land use change, which are indirect emissions processes in animal agricultural production, generally show good agreement among bottom-up and top-down assessments (Friedlingstein *et al* 2020). However, the implications for animal agriculture in developing contexts is highly uncertain, due to large geographic and seasonal variation in the discrepancies between emissions patterns and because patterns of feed crop trade through 2050 are uncertain. These complexities would make assessing the effects of indirect emissions estimates adjustments substantially more speculative, hence an assessment of indirect emissions estimate corrections was outside of our scope. By not altering indirect emissions, we produce a conservative estimate.

This case study is limited in terms of the confidence with which we can project and scale such differences, however. Uncertainties are not reported by FAO in their ESA regional emissions through 2050, which is a common tendency in bottom-up emissions estimates and projections. We discuss measures needed to improve uncertainty analysis in section 2.1. A fuller analysis regarding how uncertainties in this and other bottom-up emissions compound is outside of the scope of this review and prospective analysis, but is urgently needed.

We express emissions in our ESA case study in CO_2 equivalence (CO_2e) using GWP_{100}, although we acknowledge that this is limited in by placing short- and long-lived gases on the same scale. Recent analyses and commentary have proposed a new approach of GWP*, which includes information about the rate of change in shorter-lived pollutants like methane (Collins *et al* 2020, Lynch *et al* 2020). We share the concerns motivating the development of an alternative CO_2 equivalence metric. However, we did not adopt this new method for recalculating CO_2e due to (a) maintaining consistency for a comparison with previous FAO summary findings and (b) a lack of consensus regarding the appropriateness of assumptions embedded in GWP*, still inspiring active debate on topic (e.g. Rogelj and Schleussner 2019, Smith and Balmford 2020). Ultimately, there are limitations to any method of calculating an equivalence of all

climate pollutants to just one chemical species, rather than directly calculating their effects on temperature. However, this is only a limitation of our ESA case study and not the discrepancies found in our review of methane emissions themselves (table 1), in which we compare Tg of CH_4 directly.

Our prospective analysis demonstrates that animal emissions in the ESA region may not plateau in by 2030, as has previously been projected. While the majority of emissions increase is expected to occur by 2030 (figure 2(B)), this increase may be higher than expected (figure 2(D)) and total emissions may still slightly increase for multiple decades as consumer demand in the region continues to rise.

Despite this uncertainty, our illustrative example of ESA demonstrates that widescale adaptation of intensive production methods in low- and middle-income countries may have limited benefits to GHG emissions, especially if demand continues to grow.

4.2. The limits of intensification for sustainable development

Recommendations to intensify animal production are ubiquitous in the scientific literature (Thornton and Herrero 2010, Gerber *et al* 2013, Swain *et al* 2018, Grossi *et al* 2019). Such suggestions shape policies that disseminate intensive production technologies to low- and middle-income countries. Such policies include sustainable lending criteria from international development banks (World Bank International Finance Corporation 2012), and government subsidies and incentives, which in turn influence and are influenced by the actions of multinational meat and dairy producers (Lazarus *et al* 2021).

Policies that incentivize landless and industrialized animal production methods risk amplifying other public health and environmental harms. Low-interest loans for such animal production operations cover the capital costs of building large shed-like facilities that confine tens to hundreds of thousands of animals indoors (Wasley and Heal 2020) in a manner that often highly restricts their movement and expressions of natural behavior (Prunier *et al* 2010, Grandin 2016, Widowski *et al* 2016). Such facilities require high levels of subtherapeutic antibiotics (Silbergeld *et al* 2008), leading to antibiotic resistance, and encourage the rapid transmission and mutation of viruses with pandemic potential (Alders *et al* 2014, Millman *et al* 2017, Lycett *et al* 2019) including highly pathogenic avian influenzas (HPAI, also known as 'bird flu'). Intensified animal production poses a litany of zoonotic disease risks (UNEP and ILRI 2020). Large concentrated quantities of production and storage also create point and non-point sources of groundwater pollution and can degrade air quality (Secchi and Mcdonald 2019, Domingo *et al* 2021).

While the efficiency of feeding and fattening allowed by intensified animal production can reduce indirect land use, confined forms of animal production including landless and industrialized systems Intensification can lead to further homogeneity of food systems and exacerbates zoonotic disease risks (UNEP and ILRI 2020) including interspecies transmissions of and other infectious viruses.

Public and private institutions must fully evaluate socio-environmental externalities and risks of intensified animal production systems in their policies that finance and incentivize their expansion. Continuing to export these technologies and practices to developing regions could achieve less GHG mitigation than commonly assumed while exacerbating other socio-environmental harms.

4.3. The climate mitigation potential of agricultural development

The climate impacts of growing demand for meat and dairy have implications for keeping global warming within safe limits. Most countries have not committed to reducing non-CO_2 gases (Climate Action Tracker, Wang *et al* 2018), including methane and nitrous oxide from animals. Previous analysis has demonstrated that if countries aggressively limit CO_2 from fossil fuels, growth in meat and dairy consumption would be sufficient to cause warming of above 2 °C even with aggressive mitigation in other sectors (Harwatt *et al* 2020) and business-as-usual growth in animal sourced food production, efficiency, and consumption would exceed the entire GHG budget compatible with a 1.5 °C threshold of warming (Clark *et al* 2020). The aforementioned findings were all informed by bottom-up models, which may underestimate emissions from intensive production systems that are proliferating globally. Growth in meat and dairy production and consumption therefore may be even more incompatible with limiting global warming than previously reported.

Our prospective analysis demonstrates that GHG emissions could increase as developing regions intensify production. On one hand, intensive systems could achieve GHG mitigation with improved technologies such as anaerobic manure digestors that capture biomethane for fuel usage (Paolini *et al* 2018) and concentrated feeds supplemented with enteric fermentation suppressants such as 3-nitrooxypropanol and seaweeds (Machado *et al* 2016, Jayanegara *et al* 2018). On the other hand, ambitious interventions and improvements in efficiencies have the potential to mitigate less than a quarter of annual agricultural emissions relative to business-as-usual (Höglund-Isaksson *et al* 2020).

GHG emissions are not the only indicator of sustainability, and GHG suppression measures for intensively-raised animals could incentivize animal concentration at larger scales, exacerbating co-impacts such as water pollution load and antimicrobial resistance, especially if such technologies require additional subsidies to remain economically

viable (Eker *et al* 2019). Sustainability encompasses multiple dimensions, including multiple environmental impacts, social equity, and economic feasibility. Effective sustainable development strategies for food systems are uncommon because they must provide benefits across multiple dimensions and goals (Rasmussen *et al* 2018).

Socio-environmental benefits could be realized by providing resources in areas of pastoral production for intensification practices that do not involve confinement to similar levels of intensive US 'landless' systems. Such practices include improved animal veterinary care, improved forage seeds and pasture management, and more precise nutrient application. Improved coordination between smallholder and midsize producers, government, and NGOs can hasten these benefits (Swain *et al* 2018, FAO 2018b, IPCC 2019). Intensification may be effective in optimizing co-benefits in some circumstances, especially in regions where indirect emissions are large (e.g. ongoing land-use change, including deforestation).

Reducing externalities of further intensification also depends upon limiting overall consumer demand, particularly in regions where animal-sourced food consumption already exceeds nutritional requirements. Improved productivity and lower prices can lead to runaway effects of stimulating greater demand a feedback process known as Jevons Paradox (Garnett *et al* 2015), and stimulate more production by decreasing input costs (Kreidenweis *et al* 2018). Feedback effects between supply and demand can therefore undermine or worsen the environmental impacts that intensification efforts seek to mitigate. Mitigation policies should address the overconsumption of animal-sourced foods to avoid these feedback effects, rather than merely focusing on improving production.

Managing both supply and demand of animal-sourced foods must be considered within efforts to reform and develop food systems sustainably while mitigating climate change (IPCC 2019, Clark *et al* 2020, Harwatt *et al* 2020). Such efforts could include reforming dietary recommendations to reflect regional environmental impacts and planetary boundaries (Willett *et al* 2019, Springmann *et al* 2020), developing public-private partnerships to stimulate production and demand of plant-based proteins (Attwood *et al* 2019), and changing taxation and subsidy structures to reflect the true environmental costs of meat and dairy production across multiple impacts (IPCC 2019).

In addition to limiting overall consumption, more steps are necessary to ensure that intensification strategies maximize co-benefits and constrain potential externalities. These include (a) marrying intensification with strong environmental conservation policies (Garrett *et al* 2018, Kreidenweis *et al* 2018) (b) improving farmer livelihoods and disincentivizing industry consolidation that can crowd out smallholder producers, and (c) avoiding extreme forms of confinement entailed in many landless and industrialized systems, which also promote zoonotic disease emergence and antimicrobial resistance (UNEP and ILRI 2020). This last criterion may prove an exceedingly difficult needle to thread if demand for animal-sourced foods continues to increase unabated. All of the above and more is required to ensure that the intensification of animal agriculture does not further amplify multiple environmental risks including climate change, biodiversity loss, and the emergence of potentially pandemic zoonotic diseases.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Alders R, Awuni J A, Bagnol B, Farrell P and De Haan N 2014 Impact of avian influenza on village poultry production globally *Ecohealth* **11** 63–72

Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: the 2012 revision *FAO* **20** 375

Attwood S, Voorheis P, Mercer C, Davies K and Vennard D 2019 *Playbook for Guiding Diners toward Plant-Rich Dishes in Food Service* (Washington, DC: World Resources Institute (WRI))

Carrel M, Young S G and Tate E 2016 Pigs in space: determining the environmental justice landscape of swine concentrated animal feeding operations (CAFOS) in Iowa *Int. J. Environ. Res. Public Health* **13** 849

Cattlemen's Beef Board 2018 Beef sustainability (available at: www.beefitswhatsfordinner.com/raising-beef/beef-sustainability)

Chen Z, Griffis T J, Baker J M, Millet D B, Wood J D, Dlugokencky E J, Andrews A E, Sweeney C, Hu C and Kolka R K 2018 Source partitioning of methane emissions and its seasonality in the U.S. Midwest *J. Geophys. Res. Biogeosci.* **123** 646–59

Clark M A, Domingo N G G, Colgan K, Thakrar S K, Tilman D, Lynch J, Azevedo I L and Hill J D 2020 Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets *Science* **370** 705–8

Climate Action Tracker Climate action tracker (available at: https://climateactiontracker.org/)

Collins W J, Frame D J, Fuglestvedt J S and Shine K P 2020 Stable climate metrics for emissions of short and long-lived species—combining steps and pulses *Environ. Res. Lett.* **15** 024018

De Oliveira Silva R, Barioni L G, Queiroz Pellegrino G and Moran D 2018 The role of agricultural intensification in Brazil's nationally determined contribution on emissions mitigation *Agric. Syst.* **161** 102–12

Desjardins R L, Worth D E, Pattey E, VanderZaag A, Srinivasan R, Mauder M, Worthy D, Sweeney C and Metzger S 2018 The challenge of reconciling bottom-up agricultural methane emissions inventories with top-down measurements *Agric. For. Meteorol.* **248** 48–59

Domingo N G G *et al* 2021 Air quality–related health damages of food *Proc. Natl Acad. Sci.* **118** e2013637118

Dong H, Mangino J and McAllister T A 2006 IPCC 2006 guidelines chapter for national greenhouse gas inventories: chapter 10—emissions from livestock and manure management *Clim. Change* **4** 87

Eker S, Reese G and Obersteiner M 2019 Modelling the drivers of a widespread shift to sustainable diets *Nat. Sustain.* **2** 725–35

Enahoro D, Mason-D'Croz D, Mul M, Rich K M, Robinson T P, Thornton P and Staal S S 2019 Supporting sustainable expansion of livestock production in South Asia and Sub-Saharan Africa: scenario analysis of investment options *Glob. Food Sec.* **20** 114–21

FAO 2017 Global livestock environmental assessment model (GLEAM) 2.0—assessment of greenhouse gas emissions and mitigation potential (available at: www.fao.org/gleam/results/en/)

FAO 2018a The future of food and agriculture—alternative pathways to 2050 (Rome) (available at: www.fao.org/3/I8429EN/i8429en.pdf)

FAO 2018b World Livestock: transforming the livestock sector through the sustainable development goals (Rome: Search Results Web Result with Site Links Food and Agriculture Organization of the United Nations) (available at: www.fao.org/3/CA1201EN/ca1201en.pdf)

Fox N J, Smith L A, Houdijk J G M, Athanasiadou S and Hutchings M R 2018 Ubiquitous parasites drive a 33% increase in methane yield from livestock *Int. J. Parasitol.* **48** 1017–21

Friedlingstein P *et al* 2020 Global carbon budget 2020 *Earth Syst. Sci. Data* **12** 3269–340

Garnett T, Röös E and Little D 2015 Lean, green, mean, obscene..? What is efficiency and is it sustainable? (available at: https://decorrespondent.nl/3912/Waarom-minder-vlees-eten-zo-moeilijk-is/297946166496-3b400346%5Cnpapers3://publication/uuid/A50BCD2F-2BC4-4758-B74B-13D0CB148F1E)

Garrett R D, Koh I, Lambin E F, Le Polain De Waroux Y, Kastens J H and Brown J C 2018 Intensification in agriculture-forest frontiers: land use responses to development and conservation policies in Brazil *Glob. Environ. Change* **53** 233–43

Gavrilova O *et al* 2019 Refinement to the 2006 IPCC guidlines for national greenhouse gas inventories, volume 4: agriculture, forestry and other land use: emissions from livestock and manure management *Forestry* **4** 87

Gerber P J, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A and Tempio G 2013 *Tackling Climate Change through livestock—A Global Assessment of Emissions and Mitigation Opportunities* (Rome: Food and Agriculture Organization of the United Nations (FAO))

Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M and Toulmin C 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–8

Grandin T 2016 Evaluation of the welfare of cattle housed in outdoor feedlot pens *Vet. Anim. Sci.* **1–2** 23–8

Grossi G, Goglio P, Vitali A and Williams A G 2019 Livestock and climate change: impact of livestock on climate and mitigation strategies *Anim. Front.* **9** 69–76

Harwatt H, Ripple W J, Chaudhary A, Betts M G and Hayek M N 2020 Scientists call for renewed Paris pledges to transform agriculture *Lancet Planet. Health* **4** e9–10

Herrero M, Havlík P, Valin H, Notenbaert A, Rufino M C, Thornton P K, Blümmel M, Weiss F, Grace D and Obersteiner M 2013 Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems *Proc. Natl Acad. Sci.* **110** 20888–93

Höglund-Isaksson L, Gómez-Sanabria A, Klimont Z, Rafaj P and Schöpp W 2020 Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model *Environ. Res. Commun.* **2** 025004

Houdijk J G M, Tolkamp B J, Rooke J A and Hutchings M R 2017 Animal health and greenhouse gas intensity: the paradox of periparturient parasitism *Int. J. Parasitol.* **47** 633–41

Hristov A N, Harper M, Meinen R, Day R, Lopes J, Ott T, Venkatesh A and Randles C A 2017 Discrepancies and uncertainties in bottom-up gridded inventories of livestock methane emissions for the Contiguous United States *Environ. Sci. Technol.* **51** acs.est.7b03332

ILRI 2019 Expanding livestock production in Asia and Africa key to environmental as well as human welfare gains *ILRI News* (available at: https://news.ilri.org/2019/03/31/expanding-livestock-production-in-asia-and-africa-key-to-environmental-as-well-as-human-welfare-gains-new-study/)

IPCC 2019 Climate change and land an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems *Head of TSU (Operations) IT/Web Manager Senior Administrat* (available at: www.ipcc.ch)

Jayanegara A, Sarwono K A, Kondo M, Matsui H, Ridla M, Laconi E B and Nahrowi N 2018 Use of 3-nitrooxypropanol as feed additive for mitigating enteric methane emissions from ruminants: a meta-analysis *Ital. J. Anim. Sci.* **17** 650–6

Jeong S *et al* 2016 Estimating methane emissions in California's urban and rural regions using multitower observations *J. Geophys. Res.* **121** 13,031–13,049

Kreidenweis U, Humpenöder F, Kehoe L, Kuemmerle T, Bodirsky B L, Lotze-Campen H and Popp A 2018 Pasture intensification is insufficient to relieve pressure on conservation priority areas in open agricultural markets *Glob. Change Biol.* **24** 3199–213

Lazarus O, McDermid S and Jacquet J 2021 The climate responsibilities of industrial meat and dairy producers *Clim. Change* **165** 30

Lycett S J, Duchatel F and Digard P 2019 A brief history of bird flu *Phil. Trans. R. Soc.* B **374** 0–3

Lynch J, Cain M, Pierrehumbert R and Allen M 2020 Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants *Environ. Res. Lett.* **15** 044023

Machado L, Magnusson M, Paul N A, Kinley R, De Nys R and Tomkins N 2016 Identification of bioactives from the red seaweed Asparagopsis taxiformis that promote antimethanogenic activity *in vitro J. Appl. Phycol.* **28** 3117–26

McDonald's Canada 2018 Beef sustainability | the journey ahead | McDonald's Canada *YouTube* (available at: www.youtube.com/watch?v=w8ubbgW3jZw)

Miller S M *et al* 2013 Anthropogenic emissions of methane in the United States *Proc. Natl Acad. Sci.* **110** 20018–22

Miller S M, Hayek M N, Andrews A E, Fung I and Liu J 2015 Biases in atmospheric CO_2 estimates from correlated meteorology modeling errors *Atmos. Chem. Phys.* **15** 2903–14

Miller S M and Michalak A M 2017 Constraining sector-specific CO_2 and CH_4 emissions in the US *Atmos. Chem. Phys.* **17** 3963–85

Miller S M, Michalak A M, Detmers R G, Hasekamp O P, Bruhwiler L M P and Schwietzke S 2019 China's coal mine methane regulations have not curbed growing emissions *Nat. Commun.* **10** 303

Miller S M, Michalak A M and Wofsy S C 2014 Reply to Hristov *et al*: linking methane emissions inventories with atmospheric observations *Proc. Natl Acad. Sci.* **111** E1321

Millman C, Christley R, Rigby D, Dennis D, O'Brien S J and Williams N 2017 "Catch 22": biosecurity awareness,

interpretation and practice amongst poultry catchers *Prev. Vet. Med.* **141** 22–32
National Pork Board 2020 Pork industry releases new sustainability report *Pork Checkoff* (available at: www.pork.org/news/pork-industry-releases-new-sustainability-report/)
NRC 1989 *Nutrient Requirements of Dairy Cattle* (Washington, DC: National Academy of Sciences)
NRC 2001 *Nutrient Requirements of Dairy Cattle* 7th revised edn (Washington, DC: The National Academies Press) (available at: www.nap.edu/catalog/9825/nutrient-requirements-of-dairy-cattle-seventh-revised-edition-2001)
Owen J J and Silver W L 2015 Greenhouse gas emissions from dairy manure management: a review of field-based studies *Glob. Change Biol.* **21** 550–65
Pandey S, Houweling S, Krol M, Aben I, Nechita-Banda N, Thoning K, Röckmann T, Yin Y, Segers A and Dlugokencky E J 2019 Influence of atmospheric transport on estimates of variability in the global methane burden *Geophys. Res. Lett.* **46** 2302–11
Paolini V, Petracchini F, Segreto M, Tomassetti L, Naja N and Cecinato A 2018 Environmental impact of biogas: a short review of current knowledge *J. Environ. Sci. Health* A **53** 899–906
Poore J and Nemecek T 2018 Reducing food's environmental impacts through producers and consumers *Science* **360** 987–92
Prunier A, Heinonen M and Quesnel H 2010 High physiological demands in intensively raised pigs: impact on health and welfare *Animal* **4** 886–98
Rasmussen L V, Coolsaet B, Martin A, Mertz O, Pascual U, Corbera E, Dawson N, Fisher J A, Franks P and Ryan C M 2018 Social-ecological outcomes of agricultural intensification *Nat. Sustain.* **1** 275–82
Richter B D *et al* 2020 Water scarcity and fish imperilment driven by beef production *Nat. Sustain.* **3** 319–28
Robinson T *et al* 2011 *Global Livestock Production Systems* (available at: www.fao.org/3/i2414e/i2414e00.htm)
Rogelj J and Schleussner C-F 2019 Unintentional unfairness when applying new greenhouse gas emissions metrics at country level *Environ. Res. Lett.* **14** 114039
Saunois M *et al* 2020 The global methane budget 2000–2017 *Earth Syst. Sci. Data* **12** 1561–623
Secchi S and Mcdonald M 2019 The state of water quality strategies in the Mississippi River Basin: is cooperative federalism working? *Sci. Total Environ.* **677** 241–9
Sheng J-X, Jacob D J, Turner A J, Maasakkers J D, Sulprizio M P, Bloom A A, Andrews A E and Wunch D 2018 High-resolution inversion of methane emissions in the Southeast US using SEAC^{4}RS aircraft observations of atmospheric methane: anthropogenic and wetland sources *Atmos. Chem. Phys.* **18** 6483–91
Silbergeld E K, Graham J and Price L B 2008 Industrial food animal production, antimicrobial resistance, and human health *Annu. Rev. Public Health* **29** 151–69
Smith P and Balmford A 2020 Climate change: 'no get out of jail free card' *Vet. Rec.* **186** 71
Springmann M, Spajic L, Clark M A, Poore J, Herforth A, Webb P, Rayner M and Scarborough P 2020 The healthiness and sustainability of national and global food-based dietary guidelines: a modelling study *BMJ* **370** 1–16
Steinfeld H, Wassenaar T and Jutzi S 2006 *Livestock's Long Shadow* (available at: www.globalmethane.org/expo-docs/china07/postexpo/ag_gerber.pdf)
Swain M, Blomqvist L, McNamara J and Ripple W J 2018 Reducing the environmental impact of global diets *Sci. Total Environ.* **610–611** 1207–9
Sykes A J, Topp C F E and Rees R M 2019 Understanding uncertainty in the carbon footprint of beef production *J. Clean. Prod.* **234** 423–35
Thornton P K and Herrero M 2010 Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics *Proc. Natl Acad. Sci. USA* **107** 19667–72
Turner A J *et al* 2015 Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data *Atmos. Chem. Phys.* **15** 7049–69
UNEP and ILRI 2020 Preventing the next pandemic—zoonotic diseases and how to break the chain of transmission (Nairobi) (available at: www.unenvironment.org/resources/report/preventing-future-zoonotic-disease-outbreaks-protecting-environment-animals-and)
US EPA O 2021 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019* (available at: www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019)
USDA 2013 *Feedlot 2011—Part IV: Health and Health Management on U.S. Feedlots with a Capacity of 1,000 or More Head* (available at: www.aphis.usda.gov/animal_health/nahms/feedlot/downloads/feedlot2011/Feed11_dr_PartIV_1.pdf)
USDA 2016 *Dairy 2014—Milk Quality, Milking Procedures, and Mastitis on U.S. Dairies, 2014* (Fort Collins, CO) (available at: www.aphis.usda.gov/animal_health/nahms/dairy/downloads/dairy14/Dairy14_dr_Mastitis.pdf)
Wang L, Xue B and Yan T 2017 Greenhouse gas emissions from pig and poultry production sectors in China from 1960 to 2010 *J. Integr. Agric.* **16** 221–8
Wang X, Teng F, Zhang J, Khanna N and Lin J 2018 Challenges to addressing non-CO_2 greenhouse gases in China's long-term climate strategy *Clim. Change* **18** 1059–65
Wasley A and Heal A 2020 Revealed: development banks funding industrial livestock farms around the world *Guard.* | *Environ.* (available at: www.theguardian.com/environment/2020/jul/02/revealed-development-banks-funding-industrial-livestock-farms-around-the-world)
Wecht K J, Jacob D J, Frankenberg C, Jiang Z and Blake D R 2014 Mapping of North American methane emissions with high spatial resolution by inversion of SCIAMACHY satellite data *J. Geophys. Res. Atmos.* **119** 7741–56
Widowski T M, Hemsworth P H, Barnett J L and Rault J-L 2016 Laying hen welfare I. Social environment and space *Worlds Poult. Sci. J.* **72** 333–42
Willett W *et al* 2019 Food in the anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems *Lancet* **6736** 3–49
Wolf J, Asrar G R and West T O 2017 Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock *Carbon Balance Manage.* **12** 16
World Bank International Finance Corporation 2012 Performance standard 3: resource efficiency and pollution prevention *IFC Sustain. Stand. Policies* (available at: www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/policies-standards/performance-standards/ps3)
World Bank International Finance Corporation 2020 GXYX ASF disclosure *IFC Proj. Inf. Data Portal* (available at: https://disclosures.ifc.org/#/projectDetail/ESRS/43384)
Yu J, Peng S, Chang J, Ciais P, Dumas P, Lin X and Piao S 2018 Inventory of methane emissions from livestock in China from 1980 to 2013 *Atmos. Environ.* **184** 69–76
Yu X *et al* 2021 Aircraft-based inversions quantify the importance of wetlands and livestock for Upper Midwest methane emissions *Atmos. Chem. Phys.* **21** 951–71

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BIOMASS ACCIDENT INVESTIGATIONS – MISSED OPPORTUNITIES FOR LEARNING AND ACCIDENT PREVENTION

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ABSTRACT: The past decade has seen a major increase in the production of energy from biomass. The growth has been mirrored in an increase of serious biomass related accidents involving fires, gas explosions, combustible dust explosions and the release of toxic gasses. There are indications that the number of bioenergy related accidents is growing faster than the energy production. This paper argues that biomass accidents, if properly investigated and lessons shared widely, provide ample opportunities for improving general hazard awareness and safety performance of the biomass industry. The paper examines selected serious accidents involving biogas and wood pellets in Denmark and argues that such opportunities for learning were missed because accident investigations were superficial, follow-up incomplete and information sharing absent. In one particularly distressing case, a facility saw a repeat accident, this time with fatal outcome, still without any learning taking place. The paper presents some information on other biomass accidents in Denmark, mostly involving biogas from anaerobic digestion. Details are lacking however, precisely because the accidents were insufficiently investigated and results not communicated. The biomass industry needs to pay more attention to safety. Utmost care should be taken to avoid so-called media-shifting i.e. that the resolution of a problem within one domain, the environmental, creates a new problem in another, the workplace safety domain.
Keywords: biogas, wood pellet, explosion, ATEX, accident investigation, lessons learned, inherent safety

1 INTRODUCTION

The views of this paper run along three main lines of arguments:

- that currently, the biomass industry gives insufficient attention to safety and major accident hazards;
- that sub-optimalities have to be addressed, particularly those related to so-called media-shifting; and,
- that accident prevention opportunities are foregone due to superficial investigation when accidents do take place, because root causes are not identified and sharing of lessons learned is limited or absent.

1.1 Insufficient attention to safety

The number of major accidents in the bioenergy production and raw materials supply chain is not only increasing but seemingly growing faster than the quantity of energy produced [1]. Safety problems deserve more serious consideration and safety, in a general context, is worthy of being treated as an actual component of sustainability [2].

Biofuels have been the subject of continuous research work world-wide. Earlier studies have argued however, that apart from e.g. material compatibility issues, only limited consideration has been given to safety [2].

Several reasons for this state of affairs have been offered [3]:

(1) It is commonly believed amongst biofuel manufacturers that process safety can be achieved merely by application of common sense;

(2) There is inconsistency in applicable regulations;

(3) There are low skills and competence issues associated with the entry of new manufacturers; and

(4) There is limited information available on the process hazards and minimal appreciation on the risk involved in the production of the biofuels

Other authors argue that due to perceived simplicity of the chemical process, attention to safety is frequently omitted as is basic safety training of the personnel [4] and that poor safety culture is an issue [1]. For biogas production in particular, safety challenges and sustainability issues have become a concern [5].

1.2 Safety, a legitimate objective in industry?

Co-incidentally, the call-for-papers to this EUBCE 2017 international biomass conference provides support to the basic argument of this paper, that there is little attention to safety and limited appreciation of hazards in the biomass industry.

To classify conference contributions, the organizers have compiled a list, which as per April 2017 had 470 keywords entries. The topic of safety is conspicuous by its absence – there is not a single keyword related to safety in this long list.

The closest match is "security". Security measures relate to physical protection however, such as safeguarding an asset from unauthorized access and acts of malevolence. Security is much different from safety [6]. The following standard keywords related to biomass safety are absent in the list: safety, accident investigation, fire, combustible dust explosion, ATEX, emergency response, firefighting, oxygen depletion, off-gassing, toxic gas hazard, hydrogen sulfide and carbon monoxide.

This is remarkable bearing in mind that the conference has global attendance, with 800-900 contributions from 3800 authors from 80 countries.

1.3 Media-shifting

Environmental interventions may be undertaken with insufficient attention paid to workplace safety [7], [8]. Two types of sub-optimalities can be identified:

1) media shifting, which occurs if the 'resolution' of a problem within the environmental domain gives rise to new, and unforeseen, problems within other domains, specifically the workplace safety domain; and

2) a missed opportunity, which occurs if an opportunity exists for improving both environmental and occupational health and safety performance, but a less optimal solution is chosen that only addresses environmental performance.

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1.4 Accident investigation and learning

Having paid the price of an accident, we should use the opportunity to learn from it. Entire books have been dedicated to learning from accident case stories in the process industry [9]–[11]. The benefits of such learning are obvious – to avoid repetition, and to share the lessons learned in order to minimize the number of times the same lessons have to be learned.

What is not so obvious, however, is how to make this seemingly simple and straightforward idea work in practice [12], [13]. This challenge is reflected in common aphorisms, such as Santanyana's: Those who cannot remember the past are condemned to repeat it.

1.5 Causes

The search for accident causes has been likened to peeling an onion [14]. The skin represents the immediate technical causes but beneath lies layers and layers of underlying causes such as weaknesses in the management system, each contributing with important insights for prevention. Much theory exist on this subject, e.g. [15], [16]. It suffices here to stress that both immediate and underlying causes should be sought after an accident.

As will be argued later in this article, the biomass industry fares badly in this respect – investigations are superficial.

2 METHOD AND MATERIALS

The first sections of the paper examine three serious Danish biomass accident case stories in detail. The case stories have been selected for their following characteristics:

(1) They have major accident potential, resulting in fatal or near-fatal injury and they clearly have multiple fatality potential.

(2) They were poorly investigated, with direct causes being only superficially identified or not identified at all, and underlying organizational issues ignored.

(3) There is sparse information on the etiology of the accidents in open sources, in some cases resulting in basic facts being inaccurate or misleading.

(4) Repeat accidents took place at a later stage.

Primary sources are, unless otherwise indicated, dockets of the Danish Working Environment Authority and the police obtained through the Danish equivalent of a Freedom of Information Act. Media reporting may serve as supplementary sources.

3 ACCIDENT 1: EXPLOSION OF BIOGAS DIGESTER

3.1 The digester

In 1990, a biogas digester at Vejle municipal wastewater treatment plant (WWTP) in Denmark exploded. The anaerobic digester processed regular municipal sewage sludge.

At the time, the WWTP had four anaerobic digesters, one gasholder tank and one tank for processed sludge. Digesters #3 and #4 were identical and built in the early 1970s using concrete slipform construction methods. A rectangular building between the two digesters held shared technical installations and access stairways.

The digesters were vertical cylinders with a cone shaped roof and a cone shaped bottom. An upper horizontal ring beam between the cylinder and the top cone helped distribute structural loads. In a cut-through drawing (fig. 1), the digester would appear as a hexagon.

A circular cavity wall circled the digester. Leca-blocks were used for the inner-wall and masonry red brickwork for the outer wall. For architectonical and decorative purposes, the circumference of the outer brick wall was interrupted every five meters or so by slender concrete columns in series of three to break visual monotony. The columns were purely decorative and carried no load.

At the upper part of the digester tank, a parapet provided circumferential structural support to a horizontal roof deck. The circular cavity between the horizontal deck and upper cone of the digester served as a utility corridor for pipes and other technical installations. The parapet was an extension of the circular exterior wall, which covered the digester's thermal insulation. The parapet continued vertically above the upper ring beam and extended about 1 m above the horizontal roof deck.

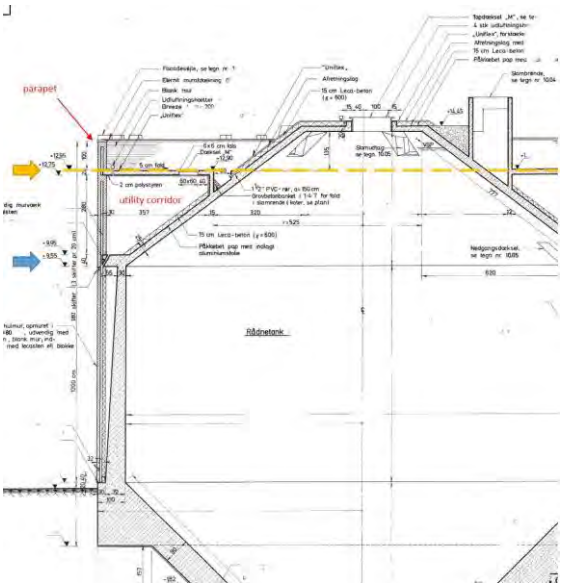

Figure 1: Part of cross-sectional drawing of the accident biogas digester. The blue arrow marks the horizontal ring beam. The yellow arrow and dotted line mark the roof deck supported by a parapet. Five contractors were present at the roof doing asphalt roofing work when the explosion took place. Drawing courtesy of Krüger, Denmark.

3.2 Roofing work

Digesters #3 and #4 were in need of roof repairs. For reasons that are no longer known, asphalt roofing was decided upon. This type of roofing material is a membrane made of a felt or fiberglass mat saturated with bitumen. The roofing material is applied using a propane fired torch which partly melts the bitumen mixture on the underside of the membrane and glues it to the roof.

3.3 Prior planning of roof work

Planning of the roof work started more than two months in advance. A project team was assembled and at least one meeting was held with representatives from the roofing contractor, the WWTP, the Danish Working Environment Authority, the municipal fire department, an

external occupational health and safety specialist from a large engineering consultancy, and others.
Work would start on Digester #4. The following procedure was agreed upon:

- No new sludge to be fed to the digester two weeks before the work was to commence
- All roof hatches to be opened one week before the work, in order to gas free the digester (natural ventilation)
- All roof hatches to be sealed closed and valves to the neighboring digester 3, and other biogas systems, to be locked closed.
- While the work is carried out, any surplus gas in the digester to be vented to a safe location. A hose, length 8-10 m, to be fitted to the digester's open 8" top vent valve. The hose to terminate at the perimeter and extend no less than 3 m above the roof. Bio methane is lighter than air and hence buoyant, which would ensure safe natural dispersion.
- Al all times should the hose outlet be downwind the work site, to keep the worksite free of gas
- At all times should an explosimeter be at the worksite. The work must stop immediately if flammable gasses are detected (alarm level 15 percent of the lower explosion limit of bio-methane).

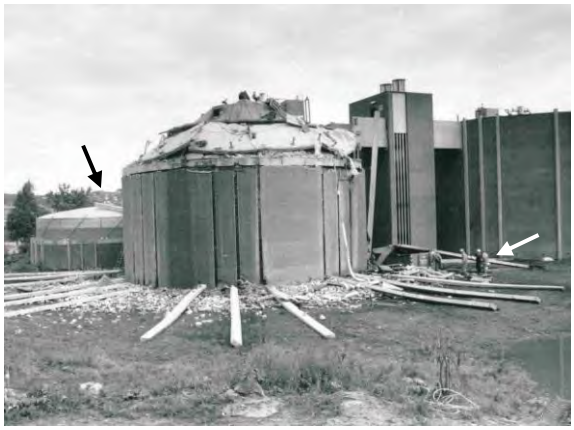

Figure 2: Aftermath. The accident Digester #4 center, the identical and apparently undamaged digester #3 to the right. The digester's roof deck collapsed and two roofing contractors fell down 11 m. At least one of the decorative concrete columns fell onto the gasholder tank behind the accident digester at center left (arrow).. Note persons for scale at center right (arrow). Photo courtesy of Vejle Amts Folkeblad.

3.4 The explosion

In the early morning of the third workday, on August 22, 1990, Digester #4 exploded. At the time of the explosion, five contractors were present doing asphalt roll roofing work.

The explosion either blew the parapet away or dislocated it, causing it to collapse (Fig. 2). With the peripheral structural support gone, the horizontal roof deck with the workers on top also collapsed (Fig. 3). Two workers fell 11 m and landed in the debris zone below. They suffered very seriously injuries, inter-alia serious head trauma. They survived but with debilitating permanent injuries.

Two workers suffered minor injuries as they fell "to a lower level", probably because they managed to cling onto what remained of the roof deck. Miraculously, one worker was unharmed.



Figure 3: The collapsed roof deck. A small section of the remains of the parapet, which provided structural support to the roof deck, is just visible to the left (arrow). Photo courtesy of Vejle Amts Folkeblad.

3.5 Cause

The investigation soon identified the cause. The hose fitted to the digester's 8" top vent valve was a simple flexible duct similar to those commonly used for household kitchen ventilation purposes – a plastic cover over a metal wire coil to shape a tube (Fig. 4). The hose did indeed terminate at the perimeter of the digester and was indeed elevated to a height of 3 m, but the hose was lying on the roof, unprotected. In a moment of inattention, a worker had grazed the flexible hose with his propane burner torch – the plastic had melted and the gas inside ignited. There was no flashback arrestor in the line and the flame could travel back into the digester, causing an explosion there.

3.6 Ignorance

A contemporary occupational health and safety magazine [17] expressed an almost heartbroken frustration with the fact that a glaringly obvious hazard was overlooked by all participants. Indeed, with the benefit of hindsight, gross ignorance in the planning phase is evident. Such ignorance however, when realized, is a prime candidate for information exchange of lessons learned and insights gained to prevent repeat accidents.

Basic combustion engineering knowledge regarding flammability limits seems to have been absent in the planning phase. The decision to open the top hatches in an attempt to free the digester of flammable gas is particularly distressing. Mixtures of gas and air will burn only if the fuel concentration lies within well-defined lower and upper bounds referred to as flammability limits. Had the top hatches not been opened and air not entered the digester, the gas in the digester would not have been in the ignitable range. With no ingress of air, a flashback into the digester would not have been possible and an explosion could not have taken place.

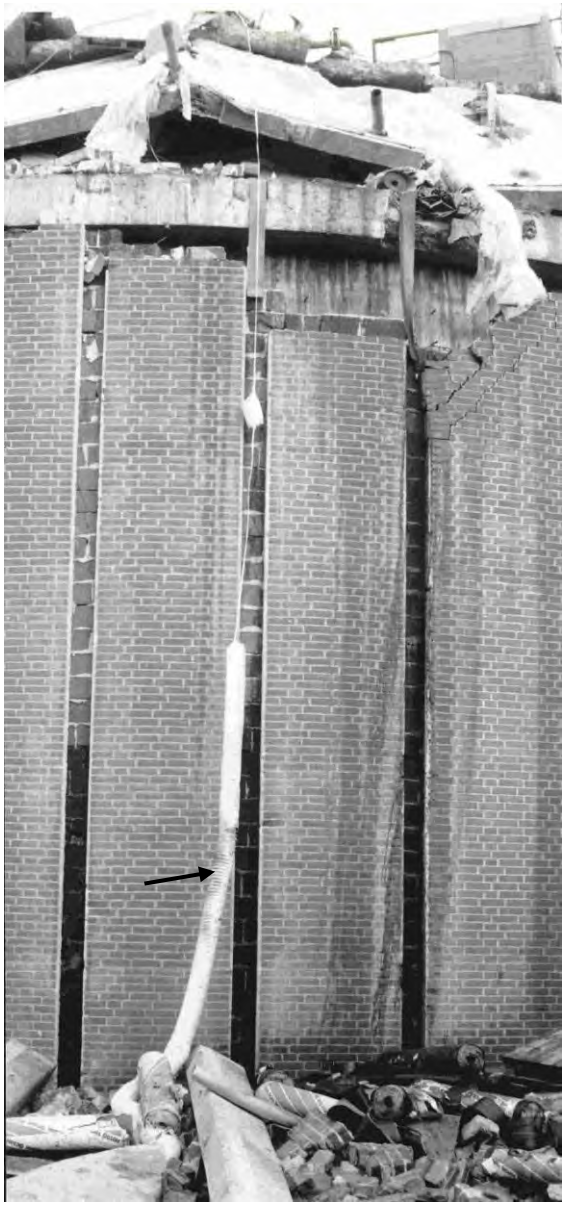

Figure 4: The "glaringly obvious hazard" (with the benefit of hindsight). The standard flexible duct of the same type commonly used for household kitchen ventilation purposes hangs from the roof (arrow), torn and burnt. It was fitted to the top valve to vent excess digester gas. The propane torch of an asphalt roofing contractor grazed the flexible duct, ignited the gas inside, and the flame flashed back into the digester, leading to explosion. Photo courtesy of Vejle Amts Folkeblad.

The decision to free the digester of flammable gas by opening the top hatches and rely on natural ventilation was also ill conceived. Although pure bio-methane indeed is lighter than air, and hence is buoyant, biogas is not. Significant quantities of carbon dioxide are created by the same anaerobic microbial processes that produce bio-methane, the typical volumetric concentration is about 1/3. The carbon dioxide molecule is denser than air and as a result, (dry) biogas often has a near-neutral density relative to air. It is not particularly buoyant and will mix only slowly with stagnant air.

The project team seems to have been singularly concerned with the risk for ignitable gas *at the workplace*, presumably because the main hazard identified was sources of ignition: the naked flame of the propane torches. The team's mental model of hazards seems to have been limited to where ignition sources were present, ignoring the hazard of ignitable gas inside the digester. This may reflect traditional explosion protection thinking prevalent at the time, which concerned itself with classification of areas to facilitate the proper selection and installation of εx (epsilon-x) classified electrical equipment to be used safely in those areas – i.e. to reduce the probability of ignition. Only with the ATEX Directive introduced later came a broader risk analysis based approach, the so-called safety principles, which directs attention to first, preventing the formation of flammable atmospheres, second, to reduce the chance of ignition, and third, to mitigate the severity of the consequences.

Mistakes in execution are also evident. The decision to use a standard flexible duct similar to those commonly used for household kitchen ventilation purposes is disturbing as is the practical implementation, with the hose lying directly on the roof, unprotected. The asphalt roofing contractors seem to have been clueless about hazards.

3.7 Forgotten

The accident is important not only for the lessons learned it provides, but also for the fact that basic knowledge about the event has passed into oblivion only 25 years after having taken place [18].

In 2014, a Google search for the accident would come back empty. The search tool REX at the Danish National Library would find nothing. Nor would Infomedia, a Danish proprietary search engine and media article repository that tracks about 1,900 Danish media.

In 2014, the staff at Vejle WWTP knew the accident had taken place but no one had any personal knowledge of the event and written records no longer exist.

Access to the records of the Danish Working Environment Authority and the police was requested through the Danish equivalent of a Freedom of Information Act. The docket obtained from the Working Environment Authority appears to be incomplete however, there is no investigation of the accident itself, only minutes of the many meetings held later, when asphalt roofing work was to be carried out on Digester #3. The police informed that their docket had been transferred to the Viborg branch of the Danish National Archives. With regrets, they informed that the docket could not be located, the archive box was empty.

Two specialist magazines with limited circulation each carried an article on the accident [17], [19]. The magazines could be retrieved only with much effort.

News media coverage was available at the microfiche archive at the Danish National Library in Copenhagen. Upon request, the regional newspaper Vejle Amts Folkeblad kindly retrieved photos from their archives and made them available for publication.

Perhaps the starkest evidence of oblivion is a 2012 safety document for a large Danish biogas facility covered by the EU Seveso Directive (lower-tier). In sweeping statements, the facility's safety document asserts that the literature is silent on biogas accidents.

3.8 Learning processes?

As stated above, ignorance, when realized, is a prime candidate for information exchange of lessons learned

and insights gained to prevent repeat accidents. Opportunities for learning after the 1990 digester explosion appear to have been wholly missed however.

Lindberg et al. [20] offer a description of the CHAIN model for experience feedback, which comprise six activities (1) reporting, (2) selection, (3) investigation, (4) dissemination, (5) prevention, and (6) evaluation.

The model summarizes well-known concepts from the literature and underlines that learning from past accidents is truly a chain in the sense that the process as a whole fails if any one of its links fails.

In the 1990 Vejle accident some of the early links in the chain failed – and the accident was simply forgotten.

3.9 Repeat accidents

The French ARIA database [21] offers a brief description of a biogas digester explosion in Peschiera Del Garda (Italy) on March 12, 1997, which appears to share many similarities with the 1990 Vejle accident.

The site was a municipal wastewater treatment plant, the digester was made of concrete and roof "repair works" were being carried out. The accident description simply says that "residue gas" was present in the digester. Welding ignited the gas and the concrete digester exploded. Two workers were thrown from the roof and killed. A third worker fell into the digester and was seriously injured. There is no description of the circumstance and of lessons learned, if any.

In 1976 a concrete biogas digester exploded in Åkeshov (Sweden). A picture is provided in [22] and large chunks of concrete at the base of the tank indicate that either the wall or the roof has been severely damaged. There are no details.

Even cursory reporting of repeat accidents is compromised if incomplete or absent reporting of biogas accidents is the norm rather than the exception. Not much is known about the propensity to report. Experience from Denmark, detailed below, suggests that reporting is very poor indeed.

3.10 Value of information sharing

An accident investigation report with detailed analysis of causes, consequences and a rich discussion of how to prevent repeat occurrences is of obvious value to operators of similar units elsewhere and to the general community of safety professionals.

Even rudimentary knowledge that a certain type of accident has occurred in not without value either. Designers of anaerobic digesters have educated this author on why internal explosions in digesters are implausible, if not impossible. Most of their assertions were based on coherent technical rationales such as lack of oxygen in the headspace, that digesters are heated and the high humidity and large amount of water vapor in the headspace inerts the atmosphere there, that sources of ignition are absent, etc. But assertions could also be less sophisticated: "it has never happened" or "never heard of it". The mere knowledge of the existence of past incidents can cool such complacency.

Knowledge of past accidents can also help populate the list of possible scenarios and consequences to consider in risk analysis work. One generic risk analysis scheme for off-site risk assessment [23] include harm from emissions (i.e.. leaks) only, as does the generic ATEX approach in [24]. Own work (unpublished) and circumstantial evidence from cursory media reporting [25] suggest that blast overpressure from an internal explosion in a digester or a gas holder might also be relevant accident scenarios for off-site risk assessment. A third generic risk analysis scheme [26] for biogas risk assessment ignores the risk for H_2S poisoning, even though such fatal accidents have occurred. Additional unusual consequences may be considered. In 1976, for example, two sewage storage tanks exploded; the tank failed catastrophically and the gush of sludge killed a teenager and seriously injured an adolescent who were fishing nearby [27]. The unusual consequence is drowning in sludge.

3.11 Other Danish biogas incidents

Starting in 2003, the Danish Safety Technology Authority has issued an annual report with a list of accidents involving flammable gasses, biogas included. The reports are partly based on mandatory self-reporting of accidents that meet certain severity characteristics. The Authority also monitors news media reporting, based on automated screening of keywords. The authority does not investigate accidents.

A review of the Annual reports for 2003-2016 yields one biogas accident (years 2014 and 2015 are not included, reports were not available at the Authority's website): On Sept 2, 2005, at Hemmet a covered tank with degassed manure from a biogas digester "exploded". The biogas is believed to have been ignited by a powertool, when an employee drilled holes in the exterior tank wall to attach a fitting. There were no casualties. There are no details as to why gas was present outside the tank or the nature of the damage caused by the explosion. The brief description is probably based on media reports, which are notoriously inaccurate.

The supplementary information below is based on media reporting retrieved through Infomedia (a proprietary Danish media article repository) or Google.

On December 2, 1999, at Ribe, a severe storm caused a digester to collapse. The digester damaged a neighboring tank, probably another digester, and partly crushed to buildings. There are no details.

Late July 2002, a lightning strike had damaged the flare at Blåbjerg biogas. While the flare was out of service, waiting for spare parts, venting of (unburnt) excess biogas led to neighbor complaints about foul odors. An inspection by the municipality the day the flare was taken back into service discovered a "torn membrane" and a "faulty valve", which had leaked foul biogas for at least 1½ weeks. Details are hazy.

On Jan 8, 2005, the outer protective membrane of a double membrane gas storage holder at Blåbjerg Biogas in Nørre Nebel was torn and dislodged in a storm. There was no damage to the inner membrane and no release of biogas.

Around March 20, 2007, the outer protective membrane of a double membrane gas storage holder at Hashøj biogas collapsed in a storm. The storm dislodged the blower duct and overpressure was lost. A week or so earlier, a batch of Norwegian "wood oil" had killed the microbes in the digester, hence the inner membrane contained little or no gas. When overpressure was lost, the outer membrane collapsed. Apparently, the two membranes were not damaged.

Early September 2013 a silo with dried sludge at Bjergmarken WWTP exploded. It appears to be self-ignition and a subsequent pyrolysis gas explosion, i.e. biogas was not involved. There are no details.

On May 25, 2014, a biogas storage in Thorsø "burned down". Seemingly, an inflatable double membrane gas storage holder was ignited by a blower motor, which caught fire due to an electrical short (personal communication). Details are hazy however, and the information should be viewed with caution.

On August 6, 2015, several people were overcome by hydrogen sulfide fumes at Hashøj Biogas while unloading food waste. Media reports misstate the gas as NO_X and garble other basic facts. This author is in the process of preparing an article on this very serious accident.

On November 29, 2015, the storm "Gorm" severely damaged the exterior insulation on digesters at Holsted biogas. There was no release of biogas.

On May 20, 2009, give and take a few days, a biogas powered public transportation bus caught fire at Jernbane Allé, Vanløse. The fire services doused the bus with copious amounts of water but were much relieved when they learned that biogas (not fossil gas) was involved. "At no time was the situation particularly dangerous, biogas does not ignite so easily", they said.

It would probably be a mistake to discard this comment as a mere competence issue. It may well reflect widespread deep-seated simplistic and astonishingly naïve beliefs that "green" and "sustainable" fuels are less hazardous than their fossil fuel equivalents.

This may indeed be the nub of the problem with limited appreciation of the major accident hazard potential of biomass fuels.

4 ACCIDENT 2: FATAL DUST EXPLOSION AT WOOD PELLET FACILITY CAUSED BY WHEEL LOADER (REPEAT ACCIDENT)

4.1 The facility

A facility located in Aars, Denmark, produced wood pellets from a wide number of waste products, mostly shavings from furniture production, waste streams from the processing of grains, and energy crops [28].

Raw materials were received and stored in a building. Conveyors transported the raw materials to a mill in another building. After milling, a conveyor dropped the (wood) dust of a specific raw material into one of several storage bays. According to recipe, wheel loaders moved material from different bays to a mixing table, which fed the wood pellet press.

4.2 Dust explosion hazards

The wood dust in the storage bays is combustible and presents a risk of dust explosions. When handled, biomass pellets also generate fine dust in quantities that pose a risk for dust explosions. There are numerous reports of fires and explosions involving biomass pellet manufacturing and handling [8].

A dust explosion is the rapid combustion of fine particles of combustible material suspended in the air. Dust explosions can either be primary or secondary. A primary dust explosion occurs when a small suspension of combustible dust is ignited and explodes. A secondary explosion occurs when dust, which has been allowed to settle and accumulate on floors or other surfaces, is made airborne by the pressure wave of primary explosion and subsequently ignited by the slower moving flame front. Depending on the extent of the dust deposits, a weak primary explosion may cause very powerful secondary dust explosions.

Dust explosion hazards can be difficult to recognize by lay persons because the undisturbed atmosphere presents as free of dust and the workplace, when superficially inspected, may falsely appear dust free, overlooking dust deposits in e.g. hard to reach overhead areas.

Dust explosions have traditionally been difficult to deal with in industry. Part of the problem lies with the limited general understanding of the complex mechanism of dust explosions among plant operating personnel as well as corporate management.

4.3 Explosion in 2002

The facility began production of wood pellets in May 2001. The facility experienced a severe explosion in one of the storage bays on March 27, 2002. The roof was blown away, a light concrete wall was pushed outwards and a section of the wall had been toppled. The building was a complete loss. At the time of the explosion, a forklift driver was present inside. The forklift's cabin protected him from the effects of the explosion and he was able to flee unharmed.

The forensic technicians of the police investigated and concluded that an unidentified foreign body had entered the mill and generated a spark that ignited dust at the mill outlet. The fire then triggered a dust explosion in the storage bay. A specialist company was called to examine the spark detection system, but found no technical fault. Specialist fire scene investigators from an external company found no technical fault in the electrical installations which resulted in the same conclusion as the police – the explosion was caused by a spark.

The facility was rebuilt to the original blueprints, with minimal modifications.

4.4 Repeat explosion in 2010

On September 16, 2010, the facility experienced a new explosion, in the same building, and almost at the same location, when a Volvo wheel loader grabbed a bucket of wood dust in a storage bay. Within seconds, the floor in the bay was on fire and the flames almost instantly expanded to fill the entire compartment. The fire then triggered a dust explosion, which damaged the roof and blew out wall panels. The intense fireball killed the driver of the wheel loader. Another worker present inside the building was injured. The building was a complete loss (Fig. 5).

Already the following day, the police informed the public that that the cause of the explosion was identified. Due to a weld failure, the universal (cardan) joint, a power transmission component, broke loose under the vehicle and damaged nearby electrical cables. Electrical shorts and arching ignited airborne dust, which resulted in a combustible dust explosion, concluded the police [28].

The manager of the facility expressed emotion and disbelief, as the facility was in full compliance with the most recent norms and guidelines. In theory, this explosion should not be possible at all, he said.

As will be discussed later however, mere compliance with rules and regulations is no guarantee that the facility is safe.



Figure 5: Light damage. The many fiber cement roofing panels and wall panels that remained in place indicate that the dust explosion overpressure was modest. The dust explosion severity certainly could have been worse. Photo courtesy of Beredskab Vesthimmerland.

4.5 Real cause of the 2010 explosion

Later analysis [28] has identified serious flaws in the swift police investigation and has argued that the real cause was a failure by the driver to release the parking brake, which then overheated and ignited airborne dust.

This difference of argument is no banality, no trivial hair-splitting objection. If the cause is a random breakdown due to a hidden weld defect in a hard to reach mechanical component, very little indeed can be done to prevent recurrence. If the cause is an overheated parking brake however, there are major implications for accident prevention efforts because it suggests that this type of wheel loader is entirely unsuitable for locations where potentially explosive atmospheres of combustible dust exist.

In fact, it can be argued that the accident has broad learning potential because of the widespread usage of front loaders in environments with combustible dust, the innocent nature of the human error and the severity of the consequence.

4.6 Root cause not identified

The safety principles of the ATEX Directive direct attention to first, preventing the formation of flammable atmospheres; second, to reduce the chance of ignition, and third; to mitigate the severity of the consequences.

These principles pay intellectual debt to the earlier concept of inherent safety, which Kletz [29] was the first to clearly articulate. Ashford [7] later argued that inherent safety is similar in concept to pollution prevention. Inherent safety, sometimes referred to a primary prevention, relies on preventing the possibility of an accident. By comparison, secondary prevention relies on reducing the probability of an accident. Mitigation seeks to reduce the seriousness of the consequences, i.e. injuries and damage to the environment or property.

Ashford [30] observes that a bias in the engineering profession, a failure to address inherent safety and primary accident prevention, is one of the reasons why progress in eliminating accidents has been relatively slow.



Figure 6: Superficial investigation. A specialist police vehicle inspector examines the accident Volvo wheel loader shortly after the dust explosion. Tires are burned away and windows in the cabin melted. Upon learning that the universal (cardan) joint had failed, he erroneously concluded the explosion was caused by a mechanical failure due to a concealed weld defect. This finding closed the police investigation, as there was no indication of wrongdoing, only of bad luck. The inspector is looking in the wrong place for causes however. In fact, the underlying cause are in the storage bays just visible in the background. Why design the wood pellet facility with a buffer storage of 500 t of combustible wood dust? It was convenient to store the dust, but not essential to do so. Had the ATEX safety principles been applied, the buffer storage, and hence the fuel source and the potential for severe dust explosions, would have been eliminated. Source: Police investigation and the Danish Working Environment Authority.

Had the safety principles been applied during the investigation of the explosion in 2002, and again in 2010, attention would have been directed towards the soundness of having a buffer storage of 500 t of combustible wood dust (Fig. 7). It was convenient to store the dust, but not essential to do so. A superior design philosophy (from the point of view of safety) would be to mix raw materials according to production recipe and immediately process wood dust from the mill into pellets, eliminating the need for buffer storage, and eliminating a major source of fuel for dust explosions.



Figure 7: The real cause. Two of the storage bays that comprised the 500 t wood dust buffer storage. Photo courtesy of Beredskab Vesthimmerland.

4.7 Evidence of learning?

The 2002 explosion was a highly significant incident as it gave clear evidence of the inherent hazards of wood dust and was an opportunity to re-consider the soundness of having a large buffer storage of combustible wood dust. So was the 2010 explosion.

Both opportunities for learning were missed however, because the investigation was carried out by law enforcement officers, who were narrowly concerned with compliance with regulations, negligence, wrongdoing and culpability.

There is no evidence of new insights gained, no attempts to share basic accident information amongst workplace inspectors or amongst peers within the wood pellet industry. The accident investigation was superficial and information sharing absent. There is no evidence of learning whatsoever.

Had the company chosen to rebuild the facility, which this time they did not, a future repeat explosion in the storage bay area would be likely.

4.8 Ignorance

Law enforcement officers have neither training nor technical background in industrial accident investigation. In fact, their natural (but narrow) concern with negligence and wrongdoing is entirely misplaced in a perspective of learning from accidents. Assigning them to this task is a policy mistake.

Ignorance is also evident at the managerial level. As stated earlier, simplistic beliefs that compliance with rules and regulations ensures a high level of safety are misplaced and naïve. Had management requested a risk analysis? Was management aware of dust explosion cases elsewhere in industry? Probably not.

Ignorance is also evident at the designer level. Why design a facility with a 500 t buffer storage of combustible dust, thereby setting the scene for future serious dust explosions? The designer appears to have been concerned with secondary prevention, on reducing the probability of ignition. Was the designer aware of dust explosion cases elsewhere? Probably not. There is not much literature on the subject, there is little information sharing in the biomass industry.

4.9 Repeat accidents

A safety professional from a large Belgian company kindly shared notes on past accidents. It appears that a Volvo loader was involved in a "dust explosion in bunker followed by fire" on February 15, 2008. Another Volvo loader appears to have been involved in a "storage fire" in February 2010. The accidents appear to have taken place in Belgium or perhaps Holland. There is no further information.

This may be of some significance, because the Volvo loader in the 2010 explosion in Aars, Denmark, had a particular handbrake design, which made it susceptible to overheating if the driver failed to release the handbrake [28]. This is pure conjecture however, and the absence of data does not warrant any further speculation.

There was a dust explosion in a warehouse at Kalundborg Havn on March 7, 2012 while loading a truck with imported wood pellets. The truck driver, who was standing outside the warehouse next to his truck, sustained superficial burns. Pellets in the warehouse were moved with a wheel loader. Evidence indicates that the explosion took place inside a cup elevator however, and that the wheel loader was not involved. It was speculated that a foreign body had become stuck in the cup elevator, creating a spark. Wood pellets in bulk are carried in multi-purpose general cargo vessels and remnants of the vessel's prior cargo often end up in the pellet import. Hence, foreign bodies "wood, rods, metal parts of all kinds" are commonly discovered in the pellets.

5 ACCIDENT 3: FATAL CARBON MONOXIDE POISONING OF TWO SEAMEN

5.1 Carbon monoxide off-gassing hazard

Freshly produced wood pellets may emit a range of gasses such as carbon monoxide, carbon dioxide, methane and volatile organic compounds (VOCs) that can accumulate in storage confinements and reach dangerous levels [31]. The release of the highly poisonous and odorless carbon monoxide is of particular concern. In addition, freshly produced wood pellets may deplete the atmosphere in storage confinements of the oxygen required to sustain life [32].

This section examines the death of two seamen aboard the vessel AMIRANTE due to carbon monoxide poisoning.

5.2 Danger in cargo holds of marine vessel

Wood pellets are often shipped in bulk in marine vessels to their final destination. Problems with oxygen deficiency and dangerous levels of carbon monoxide in the cargo hold of marine vessels at sea have been known for over a decade [33] and the gasses have been responsible for many accidents.

The International Maritime Organization IMO/SOLAS has recently revised its guidance on entering enclosed spaces aboard ships in response to the ongoing problem of confined space incidents [34]. The guidance provides examples of enclosed spaces such as fuel tanks, ballast tanks, cargo pump rooms (used on e.g. chemical tankers), etc. – i.e. compartment that are not routinely accessed by ordinary seamen.

5.3 Gasses travel and reach rooms routinely accessed

In the Danish accident below, the seamen were poisoned, not in the cargo hold, but in a room, which was part of the normal working areas of the ship and routinely accessed. Important lessons of this accident are that dangerous gasses from the cargo hold can migrate and reach rooms considered safe.

As will be shown, this lesson and opportunities for learning were wholly missed. Accident descriptions in the public domain are hazy and basic facts are corrupted.

5.4 The accident

In the afternoon of July 15, 2009, during the passage of the Baltic Sea, two of the vessel's crew decided to enter the vessel's forepeak compartment. The forepeak is a stowage room at the bow of the ship, which is reached from the deck through a stairwell. The forepeak was used for miscellaneous storage: paints, ropes, etc.

The reason why the two seamen entered the forepeak is not known. Likely, the forepeak offered a convenient refuge for a clandestine cigarette break, out of sight of the tough captain.

Unknown to them, poisonous carbon monoxide gasses from the cargo hold had travelled to the forepeak through a crevice in a door that separated the front cargo hold compartment and the forecastle (Fig. 8). When the seamen did not show up for dinner, a search was initiated, which found them lifeless in the forecastle.

5.5 Investigation

The vessel was close to Danish territorial waters. The captain radioed the Danish authorities requesting immediate medical assistance and the vessel redirected to the port of Rønne, Bornholm. The police was waiting at the quay and began a standard crime scene procedure.

The criminal investigation found no evidence of criminal intent and was satisfied that the two seamen had received the proper safety instruction for working in enclosed rooms. The investigation was closed as there was no indication of wrongdoing, only of bad luck.

Important questions aimed at understanding why the accident happened were not raised. Were the crew aware of hazardous properties of the cargo? Was the forepeak considered a compartment with properties similar to those of enclosed cargo spaces? In all likelihood the crew were clueless about the danger [32].

5.6 Information sharing?

Because the police opened the case a crime scene investigation, the case was technically registered as a criminal case. In Denmark, criminal cases are kept confidential in order to protect the privacy of the individuals concerned. As a result, very little information, if any, relevant to accident prevention professionals is available in open sources.

5.7 Basic facts corrupted, no learning

It is true that there is sporadic and passing mention of the AMIRANTE accident in the wood pellet literature, e.g. [35], [36] but descriptions are hazy and basic facts are corrupted. This is also true for the papers produced by authors in Denmark. For example, a report [37] states that the seamen entered the cargo hold, which they did not, and a paper [38] states that they died from asphyxia, which is also wrong.

Because proper sharing of correct information about an accident is a basic precondition for learning it is concluded that learning processes were derailed at a very early stage.



Figure 8: The door in the forepeak compartment, which led the front cargo hold. The door had three closing hinges but only two were engaged. Gasses travelled from the cargo hold to the forepeak through a crevice where the third hinge (arrow) was not engaged. Source: Police investigation.

5.8 Systemic deficiency by design

The accident was investigated as a criminal case and the legal system is so designed that findings are kept out of reach of safety professionals and the general public. This approach has been criticized at an earlier occasion as being entirely misplaced in an accident prevention context [28]. It is a systemic deficiency by design – the bureaucratic judiciary system did not malfunction, it worked precisely as intended.

The flag state, St. Vincent & The Grenadines, did not investigate.

There is no evidence of learning whatsoever. Repeat fatal accidents later took place in Denmark [32].

6 CONCLUSION

This paper presents cases in support of the view that learning processes to prevent repeat biomass accidents are impeded, dysfunctional or entirely absent in Denmark.

- Knowledge about an explosion of a biogas digester passed into oblivion.
- A wood pellet facility experienced a devastating dust explosion. The accident was insufficiently investigated and root causes

relating to principles of inherent safety were not identified. As a result, a repeat explosion took place eight years later, this time with fatal outcome.
The case offers a textbook example of the truism that if accidents are not investigated, and root causes not identified, accidents recur.

- Knowledge about a fatal carbon monoxide accident was kept out of reach of safety professionals and the general public. Information in open sources are hazy and basic facts are corrupted.

Currently, there appears to be a substantial untapped potential for learning and information exchange. This potential should be exploited for the renewable energy and environmentally friendly biomass pellet industry also to become sustainable from a worker safety perspective.

This paper suggests that structural barriers exist at three levels:

(1) Production/managerial level: Biomass units are often installed at agricultural enterprises that are unfamiliar with gas processing technology, combustible dusts and poisonous gasses. Farmers assume tasks of process operators and gas engineer, tasks for which they have little or no training. The limited information available in open sources on accidents at Danish biogas units indicate that limited appreciation of process dangers and the finer details of ATEX hazards play a role.

(2) Institutional level. Accident investigations are tasked with the police. But law enforcement officers have neither training nor technical background in industrial accident investigation. In fact, their concern with negligence and wrongdoing is entirely misplaced in a perspective of safety. Assigning them to this task is a policy mistake. As a result, there is no information sharing, or learning, and repeat accidents take place.

(3) Policy level. Danish environmental ambitions are very high and the institutions involved are on a mission to fight global climate change problems in order to secure our common future. They are on a mission to save the world, nothing less. In such a global perspective, sight is easily lost of the environment of the workers. Safety issues are absent, downplayed or waved away in white papers and visionary policy reports, even though interventions can run counter to long established core principles of inherent safety and risk reduction [8], [39].

In 2016, Denmark topped the World Energy Councils' so-called trilemma index that takes into account three parameters: 1) environmental sustainability, 2) energy security, and 3) energy equity. Denmark ranked 1st on the World Energy Councils' global list, not only overall but also in terms of excellently balanced trilemma performance resulting in an outstanding triple–A grade [40].

The costs to society are breathtaking [8]. In this setting, the general failure to address safety risks appears particularly disheartening. Further research is needed to provide policy guidance on how to improve this situation.

There is currently no serious mechanism to register biomass accidents. At a practical level, a natural starting point would be to rectify this shortage of fundamental data. Systematic incident information capture and exchange, understanding the fundamental root causes, widely disseminating the lessons learned, and integrating these lessons learned into safe operations, are key to improving the safety performance of the expanding bioenergy industries.

Utmost care should be taken to avoid so-called media- shifting i.e. that the resolution of a problem within one domain, the environmental, creates a new problem in another, the workplace safety domain.

7 REFERENCES

[1] V. C. Moreno and V. Cozzani, ―Major accident hazard in bioenergy production,‖ J. Loss Prev. Process Ind., vol. 35, pp. 135–144, 2015.

[2] C. Riviere and G. Marlair, ―BIOSAFUEL (R), a pre-diagnosis tool of risks pertaining to biofuels chains,‖ J. Loss Prev. Process Ind., vol. 22, no. 2, pp. 228–236, 2009.

[3] S. Nair, ―Identifying and managing process risks related to biofuel projects and plants,‖ HAZARDS XXII- Pap. 103, no. 156, pp. 331–338, 2011.

[4] S. S. Rivera, R. D. C. Olivares, P. A. Baziuk, and J. E. N. Mc Leod, ―Assessment of Biofuel Accident Risk: A Preliminary Study,‖ in Proceedings of the World Congress on Engineering, 2015, vol. 2.

[5] G. E. Scarponi, D. Guglielmi, V. Casson Moreno, and V. Cozzani, ―Assessment of Inherently Safer Alternatives in Biogas Production and Upgrading,‖ Aiche J., vol. 62, no. 8, pp. 2713–2727, 2016.

[6] F. H. Hedlund, ―Do provisions to advance chemical facility safety also advance chemical facility security? - An analysis of possible synergies,‖ in OPCW International Meeting on Chemical Safety and Security. 8-9 November 2012. Proceedings, 2012, no. November, pp. 73–82.

[7] N. A. Ashford, ―Industrial safety: the neglected issue in industrial ecology,‖ J. Clean. Prod., vol. 5, no. 1, pp. 115–121, 1997.

[8] F. H. Hedlund and J. Astad, ―Solid Biomass Climate Change Interventions Examined in a Context of Inherent Safety, Media Shifting, and Emerging Risks,‖ Hum. Ecol. Risk Assess., vol. 21, no. 5, pp. 1410–1427, 2015.

[9] T. A. Kletz, What Went Wrong?: Case Studies of Process Plant Disasters. Houston, Texas: Gulf Professional Publishing, 1998.

[10] T. A. Kletz, Still going wrong!: case histories of process plant disasters and how they could have been avoided. Elsevier, 2003.

[11] R. E. Sanders, Chemical process safety: learning from case histories. Butterworth-Heinemann, 2015.

[12] F. H. Hedlund and H. B. Andersen, ―Institutional support of learning from accidents: Some obstacles to getting a useful community-wide database in the EU,‖ in Society of Risk Analysis, SRA Europe, Annual Conference 2016, 2006, pp. 1–21.

[13] F. H. Hedlund, M. F. Nielsen, S. H. Mikkelsen, and E. K. Kragh, ―Violent explosion after inadvertent mixing of nitric acid and isopropanol - Review 15 years later finds basic accident data corrupted, no evidence of broad learning,‖ Saf. Sci., vol. 70, pp. 255–261, 2014.

[14] T. A. Kletz, Learning from Accidents in Industry. London, U.K.: Butterworths, 1988.

[15] J. Reason, Managing the Risks of Organizational Accidents. Ashgate, 1997.

[16] Y. Dien, M. Llory, and R. Montmayeul, ―Organisational accidents investigation

methodology and lessons learned," J. Hazard. Mater., vol. 111, no. 1, pp. 147–153, 2004.
[17] J. Rossen, "Alligevel røg skidtet i luften," Arbejdsmiljø, no. 1, pp. 13–16, 1991.
[18] F. H. Hedlund, "Eksplosion i rådnetank med biogas," Dansk Kemi, vol. 95, no. 12, pp. 12–15, 2014.
[19] T. S. Knudsen, "Gaseksplosion slamtank på rensningsanlæg (Vejle)," Brandværn, no. 1, pp. 27–28, 1991.
[20] A.-K. Lindberg, S. O. Hansson, and C. Rollenhagen, "Learning from accidents - What more do we need to know?," Saf. Sci., vol. 48, no. 6, pp. 714–721, 2010.
[21] "ARIA N°11345 - 12/03/1997 - Italie - 00 - Peschiera Del Garda," La base ARIA (Analyse, Recherche et Information sur les Accidents). Ministère du développement durable - DGPR / SRT / BARPI, 2015. [Online]. Available: www.aria.developpement-durable.gouv.fr. [Accessed: 12-Aug-2015].
[22] "Att skydda och rädda liv, egendom och miljö: Handbok i kommunal riskanalys inom räddningstjänsten," Räddningsverket, Karlstad, Sweden, 1989.
[23] G. E. Scarponi, D. Guglielmi, V. Casson Moreno, and V. Cozzani, "Risk Assessment of a Biogas Production and Upgrading Plant," Chem. Eng. Trans., vol. 43, pp. 1921–1926, 2015.
[24] S. R. Secondo Cividino et al., "BiogasAgriAtex, new methods of risk assessment explosion on biogas plants," Appl. Math. Sci., vol. 8, no. 129–132, pp. 6599–6619, 2014.
[25] "Verpuffung in Biogasanlage - Zwei Personen verletzt," Märkische Oderzeitung, 25-Jul-2011.
[26] B. Pietrangeli, R. Lauri, and P. A. Bragatto, "Safe operation of biogas plants in Italy," Chemical Engineering Transactions, vol. 32. Italian Association of Chemical Engineering - AIDIC, pp. 199–204, 2013.
[27] P. Gupte, "Sludge Coats Shore After L.I. Explosion; Youth, 16, Missing; Explosion of Two Sewage Tanks Apparently Kills L.I. Youth, 16; Heard Three Miles Away," New York Times, pp. A1, D17, 06-Jun-1976.
[28] F. H. Hedlund, J. Astad, and J. Nichols, "Inherent hazards, poor reporting and limited learning in the solid biomass energy sector: A case study of a wheel loader igniting wood dust, leading to fatal explosion at wood pellet manufacturer," Biomass and bioenergy, vol. 66, pp. 450–459, 2014.
[29] T. A. Kletz, Cheaper, safer plants. Or wealth and safety at work. Notes on inherently safer and simpler plants. Rugby, Warwickshire, England: The Institution of Chemical Engineers (IChemE), 1984.
[30] N. A. Ashford, "Reducing physical hazards: encouraging inherently safer production," in Designing Safer Chemicals. Handbook of Green Chemistry, R. Boethling, A. Voutchkova, and P. Anastas, Eds. Wiley Online Library, 2012, pp. 485–500.
[31] G. Thek and I. Obernberger, The pellet handbook: the production and thermal utilization of biomass pellets. Routledge, 2012.
[32] F. H. Hedlund and Ø. J. Hilduberg, "Fatal Accidents During Marine Transport of Wood Pellets Due to Off-gassing – Experiences from Denmark," in Biomass Volume Estimation and Valorization for Energy, J. S. Tumuluru, Ed. Rijeka, Croatia: InTech, 2017, pp. 73–97.
[33] S. Melin, U. Svedberg, and J. Samuelsson, "Emissions from wood pellets during ocean transportation (EWDOT). Research report," Wood Pellet Association of Canada (lead), 2008.
[34] "IMO Revised Recommendations for Entering Enclosed Spaces Aboard Ships. IMO Resolution A.1050(27)," The International Maritime Organization (IMO), 2012.
[35] S. Gauthier, H. Grass, M. Lory, T. Krämer, M. Thali, and C. Bartsch, "Lethal carbon monoxide poisoning in wood pellet storerooms—two cases and a review of the literature," Ann. Occup. Hyg., vol. 56, no. 7, pp. 755–763, 2012.
[36] U. Svedberg and A. Knutsson, "Faror och hälsorisker vid förvaring och transport av träpellets, träflis och timmer i slutna utrymmen. Kunskapsöversikt. Rapport 2011:2 (in Swedish). [Hazards and health risk with storage and transport of wood pellets, wood shavings and timber in enclosed," Arbetsmiljöverket, Stockholm, Sweden, 2011.
[37] W. Stelte, "Guideline: Storage and handling of wood pellets. Resultat Kontrakt (RK) report," Danish technological institute, Taastrup, Denmark, 2012.
[38] B. K. Sovacool et al., "Balancing safety with sustainability: assessing the risk of accidents for modern low-carbon energy systems," J. Clean. Prod., vol. 112, pp. 3952–3965, 2016.
[39] F. H. Hedlund, "LNG safety – an emerging and ignored issue in the climate change debate," Eur. Saf. Reliab. Assoc. Newsl., no. September, p. 2, 2014.
[40] World Energy Council, "World Energy Trilemma, 2016. Benchmarking the sustainability of national energy systems," London, U.K., 2016.

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CLIMATE CHANGE:

The IPCC 1990 and 1992 Assessments

World Meteorological Organization/
United Nations Environment Programme

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

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CLIMATE CHANGE:
The 1990 and 1992 IPCC Assessments

IPCC First Assessment Report

Overview and Policymaker Summaries

and

1992 IPPC Supplement

June, 1992

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Bottom Image

A full earth disc view of cloud patterns over the Australian region on 19 February 1991 from the Japanese Geostationary Satellite (GMS4). This image is a colour enhanced composite of information from the visible and infrared channels produced by the Australian Centre for Remote Sensing of the Australian Survey and Land Information Group.

**Notes*

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PREFACE

With the formation of the World Climate Programme after the 1979 World Climate Conference, the World Meteorological Organization and the United Nations Environment Programme – together with the International Council of Scientific Unions – signalled their determination to pursue climate and climate change studies. Their joint efforts reached a decision stage at the International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts (Villach, Austria, 1985); the findings of the Conference and subsequent meetings on the subject laid the foundation for the current international activities on global warming. A major contributor to the activities is the Intergovernmental Panel on Climate Change (IPCC), jointly established by our two organizations in 1988 under the Chairmanship of Professor Bert Bolin.

The Panel formed three Working Groups

(a) to assess available scientific information on climate change (Working Group I),

(b) to assess environmental and socio-economic impacts of climate change (Working Group II), and

(c) to formulate response strategies (Working Group III)

and a Special Committee on the Participation of Developing Countries to promote the participation of those countries in its activities.

The IPCC First Assessment Report was completed in August 1990 and consists of: the Overview, the IPCC Scientific Assessment, the IPCC Impacts Assessment, the IPCC Response Strategies (the last three including the respective Policymaker Summaries) and the Policymaker Summary of the IPCC Special Committee. The Report has now become a standard work of reference, widely used by policymakers, scientists and other experts and represents a remarkable co-ordinated effort by hundreds of specialists from all over the world.

Anticipating a continuing need for the most current information on climate change in the context of the ongoing negotiations on the Framework Convention on Climate Change and the United Nations Conference on Environment and Development (Rio de Janeiro, June 1992), and as mandated by the governing bodies of our two organizations, the IPCC requested its three Working Groups in March 1991 to produce updates of their 1990 reports. The result is the 1992 IPCC Supplement which was completed in February 1992. This volume contains the Supplement and the 1990 Overview and Policymaker Summaries.

Success in producing the Supplement has depended as in the past upon the whole-hearted enthusiasm and dedicated hard work of scientists and other experts worldwide. We admire, applaud and are very grateful for their commitment to the IPCC process. We take this opportunity to express our gratitude to Prof. Bolin for his exemplary leadership of the IPCC. We congratulate the Chairmen of the three IPCC Working Groups, Sir John Houghton (Working Group I), Prof. Yuri A. Izrael (Working Group II) and Mr. Robert A. Reinstein (Working Group III) for a job well done.

We thank the consortium of 11 States that contributed financially towards this publication.

G.O.P. Obasi
Secretary-General
World Meteorological
Organization

M.K. Tolba
Executive Director
United Nations Environment
Programme

FOREWORD

The Intergovernmental Panel on Climate Change (IPCC), which I have been privileged to chair since its inception, completed a comprehensive assessment of the climate change issue in 1990 and an update to that assessment in February 1992. The Panel is going on to make another comprehensive assessment, as mandated by its sponsoring bodies (the World Meteorological Organization and the United Nations Environment Programme), by the middle of the 1990s.

The Supplement is an update of key issues addressed in the 1990 IPCC assessment. Six tasks were chosen by the IPCC in March 1991 for inclusion in the Supplement, after taking into account views expressed by a number of nations during the first session of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC).

It has become clear in the course of the past year that common or consistent methodologies in a number of subject areas of climate change are of critical importance for uniform application by countries so as to enable intercomparisons among them. Some examples are methodology for assessing national net emissions of greenhouse gases, methodology for national environmental impacts assessments and methodology for assessing national vulnerability to sea level rise. Development of methodologies has been initiated and more will be given high priority in the next few years.

It is well known that there are a number of uncertainties in the IPCC estimates of climate warming. The Panel has neither hidden nor ignored them. It has made every effort – and will continue to do so – to assess both their qualitative and quantitative nature. In this effort, the IPCC welcomes critical examinations of its conclusions by all who are interested in the issue, and invites the active participation of all the scientists and other experts who may disagree with its findings and the presentation in detail of their scientific analyses of alternative points of view.

The completion of the 1990 assessment and the 1992 Supplement would not at all have been possible without the impressive amount of work put in by a large number of scientists and other experts from many parts of the world, including developing nations. I take this opportunity to thank each and everyone of them. I hope that they found the experience stimulating – albeit perhaps a little exhausting – and that in the future they would find it worthwhile to continue to contribute to the work of the IPCC.

I am particularly grateful to the Chairmen of the three IPCC Working Groups and the Special Committee on the Participation of Developing Countries, their Vice-Chairs, Co-Chairs of the subgroups and lead authors. The credit for the successful accomplishment of each IPCC effort belongs very much to them.

I am also grateful for the support provided by the two Executive Heads of the sponsoring organizations and to the Governments who have given support in spirit as well as in cash and kind.

Finally, I wish to extend my thanks to Mr. N. Sundararaman, the Secretary of IPCC, Mr. S. Tewungwa and the staff of the IPCC Secretariat whose commitment greatly facilitated the timely completion of the tasks of the IPCC.

B. Bolin
Chairman,
Intergovernmental Panel on Climate Change

1992 IPCC Supplement

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SECTION I. INTRODUCTION

At its fifth session (Geneva, March 1991), the Intergovernmental Panel on Climate Change (IPCC) decided to address the six following tasks in a short-term effort to produce an update of its First Assessment Report (August 1990):

TASK 1: Assessment of national net greenhouse gas emissions:

Sub-section 1: Sources and sinks of greenhouse gases;

Sub-section 2: Global Warming Potentials;

TASK 2: Predictions of the regional distributions of climate change and associated impact studies, including model validation studies:

Sub-section 1: Update of regional climate models;

Sub-section 2: Analysis of sensitivity to regional climate change;

TASK 3: Energy and industry related issues;

TASK 4: Agriculture and forestry related issues;

TASK 5: Vulnerability to sea-level rise;

TASK 6: Emissions scenarios.

Each Working Group presented material consisting of a supplement to the IPCC First Assessment Report (1990) together with supporting documents. The supplementary reports have been prepared by subgroups, and have been extensively scrutinized and agreed on by open-ended plenary meetings of the three Working Groups. The supporting documents are being prepared by the Working Groups, subgroups or lead authors and have been or will be extensively refereed.

The IPCC, at its seventh session (Geneva, 10-12 February 1992), recognized with appreciation the dedicated work of many scientists in preparing the reports and supporting documents, especially considering the short time available for their preparation. The IPCC considered and included the supplementary reports from the Working Groups as contributions to the 1992 IPCC Supplement. The IPCC requested that any minor inconsistencies between the Working Group reports be removed so far as possible. Other inconsistencies will be resolved in follow-up work. It was noted that the supplementary reports are overviews of the work which has been carried out and that the supporting documents provide a great deal of additional detailed information, and it was requested that these documents be made available as soon as possible. Issues common to all three working groups as well as other issues raised by members of the IPCC (in particular matters requiring further work) were discussed during the seventh session and are included in section VIII of the Supplement.

Publication of the 1992 IPCC Supplement completes the short-term work on the six Tasks agreed on at the fifth session of the IPCC (IPCC-V). Long-term work on the same Tasks was also agreed on at IPCC-V and this continues.

SECTION II. SCIENTIFIC ASSESSMENT

TASK 1: Assessment of national net greenhouse gas emissions and their implications

TASK 2: Predictions of the regional distributions of climate change and associated impact studies, including model validation studies (part on predictions of the regional distributions of climate change, including model validation studies)

TASK 6: Emissions scenarios

By Working Group I

CURRENT TASK

The fifth session of the Intergovernmental Panel on Climate Change (IPCC) (Geneva, March 1991) adopted six tasks for the ongoing work of its three working groups. While successful completion of these tasks required cooperation between all three groups, particular responsibility fell to the Scientific Assessment working group (WGI) for Tasks 1, 2 and 6:

Task 1: Assessment of net greenhouse gas emissions.

Sub-section 1: Source and sinks of greenhouse gases.

Sub-section 2: Global Warming Potentials.

Task 2: Predictions of the regional distributions of climate change and associated impact studies; including model validation studies.

Task 6: Emissions scenarios.

The tasks were divided into long- and short-term components. The purpose of the short-term workplan, whose results are reported in the present document, was to provide an update to the 1990 IPCC Scientific Assessment, addressing some of the key issues of that report. This update is by definition less comprehensive than the 1990 assessment - for example sea level rise apart from the effect of thermal expansion is not included. It is against the background of that document that the findings of this update should be read.

This assessment, in order to incorporate as much recent material as possible, necessarily includes discussion of new results which have not yet been through, or are currently undergoing, the normal process of peer review. Where such is the case the provisional nature of the results has been taken into account.

A brief progress report on the preparation of guidelines for the compilation of national inventories of greenhouse gas emissions, part of WGI's long-term work under Task 1, appears as an Annex to this Supplement.

OUR MAJOR CONCLUSIONS

Findings of scientific research since 1990 do not affect our fundamental understanding of the science of the greenhouse effect and either confirm or do not justify alteration of the major conclusions of the first IPCC Scientific Assessment, in particular the following:

- emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide;
- the evidence from the modelling studies, from observations and the sensitivity analyses indicate that the sensitivity of global mean surface temperature to doubling CO_2 is unlikely to lie outside the range 1.5° to 4.5°C;
- there are many uncertainties in our predictions particularly with regard to the timing, magnitude and regional patterns of climate change due to our incomplete understanding;
- global mean surface air temperature has increased by 0.3° to 0.6°C over the last 100 years;
- the size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming;
- the unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.

There are also a number of significant new findings and conclusions which we summarize as follows:

Gases and aerosols

- Depletion of ozone in the lower stratosphere in the middle and high latitudes results in a decrease in radiative forcing which is believed to be comparable in magnitude to the radiative forcing contribution of chlorofluorocarbons (CFCs) (globally-averaged) over the last decade or so.

- The cooling effect of aerosols* resulting from sulphur emissions may have offset a significant part of the greenhouse warming in the Northern Hemisphere (NH) during the past several decades. Although this phenomenon was recognized in the 1990 report, some progress has been made in quantifying its effect.

- The Global Warming Potential (GWP) remains a useful concept but its practical utility for many gases depends on adequate quantification of the indirect effects as well as the direct. We now recognize that there is increased uncertainty in the calculation of GWPs, particularly in the indirect components and, whilst indirect GWPs are likely to be significant for some gases, the numerical estimates in this Supplementary Report are limited to direct GWPs.

- Whilst the rates of increase in the atmospheric concentrations of many greenhouse gases have continued to grow or remain steady, those of methane and some halogen compounds have slowed.

- Some data indicate that global emissions of methane from rice paddies may amount to less than previously estimated.

Scenarios

- Steps have been taken towards a more comprehensive analysis of the dependence of future greenhouse gas emissions on socio-economic assumptions and projections. A set of updated scenarios have been developed for use in modelling studies which describe a wide range of possible future emissions in the absence of coordinated policy response to climate change.

Modelling

- Climate models have continued to improve in respect of both their physical realism and their ability to simulate present climate on large scales, and new techniques are being developed for the simulation of regional climate.

- Transient (time-dependent) simulations with coupled ocean-atmosphere models (CGCMs), in which neither aerosols nor ozone changes have been included, suggest a rate of global warming that is consistent, within the range of uncertainties, with the 0.3°C per decade warming rate quoted by IPCC (1990) for Scenario A of greenhouse gas emissions.

- The large-scale geographical patterns of warming produced by the transient model runs with CGCMs are generally similar to the patterns produced by the earlier equilibrium models except that the transient simulations show reduced warming over the northern North Atlantic and the southern oceans near Antarctica.

- CGCMs are capable of reproducing some features of atmospheric variability on intra-decadal time-scales.

- Our understanding of some climate feedbacks and their incorporation in the models has improved. In particular, there has been some clarification of the role of upper tropospheric water vapour. The role of other processes, in particular cloud effects, remains unresolved.

Climate observations

- The anomalously high global mean surface temperatures of the late 1980s have continued into 1990 and 1991 which are the warmest years in the record.

- Average warming over parts of the Northern Hemisphere mid-latitude continents has been found to be largely characterized by increases in minimum (night-time) rather than maximum (daytime) temperatures.

- Radiosonde data indicate that the lower troposphere has warmed over recent decades. Since meaningful trends cannot be assessed over periods as short as a decade, the widely reported disagreements between decadal trends of air temperature from satellite and surface data cannot be confirmed because the trends are statistically indistinguishable.

- The volcanic eruption of Mount Pinatubo in 1991 is expected to lead to transitory stratospheric warming. With less certainty, because of other natural influences, surface and tropospheric cooling may occur during the next few years.

- Average warming over the Northern Hemisphere during the last four decades has not been uniform, with marked seasonal and geographic variations; this warming has been especially slow, or absent, over the extratropical north west Atlantic.

- The consistency between observations of global temperature changes over the past century and model simulations of the warming due to greenhouse gases over the same period is improved if allowance is made for the increasing evidence of

* *The scientific definition of 'aerosol' is an airborne particle or collection of particles, but the word has become associated, erroneously, with the* ith t *propellant used in 'aerosol sprays' Throughout this report the term 'aerosol' means airborne particle or particles*

a cooling effect due to sulphate aerosols and stratospheric ozone depletion.

The above conclusions have implications for future projections of global warming and somewhat modify the estimated rate of warming of 0.3°C per decade for the greenhouse gas emissions Scenario A of the IPCC First Assessment Report (1990). If sulphur emissions continue to increase, this warming rate is likely to be reduced, significantly in the Northern Hemisphere, by an amount dependent on the future magnitude and regional distribution of the emissions. Because sulphate aerosols are very short-lived in the atmosphere their effect on global warming rapidly adjusts to increases or decreases in emissions. It should also be noted that while partially offsetting the greenhouse warming, the sulphur emissions are also responsible for acid rain and other environmental effects. There is a further small net reduction likely in the rate of global warming during the next few decades due to decreases in stratospheric ozone, partially offset by increases in tropospheric ozone.

Research carried out since the 1990 IPCC assessment has served to improve our appreciation of key uncertainties. There is a continuing need for increased monitoring and research into climate processes and modelling. This must involve, in particular, strengthened international collaboration through the World Climate Research Programme (WCRP), the International Geosphere Biosphere Programme (IGBP) and the Global Climate Observing System (GCOS).

How does the climate system work, and what information do we need to estimate future changes?

- **How does the climate system work?**

The Earth absorbs radiation from the Sun, mainly at the surface. This energy is then redistributed by the atmosphere and ocean and re-radiated to space at longer ('thermal', 'terrestrial' or 'infrared') wavelengths. Some of the thermal radiation is absorbed by radiatively-active ('greenhouse') gases in the atmosphere, principally water vapour, but also carbon dioxide, methane, the CFCs, ozone and other greenhouse gases. The absorbed energy is re-radiated in all directions, downwards as well as upwards such that the radiation that is eventually lost to space is from higher, colder levels in the atmosphere (see diagram below). The result is that the surface loses less heat to space than it would do in the absence of the greenhouse gases and consequently stays warmer than it would otherwise be. This phenomenon, which acts rather like a 'blanket' around the Earth, is known as the greenhouse effect.

- **What factors can change climate?**

Any factor which alters the radiation received from the Sun or lost to space, or which alters the redistribution of energy within the atmosphere, and between the atmosphere, land and ocean, will affect climate.

The Sun's output of energy is known to change by small amounts over an 11-year cycle, and variations over longer periods may occur. On time-scales of tens to thousands of years, slow variations in the Earth's orbit have led to changes in the seasonal and latitudinal distribution of solar radiation; these changes have played an important part in controlling the variations of past climate.

Increases in the concentration of the greenhouse gases will reduce the efficiency with which the Earth cools to

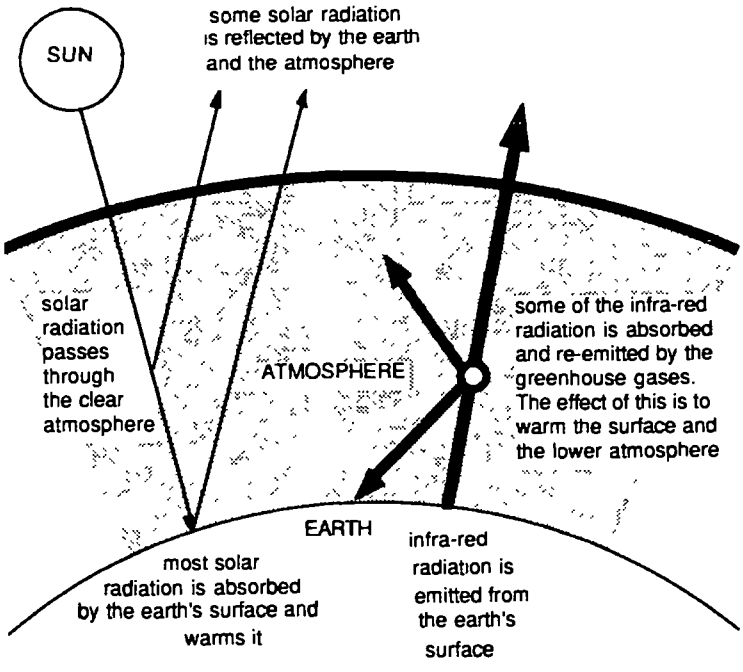

space and will tend to warm the lower atmosphere and surface. The amount of warming depends on the size of the increase in concentration of each greenhouse gas, the radiative properties of the gases involved, and the concentration of other greenhouse gases already present in the atmosphere. It also can depend on local effects such as the variation with height of the concentration of the greenhouse gas, a consideration that may be particularly germane to water vapour which is not uniformly mixed throughout the atmosphere. The effect is not a simple one and the balance which is struck between these factors depends on many aspects of the climate system.

Aerosols (small particles) from volcanoes, emissions of sulphates from industry and other sources can absorb and reflect radiation. Moreover, changes in aerosol concentrations can alter cloud reflectivity through their effect on cloud properties. In most cases aerosols tend to cool climate. In general, they have a much shorter lifetime than greenhouse gases so their concentrations respond much more quickly to changes in emissions.

Any changes in the radiative balance of the Earth, including those due to an increase in greenhouse gases or in aerosols, will tend to alter atmospheric and oceanic temperatures and the associated circulation and weather patterns. However climate varies naturally on all timescales due to both external and internal factors. To distinguish man-made climate variations from those natural changes, it is necessary to identify the man-made 'signal' against the background 'noise' of natural climate variability.

A necessary starting point for the prediction of changes in climate due to increases in greenhouse gases and aerosols is an estimate of their future concentrations. This requires a knowledge of both the strengths of their sources (natural and man-made) and also the mechanisms of their eventual removal from the atmosphere (their sinks). The projections of future concentrations can then be used in climate models to estimate the climatic response. We also need to determine whether or not the predicted changes will be noticeable above the natural variations in climate. Finally, observations are essential in order to monitor climate, to study climatic processes and to help in the development and validation of models.

RECENT IMPROVEMENTS IN SCIENTIFIC UNDERSTANDING

HOW HAS OUR UNDERSTANDING OF THE SOURCES AND SINKS OF GREENHOUSE GASES AND AEROSOLS CHANGED?

During the last eighteen months there have been a number of important advances in our understanding of greenhouse gases and aerosols. These advances include an improved quantitative understanding of the atmospheric distributions, trends, sources and sinks of greenhouse gases, their precursors and aerosols, and an improved understanding of the processes controlling their global budgets.

Atmospheric concentrations and trends of long-lived greenhouse gases: The atmospheric concentrations of the major long-lived greenhouse gases [carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and carbon tetrachloride (CCl_4)] continue to increase because of human activities. While the growth rates of most of these gases have been steady or increasing over the past decade, that of CH_4 and some of the halocarbons has been decreasing. The rate for CH_4 has declined from about 20 ppbv/yr in the late 1970s to possibly as low as 10 ppbv/yr in 1989. While a number of hypotheses have been forwarded to explain these observations, none is completely satisfactory.

Atmospheric concentrations and trends of other gases that influence the radiative budget: Ozone (O_3) is an effective greenhouse gas both in the stratosphere and in the troposphere. Significant decreases have been observed during the last one to two decades in total column O_3 at all latitudes - except the tropics - in spring, summer and winter. The downward trends were larger during the 1980s than in the 1970s. These decreases have occurred predominantly in the lower stratosphere (below 25km), where the rate of decrease has been up to 10% per decade depending on altitude. In addition, there is evidence to indicate that O_3 levels in the troposphere up to 10km altitude above the few existing ozonesonde stations at northern middle latitudes have increased by about 10% per decade over the past two decades. Also, the abundance of carbon monoxide (CO) appears to be increasing in the NH at about 1% per year. However, there is little new information on the global trends of other tropospheric O_3 precursors, (non-methane hydrocarbons (NMHC) and oxides of nitrogen (NO_x)).

Sources and sinks of carbon dioxide: The two primary sources of the observed increase in atmospheric CO_2 are combustion of fossil fuels and land-use changes: cement production is a further important source.

The emission of CO_2 from the combustion of fossil fuels grew between 1987 and 1989. Preliminary data for 1990 indicate similar emissions to 1989. The best estimate for global fossil fuel emissions in 1989 and 1990 is 6.0±0.5 GtC*, compared to 5.7±0.5 GtC in 1987 (IPCC, 1990). The

* *1 GtC (gigatonne of carbon) equals one billion [one thousand million (10^9)] tonnes of carbon*

estimated total release of carbon in the form of CO_2 from oil well fires in Kuwait during 1991 was 0.065 GtC, about one percent of total annual anthropogenic emissions.

The direct net flux of CO_2 from land use changes (primarily deforestation), integrated over time, depends upon the area of land deforested, the rate of reforestation and afforestation, the carbon density of the original and replacement forests, and the fate of above-ground and soil carbon. These and other factors are needed to estimate annual net emissions but significant uncertainties exist in our quantitative knowledge of them. Since IPCC (1990) some progress has been made in reducing the uncertainties associated with the rate of deforestation, at least in Brazil. A comprehensive, multi-year, high spatial resolution satellite data set has been used to estimate that the average rate of deforestation in the Brazilian Amazonian forest between 1978 and 1989 was 2.1 million hectares (Mha) per year. The rate increased between 1978 and the mid-1980s, and has decreased to 1.4 Mha/yr in 1990. The Food and Agriculture Organization (FAO), using information supplied by individual countries, recently estimated that the rate of global tropical deforestation in closed and open canopy forests for the period 1981-1990 was about 17 Mha/yr, approximately 50% higher than in the period 1976-1980.

Despite the new information regarding rates of deforestation, the uncertainties in estimating CO_2 emissions are so large that there is no strong reason to revise the IPCC 1990 estimate of annual average net flux to the atmosphere of 1.6±1.0 GtC from land-use change during the decade of the 1980s.

Since IPCC (1990) particular attention has focussed on understanding the processes controlling the release and uptake of CO_2 from both the terrestrial biosphere and the oceans, and on the quantification of the fluxes. Based on models and the atmospheric distribution of CO_2, it appears that there is a small net addition of carbon to the atmosphere from the equatorial region, a combination of outgassing of CO_2 from warm tropical waters and a terrestrial biospheric component that is the residual between large sources (including deforestation) and sinks. There appears to be a strong Northern Hemisphere sink, containing both oceanic and terrestrial biospheric components, and a weak Southern Hemisphere (SH) sink. The previous IPCC global estimate for an ocean sink of 2.0±0.8 GtC per year is still a reasonable one. The terrestrial biospheric processes which are suggested as contributing to the sinks are sequestration due to forest regeneration, and fertilization arising from the effects of both CO_2 and nitrogen (N), but none of these can be adequately quantified. This implies that the imbalance (of order 1-2 GtC/yr) between sources and sinks, i.e., "the missing sink", has not yet been resolved. This fact has significant consequences for estimates of future atmospheric CO_2 concentrations and the analysis of the concept of the Greenhouse Warming Potential.

Sources of methane: A total (anthropogenic plus natural) annual emission of CH_4 of about 500Tg can be deduced from the magnitude of its sinks combined with its rate of accumulation in the atmosphere. While the sum of the individual sources is consistent with a total of 500Tg CH_4, there are still many uncertainties in accurately quantifying the magnitude of emissions from individual sources. Significant new information includes a revised rate of removal of CH_4 by atmospheric hydroxyl (OH) radicals (because of a lower rate constant), a new evaluation of some of the sources (e.g., from rice fields) and the addition of new sources (e.g., animal and domestic waste). Recent CH_4 isotopic studies suggest that approximately 100Tg CH_4 (20% of the total CH_4 source) is of fossil origin, largely from the coal, oil, and natural gas industries. Recent studies of CH_4 emissions from rice agriculture, in particular Japan, India, Australia, Thailand and China, show that the emissions depend on growing conditions, particularly soil characteristics, and vary significantly. While the overall uncertainty in the magnitude of global emissions from rice agriculture remains large, a detailed analysis now suggests significantly lower annual emissions than reported in IPCC 1990. The latest estimate of the atmospheric lifetime of CH_4 is about 11 years.

Sources of nitrous oxide: Adipic acid (nylon) production, nitric acid production and automobiles with three-way catalysts have been identified as possibly significant anthropogenic global sources of nitrous oxide. However, the sum of all known anthropogenic and natural sources is still barely sufficient to balance the calculated atmospheric sink or to explain the observed increase in the atmospheric abundance of N_2O.

Sources of halogenated species: The worldwide consumption of CFCs 11, 12, and 113 is now 40% below 1986 levels, substantially below the amounts permitted under the Montreal Protocol. Further reductions are mandated by the 1990 London Amendments to the Montreal Protocol. As CFCs are phased out, HCFCs and HFCs will substitute, but at lower emission rates.

Stratospheric ozone depletion: Even if the control measures of the 1990 London amendments to the Montreal Protocol were to be implemented by all nations, the abundance of stratospheric chlorine and bromine will increase over the next several years. The Antarctic ozone hole, caused by industrial halocarbons, will therefore recur each spring. In addition, as the weight of evidence suggests that these gases are also responsible for the observed reductions in middle- and high-latitude stratospheric O_3, the depletion at these latitudes is predicted to continue unabated through the 1990s.

Sources of precursors of tropospheric ozone: Little new information is available regarding the tropospheric ozone precursors (CO, NMHC, and NO_x), all of which have significant natural and anthropogenic sources. Their detailed budgets therefore remain uncertain.

Sources of aerosols: Industrial activity, biomass burning, volcanic eruptions, and sub-sonic aircraft contribute sub-

stantially to the formation of tropospheric and stratospheric aerosols. Industrial activities are concentrated in the Northern Hemisphere where their impact on tropospheric sulphate aerosols is greatest. Sulphur emissions, which are due in large part to combustion effluents, have a similar emissions history to that of anthropogenic CO_2. Estimates of emissions of natural sulphur compounds have been reduced from previous figures, thereby placing more emphasis on the anthropogenic contribution.

SCENARIOS OF FUTURE EMISSIONS

Scenarios of net greenhouse gas and aerosol precursor emissions for the next 100 years or more are necessary to support study of potential anthropogenic impacts on the climate system. The scenarios provide inputs to climate models and assist in the examination of the relative importance of relevant trace gases and aerosol precursors in changing atmospheric composition and climate. Scenarios can also help in improving the understanding of key relationships among factors that drive future emissions.

Scenario outputs are not predictions of the future, and should not be used as such; they illustrate the effect of a wide range of economic, demographic and policy assumptions. They are inherently controversial because they reflect different views of the future. The results of short-term scenarios can vary considerably from actual outcomes even over short time horizons. Confidence in scenario outputs decreases as the time horizon increases, because the basis for the underlying assumptions becomes increasingly speculative. Considerable uncertainties surround the evolution of the types and levels of human activities (including economic growth and structure), technological advances, and human responses to possible environmental, economic and institutional constraints. Consequently, emission scenarios must be constructed carefully and used with great caution.

Since completion of the 1990 IPCC Scenario A (SA90) events and new information have emerged which relate to that scenario's underlying assumptions. These developments include: the London Amendments to the Montreal Protocol; revision of population forecasts by the World Bank and United Nations; publication of the IPCC Energy and Industry Sub-group scenario of greenhouse gas emissions to 2025; political events and economic changes in the former USSR, Eastern Europe and the Middle East; re-estimation of sources and sinks of greenhouse gases (reviewed in this Assessment); revision of preliminary FAO data on tropical deforestation; and new scientific studies on forest biomass. There has also been recognition of considerable uncertainty regarding other important factors that drive future emissions.

These factors have led to an update of the SA90. Six alternative IPCC Scenarios (IS92 a-f) now embody a wide array of assumptions, summarized in Table 1, affecting how future greenhouse gas emissions might evolve in the absence of climate policies beyond those already adopted. This constitutes a significant improvement over the previous methodology. However, the probability of any of the resulting emission paths has not been analyzed. IPCC WGI does not prefer any individual scenario. Other combinations of assumptions could illustrate a broader variety of emission trajectories. The different worlds which the new scenarios imply, in terms of economic, social and environmental conditions, vary widely. The current exercise provides an interim view and lays a basis for a more complete study of future emissions of greenhouse gas and aerosol precursors.

Table 1: Summary of Assumptions in the Six IPCC 1992 Alternative Scenarios. †

Scenario	Population	Economic	Growth	Energy Supplies ††	Other †††	CFCs
IS92a	World Bank 1991 11 3 B by 2100	1990-2025 1990-2100	2.9% 2.3%	12,000 EJ Conventional Oil 13,000 EJ Natural Gas Solar costs fall to $0 075/kWh 191 EJ of biofuels available at $70/barrel	Legally enacted and internationally agreed controls on SO_x, NO_x and NMVOC emissions	Partial compliance with Montreal Protocol. Technological transfer results in gradual phase out of CFCs also in non-signatory countries by 2075
IS92b	World Bank 1991 11.3 B by 2100	1990-2025 1990-2100	2.9% 2.3%	Same as "a"	Same as "a" plus commitments by many OECD countries to stabilize or reduce CO_2 emissions	Global compliance with scheduled phase out of Montreal Protocol.
IS92c	UN Medium Low Case 6.4 B by 2100	1990-2025 1990-2100	2.0% 1 2%	8,000 EJ Conventional Oil 7,300 EJ Natural Gas Nuclear costs decline by 0 4% annually	Same as "a"	Same as "a"
IS92d	UN Medium Low Case 6.4 B by 2100	1990-2025 1990-2100	2 7% 2.0%	Oil and gas same as "c" Solar costs fall to $0 065/kWh 272 EJ of biofuels available at $50/barrel	Emission controls extended worldwide for CO, NO_x, NMVOC, and SO_x. Halt deforestation. Capture and use of emissions from coal mining and gas production and use	CFC production phase out by 1997 for industrialised countries. Phase out of HCFCs
IS92e	World Bank 1991 11 3 B by 2100	1990-2025 1990-2100	3.5% 3.0%	18,400 EJ conventional oil Gas same as "a" Phase out nuclear by 2075	Emission controls (30 % pollution surcharge on fossil energy).	Same as "d"
IS92f	UN Medium High Case 17 6 B by 2100	Same as "a"		Oil and gas same as "e" Solar costs fall to $0 083/kWh Nuclear costs increase to $0.09/kWh	Same as "a"	Same as "a"

† The assumptions for the 1990 Scenario A are described in IPCC (1990) Annex A, pp 331-339

†† All scenarios assume coal resources up to 197,000 EJ Up to 15% of this resource is assumed to be available at $1 30/gigajoule at the mine

††† Tropical deforestation rates (for closed and open forests) begin from an average rate of 17 0 million hectares/year (FAO, 1991) for 1981-1990, then increase with population until constrained by availability of land not legally protected IS91d assumes an eventual halt of deforestation for reasons other than climate Above-ground carbon density per hectare varies with forest type from 16 to 117 tons C/hectare, with soil C ranging from 68 to 100 T C/ha However, only a portion of carbon is released over time with land conversion, depending on type of land conversion

Scenario results: The range of possible greenhouse gas futures is very wide, as the Figure below illustrates (showing only CO_2). All six scenarios can be compared to SA90. IS92a is slightly lower than SA90 due to modest and largely offsetting changes in the underlying assumptions. (For example, compared to SA90, higher population forecasts increase the emission estimates, while phaseout of halocarbons and more optimistic renewable energy costs reduce them.) The highest greenhouse gas levels result from the new scenario IS92e which combines, among other assumptions, moderate population growth, high economic growth, high fossil fuel availability and eventual hypothetical phaseout of nuclear power. The lowest greenhouse gas levels result from IS92c which assumes that population grows, then declines by the middle of the next century, that economic growth is low and that there are severe constraints on fossil fuel supplies. The results of all six scenarios appear in Table 2. Overall, the scenarios indicate that greenhouse gas emissions could rise substantially over the coming century in the absence of new measures explicitly intended to reduce their emission. However, IS92c has a CO_2 emission path which eventually falls below its starting 1990 level. IS92b, a modification of IS92a, suggests that current commitments by many OECD Member countries to stabilize or reduce CO_2 might have a small impact on greenhouse gas emissions over the next few decades, but would not offset substantial growth in possible emissions in the long run. IS92b does not take into account that such commitments could accelerate development and diffusion of low greenhouse gas technologies, nor possible resulting shifts in industrial mix.

Carbon dioxide: The new emissions scenarios for CO_2 from the energy sector span a broad range of futures (see Figure below).

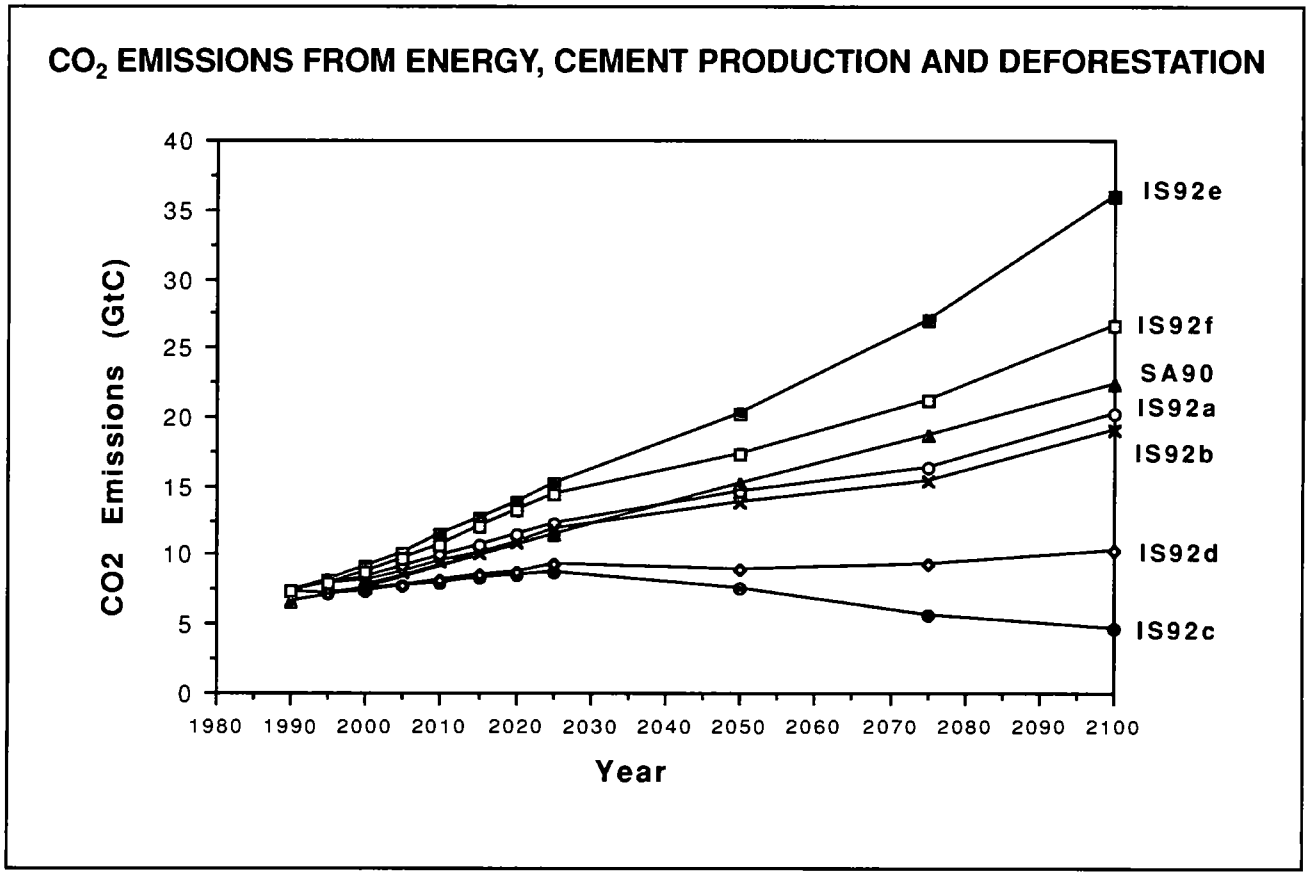

Population and economic growth, structural changes in economies, energy prices, technological advance, fossil fuel supplies, nuclear and renewable energy availability are among the factors which could exert major influence on future levels of CO_2 emissions. Developments such as those in the republics of the former Soviet Union and in Eastern Europe, now incorporated into all the scenarios, have important implications for future fossil fuel carbon emissions, by affecting the levels of economic activities and the efficiency of energy production and use. Biotic carbon emissions in the early decades of the scenarios are higher than SA90, reflecting higher preliminary FAO estimates of current rates of deforestation in many - though not all - parts of the world, and higher estimates of forest biomass.

Table 2: Selected Results of Six 1992 IPCC Greenhouse Gas Scenarios

Scenario	Years	Decline in TPER/GNP (average annual change)	Decline in C intensity (average annual change)	Tropical Deforestation: Cumulative Net Fossil C Emissions (GtC)	Tropical Deforestation: Total Forest Cleared (million hectares)	Tropical Deforestation: Cumulative Net C Emissions (GtC)	Year	Emissions Per Year: CO_2 (GtC)	CH_4 (tg)	N_2O (TgN)	CFCs (Kt)	SO_x (Tg S)
IS92a	1990-2025	0.8%	0.4%	285	678	42	1990	7.4	506	12.9	827	98
	1990-2100	1.0%	0.2%	1386	1447	77	2025	12.2	659	15.8	217	141
							2100	20.3	917	17.0	3	169
IS92b	1990-2025	0.9%	0.4%	275	678	42	2025	11.8	659	15.7	36	140
	1990-2100	1.0%	0.2%	1316	1447	77	2100	19.0	917	16.9	0	164
IS92c	1990-2025	0.6%	0.7%	228	675	42	2025	8.8	589	15.0	217	115
	1990-2100	0.7%	0.6%	672	1343	70	2100	4.6	546	13.7	3	77
IS92d	1990-2025	0.8%	0.9%	249	420	25	2025	9.3	584	15.1	24	104
	1990-2100	0.8%	0.7%	908	651	30	2100	10.3	567	14.5	0	87
IS92e	1990-2025	1.0%	0.2%	330	678	42	2025	15.1	692	16.3	24	163
	1990-2100	1.1%	0.2%	2050	1447	77	2100	35.8	1072	19.1	0	254
IS92f	1990-2025	0.8%	0.1%	311	725	46	2025	14.4	697	16.2	217	151
	1990-2100	1.0%	0.1%	1690	1686	93	2100	26.6	1168	19.0	3	204

TPER = Total Primary Energy Requirement
Carbon intensity is defined as units of carbon per unit of TPER
CFCs include CFC-11, CFC-12, CFC-113, CFC-114 and CFC-115

Halocarbons: The revised scenarios for CFCs and other substances which deplete stratospheric ozone are much lower than in SA90. This is consistent with wide participation in the controls under the 1990 London Amendments to the Montreal Protocol. However, the future production and composition of CFC substitutes (HCFCs and HFCs) could significantly affect the levels of radiative forcing from these compounds.

Methane, nitrous oxide, ozone precursors and sulphur gases: The distribution of CH_4 and N_2O emissions from the different sources has changed from the SA90 case. Methane from rice paddies are lower, and emissions from animal waste and domestic sewage have been added. N_2O emission factors for stationary sources and biomass burning have been revised downwards. Adipic and nitric acid have been included as additional sources of N_2O. Preliminary analysis of the emissions of volatile organic compounds and sulphur dioxide suggests that the global emissions of these substances are likely to grow in the coming century if no new limitation strategies are implemented.

RELATIONSHIP BETWEEN EMISSIONS AND ATMOSPHERIC CONCENTRATIONS AND THE INFLUENCE ON RADIATIVE BUDGET

A key issue is to relate emissions of greenhouse gases, greenhouse gas precursors and aerosol precursors to future concentrations of greenhouse gases and aerosols in order to assess their impact on the radiative balance. A number of different types of model have been developed.

Carbon cycle models: While there is a variety of carbon cycle models (including 3-D ocean-atmosphere models, 1-D ocean-atmosphere box-diffusion models, and box models that incorporate a terrestrial biospheric sink) all such models are subject to considerable uncertainty because of an inadequate understanding of the processes controlling the uptake and release of CO_2 from the oceans and terrestrial ecosystems. Some models assume a net neutral terrestrial biosphere, balancing fossil fuel emissions of CO_2 by oceanic uptake and atmospheric accumulation, others achieve balance by invoking additional assumptions regarding the effect of CO_2 fertilization on the different parts of the biosphere. However even models that balance the past and contemporary carbon cycle may not predict future atmospheric concentrations accurately because they do not necessarily represent the proper mix of processes on land and in the oceans. The differences in predicted changes in CO_2 concentrations are up to 30%. This does not represent the major uncertainty in the prediction of future climate change compared with uncertainties in estimating future patterns of trace gas emissions, and in quantifying climate feedback processes. A simple empirical estimate can be based on the assumption that the fraction of emissions which remains in the atmosphere is the same as that observed over the last decade; i.e., 46±7%.

Atmospheric gas phase chemistry models: Current tropospheric models exhibit substantial differences in their predictions of changes in O_3, in the hydroxyl radical (OH) and in other chemically active gases due to emissions of CH_4, non-methane hydrocarbons, CO and, in particular, NO_x. These arise from uncertainties in the knowledge of background chemical composition and our inability to represent small-scale processes occurring within the atmosphere. These deficiencies limit the accuracy of predicted changes in the abundance and distribution of tropospheric O_3, and in the lifetimes of a number of other greenhouse gases, including the HCFCs and HFCs, all of which depend upon the abundance of the OH radical. Increases in CH_4, NMHCs, and CO all lead to increases in O_3, and decreases in OH, thus leading to an increase in radiative forcing. On the other hand because increases in NOx lead to an increase in both O_3 and OH, the net effect on radiative forcing is uncertain.

Atmospheric sulphate aerosol models: The atmospheric chemistry of sulphate aerosols and their precursors has been extensively studied in relation to the acid rain issue. While our understanding of processes related to chemical transformations has increased significantly in recent years, substantial uncertainties remain, especially regarding the microphysics of aerosol formation, interaction of aerosols with clouds, and the removal of aerosol particles by precipitation.

HOW HAS OUR UNDERSTANDING OF CHANGES IN RADIATIVE FORCING CHANGED?

Since IPCC (1990), there have been significant advances in our understanding of the impact of ozone depletion and sulphate aerosols on radiative forcing and of the limitations of the concept of the Global Warming Potential.

Radiative forcing due to changes in stratospheric ozone: For the first time observed global depletions of O_3 in the lower stratosphere have been used to calculate changes in the radiative balance of the atmosphere. Although the results are sensitive to atmospheric adjustments, and no GCM studies of the implications of the O_3 changes on surface temperature have been performed, the radiative balance calculations indicate that the O_3 reductions observed during the 1980s have caused reductions in the radiative forcing of the surface-troposphere system at mid- and high- latitudes. This reduction in radiative forcing resulting from O_3 depletion could, averaged on a global scale and over the last decade, be approximately equal in magnitude and opposite in sign to the enhanced radiative forcing due to increased CFCs during the same time period. The effect at high latitudes is particularly pronounced and, because of these large variations with latitude and region, studies using GCMs are urgently required to further test these findings

Radiative forcing due to changes in tropospheric ozone: While there are consistent observations of an increase in tro-

pospheric ozone (up to 10% per decade) at a limited number of locations in Europe, there is not an adequate global set of observations to quantify the magnitude of the increase in radiative forcing. However, it has been calculated that a 10% uniform global increase in tropospheric ozone would increase radiative forcing by about a tenth of a watt per square metre.

Radiative effects of sulphur emissions: Emissions of sulphur compounds from anthropogenic sources lead to the presence of sulphate aerosols which reflect solar radiation. This is likely to have a cooling influence on the Northern Hemisphere (there is negligible effect in the Southern Hemisphere). For clear-sky conditions alone, the cooling caused by current rates of emissions has been estimated to be about $1 Wm^{-2}$ averaged over the Northern Hemisphere, a value which should be compared with the estimate of $2.5 Wm^{-2}$ for the heating due to anthropogenic greenhouse gas emissions up to the present. The non-uniform distribution of anthropogenic sulphate aerosols coupled with their relatively short atmospheric residence time produce large regional variations in their effects. In addition, sulphate aerosols may affect the radiation budget through changes in cloud optical properties.

Global Warming Potentials: Gases can exert a radiative forcing both directly and indirectly: direct forcing occurs when the gas itself is a greenhouse gas; indirect forcing occurs when chemical transformation of the original gas produces a gas or gases which themselves are greenhouse gases. The concept of the Global Warming Potential (GWP) has been developed for policymakers as a measure of the possible warming effect on the surface-troposphere system arising from the emission of each gas relative to CO_2. The indices are calculated for the contemporary atmosphere and do not take into account possible changes in chemical composition of the atmosphere. Changes in radiative forcing due to CO_2, on a kg basis, are non-linear with changes in the atmospheric CO_2 concentrations. Hence, as CO_2 levels increase from present values, the GWPs of the non-CO_2 gases would be higher than those evaluated here. For the concept to be most useful, both the direct and indirect components of the GWP need to be quantified.

Direct Global Warming Potentials: The direct components of the Global Warming Potentials (GWPs) have been recalculated, taking into account revised estimated lifetimes, for a set of time horizons ranging from 20 to 500 years, with CO_2 as the reference gas. The same ocean-atmosphere carbon cycle model as in IPCC (1990) has been used to relate CO_2 emission to concentrations. Table 3 shows values for a selected set of key gases for the 100 year time horizon. While in most cases the values are similar to the previous IPCC (1990) values, the GWPs for some of the HCFCs and HFCs have increased by 20 to 50% because of revised estimates of their lifetimes. The direct GWP of CH_4 has been adjusted upward, correcting an error in the previous IPCC report. The carbon cycle model used in these calculations probably underestimates both the direct and indirect GWP values for all non-CO_2 gases. The magnitude of the bias depends on the atmospheric lifetime of the gas, and the GWP time horizon.

Table 3: Direct GWPs for 100 year Time Horizon

Gas	Global Warming Potential (GWP)	Sign of the Indirect Component of the GWP
Carbon dioxide	1	none
Methane	11	positive
Nitrous oxide	270	uncertain
CFC-11	3400	negative
CFC-12	7100	negative
HCFC-22	1600	negative
HFC-134a	1200	none

Indirect Global Warming Potentials: Because of our incomplete understanding of chemical processes, most of the indirect GWPs reported in IPCC (1990) are likely to be in substantial error, and none of them can be recommended. Although we are not yet in a position to recommend revised numerical values, we know, however, that the indirect GWP for methane is positive and could be comparable in magnitude to its direct value. In contrast, based on the sub-section above, the indirect GWPs for chlorine and bromine halocarbons are likely to be negative. The concept of a GWP for short-lived, in homogeneously distributed constituents, such as CO, NMHC, and NO_x may prove inapplicable, although, as noted above, we know that these constituents will affect the radiative balance of the atmosphere through changes in tropospheric ozone and OH. Similarly, a GWP for SO_2 is viewed to be inapplicable because of the non-uniform distribution of sulphate aerosols.

Influence of changes in solar output: The existence of strong correlations between characteristics of the solar activity cycle and global mean temperature has been reported. The only immediately plausible physical explanation of these correlations involves variability of the sun's total irradiance on time-scales longer than that of the 11-year activity cycle. Since precise measurements of the irradiance are only available for the last decade, no firm conclusions regarding the influence of solar variability on climate change can be drawn.

WHAT TOOLS DO WE USE AND WHAT INFORMATION DO WE NEED TO PREDICT FUTURE CLIMATE?

Models

The most highly developed tool which we have to model climate and climate change is known as a general circulation model or GCM. These models are based on the laws of physics and use descriptions in simplified physical terms (called parametrizations) of the smaller-scale processes such as those due to clouds and deep mixing in the ocean. 'Coupled' general circulation models

(CGCMs) have the atmospheric component linked to an oceanic component of comparable complexity.

Climate forecasts are derived in a different way from weather forecasts. A weather prediction model gives a description of the atmosphere's state up to 10 days or so ahead, starting from a detailed description of an initial state of the atmosphere at a given time. Such forecasts describe the movement and development of large weather systems, though they cannot represent very small-scale phenomena; for example, individual shower clouds.

To estimate the influence of greenhouse gases or aerosols in changing climate, the model is first run for a few (simulated) decades. The statistics of the model's output are a description of the model's simulated climate which, if the model is a good one and includes all the important forcing factors, will bear a close resemblance to the climate of the real atmosphere and ocean. The above exercise is then repeated with increasing concentrations of the greenhouse gases or aerosols in the model. The differences between the statistics of the two simulations (for example in mean temperature and interannual variability) provide an estimate of the accompanying climate change.

We also need to determine whether or not the predicted changes will be noticeable above the natural variations in climate. Finally, observations are required in order to monitor climate, to improve the understanding of climate processes and to help in the validation of models.

The long-term change in surface air temperature following a doubling of carbon dioxide (referred to as the climate sensitivity) is generally used as a benchmark to compare models. The range of values for climate sensitivity reported in the 1990 Assessment, and re-affirmed in this Supplement, was 1.5° to 4.5°C, with a best estimate, based on model results and taking into account the observed climate record, of 2.5°C.

Simpler models, which simulate the behaviour of GCMs, are also used to make predictions of the evolution with time of global temperature from a number of emission scenarios. These so-called box-diffusion models contain highly simplified physics but give similar results to GCMs when globally averaged. Only comprehensive GCMs, however, can provide three-dimensional distributions of the changes in other climate variables, including the changes due to non-linear processes that are not given by simplified models. The extraction of this information from the results of coupled GCMs has only just begun.

Future concentrations of greenhouse gases and aerosols

A necessary starting point for the prediction of changes in climate due to changes in atmospheric constituents is an estimate of their future concentrations. This requires a knowledge of their sources and sinks (natural and man-made) and an estimate of how the strengths of these sources and sinks might change in the future (an emissions scenario). The projections of future concentrations can then be used in climate models to estimate the climatic response.

Do GCMs predict future climate?

To make a prediction of future climate it is necessary to fulfil two conditions: (a) include all of the major human and natural factors known to affect climate, and (b) predict the future magnitudes of atmospheric concentrations of greenhouse gases. So far, GCMs (and CGCMs) have included only radiative forcing induced by greenhouse gases, and therefore their results relate only to the greenhouse gas component of climate change.

At the time of IPCC (1990), it was recognized that sulphate aerosols exert a significant negative radiative forcing on climate but this forcing was not well quantified. Since then progress has been made in understanding radiative forcing by sulphate aerosols, and an additional source of negative forcing has been identified in the depletion of stratospheric ozone due to halocarbons. The lack of these negative forcing factors in GCMs does not negate the results obtained from them so far. For example the estimates of climate sensitivity, which is defined purely in terms of CO_2 concentrations, are unchanged, and it is still believed that anthropogenic greenhouse gases, now and even more so in the future, represent the largest perturbation to the natural radiative balance of the atmosphere. However it does mean that the rates of change of, say, surface temperature do need to be adjusted for additional forcing factors before they can fulfil condition (a). The second condition is fulfilled when we use a specific prediction (as opposed to a scenario) of future atmospheric concentrations of greenhouse gases.

CONFIDENCE IN MODEL PREDICTIONS

There continues to be slow improvement in the ability of models to simulate present climate, although further improvements in the model resolution and the parametrization of physical processes are needed. Since the last report, further evidence has accumulated that atmospheric models are capable of reproducing a range of aspects of atmospheric variability. Coupled ocean-atmosphere models produce variability on decadal time-scales similar in some respects to that observed, and ocean models show longer term fluctuations associated with changes in the thermohaline circulation.

There has been some clarification of the nature of water vapour feedback, although the radiative effects of clouds and related processes continue to be the major source of uncertainty and there remain uncertainties in the predicted changes in upper tropospheric water vapour in the tropics. Biological feedbacks have not yet been taken into account in simulations of climate change.

Increased confidence in the geographical patterns of climate change will require new simulations with improved coupled models and with radiative forcing scenarios that include aerosols.

Confidence in regional climate patterns based directly on GCM output remains low and there is no consistent evidence regarding changes in variability or storminess. GCM results can be interpolated to smaller scales using statistical methods (correlating regional climate with the large-scale flow) or a nested approach (high-resolution, regional climate models driven by large-scale GCM results). Both methods show promise but an insufficient number of studies have yet been completed to give an improved global picture of regional climate change due to increases in greenhouse gases; in any event both interpolation methods depend critically on the quality of the large-scale flow in the GCM. Given our incomplete knowledge of climate, we cannot rule out the possibility of surprises.

SIMULATED RATES OF CHANGE IN CLIMATE AND THEIR GEOGRAPHICAL DISTRIBUTION

Results of General Circulation Models (GCMs) available to IPCC (1990) mainly concerned *equilibrium* simulations. Only one *transient* model run (i.e., where the time-varying response of the climate to steadily increasing greenhouse gas concentrations is simulated) had been completed.

Since then many papers have appeared in the refereed literature concerned with climate models and their results. Significant progress has been made in the area of transient models, with four modelling groups having carried out climate simulations for up to 100 years using coupled atmosphere-ocean global climate models (CGCMs) which incorporate a detailed description of the deep ocean and therefore can simulate the climate lag induced by the deep ocean circulation. These models require substantial adjustments to fluxes of heat and fresh water in order to achieve a realistic simulation of present climate and this may distort the models' response to small perturbations such as those associated with increasing greenhouse gases. For simulations of future climate with these models, carbon dioxide concentrations have been increased at rates close to 1% per year (approximately the equivalent radiatively to the current rate of increase of greenhouse gases).

Internal variability obscures the geographical patterns of change during the first few decades of the experiments. However, once these patterns become established, they vary relatively little as the integrations progress and are similar to those produced by equilibrium models in a number of ways for instance:

(i) surface air temperatures increase more over land than over oceans;
(ii) precipitation increases on average at high latitudes, in the monsoon region of Asia and in the winter at mid-latitudes;
(iii) over some mid-latitude continental areas values of soil moisture are lower on average in summer.

The transient CO_2 simulations, however, show that over the northern North Atlantic and the southern oceans near Antarctica the warming is reduced by 60% or more relative to equilibrium simulations at the time of doubling CO_2.

Much further development and validation of coupled models is required.

WHAT WOULD WE NOW ESTIMATE FOR CLIMATE CHANGE?

The new simulations using coupled ocean-atmosphere GCMs, which do not include the effects of sulphates and ozone depletion, generally confirm the IPCC 1990 estimates of future warming at rates of about 0.3°C/decade (range 0.2 to 0.5°C/decade) over the next century for IPCC 1990 scenario A. Because GCMs do not yet include possible opposing anthropogenic influences, including the forcing from sulphate aerosols and stratospheric ozone depletion, the net rate of increase in surface temperature is expected to be less, at least during the period for which sulphur emissions continue to increase, than would be expected from greenhouse gas forcing alone. However, the globally averaged magnitude of the effect of sulphate aerosols has not yet been calculated accurately and further work is needed.

The simulated rate of change of sea level *due to oceanic thermal expansion only* ranges from 2 to 4cm per decade, again consistent with the previous report.

New IPCC 1992 emissions scenarios (IS92a-f; see para. on "SCENARIOS OF FUTURE EMISSIONS") have been derived in the light of new information and international agreements. In order to provide an initial assessment of the effect of the new scenarios, the change in surface temperature has been estimated with the simple climate model used in IPCC (1990) which has been calibrated against the more comprehensive coupled ocean-atmosphere models (see box on models). These calculations include, in the same way as did the 1990 calculations, the direct radiative forcing effects of all the greenhouse gases included in the scenarios.

The effect of stratospheric ozone depletion and of sulphate aerosols have not been included, which again parallels the 1990 calculations. The accompanying diagrams show (i) the temporal evolution of surface temperature for IS92a, assuming the high, "best estimate" and low climate sensitivities (4.5, 2.5 and 1.5°C), and (ii) the temperature changes for the six 1992 IPCC scenarios and the 1990 Scenario A, assuming the "best estimate" of climate sensitivity (see earlier box on "What tools do we use ....?" for the definition of climate sensitivity).

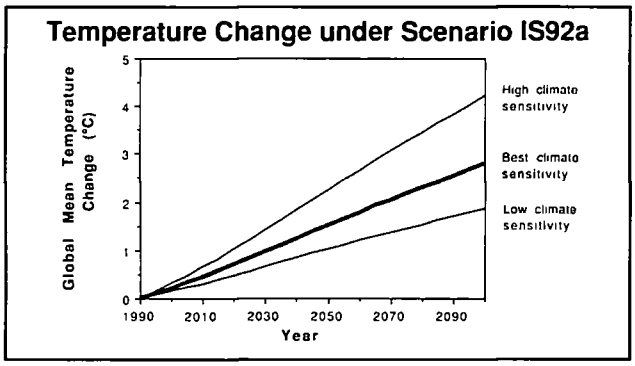

Estimates of global mean temperature change for IS92a using high (4.5°C) 'best estimate' (2.5°C) and low (1.5°C) values of climate sensitivity. The effects of sulphate aerosol and ozone depletion have not been taken into account

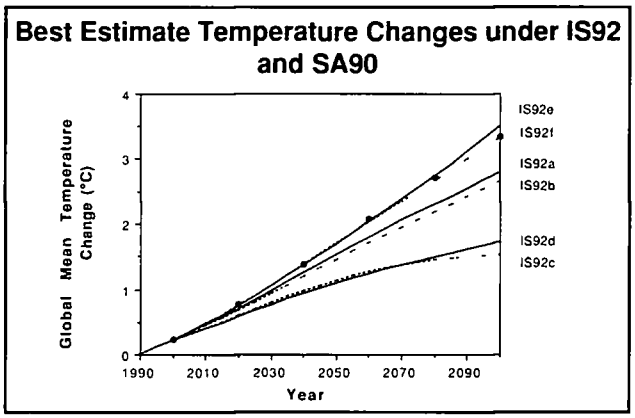

Estimates of global mean temperature change for the IPCC 1992 scenarios (IS92a-f) assuming the IPCC 'best estimate' climate sensitivity. The effects of sulphate aerosol and ozone depletion have not been taken into account. SA90 is represented by solid circles

THE UPDATED RECORD OF GLOBAL MEAN TEMPERATURES

Continuing research into the 19th century ocean temperature record has not significantly altered our calculation of surface temperature warming over the past 100-130 years of 0.45±0.15°C. Furthermore, global surface temperatures for 1990 and 1991 have been similar to those of the warmest years of the 1980s and continue to be warmer than the rest of the record. The research has, however, led to a small adjustment in hemispheric temperatures. The long-term warming trends assessed in each hemisphere are now more nearly equal, with the Southern Hemisphere marginally warmer in the late nineteenth century and the Northern Hemisphere trend unchanged from previous estimates.

A notable feature over considerable areas of the continental land masses of the Northern Hemisphere is that warming over the last few decades is primarily due to an increase of night-time rather than daytime temperatures. These changes appear to be partly related to increases in cloudiness but other factors cannot be excluded such as a direct cooling effect of aerosols on maximum temperatures in sunny weather, an influence of increasing concentrations of greenhouse gases and some residual influence of urbanisation on minimum temperatures. A more complete study is needed as only 25% of the global land area has been analysed. In this regard, regional changes in maximum, minimum and mean temperature related to changes in land use (e.g., desertification, deforestation or widespread irrigation) may need to be identified separately.

A new source of information that supports higher sea surface temperatures in many tropical regions over the last decade concerns evidence that the bleaching of tropical corals has apparently increased. Bleaching has been shown to be related (in part) to episodes of sea surface temperature warmer than the normal range of tolerance of these animals, though increasing pollution may be having an influence.

There has been considerable interest in mid-tropospheric temperature observations made since 1979 from the Microwave Sounding Unit (MSU) aboard the TIROS-N satellites. The MSU data have a truly global coverage but there is only a short record (13 years) of measurements; the surface and the radiosonde data are less spatially complete but have much longer records (over 130 and near 30 years respectively). Globally-averaged trends in MSU, radiosonde and surface data sets between 1979 and 1991 differ somewhat (0.06, 0.17, and 0.18°C per decade, respectively), although the differences are not statistically significant. Satellite sounders, radiosonde and surface instruments all have different measurement characteristics, and, in addition, geographical and temporal variations in mid-tropospheric and surface temperatures are not expected to be identical. Despite this, correlations between global annual values of the three data sets are quite high.

Note that it is not possible to rank recent warm years in an absolute way; it depends on which record is used, what level is referred to and how much uncertainty is attached to each value.

MSU data have been able to detect the impact on lower stratospheric temperature of volcanic eruptions in a striking way. Variability in these data between 1979 and 1991 is dominated by short-term temperature fluctuations (greatest in the tropics) following the injection of large amounts of aerosol into the stratosphere by the eruptions of El Chichon (1982) and Mt. Pinatubo (1991). Globally, temperature rises in the lower stratosphere were about 1°C and 1.3°C respectively; stratospheric warming due to El Chichon lasted nearly two years while that due to Mt. Pinatubo is still underway. The longer radiosonde record, however, shows a significant global cooling trend of about 0.4°C per decade since the middle 1960s in the lower stratosphere.

ARE THERE ANY TRENDS IN OTHER CLIMATICALLY IMPORTANT QUANTITIES?

Precipitation variations of practical significance have been documented on many time and space scales, but due to data coverage and inhomogeneity problems nothing can be said about global-scale changes. An apparent increase of water vapour in the tropics parallels the increase in lower tropospheric temperature but it is not yet possible to say to what

extent the changes are real and whether they are larger than natural variability.

A small, irregular, decrease of about 8% has been observed in annually averaged snow cover extent over the Northern Hemisphere since 1973 in a new, improved, compilation of these data. The reduction is thought to be real because annual values of snow cover extent and surface air temperatures over the extratropical Northern Hemisphere land have a high correlation of -0.76.

There is evidence that, regionally, relatively fast (sometimes called abrupt) climate changes can occur. These changes may persist for up to several decades but are often a function of season. These fast changes are poorly understood, but can be of considerable practical importance.

ARE THE OBSERVED TEMPERATURE CHANGES CONSISTENT WITH PREDICTED TEMPERATURE CHANGES?

CGCMs, which do not yet take into account changes in aerosols, predict a greater degree of warming in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH), a result of the greater extent of land in the NH which responds more rapidly to forcing. The observed larger warming of the SH in recent decades (0.3°C between 1955 and 1985) than in the NH (which hardly warmed at all over the same period) is at first sight in conflict with this prediction. Recently, however, the NH has started to warm quite rapidly. The reasons for the differences in observed warming rates in the two hemispheres are not known though man-made aerosols (see para. on "HOW HAS OUR UNDERSTANDING .....?) and changes in ocean circulation may have played a part.

Furthermore, increases in CFCs may have reduced ozone levels sufficiently to offset in a globally-averaged sense the direct greenhouse effect of CFCs. Consequently, the estimates of warming over the last 100 years due to increases in greenhouse gases made in the original report may be somewhat too rapid because they did not take account of these cooling influences. Taking this into account could bring the results of model simulations closer to the observed changes.

Individual volcanic eruptions, such as that of El Chichon, may have led to surface cooling over several years but should have negligible effect on the long-term trend. Some influence of solar variations on time-scales associated with several sunspot cycles remains unproven but is a possibility.

The conclusion of IPCC (1990) remains unchanged:
"the size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming".

KEY UNCERTAINTIES AND FURTHER WORK REQUIRED

The prediction of future climate change is critically dependent on scenarios of future anthropogenic emissions of greenhouse gases and other climate forcing agents such as aerosols. These depend not only on factors which can be addressed by the natural sciences but also on factors such as population and economic growth and energy policy where there is much uncertainty and which are the concern of the social sciences. Natural and social scientists need to cooperate closely in the development of scenarios of future emissions.

Since IPCC (1990) there has been a greater appreciation of many of the uncertainties which affect our predictions of the timing, magnitude and regional patterns of climate change. These continue to be rooted in our inadequate understanding of:

- sources and sinks of greenhouse gases and aerosols and their atmospheric concentrations (including their indirect effects on global warming)
- clouds (particularly their feedback effect on greenhouse gas-induced global warming, also the effect of aerosols on clouds and their radiative properties) and other elements of the atmospheric water budget, including the processes controlling upper level water vapour
- oceans, which through their thermal inertia and possible changes in circulation, influence the timing and pattern of climate change
- polar ice sheets (whose response to climate change also affects predictions of sea level rise)
- land surface processes and feedbacks, including hydrological and ecological processes which couple regional and global climates

Reduction of these uncertainties requires:

- improvements in the systematic observation and understanding of climate-forcing variables on a global basis, including solar irradiance and aerosols
- development of comprehensive observations of the relevant variables describing all components of the climate system, involving as required new technologies and the establishment of data sets
- better understanding of climate-related processes, particularly those associated with clouds, oceans and the carbon-cycle
- an improved understanding of social, technological and economic processes, especially in developing countries, that are necessary to develop more realistic scenarios of future emissions

- the development of national inventories of current emissions

- more detailed knowledge of climate changes which have taken place in the past

- sustained and increased support for climate research activities which cross national and disciplinary boundaries; particular action is still needed to facilitate the full involvement of developing countries

- improved international exchange of climate data.

Many of these requirements are being addressed by major international programmes in particular by the World Climate Research Programme (WCRP), the International Geosphere Biosphere Programme (IGBP) and the Global Climate Observing System (GCOS). Adequate resources need to be provided both to the international organisation of these programmes and to the national efforts supporting them if the new information necessary to reduce the uncertainties is to be forthcoming. Resources also need to be provided to support on a national or regional basis, and especially in developing countries, the analysis of data relating to a wide range of climate variables and the continued observation of important variables with adequate coverage and accuracy.

Reference:

IPCC, 1990: Climate Change, The IPCC Scientific Assessment, Press Syndicate of the University of Cambridge, Cambridge CB2 1RP, UK.

ANNEX

Progress in the development of an IPCC methodology for national inventories of net emissions of greenhouse gases

Scientific assessment is primarily concerned with sources and sinks at the global, and large region level but, in order to support national and international responses to climate change, it is necessary to estimate emissions and sinks at the national level in an agreed and consistent way.

IPCC (1991) has established a work programme to:

i) develop an approved detailed methodology for calculating national inventories of greenhouse gas emissions and sinks

ii) assist all participating countries to implement this methodology and provide results by the end of 1993.

This programme is based on preliminary work sponsored by the Organization for Economic Cooperation and Development (OECD, 1991). OECD and the International Energy Agency (IEA) are continuing to provide technical support to the IPCC work programme. The programme will manage the development and approval of inventory methods and procedures, and the collection and evaluation of data. It will collaborate with other sponsors including the Global Environment Facility (GEF), the Asian Development Bank, the European Community, UNECE and individual donor countries, to encourage funding of technical cooperation projects in greenhouse gas (GHG) inventories.

The IPCC requested that participating countries provide any available GHG emissions inventory data to the IPCC by the end of September 1991. As of January 1992, 18 countries have submitted complete or partial GHG inventories (see Table below); most relate to average emissions over one, two or three years in the period 1988 to 1990. This process has been particularly useful in identifying problems in coverage and consistency of currently available inventories.

An IPCC Workshop on National GHG Inventories, held in Geneva from 5-6 December 1991, provided guidance on needed improvements in the draft methodology and priorities for the work programme. Numerous improvements to the methodology were agreed upon, and priorities were proposed for the work programme and for technical cooperation activities. As a result of the preliminary data collection, the workshop, and other comments received, the following major priorities for the IPCC work programme have been established:

Methodology

- Develop a simpler methodology and streamlined "workbook" document to assist users in its implementation
- Work with experts to develop a new and simpler method for calculating CO_2 emissions from forestry and land-use change
- Establish technical expert groups to improve the methodology for CH4 from rice and fossil fuel production, and other key gases and source types
- Work with experts to include halocarbons in the GHG inventory starting with data available from the Montreal Protocol process
- Develop and disseminate regionally-applicable emissions factors and assumptions.

Work programme

- Priorities for national inventories are: (a) CO_2 from energy for all countries, (b) CO_2 from forestry and land use if important for the country, and (c) CH_4 for important source categories by country
- Initiate intercomparison studies of existing detailed inventories
- Include a scientific review of national inventory data and aggregated totals by region and globally in the work programme.

Technical cooperation

- IPCC will improve communications among technical focal points in all participating countries and with other interested international organizations
- High priority should be placed on country case studies, training, regional cooperation and other activities to assist non-OECD countries in testing and implementing the GHG inventory methodology
- Provide methods in the form of a streamlined workbook in several languages. A user-friendly computer spreadsheet version will also be developed as a high priority.

Annex Table: Countries which have submitted complete or partial inventories of national greenhouse gas emissions (by January 1992).

Australia	Germany	Sweden
Belgium	Italy	Switzerland
Canada	Netherlands	Thailand
Denmark	New Zealand	Vietnam
Finland	Norway	United Kingdom
France	Poland	United States

References

IPCC, 1991: Report of the Fifth Session of the WMO/UNEP Intergovernmental Panel on Climate Change (IPCC) 13-15 March 1991, Geneva.

OECD, 1991: Estimation of Greenhouse Gas Emissions and Sinks: Final Report from the OECD Experts Meeting, 18-21 February 1991, Paris. Revised August 1991.

SECTION III. ASSESSMENT OF POTENTIAL IMPACTS OF CLIMATE CHANGE

TASK 2: Prediction of the regional distributions of climate change and associated impacts studies, including model validation studies

TASK 3: Energy and industry related issues (part on impacts of climate change)

TASK 4: Agriculture and forestry related issues (part on impacts of climate change)

TASK 5: Vulnerability to sea level rise (part on impacts of climate change)

BY WORKING GROUP II

Introduction

Working Group II examined aspects of four of the tasks approved at the fifth session of IPCC (March 1991). These tasks include:

- prediction of the regional distributions of climate change and associated impacts studies, including model validation studies;
- energy and Industry related issues;
- agriculture and Forestry related issues;
- vulnerability to sea level rise.

The first of these includes the development of guidelines for assessment of impacts, and the identification of regional/national components of monitoring systems which could be used for impact studies.

Also included here is additional work on water resources and hydrology, a subject mentioned most frequently as the area of maximum concern by nations in response to a questionnaire circulated by the Working Group (and on other topics related to the structure of the Working Group itself). The work reported focuses only on the portions of these tasks that directly relate to the impacts of climate change.

Since the IPCC First Impacts Assessment Report (1990), studies have been included which have served to extend our knowledge of the potential impacts of climate change. These, however, do not radically alter the conclusions despite uncertainties of that report.

From the stimulus provided by the publication of the IPCC First Impacts Assessment Report, a large number of regional studies have been carried out on assessment of impacts of climate change. A questionnaire circulated by Working Group II was valuable in revealing new information, and in defining areas of common concern to many countries. Thus, roughly 50% of the responses highlighted the impacts of climate change on hydrology and water resources, emphasizing the importance of water in most countries. Other topics of priority interest, particularly for developing countries, were agriculture and forestry, and world's oceans and coastal zones. Both reflect the concerns of countries over availability of food supplies from land and sea sources.

Additional areas of concern identified in the questionnaire were desertification (particularly in Africa and Asia), cyclones and other extreme events (particularly for island nations and deltaic areas), recreation and tourism (particularly their economic impacts), and climate variability associated with the El-Niño - Southern Oscillation (ENSO) phenomenon, prolonged droughts and extreme events. The national responses included concern that changes in climate variability as a consequence of climate change may create increased risks, especially in those parts of the world where climate variability is known to have significant social and economic impacts. It is important to note that many countries, particularly in the Southern Hemisphere, also identified increases in UV-B radiation as a significant area of concern.

THE ENERGY, HUMAN SETTLEMENT, TRANSPORT AND INDUSTRIAL SECTORS, HUMAN HEALTH AND AIR QUALITY

Recent studies for the Maldives and for the Pacific island states including Tuvalu, Kiribati, Tokelau and the Marshall Islands have reconfirmed that small low-lying island states and large populations living in low-lying coastal areas will be increasingly vulnerable, particularly if adaptive measures are inadequate, to the combination of sea level rise, storm surges and coastal flooding.

The high dependency on biomass and hydropower in many developing countries indicates that these countries are quite sensitive to the impacts of climate change. Biomass production, on which developing countries such as Bangladesh depend for 90 to 100% of their energy needs, could be damaged by a combination of climate-change-induced drought or inundation.

On the other hand, there has been little work that has shed new light on the question of socio-economic impacts in the areas of energy, human settlement, transport and industrial sectors, human health and air quality.

A UK study shows soil shrinkage and swelling as a result of climate change in clay-rich areas has major implications for the construction and insurance industries and for human settlement. Water-dependent industries such as food processing, paper making, and power generation could be affected by hydrological changes under changed climate conditions.

Knowledge of climate change on human health has extended and confirmed the previously reported results with greater understanding of potential shifts in disease vector habitats with global warming particularly in New Zealand and Australia. Diseases such as malaria, lymphatic filariases, schistosomiasis, leishmaniasis, onchocerciasis (river blindness), dengue fever, and Australian and Japanese encephalitis could increase or be reintroduced in many countries as a consequence of global warming. Regarding the impact of UV-B radiation on health, recent studies show that it affects human immunosuppression system and vision.

AGRICULTURE AND FORESTRY

New studies, such as those in the European Community, North America, and Southeast Asia highlight the IPCC First Impacts Assessment Report (1990) conclusions that impacts will vary greatly depending on the extent of climate change and on the type of agriculture. These findings largely amplify, but do not radically alter, the conclusions made in the 1990 report. They do, however, confirm that the impact of global warming on agriculture may be serious if warming is at the upper end of the range projected by the IPCC Working Group I.

Recent studies have reinforced concern that drought is the area in which climate change poses the greatest risk for agriculture and consequently arid and semi-arid regions are likely to be most vulnerable to climate change.

Other recent studies confirm the IPCC earlier conclusions that climate change may benefit ecological conditions for insect growth and abundance which is likely to have a negative effect on crop, livestock and forest production in some regions.

Research continues to address the relative importance of direct and indirect effects of CO_2, in combination with a rise in temperatures, on future crop production. While some scientists emphasize enhanced photosynthesis and more efficient water use seen in controlled settings, others are sceptical that these benefits will be seen in farmer's fields under changing climate conditions.
The effects on plant growth may result in the maintenance of present-day soil conditions in some regions, as greater soil organic matter and denser ground cover may counter the effects of soil erosion caused by increased rainfall intensities and oxidation rates of organic matter in soils caused by higher temperatures.

Adaptation to climate change by the existing agricultural production system should be possible, and the worldwide systems of agricultural research should be able to provide new crop cultivars that maintain high yields and nutritional quality. However, efforts will be needed to make such developments available to small farmers in developing countries in time to respond to changes in local climatic conditions.

New analyses support the 1990 report conclusion that the impacts of climate change on forests could have significant socio-economic consequences. This is especially important for those countries and regions where economic and social welfare and economic development are highly dependent on the forest sector.

Key uncertainties require continued data collection and research for policy development and decision-making. These include: (1) the extent of managed and natural forests, their spatial and temporal variation and their roles in the global carbon cycle; (2) genetics and physiology of tree species and the relationships among subordinate and competitive species; (3) regional impacts; and, (4) the linkages among the regional impacts, socio-economic structures, and the thresholds and critical limits where changes take place.

NATURAL TERRESTRIAL ECOSYSTEMS

Analyses subsequent to those included in the IPCC First Assessment Report (1990) reinforce the major conclusion of that report that natural terrestrial ecosystems could face significant environmental impacts as a result of the global increases in the atmospheric concentration of greenhouse gases and associated climatic changes. In particular, these studies continue to suggest that the rate of these changes will be the major factor in determining the type and degree of impacts with a variety of responses expected for different regions and for different communities within ecosystems. Current climatic projections continue to suggest that the rates of change are likely to be faster than the ability of some component species to respond and that species and ecosystem responses may be sudden, potentially leading to ecosystem destabilization or degradation.

The promotion of heightened public awareness of the general values of natural terrestrial ecosystems is essential to gaining public support for sustaining these ecosystems in a changing climate. Particular emphasis should be placed on involving ecosystem managers and local people in the assessment of the impacts, consequences and response strategies.

One of the major issues regarding the impacts of climate change on terrestrial ecosystems is water availability with recent studies suggesting that while water use efficiency of vegetation could increase in an enriched CO_2 atmosphere, the same amount of water per unit soil area may be necessary because of increased leaf area ratios due to greater biomass produced in that enriched atmosphere.

Projected climate changes are expected to result in an accelerated reduction of tropical forest on the African continent and an encroachment of the Sahel syndrome into the savannas. These changes could worsen the already precarious production systems in the affected regions of Africa, further stressing the associated natural ecosystems and component species. Degradation of wetlands and shallow lakes (e.g., within savanna ecosystems in Africa and within the Great Plains of North America) as a result of projected decreases in rainfall or soil moisture could adversely impact on resident animals and migratory species.

With projected climate change, profound impacts, both beneficial and destructive, can be expected for the distribution and productivity of valuable fisheries and the industries associated with them. The added stresses to freshwater ecosystems as a result of climate change can be expected to reduce species numbers and genetic diversity within freshwater populations in the short term. With warming, a longer growing season could lead to greater fish productivity where temperature is currently limiting factor.

Uncertainties and gaps in the knowledge base continue to exist in terms of our understanding of the environmental impacts and associated socio-economic consequences of climate changes. National, regional and global efforts need to cooperatively focus on reducing these deficiencies which primarily exist as a result of the lack of sufficient information and data on: a) fundamental ecological processes; b) the links between climate and atmospheric chemistry on the one hand and the response of natural terrestrial ecosystems and their component species on the other; and c) the links between natural terrestrial ecosystem changes and social and economic welfare under a changing climate. In particular, there is a lack of information on the sensitivity of these ecosystems and their component species to climate change, the vulnerability of social and economic systems to ecosystem changes, and thresholds/critical levels for these ecosystems and associated social and economic systems. Existing international programmes such as GEMS and MAB can provide one means of examining these deficiencies.

WORLD OCEANS AND COASTAL ZONES: ECOLOGICAL EFFECTS

Since the IPCC First Impacts Assessment Report (1990), new studies reconfirm that rising sea level is of more concern in low-lying coastal ecosystems than rising water temperatures. However, the combination of sea level and temperature rise, along with changes in precipitation and UV-B radiation, are expected to have strong impacts on marine ecosystems, including redistributions and changes in biotic production.

The impact of sea level rise depends on the total net rise resulting from the relative vertical movements of the land and of the sea. In areas undergoing natural eustatic uplifting of the land due to tectonic plate movement, glacial rebound, and vulcanism, there will be little relative rise of sea level. In land areas that are naturally falling as in the southeastern USA, due to tectonic and compaction forces, impacts of sea level rise will be more important. A new study of the Bering Sea indicates that in areas without natural land uplift, there could be important impacts where there is a high density of marine organisms dependent on certain types of on-shore and near-shore marine environments that may be affected by sea level change. Nevertheless, sea level rise is of far less consequence in northern areas than are other impacts of climate change to northern ecosystems and to global carbon cycling. These regions are very important in the global carbon cycle and a small temperature rise may cause significant increases in bioproductivity and in carbon flux to the oceans.

Coral organisms grow 1-20 cm/year and reef growth rates as a whole are known to be up to 1.5 cm/year. Not all reefs accumulate at these rates, but most should keep pace with the expected rise in sea level if other factors do not alter growth conditions. Stress on the reefs from other variables (storms, sedimentation, disease, rainfall, radiation, turbidity, overfishing, mass mortality in algal grazers, etc.) may prevent some reefs from keeping pace with rising sea level, resulting in changes to nearshore hydrodynamics.

With respect to temperature rise, marine organisms in the tropics live closer to their maximum thermal tolerance than those in more temperate climates. Although a 1-2°C temperature rise would raise the summertime mean temperature to over 30°C over much of the tropical/subtropical region, most migratory organisms are expected to be able to tolerate such a change. Temperature rise may trigger bleaching events in some corals, but it is expected that the other stresses mentioned above will be more important.

Intertidal plants, such as mangroves, can withstand high temperature, and unless temperature rise affects reproduction, it is unlikely to have any effect. Because mangroves grow best in moderately saline environments, mangroves can probably keep pace with sea level rise in rainfed humid areas, but may be overstepped and abandoned in more arid areas, particularly if inland retreat is not possible. Thus, future changes in patterns of rain and runoff and of overcutting may be more important than sea level rise. With respect to marshes, new studies indicate that mid-latitude plants seem to tolerate salinity better and are more productive under elevated CO_2.

New findings of WMO/UNEP indicate that UV-B radiation reaching oceanic and coastal zone environments will increase faster than expected when the first Report was written. Since so many marine resources spend all or vulnerable parts of their lives near the water surface, there is a significant threat to some fisheries. The first Report expressed concern about leaching of contaminants during sea level rise, from coastal waste disposal sites. There are also bacteria and viral agents in such sites and in coastal septic sewerage systems which could be increasingly released into coastal waters. There are potential impacts on coastal resources, but the primary concern is for the humans who consume them and the loss of commerce due to the closure of fish and shellfish areas by health authorities. Lastly, potential changes in storm frequency or intensity could have important ecological consequences to coastal resources.

HYDROLOGY AND WATER RESOURCES

Since the publication of the IPCC First Impacts Assessment Report (1990), a number of studies on impacts of climate change on hydrology and water resources have been conducted. Unfortunately, there is not yet adequate information on regions affected by aridity and desertification, and an effort should be undertaken to fill that gap. The new studies expanded on the geographic scope of the original

surveys, but few new insights were offered on hydrologic sensitivities and vulnerability of existing water resources management systems, while confirming many previous conclusions.

The principal conclusions suggested by the new studies are:

- Significant progress has been made in hydrologic sensitivity analyses in developed countries, yet large gaps exist in the information base regarding the implications of climate change for less developed nations;

- Comparative sensitivity analyses that rely on existing GCMs offer generic insights regarding the physical hydrologic effects and water resources management impacts, but the differences in the outputs of the GCMs coupled with large differences in hydrologic sensitivity analyses makes it difficult to offer region-specific impact assessments.

- Temporal streamflow characteristics in virtually all regions exhibited greater variability and amplification of extremes, with larger flood volumes and peak flows as well as increased low flow episodes and a shift in the turning of the seasonal runoff;

- The higher the degree of water control, regulation and management of sectoral water demands, the smaller the anticipated adverse effects of global warming. Conversely, unregulated hydrologic systems are more vulnerable to potential hydrologic alterations;

The principal recommendations are:

- Increased variability of floods and droughts will require a re-examination of engineering design assumptions, operating rules, system optimization, and contingency planning for existing and planned water management systems;

- More studies on hydrologic sensitivity and water resource management vulnerability need to be focused in arid and semi-arid regions and small island states.

- A uniform approach to the climate change hydrologic sensitivity analyses needs to be developed for comparability of results.

CRYOSPHERE

Analyses continue to support the conclusion that projected changes in climate associated with enhanced atmospheric concentrations of greenhouse gases are expected to substantially reduce the areal extent and volume of seasonal snow cover, mountain glaciers, terrestrial ice sheets and frozen ground including permafrost and seasonally frozen ground.

Recent analyses have shed some further light on the potential impacts for these elements of the terrestrial cryosphere.

- Analysis of satellite-derived snow cover data has shown that the extent of northern hemispheric snow to be at record low levels since the middle of 1987 with the largest negative anomalies occurring in the Spring.

- Above normal temperatures throughout much of the Northern Hemisphere in 1989 led to the initiation of extensive active layer detachment slides within permafrost in some regions of the Canadian and Russian Arctic with damming and degradation of water quality in affected streams and further failures initiated.

- Emissions in Arctic regions of methane from hydrates as a result of permafrost degradation may have been underestimated.

- There is some evidence to suggest that glaciers in the Northern Hemisphere polar and subpolar regions are receding at a slower rate than previously suggested with some having advanced in the past 30 years. Although the Southern Hemisphere record is not as detailed, records for several New Zealand glaciers show that these have retreated since the mid-1800s with the suggestion that this has been the result of an increase in temperature and an accompanying decrease in precipitation.

Key uncertainties are associated with understanding fundamental cryological processes, the relationship among these elements (e.g., impacts of changes in snow cover on permafrost and glacier dynamics), the impacts of climate change on these elements of the cryosphere, the interdependency of associated ecosystems (e.g., soil erosion and stability changes associated with permafrost degradation) and human systems (e.g., structures, transportation, transmission lines), and the role of the cryosphere in local, regional and global climate and climate change.

REGIONAL CLIMATE CHANGE PREDICTION

The prediction of climate change at regional level precision is subject to great uncertainty. Precipitation changes are particularly uncertain, although these changes are of great practical significance. Progress in the development of GCM models is urgently needed, particularly in terms of improving their capability for regional predictions, especially to understand changes in the arid and semi-arid regions. Work on improving regional predictions using the paleo-analogue method continues in Russia and other countries. In the fur-

ther work of IPCC, all methods of regional climate prediction should be reviewed and assessed together.

GUIDELINES FOR ASSESSING IMPACTS OF CLIMATE CHANGE

Working Group II is preparing guidelines to assess the socio-economic and environmental impacts of potential climate change. These guidelines will outline a framework for the study of climate-environment-society interactions and the estimation of the impacts of climate change that will allow comparisons and integration of impacts across various geographical areas and economic sectors. Preliminary guidelines will be available, after peer review, in 1992. Further work will continue as a long-term task.

Impact assessments involve several steps: (i) definition of the problem; (ii) selection of analytical method(s); (iii) testing the method; (iv) development of climatic and socio-economic scenarios; (v) assessment of potential impacts; (vi) evaluation of technical adjustments; and (vii) consideration of policy options.

Definition of the problem includes identifying the specific goals of the assessment, the sector(s) and geographical area(s) of interest, the time horizon of the study, the data needs and the wider context of the work.

Selection of analytical method(s) depends upon the availability of resources, models and data. Impact assessment analyses could range from the qualitative and descriptive to the quantitative and prognostic. Thoroughly testing the method(s), including model validation and sensitivity studies, prior to undertaking the full assessment is necessary to ensure credibility.

Development of the climatic and socio-economic scenarios involves several steps. The current and projected climatic, socio-economic and environmental conditions expected to exist over the study period in the absence of climate change should be established. Scenarios of regional climate change over the study time frame must also be developed. Third, biophysical and environmental effects should be projected under the altered climate. Then these projections should be used, preferably in integrated environment-economic models, to calculate the socio-economic effects under the altered climate. Assessment of potential impacts for the sector(s) or area(s) of interest involves estimating the differences in environmental and socio-economic conditions projected to occur with and without climate change.

Projections of effects with and without climate change should incorporate "automatic" adjustments. However, the impact assessment should seek to evaluate the additional technical adjustments resulting from application of existing and new technologies or practices that may be available over the study period, assuming no changes in the current legal and institutional framework.

The costs and benefits of climate change should be assessed, to the extent possible, using a common measure and discounted to net present value. Alternatively, costs and benefits should be described qualitatively. The above general framework would also allow consideration of policy options and their socio-economic and environmental impacts.

MONITORING TO IDENTIFY CLIMATE CHANGE CONSEQUENCES

There is a need to increase the available information and data to support impact studies, particularly in developing countries. This need can be met through enhancing and, where appropriate, establishing integrated monitoring programmes including biological, chemical, physical and climatological parameters, as well as constructing concurrent social and economic assessments, at the national, regional and global levels to identify climate change consequences. Data quality needs to be assured and data analyses and their interpretation need to be carried out carefully. The use of common protocols for collection and analysis processes (including Geographical Information Systems or GIS) and for equipment will aid in assuring intercomparability and further encourage international cooperation. The development of the preliminary IPCC guidelines for assessing the impacts of climate change is an important contribution to this end.

Monitoring of sensitive terrestrial and marine ecosystems, including the cryosphere, and component species should be given priority as they could provide early detection/warning of climate change and its impacts. Also to be given priority are those species and ecosystems which have significant (locally/regionally defined) social and/or economic values. The classic ground station approach (including points, plots and transects) should provide the basic building blocks of monitoring programmes, however, these should also be supplemented with remotely sensed observations (e.g., satellite, radar, and photogrammetry). Advantage should be taken of automatic data transmission and processing systems.

At present, international organizations such as UNEP, WMO and IOC are implementing monitoring programmes to help identify ecological and socio-economic consequences of climate change. UNEP has an initial programme for observing terrestrial ecosystems with observations extending on either side of the present boundaries of plant zones for early detection of possible shifts of these boundaries. WMO and IOC, among their many monitoring activities, have designed a satellite observation system for climatic and ocean parameters. Current planning of the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS) should consider the value of including the monitoring of terrestrial and marine ecological impacts of climate change. These can provide an early indication of the integrated effect of climate change.

SECTION IV.

TASK 3: ENERGY AND INDUSTRY RELATED ISSUES

BY WORKING GROUP III

INTRODUCTION

In March 1991, the Panel identified key areas for further study by the Energy and Industry Subgroup. Their purposes were:

(a) to fill significant gaps in the analysis achieved to date on energy and industry sector responses to limit climate change: and

(b) to begin new areas of analysis and suggest areas of research which were too difficult to address in the first phase of the IPCC.

These studies, which have not yet been peer-reviewed, or progress reports thereon are presented below in a summary manner. Peer review will take place later this year. Nevertheless, in the interim, these studies may provide useful information for policy analysis and decision making. Although attempts have been made to reflect all available material, some studies were confined to a limited number of sources or data bases. Some studies had to rely upon works which were not conducted with consistent methodologies or data bases.

SUMMARY OF SUBTASKS

1) Comprehensive assessment of technological options for mitigating global warming

The objective of this study is to assess various technological options for reducing greenhouse gases, particularly CO_2, in a comprehensive way. Building upon the IPCC Response Strategies Report (1990) (see table 3.2), this paper reports some tentative findings in the survey of technologies as the first part of the work. The results of the second part of the work, building future scenarios on the use of these technologies, will be available with an updated first part in late 1992.

The tentative findings are:

(a) Energy conservation and improved efficiency in the production, conversion distribution and end use of energy is one of the most effective options available now and in the future. System restructuring, such as energy cascading and infrastructure improvement, has promising potential.

(b) The technologies to capture and sequester CO2 from fossil fuel combustion deserve investigation, considering the expected continuing dependence on fossil fuels as primary energy sources.

(c) Nuclear power has the technological potential to be one of the major energy sources in the next century, but faces various socio-economic, security and safety constraints.

(d) There are various existing and promising non-fossil fuel technologies such as photovoltaics (PV), wind, hydropower, geothermal, biomass and solar thermal systems. PV may be first applied in a small scale on roofs, and then in larger scale on deserts and ocean surface if energy distribution technology can be advanced substantially.

(e) The physical potential of biomass for energy use is apparently high but in some regions, competition in land use for food may limit its production. Environmentally sound intensification of agriculture for more efficient production of food may be considered. (see also para. on biomass below).

2) The IPCC Technology Characterization Inventory (TCI)

The IPCC Technology Characterization Inventory (TCI) provides an information source of consistent, well-documented technology data for analysis and planning activities to limit greenhouse gas emissions. Special emphasis is given to technologies having potential interest to developing countries and economies in transition. Information from many sources is used to describe technologies in five catgories: (1) Primary Energy Production (2) Secondary Energy Conservation and Processing (3) Energy Transfer (4) End-Use Technologies and (5) Greenhouse Gases Control Technologies.

Because information and data are not sufficiently detailed for design of specific technology installations, addresses for specialists around the world are provided. The data base includes information for energy sources and major regions of the world. Country-specific information can be included as it becomes available from specific applications and analyses.

Phase I consists of a preliminary design of the data base and descriptions of eighteen technologies. These eighteen technologies shown in Table 1 were submitted to the IPCC for review in February 1992. The Phase II effort began in December 1991. By June 1992, the TCI will include about 90 technologies. Future versions of the data base are expected, including both updated and added technologies.

Table 1: TCI Phase I Technologies

SUPPLY TECHNOLOGY

- Pulverized Coal Steam Generation
- Gas Turbine-Steam injected, inter-cooled (ISTIG)
- Atmospheric Fluidized Bed Combustion
- Diesel Cogeneration
- Solar Thermal Electric-Parabolic trough
- Mass Burning of Municipal Solid Waste
- Efficient Electrical Transformers

ENERGY END-USE TECHNOLOGY

- Electric Motors
- Lighting-Compact fluorescent lighting
- Lighting-Electronic Fluorescent Ballasts
- Alternative Fuelled Vehicles-methanol
- Alternative Fuelled Vehicles-CNG
- Advanced Road Traffic Signalization

MANUFACTURING TECHNOLOGY

- Motors-Industrial electric motors
- High Efficiency Welding Power Supply
- Chemicals-Efficient fertilizer production
- Pulp & Paper-Mechanical dewatering
- Petroleum Refining-Process (Distillation) control systems

3) Technological options for reducing methane emissions

Reducing global anthropogenic methane emissions by about 15-20 percent can halt rising atmospheric concentration of methane. A technological assessment of options for reducing methane emissions from anthropogenic sources (about 60 percent of global methane emissions) has been developed through the United States/Japan Working Group on Methane, which compiled information submitted by IPCC participating countries. Technological options are available for limiting emissions from the major sources, other than flooded rice cultivation and biomass burning. These options may be economically viable at suitable locations in many regions of the world, and represent different levels of technical and capital needs (summarized in Table 2). In many cases, these options provide a range of benefits, including better air quality, better protection of surface and groundwater, enhanced productivity, reduced risk of explosion, and improved availability and use of energy resources. Some of these technologies are already established and proven beneficial in certain markets. Barriers which hinder the further implementation of these options in many countries, especially developing countries include availability of capital, lack of technical information, and conflicting incentive systems. These barriers need to be addressed on a country and site-specific basis.

Table 2: Summary of Characteristics of Methane Emissions Reduction Options

			Availability					Benefits			
Source	Emissions (Tg)[1]	Methane Reductions from Individual Options	by 1995	by 2005	post 2005	Includes Profitable Options	Includes Low-Tech Options	Air/Water Quality	Safety	Productivity	Energy Recovery
EIS Sources											
Coal Mining		up to 90%	X	X		X	X	X	X	X	X
Oil & Gas	70-120	up to 80%	X	X		X	X	X	X	X	X
Combustion		NQ	X	X		X		X			
AFOS Sources											
Ruminants	65-100	up to 75%[2]	X	X	X	X	X			X	
Animal Wastes	20-35	up to 80%	X			X	X	X		X	X
Landfills	20-70	up to 90%	X			X	X	X	X		X
Wastewater		up to 80%	X			X	X	X			X
Biomass Burning[3]	20-80	NQ		X			X	X	X	X	
Rice Growing	20-150	up to 30%			X					X	

[1] Estimates prepared by IPCC Working Group I

[2] Methane reductions per unit product

[3] In situ burning and cook stove use

NQ = Not Quantified

4) Increasing electricity end-use efficiency

The study addresses the topic of increasing electricity end-use efficiency by providing an in-depth review of the following: (a) the status of available technologies for increasing electric end-use efficiency; (b) factors that limit the application and widespread deployment of these technologies; and (c) policies that have been implemented to increase the efficiency of electricity end-use.

The conclusions of the report are summarized as follows. A substantial fraction of increased anthropogenic carbon emission over the next several decades is likely to come from electricity generation. Increases in end-use efficiency improvements beyond those expected to occur under current technologies and policies could cut significantly the growth of electricity use and associated growth in projected carbon emissions. Based on experience among industrialized and developing countries concerning the technologies and programmes and policies, significant increases in electricity end-use efficiency are possible. It appears that many of these increases can be achieved in a cost-effective manner. Enhancing adoption of these efficient technologies by developing countries is an essential part of a successful strategy to curtail growth in emissions of greenhouse gases.

5) Natural gas prospects and policies

One option for reducing CO2 emissions is the substitution of natural gas for more carbon-intensive fuels. The demand for gas is growing worldwide and is expected to nearly double by the year 2005. As the starting point for its analysis, the IPCC has reviewed the International Energy Agency's (IEA) natural gas study. Natural Gas Prospects and Policies (October 1991). This study provides a comprehensive analysis of demand and supply for natural gas including the institutional framework surrounding the production, transmission and use of natural gas. The study's primary focus is on demand for natural gas in OECD countries, but sources from outside the OECD are extensively treated. The IEA forecasts that demand for natural gas outside OECD will be approximately twice that of OECD by 2005. The study indicates that ample gas resources exist worldwide even with the expected doubling of demand in some of the regions through the year 2005 at prices ranging from $3 to $6 per MBtu (in 1990 US$). However, the study did not address the ability to meet demand after 2005. Intergovernmental agreements to facilitate and maintain competitive markets, access to resources and transmission systems, and commercial contracts on a non-discriminatory international basis are likely to be required before private capital can be mobilized to back very large, long term gas development in remote parts of the world.

Further IPCC analysis should be devoted particularly to non-OECD countries, greatly increased global and regional demand, and supply and demand issues beyond 2005.

6) Thematic assessment of the road transport sector

Because of the importance of the road transport sector, to present and future emissions of greenhouse gases, the Panel decided to carry out a thematic analysis of the sector. The work will concentrate on such measures as fuel efficiency, alternative transport fuels, emission reduction devices and structural, institutional, and organizational changes. The work is just beginning so no conclusions are available at this time.

7) Biomass, bioenergy and limitation of greenhouse gas emissions

A review of the use of biomass as a source of energy concludes that bioenergy offers important opportunities to reduce greenhouse gases through displacement of fossil fuels. It is noted that CO_2 emissions from renewed or waste biomass do not add to the overall atmospheric burden of carbon on a life cycle basis. Some biomass combustion technologies are available that, additionally, reduce other greenhouse gases (e.g., CH_4 and N_2O).

Greenhouse gas emissions can be reduced both by sequestration of carbon and production of bioenergy. The following measures should be considered: use of waste biomass as a fuel and production of biomass by intensive but environmentally sound forestry and agriculture practices, consistent with conservation of carbon in forests and soils.

Combustion of biomass can already be competitive with fossil fuels for (1) production of heat or steam and (2) cogeneration of steam and electricity. Environmentally sound production of liquid biofuels should also be considered.

The first part of the report is available for review. The second part of the report dealing with technologies will be available late in 1992 for review.

8) World economic impacts of response measures by industrialized countries

Carbon dioxide and carbon taxes in the energy sector have been the focus of several available studies. The economic impacts of such measures to control greenhouse gas emissions would vary among industrialized countries, because of the difference existing among them in their resource endowments, the relative structure of energy prices, the ability for fuel substitution and the achieved levels of energy efficiency. The studies reviewed to date in this effort indicate that the costs of applying carbon tax measures could reduce GDP growth in industrialized countries. The costs could be reduced if flexible, phased, comprehensive and concerted response strategies were adopted to control greenhouse gases. Further systematic and comprehensive analysis of available studies is needed on this important and complex subject.

The impacts of these measures will not be limited to industrialized economies, but will also affect the economies of developing countries. One general economic study by the World Bank indicates that a change in OECD growth could affect the growth rate of developing countries rather significantly without off-setting programmes. Factors of this economic interdependency include energy prices, balance of trade, developing country revenue, external debt, investment and aid flows.

9) Analysis of factors affecting energy consumption and CO_2 emissions and their regional and sectoral differences

This assessment deals with factors affecting regional and sectoral differences in energy consumption and related CO_2 emissions. The supporting material contains: (a) analysis of factors affecting total and sectoral CO_2 emissions; (b) regional comparison of changing rates of factors; (c) long run changes in carbon intensity and technology improvements; and (d) non-commercial energy consumption in developing countries. The assessment indicates that such factors as economic development, population growth, energy conservation, changes in industrial structure, fuel switching, and technological advance influence the regional and sectoral patterns of historical energy consumption and CO_2 emissions. Other factors such as climatic conditions could be also considered. These factors function differently in different countries and regions.

Analysis of energy consumption and CO_2 emissions would be important to select and plan a suitable set of options for mitigating global warming. The analytical methods reviewed in the assessment underway can be useful tools. Some methods discussed can provide a common analytical framework for countries, even with present limitations on data availability. The analysis will also deepen common understanding of historical and current situations of individual countries.

Future subjects of this interim assessment include: (a) separation of industrial structure changes and energy efficiency improvements in the energy conservation factors; and (b) sectoral analysis of factors affecting energy consumption and CO_2 emissions in developing countries. The analyses discussed in this study could serve as starting points. Further detailed research would be useful on more factors affecting energy consumption, economic cycles and CO_2 emissions in each sector, on the basis of results obtained in the work now underway.

10) Country studies

A survey of country studies has been developed in cooperation with UNEP and through a review of other sources. The term "country studies" is defined to include any official national study on greenhouse gas emission inventories, impact assessments, and emission mitigation analyses. It includes energy and industry, agriculture, forests and other sectors. Numerous other studies have been undertaken by institutions in various countries which are not reflected in this survey, since they have not been endorsed as official national studies. As of February 1992, more than fifty countries have or plan to initiate some form of country study through internal, bilateral or multilateral support *. In addition, several countries have indicated a wish to participate in country studies, but lack the financial and/or technical resources to carry out such studies.

As yet, a comprehensive methodology for country studies has not been developed, although work is underway in several IPCC working groups and elsewhere to partially address this need. Current efforts include a project supported by UNEP to establish a consistent methodological framework for undertaking cost assessments of greenhouse gas abatement options. The project is being implemented by Riso National Laboratory in Denmark. In addition, draft guidelines have been prepared by Finland and the US. All these activities may assist countries in preparing future studies, but there is an urgent need to give a higher priority to these activities.

FUTURE WORK

Draft final reports from subtasks (2), (3), and (4) and draft preliminary reports from subtasks (1), (7), (8), (9), and (10) were distributed to IPCC participants in February 1992. After the review comments are incorporated, these reports will be produced as final or interim reports in June 1992. Subtask (5) was met by use of a complete IEA report. Subtask (6) is just beginning under Austrian leadership with a contribution from IEA.

As can be seen from the foregoing summaries, several ongoing projects require continuing work. Several of the studies need to be expanded to include other regions.

An element of Task 3 which has not yet been undertaken is the "identification of the full economic, environmental and other types of costs and benefits." It may be useful to initiate a review and assessment of alternative methodologies or concepts which could be of value in such analyses.

* *Argentina, Australia, Austria, Bangladesh, Belgium, Brazil, Canada China, Congo, Costa Rica, Czechoslovakia, Denmark, Finland, France, Gambia, Germany, India, Italy, Indonesia, Ireland, Japan, Kenya, Korea DPR, Korea, Rep , Malaysia, Mauritius, Mexico, Mongolia, Morocco, Myanmar, Netherlands, New Zealand, Nigeria, Norway, Pakistan, Philippines, Poland, Romania, Senegal, Seychelles, Sri Lanka, Sweden, Switzerland, Tanzania, Thailand, Turkey, Tuvalu Uganda, United Kingdom, United States, Venezuela, Vietnam, Zimbabwe*

SECTION V.

TASK 4: AGRICULTURE AND FORESTRY RELATED ISSUES BY WORKING GROUP III.

INTRODUCTION

During the session of WG III on 1 November 1991 and in accordance with decisions of the Fifth Session of IPCC (Geneva, March, 1991), the Subgroup (AFOS) was charged to contribute to the ongoing update of the IPCC Response Strategies Report (1990) by:

(a) an assessment of the greenhouse gas (GHG) emissions, taking into consideration sources and sinks in agriculture, forestry and other related human activities, and

(b) an assessment of technologies and management systems in these areas for mitigation and adaptation to climate change.

AGRICULTURE

Present and future agricultural GHG emissions

Recent improvements in scientific understanding support the previous findings of the 1990 report, in particular the following.

As far as the net carbon dioxide release from agricultural activities is concerned, forest clearing in the tropical and subtropical areas of the world continue to be the major source. Additionally, the cultivation of virgin land, whether in tropical or temperate agricultural areas, results in gradual carbon losses. Its relative contribution, however, to CO_2 concentrations is still to be determined. At the other extreme, long-standing arable soils do not constitute a major net source of CO_2, because their carbon contents reach equilibria which do not change very much unless cropping and management practices are altered.

Projections of the future GHG emissions related to land use depend on the initial use, the rate of land conversion, and productivity including cultivation density. If production did not increase, expected population growth and rising food demand would require the area of tropical agriculture to expand by over 60% by the year 2025. It is unlikely this additional land would be available. If all the additional land were to come from forest or grassland, it would cause a gradual breakdown of soil organic matter, releasing CO_2.

There may be another effect in that global warming will speed up the decomposition of soil organic matter, thereby releasing additional CO_2 to the atmosphere. Model calculations, assuming no increase in organic residue returns, predict this soil carbon loss to be up to 60 Gtons within about 60 years. This corresponds to a current global CO_2 release from fossil fuel of about 10 years. On the other hand, there are indications that this could be offset by an enhanced plant residue formation both above and below ground, due to the CO_2 fertilization effect.

As for the release of methane, total global and individual source emission estimates remain essentially as presented in the IPCC First Assessment Report (1990), but with some individual source changes. There has been a reevaluation of some sources, particularly rice, and the additional sources such as animal and domestic wastes. A large portion of these emissions comes from liquid waste handling systems. Uncertainties in global and regional emissions remain significant. A detailed analysis of new information on rice suggests annual emissions in the lower end of the 20-150 Tg/year range.

In the absence of mitigation measures, methane emissions are likely to continue to increase from each source as increases in animal products and rice are required in order to feed the world population. Current emissions for animals, rice, and animal wastes could grow by about 40-60%, 50-60% and 30-40% respectively by 2025.

Unfortunately, the data concerning the release of nitrous oxide from agriculture still cannot be reliably derived. Keeping in mind that the annual increase of N_2O in the atmosphere is 3 - 4.5 Tg of nitrogen as N_2O, and knowing that the release from combustion processes has thus far been overestimated, most of this net increase may be due to anthropogenic nitrogen inputs. About 80 Tg of industrially-fixed nitrogen is presently applied to world agriculture. Taking the upper value of estimates for the conversion of fertilizer nitrogen into N_2O, which is 3.2 %, the fertilizer-induced release for 1990 could be calculated as 2.5 Tg of nitrogen as N_2O. Since another 90 Tg of nitrogen or so are fixed by managed leguminous plants, this combination could account for most of the increase of N_2O in the atmosphere.

Large nitrogen surpluses are frequent, especially in intensive agricultural systems. This excess nitrogen is prone to both nitrate leaching and denitrification, although the ratio of N_2 to N_2O formation varies considerably from case to case. However, it should also be borne in mind that not only the unused but virtually the whole nitrogen introduced by mankind into the world ecosystem will sooner or later become denitrified, thus adding to the overall N_2O increase in the atmosphere. The significant unknown is the time scale over which this will occur.

Background assumptions about future food and land demand being the same as above, nitrogen fertilizer consumption may increase by the year 2025 from 80 to more

than 120 Tg of nitrogen per year. Without changes in technology, the fertilizer-derived release of nitrous oxide is likely to increase by some 50%.

Agricultural potentials for mitigation and adaptation

In order to reduce the net carbon dioxide release from agriculture, improving the productivity of existing arable land should be given priority over the cultivation of virgin soils. Furthermore, in the less populated areas of the world, marginal farmland could be set aside for either rangeland or forest use.

Reduced soil tillage, improved utilization of organic wastes as amendments of carbon into the soil and crop rotations including forages are agricultural practices which reduce carbon losses and/or sequester additional carbon in soils. Although these practices may sequester several gigatonnes (Gt) of carbon over a few decades, this represents only a fraction of the release of carbon from fossil fuels over the same period. This is because soils have a finite capacity for accumulating organic matter. Nevertheless, these management practices are essential if soil fertility is to be maintained or enhanced.

As for the control of methane, while investigations are continuing on emission reducing options, the principal approaches remain as reported in 1990 report. Opportunities exist to reduce methane from enteric fermentation and animal waste storage, for example, by modifying feeding practices, using productivity enhancing practices and agents, and modifying waste management practices. Emissions reductions of 25 to 75% per unit product in some animal management systems appear feasible. Due to the diversity of animal management systems, including economic and socio-cultural factors, the importance of categorizing management systems and matching emission-reducing options to the systems is now being emphasized. Additionally, the implications of reduction options for the emissions from animal waste of other greenhouse gases, including nitrous oxide, are now being addressed.

Methane emissions from rice cultivation may potentially be reduced while maintaining or enhancing productivity. Mitigative practices may include modifying water depth and timing of irrigation, the type, rate, and application method of fertilizer, alternative cultivation technologies, and cultivar selection. Much research is still required in order to realize these opportunities, and therefore a short-term reduction of methane emissions from rice growing cannot be expected. However, over a number of decades, while doubling rice production, an integrated management approach may succeed in reducing methane releases by 20 - 40%.

Better balanced nitrogen budgets, especially in intensive agriculture, are a key measure for reducing overall nitrous oxide emissions. This should also include a better accounting for the nitrogen from livestock wastes within fertilizer application regimes. Other options include nitrification inhibitors or improved fertilizer formulations and application. However, the most promising way to reduce N_2O losses is an integrated nitrogen-management system which maximises nitrogen recycling while minimising fertilizer inputs. This is all the more important since N_2O, due to its long lifetime, will accumulate in the atmosphere, constituting an increasing threat to the ozone layer.

In addition to these mitigation strategies, future efforts of AFOS should assess the ability of agricultural systems to adapt to climate change.

FORESTRY

Forests provide mankind with a wide range of economic, social and environmental benefits, but they are increasingly being threatened by unsustainable forest management practices, air pollution, and climate change. Concerted action needs to be taken at national and international levels to protect the world's forests. Action will be successful only if it takes into account the interdependence of the economic, social and cultural factors that bear on the management of forests.

Status of forests

It is difficult to determine the present extent of tropical forest cover. Recent estimates on a country basis indicate that there are approximately 1.9 billion hectares of tropical forests.

One concern has been given particular attention since the 1990 report is the rate of deforestation globally and in individual countries. The FAO estimated rates of global deforestation for the 1980's in closed forests (about 14 million hectares/year) and in closed and open forests (about 17 million hectares/year) are much higher than for the late 1970's), by 90% and 50%, respectively. Calculations by other authoritative sources show significantly lower figures in the order of about 10 million hectares.

Approximately 770 million hectares of forests belong to the temperate zones with an estimated carbon storage of 25 Gt in biomass excluding soils. Forest area in boreal zones amounts to about 920 million hectares, storing 150-190 Gt of carbon in biomass including soils. In addition a considerable amount of carbon is stored in forest soils and peatlands, especially in boreal zones.

Forestry options

The following four options were identified:

Slowing currently ongoing deforestation and forest degradation

For an accurate assessment of cost effectiveness, it would be necessary to quantify the reduction of the amount of carbon released to the atmosphere. So far, only preliminary

estimates can be given. Nevertheless, it seems evident that first priority should be given to this option, thus maintaining already existing biomass in natural as well as in managed forests. In tropical regions, it is necessary to involve local people in sustainable silvicultural practices. In temperate and boreal zones, this refers especially to the new type of forest decline attributed to man-made air pollution, logging, and to the potential effects of climate change itself. Slowing deforestation and forest degradation bears a significant potential to keep carbon stored in biomass, retards desertification and is the requirement for further action.

Increasing forest biomass

There is generally a significant potential for increasing biomass in forests, especially in young, understocked, overlogged and/or misused forests. However, the costs and time-frame are uncertain.

Improved use of wood

The use of wood for long-lived products provides benefits in terms of carbon storage as well as sustainable forest management. Industrialised countries have possibilities for improved use of wood, such as the recycling of paper and paperboard, and the replacement of more fossil energy intensive raw-materials by wood. The use of wood as a source of energy offers important opportunities for reducing GHG emissions by substituting fossil fuels (as described in the EIS report).

Afforestation

The potential for afforestation in boreal, temperate and tropical biomes is uncertain. However, the current estimates for afforestation are 50-150 million hectares in boreal, 50-125 million hectares in temperate and 400-750 million hectares in tropical zones (200-300 million hectares in dry tropical areas). For tropical zones, the land potentially available will be less than the amount physically capable of afforestation because the ultimate decisions on land use are based on many other factors. For the boreal zones, the potential to increase the forest area is limited because not all non-forested land is environmentally capable of supporting forest ecosystems.

At present, plantations account for most of the afforestation in temperate zones. Preliminary assessments of gross costs of afforestation have recently become available and range from US$ 30 - US$ 60 per ton of carbon in boreal and temperate zones and US$ 10 - US$ 30 per ton of carbon in the tropical zone. However, it is uncertain how much carbon could be sequestered at such costs.

Noordwijk request

The Noordwijk Conference on 'Atmospheric Pollution and Climate Change' in November 1989 established the target of a net global increase in forest area of 12 million hectare a year by the beginning of the next century. The Bangkok Workshop (1991) concluded that the prospect of attaining the target was very limited, and that the net rate of forest loss would be slowed or reversed over a longer period of time. However, the option of afforestation would still be important and better data need to be developed to assess the potential.

OTHER HUMAN ACTIVITIES

Present and future emissions

Efforts to better understand the emissions of methane from domestic wastes managed in landfills have produced results which are consistent with the previously estimated 20-70 Tg/year from this source and better describe the regional differences in waste generated per capita and quantities of waste landfilled. Currently, about 60% of these emissions are from the OECD countries. No additional information is available to describe the 20-25 Tg/year of estimated methane emissions from wastewater lagoons primarily in developing countries.

Forecasting efforts continue to estimate 50-90 Tg/year from landfills globally by 2025. Developing countries will represent an increasing share of these emissions, over 50% by 2025. This is due to the expected increases in urban populations over the next 30 years and the increasing prevalence in these countries of landfilling, which generates more methane than waste piles. No additional work appears to have been performed for wastewater lagoons.

Potentials for mitigation

Recent work better characterizes the technological options for reducing methane emissions identified in the 1990 report. This work continues to show a range of options are available that can reduce methane emissions at modern landfill sites by 60 to 90% and up to 80% from wastewater lagoons. These options require varying degrees of initial capital and are of varying levels of technical complexity. They generally provide other benefits such as increased safety, better air quality, better waste management and fuel recovery, and therefore can have positive economic returns. Continued efforts need to address barriers which limit the further implementation of these options such as availability of capital and technical information.

Competing land use

Currently, most developed countries have virtually static populations and have achieved high productivity growth rates. In developing countries, the situation is the reverse, with low productivity, high population growth, unfavourable climatic conditions, lack of appropriate technology and inadequate infrastructure. Consequently, food security in these countries remains uncertain and economic growth may continue to be slow or even stagnant. It is clear that the historic growth pattern for land use cannot be sustained

over the next century. For example, between 1882 and 1991, arable land use expanded by 74%. Similar rates of expansion in the future would exceed the area of land potentially suitable for ecologically sound and sustainable agriculture. It is also clear that the pressure for additional land use for agriculture is largely an issue for the developing countries, with competing demands for agriculture and forestry.

CONCLUDING REMARKS

This updated report supports and confirms that some individual options in the different sectors of agriculture and forestry to mitigate GHG emissions or even to sequester existing CO_2 are relatively small on a global basis, but together they may contribute significantly to national or global abatement strategies.

SECTION VI.

TASK 5: VULNERABILITY TO SEA LEVEL RISE BY WORKING GROUP III

INTRODUCTION

In 1991, the Coastal Zone Management Subgroup (CZMS) of Working Group III, began to implement the recommendations in its report entitled: STRATEGIES FOR ADAPTATION TO SEA LEVEL RISE (CZMS REPORT, 1990). Among the recommendations was the need to provide to coastal countries, including small island nations, in the context of their socio-economic development, technical assistance to:

(i) identify coastal areas at risk;

(ii) assess their vulnerability to potential impacts of an accelerated sea level rise (ASLR) as described in the IPCC First Assessment Report 1990); and,

(iii) idevelop and, where possible, implement comprehensive coastal zone management plans to reduce vulnerability to ASLR before the year 2000, especially for countries with vulnerable coastal areas.

The benefits of these steps should be seen in the context of accelerating socio-economic development worldwide in coastal areas and the related increasing environmental stress on coastal resources. In this regard, integrated coastal planning would facilitate sustainable development of coastal areas and conservation of natural ecosystems.

Capacity building and institutional strengthening to develop and implement coastal zone management is identified as a priority for low-lying coastal areas. Related to this, the present international framework for cooperation should be strengthened.

In order to better assess and respond to the needs of coastal countries, the CZMS has:

(1) developed a common methodology to be used in country studies to assess vulnerability and consider possible response strategies;

(2) assisted in coordinating a number of case studies which incorporate the assessment steps identified in the common methodology; and have initiated work on global vulnerability assessment in close cooperation with IPCC Working Groups I and II;

(3) identified the need for strengthening the capabilities of vulnerable developing countries in implementing adaptive CZM programmes, aiming at sustainable and ecologically sound development, and identified the need for structural facilities for bilateral and multilateral financing of:

- sharing information, data and methodologies; and
- assisting in implementation of CZM programmes; and
- strengthening institutional capabilities.

While all of the assessment work has not been completed, what has been learned to date is in line with the conclusions and findings of the CZMS as presented in the IPCC First Assessment Report (FAR).

IPCC TASK 5 OBJECTIVES

Following the conclusions of the FAR, the CZMS was tasked at the March 1991 IPCC Plenary to address the following:

- commence an assessment of the vulnerability of developing and developed countries to ASLR;
- develop a common methodology for assessing vulnerability through country case studies;
- undertake developing country case studies on a bilateral basis and in cooperation with the UNEP Regional Seas Programme;
- support the development of CZM plans that incorporate response measures to reduce vulnerability to ASLR and address pressing coastal management concerns, where appropriate, by the year 2000;

- develop links with the coastal zone impacts studies being undertaken by WGII while undertaking the country case study assessments;
- convene workshops to assess the results of the case studies undertaken;
- identify the appropriate response strategies and mechanisms for implementing them;
- estimate the level and kind of assistance needed from international organizations and donor nations for further assessments and implementation of coastal management plans; and,
- consider recommendations for proposed future work.

Completion of the task is a long-term objective. In the short-term, the task requires the development of a methodology to assess vulnerability to ASLR, the application of the methodology to assessment work underway, and the consideration of the needs of coastal developing countries for assistance.

ASSESSMENT WORK COMPLETED

IPCC First Assessment Report. The CZMS contributed to the IPCC FAR by producing a CZMS Report on the STRATEGIES FOR ADAPTATION TO SEA LEVEL RISE. As a result of the significant participation from developing countries at two major international workshops held in Miami (November 1989) and Perth (February 1990), the CZMS report identified the response strategies for coastal areas: to retreat, to accommodate, or to protect from the potential adverse impacts associated with ASLR (including the conservation and protection of natural coastal defense, e.g., tidal flats, mangroves, sea grass beds and coral reefs). Each response strategy has implications for trade-offs and can be implemented within a framework of integrated coastal zone management planning.

The CZMS Report. The CZMS made 10 recommendations divided among three major categories: National Coastal Planning; International Cooperation; and Research, Data and Information. A suggested ten-year timeline for the implementation of comprehensive CZM planning was included, along with an estimated cost for providing five years of technical assistance to support this effort. Lastly, the Report provided a "World-wide Cost Estimate of Basic Coastal Protection Measures."

Common Methodology. The CZMS developed "The Seven Steps to the Assessment of the Vulnerability of Coastal Areas to Sea Level Rise - A Common Methodology" in early 1991. After a detailed process of review, comments and revisions made by IPCC participants, the CZMS feels that the Common Methodology provides a useful methodological framework for coastal countries to assess their vulnerability to ASLR and consider response strategies. The use of this common methodology could for many countries, be a first step in the establishment of a systematic approach in the management of coastal areas. Such CZM planning would facilitate the decision making process for socio-economic development and the mitigation of vulnerability of coastal areas and resources. As more countries conduct vulnerability analysis assessments, the Common Methodology would provide a framework for global assessments based on a global database. In addition, this information could facilitate priority setting by institutional bodies. The Common Methodology has been translated into French, Spanish and Arabic.

Case studies. In many instances, the CZMS has been successful in serving as a coordination body bringing together countries to conduct case studies assessing vulnerability. For example, Australia, France, Japan, The Netherlands, the United Kingdom and the United States are sponsoring, on a bilateral basis, more than two dozen case studies in developing countries, as well as conducting studies within their own borders. The UNEP is also conducting a number of case studies. Coordination between the two efforts has provided mutual benefits. The results of the case studies will be presented at a CZMS workshop hosted by Venezuela in March 1992, after which a report will be produced. A full list of countries participating in the vulnerability programmes and list of countries still desiring assistance is presented in the supporting IPCC CZMS report.

The interest expressed by developing countries for conducting vulnerability analysis and identifying response strategies has been tremendous, with a number of countries asking for country study assistance. A number of developing countries have also conducted their own country studies, which indicates the seriousness of the matter to them. However, because much of the work is being done on an ad hoc basis, the CZMS is not able to satisfy the demand. To better respond to the many requests that arise from vulnerable developing coastal countries, both the institutional and the financial aspects need further attention.

Status of country activities. The CZMS prepared a one-page questionnaire regarding the current status of country activities concerning ASLR and CZM planning. This questionnaire was answered by 37 countries. The preliminary results indicate that nearly 90 percent of those who responded expect that all or portions of their coastlines will be vulnerable to sea level rise, that only 30 percent have conducted an impact study of sea level rise on their coastal zone resources with even fewer (20 percent) studying response options, and that only 20 percent have some form of coastal zone management which includes policies that incorporate sea level rise. On the positive side is the fact that more than 50 percent of those responding have some form of coastal management policy "in-place". On the potential demand side, more than 80 percent expressed a willingness to cooperate with assisting countries in conducting vulnerability assessment studies.

COMMON METHODOLOGY

The Common Methodology is a guideline for assessing vulnerability to ASLR. In assessing vulnerability, three levels of boundary conditions and scenarios are incorporated in the methodology: (1) the impacts on socio-economic developments; (2) the impacts on the natural coastal systems; and (3) the implications of possible response strategies for adaptation.

The Common Methodology now includes consideration of the present situation and a rise of 0.3 meters and 1.0 meters by the year 2100. These scenarios represent the low and the high estimates of the 1990 IPCC FAR. Appropriate modifications are made for subsidence, uplift and storm surges and any other circumstances peculiar to a study area. At the present stage, the focus of the Common Methodology is on the effects of ASLR (and existing storm patterns). In the future, more attention will have to be given to the vulnerability of coastal areas with regard to other aspects of climate change, such as changing storm intensities, storm patterns, and soil moisture.

The objectives of the present Common Methodology are:

(a) to provide a basis for coastal countries to assess the vulnerability of their coastal areas to ASLR;

(b) to provide a basis for a world-wide comparative assessment of vulnerability of coastal areas;

(c) to provide a mechanism for identifying priority needs of developing coastal countries; and

(d) to provide a basis for decisions on responsive measure.

The process, therefore, helps each country to identify the actions needed to plan for and cope with the impacts associated with potential ASLR. These steps will help each country: to define its vulnerability; to examine the feasibility of response options, including their institutional, economical, technical and social implications; and to identify needs for assistance in order to apply the response options.

CASE STUDIES AND WORKSHOPS

The evaluation of vulnerability to ASLR is being undertaken in a number of countries. As of 1 January 1992, studies were either completed, in progress or in planning in 27 countries by members of the CZMS with an additional 14 cases being sponsored through the UNEP Regional Seas Programme. These case studies represent different types of coasts and a wide range of techniques and methodologies. Some studies are a portion of a larger country study on climate change impacts, while others are focused on ASLR. Some have evaluated response options, including the need for CZMS planning to reduce vulnerability to ASLR.

As each coastal country undertakes vulnerability assessment studies, that information will assist in providing a better global picture of the potential problems of ASLR on coastal resources and level of effort that may be required in response. The CZMS is now working on a world-wide estimate of socio-economic and ecological implications of sea level rise (e.g., the number of people at risk and an estimate of ecological impacts). This analysis will be based on information made available through case studies, questionnaires, and additional fact finding.

The Common Methodology is being used and tested in more than a dozen case studies. From these efforts, advantages and disadvantages are being revealed which are proving very valuable to the development of the methodology. The Common Methodology will be updated based on the case studies discussed at the Venezuela workshop in March 1992 and as appropriate in the future.

The consensus is that the Common Methodology provides a broad basis for coastal countries to assess their vulnerability to ASLR and to identify, evaluate and select response

The Common Methodology utilizes a seven-step approach as shown in Table A:

Table A
Common Methodological Steps to Determine and Reduce Vulnerability from Future Sea Level Rise

1. Delineate case study area and specify ASLR and Climate Change conditionds.
2. Inventory study area characteristics.
3. Identify relevant development factors.
4. Assess physical changes and natural system responses.
5. Formulate response strategies identifying potential costs and benefits.
6. Assess the vulnerability profile and interpret results.
7. Identify future needs and develop plan of action.

options to reduce their vulnerability to ASLR. This broad basis allows for flexibility such that local and national conditions can be fully taken into account. The studies indicate that coastal planning can reduce vulnerability to ASLR. Vulnerability to ASLR is the cumulative effect of natural processes, coastal development and climate change. CZM can reduce the effects of development on natural processes and the effects of natural processes on development. As a result, coastal planning can reduce vulnerability to ASLR while promoting sustainable development.

International workshops. International workshops have played a significant role in the gathering of information from a wide variety of sources. Two international workshops will be convened to discuss the results of the case studies. At the Venezuela workshop, representatives of 25 countries will present reports on their case studies. Much will be learned, including information on the potential costs and benefits of various response options or strategies, and on each country's capability to respond to ASLR within the framework of comprehensive CZM planning. Another workshop will be held in New Caledonia in April 1992 that will focus on climate change, sea level rise and coastal zone management in the South Pacific.

INTERNATIONAL COOPERATION

The CZMS was asked to estimate the level and kind of assistance needed from international organizations and donor nations for further assessments and implementation of national management plans. So far, there is only a rough estimate of resources required to meet the target: "by the year 2000 all relevant coastal countries should have comprehensive coastal management programs to reduce their vulnerability to ASLR and other impacts of climate change". Considerable resources would be required and many countries would need financial support.

To support an efficient and effective development of such plans, international cooperation is important, especially to ensure:

- the continuation of vulnerability assessments;
- the development of guidelines for CZM planning programs; and
- an efficient coordination through bilateral and multilateral cooperation.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions. Since its creation in 1989, the CZMS has:

- held international workshops that were widely attended by developing and developed nations and initiated global assessments of vulnerability to ASLR;
- developed a common methodology for conducting assessments of the vulnerability of coastal areas to ASLR; and
- served as a coordinator of 30 case studies conducted on a bilateral basis between CZMS member countries.

Throughout this period, it has become increasingly clear of the need for coastal countries:

- to assess the multiple components of their vulnerabilities to future sea level rise and related extreme events in relation to development and the protection of coastal ecosystems;
- to understand its implications to their natural, social, legal and economic systems; and
- to begin to plan appropriate response strategies in areas of awareness and institution building.

Part of this response would be to develop integrated coastal management planning capable of addressing, in a comprehensive way, the impacts of ASLR, along with the other pressing problems impacting coastal resources. This integrated planning in coastal areas must focus on sustainable development. Strengthening the institutional and legal capability of vulnerable developing countries is a base line condition and can be stimulated by information exchange and technology cooperation within the framework of a network as established by the IPCC CZMS in association with UNEP.

The CZMS has identified a growing awareness in coastal countries of the potential impacts on the coastal resources due to ASLR and other impacts of climate change. This awareness has manifested itself in their interest in integrated management planning. This interest must be encouraged and assisted. Most coastal developing countries have not developed CZM planning capabilities, or made assessments of their vulnerability to ASLR. Even though, in many cases, long lead times are required to begin the process of adaptation to sea level rise, very few have begun any planning or taken any measures as might be necessary.

The CZMS still has much to accomplish. Preliminary findings indicate there is a need to:

- Complete current and requested country case studies and conduct additional studies in the framework of CZMS, in cooperation with the UNEP, WMO, IOC and other international organizations.
- Promote further research on the effects of climate change on coastal areas, in particular with regard to extreme events.

- Include, as regional climate models improve, their results (e.g., the potential changing intensity and patterns of cyclones, hurricanes and typhoons), in the assessment of vulnerability of coastal areas to ASLR and other impacts of global climate change.

Recommendations. The following recommendations are made based on the progress to date:

- Coastal countries, that have not already done so, should:

  (1) assess their vulnerability to ASLR and other potential impacts of global climate change and assess the assets at risk;

  (2) start the planning process for appropriate response strategies; and

  (3) adevelop, by the year 2000, comprehensive coastal management programmes to reduce their vulnerability to ASLR and other impacts of global climate change.

- Countries should continue to support relevant intergovernmental and international organizations and programmes and their members should continue to:

  (1) support research and observations on ASLR and related severe storms, (e.g., under the Global Ocean Observing System and the Global Climate Observing System) and on other coastal impacts of global climate change (e.g., coastal inundation and habitat destruction resulting from changes in the frequency and intensity of severe storms);

  (2) assist developing countries in building their own national capacity to participate in international activities on research and observations in these areas;

  (3) support research on cost-effective response measures to assist coastal nations to adapt to the adverse impacts of global climate change;

  (4) promote public education and initiatives which increase awareness of the implications of ASLR and other potential impacts of global climate change on coastal resources and of the feasibility of response options to mitigate or adapt to those impacts;

  (5) strengthen national, regional and international programmes and institutions, with a view to coordinating the assessment of the vulnerability of coastal areas to ASLR and the needs, in this regard, of developing countries for assistance; and

  (6) recognize the effectiveness of a world-wide cooperation between coastal nations and international organizations as has been developed under the IPCC framework, and to give further support to the CZMS and its network as a catalyst for strengthening world-wide cooperation by data and information exchange, technology cooperation, integrated coastal zone management, training programmes and communications.

FUTURE ACTIVITIES

The following CZMS future activities are proposed:

- The CZMS envisages producing additional global vulnerability assessment reports working jointly with Working Group I and Working Group II, and in cooperation with other relevant United Nations organizations. Because of the close links between impacts and response strategies, the CZMS has coordinated with WGII, which has a major focus on the concern impacts of climate change, including ASLR, on coral and mangrove ecosystems and on commercial and subsistence fisheries. The focus of CZMS is to identify response options to manage these resources to reduce their vulnerability to ASL;

- The development of CZM guidelines,as being discussed in the United Nations Conference on Environment and Development process, in cooperation with UNEP by the year 1994;

- IPCC Second Assessment Report (1994 or 1995) In cooperation with WGI and WGII, complete a global assessment of the vulnerability of coastal areas to ASLR, as a first step to CZM planing and programs, using the Common Methodology; and

- Support Coastal Zone Management Planning, in cooperation with the UNEP and other organizations, and provide technical cooperation, as requested, to assist coastal countries to develop integrated coastal management plans by the year 2000.

In order to execute the above-mentioned activities, it would be necessary to seek funding for the work of IPCC CZMS as mentioned in the recommendations. Further analysis should be made to assess the availability of funds from UNEP, other international organizations and donor countries and the pace and scope of work which could thereby be supported. International cooperation is essential for the success of these activities.

SECTION VII.

RESUME OF THE POLICYMAKER SUMMARY (1990) OF THE IPCC SPECIAL COMMITTEE ON THE PARTICIPATION OF DEVELOPING COUNTRIES

INTRODUCTION

The IPCC, in its sixth session (Geneva, 29-31 October 1991), decided that a resume of the recommendations of its Special Committee on the Participation of Developing Countries would be included in the 1992 IPCC Supplement. Further, it "agreed with the Chairman's proposal that the IPCC Secretariat be tasked to draft the resume from the Policymaker Summary of the Special Committee (see the IPCC First Assessment Report, 1990) for review by all countries". This contribution is the result of that decision.

Resume of the Executive Summary of the Special Committee

Full participation includes the development of national competence to address all issues of concern such as the appreciation of the scientific basis of climate change, the potential impacts on society of such change and evaluations of practical response strategies for national/regional applications.

Actions to promote the full participation of the developing countries in climate change issues should not await the outcome of negotiations on the Framework Convention on Climate Change. They need to be taken now, through existing arrangements and should be planned and carried out for several years.

The factors identified by the Special Committee as inhibiting the full participation of the developing countries in the IPCC process, inter alia, are:

- insufficient information;
- insufficient communication;
- limited human resources;
- institutional difficulties;
- limited financial resources.

(i) Insufficient information: Many developing countries do not have sufficient information on the issue of potential climate change to appreciate the concern it evokes elsewhere in the world. Information is often insufficient with respect to the scientific basis for concern, on the potential physical and socio-economic impacts of climate change as well as on response options. This applies not only to scientific milieux but also to policymakers and public opinion.

(ii) Insufficient communication: Even if the situation with respect to information were to improve, there is the problem of insufficient internal and external communication mechanisms for the proper dissemination of the information on matters related to climate change.

(iii) Limited human resources: Lack of adequate number of trained personnel in almost all areas ranging from academic, scientific efforts to applications of knowledge to food and energy production, to water management, to human settlements problems, to trade and economic growth, and to a host of other related endeavours is common to many developing nations. Most of them, if not all, can command only limited pool of experts and responsible and knowledgeable officials, and even that only in a few of these areas.

(vi) Institutional difficulties: The multi-disciplinary and cross-cutting nature of the issues involved demands relatively high degree of co-ordination among the various departments/ ministries of governments.

(v) Limited financial resources: Survival needs come first. After that, the limited financial, and consequent general lack of technological, resources dictate the priorities. Means of meeting the incremental costs of ensuring a viable environment frequently cannot be found. Also, local immediate, environmental concerns generally receive political priority over impersonal, global concerns.

The legitimate concerns on the part of the developing countries that, although their impact on global climate change is minimal, its impact on them can be grave, need to be taken into account.

RECOMMENDED ACTIONS

Uninterrupted travel assistance to the developing countries for attendance at the meetings of IPCC and follow-up activities should be ensured. The Special Committee called the attention of the Panel to the importance of continuing this effort and of the donor nations continuing and increasing their financial support to the effort.

Serious consideration should be given to supporting more than one expert from each participating developing country to those climate-change-related meetings that deal with several aspects of the problem.

Governments and organizations from the industrialized nations are encouraged to continue and increase their efforts

in organizing seminars. Developing countries could organize, under the sponsorship of international organizations or otherwise, regional seminars and workshops in order to exchange scientific and technical information. For this purpose, necessary programmes and lists of experts should be developed. As part of the continuing process of information exchange, the Special Committee recommended that IPCC circulate the Policymaker Summary (of the Special Committee) to all concerned. The developing countries on their part could where appropriate designate focal points, as soon as possible, for transmittal of reports, documentation, data and information on seminars. Such focal points should be briefed on forwarding the material to appropriate recipients within the nation for response, review etc.

The establishment of mechanisms for national co-ordination of all (national) activities related to climate change could be considered by the developing countries. The mechanisms could aid such areas as information dissemination, development and implementation of plans for research and monitoring, and formulation of policy options. The industrialized countries could consider assisting the developing countries in setting up the mechanisms.

The Special Committee recommended that acquisition, analyses and interpretation of information on climatic and related data would enable developing countries to take more effective account of climate change considerations in formulating national policies. Such actions are necessary also at regional levels to undertake and refine impact studies. The current unevenness in the acquisition and use of such data which is evident between the hemispheres should be eliminated. The Special Committee further recommended that the developing countries take immediate action to identify their specific financial needs in this regard. It would also be necessary to mobilize appropriate funding in order to mount a sustained programme and create regional centres to organize information networks on climate change.

In many developing countries the meteorological/ hydrological service is the main and often the only institution collecting and recording data with relevance to climate. If associated weather patterns are modified, as some predict they would as a result of climate change, then the capabilities of such services need to be reinforced to enhance their contributions to sustainable development.

The Special Committee further recommended that its findings be duly taken into account in all relevant areas of the work of IPCC. Programmes of action should be developed and implemented (and the concepts which would lead to such programmes of action developed where needed) without delay, with a view to ensure, provided the necessary means are made available, the full participation of developing countries in the future work and activities on climate change. UNEP and WMO should take the lead in this regard and initiate the necessary consultations. Other multilateral or bilateral organizations should also be contacted for elaborating and implementing these programmes of action.

SECTION VIII.

SUMMARY OF COMMENTS AND ISSUES FOR FURTHER CONSIDERATION BROUGHT OUT AT THE SEVENTH SESSION OF IPCC

Discussion of the results described in the reports of the three Working Groups identified a number of areas for priority emphasis in the future work of IPCC. In the plenary meetings, references were made to issues and recent work not fully taken into account or peer-reviewed during the preparation of the Working Groups' supplementary reports. All available studies should be thoroughly peer-reviewed as part of the IPCC follow-up process.

Desertification

Climate change and drought and desertification are issues of great importance in many parts of the world. Extensive study of the links between climatic variations, climate change and desertification is urgent and has been requested by numerous affected countries in Sahelian and other parts of Africa, in Latin America, and in Australia, India, China and other parts of Asia. Desertification is a complex phenomenon largely associated with human causes such as land degradation exacerbated by climatic variability; the affected arid and semi-arid regions are therefore most likely to be vulnerable to climate change. The declaration following the International Congress on Impacts of Climate Variations and Sustainable Development in Semi-Arid Regions (Fortaleza, Brazil, 1992)) emphasizes the urgency of addressing the issue of desertification in respect of its causes of observed impacts on affected human societies.

Fluorinated greenhouse gas species, not included in the Montreal Protocol

There are two species concerned: firstly, the hydrofluorocarbons (HFCs), now replacing the chlorofluorocarbons (CFCs); secondly, some fully fluorinated species with high GWPs and very long lifetimes such as tetrafluoromethane (CF_4), hexafluoroethane (C_2F_6) and sulphur hexafluoride (SF_6). Consideration should be given to achieving a better understanding of sources and sinks and to including these gases in the IPCC methodology for national inventories of greenhouse gas emissions and sinks, as well as to assessing response options.

Regional climate predictions

The Panel continued to stress that research leading to information on likely regional climate change (and its association with global change) was of the highest priority, and noted that there are certain aspects of regional climate change which are particularly important in some areas. Among these are tropical cyclones and the tidal surges associated with such storms. Guidance on likely changes in frequency, intensity and distribution of such events, as a result of climate change, is urgently needed in states in and bordering the Pacific, Indian and Atlantic Oceans. Special attention should be given to the needs of small island states which are particularly vulnerable to climate change. Prediction of regional precipitation is another area of particular concern. Moreover, the connections between local, regional and global pollution requires further study.

The question of the validity of the technique of palaeo-analogue for the prediction of regional climate change was raised. Although, palaeo-data concerning past climate are of great value, clear analogues from the past which can be applied to future climate change have not yet been identified. In the further work of IPCC, all methods of regional climate prediction should be reviewed and assessed on a continuing basis.

Country studies and methodologies

The Panel recognized the valuable work on methodologies for country studies - such as those for national inventories of greenhouse gas emissions and sinks, vulnerability to sea level rise and other impacts assessments - which were being carried out by the three Working Groups and elsewhere. It acknowledged that this is a cross-cutting issue. It recognized the utility of further work on methodologies for both limitation and adaptation and, in particular, their integration into a broader framework. There was a consensus that priority should be given to further assessing the work in progress and to development of coherent guidelines for country studies, keeping in mind the circumstances of different countries and the evolving nature and pattern of their natural resource use. The next step in this process should be the convening of a workshop possibly prior to the eighth Session of the Panel, with a report to be reviewed at that time.

Nuclear energy technologies

Nuclear power, along with safety and waste disposal issues, should be fully evaluated by the IPCC as an alternative energy source to mitigate climate change.

Inventory of possible response options

Future work should include the preparation of a broad inventory of possible response options to identify an evolving list of measures that countries may wish to consider in their national context. With regard to each option, the inventory should include feasibility factors that will enable countries to assess the applicability of an individual option to national situations. These factors include

- technical factors
- economic factors
- other factors

that may inhibit the introduction of these technologies or practices in a specific national situation.

The options considered should include management practices, techniques and technologies, and should cover all sectors, including energy, industry, transportation, agriculture and forestry as well as adaptation measures for natural and developed areas.

The Technology Characterization Inventory is the first step towards this goal. The report on task 4 also identifies specific response options, and the report on task 5 notes coastal zone management practices that can facilitate adaptation to sea-level rise.

Natural gas prospects

The concern over the future availability of natural gas to meet expected higher demand, including its relation to reducing greenhouse gas emissions, was raised. Assessment of natural gas availability, deliverability and demand beyond the year 2005 is needed, particularly in non-OECD countries.

Economic impacts of response measures

Some studies very recently became available and could not be considered by the IPCC in the review described in this report. These studies indicate mixed results and show the need for a continuing examination of the question of the effects of carbon taxes and other measures on national GDP growth.

Other areas to be considered for future work

- Specification of a minimum set of parameters for monitoring for impact analyses, and how to measure them.
- Impacts on mountain ecosystems (forests, water resources, socio-economic impacts, etc.).
- Impacts of climate change on urban areas and other human settlements.
- Indirect GWPs.
- Monitoring and databases.
- Further follow-up on the Noordwijk afforestation targets.

- Emissions from road transportation and other transportation sectors which could be used as alternative options.

- Development of an action plan to fulfil the recommendations of the IPCC Special Committee on the Participation of Developing Countries, especially the long-term objectives (see section VII).

Dissemination of IPCC information

With financial support provided by some countries, the IPCC has conducted a series of information exchange seminars in several developing countries, and the IPCC First Assessment Report (1990) and some other IPCC reports have been translated into several languages. Non-governmental organizations are also contributing significantly to the dissemination of information on climate change. The seminars have attracted participation from all levels of society, including heads of state and government ministers, experts, non-governmental organisations and the public. They have contributed significantly to the understanding of the various aspects of the climate change issue. Further seminars in other developing countries could be undertaken in response to requests, but this depends on the availability of financial and human resources.

Resource issues

The IPCC assessments are fundamentally dependent on research and development carried out under international programmes and by research teams within countries of the world. The need to increase these research efforts has become obvious in the course of the IPCC work. Insufficient knowledge and understanding of both the climate change issue itself as well as all socio-economic impacts and further societal implications exist at all levels of society. The IPCC strongly urges that increasing resources be made available for these activities and that the major international global programmes be adequately resourced. It is particularly important that means are made available to permit developing countries to become genuine partners in this global research effort. The progress of our understanding is indeed dependent upon addressing the global environment in its entirety.

LIST OF ACRONYMS AND CHEMICAL SYMBOLS

ASLR	Accelerated Sea Level Rise
CF_4	Tetrafluoromethane
CFCs	Chlorofluorocarbons
C_2F_6	Hexafluoroethane
CGCM	Coupled General Circulation Model
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CNG	Compressed Natural Gas
ENSO	El-Niño Southern Oscillation
GCOS	Global Climate Observing System
GEF	Global Environment Facility
GHG	Greenhouse Gas
GtC	Gigatonnes (10^9 tonnes) carbon
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
ISTIG	Intercooled, Steam Injected Gas Turbine
IS92a-f	1992 IPCC Emissions Scenarios
Mha	Million hectares
MSU	Microwave Sounding Unit
Mt	Megatonne (10^6 tonnes)
N_2O	Nitrous oxide
NOx	Nitrogen oxides
NH	Northern Hemisphere
NMHC	Non-methane hydrocarbons
O_3	Ozone
OECD	Organization for Economic Cooperation and Development
pa	Per annum
ppm	Part per million
SF_6	Sulphur hexafluoride
tC	Tonnes Carbon
Tg	Teragram (10^{12} grams)
UN	United Nations
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

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Overview

Preface to the IPCC Overview

The IPCC First Assessment Report consists of

- this IPCC Overview,
- the Policymaker Summaries of the three IPCC Working Groups (concerned with assessment respectively of the science, impacts and response strategies) and the IPCC Special Committee on the Participation of Developing Countries, and
- the three reports of the Working Groups.

The Overview brings together material from the four Policymaker Summaries. It presents conclusions, proposes lines of possible action (including suggestions as to the factors which might form the basis for negotiations) and outlines further work which is required for a more complete understanding of the problems of climate change resulting from human activities.

Because the Overview cannot reflect all aspects of the problem which are presented in the three full reports of the Working Groups and the four Policymaker Summaries, it should be read in conjunction with them.

The issues, options and strategies presented in the Report are intended to assist policymakers and future negotiators in their respective tasks. Further consideration of the Report should be given by every government as it cuts across different sectors in all countries. It should be noted that the Report reflects the technical assessment of experts rather than government positions, particularly those governments that could not participate in all Working Groups of IPCC.

This Overview reflects the conclusions of the reports of (i) the three IPCC Working Groups on science, impacts, and response strategies, and (ii) the Policymaker Summaries of the IPCC Working Groups and the IPCC Special Committee on the Participation of Developing Countries.

1. Science

This section is structured similarly to the Policymaker Summary of Working Group I.

1.0.1 *We are certain of the following:*

- There is a natural greenhouse effect which already keeps the Earth warmer than it would otherwise be.

- Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. The main greenhouse gas, water vapour, will increase in response to global warming and further enhance it.

1.0.2 *We calculate with confidence that:*

- Some gases are potentially more effective than others at changing climate, and their relative effectiveness can be estimated. Carbon dioxide has been responsible for over half of the enhanced greenhouse effect in the past, and is likely to remain so in the future.

- Atmospheric concentrations of the long-lived gases (carbon dioxide, nitrous oxide and the CFCs) adjust only slowly to changes of emissions. Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead. The longer emissions continue to increase at present-day rates, the greater reductions would have to be for concentrations to stabilize at a given level.

- For the four scenarios of future emissions which IPCC has developed as assumptions (ranging from one where few or no steps are taken to limit emissions, viz., Scenario A or Business-as-Usual Scenario, through others with increasing levels of controls respectively called Scenarios B, C and D), there will be a doubling of equivalent carbon dioxide concentrations from pre-industrial levels by about 2025, 2040 and 2050 in Scenarios A, B, and C respectively (see the section "Which gases are the most important?" in the Policymaker Summary of Working Group I for a description of the concept of equivalent carbon dioxide). See the Appendix for a description of the IPCC emissions scenarios.

- Stabilization of equivalent carbon dioxide concentrations at about twice the pre-industrial level would occur under Scenario D towards the end of the next century. Immediate reductions of over 60% in the net (sources minus sinks) emissions from human activities of long-lived gases would achieve stabilization of concentration at today's levels; methane concentrations would be stabilized with a 15—20% reduction.

- The human-caused emissions of carbon dioxide are much smaller than the natural exchange rates of carbon dioxide between the atmosphere and the oceans, and between the atmosphere and the terrestrial system. The natural exchange rates were, however, in close balance before human-induced emissions began; the steady anthropogenic emissions into the atmosphere represent a significant disturbance of the natural carbon cycle.

1.0.3 *Based on current model results, we predict:*

- An average rate of increase of global mean temperature during the next century of about 0.3°C per decade (with an uncertainty range of 0.2—0.5°C per decade) assuming the IPCC Scenario A (Business-as-Usual) emissions of greenhouse gases; this is a more rapid increase than seen over the past 10,000 years. This will result in a likely increase in the global mean temperature of about 1°C above the present value by 2025 (about 2°C above that in the pre-industrial period), and 3°C above today's value before the end of the next century (about 4°C above pre-industrial). The rise will not be steady because of other factors.

- Under the other IPCC emissions scenarios which assume progressively increasing levels of controls, rates of increase in global mean temperature of about 0.2°C per decade (Scenario B), just above 0.1°C per decade (Scenario C) and about 0.1°C per decade (Scenario D). The rise will not be steady because of other factors.

- Land surfaces warm more rapidly than the oceans, and higher northern latitudes warm more than the global mean in winter.

- The oceans act as a heat sink and thus delay the full effect of a greenhouse warming. Therefore, we would be committed to a further temperature rise which would progressively become apparent in the ensuing decades and centuries. Models predict that as greenhouse gases increase, the realized temperature rise at any given time is between 50 and 80% of the committed temperature rise.

- Under the IPCC Scenario A (Business-as-Usual) emissions, an average rate of global mean sea-level rise of about 6 cm per decade over the next century (with an uncertainty range of 3—10 cm per decade),

mainly due to thermal expansion of the oceans and the melting of some land ice. The predicted rise is about 20 cm in global mean sea level by 2030, and 65 cm by the end of the next century. There will be significant regional variations.

1.0.4 ***With regard to uncertainties, we note that:***

- There are many uncertainties in our predictions particularly with regard to the timing, magnitude and regional patterns of climate change, especially changes in precipitation.

  - These uncertainties are due to our incomplete understanding of sources and sinks of greenhouse gases and the responses of clouds, oceans and polar ice sheets to a change of the radiative forcing caused by increasing greenhouse gas concentrations.

  - These processes are already partially understood, and we are confident that the uncertainties can be reduced by further research. However, the complexity of the system means that we cannot rule out surprises.

1.0.5 ***Our judgement is that:***

- Global mean surface air temperature has increased by 0.3 to 0.6°C over the last 100 years, with the five global-average warmest years being in the 1980's. Over the same period global sea-level increased by 10 to 20 cm. These increases have not been smooth in time, nor uniform over the globe.

- The size of the warming over the last century is broadly consistent with the prediction by climate models, but is also of the same magnitude as natural climate variability. If the sole cause of the observed warming were the human-made greenhouse effect, then the implied climate sensitivity would be near the lower end of the range inferred from models. Thus the observed increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.

- Measurements from ice cores going back 160,000 years show that the Earth's temperature closely paralleled the amount of carbon dioxide and methane in the atmosphere. Although we do not know the details of cause and effect, calculations indicate that changes in these greenhouse gases were part, but not all, of the reasons for the large (5—7°C) global temperature swings between ice ages and interglacial periods.

- Natural sources and sinks of greenhouse gases are sensitive to a change in climate. Although many of the response (feedback) processes are poorly understood, it appears that, as climate warms, these feedbacks will lead to an overall increase, rather than a decrease, in natural greenhouse gas abundances. For this reason, climate change is likely to be greater than the estimates given above.

2. Impacts

2.0.1 The report on impacts of Working Group II is based on the work of a number of subgroups, using independent studies which have used different methodologies. Based on the existing literature, the studies have used several scenarios to assess the potential impacts of climate change. These have the features of:

i) an effective doubling of CO_2 in the atmosphere between now and 2025 to 2050;

ii) a consequent increase of global mean temperature in the range of 1.5°C to 4.5°C;

iii) an unequal global distribution of this temperature increase, namely a smaller increase of half the global mean in the tropical regions and a larger increase of twice the global mean in the polar regions;

iv) a sea-level rise of about 0.3—0.5 m by 2050 and about 1 m by 2100, together with a rise in the temperature of the surface ocean layer of between 0.2° and 2.5°C.

2.0.2 These scenarios pre-date, but are in line with, the assessment of Working Group I which, for Scenario A (Business-as-Usual) has estimated the magnitude of sea-level rise at about 20 cm by 2030 and about 65 cm by the end of the next century. Working Group I has also predicted the increase in global mean temperatures to be about 1°C above the present value by 2025 and 3°C before the end of the next century.

2.0.3 Any predicted effects of climate change must be viewed in the context of our present dynamic and changing world. Large-scale natural events such as El Niño can cause significant impacts on agriculture and human settlement. The predicted population explosion will produce severe impacts on land use and on the demands for energy, fresh water, food and housing, which will vary from region to region according to national incomes and rates of development. In many cases, the impacts will be felt most severely in regions already under stress, mainly the developing countries. Human-induced climate change due to continued uncontrolled emissions will accentuate these impacts. For instance, climate change, pollution and ultraviolet-B radiation from ozone depletion can interact, reinforcing their damaging effects on materials and organisms. Increases in atmospheric concentrations of greenhouse gases may lead to irreversible change in the climate which could be detectable by the end of this century.

2.0.4 Comprehensive estimates of the physical and biological effects of climate change at the regional level are difficult. Confidence in regional estimates of critical climatic factors is low. This is particularly true of precipitation and soil moisture, where there is considerable disagreement between various general circulation model and palaeo-analogue results. Moreover, there are several scientific uncertainties regarding the relationship between climate change and biological effects and between these effects and socioeconomic consequences.

2.0.5 This impact study part of the Overview does not attempt to anticipate any adaptation, technological innovation or any other measures to diminish the adverse effects of climate change that will take place in the same time frame. This is especially important for heavily managed sectors, eg, agriculture, forestry and public health.

2.0.6 Finally, the issue of timing and rates of change need to be considered; there will be lags between:

i) emissions of greenhouse gases and doubling of concentrations;

ii) doubling of greenhouse gas concentrations and change in climate;

iii) changes in climate and resultant physical and biological effects; and

iv) changes in physical and ecological effects and resultant socioeconomic (including ecological) consequences. The shorter the lags, the less the ability to cope and the greater the socioeconomic impacts.

2.0.7 There is uncertainty related to these time lags. The changes will not be steady and surprises cannot be ruled out. The severity of the impacts will depend to a large degree on the rate of climate change.

2.0.8 Despite these uncertainties, Working Group II has been able to reach some major conclusions. These are presented below.

2.1 Agriculture and forestry

2.1.1 Sufficient evidence is now available from a variety of different studies to indicate that changes of climate would have an important effect on agriculture and livestock. Studies have not yet conclusively determined whether, on average, global agricultural potential will increase or decrease. Negative impacts could be felt at the regional level as a result of changes in weather and pests associated with climate change, and changes in ground-level ozone associated with pollutants, necessitating innovations in technology and agricultural management practices. There may be severe effects in some regions, particularly decline in production in regions of high present-day vulnerability that are least able to adjust. These include Brazil, Peru, the Sahel Region of Africa, Southeast Asia, and the Asian region of the USSR and China. There is a possibility that potential productivity of high and mid latitudes may increase because of a prolonged growing season, but it is not likely to open up large new areas for production and it will be mainly confined to the Northern Hemisphere.

2.1.2 Patterns of agricultural trade could be altered by decreased cereal production in some of the currently high-production areas, such as western Europe, southern USA, parts of South America and western Australia. Horticultural production in mid-latitude regions may be reduced. On the other hand, cereal production could increase in northern Europe. Policy responses directed to breeding new plant cultivars, and agricultural management designed to cope with changed climate conditions, could lessen the severity of regional impacts. On the balance, the evidence suggests that in the face of estimated changes of climate, food production at the global level can be maintained at essentially the same level as would have occurred without climate change; however, the cost of achieving this is unclear. Nonetheless, climate change may intensify difficulties in coping with rapid population growth. An increase or change in UV-B radiation at ground level resulting from the depletion of stratospheric ozone will have a negative impact on crops and livestock.

2.1.3 The rotation period of forests is long and current forests will mature and decline during a climate in which they are increasingly more poorly adapted. Actual impacts depend on the physiological adaptability of trees and the host-parasite relationship. Large losses from both factors in the form of forest declines can occur. Losses from wildfire will be increasingly extensive. The climate zones which control species distribution will move poleward and to higher elevations. Managed forests require large inputs in terms of choice of seedlot and spacing, thinning and protection. They provide a variety of products from fuel to food.

2.1.4 The degree of dependency on products varies among countries, as does the ability to cope with and to withstand loss. The most sensitive areas will be where species are close to their biological limits in terms of temperature and moisture. This is likely to be, for example, in semi-arid areas. Social stresses can be expected to increase and consequent anthropogenic damage to forests may occur. These increased and non-sustainable uses will place more pressure on forest investments, forest conservation and sound forest management.

2.2 Natural terrestrial ecosystems

2.2.1 Natural terrestrial ecosystems could face significant consequences as a result of the global increases in the atmospheric concentrations of greenhouse gases and the associated climatic changes. Projected changes in temperature and precipitation suggest that climatic zones could shift several hundred kilometres towards the poles over the next fifty years. Flora and fauna would lag behind

these climatic shifts, surviving in their present location and, therefore, could find themselves in a different climatic regime. These regimes may be more or less hospitable and, therefore, could increase productivity for some species and decrease that of others. Ecosystems are not expected to move as a single unit, but would have a new structure as a consequence of alterations in distribution and abundance of species.

2.2.2 The rate of projected climate changes is the major factor determining the type and degree of climatic impacts on natural terrestrial ecosystems. These rates are likely to be faster than the ability of some species to respond and responses may be sudden or gradual.

2.2.3 Some species could be lost owing to increased stress leading to a reduction of global biological diversity. Increased incidence of disturbances such as pest outbreaks and fire are likely to occur in some areas and these could enhance projected ecosystem changes.

2.2.4 Consequences of CO_2 enrichment and climate change for natural terrestrial ecosystems could be modified by other environmental factors, both natural and man-induced (e.g. by air pollution).

2.2.5 Most at risk are those communities in which the options for adaptability are limited (e.g. montane, alpine, polar, island and coastal communities, remnant vegetation, and heritage sites and reserves) and those communities where climatic changes add to existing stresses. The socioeconomic consequences of these impacts will be significant, especially for those regions of the globe where societies and related economies are dependent on natural terrestrial ecosystems for their welfare. Changes in the availability of food, fuel, medicine, construction material and income are possible as these ecosystems are changed. Important fibre products could also be affected in some regions.

2.3 Hydrology and water resources

2.3.1 Relatively small climate changes can cause large water resource problems in many areas, especially arid and semi-arid regions and those humid areas where demand or pollution has led to water scarcity. Little is known about regional details of greenhouse-gas-induced hydrometeorological change. It appears that many areas will have increased precipitation, soil moisture and water storage, thus altering patterns of agricultural, ecosystem and other water use. Water availability will decrease in other areas, a most important factor for already marginal situations, such as the Sahelian zone in Africa. This has significant implications for agriculture, for water storage and distribution, and for generation of hydroelectric power. In some limited areas, for example, under an assumed scenario of a 1°C to 2°C temperature increase, coupled with a 10% reduction in precipitation, a 40—70% reduction in annual runoff could occur. Regions such as southern Asia, that are dependent on unregulated river systems, are particularly vulnerable to hydrometeorological change. On the other hand, regions such as the western USSR and western United States that have large regulated water resource systems are less sensitive to the range of hydrometeorological changes in the assumed scenario. In addition to changes in water supply, water demand may also change through human efforts to conserve, and through improved growth efficiency of plants in a higher CO_2 environment. Net socioeconomic consequences must consider both supply and demand for water. Future design in water resource engineering will need to take possible impacts into account when considering structures with a life span to the end of the next century. Where precipitation increases, water management practices, such as urban storm drainage systems, may require upgrading in capacity. Change in drought risk represents potentially the most serious impact of climate change on agriculture at both regional and global levels.

2.4 Human settlements, energy, transport, and industrial sectors, human health and air quality

2.4.1 The most vulnerable human settlements are those especially exposed to natural hazards, e g coastal or river flooding, severe drought, landslides, severe wind storms and tropical cyclones. The most vulnerable populations are in developing countries, in the lower-income groups: residents of coastal lowlands and islands, populations in semi-arid grasslands, and the urban poor in squatter settlements, slums and shanty towns, especially in megacities. In coastal lowlands such as in Bangladesh, China and Egypt, as well as in small island nations, inundation due to sea-level rise and storm surges could lead to significant movements of people. Major health impacts are possible, especially in large urban areas, owing to changes in availability of water and food and increased health problems due to heat stress spreading of infections. Changes in precipitation and temperature could radically alter the patterns of vector-borne and viral diseases by shifting them to higher latitudes, thus putting large populations at risk. As similar events have in the past, these changes could initiate large migrations of people, leading over a number of years to severe disruptions of settlement patterns and social instability in some areas.

2.4.2 Global warming can be expected to affect the availability of water resources and biomass, both major sources of energy in many developing countries. These effects are likely to differ between and within regions with some areas losing and others gaining water and biomass. Such changes in areas which lose water may jeopardize energy supply and materials essential for human habitation and energy. Moreover, climate change itself is also likely to have different effects between regions on the availability of other forms of renewable energy such as wind and solar power. In developed countries some of the greatest impacts on the energy, transport and industrial sectors may be determined by policy responses to climate change such as

fuel regulations, emission fees or policies promoting greater use of mass transit. In developing countries, climate-related changes in the availability and price of production resources such as energy, water, food and fibre may affect the competitive position of many industries.

2.4.3 Global warming and increased ultraviolet radiation resulting from depletion of stratospheric ozone may produce adverse impacts on air quality such as increases in ground-level ozone in some polluted urban areas. An increase of ultraviolet-B radiation intensity at the Earth's surface would increase the risk of damage to the eye and skin and may disrupt the marine food chain.

2.5 Oceans and coastal zones

2.5.1 Global warming will accelerate sea-level rise, modify ocean circulation and change marine ecosystems, with considerable socioeconomic consequences. These effects will be added to present trends of rising sea-level, and other effects that have already stressed coastal resources, such as pollution and over-harvesting. A 30—50 cm sea-level rise (projected by 2050) will threaten low islands and coastal zones. A 1 m rise by 2100 would render some island countries uninhabitable, displace tens of millions of people, seriously threaten low-lying urban areas, flood productive land, contaminate fresh water supplies and change coastlines. All of these impacts would be exacerbated if droughts and storms become more severe. Coastal protection would involve very significant costs. Rapid sea-level rise would change coastal ecology and threaten many important fisheries. Reductions in sea ice will benefit shipping, but seriously impact on ice-dependent marine mammals and birds.

2.5.2 Impacts on the global oceans will include changes in the heat balance, shifts in ocean circulation which will affect the capacity of the ocean to absorb heat and CO_2 and changes in upwelling zones associated with fisheries. Effects will vary by geographic zones, with changes in habitats, a decrease in biological diversity and shifts in marine organisms and productive zones, including commercially important species. Such regional shifts in fisheries will have major socioeconomic impacts.

2.6 Seasonal snow cover, ice and permafrost

2.6.1 The global areal extent and volume of elements of the terrestrial cryosphere (seasonal snow cover, near-surface layers of permafrost and some masses of ice) will be substantially reduced. These reductions, when reflected regionally could have significant impacts on related ecosystems and social and economic activities. Compounding these impacts in some regions is that, as a result of the associated climatic warming positive feedbacks, the reductions could be sudden rather than gradual.

2.6.2 The areal coverage of seasonal snow and its duration are projected to decrease in most regions, particularly at mid latitudes, with some regions at high latitudes possibly experiencing increases in seasonal snow cover. Changes in the volume of snow cover, or the length of the snow cover season, will have both positive and negative impacts on regional water resources (as a result of changes in the volume and the timing of runoff from snowmelt), on regional transportation (road, marine, air and rail), and on recreation sectors.

2.6.3 Globally, the ice contained in glaciers and ice sheets is projected to decrease, with regional responses complicated by the effect of increased snowfall in some areas which could lead to accumulation of ice. Glacial recession will have significant implications for local and regional water resources, and thus impact on water availability and on hydroelectric power potential. Glacial recession and loss of ice from ice sheets will also contribute to sea-level rise. Permafrost, which currently underlies 20—25% of the land mass of the Northern Hemisphere, could experience significant degradation within the next 40—50 years. Projected increases in the thickness of the freeze-thaw (active) layer above the permafrost and a recession of permafrost to higher latitudes and altitudes could lead to increases in terrain instability, erosion and landslides in those areas which currently contain permafrost. As a result, overlying ecosystems could be significantly altered and the integrity of man-made structures and facilities reduced, thereby influencing existing human settlements and development opportunities.

3. Response strategies

3.0.1 The consideration of climate change response strategies presents formidable difficulties for policymakers. The information available to make sound policy analyses is inadequate because of:

(a) uncertainty with respect to how effective specific response options or groups of options would be in actually averting potential climate change;

(b) uncertainty with respect to the costs, effects on economic growth, and other economic and social implications of specific response options or groups of options.

3.0.2 The IPCC recommends a programme for the development and implementation of global, comprehensive and phased action for the resolution of the global warming problem under a flexible and progressive approach.

- A major dilemma of the issue of climate change due to increasing emission of greenhouse gases in the atmosphere is that actions may be required well before many of the specific issues that are and will be raised can be analyzed more thoroughly by further research.

- The CFCs are being phased out to protect the stratospheric ozone layer. This action will also effectively slow down the rate of increase of radiative

forcing of greenhouse gases in the atmosphere. Every effort should be made to find replacements that have little or no greenhouse warming potential or ozone depletion potential rather than the HCFCs and HFCs that are now being considered.

- The single largest anthropogenic source of radiative forcing is energy production and use. The energy sector accounts for an estimated 46% (with an uncertainty range of 38—54%) of the enhanced radiative forcing resulting from human activities.

- It is noted that emissions due to fossil fuel combustion amount to about 70—90% of the total anthropogenic emissions of CO_2 into the atmosphere, whereas the remaining 10—30% is due to human use of terrestrial ecosystems. A major decrease of the rate of deforestation as well as an increase in afforestation would contribute significantly to slowing the rate of CO_2 concentrations increase in the atmosphere; but it would be well below that required to stop it. This underlines that when forestry measures have been introduced, other measures to limit or reduce greenhouse emissions should not be neglected.

3.1 Roles of industrialized and developing countries

- Industrialized and developing countries have a common but varied responsibility in dealing with the problem of climate change and its adverse effects. The former should take the lead in two ways:

  i) A major part of emissions affecting the atmosphere at present originates in industrialized countries where the scope for change is greatest. Industrialized countries should adopt domestic measures to limit climate change by adapting their own economies in line with future agreements to limit emissions.

  ii) To co-operate with developing countries in international action, without standing in the way of the latter's development by contributing additional financial resources, by appropriate transfer of technology, by engaging in close co-operation in scientific observation, analysis and research, and finally by means of technical co-operation geared to forestalling and managing environmental problems.

- Sustainable development[1] in industrialized as well as developing countries requires proper concern for environmental protection as the basis for continued economic growth. Environmental considerations must be systematically integrated into all plans for development. The right balance must be struck between economic growth and environmental objectives.

- Emissions from developing countries are growing in order to meet their development requirements and thus, over time, are likely to represent an increasingly significant percentage of global emissions. As the greenhouse gas emissions in developing countries are increasing with their population and economic growth, rapid transfer, on a preferential basis, to developing countries, of technologies which help to monitor, limit or adapt to climate change, without hindering their economic development, is an urgent requirement. Developing countries should, within the limits feasible, take measures to suitably adapt their economies. Recognizing the poverty that prevails among the populations of developing countries, it is natural that achieving economic growth is given priority by them. Narrowing the gap between the industrialized and developing world would provide a basis for a full partnership of all nations in the world and would assist developing countries in dealing with the climate change issue.

3.2 Options

- The climate scenario studies of Working Groups I and III outline control policies on emissions that would slow global warming from the presently predicted value of about 0.3°C per decade to about 0.1°C per decade (see Appendix).

- The potentially serious consequences of climate change give sufficient reasons to begin adopting response strategies that can be justified immediately even in the face of significant uncertainties. The response strategies include:

  – phasing out of CFC emissions and careful assessment of the greenhouse gas potential of proposed substitutes;

  – efficiency improvements and conservation in energy supply, conversion and end use, in particular through improving diffusion of energy-efficient technologies, improving the efficiency of mass-produced goods, reviewing energy-related price and tariff systems to better reflect environmental costs;

  – sustainable forest management and afforestation;

  – use of cleaner, more efficient energy sources with lower or no emissions of greenhouse gases;

  – review of agriculture practices.

[1] Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs and does not imply in any way encroachment upon national sovereignty. (Annex II to decision 15/2 of the 15th session of the UNEP Governing Council, Nairobi, May 1989

- There is no single quick-fix technological option for limiting greenhouse gas emissions. Phased and flexible response strategies should be designed to enhance relevant technological research, development and deployment, including improvement and reassessment of existing technologies. Such strategies should involve opportunities for international co-operation. A comprehensive strategy addressing all aspects of the problem and reflecting environmental, economic and social costs and benefits is necessary.

- Because a large, projected increase in world population will be a major factor in causing the projected increase in global greenhouse gases, it is essential that global climate change strategies take into account the need to deal with the issue of the rate of growth of the world population.

- Subject to their particular circumstances, individual nations, or groups of nations, may wish to consider taking steps now to attempt to limit, stabilize or reduce the emission of greenhouse gases resulting from human activities and prevent the destruction and improve the effectiveness of sinks. One option that governments may wish to consider is the setting of targets for CO_2 and other greenhouse gases.

- A large number of options were preliminarily assessed by IPCC Working Group III. It appears that some of these options may be economically and socially feasible for implementation in the near-term while others, because they are not yet technically or economically viable, may be more appropriate for implementation in the longer term. In general, the Working Group found that the most effective response strategies, especially in the short term, are those which are:

  – beneficial for reasons other than climate change and justifiable in their own right, for example increased energy efficiency and lower greenhouse gas emission technologies, better management of forests, and other natural resources, and reductions in emissions of CFCs and other ozone depleting substances that are also radiatively important gases;

  – economically efficient and cost effective, in particular those that use market-based mechanisms;

  – able to serve multiple social, economic and environmental purposes;

  – flexible and phased, so that they can be easily modified to respond to increased understanding of scientific, technological and economic aspects of climate change;

  – compatible with economic growth and the concept of sustainable development;

  – administratively practical and effective in terms of application, monitoring and enforcement;

  – reflecting obligations of both industrialized and developing countries in addressing this issue, while recognizing the special needs of developing countries, in particular in the areas of financing and technology.

3.2.1 The degree to which options are viable will also vary considerably depending on the region or country involved. For each country, the implications of specific options will depend on its social, environmental and economic context. Only through careful analysis of all available options will it be possible to determine which are best suited to the circumstances of a particular country or region. Initially, the highest priority should be to review existing policies with a view to minimizing conflicts with the goals of climate change strategies. New policies will be required.

- In the long-term perspective, work should begin on defining criteria for selection of appropriate options which would reflect the impacts of climate change and its costs and benefits on the one hand, and social and economic costs and benefits of the options on the other.

- Consideration of measures for reducing the impacts of global climate change should begin as soon as possible, particularly with regard to disaster preparedness policies, coastal zone management and control measures for desertification, many of these being justified in their own right. Measures to limit or adapt to climate change should be as cost-effective as possible while taking into account important social implications. Limitation and adaptation should be considered as an integrated package.

- Assessing areas at risk from sea-level rise and developing comprehensive management plans to reduce future vulnerability of populations and coastal developments and ecosystems as part of coastal zone management plans should begin as soon as possible.

- Environmental objectives can be pursued through regulations and/or through market-based economic instruments. The latter, through their encouragement of flexible selection of abatement measures, tend to encourage innovation and the development of improved technologies and practices for reducing emissions and therefore frequently offer the possibility of achieving environmental improvements at lower costs than through regulatory mechanisms. It is not likely, however, that economic instruments will be applicable to all circumstances.

- Three factors are considered as potential barriers to the operation of markets and/or the achievement of environmental objectives through market mechanisms. These are:

i) information problems, which can often cause markets to produce less effective or unfavourable environmental outcomes;

ii) existing measures and institutions, which can encourage individuals to behave in environmentally damaging ways; and

iii) balancing competing objectives (social, environmental and economic).

3.2.2 An initial response strategy may therefore be to address information problems directly and to review existing measures which may be barriers. For example, prior to possible adoption of a system of emission charges, countries should examine existing subsidies and tax incentives on energy and other relevant greenhouse gas producing sectors.

- With respect to institutional mechanisms for providing financial co-operation and assistance to developing countries, a two track approach was considered:

  i) one track built on work underway or planned in existing institutions. Bilateral donors could further integrate and reinforce the environmental components of their assistance programmes and develop cofinancing arrangements with multilateral institutions while ensuring that this does not impose inappropriate environmental conditions;

  ii) parallel to this track the possibility of new mechanisms and facilities was considered. Some developing and industrialized countries suggested that new mechanisms directly related to a future climate convention and protocols that might be agreed upon, such as a new international fund, were required.

- Governments should undertake now:

  – accelerated and co-ordinated research programmes to reduce scientific and socioeconomic uncertainties with a view towards improving the basis for response strategies and measures;

  – review of planning in the fields of energy, industry, transportation, urban areas, coastal zones and resource use and management;

  – encouragement of beneficial behavioral and structural (e.g. transportation and housing infrastructure) changes;

  – expansion of the global ocean observing and monitoring systems.

3.2.3 It should be noted that no detailed assessments have been made as of yet of the economic costs and benefits, technological feasibility or market potential of the underlying policy assumptions.

4. Participation of developing countries

4.0.1 It is obvious that the impact on and the participation by the developing countries in the further development of a future strategy is essential. The IPCC has attempted to address this specific issue by establishing a Special Committee on the Participation of Developing Countries and requested it to identify factors inhibiting the full participation of the developing countries in IPCC and recommend remedial measures where possible. The Committee stressed that full participation includes not only the physical presence at meetings but also the development of national competence to address all issues of concern such as the appreciation of the scientific basis of climate change, the potential impacts on society of such change and evaluations of practical response strategies for national/regional applications.

4.0.2 The factors that kept developing countries from fully participating were identified by the Special Committee as:

- insufficient information;
- insufficient communication;
- limited human resources;
- institutional difficulties;
- limited financial resources.

4.0.3 On some of these factors, the IPCC Working Groups have developed policy options which are to be found in their respective reports.

- Developing countries will, in some cases, need additional financial resources for supporting their efforts to promote activities which contribute both to limiting greenhouse gas emissions and/or adapting to the adverse effects of climate change, while at the same time promote economic development. Areas of co-operation could include, inter alia:

  – efficient use of energy resources, the use of fossil fuels with lower greenhouse gas emission rates or non-fossil sources, the development of clean and renewable energy sources, such as: biomass, wind-power, wave-power, hydroelectric and solar, wherever applicable;

  – increased rational utilization of forest products, sound forest management practices and agricultural techniques which reduce the negative effects on climate;

  – facilitating the development and transfer of clean and safe technologies in areas which could include:

+ the building and manufacturing industries;

+ public transport systems;

+ industry;

– measures which enhance the capacity of developing countries to develop programmes to address climate change, including research and development activities and public awareness and education programmes, such as:

+ the development of the human resources necessary to tackle the problem of climate change and its adverse effects;

+ the provision of study and training programmes in subjects and techniques related to climate change;

+ the provision of skilled personnel and the material necessary to organize education programmes to develop locally the skills necessary to assess climate change and combat its adverse effects;

+ the development of climate-related research programmes organized on a regional basis;

– facilitating the participation of developing countries in fora and organizations such as: the International Geosphere-Biosphere Programme, the Land-Ocean Interactions in the Coastal Zone, the Biosphere Aspects of the Hydrological Cycle, the Global Change Impact on Agriculture and Society, the World Climate Programme, the Man and the Biosphere Programme;

– facilitating participation by developing countries in international fora on global climate change such as the IPCC;

– strengthening existing education and research institutions and the development of new ones at national and regional levels.

- Further, co-operation and assistance for adaptive measures would be required, noting that for some regions and countries, adaptation rather than limitation activities are potentially most important.

- The IPCC concludes that the recommendations of the Special Committee need not and should not await the outcome of future negotiations on a climate convention. It appeals to the multilateral and bilateral funding organizations to implement its recommendations. It further appeals to governments for continuing and increased contributions to the IPCC Trust Fund on an urgent basis.

5. International co-operation and future work

- The measures noted above require a high degree of international co-operation with due respect for national sovereignty of states. The international negotiations on a framework convention should start as quickly as possible after presentation of this Report in line with Resolution SS II/3 Climate.C. (August 1990) of the UNEP Governing Council and Resolution 8 (EC-XLII, June 1990) of the WMO Executive Council. Many, essentially developing, countries stressed that the negotiations must be conducted in the forum, manner and with the timing to be decided by the UN General Assembly.

5.0.1 This convention, and any additional protocols that might be agreed upon, would provide a firm basis for effective co-operation to act on greenhouse gas emissions and adapt to any adverse effects of climate change. The convention should recognize climate change as a common concern of mankind and, at a minimum, contain general principles and obligations. It should be framed in such a way as to gain the adherence of the largest possible number and most suitably balanced range of countries while permitting timely action to be taken.

5.0.2 Key issues for negotiations will include the criteria, timing, legal form and incidence of any obligations to control the net emissions of greenhouse gases, how to address equitably the consequences for all, any institutional mechanisms including research and monitoring that may be required, and in particular, the requests of the developing countries for additional financial resources and for the transfer of technology on a preferential basis. The possible elements of a framework convention on climate change were identified and discussed by Working Group III in its legal measures topic paper, appended to its Policymaker Summary.

- The IPCC recommends that research regarding the science of climate change in general, technological development and the international economic implications, be intensified.

- Because climate change would affect, either directly or indirectly, almost every sector of society, broad global understanding of the issue will facilitate the adoption and the implementation of such response options as deemed necessary and appropriate. Further efforts to achieve such global understanding are urgently needed.

APPENDIX

Emissions scenarios developed by IPCC

The IPCC used two methods to develop scenarios of future emissions:

- One method used global models to develop four scenarios which were subsequently used by Working Group I to develop scenarios of future warming. All of these four scenarios assumed the same global economic growth rates taken from the World Bank projections and the same population growth estimates taken from the United Nations studies. The anthropogenic emissions of carbon dioxide and methane from these scenarios are shown in Figures 1 and 2 below.

- The second method used studies of the energy and agriculture sectors submitted by over 21 countries and international organizations to estimate CO_2 emissions.

Both scenario approaches indicate that CO_2 emissions will grow from about 7 BtC (billion or 1000 million tonnes carbon) per year now to 12-15 BtC per year by the year 2025. Scenario A (Business-as-Usual) includes a partial phase-out of CFCs under the Montreal Protocol and lower CO_2 and CH_4 emissions than the Reference Scenario. The Reference Scenario developed through country and international studies of the energy and agriculture groups, includes higher CO_2 emissions and assumed a total CFC phase-out. The results indicate that the CO_2 equivalent concentrations and their effects on global climate are similar.

Method 1[2]

Scenario A (Business-as-Usual) assumes that few or no steps are taken to limit greenhouse gas emissions. Energy use and clearing of tropical forests continue and fossil fuels, in particular coal, remain the world's primary energy source. The Montreal Protocol comes into effect but without strengthening and with less than 100 percent compliance. Under this scenario, the equivalent of a doubling of pre-industrial CO_2 levels occurs, according to Working Group I, by around 2025.

Scenario B (Low Emissions Scenario) assumes that the energy supply mix of fossil fuels shifts towards natural gas, large efficiency increases are achieved, deforestation is reversed and emissions of CFCs are reduced by 50% from their 1986 levels. This results in an equivalent doubling of pre-industrial carbon dioxide by about 2040.

Scenario C (Control Policies Scenario) assumes that a shift towards renewable energies and safe nuclear energy takes place in the latter part of the next century, CFC gases are phased out and agricultural emissions (methane and nitrous oxide) are limited; an equivalent doubling of pre-industrial carbon dioxide will occur in about 2050.

Scenario D (Accelerated Policies Scenario) assumes that a rapid shift to renewable energies and safe nuclear energy takes place early in the next century, stringent emission controls in industrial countries and moderate growth of emissions in developing countries. This scenario, which assumes carbon dioxide emissions are reduced to 50% of 1985 levels, stabilizes equivalent carbon dioxide concentrations at about twice the pre-industrial levels towards the end of the next century.

Figure 1 Projected man-made CO_2 emmissions (Billion or 1000 million tonnes carbon per year)

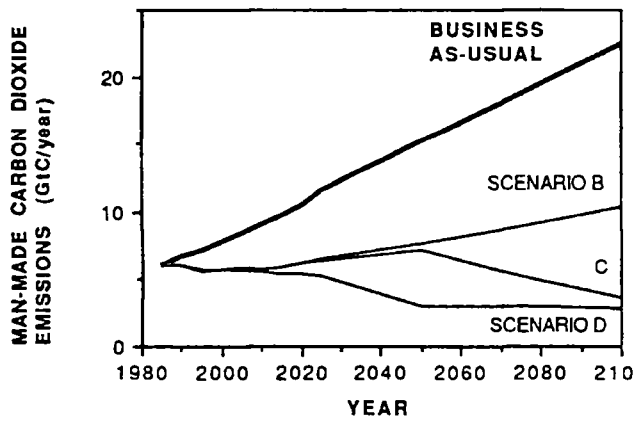

Figure 2 Projected man-made Methane emmissions (Million tonnes per year)

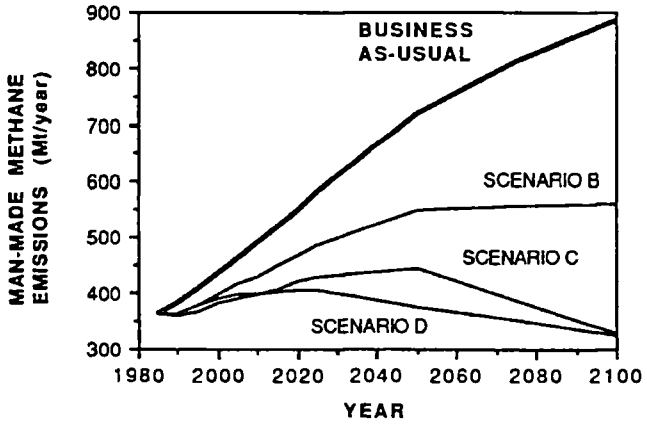

[2] All of the scenarios assumed some level of compliance with the Montreal Protocol but not with all of the (June 1990) amendments agreed to in London. The London amendments to the Montreal Protocol, when fully implemented, would result in a virtually complete elimination of production of fully halogenated CFCs, halons, carbon tetrachloride and methyl chloroform early in the 21st century. The Parties of the Protocol also call for later elimination of HCFCs. Thus, the assumptions of Scenarios A and B overestimate the radiative forcing potential of CFCs and halons. Additionally, the UN has provided recent population projections that estimate higher population than used in the global model scenarios (Scenarios A through D); use of these newer projections would increase future CO_2 emissions. Additionally, the Reference Scenario CO_2 emissions are higher than Scenario A (Business-as-Usual), suggesting Scenario A (Business-as-Usual) may be an underestimate.

Method 2 (see footnote 2 on previous page)

Using the second method, the so-called Reference Scenario was developed by the Energy and Industry Subgroup and Agriculture and Forestry Subgroup of Working Group III. Under the Reference Scenario, global CO_2 emissions from all sectors grow from approximately 7.0 BtC (per year) in 1985 to over 15 BtC (per year) in 2025. The energy contribution grows from about 5 BtC (per year) to over 12 BtC (per year). Primary energy demand more than doubles between 1985 and 2025 with an average growth rate of 2.1%. The per capita energy emissions in the industrialized countries increase from 3.1 tonnes carbon (TC) in 1985 to 4.7 TC in 2025; for the developing countries, they rise from 0.4 TC in 1985 to 0.8 TC in 2025.

Summary

All of the above scenarios provide a conceptual basis for considering possible future patterns of emissions and the broad responses that might affect those patterns. No full assessment was made of the total economic costs and benefits, technological feasibility, or market potential of the underlying policy assumptions. Because of the inherent limitations in our ability to estimate future rates of population and economic growth, individual behaviour, technological innovation, and other factors which are crucial for determining emission rates over the course of the next century, there is some uncertainty in the projections of greenhouse gas emissions. Reflecting these inherent difficulties, the IPCC's work on emissions scenarios are the best estimates at this time covering emissions over the next century, but continued work to develop improved assumptions and methods for scenario estimates will be useful to guide the development of response strategies.

Policymaker Summary of Working Group I (Scientific Assessment of Climate Change)

Executive Summary

1. ***We are certain of the following:***

- there is a natural greenhouse effect which already keeps the Earth warmer than it would otherwise be;

- emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. The main greenhouse gas, water vapour, will increase in response to global warming and further enhance it.

2. ***We calculate with confidence that:***

- some gases are potentially more effective than others at changing climate, and their relative effectiveness can be estimated. Carbon dioxide has been responsible for over half the enhanced greenhouse effect in the past, and is likely to remain so in the future;

- atmospheric concentrations of the long-lived gases (carbon dioxide, nitrous oxide and the CFCs) adjust only slowly to changes in emissions. Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead. The longer emissions continue to increase at present day rates, the greater reductions would have to be for concentrations to stabilize at a given level;

- the long-lived gases would require immediate reductions in emissions from human activities of over 60% to stabilize their concentrations at today's levels; methane would require a 15-20% reduction.

3. ***Based on current model results, we predict:***

- under the IPCC Business-as-Usual (Scenario A) emissions of greenhouse gases, a rate of increase of global-mean temperature during the next century of about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C per decade); this is greater than that seen over the past 10,000 years. This will result in a likely increase in global-mean temperature of about 1°C above the present value by 2025 and 3°C before the end of the next century. The rise will not be steady because of the influence of other factors;

- under the other IPCC emission scenarios which assume progressively increasing levels of controls, rates of increase in global-mean temperature of about 0.2°C per decade (Scenario B), just above 0.1°C per decade (Scenario C) and about 0.1°C per decade (Scenario D);

- that land surfaces warm more rapidly than the ocean, and high northern latitudes warm more than the global-mean in winter;

- regional climate changes different from the global-mean, although our confidence in the prediction of the detail of regional changes is low. For example, temperature increases in Southern Europe and central North America are predicted to be higher than the global-mean, accompanied on average by reduced summer precipitation and soil moisture. There are less consistent predictions for the tropics and the southern hemisphere;

- under the IPCC Business-as-Usual emissions scenario, an average rate of global mean sea-level rise of about 6 cm per decade over the next century (with an uncertainty range of 3—10 cm per decade), mainly due to thermal expansion of the oceans and the melting of some land ice. The predicted rise is about 20 cm in global-mean sea level by 2030, and 65 cm by the end of the next century. There will be significant regional variations.

3.1 There are many uncertainties in our predictions particularly with regard to the timing, magnitude and regional patterns of climate change, due to our incomplete understanding of:

- sources and sinks of greenhouse gases, which affect predictions of future concentrations;

- clouds, which strongly influence the magnitude of climate chang;

- oceans, which influence the timing and patterns of climate chang;

- polar ice sheets which affect predictions of sea-level riee.

3.2 These processes are already partially understood, and we are confident that the uncertainties can be reduced by further research. However, the complexity of the system means that we cannot rule out surprises.

4. ***Our judgement is that:***

- Global mean surface air temperature has increased by 0.3°C to 0.6°C over the last 100 years, with the five global average warmest years being in the 1980s. Over

the same period global sea level has increased by 10-20 cm. These increases have not been smooth with time, nor uniform over the globe.

- The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.

- There is no firm evidence that climate has become more variable over the last few decades. However, with an increase in the mean temperature, episodes of high temperatures will most likely become more frequent in the future, and cold episodes less frequent.

- Ecosystems affect climate, and will be affected by a changing climate and by increasing carbon dioxide concentrations. Rapid changes in climate will change the composition of ecosystems; some species will benefit while others will be unable to migrate or adapt fast enough and may become extinct. Enhanced levels of carbon dioxide may increase productivity and efficiency of water use of vegetation. The effect of warming on biological processes, although poorly understood, may increase the atmospheric concentrations of natural greenhouse gases.

5. ***To improve our predictive capability, we need:***

- to understand better the various climate-related processes, particularly those associated with clouds, oceans and the carbon cycle;

- to improve the systematic observation of climate-related variables on a global basis, and further investigate changes which took place in the past;

- to develop improved models of the Earth's climate system;

- to increase support for national and international climate research activities, especially in developing countries;

- to facilitate international exchange of climate data.

1. Introduction: what is the issue?

1.0.1 There is concern that human activities may be inadvertently changing the climate of the globe through the enhanced greenhouse effect, by past and continuing emissions of carbon dioxide and other gases which will cause the temperature of the Earth's surface to increase—popularly termed the "global warming". If this occurs, consequent changes may have a significant impact on society.

1.0.2 The purpose of the Working Group I report, as determined by the first meeting of IPCC, is to provide a scientific assessment of:

1) the factors which may affect climate change during the next century especially those which are due to human activity;

2) the responses of the atmosphere-ocean-land-ice system;

3) current capabilities of modelling global and regional climate changes and their predictability:

4) the past climate record and presently observed climate anomalies.

1.0.3 On the basis of this assessment, the report presents current knowledge regarding predictions of climate change (including sea-level rise and the effects on ecosystems) over the next century, the timing of changes together with an assessment of the uncertainties associated with these predictions.

1.0.4 This Policymaker Summary aims to bring out those elements of the main report which have the greatest relevance to policy formulation, in answering the following questions:

- What factors determine global climate?
- What are the greenhouse gases, and how and why are they increasing?
- Which gases are the most important?
- How much do we expect the climate to change?
- How much confidence do we have in our predictions?
- Will the climate of the future be very different?
- Have human activities already begun to change global climate?
- How much will sea-level rise?
- What will be the effects on ecosystems?
- What should be done to reduce uncertainties, and how long will this take?

1.0.5 This report is intended to respond to the practical needs of the policymaker. It is neither an academic review, nor a plan for a new research programme. Uncertainties attach to almost every aspect of the issue, yet policymaker are looking for clear guidance from scientists; hence authors have been asked to provide their best estimates wherever possible, together with an assessment of the uncertainties.

1.0.6 This report is a summary of our understanding in 1990. Although continuing research will deepen this understanding and require the report to be updated at frequent intervals, basic conclusions concerning the reality of the enhanced greenhouse effect and its potential to alter global climate are unlikely to change significantly. Nevertheless, the complexity of the system may give rise to surprises.

2. What factors determine global climate ?

2.0.1 There are many factors, both natural and of human origin, that determine the climate of the earth. We look first at those which are natural, and then see how human activities might contribute.

2.1 What natural factors are important?

2.1.1 The driving energy for weather and climate comes from the sun. The Earth intercepts solar radiation (including that in the short-wave, visible, part of the spectrum); about a third of it is reflected, the rest is absorbed by the different components (atmosphere, ocean, ice, land and biota) of the climate system. The energy absorbed from solar radiation is balanced (in the long term) by outgoing radiation from the Earth and atmosphere; this terrestrial radiation takes the form of long-wave invisible infra-red energy, and its magnitude is determined by the temperature of the Earth-atmosphere system.

2.1.2 There are several natural factors which can change the balance between the energy absorbed by the Earth and that emitted by it in the form of longwave infra-red radiation; these factors cause the radiative forcing on climate. The most obvious of these is a change in the output of energy from the Sun. There is direct evidence of such variability over the 11-year solar cycle, and longer period changes may also occur. Slow variations in the Earth's orbit affect the seasonal and latitudinal distribution of solar radiation; these were probably responsible for initiating the ice ages.

2.1.3 One of the most important factors is the greenhouse effect; a simplified explanation of which is as follows. Short-wave solar radiation can pass through the clear atmosphere relatively unimpeded. But long-wave terrestrial radiation emitted by the warm surface of the Earth is partially absorbed and then re-emitted by a number of trace gases in the cooler atmosphere above. Since, on average, the outgoing long-wave radiation balances the incoming solar radiation, both the atmosphere and the

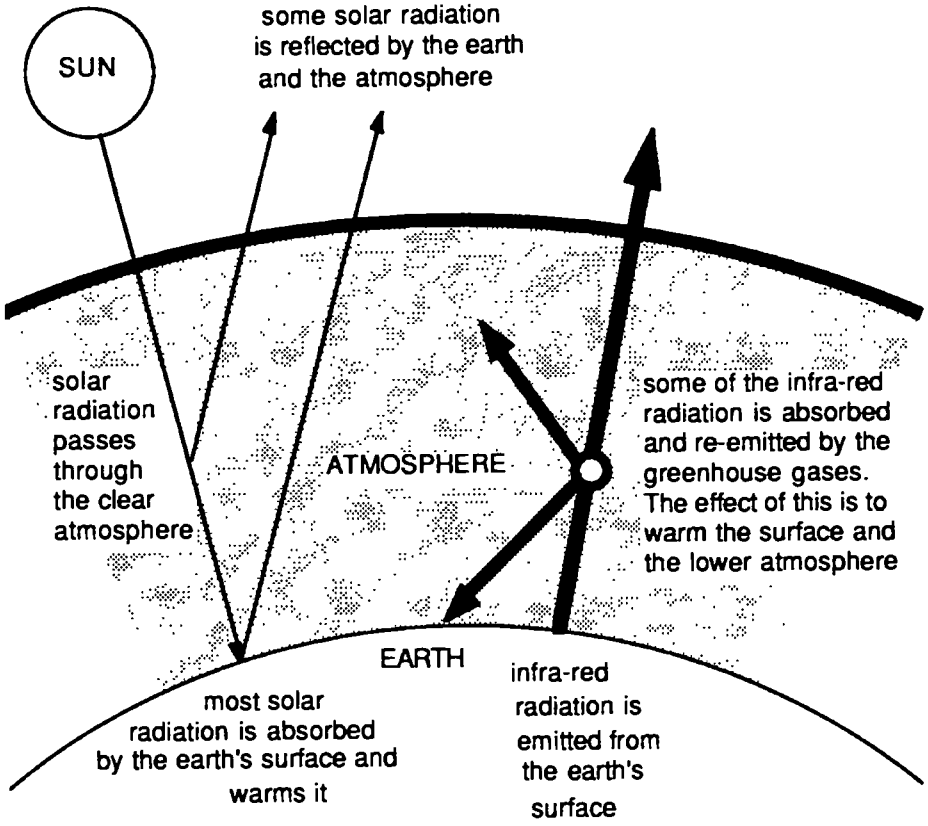

Figure 3 A simplified diagram illustrating the greenhouse effect

surface will be warmer than they would be without the greenhouse gases.

2.1.4 The main natural greenhouse gases are not the major constituents, nitrogen and oxygen, but water vapour (the biggest contributor), carbon dioxide, methane, nitrous oxide, and ozone in the troposphere (the lowest 10—15 km of the atmosphere) and stratosphere.

2.1.5 Aerosols (small particles) in the atmosphere can also affect climate because they can reflect and absorb radiation. The most important natural perturbations result from explosive volcanic eruptions which affect concentrations in the lower stratosphere. Lastly, the climate has its own natural variability on all timescales and changes occur without any external influence.

2.2 How do we know that the natural greenhouse effect is real?

2.2.1 The greenhouse effect is real; it is a well understood effect, based on established scientific principles. We know that the greenhouse effect works in practice, for several reasons.

2.2.2 Firstly, the mean temperature of the Earth's surface is already warmer by about 33°C (assuming the same reflectivity of the earth) than it would be if the natural greenhouse gases were not present. Satellite observations of the radiation emitted from th eEarth's surface and through the atmosphere demonstrate the effect of the greenhouse gases.

2.2.3 Secondly, we know the composition of the atmospheres of Venus, Earth and Mars are very different, and their surface temperatures are in general agreement with greenhouse theory.

2.2.4 Thirdly, measurements from ice cores going back 160,000 years show that the Earth's temperature closely paralleled the amount of carbon dioxide and methane in the atmosphere. Although we do not know the details of cause and effect, calculations indicate that changes in these greenhouse gases were part, but not all, of the reason for the large (5-7°C) global temperature swings between ice ages and interglacial periods.

2.3 How might human activities change global climate ?

2.3.1 Naturally occurring greenhouse gases keep the Earth warm enough to be habitable. By increasing their concentrations, and by adding new greenhouse gases like chlorofluorocarbons (CFCs), humankind is capable of raising the global-average annual-mean surface-air temperature (which, for simplicity, is referred to as the "global temperature"), although we are uncertain about the rate at which this will occur. Strictly, this is an enhanced greenhouse effect—above that occurring due to natural greenhouse gas concentrations; the word "enhanced" is usually omitted, but it should not be forgotten. Other changes in climate are expected to result, for example changes in precipitation, and a global warming will cause sea levels to rise; these are discussed in more detail later.

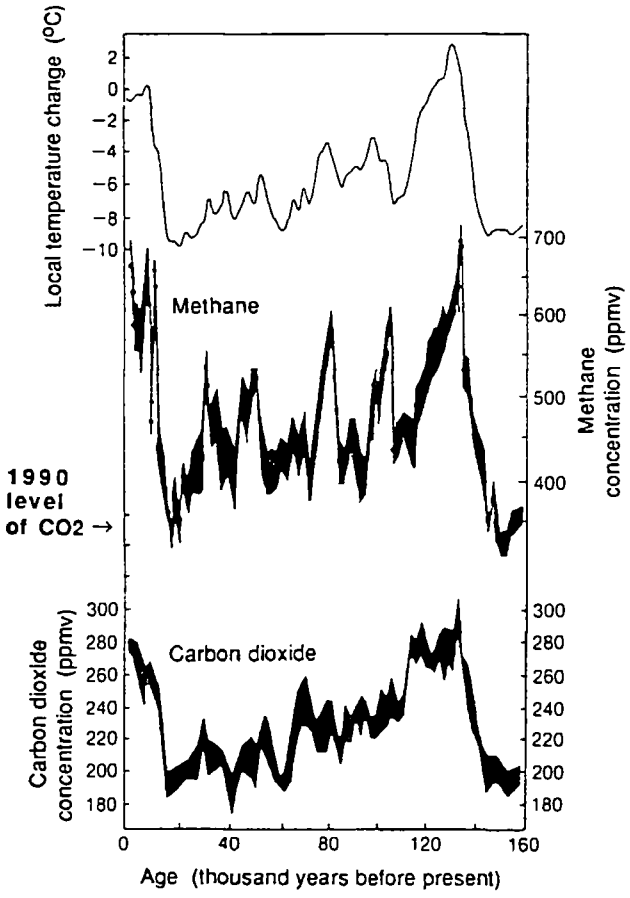

Analysis of air trapped in Antarctic ice cores shows that methane and carbon dioxide concentrations were closely correlated with the local temperature over the last 160 000 years. Present-day concentrations of carbon dioxide are indicated.

2.3.2 There are other human activities which have the potential to affect climate. A change in the albedo (reflectivity) of the land, brought about by desertification or deforestation affects the amount of solar energy absorbed at the Earth's surface. Human-made aerosols, from sulphur emitted largely in fossil fuel combustion, can modify clouds and this may act to lower temperatures. Lastly, changes in ozone in the stratosphere due to CFCs may also influence climate.

3. What are the greenhouse gases and why are they increasing?

3.0.1 We are certain that the concentrations of greenhouse gases in the atmosphere have changed naturally on ice-age time-scales, and have been increasing since pre-industrial times due to human activities. The table below summarizes the present and pre-industrial abundances, current rates of change and present atmospheric lifetimes of greenhouse gases influenced by human activities. Carbon dioxide, methane, and nitrous oxide all have significant natural and human sources, while the chlorofluorocarbons are only produced industrially.

3.0.2 Two important greenhouse gases, water vapour and ozone, are not included in the tableoverleaf. Water vapour has the largest greenhouse effect, but its concentration in the troposphere is determined internally within the climate system, and, on a global scale, is not affected by human sources and sinks. Water vapour will increase in response to global warming and further enhance it; this process is included in climate models. The concentration of ozone is changing both in the stratosphere and the troposphere due to human activities, but it is difficult to quantify the changes from present observations.

3.0.3 For a thousand years prior to the industrial revolution, abundances of the greenhouse gases were relatively constant. However, as the world's population increased, as the world became more industrialized and as agriculture developed, the abundances of the greenhouse gases increased markedly. The figures overleaf illustrate this for carbon dioxide, methane, nitrous oxide and CFC-11.

3.0.4 Since the industrial revolution the combustion of fossil fuels and deforestation have led to an increase of 26% in carbon dioxide concentration in the atmosphere. We know the magnitude of the present day fossil-fuel source, but the input from deforestation cannot be estimated accurately. In addition, although about half of the emitted carbon dioxide stays in the atmosphere, we do not know well how much of the remainder is absorbed by the oceans and how much by terrestrial biota. Emissions of chlorofluorocarbons, used as aerosol propellants, solvents, refrigerants and foam blowing agents, are also well known; they were not present in the atmosphere before their invention in the 1930s.

3.0.5 The sources of methane and nitrous oxide are less well known. Methane concentrations have more than doubled because of rice production, cattle rearing, biomass burning, coal mining and ventilation of natural gas; also, fossil fuel combustion may have also contributed through chemical reactions in the atmosphere which reduce the rate of removal of methane. Nitrous oxide has increased by about 8% since pre-industrial times, presumably due to human activities; we are unable to specify the sources, but it is likely that agriculture plays a part.

3.0.6 The effect of ozone on climate is strongest in the upper troposphere and lower stratosphere. Model calculations indicate that ozone in the upper troposphere should have increased due to human-made emissions of nitrogen oxides, hydrocarbons and carbon monoxide. While at ground level ozone has increased in the northern hemisphere in response to these emissions, observations are insufficient to confirm the expected increase in the upper troposphere. The lack of adequate observations prevents us from accurately quantifying the climatic effect of changes in tropospheric ozone.

3.0.7 In the lower stratosphere at high southern latitudes ozone has decreased considerably due to the effects of CFCs,

	Carbon Dioxide	Methane	CFC-11	CFC-12	Nitrous Oxide
Atmospheric concentration	ppmv	ppmv	pptv	pptv	ppbv
Pre-industrial (1750-1800)	280	0.8	0	0	288
Present day (1990)	353	1 72	280	484	310
Current rate of change per year	1.8 (0.5%)	0 015 (0.9%)	9 5 (4%)	17 (4%)	0 8 (0.25%)
Atmospheric lifetime (years)	(50-200)†	10	65	130	150

ppmv = parts per million by volume;

ppbv = parts per billion (thousand million) by volume,

pptv = parts per trillion (million million) by volume

† The way in which CO_2 is absorbed by the oceans and biosphere is not simple and a single value cannot be given; refer to the main report for further discussion

Summary of key greenhouse gases affected by human activities

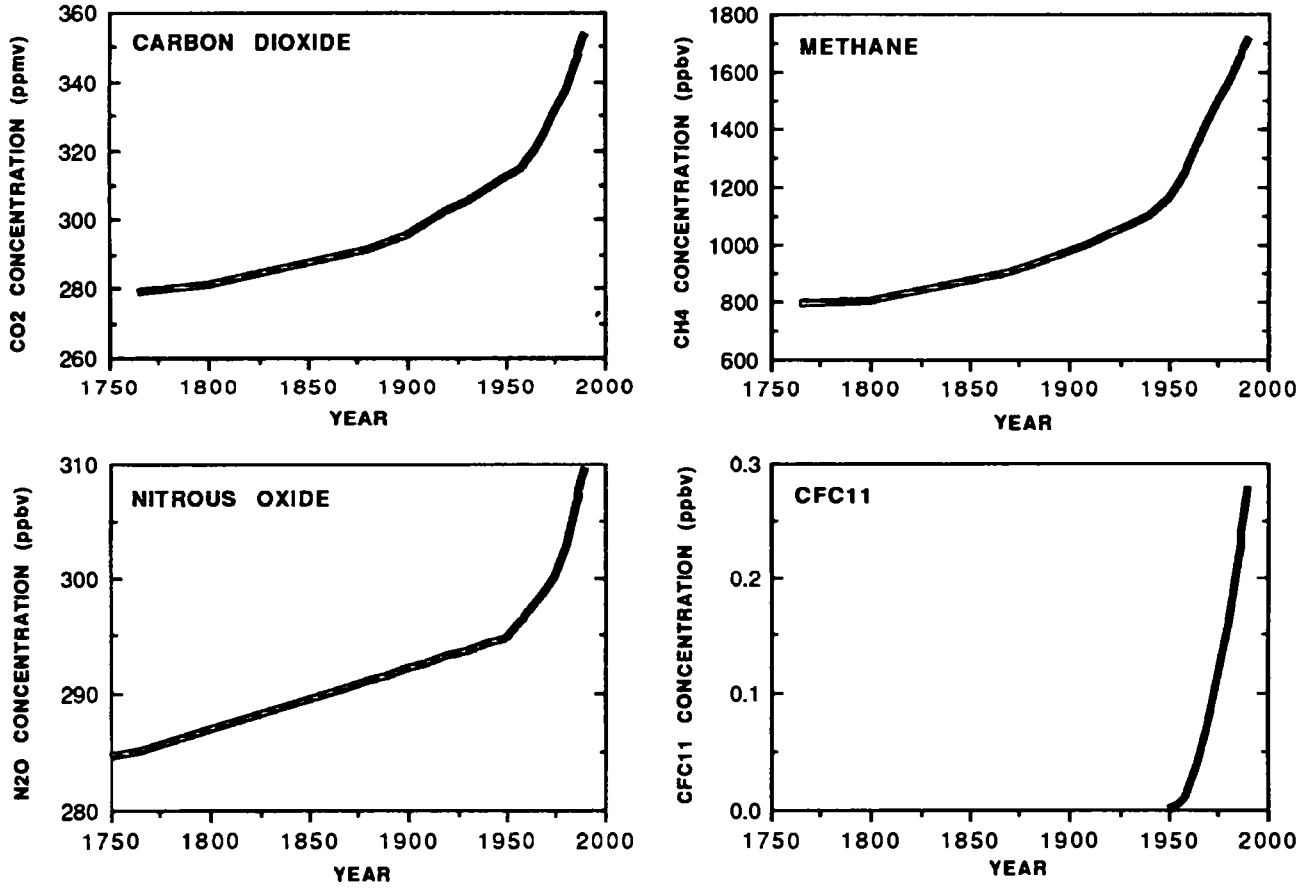

Concentrations of carbon dioxide and methane, after remaining relatively constant up to the 18th century, have risen sharply since then due to man's activities. Concentrations of nitrous oxide have increased since the mid-18th century, especially in the last few decades CFCs were not present in the atmosphere until the 1930s

and there are indications of a global-scale decrease which, while not understood, may also be due to CFCs. These observed decreases should act to cool the earth's surface, thus providing a small offset to the predicted warming produced by the other greenhouse gases. Further reductions in lower stratospheric ozone are possible during the next few decades as the atmospheric abundances of CFCs continue to increase.

3.1 Concentrations, lifetimes and stabilization of the gases

3.1.1 In order to calculate the atmospheric concentrations of carbon dioxide which will result from human-made emissions, we use computer models which incorporate details of the emissions and which include representations of the transfer of carbon dioxide between the atmosphere, oceans and terrestrial biosphere. For the other greenhouse gases, models which incorporate the effects of chemical reactions in the atmosphere are employed.

3.1.2 The atmospheric lifetimes of the gases are determined by their sources and sinks in the oceans, atmosphere and biosphere. Carbon dioxide, chlorofluorocarbons and nitrous oxide are removed only slowly from the atmosphere and hence, following a change in emissions, their atmospheric concentrations take decades to centuries to adjust fully. Even if all human-made emissions of carbon dioxide were halted in the year 1990, about half of the increase in carbon dioxide concentration caused by human activities would still be evident by the year 2100.

3.1.3 In contrast, some of the CFC substitutes and methane have relatively short atmospheric lifetimes so that their atmospheric concentrations respond fully to emission changes within a few decades.

3.1.4 To illustrate the emission-concentration relationship clearly, the effect of hypothetical changes in carbon dioxide fossil fuel emissions is shown below:

Stabilization of atmospheric concentrations.

Reductions in the human-made emissions of greenhouse gases required to stablize concentrations at present day levels:

Carbon Dioxide	>60%
Methane	15—20%
Nitrous Oxide	70—80%
CFC-11	70—75%
CFC-12	75—85%
HCFC-22	40—50%

Note that the stabilization of each of these gases would have different effects on climate, as explained in the next section.

(a) continuing global emissions at 1990 levels; (b) halving of emissions in 1990; (c) reductions in emissions of 2% per year (pa) from 1990 and (d) a 2% pa increase from 1990-2010 followed by a 2% pa decrease from 2010.

3.1.5 Continuation of present day emissions is committing us to increased future concentrations, and the longer emissions continue to increase, the greater would reductions have to be to stabilize at a given level. If there are critical concentration levels that should not be exceeded, then the earlier emission reductions are made the more effective they are.

3.1.6 The term "*atmospheric stabilization*" is often used to describe the limiting of the concentration of the greenhouse gases at a certain level. The amount by which human-made emissions of a greenhouse gas must be reduced in order to stabilize at present day concentrations, for example, is shown in the table above. For most gases the reductions would have to be substantial.

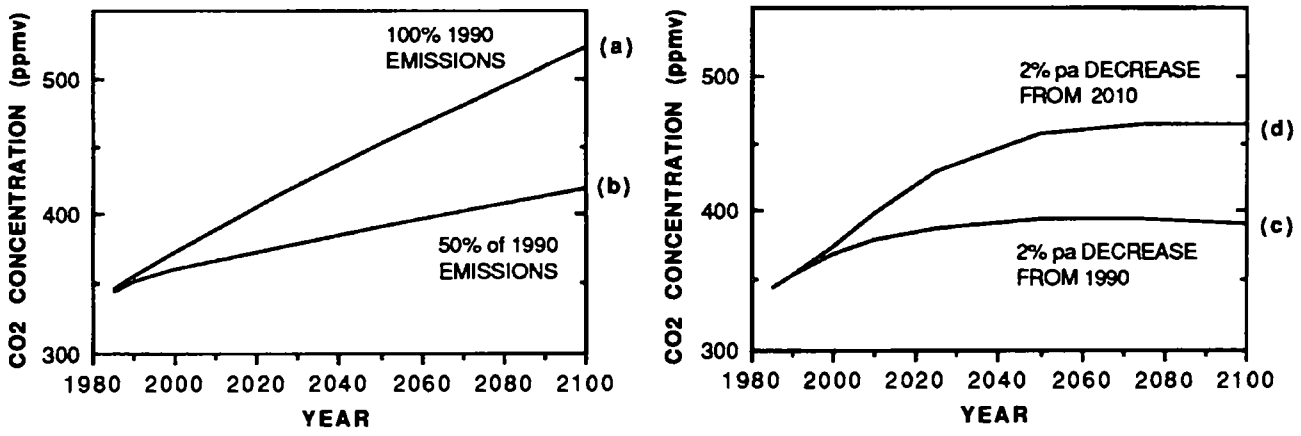

The relationship between hypothetical fossil fuel emissions of carbon dioxide and its concentration in the atmosphere is shown in the case where (a) emissions continue at 1990 levels, (b) emissions are reduced by 50% in 1990 and continue at that level, (c) emissions are reduced by 2% pa from 1990, and (d) emissions, after increasing by 2% pa until 2020, are then reduced by 2% pa thereafter.

3.2 How will greenhouse gas abundances change in the future?

3.2.1 We need to know future greenhouse gas concentrations in order to estimate future climate change. As already mentioned, these concentrations depend upon the magnitude of human-made emissions and on how changes in climate and other environmental conditions may influence the biospheric processes that control the exchange of natural greenhouse gases, including carbon dioxide and methane, between the atmosphere, oceans and terrestrial biosphere—the greenhouse gas "feedbacks".

3.2.2 Four scenarios of future human-made emissions were developed by Working Group III. The first of these assumes that few or no steps are taken to limit greenhouse gas emissions, and this is therefore termed Business-as-Usual (BaU). (It should be noted that an aggregation of national forecasts of emissions of carbon dioxide and methane to the year 2025 undertaken by Working Group III resulted in global emissions 10-20% higher than in the BaU scenario.) The other three scenarios assume that progressively increasing levels of controls reduce the growth of emissions; these are referred to as scenarios B, C, and D. They are briefly described in the Annex. Future concentrations of some of the greenhouse gases which would arise from these emissions are shown opposite.

3.3 Greenhouse gas feedbacks

3.3.1 Some of the possible feedbacks which could significantly modify future greenhouse gas concentrations in a warmer world are discussed in the following paragraphs.

3.3.2 The net emissions of carbon dioxide from terrestrial ecosystems will be elevated if higher temperatures increase respiration at a faster rate than photosynthesis, or if plant populations, particularly large forests, cannot adjust rapidly enough to changes in climate.

3.3.3 A net flux of carbon dioxide to the atmosphere may be particularly evident in warmer conditions in tundra and boreal regions where there are large stores of carbon. The opposite is true if higher abundances of carbon dioxide in the atmosphere enhance the productivity of natural ecosystems, or if there is an increase in soil moisture which can be expected to stimulate plant growth in dry ecosystems and to increase the storage of carbon in tundra peat. The extent to which ecosystems can sequester increasing atmospheric carbon dioxide remains to be quantified.

3.3.4 If the oceans become warmer, their net uptake of carbon dioxide may decrease because of changes in (i) the chemistry of carbon dioxide in seawater (ii) biological activity in surface waters and (iii) the rate of exchange of carbon dioxide between the surface layers and the deep ocean. This last depends upon the rate of formation of deep water in the ocean which, in the North Atlantic for example, might decrease if the salinity decreases as a result of a change in climate.

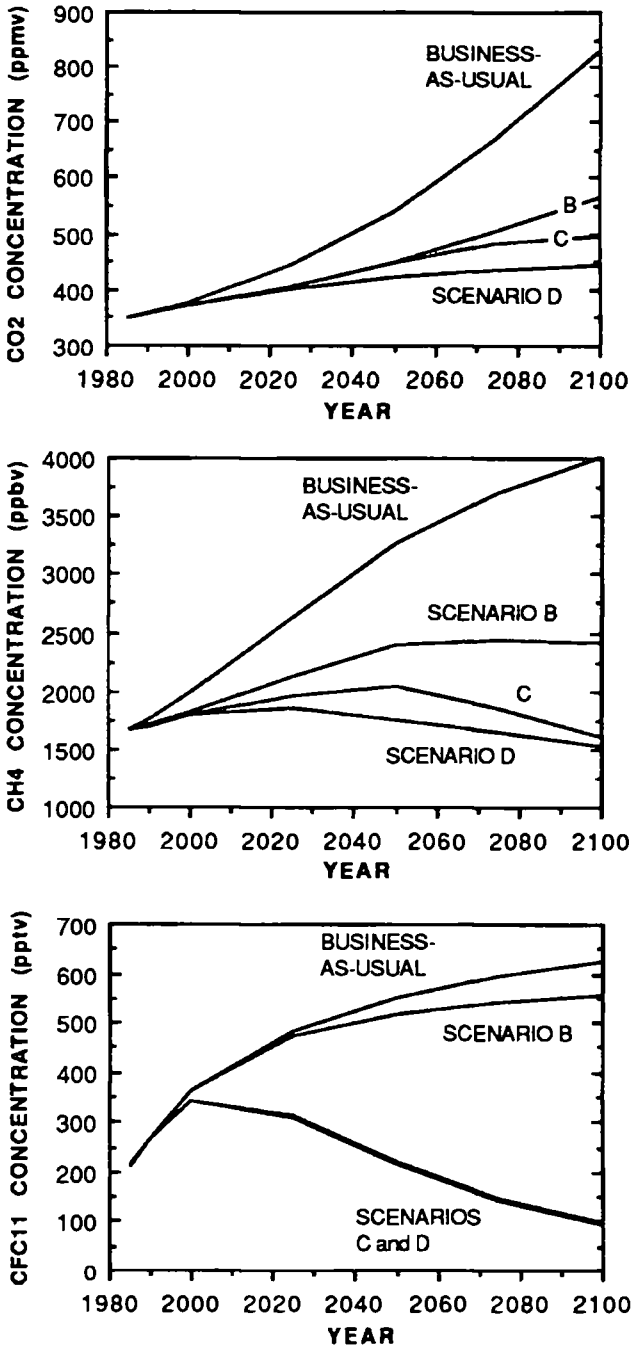

Atmospheric concentrations of carbon dioxide, methane and CFC-11 resulting from the four IPCC emissions scenarios

3.3.5 Methane emissions from natural wetlands and rice paddies are particularly sensitive to temperature and soil moisture. Emissions are significantly larger at higher temperatures and with increased soil moisture; conversely, a decrease in soil moisture would result in smaller emissions. Higher temperatures could increase the emissions of methane at high northern latitudes from decomposable organic matter trapped in permafrost and methane hydrates.

3.3.6 As illustrated earlier, ice core records show that methane and carbon dioxide concentrations changed in a similar sense to temperature between ice ages and interglacials.

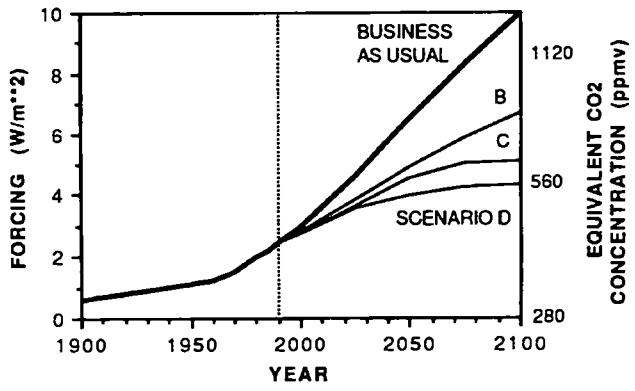

Increase in radiative forcing since the mid-18th century, and predicted to result from the four IPCC emissions scenarios, also expressed as equivalent carbon dioxide concentrations

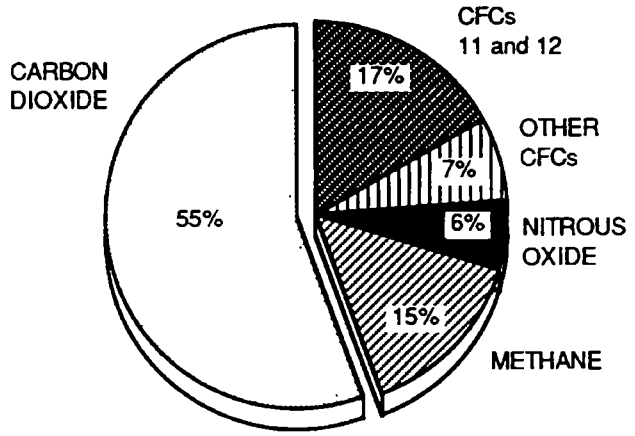

The contribution from each of the human-made greenhouse gases to the change in radiative forcing from 1980 to 1990. The contribution from ozone may also be significant, but cannot be quantified at present

3.3.7 Although many of these feedback processes are poorly understood, it seems likely that, overall, they will act to increase, rather than decrease, greenhouse gas concentrations in a warmer world.

4. Which gases are the most important?

4.0.1 We are certain that increased greenhouse gas concentrations increase radiative forcing. We can calculate the forcing with much more confidence than the climate change that results because the former avoids the need to evaluate a number of poorly understood atmospheric responses. We then have a base from which to calculate the relative effect on climate of an increase in concentration of each gas in the present-day atmosphere, both in absolute terms and relative to carbon dioxide. These relative effects span a wide range; methane is about 21 times more effective, molecule-for-molecule, than carbon dioxide, and CFC-11 about 12,000 times more effective. On a kilogram-per-kilogram basis, the equivalent values are 58 for methane and about 4,000 for CFC-11, both relative to carbon dioxide. Values for other greenhouse gases are to be found in the full report.

4.0.2 The total radiative forcing at any time is the sum of those from the individual greenhouse gases. We show in the figure below how this quantity has changed in the past (based on observations of greenhouse gases) and how it might change in the future (based on the four IPCC emissions scenarios). For simplicity, we can express total forcing in terms of the amount of carbon dioxide which would give that forcing; this is termed the equivalent carbon dioxide concentration. Greenhouse gases have increased since pre-industrial times (the mid-18th century) by an amount that is radiatively equivalent to about a 50% increase

GLOBAL WARMING POTENTIALS

The warming effect of an emission of 1 kg of each gas relative to that of CO_2
These figures are best estimates calculated on the basis of the present day atmospheric composition

	Time Horizon		
	20 yr	100 yr	500 yr
Carbon dioxide	1	1	1
Methane (including indirect)	63	21	9
Nitrous oxide	270	290	190
CFC-11	4500	3500	1500
CFC-12	7100	7300	4500
HCFC-22	4100	1500	510

Global Warming Potentials for a range of CFCs and potential replacements are given in the full text

in carbon dioxide, although carbon dioxide itself has risen by only 26%; other gases have made up the rest.

4.0.3 The contributions of the various gases to the total increase in climate forcing during the 1980s is shown above as a pie diagram; carbon dioxide is responsible for about half the decadal increase. (Ozone, the effects of which may be significant, is not included)

4.1 How can we evaluate the effect of different greenhouse gases?

4.1.1 To evaluate possible policy options, it is useful to know the relative radiative effect (and, hence, potential climate effect) of equal emissions of each of the greenhouse gases. The concept of relative Global Warming Potentials (GWP) has been developed to take into account the differing times that gases remain in the atmosphere.

4.1.2 This index defines the time-integrated warming effect due to an instantaneous release of unit mass (1 kg) of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide. The relative importances will change in the future as atmospheric composition changes because, although radiative forcing increases in direct proportion to the concentration of CFCs, changes in the other greenhouse gases (particularly carbon dioxide) have an effect on forcing which is much less than proportional.

4.1.3 The GWPs in the following table are shown for three time horizons, reflecting the need to consider the cumulative effects on climate over various time scales. The longer time horizon is appropriate for the cumulative effect; the shorter timescale will indicate the response to emission changes in the short term. There are a number of practical difficulties in devising and calculating the values of the GWPs, and the values given here should be considered as preliminary. In addition to these direct effects, there are indirect effects of human-made emissions arising from chemical reactions between the various constituents. The indirect effects on stratospheric water vapour, carbon dioxide and tropospheric ozone have been included in these estimates.

4.1.4 The table indicates, for example, that the effectiveness of methane in influencing climate will be greater in the first few decades after release, whereas emission of the longer-lived nitrous oxide will affect climate for a much longer time. The lifetimes of the proposed CFC replacements range from 1 to 40 years; the longer lived replacements are still potentially effective as agents of climate change. One example of this, HCFC-22 (with a 15–year lifetime), has a similar effect (when released in the same amount) as CFC-11 on a 20–year timescale; but less over a 500–year timescale.

4.1.5 The table shows carbon dioxide to be the least effective greenhouse gas per kilogramme emitted, but its contribution to global warming, which depends on the product of the GWP and the amount emitted, is largest. In the example in the box below, the effects over 100 years of emissions of greenhouse gases in 1990 are shown relative to carbon dioxide. This is illustrative; to compare the effect of different emission projections we have to sum the effect of emissions made in future years.

4.1.6 There are other technical criteria which may help policymakers to decide, in the event of emissions reductions being deemed necessary, which gases should be considered. Does the gas contribute in a major way to current, and future, climate forcing? Does it have a long lifetime, so earlier reductions in emissions would be more effective than those made later? And are its sources and sinks well enough known to decide which could be controlled in practice? The table **opposite** illustrates these factors.

The Relative Cumulative Climate Effect of 1990 Man-Made Emissions

	GWP (100yr horizon)	1990 emissions (Tg)	Relative contribution over 100yr
Carbon dioxide	1	26000†	61%
Methane*	21	300	15%
Nitrous oxide	290	6	4%
CFCs	Various	0.9	11%
HCFC-22	1500	0.1	0.5%
Others*	Various		8.5%

* These values include the indirect effect of these emissions on other greenhouse gases via chemical reactions in the atmosphere. Such estimates are highly model dependent and should be considered preliminary and subject to change. The estimated effect of ozone is included under "others". The gases included under "others" are given in the full report.

† 26 000 Tg (teragrams) of carbon dioxide = 7 000 Tg (=7 Gt) of carbon

Characteristics of Greenhouse Gases

GAS	MAJOR CONTRIBUTOR?	LONG LIFETIME?	SOURCES KNOWN?
Carbon dioxide	yes	yes	yes
Methane	yes	no	semi-quantitatively
Nitrous oxide	not at present	yes	qualitatively
CFCs	yes	yes	yes
HCFCs, etc	not at present	mainly no	yes
Ozone	possibly	no	qualitatively

5. How much do we expect climate to change?

5.0.1 It is relatively easy to determine the direct effect of the increased radiative forcing due to increases in greenhouse gases. However, as climate begins to warm, various processes act to amplify (through positive feedbacks) or reduce (through negative feedbacks) the warming. The main feedbacks which have been identified are due to changes in water vapour, sea-ice, clouds and the oceans.

5.0.2 The best tools we have which take the above feedbacks into account (but do not include greenhouse gas feedbacks) are three-dimensional mathematical models of the climate system (atmosphere-ocean-ice-land), known as General Circulation Models (GCMs). They synthesize our knowledge of the physical and dynamical processes in the overall system and allow for the complex interactions between the various components. However, in their current state of development, the descriptions of many of the processes involved are comparatively crude. Because of this, considerable uncertainty is attached to these predictions of climate change, which is reflected in the range of values given; further details are given in a later section.

5.0.3 The estimates of climate change presented here are based on

i) the "best estimate" of equilibrium climate sensitivity (i.e the equilibrium temperature change due to a doubling of carbon dioxide in the atmosphere) obtained from model simulations, feedback analyses and observational considerations (see later box: "What tools do we use?")

ii) a "box diffusion upwelling" ocean-atmosphere climate model which translates the greenhouse forcing into the evolution of the temperature response for the prescribed climate sensitivity. (This simple model has been calibrated against more complex atmosphere-ocean coupled GCMs for situations where the more complex models have been run).

5.1 How quickly will global climate change?

a. If emissions follow a Business-as-Usual pattern

5.1.1 Under the IPCC Business-as-Usual (Scenario A) emissions of greenhouse gases, the average rate of increase of global-mean temperature during the next century is estimated to be about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C). This will result in a likely increase in global-mean temperature of about 1°C above the present value (about 2°C above that in the pre-industrial period) by 2025 and 3°C above today's (about 4°C above pre-industrial) before the end of the next century.

5.1.2 The projected temperature rise out to the year 2100, with high, low and best-estimate climate responses, is shown in the diagram below. Because of other factors which influence climate, we would not expect the rise to be a steady one.

5.1.3 The temperature rises shown above are realized temperatures; at any time we would also be committed to a further temperature rise toward the equilibrium temperature (see box: "Equilibrium and Realized Climate Change"). For the BaU "best estimate" case in the year 2030, for example, a further 0.9°C rise would be expected, about 0.2°C of which would be realized by 2050 (in addition to changes due to further greenhouse gas increases); the rest would become apparent in decades or centuries.

5.1.4 Even if we were able to stabilize emissions of each of the greenhouse gases at present day levels from now on, the temperature is predicted to rise by about 0.2°C per decade for the first few decades.

5.1.5 The global warming will also lead to increased

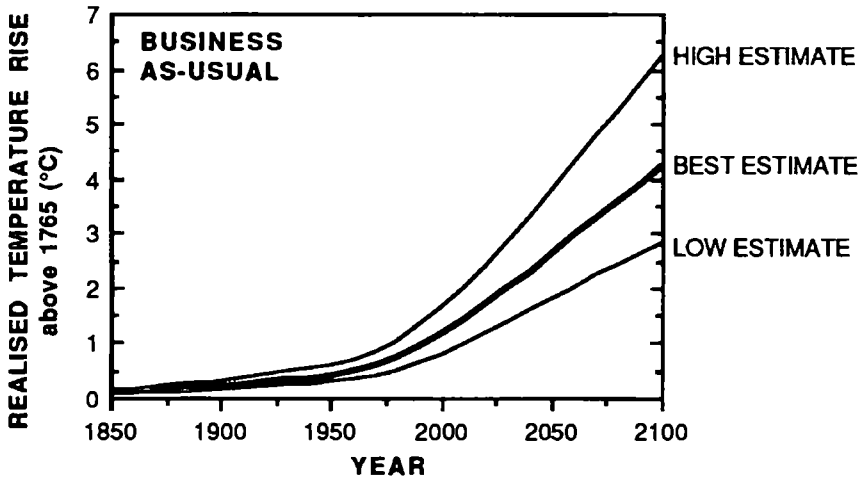

Simulation of the increase in global mean temperature from 1850-1990 due to observed increases in greenhouse gases, and predictions of the rise between 1990 and 2100 resulting from the Business-as-Usual scenario.

global average precipitation and evaporation of a few percent by 2030. Areas of sea-ice and snow are expected to diminish.

b. If emissions are subject to controls

5.1.6 Under the other IPCC emission scenarios which assume progressively increasing levels of controls, average rates of increase in global-mean temperature over the next century are estimated to be about 0.2°C per decade (Scenario B), just above 0.1°C per decade (Scenario C) and about 0.1°C per decade (Scenario D). The results are illustrated below with the Business-as-Usual case for comparison. Only the best-estimate of the temperature rise is shown in each case.

5.1.7 The indicated range of uncertainty in global temperature rise given above reflects a subjective assessment of uncertainties in the calculation of climate response, but does not include those due to the transformation of emissions to concentrations, nor the effects of greenhouse gas feedbacks.

5.2 What will be the patterns of climate change by 2030?

5.2.1 Knowledge of the global-mean warming and change in precipitation is of limited use in determining the impacts of climate change, for instance on agriculture. For this we need to know changes, regionally and seasonally.

5.2.2 Models predict that surface air will warm faster over land than over oceans, and a minimum of warming will occur around Antarctica and in the northern North Atlantic region.

5.2.3 There are some continental-scale changes which are consistently predicted by the highest resolution models and for which we understand the physical reasons. The warming is predicted to be 50-100% greater than the global-mean in high northern latitudes in winter, and substantially smaller than the global-mean in regions of sea ice in summer. Precipitation is predicted to increase on average in middle and high latitude continents in winter (by some 5—10% over 35-55°N).

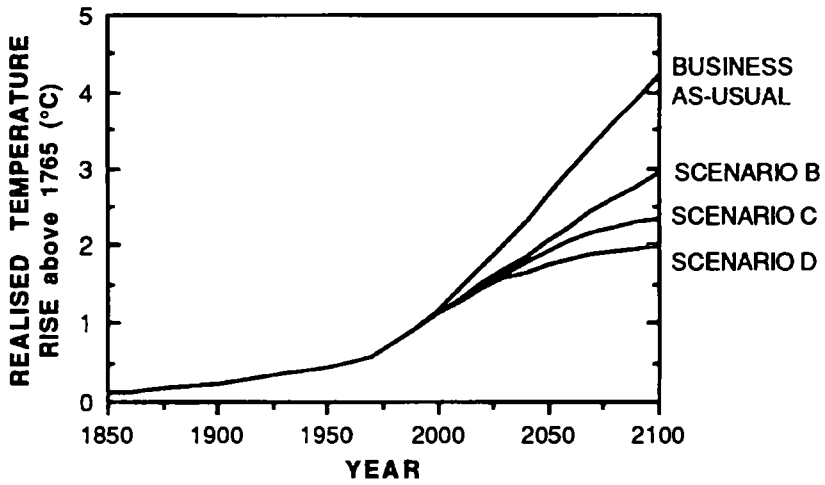

Simulations of the increase in global mean temperature from 1850-1990 due to observed increases in greenhouse gases, and predictions of the rise between 1990 and 2100 resulting from the IPCC Scenario B, C and D emissions, with the Business-as-Usual case for comparison.

What tools do we use to predict future climate, and how do we use them?

The most highly developed tool which we have to predict future climate is known as a general circulation model or GCM. Such models are based on the laws of physics and use descriptions in simplified physical terms (called parameterisations) of the smaller-scale processes such as those due to clouds and deep mixing in the ocean. In a climate model an atmospheric component, essentially the same as a weather prediction model, is coupled to a model of the ocean, which can be equally complex.

Climate forecasts are derived in a different way from weather forecasts. A weather prediction model gives a description of the atmosphere's state up to 10 days or so ahead, starting from a detailed description of an initial state of the atmosphere at a given time. Such forecasts describe the movement and development of large weather systems, though they cannot represent very small scale phenomena; for example, individual shower clouds.

To make a climate forecast, the climate model is first run for a few (simulated) decades. The statistics of the model's output is a description of the model's simulated climate which, if the model is a good one, will bear a close resemblance to the climate of the real atmosphere and ocean. The above exercise is then repeated with increasing concentrations of the greenhouse gases in the model. The differences between the statistics of the two simulations (for example in mean temperature and interannual variability) provide an estimate of the accompanying climate change.

The long-term change in surface air temperature following a doubling of carbon dioxide (referred to as the climate sensitivity) is generally used as a benchmark to compare models. The range of results from model studies is 1.9 to 5.2°C. Most results are close to 4.0°C but recent studies using a more detailed but not necessarily more accurate representation of cloud processes give results in the lower half of this range. Hence the models results do not justify altering the previously accepted range of 1.5 to 4.5°C.

Although scientists are reluctant to give a single best estimate in this range, it is necessary for the presentation of climate predictions for a choice of best estimate to be made. Taking into account the model results, together with observational evidence over the last century which is suggestive of the climate sensitivity being in the lower half of the range, (see section: "Has man already begun to change global climate?") a value of climate sensitivity of 2.5°C has been chosen as the best estimate.

In this Assessment, we have also used much simpler models, which simulate the behaviour of GCMs, to make predictions of the evolution with time of global temperature from a number of emission scenarios. These so-called box-diffusion models contain highly simplified physics but give similar results to GCMs when globally averaged.

A completely different, and potentially useful, way of predicting patterns of future climate is to search for periods in the past when the global mean temperatures were similar to those we expect in future, and then use the past spatial patterns as analogueues of those which will arise in the future. For a good analogueue, it is also necessary for the forcing factors (for example, greenhouse gases, orbital variations) and other conditions (for example, ice cover, topography, etc.) to be similar; direct comparisons with climate situations for which these conditions do not apply cannot be easily interpreted. Analogueues of future greenhouse-gas-changed climates have not been found.

We cannot therefore advocate the use of palaeo-climates as predictions of regional climate change due to future increases in greenhouse gases. However, palaeo-climatological information can provide useful insights into climate processes, and can assist in the validation of climate models.

5.2.4 Five regions, each a few million square kilometres in area and representative of different climatological regimes, were selected by IPCC for particular study (see map below). In the box below are given the changes in temperature, precipitation and soil moisture, which are predicted to occur by 2030 on the Business-as-Usual scenario, as an average over each of the five regions. There may be considerable variations within the regions. In general, confidence in these regional estimates is low, especially for the changes in precipitation and soil moisture, but they are examples of our best estimates. We cannot yet give reliable regional predictions at the smaller scales demanded for impacts assessments.

5.3 How will climate extremes and extreme events change?

5.3.1 Changes in the variability of weather and the frequency of extremes will generally have more impact than changes in the mean climate at a particular location. With the possible exception of an increase in the number of intense showers, there is no clear evidence that weather

Equilibrium and realized climate change

When the radiative forcing on the earth-atmosphere system is changed, for example by increasing greenhouse gas concentrations, the atmosphere will try to respond (by warming) immediately. But the atmosphere is closely coupled to the oceans, so in order for the air to be warmed by the greenhouse effect, the oceans also have to be warmed; because of their thermal capacity this takes decades or centuries. This exchange of heat between atmosphere and ocean will act to slow down the temperature rise forced by the greenhouse effect.

In a hypothetical example where the concentration of greenhouse gases in the atmosphere, following a period of constancy, rises suddenly to a new level and remains there, the radiative forcing would also rise rapidly to a new level. This increased radiative forcing would cause the atmosphere and oceans to warm, and eventually come to a new, stable, temperature. A commitment to this equilibrium temperature rise is incurred as soon as the greenhouse gas concentration changes. But at any time before equilibrium is reached, the actual temperature will have risen by only part of the equilibrium temperature change, known as the realized temperature change.

Models predict that, for the present day case of an increase in radiative forcing which is approximately steady, the realized temperature rise at any time is about 50% of the committed temperature rise if the climate sensitivity (the response to a doubling of carbon dioxide) is 4.5°C and about 80% if the climate sensitivity is 1.5°C. If the forcing were then held constant, temperatures would continue to rise slowly, but it is not certain whether it would take decades or centuries for most of the remaining rise to equilibrium to occur.

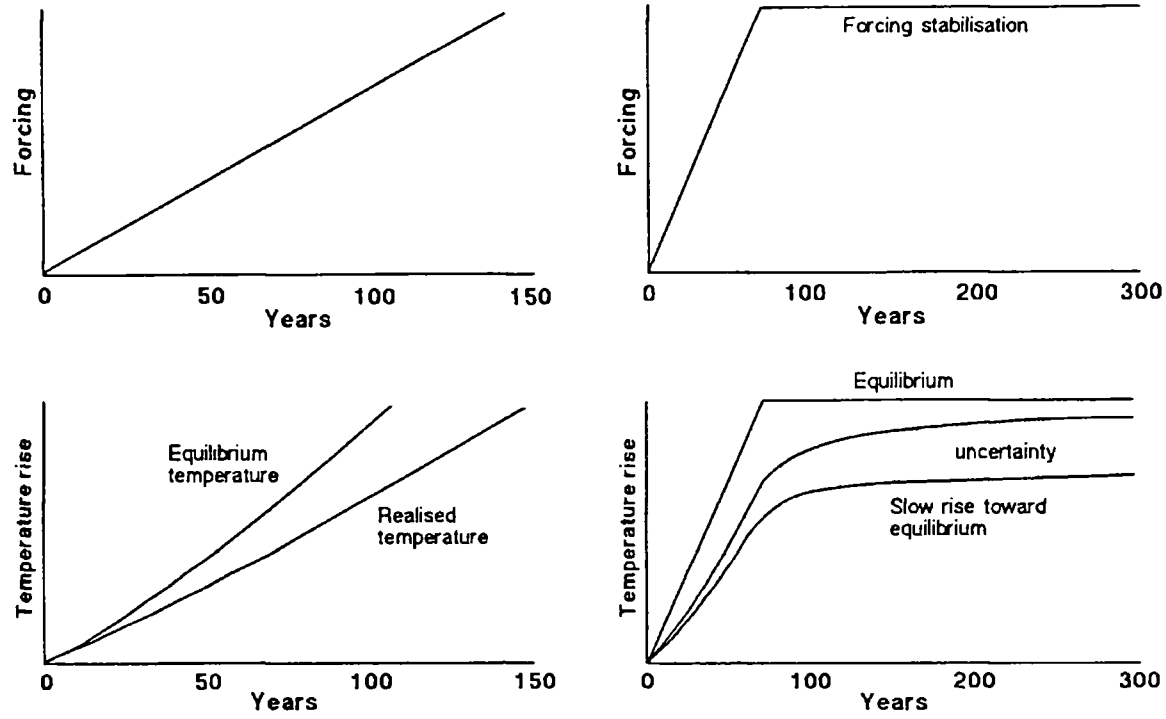

variability will change in the future. In the case of temperatures, assuming no change in variability, but with a modest increase in the mean, the number of days with temperatures above a given value at the high end of the distribution will increase substantially. On the same assumptions, there will be a decrease in days with temperatures at the low end of the distribution. So the number of very hot days or frosty nights can be substantially changed without any change in the variability of the weather. The number of days with a minimum threshold amount of soil moisture (for viability of a certain crop, for example) would be even more sensitive to changes in average precipitation and evaporation.

5.3.2 If the large scale weather regimes, for instance depression tracks or anticyclones, shift their position, this would effect the variability and extremes of weather at a particular location, and could have a major effect. However, we do not know if, or in what way, this will happen.

5.4 Will storms increase in a warmer world?

5.4.1 Storms can have a major impact on society. Will their frequency, intensity or location increase in a warmer world?

5.4.2 Tropical storms, such as typhoons and hurricanes, only develop at present over seas that are warmer than about

Estimates for changes by 2030

(IPCC Business-as-Usual scenario; changes from pre-industrial)

The numbers given below are based on high resolution models, scaled to be consistent with our best estimate of global mean warming of 1.8°C by 2030. For values consistent with other estimates of global temperature rise, the numbers below should be reduced by 30% for the low estimate or increased by 50% for the high estimate. Precipitation estimates are also scaled in a similar way.

Confidence in these regional estimates is low

Central North America (35°—50°N 85°—105°W)

The warming varies from 2 to 4°C in winter and 2 to 3°C in summer. Precipitation increases range from 0 to 15% in winter whereas there are decreases of 5 to 10% in summer. Soil moisture decreases in summer by 15 to 20%.

Southern Asia (5°—30°N 70°—105°E)

The warming varies from 1 to 2°C throughout the year. Precipitation changes little in winter and generally increases throughout the region by 5 to 15% in summer. Summer soil moisture increases by 5 to 10%.

Sahel (10°—20°N 20°W—40°E)

The warming ranges from 1 to 3°C. Area mean precipitation increases and area mean soil moisture decreases marginally in summer. However, throughout the region, there are areas of both increase and decrease in both parameters.

Southern Europe (35°—50°N 10°W—45°E)

The warming is about 2°C in winter and varies from 2 to 3°C in summer. There is some indication of increased precipitation in winter, but summer precipitation decreases by 5 to 15%, and summer soil moisture by 15 to 25%.

Australia (12°—45°S 110°—115°E)

The warming ranges from 1 to 2°C in summer and is about 2°C in winter. Summer precipitation increases by around 10%, but the models do not produce consistent estimates of the changes in soil moisture. The area averages hide large variations at the sub-continental level.

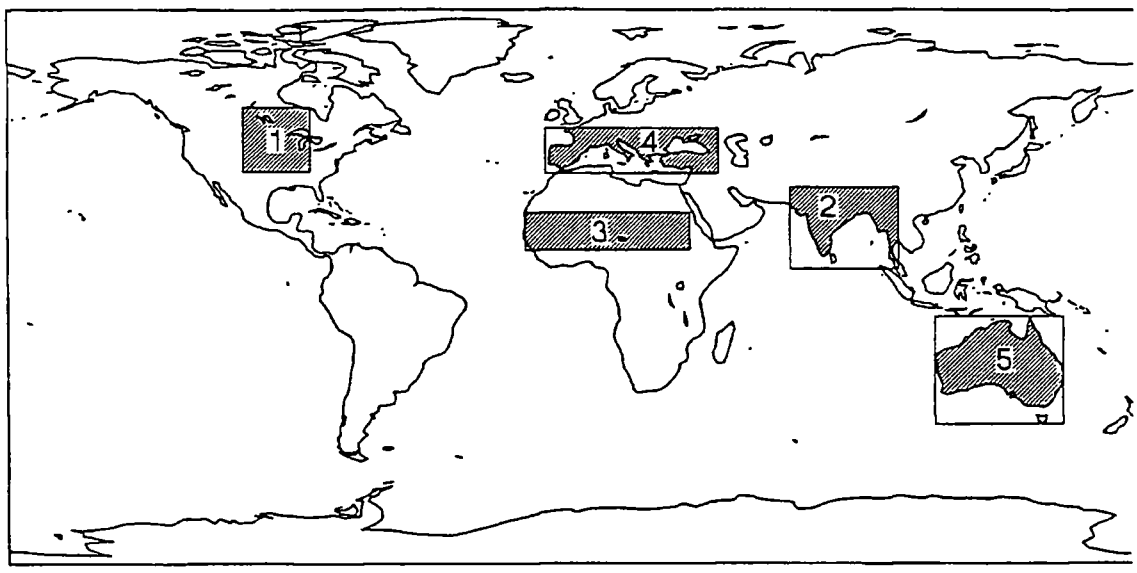

Map showing the locations and extents of the five areas selected by IPCC

26°C. Although the area of sea having temperatures over this critical value will increase as the globe warms, the critical temperature itself may increase in a warmer world. Although the theoretical maximum intensity is expected to increase with temperature, climate models give no consistent indication whether tropical storms will increase or decrease in frequency or intensity as climate changes; neither is there any evidence that this has occurred over the past few decades.

5.4.3 Mid-latitude storms, such as those which track across the North Atlantic and North Pacific, are driven by the equator-to-pole temperature contrast. As this contrast will probably be weakened in a warmer world (at least in the northern hemisphere), it might be argued that mid-latitude storms will also weaken or change their tracks, and there is some indication of a general reduction in day-to-day variability in the mid-latitude storm tracks in winter in model simulations, though the pattern of changes vary from model to model. Present models do not resolve smaller-scale disturbances, so it will not be possible to assess changes in storminess until results from higher resolution models become available in the next few years.

5.5 Climate change in the longer term

5.5.1 The foregoing calculations have focussed on the period up to the year 2100; it is clearly more difficult to make calculations for years beyond 2100. However, while the timing of a predicted increase in global temperatures has substantial uncertainties, the prediction that an increase will eventually occur is more certain. Furthermore, some model calculations that have been extended beyond 100 years suggest that, with continued increases in greenhouse climate forcing, there could be significant changes in the ocean circulation, including a decrease in North Atlantic deep water formation.

5.6 Other factors which could influence future climate

5.6.1 Variations in the output of solar energy may also affect climate. On a decadal timescale solar variability and changes in greenhouse gas concentration could give changes of similar magnitudes. However the variation in solar intensity changes sign so that over longer timescales the increases in greenhouse gases are likely to be more important. Aerosols as a result of volcanic eruptions can lead to a cooling at the surface which may oppose the greenhouse warming for a few years following an eruption. Again, over longer periods the greenhouse warming is likely to dominate.

5.6.2 Human activity is leading to an increase in aerosols in the lower atmosphere, mainly from sulphur emissions. These have two effects, both of which are difficult to quantify but which may be significant particularly at the regional level. The first is the direct effect of the aerosols on the radiation scattered and absorbed by the atmosphere. The second is an indirect effect whereby the aerosols affect the microphysics of clouds leading to an increased cloud reflectivity. Both these effects might lead to a significant regional cooling; a decrease in emissions of sulphur might be expected to increase global temperatures.

5.6.3 Because of long-period couplings between different components of the climate system, for example between ocean and atmosphere, the earth's climate would still vary without being perturbed by any external influences. This natural variability could act to add to, or subtract from, any human-made warming; on a century timescale this would be less than changes expected from greenhouse gas increases.

6. How much confidence do we have in our predictions?

6.0.1 Uncertainties in the above climate predictions arise from our imperfect knowledge of:

- future rates of human-made emissions
- how these will change the atmospheric concentrations of greenhouse gases
- the response of climate to these changed concentrations.

6.0.2 Firstly, it is obvious that the extent to which climate will change depends on the rate at which greenhouse gases (and other gases which affect their concentrations) are emitted. This in turn will be determined by various complex economic and sociological factors. Scenarios of future emissions were generated within IPCC WG III and are described in the annex.

6.0.3 Secondly, because we do not fully understand the sources and sinks of the greenhouse gases, there are uncertainties in our calculations of future concentrations arising from a given emissions scenario. We have used a number of models to calculate concentrations and chosen a best estimate for each gas. In the case of carbon dioxide, for example, the concentration increase between 1990 and 2070 due to the Business-as-Usual emissions scenario spanned almost a factor of two between the highest and lowest model result (corresponding to a range in radiative forcing change of about 50%)

6.0.4 Furthermore, because natural sources and sinks of greenhouse gases are sensitive to a change in climate, they may substantially modify future concentrations (see earlier section: "Greenhouse gas feedbacks"). It appears that, as climate warms, these feedbacks will lead to an overall increase, rather than decrease, in natural greenhouse gas abundances. For this reason, climate change is likely to be greater than the estimates we have given.

Confidence in predictions from climate models

What confidence can we have that climate change due to increasing greenhouse gases will look anything like the model predictions? Weather forecasts can be compared with the actual weather the next day and their skill assessed; we cannot do that with climate predictions. However, there are several indicators that give us some confidence in the predictions from climate models.

When the latest atmospheric models are run with the present atmospheric concentrations of greenhouse gases and observed boundary conditions their simulation of present climate is generally realistic on large scales, capturing the major features such as the wet tropical convergence zones and mid-latitude depression belts, as well as the contrasts between summer and winter circulations. The models also simulate the observed variability: for example, the large day-to-day pressure variations in the middle latitude depression belts and the maxima in interannual variability responsible for the very different character of one winter from another both being represented. However, on regional scales (2,000 km or less), there are significant errors in all models.

Overall confidence is increased by atmospheric models' generally satisfactory portrayal of aspects of variability of the atmosphere, for instance those associated with variations in sea surface temperature. There has been some success in simulating the general circulation of the ocean, including the patterns (though not always the intensities) of the principal currents, and the distributions of tracers added to the ocean.

Atmospheric models have been coupled with simple models of the ocean to predict the equilibrium response to greenhouse gases, under the assumption that the model errors are the same in a changed climate. The ability of such models to simulate important aspects of the climate of the last ice age generates confidence in their usefulness. Atmospheric models have also been coupled with multilayer ocean models (to give coupled ocean-atmosphere GCMs) which predict the gradual response to increasing greenhouse gases. Although the models so far are of relatively coarse resolution, the large scale structures of the ocean and the atmosphere can be simulated with some skill. However, the coupling of ocean and atmosphere models reveals a strong sensitivity to small scale errors which leads to a drift away from the observed climate. As yet, these errors must be removed by adjustments to the exchange of heat between ocean and atmosphere. There are similarities between results from the coupled models using simple representations of the ocean and those using more sophisticated descriptions, and our understanding of such differences as do occur gives us some confidence in the results.

6.0.5 Thirdly, climate models are only as good as our understanding of the processes which they describe, and this is far from perfect. The ranges in the climate predictions given above reflect the uncertainties due to model imperfections; the largest of these is cloud feedback (those factors affecting the cloud amount and distribution and the interaction of clouds with solar and terrestrial radiation), which leads to a factor of two uncertainty in the size of the warming. Others arise from the transfer of energy between the atmosphere and ocean, the atmosphere and land surfaces, and between the upper and deep layers of the ocean. The treatment of sea-ice and convection in the models is also crude. Nevertheless, for reasons given in the box below, we have substantial confidence that models can predict at least the broad-scale features of climate change.

6.0.6 Furthermore, we must recognize that our imperfect understanding of climate processes (and corresponding ability to model them) could make us vulnerable to surprises; just as the human-made ozone hole over Antarctica was entirely unpredicted. In particular, the ocean circulation, changes in which are thought to have led to periods of comparatively rapid climate change at the end of the last ice age, is not well observed, understood or modelled.

7. Will the climate of the future be very different?

7.0.1 When considering future climate change, it is clearly essential to look at the record of climate variation in the past. From it we can learn about the range of natural climate variability, to see how it compares with what we expect in the future, and also look for evidence of recent climate change due to man's activities.

7.0.2 Climate varies naturally on all time scales from hundreds of millions of years down to the year to year. Prominent in the Earth's history have been the 100,000 year glacial-interglacial cycles when climate was mostly cooler than at present. Global surface temperatures have typically varied by 5-7°C through these cycles, with large changes in ice volume and sea level, and temperature changes as great as 10-15°C in some middle and high latitude regions of the northern hemisphere. Since the end of the last ice age, about 10,000 years ago, global surface temperatures have probably fluctuated by little more than 1°C. Some fluctuations have lasted several centuries, including the Little Ice Age which ended in the nineteenth century and which appears to have been global in extent.

7.0.3 The changes predicted to occur by about the middle of the next century due to increases in greenhouse gas concentrations from the Business-as-Usual emissions will make global-mean temperatures higher than they have been in the last 150,000 years.

7.0.4 The rate of change of global temperatures predicted for Business-as-Usual emissions will be greater than those which have occurred naturally on earth over the last 10,000 years, and the rise in sea level will be about three to six times faster than that seen over the last 100 years or so.

8. Has man already begun to change the global climate?

8.0.1 The instrumental record of surface temperature is fragmentary until the mid- nineteenth century, after which it slowly improves. Because of different methods of measurement, historical records have to be harmonized with modern observations, introducing some uncertainty. Despite these problems we believe that a real warming of the globe of 0.3°C—0.6°C has taken place over the last century; any bias due to urbanization is likely to be less than 0.05°C.

8.0.2 Moreover since 1900 similar temperature increases are seen in three independent data sets: one collected over land and two over the oceans. The figure below shows current estimates of smoothed global mean surface temperature over land and ocean since 1860. Confidence in the records has been increased by their similarity to recent satellite measurements of mid-tropospheric temperatures.

8.0.3 Although the overall temperature rise has been broadly similar in both hemispheres, it has not been steady, and differences in their rates of warming have sometimes persisted for decades. Much of the warming since 1900 has been concentrated in two periods, the first between about 1910 and 1940 and the other since 1975; the five warmest years on record have all been in the 1980s. The northern hemisphere cooled between the 1940s and the early 1970s when southern hemisphere temperatures stayed nearly constant. The pattern of global warming since 1975 has been uneven with some regions, mainly in the northern hemisphere, continuing to cool until recently. This regional diversity indicates that future regional temperature changes are likely to differ considerably from a global average.

8.0.4 The conclusion that global temperature has been rising is strongly supported by the retreat of most mountain glaciers of the world since the end of the nineteenth century and the fact that global sea level has risen over the same period by an average of 1 to 2 mm per year. Estimates of thermal expansion of the oceans, and of increased melting of mountain glaciers and the ice margin in West Greenland over the last century, show that the major part of the sea-level rise appears to be related to the observed global warming. This apparent connection between observed sea-level rise and global warming provides grounds for believing that future warming will lead to an acceleration in sea-level rise.

8.0.5 The size of the warming over the last century is broadly consistent with the predictions of climate models, but is also of the same magnitude as natural climate variability. If the sole cause of the observed warming were the human-made greenhouse effect, then the implied climate sensitivity would be near the lower end of the range inferred from the models. The observed increase could be largely due to natural variability; alternatively this variability and other man-made factors could have offset a still larger man-made greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more, when the commitment to future climate change will then be considerably larger than it is today.

8.0.6 Global mean temperature alone is an inadequate indicator of greenhouse-gas-induced climatic change.

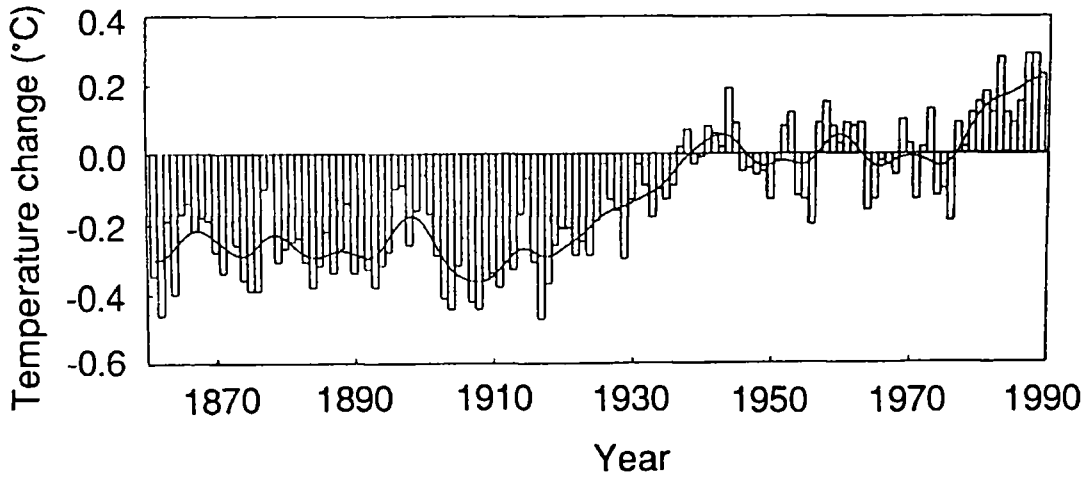

Global mean combined land-air and sea-surface temperatures, 1861—1989, relative to the average for 1951—1980

Identifying the causes of any global mean temperature change requires examination of other aspects of the changing climate, particularly its spatial and temporal characteristics—the man-made climate change "signal". Patterns of climate change from models such as the northern hemisphere warming faster than the southern hemisphere, and surface air warming faster over land than over oceans, are not apparent in observations to date. However, we do not yet know what the detailed "signal" looks like because we have limited confidence in our predictions of climate change patterns. Furthermore, any changes to date could be masked by natural variability and other (possibly man-made) factors, and we do not have a clear picture of these.

9. How much will sea level rise ?

9.0.1 Simple models were used to calculate the rise in sea level to the year 2100; the results are illustrated below. The calculations necessarily ignore any long-term changes, unrelated to greenhouse forcing, that may be occurring but cannot be detected from the present data on land ice and the ocean. The sea-level rise expected from 1990-2100 under the IPCC Business-as-Usual emissions scenario is shown below. An average rate of global mean sea-level rise of about 6 cm per decade over the next century (with an uncertainty range of 3—10 cm per decade). The predicted rise is about 20 cm in global mean sea level by 2030, and 65 cm by the end of the next century. There will be significant regional variations.

9.0.2 The best estimate in each case is made up mainly of positive contributions from thermal expansion of the oceans and the melting of glaciers. Although, over the next 100 years, the effect of the Antarctic and Greenland ice sheets is expected to be small, they make a major contribution to the uncertainty in predictions.

9.0.3 Even if greenhouse forcing increased no further, there would still be a commitment to a continuing sea-level

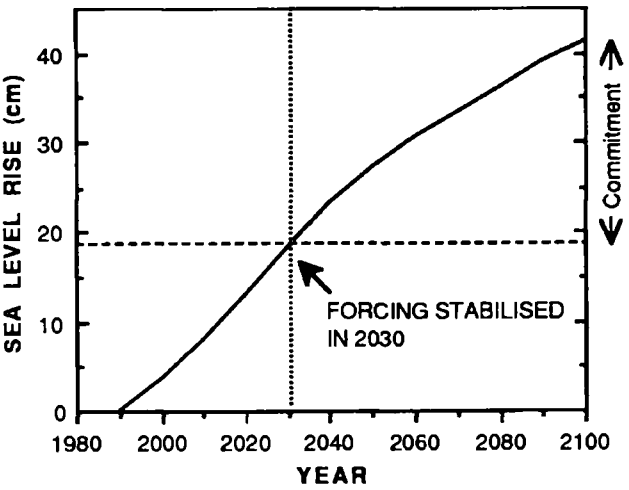

Commitment to sea level rise in the year 2030. The curve shows the sea level rise due to Business-As-Usual emissions to 2030, with the additional rise that would occur in the remainder of the century even if climate forcing was stablised in 2030.

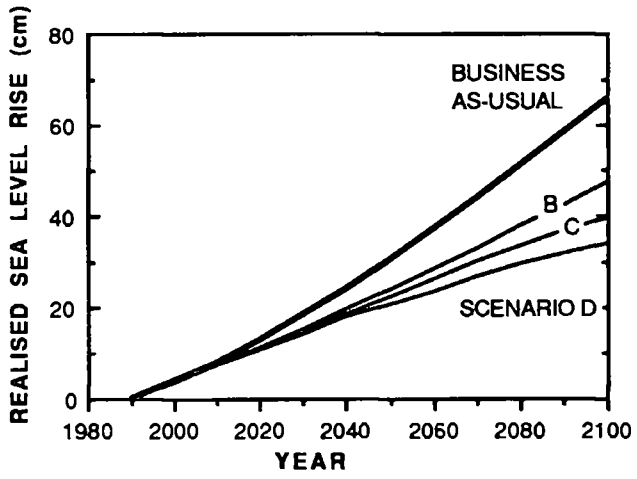

Model estimates of sea-level rise from 1990—2100 due to all four emissions scenarios.

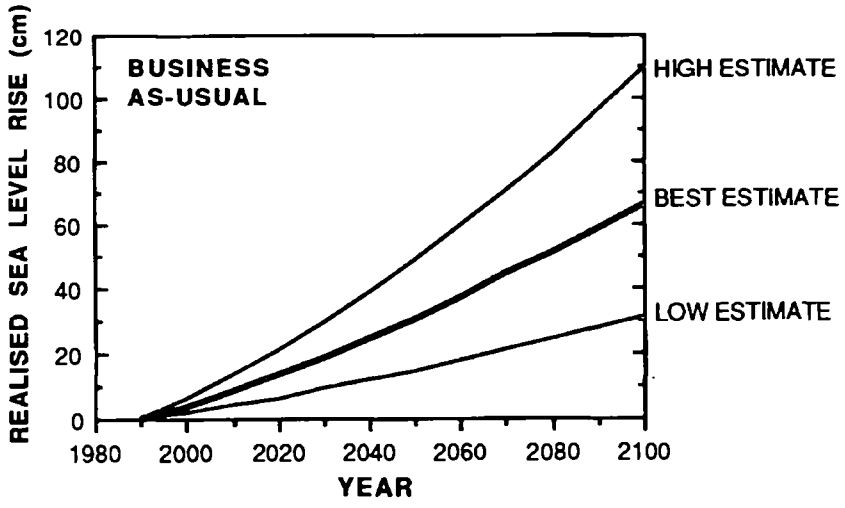

Sea level rise predicted to result from Business-as-Usual emissions, showing the best-estimate and range

rise for many decades and even centuries, due to delays in climate, ocean and ice mass responses. As an illustration, if the increases in greenhouse gas concentrations were to suddenly stop in 2030, sea level would go on rising from 2030 to 2100, by as much again as from 1990-2030, as shown in the diagram on p.35.

9.0.4 Predicted sea level rises due to the other three emissions scenarios arealso shown, with the Business-as-Usual case for comparison; only best-estimate calculations are shown.

9.0.5 The West Antarctic Ice Sheet is of special concern. A large portion of it, containing an amount of ice equivalent to about 5 m of global sea level, is grounded far below sea level. There have been suggestions that a sudden outflow of ice might result from global warming and raise sea level quickly and substantially. Recent studies have shown that individual ice streams are changing rapidly on a decade-to-century timescale; however this is not necessarily related to climate change. Within the next century, it is not likely that there will be a major outflow of ice from West Antarctica due directly to global warming.

9.0.6 Any rise in sea level is not expected to be uniform over the globe. Thermal expansion, changes in ocean circulation, and surface air pressure will vary from region to region as the world warms, but in an as yet unknown way. Such regional details await further development of more realistic coupled ocean-atmosphere models. In addition, vertical land movements can be as large or even larger than changes in global mean sea level; these movements have to be taken into account when predicting local change in sea level relative to land.

9.0.7 The most severe effects of sea-level rise are likely to result from extreme events (for example, storm surges) the incidence of which may be affected by climatic change.

10. What will be the effect of climate change on ecosystems?

10.0.1 Ecosystem processes such as photosynthesis and respiration are dependent on climatic factors and carbon dioxide concentration in the short term. In the longer term, climate and carbon dioxide are among the factors which control ecosystem structure, i .e, species composition, either directly by increasing mortality in poorly adapted species, or indirectly by mediating the competition between species. Ecosystems will respond to local changes in temperature (including its rate of change), precipitation, soil moisture and extreme events. Current models are unable to make reliable estimates of changes in these parameters on the required local scales.

10.0.2 Photosynthesis captures atmospheric carbon dioxide, water and solar energy and stores them in organic compounds which are then used for subsequent plant growth, the growth of animals or the growth of microbes in

Deforestation and reforestation

Man has been deforesting the Earth for millennia. Until the early part of the century, this was mainly in temperate regions, more recently it has been concentrated in the tropics. Deforestation has several potential impacts on climate: through the carbon and nitrogen cycles (where it can lead to changes in atmospheric carbon dioxide concentrations), through the change in reflectivity of terrain when forests are cleared, through its effect on the hydrological cycle (precipitation, evaporation and runoff) and surface roughness and thus atmospheric circulation which can produce remote effects on climate.

It is estimated that each year about 2 Gt of carbon (GtC) is released to the atmosphere due to tropical deforestation. The rate of forest clearing is difficult to estimate; probably until the mid-20th century, temperate deforestation and the loss of organic matter from soils was a more important contributor to atmospheric carbon dioxide than was the burning of fossil fuels. Since then, fossil fuels have become dominant; one estimate is that around 1980, 1.6 GtC was being released annually from the clearing of tropical forests, compared with about 5 GtC from the burning of fossil fuels. If all the tropical forests were removed, the input is variously estimated at from 150 to 240 GtC; this would increase atmospheric carbon dioxide by 35 to 60 ppmv.

To analyse the effect of reforestation we assume that 10 million hectares of forests are planted each year for a period of 40 years, i.e., 4 million km^2 would then have been planted by 2030, at which time 1 GtC would be absorbed annually until these forests reach maturity. This would happen in 40—100 years for most forests. The above scenario implies an accumulated uptake of about 20GtC by the year 2030 and up to 80GtC after 100 years. This accumulation of carbon in forests is equivalent to some 5-10% of the emission due to fossil fuel burning in the Business-as-Usual scenario.

Deforestation can also alter climate directly by increasing reflectivity and decreasing evapotranspiration. Experiments with climate models predict that replacing all the forests of the Amazon Basin by grassland would reduce the rainfall over the basin by about 20%, and increase mean temperature by several degrees.

the soil. All of these organisms release carbon dioxide via respiration into the atmosphere. Most land plants have a system of photosynthesis which will respond positively to increased atmospheric carbon dioxide ("the carbon dioxide fertilization effect") but the response varies with species. The effect may decrease with time when restricted by other ecological limitations, for example, nutrient availability. It should be emphasized that the carbon content of the terrestrial biosphere will increase only if the forest ecosystems in a state of maturity will be able to store more carbon in a warmer climate and at higher concentrations of carbon dioxide. We do not yet know if this is the case.

10.0.3 The response to increased carbon dioxide results in greater efficiencies of water, light and nitrogen use. These increased efficiencies may be particularly important during drought and in arid/semi-arid and infertile areas.

10.0.4 Because species respond differently to climatic change, some will increase in abundance and/or range while others will decrease. Ecosystems will therefore change in structure and composition. Some species may be displaced to higher latitudes and altitudes, and may be more prone to local, and possibly even global, extinction; other species may thrive.

10.0.5 As stated above, ecosystem structure and species distribution are particularly sensitive to the rate of change of climate. We can deduce something about how quickly global temperature has changed in the past from paleoclimatological records. As an example, at the end of the last glaciation, within about a century, temperature increased by up to 5°C in the North Atlantic region, mainly in Western Europe. Although during the increase from the glacial to the current interglacial temperature simple tundra ecosystems responded positively, a similar rapid temperature increase applied to more developed ecosystems could result in their instability.

11. What should be done to reduce uncertainties, and how long will this take?

11.0.1 Although we can say that some climate change is unavoidable, much uncertainty exists in the prediction of global climate properties such as the temperature and rainfall. Even greater uncertainty exists in predictions of regional climate change, and the subsequent consequences for sea level and ecosystems. The key areas of scientific uncertainty are:

- *clouds:* primarily cloud formation, dissipation, and radiative properties, which influence the response of the atmosphere to greenhouse forcing;
- *oceans:* the exchange of energy between the ocean and the atmosphere, between the upper layers of the ocean and the deep ocean, and transport within the ocean, all of which control the rate of global climate change and the patterns of regional change;
- *greenhouse gases:* quantification of the uptake and release of the greenhouse gases, their chemical reactions in the atmosphere, and how these may be influenced by climate change.
- *polar ice sheets:* which affect predictions of sea level rise

11.0.2 Studies of land surface hydrology, and of impact on ecosystems, are also important.

11.0.3 To reduce the current scientific uncertainties in each of these areas will require internationally coordinated research, the goal of which is to improve our capability to observe, model and understand the global climate system. Such a programme of research will reduce the scientific uncertainties and assist in the formulation of sound national and international response strategies.

11.0.4 Systematic long-term observations of the system are of vital importance for understanding the natural variability of the Earth's climate system, detecting whether man's activities are changing it, parametrizing key processes for models, and verifying model simulations. Increased accuracy and coverage in many observations are required. Associated with expanded observations is the need to develop appropriate comprehensive global information bases for the rapid and efficient dissemination and utilization of data. The main observational requirements are:

i) the maintenance and improvement of observations (such as those from satellites) provided by the World Weather Watch Programme of WMO;

ii) the maintenance and enhancement of a programme of monitoring, both from satellite-based and surface-based instruments, of key climate elements for which accurate observations on a continuous basis are required, such as the distribution of important atmospheric constituents, clouds, the Earth's radiation budget, precipitation, winds, sea surface temperatures and terrestrial ecosystem extent, type and productivity;

iii) the establishment of a global ocean observing system to measure changes in such variables as ocean surface topography, circulation, transport of heat and chemicals, and sea-ice extent and thickness;

iv) the development of major new systems to obtain data on the oceans, atmosphere and terrestrial ecosystems using both satellite-based instruments and instruments based on the surface, on automated instrumented vehicles in the ocean, on floating and deep sea buoys, and on aircraft and balloons;

v) the use of paleoclimatological and historical instrumental records to document natural variability and changes in the climate system, and subsequent environmental response.

11.0.5 The modelling of climate change requires the development of global models which couple together atmosphere, land, ocean and ice models and which incorporate more realistic formulations of the relevant processes and the interactions between the different components. Processes in the biosphere (both on land and in the ocean) also need to be included. Higher spatial resolution than is currently generally used is required if regional patterns are to be predicted. These models will require the largest computers which are planned to be available during the next decades.

11.0.6 Understanding of the climate system will be developed from analyses of observations and of the results from model simulations. In addition, detailed studies of particular processes will be required through targeted observational campaigns. Examples of such field campaigns include combined observational and small scale modelling studies for different regions, of the formation, dissipation, radiative, dynamical and microphysical properties of clouds, and ground-based (ocean and land) and aircraft measurements of the fluxes of greenhouse gases from specific ecosystems. In particular, emphasis must be placed on field experiments that will assist in the development and improvement of sub-grid-scale parametrizations for models.

11.0.7 The required programme of research will require unprecedented international cooperation, with the World Climate Research Programme (WCRP) of the World Meteorological Organization and International Council of Scientific Unions (ICSU), and the International Geosphere-Biosphere Programme (IGBP) of ICSU both playing vital roles. These are large and complex endeavours that will require the involvement of all nations, particularly the developing countries. Implementation of existing and planned projects will require increased financial and human resources; the latter requirement has immediate implications at all levels of education, and the international community of scientists needs to be widened to include more members from developing countries.

11.0.8 The WCRP and IGBP have a number of ongoing or planned research programs, that address each of the three key areas of scientific uncertainty. Examples include:

- ***clouds:***
  International Satellite Cloud Climatology Project (ISCCP);
  Global Energy and Water Cycle Experiment (GEWEX).

- ***oceans:***
  World Ocean Circulation Experiment (WOCE);
  Tropical Oceans and Global Atmosphere (TOGA).

- ***trace gases:***
  Joint Global Ocean Flux Study (JGOFS);
  International Global Atmospheric Chemistry (IGAC)
  Past Global Changes (PAGES).

11.0.9 As research advances, increased understanding and improved observations will lead to progressively more reliable climate predictions. However considering the complex nature of the problem and the scale of the scientific programmes to be undertaken we know that rapid results cannot be expected. Indeed further scientific advances may expose unforeseen problems and areas of ignorance.

11.0.10 Timescales for narrowing the uncertainties will be dictated by progress over the next 10—15 years in two main areas:

- Use of the fastest possible computers, to take into account coupling of the atmosphere and the oceans in models, and to provide sufficient resolution for regional predictions.

- Development of improved representation of small scale processes within climate models, as a result of the analysis of data from observational programmes to be conducted on a continuing basis well into the next century.

Annex

EMISSIONS SCENARIOS FROM WORKING GROUP III OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The Steering Group of the Response Strategies Working Group requested the USA and the Netherlands to develop emissions scenarios for evaluation by the IPCC Working Group I. The scenarios cover the emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), carbon monoxide (CO) and nitrogen oxides (NOx) from the present up to the year 2100. Growth of the economy and population was taken common for all scenarios. Population was assumed to approach 10.5 billion in the second half of the next century. Economic growth was assumed to be 2—3% annually in the coming decade in the OECD countries and 3—5 % in the Eastern European and developing countries. The economic growth levels were assumed to decrease thereafter. In order to reach the required targets, levels of technological development and environmental controls were varied.

In the *Business-as-Usual scenario* (Scenario A) the energy supply is coal intensive and on the demand side only modest efficiency increases are achieved. Carbon monoxide controls are modest, deforestation continues until the tropical forests are depleted and agricultural emissions of methane and nitrous oxide are uncontrolled. For CFCs the Montreal Protocol is implemented albeit with only partial participation. Note that the aggregation of national projections by IPCC Working Group III gives higher emissions (10—20%) of carbon dioxide and methane by 2025.

In *Scenario B* the energy supply mix shifts towards lower carbon fuels, notably natural gas. Large efficiency increases are achieved. Carbon monoxide controls are stringent, deforestation is reversed and the Montreal Protocol implemented with full participation.

In *Scenario C* a shift towards renewables and nuclear energy takes place in the second half of next century. CFCs are now phased out and agricultural emissions limited.

For *Scenario D* a shift to renewables and nuclear in the first half of the next century reduces the emissions of carbon dioxide, initially more or less stabilizing emissions in the industrialized countries. The scenario shows that stringent controls in industrialized countries combined with moderated growth of emissions in developing countries could stabilize atmospheric concentrations. Carbon dioxide emissions are reduced to 50% of 1985 levels by the middle of the next century.

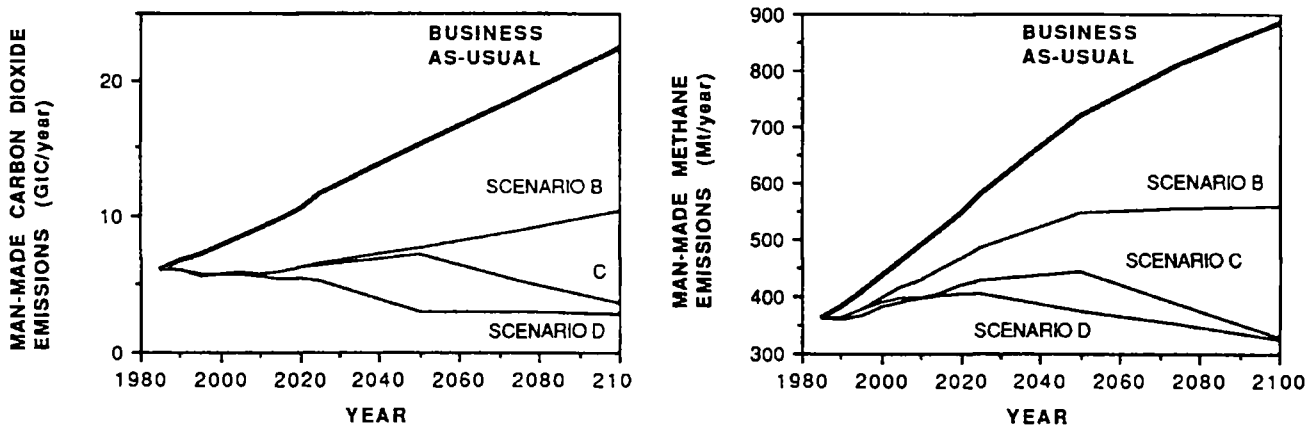

Emissions of carbon dioxide and methane (as examples) to the year 2100, in the four scenarios developed by IPCC Working Group III.

Policymaker Summary of Working Group II (Potential Impacts of Climate Change)

Executive Summary

1. The IPCC Working Groups on scientific analysis (Working Group I), impacts (Working Group II) and response strategies (Working Group III) were established in November 1988 and proceeded to work in parallel under instructions from IPCC. The responsibility of Working Group II is to describe the environmental and socio-economic implications of possible climate changes over the next decades caused by increasing concentrations of greenhouse gases.

2. The report of Working Group II is based on the work of a number of subgroups, using independent studies which have used different methodologies. Based on the existing literature, the studies have used several scenarios to assess the potential impacts of climate change. These have the features of:

(i) an effective doubling of CO_2 in the atmosphere between now and 2025 to 2050 for a 'business-as-usual' scenario;

(ii) a consequent increase of global mean temperature in the range of 1.5°C to 4.5°C;

(iii) an unequal global distribution of this temperature increase, namely a smaller increase of half the global mean in the tropical regions and a larger increase of twice the global mean in the polar regions; and

(iv) a sea-level rise of about 0.3—0.5 m by 2050 and about 1 m by 2100, together with a rise in the temperature of the surface ocean layer of between 0.2° and 2.5°C.

3. These scenarios pre-date, but are in line with, the recent assessment of Working Group I which, for a 'business-as-usual' scenario (scenario A in Working Group I Report) has estimated the magnitude of sea-level rise at about 20 cm by 2030 and about 65 cm by the end of the next century. Working Group I has also predicted the increase in global mean temperatures to be about 1°C above the present value by 2025 and 3°C before the end of the next century.

4. Any predicted effects of climate change must be viewed in the context of our present dynamic and changing world. Large-scale natural events such as El Niño can cause significant impacts on agriculture and human settlement. The predicted population explosion will produce severe impacts on land use and on the demands for energy, fresh water, food and housing, which will vary from region to region according to national incomes and rates of development. In many cases, the impacts will be felt most severely in regions already under stress, mainly the developing countries. Human-induced climate change due to continued uncontrolled emissions will accentuate these impacts. For instance, climate change, pollution and ultraviolet-B radiation from ozone depletion can interact, reinforcing their damaging effects on materials and organisms. Increases in atmospheric concentrations of greenhouse gases may lead to irreversible change in the climate which could be detectable by the end of this century.

5. Comprehensive estimates of the physical and biological effects of climate change at the regional level are difficult. Confidence in regional estimates of critical climatic factors is low. This is particularly true of precipitation and soil moisture, where there is considerable disagreement between various general circulation model and palaeoanalog results. Moreover, there are several scientific uncertainties regarding the relationship between climate change and biological effects and between these effects and socioeconomic consequences.

6. This report does not attempt to anticipate any adaptation, technological innovation or any other measures to diminish the adverse effects of climate change that will take place in the same time frame. This is especially important for heavily managed sectors, e.g. agriculture, forestry and public health. This is one of the responsibilities of Working Group III.

7. Finally, the issue of timing and rates of change need to be considered; there will be lags between:

i) emissions of greenhouse gases and doubling of concentrations;

ii) doubling of greenhouse gas concentrations and changes in climate;

iii) changes in climate and resultant physical and biological effects; and

iv) changes in physical and ecological effects and resultant socioeconomic (including ecological) consequences. The shorter the lags, the less the ability to cope and the greater the socioeconomic impacts

8. There is uncertainty related to these time lags. The changes will not be steady and surprises cannot be ruled out. The severity of the impacts will depend to a large degree on the rate of climate change.

9. Despite these uncertainties, Working Group II has been able to reach some major conclusions, which are:

Agriculture and forestry

10. Sufficient evidence is now available from a variety of different studies to indicate that changes of climate would

have an important effect on agriculture and livestock. Studies have not yet conclusively determined whether, on average, global agricultural potential will increase or decrease. Negative impacts could be felt at the regional level as a result of changes in weather and pests associated with climate change, and changes in ground-level ozone associated with pollutants, necessitating innovations in technology and agricultural management practices. There may be severe effects in some regions, particularly decline in production in regions of high present-day vulnerability that are least able to adjust. These include Brazil, Peru, the Sahel Region of Africa, Southeast Asia, the Asian region of the USSR and China. There is a possibility that potential productivity of high and mid latitudes may increase because of a prolonged growing season, but it is not likely to open up large new areas for production and it will be mainly confined to the Northern Hemisphere.

11. Patterns of agricultural trade could be altered by decreased cereal production in some of the currently high-production areas, such as Western Europe, southern US, parts of South America and western Australia. Horticultural production in mid-latitude regions may be reduced. On the other hand, cereal production could increase in northern Europe. Policy responses directed to breeding new plant cultivars, and agricultural management designed to cope with changed climate conditions, could lessen the severity of regional impacts. On balance, the evidence suggests that in the face of estimated changes of climate, food production at the global level can be maintained at essentially the same level as would have occurred without climate change; however, the cost of achieving this is unclear. Nonetheless, climate change may intensify difficulties in coping with rapid population growth. An increase or change in UV-B radiation at ground level resulting from the depletion of stratospheric ozone will have a negative impact on crops and livestock.

12. The rotation period of forests is long and current forests will mature and decline during a climate in which they are increasingly more poorly adapted. Actual impacts depend on the physiological adaptability of trees and the host-parasite relationship. Large losses from both factors in the form of forest declines can occur. Losses from wildfire will be increasingly extensive. The climate zones which control species distribution will move poleward and to higher elevations. Managed forests require large inputs in terms of choice of seedlot and spacing, thinning and protection. They provide a variety of products from fuel to food. The degree of dependency on products varies among countries, as does the ability to cope with and to withstand loss. The most sensitive areas will be where species are close to their biological limits in terms of temperature and moisture. This is likely to be, for example, in semi-arid areas. Social stresses can be expected to increase and consequent anthropogenic damage to forests may occur. These increased and non-sustainable uses will place more pressure on forest investments, forest conservation and sound forest management.

Natural terrestrial ecosystems

13. Natural terrestrial ecosystems could face significant consequences as a result of the global increases in the atmospheric concentrations of greenhouse gases and the associated climatic changes. Projected changes in temperature and precipitation suggest that climatic zones could shift several hundred kilometres towards the poles over the next fifty years. Flora and fauna would lag behind these climatic shifts, surviving in their present location and, therefore, could find themselves in a different climatic regime. These regimes may be more or less hospitable and, therefore, could increase productivity for some species and decrease that of others. Ecosystems are not expected to move as a single unit, but would have a new structure as a consequence of alterations in distribution and abundance of species.

14. The rate of projected climate changes is the major factor determining the type and degree of climatic impacts on natural terrestrial ecosystems. These rates are likely to be faster than the ability of some species to respond and responses may be sudden or gradual.

15. Some species could be lost owing to increased stress leading to a reduction in global biological diversity. Increased incidence of disturbances such as pest outbreaks and fire are likely to occur in some areas and these could enhance projected ecosystem changes.

16. Consequences of CO_2 enrichment and climate change for natural terrestrial ecosystems could be modified by other environmental factors, both natural and man-induced (e.g. by air pollution).

17. Most at risk are those communities in which the options for adaptability are limited (e.g. montane, alpine, polar, island and coastal communities, remnant vegetation, and heritage sites and reserves) and those communities where climatic changes add to existing stresses.

18. The socioeconomic consequences of these impacts will be significant, especially for those regions of the globe where societies and related economies are dependent on natural terrestrial ecosystems for their welfare. Changes in the availability of food, fuel, medicine, construction materials and income are possible as these ecosystems are changed. Important fibre products could also be affected in some regions.

Hydrology and water resources

19. Relatively small climate changes can cause large water resource problems in many areas, especially arid and semi-arid regions and those humid areas where demand or pollution has led to water scarcity. Little is known about regional details of greenhouse-gas-induced hydrometeorological change. It appears that many areas will have increased precipitation, soil moisture and water storage, thus altering patterns of agricultural, ecosystem and other water use. Water

availability will decrease in other areas, a most important factor for already marginal situations, such as the Sahelian zone in Africa. This has significant implications for agriculture, for water storage and distribution, and for generation of hydroelectric power. In some limited areas, for example, under the assumed scenario of a 1°C to 2°C temperature increase, coupled with a 10% reduction in precipitation, a 40-70% reduction in annual runoff could occur. Regions such as Southeast Asia, that are dependent on unregulated river systems, are particularly vulnerable to hydrometeorological change. On the other hand, regions such as the western USSR and western United States that have large regulated water resource systems are less sensitive to the range of hydrometeorological changes in the assumed greenhouse scenario.

20. In addition to changes in water supply, water demand may also change through human efforts to conserve, and through improved growth efficiency of plants in a higher CO_2 environment. Net socio-economic consequences must consider both supply and demand for water. Future design in water resource engineering will need to take possible impacts into account when considering structures with a life span to the end of the next century. Where precipitation increases, water management practices, such as urban storm drainage systems, may require upgrading in capacity. Change in drought risk represents potentially the most serious impact of climate change on agriculture at both regional and global levels.

Human settlements, energy, transport, and industrial sectors, human health and air quality

21. The most vulnerable human settlements are those especially exposed to natural hazards, e.g. coastal or river flooding, severe drought, landslides, severe wind storms and tropical cyclones. The most vulnerable populations are in developing countries, in the lower income groups, residents of coastal lowlands and islands, populations in semi-arid grasslands, and the urban poor in squatter settlements, slums and shanty towns, especially in megacities. In coastal lowlands such as in Bangladesh, China and Egypt, as well as in small island nations, inundation due to sea-level rise and storm surges could lead to significant movements of people. Major health impacts are possible, especially in large urban areas, owing to changes in availability of water and food and increased health problems due to heat stress spreading of infections. Changes in precipitation and temperature could radically alter the patterns of vector-borne and viral diseases by shifting them to higher latitudes, thus putting large populations at risk. As similar events have in the past, these changes could initiate large migrations of people, leading over a number of years to severe disruptions of settlement patterns and social instability in some areas.

22. Global warming can be expected to affect the availability of water resources and biomass, both major sources of energy in many developing countries. These effects are likely to differ between and within regions with some areas losing and others gaining water and biomass. Such changes in areas which lose water may jeopardize energy supply and materials essential for human habitation and energy. Moreover, climate change itself is also likely to have different effects between regions on the availability of other forms of renewable energy such as wind and solar power. In developed countries some of the greatest impacts on the energy, transport and industrial sectors may be determined by policy responses to climate change such as fuel regulations, emission fees or policies promoting greater use of mass transit. In developing countries, climate-related changes in the availability and price of production resources such as energy, water, food and fibre may affect the competitive position of many industries.

23. Global warming and increased ultraviolet radiation resulting from depletion of stratosphere ozone may produce adverse impacts on air quality such as increases in ground-level ozone in some polluted urban areas. An increase of UV-B radiation intensity at the earth's surface would increase the risk of damage to the eye and skin and may disrupt the marine food chain.

Oceans and coastal zones

24. Global warming will accelerate sea-level rise, modify ocean circulation and change marine ecosystems, with considerable socioeconomic consequences. These effects will be added to present trends of rising sea-level, and other effects that have already stressed coastal resources, such as pollution and over-harvesting. A 30—50 cm sea-level rise (projected by 2050) will threaten low islands and coastal zones. A 1 m rise by 2100 would render some island countries uninhabitable, displace tens of millions of people, seriously threaten low-lying urban areas, flood productive land, contaminate fresh water supplies and change coastlines. All of these impacts would be exacerbated if droughts and storms become more severe. Coastal protection would involve very significant costs. Rapid sea-level rise would change coastal ecology and threaten many important fisheries. Reductions in sea ice will benefit shipping, but seriously impact on ice-dependent marine mammals and birds.

25. Impacts on the global oceans will include changes in the heat balance, shifts in ocean circulation which will affect the capacity of the ocean to absorb heat and CO_2, and changes in upwelling zones associated with fisheries. Effects will vary by geographic zones, with changes in habitats, a decrease in biological diversity and shifts in marine organisms and productive zones, including commercially important species. Such regional shifts in fisheries will have major socioeconomic impacts.

Seasonal snow cover, ice and permafrost

26. The global areal extent and volume of elements of the terrestrial cryosphere (seasonal snow cover, near-surface

layers of permafrost and some masses of ice) will be substantially reduced. These reductions, when reflected regionally, could have significant impacts on related ecosystems and social and economic activities. Compounding these impacts in some regions is that, as a result of the associated climatic warming positive feedbacks, the reductions could be sudden rather than gradual.

27. The areal coverage of seasonal snow and its duration are projected to decrease in most regions, particularly at mid-latitudes, with some regions at high latitudes possibly experiencing increases in seasonal snow cover. Changes in the volume of snow cover, or the length of the snow cover season, will have both positive and negative impacts on regional water resources (as a result of changes in the volume and the timing of runoff from snowmelt); on regional transportation (road, marine, air and rail); and on recreation sectors.

28. Globally, the ice contained in glaciers and ice sheets is projected to decrease, with regional responses complicated by the effect of increased snowfall in some areas which could lead to accumulation of ice. Glacial recession will have significant implications for local and regional water resources, and thus impact on water availability and on hydroelectric power potential. Glacial recession and loss of ice from ice sheets will also contribute to sea-level rise.

29. Permafrost, which currently underlies 20—25% of the land mass of the Northern Hemisphere, could experience significant degradation within the next 40—50 years. Projected increases in the thickness of the freeze-thaw (active) layer above the permafrost and a recession of permafrost to higher latitudes and altitudes could lead to increases in terrain instability, erosion and landslides in those areas which currently contain permafrost. As a result, overlying ecosystems could be significantly altered and the integrity of man-made structures and facilities reduced, thereby influencing existing human settlements and development opportunities.

Future action

30. The results of the Working Group II studies highlight our lack of knowledge, particularly at the regional level and in areas most vulnerable to climate change. Further national and international research is needed on:

- regional effects of climate change on crop yields, livestock productivity and production costs;
- identification of agricultural management practices and technology appropriate for changed climate;
- factors influencing distribution of species and their sensitivity to climate change;
- initiation and maintenance of integrated monitoring systems for terrestrial and marine ecosystems;
- intensive assessment of water resources and water quality, especially in arid and semi-arid developing countries and their sensitivity to climate change;
- regional predictions of changes in soil moisture, precipitation, surface and subsurface runoff regimes and their interannual distributions as a result of climate change;
- assessment of vulnerability of countries to gain or loss of energy resources, particularly biomass and hydroelectric power in developing countries;
- adaptability of vulnerable human populations to heat stress and vector-borne and viral diseases;
- global monitoring of sea-level changes, particularly for island countries;
- identification of populations and agricultural and industrial production at risk in coastal areas and islands;
- better understanding of the nature and dynamics of ice masses and their sensitivity to climate change;
- integration of climate change impact information into the general planning process, particularly in developing countries; and
- development of methodology to assess sensitivity of environments and socioeconomic systems to climate change.

31. Some of these topics are already being covered by existing and proposed programmes and these will need continuing support. In particular, there are three core projects of the International Geosphere-Biosphere Program, namely:

- Land-Ocean Interactions in the Coastal Zone
- Biosphere Aspects of the Hydrological Cycle
- Global Change Impact on Agriculture and Society

that will provide valuable data in the coming years.

1. Scenarios

1.0.1 Any changes which take place as the results of increasing emissions must be viewed against a background of changes which are already occurring and which will continue to occur as a result of other factors such as:

- natural changes—these include long-term changes which are driven by solar and tectonic factors, and short-to-medium term changes which are driven by ocean and atmospheric circulation patterns;
- population increase—the predicted world population is expected to be above 10 billion by the middle of the next century; this growth will be unevenly distributed on a regional basis and will impact on already vulnerable areas;
- land use changes—the clearing of forests for new agricultural production, together with more intensive use of existing agricultural land, will contribute to land degradation and increase demands for water resources.

1.0.2 In an ideal world, Working Group I would have had the time to produce scenarios for emission-induced climate change which could have been used as a basis for the analyses of this Working Group. However, this was precluded because work proceeded in parallel. As a result, and in order to complete its work in time, Working Group II has used a number of scenarios based on existing models in the literature.

1.0.3 The scenarios generally have the following features:

(i) an effective doubling of CO_2 in the atmosphere over pre-industrial levels between now and 2025 to 2050 for a 'business-as-usual' scenario, with no changes to present policy;

(ii) an increase of mean global temperature in the range 1.5°C to 4.5°C corresponding to the effective doubling of CO_2;

(iii) an unequal global distribution of this temperature increase, namely half the global mean in the tropical regions and twice the global mean in the polar regions;

(iv) a sea-level rise of about 0.3 to 0.5 m by 2050 and about 1 m by 2100, together with a rise in temperature of the surface ocean layer of between 0.2° and 2.5°.

1.0.4 These scenarios can be compared with the recent assessment of Working Group I which, for a 'business-as-usual' scenario, has predicted the increase in global temperatures to be about 1°C above the present value by 2025 and 3°C before the end of next century. However, it has also estimated the magnitude of sea-level rise to be about 20 cm by 2030 and about 65 cm by the end of next century. Nevertheless, the impacts based on 1—2 m rise serve as a warning of the consequences of continued uncontrolled emissions.

1.0.5 The smaller rise does not lessen the anxiety, for their continued existence, of the small island countries, particularly the Pacific and Indian Oceans and the Caribbean, or of the larger populations in low-lying coastal areas such as Bangladesh. It is difficult to predict the regional effects of sea-level rise with any certainty. Significant variations of sea-level already occur for a variety of reasons, while there are considerable shifts in land levels associated with tectonic plate movements which can also lead to rises and falls.

1.0.6 The scenarios of Working Group II are derived both from General Circulation Models and from palaeoanalog techniques. Palaeoclimate analogs are proposed by Soviet scientists as a means by which climate changes can be assessed. The methodology assumes that past warm geologic intervals provide insight into possible future climate conditions. The General Circulation Models, developed by Western scientists, are based on three-dimensional mathematical representations of the physical processes in the atmosphere and the interactions of the atmosphere with the earth's surface and the oceans. There is considerable scientific debate about the merits and demerits of each of these, as discussed in the report of Working Group I.

1.0.7 The palaeoclimate scenarios used by Soviet scientists are based on three warm geological periods with estimated future levels of concentration of CO_2 applied to them. The details of these are shown in the table overleaf. While these are superficially similar to the predictions of the general circulation model approach for different CO_2 concentrations, the factors which caused the climate changes in geologic times are not clear. Nevertheless, they have been used to make predictions of climate change of regions in the USSR.

1.0.8 The General Circulation Models are, in their current state of development, comparatively crude in their description of many of the processes involved. However they can be used to simulate regional changes resulting from a range of concentrations of CO_2 in the atmosphere. Working Group I has favoured the general circulation model approach in producing its predictions of temperature rise and precipitation changes. In its report, estimates for 2030 have been given for central North America, southern Asia, Sahel, southern Europe and Australia. These are reproduced in the table overleaf and are broadly similar to those used by Working Group II.

1.0.9 Despite the current uncertainties, both techniques have been used by Working Group II in the development of regional impacts to assist policy makers. There are problems with prediction of regional precipitation since there is disagreement between various general circulation model outputs as a result of simplifications to the representation of complex physical processes. Current research is seeking to improve the general circulation model approach and to increase resolution to enable better regional predictions. There are also problems with the palaeoanalog approach which yields differing scenarios for precipitation from the general circulation model approach. This leads to different assessments of impact on water resources and agriculture. Soviet scientists are working to validate their techniques and improve regional scenarios.

Estimates for regional changes by Working Group I

(IPCC Business-as-Usual scenario; changes from pre-industrial)

The estimates are based on high resolution models, scaled to give a global mean warming of 1.8°C consistent with the best estimate (2.5°C) of climate response to greenhouse gases. With the low estimate of 1.5°C, these values should be reduced by 30%; with the high estimate of 4.5°C, they should be increased by 50%. Confidence in these regional estimates is low.

Central North America (35°-50°N 85°-105°W)
The warming varies from 2 to 4°C in winter and 2 to 3°C in summer. Precipitation increases range from 0 to 15% in winter whereas there are decreases of 5 to 10% in summer. Soil moisture decreases in summer by 15 to 20%.

Southern Asia (5°-30°N 70°-105°E)
The warming varies from 1 to 2°C throughout the year. Precipitation changes little in winter and generally increases throughout the region by 5 to 15% in summer. Summer soil moisture increases by 5 to 10%.

Sahel (10°-20°N 20°W-40°E)
The warming ranges from 1 to 3°C. Area mean precipitation increases and area mean soil moisture decreases marginally in summer. However, throughout the region, there are areas of both increase and decrease in both parameters throughout the region.

Southern Europe (35°-50°N 10°W- 45°E)
The warming is about 2°C in winter and varies from 2 to 3°C in summer. There is some indication of increased precipitation in winter, but summer precipitation decreases by 5 to 15%, and summer soil moisture by 15 to 25%.

Australia (12°-45°S 110°-115°E)
The warming ranges from 1 to 2°C in summer and is about 2°C in winter. Summer precipitation increases by around 10%, but the models do not produce consistent estimates of the changes in soil moisture. The area averages hide large variations at the sub-continental level.

1.0.10 It should be noted that, in many situations, the overall impact is determined more by the changes in the magnitude and frequency of extreme events than by changes in the average. This is especially the case for tropical storms and droughts. The assessment of Working Group I of possible climate changes suggests a low probability of increased frequency of extreme events. However, it is entirely possible that shifts in climate regimes will result in changes in frequency in certain regions.

1.0.11 An issue of importance not considered in any detail is the impact of possible response strategies (developed by Working Group III) on the scenarios used here. Thus, a major change in energy production from fossil fuel to nuclear or renewable energy sources could drastically alter our assessments. Further, changes in agricultural practice could dramatically alter yields of particular crops in certain regions. These impacts of response strategies require much additional work.

1.0.12 Despite all these uncertainties, it is possible to make assessments of potential impacts of climate change by considering the sensitivity of natural systems to significant variations. These are summarised in the following sections under: agriculture and forestry; terrestrial ecosystems; hydrology and water resources; human settlement, energy, transport, industry, human health and air quality; world ocean and coastal zones; seasonal snow cover, ice and permafrost.

Paleoclimatic analogues used by Soviet scientists

Period	Analogue (year)	Temperature (difference from present)	Past CO_2 concn. (ppm)	Assumed CO_2 concn (ppm)
Holocene Optimum	2000	+1	280	380
Eemian Interglacial	2025	+2	280	420
Pliocene	2050	+4	500-600	560

SUMMARY OF FINDINGS

2 Potential impacts of climate change on agriculture, land use and forestry

2.1 Potential impacts on agriculture

Major findings

- Sufficient evidence is now available from a variety of different studies to indicate that changes of climate would have an important effect on agriculture, including livestock. Yet the fact that there are major uncertainties regarding likely effects in specific regions should be a cause for concern. Studies have not yet conclusively determined whether, on average, global agricultural potential will increase or decrease.

- Negative impacts could be felt at the regional level as a result of changes in weather, diseases, pests and weeds associated with climate change, necessitating innovation in technology and agriculture management practices. There may be severe effects in some regions, particularly in regions of high present-day vulnerability that are least able to adjust technologically to such effects.

- There is a possibility that potential productivity of high and mid-latitudes may increase because of a prolonged growing season, but it is not likely to open up large new areas for production, and will be largely confined to the Northern Hemisphere.

- On balance, the evidence is that in the face of estimated changes of climate, food production at the global level can be maintained at essentially the same level as would have occurred without climate change; but the cost of achieving this is unclear. Nonetheless, climate changes may intensify difficulties in coping with rapid population growth.

Principal issues

Magnitudes of possible dislocation

2.1.1 Under the estimate of changes in productive potential for the changes of climate outlined in this report, the cost of producing some mid-latitude crops, such as maize and soybean, could increase, reflecting a small net decrease in the global food production capability of these crops. Rice production could, however, increase if available moisture increased in Southeast Asia, but these effects may be limited by increased cloudiness and temperature. The average global increase in overall production costs due to climate change could thus be small.

2.1.2 Much depends on the possible benefits of the so-called 'direct' effects of increased CO_2 on crop yield. If plant productivity were substantially enhanced and more moisture were available in some major production areas, then world production of staple cereals could increase relative to demand. If, on the contrary, there is little beneficial direct CO_2 effect and climate changes are negative for agricultural potential in all or most of the major food-exporting areas, then the average costs of world agricultural production due to climate change could increase significantly.

Most vulnerable regions and sectors

2.1.3 On the basis of both limited resource capacity in relation to present-day population and possible future diminution of the agricultural resource base as a consequence of reduced cropwater availability, two broad sets of regions appear most vulnerable to climate change: (i) some semi-arid, tropical and subtropical regions (such as western Arabia, the Maghreb, western West Africa, Horn of Africa and southern Africa, eastern Brazil), and (ii) some humid tropical and equatorial regions (such as Southeast Asia and Central America).

2.1.4 In addition, certain regions that are currently net exporters of cereals could also be characterized by reduced productive potential as a result of climate changes. Any decrease in production in these regions could markedly affect future global food prices and patterns of trade. These regions might include, for example, Western Europe, southern US, parts of South America, and Western Australia.

Effect of altered climate extremes

2.1.5 Relatively small changes in the mean values of rainfall and temperature can have a marked effect on the frequency of extreme levels of available warmth and moisture. For example, the number of very hot days which can cause damaging heat stress to temperate crops and livestock could increase significantly in some regions as a result of a 1°C to 2°C increase in mean annual temperatures. Similarly, reduction in average levels of soil moisture as a result of higher rates of evapotranspiration could increase substantially the number of days below a minimum threshold of water availability for given crops.

2.1.6 Although at present we know little about how the frequency of extreme events may alter as a result of climate change, the potential impact of concurrent drought or heat stress in the major food-exporting regions of the world could be severe. In addition, relatively small decreases in rainfall, changes in rainfall distribution or increases in evapotranspiration could markedly increase the probability, intensity and duration of drought in currently drought-prone (and often food-deficient) regions. Increase in drought risk represents potentially the most serious impact of climate change on agriculture at both the regional and global level.

Effects on crop growth potential, land degradation, pests and diseases

2.1.7 Higher levels of atmospheric CO_2 are expected to enhance the growth rate of some staple cereal crops, such as wheat and rice, but not of others such as millet, sorghum and maize. The use of water by crop plants may also be more efficient under higher CO_2 levels. However, it is not clear how far the potentially beneficial 'direct' effects of enhanced atmospheric CO_2 will be manifested in the farmer's field.

2.1.8 Warming is likely to result in a poleward shift of thermal limits of agriculture, which may increase productive potential in high-latitude regions. But soils and terrain may not enable much of this potential to be realized. Moreover, shifts of moisture limits in some semi-arid and sub-humid regions could lead to significant reductions of potential with serious implications for regional food supplies in some developing countries. Horticultural production in mid-latitude regions may be reduced owing to insufficient accumulated winter chilling. The impact of climate change will be far greater for long-lived horticultural fruit crops, with long establishment periods, than for annual crops where new cultivars can quickly replace others.

2.1.9 Temperature increases may extend the geographic range of some insect pests, diseases and weeds, allowing their expansion to new regions as they warm and become suitable habitats. Changes in temperature and precipitation may also influence soil characteristics.

Regional impacts

2.1.10 Impacts on potential yields are likely to vary greatly according to types of climate change and types of agriculture.

2.1.11 In the northern mid-latitude regions, where summer drying may reduce productive potential (e.g. in the south and central US and in southern Europe), yield potential is estimated to fall by 10—30% under an equilibrium 2 x CO_2 climate by the middle of the next century. Towards the northern edge of current core producing regions, however, warming may enhance productive potential in climatic terms. When combined with direct CO_2 effects, increased climatic potential could be substantial—though in actuality it may be limited by soils, terrain and land use.

2.1.12 There are indications that warming could lead to an overall reduction of cereal production potential in North America and to southern Europe, but increased potential in northern Europe. Warming could allow increased agricultural output in regions near the northern limit of current production in the USSR and North America, but output in the southern areas of these regions could only increase if corresponding increases in soil moisture were to occur; this is at present uncertain.

2.1.13 Little is known about likely impacts in semi-arid and humid tropical regions, because production potential here largely depends on cropwater availability, and the regional pattern of possible changes in precipitation is unclear at present. It is prudent, however, to assume that cropwater availability could decrease in some regions. Under these circumstances there could be substantial regional dislocation of access to food.

Adaptation in agriculture

2.1.14 In some parts of the world, climatic limits to agriculture are estimated to shift poleward by 200—300 km per degree of warming. The warming-induced upwards shift in thermal zones above mountain slopes could be in the order of 150—200 m.

2.1.15 Agriculture has an ability to adjust, within given economic and technological constraints, to a limited rate and range of climate change. This capability varies greatly between regions and sectors, but no thorough analysis of adaptive capacity has yet been conducted for the agriculture sector.

2.1.16 In some currently highly variable climates, farmers may be more adaptable than those in regions of more equable climate. But in developing economies, and particularly in some marginal types of agriculture, this intrinsic adaptive capability may be much lower. It is important to establish in more detail the nature of this adaptability and thus help to determine critical rates and ranges of climatic change that would exceed those that could be accommodated by adjustments within the system.

Recommendations for action

2.1.17 This study has emphasized the inadequacy of our present knowledge. It is clear that more information on potential impacts would help to identify the full range of potentially useful responses and assist in determining which of these may be most valuable.

2.1.18 Some priorities for future research may be summarised as follows:

- Improved knowledge is needed of effects of changes in climate on crop yields and livestock productivity in different regions and under varying types of management. To date, less than a dozen detailed regional studies have been completed, and these are insufficient as a basis for generalizing about effects on food production at the regional or world scale. Further research in vulnerable regions in particular should be encouraged.

- Improved understanding of the effects of changes in climate on other physical processes is needed: for example on rates of soil erosion and salinization; on soil nutrient depletion; on pests, diseases and soil microbes, and their vectors; on hydrological conditions as they affect irrigation water availability.

- An improved ability is required to 'scale-up' our understanding of effects on crops and livestock, effects on farm production, on village production, and on national and global food supply. This is particularly important because policies must be designed to respond to impacts at the national and global levels. Further information is needed on the effects of changes in climate on social and economic conditions in rural areas (e.g. employment and income, equity considerations, farm infrastructure, and support services).

- Further information is needed on the range of potentially effective technical adjustments at the farm and village level (e.g. irrigation, crop selection, fertilizing, etc) and on the economic and political constraints on such adjustments. In particular, it is recommended that national and international centres of agricultural research consider the potential value of new research programs aimed at identifying or developing cultivars and management practices appropriate for altered climates.

- Further information is needed on the range of potentially effective policy responses at regional, national and international levels (e.g. reallocation of land use, plant breeding, improved agricultural extension schemes, large-scale water transfers etc).

2.2 Potential impacts on managed forests and the forest sector

2.2.1 All impacts referred to in this section reflect the current uncertainty in the extent of warming, and levels and distribution of precipitation. They reflect the consensus that anthropogenic change is occurring; the direction is towards higher temperatures, with the extent affected by latitude and continentality.

2.2.2 The distinction between managed and unmanaged forests is often unclear, but it is taken here to be one of degree in the intensity of human intervention. In managed forests, harvesting takes place and the forests are renewed, replaced or restructured in such a way that actual physical inputs are needed to achieve goals.

2.2.3 Managed forests are quite distinct from the unmanaged forests. They supply a wide variety of products and are found in a wide variety of countries with different social, physical and political environments. The intensity of forest management may not necessarily parallel the degree of economic development; different countries depend to different degrees on the products from forests. Therefore the severity of the impacts will vary among countries as will the ability to respond. In tropical countries the managed forests characteristically employ exotic species, whereas in the northern countries greater reliance is placed on indigenous species.

Biophysical effects on forest ecosystems

2.2.4 Impacts on forest ecosystems will be at the tree and microsite levels, at the stand/watershed level and at the regional level. Impacts on individual trees include tolerance of drought and winds, the possible effects of altered seasonality (active vs dormant stages), altered photosynthetic rates and increased water use efficiency. At the microsite level, moisture may be limited and biological soil processes may be enhanced. Forest renewal will be adversely affected if there is a shortage of moisture at the critical establishment phase.

2.2.5 On stand levels, insects and diseases can be expected to cause significant losses to forests and these losses can be expected to increase with increasing change. Fire severity will increase, and while managed forests may have less fuel available than unmanaged ecosystems, this will not lessen the incidence of fire, nor will it affect the weather conditions giving rise to the rates of spread or the extent of the areas burned. Developed countries can barely cope with the current state and the extent of areas burned seem to be rising. The incidence of fire may be less in the tropics as the climate there changes less, but many plantations are in semi-arid zones and will suffer adverse impacts. Costs associated with flooding, resulting from rising sea-levels and disruption of weather patterns, can be expected. There will be problems in using the lower quality wood grown under stress and large costs associated with moving processing facilities and infrastructure as the wood supply zones move northward. The most important feature of these costs and disruptions from a global point of view is that the changes will differ among countries and that some countries are better able than others to cope with the impacts.

2.2.6 Major forest-type zones and species ranges could shift significantly as a result of climate change. Results of several Northern Hemisphere studies show that both high-latitude and low-latitude boundaries of temperate and northern forests (and tree species) may shift hundreds of kilometres poleward. In contrast, studies in the Southern Hemisphere suggest that Australian species could adapt and grow at temperatures much warmer than those of their natural distribution.

2.2.7 At the stand level, the following effects of climate change on forests are likely: increased mortality owing to physical stress: increased susceptibility to and infestations of insects and diseases; increased susceptibility to and incidences of fire; changed stand growth rates, both increases and decreases; more difficult stand establishment by both natural and artificial regeneration; and changed composition of species.

2.2.8 Two broad types of forests are likely to be sensitive to a changing climate: (i) boreal forests, where stands are mainly even-aged and often temperature-limited, and where temperature changes are expected to be large; and (ii) forests in arid and semi-arid regions where increased temperatures and stable or decreasing precipitation could render sites inhospitable to the continued existence of current forest stands. However, there could be compensating effects of faster growth owing to higher ambient CO_2.

Socioeconomic implications

2.2.9 All countries use forests for heating, cooking and food. The degree to which people are dependent on these, however, varies widely. Forest ecosystem changes and tree distribution have no regard for political or administrative boundaries. Managed forests have, by definition, high levels of investment in them; some countries are better able than others to tolerate the risk to, and possible loss, of these investments.

2.2.10 Intensively managed forests have high inputs from choice of species, sites, spacing, tending, thinning, fertilization and protection. These interventions are costly and some countries may not be able to supply the inputs necessary to establish, maintain and protect the investments.

2.2.11 Increased protection costs will be unevenly borne and could encourage poorer countries to accelerate harvesting, reduce rotation periods and engage in other practices, which may not be sustainable. More data are needed on these secondary and insidious effects of climate change. Associated disruptions in the social fabric of many countries may impact adversely on forests, as instances of arson or other damage do now.

2.2.12 The socioeconomic implications of shifts in the ranges of tree species will be influenced by the fact that climate will probably change much faster than tree species can naturally respond (e.g. through migration).

2.2.13 Moreover, new sites may not be hospitable, having evolved over thousands of years under other climatic and vegetative regimes. The suitability of new ranges and the actual composition and growth patterns of forests under new climates will have no regard for non-ecological boundaries such as watersheds, ownerships, parks, nature reserves and recreation areas.

2.2.14 It is concluded that climate change could more likely exacerbate most current and near-term issues and tensions rather than relieve them. This finding is very dependent on the assumption that during the next 30—50 years, in response to climate change, forests everywhere in the world will be prone to some measure and form of decline. These changes will be taking place at the same time as a substantial increase in population with increased demands. If, on the other hand, forests in some regions are largely unaffected by climate change, or actually experience increased growth rates, then perhaps most of the issues and tensions could be at least partly relieved.

Adaptation

2.2.15 Much can be done to reduce the susceptibility of socioeconomic systems to climate-induced forest declines. Appropriate measures include the whole array of forest-management tools, to be chosen and implemented as local conditions warrant, but some may be detrimental to other indicators, for example, wildlife or recreation.

2.2.16 For wood supply, the forest-products industry can move processing technology towards new kinds and qualities of fibre, and plan new mills in areas improving in wood-supply potential. Governments can support efforts in economic diversification in forest-based communities, and engage in improved long-range planning for future changes in land potential for forestry. The provision of recreational facilities is another example of an important forest-based economic sector. Governments and private firms must anticipate how forested landscapes might change, and plan accordingly to divest themselves of the old facilities and invest in the new.

Recommendations for action

2.2.17 The ability to deal with climate change and the forest sector is related to the amount of knowledge available. There are uncertainties to be considered: for instance, in the future, will the same tensions and issues have similar high priority? Studies of the socioeconomic impacts must be global in scope, international in organization, institutional in focus and historical in breadth. We need regional climate scenarios and better information on stand-level responses, the biological relationship between species and sites and the inherent variability of species. Changing climates demonstrate the need for strategies in active management in the forest sector. Even better knowledge is needed of the potential role of forest management in mitigating impacts and exploiting opportunities from climate change.

2.2.18 A major impact, of which there is evidence now, will be considerable apprehension on the part of the general public, particularly those dependent on the forest sector for their livelihood. Public cooperation in the implementation of decisions will be required for dealing with a problem which has biological rather than ideological solutions.

2.2.19 Research on the socioeconomic impacts of climate change must focus on the transitional climates occurring over the next several decades, not only at specific points in time. This reflects the way people live—in specific localities and in real time. It makes sense to prepare for serious impacts by implementing policies which are biologically sustainable, even if the eventual changes are minimal.

2.2.20 Examining biogeochemical changes on a global scale is complex enough; adding humans as a variable factor complicates the issue even more. Nevertheless, humans are the critical element in the study of ecological systems. We must consider the institutional imperatives and the economic and political influences on people in different nations, together with the cultural diversity that distinguishes and may dominate our actions.

2.2.21 The nature and temporal/spatial distribution of climate change itself is highly uncertain, as are the various ways by which a changing climate could influence forests

and their growing sites, and the various repercussions this might have on our uses of forests. Moreover, the means by which society might cope with the changing environmental and socio-economic conditions, in a context in which those conditions are rapidly changing quite independently of climate change, are largely unexplored so far.

2.2.22 The following major research and assessment initiatives should be developed and pursued in the near future (early 1990s) to begin to shed light on the impacts discussed in this section: (i) more secure regional climate scenarios; (ii) simulation of impacts of climate change on managed forest stands; (iii) modelling studies for better understanding of matches between species and sites; (iv) analyses of the potential role of forest management in mitigating undesirable impacts and capitalizing on desirable impacts of climate change; (v) regional analyses of potential disruption of wildlife habitat and the recreational potential of forests due to forest-structure changes brought on by climate change; (vi) regional analyses of potential socioeconomic repercussions of fluctuations in timber supply due to climate change on rural communities, industrial concerns, markets and trade in forest products, and government;. (vii) synthesis studies of the policy possibilities for the forest sector to prepare for climate change; and (viii) periodical assessment of the destruction of tropical forests using remote sensing.

3 Potential impacts of climate change on natural terrestrial ecosystems and the socio-economic consequences

Major findings

3.0.1 Major findings include;

- Global increases in the atmospheric concentration of greenhouse gases and related climatic changes will have significant consequences for natural terrestrial ecosystems and related socioeconomic systems.

- Climatic zones could shift several hundred kilometres towards the poles. Flora and fauna would lag behind these climatic shifts, surviving in their present location; they would therefore find themselves in a different climatic regime.

- The rate of projected climatic changes is the major factor determining the type and degree of climatic impacts on natural terrestrial ecosystems. These rates are likely to be faster than the ability of some species to respond and these responses may be sudden or gradual.

- New climatic regimes may be less hospitable under some circumstances (e.g. towards lower latitudes and lower altitudes) and may be more hospitable under others (e.g. towards higher latitudes). Vegetation zone changes are projected to be greatest where the land is classified as polar desert, tundra and boreal forest.

- Ecosystems are not expected to move as a single unit, but would have a new structure as a consequence of alterations in species distributions and abundance.

- Some species could be lost owing to increased stresses leading to a reduction in global biological diversity, whereas other species may thrive as stresses decrease.

- Most sensitive are those communities in which the options for adaptability are limited (e.g. montane, alpine, polar, island and coastal communities, remnant vegetation, and heritage sites and reserves) and those communities where climatic change adds to existing stresses.

- Increased incidents of disturbances such as pest outbreaks and fire are likely to occur in some areas and these could enhance projected ecosystem changes.

- The direct effects of increased atmospheric concentrations of CO_2 may increase plant growth, water use efficiency and tolerance to salinity, though this positive effect could be reduced over time by ecosystem feedbacks. Enhanced levels of air pollution could also reduce this positive effect.

- Socioeconomic consequences of these impacts will be significant, especially for those regions of the globe where societies and related economies are dependent on natural terrestrial ecosystems for their welfare. Changes in the availability of food, fuel, medicine, construction materials and income are possible as these ecosystems are affected. Important fibre products, recreation and tourism industries could also be affected in some regions.

Principal issues

3.0.2 The projected changes in climate will present these ecosystems with a climate warmer than that experienced during their recent evolution and there will be warming at a rate 15—40 times faster than past glacial-interglacial transitions. This combination of relatively large and fast changes in climate will cause disruption of ecosystems, allowing some species to expand their ranges while others will become less viable and, in some cases, may disappear.

3.0.3 Current knowledge does not allow a comprehensive and detailed analysis of all aspects of the impacts of climate change on natural terrestrial ecosystems. It is possible, however, to make some plausible implications. All estimates presented below are based on scenarios of enhanced atmospheric concentrations of greenhouse gases and related changes in global climate. It is impossible to

evaluate the consequences of change in climatic variability since the required climatic analyses are not available.

Particularly sensitive species

3.0.4 The species which are particularly sensitive to climatic changes are:

- species at the edge of (or beyond) their optimal range;
- geographically localized species (e.g. those found on islands, on mountain peaks, in remnant vegetation patches in rural areas, and in parks and reserves);
- genetically impoverished species;
- specialized organisms with specific niches;
- poor dispersers;
- more slowly reproducing species; and
- localized populations of annual species.

3.0.5 This would suggest that montane and alpine, polar, island and coastal communities, and heritage sites and reserves are particularly at risk, since their component species may not be able to survive or adapt to climate change because of the limited number of adaptive options available to them.

Changes in the boundaries of vegetation zones

3.0.6 Projected changes in global temperature of 1.5°—4.5°C and changes in precipitation will result in the movement of the boundaries of vegetation zones, and will impact on their floristic composition and associated animal species. Boundaries (e.g. boreal-tundra, temperate forests, grasslands etc) are expected to shift several hundreds of kilometres over the next 50 years. Real rates of the movement of species, however, will be restricted by limits on their ability to disperse and the presence of barriers to dispersion: they will, therefore, average approximately 10-100 m/year.

3.0.7 Both coniferous and broad-leaved thermophilic tree species will find favourable environments much further poleward than their current limits. In the northern parts of the Asian USSR, the boundary of the zone will move northward 40°-50° of latitude (500—600 km). The tundra zone is expected to disappear from the north of Eurasia.

3.0.8 Expected changes in precipitation will allow species to extend their boundaries equatorward. As a result, the broad-leaved species range will expand and these ecosystems will be more maritime in terms of species composition. The forest steppe subzone in the European USSR will change while in southern portions of western Siberia the forest-steppe boundary could move up to 200 km.

3.0.9 In the semi-arid, arid and hyper-arid ecoclimatic zones of the Mediterranean, greenhouse-gas-induced climate change will reduce plant productivity and result in desertification of the North African and Near Eastern steppes owing to increased evapotranspiration. The upper limit of the deserts would migrate under the influence of climate change and most likely extend into the area that currently corresponds to the lower limits of the Semi-Arid Zone (ie foothills of the high, Mid and Tell Atlas and Tunisian Dorsal in Northern Africa, and of the main mountain ranges of the Near-Middle East: Taurus, Lebanon, Alaoui, Kurdistan, Zagros and Alborz).

3.0.10 The impact of climate changes on the present tropical and temperate rainforest is uncertain. For example, almost all of Tasmania is expected to become, at best, climatically 'marginal' in terms of temperate rainforests, largely owing to a rise in winter temperatures suggested by climate scenarios. This increase in temperature is unlikely to have a direct effect on the forest, but may facilitate the invasion of less frost-tolerant species.

Changes within ecosystems

3.0.11 Projected greenhouse-gas-induced climate changes will profoundly affect hydrologic relationships in natural terrestrial ecosystems, both directly by altering inputs of precipitation, runoff, soil moisture, snow cover and melt, and evapotranspiration, as well as indirectly by altering sea and lake levels which influence water levels in coastal and shoreline ecosystems.

3.0.12 The seasonality of rainfall also affects its impact. A lengthening of the dry season or, conversely, an increase in ground-water table levels could both accentuate salinization problems. In Mediterranean and semi-arid climates, where evapotranspiration exceeds precipitation for long periods and increased percolation from vegetation clearing or excessive irrigation may have raised the water table, surface soil salinization can be a major problem. Such salinization can kill all but the most halophytic vegetation, increase soil erosion and reduce water quality. Salinization is already a problem in many Mediterranean and semi-arid regions (e.g. coastal Western Australia, the Mediterranean, subtropical Africa) and is a major cause of increased desertification.

3.0.13 Greenhouse-gas-induced climatic changes will affect the structure and composition of natural terrestrial ecosystems as a result of altered relationships within these ecosystems, perhaps leading to the introduction of new species.

3.0.14 Given the new associations of species that could occur as climate changes, many species will face 'exotic' competitors for the first time. Local extinctions may occur as climate change causes increased frequencies of droughts and fires, and invasion of species. One species that might spread, given such conditions, is Melaleuca quinquenervia,

a bamboo-like Australian plant. This species has already invaded the Florida Everglades, forming dense monotypic stands where drainage and frequent fires have dried the natural marsh community.

3.0.15 Pests and pathogens, in some cases, are expected to increase their ranges as a result of climate change and, in the case of insects, their population densities. This could place at risk the health of ecosystems, and thereby play an important role in determining future vegetation and animal distributions

3.0.16 Pest outbreaks can also be expected as a result of the increased stress and mortality of standing vegetation resulting from a combination of climate-driven stressors. An example from New Zealand concerns hard beech (Nothofagus truncata). A 3°C rise in temperature would increase annual respiratory carbon losses by 30%; such a loss exceeds the total annual amount allocated to stem and branch growth for this species. With insufficient reserves to replace current tissue, the tree is weakened, and becomes more susceptible to pathogens and insects. Following repeated drought episodes, several (Nothofagus) species succumbed to defoliation insects. This would be exacerbated by non-induced climate change.

3.0.17 Since wetlands, particularly seasonal wetlands in warmer regions, provide habitat for the breeding and growth of vectors of a number of serious diseases such as malaria, filariasis and schistosomiasis, an increase in average temperature and any change in the distribution of seasonal wetlands will alter the temporal and spatial distribution of these diseases.

3.0.18 Higher temperatures and changed precipitation may well lead to increased drought frequency and fire risk in many forested areas. Coupled with probably increased fuel density because of the direct effects of increased ambient CO_2 on forest understorey, this could lead to increased exposure of forests to fire, which would tend to accelerate changes in ecosystem composition under conditions of changing climate.

3.0.19 In areas with a distinct wet and dry season (parts of the tropic, and all of the Mediterranean-climate regions), change in the amount of precipitation in rainy months could alter fuel loads by influencing growth. The altered fuel loads, along with changes in precipitation, could affect fire intensities during the dry season. A shift towards a slightly wetter climate during the summer rainy season could increase fuel loadings in most of the subtropical and temperate woodlands of Mexico, which would suggest increased fire frequencies.

3.0.20 Global biological diversity is expected to decrease with possible socioeconomic consequences as a result of climate change; however, some local increases may also result, especially over the longer term. The resulting impacts on biological diversity are dependent on the balance between changes in species interactions and adaptation through migration.

3.0.21 Warming could set off a chain of extinctions by eliminating keystone herbivores or their functional counterparts in other ecosystems. For example, in the 100 years following the disappearance of elephants in the Hluhluwe Game reserve in Natal, several species of antelope have been extirpated and populations of open country grazers, such as wildebeest and waterbuck, have been greatly reduced.

3.0.22 The direct effects of increased atmospheric concentrations of CO_2 may increase the rate of plant growth; however, man-induced changes in the chemical composition of the atmosphere (e.g. ozone) and ecosystem feedbacks could reduce this positive effect over time.

Recommendations for action

3.0.23 While the specific impacts of global warming on any one region or a single species are to some degree matters of conjecture, there are some clear conclusions that can be made. Natural terrestrial ecosystems will change in make-up and shift in location, and those species which can adapt and shift will survive. The sensitive species, especially those for which options are limited, will dwindle and disappear.

3.0.24 Examination of the environmental impacts of climate change on natural terrestrial ecosystems and the associated socioeconomic consequences is in its infancy. The studies that have been carried out are limited; only specific regions and sectors have been examined. Further limiting this work is that, for the most part, existing studies have taken a narrow view of the problem and not looked at it from a multi-disciplinary perspective. In addition, most of the studies have examined the effects of climate change on current social, economic and environmental systems and have not considered social and economic adjustments nor impacts and consequences during ecosystem transitional periods.

3.0.25 These limitations can be addressed by:

- assembling relevant inventories of species and ecosystems;
- initiating and maintaining integrated monitoring programs;
- gathering information on relative species and ecosystems sensitivities to climate change;
- initiating and supporting regional, national and international research and impacts programs; and
- educating resource managers and the public about the potential consequences of climatic change for natural terrestrial ecosystems.

4 Potential impacts of climate change on hydrology and water resources

Major findings

4.0.1 Major findings include:

- For many watersheds worldwide, especially those in arid and semi-arid regions, runoff is very sensitive to small changes and variations in climate. For example, a 1°C to 2°C temperature increase coupled with a 10% reduction in precipitation could conceivably produce a 40—70% reduction in annual runoff.

- Based on empirical data and hydrological models, annual runoff appears to be more sensitive to changes in precipitation than to changes in temperature. However, in regions where seasonal snowfall and snowmelt are a major part of the total water supply, the monthly distribution of runoff and soil moisture is more sensitive to temperature than to precipitation.

- The construction of hypothetical scenarios provides a range of runoff responses and the characteristics of those responses for particular areas. However, credible forecasts for any specific region, sufficient to designate either direction or magnitude of change, are not yet available. We can conduct warm sensitivity analysis using General Circulation Models while the scientific basis slowly improves.

- Vulnerabilities in present water uses (ie where demand exceeds firm yield) and conflicts among current uses are likely to be exacerbated by global warming in most arid and semi-arid regions.

- The regions that appear to be at greatest risk, in terms of serious threats to sustaining the population are: Africa—Maghreb, Sahel, the north of Africa, southern Africa; Asia—western Arabia, Southeast Asia, the Indian subcontinent; North America—Mexico, Central America, southwest US; South America—parts of eastern Brazil; Europe—Mediterranean zone.

- The relative degree of water management (storage versus mean annual flow) is a primary determinant in adapting to changes in the mean annual variability.

- It is essential that future design of water resource engineering takes into account that climate is a non-stationary process, and that structures with a design life of 50 to more than 100 years should be designed to accommodate climatic and hydrometeorological conditions which may exist over the entire life of the structure.

Principal issues

4.0.2 If worthwhile estimates of water resources conditions, appropriate for planning and policy formulation, are to be produced, then studies must include estimates on the frequency, intensity and duration of potential future hydrologic events. This is especially critical for evaluating effects on agriculture, the design of water resource management systems, and for producing reasonably accurate water supply estimates.

4.0.3 In many instances it can be expected that changes in hydrologic extremes in response to global warming will be more significant than changes in hydrologic mean conditions. Thus, attention must be focused on changes in the frequency and magnitude of floods and droughts in evaluating the societal ramifications of water resource changes.

4.0.4 Initial water resource planning and policy making will continue to be implemented even in the face of uncertainty about global change. Clarification and specification of the useful information about the various methods for estimating future change must be made available to the management community.

Regional impacts

Continental/national

4.0.5 Based on palaeoclimatic analogs coupled with physically based water-balance models, annual runoff over the whole of the USSR is projected to rise, although runoff is expected to decrease slightly in the forest steppe and southern forest zones. In any case, winter runoff is expected to increase in the regions with snowfall and snowmelt. Serious flooding problems could arise in many northern rivers of the USSR.

4.0.6 An assessment of all the river basins in the US shows that the arid and semi-arid regions of the US would be most severely affected by global warming, even though there is a high degree of water control. The competing uses of agricultural irrigation, municipal water supply, and generation of hydroelectric power, have stressed even the present system. All other regions in the US will probably suffer adverse water-resource impacts to some degree, whether for generation of hydroelectric power, municipal water supply shortages, or agricultural irrigation.

4.0.7 An assessment of the general circulation model studies for the nations of the European Economic Community (EEC) indicates that precipitation and runoff may increase in the northern nations, possibly causing flooding problems in low-lying countries. The Mediterranean countries of the EEC may experience a decline in runoff, thereby increasing the already serious and frequent water supply shortages occurring in that region. It is most probable that agriculture will suffer the most adverse effects.

4.0.8 In Japan, prolonged periods of droughts and shorter periods of intense precipitation may be likely. Current storage capacity is limited and a large proportion of the population is located on flood-plains. Water demand can be expected to increase, which will seriously stress the existing water management system.

4.0.9 An increase in precipitation and consequent flooding, along with overloads of stormwater/sewerage systems leading to degradation of surface water quality, is possible in New Zealand.

4.0.10 The UK can expect an increase in mean annual runoff over most of the country, but with a stronger seasonal variation in peak flows, imposing the need for redesigning existing water management systems.

River basins and critical environments

4.0.11 Runoff in the Volga River basin, after undergoing an initial decrease through the year 2000, is expected to increase after that year.

4.0.12 Studies indicate that hydrological conditions in the Sahelian zone are very sensitive to climatic conditions, especially precipitation. Research suggests, for example, that a 20% to 30% decrease in precipitation could lead to a 15% to 59% reduction in runoff. As for potential changes in water resources in the future, it can be said that the situation is very uncertain. Therefore, additional comprehensive studies of this problem, which is very important for the region, are required.

4.0.13 A study of the Sacramento-San Joaquin River basin showed how a highly managed water resource system, dependent on snowmelt-generated runoff, would be affected by global warming. Air temperature increases changed the timing and increased the magnitude of snowmelt-generated runoff by 16% to 81%, severely stressing the flood-control capabilities of existing reservoirs. However, summer runoff decreases of 30% to 68%, coupled with soil moisture decreases of 14% to 36% and a doubling of water demand by the year 2020, suggest that serious water use conflicts and periodic shortages are a distinct possibility for this system.

4.0.14 In the Murray-Darling basin of Australia, the use of spatial analogs indicates that precipitation could decrease by 40% to 50%. However, based on general circulation model outputs, the summer-dominant rainfall area of Australia will possibly expand to encompass 75% of the continent by 2035. Runoff could double on the Darling River.

4.0.15 A water supply-demand stochastically-based sensitivity analysis was conducted for the Delaware River basin, a highly urbanized watershed in the northeastern US. Basin-wide estimates of annual runoff indicate a possible decrease of 9% to 25%. Also, the probability of drought increases substantially throughout the basin. The Delaware River supplies a large percentage of New York City's water supply, which is already operating below its safe yield. Reduced flows in the Delaware River would threaten the city of Philadelphia's water supply intakes in the estuarine portion of the river through upstream movement of the freshwater-saltwater interface.

Large lakes/seas

4.0.16 The Caspian Sea is the largest closed water body in the world. It receives nearly 80% of its runoff from the Volga River and will respond to the initial decrease in projected Volga River flows to the year 2000, but will increase thereafter. This will greatly improve the severely degraded water quality and ecological conditions in the Sea.

4.0.17 Based on general circulation model results, the Great Lakes are expected to incur net basin runoff decreases of 23% to 51% under an effective doubling of CO_2 scenario. Generation of hydro-electric power, the very important commercial navigational uses, and lake water quality which is due to thermal stratification, are expected to be adversely affected.

4.0.18 The Aral Sea would continue to experience water-quality degradation by polluted irrigation return flows, as the precipitation-runoff increases projected for the area would not be enough to compensate for increased expansion of irrigated agriculture.

Recommendations for action

4.0.19 The most essential need is for more reliable and detailed (both in space and time) estimates of future climatic conditions. These estimates must be regionally specific and provide information on both the frequency and magnitude of events. Increased understanding of relations between climatic variability and hydrologic response must be developed. Such work should include the development of methods for translating climate model information into a form that provides meaningful input data to watershed and water resource system models.

4.0.20 Areas particularly vulnerable to even small changes in climate must be identified worldwide. Vulnerabilities must be ascertained considering both natural and anthropogenic conditions and potential changes.

4.0.21 Intensive assessments of water resource sensitivities are necessary in developing countries, especially those located in environmentally sensitive arid and semi-arid regions, where the potential for conflicts associated with low water resource system development and rapidly increasing water demands is high.

4.0.22 Studies are needed that produce improved procedures for operating water management systems in consideration of climate uncertainty. A related aspect of this work is the development of design criteria for engineered

structures that specifically incorporate estimates of climatic variability and change.

4.0.23 Very little is currently known about the effects of climate change on water quality. Although concerns about water quality are becoming increasingly important, the separation of human-induced versus climate-induced changes in water quality is a very difficult problem. Specifically, there is an immediate need to identify those aspects of this problem that hold the most promise for yielding credible evaluations of climatic effects on water quality.

5. Potential impacts of climate change on human settlement, the energy, transport and industrial sectors, human health and air quality

Major findings

5.0.1 Major findings include:

- Throughout the world the most vulnerable populations are farmers engaged in subsistence agriculture, residents of coastal lowlands and islands, populations in semi-arid grasslands and the urban poor in slums in shanty towns, especially in megacities—those with several millions of inhabitants.

- Climate change and even a modest global sea-level rise can be expected to prove disruptive to human settlement in many vulnerable coastal areas of some island nations and communities where drought, floods and changed agricultural growing conditions have affected water resources, energy, public health and sanitation, and industrial or agricultural production.

- Global warming can be expected to cause a significant shift in the permafrost zone; such rapid change will prove quite disruptive to roads, railways, buildings, oil and gas pipelines, mining facilities and infrastructure in the permafrost region.

- Global warming can be expected to affect the availability of water resources and biomass, both major energy sources in a large number of developing countries. Such changes in areas which lose water may jeopardize energy supply and materials essential for human habitation and energy. Climate change will also affects the regional distribution of other renewable energy resources such as wind and solar power.

- Vector-borne and viral diseases such as malaria, schistosomiasis and dengue can be expected under warmer climatic conditions to shift to higher latitudes.

- Should severe weather, such as tropical cyclones, occur more frequently or become more intense as a result of climate changes, human settlement and industry may be seriously affected, with large loss of human life.

Principal issues

5.0.2 The impact on developing countries, many of which lack resources for adaptation, may be particularly disruptive. Understanding likely impacts of climate change on human settlement, energy, transport, industry and human health in such countries should be a high priority, together with reinforcing indigenous capability to design and implement strategies to reduce adverse impacts of climate change.

5.0.3 The impacts of climate change on human settlement and related socioeconomic activity, including the energy, transport and industry sectors, will differ regionally, depending on regional distribution of changes in temperature, precipitation, soil moisture, patterns of severe storm, and other possible manifestations of climate change. As the general circulation model scenarios provided by Working Group I have indicated, changes in some of these climatic characteristics may differ considerably among regions. In addition, the vulnerability to change in climate of human settlement and related economic activity varies considerably among regions and within regions. For example, coastal areas may generally be more vulnerable to climate change than inland areas within the same region.

5.0.4 Development of effective strategies to respond to climate change will require much better capability to predict and detect regional climate change and occurrence of severe meteorological phenomena. A major issue is that of timing. For example, a sea-level rise of 0.5 m over 50 years would have substantially different impacts than the same rise over 100 years. Not only are present-value costs for adaptation measures vastly different, but also much of the present-day infrastructure would have undergone replacement in the longer time period.

Human settlement

5.0.5 A principal difficulty in determining the impact of climate change on human habitat is the fact that many other factors, largely independent of climate change, are also important. One can reliably predict that certain developing countries will be extremely vulnerable to climate changes because they are already at the limits of their capacity to cope with climatic events. These include populations in low-lying coastal regions and islands, subsistence farmers, populations in semi-arid grasslands, and the urban poor.

5.0.6 The largest impacts on humanity of climate change may be on human settlement, with the existence of entire countries such as the Maldives, Tuvalu, and Kiribati imperilled by a rise of only a few metres in sea-levels and populous river delta and coastal areas of such countries as

Egypt, Bangladesh, India, China and Indonesia, threatened by inundation from even a moderate global sea-level rise. Coastal areas of such industrialized nations as the United States and Japan will also be threatened, although these nations are expected to have the requisite resources to cope with this challenge. The Netherlands has demonstrated how a small country can effectively marshal resources to deal with such a threat.

5.0.7 Besides flooding of coastal areas, human settlement may be jeopardized by drought, which could impair food supplies and the availability of water resources. Water shortages caused by irregular rainfall may especially affect developing countries, as seen in the case of the Zambezi river basin. Biomass is the principal source of energy for most of the countries of sub-Saharan Africa, and changed moisture conditions in some areas, reducing this biomass, could pose grave problems for domestic energy production and construction of shelter.

5.0.8 Although there has been only a handful of city-specific studies, they suggest that climate change could prove costly to major urban areas in developed nations. A study has projected that an effective CO_2 doubling could produce a major water shortfall for New York City equal to 28% to 42% of the planned supply in the Hudson River Basin, requiring a $3 billion project to skim Hudson River flood waters into additional reservoirs.

5.0.9 Although in the permafrost region global warming may result in expansion of human settlement poleward, thawing of the permafrost may also disrupt infrastructure and transport and adversely affect stability of existing buildings and conditions for future construction.

5.0.10 The gravest effects of climate change may be those on human migration as millions are displaced by shoreline erosion, coastal flooding and severe drought. Many areas to which they flee are likely to have insufficient health and other support services to accommodate the new arrivals. Epidemics may sweep through refugee camps and settlements, spilling over into surrounding communities. In addition, resettlement often causes psychological and social strains, and this may affect the health and welfare of displaced populations.

Energy

5.0.11 Among the largest potential impacts of climate change on the developing world are the threats in many areas to biomass, a principal source of energy in most sub-Saharan African nations and many other developing countries. More than 90% of the energy in some African countries depends on biomass energy (fuelwood). Owing to uncertainties in water resource projections derived from current climate models, it is very difficult to provide reliable regional projections of future moisture conditions in these countries. Drier conditions could be expected in some countries or regions, and in those situations energy resources could be severely impaired. There could be possible compensating effects of faster growth of fuelwood due to higher ambient CO_2. Analysis of this situation should be a top priority for energy planners.

5.0.12 In addition to affecting the regional distribution of water and biomass, climate-related changes in cloud cover, precipitation and wind circulation intensity will affect the distribution of other forms of potential renewable energy such as solar and wind power. Understanding these impacts on hydro, biomass, solar and wind energy is particularly important because renewable energy sources are playing a significant role in the energy planning of many countries. This could become an increasingly important concern in developing countries, many of which are facing serious economic pressures from the need to import conventional energy resources.

5.0.13 Developing countries, including many in Africa, depend significantly on hydroelectric power. By changing water resource availability, climate change may make some present hydroelectric power facilities obsolete and future energy planning more troubled, although others may benefit from increased runoff.

5.0.14 Major studies to date of the likely impact of global warming on the energy sector in developed countries are confined largely to six countries: Canada, the Federal Republic of Germany, Japan, the UK, the USSR and the US. Generally, they show differing overall aggregate impacts, depending on how much energy use is related to residential and office heating and cooling. Climate warming will increase energy consumption for air-conditioning and, conversely, lower it for heating.

5.0.15 In addition, the energy sector may be affected by response strategies against global warming, such as a policy on emission stabilization. This may be among the most significant energy sector impacts in many developed countries, enhancing opportunities for technologies that produce low quantities of greenhouse gases. Controversy on the way to obtain CO_2-free energy has already risen, particularly the options of increased reliance on nuclear power or hydro-electric power, weighed against related safety and environmental concerns. Energy sector changes in both developing and developed countries may have broad economic impacts affecting regional employment, migration and patterns of living.

Transport

5.0.16 Generally, the impacts of climate change on the transport sector appear likely to be quite modest, with two exceptions. Ultimately, the greatest impact of climate change on the transport sector in developed countries would appear to be changes produced by regulatory policies or consumer shifts designed to reduce transport-related emissions of greenhouse gases. Because of the importance of the transport sector as a source of greenhouse gases, it is already being

targeted as a major source of potential reductions in greenhouse gas emissions, with potentially added constraints on private automobile traffic, automotive fuel and emissions, and increased use of efficient public transport.

5.0.17 A second large impact on the transport sector concerns inland shipping, where changes in water levels of lakes and rivers may seriously affect navigation and the costs of barge and other transport. Studies to date, focused entirely on the Great Lakes region of Canada and the US, have shown quite large potential impacts. Climate scenarios have shown a likely drop of lake levels of as much as 2.5 m resulting from an effective CO_2 doubling. Such changes could increase shipping costs, but the shipping season could be longer than at present due to decreased ice. Lake and river levels may rise in some other regions with potentially enhanced opportunities for shipping.

5.0.18 Generally, impacts on roads appear likely to be quite modest, except in coastal areas where highways or bridges may be endangered by sea-level rise or in mountainous regions where potentially increased intensity in rainfall might pose the risk of mudslides. Studies in Atlantic Canada and Greater Miami, US, indicate that highway infrastructure costs could prove very costly in such exposed coastal areas. Reduced snow and ice and lessened threat of frost heaves should generally produce highway maintenance savings as suggested by a study of Cleveland, Ohio, US.

5.0.19 Impacts on railways appear likely to be modest, although heat stress on tracks could increase summertime safety concerns on some railways and reduce operational capability during unusually hot periods. Dislocations due to flooding may increase.

5.0.20 There has been little analysis of likely impacts on ocean transport. The greatest effect would appear likely to be some jeopardy to shipping infrastructure such as ports and docking facilities, threatened both by sea-level rise and storm surge. Some climate projections indicate the possibility that tropical cyclone intensity may increase. This could have adverse implications for ocean shipping and infrastructure. On the other hand, decreased sea ice could provide greater access to northern ports and even enable regular use of the Arctic Ocean for shipping. Moderate sea-level rise could also increase the allowable draught for ships using shallow channels.

5.0.21 There is a strong need for analysis of likely impacts of climate change for the transport sector in developing countries, as efficiency of the transport sector is likely to be an essential element in the ability of countries to respond to climate change.

Industry

5.0.22 Studies of likely impacts of climate change on the industrial sector tend to be concentrated heavily on certain sectors such as recreation and only on a handful of developed countries, principally Australia, Canada, Japan, the UK and the US. There is very little analysis of the likely impacts of climate change on industry in developing countries, although there is some evidence to suggest that industry of developing countries may be particularly vulnerable to climate change. An especially important factor is the likely change in the production map of primary products as a result of climate change.

5.0.23 Changes in the regional and global availability and cost of food and fibre may significantly affect the competitiveness and viability of such derivative industries as food processing, forest and paper products, textiles and clothing. Climate change may be expected to have impacts on the availability and cost of food, fibre, water and energy which would differ markedly from region to region.

5.0.24 Just as the motor vehicle and the energy sectors are likely to be influenced by regulatory decisions and shifts in consumer patterns emanating from concerns about limiting greenhouse gas emissions, heavy manufacturing may face readjustment to new situations such as transboundary siting constraints and international mechanisms for development and transfer of new technology. Efficiency in the use of energy may become an even more significant competitive factor in steel, aluminium and other metal industries, and automotive manufacturing. Public concerns about limiting greenhouse gas emissions may also create opportunities for energy conservation or for industries based on 'clean technology'. Studies of likely impacts of climate change on industry tend to be clustered in the recreational sector, where direct impacts of climate change are more ascertainable.

5.0.25 With sufficient lead time, industry may be able to adjust to many of the changes accompanying global warming. Shortages of capital in developing countries which may be vulnerable to flood, drought or coastal inundation may, however, constrain such industry's ability to design effective response strategies.

Human health

5.0.26 Humans have a great capacity to adapt to climatic conditions. However, adaptations have occurred over many thousands of years. The rate of projected climatic changes suggest that the cost of future adaptation may be significant.

5.0.27 A greater number of heatwaves could increase the risk of excess mortality. Increased heat stress in summer is likely to increase heat-related deaths and illnesses. Generally, the increase in heat-related deaths would be likely to exceed the number of deaths avoided by reduced severe cold in winter. Global warming and stratospheric ozone depletion appear likely to worsen air pollution conditions, especially in many heavily populated and polluted urban areas. Climate change-induced alterations in photochemical reaction rates among chemical pollutants in the atmosphere may increase oxidant levels, adversely affecting human health.

5.0.28 There is a risk that increased ultraviolet-B radiation resulting from depletion of the stratospheric ozone layer could raise the incidence of skin cancer, cataracts and snow blindness. The increased skin cancer risks are expected to rise most among fair-skinned Caucasians in high-latitude zones.

5.0.29 Another major effect of global warming may be the movement poleward in both hemispheres of vector-borne diseases carried by mosquitoes and other parasites. Parasitic and viral diseases have the potential for increase and reintroduction in many countries.

5.0.30 Changes in water quality and availability may also affect human health. Drought-induced famine and malnutrition have enormous consequences for human health and survival.

5.0.31 The potential scarcity in some regions of biomass used for cooking, and the growing difficulty in securing safe drinking water because of drought, may increase malnutrition in some developing countries.

Air pollution

5.0.32 SOx, NOx and auto-exhaust controls are already being implemented to improve air quality in urban areas in some developed countries. Concerns about possible energy penalties and overall implications of such control measures for greenhouse gas emissions will need to be incorporated in future planning. Moreover, global warming and stratospheric ozone depletion appear likely to aggravate tropospheric ozone problems in polluted urban areas. The tropospheric temperature rise induced by the enhanced greenhouse effect could change homogeneous and heterogeneous reaction rates, solubility to cloud water, emission from marine, soil and vegetative surfaces, and deposition to plant surfaces of various atmospheric gases, including water vapour and methane. A change in water vapour concentration will lead to changes in the concentration of HOx radicals and H_2O_2, which are important for the oxidation of SO_2 and NOx in the atmosphere The predicted change of the patterns of cloud cover, stability in the lower atmosphere, circulation and precipitation, could concentrate or dilute pollutants, and change their distribution patterns and transformation rates in regional or local sectors. A change in aerosol formation by atmospheric conversion from NOx, and SO_2 and windblown dust from arid land could lead to changes in visibility and albedo. Material damage caused by acidic and other types of air pollutants may be aggravated by higher levels of humidity.

Ultraviolet-B radiation

5.0.33 Besides the human health implications of increased ultraviolet-B radiation already discussed, such radiation may also significantly affect terrestrial vegetation, marine organisms, air quality and materials. Increased ultraviolet-B radiation may adversely affect crop yields. There are some indications that increased solar ultraviolet-B radiation which penetrates into the ocean surface zone where some marine organisms live, may adversely affect marine phytoplankton, potentially reducing marine productivity and affecting the global food supply. Increased ultraviolet-B radiation can also be expected to accelerate degradation of plastic and other coating used outdoors. The enhanced greenhouse effect is expected to decrease stratospheric temperatures and this may affect the state of the stratospheric ozone layer.

Recommendations for action

- Assessment of the vulnerability of countries, especially in the developing world, to gain or loss of energy resources such as hydroelectric power, biomass, wind and solar, and an examination of available substitutes under new climate conditions, should be a high priority.

- Research is critically needed into the adaptability of vulnerable human populations, especially the elderly and the sick, to the occurrence of increased heat stress as well as the potential for vector-borne and viral diseases to shift geographically.

- Policy makers should give priority to the identification of population and agricultural and industrial production at risk in coastal areas subject to inundation from sea-level rise of various magnitudes and to storm surge.

- It is important that developing countries have the capability to assess climate change impacts and to integrate this information into their planning. The world community should assist countries in conducting such assessments and work to create indigenous climate-change impact assessment capabilities in such countries.

6. Potential impacts of climate change on the world ocean and coastal zones

Major findings

6.0.1 The projected global warming will cause sea-level rise, modify ocean circulation, and cause fundamental changes to marine ecosystems, with considerable socioeconomic consequences.

6.0.2 Sea level is already rising on average over 6 cm per 50 years, with important regional variations because of local geological movements. The Greenland and perhaps the Antarctic ice sheets may still be responding to changes since the last glaciation. Fisheries and various coastal resources are presently under growing stress from pollution,

exploitation and development, creating serious problems for populations dependent on them. Impacts from the enhanced greenhouse effect, which have been considered by the IPCC, will be added to these present trends.

6.0.3 A 20—30 cm sea-level rise (projected by the year 2050) poses problems for the low-lying island countries and coastal zones, destroying productive land and the freshwater lens. Protecting these areas entails considerable cost.

6.0.4 A 1 m sea-level rise (the maximum projected by the year 2100) would eliminate several sovereign states, displace populations, destroy low-lying urban infrastructure, inundate productive lands, contaminate freshwater supplies and alter coastlines. These effects could not be prevented except at enormous cost. The severity would vary among coastal regions and would depend on the actual rate of rise.

6.0.5 Coastal ecology is affected by the rate of sea-level rise. Too rapid a rise could reduce or eliminate many coastal ecosystems, drown coral reefs, reduce biological diversity and disrupt the life cycles of many economically and culturally important species.

6.0.6 Erosion of wetlands and increasing availability of organic matter from sea-level rise can increase estuarine and near-shore productivity for some decades.

6.0.7 Global warming will change the thermal budget of the World Ocean and shift the global ocean circulation. Changes in ocean circulation, including high-latitude deep water formation, will affect the capacity of the ocean as a sink of atmospheric heat and CO_2. Upwellings of nutrient-rich waters associated with major fisheries are also expected to change, causing a decrease in primary production in open ocean upwelling zones and an increase in primary production in coastal upwelling zones. The expected impacts will include chemical changes in biogeochemical cycles such as the global carbon cycle which affects the rate of accumulation of atmospheric CO_2.

6.0.8 Adverse ecological and biological consequences will vary by geographic zones of the world's oceans. The loss of habitat will cause changes in biological diversity, redistribution of marine organisms and a shift in the ocean production zones.

6.0.9 A simultaneous rise in both water temperature and sea-level may lead to the redistribution of commercially important species and benthic organisms. Changes in fisheries production may well balance globally in the long term, but there could be important regional shifts in areas of fisheries, with major socioeconomic impacts.

6.0.10 Shipping and ocean transportation will benefit from less sea ice and small increases in depth in harbours, but some ice-dependent marine mammals and birds will lose migratory and hunting routes and essential habitats.

6.0.11 Increase in ultraviolet-B radiation can have widespread effects on biological and chemical processes, on life in the upper layer of the open ocean, on corals, and on wetlands. These impacts are of concern but not well understood.

Impacts of sea-level rise on coastal zones

6.0.12 The magnitude and rate of sea-level rise will determine the ability of social and natural ecosystems to adapt to the rise. Direct effects of the rise are straightforward: inundation of low-lying coastal areas; erosion and recession of sandy shorelines and wetlands; increased tidal range and estuarine salt-front intrusion; increases in sedimentation in the zone of tidal excursion; and increase in the potential for salt water contamination of coastal freshwater acquifers. The predicted changes in climate may also affect the frequency and intensity of coastal storms and hurricanes, which are the major determinants of coastal geomorphic features and extreme high sea-level events.

6.0.13 The socioeconomic impacts of these direct physical effects are uncertain and more difficult to assess, and are region- and site-specific. There are three general impact categories that encompass the physical effects:

- threatened populations in low-lying areas and island nations;
- alteration and degradation of the biophysical properties of beaches, estuaries and wetland;.
- inundation, erosion and recession of barrier beaches and shorelin;.

Threatened populations in low-lying areas and island nations

6.0.14 The most important socioeconomic impact of sea-level rise is the inundation of intensely utilized and densely populated coastal plains. A 1 m rise would produce a coastline recession of several kilometres in a number of countries. Other countries have a substantial proportion of land area between 1 m and 5 m above sea-level, with high density coastal populations. For example, a 1 m sea-level rise could inundate 12—15% of Egypt's arable land and 14% of Bangladesh's net cropped area, displacing millions of inhabitants.

6.0.15 Sea-level rise would also expose a greater proportion of low-lying areas to coastal storm flooding from storm surges. Densely populated urban areas could be protected at great cost, but less densely populated areas stretched out along the coastline could not be protected. In these situations, large-scale resettlement might be necessary. Another consequence of sea-level rise is greater incursion of salt water into freshwater estuarine areas, along with larger tidal excursion. This would reduce the freshwater portion

of estuarine rivers, especially during drought periods, adversely affecting municipal and industrial freshwater supplies, and could contaminate coastal groundwater acquifers, which also supply water for municipal purposes in many areas. Many estuarine areas across the world, with large population centres, would be affected, particularly those where a decrease in net freshwater runoff is also projected as a consequence of global warming.

6.0.16 Finally, as sea-level rises, much of the infrastructure in low-lying urban areas would be affected, requiring major engineering design adjustments and investments. In particular, stormwater drainage and sewerage systems of many cities will be affected. Coastal protection structures, highways, power plants and bridges may require redesign and reinforcement to withstand increased flooding, erosion, storm surges, wave attack and sea-water intrusion.

Alteration of the biophysical properties of estuaries and wetlands

6.0.17 An accelerated rise in sea-level could severely redistribute coastal wetlands. Salt, brackish and fresh marshes as well as mangrove and other swamps would be lost to inundation and erosion; others would transform and adapt to the new hydrologic and hydraulic regime or would migrate inland through adjacent lowlands not impeded by protective structures. The value of these wetlands as habitat for wildlife would be impaired during the transitional period and their biodiversity may decrease. Although many wetlands have kept pace or have increased in area under the historic rate of sea-level rise owing to sediment entrapment and peat formation, vertical accretion of wetlands has not been observed to occur at rates comparable to those projected for sea-level rise in the next century.

6.0.18 Wetlands are vital to the ecology and economy of coastal areas. Their biological productivity is equal to or exceeds that of any other natural or agricultural system, although little of that productivity may be available to marsh animals and coastal fisheries. Over half the species of commercially important fishes in the southeastern US use salt marshes as nursery grounds. Wetlands also serve as sinks for pollutants and provide a degree of protection from floods, storms and high tides. Based on these functions, marshes can provide a present value to society of as much as $US5,500/acre or over $US10,000/ha.

6.0.19 Coastal wetlands and estuaries are important to many species. If sea-level rise is too rapid, natural succession of the coastal ecology will not take place and will lead to great disruption in life cycles. In the short term, production of fisheries could rise as marshes flood, die and decompose, thus improving fisheries habitat in some cases and providing more nutrients. Further nutrients will become available from the leaching of soils and peat which become more frequently flooded. This temporary increase in productivity appears to be happening now in the southeast US where sea-level rise is compounded by land subsidence. However, this temporary benefit for fisheries may be balanced by negative impacts on birds and other wildlife as the habitat area is decreased. In the longer term, by 2050 the overall impact on fisheries and wildlife is likely to be negative.

6.0.20 While considering potential changes in the biogeochemical cycles of chemicals from sea-level rise, it should be noted that (i) growth of nitrogen and phosphorus concentrations on a regional scale (in subpolar and mid latitudes, in the Bering Sea in particular) would result from flooding of coastal areas and from soil erosion; and (ii) many pesticides which are presently held in sediments could be released into the marine environment by coastal flooding.

6.0.21 The combination of climatic changes will cause coastal ecosystems to move inland, unless humankind intervenes, and poleward. Also, if sea-level rise is rapid, as predicted, productivity will probably fall, but there may be some decades during which wetlands-based productivity increases before it falls. Once the ocean begins to stabilize at its new level (if this were to occur in the foreseeable future), productivity will begin to decrease.

Inundation and recession of barrier islands, coral atolls and other shorelines

6.0.22 Sea-level rise would cause inundation and recession of all types of shorelines, especially low-lying coastal areas. Many beaches have very small gradients of 1:100 or less. A 1 m rise in sea-level would inundate 100 m of beach. Additional shoreline recession would result from normal erosive processes including storm surges and wave attack. The potential destruction of coral atolls is perhaps most significant, because these island areas serve both as contained human habitats as well as important ecological habitats with high biodiversity. Unlike continental areas with receding coastlines, where areas for resettlement are available landward of the coasts, coral islands have very limited possibilities. If the rate of sea-level rise exceeds the maximum rate of vertical coral growth (8 mm/yr), then inundation and erosive processes begin to dominate, leading to the demise of the coral atoll. However, if the rate of sea-level rise is small, then coral growth may be able to keep pace. Although there are engineering solutions for retarding erosion and protecting against storm damage of continental coasts, coral atolls cannot be effectively protected.

6.0.23 Barrier beaches are important for human use, both for subsistence and recreation, and as protection for lagoons and mainland areas from coastal storms. Coastal areas have always been hazardous. Societies have adapted to or sought to control the most extreme conditions resulting from natural climate variability. The loss of habitable coastal areas, which are typically densely populated will undoubtedly lead to large-scale resettlement. Since most commercial and subsistence fisheries are de facto located in the very same

vulnerable areas, the impacts are twofold: reduction in ecological (wetlands) habitat that sustains fish populations, coupled with increased threats to habitable coastal areas. Many areas around the globe, comprising thousands of kilometres of shoreline and affecting millions of people would be adversely affected by a rise of 1 m, or even 0.5 m. For the most part, prevention of the primary physical effects is not economical for most of the threatened coastline. Therefore, the prospect for adverse impacts should be considered to be extremely important and virtually irreversible.

Impacts on the World Ocean

6.0.24 Global climate warming can change the physical, chemical and biological processes in the oceans, and affect productivity of the oceans and fisheries. Effective CO_2 doubling could lead to an increase of sea-surface temperature by 0.2°—2°C and to changed heat balance components. Impacts will differ among geographic zones.

6.0.25 In addition, an increase in atmospheric CO_2 could cause an increase in sea-water acidity up to 0.3 pH and elevation of the lysocline (because of solution of additional amounts of $CaCO_3$). These processes might be accompanied by a decrease in the stability of the complexes of trace metals with aquatic humus, strengthening the toxic impacts of these substances on marine organisms as well as a change in the conditions of accumulation of deposits.

6.0.26 Coastal ecosystems will be exposed to the most severe impact owing to a water temperature increase and, especially, to sea-level rise. Disturbances by hydrological and hydrochemical conditions in these regions will be accompanied by a shift of feeding zones of many commercial fish species and benthic organisms, a change in the trophic structure of coastal communities and, as a consequence, a decrease in their productivity. At the first stage, as the flux of nutrient increases, in the process of land flooding, a certain increase in the productivity of coastal areas might be observed.

6.0.27 A change in heat balance and the circulation system in the oceans will produce a direct effect on the productivity of marine ecosystems. Taking into consideration the fact that 45% of the total annual production is in the zones of oceanic and coastal upwellings and subpolar regions, a change in these regions would determine the future productivity of the oceans.

6.0.28 According to the results of numerical experiments with the use of General Circulation Models of the atmosphere-ocean system, as well as palaeo-oceanographical data, the global warming would be accompanied by a weakening of the intensity of oceanic upwellings because of a decrease in the meridional temperature gradient. This process will involve a decrease in the productivity of these ecosystems. However, some increase in the intensity of coastal upwellings as a result of increasing temperature difference between land and water surface, would partially compensate for the reduction of oceanic upwellings. Besides, an increase in the temperature at high latitudes will be accompanied by an increase in their productivity. As a result of the above changes, a redistribution of productive zones will probably occur. This could lead to disturbances in the trophic structure of marine ecosystems and to a change in the conditions of the formation of the stocks of commercial fishes.

6.0.29 An increase in the zone of the area of warm equatorial and tropical waters would cause the movement of pelagic and benthic communities of these areas to the boreal and temperate regions. This circumstance might significantly affect the structure of world fisheries. Under conditions of climate warming, the intensification of biodegradation processes will occur by up to 30—50% in the zone of high latitudes. This factor, along with the expected increase of ultraviolet-B radiation, resulting from the depletion of the ozone layer, could accelerate bacterial and photochemical degradation of pollutants and reduction of their 'residence time' in the marine environment. Ecological and biological consequences of climate changes will vary among geographic zones. A regional approach is needed to study the biogeochemical carbon cycle, especially in the most productive and vulnerable ecosystems of the ocean.

6.0.30 The highly productive subpolar and polar ecosystems of the Bering Sea, Arctic Seas and Southern Ocean are important to study because the high-latitude areas will see the greatest changes. These areas are important to the total global carbon cycle in the ocean, in climate-forming processes, in fisheries, and in marine mammal and bird production.

6.0.31 International investigations, for example those planned for the region of the Bering Sea, will contribute to the determination of the role of subpolar ecosystems in the formation of earth's climate, as well as to a more comprehensive study of possible ecological impacts of global warming on the ocean, in particular on fisheries.

6.0.32 Many fisheries and marine mammal populations are heavily stressed from fishing pressure. Climate changes will increase stress and the chance of collapse. However, for some species, the new climate may be more advantageous to their wellbeing.

6.0.33 One benefit of warming will be the reduction of sea ice and thus improved access for shipping. However, there are ecological concerns. Land animals use sea ice for migratory and hunting routes, while for many species of marine mammals (e.g. seals, polar bears, penguins) sea ice is an essential part of their habitat. Thus, reduction of the amount or duration of ice can cause difficulties for such animals. Moderate rises in sea-level, provided they are insufficient to threaten port installations, may prove to be beneficial by increasing the allowable draught of ships in shallow ports and channels.

Recommendations for action

- Identification and assessment of the risks to coastal areas and islands and living resources of a 0.3—0.5 m rise in sea-level.
- Assessment of potential leaching of toxic chemicals with sea-level rise.
- Improvement of the methods for analyzing the major components of oceanic branch of carbon cycle (the carbonate system and organic carbon).
- Assessment of the possible impacts of increased UV-B radiation from stratospheric ozone depletion on oceanic and estuarine ecosystems.
- Determination of ecological impacts of Arctic and Antarctic sea ice reductions.
- Development of methodologies to assess the impacts on living marine resources, and socioeconomic impacts, of changes in the ocean and coastal zones.
- Development and implementation of multinational systems to detect and monitor expected environmental and socioeconomic impacts of ocean and coastal zone changes.

7. Impacts of climate change on seasonal snow cover, ice and permafrost, and socioeconomic consequences

Major findings

7.0.1 Major findings are:

- The global areal extent and volume of the terrestrial cryosphere (seasonal snow cover, near-surface layers of permafrost and some masses of ice) will be substantially reduced. These reductions, when reflected regionally, could have significant impacts on related ecosystems and social and economic activities.
- Thawing and reduction in the areal extent of the terrestrial cryosphere can enhance global warming (positive feedback on climate warming) through changes in the global and local radiation and heat balances, and the release of greenhouse gases. This positive feedback could increase the rate of global warming and, in some regions, could result in changes that are sudden rather than gradual. The possibility of relatively rapid changes, increases the potential significance of the associated impacts.
- The areal coverage of seasonal snow and its duration are projected to decrease in most regions, particularly at mid latitudes, with some regions at high latitudes in the Arctic and Antarctic possibly experiencing increases in seasonal snow cover.
- Decreases in seasonal snow cover can have both positive and negative socioeconomic consequences owing to impacts on regional water resources, winter transportation and winter recreation.
- Globally, the ice contained in glaciers and ice sheets is projected to decrease. Regional responses, however, are complicated by the effect of increased snowfall in some areas which could lead to accumulation of ice. Glacial recession will have significant implications for local and regional water resources and thus impact on water availability and on hydroelectric power potential. Enhanced melt rates of glaciers may initially increase the flow of melt-waters; however, flows will decrease and eventually be lost as glacial ice mass decreases. Glacial recession and loss of ice from ice sheets will also contribute to sea-level rise.
- Degradation of permafrost is expected with an increase in the thickness of the seasonal freeze-thaw (active) layer and a recession of permafrost to higher latitudes and higher altitudes. The thickness of the active layer is expected to increase by 1 m over the next 40—50 years. Although major shifts are expected in climatic zones, recession of permafrost will significantly lag behind, receding only 25—50 km during the next 40—50 years. These changes could lead to increases in terrain instability, erosion and landslides in those areas which are currently underlaid by permafrost.
- The socioeconomic consequences of these changes in permafrost could be significant. Ecosystems which are underlaid by permafrost could be substantially altered owing to terrain disturbances and changes in the availability of water. The integrity of existing and planned structures and associated facilities and infrastructure could be reduced by changes in the underlying permafrost. Retrofitting or redesigning would be required at a minimum; however, in some situations the associated terrain disruptions and/or costs (environmental, social and economic) may be too large, necessitating abandonment. Development opportunities could also be affected in areas where the risks associated with developing in an area susceptible to permafrost degradation are assessed as too high.
- The terrestrial cryosphere, because of its relative responsiveness to climate and climatic changes, provides an effective means of monitoring and detecting climatic change.
- Lack of sufficient data and gaps in the understanding of associated processes limits more quantitative assessments at this time.

Principal issues

7.0.2 The terrestrial component of the cryosphere consists of seasonal snow cover, mountain glaciers, ice sheets, and frozen ground, including permafrost and seasonally frozen ground. These elements of the terrestrial cryosphere currently cover approximately 41 million km^2, with seasonal snow cover covering as much as 62% of the Eurasian continent and virtually all of North America north of 35° latitude.

7.0.3 Projected changes in climate will dramatically reduce the areal extent and volume of these elements of the terrestrial cryosphere. This has implications not only with respect to changes in the availability of fresh water, changes in sea-level and in terrain characteristics, but also for societies and related economic systems which have come to depend on, or are limited by, the existence of a terrestrial cryosphere.

7.0.4 Feedback mechanisms are an important factor in understanding the impacts of climatic change on the terrestrial cryosphere. Reduced areal coverage of these elements and degradation of permafrost as a result of climatic warming can enhance warming through changes in surface characteristics and release of greenhouse gases.

7.0.5 The impacts of socioeconomic consequences of changes in the terrestrial cryosphere will depend to a large extent on the rate at which the changes occur. Where the rate of change is quick or sudden, environment and associated social and economic systems will have little time to adapt. Under these circumstances the impacts and socioeconomic consequences could be large.

Seasonal snow cover

7.0.6 General Circulation Models indicate that in most parts of the Northern and Southern Hemispheres the area of snow cover is expected to decrease as a result of increased temperature and, in most regions, a corresponding decrease in total mass of the snow. Areas where snow cover is projected to increase include latitudes south of 60°S and higher elevations of inland Greenland and Antarctica (though the latter is, and will remain, largely a cold desert).

7.0.7 A reduction in the areal snow coverage and in the length of the snow cover season will result in a positive climatic feedback, increasing global warming as a result of the greater amount of solar radiation that a snow-free surface can absorb relative to one that is snow-covered.

7.0.8 Loss of snow cover has both negative and positive socioeconomic consequences. Decreases in snow cover will result in increased risks of damages and losses for those systems which rely on snow as protection (ie insulation) from cold winter climates. Included are agricultural crops such as winter wheat, trees and shrubs, hibernating animals, and construction and maintenance of municipal infrastructures.

7.0.9 Reductions in both the temporal and spatial coverage of seasonal snow cover will have significant ramifications for water resources as the amount of water available for consumptive (e.g. potable and irrigation water) and non-consumptive (e.g. hydroelectric power and waste management) uses decreases. Particularly sensitive are those areas such as the Alps and Carpathians, the Altai mountains of Central Asia, the Syr Dar'ya and Amu Dar'ya region of the USSR, the Rocky Mountains and the North American Great Plains, all of which are dependent on snowmelt for the majority of their spring and summer water resources.

7.0.10 Changes in snow cover will also affect tourism and recreation-based industries and societies, particularly winter recreation sports such as skiing. Projected climate change could eliminate a $50 million per annum ski industry in Ontario, Canada.

7.0.11 From a positive impacts perspective, reductions of seasonal snow cover will reduce expenditures on snow removal and will increase access opportunities and ease transportation problems. A reduction in snow cover, however, will also have adverse impacts for transportation in those areas which rely on snow roads in winter. Inability to use snow roads will result in the necessity of using other more costly methods of transportation.

Ice sheets and glaciers

7.0.12 The relationships between climate and ice sheets and glaciers are complex, and because of relatively limited monitoring and research, not fully understood at this time. Increased temperatures generally result in increased ablation and, hence, a decrease in ice mass. Conversely, increased snowfall usually increases ice mass. Since projected changes in climate for some ice-covered regions include both increases in temperature and snowfall, understanding the impact of climatic changes on glaciers and ice sheets must consider the combined impact.

7.0.13 The bulk of the earth's ice mass is stored in the Antarctic ice sheet, divided between an eastern portion resting on continental crust and a large western portion which is underlaid both by continental crust and ocean. Much of the remaining ice mass is contained in the Greenland ice sheet, with smaller quantities stored in glaciers throughout the world.

7.0.14 Although observed data are limited, it is estimated that both the Antarctic and Greenland ice sheets are at present roughly in equilibrium, with annual gains close to annual losses. There is some evidence that suggests that the Greenland ice sheet has been thickening since the late 1970s, which has been attributed to new snow accumulations on the ice sheet.

7.0.15 Greenhouse-gas-induced climatic change will tend gradually to warm these sheets and bring them out of balance with the new climate regime. Change in ice-sheet

volume is likely to be slow, however, with significant loss unlikely to occur until after 2100. Calculations for Greenland suggest that a 3% loss of ice volume in the next 250 years is possible, based on the projected changes in climate. In the case of the Antarctic ice sheet the situation is more complex. The mass of the eastern ice sheet is expected to remain virtually the same or increase slowly as a result of expected increases in precipitation and temperatures. In contrast, the western ice sheet, like other marine ice sheets is inherently unstable.

7.0.16 Climatic warming could cause groundline retreat and rapid dispersal of ice into the surrounding ocean by way of relatively fast-flowing ice streams. These changes in behaviour could lead to collapse of a portion of the western Antarctic ice sheet which, depending on the amount of ice involved, could have a dramatic impact on sea-level and the surrounding environment.

7.0.17 The response of glaciers to climatic change will depend on their type and geographic location. In general, however, they have been shrinking for the last 100 years and are expected to continue to do so in response to projected changes in climate. In Austria a 3°C warming by 2050 is projected to cause a reduction by about one-half in the extent of alpine glaciers. Melting of glaciers in the Soviet arctic archipelagoes may result in their disappearance in 150—250 years. In contrast, an assessment of mountain glaciers in the temperate zone of Eurasia indicates that up to 2020 these glaciers will, in general, remain essentially unchanged, with increased precipitation compensating for increased melt.

7.0.18 Ice sheet and glacier melting will result in higher sea-levels. Observations over the last century indicate that levels have been rising between 1 and 3 mm/year primarily as a result of mass loss from alpine glaciers. Current projections suggest an accelerated rise with greenhouse gas warming to a most probable rise of 65 cm by the end of the next century.

7.0.19 Glacial melting can act as a negative feedback to regional and global warming, with heat extracted from the air to melt glacial ice and snow, thereby reducing the degree of warming.

7.0.20 The melting of glaciers will also alter regional hydrologic cycles. In New Zealand it has been estimated that a 3°C increase in temperature would, in the short term, increase glacier-fed river flow in some western rivers, increasing hydroelectric power generation by 10%. Another effect of glacier retreat is possible increased debris flows. Large amounts of debris masses on steep slopes will become exposed as a result of glacial retreat and, therefore, would be unstable and vulnerable to the effects of erosion. Landslides would result, leading to burial of structures, traffic routes and vegetation. Obstructions of river flows and increased sediment loads resulting in changes in water quantity (e.g. local floods and reduced flows downstream) and water quality would also be likely to occur as a result of debris flows.

Permafrost

7.0.21 Permafrost is the part of the terrestrial cryosphere consisting of ground (soil and rock) that remains at or below freezing throughout the year. It usually contains ice which can take a variety of forms from ice held in soil pores to massive bodies of more or less pure ice many metres thick. The presence of this ice in the ground makes it behave uniquely as an earth material, and makes its properties vulnerable to climatic warming.

7.0.22 At present about 20—25% of the land surface of the earth contains permafrost, primarily in the polar regions but also in the alpine areas at lower latitudes. It occupies approximately 10.7 million km^2 in the USSR, 5 million km^2 in Canada, 2 million km^2 in China and 1.5 million km^2 in Alaska. Present and past climate is the major determinant of permafrost occurrence and characteristics; however, a variety of other factors is also important, for example, the properties of the soil, and overlying terrain, vegetation and snow cover.

7.0.23 Permafrost is usually present where the mean annual air temperature is less than -1°C. At temperatures near this value it is discontinuous in extent (discontinuous permafrost zone). Both its extent and thickness increase at progressively higher latitudes where temperatures are lower. It has been found to extend to depths of approximately 1000 m or more in parts of Canada, approximately 1500 m in the USSR and 100—250 m in China.

7.0.24 Permafrost can also exist in seabeds. There is extensive ice-bound material in the continental shelf beneath the Arctic Ocean; however, this permafrost is commonly relict (ie it formed under past conditions and would not form under current ones).

7.0.25 Permafrost is to a large extent inherently unstable since it exists so close to its melting point. Most responsive to changes in climate would be those portions nearest the surface. Climate warming would thicken the active layer, leading to a decrease in soil stability. This permafrost degradation would lead to thaw settlement of the surface (thermokarst), ponding of surface water, slope failures (landslides) and increased soil creep. This terrain instability would result in major concerns for the integrity and stability of roads, pipelines, airfields, dams, reservoirs and other facilities in areas which contain permafrost. Terrain instability of the surface layer can also occur as a result of permafrost degradation in alpine areas, such as the Alps. This instability could result in dangerous debris falls from thawed rocks and mudflows.

7.0.26 Slope failures, thermokarst and loss of near-surface moisture, as the increased depth of the active layer moved

limited water supplies further from the surface, would have detrimental effects on vegetation and could lead to significant decreases in plant populations. In the longer term, permafrost degradation would allow the growth of deeper rooted, broadleaved species and the establishment of denser forest of coniferous species. Wildlife could also be affected through changes in terrain, surface hydrology and food availability. Loss of species and habitats can be expected, especially where wetlands dry out or areas are flooded as a result of melt.

7.0.27 Assessment of the effects of climate change on permafrost in any particular location must consider factors other than temperature, e.g. changes in summer rainfall and snow cover. In general, however, the projected warming during the next several decades would significantly deepen the active layer and initiate a northward retreat of permafrost. It is expected that a 2°C global warming would shift the southern boundary of the climatic zone currently associated with permafrost over most of Siberia north and northeast by at least 500—700 km. The southern extent of permafrost will lag behind this, moving only 25—50 km in the next 40—50 years (up to 10% reduction in an area underlaid by continuous permafrost). The depth of the active layer is expected to increase by 1 m during the next 40—50 years. Projected changes in permafrost in Canada are of similar magnitude.

7.0.28 The melting of permafrost would result in the release of methane and, to a lesser extent, CO_2 from previously frozen biological material and from gas hydrates. The extent to which this will enhance the greenhouse effect is uncertain, but could be about 1°C by the middle of the next century.

7.0.29 The socioeconomic impacts of permafrost degradation will be mixed. Maintenance costs of existing northern facilities such as buildings, roads and pipelines will tend to rise with abandonment and relocation needed in some cases. Changes in current construction practices will be necessary, as may be changes in sanitary waste disposal. Benefits from climate warming and permafrost melt are likely for agriculture, forestry, and hunting and trapping.

Recommendations for action

7.0.30 Projected greenhouse-gas-induced changes in climate will lead to ablation of global ice masses. Uncertainty exists, however, regarding how this global response will be reflected at the regional/local level and how the individual ice masses and seasonal ice and snow will respond. The most important effects of climatic change at high latitudes and elevated regions will be on and through changes in the terrestrial cryosphere. Furthermore, the terrestrial cryosphere is particularly suited for early detection of the effects of climate change. These two points necessitate a better understanding of the nature and dynamics of these ice masses and the factors that control them. This will require:

- establishment or enhancement of integrated, systematic observation programmes commensurate with research on the use of more efficient ground-based systems and remote sensing technologies designed to provide baseline information and trends;
- concurrent monitoring of those facilities, structures and natural resources that are at risk owing to projected changes in the terrestrial cryosphere;
- establishment of new guidelines and procedures for design and construction practices that consider the impacts of climatic changes on permafrost;
- research, including international cooperative efforts, on the relationships between components of the terrestrial cryosphere and climate in conjunction with other determining factors, including feedback mechanisms;
- refinement of existing climate-terrestrial cryosphere models;
- impacts assessments nationally and regionally that will provide data and information on the impacts of climate change on areas in which components of the terrestrial cryosphere occur and the resulting socioeconomic consequences;
- assessment of the needs for protected areas (natural reserves) for affected species and habitats; and
- development and distribution of relevant educational material and information on climatic changes, their impacts on the terrestrial cryosphere and socioeconomic consequences, as well as a wider distribution of research results.

8. Summary of major future actions

8.0.1 The results of the Working Group II studies highlight our lack of knowledge, particularly at the regional level and in areas most vulnerable to climate change. Further national and international research is needed on:

- regional effects of climate change on crop yields, livestock productivity and production costs;
- identification of agricultural management practices and technology appropriate for changed climate;
- factors influencing distribution of species and their sensitivity to climate change;
- initiation and maintenance of integrated monitoring systems for terrestrial and marine ecosystems;

- intensive assessment of water resources and water quality, especially in arid and semi-arid developing countries and their sensitivity to climate change;
- regional predictions of changes in soil moisture, precipitation, surface and subsurface runoff regimes and their interannual distributions as a result of climate change;
- assessment of vulnerability of countries to gain or loss of energy resources, particularly biomass and hydroelectric power in developing countries;
- adaptability of vulnerable human populations to heat stress and vector-borne and viral diseases;
- a global monitoring of sea-level changes, particularly for island countries;
- identification of populations and agricultural and industrial production at risk in coastal areas and islands;
- better understanding of the nature and dynamics of ice masses and their sensitivity to climate change;
- integration of climate change impact information into the general planning process, particularly in developing countries; and
- development of methodology to assess sensitivity of environments and socioeconomic systems to climate change.
- Some of these topics are already being covered by existing and proposed programs and these will need continuing support. In particular, there are three core projects of the International Geosphere-Biosphere Program, namely:
  - Land-Ocean Interactions in the Coastal Zone
  - Biosphere Aspects of the Hydrological Cycle
  - Global Change Impact on Agriculture and Society

  that will provide valuable data in the coming years.

9 Concluding remarks

9.0.1 Human-induced climate change can have profound consequences for the world's social, economic and natural systems. Each country should take steps to understand the impacts on its population and land resources resulting from such a change, and the consequences of sea-level rise, the changed character of atmospheric circulation and the resulting changes in typical weather patterns, reduction of freshwater resources, increased ultraviolet-B radiation and spreading of pests and diseases. These can affect the potential of food and agricultural production and adversely affect human health and well-being.

9.0.2 Too rapid a change in climate may not allow species to adapt and, thus, biodiversity could be reduced. This reduction could occur equally as well in the cryosphere regions, where melting of sea ice could accelerate, and in the equatorial regions where sea surface temperatures could increase. Traditional cost-benefit analyses do not allow for assessment of these risks. Although substantial scientific uncertainty remains concerning the precise time, location and nature of particular impacts, it is inevitable, under the scenario developed by Working Group I, that in the absence of major preventive and adaptive actions by humanity, significant and potentially disruptive changes in the earth's environment will occur.

9.0.3 The world community recognizes the need to undertake certain actions to reduce and mitigate the impact of climate change. Specific measures should follow the assessments of potential impact on the biosphere and on human activity, and a comparison of the net costs of adaptation and mitigation measures. Some of these impacts, such as sea-level rise, are likely to proceed slowly but steadily while others such as shifts in climate zones—which will affect the occurrence of such events as floods, droughts and severe storms—may occur unpredictably. Regions and nations differ considerably in their vulnerability to such changes and subsequent impacts. Generally human activity in developing countries is more vulnerable than that in developed countries to the disruption associated with climate change. Global warming and its impact must not widen the gap between developed and developing countries.

9.0.4 The capacity of developing nations to adapt to likely climate changes and to minimize their own contributions to it through greenhouse gas emissions, is constrained by their limited resources, by their debt problems and by their difficulties in developing their economies on a sustainable and equitable basis. These countries will need assistance in developing and implementing appropriate response options (including consideration of technological development and transfer, additional financial assistance, public education and information). As they possess greater resources to cope with climate change, developed countries must recognize the need to assist developing countries to assess and deal with the potential impacts of climate change.

Policymaker Summary of Working Group III (Formulation of Response Strategies)

Chairman's Introduction

The First Plenary Meeting of Working Group III of the IPCC, the Response Strategies Working Group (RSWG), was held in Washington, 30 January—2 February 1989. This meeting was largely organizational (see Figure 1), and it was not until after a subsequent RSWG Officers Meeting in Geneva, 8—12 May 1989, that the real work by the four RSWG subgroups, the Emissions Scenarios Task Force (Task A), and "Implementation Measures" Topic Coordinators (Task B) began.

The Second RSWG Plenary Session was held in Geneva, from 2 to 6 October 1989, to discuss the implementation measures:

1) public education and information;

2) technology development and transfer;

3) financial measures;

4) economic measures; and

5) legal measures, including elements of a framework climate convention. A consensus was reached on five topical papers dealing with these measures, with the understanding that they would be "living documents" subject to further modification as new information and developments might require.

The Third Plenary Meeting of RSWG, held in Geneva, 5—9 June 1990, achieved three objectives:

1) It reached consensus on the attached "policy summary", the first interim report of the RSWG.

2) It completed final editing and accepted the reports of the four RSWG subgroups, of the coordinators of Task A, and of the coordinators of the five Task B topical papers. These documents comprise the underlying material for the consensus report of this meeting, the policymaker summary; they are not themselves the product of a RSWG plenary consensus although many governments participated in their formulation.

Finally,

3) The Working Group agreed to submit comments on its suggested future work programme to the RSWG Chairman by 1 July 1990, for transmission to the Chair of the IPCC. There was general agreement that the work of the RSWG should continue.

The primary task of the RSWG was, in the broad sense, technical, not political. The charge of IPCC to RSWG was to lay out as fully and fairly as possible a set of response policy options and the factual basis for those options.

Consistent with that charge, it was not the purpose of the RSWG to select or recommend political actions, much less to carry out a negotiation on the many difficult policy questions that attach to the climate change issue, although clearly the information might tend to suggest one or another option. Selection of options for implementation is appropriately left to the policymakers of governments and/or negotiation of a convention.

The work of RSWG continues. The Energy and Industry Subgroup has, since the June RSWG Plenary Meeting, held another very productive meeting in London, the results of which are not reflected in this report.

It should be noted that quantitative estimates provided in the report regarding CFCs, including those in Scenario A (Business-as-Usual), generally do not reflect decisions made in June 1990 by the Parties to the Montreal Protocol. Those decisions accelerate the timetable to phase out production and consumption of CFCs, halons, carbon tetrachloride and methyl chloroform.

It should further be noted that quantitative estimates of forestry activities (eg, deforestation, biomass burning, including fuel wood, and other changes in land-use practices), as well as agricultural and other activities, provided in the Report continue to be reviewed by experts.

Two specific items of unfinished business submitted to RSWG by the Ministers at the November 1989 meeting in Noordwijk are the consideration of the feasibility of achieving: (1) targets to limit or reduce CO_2 emissions, including e g a 20 percent reduction of CO_2 emission levels by the year 2005; (2) a world net forest growth of 12 million hectares a year in the beginning of the next century. The RSWG hopes to complete this analysis before the Second World Climate Conference in November of this year.

The subgroup chairs and topic coordinators took the responsibility for completing their individual reports and, along with their respective governments, contributed generously of their time and resources to that end.

The RSWG Policymaker Summary is the culmination of the first year of effort by this body. The RSWG has gone to considerable lengths to ensure that the summary accurately reflects the work of the various subgroups and tasks. Given the very strict time schedule under which the RSWG was asked to work, this first report can only be a beginning.

Frederick M. Bernthal
Chairman,
Response Strategies Working Group

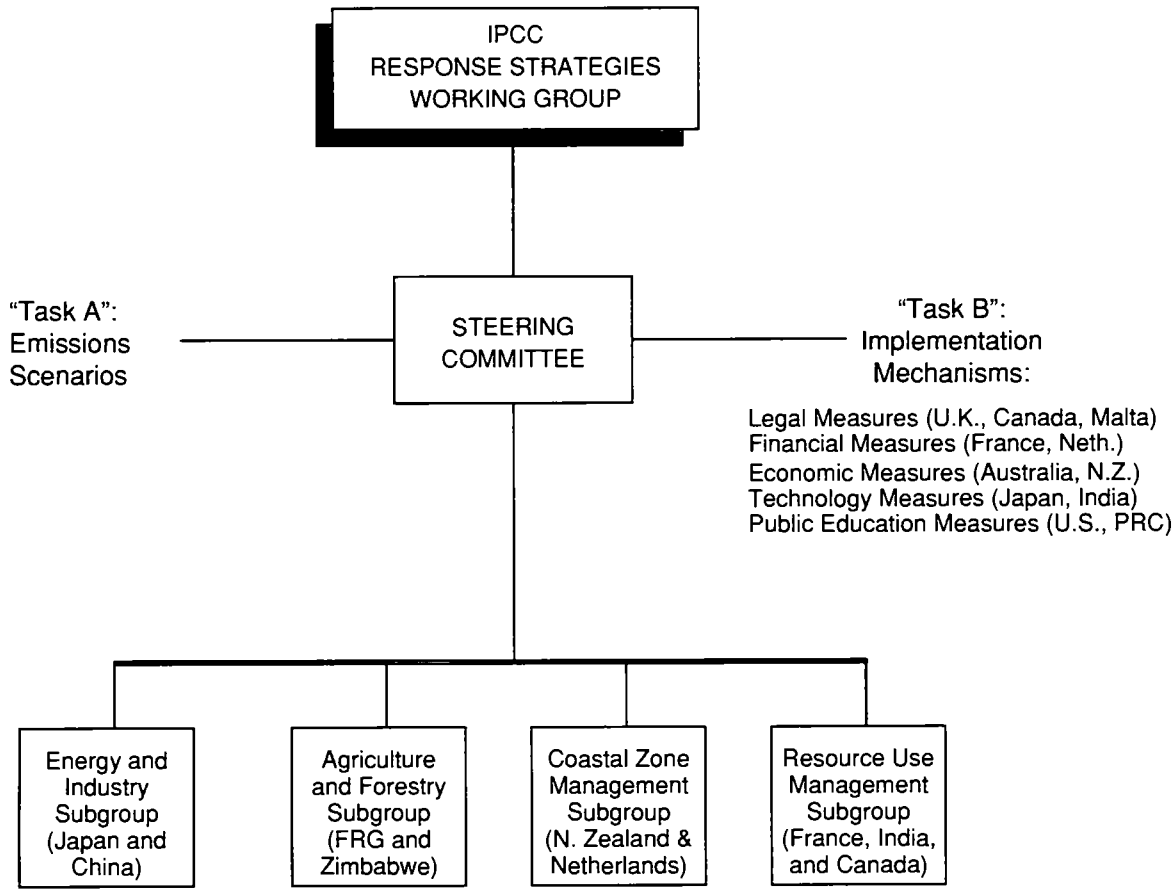
IPCC
RESPONSE STRATEGIES
WORKING GROUP
"Task A":
Emissions
Scenarios
STEERING
COMMITTEE
"Task B":
Implementation
Mechanisms:
Legal Measures (U.K., Canada, Malta)
Financial Measures (France, Neth.)
Economic Measures (Australia, N.Z.)
Technology Measures (Japan, India)
Public Education Measures (U.S., PRC)
Energy and Industry Subgroup (Japan and China)
Agriculture and Forestry Subgroup (FRG and Zimbabwe)
Coastal Zone Management Subgroup (N. Zealand & Netherlands)
Resource Use Management Subgroup (France, India, and Canada)

Figure 1.

Executive Summary

1. Working Group III (Response Strategies Working Group) was tasked to formulate appropriate response strategies to global climate change. This was to be done in the context of the work of Working Group I (Science) and Working Group II (Impacts) which concluded that:

> "We are certain emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface.
>
> "The longer emissions continue at present day rates, the greater reductions would have to be for concentrations to stabilize at a given level.
>
> "The long-lived gases would require immediate reductions in emissions from human activities of over 60% to stabilize their concentrations at today's levels.
>
> "Based on current model results, we predict under the IPCC Business-as-Usual emissions of greenhouse gases, a rate of increase of global mean temperature during the next century of about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C per decade), greater than that seen over the past 10,000 years; under the same scenario, we also predict an average rate of global mean sea level rise of about 6 cm per decade over the next century (with an uncertainty range of 3—10 cm per decade).
>
> "There are many uncertainties in our predictions particularly with regard to the timing, magnitude and regional patterns of climate change.
>
> "Ecosystems affect climate, and will be affected by a changing climate and by increasing carbon dioxide concentrations. Rapid changes in climate will change the composition of ecosystems; some species will benefit while others will be unable to migrate or adapt fast enough and may become extinct. Enhanced levels of carbon dioxide may increase productivity and efficiency of water use of vegetation.
>
> "In many cases, the impacts will be felt most severely in regions already under stress, mainly the developing countries.
>
> "The most vulnerable human settlements are those especially exposed to natural hazards, e g, coastal or river flooding, severe drought, landslides, severe storms and tropical cyclones".

2. Any responses will have to take into account the great diversity of different countries' situations and their responsibility for and negative impacts on different countries and consequently would require a wide variety of responses. Developing countries for example are at widely varying levels of development and face a broad range of different problems. They account for 75% of the world population and their primary resource bases differ widely. Nevertheless, they are most vulnerable to the adverse consequences of climate change because of limited access to the necessary information, infrastructure, and human and financial resources.

Main findings

3. The main findings are:

i) Climate change is a global issue; effective responses would require a global effort which may have a considerable impact on humankind and individual societies.

ii) Industrialized countries and developing countries have a common responsibility in dealing with problems arising from climate change.

ii) Industrialized countries have specific responsibilities on two levels:

a) major part of emissions affecting the atmosphere at present originates in industrialized countries where the scope for change is greatest. Industrialized countries should adopt domestic measures to limit climate change by adapting their own economies in line with future agreements to limit emissions;

b) to co-operate with developing countries in international action, without standing in the way of the latter's development, by contributing additional financial resources, by appropriate transfer of technology, by engaging in close co-operation concerning scientific observation, by analysis and research, and finally by means of technical co-operation geared to forestalling and managing environmental problems.

iv) Emissions from developing countries are growing and may need to grow in order to meet their development requirements and thus, over time, are likely to represent an increasingly significant percentage of global emissions. Developing countries have the responsibility, within the limits feasible, to take measures to suitably adapt their economies.

v) Sustainable development requires the proper concern for environmental protection as the necessary basis for continuing economic growth. Continuing economic development will increasingly have to take into account the issue of climate change. It is imperative that the right balance between economic and environmental objectives be struck.

vi) Limitation and adaptation strategies must be considered as an integrated package and should complement each other to minimize net costs. Strategies that limit greenhouse gases emissions also make it easier to adapt to climate change.

vii) The potentially serious consequences of climate change on the global environment give sufficient reasons to begin by adopting response strategies that can be justified immediately, even in the face of significant uncertainties.

viii) A well-informed population is essential to promote awareness of the issues and provide guidance on positive practices. The social, economic and cultural diversity of nations will require tailored approaches.

A flexible and progressive approach

4. Greenhouse gas emissions from most sources are likely to increase significantly in the future if no response measures are taken. Although some controls have been put in place under the Montreal Protocol for CFCs and halons, emissions of CO_2, CH_4, N_2O and other gases such as several CFC-substitutes will grow. Under these scenarios, it is estimated that CO_2 emissions will increase from approximately 7 billion (or 1,000 million) tonnes carbon (BtC)in 1985 to between 11—15 BtC by 2025. Similarly, man-made methane emissions are estimated to increase from about 300 teragrams (Tg) to over 500 Tg by the year 2025. Based on these projections, Working Group I estimated that global warming of 0.3°C/decade could occur.

5. The climate scenario studies of Working Group I further suggest that control policies on emissions can indeed slow global warming, perhaps from 0.3°C/decade to 0.1°C/decade. The social, economic and environmental costs and benefits of these control policies have not been fully assessed. It must be emphasized that implementation of measures to reduce global emissions are very difficult as energy use, forestry, and land use patterns are primary factors in the global economy. To take maximum advantage of our increasing understanding of scientific and socioeconomic aspects of the issue, a flexible and progressive approach is required. Subject to their particular circumstances, individual nations may wish to consider taking steps now to attempt to limit, stabilize or reduce the emission of greenhouse gases resulting from human activities and prevent the destruction and improve the effectiveness of sinks. One option that governments may wish to consider is the setting of targets for CO_2 and other greenhouse gases.

6. Because the [9]large, projected increase in world population will be a major factor in causing the projected increase in global greenhouse gases, it is essential that global climate change strategies include strategies and measures to deal with the rate of growth of the world population.

Shorter-term

7. The Working Group has identified measures at the national, regional and international levels as applicable which, while helping to tackle climate change, can yield other benefits.

8. **Limitation**

- Improved energy efficiency reduces emissions of carbon dioxide, the most significant greenhouse gas, while improving overall economic performance and reducing other pollutant emissions and increasing energy security.

- Use of cleaner energy sources and technologies reduces carbon dioxide emissions, while reducing other pollutant emissions that give rise to acid rain and other damaging effects.

- Improved forest management and, where feasible, expansion of forest areas as possible reservoirs of carbon.

- Phasing out of CFCs under the Montreal Protocol, thus removing some of the most powerful and long-lived greenhouse gases, while also protecting the stratospheric ozone layer.

- Agriculture, forestry and other human activities are also responsible for substantial quantities of greenhouse gas emissions. In the short term, reductions can be achieved through improved livestock waste management, altered use and formulation of fertilizers, and other changes to agricultural land use, without affecting food security, as well as through improved management in landfill and wastewater treatment.

9. **Adaptation**

- Developing emergency and disaster preparedness policies and programmes.

- Assessing areas at risk from sea-level rise and developing comprehensive management plans to reduce future vulnerability of populations and coastal developments and ecosystems as part of coastal zone management plans.

- Improving the efficiency of natural resource use, research on control measures for desertification and enhancing adaptability of crops to saline regimes.

Longer-term

10. Governments should prepare for more intensive action which is detailed in the report. To do so, they should undertake now:

- Accelerated and coordinated research programmes to reduce scientific and socioeconomic uncertainties with a view towards improving the basis for response strategies and measures.

- Development of new technologies in the fields of energy, industry and agriculture.

- Review planning in the fields of energy, industry, transportation, urban areas, coastal zones and resource use and management.

- Encourage beneficial behavioral and structural (eg, transportation and housing infrastructure) changes.

- Expand the global ocean observing and monitoring systems.

11. It should be noted that no detailed assessments have been made as of yet of the economic costs and benefits, technological feasibility or market potential of the underlying policy assumptions.

International cooperation

12. The measures noted above require a high degree of international cooperation with due respect for national sovereignty of states. The international negotiation on a framework convention should start as quickly as possible after the completion of the IPCC First Assessment Report. This, together with any additional protocols that might be agreed upon, would provide a firm basis for effective cooperation to act on greenhouse gas emissions and adapt to any adverse effects of climate change. The convention should, at a minimum, contain general principles and obligations. It should be framed in such a way as to gain the adherence of the largest possible number and most suitably balanced range of countries while permitting timely action to be taken.

13. Key issues for negotiation will include the criteria, timing, legal form and incidence of any obligations to control the net emissions of greenhouse gases, how to address equitably the consequences for all, any institutional mechanisms that may be required, the need for research and monitoring, and in particular, the request of the developing countries for additional financial resources and for the transfer of technology on a preferential basis.

Further consideration

14. The issues, options and strategies presented in this document are intended to assist policymakers and future negotiators in their respective tasks. Further consideration of the summary and the underlying reports of Working Group III should be given by every government as they cut across different sectors in all countries. It should be noted that the scientific and technical information contained in the Policymaker Summary and the underlying reports of Working Group III do not necessarily represent the official views of all governments, particularly those that could not participate fully in all Working Groups.

1. Sources of anthropogenic greenhouse gases

1.0.1 A wide range of human activities result in the release of greenhouse gases, particularly CO_2, CH_4, CFCs and N_2O, into the atmosphere. Anthropogenic emissions can be categorized as arising from energy production and use, non-energy industrial activities (primarily the production and use of CFCs), agricultural systems, and changes in land-use patterns (including deforestation and biomass burning). The relative contributions of these activities to radiative forcing during the 1980s are discussed in the text and shown in Figure 2 (see Working Group I report for further explanation of the radiative forcing of the various greenhouse gases; see also the Chairman's introduction regarding the quantitative estimates of the contributions to radiative forcing from these activities).

1.0.2 IPCC Working Group I calculated that the observed increases in the atmospheric concentrations of CO_2,, CH_4, CFCs and N_2O during the 1980s, which resulted from human activities, contributed to the enhanced radiative forcing by 56%, 15%, 24% and 5%, respectively.

1.1 Energy

1.1.1 The single largest anthropogenic source of radiative forcing is energy production and use. The consumption of energy from fossil fuels (coal, petroleum and natural gas excluding fuel wood) for industrial commercial, residential, transportation and other purposes results in large emissions of CO_2 accompanied by much smaller emissions of CH_4 from coal mining and the venting of natural gas; the energy sector accounts for an estimated 46% (with an uncertainty range of 38—54%) of the enhanced radiative forcing resulting from human activities.

1.1.2 Natural fluxes of CO_2, into the atmosphere are large (200 Bt/yr[1]), but inputs of man-made sources are large enough to significantly disturb the atmospheric balance.

1.2 Industry

1.2.1 The production and use of CFCs and other halocarbons in various industrial processes comprise about 24% of the enhanced radiative forcing.

Forestry

1.2.2 Deforestation, biomass burning including fuel wood, and other changes in land-use practices, release CO_2, CH_4, and N_2O into the atmosphere and together comprise about 18% (with an uncertainty range of 9—26%) of the enhanced radiative forcing.

[1] Billion (or 1000 million) tonnes per year

*Figure 2: **Estimated contribution of different human activities to the change in radiative forcing during the decade from 1980 to 1990****

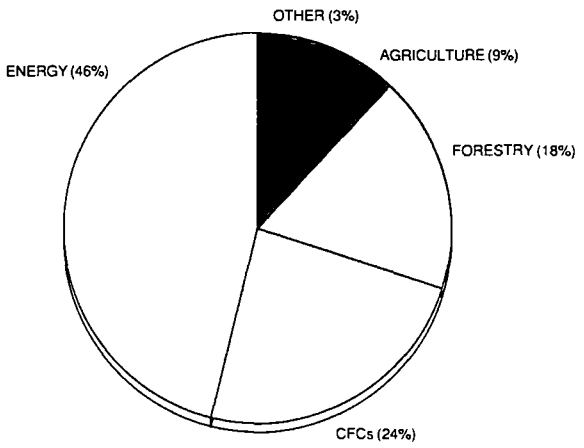

**Percentages derived from estimated greenhouse gas concentrations in the atmosphere and the global warming potentials of these greenhouse gases given in the Policymakers Summary of Working Group I*

Agriculture

1.2.3 Methane releases from rice cultivation and from livestock systems, and nitrous oxide released during the use of nitrogenous fertilizers together comprise about 9% (with an uncertainty range of 4—13%) of the enhanced radiative forcing.

Other sources

1.2.4 Carbon dioxide from cement manufacturing and methane from land-fills together comprise about 3% (with an uncertainty range of 1—4%) of the enhanced radiative forcing.

1.2.5 Estimates of current greenhouse gas emissions are not precise because of uncertainties regarding both total emissions and emissions from individual sources. Global emissions from certain sources are particularly difficult to determine, e g, CO_2 emission from deforestation, CH_4 emission from rice cultivation, livestock systems, biomass burning, coal mining and venting of natural gas, and N_2O emissions from all sources. The range of such estimates can be quite large, typically, a factor of 1.5 for methane from livestock, a factor of 4 for CO_2 from deforestation, and up to a factor of 7 for rice.

2. Future emissions of greenhouse gases

2.0.1 Greenhouse gas emissions from most sources are likely to increase significantly in the future if no policy

measures are taken. As economic and population growth continue, in particular in the developing countries, there is expected to be an increase in energy use, industrial and agricultural activity, deforestation, and other activities which result in a net increase of greenhouse gas emissions. Although some controls have been put in place under the Montreal Protocol for certain CFCs and halons, emissions of CO_2, methane, nitrous oxide, and other greenhouse gases are likely to increase under current patterns of economic activity and growth.

2.0.2 However, because of the inherent limitations in our ability to estimate future rates of population and economic growth, etc, there is some uncertainty in the projections of greenhouse gas emissions, individual behaviour, technological innovation, and other factors which are crucial for determining emission rates over the course of the next century. This lends uncertainty to projections of greenhouse gas emissions over several decades or longer. Reflecting these inherent difficulties, the RSWG's work on emissions scenarios are the best estimates at this time covering emissions over the next century but further work needs to be done.

2.0.3 The RSWG used two methods to develop scenarios of future emissions as discussed in Sections 2.1. and 2.2. One method used global models to develop four scenarios which were subsequently used by Working Group I to develop estimates of future warming. The second method used studies of the energy and agriculture sectors submitted by over 21 countries and international organizations to estimate emissions. These latter studies were aggregated into a reference scenario. Both approaches show that emissions of CO_2 and CH_4 will increase in the future. Both approaches indicate that CO_2 emissions will grow from approximately 7 BtC to between 11—15 BtC by the year 2025.

2.1 Emissions scenarios

2.1.1 One of the RSWG's first tasks was to prepare some initial scenarios of possible future greenhouse gas emissions for the use of the three IPCC Working Groups. An experts' group was formed which looked at four hypothetical future patterns of greenhouse gas emissions and their effect on the atmosphere. The cumulative effect of these emissions was calculated using the concept of equivalent CO_2 concentrations (e g, the contributions of all greenhouse gases to radiative forcing are converted into their equivalent in terms of CO_2concentrations). Global economic growth rates were taken from World Bank projections and population estimates were taken from UN studies and assumed equal for all scenarios.

2.1.2 The first of the scenarios, called the Business-as-Usual or the 2030 High Emissions Scenario, assumes that few or no steps are taken to limit greenhouse gas emissions. Energy use and clearing of tropical forests continue and fossil fuels, in particular coal, remain the world's primary energy source. The Montreal Protocol comes into effect but without strengthening and with less than 100 percent compliance. Under this scenario, the equivalent of a doubling of pre-industrial CO_2 levels occurs, according to Working Group I, by around 2025.

2.1.3 The predicted anthropogenic contributions to greenhouse gas emissions in 2025 are shown in Table 1. The RSWG attempted to synthesize and compare the results of the AFOS/EIS Reference Scenario and the Task A "Business-as-Usual" (or "2030 High Emissions") Scenario (see figure 3). The figure shows the equivalent CO_2 concentrations for the Task A "Business-as-Usual" Scenario and the AFOS/EIS Reference Scenario with its higher CO_2 emissions and the CFC phaseout agreed to by the Parties to the Montreal Protocol. The results indicate that the CO_2 equivalent concentrations and thus the effect on the global climate are similar for both scenarios.

2.1.4 The second of the scenarios, the 2060 Low Emissions Scenario, assumes that a number of environmental and economic concerns result in steps to reduce the growth of greenhouse gas emissions. Energy efficiency measures, which might only be possible with government intervention, are implemented, emissions controls are adopted globally, and the share of the world's primary energy provided by natural gas increases. Full compliance with the Montreal Protocol is achieved and tropical deforestation is halted and reversed. Under this scenario, the cumulative effect of such measures is a CO_2 equivalent doubling around 2060.

2.1.5 The remaining two scenarios reflect futures where steps in addition to those in the 2060 Low Emissions Scenario are taken to reduce greenhouse gas emissions. These steps include rapid utilization of renewable energy sources, strengthening of the Montreal Protocol, and adoption of agricultural policies to reduce emissions from livestock systems, rice paddies, and fertilizers.

2.1.6 All of the above scenarios provide a conceptual basis for considering possible future patterns of emissions and the broad responses that might affect those patterns. However, they represent assumptions rather than cases derived from specific studies. In addition, no full assessment was made as yet of the total economic costs and benefits, technological feasibility, or market potential of the underlying policy assumptions.

2.2 Reference scenario

2.2.1 Table 2 shows the results of the EIS Reference Scenario (for CO_2 emissions from the energy sector only) divided by region. The table is incomplete and does not include CO_2 emissions from non-energy sources nor other greenhouse gases and sinks. While it is not directly a measure of a region's climate forcing contribution, this table does portray a future where, in the absence of specific policy measures, global emissions of one major gas, CO_2, grow

TABLE 1:Anthropogenic Greenhouse Gas Emissions From Working Group III Scenarios

	AFOS/EIS Reference Scenario modified to include CFC phaseout [2]		Task A "Business-as-Usual" Scenario	
	1985	**2025**	**1985**	**2025**
CO_2 Emissions (BtC)				
Energy	5.1	12.4	5.1	9.9
Deforestation	1.7[3]	2.6	0.7[4]	1.4
Cement	0.1	0.2	0.1	0.2
Total	6.9	15.2	5.9	11.5
CH_4 Emission ($TgCH_4$)				
Coal Mining	44	126	35	85
Natural Gas	22	59	45	74
Rice	110	149	110	149
Enteric Ferm.	75	125	74	125
Animal Wastes	37	59	-	-
Landfills	30	60	40	71
Biomass Burning	53	73	53	73
Total	371	651	357	577
N_2O (TgN)[5]	4.6	8.7	4.4	8.3
CO (TgC)[5]	473	820	443	682
NO_x (TgN)[5]	38	69	29	47
CFCs (Gg)				
CFC-11	278	11	278	245
CFC-12	362	10	362	303
HCFC-22	97	1572	97	1340
CFC-113	151	151	122	
CFC-114	15	0	15	9
CFC-115	5	0	5	5
CCl_4	87	110	87	300
CH_3CCl_3	814	664	814	1841
Halon 1301	2.1	1.8	2.1	7.4

[2] The estimates for emissions of CFCs in 1985 and 2025 reflect the decisions taken at the meeting of the Parties to the Montreal Protocol in London in June 1990. At that meeting, the parties agreed to accelerate the phase out of the production and consumption of CFCs, halons, carbon tetrachloride and methyl chloroform.

[3] Midrange estimates for deforestation and biomass consistent with preferred value from Working Group I

[4] Assuming low biomass per hectare and deforestation rates.

[5] Differences in the 1985 emissions figures are due to differences in definitions and qualifying the emissions from these particular sources.

EIS/AFOS Reference Scenario – Task A: Business as Usual

CO_2 Equivalent Concentrations

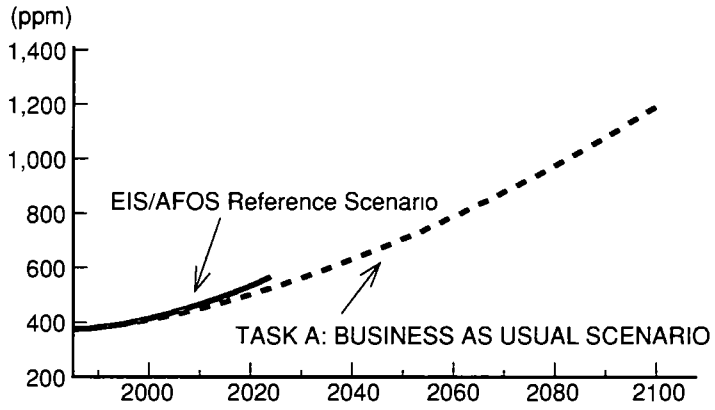

Figure 3.

from 5.15 BtC in 1985, to 7.30 BtC in 2000 and 12.43 BtC in 2025. Primary energy demand more than doubles between1985 and 2025, an average annual growth rate of 2.1%.

2.2.2 The annual rate of growth in CO_2 emissions varies between 0.7% in Western Europe, 1.3% in North America and the Pacific OECD Countries, and 3.6% in developing countries. The share of emissions between regions varies over time.

2.2.3 Under this scenario, the per capita emissions in the industrialized countries increase from 3.1 tonnes carbon (TC) per capita in 1985 to 4.7 TC per capita in 2025. For the developing countries, the per capita emissions rise from 0.4 TC per capita in 1985 to 0.8 TC per capita in 2025.

2.2.4 The Reference Scenario sets out an example of the scope of the reductions in total global emissions which might be necessary to stabilize or reduce CO_2 emissions. The stabilization of global emissions at 1985 levels would require reductions of 29% by 2000 and 59% by 2025. A reduction of global emissions to 20% below 1985 levels would require reductions of 44% in 2000 and 67% by 2025.

2.2.5 The carbon intensity figures show, for each region, the amount of carbon emitted per unit of energy consumed. The contribution of energy consumption in a region to global warming is largely a function of its carbon intensity, total fuel use, and of the efficiency with which it consumes fossil fuels. Carbon intensity for industrialized countries changes from 16.3 tonnes carbon per gigajoule (TC-GJ) in 1985 to 15.5 in 2025. In the developing world the change is from 14.2 TC-GJ to 15.6.

3. Response strategies for addressing global climate change

3.0.1 Because climate change could potentially result in significant impacts on the global environment and human activities, it is important to begin considering now what measures might be taken in response. Working Group I found that under a "Business-as-Usual" scenario global average temperature could rise by 0.3 degrees centigrade per decade; it also found that under the Accelerated Control Policies Scenario (scenario D) with extremely stringent emissions reductions the temperature rise could perhaps be reduced to 0.1 degree centigrade per decade. The RSWG identified a wide range of options for the international community to consider. These include measures both to limit net greenhouse gas emissions and to increase the ability of society and managed ecosystems to adapt to a changing climate.

3.0.2 Strategies which focus only on one group of emission sources, one type of abatement option or one particular greenhouse gas will not achieve this. Policy responses should, therefore, be balanced against alternative abatement options among the energy, industry, forestry and agricultural sectors, and adaptation options and other policy goals where applicable at both national and international levels. Ways should be sought to account for other countries, and intergenerational issues, when making policy decisions.

3.0.3 The consideration of climate change response strategies, however, presents formidable difficulties for

TABLE 2 GROSS CO_2 EMISSIONS FROM THE ENERGY SECTOR*

(From the Reference Scenario)

CO_2 Emissions in the Reference Scenario (billion tonnes carbon/year)

	1985	%	2000	%	2025	%
Global Totals	5.15	(100)	7.30	(100)	12.43	(100)
Industrialized	3.83	(74)	4.95	(68)	6.95	(56)
North America	1.34	(26)	1.71	(23)	2.37	(19)
Western Europe	0.85	(16)	0.98	(13)	1.19	(10)
OECD Pacific	0.31	(6)	0.48	(7)	0.62	(5)
Centrally Planned Europe	1.33	(26)	1.78	(24)	2.77	(22)
Developing	1.33	(26)	2.35	(32)	5.48	(44)
Africa	0.17	(3)	0.28	(4)	0.80	(6)
Centrally Planned Asia	0.54	(10)	0.88	(12)	1.80	(14)
Latin America	0.22	(4)	0.31	(4)	0.65	(5)
Middle East	0.13	(3)	0.31	(4)	0.67	(5)
South and East Asia	0.27	(5)	0.56	(8)	1.55	(12)

	1985		2000		2025	
	PC**	CI***	PC	CI	PC	CI
Global Totals	1.06	15.7	1.22	15.8	1.56	16.0
Industrialized	3.12	16.3	3.65	16.1	4.65	16.0
North America	5.08	15.7	5.75	15.8	7.12	16.6
Western Europe	2.14	15.6	2.29	15.1	2.69	14.6
OECD Pacific	2.14	16.1	3.01	16.1	3.68	14.8
Non OECD Europe	3.19	17.5	3.78	16.9	5.02	16.4
Developing	0.36	14.2	0.51	15.2	0.84	16.0
Africa	0.29	12.3	0.32	13.2	0.54	15.2
Centrally Planned Asia	0.47	17.3	0.68	18.8	1.15	19.6
Latin America	0.55	11.5	0.61	11.4	0.91	11.8
Middle East	1.20	16.7	1.79	16.1	2.41	15.5
South and East Asia	0.19	12.3	0.32	14.3	0.64	15.6

* This table presents regional CO_2 emissions and does not include CFCs, CH_4, O_3, N_2O, or sinks. Climate change critically depends on all GHG from all economic sectors. This table should be interpreted with care.

** PC - Per capita carbon emissions in tonnes carbon per person.

*** CI - Carbon Intensity in kilograms carbon per gigajoule.

policymakers. On the one hand, the information available to make sound policy analyses is inadequate because of:

(a) remaining scientific uncertainties regarding the magnitude, timing, rate, and regional consequences of potential climate change;

b) uncertainty with respect to how effective specific response options or groups of options would be in actually averting potential climate change: and

(c) uncertainty with respect to the costs, effects on economic growth, and other economic and social implications of specific response options or groups of options.

3.0.4 The potentially serious consequences of climate change on the global environment, however, give sufficient reasons to begin by adopting response strategies that can be justified immediately even in the face of such significant uncertainties.

3.0.5 Recognizing these factors, a large number of options were preliminarily assessed. It appears that some of these options may be economically and socially feasible for implementation in the near-term while others, because they are not yet technically or economically viable, may be more appropriate for implementation in the longer-term. In general, the RSWG found that the most effective response strategies, especially in the short-term, are those which are:

- beneficial for reasons other than climate change and justifiable in their own right, for example increased energy efficiency and lower greenhouse gas emission technologies, better management of forests and other natural resources, and reductions in emissions of CFCs and other ozone depleting substances that are also radiatively important gases;
- economically efficient and cost effective, in particular those that use market-based mechanisms;
- able to serve multiple social, economic, and environmental purposes;
- flexible and phased, so that they can be easily modified to respond to increased understanding of scientific, technological and economic aspects of climate change;
- economic growth and the concept of sustainable development;
- administratively practical and effective in terms of application, monitoring, and enforcement; and
- reflecting obligations of both industrialized and developing countries in addressing this issue, while recognizing the special needs of developing countries, in particular in the areas of financing and technology.

3.0.6 The degree to which options are viable will also vary considerably depending on the region or country involved. For each country, the implications of specific options will depend on its social, environmental, and economic context. Only through careful analysis of all available options will it be possible to determine which are best suited to the circumstances of a particular country or region. Initially, the highest priority should be to review existing policies with a view to minimizing conflicts with the goals of climate change strategies. New policies will be required.

4. Options for limiting greenhouse gas emissions

4.0.1 The RSWG reviewed potential measures for mitigating climate change by limiting net emissions of greenhouse gases from the energy, industry, transportation, housing and building, forestry, agriculture, and other sectors. These measures include those which limit emissions from greenhouse gas sources (such as energy production and use), those which increase the use of natural sinks (such as immature forests and other biomass) for sequestering greenhouse gases, as well as those measures aimed at protecting reservoirs such as existing forests. While RSWG was not mandated to consider the role of the oceans, Working Group I noted that oceans also play an equally important role as sinks and reservoirs for carbon dioxide. A discussion of both short and long-term options for each major emissions sector is provided below.

4.0.2 It also should be recognized that the large, projected increase in the world population, to as much as ten billion people during the next century, will be a major factor in causing the projected increase in global greenhouse gases. This is because larger populations will be accompanied by increased consumption of energy and of food, more land clearing, and other activities, all of which will cause an increase in net greenhouse gas emission. It is essential, therefore, that policies designed to deal effectively with the issue of potential global climate change include strategies and measures to reduce the rate of growth of the world population.

4.1 Limitation of net emissions from the energy sector

4.1.1 The energy sector plays a vitally important role in economic well-being and development for all nations. At the same time, because energy production and use accounts for approximately one half of the radiative forcing from human activities, energy policies need to ensure that continued economic growth occurs in a manner that, globally, conserves the environment for future generations. However, there is no single, quick-fix technological option for limiting greenhouse gas emissions from energy sources. A comprehensive strategy is necessary which deals with improving efficiency on both the demand and supply sides as a priority and emphasizes technological research, development, and deployment.

4.1.2 The RSWG recognizes the particular difficulties which will be faced by countries, particularly developing countries, whose economy is heavily dependent on the production and/or export of fossil fuels, as a consequence of actions taken by other countries to limit or reduce energy related greenhouse gas emissions. These difficulties should be taken into account when elaborating international strategies.

4.1.3 Various potential options have been identified for reducing greenhouse gas emissions from energy systems. The most relevant categories of options appear to be:

- efficiency improvements and conservation in energy supply, conversion, and end use;
- fuel substitution by energy sources which have lower or no greenhouse gas emissions;

TABLE 3

Examples of Short-Term Options

I. IMPROVE EFFICIENCY IN THE PRODUCTION, CONVERSION AND USE OF ENERGY

Electricity Generation	Industry Sector	Transport Sector	Building Sector
• Improved efficiency in electricity generation – Repowering of existing facilities with high efficiency systems; – Introduction of integrated gasification combined cycle systems; – Introduction of atmospheric fluidised bed combustion; – Introduction of pressurised fluidised bed combustion with combined cycle power systems; – Improvement of boiler efficiency. • Improved system for co-generation of electricity and steam. • Improved operation and maintenance. • Introduction of photovoltaics, especially for local electricity generation. • Introduction of fuel cells.	• Promotion of further efficiency improvements in production process; • Materials recycling (particularly energy-intensive materials); • Substitution with lower energy intensity materials; • Improved electromechanical drives and motors; • Thermal process optimisation, including energy cascading and co-generation. • Improved operation and maintenance.	• Improved fuel efficiency of road vehicles; – Electronic engine management and transmission control systems; – advanced vehicle design; reduced size and weight, with use of lightweight composite materials and structural ceramics; improved aerodynamics, combustion chamber components, better lubricants and tyre design, etc.). – regular vehicle maintenance; – higher capacity trucks; – improved efficiency in transport facilities; – regenerating units; • Technology development in public transportation; – Intra-city modal shift (e.g. car to bus or metro); – advanced train control system to increase traffic density on urban rail lines; – High-speed inter-city trains; – Better intermodal integration. • Driver behaviour, traffic management, and vehicle maintenance.	• Improved heating and cooling equipment and systems; – Improvement of enegery efficiency of air conditioning; – Promotion of introduction of area heating and cooling including use of heat pumps; – Improved burner efficiency; – Use of heat pumps in buildings; – Use of advanced electronic energy management control systems. • Improved space conditioning efficiency in house/building; – Improved heat efficiency through highly efficient insulating materials; – Better building design (orientation, window building, envelope, etc.): – Improved air-to-air heat exchangers. • Improved lighting efficiency. • Improved appliance efficiency. • Improved operation and maintenance. • Improved efficiency of cook stoves (in developing countries).

TABLE 3 (CONTINUED)

II. NON FOSSIL AND LOW EMISSION ENERGY SOURCES

Electricity Generation	Other Sector
– Construction of small-scale and large-scale hydro projects; – Expansion of conventional nuclear power plants; – Construction of gas-fired power plants; – Standardised design of nuclear power plants to improve economics and safety; – Development of geothermal energy projects; – Introduction of wind turbines; – Expansion of sustainable biomass combustion. – Replacement of scrubbers and other energy consuming control technology with more energy efficient emission control.	• Substitution of natural gas and biomass for heating oil and coal; • Solar heating. • Technologies for producing and utilising alternative fuels; – Improved storage and combustion systems for natural gas; – Introduction of flexible-fuel and alcohol fuel vehicles.

III. REMOVAL, RECIRCULATION OR FIXATION

Energy/Industry	Landfills
• Recovery and use of leaked or released CH4 from fossil fuel storage, coal mining; • Improved maintenance of oil and natural gas and oil production and distribution systems to reduce CH_4 leakage; • Improved emission control of CO, SO_x, NO_x, and VOCs to protect sinks of greenhouse gases.	• Recycle and incineration of waste materials to reduce CH_4 emissions; • Use or flaring of CH_4 emissions; • Improved maintenance of landfill to decrease CH_4 emissions

TABLE 4

Examples of Medium-/Long-Term Options

I. IMPROVE EFFICIENCY IN THE PRODUCTION, CONVERSION AND USE OF ENERGY

Electricity Generation	Industry Sector	Transport Sector	Building Sector
• Advanced technologies for storage of intermittent energy; • Advanced batteries; • Compressed air energy storage; • Superconducting energy storage;	• Increased use of less energy-intensive materials; • Advanced process technologies; • Use of biological phenomena in processes; • Localised process energy conversion; • Use of fuel cells for co-generation.	• Improved fuel efficiency of road vehicles; • Improvements in aircraft and ship design: – Advanced propulsion concepts; – Ultra high-bypass aircraft engines; – Contra-rotating ship propulsion.	• Improved energy storage systems; – Use of information technology to anticipate and satisfy energy needs; – Use of hydrogen to store energy for use in buildings. • Improved building systems; – New Building materials for better insulation at reduced cost; – Windows which adjust opacity to maximise solar gain. • New food storage systems which eliminate refrigeration requirements.

TABLE 4 (CONTINUED)

II. NON FOSSIL AND LOW EMISSION ENERGY SOURCES

Electricity Generation	Other Sector
• Nuclear power plants: – Passive safety features to improve reliability and acceptability • Solar power technologies: – Solar thermal; – Solar photovoltaic (expecially for local electricity generation). • Advanced fuel cell technologies	• Other technologies for producing and utilising alternative fuels; – Improved storage and combustion systems for hydrogen; – Control of gases boiled off from cryogenic fuels; – Improvements in performance of metal hydrides; – High-yield processes to convert lingo-cellulosic biomass into alcohol fuels; – Introduction of electric and hybrid vehicles; – Reduced re-charging time for advanced batteries.

III. REMOVAL, RECIRCULATION OR FIXATION

- Improved combustion conditions to reduce N_2O emissions.
- Treatment of exhaust gas to reduce N_2O emissions.
- CO_2 separation and geological and marine disposal.

- reduction of greenhouse gas emissions by removal, recirculation or fixation;

- management and behavioural changes (e.g. increased work in homes through information technology) and structural changes (e.g. modal shift in transport).

4.1.4 From an analysis of the technologies in these categories, it appears that some technologies are available now or in the short-term while others need further development to lower costs or to improve their environmental characteristics.

4.1.5 Tables 3 and 4 provide various examples of technological options within each of the broad categories defined above, and their possible application in the short, medium, and longer-term. This distinction among time frames is used in order to reflect the remaining technological needs in each category and to assist in formulating technological strategies. Short-term technologies are those which apparently are or will be both technically and economically ready for introduction and/or demonstration up to the year 2005 and beyond. Mid-term technologies are those which, while technically available now, are not yet economic and thus may not be implemented until the period from 2005 to 2030. Longer-term technologies are not yet available but may emerge after 2030 as a result of research and development. Such time frames could be influenced by such factors as the pace of the technological changes and economic conditions.

4.1.6 The technical, economic, and market potential of technological options will vary depending upon the sector in which they are to be applied. The technical potential of an energy technology is its capacity to reduce potential emissions, irrespective of the costs involved, and is largely a function of technical feasibility and resource availability. Economic potential refers to whether the application of the options is economically efficient and cost-effective—it may be significantly less than technical potential where there are positive resource costs. Market potential refers to whether the consumer or user is likely to adopt the option—it might be even less than economic potential due to market imperfections, attitudes to risk, and the presence of non-monetary costs.

4.1.7 There is, in general, extensive information available on the technical potential of the many technological options listed. For example:

- in the Transportation sector, vehicle efficiency improvements have very high technical potential (e.g. 50 percent improvement from the average vehicle on the road in some countries);

- in the Electricity Generation sector, efficiency improvements of 15 to 20 percent could be achieved for retrofits of coal plants and up to 65 percent for new generation versus average existing coal plants; fuel substitution could achieve 30 percent (for oil to natural gas) to 40 percent (for coal to natural gas) reduction in emissions of CO_2;

- in the Buildings sector, new homes could be roughly twice as energy efficient and new commercial buildings up to 75 percent as energy efficient as existing buildings; retrofitting existing homes could average 25 percent improvement and existing commercial buildings around 50 percent;

- in the Industry sector, the technical potential for efficiency improvements ranges from around 15 percent in some sub-sectors to over 40 percent in others (i.e. the best available technology versus the stock average).

4.1.8 The constraints to achieving the technical potential in these sectors can be generally categorized as:

- capital costs of more efficient technologies vis-à-vis the cost of energy;

- relative prices of fuels (for fuel substitution);

- lack of infrastructure;

- remaining performance drawbacks of alternative technologies;

- replacement rates;

- reaching the large number of individual decision-makers involved.

4.1.9 Each of these constraints may be more or less significant depending on the sector in question. While not a constraint, behavioural changes (eg, improved driver behaviour, better vehicle maintenance and turning off unused lights) can make significant contributions to emissions reduction in all sectors. Achieving such changes requires the engagement of both the energy supplier and the consumer. Likewise, improvements in operational practices on the part of industry and government (e.g. better traffic management or boiler operation) offer significant potential but require increased attention. Transport and housing policies (e.g. promotion of public transport, home insulation) could also reduce greenhouse gas emissions. A more comprehensive assessment of the measures to overcome these constraints is contained in section 7 of this Policymaker Summary.

4.1.10 Factors external to the energy sector also significantly constrain potential. These include the difficulty of:

- making basic changes in the structure of economies (e.g. development of new transportation and housing infrastructure);

- making fundamental changes in attitudinal and social factors (e.g. preferences for smaller and higher efficiency vehicles).

4.1.11 The challenge to policymakers is to enhance the market uptake of technological options and behavioural and operational changes as well as to address the broader issues outside the energy sector in order to capture more of the potential that exists.

Options and strategies

4.1.12 Tables 3 and 4 summarize the technological, regulatory, and institutional approaches which could form elements of strategies to control greenhouse gases.

4.1.13 A list of options recommended by EIS as measures for addressing greenhouse gas emissions is given below. Countries are encouraged to evaluate the social, economic and environmental consequences of these options.

- taking steps now[6] to attempt to limit, stabilize or reduce the emission of energy-related greenhouse gases and prevent the destruction and improve the effectiveness of sinks. One option that governments may wish to consider is the setting of targets for CO_2 and other greenhouse gases;

- adopting a flexible progressive approach, based on the best available scientific, economic and technological knowledge, to action needed to respond to climate change;

- drawing up specific policies and implementing wide-ranging comprehensive programmes which cover all energy-related greenhouse gases;

- starting with implementing strategies which have multiple social, economic and environmental benefits, are cost effective, are compatible with sustainable development and make use of market forces in the best way possible;

- intensifying international, multilateral and bilateral co-operation in developing new energy strategies to cope with climate change. In this context, industrialized countries are encouraged to promote the development and the transfer of energy-efficient and clean technologies to other countries;

- increasing public awareness of the need for external environmental costs to be reflected in energy prices, markets and policy decisions to the extent that they can be determined;

- increasing public awareness of energy-efficiency technologies and products and alternatives, through public education and information (e.g. labelling);

- strengthening research and development and international collaboration in energy technologies, and economic and energy policy analysis, which are relevant for climate change;

- encouraging the participation of industry, the general public, and NGOs in the development and implementation of strategies to limit greenhouse gas emissions.

Short-term strategy options

4.1.14 Short-term strategies for all individual nations include:

- improving diffusion of energy-efficient and alternative energy technologies which are technically and commercially proven;

- improving energy efficiency of mass produced goods including motor vehicles and electrical appliances and equipment and buildings (eg, through improved standards);

- developing, diffusing and transferring technologies to limit energy-related greenhouse gas emissions;

- reviewing energy-related price and tariff systems and policy decisions on energy planning to better reflect environmental costs.

Long-term strategy options

4.1.15 Over the longer term, sustainable development will remain a central theme of policies and strategies. Specific approaches within a sustainable development policy framework will evolve as our understanding of climate change and its implications improves.

4.1.16 Long-term strategies for all individual nations include:

- accelerating work to improve the long-term potential of efficiency in the production and use of energy; encouraging a relatively greater reliance on no or lower greenhouse gas emissions energy sources and technologies; and enhancing natural and man-made means to sequester greenhouse gases;

- further reviewing, developing and deploying policy instruments, which may include public information, standards, taxes and incentives, tradeable permits, and environmental impact assessments, which will induce sustainable energy choices by producers and consumers without jeopardizing energy security and economic growth;

[6] There was significant concern expressed at the RSWG meeting about the immediacy implied by the word now in option one, when implementation could only be considered at a rate consistent with countries' level of knowledge and particular circumstances.

- developing methodologies to evaluate the trade-off between limitation and adaptation strategies and establishing changes in infrastructure (e.g. pipelines, electrical grids, dams) needed to limit or adapt to climate change.

4.2 Limitation of net emissions from the industry sector

4.2.1 The most significant source of greenhouse gases associated with industrial activity not related to energy use is the production and use of CFCs and other halocarbons. CFCs represent a very important source of greenhouse gas emissions and account for about 24% of the total contributions to the enhanced radiative forcing for the period of the 1980s. While the RSWG did not consider control strategies for these gases since the issue is already addressed under the Montreal Protocol on Substances that Deplete the Ozone Layer, it noted that the review of the Montreal Protocol now under way should take into account the global warming potential of potential CFC substitutes.

4.2.2 The RSWG did develop future emission scenarios for CFCs and HCFC-22 (HCFC-22 was used as a surrogate for a potential mix of HCFCs and HFCs substitutes). The potential impact of such substitutes on radiative forcing was assessed by Working Group I. For a given emission rate, HCFCs and HFCs are less effective greenhouse gases than the CFCs because of their shorter lifetimes. The growth rates assumed in the IPCC scenarios will result in the atmospheric concentrations of HFCs and HCFCs becoming comparable to the CFCs during the next several decades assuming that the CFCs had continued to be used at current rates. Assuming the IPCC scenarios for HFCs and HCFCs, Working Group I calculated that these gases would contribute up to 10% of the total additional radiative forcing for the period 2000—2050.

4.3 Limitation of net emissions from the agriculture sector

4.3.1 About 9 percent of anthropogenic greenhouse gas emissions can be attributed to the agricultural sector, in particular livestock systems, rice cultivation, and the use of nitrogenous fertilizers. Limitation of emissions from this sector presents a challenge because the processes by which greenhouse gases, in particular methane and nitrous oxide, are released in agricultural activities are not well understood. In addition, response options in the agricultural sector must be designed to ensure maintenance of food supply. There appear, however, to be a number of short-term response options, some economically beneficial in their own right, which could contribute to a limitation of net emissions from agricultural sources. Where appropriate the removal of subsidies, incentives and regulatory barriers that encourage greenhouse gas emissions from the agricultural sector would be both environmentally and economically beneficial. In addition, there are a number of promising technologies and practices which, in the longer term, could significantly reduce greenhouse gas emissions.

Short-term options:

4.3.2 *Livestock systems*: Methane emissions could be reduced through improved management of livestock wastes, expansion of supplemental feeding practices, and increased use of production and growt-enhancing agents with safeguards for human health.

4.3.3. *Fertilizer use*: Nitrous oxide emissions may be reduced by using existing improved fertilizer formulations, judicious use of animal manures and compost, and improved application technology and practices.

4.3.4 *Marginal lands:* Areas marginally suitable for annual cropping systems may be shifted to perennial cover crops for fodder, pastoral land uses or forests if soils are suitable. Such actions would increase carbon uptake, both in the vegetation and soil, and would yield other benefits.

4.3.5 *Sustainable agricultural practices:* Where possible, minimum or no-till systems should be introduced for those countries currently using tillage as part of the annual cropping sequence, thus maintaining and increasing soil organic matter.

Longer-term options:

4.3.6 *Rice cultivation*: A comprehensive approach, including management of water regimes, improvement of cultivars, efficient use of fertilizers, and other management practices, could lead to a 10 to 30 percent reduction in methane emissions from flooded rice cultivation although substantial research is necessary to develop and demonstrate these practices. It is estimated that at least 20 years would be needed to introduce such practices. Adaptable alternative crops research is needed to provide a more diverse crop base for rice growing regions.

4.3.7 *Livestock:* Through a number of technologies it appears that methane emissions may be reduced from livestock systems by up to 25—75 percent per unit of product in dairy and meat production, although many uncertainties exist.

4.3.8 *Fertilizers*: Fertilizer-derived emissions of nitrous oxide potentially can be reduced (although to what extent is uncertain) through changes in practices such as using fertilizers with controlled nitrogen conversion rates, improving fertilizer-use efficiency, and adopting alternative agricultural systems where possible.

4.3.9 *Desertification:* Enhanced research on control measures.

4.4 Limitation of net emissions from forestry and other activities

4.4.1 Forestry and related aspects of land use cannot be considered in isolation, and solutions must be based on an integrated approach which links forestry to other policies, such as those concerned with poverty and land resources, which should be supported by strong institutions in order to enhance overall forest management. The forest crisis is rooted in the agricultural sector and in people's needs for employment and income. Deforestation will be stopped only when the natural forest is economically more valuable for the people who live in and around the forests than alternative uses for the same land.

4.4.2 Forestry practices and other human activities associated with land use, such as biomass burning and landfills, account for about 18 percent of anthropogenic greenhouse gas emissions. A number of short and long-term response options for limiting net emissions from these sectors have been identified.

Short-term options:

4.4.3 Improvement of forest-management and reduction of deforestation and forest degradation which should be supported by:

- reduction of air pollution which contributes to forest degradation;
- elimination of inappropriate economic incentives and subsidies that contribute to forest loss, where appropriate;
- integration of forest conservation requirements and sustainable development in all relevant sectors of national development planning and policy, taking account of the interests of local communities;
- co-ordinated remote sensing, data collection and analyses to provide the required data;
- a meeting of interested countries from the developing and the industrialized worlds and of appropriate international agencies to identify possible key elements of a world forest conservation protocol in the context of a climate convention process that also addresses energy supply and use, and practical means of implementing it. Such a meeting should also develop a framework and methodology for analyzing the feasibility of the Noordwijk remit including alternative targets, as well as the full range of costs and benefits;
- strengthening the Tropical Forestry Action Plan (TFAP) and in the light of the independent review which is being undertaken, the International Tropical Timber Organization (ITTO), and other international organizations whose objective is to help developing countries in achieving conservation, and sustainable development and management of forests;
- an assessment of incentives and disincentives for sustainable forest management, for example, the feasibility of labelling;
- introduction of sustainable forest harvesting and management;
- development of enhanced regeneration methods;
- development and implementation of (large-scale) national afforestation and forest conservation plans, where feasible.

4.4.4 Where appropriate expand forest areas, especially by afforestation, agroforestry and regreening of available surplus agricultural, urban and marginal lands.

4.4.5 Where appropriate strengthen and improve the use of forest products and wood through measures such as substituting a portion of fossil energy sources by wood or other sustainable managed biomass; partial replacement of high energy input materials by wood; further recycling of forest products; and improved efficiency of use of fuel wood.

4.4.6 Development of methane recovery systems for landfill and waste water treatment facilities and their use, in particular, in industrialized countries

Longer-term options:

4.4.7 Maintain the health and the continuance of existing forests as major natural carbon reservoirs, especially through the development and implementation of:

- silvicultural adjustment and stress management strategies;
- special forest protection strategies (developed under climate change scenarios);
- environmentally sound treatment practices for peatlands;
- standardization of methods of forest inventory and bio-monitoring to facilitate global forest management.

4.4.8 Expand forest biomass, especially of intensively managed temperate forests, by silviculture measures and genetically improved trees.

4.4.9 With regard to waste management, use of gas collection and flaring to reduce methane emissions from landfills and development of biogas plants to reduce methane emissions from wastewater treatment.

Demonstration, training and technology transfer are necessary to realize these potentials, which may range from 30 to 90 percent for landfills and up to 100 percent for wastewater treatment.

5. Further work on greenhouse gas emission limitation loals

5.0.1 There has been considerable international discussion of targets for specific greenhouse gas emissions, in particular, CO_2, which is the most abundant of the greenhouse gases. The final declaration at the November 1989 Noordwijk Conference on Atmospheric Pollution and Climate Change encouraged the IPCC to include in its First Assessment Report an analysis of quantitative targets to limit or reduce CO_2 emissions, and urged all industrialized countries to investigate the feasibility of achieving such targets, including, for example, a 20 percent reduction of CO_2 emissions by the year 2005. The Conference also called for assessing the feasibility of increasing net global forest growth by 12 million hectares per year. During its Third Plenary, the IPCC accepted the mandate.

5.0.2 Although the feasibility of quantitative targets on greenhouse gas emissions fell within the RSWG's original mandate through its Energy and Industry Subgroup (EIS), it was agreed that these new, specific tasks would require more time, data and analyses in order to be dealt with properly. It was decided, therefore, that the results of the deliberations of the EIS on these remits could not be fully included in its report, but only treated in an incomplete and preliminary way. A progress report is to be presented to the Fourth IPCC Plenary following an international workshop to be hosted by the United Kingdom in June 1990. As for the Noordwijk remit on global forest growth, the RSWG through its Agriculture, Forestry and Other Human Activities Subgroup (AFOS) noted that a framework and methodology for analyzing its feasibility should be developed.

5.0.3 While the technical potential of a number of options has been demonstrated, there is very little information available on the actual economic and social feasibility associated with implementation of such options. An adequate understanding of the benefits, in terms of changes in climate variables that are avoided, is also seriously lacking. It is imperative that further work on the cost and benefit implications of response strategies be undertaken. These issues have been identified as one of the most important areas for future research by the RSWG, concerned international organizations, and individual countries.

5.0.4 The material available to the EIS demonstrates the important role emissions of industrialized countries play in total global emissions in the near term. The material also indicates that the technical potential for reduction is large, and differs greatly between regions and countries. Therefore, in the near term, no significant progress in limiting global emissions will occur without actions by the industrialized countries. Some countries have already decided to stabilize or reduce their emissions.

6. Measures for adapting to global climate change

6.0.1 In addition to the limitation options discussed above, the RSWG reviewed measures for adapting to potential climate change. The consideration of adaptation options is critical for a number of reasons. First, because it is believed that there is likely to be a lag time between emissions and subsequent climate change, the climate may already be committed to a certain degree of change. Implementation of adaptation measures may thus be necessary regardless of any limitation actions which may be taken. Secondly, natural climatic variability itself necessitates adaptation.

6.0.2 Furthermore, should significant adverse climate change occur, it would be necessary to consider limitation and adaptation strategies as part of an integrated package in which policies adopted in the two areas complement each other so as to minimize costs. Limitation and adaptation options should be developed and analyzed recognizing the relationship between the timing and costs of limitation and adaptation. For example, the more net emissions are reduced and the rate of climate change potentially slowed, the easier it would be to adapt. A truly comprehensive approach should recognize that controlling the different gases might have different effects on the adaptive capacity of natural resources.

6.0.3 The RSWG explored two broad categories of adaptation options:

- *Coastal zone management*, or options which maximize the ability of coastal regions to adapt to the projected sea level rise and to reduce vulnerability to storms; and
- *Resource use and management*, or options which address the potential impacts of global climate change on food security, water availability, natural and managed ecosystems, land, and biodiversity.

6.1 Coastal zone management

6.1.1 Under the 2030 high emissions scenario, global climate change is predicted to raise global mean sea level 65 cm (with an uncertainty range of 30 to 100 cm) by the year 2100. If sea level rises by 1 metre, hundreds of thousands of square kilometres of coastal wetlands and other lowlands could be inundated, while ocean beaches could erode by as much as a few hundred metres over the next century. Flooding would threaten lives, agriculture, livestock, and structures, while saltwater would advance inland into

aquifers, estuaries, and soils, thus threatening water supplies and agriculture in some areas. Loss of coastal ecosystems would threaten fishery resources.

6.1.2 Some nations would be particularly vulnerable to such changes. Eight to ten million people live within one metre of high tide in each of the unprotected river deltas of Bangladesh, Egypt, and Vietnam. Half a million people live in coral atoll nations that lie almost entirely within three metres of sea level, such as the Maldives, the Marshal Islands, Tuvalu, Kiribati, and Tokelau. Other states with coastal areas, archipelagos and island nations in the Pacific and Indian Oceans and the Caribbean could lose much of their beaches and arable lands, which would cause severe economic and social disruption.

6.1.3 Available responses to sea-level rise fall broadly into three categories:

- *Retreat:* Under this option no actions would be taken to protect the land from the sea—the focus would instead be on providing for people and ecosystems to shift landward in an optimal fashion. This choice could be motivated by either excessive costs of protection or by a desire to maintain ecosystems.

- *Accommodation:* Under this strategy, while no attempt would be made to protect the land at risk, measures would be taken to allow for continued habitation of the area. Specific responses under this options would include erecting flood shelters, elevating buildings on pilings, converting agriculture to fish farming, or growing flood- or salt-tolerant species.

- *Protection:* A protection strategy uses site-specific features such as sea walls, dikes, dunes, and vegetation to protect the land from the sea so that existing land uses can be retained.

6.1.4 There are various environmental, economic, social, cultural, legal, institutional and technological implications for each of these options. Retreat could lead to a loss of property, potentially costly resettlement of populations, and, in some notable cases, refugee problems. Accommodation could result in declining property values, and costs for modifying infrastructure. Protecting existing development from a one metre sea level rise would require about 360,000 kilometres of coastal defences at a total cost of US$ 500 billion, over the next 100 years. The annual cost of protection represents, on average, 0.04 percent of total gross national product (GNP), and ranges from zero to 20 percent for individual countries. The estimate is not discounted and does not reflect present coastal defence needs or impacts of salt water intrusion or flooding of unprotected lands. Further, the protection could have negative impacts on fisheries, wildlife and recreation. The loss of traditional environments could potentially disrupt family life and create social instability.

Actions to prepare for possible sea level rise

6.1.5 A number of response options are available which not only enhance the ability of coastal nations to adapt to sea level rise, but are also beneficial in their own right. Implementation of such options would be most effective if undertaken in the short-term, not because there is an impending catastrophe, but because there are opportunities to avoid adverse impacts by acting now—opportunities which may not be as effective if the process is delayed. These options include:

National coastal planning:

- Development and implementation in the short term of comprehensive national coastal zone management plans which (a) deal with both sea level rise and other impacts of global climate change and (b) ensure that risks to populations are minimized while recognizing the need to protect and maintain important coastal ecosystems.

- Identification of coastal areas at risk. National efforts are needed to (a) identify functions and resources at risk from a one metre rise in sea level and (b) assess the implications of adaptive response measures on them.

- Provisions to ensure that coastal development does not increase vulnerability to sea-level rise. Actions in particular need of review include river levees and dams, conversions of mangroves and other wetlands for agriculture and human habitation, harvesting of coral and increased settlement in low-lying areas. In addition, while structural measures to prepare for sea-level rise are not yet warranted, the design and location of coastal infrastructure and coastal defenses should include consideration of sea-level rise and other coastal impacts of climate change. It is sometimes less expensive to design a structure today, incorporating these factors, than to rebuild it later.

- Review and strengthening of emergency preparedness and coastal zone response mechanisms. Efforts are needed to develop emergency preparedness plans for reducing vulnerability to coastal storms through better evacuation planning and the development of coastal defense mechanisms that recognize the impact of sea level rise.

International cooperation:

- Maintenance of a continuing international focus on the impacts of sea-level rise. Existing international organizations should be augmented with new mechanisms to focus attention and awareness on sea-level change and to encourage the nations of the world to develop appropriate responses.

- Provision of technical assistance and co-operation to developing nations. Institutions offering financial support should take into account the need for technical assistance and co-operation in developing coastal management plans, assessing coastal resources at risk, and increasing a nation's ability—through education, training, and technology transfer—to address sea level rise.

- Support by international organizations for national efforts to limit population growth in coastal areas. In the final analysis, rapid population growth is the underlying problem with the greatest impact on both the efficacy of coastal zone management and the success of adaptive response options.

Research, data, and information:

- Strengthening of research on the impacts of global climate change on sea-level rise. International and national climate research programmes need to be directed at understanding and predicting changes in sea-level, extreme events, precipitation, and other impacts of global climate change on coastal areas.

- Development and implementation of a global ocean observing network, for example through the efforts of the IOC, WMO and UNEP, to establish a coordinated international ocean observing network that will allow for accurate assessment and continuous monitoring of changes in the world's oceans and coastal areas, particularly sea-level change and coastal erosion.

- Dissemination of data and information on sea-level change and adaptive options. An international mechanism could be identified with the participation of the parties concerned for collecting and exchanging data and information on climate change and its impact on sea-level and the coastal zone and on various adaptive options. Sharing this information with developing countries is critically important for preparation of coastal management plans.

6.1.6 A programme could begin now to enable developing countries to implement coastal zone management plans by the year 2000. The programme would provide for training of country experts, data collection and technical assistance and co-operation. Estimated funding to provide the necessary support over the next 5 years is US$ 10,000,000. It is suggested that international organizations such as UNEP and WMO consider co-ordinating this programme in consultation with interested nations.

6.2 Resource use and management

6.2.1 The reports of Working Groups I and II indicate significant and unavoidable impacts, both positive and negative, upon the very resources that humans and other species rely on to live. These resources include water, agriculture, livestock, fisheries, land, forests, and wildlife. The RSWG addressed these resource issues in the context of considering options for ensuring food security; conserving biological diversity; maintaining water supplies; and using land rationally for managed and unmanaged ecosystems.

6.2.2 The potential impacts of climate change on natural resources and human activities are poorly understood. First, credible regional estimates of changes in critical climatic factors, such as temperature, soil moisture, annual and seasonal variability, and frequencies of droughts, floods and storms, are simply not available. For many of these critical climatic factors even the direction of change is uncertain. Secondly, methods for translating these changes into effects on the quantity and quality of resources are generally lacking. While it is clear that some of the impacts of climate change on resources could be negative and others positive, a more specific quantification of those impacts is not possible at this time. Nevertheless, these uncertainties do not preclude taking appropriate actions, especially if they are worthwhile for other non-climate related reasons. However, it can be said that:

(a) those resources which are managed by humans (e.g. agriculture, forestry) are more suited to successful adaptation than unmanaged ecosystems; and

(b) the faster the rate of change, the greater the impact. In that regard, it is very important to realize that some species will not be able to survive rapid climate changes.

6.2.3 Through the ages societies and living things have developed the capability to adapt to the climate's natural variability and to extreme events. Several climatic zones span the globe, and resource use and management is an ongoing challenge in each of these zones. Therefore, society could borrow from this existing large reservoir of experience and knowledge in developing policies to adapt to possible climate change. In addition, expected future economic and technological progress would provide the financial and technical resources required to better adapt to a changing climate. Nevertheless, significant costs, and legal, institutional and cultural adjustments may be necessary to implement adaptation measures.

6.2.4 In recognition of the uncertainties regarding the impacts of climate change on resource use and management, the following sections provide general, rather than specific, options in three categories. The appropriateness of these options for individual countries may vary depending on the specific social, environmental and economic context.

Short-term research related options

6.2.5 There are a number of actions which would augment our knowledge base for making reasoned

judgments about response strategies. These include:

- Developing inventories, data bases, monitoring systems, and catalogues of the current state of resources and resource use and management practices.

- Improving our scientific understanding of and predictive tools for critical climatic factors, their impacts on natural resources, and their socio-economic consequences.

- Undertaking studies and assessments to gauge the resilience and adaptability of resources and their vulnerability to climate change.

- Encouraging research and development by both public and private enterprises directed toward more efficient resource use and biotechnological innovation (with adequate safeguards for health, safety, and the environment), including allowing innovators to benefit from their work.

- Continuing existing research and development of methods to cope with the potentially worst consequences of climate change, such as developing more drought- or salinity-resistant cultivars or using classical and modern breeding techniques to help keep farming and forestry options open, and research on agrometeorology or agroclimatology.

- Increasing research on the preservation of biological resources in situ and ex situ, including investigations into the size and location of protected natural areas and conservation corridors.

Short-term policy options

6.2.6 Some response strategies are available which are probably economically justified under present-day conditions and which could be undertaken for sound resource management reasons, even in the absence of climate change. In general, these relate to improving the efficiency of natural resource use, fuller utilization of the "harvested" component of resources, and waste reduction. Measures that could be implemented in the short-term include:

- Increased emphasis on the development and adoption of technologies which may increase the productivity or efficiency (per unit of land or water) of crops, forests, livestock, fisheries, and human settlements, consistent with the principles of sustainable development. Such efficiencies reduce the demand for land for human activities and could also help reduce emissions of greenhouse gases. Examples of specific options include more efficient milk and meat production; improved food storage and distribution: and better water management practices.

- Increased promotion and strengthening of resource conservation and sustainable resource use—especially in highly vulnerable areas. Various initiatives could be explored for conserving the most sensitive and valuable resources, including strengthening conservation measures, managing development of highly vulnerable resources, and promoting reforestation and afforestation.

- Acceleration of economic development efforts in developing countries. Because these countries often have largely resource-based economies, efforts at improving agriculture and natural resource use would be particularly beneficial. Such efforts would also promote capital formation, which would generally make adaptation to climate change and sustainable development more feasible.

- Developing methods whereby local populations and resource users gain a stake in conservation and sustainable resource use, for example by investing resource users with clear property rights and long-term tenure, and allowing voluntary water transfer or other market mechanisms.

- Decentralizing, as practicable, decision-making on resource use and management.

Longer-term options

6.2.7 There are also a number of other possible responses which are costly or otherwise appear to be more appropriate for consideration in the longer term, once uncertainties regarding climate change impacts are reduced. Options in this category include:

- Building large capital structures (such as dams) to provide for enhanced availability of water and other resources.

- Strengthening and enlarging protected natural areas and examining the feasibility of establishing conservation corridors to enhance the adaptation prospects for unmanaged ecosystems.

- As appropriate, reviewing and eliminating direct and indirect subsidies and incentives for inefficient resource use, and other institutional barriers to efficient resource use.

7. Mechanisms for implementing response strategies

7.0.1 The RSWG also considered several priority areas which must be addressed in order to adequately implement limitation or adaptation responses. These "implementation mechanisms" represent the primary vehicles through which national, regional and international responses to climate can

be brought into force. The specific implementation mechanisms considered were:

- public information and education;
- technology development and transfer;
- economic (market) mechanisms;
- financial mechanisms;
- legal and institutional mechanisms, including possible elements of a framework convention on climate change.

7.0.2 The results of the RSWG's deliberations on these issues are provided below.

7.1 Public information and education

7.1.1 A well informed global population is essential for addressing and coping with an issue as complex as climate change. Because climate change would affect, either directly or indirectly, almost every sector of society, broad global understanding of the issue will facilitate the adoption and implementation of such response options as deemed necessary and appropriate. The dissemination of information also represents a powerful economic instrument for ensuring that markets accurately take into account potential consequences and/or opportunities of climate change.

7.1.2 The core aims of public education and information programmes are to:

- promote awareness and knowledge of climate change issues;
- provide guidance for positive practices to limit and/or adapt to climate change;
- encourage wide participation of all sectors of the population of all countries, both developed and developing, in addressing climate change issues and developing appropriate responses; and
- especially emphasize key target groups, such as children and youth, as well as individuals at household levels, policymakers and leaders, media, educational institutions, scientists, business and agricultural sectors.

7.1.3 Given the importance of a well-informed population, the RSWG developed suggestions and approaches for improving international awareness of the potential causes and impacts of climate change. In this process it was recognized that, while broad-based understanding is essential, no single mechanism can work for every group or in every culture or country. The social, economic, and cultural diversity of nations will likely require educational approaches and information tailored to the specific requirements and resources of particular locales, countries or regions. The importance of education and information for developing countries cannot be overemphasized.

7.1.4 A number of national and international actions should be taken to disseminate broadly information on climate change. These include the:

- Establishment of national committees or clearing houses to collect, develop, and disseminate objective materials on climate change issues. This could help provide focal points for information on issues such as energy efficiency, energy savings, forestry, agriculture, etc.
- Use by international organizations (UNESCO, UNEP, WMO, etc.) and non-governmental organizations of IPCC and other relevant reports in developing and providing to all countries an adequate understanding for future actions.
- Use of an existing international institution, or development of a new institution, if necessary, to serve as a clearing house for informational and educational materials.
- Upon completion of the IPCC reports, or earlier, arrange a series of short seminars targeted to inform high priority decision makers, world leaders and others of causes and effects of climate change.

7.2 Technology development and transfer

7.2.1 The development and transfer of technologies is vital to any effort to address global climate change. The development of new technologies may provide the means by which societies can meet their energy, food, and other needs in the face of changes in global climate, while at the same time minimizing emissions of greenhouse gases. Prompt transfer of technologies, especially to developing countries, is likewise an important aspect of any effort to limit or adapt to climate change.

Technology research and development

7.2.2 Technological development, including improvement and reassessment of existing technologies, is needed to limit or reduce anthropogenic greenhouse gas emissions; absorb such gases by protecting and increasing sinks; adapt human activities and resource use and management to the impacts of climate change; and detect, monitor and predict climate change and its impacts. Technological development could be pursued in a wide range of activities such as energy, industry, agriculture, transport, water supply, coastal protection, management of natural resources, and housing and building construction.

7.2.3 Adequate and trained human resources are a prerequisite for development and transfer of technologies, and technological actions, founded on a sound scientific basis, must be consistent with the concept of sustainable development.

7.2.4 Criteria for selecting technologies include such factors as the existence of economic and social benefits in addition to environmental benefits, economic efficiency taking into account all the external costs, suitability to local needs, ease of administration, information needs, acceptability to the public.

7.2.5 Appropriate pricing policies where applicable, information exchange on the state of development of technologies, and the support of governments are important measures that can promote technology development. Also of importance are international collaborative efforts, especially between the industrialized and the developing countries in the bilateral and multilateral context.

Technology transfer

7.2.6 There is a need for the rapid transfer to the developing countries, on a preferential basis, of technologies for addressing climate change. Developing countries are of the view that transfer of technologies on a non-commercial basis is necessary and that specific bilateral and multilateral arrangements should be established to promote this. Some other countries where technologies are not owned by the government believe that transfer of technologies would be a function of commercial negotiations. The issue of intellectual property rights also presents a case where international opinion is mixed.

7.2.7 A number of impediments also exist which hinder the effective transfer of technologies to developing countries. These include lack of financial resources, necessary institutions, and trained human resources. Existing institutions could be strengthened, or new mechanisms established, where appropriate, to finance technology transfers, train human resources, and evaluate, introduce and operate existing or new technologies. Legal barriers and restrictive trade practices are also impeding factors.

7.2.8 It has not been possible to bridge the difference of views on some of the questions mentioned above. It is extremely important to reach early international agreement on these issues in order to promote effective flow of technologies to monitor, limit or adapt to climate change. One area where international agreement may be possible is the promotion of CFC substitutes and provision of assistance and cooperation to the developing countries in the acquisition and manufacture of such substitutes.

7.2.9 Several countries have suggested that the issue of technology transfer to Eastern European countries be addressed.

7.3 Economic mechanisms

7.3.1 It is important that any potential measures to limit or adapt to global climate change be as economically efficient and cost-effective as possible, while taking into account important social implications. In general, environmental objectives can be achieved either through regulations requiring the use of a specific technology or attainment of specified goals, or economic instruments such as emissions fees, subsidies, tradeable permits or sanctions.

7.3.2 Economic instruments, through their encouragement of flexible selection of abatement measures, frequently offer the possibility of achieving environmental improvements at lower cost than regulatory mechanisms. Unlike many regulations, they tend to encourage innovation and the development of improved technologies and practices for reducing emissions. Economic mechanisms also have the potential to provide the signals necessary for more environmentally sensitive operation of markets. It is unlikely, however, that economic instruments will be applicable to all circumstances.

7.3.3 Three factors are considered as potential barriers to the operation of markets and/or the achievement of environmental objectives through market mechanisms. These are: information problems, which can often cause markets to produce less effective or unfavourable environmental outcomes; existing measures and institutions, which can encourage individuals to behave in environmentally damaging ways; and balancing competing objectives (social, environmental, and economic). An initial response strategy may therefore be to address information problems directly and to review existing measures which may be barriers. For example, prior to possible adoption of a system of emission charges, countries should examine existing subsidies and tax incentives on energy and other relevant greenhouse-gas-producing sectors.

7.3.4 A general advantage of market based *economic instruments* is that they encourage limitations or reductions in emissions by those who can achieve them at least cost. They also provide an ongoing incentive for industry and individual consumers to apply the most efficient limitation/reduction measures through, for example, more efficient and cleaner technologies. Such incentives may be lacking in the case of regulations.

7.3.5 *Regulations*, are the customary means of controlling pollution in both market and centrally planned economies. An advantage of regulations is that, in certain circumstances, they create more certainty as to desired outcomes, whereas major disadvantages are that they may discourage innovation, introduce inflexibilities in meeting objectives, can discourage resource use efficiency, and offer few or no incentives to reduce emissions below specified levels.

7.3.6 It is evident that the question of adoption of any form of economic instrument, whether domestically or

internationally, raises many complex and difficult issues. Careful and substantive analysis of all implications of such instruments is needed. Possible specific economic instruments which have been identified for consideration include:

- *A system of tradeable emissions permits:* An emission permit system is based on the concept that the economic costs of attaining a given environmental goal can be minimized by allowing for the trading of emissions rights. Once an overall limit on emissions has been set, emissions entitlements amounting to that limit could be provided to emitting sources and free trading of such entitlements allowed. This would reduce the costs of meeting a given emission target because: (a) as in trade, comparative advantages between trading entities would be maximized; and (b) economic incentives would be created for the development of improved greenhouse gas limitation technologies, sink enhancement, and resource use efficiency (energy conservation). Concerns with this approach include the limited experience with this instrument, the potential scope and size of trading markets and the need for the development of an administrative structure not currently in place.

- *A system of emission charges:* Emission charges are levied on specified emissions depending on their level of contribution to climate change. Such charges may provide a means of encouraging emitters to limit or reduce emissions and provide an incentive for diverse parties to implement efficient means of limiting or reducing emissions. Another advantage of charges is that they generate revenue which could provide a funding base for further pollution abatement, research, and administration, or allow other taxes to be lowered. Concerns with this approach include the difficulty of deciding on the basis and size of the tax, and the lack of certainty that the tax will achieve the agreed emission reduction target.

- *Subsidies:* Subsidies are aimed at encouraging environmentally sound actions by lowering their costs. Subsidies could be used, inter alia, to encourage the use of energy-efficient equipment and non-fossil energy sources, and the development and greater use of environmentally sound technologies. Concerns with subsidies include the possible size of the required financial commitment of governments, the need for careful design, the need for review, and the international trade aspects of such measures.

- *Sanctions*: A final type of economic instrument is the use of economic sanctions for the enforcement of international agreements. This would require an international convention to establish a system of agreed trade or financial sanctions to be imposed on countries not adhering to agreed regimes. Many contributors expressed considerable reservations about applying this approach to greenhouse gas emissions because of the complexity of the situation. The concerns include a belief that sanctions could appear to be arbitrary, could create confusion and resentment and could be used as a pretext to impose new non-tariff trade barriers.

7.3.7 It has also been suggested that environmental protection could be advanced and economic costs of meeting greenhouse-gas limitation targets, if any, minimized by addressing, to the extent feasible, all greenhouse gas sources and sinks comprehensively. This approach could employ an "index" relating net emissions of various greenhouse gases by further development of the index formulated by Working Group I.

7.3.8 Each of the approaches outlined above, however, poses potentially significant challenges in terms of implementation and acceptability. There is an incomplete understanding of the economic and social consequences of these various approaches. It is evident that further work is required in all countries, and in ongoing IPCC work, to fully evaluate the practicality of such measures and costs and benefits associated with different mechanisms, especially with their use internationally. It has, however, been pointed out that an international system of tradeable permits, or, alternatively, an international system of emissions charges, could offer the potential of serving as a cost-efficient main instrument for achieving a defined target for the reduction of greenhouse gas emissions.

7.3.9 Finally, it was stressed that in order to share equitably the economic burdens, implementation of any of the international economic instruments discussed above should take into account the circumstances that most emissions affecting the atmosphere at present originated in the industrialized countries, where the scope for change is the greatest, and that, under present conditions, emissions from developing countries are growing and may need to grow in order to meet their development requirements and thus, over time, are likely to represent an increasingly significant percentage of global emissions. It is appreciated that each instrument assessed has a role in meeting greenhouse-gas emission objectives, but the suitability of particular instruments is dependent on the particular circumstances and at this stage no measure can be considered universally superior to any other available mechanisms.

7.4 Financial mechanisms

7.4.1 Industrialized and developing countries consider it important that assurances of financial mechanisms are needed for undertaking adequate measures to limit and/or adapt to climate change.

Guiding Principles

7.4.2 The following principles should guide the financial approach:

a) Industrialized countries and developing countries have a common responsibility in dealing with problems arising from climate change, and effective responses require a global effort.

b) Industrialized countries should take the lead and have specific responsibilities on two levels:

i) a major part of emissions affecting the atmosphere at present originates in industrialized countries where the scope for change is greatest. Industrialized countries should adopt domestic measures to limit climate change by adapting their own economies in line with future agreements to limit emissions;

ii) to cooperate with developing countries in international action, without standing in the way of the latter's development, by contributing additional financial resources, by appropriate transfer of technology, by engaging in close cooperation concerning scientific observation, by analysis and research, and finally by means of technical co-operation geared to forestalling and managing environmental problems;

c) emissions from developing countries are growing and may need to grow in order to meet their development requirements and thus, over time, are likely to represent an increasingly significant percentage of global emissions. Developing countries should, within the limits feasible, take measures to suitably adapt their economies.

7.4.3 Financial resources channelled to developing countries would be most effective if focused on those activities which contribute both to limiting greenhouse gas emissions and promoting economic development. Areas for cooperation and assistance could include:

- efficient use of energy resources and the increased use of fossil fuels with lower greenhouse gas emission rate or non-fossil sources;
- rational forest management practices and agricultural techniques which reduce greenhouse gas emissions;
- facilitating technology transfer and technology development;
- measures which enhance the capacity of developing countries to develop programmes to address climate change, including research and development activities and public awareness and education;
- participation by developing countries in international fora on global climate change, such as the IPCC.

7.4.4 It was also recognized that co-operation and assistance for adaptive measures would be required, noting that for some regions and countries, adaptation rather than limitation activities are potentially most important.

7.4.5 A number of possible sources for generating financial resources were considered. These include general taxation, specific taxation on greenhouse gas emissions, and emissions trading. For the significant complexities and implications of such taxes, reference is made to the economic measures paper (section 7.3). Creative suggestions include using undisbursed official resources, which might result from savings on government energy bills and lower levels of military expenditures, a fixed percentage tax on travel tickets, and levies on countries that have been unable to meet their obligations. The question has also been raised of whether such financial cooperation and assistance should only be given to those countries which abstain from activities producing greenhouse gases. A positive international economic environment, including further reduction of trade barriers, and implementation of more equitable trade practices would help to generate resources which can be applied towards pressing needs.

7.4.6 With respect to institutional mechanisms for providing financial co-operation and assistance to developing countries, a two-track approach was considered:

i) one track built on work under way or planned in existing institutions. In this regard, the World Bank, a number of regional banks, other multilateral organizations, and bilateral agencies have initiated efforts to incorporate global climate change issues into their programmes. Bilateral donors could further integrate and reinforce the environmental components of their assistance programmes and develop co-financing arrangements with multilateral institutions while ensuring that this does not impose inappropriate environmental conditions;

ii) parallel to this track the possibility of new mechanisms and facilities was considered. Some developing and industrialized countries suggested that new mechanisms directly related to a future climate convention and protocols, such as a new international fund, were required. It was added that such new instruments could be located within the World Bank (with new rules) or elsewhere. It was also noted that the Global Environmental Facility proposed by the World Bank in collaboration with UNEP and UNDP was welcomed by industrialized and developing countries at the World Bank Development Committee meeting in May 1990.

7.4.7 It was noted that the issue of generating financial resources was distinct from that of allocating those resources.

7.4.8 Areas identified for future work include studies, with donor assistance, for developing countries on their current and projected net emissions levels and assistance and

cooperation needs for limiting such emissions. Further consideration is also needed of the important role which the private sector might play, through technology transfer, foreign direct investment and other means to assist and cooperate with developing countries to respond to climate change.

7.5 Legal and institutional mechanisms

7.5.1 A number of institutions and international legal mechanisms exist which have a bearing on the climate change issue, in particular those dealing with the environment, science and technology, energy, natural resources, and financial assistance. One of these existing international legal mechanisms, the Vienna Convention on the Protection of the Ozone Layer and its associated Montreal Protocol on Substances that Deplete the Ozone Layer, deals specifically with reducing emissions of important greenhouse gases which also deplete the ozone layer. However, there is a general view that, while existing legal instruments and institutions related to climate change should be fully utilized and further strengthened, they are insufficient alone to meet the challenge.

7.5.2 A consensus emerged at the 44th session of the UN General Assembly on the need to prepare, as a matter of urgency, a framework convention on climate change, laying down, as a minimum, general principles and obligations. It should, in the view of RSWG, be framed in such a way as to gain the adherence of the largest possible number and most suitably balanced range of countries while permitting timely action to be taken. It may contain provision for separate annexes/protocol(s) to deal with specific obligations. As part of the commitment of the parties to action on greenhouse gas emissions and adverse effects of climate change, the convention should also address the particular financial and other needs of the developing countries (notably those most vulnerable to climate change agriculturally or otherwise), the question of access to and transfer of technology, the need for research and monitoring, and institutional requirements.

7.5.3 Decisions will have to be taken on a number of key issues. These include:

- the political imperative of striking the correct balances (a) between the arguments for a far-reaching, action-oriented convention and the need for urgent adoption of a convention so as to begin tackling the problem of climate change; and (b) among the risks of inaction, the costs of action and current levels of scientific uncertainty;
- the extent to which specific obligations, particularly on the control of emissions of greenhouse gases, should be included in the convention itself, possibly as annexes, or be the subject of a separate protocol(s);
- the timing of negotiation of protocol(s) in relation to the negotiations on the convention;
- the introduction as appropriate of sound scientific bases for establishing emission targets (such as total emission levels, per capita emissions, emissions per GNP, emissions per energy use, climatic conditions, past performance, geographic characteristics, fossil fuel resource base, carbon intensity per unit of energy, energy intensity per GNP, socio-economic costs and benefits or other equitable considerations);
- the extent to which specific goals with respect to global levels of emissions or atmospheric concentrations of greenhouse gases should be addressed;
- whether obligations should be equitably differentiated according to countries' respective responsibilities for causing and combatting climate change and their level of development;
- the need for additional resources for developing countries and the manner in which this should be addressed, particularly in terms of the nature, size and conditions of the funding, even if detailed arrangements form the subject of a separate protocol;
- the basis on which the promotion of the development and transfer of technology and provision of technical assistance and co-operation to developing countries should take place, taking into account considerations such as terms of transfer (preferential or non-preferential, commercial or non-commercial), assured access, intellectual property rights, the environmental soundness of such technology, and the financial implications;
- the nature of any new institutions to be created by the convention (such as a Conference of the Parties, an Executive Organ, as well as other bodies), together with their functions, composition and decision-making powers, e.g. whether or not they should exercise supervision and control over the obligations undertaken.

7.5.4 The international negotiation on a framework convention should start as quickly as possible after the completion of the IPCC interim report. The full and effective participation of developing countries in this process is essential. Many, essentially developing, countries stressed that the negotiation must be conducted in the forum, manner and with the timing to be decided by the UN General Assembly. This understanding also applies to any associated protocols. In the view of many countries and international and non-governmental organizations, the process should be conducted with a view of concluding it not later than the 1992 UN Conference on Environment and Development.

7.5.5 The foregoing does not necessarily constitute an exclusive list of issues which will arise in the negotiations. However, a readiness to address these fundamental problems will be a prerequisite for ensuring the success of the negotiations and the support of a sufficiently wide and representative spread of nations.

7.5.6 The legal measures topic paper developed by the Working Group is given in Annex I.

ANNEX I

LEGAL AND INSTITUTIONAL MECHANISMS: REPORT OF TOPIC CO-ORDINATORS (Canada, Malta and the UK)

Executive Summary

1. The co-ordinators' report has as its primary objective the compilation of elements that might be included in a future framework Convention on Climate Change, and a discussion of the issues that are likely to arise in the context of developing those elements.

2. There is a general view that while existing legal instruments and institutions with a bearing on climate should be fully utilized and further strengthened, they are insufficient alone to meet the challenge. A very broad international consensus has therefore emerged in the IPCC, confirmed notably at the 44th United Nations General Assembly, on the need for a framework Convention on Climate Change. Such a Convention should generally follow the format of the Vienna Convention for the Protection of the Ozone Layer, in laying down, as a minimum, general principles and obligations. It should further be framed in such a way as to gain the adherence of the largest possible number and most suitably balanced spread of countries while permitting timely action to be taken; it should contain provision for separate annexes/protocols to deal with specific obligations. As part of the commitment of the parties to action on greenhouse gas emissions and the adverse effects of global warming, the Convention would also address the particular financial needs of the developing countries, the question of the access to and transfer of technology, and institutional requirements.

3. The paper points out a number of issues to be decided in the negotiation of a Convention. In general these are:

- the political imperative of striking the correct balances: on the one hand, between the arguments for a far-reaching, action-oriented Convention and the need for urgent adoption of such a Convention so as to begin tackling the problem of climate change; and, on the other hand, between the cost of inaction and the lack of scientific certainty;

- the extent to which specific obligations, particularly on the control of emissions of carbon dioxide and other greenhouse gases, should be included in the Convention itself or be the subject of separate protocol(s):

- the timing of negotiation of such protocol(s) in relation to the negotiations on the Convention.

4. In particular, within the Convention the following specific issues will need to be addressed:

a) *Financial needs of developing countries:* The need for additional resources for developing countries and the manner in which this should be addressed, particularly in terms of the nature, size and conditions of the funding, even if detailed arrangements form the subject of a separate protocol, will have to be considered by the negotiating parties.

b) *Development and transfer of technology:* The basis on which the promotion of the development and transfer of technology and provision of technical assistance to developing countries should take place will need to be elaborated, taking into account considerations such as terms of transfer, assured access, intellectual property rights and the environmental soundness of such technology.

c) *Institutions:* Views differ substantially on the role and powers of the institutions to be created by the Convention, particularly in exercising supervision and control over the obligations undertaken.

5. The inclusion of any particular element in the paper does not imply consensus with respect to that element, or the agreement of any particular government to include that element in a Convention.

6. The co-ordinators have not sought to make a value judgement in listing and summarizing in the attached paper the elements proposed for inclusion in a framework Convention: their text seeks merely to assist the future negotiators in their task. They note however that a readiness to address the foregoing fundamental problems in a realistic manner will be a prerequisite for ensuring the success of the negotiations and the support of a sufficiently wide and representative spread of nations.

Possible elements for inclusion in a Framework Convention on Climate Change

Preamble

In keeping with common treaty practice including the format of the Vienna Convention, the Climate Change Convention would contain a preamble which might seek to address some or all of the following items:

- a description of the problem and reasons for action (need for timely and effective response without awaiting absolute scientific certainty);
- reference to relevant international legal instruments (such as the Vienna Convention and Montreal Protocol) and declarations (such as UNGA Resolution 43/53 and Principle 21 of the Stockholm Declaration);
- recognition that climate change is a common concern of mankind, affects humanity as a whole and should be approached within a global framework, without prejudice to the sovereignty of states over the airspace superadjacent to their territory as recognized under international law;
- recognition of the need for an environment of a quality that permits a life of dignity and well-being for present and future generations;
- reference to the balance between the sovereign right of states to exploit natural resources and the concomitant duty to protect and conserve climate for the benefit of mankind, in a manner not to diminish either;
- endorsement and elaboration of the concept of sustainable development;
- recognition of the need to improve scientific knowledge (e.g. through systematic observation) and to study the social and economic impacts of climate change, respecting national sovereignty;
- recognition of the importance of the development and transfer of technology and of the circumstances and needs, particularly financial, of developing countries; need for regulatory, supportive and adjustment measures to take into account different levels of development and thus differing needs of countries;
- recognition of the responsibility of all countries to make efforts at the national, regional and global levels to limit or reduce greenhouse gas emissions and prevent activities which could adversely affect climate, while bearing in mind that:
- most emissions affecting the atmosphere at present originate in industrialized countries where the scope for change is greatest;
- implementation may take place in different time frames for different categories of countries and may be qualified by the means at the disposal of individual countries and their scientific and technical capabilities;
- emissions from developing countries are growing and may need to grow in order to meet their development requirements and thus, over time, are likely to represent an increasingly significant percentage of global emissions;
- recognition of the need to develop strategies to absorb greenhouse gases, i e. protect and increase greenhouse gas sinks; to limit or reduce anthropogenic greenhouse gas emissions; and to adapt human activities to the impacts of climate change.
- Other key issues which will have to be addressed during the development of the preambular language include:
- should mankind's interest in a viable environment be characterized as a fundamental right?
- is there an entitlement not to be subjected, directly or indirectly, to the adverse effects of climate change?
- should there be a reference to the precautionary principle?
- in view of the inter-relationship among all greenhouse gases, their sources and sinks, should they be treated collectively?
- should countries be permitted to meet their aggregate global climate objectives through joint arrangements?
- should reference be made to weather modification agreements such as the ENMOD treaty as relevant legal instruments?
- is there a common interest of mankind in the development and application of technologies to protect and preserve climate?
- does the concept of sustainable development exclude or include the imposition of new conditionality in the provision of financial assistance to developing countries, and does it imply a link between the protection and preservation of the environment, including climate change, and economic development so that both are to be secured in a coherent and consistent manner?
- should the preamble address the particular problems of countries with an agricultural system vulnerable to

climate change and with limited access to capital and technologies, recognizing the link with sustainable development?

- is there a minimum standard of living which is a prerequisite to adopting response strategies to address climate change?

Definitions

As is the practice, definitions will need to be elaborated in a specific article on definitions. The terms which will need to be defined will depend on the purpose of the Convention and thus the language used by the negotiating parties.

General obligations

Following the format of such treaties as the Vienna Convention, an article would set out the general obligations agreed to by the parties to the Convention. Such obligations may relate to, for example:

- the adoption of appropriate measures to protect against the adverse effects of climate change, to limit, reduce, adapt to and, as far as possible, prevent climate change in accordance with the means at the disposal of individual countries and their scientific and technical capabilities; and to avoid creating other environmental problems in taking such measures;

- the protection, stabilization and improvement of the composition of the atmosphere in order to conserve climate for the benefit of present and future generations;

- taking steps having the effect of limiting climate change but which are already justified on other grounds;

- the use of climate for peaceful purposes only, in a spirit of good neighbourliness;

- co-operation by means of research, systematic observation and information exchange in order to understand better and assess the effects of human activities on the climate and the potential adverse environmental and socio-economic impacts that could result from climate change, respecting national sovereignty;

- the encouragement of the development and transfer of relevant technologies, as well as the provision of technical and financial assistance, taking into account the particular needs of developing countries to enable them to fulfill their obligations;

- co-operation in the formulation and harmonization of policies and strategies directed at limiting, reducing, adapting to and, as far as possible, preventing climate change;

- co-operation in the adoption of appropriate legal or administrative measures to address climate change;

- provision for bilateral, multilateral and regional agreements or arrangements not incompatible with the Convention and any annex/protocol, including opportunities for groups of countries to fulfill the requirements on a regional or sub-regional basis;

- co-operation with competent international organizations effectively to meet the objectives of the Convention;

- the encouragement of and co-operation in the promotion of public education and awareness of the environmental and socio-economic impacts of greenhouse gas emissions and of climate change;

- the strengthening or modification if necessary of existing legal and institutional instruments and arrangements relating to climate change;

- a provision on funding mechanisms.

Other key issues which will have to be addressed in the process of elaborating this article include the following:

- Should there be a provision setting any specific goals with respect to levels of emissions (global or national) or atmospheric concentrations of greenhouse gases while ensuring stable development of the world economy, particularly stabilization by industrialized countries, as a first step, and later reduction of CO_2 emissions and emissions of other greenhouse gases not controlled by the Montreal Protocol? Such provision would not exclude the application of more stringent national or regional emission goals than those which may be provided for in the Convention and/or any annex/protocol.

- In light of the preambular language, should there be a provision recognizing that implementation of obligations may take place in different time frames for different categories of country and/or may be qualified by the means at the disposal of individual countries and their scientific and technical capabilities?

- Should there be a commitment to formulate appropriate measures such as annexes, protocols or other legal instruments and, if so, should such formulation be on a sound scientific basis or on the basis of the best available scientific knowledge?

- In addressing the transfer of technology particularly to developing countries, what should be the terms of such transfers (i e. commercial vs. non-commercial, preferential vs. non-preferential, the relationship between transfers and the protection of intellectual property rights)?

- Should funding mechanisms be limited to making full use of existing mechanisms or also entail new and additional resources and mechanisms?

- Should provision be made for environmental impact assessments of planned activities that are likely to cause significant climate change as well as for prior notice of such activities?

- What should be the basis of emission goals eg. total emission levels, per capita emissions, emissions per GNP, emissions per energy use, climatic conditions, past performance, geographic characteristics, fossil fuel resource base, carbon intensity per unit of energy, energy intensity per GNP, socio-economic costs and benefits, or other equitable considerations?

- Should the particular problem of sea-level rise be specifically addressed?

- Is there a link between nuclear stockpiles and climate change?

Institutions

It has been the general practice under international environmental agreements to establish various institutional mechanisms. The parties to a Climate Change Convention might, therefore, wish to make provision for a Conference of the Parties, an Executive Organ and a Secretariat.

The Conference of the Parties may, among other things: keep under continuous review the implementation of the Convention and take appropriate decisions to this end; review current scientific information; and promote harmonization of policies and strategies directed at limiting, reducing, adapting to and, as far as possible, preventing climate change.

Questions that will arise in developing provisions for appropriate institutional mechanisms include:

- Should any of the Convention's institutions (e.g. the Conference of the Parties and/or the Executive Organ) have the ability to take decisions inter alia on response strategies or functions in respect of surveillance, verification and compliance that would be binding on all the parties and, if so, should such an institution represent all of the parties or be composed of a limited number of parties e.g. based on equitable geographic representation?

- What should be the role of the Secretariat?

- What should be the decision-making procedures, including voting requirements (e.g. consensus, majority)?

- If a trust fund or other financial mechanism were established under the Convention, how should it be administered?

- Should scientific and/or other bodies be established on a permanent or ad hoc basis, to provide advice and make recommendations to the Conference of the Parties concerning research activities and measures to deal with climate change?

- Should the composition of the above bodies reflect equitable climatic or geographic representation?

- Should there be a provision for working groups, e.g. on scientific matters as well as on socio-economic impacts and response strategies?

- Is there a need for innovative approaches to institutional mechanisms in the light of the nature of the climate change issue?

- What should be the role of non-governmental organizations?

Research, Systematic Observations and Analysis

It would appear to follow general practice to include provision for co-operation in research and systematic monitoring. In terms of research, each party might be called upon to undertake, initiate, and/or co-operate in, directly or through international bodies, the conduct of research on and analysis of:

- physical and chemical processes that may affect climate;

- substances, practices, processes and activities that could modify the climate;

- techniques for monitoring and measuring greenhouse gas emission rates and their uptake by sinks;

- improved climate models, particularly for regional climates;

- environmental, social and economic effects that could result from modifications of climate;

- alternative substances, technologies and practices;

- environmental, social and economic effects of response strategies;

- human activities affecting climate;

- coastal areas with particular reference to sea-level rise;

- water resources; and

- energy efficiency.

The parties might also be called upon to co-operate in establishing and improving, directly or through competent international bodies, and taking fully into account national legislation and relevant on-going activities at the national, regional and international levels, joint or complementary programmes for systematic monitoring and analysis of climate, including a possible worldwide system; and co-operate in ensuring the collection, validation and transmission of research, observational data and analysis through appropriate data centres.

Other issues that will arise in developing this provision include:

- Should consideration be given to the establishment of panels of experts or of an independent scientific board responsible for the co-ordination of data collection from the above areas of research and analysis and for periodic assessment of the data?
- Should provision be made for on-site inspection?
- Should there be provision for open and non-discriminatory access to meteorological data developed by all countries?
- Should a specific research fund be established?

Information exchange and reporting

Precedents would suggest the inclusion of a provision for the transmission of information through the Secretariat to the Conference of the Parties on measures adopted by them in implementation of the Convention and of protocols to which they are party. In an annex to the Vienna Convention, the types of information exchanged are specified and include scientific, technical, socio-economic, commercial and legal information.

For the purposes of elaborating this provision, issues having to be addressed by the negotiating parties include the following:

- Is there a need for the elaboration of a comprehensive international research programme in order to facilitate co-operation in the exchange of scientific, technological and other information on climate change?
- Should parties be obliged to report on measures they have adopted for the implementation of the Convention, with the possible inclusion of regular reporting on a comparable basis of their emissions of greenhouse gases?
- Should each party additionally be called upon to develop a national inventory of emissions, strategies and available technologies for addressing climate change? If so, the Convention might also call for the exchange of information on such inventories, strategies and technologies.

Development and transfer of technology

While the issue of technology has been addressed in the section on General Obligations, it might be considered desirable to include separate provisions on technology transfer and technical co-operation. Such provisions could call upon the parties to promote the development and transfer of technology and technical co-operation, taking into account particularly the needs of developing countries, to enable them to take measures to protect against the adverse effects of climate change, to limit, reduce and, as far as possible, prevent climate change, or to adapt to it.

Another issue which will arise is: should special terms be attached to climate-related transfers of technology (such as a preferential and/or non-commercial basis and assured access to, and transfer of, environmentally sound technologies on favourable terms to developing countries), taking into consideration the protection of intellectual property rights?

Settlement of disputes

It would be usual international practice to include a provision on the settlement of disputes that may arise concerning the interpretation or application of the Convention and/or any annex/protocol. Provisions similar to those in the Vienna Convention for the Protection of the Ozone Layer might be employed, i.e. voluntary resort to arbitration or the International Court of Justice (with a binding award) or, if neither of those options is elected, mandatory resort to conciliation (with a recommendatory award).

Other provisions

It would be the usual international practice to include clauses on the following topics:

- amendment of the Convention;
- status, adoption and amendment of annexes;
- adoption and entry into force of, and amendments to, protocols;
- signature;
- ratification;
- accession;
- right to vote;
- relationship between the Convention and any protocol(s);

- entry into force;
- reservations;
- withdrawal;
- depositary;
- authentic texts.

Annexes and protocols

The negotiating parties may wish the Convention to provide for the possibility of annexes and/or protocols. Annexes might be concluded as integral parts of the Convention, while protocols might be concluded subsequently (as in the case of the Montreal Protocol to the Vienna Convention on Protection of the Ozone Layer). While it is recognized that the Convention is to be all-encompassing, the negotiating parties will have to decide whether greenhouse gases, their sources and sinks, are to be dealt with: individually, in groups or comprehensively; in annexes or protocols to the Convention. The following, among others, might also be considered as possible subjects for annexes or protocols to the Convention:

- agricultural practices;
- forest management;
- funding mechanisms;
- research and systematic observations;
- energy conservation and alternative sources of energy;
- liability and compensation;
- international emissions trading;
- international taxation system;
- development and transfer of climate change-related technologies.
- Issues that will arise in connection with the development of annexes and protocols include:
- timing, i e. negotiating parties advocating a more action-oriented Convention may seek to include specific obligations in annexes as opposed to subsequent protocols and/or negotiate one or more protocols in parallel with the Convention negotiations;
- sequence, i e. if there is to be a series of protocols, in what order should they be taken up?

LIST OF ACRONYMS AND CHEMICAL SYMBOLS

AFOS	Agriculture, Forestry and Other Human Activities Subgroup of IPCC Working Group III
BaU	Business-as-Usual Scenario. Same as Scenario A of Working Group III
Bt	Billion (1000 million) tonnes
BTC	Billion (or 1000 millions) tonnes Carbon
CFCs	Chlorofluorocarbons
CH_4	Methane
CI	Carbon Intensity in kilogram carbon per gigajoule
CO	Carbon monoxide
CO_2	Carbon dioxide
EIS	Energy and Industry Subgroup of Working Group III
Gg	Gigagram (10^9 grams)
GHG	Greenhouse Gas
GDP	Gross Domestic Product
GNP	Gross National Product
GtC	Gigatonnes (10^9 tonnes) carbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
IOC	Intergovernmental Oceanographic Commission of UNESCO
IPCC	Intergovernmental Panel on Climate Change
ICSU	International Council of Scientific Unions
ITTO	International Tropical Timber Organization
Mt	Megatonnes (10^6 tonnes)
N_2O	Nitrous oxide
NGOs	Non-Governmental Organizations
NOx	Nitrogen oxides
O_3	Ozone
OECD	Organization for Economic Cooperation and Development
pa	per annum
PC	per capita carbon emissions in tonne carbon
ppm	part per million
RSWG	Respone Strategies Working Group of IPCC Working Group III
SOx	Sulphur oxides
TC	Tonne Carbon
TC-GJ	Tonne Carbon per GigaJoule
TFAP	Tropical Forstry Action Plan
Tg	Teragrams (10^{12} grams)
TgC	Teragram Carbon
TgCH4	Teragram Methane
TgN	Teragram Nitrogen
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
VOCs	Volatile Organic Compounds
WMO	World Meteorological Organization

Policymaker Summary of the IPCC Special Committee on the Participation of Developing Countries

Executive Summary

1. The Special Committee on the Participation of Developing Countries was established by the IPCC to promote, as rapidly as possible, full participation of the developing countries in IPCC activities. Action was taken, funds were raised and attendance of the developing countries increased.

2. Full participation includes the development of national competence to address all issues of concern such as the appreciation of the scientific basis of climate change, the potential impacts on society of such change and evaluations of practical response strategies for national/regional applications.

3. There is a close link between issues addressed by the IPCC Working Groups such as access to technology and financial resources and the participation of the developing countries in IPCC. The work of the Special Committee was carried out in parallel, necessitated by the tight timetable and limited resources, with work on such issues carried out in Working Group III. The Committee will need to meet periodically to co-ordinate the integration of its conclusions and other concerns of the developing countries in the work of the Working Groups, particularly Working Group III, and the implementation of its recommendations.

4. The industrialized world today emits about 75% of the world total greenhouse gas emissions, and although the emissions are increasing in the developing countries, where 75% of the world population lives, they emit the balance. The legitimate concerns on the part of the developing countries that, although their impact on global climate change is minimal, its impact on them can be grave, need to be taken into account.

5. Any significant climate change would affect every sector of individual and social activity. Thus a single nation or even a group of nations cannot hope to manage the issue adequately by itself. It would take the concerted action of all nations to achieve that end, taking into account not only the past and present responsibility of the industrialized world in the accumulation of the greenhouse gases, but also the present economic and financial capacities of the developing countries.

6. While the global environment has assumed today greater significance for the industrialized countries, the priority for the alleviation of poverty continues to be the overriding concern of the developing countries; they rather conserve their financial and technical resources for tackling their immediate economic problems than make investments to avert a global problem which may manifest itself after two generations, particularly when their contribution to it is significantly less than that of the industrialized countries.

7. The Committee noted that developing countries consider the lack of sufficient assurance so far on the provision and requisite, adequate, new and additional funding particularly for the identification, transfer, adaptation and implementation of alternative safer technologies on a preferential, non-commercial and grant basis, added substantially to the inhibition of the developing countries in taking active part in IPCC activities. It further noted that these countries consider that the formulation of guidelines for funding mechanisms for transfer, adaptation and implementation of clean technologies as against legal and economic measures would create healthier conditions for the participation of the developing countries.

8. These considerations have led the Special Committee to focus on the following five factors that inhibit the full participation of the developing countries in the IPCC process:

- insufficient information;
- insufficient communication;
- limited human resources;
- institutional difficulties;
- limited financial resources.

(i) *Insufficient information*: Many developing countries do not have sufficient information on the issue of potential climate change to appreciate the concern it evokes elsewhere in the world. Information is often insufficient with respect to the scientific basis for concern, on the potential physical and socio-economic impacts of climate change as well as on response options. This applies not only to scientific milieux but also to policymakers and public opinion.

(ii) *Insufficient communication*: Even if the situation with respect to information were to improve, there is the problem of insufficient internal and external communication mechanisms for the proper dissemination of the information on matters related to climate change.

(iii) *Limited human resources*: Lack of adequate number of trained personnel in almost all areas ranging from academic, scientific efforts to applications of knowledge to food and energy production, to water management, to human settlements problems, to trade and economic growth, and to a host of other related endeavours is common to many developing nations. Most of them, if not all, can command only a limited pool of experts and responsible and knowledgeable officials, and even that only in a few of these areas.

(iv) *Institutional difficulties*: The multi-disciplinary and cross-cutting nature of the issues involved demands a relatively high degree of co-ordination among the various departments/ ministries of governments.

(v) *Limited financial resources:* Survival needs come first. After that. the limited financial, and consequent general lack of technological, resources dictate the priorities. Means of meeting the incremental costs of ensuring a viable environment frequently cannot be found. Also, local immediate, environmental concerns generally receive political priority over impersonal, global concerns.

9. The Committee did not consider in detail topics such as financial assistance, economic incentives/ disincentives, formulation of legal instruments, and development of, and access to, environmentally-benign and energy-efficient technologies. These were dealt with by Working Group III and are likely to form the substance of future negotiations among governments. However, the Committee expressed the view that actions to promote the full participation of the developing countries in climate change issues should not await the outcome of such negotiations.

10. Also, there are actions that will arise as a result of negotiations and agreements, and machinery will have to be put in place to implement these. But there are others that need to be taken now, that can be done through existing arrangements; most in this category should be planned and carried out for several years.

11. The impacts of climate change will vary from region to region and nation to nation. Although response strategies for developing countries have to take into account the need for adequate funding and safer technologies, country-specific and/or region-specific approaches will be necessary. For example, response measures that small island states require could be very different from those for large industrializing countries within the developing world. Success in the implementation of many of the recommended actions depend not only on national initiatives but also on stronger regional or sub-regional co-operation.

Recommended actions

12. Uninterrupted travel assistance to the developing countries for attendance at the meetings of IPCC and follow-up activities should be ensured. The Committee wishes to call the attention of the Panel to the importance of continuing this effort and of the donor nations continuing and increasing contributions to the effort, with no cessation after the fourth plenary of IPCC.

13. Serious consideration should be given to supporting more than one expert from each participating developing country to those climate change-related meetings that deal with several aspects of the problem. The developing countries on their part should facilitate action in this regard as much as possible.

14. Governments and organizations from the industrialized nations are encouraged to continue and increase their efforts in organizing seminars. Developing countries could organize, under the sponsorship of international organizations or otherwise, regional seminars and workshops in order to exchange scientific and technical information. For this purpose, necessary programmes and lists of experts should be developed. As part of the continuing process of information exchange, the Committee recommends that IPCC circulate this Policymaker Summary to all concerned including those attending the Second World Climate Conference. The developing countries on their part could where appropriate designate focal points, as soon as possible, for transmittal of reports, documentation, data and information on seminars. Such focal points should be briefed on forwarding the material to appropriate recipients within the nation for response, review etc.

15. The establishment of mechanisms for national co-ordination of all their activities related to climate change could be considered by the developing countries. The mechanisms could aid such areas as information dissemination, development and implementation of plans for research and monitoring, and formulation of policy options. The industrialized countries could consider assisting the developing countries in these areas with easy access to needed technologies.

16. The Committee recommends that acquisition, analyses and interpretation of information on climatic and related data would enable developing countries to take more effective account of climate change considerations in formulating national policies. Such actions are necessary also at regional levels to undertake and refine impact studies. The current unevenness in the acquisition and use of such data which is evident between the hemispheres should be eliminated. The Committee further recommends that the developing countries take immediate action to identify their specific needs to determine the financial implications of such action. It would be necessary to mobilize appropriate funding in order to mount a sustained programme and create regional centres to organize information networks on climate change.

17. In many developing countries the meteorological/ hydrological service is the main and often the only institution collecting and recording data with relevance to climate. If associated weather patterns are modified, as some predict they would as a result of climate change, then the capabilities of such services need to be reinforced to enhance their contributions to sustainable development.

18. The Committee recommends that considerations of climate change should be integrated in development policies. National environmental studies should also take into account predicted climate change in order to determine sustainable

development strategies. To reach these objectives, the developing countries and many industrialized countries consider it essential that additional funding be available to enable developing countries to meet the incremental costs resulting from their efforts to combat climate change.

19. The Committee further recommends that its findings be duly taken into account in all relevant areas of the work of IPCC. Programmes of action should be developed and implemented (and the concepts which would lead to such programmes of action developed where needed) without delay, with a view to ensure, provided the necessary means are made available, the full participation of developing countries in the future work and activities on climate change. UNEP and WMO should take the lead in this regard and initiate the necessary consultations. Other multilateral or bilateral organizations should also be contacted for elaborating and implementing these programmes of action.

20. The Committee also recommends that serious consideration be given by IPCC to the provision of simultaneous interpretation and documentation in the customary UN languages for the meetings of the Special Committee, given the complex nature of the subject matter covered and the particular difficulties encountered by the developing countries.

21. The Special Committee is ready to assist in monitoring and reviewing the preparation and the implementation of the above mentioned and other relevant programmes of action.

1. Introduction

1.1 Establishment of the Special Committee

1.1.1 When the IPCC began its work in November 1988, only a few developing countries attended. The reason was not that they were indifferent to the issue of climate change. They were lacking in neither interest nor concern. Climate change had appeared only a short while earlier on the international agenda. By its nature, it is a complex and multi-sectoral issue. Few developing countries have adequate data bases and research facilities to address the problem directly. For most of them, national spending priorities for rapid economic growth precluded expenditure of scarce resources on travel to attend IPCC meetings.

1.1.2 The Special Committee on the Participation of Developing Countries was established by IPCC (in June 1989) to promote, as rapidly as possible, active participation of the developing countries in IPCC activities. This action followed the report of an Ad Hoc Subgroup which was established by the IPCC Bureau in February 1989 to promote ways and means of increasing such participation. The Subgroup was under the chairmanship of Dr. A. Al-Gain, who is also the Vice-Chairman of IPCC. The members of the Ad Hoc Subgroup were Brazil, Saudi Arabia, Senegal and Zimbabwe.

1.1.3 The Special Committee's deliberations owe much to the report of the Ad Hoc Subgroup. The Committee consists of the following members: France (Chair), Algeria, Brazil, India, Indonesia, Japan, Kenya, Norway, USA and USSR. Dr. Al-Gain is a co-opted member of the Committee. (The Committee met as an open-ended group during its plenary session held in Geneva on 31 May and 1 June 1990 following a decision made at the third plenary session of IPCC in Washington DC, on 5 to 7 February 1990.) The Committee's terms of reference are given in Annex I to this Policymaker Summary.

1.1.4 There is a close link between issues addressed by the Working Groups of IPCC such as access to technology and financial resources and the participation of the developing countries in IPCC. The work of the Committee was carried out in parallel with work on such issues carried out within the subgroups, and the topics groups on implementation measures, of Working Group III. This parallel work was necessitated by the tight timetable and limited resources available to the Committee. The Special Committee stresses the importance of taking into account, to the extent feasible, the conclusions of this Policymaker Summary in the report of Working Group III. Further, the Committee will need to meet periodically to co-ordinate the integration of the concerns of the developing countries in the work of Working Group III and the implementation of its recommendations.

1.2 Joint partnership of the industrialized and developing countries

1.2.1 Global warming of current concern results from emissions of the so-called greenhouse gases into the atmosphere. While many of these gases occur in the natural atmosphere, recently observed increases in them come about because of activities that have contributed in a very big way to human survival and welfare such as industrialization, food production and general economic development.

1.2.2 The industrialized world today emits about 75% of the world total greenhouse gas emissions, and although the emissions are increasing in the developing countries, where 75% of the world population lives, they emit the balance. The source of the emissions can be any nation but any warming will not be confined to that nation alone; it will go beyond, encompassing the entire globe. Any significant climate change would affect every sector of individual and social activity. Thus a single nation or even a group of nations cannot hope to manage the issue adequately by itself. It would take the concerted action of all nations to achieve that end. That is, both the industrialized and the developing worlds have to join hands in the action, taking into account not only the past and present responsibility of the industrialized world in the accumulation of greenhouse gases, but also the present economic and financial capacities of the developing countries. This is imperative.

1.2.3 While the management of climate change has to be based on globally agreed-upon action, the deciding factors in arriving at such agreements will be dictated by national and regional considerations. The impact of the predicted warming will be uneven, ranging from beneficial to harmful in various sectors of the economy, and differing from nation to nation and from region to region. Thus, nations and groups of nations will need a sound knowledge base to embark on the agreement process. This need is especially dire in the case of the developing countries. Their access to scientific and other information, and resources will have to be attended to, if they are to share in, and contribute to, the solution. In the process, legitimate concerns on the part of the developing countries that, although their impact on global climate change is minimal, its impact on them could be grave, need to be taken account. Their differing stages of development, and hence their country-specific needs to adjust to climate change, will have to be taken into account also.

1.2.4 The developing world faces special problems. Greater investments for rapid economic development and better satisfaction of basic needs such as food, shelter and income assume paramount importance. At the same time the habitability of the planet cannot be compromised. The developing countries, thus, have to participate fully, willingly and knowingly in the planetary decision-making and the follow-up actions on climate change.

1.2.5 Full participation includes the development of national capacity to address the issues of concern such as the

appreciation of the scientific basis for climate change, the potential impacts of such change and evaluations of practical response strategies for national applications. It is intertwined with the general process of sustainable and steady development.

1.3 Structure of the Policymaker Summary

1.3.1 After introduction, the Policymaker Summary discusses factors inhibiting full participation by the developing countries (section 2), areas of possible action (section 3) and the Committee's conclusions and recommendations (section 4).

2. Full participation of the developing countries

2.1 Objectives

2.1.1 The Committee recognized that achieving full participation of the developing countries in the IPCC process is a necessary but difficult goal: it embraces a number of related objectives. These objectives are both quantitative and qualitative. With respect to quantitative objectives, the Committee acknowledged the need to:

(i) increase the number of developing countries taking part in IPCC meetings and actions arising therefrom; these include seminars, meetings of the Working Groups and their subgroups etc.;

(ii) expand the travel support so as to enable a number of experts from each developing country to attend meetings on climate change and related issues to provide for meaningful participation particularly when meetings consider different but related issues simultaneously;

(iii) expand the opportunities for developing countries to increase their knowledge of the science on climate change and policy-making (eg, energy policy), impacts, and response options appropriate to them, with respect to climate change;

(iv) expand the opportunities for developing countries to train and enhance the skills of experts in climate-related and climate-change-related research.

2.1.2 With respect to qualitative objectives, the Committee acknowledged the need to:

(i) provide for continuity of participation from developing countries in the IPCC process to further their involvement;

(ii) encourage dissemination within the developing countries of information and data on climate issues to increase awareness and knowledge;

(iii) encourage that climate issues are rationally considered in developing national policies with respect to science, economics and the environment to achieve sustainable development;

(iv) promote effective co-operation within developing countries among those responsible for the different aspects of climate issues to foster informed decision-making.

2.2 Factors inhibiting full participation

2.2.1 The factors identified by the Special Committee which inhibit the active participation of the developing countries in IPCC activities can be grouped into the following categories:

(i) insufficient information;

(ii) insufficient communication;

(iii) limited human resources;

(iv) institutional difficulties;

(v) limited financial resources.

2.2.2 The above factors have been elaborated at length in the paragraphs below. Without prejudice to their generality, the Committee also took note of the fact that most of the developing countries faced the dilemma of deciding allocation of priorities between environmental issues and economic development. While the global environment has assumed today greater significance for the industrialized countries, the priority for the alleviation of poverty continues to be the overriding concern of the developing countries; they rather conserve their financial and technical resources for tackling their immediate economic problems than make investments to avert a global problem which may manifest itself after two generations, particularly when their contribution to it is significantly less than that of the industrialized countries.

2.2.3 The Committee acknowledged that the above dilemma of priorities poses a serious obstacle to enhancing the participation by developing countries in the IPCC process. The Committee further acknowledged that, even as the process of effective economic development in the course of time would increase the understanding that developmental goals and environmental concerns need not be mutually exclusive, it was necessary to enable the developing countries to perceive the problem in its correct perspective by deepening their understanding of the science of global climate change, its potential physical and socio-economic impacts and response options.

2.2.4 The Committee noted that developing countries consider the lack of sufficient assurance so far on the

provision and requisite, adequate, new and additional funding particularly for the identification, transfer, adaptation and implementation of alternative safer technologies on a preferential, non-commercial and grant basis added substantially to the inhibition of the developing countries in taking active part in IPCC activities. It further noted that these countries consider that the formulation of guidelines for funding mechanisms for transfer, adaptation and implementation of clean technologies as against legal and economic measures would create healthier conditions for the participation of the developing countries.

2.3 Insufficient information

2.3.1 The Committee noted that many developing countries do not have sufficient information on the issue of potential climate change to appreciate the concern it evokes elsewhere in the world. Information is often insufficient with respect to the scientific basis for concern, on the potential physical and socio-economic impacts of climate change as well as on response options (see also para 2.2.3). This applies not only to scientific milieux but also to policymakers and public opinion.

2.3.2 Access to scientific data is limited in the developing countries. Many are unable to participate in regional monitoring programmes, where these exist, or to monitor weather and climate continuously within their national boundaries and in accordance with international requirements.

2.3.3 As stated above, information available in developing countries on the likely impacts of climate change within their national boundaries is limited. While Working Group I of IPCC has noted the inability of current scientific models to anticipate specific regional distributions of climate change, the problem in developing countries is more basic. Many do not have the ability, for example, to project how various increases in sea-level rise would affect them, and hence what steps might be necessary to adapt to it. Similarly, many developing countries do not have sufficient information to judge how best to achieve energy efficiency, or to gauge its costs, security and trade implications. Another area where there is lack of information is that of environmentally less harmful technologies and products. Gaps in information about proper technologies in moisture conservation, afforestation and soil protection were noted as glaring examples in this regard.

2.3.4 With adequate information, developing countries would be able to take more effective account of climate change considerations in formulating national policies. They would also then be in a better position to appreciate that the deliberations on climate change had far-reaching implications on their economic and developmental strategies, and to identify their specific needs to determine which may be met from existing resources and which may require additional resources.

2.4 Insufficient communication

2.4.1 The Committee noted that even if information on climate change and related activities were to be provided, there was a need to improve internal and external communication to ensure the flow of information to appropriate recipients including economists, scientists and policy-level officials in the developing countries. Internal communication is important for informed considerations of national policy issues while improved external communication facilitates the flow of information to and from the outside world.

2.4.2 The Committee also noted that within the developing countries there was need to strengthen and streamline mechanisms to co-ordinate, receive, store and disseminate relevant information either originating from within the country and/or flowing from outside. Lack of such mechanisms often resulted in insufficient appreciation of the need to participate in the international discussions on climate change.

2.4.3 In a similar manner, the Committee noted that existing international arrangements, to transmit information on climate change and related activities among the developing countries were not yet effective enough.

2.5 Limited human resources

2.5.1 The Committee noted that to receive, communicate and disseminate information on climate change and related activities, there was not sufficient informed manpower available within the developing countries. Full participation by developing countries has sometimes been hampered by the limited pool of expertise available in each country. Those few experts as are available shoulder heavy responsibilities and are extremely hard pressed to take time away from important national tasks.

2.5.2 Developing countries seek to alleviate the problem in some instances by having their embassy representatives take part in those IPCC activities that are scheduled in various capitals. Even this measure is difficult for smaller developing countries with sparse representation. Another approach, albeit less used at present, is to designate regional experts to represent a group of countries. There are drawbacks inherent in both approaches. Embassy officials may lack the background information in the issues to take effective part in meetings, particularly those calling for specific expertise in science, impacts, policy and legal analyses, problems of human settlements in coastal and low-lying areas, behavioural sciences, and cost and economic analyses. In addition, because IPCC meetings take place in many areas of the globe, it is difficult to provide for continuity of representation through the use of embassy officials. On the other hand, designating regional experts to represent a group of countries invariably requires a high degree of co-operation among such countries and a relatively long preparatory process, unless experts are designated to serve on a long-term basis.

2.6 Institutional difficulties

2.6.1 The Committee noted that in many developing countries the manpower engaged in co-ordinating receiving, transmitting, disseminating and effectively using information on climate change and related activities was not sufficiently supported by institutional infrastructure.

2.6.2 While this requirement for national infrastructure has been met successfully in some of the developing nations, such is not the general case. It is often not clear which ministry or agency is responsible or should have responsibility for a particular climate issue or decision. In addition, co-ordination mechanisms among ministries and agencies in many developing countries are not as well established or effective as climate issues may demand.

2.7 Limited financial resources

2.7.1 For the reasons stated elsewhere in the Policymaker Summary, the Committee did not consider in detail topics such as financial assistance, economic incentives/disincentives, formulation of legal instruments, and development of, and access to, environmentally-benign and energy-efficient technologies. These are being dealt with by Working Group III and are likely to form the substance of future negotiations among governments. However, the Committee expressed the view that actions to promote the full participation of the developing countries in climate change issues should not await the outcome of such negotiations. Some of them could be taken now.

2.7.2 Limited financial resources are intimately tied to a general lack of access to new and better technologies. In addition, survival needs have to be satisfied first. Means of meeting the incremental costs of ensuring a viable environment frequently cannot be found. Also, local, immediate environmental concerns generally receive political priority over impersonal, invisible, somewhat remote, global concerns.

2.7.3 While the root causes of the problem of lack of financial resources may lie in the past patterns of economic development, there are simpler but nonetheless indispensable needs such as travel funds, so that a nation can keep itself informed of activities elsewhere in climate change and related fields.

2.7.4 Developing countries require support for the attendance of their experts at IPCC meetings. Travel needs compete with other national priorities for funds. Without travel support, many developing countries simply would not be able to attend even a single meeting; for others, adequate and effective representation would not be possible. Here, as elsewhere, the issue is not so much an absolute lack of financial resources as the absolute necessity of establishing spending priorities amid a large and growing number of international environmental and other meetings and conferences. This is particularly problematic for the least developed countries as well as for smaller developing countries, particularly those in the Southern Hemisphere since the majority of these meetings are held in the Northern Hemisphere.

2.7.5 The Committee noted that the attendance of the developing countries in IPCC meetings has shown a steady improvement (see sub-section 2.8 below). Ironically, as the IPCC succeeds in increasing the participation of developing countries, the problem becomes more complex unless funding assistance for participation increases commensurately. To date, IPCC has not established specific criteria or priorities by which requests from developing countries for travel assistance should be considered.

2.7.6 In addition, while pledges to the IPCC Trust Fund for the travel support of invited experts from the developing countries have been generous and increasing, the process has been ad hoc and the remittances have not been timely to prevent periodic acute shortfalls.

2.8 Progress in IPCC

2.8.1 In spite of the factors discussed in the previous sections which inhibit full participation by the developing countries, it is clear that IPCC has accomplished much in its brief existence.

2.8.2 For example, the number of developing countries attending the first plenary of the Panel in November 1988 was 11; this number rose to 17 at the second plenary (June 1989) and to 33 at the third (February 1990). The number of developing countries at the third plenary surpassed that of the industrialized countries (27).

2.8.3 In addition, the Panel had initially allocated SFr222,510 for travel support for the developing countries in its 1989 budget estimate. The actual amount spent was approximately SF 383,904 (see Annex II for a listing of contributions). This amount paid for 85 trips by 80 experts to attend the meetings of the Panel, the Bureau, the Working Groups and their subgroups, and the Special Committee in 1989. The budget for 1990 for similar support is SFr794,000, which is one half of the IPCC 1990 budget. This has already been exceeded at the time of the writing of this Policymaker Summary and is in addition to that channelled through bilateral arrangements.

2.8.4 Moreover, several governments (from the industrialized and developing parts of the world) and regional intergovernmental organizations are holding information exchange and other seminars, for the developing countries, in 1990 and 1991 on the specific issue of climate change. These are designed to build awareness and assist the understanding of the complex interrelationship of the various aspects of the subject.

2.8.5 The IPCC process itself has served to increase awareness and knowledge of the industrialized and the

developing countries with respect to climate change issues. In this sense, while more remains to be done to increase the participation of developing countries, IPCC has succeeded partially in an essential function. The improving situation cannot yet be termed satisfactory by any means, as the full participation by the developing countries is a prerequisite for any successful action such as the adoption of a climate convention.

2.8.6 As a result of the combined efforts and initiative of a few governments, major financial institutions have undertaken to raise fresh funds to be allocated to the problems associated with climate change. Specifically, the World Bank has targeted climate change as one of the four issues of global importance eligible for additional funding at concessional rates.

3. Areas of action

3.0.1 The impacts of climate change will vary from region to region and nation to nation, as already stated elsewhere in the Policymaker Summary. Although response strategies for developing countries have to take into account the needs for adequate funding and safer technologies, country-specific and/or region-specific approaches will be necessary. For example, response measures that small island states require could be very different from those for large industrializing countries within the developing world. Nevertheless, the discussion in this section is relevant in general to all developing nations (and, indeed, to all nations) and the Special Committee will need to devote more attention to specific requirements in its future work.

3.0.2 Success in the implementation of many of the recommended actions (see section 4) depends not only on national initiatives but also on stronger regional or sub-regional co-operation. Co-operation between countries of the same region, between countries and regional or sub-regional institutions, and between institutions themselves will achieve cost savings and efficiency. This is particularly indispensable for the smaller countries, including island nations.

3.0.3 Advantages of regional co-operation are obvious for research activities but they are there also for many other sectors. For example, with regards to energy savings, countries could benefit from the know-how of regional "technical centres" which encourage research. Together they could develop technologies adapted to their particular situation by sharing their equipment and existing infrastructures. The creation or strengthening, for example, of regional "departments" of energy and environment would assist the mobilization of support and the co-ordination of research and approaches common to many countries.

3.0.4 Also, there are actions that will arise as a result of negotiations and agreements, and machinery will have to be put in place to implement these. But there are others that need to be taken now, that can be done through existing arrangements; most in this category should be planned and carried out for several years.

3.0.5 The Committee compiled a list of areas of possible action. This list is not to be viewed as all-inclusive. It is a beginning and is expected to be reviewed periodically and modified and added to as needed. The recommendations of the Committee on specific action items are given in section 4.

3.1 Development of information

3.1.1 While insufficient information is not unique to the developing countries, rectification of the associated problems is likely to take longer in their case.

3.1.2 The kind of information that is insufficient includes:

- reliable scientific data, predictions and interpretation;
- techniques of designing numerical (computer) models;
- analytical tools for performing impact analyses;
- cost and other implications of addressing climate change;
- state-of-the-art methods of energy production;
- availability and the nature of possible policy options.

3.1.3 Such insufficiency can be partially redressed, inter alia, through:

- information exchange seminars;
- skill enhancement seminars;
- development of information centres.

3.1.4 Information exchange seminars should be undertaken on global, regional and national levels. A few governments and international organizations have already planned some. The seminars should be periodic or cyclical to maximize retention and wider dissemination of information. They should be aimed at senior officials, the media and the public. Opportunities such as World Meteorological Day, World Health Day, Earth Day and World Environment Day could be taken advantage of. The seminars could include novel initiatives such as conferences of planners. In this respect, for example, a seminar organized by UNEP in Paris has as its objective raising the awareness of policy and opinion makers on the issue of climate change and of organizing, at the same time, training activities on the actions to be taken.

3.1.5 Skill enhancement seminars are similar to training sessions. These are best achieved in a regional setting. A number of bilateral, multilateral and international

organizations have such programmes. These may require co-ordination to increase their effectiveness.

3.1.6 As stressed in the relevant part of the report of Working Group III, an important component of this effort is the introduction at all stages of education and, on a continuing basis, curricula to inform future citizens and decision-makers. Wider public information programmes are also important to strengthen the mandate of governments to act.

3.2 Development of communication

3.2.1 Networking of scientific and other experts on climate change and related matters at national, regional and international levels is a valuable mechanism for rapid flow of information. National, regional and international conferences planned and held in the developing countries would provide good opportunities for such flow. Existing plans of international organizations such as UNEP and WMO could play a critical catalytic role in this regard.

3.2.2 One of the difficulties for the timely transmittal of documents, letters and requests for information and action between, for example, the IPCC Secretariat and governments is that only a few countries have designated focal/contact points for the purpose. A related problem is that often the focal/contact point is not instructed as to where, for example, a given document should be sent for review etc. Governments are urged to improve appropriate national communication mechanisms to ensure timely dissemination of documents to relevant officials and authorities. The establishment of national climate committees composed of all relevant expertise would be one way to approach this issue (see also section 2 and sub-section 3.4.)

3.2.3 In the past, national embassies have been used by governments to promote this communication. This practice could be helpful in selected cases. Embassy staff, where available, can also be designated to represent governments at IPCC meetings. This can especially be helpful when designated experts, for one reason or another, are unable to attend.

3.3 Development of human resources

3.3.1 Development of informed manpower is crucial if a developing country is to contribute fully and effectively to managing climate change. Any programme in this area should address simultaneously the related issues of education, training and technical assistance (i.e., ready access to analytical tools, techniques and methodologies, etc).

3.3.2 Programmes for the training of experts in the specific field which is relatively new, namely, climate change, are needed. Specialization must be achieved in such areas as the construction and use of numerical models (eg, climate prediction models, biospheric models, econometric models), observations and surveys (eg, atmospheric observations for climate and related data, socio-economic surveys), laboratory and engineering techniques, human settlements in coastal and other low-lying regions, and data analyses and interpretation for policy applications. Programmes specifically tailored to regional questions would be helpful in addressing common concerns such as policy considerations.

3.3.3 Exchange of visits of experts on climate change and related issues between the industrialized and the developing worlds should be instituted on a continuing, long-term basis. Academic staff from the industrialized countries could be encouraged to spend their sabbaticals in the developing countries with fellowships dedicated for the purpose. Exchange between academic institutions could be encouraged. Account should be taken of the particular difficulties that will be encountered in those developing countries with poorly developed educational infrastructures where the capacity to respond to new educational demands is limited.

3.3.4 Involvement of local expertise should be sought and encouraged when studies in given geographical areas are undertaken, and advantage taken of opportunities for training which arise as a result.

3.3.5 Programmes to provide ready access to state-of-the-art technology and investigative and implementation tools and methodologies (eg, computers of adequate power that could be shared on a regional basis, mass communication methods) should be instituted.

3.3.6 In this context, the Committee is of the view that assistance be provided at the regional level by the UNDP and specialized agencies such as WMO and UNEP. Their assistance should cover, inter alia, the development of expertise in such areas as climate modeling, formulation of scenarios for decision makers, human settlements programmes, and for transfer of adaptive and updated technology. Existing regional centres of relevance in this regard should also be strengthened.

3.4 Functioning of institutions

3.4.1 Difficulties in national co-ordination are evident to most of the developing countries. In the case of IPCC activities, for example, only a few countries have designated national focal points (see also sub-section 3.2). This not only hampers the flow of information and the continuing participation of the developing countries, but also the follow-up actions needed to be taken at the national level.

3.4.2 Efforts to promote national co-ordination of activities on all aspects of climate change should be redoubled. This is imperative for information flow, planning and implementation of data collection and analyses programmes, studies on cost, international treaty and trade implications, and policy options, and to establish and maintain national review and implementation machineries.

Achieving co-operation among the many national agencies engaged in climate change in one way or another is a long process requiring many steps. Any delay in initiating this effort will make it that much more difficult to respond to climate change and maintain sustainable development. Information on effective institutional arrangements and their establishment should be exchanged between countries.

3.4.3 National centres would provide natural foci for timely and effective flow of internal and external information. This is important in view of the possibility of concerted regional and international actions in addition to purely national ones. The centres would facilitate communication among experts in different discipline areas; the necessity for such communication cannot be overemphasized in the context of climate change, which is inherently multi-disciplinary.

3.4.4 There are many international organizations that are involved in climate change studies and issues such as ICSU, UNEP, WMO, WHO, FAO and the World Bank. While their work is necessarily mission specific as mandated by their respective governing bodies, the efforts are quite complementary to each other and can profit from more cross referencing. In this regard, it would be very helpful if the same briefs are provided on the climate change issue to all delegations from a nation to the different meetings of the various international organizations. The respective governing bodies would then be kept fully in the picture and can make decisions in a wider context. This would avoid unintended duplication of work and at the same time help identify questions that are likely to be missed because of novel inter-disciplinary and multi-disciplinary characteristics. All this can, in turn, only strengthen national co-ordination. The offices of the UNDP resident representatives and resident co-ordinators could assist recipient governments in their efforts of co-ordination at country level in this regard.

3.5 Development of financial resources

3.5.1 Plans and action strategies of developing countries for their economic development should be respected. Developmental assistance should in general be enlarged and accelerated.

3.5.2 The question of access to new technologies and methodologies for undertaking studies as well as putting into effect implementation measures is intertwined with that of general lack of financial resources. Bilateral and multilateral technical assistance is imperative for initiating and/or modernizing existing installations and practices to address climate change. (The problem of technology development and its transfer to the developing countries, and financial assistance, is dealt with by Working Group III, as already stated.)

3.5.3 The Committee, however, wants to stress that developing countries would require financial assistance to meet the incremental costs of incorporating climate change considerations in their current developmental planning. Such assistance should be extended. Wherever it is feasible for the developing countries to incorporate climate change considerations in their action strategies without incurring additional costs, such incorporation should be made. The modalities (the amount and method of funding, for example) form part of the consideration of Working Group III. The Committee noted the conclusions of the Working Group III financial measures paper on a future work programme, including the need to advance the concept of a new mechanism, in the context of a future climate convention or its protocols. It considered that this issue should be given a high priority.

3.5.4 Recognizing the need to incorporate measures for adjusting to climate change with developmental planning, all developing countries which are in a position to integrate activities such as climate monitoring, impact analyses and studies on adaptation options should be encouraged to promote them and carry out research with financial assistance that primarily aims at securing the following:

- data acquisition and exchange;
- data archival, retrieval and analyses;
- correlative studies (eg, precipitation & vegetation, energy production & climate factors, health indicators & desertification, policy responses & cost implications);
- education and training including provision of scholarships and fellowships;
- specific technological development.

3.5.5 Continuity of travel assistance to experts from developing countries to attend IPCC meetings should be ensured. Such assistance should be extended for attendance at follow-up activities and other climate and climate change meetings (eg, the Second World Climate Conference, Geneva, 29 October—7 November 1990). As has already been stated, full participation implies more than physical presence at meetings.

4. Concluding remarks and recommendations

4.1 Overview and need for action

4.1.1 The Special Committee on the Participation of Developing Countries was set up by IPCC to seek ways and means of promoting, as quickly as possible, effective participation by the developing countries in its activities. There is a clear need to continue the efforts of the Committee.

4.1.2 The Committee hopes that the views expressed here and its recommendations would be helpful in ongoing

international efforts to draft and adopt a convention on climate change and protocols.

4.1.3 The Committee takes the opportunity to express its gratitude to the countries that have contributed generously to the IPCC Trust Fund so that support can be extended to experts from the developing countries to participate in the meetings of IPCC. It urges that contributions for such purpose continue and be increased in the future.

4.1.4 It is necessary to prepare specific programmes of action for the furtherance of the participation by the developing countries in the IPCC process and in the activities based on that process. Such programmes should include, as extensively as possible, action items, time schedules, identification of requisite resources and institutions, and implementation and review procedures. The Committee will give priority to the promotion of such programmes.

4.1.5 It should be noted that action on the Committee's recommendations should be initiated and developed as quickly as possible. Action on some has already begun and needs to be sustained. It is likely that IPCC will continue its work after its fourth plenary when it will complete its First Assessment Report. Thus the recommended actions should continue through the life of IPCC. Some of the actions are of such a nature that international organizations (eg, WMO, UNDP, UNEP, ICSU, WHO) can implement them.

4.1.6 The Committee emphasizes that having regard to the global nature of climate change and the need for participation by all States if the objectives of the recommended activities are to be achieved, the total programme will stand or fall depending on the availability of adequate funding to those countries in need.

4.2 Specific recommendations

4.2.1 The Committee recognizes that there are several issues justifying actions in their own right and which will contribute to dealing with the longer term climate change issues. It is thus evident that no country should rely solely on the international processes leading to protection of the climate to deal with all the issues which have been identified.

4.2.2 Uninterrupted travel assistance to the developing countries for attendance at the meetings of IPCC should be ensured. The Committee wishes to call the attention of the Panel to the importance of continuing this effort and of the donor nations continuing and increasing contributions to the effort, with no cessation after the fourth plenary of IPCC.

4.2.3 Serious consideration should be given to supporting more than one expert from each participating developing country to those climate change-related meetings that deal with several aspects of the problem. The developing countries on their part:

- should compile a list of national experts and make it available for travel assistance;
- should agree to contribute to the effort through travel subsidies when their national air carriers fly to meeting places;
- should agree to designate jointly an expert or a single group of experts to attend meetings where their interests can be commonly represented.

4.2.4 Governments and organizations from the industrialized nations are encouraged to continue and increase their efforts in organizing seminars. Developing countries could organize, under the sponsorship of international organizations or otherwise, regional seminars and workshops in order to exchange scientific and technical information. For this purpose, necessary programmes and lists of experts should be developed. As part of the continuing process of information exchange, the Committee recommends that IPCC circulate this Policymaker Summary to all concerned including those attending the Second World Climate Conference. The developing countries on their part should designate focal points, as soon as possible, for transmittal of reports, documentation, data and information on seminars. Such focal points should be briefed on forwarding the material to appropriate recipients within the nation for response, review etc.

4.2.5 Developing countries should consider the establishment of mechanisms for national co-ordination of all their activities related to climate change. The mechanisms would aid such areas as information dissemination, development and implementation of plans for research and monitoring, and formulation of policy options. The industrialized countries should consider assisting the developing countries in these areas with easy access to needed technologies.

4.2.6 The Committee recommends that acquisition, analyses and interpretation of information on climatic and related data would enable developing countries to take more effective account of climate change considerations in formulating national policies. Such actions are necessary also at regional levels to undertake and refine impact studies. The current unevenness in the acquisition and use of such data which is evident between the hemispheres should be eliminated. The Committee further recommends that the developing countries take immediate action to identify their specific needs to determine the financial implications of such action. It would be necessary to mobilize appropriate funding in order to mount a sustained programme and create regional centres to organize information networks on climate change.

4.2.7 In many developing countries the meteorological/ hydrological service is the main and often the only institution collecting and recording data with relevance to climate. If associated weather patterns are modified, as some

predict they would be as a result of climate change, then the capabilities of such services need to be reinforced to enhance their contributions to sustainable development.

4.2.8 The Committee recommends that considerations of climate change should be integrated in development policies. These policies could favour projects which have as their objective the prevention of and adjustment to adverse effects of climate change, promotion of the awareness of, and education on, the problem and the development and deployment of appropriate techniques and methodologies. National environmental studies should also take into account predicted climate change in order to determine sustainable development strategies. To reach these objectives, the developing countries and many industrialized countries consider it essential that additional funding be available to enable developing countries to meet the incremental costs resulting from their efforts to combat climate change.

4.2.9 The Committee further recommends that its findings be duly taken into account in all relevant areas of the work of IPCC. Programmes of action should be developed and implemented (and the concepts which would lead to such programmes of action developed where needed) without delay, with a view to ensure, provided the necessary means are made available, the full participation of developing countries in the future work and activities on climate change. UNEP and WMO should take the lead in this regard and initiate the necessary consultations. Other multilateral or bilateral organizations should also be contacted for elaborating and implementing these programmes of action, such as:

(i) In the field of research and monitoring:

- the UN and its Specialized Agencies
- regional intergovernmental organizations such as the European Community
- non-governmental organizations such as the International Council of Scientific Unions.

(ii) On seminars and workshops in such areas as public information, negotiations and legal aspects:

- non-governmental organizations in addition to the UN and its Specialized Agencies and regional intergovernmental organizations.

(iii) On education and training and technical assistance:

- UN and its Specialized Agencies

(iv) On financing or funding:

- multilateral financing institutions such as the World Bank, the Regional Development Banks, the UNDP etc.

4.2.10 The Committee also recommends that serious consideration be given by IPCC to the provision of simultaneous interpretation and documentation before, during and after a session in the customary UN languages for the meetings of the Special Committee, given the complex nature of the subject matter covered and the particular difficulties encountered by the developing countries.

4.2.11 The Special Committee should be mandated by IPCC to monitor and review the preparation and the implementation of the above mentioned and other relevant programmes of action.

4.2.12 To provide a basis for future programmes of action, the Committee requested the Chairman, within the financial resources available, to arrange for the extraction of the recommendations and action options arrived at by the Working Groups of IPCC; this document should be circulated, after review by the Special Committee, to donor and other countries, international organizations and regional groups.

ANNEX 1

TERMS OF REFERENCE OF THE IPCC SPECIAL COMMITTEE ON THE PARTICIPATION OF DEVELOPING COUNTRIES

1. The Committee will recommend to IPCC and its Bureau, specific measures to be undertaken for promoting the full participation of the developing countries in all IPCC activities.

2. It will include in such recommendation institutional arrangement(s) and implementation schedule(s) if and as needed.

3. It will develop action plans for the implementation of its recommendations.

4. It will identify the resource requirements and the means of meeting them to accomplish the task outlined in (1) above.

5. It will periodically review the progress of the implementation of its recommendations and make modifications thereof, as appropriate.

6. It will work closely with IPCC Working Groups.

7. It will continue its work until its dissolution by IPCC.

ANNEX 2

Table 1: 1989 Contributions to the joint WMO/UNEP IPCC Trust Fund

CONTRIBUTOR	AMOUNT SFR	CURRENCY RECEIVED
Australia	24 963.05	$ 15 175.00
Canada	14 519.50	C$ 11 000.00
China	16 400.00	$ 10 000.00
Denmark	7 550.00	$ 5 000.00
Finland	7 950.00	$ 5 000.00
France	25 303.00	FF 100 000.00
Federal Republic of Germany	43 750.00	Sfr 43 750.00
Japan	75 500.00	$ 50 000.00
Netherlands	40 250.00	$ 25 000.00
Norway	25 050.00	$ 15 000.00
Saudi Arabia	16 500.00	$ 10 000.00
Switzerland	55 000.00	SFr 55 000.00
UK	90 578.85	£ 35 000.00
USA	199 500.00	$ 120 000.00
UNEP	125 000.00	SFr 125 000.00
WMO	125 000.00	SFr 125 000.00
TOTAL	**SFr 892 814.40**	

a. The IPCC budget is in Swiss francs (SFr) since this is the currency of the WMO budget. The joint WMO/UNEP IPCC Trust Fund is administered by the Secretary-General of WMO in accordance with WMO Financial Regulations.

b. The amount contributed exclusively for travel support to developing countries in 1989 was SFr 182,000. Many contributors gave flexibility to the IPCC Secretariat on expenditures, while all affirmed their desire that at least part of their contributions should be spent on travel support to developing countries to attend IPCC meetings.

c. One-half of the 1989 expenditures in the IPCC Trust Fund was devoted to the travel support of the developing countries.

d. The 1989 account of the IPCC Trust Fund showed a surplus which was carried over to 1990. Nevertheless, the Fund was experiencing acute and continuing cash shortages throughout 1989.

e. The Government of Norway has given Nkr 700,000 to the IPCC Secretariat for organizing an information exchange seminar for the developing countries on climate change issues. This has not been shown in the table, since this contribution is through a special Memorandum of Understanding and not to the Trust Fund.

In this connection, it may be noted that several countries are planning regional seminars on the same and related topics. These countries are:

- France: Seminar on greenhouse warming in late 1990/early 1991 jointly with the Energy and Industry Office of UNEP;
- Japan: Seminar on the environment and fossil fuel consumption in the Pacific Region, mid-December 1990; information exchange seminar for the developing countries in Asia at the end of January 1991;
- Spain: Seminar for the Spanish-speaking developing countries in the third quarter of 1990;
- Australia: possible joint seminar with the Economic and Social Commission for Asia and the Pacific (ESCAP).

Table 2 Receipts, IPCC Trust Fund, for 1990	
MEMBER	**AMOUNT EQ.SFR**
Australia	83 490 (4)
Canada	30 506 (7)
Denmark	153 000 (3)
Finland	15 743
France	48 573 (5)
Federal Republic of Germany	70 494 (2)
Italy	83 500
Japan	75 500 paid in 1989
Netherlands	151 384
Norway	33 985 (6)
Sweden	43 075 (8)
Switzerland	30 000
UK	86 224 (10)
USA	298 970 (1)
UNEP	329 000
WMO	125 000
Rockefeller Foundation	68 000
TOTAL	**1 726 444**
USSR	$85 000 (9)

(1) Of the US contribution, $ 100,000 is earmarked for the travel support to the developing countries.

(2) The Federal Republic of Germany contribution is DM 160,000 for both IPCC and the Second World Climate Conference. The contribution to IPCC is one-half of this amount.

(3) The Denmark contribution is specifically for travel and other assistance to the low income developing countries for 1989 and 1990 (see the following page for a listing).

(4) Of the Australian contribution, AUD 20,000 was earmarked for the travel support of South Pacific delegates to the meeting of the Coastal Zone Management Subgroup of Working Group III (Perth, 19-23 February 1990).

(5) In addition, France has contributed Ffr 200,000 to augment the staff of the IPCC Secretariat; the Secretary-General of WMO has assigned to the IPCC Secretariat a full-time Scientific Officer seconded to WMO by the Government of France.

(6) In addition, Norway has given Nkr 700,000 for the purpose of holding an IPCC Information Exchange Seminar for the developing countries on climate change issues through a special Memorandum of Understanding.

(7) The Canadian contribution is part of Can$ 100,000; the full Canadian contribution includes translation of the three IPCC Working Group reports into French.

(8) This is in addition to the support provided by Sweden to the 4th Plenary of IPCC.

(9) The equivalent in roubles was provided by the USSR to support travel of experts from developing countries to meetings of Working Group II.

(10) In addition, UK may give £ 100,000 for a series of seminars for policymakers in developing countries, through a special Memorandum of Understanding, in a manner similar to the contribution of Norway reflected in (6) above.

WORLD METEOROLOGICAL ORGANIZATION

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNITED NATIONS ENVIRONMENT PROGRAMME

IPCC

CHAIR : SWEDEN **VICE CHAIR :** SAUDI ARABIA
RAPPORTEUR : NIGERIA

IPCC BUREAU
(16 MEMBERS)

CO-ORDINATING BODY DURING IPCC INTERSESSIONALS

WORKING GROUP I

SCIENCE

CHAIR: UK

VICE CHAIRS:
- BRAZIL
- SENEGAL

WORKING GROUP II

IMPACTS

CHAIR: USSR

VICE CHAIRS:
- AUSTRALIA
- JAPAN

WORKING GROUP III

RESPONSE STRATEGIES

CHAIR: USA

VICE CHAIRS:
- CANADA
- CHINA
- MALTA
- NETHERLANDS
- ZIMBABWE

SPECIAL COMMITTEE ON THE PARTICIPATION OF DEVELOPING COUNTRIES

CHAIR: FRANCE

WMO/UNEP JOINT IPCC SECRETARIAT
(LOCATED AT WMO, GENEVA)

1988-1990

WORLD METEOROLOGICAL ORGANIZATION

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNITED NATIONS ENVIRONMENT PROGRAMME

IPCC

CHAIR : SWEDEN **VICE CHAIR :** SAUDI ARABIA

RAPPORTEUR : NIGERIA

IPCC BUREAU

(20 MEMBERS)

CO-ORDINATING BODY DURING IPCC INTERSESSIONALS

WORKING GROUP I

SCIENCE

CHAIR: UK

VICE CHAIRS:

- BRAZIL
- GERMANY
- INDIA
- SENEGAL

WORKING GROUP II

IMPACTS

CHAIR: USSR

VICE CHAIRS:

- ARGENTINA
- AUSTRALIA
- JAPAN
- KENYA

WORKING GROUP III

RESPONSE OPTIONS

CHAIR: USA

VICE CHAIRS:

- CANADA
- CHINA
- MALTA
- NETHERLANDS
- PERU
- ZIMBABWE

WMO/UNEP JOINT IPCC SECRETARIAT

(LOCATED AT WMO, GENEVA)

NOTE: The Special Committee on the Participation of Developing Countries has not met since the completion of the IPCC First Assessment Report (1990)

CH_4 AND N_2O EMISSIONS FROM LIVESTOCK MANURE

ACKNOWLEDGEMENTS

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ABSTRACT

Livestock are produced throughout the world and are a significant contributor to global methane (CH_4) emissions. Methane, a greenhouse gas, is produced from the decomposition of livestock manure under anaerobic conditions. These conditions often occur when large numbers of animals are managed in a confined area (e.g., dairy farms, beef feedlots, and swine and poultry farms) where manure is typically stored in large piles or disposed of in lagoons. Nitrous oxide, also a greenhouse gas, is produced during the nitrification-denitrification of nitrogen contained in livestock waste.

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*) provide a general guide to estimating methane emissions from livestock manure. Two approaches may be used to estimate emissions: the Tier 1 approach relies on default emission factors drawn from previous studies, while the more complex Tier 2 approach requires country-specific information on livestock manure characteristics and manure management practices. The Tier 2 approach is recommended when the data used to develop the default values does not correspond well with the country's livestock and manure management conditions or when a country has large dairy and swine populations.

To prepare methane estimates, livestock population data characterized by subgroup are required. For Tier 1 estimates, necessary population data should be readily obtainable within the country or from the Food and Agricultural Organization (FAO). The Tier 2 estimates require additional data on manure characteristics and manure management practices, for which country-specific data should be used. These data should be obtained through data collection activities. If necessary, IPCC default values can be used for some of the factors in the Tier 2 calculation.

Nitrous oxide estimates also require livestock population and manure management practice data. The value and source of these data should correspond with that used for estimating methane emissions.

Reporting of emission estimates for both methane and nitrous oxide is clearly described in the *IPCC Guidelines.* With few exceptions, confidentiality is not expected to pose a challenge.

Ensuring the quality of the inventory will be an important activity, particularly where Tier 2 methods are used. The most important aspect of QA/QC (quality assurance/quality control) is thorough and transparent documentation of the emissions calculation steps, including all activity data and emission factor values.

1 INTRODUCTION

1.1 Nature, magnitude, and distribution of source

1.1.1 Overview

Methane Generation

The principal factors affecting methane emission from livestock manure are the amount of manure that is produced and the portion of the manure that decomposes anaerobically. The total amount of manure produced can be estimated using an average amount of manure produced per animal and the number of animals. The type of manure management system used and the climate (primarily temperature) are the primary factors that determine the extent of anaerobic decomposition that takes place.

Some livestock producers reduce the amount of methane that escapes into the atmosphere by constructing lids or caps for lagoons or tanks where manure is kept. This recovered methane is often flared or used as a fuel in a boiler, heater, or an engine-generator.

Nitrous Oxide Generation

Production of N_2O during storage and treatment of animal wastes can occur via combined nitrification-denitrification of nitrogen contained in the wastes. The amount of N_2O released depends on the system and duration of waste management. Because N_2O production requires an initial aerobic reaction and then an anaerobic process, it is theorized that dry, aerobic management systems may provide an environment more conducive for N_2O production.

1.1.2 Process description

Methane

Livestock manure is primarily composed of organic material and water. Under anaerobic conditions, the organic material is decomposed by anaerobic and facultative bacteria. The end products of anaerobic decomposition are methane, carbon dioxide, and stabilized organic material. The methane production potential of manure depends on the specific composition of the manure, which in turn depends on the composition and digestibility of the animal diet.

The amount of methane produced during decomposition is influenced by the climate and the manner in which the manure is managed. The management system determines key factors that affect methane production, including contact with oxygen, water content, pH levels, and nutrient availability. Climate factors include temperature and rainfall. Optimal conditions for methane production include an anaerobic, water-based environment, a high level of nutrients for bacterial growth, a neutral pH (close to 7.0), and warm temperatures.

The key factors affecting methane production from livestock manure are the quantity of manure produced, manure characteristics, the manure management system, and climate.

Quantity of Manure Production

Manure production varies by animal type and is proportional to the animal's weight and feed intake.

Manure Characteristics

The portion of manure that can generate methane is the volatile solids portion (VS)[1]. The VS portion depends on livestock type and diet, which also affect the quantity of methane that can be produced per kilogram of volatile solids (VS) in the manure.

Manure Management System

Methane production depends on the type of manure management system, which can be broadly divided into "liquid" and "dry" systems. Dry systems include solid storage, dry feedlots, deep pit stacks, and daily spreading of the manure. In addition, unmanaged manure from animals grazing on pasture falls into this category. Liquid

[1] Volatile solids (VS) are the organic fraction of total solids in manure that will oxidize and be driven off as gas at a temperature of 600°C.

management systems often use water to facilitate manure handling. These systems include tanks and lagoons which store manure until it is applied to cropland. Liquid systems create the ideal anaerobic environment for methane production. Detailed descriptions of these systems are provided in Table 10 in Annex 2.

Climate

Manure decomposes more rapidly when the climate encourages bacterial growth. For liquid manure systems, warm temperatures increase methane generation. For solid systems, rainfall can affect methane production, with wet climates having higher emissions than arid climates. In either case, emissions from solid systems tend to be very low.

Nitrous Oxide

Nitrous oxide is produced from the combined nitrification-denitrification process that occurs on the nitrogen in manure. The majority of nitrogen in manure is in ammonia (NH_3) form. Nitrification occurs aerobically and converts this ammonia into nitrate, while denitrification occurs anaerobically, and converts the nitrate to N_2O. Temperature, pH, biochemical oxygen demand (BOD), and nitrogen concentration affect N_2O generation. BOD is the amount of dissolved oxygen used by aerobic microorganisms to completely consume the available organic matter.

Increasing aeration initiates the nitrification-denitrification reactions, and hence makes release of N_2O possible. Therefore, as fresh dung and slurry is highly anoxic and well-buffered with near neutral pH, N_2O production is expected to increase with increasing aeration. However, the denitrification process that produces N_2O requires an anaerobic environment. Currently, there is not enough quantitative data to derive a relationship between the degree of aeration and N_2O emissions. This makes N_2O emissions estimates from this source highly uncertain.

2 METHODOLOGICAL ISSUES

2.1 Selection of good practice methods

The *IPCC Guidelines* provides a general approach to estimate methane emissions from livestock. The three main steps used to estimate methane emissions from livestock manure are as follows: a) collect activity data for livestock population groups and subgroups; b) estimate emissions factors for each subgroup or use default emission factors; and c) multiply the emission factor by the population to obtain total methane emission estimate for the population. The total emissions estimates should be reported in gigagrams (Gg). Because the emission factors are reported in kilograms per head per year, the total emissions in Gg is estimated as follows:

$$\text{Emission Factor (kg/head/yr)} \bullet \text{Population (head)} / (10^6 \text{ kg/Gg}) = \text{Emissions Gg/yr.}$$

To execute this process in the most efficient manner, the *IPCC Guidelines* recommends two approaches to estimate methane emissions from livestock manure.

The **Tier 1** approach is simplified so that only readily available animal population data are needed to estimate emissions. Default emission factors are presented for each of the recommended population subgroups.

The **Tier2** approach provides a more detailed method for estimating methane emissions from manure management systems. This approach is recommended for countries with large livestock populations managed under confined conditions because the Tier 1 method will not accurately account for the higher level of emissions that are generally produced in confined facilities. This method requires detailed information on animal characteristics and the manner in which manure is managed. Using this additional information, emission factors specific to the conditions of the country are estimated and the default emission factors from Tier 1 are not used.

Countries are encouraged to carry out emissions inventory calculations at a finer level of detail beyond Tier 2 if possible. This can include conducting regional analyses of emissions to account for differences in livestock and manure characteristics, climate, and manure management practices across specified regions.

For N_2O, the *IPCC Guidelines* recommends an approach similar to the Tier 2 methane approach. Information on how manure is managed is used to identify default emission factors. These are used with nitrogen excretion estimates for each livestock group based on animal population data to estimate N_2O emissions.

N_2O emissions from all waste management systems are reported under this emissions source category with three exceptions:

- Manure that is applied to agricultural soils (e.g., daily spread);
- Manure deposited by grazing animals on fields (pasture range and paddock), and

- Manure used for fuel.

N_2O emissions from manure that is managed in these systems are instead accounted for in the methodology for estimating direct emissions from agricultural soils, direct soil emissions of N_2O from animal production, and manure used as fuel, respectively. The class "used for fuel" is not included here as a source of N_2O because it is considered an energy-related emission. Currently, this class incorrectly includes manure managed in anaerobic digesters.

2.2 Emissions factors

Methane

Emission factors are estimates of methane produced in kilograms per animal. Emission factors help to standardize emissions across many different livestock groups so that relatively correct total emission estimates can be made.

Tier 1 In this step, emission factors that are most appropriate for the country's livestock characteristics are selected. The *IPCC Guidelines* include default emission factors, which have been drawn from previous studies and are organized by region (Tables 4.5 and 4.6 from the *IPCC Guidelines* are included in Annex 1).

The Tier 1 emission factors incorporate assumptions about manure composition, climate, and manure system usage for developed and developing countries, as described in the Tier 2 discussion below.

The climate data collected as part of the activity data is used to select the appropriate emission factors. If a country manages livestock in more than one climate zone, a weighted average emission factor for each animal type should be computed by multiplying the percentages of the animal populations in each climate region by the emission factor for each climate region.

Weighted Emission Factor = Percentage of Animal Population in Climate • Climate Emission Factor

Tier 2 The Tier 2 emission factors are calculated based on country-specific data on manure composition, manure methane producing capacity, climate, and waste system usage. The major components of the emission factor calculation are as follows:

- *Volatile Solids (VS)* is the portion of the manure that produces methane. Often, data on average daily VS excretion are not available. Therefore, the VS values may need to be estimated from feed intake levels and characteristics. Feed intake data for cattle should be determined by selecting a representative animal from each animal type. The IPCC's suggested methodology for estimating VS using feed data is shown in Annex 2, which reprints Equation 15 from the *IPCC Guidelines.*
- *Methane Producing Potential (B_O)* is the maximum amount of methane that can be produced from a given quantity of manure. The methane producing potential varies by animal type and diet. The *IPCC Guidelines* provide default values for each major global region. The values determined for US livestock are used for all of the developed country regions, and a slightly modified value is used for some categories in the developing country regions. Using country-specific B_O factors based on recent measurement data or research should improve the reliability of the resulting emissions factor.
- *Methane Conversion Factor (MCF)* defines the portion of the methane producing potential (B_O) that is achieved. The MCF varies with the manner in which the manure is managed and the climate, and can theoretically range from 0 to 100 percent. Manure managed as a liquid under warm conditions has a high MCF of 65 to 90 percent. Manure managed as dry material in cold climates has a low MCF at 1 percent. Default MCFs by manure system have been developed from previous studies; the IPCC's recommended MCF's are shown in Annex 2, in Table 11, which was taken from the *IPCC Guidelines.* Incorporating additional research on methane production under various management scenarios may improve the accuracy of these factors.
- *Fraction of Manure in Management System (MS%)* describes the portion of each livestock group's manure that is handled by a specific manure management technique. This factor is collected as activity data, discussed in Section 2.3.

These four variables are used in the equation to calculate emission factors as follows:

EQUATION 1

$$EF_i = VS_i \bullet 365 \text{ days/yr} \bullet B_{oi} \bullet 0.67 \text{ kg/m}^3 \bullet \sum_{jk} MCF_{jk} \bullet MS\%_{ijk}$$

Where:

EF_i: annual emission factor (kg) for animal type i (e.g., dairy cows);

VS_i: daily VS excreted (kg) for animal type i;

B_{oi}: maximum methane producing capacity (m^3/kg of VS) for manure produced by animal type i;

MCF_{jk}: methane conversion factors for each manure management system j by climate region k; and

$MS\%_{ijk}$: fraction of animal type i's manure handled using manure system j in climate region k.

Nitrous Oxide

Nitrous oxide emission factors are estimates of kilogram of nitrous oxide nitrogen produced per kilogram of nitrogen excreted. These factors vary by waste management system, as shown in Table 1

TABLE 1

TENTATIVE DEFAULT VALUES FOR N_2O EMISSION FACTORS FROM ANIMAL WASTE PER ANIMAL WASTE MANAGEMENT SYSTEM (KG N_2O - N/KG NITROGEN EXCRETED)

Animal Waste Management System	Emission Factor EF
Anaerobic lagoons	0.001 (<0.002)
Liquid systems	0.001 (<0.001)
Daily spread[a]	0.0 (no range)
Solid storage and drylot[a]	0.02 (0.005-0.03)
Pasture range and paddock (grazing)[b]	0.02 (0.005-0.03)
Used as fuel[c]	Not Applicable
Other systems[b]	0.005

[a] Considered to be a part of direct soil emissions from agricultural fields after spreading.

[b] Considered to be a part of direct soil emissions from animal production.

[c] Considered to be a part of emissions from energy.

Source: IPCC, 1996.

2.3 Activity data

Activity data include data on livestock population, and manure management system usage. The Tier 1 methodology for methane emissions requires data on livestock population by livestock group. Both the Tier 2 methodology for methane and the nitrous oxide methodology require livestock population data and data on manure system usage.

Methane

Tier 1: The *IPCC Guidelines* recommend collecting the average annual population of livestock listed in Table 2. It is recommended that countries collect their own population data. The number of animals recorded depends on the time at which the census is taken. For example, a census taken before most calves are born yields a lower number of animals than a census taken after most calves are born. Data should represent an average estimate for the entire year. If population data cannot be collected, it can be obtained from an outside source such as the Food and Agriculture Organization (FAO) or similar country-specific livestock census reports.

TABLE 2 DOMESTIC LIVESTOCK INCLUDED IN THE TIER 1 METHODOLOGY
Livestock
Dairy Cattle
Non-Dairy Cattle
Buffalo
Sheep
Goats
Camels
Horses
Mules and Asses
Swine
Poultry

As shown in Table 2, IPCC recommends recording data on dairy cattle separate from other cattle. Dairy cattle are defined as mature cows producing milk in commercial quantities for human consumption, and are managed differently from non-dairy cattle. This generally results in differences in composition and methane production potential between dairy and non-dairy cattle manure. Additionally, dairy cattle manure is often managed differently from cattle manure.

In some countries, there are two types of dairy cows: high-producing, “improved” breeds in commercial operations and low-producing breeds managed with traditional methods. If possible, countries can separate the dairy cow population into two groups. The dairy cow group does not include cows used mainly for producing calves or for draft power. These cows are accounted for in non-dairy cattle data.

In addition, livestock populations must be described in terms of warm or cool temperature climates for purposes of estimating livestock manure emissions. Data on the annual average temperature of the regions where livestock are managed should be used as follows:

- Areas with annual average temperatures less than 15° C are defined as cool;
- Areas with annual average temperatures from 15° C to 25° C inclusive are defined as temperate, and
- Areas with annual average temperatures greater than 25° C are defined as warm.

The fraction of each livestock population should be estimated for each climate. This data can be developed from country-specific climate maps and livestock census reports. To the extent possible, the temperature data should reflect the locations where the livestock are managed.

Tier 2: In addition to the livestock population data described for Tier 1, the Tier 2 approach also requires data on the percentage of manure managed with each management system. Data should be collected for each management system. Table 12 in Annex 2 summarizes the main types of manure management systems, which can be broadly divided into "wet" and "dry" systems. If specific management system data does not exist, there should be at least a division of manure production into wet and dry systems. The IPCC provides default manure management practice data for major regions based on Safley, et al. (1992). If country-specific data exists or can be collected, it should be used. Additionally, if the current data predates known changes in manure management practices, they should be updated to reflect the current practices.

Nitrous Oxide

In addition to livestock population and manure management system data (described above), the nitrous oxide emissions estimation approach also requires nitrogen excretion data by animal type. It is recommended that country-specific data be collected and used. This may require manure composition analysis, which should be coordinated with any research to determine volatile solids content. If this is not feasible, regional default values can be used. These are provided in Table 3.

TABLE 3

TENTATIVE DEFAULT VALUES FOR NITROGEN EXCRETION PER HEAD OF ANIMAL PER REGION (KG/ANIMAL/YR)

Region	Type of Animal					
	Non-Dairy Cattle	Dairy Cattle	Poultry	Sheep	Swine	Other Animals
North America	70	100	0.6	16	20	25
Western Europe	70	100	0.6	20	20	25
Eastern Europe	50	70	0.6	16	20	25
Oceania	60	80	0.6	20	16	25
Latin America	40	70	0.6	12	16	40
Africa	40	60	0.6	12	16	40
Near East & Mediterranean	50	70	0.6	12	16	40
Asia & Far East	40	60	0.6	12	16	40

Source: IPCC, 1996.

2.4 Uncertainty

Parallel to the IPCC sector-specific meetings on good practice guidance, the IPCC is completing a programme of work on emissions inventory uncertainty. This work will result in recommendations to the United Nations Framework Convention on Climate Change (UNFCCC) on approaches to assessing and managing uncertainty. During the IPCC Inventory Experts Group Meeting in Paris (October 1998), technical experts in the uncertainty programme came up with a series of questions to be answered in the sector meetings. Specifically, the sector meetings should provide answers to these questions in the individual source context. The questions are listed in the general background paper.

Methane

Tier 1: Given that the emissions factors for Tier 1 are not based on country-specific data, they do not represent accurately the manure management system characteristics for any given country. The emissions factors are highly uncertain as a result. Emission factors should be updated for regions that have experienced significant changes in manure management practices.

Tier 2: One source of uncertainty in the Tier 2 emissions factors is the manure system usage data. The level of confidence in this data depends on the methods used to collect the data for each country. Additionally, there is uncertainty in the MCFs used to estimate the portion of the methane production potential that is realized in each manure management system. Conditions can vary significantly, particularly in liquid systems. The default MCFs may not account for all of the variability in methane production that can exist within systems. A secondary source of uncertainty lies in the equations used to calculate the emissions factor (presented in Annex 2). Generally, uncertainty in the equations is low compared to the uncertainty in the manure system usage data. Consequently, efforts undertaken to reduce uncertainty should focus first on improving this data.

Nitrous Oxide

In addition to the uncertainty in the manure system usage data, there is also uncertainty in the nitrogen excretion data. Similar to manure system usage, the level of uncertainty in nitrogen excretion data depends on the methods used to collect the data. As discussed before, there is also a high level of uncertainty in the emission factors that arises from a lack of data on N_2O production from manure.

2.5 Completeness

Given that the different livestock species are distinct and population data are generally available, each country is expected to create a complete inventory comprised of emissions estimates for each required livestock species. If population data are unavailable, countries can use data collected by FAO (FAO, 1999).

2.6 Other important issues

2.6.1 Baseline

An emission baseline is an important component of an inventory programme. Below is a description of issues related to creating a baseline for the methane and nitrous oxide methods recommended by the IPCC.

Methane

Tier 1: Developing a baseline for Tier 1 requires collecting and compiling animal population data during the baseline period. For the Tier 1 methodology, difficulties arise when

- Animal population data are not available for the baseline period;
- Animal population data during the baseline period are not broken down into the animal groups recommended by IPCC, and
- Changes in manure management practices over time affect methane emissions.

Approaches to overcoming these difficulties include collecting aggregate historical data from FAO and using current data to break out historical population data into the animal groups. If changes in manure management practices affect methane emissions significantly, the Tier 1 method is unreliable, and the Tier 2 method should be used.

Tier 2: Developing a baseline for Tier 2 requires the collection and compilation of manure management system usage data during or following the baseline period. In addition to the issues related to animal population data described for Tier 1, difficulties arise in the Tier 2 methodology when:

- Manure management system data are not available for the baseline period;
- Manure management system data during the baseline period are not broken down into the systems recommended by IPCC, and
- The Tier 2 methodology was not used throughout the baseline period.

Approaches to overcoming a lack of substantial management system data include applying a sample area or region's manure management practice trends to the entire country. If emission estimation methodologies have changed, historical data that are required by the current methodology should be collected and used to re-estimate emissions for that period. If these data do not exist, it may be appropriate to create a trend with recent data and use the trend to back-estimate management practices for the baseline period. Among other sources, publications, industry and university experts can be used to estimate trends for the livestock and feed characteristics.

Nitrous Oxide

The issues related to animal population and manure management practices described for methane also apply to emissions from nitrous oxide.

2.6.2 Accurate detection of mitigation measures

Efforts to reduce methane emissions through improved productivity, and thus declining livestock populations, would be reflected in the livestock population data. This decline would directly affect manure and volatile solids production, as well as nitrogen production. All other factors kept constant, decreases in volatile solids and nitrogen production would reduce methane and nitrous oxide emissions.

Shifts in manure management practices towards dry systems would have a similar affect on methane emissions. On a weight basis, manure in dry systems produces significantly less methane than liquid systems. Even with increased manure production, shifts toward dry systems could decrease methane emissions dramatically. Based on default emission factors, such shifts would presumably have an opposite effect on nitrous oxide emissions. However, the high uncertainty associated with these factors may diminish any effects of such changes.

The current methodology accounts for manure handled in anaerobic digesters. The IPCC default MCF for these digesters is 5-15%, which is much lower than the MCF values for anaerobic lagoons (90%) and liquid/slurry systems (10-65%). Thus, increased handling of manure in such systems could significantly decrease methane emissions.

2.6.3 Consistency with inventory for livestock digestive systems

The livestock characterization used to estimate methane and nitrous oxide emissions from livestock manure should be consistent with the characterization used for methane emissions from livestock digestive systems. If there are conflicts or inconsistencies, these should be resolved as soon as possible.

3 REPORTING AND DOCUMENTATION

A recent report from the UNFCCC Secretariat "Methodological Issues Identified While Processing Second National Communications" (UNFCCC/SBSTA/1998/7) noted that almost all countries reported methane emissions from manure, and all countries, with the exception of two countries, reported emissions from manure separately from enteric fermentation emissions. Specifically, Belgium included emissions from manure with emissions from enteric fermentation and Estonia reported methane emissions from all agriculture rather than separating each agricultural source (Estonia, 1998).

In reporting emissions, countries should include all activity data, and document the source of the data. Countries using the methane Tier 2 approach should also explicitly show the emission factor calculation method. This includes the calculation method and steps to determine the respective emission factors that are weighted and aggregated across manure management systems to produce a single factor for each livestock category.

3.1 Current IPCC reporting guidelines

The *IPCC Guidelines* are used to guide countries in the preparation and submissions of annual greenhouse gas emissions inventories to the UNFCCC Secretariat. The Guidelines establish:

- Standard tables, definitions, units, and time intervals for reporting all types of emissions;
- Necessary documentation to enable comparison of national inventories, including worksheets, major assumptions, methodological descriptions, and enough data to allow a third party to reconstruct the inventory from national activity data and assumptions, and
- An uncertainty assessment.

Both methane and nitrous oxide emissions from livestock manure are reported in Table 4, Volume 2 of the *IPCC Guidelines* - Sectoral Report for Agriculture. This table requires recording emissions from each livestock source, and also across the major manure management systems.

3.2 Confidential business information

In isolated cases, reporting population data and information on management practices may be a problem in regions with a small number of large, commercial operations. Confidentiality is not expected to be a significant issue for this source.

4 INVENTORY QUALITY

4.1 Introduction

Inventory quality assurance and quality control (QA/QC) is a process integral to the development of a credible inventory. A well-developed and well-implemented quality assurance programme fosters confidence in the final inventory results regardless of the purpose and goal of the inventory. A successful quality assurance programme requires internal quality control procedures and an unbiased, external review and audit. The internal QC activities are designed to ensure accuracy, documentation, and transparency. The external review process is designed to minimize errors that occur in the preparation of emissions inventories, and reduce or eliminate potential inherent bias. Figure 1 outlines the flow of information and processes followed at each step.

Figure 1 Inventory QA/QC Process

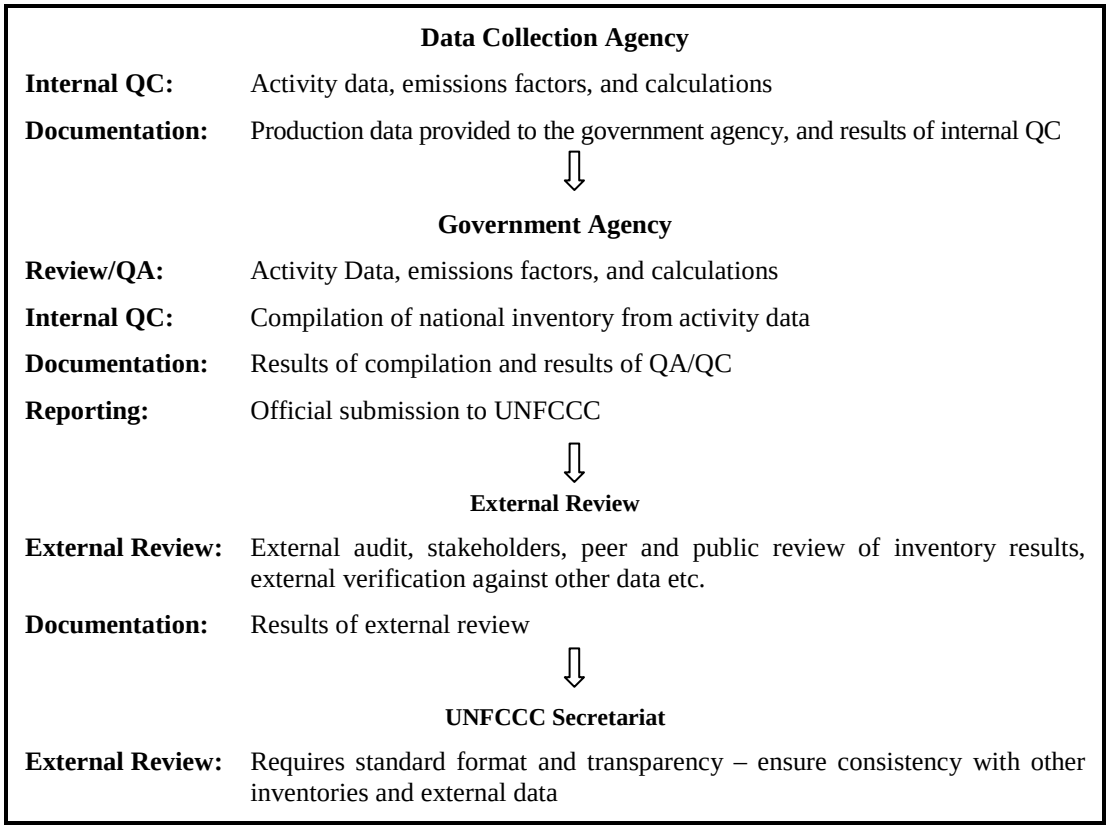

4.2 Internal inventory QA/QC systems

4.2.1 Emissions factors

Emissions Factors QC

Methane

Tier 1: The emissions factors are based on default data. QC procedures include reviewing the available default values and documenting the rationale for selecting specific values. Other QC procedures are not required.

Tier 2: QC procedures for the Tier 2 emissions factors involve checking the equations and calculations used to calculate the emissions factor. The Tier 2 emissions factors are based on country-specific information on animal and feed characteristics. QC procedures on these data are described below in the Activity Data section.

Nitrous Oxide

The emissions factors are based on default data. QC procedures include reviewing the available default values and documenting the rationale for selecting specific values. Other QC procedures are not required.

Emissions Factors Documentation

Documentation is a crucial component of the review process because it enables reviewers to identify mistakes and suggest improvements. Among other elements, a detailed description of the equations used to estimate emissions factors is needed. In addition, a standardized reporting form is recommended to provide transparent information on the steps taken to calculate the emissions factors. Each step should contain the numbers used in each calculation, including the source of any data collected.

4.2.2 Activity data

Activity Data QC

Tier 1 and Tier 2 ***Livestock Population Data:*** The annual livestock population data are generally collected by a country's ministry of agriculture or a similar organization focused on the agriculture sector. The personnel that

collect data are responsible for reviewing the data collection methods, checking the data to ensure they were collected and aggregated correctly, and cross-checking the data with previous years to ensure the data are reasonable. The basis for the estimates, whether statistical surveys or "desk estimates," must be reviewed and described as part of the QC effort.

Tier 2 ***Manure Management Practices Data:*** There are generally two approaches to collecting manure management system usage data: a) a government agency or related body collects the data by surveying farms; or b) the agency or related body interviews industry and university experts. The QC activities for the two approaches are described below:

- *Farm Survey*: Government agencies, such as the ministry of agriculture or a related body, collect the animal and feed characteristics data required for the inventory. The personnel collecting the data are responsible for reviewing the collection methods, checking to ensure the data were collected and aggregated correctly, and comparing data with data from previous years to ensure the data are reasonable.
- *Industry and University Experts*: Manure system usage data may be obtained by surveying and interviewing industry and university experts. The personnel collecting the data are responsible for reviewing surveys used to collect the data to make sure the survey is appropriate for the data needs. Questions used in interviews should also be reviewed.

Activity Data Documentation

Documentation is a crucial component of the review process, because it enables reviewers to identify mistakes and suggest improvements. Among other information, the following is needed for the reviewing/auditing agency:

- A highly detailed description of the methods used to collect the activity data, and
- A discussion of potential areas of bias in the data, including a discussion of whether the manure management practices are representative of the country.

4.2.3 Inventory agency level activities

Inventory Agency Review of Activity Data QA

Before accepting the activity data, the inventory agency should assess them, including all data on the animal population and manure management practices. This review involves close cooperation with the personnel responsible for collecting, compiling, and analyzing the data. The assessment should include a review of the detailed methods used to collect the data, including a review of any surveys and interviews performed to collect the data. In addition, the assessment should include a comparison of the activity data with historical data, a discussion of the potential for bias, and recommendations for improvement.

Inventory Agency QC on Compiling National Emissions

In addition to a thorough quality assessment of data discussed above, the inventory agency should ensure that the process of aggregating data to develop the national inventory undergoes quality control. This should include, among other things:

- Cross-referencing the aggregated population data with the national totals;
- Back-calculating national and regional emissions factors from the Tier 2 management system usage data (if using Tier 2);
- Ensuring that the manure management practices are representative of the country (if using Tier 2);
- Ensuring that all farms are included in the population data, and
- Comparing with national trends to look for anomalies.

Inventory Agency Documentation on Compiling National Emissions

For the CH_4 emission inventory for enteric fermentation, a QA/QC management plan should address the specific items needed to perform audits and reviews. Examples of the types of information needed for documentation and external audit include:

- A detailed description of the inventory methodology;
- Identification of the input parameters that are needed and how the input parameters are obtained, and
- Frequency of data collection and estimation and results of determinations of accuracy and precision.

4.3 External inventory QA/QC systems

External QA activities include a planned system of review and audit procedures conducted by personnel not actively involved in the inventory development process. The key concept is an independent, objective review to assess the effectiveness of the internal QC programme, the quality of the inventory, and to reduce or eliminate any inherent bias in the inventory processes. Several types of external reviews, or audits, may be appropriate for the inventory of CH_4 and N_2O emissions from livestock manure.

- **Third party audit by an accredited organization, expert, independent third party:** An audit of the documentation and calculations ensures that each number is traceable to its origin.
- **Expert (peer) review:** Although a detailed peer review would be appropriate when a procedure for determining CH_4 emissions is first adopted or revised; it would not be needed on an annual basis. Such a review is designed to ensure that the methodology is rigorous, accurate, and that the data and assumptions reflect the best available information.
- **Stakeholder review:** Review by industrial organizations and government can provide a forum for review of the methods used.
- **Public review:** Some countries make their entire inventory available for public review and comment. This process may result in a range of comments and issues broader than those from other review processes.

Confidential Business Information Issues

Confidentiality is not a major issue when private parties review the data. However, in areas with several large, commercial producers, there may be opposition to releasing the activity data to the public.

5 UPDATES TO ESTIMATION METHODS

At the IPCC workshop on Good Practices in Inventory Methods held in the Netherlands on February 24-26, 1999, participants recommended updates to the Tier 2 method used to estimate methane emissions from livestock manure. These updates included the following:

- Modifications to the maximum methane producing capacity of cattle, poultry, and swine based on recent research;
- New MCF values for liquid/slurry and pit storage manure management systems;
- Revised definitions for several management systems, and
- The addition of new manure management systems into the IPCC list of systems.

Recent work by Zeeman and Gerbens (1999) showed that B_o values for swine manure may be lower than the IPCC default value. The latter would suggest an unrealistic high biodegradability of 92% (Zeeman and Gerbens, 1999), in contradiction to the observed biodegradability of 70% (Zeeman, 1994). Therefore it is proposed that the estimated B_o (Zeeman and Gerbens, 1999) values should be used as the default values in the *IPCC Guidelines*. A comparison of these values is shown in Table 4.

TABLE 4

RANGE IN B_O VALUES REPORTED BY SAFLEY ET AL.(1992) AND ESTIMATED B_O VALUES FOR DEVELOPED AND DEVELOPING COUNTRIES (ZEEMAN AND GERBENS,1999) IN COMPARISON TO IPCC DEFAULT VALUES (M^3 CH_4/KG VS)

	IPCC (1996) Developed Countries	IPCC (1996) Developing Countries	Safley et al. (1992)	Zeeman and Gerbens (1999) Developed	Zeeman and Gerbens (1999) Developing
	Default	Default	range	estimated	estimated
Non-dairy	0.17	0.10	0.17-0.33		
Dairy	0.24	0.13	0.10-0.24	0.25	0.14[1]
Poultry	0.32	0.24	0.24-0.39		
Swine	0.45	0.29	0.32-0.52	0.34	0.22[1]

Estimated B_o values for developing countries (Zeeman and Gerbens, 1999) are proportionally lower and similar to the IPCC estimate for B_o values for developinged regions.

The participants also proposed using revised MCF values based on values observed by Zeeman(1994) shown in Table 5.

TABLE 5

COMPARISON BETWEEN IPCC DEFAULT MCF VALUES AND PROPOSED MCF VALUES

Manure management Strategy	Climatic condition	MCF (%) (IPCC, 1995)	MCF (%) (Zeeman and Gerbens, 1999)
Liquid/slurry	Cool	10	39
	Temperate	35	45
	Warm	65	72
Pit < 1 month	Cool	5	0
	Temperate warm	18 33	0 30
Pit > 1 month	Cool	10	39
	Temperate	35	45
	Warm	65	72

In addition, it was recommended that digesters and anaerobic lagoons be subdivided to account for recovery, flaring and use of the biogas including the gas produced/emitted during manure storage after digestion. The proposed revisions to the manure management system definitions and MCF values are shown in Table 6. The proposed additional management systems are shown in Table 7.

TABLE 6

MANURE MANAGEMENT SYSTEMS (BLANK MEANS NO CHANGE FROM CURRENT IPCC DEFINITIONS/MCFS)

System	Definition	MCFs by Climate			Comments
		Cool	Temperate	Warm	
Pasture/Range/ Paddock					
DailySpread	Dung and urine is collected by some means such as scraping. The collected waste is applied to fields.				
Solid Storage	Dung and urine are excreted in a stall. The solids (with or without litter) are collected and stored in bulk for a long time (months) before disposal, with or without liquid runoff into a pit system.				
Drylot					
Liquid/Slurry	Dung and urine are collected and transported in liquid state to tanks for storage. Liquid may be stored for a long time (months). To facilitate handling water maybe added.	39%	45%	72%	When slurry tanks are used as fed-batch storage/digesters, MCF should be calculated according to formula 1.
Anaerobic Lagoon		0-100%	0-100%	0-100%	Should be subdivided in different categories, considering percentage recovery of the biogas and flaring of the biogas.
Pit Storage Below Animal Confinements	Combined storage of dung and urine below animal confinements <1 month >1 month	0-39%	0-45%	30%-72%	When pits are used as fed-batch storage/digesters, MCF should be calculated according to formula 1. The stable temperature, not the ambient temperature, is to be used for determining the climatic conditions.

TABLE 6 (CONTINUED)

MANURE MANAGEMENT SYSTEMS (BLANK MEANS NO CHANGE FROM CURRENT IPCC DEFINITIONS/MCFS)

System	Definition	MCFs by Climate			Comments
		Cool	Temperate	Warm	
Drylot					
Anaerobic Digester	The dung and urine in liquid/slurry is collected and anaerobically digested. Methane may be burned flared or vented.	0-100%	0-100%	0-100%	Should be subdivided in different categories, considering amount of recovery of the biogas, flaring of the biogas and storage after digestion .
Burned for Fuel	The dung and urine are excreted on fields. The sun dried dung cakes are burned for fuel.				

TABLE 7

PROPOSED NEW MANURE MANAGEMENT SYSTEMS

Recommended Additional Systems	Definition	MCFs by Climate			Comments
		Cool	Temperate	Warm	
Cattle Deep Litter	Cattle dung and urine is excreted on stall floor. The accumulated waste is removed after a long time.	10%	35%	65%	MCF's are similar to liquid/slurry; temperature dependant.
Composting – Intensive	Dung and urine is collected and placed in a vessel or tunnel, there is forced aeration of the waste.	0.5%	0.5%	0.5%	MCF's are less than half of solid storage. Not temperature dependant.
Composting – Extensive	Dung and urine collected, stacked and regularly turned for aeration.	0.5%	1%	1.5%	MCF's are slightly less than solid storage. Less temperature dependant.
Poultry manure with bedding	Manure is excreted on floor with bedding. Birds walk on waste.	1.5%	1.5%	1.5%	MCF's are similar to solid storage but with generally constant warm temperatures.
Poultry manure without bedding	Manure is excreted on floor without bedding. Birds do not walk on waste.	1.5%	1.5%	1.5%	MCF's are similar to dry lot at a warm climate.
Aerobic Treatment	Dung and manure is collected as a liquid. The waste undergoes forced aeration, or treated in aerobic pond or wetland systems to provide nitrification and denitrification.	0.1%	0.1%	0.1%	MCF's are near zero.

6 CONCLUSIONS

The key issues for estimating emissions from manure management relate to the actual methodology as well as to the creation of a baseline for methane and nitrous oxide emissions. Major issues concerning the Tier 1 methodology include lack of animal population data by animal groups. Approaches to overcoming this difficulty include collecting aggregate historical data from FAO and using current data to break out historical population data into the animal groups. For the Tier 2 methodology, the key issue is obtaining an accurate representation of manure management systems for any particular additional country. Approaches to overcoming this issue include applying a sample area or region's manure management practice trends to the entire country.

Issues to be addressed when developing a baseline include lack of available data, historic data not having been organized as recommended by IPCC, and changes in manure management practices over time that affect emissions results. The approaches for resolving issues include re-examination of historical data by means of the current methodology, the application of data from a representative region to the entire country as well as the creation of a trend with recent data and back-estimating historic data using this trend.

Updates to the Tier 2 method recommended at the IPCC Workshop in *Good Practices* in Inventory Methods held on February 24-26, 1999 in the Netherlands included the results of recent research such as modifications to the maximum methane producing capacity of livestock (B_o values), new MCF values for liquid slurry and pit storage as well as the revision and incorporation of the additional manure management systems currently being used (i.e. daily spread, solid storage, drylot, and anaerobic lagoon were revised; pit storage is a new system that has been incorporated).

REFERENCES

Estonia. 1998. *Second National Report under the United Nation's Framework Convention on Climate Change*.

Food and Agriculture Organization (FAO). 1999. Statistical Database. << http://apps.fao.org/lim500/nph-wrap.pl?Production.Livestock.Stocks&Domain=SUA&servlet=1 >>

Hashimoto, A. and J. Steed (1993), *Methane Emissions from Typical U.S. Livestock Manure Management Systems*. Draft report prepared for ICF Incorporated under contract to the Global Change Division of the Office of Air and Radiation, US Environmental Protection Agency, Washington D.C., U.S.A.

International Panel on Climate Change (IPCC). 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Reference Manual (Revised)*. v.3.

International Panel on Climate Change (IPCC). 1995. *IPCC Guidelines for National Greenhouse Gas Inventory*.

Lichtman, R.J. (1983), *Biogas Systems in India*, Volunteers In Technical Assistance (VITA), Arlington, Virginia, U.S.A.

Safely, L.M., M.E. Casada, J.W. Woodbury, and K.F. Roos (1992), *Global Methane Emissions from Livestock and Poultry Manure*. US Environmental Protection Agency, Global Change Division, Washington D.C., February 1992, EPA/400/1091/048.

Safley, L.M. Jr. and P.W. Westerman, (1992), "Performance of a low temperature lagoon digester," *Bioresource Technology* 41:167-175.

Stuckey, D.C. (1984), "Biogas: a global perspective." In: *Biogas Technology, Transfer and Diffusion*, M.M. El-Halwagi (ed.), Elsevier, New York, U.S.A., pp. 18-44.

Woodbury, J.W. and A. Hashimoto (1993), "Methane Emissions from Livestock Manure." In *International Methane Emissions*, US Environmental Protection Agency, Climate Change Division, Washington D.C., U.S.A.

Yancun, C., H. Cong and Liang Pusen (1985), "Development of a new energy village - Xinbu, China." In: *Integrated Rural Energy Planning*, Y. El Mahgary and A.K. Biswas (eds.), Butterworths Publishing, Guildford, England, pp. 99-108.

Zeeman, G. (1994). "Methane production/emission in storage's for animal manure," *Fertilizer Research* 37: 207-211.

Zeeman, G. and Gerbens, S. (1999) *Expert group meeting on good practice in inventory preparation. Workgroup 2: "Methane emission from animal manure,* Background paper for IPCC Workshop, February 24-26 1999, Wageningen, The Netherlands

ANNEX 1 TIER 1 EMISSION FACTORS

TABLE 8

MANURE MANAGEMENT EMISSION FACTORS (KG PER HEAD PER YR.)

	Developed Countries			Developing Countries		
Livestock	Cool	Temp.[a]	Warm	Cool	Temp.[a]	Warm
Sheep	0.19	0.28	0.37	0.10	0.16	0.21
Goats	0.12	0.18	0.23	0.11	0.17	0..22
Camels	1.6	2.4	3.2	1.3	1..9	2.6
Horses	1.4	2.1	2.8	1.1	1..6	2.2
Mules and Asses	0.76	1.14	1.51	0.60	0.90	1.2
Poultry[b]	0.078	0.117	0.157	0.012	0.018	0.023

The range of estimates reflects cool to warm climates. Climate regions are defined in terms of annual average temperature as follows: Cool = less than 15° C; Temperate = 15° C to 25° C inclusive; and Warm = greater than 25° C. The Cool, Temperate, and Warm regions are estimated using MCFs of 1% and 2%, respectively.

[a] Temp. = Temperate climate region.

[b] Chickens, ducks, and turkeys.

All estimates are ±20%.

Sources: Emission factors developed from: feed intake values and feed digestibilities used to develop the enteric fermentation emission factors; MCF, and B_O values reported in Woodbury and Hashimoto (1993). All manure is assumed to be managed in dry systems, which is consistent with the manure management system usage reported in Woodbury and Hashimoto (1993).

Source: IPCC, 1996 (Chapter 4, Table 4.5).

TABLE 9

TIER 1 MANURE MANAGEMENT EMISSION FACTORS FOR CATTLE, SWINE, AND BUFFALO

Regional Characteristics	Livestock Type	Emission Factor by Climate Region (kg/head/yr)		
		Cool	Temperate	Warm
North America: Liquid-based systems are commonly used for dairy and swine manure. Non-dairy manure is usually managed as a solid and deposited on pastures or ranges.	Dairy Cattle	36	54	76
	Non-dairy Cattle	1	2	3
	Swine	10	14	18
	Buffalo			
Western Europe: Liquid/slurry and pit storage systems are commonly used for cattle and swine manure. Limited cropland is available for spreading.	Dairy Cattle	14	44	81
	Non-dairy Cattle	6	20	38
	Swine	3	10	19
	Buffalo	3	8	17
Eastern Europe: Solid based systems are used for the majority of manure. About one-third of livestock manure is managed in liquid-based systems.	Dairy Cattle	6	19	33
	Non-dairy Cattle	4	13	23
	Swine	4	7	11
	Buffalo	3	9	16
Oceania: Virtually all livestock manure is managed as a solid on pastures and ranges. About half of the swine manure is managed in anaerobic lagoons.	Dairy Cattle	31	32	33
	Non-dairy Cattle	5	6	7
	Swine	20	20	20
	Buffalo			

TABLE 9 (CONTINUED)

TIER 1 MANURE MANAGEMENT EMISSION FACTORS FOR CATTLE, SWINE, AND BUFFALO

Regional Characteristics	Livestock Type	Emission Factor by Climate Region (kg/head/yr)		
		Cool	Temperate	Warm
Latin America: Almost all livestock manure is managed as a solid on pastures and ranges. Buffalo manure is deposited on pastures and ranges.	Dairy Cattle	0	1	2
	Non-dairy Cattle	1	2	1
	Swine	0	1	2
	Buffalo	1	1	2
Africa: Almost all livestock manure is managed as a solid on pastures and ranges.	Dairy Cattle	1	1	1
	Non-dairy Cattle	0	1	1
	Swine	0	1	2
	Buffalo			
Middle East: Over two-thirds of cattle manure is deposited on pastures and ranges. About one-third of swine manure is managed in liquid-based systems. Buffalo manure is burned for fuel or managed as a solid.	Dairy Cattle	1	2	2
	Non-dairy Cattle	1	1	1
	Swine	1	3	6
	Buffalo	4	5	5
Asia: About half of cattle manure is used for fuel with the remainder managed in dry systems. Almost 40% of swine manure is managed as a liquid. Buffalo manure is managed in drylots and deposited in pastures and ranges.	Dairy Cattle	7	16	27
	Non-dairy Cattle	1	1	2
	Swine	1	4	7
	Buffalo	1	2	3
Indian Subcontinent: About half of cattle and buffalo manure is used for fuel with the remainder managed in dry systems. About one-third of swine manure is managed as a liquid.	Dairy Cattle	5	5	6
	Non-dairy Cattle	2	2	2
	Swine	3	4	6
	Buffalo	4	5	5

The range of estimates reflects cool to warm climates. Climate regions are defined in terms of annual average temperature as follows: Cool = less than 15° C; Temperate = 15° C to 25° C inclusive; and Warm = greater than 25° C. All climate categories are not necessarily represented within every region. For example, there are no significant warm areas in Eastern or Western Europe.

Note: Significant buffalo populations do not exist in North America, Oceania, or Africa.

Source: IPCC, 1996 (Chapter 4, Table 4.6).

ANNEX 2 TIER 2 EMISSION FACTORS

IPCC VS Excretion Rate Equation (Equation 15 in the IPCC Guidelines)

EQUATION 15

$$VS\ (kg\ dm/day) = Intake\ (MJ/day) \bullet (1kg\ dm / 18.45\ MJ) \bullet (1 - DE\% / 100) \bullet (1 - ASH\% / 100)$$

Where:

VS: VS excretion per day on a dry weight basis;

dm: dry matter;

Intake: the estimated daily average feed intake in MJ/day;

DE%: the digestibility of the feed in percent;

ASH%: the ash content of the manure in percent.

TABLE 10

MANURE MANAGEMENT SYSTEMS AND METHANE CONVERSION FACTORS (MCFS)

System		MCF by Climate			Source
		Cool	Temperate	Warm	
Pasture/Range/Paddock: the manure from pasture and range grazing animals is allowed to lie as is, and is not managed.		1%	1.5%	2%	b
Daily Spread: manure is collected in solid form by some means such as scraping. The collected manure is applied to fields regularly (usually daily).		0.1%	0.5%	1%	b
Solid Storage: manure is collected as in the daily spread system, but is stored in bulk for a long period of time (months) before any disposal.		1%	1.5%	2%	b
Drylot: in dry climates animals may be kept on unpaved feedlots where the manure is allowed to dry until it is periodically removed. Upon removal, the manure may be spread on fields.		1%	1.5%	5%	b
Liquid/Slurry: these systems are characterized by large concrete-lined tanks built into the ground. Manure is stored in the tank for six or more months until it can be applied to fields. To facilitate handling as a liquid, water may be added to the manure.		10%	35%	65%	b
Anaerobic Lagoon: anaerobic lagoon systems are characterized by flush systems that use water to transport manure to lagoons. The manure resided in the lagoon for periods from 30 days to over 200 days. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields.		90%	90%	90%	c
Pit Storage: liquid swine manure may be stored in a pit while awaiting final disposal. The length of storage time varies, and for this analysis is divided into two categories: less than one month or greater than one month.	<1 month	5%	18%	33%	b
	> 1 month	10%	35%	65%	b
Anaerobic Digester: the manure, in liquid or slurry form, is anaerobically digested to produce methane gas for energy. Emissions are from leakage and vary with the type of digester.		5-15%	5-15%	5-15%	d
Burned for Fuel: manure is collected and dried in cakes and burned for heating or cooking. Emissions occur while the manure is stored before it is burned. Methane emissions associated with the combustion of the manure are not considered here. Combustion-related emissions are estimated in the *Traditional Biomass Fuels* Section of the *Energy* chapter.		5-10%	5-10%	5-10%	e

a The range of estimates reflects cool to warm climates. Climate regions are defined in terms of annual average temperature as follows: Cool = less than 15° C; Temperate = 15° C to 25° C inclusive; and Warm = greater than 25° C.

b Hashimoto and Steed (1993).

c Safley et al., (1992) and Safley and Westerman (1992).

d Yancun et al. (1985), Stuckey (1984) and Lichtman (1983).

e Safely et al., (1992).

Source: IPCC, 1996.

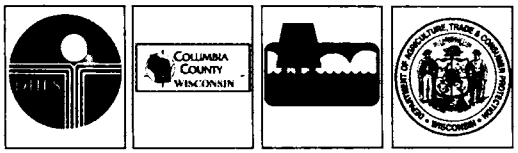

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Columbia County Health Department and Human Services,
Wisconsin Department of Natural Resources,
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Blue Babies and Nitrate-Contaminated Well Water

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The use of nitrate-contaminated drinking water to prepare infant formula is a well-known risk factor for infant methemoglobinemia. Affected infants develop a peculiar blue-gray skin color and may become irritable or lethargic, depending on the severity of their condition. The condition can progress rapidly to cause coma and death if it is not recognized and treated appropriately. Two cases of blue baby syndrome were recently investigated. Both cases involved infants who became ill after being fed formula that was reconstituted with water from private wells. Water samples collected from these wells during the infants' illnesses contained nitrate–nitrogen concentrations of 22.9 and 27.4 mg/L. *Key words*: blue baby syndrome, methemoglobinemia, nitrate, nitrate-contaminated well water. *Environ Health Perspect* 108:675–678 (2000). [Online 6 June 2000]
http://ehpnet1.niehs.nih.gov/docs/2000/108p675-678knobeloch/abstract.html

Blue baby syndrome is a potentially fatal condition that occurs when the hemoglobin (Fe^{2+}) in an infant's red blood cells is oxidized to methemoglobin (Fe^{3+}). Because methemoglobin is unable to transport oxygen, the condition produces symptoms of cyanosis. Affected infants develop an unusual blue-gray or lavender skin color and are often described as irritable or lethargic, depending on the severity of their illness. Methemoglobin levels > 50% can quickly lead to coma and death if the condition is not recognized and treated.

A variety of risk factors including inherited enzyme deficiencies, infectious and inflammatory conditions, drug reactions, and chemical exposures can increase methemoglobin levels. The most common environmental agent associated with this diagnosis is nitrate-contaminated water; however, foods that are high in nitrate or nitrite may also be involved. Infants are particularly susceptible to the condition during their first 6 months of life because they have low amounts of methemoglobin reductase, a red blood cell enzyme that converts methemoglobin back to hemoglobin. The impact of these risk factors is additive.

The association between nitrate-contaminated well water and blue baby syndrome was first described by Hunter Comly, an Iowa City physician, who treated two infants for symptoms of cyanosis during the early 1940s (*1*). He found that both infants became ill after they were fed formulas that were diluted with water from shallow wells. Nitrate–nitrogen (nitrate-N) concentrations in the related wells were 90 and 150 mg/L. After Comly's findings were published, many similar cases were reported. In 1951, Walton (*2*) reviewed data from 278 cases that had been reported by 14 different states. Although health care providers and water quality experts have greatly reduced infant exposure to nitrate-contaminated water, emergency room physicians and pediatricians continue to diagnose and treat infants for this condition. The Wisconsin Department of Health and Family Services (Madison, Wisconsin) has an active surveillance program for methemoglobinemia. In this paper, we summarize findings from two recent case investigations.

Case Summaries

Case 1. During June 1998, public health nurses in Columbia County, Wisconsin, noted that a 6-month-old white male, who had been brought to a clinic in the Village of Cambria for immunizations, appeared cyanotic. The skin around his mouth and nose was unusually gray. According to his parents, the infant's skin color had been "gray" and he had been "crabbier than normal" for a couple of weeks. The infant also had a 6-week history of vomiting after feedings, which began shortly after the family moved to a new home that had a private water supply. Their previous residence was served by a municipal water system. The infant's daily diet consisted of 24 oz formula, 6 oz cereal, and 4–6 oz fruit (type not specified). The formula consisted of a powdered concentrate that was diluted with water from the family's well. Because of concern that the infant's illness might have been caused by nitrate-contaminated water, a public health nurse visited the family's home the following day to collect a water sample. The laboratory analysis indicated that the well was bacteriologically safe but had a nitrate-N concentration of 22.9 mg/L. The family was notified of these results and advised to use bottled water for formula preparation. They were also urged to have the infant examined by a physician.

This infant's parents reported that his skin color and temperament improved within a week after they began using bottled water to prepare his formula. The infant was examined by a physician's assistant 12 days after being placed on bottled water. At that time he appeared healthy and had a methemoglobin level of 0.5% (normal range 0.1–1.9%). His cardiac and pulmonary functions were normal.

This family shared a well with a neighboring home. The 178-ft well was drilled in 1989 and was cased to a depth of 42 ft. The family's home is situated in an area of rolling hills that is intensively farmed. Local crops include hay, corn, and soybeans. Both homes have mound-type septic systems that comply with local and state codes. Water collected from the well during August 1998 had a nitrate-N concentration of 30.5 mg/L. First draw and flushed tap water samples were low in copper (48 and 31 µg/L, respectively).

Case 2. During April 1999, a 3-week-old white female was admitted to an emergency room in Grant County, Wisconsin. According to her parents, she had been healthy until the night before admission when she became irritable and fussy. On the

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day of her admission, the parents reported that the infant had turned "completely blue" and was having breathing difficulties. Local emergency room staff noted that the infant was dehydrated, dusky, and cold to the touch. Her temperature was 90°F and her oxygen saturations remained in the low 80s while on 100% oxygen per nasal cannula. She was given a dose of intramuscular ceftriaxone, stabilized with warming blankets and intravenous fluids, and transported by MedFlight to a regional medical center.

On arrival, the infant was described as irritable. Her skin appeared pale, cyanotic, and mottled. An echocardiogram revealed a normal functioning, well-formed heart. Laboratory studies indicated a hemoglobin concentration of 11.5 g/dL, with a methemoglobin concentration of 91.2%. Blood gas analyses also indicated a profound metabolic acidosis (pH 6.72). This infant responded rapidly to treatment with methylene blue, oral bicarbonate, and intravenous fluids.

This infant lived with her parents and grandparents on a goat dairy farm in southwestern Wisconsin. She was born at 37 weeks gestation, weighed 5 lb 2 oz at birth, and had been doing well on a liquid concentrate formula that was diluted with bottled water. She became ill 1–2 days after her parents ran out of bottled water and began using water from the farm well to prepare her formula. The parents boiled the well water several minutes before using it. Water samples collected from the well 2 days after the infant was hospitalized tested positive for *E. coli* bacteria and had a nitrate-N concentration of 27.4 mg/L. Copper and lead concentrations were low at 29 and 0.9 µg/L, respectively.

The physicians who cared for this infant concluded that her illness was caused by ingestion of nitrate-contaminated well water. Metabolic disorders were ruled out after serum amino acids, urine organic acids, and metabolic screening were all determined to be within normal limits. Infectious illnesses apparently did not contribute to her illness. She remained afebrile throughout her hospitalization and did not receive antibiotic therapy. The infant was discharged 17 days after admission. At this time her parents were instructed not to use well water to prepare her formula.

Based on available well logs, it appears that the family's well was built in 1951. The well was originally constructed to a depth of 85 ft and had 30 ft of casing. In 1952 the well was drilled deeper, from 85 ft to 228 ft. An unused tin-cased well was also located on the property approximately 200 ft from the active well and immediately downgradient from the barnyard. Potential sources of nitrate were identified as barnyard runoff, septic tank effluent, and agricultural fertilizers.

Discussion

Since 1990, the Wisconsin Department of Health and Family Services has investigated three cases of methemoglobinemia in infants who were exposed to nitrate-contaminated well water. The first of these occurred in 1992 and was described in a 1993 issue of *Morbidity Mortality Weekly Report* (*3*). That case involved a 6-week-old infant who was hospitalized twice for symptoms of vomiting, diarrhea, and cyanosis. On her second admission, she was found to have a methemoglobin concentration of 21.4%. A detailed investigation concluded that her illness was caused by exposure to water that contained elevated levels of nitrate and copper. Although vomiting and diarrhea are frequently signs of gastrointestinal infection, in this case there was no evidence of a concurrent infectious process. Investigators concluded that these symptoms were caused by the irritant effects of copper that had leached from the household plumbing.

The occurrence of two additional cases during 1998 and 1999 suggests that nitrate-contaminated groundwater continues to be an important infant health problem in rural Wisconsin. Although case 1 was not confirmed by a laboratory analysis, the infant's cyanotic appearance and nitrate exposure history support a presumptive diagnosis of methemoglobinemia as described by Bosch et al. (*4*). Spontaneous improvement of the infant's condition after he was switched to bottled water lends further support to this diagnosis. The manner in which this case was handled by the county health department is typical of public health interventions practiced throughout Wisconsin and in many other regions of the United States. In rural areas where private well use is common, awareness of blue baby syndrome is widespread. Health care providers and others who are familiar with the condition frequently advise parents of sick infants to use bottled water for formula preparation or to use prepared formula. The combination of community awareness and early intervention has reduced the number of infants who require medical treatment for the condition.

Unfortunately, this safety net is not always effective. Case 2 illustrates the devastating consequences of neonatal nitrate exposure. That case involved a 3-week-old infant who was transported by helicopter to a regional pediatric intensive care unit with a life-threatening methemoglobin concentration. The nitrate-N concentration in the well water that was used to prepare her formula was 27.4 mg/L—less than 3 times the current federal drinking water standard for this contaminant. Extensive medical diagnostics ruled out underlying metabolic disorders and infectious illnesses as contributing factors to her illness.

Other reports of nitrate-induced methemoglobinemia. In a 1999 case report, Herman et al. (*5*) described the treatment of a 6-week-old infant with an intraosseous infusion of methylene blue after she was hospitalized with a methemoglobin concentration of 29.3%. Herman et al. (*5*) concluded that her

> ... methemoglobinemia was ... caused by the well water used to prepare the child's feedings, and ... may have been exacerbated by a recent diarrheal illness.

Unfortunately, their case report did not provide specific information about the well or the results of water quality tests.

The national death certificate database maintained by the Center for Disease Control and Prevention (Atlanta, GA) includes six infant deaths that were attributed to methemoglobinemia [*International Classification of Diseases, Revision* 9 (ICD-9 code 289.7)] between 1979 and 1996. These included two male and four female infants who were residents of Jim Wells County, Texas (1980); Kingsbury County, South Dakota (1986); New Orleans Parish, Louisiana (1986); Henry County, Virginia (1988); Garfield County, Colorado (1994); and Mesa County, Colorado (1996). It is unclear how many of these deaths might have been caused by exposure to nitrate-contaminated water because only the case in South Dakota was reported in the literature (*6*). The South Dakota case involved an infant who experienced several episodes of cyanosis after her mother stopped breast-feeding and began feeding her powdered formula that was reconstituted with water from the family's private well. At 8 weeks of age, the infant became acutely ill with symptoms of vomiting, diarrhea, and severe cyanosis. Her parents rushed her to a local physician who administered oxygen for several minutes. When the infant's color did not improve, the family was referred to a hospital 33 miles away. The infant stopped breathing on the way to the hospital and could not be resuscitated. The nitrate-N concentration in a water sample collected from the family's well after her death was 150 mg/L.

Infant exposure to nitrate-contaminated water continues to be a common public health problem in Eastern Europe. Ayebo et al. (*7*) found methemoglobinemia incidence rates ranging from 24 to 363 cases per 100,000 live births in the Transylvania region of Romania between 1990 and 1994. The average age at diagnosis was 39 days. Investigators identified the primary cause of methemoglobinemia to be the use of polluted well water to dilute formula concentrates. Over a 14-year period, the Poison Information Center in Krakow,

Poland, investigated 239 cases of infant methemoglobinemia, and reported that 90% of these illnesses were associated with ingestion of contaminated water (*8*).

Regulation of nitrate in drinking water. The Safe Drinking Water Act (*9*) established a maximum contaminant concentration for nitrate-N of 10 mg/L. This federal standard is used to ensure the safety of public water supplies, but does not apply to private wells. According to a recent report to Congress, approximately 15 million families in the United States obtain their drinking water from unregulated, domestic wells (*10*). In a 1994 survey of 5,500 private water supplies in nine Midwestern states, 13% of the wells were found to have nitrate-N concentrations > 10 mg/L (*11*). If the rate of contamination is similar in other regions of the nation, an estimated 2 million household water supplies may fail to meet the federal standard. Based on current birth rates (*12*), approximately 40,000 infants < 6 months of age are expected to be living in homes that have nitrate-contaminated water supplies.

In a paper titled "Infantile Methemoglobinemia: Reexamining the Role of Drinking Water Nitrates," Avery (*13*) stated that

> Reports of infantile methemoglobinemia linked to contaminated drinking water are now virtually non-existent in the United States, with only two cases reported since the mid-1960s.

Avery (*13*) discussed several recent reports of elevated methemoglobin levels in infants who were hospitalized because of prematurity or severe diarrhea and concluded that

> ... endogenous nitrite production, not exogenous nitrate contamination of drinking water, is the primary cause of methemoglobinemia.

In the final paragraph of his paper, Avery (*13*) wrote,

> ... there is little indication that relaxing the drinking water standard for nitrate (not nitrite) to 15 or 20 ppm nitrate-N would increase the health risk to infants.

Our findings do not support Avery's conclusions regarding the roles of gastrointestinal infections and nitrate-contaminated water in the etiology of infant methemoglobinemia, nor do they support a higher drinking water standard for nitrate. Avery's statements regarding the low incidence of nitrate-induced illness (*13*) are based on an assumption that all cases of infant methemoglobinemia are investigated to determine their cause and are then described in the literature. Unfortunately, this is not the case. For example, only one of the six methemoglobinemia deaths in the national death index was reported in the literature. Upon investigation, we found that the respective state and local health departments were often unaware of these deaths. Most physicians and state and local public health officials do not have time to conduct detailed investigations and have even less time to prepare case reports for publication. These case reports, if written, might not be published if the topics were not deemed newsworthy.

Investigation during the infant illness is essential. However, cases are often identified using data systems such as electronic death certificates and hospital discharge records. Such data is typically not available until 6 months to 1 year after the illness. Retrospective investigation and analysis of these illnesses is difficult because the condition can be induced by a wide variety of chemical exposures (Table 1). It is often impossible to reconstruct an infant's exposure to environmental agents, nitrate-rich foods, contaminated water, and medications.

Almost 20 years ago Hegesh and Shiloah (*15*) described the role of endogenous nitrate production in the etiology of infant methemoglobinemia. They studied 58 infants (1 week to 1.5 years of age) who were hospitalized for treatment of diarrhea. After finding that some of the infants were excreting more nitrate than was provided in their diets, Hegesh and Shiloah (*15*) concluded that infants with diarrhea were able to synthesize up to 875 µmol (12.2 mg) nitrate-N per day. Methemoglobin levels in these infants ranged from < 0.4% to > 8%, and were positively correlated with blood nitrate concentrations. None of the infants were described as having symptoms consistent with clinically significant methemoglobinemia, such as cyanosis or tachycardia. Two conclusions can be drawn from this research: *a*) exposure to as little as 12 mg nitrate-N per day can significantly increase an infant's methemoglobin level, and *b*) infants with diarrhea are at risk of developing methemoglobinemia, even in the absence of dietary nitrate exposure.

Since Hegesh and Shiloah's research (*15*) was published, several similar studies have confirmed their findings (*16–18*). Most have found mildly elevated methemoglobin levels in infants who were hospitalized due to prematurity or gastrointestinal infections. Only a small percentage of infants in these cohorts had clinically significant methemoglobin levels. Unfortunately, none of the case reports provides detailed information about secondary risk factors such as *a*) inherited enzyme deficiencies, or *b*) exposure to methemoglobin-inducing agents such as local anesthetics (*19*) or nitric oxide, which is used to enhance oxygenation in premature infants (*20*).

Other potential health concerns. Although approximately 2 million U.S. families drink water from private wells that fail to meet the federal drinking water standard for nitrate-N, little is known about the reproductive and chronic health effects of their exposure to nitrate. Families with nitrate-contaminated wells should not use the water to prepare infant formula. Experts disagree about the need to issue advisories to pregnant women. In a recent study in Indiana, high nitrate concentrations were found in several wells used by women who had suffered miscarriages (*21*). Some of the women had successful pregnancies after they stopped drinking water from these wells. Most state health agencies provide no specific guidance on the use of nitrate-contaminated water by other household members, despite recent reports that prolonged exposure might increase the risk of a variety of health problems.

Studies conducted in Spain (*22*), China (*23*), and Taiwan (*24*) suggest that long-term ingestion of nitrate-contaminated water may increase the risk of gastric cancer. The proposed mechanism involves the conversion of ingested nitrate to nitrite, followed by the transformation of nitrite to nitrosamines. An ecologic study of cancer incidence in the United Kingdom (*25*) failed to confirm an association between nitrate exposure and gastric cancer, but higher incidences of brain and central nervous system cancers were found in areas with elevated nitrate concentrations. In addition to these findings, Ward et al. (*26*) reported that long-term exposure to nitrate-contaminated drinking water may contribute to the risk of non-Hodgkin lymphoma.

In 1992, Kostraba et al. (*27*) suggested that low-level nitrate exposure may play a role in the etiology of insulin-dependent diabetes mellitus. The authors theorized that ingested nitrate damages the insulin-producing cells in

Table 1. Methemoglobin-inducing substances.

Substance	Uses
Aniline dyes	Laundry inks, markers
Benzocaine, lidocaine	Local anesthetics
Chlorates	Matches
Isobutyl nitrite	Room deodorizers
Naphthalene	Moth balls
Nitrate/nitrite	Drinking water, fruits, vegetables, cured meats
Nitric oxide	Inhalant used to treat pulmonary hypertension in newborns
Nitrobenzene	Metal cleaners
Nitroethane	Nail care products
Nitrogen oxides	Auto emissions, wood smoke, gas-burning appliances
Nitroglycerine	Angina drug, explosives
Resorcinol	Antipruritic, over-the-counter medications
Sodium nitrite	Pickling salts, boiler conditioners, cleaning solutions
Sulfonamides	Antibiotics

Adapted from the ATSDR (*14*).

the pancreas through the generation of free radicals. In 1994, Virtanen et al. (*28*) reported results from a nationwide case–control study of childhood diabetes in Finland. They found that case children and their mothers had higher intakes of nitrite-rich foods than did control children and their mothers. Virtanen et al. (*28*) did not find an association between diabetes and exposure to nitrate-contaminated water. In a 1997 study conducted at the University of Leeds, Parslow et al. (*29*) reported that the risk of childhood diabetes increased from a baseline of 1.00 at nitrate concentrations < 3.22 mg/L to 1.27 at concentrations > 14.85 mg/L. These concentrations correspond to 0.7 and 3.34 mg nitrate-N per liter, respectively.

Nitrate exposure may also play a role in the development of thyroid disease. In the Netherlands, Van Maanen et al. (*30*) recently evaluated thyroid volume and function in populations exposed to different nitrate concentrations in their drinking water. Their research revealed a dose-dependent difference in the volume of the thyroid between low and medium nitrate-exposure groups versus high nitrate-exposure groups. The authors observed thyroid hypertrophy at nitrate concentrations > 50 mg/L (11mg/L as nitrogen) (*30*). An inverse relationship was established between the volume of the thyroid and serum thyroid stimulating hormone levels (*30*).

Conclusions

In this paper we describe two recent cases of infant methemoglobinemia, or blue baby syndrome, that were associated with the use of water from shallow private wells to dilute formula concentrates. Nitrate-N concentrations in these water supplies ranged from 22.9 to 27.4 mg/L. These cases serve as reminders of the hazard that nitrate-contaminated water poses to infants during the first 6 months of life. Chronic exposure to nitrate-contaminated drinking water has also been linked to cancer, thyroid disease, and diabetes. In an effort to ensure the safety of rural water supplies, action should be taken to reduce nitrate inputs to groundwater. In addition, families with private water supplies should conduct annual or semiannual testing and avoid drinking the water if the nitrate-N concentration exceeds the federal drinking water standard of 10 mg/L.

References and Notes

1. Comly H. Cyanosis in infants caused by nitrates in well water. JAMA129:112–116 (1945).
2. Walton G. Survey of literature relating to infant methemoglobinemia due to nitrate-contaminated water. Am J Public Health 41:987–995 (1951).
3. Methemoglobinemia in an infant—Wisconsin 1992. MMWR 42(12):217–219 (1993).
4. Bosch HM, Rosenfield AB, Huston R, Shipman HR, Woodward FL. Methemoglobinemia and Minnesota well supplies. JAWWA 42(2):161–170 (1950).
5. Herman MI, Chyka PA, Butler AY, Rieger SE. Methylene blue by intraosseous infusion of methemoglobinemia. Ann Emerg Med 33(1):111–113 (1999).
6. Johnson CJ, Bonrud P. Methemoglobinemia: is it coming back to haunt us? Health Environ Digest 1(12):3–4 (1988).
7. Ayebo A, Kross BC, Vlad M, Sinca A. Infant methemoglobinemia in the Transylvania region of Romania. Int J Occup Environ Health 3(1):20–29 (1997).
8. Lutynski R, Steczek-Wojdyla Z, Kroch S. The concentrations of nitrates and nitrites in food products and environment and the occurrence of acute toxic methemoglobinemias. Przegl Lek 53(4):351–355 (1996).
9. The Safe Drinking Water Act. 43USC§300f (1974).
10. GAO. Information on the Quality of Water Found at Community Water Systems and Private Wells. GAO/RCED-97-123. Washington, DC:U.S. General Accounting Office, 1997.
11. CDC. A Survey of the Quality of Water Drawn from Domestic Wells in Nine Midwestern States. Atlanta, GA: Centers for Disease Control and Prevention, 1998.
12. NCHS. Trends in Pregnancy and Pregnancy Rates by Outcome: Estimates for the United States, 1976–1996. Hyattsville, MD:National Center for Health Statistics, 2000.
13. Avery AA. Infantile methemoglobinemia: reexamining the role of drinking water nitrates. Environ Health Perspect 107:583–586 (1999).
14. ATSDR. Case Studies in Environmental Medicine: Nitrate/Nitrite Toxicity. Atlanta, GA:Agency for Toxic Substances and Disease Registry, 1991.
15. Hegesh E, Shiloah J. Blood nitrates and infantile methemoglobinemia. Clin Chim Acta 125:107–115 (1982).
16. Hanukoglu A, Danon PH. Endogenous methemoglobinemia associated with diarrheal disease in infancy. J Pediatr Gastroenterol Nutr 23:1–7 (1996).
17. Krafte-Jacobs B, Brilli R, Szabo C, Denenberg A, Moore L, Salzman AL. Circulating methemoglobin and nitrite/nitrate concentrations as indicators of nitric oxide overproduction in critically ill children with septic shock. Crit Care Med 25(9):1588–1593 (1997).
18. Hjelt K, Lund JT, Scherling B, Bendixen S, Lundstrom K, Stovring S, Voldsgarrd P, Linnet K. Methaemoglobinaemia among neonates in a neonatal intensive care unit. Acta Pediatr 84(4):365–370 (1995).
19. Wilburn-Goo D, Lloyd LM. When patients become cyanotic. J Am Dent Assoc 130(6):826–831 (1999).
20. Davidson D, Barefield ES, Kattwinkel J, Dudell G, Damask M, Straube R, Rhines J, Chang CT. Inhaled nitric oxide for the early treatment of persistent pulmonary hypertension of the term newborn: a randomized, double-masked, placebo-controlled, dose-response, multicenter study. Pediatrics 101:325–334 (1998).
21. Spontaneous abortions possibly related to ingestion of nitrate-contaminated well water—LaGrange County, Indiana, 1991–1994. MMWR 45(26):569–572 (1996).
22. Morales-Suarez-Varela MM, Llopis-Gonzales A, Tejerizo-Perez ML. Impact of nitrates in drinking water on cancer mortality in Valencia, Spain. Eur J Epidemiol 11(1):15–21 (1995).
23. Xu G, Song P, Reed PI. The relationship between gastric mucosal changes and nitrate intake via drinking water in a high-risk population for gastric cancer in Moping county, China. Eur J Cancer Prev 1(6):437–443 (1992).
24. Yang CY, Cheng MF, Tsai SS, Hsieh YL. Calcium, magnesium, and nitrate in drinking water and gastric cancer mortality. Jpn J Cancer Res 89(2):124–130 (1998).
25. Barrett JH, Parslow RC, McKinney PA, Law GR, Forman D. Nitrate in drinking water and the incidence of gastric, esophageal, and brain cancer in Yorkshire, England. Cancer Causes Control 9:153–159 (1998).
26. Ward MH, Mark SD, Cantor KP Weisenburger DD, Correa-Villasenor A, Zahm SH. Drinking water nitrate and the risk of non-Hodgkin's lymphoma. Epidemiology 7(5):465–471 (1996).
27. Kostraba JN, Gay EC, Rewers M, Hamman RF. Nitrate levels in community drinking waters and risk of IDDM. An ecological analysis. Diabetes Care 15(11):1505–1508 (1992).
28. Virtanen SM, Jaakkola L, Rasanen L, Ylonen K, Aro A, Lounamaa R, Akerblom HK, Tuomilehto J. Nitrate and nitrite intake and the risk for type 1 diabetes in Finnish children. Childhood Diabetes in Finland Study Group. Diabet Med 11(7):656–662 (1994).
29. Parslow RC, McKinney PA, Law GR, Staines A, Williams R, Bodansky HJ. Incidence of childhood diabetes mellitus in Yorkshire, northern England, is associated with nitrate in drinking water: an ecological analysis. Diabetologia 40(5):550–556 (1997).
30. van Maanen JMS, van Dijk A, Mulder K, de Baets MH, Menheere PCA, van der Heide D, Mertens PLJM, Kleinjans JCS. Consumption of drinking water with high nitrate levels causes hypertrophy of the thyroid. Toxicol Lett 72:365–374 (1994).

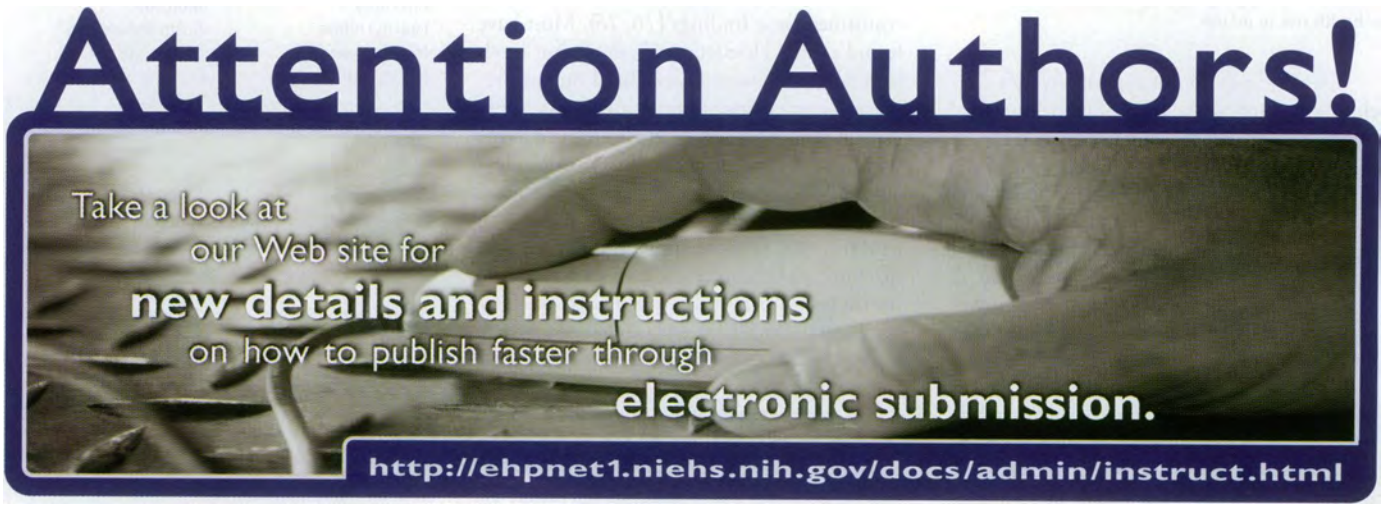

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Ammonia and greenhouse gas emissions from slurry storage - A review

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ABSTRACT

Storage of slurry is an important emission source for ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2) and hydrogen sulfide (H_2S) from livestock production. Therefore, this study collected published emission data from stored cattle and pig slurry to determine baseline emission values and emission changes due to slurry treatment and coverage of stores. Emission data were collected from 120 papers yielding 711 records of measurements conducted at farm-, pilot- and laboratory-scale. The emission data reported in a multitude of units were standardized and compiled in a database. Descriptive statistics of the data from untreated slurry stored uncovered revealed a large variability in emissions for all gases. To determine baseline emissions, average values based on a weighting of the emission data according to the season and the duration of the emission measurements were constructed using the data from farm-scale and pilot-scale studies. Baseline emissions for cattle and pig slurry stored uncovered were calculated. When possible, it was further distinguished between storage in tanks without slurry treatment and storage in lagoons which implies solid-liquid separation and biological treatment. The baseline emissions on an area or volume basis are: for NH_3: 0.12 g m^{-2} h^{-1} and 0.15 g m^{-2} h^{-1} for cattle and pig slurry stored in lagoons, and 0.08 g m^{-2} h^{-1} and 0.24 g m^{-2} h^{-1} for cattle and pig slurry stored in tanks; for N_2O: 0.0003 g m^{-2} h^{-1} for cattle slurry stored in lagoons, and 0.002 g m^{-2} h^{-1} for both slurry types stored in tanks; for CH_4: 0.95 g m^{-3} h^{-1} and 3.5 g m^{-3} h^{-1} for cattle and pig slurry stored in lagoons, and 0.58 g m^{-3} h^{-1} and 0.68 g m^{-3} h^{-1} for cattle and pig slurry stored in tanks; for CO_2: 6.6 g m^{-2} h^{-1} and 0.3 g m^{-2} h^{-1} for cattle and pig slurry stored in lagoons, and 8.0 g m^{-2} h^{-1} for both slurry types stored in tanks; for H_2S: 0.04 g m^{-2} h^{-1} and 0.01 g m^{-2} h^{-1} for cattle and pig slurry stored in lagoons. Related to total ammoniacal nitrogen (TAN), baseline emissions for tanks are 16% and 15% of TAN for cattle and pig slurry, respectively. Emissions of N_2O and CH_4 relative to nitrogen (N) and volatile solids (VS) are 0.13% of N and 0.10% of N and 2.9% of VS and 4.7% of VS for cattle and pig slurry, respectively. Total greenhouse gas emissions from slurry stores are dominated by CH_4. The records on slurry treatment using acidification show a reduction of NH_3 and CH_4 emissions during storage while an increase occurs for N_2O and a minor change for CO_2 as compared to untreated slurry. Solid-liquid separation causes higher losses for NH_3 and a reduction in CH_4, N_2O and CO_2 emissions. Anaerobically digested slurry shows higher emissions during storage for NH_3 while losses tend to be lower for CH_4 and little changes occur for N_2O and CO_2 compared to untreated slurry. All cover types are found to be efficient for emission mitigation of NH_3 from stores. The N_2O emissions increase in many cases due to coverage. Lower CH_4 emissions occur for impermeable covers as compared to uncovered slurry storage while for permeable covers the effect is unclear or emissions tend to increase. Limited and inconsistent data regarding emission changes with covering stores are available for CO_2 and H_2S. The compiled data provide a basis for improving emission inventories and highlight the need for further research to reduce uncertainty and fill data gaps regarding emissions from slurry storage.

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1. Introduction

Livestock production systems around the world generate slurry—a mixture of feces and urine from housed livestock, mixed with bedding material and cleaning water (Pain and Menzi, 2011). Storage of slurry is required to enable the spreading in the field at appropriate time to supply nutrients to crops. Thus, a major part of the slurry is transferred from housings to outdoor stores such as tanks (at or above ground level) or earthen lagoons. Stores have variable forms and dimensions (e.g. up to several hectares for lagoons) according to the required storage volume. They have been identified as important emission sources for ammonia (NH_3), hydrogen sulfide (H_2S) and greenhouse gases (GHGs) including nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) from livestock production. Slurry stores are complex systems which influence emissions in many ways (Sommer et al., 2006; VanderZaag et al., 2008; Sommer et al., 2013).

A thorough description on principal mechanisms influencing the release of NH_3, GHGs and H_2S from slurry stores can be obtained from several studies (Olesen and Sommer, 1993; Ni, 1999; Sommer et al., 2006; VanderZaag et al., 2008; Sommer et al., 2013). Some important basic principles are summarized here. Slurry stores have a defined area where the gas exchange with the atmosphere takes place. It is a diffusive process and is quantified by emission rate values with the unit mass per area and time. Dissolved species of the gases are produced through microbial breakdown of nitrogen or organic compounds in the bulk slurry. Depending on prevailing chemical equilibria (e.g. NH_3/NH_4^+ which shifts to NH_4^+ at a low pH-value) and absence of microbial consumption, the gases move towards the emitting surface driven by diffusion (i.e. movement due to concentration gradients) and convection where parcels of air or liquid induce a movement of the compounds in the slurry (Sommer et al., 2013). At the slurry-air interface, the compounds pass gas- and liquid-phase resistances and diffuse into the air where they are transported to the atmosphere by convection. Transport within the liquid phase is temperature dependent and the gas-phase transfer is dependent on both temperature and turbulence (VanderZaag et al., 2015). Depending on the dry matter content of the slurry or more precisely, the amount of particles in the slurry which is influenced by the slurry type, animal species, animal diets, the thickness of the slurry bulk layer in the stores and meteorological conditions (Smith et al., 2007), a natural crust at the slurry surface can develop. It constitutes a barrier to the gas molecules between the liquid and the air. NH_3 and CH_4 may be consumed due to microbial activity in the crust leading to an emission reduction (Petersen and Ambus, 2006; Nielsen et al., 2010) while N_2O production may be enhanced (VanderZaag et al., 2009).

Ammonia has a large variety of negative environmental impacts which encompass the quality of air, soil and water, ecosystems and biodiversity. Moreover, it contributes to the formation of particulate matter which impairs human health (Sutton et al., 2011). N_2O and CH_4 are strong GHGs (Myhre et al., 2013). H_2S is often related to odor nuisances and can be lethal to animals and humans at high exposure levels (Sommer et al., 2013). NH_3 and GHG emissions have been regulated by the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (UNECE, 1999) and by the Kyoto protocol arising from the UN Framework Convention on climatic change (UN, 1997), respectively. Member countries of these protocols are obliged to calculate and report their national emissions annually, to track changes and compare to national emission ceilings where applicable. The methods for emission reporting are defined in EEA (2016) for NH_3 and in IPCC (2006) for N_2O and CH_4.

EEA (2016); IPCC (2006) and UNECE (2014) provide emission factors for slurry storage or numbers for emission reduction related to mitigation techniques which are used for emission reporting in emission inventories. However, a considerable number of recent studies on emissions from slurry storage provide updated information. The present review paper aims therefore to collect the data on NH_3, GHGs (CH_4, N_2O, CO_2) and H_2S emissions from these recent but also from previous studies and to provide a comprehensive overview on emissions from cattle or pig slurry stored uncovered and emission changes due to slurry treatment and coverage of slurry stores. This information can be used for the purpose of guide values, e.g. for the evaluation of emission data, and for improving emission inventories (greater accuracy, reduced uncertainty), e.g. for the determination of baseline emissions or emission reductions due to slurry treatment or coverage of slurry stores. The compiled data is entirely provided in the Supplementary data 2 for tracking the present or conducting future analyses.

2. Material and methods

2.1. Data search and data selection

A literature research was carried out with Web of Science [5.3] using the following search terms: “storage”, “slurry”, “emission”; “lagoon”, “slurry”, “emission”. These searches were done on January 10, 2018 and yielded 601 papers in total. In a first screening, 290 papers were eliminated because they did not encompass livestock slurry. The remaining 311 articles were retained. In addition, 58 papers were found in the reference list of the screened articles. Therefore, in total, 369 articles were retained for further screening according to the following criteria:

(i) The investigated slurry was produced in an animal operation and consisted of urine and feces excreted from the animals onto a floor of a barn, a hardstanding or a milking parlor. The slurry might contain solids like bedding material or feed residues and be diluted with water. The investigated slurry was untreated or submitted to a treatment such as solid-liquid separation, anaerobic digestion, addition of an acid (acidification), additives or co-substrates. The treatment occurred under real-world conditions or after slurry sampling in the laboratory. Studies based on synthetic slurry, e.g. urine and feces collected separately from animals and subsequently combined in the laboratory, were excluded since fresh animal excretions substantially differ in chemical composition from stored slurry (Table 6). Moreover, urine and feces deposited onto a floor can rapidly undergo processes leading to gaseous losses. Hence, synthetic slurries might induce different emission levels as compared to slurries submitted to real-world conditions.

(ii) The untreated or treated slurry was transferred from the animal operation to a storage tank or a lagoon outside of animal housings and then submitted to measurements under real-world conditions or the slurry as characterized under point (i) was collected from a floor, an underfloor pit or an outside store and subsequently transferred to an experimental vessel where emissions were measured at pilot- or laboratory-scale. Studies encompassing e.g. emissions from a pit below an animal confinement were excluded since such facilities provide an environment which substantially differs from outside stores (e.g. exposure to outdoor climate, disturbance of the slurry surface due to continuous addition of animal excretions over almost the whole area of a pit).

(iii) The reported emission data are based on experimental determination of emission rates as defined by VanderZaag et al. (2008). Studies providing gas concentrations only were excluded.

(iv) The article provides numerical data encompassing emission data or percent differences in emissions between a slurry submitted to a treatment or slurry stored with covering and a reference system with untreated slurry or uncovered storage, respectively.

After evaluation, 120 papers complied with criteria (i) to (iv). 93 papers did not provide numerical data or comply with these criteria but included substantial information on emissions from slurry storage, e.g. basic mechanisms driving emissions. The remaining 156 papers were excluded because they were out of topic or did not provide substantial

information. An overview on the screened papers is in Supplementary data 1.

2.2. Data extraction

Data from the 120 papers were extracted. The parameters as shown in Table 1 were transformed, standardized or aggregated where necessary and then compiled in a database. Overall, 711 records were available for the analysis where one record is defined as an ensemble of entries listed in Table 1 (i.e. multiple records may be created from a single paper). Each record may differ in completeness according to the information provided in a paper.

2.3. Standardization of emission data

Emissions were reported in the papers using numerous units involving the gas molecule (i.e. NH_3, N_2O, CH_4, CO_2 and H_2S) or N, C or S included therein and various units for weight, time and surface or volume. Also, cumulative emissions were given over the entire experimental period. Overall, 36, 22, 31, 13 and 3 different ways for emission reporting were found for NH_3, N_2O, CH_4, CO_2 and H_2S, respectively. Standardization was performed in the present study to obtain comparable values over all records. For all emission rates, the unit g of molecules was used according to UNECE, (2015) and IPCC (2006). An emission on an area basis was applied for NH_3, N_2O, CO_2 and H_2S. For CH_4, the emission relative to the bulk volume was employed. Due to the availability of numerous additional records, data relative to the area were also provided for CH_4. For the area and the volume, the unit m^2

Table 1
Parameters extracted from the papers after transformation or standardization and transferred into the database. Explanations are given for parameters marked with symbols in the table footnote. The complete extracted data are provided in the Supplementary data 2.

Parameter	Explanation
Year	Date the study was published
Country	Location where the study was done
Slurry type	Cattle or pig
Slurry treatment	Untreated, solid-liquid separation, anaerobic digestion, acidification, aeration, addition of additives, dilution with water, addition of co-substrates (also denoted off-farm materials; mostly organic residues from e.g. food industry or energy crops) and combinations of treatments (e.g. solid-liquid separation and anaerobic digestion)
Slurry characteristics	Chemical analysis of the slurry: dry matter (DM), volatile solids (VS), total nitrogen (N_{tot}), ammonium (NH_4^+; TAN (total ammoniacal nitrogen) is often used instead of NH_4^+), total carbon (C), total sulfur (S) in g L^{-1}, pH
Type of study*	Farm-scale, pilot-scale, laboratory-scale
Type of store	For farm-scale studies: tank, lagoon according to Pain and Menzi (2011)**
Replicates	Number of replicates of real-world stores or experimental vessels
Store characteristics	Investigated store surface (m^2), depth (m), and volume (m^3); agitation of slurry (number of agitation events); other producer events or meteorological conditions; slurry temperature (°C)
Experimental conditions	Duration of storage of investigated slurry (days); duration of the study (days); number of measurement periods and total duration of the measurement (hours); season of measurements: cold, temperate, warm; for the determination of the season, the meteorological winter, spring or fall and summer were considered
Meteorological conditions	Air temperature during measurements (°C); air speed over the emitting surface during measurements (m s^{-1}); rainfall (cumulative amount during measurements in mm)
Measurement methods applied	Measurement method for the gases: dispersion modeling based on a backward Lagrangian stochastic (bLS) dispersion model or UK-ADMS atmospheric dispersion model, flux chamber method, flux gradient method, micrometeorological mass balance method (e.g. integrated horizontal flux, IHF; vertical radial plume mapping, VRPM), sampling at exhaust chimney, tracer gas method, method not further defined; instrument used for the concentration measurements of the gases
Cover type	Storage uncovered or covered; For covered storage: cover type according to VanderZaag et al. (2015): impermeable structural covers: lid (wood or concrete), tent covering; impermeable floating covers: plastic film; permeable synthetic floating covers: plastic fabrics, expanded clay, other materials such as expanded polystyrene, plastic tiles; permeable natural floating covers: peat, straw, vegetable oil, other organic materials (wood chips, sawdust etc.), other cover types such as storage bag
Occurrence of a natural crust at the store's surface	Formation of natural crust: yes or no, crust thickness (cm), time for natural crust formation (days)***
Measurement data****	NH_3 (g NH_3 m^{-2} h^{-1}, g NH_3 m^{-3} h^{-1}, g NH_3 AU^{-1} h^{-1}), NH_3-N in % TAN and in % N, N_2O (g N_2O m^{-2} h^{-1}, g N_2O m^{-3} h^{-1}, g N_2O AU^{-1} h^{-1}), N_2O-N in % TAN and % N, CH_4 (g CH_4 m^{-2} h^{-1}, g CH_4 m^{-3} h^{-1}, g CH_4 AU^{-1} h^{-1}), CH_4-C % VS, CO_2 (g CO_2 m^{-2} h^{-1}, g CO_2 m^{-3} h^{-1}, g CO_2 AU^{-1} h^{-1}), CO_2-C in % VS, CO_2eq (g CO_2eq m^{-2} h^{-1}, g CO_2eq m^{-3} h^{-1}, g CO_2eq AU^{-1} h^{-1}), H_2S (g H_2S m^{-2} h^{-1}, g H_2S m^{-3} h^{-1}, g H_2S AU^{-1} h^{-1}); Difference between untreated and treated slurry or between slurry stored uncovered and stored covered in percent for NH_3, N_2O, CH_4, CO_2, CO_2eq, H_2S

* Type of study: Farm-scale: measurements carried out at real-world storage facilities at a farm site. This information could be obtained from the description of the experimental setup given in the papers. Pilot-scale and laboratory-scale: measurements conducted under controlled conditions in experimental vessels. Due to a lack of definition for these study types, a discrimination according to the following characteristics was employed: Pilot-scale: volume of slurry investigated: ≥ 500 L with experimental vessels situated outdoors, with or without a shelter and submitted to ambient meteorological conditions. Laboratory-scale: volume of slurry investigated: < 500 L. Most of the studies defined as laboratory-scale studies were conducted indoors in a temperature-controlled room. Three studies deviated from the conditions regarding study situation or temperature control and for four studies, this information was not available (Supplementary data 2). Despite these gaps in information, the studies were retained.

** A tank is a large, normally open-top, in most cases circular vessel made from pre-fabricated vitreous enameled steel, concrete or wood panels charged from a reception pit and emptied using a pump. It is a facility constructed at or below ground level and may extend above ground with a depth of several meters. Earthen storage basins not designed for biological treatment of slurry are considered as stores equivalent to tanks. Like earthen storage basins, a lagoon is a large rectangular or square shaped structure with sloping earth bank walls and may be lined with water impermeable material. Lagoons are designed for both storage and biological treatment (Pain and Menzi, 2011). They are not emptied below a specific depth necessary for slurry treatment except for maintenance (Hamilton et al., 2001).

*** We did not consider a natural crust as a mitigation technique equivalent to covering of slurry stores. The significance of crusting and considerations regarding distinction between crusting and storage covering are specifically addressed in Section 4.2.4.

**** For units: see Section 2.3. Acronyms: AU: animal unit = animal with a live weight of 500 kg; CO_2eq: carbon dioxide equivalent. CO_2eq is a standardized unit for different greenhouse gases. The numbers reported rest on data provided by the authors of the papers which were mostly based on IPCC (2007); TAN: total ammoniacal nitrogen; N: nitrogen; VS: volatile solids.

and m^3 was used, respectively. For all gases, the time unit hour was applied (reasons are given in section 4.1). Where useful for inventories, the time unit year was additionally provided for emissions. In this paper, the emission data standardized as explained above are denoted emission on an area or volume basis.

Since emission inventories do usually not apply emissions on an area or volume basis but emission factors which express emissions as a proportion of a compound present in the slurry store, data were additionally scaled as follows: percent of TAN for ammonia (EEA, 2016), percent of N for N_2O (IPCC, 2006) and percent of VS for CH_4 (IPCC, 2006) and CO_2. To be consistent with the notion "emission on an area or volume basis" regarding terminology, we used the term flow-based emission. Flow-based emissions were either taken from the papers or determined based on the emission rate, the N, TAN or VS content of the slurry, the volume of the store and the duration of the experiment. Dividing the cumulative emission which was derived from the emission rate and the duration of the study by the amount of the compounds present in the store at the beginning of the experiment (derived from the slurry content of N, TAN or VS and the slurry volume) yielded the flow-based emission. It was only calculated if no slurry addition or discharge occurred during the experiment.

2.4. Data analysis

2.4.1. Descriptive statistics of the emission data

In a first step, descriptive statistics (number of records, minimum, 1 st quantile, median, average, 3rd quantile, maximum, standard deviation) were calculated over all records encompassing slurry stored uncovered. There were eight categories for data reporting resulting from the combination of two slurry types (cattle and pig) with four study types (farm-scale lagoon comprising solid-liquid separation and biological treatment of slurry; farm-scale tank, pilot-scale and laboratory-scale which include untreated slurry).

2.4.2. Baseline emissions

2.4.2.1. Definition. We define the term baseline emission as the average emission occurring with slurry storage according to the reference technology without emission control similar to VanderZaag et al. (2015). This implies uncovered storage in the following types of store: i) tanks or earthen stores without slurry treatment; ii) lagoons with solid-liquid separation and biological treatment occurring during storage (Hamilton et al., 2001). The baseline emission is considered as representative for average emissions over the whole course of a year. According to EEA (2016), baseline emissions are given separately for cattle and pig slurry. We further distinguished between storage in tanks (or earthen stores) and lagoons. Baseline emissions were calculated from uncovered slurry stores regardless of the occurrence of a natural crust because its formation can be only partially controlled and thus varies widely between stores (Smith et al., 2007). Moreover, there was insufficient information about the presence of crusts in the data impeding a distinction between crusted and non-crusted store's surfaces.

2.4.2.2. Determination. Baseline emissions were calculated using farm-scale and pilot-scale studies published in peer-review papers. For the calculation of representative emissions, important influencing factors should be considered such as the meteorological conditions (mainly air temperature, wind speed, precipitation) and operations at storage facilities (Sommer et al., 2013). Among these factors, we were able to include air temperature since the season used for emission measurements which can be used as surrogate for the temperature was available for more than 90% of the records. Records were dropped where conditions prevailed which are not representative for slurry storage in practice over a longer period, e.g. if daily agitation of slurry occurred. More detailed information on meteorological conditions and operations at storage facilities was not available and could not be included in the evaluation of emissions (e.g. only approx. 60% of records provided numerical air temperature data). Information on wind speed, precipitation and crust formation was available for less than half of the records.

We hypothesized that for generating emission data which are representative over the whole course of a year, emission values generated during the cold, the warm and the temperate season (spring, fall) should be equally covered. To achieve this, a weighting of the emission data for season was done. Values were aggregated according to the categorization "Season code" ("c": cold season = winter, "t": temperate season = spring or fall, "w": warm season = summer, "c,t": cold and temperate season, "c,w": cold and warm season, "t,w": temperate and warm season, "c,t,w": cold, temperate and warm season), "Slurry type" (cattle, pig), "Type of study" (farm-scale, pilot-scale) and "Type of store" (for farm-scale studies: lagoon, tank). For some papers, emission values for each individual season "c", "t", and "w" were provided and also the average value over the year, i.e. the "c,t,w" value. In these cases, the "c,t,w" value is denoted as redundant in the database (Supplementary data 2). It was used for the further calculations and not the values of the individual seasons. The aggregated values were averaged afterwards in the following manner:

i) Study duration varied considerably, i.e. individual experiments ranged from less than one day up to several months. The individual records were thus weighted according to measurement durations of records within each "Season code" category. The individual records were aggregated to four classes of measurement durations: a) ≥1 month, b) ≥1 week to < 1 month, c) ≥1 day to < 1 week, d) < 1 day. Weighting was done based on the square-root of the median of the measurement duration for each class to avoid over-emphasis of long-term measurements. The median values of the measurement duration for the 4 classes a, b, c and d were 146.5 days, 16.9 days, 4.5 days and 0.34 days, respectively. This implied the following respective weights 12.1, 4.1, 2.1 and 0.6. Therefore, a record based on a measurement of more than one month received a weighting 20.8 times higher than a record based on a measurement over less than a day.
ii) Average values for each season "c", "t" and "w" were calculated from all available values within one category (based on "Slurry type", "Type of study" and "Type of store"). Averaging was done in a way that values spanning over more than one season were attributed to the respective seasons, i.e. a value for "c,t" was attributed half to "c" and half to "t", a value of "c,t,w" was counted one fourth to seasons "c" and "w" and one half to season "t". For example, to average a "c" value based on a 2 weeks measurement (c_{2weeks}), a "c" value based on a 2 days measurement (c_{2days}) and a "c,w" value that based on a 2 months measurement ($cw_{2months}$) led to the following average "c" value: "c_{avg}" = (c_{2weeks}*$weight_{2weeks}$ + c_{2days}*$weight_{2days}$ + $cw_{2months}$*0.5*$weight_{2months}$)/($weight_{2weeks}$ + $weight_{2days}$ + 0.5*$weight_{2months}$).
iii) These average values were further averaged to annual emission rates "c,t,w" by weighting the value for season code "t" twice as high as the seasons "c" and "w" (i.e. "c,t,w_{avg}" = ¼*"c" + ½*"t" + ¼*"w") since the temperate season code "t" includes two seasons (spring and fall). These final averaged values are listed in column "Avg" in Tables 8, 9 and Supplementary data 4.

Numbers for baseline emissions are reported as average emission values if at least one record for each of the season "c", "t" and "w" was available. Included can be a record from an individual season (i.e. "c", "t" or "w"), or any kind of seasons combination (i.e. "c,t" "c,w" "t,w" or "c,t,w"). The lower and upper 95% confidence bounds (l95, u95) for baseline emissions were determined using bias-corrected and accelerated bootstrap intervals (Efron, 1987) if at least three individual records for each of the season "c", "t" and "w" were available. Again, this can be in the form of an individual season or any kind of seasons

combination as for the calculation of the average. The bootstrapping was done as non-parametric bootstrapping with sampling stratified by season. To test whether there are significant ($p < 0.05$) differences in these baseline emission values, 95% confidence intervals were obtained from bootstrapping the differences between each combination of values. If a confidence interval of a difference did not include 0, the difference was marked as statistically significant.

The data resulting from this procedure related to emissions on an area or volume basis were aggregated according to the slurry type (cattle and pig) and the study types farm-scale tank and pilot-scale and for the two study types combined which were denoted as baseline emissions tank. The baseline emissions for lagoons are based on measurements carried out at farm-scale for lagoons. Baseline emissions expressed as flow-based emissions were given separately for cattle and pig slurry for tanks only due to a lack of appropriate data for lagoons. The calculation procedure is additionally illustrated based on an example in the Supplementary data 9.

2.4.3. Emissions and emission changes due to slurry treatment and covering of slurry stores

We determined the emission changes due to slurry treatment techniques and covering of slurry stores using records with a treatment or a cover and a reference system (uncovered storage with untreated slurry) to compare the emissions on an area or volume basis from both. Due to the limited number of available records, the restriction to peer review papers and exclusion of laboratory-scale studies was not applied. For storage covering, all records with less than 20 cm of slurry depth were excluded from the data analysis since it is likely that such conditions differ too much from the real-world and even more evident if the thickness of the cover material is similar to that of the bulk slurry layer. Studies where slurry depth was not provided were excluded.

Although a natural crust is often listed as abatement measure together with slurry store covers (Bittman et al., 2014) we did not consider it as a mitigation technique equivalent to covering of slurry stores. In contrast to coverings such as impermeable floating covers, it is not applicable for all stores since it does not form at each slurry type. Crusting was neither considered for the analysis on emission changes due to slurry treatment and covering of slurry stores because of insufficient information about the presence of crusts in the experimental data. The significance of crusting is specifically addressed in Section 4.2.4.

The numbers from different studies were aggregated without a weighting for season or measurement duration due to the limited number of records. We tested whether the differences between treatments or covers and the reference system (untreated slurry or uncovered storage) were significantly different from zero by a two-sided t-test.

3. Results

3.1. Characterization of the database

3.1.1. General characteristics

The literature review yielded a total of 711 records. Among them, 13% were from before 2000. The period between 2000 and 2010 contributed 43%, and 44% were published after 2010 (Table 2). US and CA generated 28% and 19%, respectively, of the records while 11 European countries provided 48%. Two countries from Asia and Oceania contributed 3% and 2% of the records. Ammonia was studied in 38% of the records, while 59% were on GHGs, and 3% on H_2S. Among GHGs, CH_4 was most often investigated with a share of 30% of all records. 47% of the records included one gas and 53% several gases.

Table 3 shows the types of studies. A share of 46% of the records are based on studies conducted at farm-scale. Pilot-scale studies contributed 31% and laboratory-scale 23% of the records. Records from pilot-scale studies are similarly represented over all three periods before 2000, between 2000 and 2010 and after 2010. In contrast, data from farm-scale studies and conducted in the laboratory occur more frequently from 2000 onwards.

An overview of the investigated slurry types is shown in Table 4. Cattle and pig slurry each account for about 50% of the investigated slurries. Cattle slurry mostly originated from dairy cows while for pig slurry fattening pigs and breeding pigs or a mixture of both was studied. Other types of slurry were included in measurements as well, but these occur much less. The proportion of untreated slurries is 65% and 87% for cattle slurry and pig slurry, respectively. Solid-liquid separation occurs for 16% (cattle slurry) and 3.7% (pig slurry) of the records. Anaerobic digestion of unseparated slurry applies for 7.2% (cattle slurry) and 3.7% (pig slurry) of the records while for anaerobically digested and separated slurry, the numbers are 8.1% for cattle slurry and 0.6% for pig slurry, respectively. Other treatments encompass acidification, aeration, supplementation with additives or dilution of slurry, but these treatments occur less.

Approximately 140 records compare the emissions between covered and uncovered storage. More than 80% of these data are from pilot and laboratory studies. Straw covers and other natural materials such as wood chips or maize stalks were most often investigated (51 in total). Also, cover types such as a lid, plastic film and fabrics were frequently addressed resulting in approximately 15 records for each.

Measurement methods employed in the experiments are shown in Table 5. Roughly, two thirds of all measurements were carried out using a flux chamber method. While this is almost the only option for pilot- and laboratory-scale studies, this system was also used for approximately 30% of the measurements conducted at farm sites. Methods like dispersion modeling or micrometeorological mass balance method make up about 60% of the records from farm-scale studies. Other methods e.g. using a tracer gas were rarely applied.

Slurry analyses are shown in Table 6. Not all studies provided analytical data of the slurry (e.g., only 84% of NH_3 studies presented TAN values). While most laboratory studies analyzed TAN, only 67% of the studies carried out at farm sites reported this parameter. Pilot-scale studies lie in between with 92% of records reporting TAN data. The availability of analytical data is similar for other parameters (e.g. DM) as for TAN but with somewhat lower numbers. The composition of the mixture of urine and feces as excreted by animals published by ASAE (2005) and Richner et al. (2017) is added at the bottom of Table 6. They provide numbers for cattle on DM, VS and TAN in the range of 80 to 90 g L^{-1}, 53 to 70 g L^{-1} and 1.4 to 2.1 g L^{-1}, respectively. For pigs, the values for DM, VS and TAN are in the range of 50 to 90 g L^{-1}, 36 g L^{-1} and 3.4 to 5.0 g L^{-1}. The slurry analyses given in the records show substantially lower numbers for DM and VS contents for untreated slurries which is most likely due to dilution with water from farm operation and rainfall at the farms (Table 6). Studies at farm-scale based on tanks, at pilot-scale and at laboratory-scale exhibit DM contents which are in a similar range within cattle and pig slurry. Numbers for DM are lower for pig slurries compared to cattle slurry except for laboratory scale studies. Pig slurry exhibits higher N_{tot} and TAN contents than cattle slurry. Within farm-scale studies, the numbers for all analytes strongly differ between slurry from tanks and from lagoons. Values for DM, VS, N_{tot} and TAN are lower for lagoons by a factor of approximately two to eight as compared to slurry stored in tanks. Slurries from lagoons compare better with slurries after solid-liquid separation (Table 6) than with untreated slurries.

3.1.2. Descriptive statistics of emission data from cattle and pig slurry stored uncovered

Descriptive statistics are shown in Table 7 for NH_3, N_2O, CH_4, CO_2 and H_2S over all records encompassing untreated cattle and pig slurry stored uncovered from studies conducted at farm-, pilot- and laboratory-scale (farm-scale studies with lagoons include biologically treated and separated slurry; see section 2.4.2.1). Data from measurements conducted during warm, temperate and cold seasons are unevenly

Table 2
Number of records listed by country and year of publication and share of total records by country.

Country	Before 2000		2000 to 2010		After 2010		total			Share of total
	Cattle	Pig	Cattle	Pig	Cattle	Pig	Cattle	Pig	Cattle and pig	
AT	0	0	15	6	0	0	15	6	21	3%
AU	0	0	0	0	0	4	0	4	4	1%
CA	1	1	47	10	72	5	120	16	136	19%
CN	0	0	0	0	0	17	0	17	17	2%
DE	8	9	4	2	0	0	12	11	23	3%
DK	20	17	0	0	6*	14	22	35	57	8%
ES	0	0	0	0	1	0	1	0	1	0.1%
FR	0	0	2	33	0	6	2	39	41	6%
IT	0	0	23	32	12	12	35	44	79	11%
JP	0	0	0	0	3	0	3	0	3	0.4%
LT	0	0	0	0	0	21	0	21	21	3%
NL	13	11	4	4	0	0	17	15	32	5%
NZ	6	0	1	1	2	0	9	1	10	1%
PT	0	0	4	0	4	8	8	8	16	2%
SE	0	0	1	0	6	3	7	3	10	1%
UK	1	3	13	2	6	13	20	18	38	5%
US	1	3	13	86	74	25	88	114	202	28%
Total	50	44	127	176	182	132	359	352	711	100%
Share of total	13%		43%		44%		100%			

* Cattle slurry with addition of other types of manure and feedstock materials.

Table 3
Number of records classified by type of study (farm-scale, pilot-scale, laboratory-scale) and time periods of publication and in percent of the total.

Type of study	Before 2000	2000 - 2010	After 2010	Total	Share of study types
Farm-scale	27	157	141	325	46%
Pilot-scale	54	75	90	219	31%
Laboratory-scale	13	77	77	167	23%
Total	94	309	308	711	100%
Publication of study types over time (in percent of total)					
Farm-scale	8%	48%	43%	100%	
Pilot-scale	25%	34%	41%	100%	
Laboratory-scale	8%	46%	46%	100%	

Table 4
Overview on investigated slurry types stored uncovered or covered: number of records listed by slurry treatments, slurry types and share of the total records in percent.

Slurry treatment	Cattle n	Pig	Other*	Cattle Percent of total	Pig	Other*
Untreated	233	302	–	65%	87%	–
Solid-liquid separation	57	13	–	16%	3.7%	–
Anaerobic digestion	26	13	–	7.2%	3.7%	–
Anaerobic digestion, solid-liquid separation	29	2	4	8.1%	0.6%	100%
Acidification	5	3	–	1.4%	0.9%	–
Acidification, anaerobic digestion	–	2	–	–	0.6%	–
Acidification, anaerobic digestion, solid-liquid separation	–	1	–	–	0.3%	–
Acidification, solid-liquid separation	–	1	–	–	0.3%	–
Dilution	5	2	–	1.4%	0.6%	–
Addition of additives	3	3	–	0.8%	0.9%	–
Aeration	1	4	–	0.3%	1.1%	–
Aerobic treatment	–	2	–	–	0.6%	–
Total	359	348	4	100%	100%	100%

* Cattle slurry with addition of other types of manure and feedstock materials.

Table 5
Number of records classified by the measuring method and by the type of study.

Measuring method	Farm-scale	Pilot-scale	Laboratory-scale	Total	
Dispersion modeling based on bLS* or ADMS**	107	2		109	15%
Dispersion modeling based on bLS* and VRPM***	8			8	1.1%
Flux chamber method	98	213	167	478	67%
Flux gradient method	4			4	0.8%
Micrometeorological mass balance method	92			92	13%
Sampling at exhaust chimney	4			4	0.6%
Tracer gas method	7			7	1.0%
Method not defined	5	4		9	1.3%
Total	325	219	167	711	100%

* backward Lagrangian stochastic (bLS) dispersion model.
** UK-ADMS atmospheric dispersion model (Hill et al., 2008).
*** Vertical Radial Plume Mapping.

distributed over all records (Supplementary data 3). The minimum and maximum emission values differ by one to several orders of magnitude for all gases. The average often exceeds the median by a factor of two or more which is most pronounced for N_2O. This indicates a distribution of data being right skewed by high values. The variability of data and the occurrence of high maximum values is most pronounced for laboratory-scale studies. Striking high values exceeding the median by at least one order of magnitude for NH_3, CH_4 and CO_2 are reported in the laboratory-scale study of Guarino et al. (2006). For N_2O, high values were found from three studies conducted at farm- and pilot-scale (Clemens et al., 2006; Amon et al., 2007; Leytem et al., 2011) (Supplementary data 2,8,11). For H_2S, one figure from a laboratory-scale study stands out which exceeds all other values by two orders of magnitude (Hobbs et al., 1999).

Table 6
Number of records of a slurry type (cattle, pig), type of study (f: farm-scale; p: pilot-scale; l: laboratory-scale), type of store for farm-scale studies, and slurry treatment (untreated, sol-liq sep: solid-liquid separation) in the database. Number of records (n) with analytical data on DM, VS, N_{tot}, TAN and average contents of DM, VS, N_{tot}, TAN in g L^{-1} for untreated slurry.

Slurry type	Type of study*	Type of store	Slurry treatment**	Total number of records	DM	VS	N_{tot}	TAN	DM	VS	N_{tot}	TAN
				n	n				g L^{-1}			
Cattle	f	lagoon	untreated	73	19	7	13	14	17	3.7	1.2	0.2
Cattle	f	tank	untreated	39	21	9	19	25	67	48	3.1	1.5
Cattle	p		untreated	106	97	36	93	97	62	53	3.2	1.6
Cattle	l		untreated	35	31	24	29	31	57	43	3.0	1.3
Pig	f	lagoon	untreated	109	19	23	50	76	9.7	4.5	0.8	0.6
Pig	f	tank	untreated	55	35	9	33	35	42	37	3.3	1.9
Pig	p		untreated	63	56	30	56	54	50	33	4.6	3.2
Pig	l		untreated	68	68	43	64	64	59	56	4.7	2.9
Cattle	f tank, p, l		sol-liq sep	23	19	10	17	17	39	29	2.4	1.2
Pig	f tank, p, l		sol-liq sep	14	10	5	8	12	29	23	3.8	2.3
Cattle	Contents of mixture of urine and feces obtained from ASAE (2005)								*80*	*53*	*3.0*	*1.4*
Pig									*61-90*	*n.a.*	*4.7-7.0*	*3.4-5.0*
Cattle	Contents of mixture of urine and feces obtained from Richner et al. (2017)								*90*	*70*	*3.9*	*2.1*
Pig									*50*	*36*	*6.5*	*4.6*

n.a.: not available.
* f: farm-scale; p: pilot-scale; l: laboratory-scale.
** sol-liq sep: solid-liquid separation.

Table 7
Emissions from cattle and pig slurry stored uncovered in tanks at farm-scale, pilot-scale and laboratory-scale without slurry treatment and in lagoons with solid-liquid separation and biological treatment; descriptive statistics for NH_3, N_2O, CH_4, CO_2 and H_2S in g m^{-2} h^{-1} or g m^{-3} h^{-1}. n: number of records; Min: minimum; 1 st Qu: first quartile; 3 st Qu: third quartile; Max: maximum; Std: standard deviation. Additional information is provided in Supplementary data 3.

Slurry type	Study type		n	Min	1 st Qu	Median	Average	3rd Qu	Max	Std
				NH_3 g m^{-2} h^{-1}						
Cattle	Farm-scale	lagoon	35	< 0.01	0.03	0.10	0.13	0.21	0.36	0.11
Cattle	Farm-scale	tank	20	0.02	0.04	0.06	0.13	0.16	0.68	0.15
Cattle	Pilot-scale		53	< 0.01	0.03	0.07	0.09	0.11	0.44	0.08
Cattle	Laboratory-scale		19	< 0.01	0.02	0.04	0.26	0.33	1.4	0.43
Pig	Farm-scale	lagoon	74	< 0.01	0.04	0.08	0.15	0.18	0.68	0.18
Pig	Farm-scale	tank	23	0.03	0.06	0.10	0.22	0.27	1.0	0.26
Pig	Pilot-scale		22	0.01	0.06	0.20	0.24	0.26	0.92	0.23
Pig	Laboratory-scale		20	< 0.01	0.03	0.23	0.69	0.71	4.5	1.16
				N_2O g m^{-2} h^{-1}						
Cattle	Farm-scale	lagoon	13	< 0.001	< 0.001	< 0.001	0.002	0.001	0.02	0.006
Cattle	Farm-scale	tank	3	< 0.001	0.001	0.002	0.002	0.003	0.003	0.002
Cattle	Pilot-scale		46	< 0.001	< 0.001	0.001	0.003	0.004	0.04	0.007
Cattle	Laboratory-scale		6	< 0.001	< 0.001	< 0.001	0.005	0.001	0.03	0.01
Pig	Farm-scale	lagoon	6	< 0.001	< 0.001	< 0.001	0.003	0.002	0.01	0.005
Pig	Farm-scale	tank	5	Not detected						
Pig	Pilot-scale		17	< 0.001	< 0.001	< 0.001	0.01	0.001	0.06	0.02
Pig	Laboratory-scale		4	< 0.001	< 0.001	< 0.001	0.003	0.003	0.01	0.006
				CH_4 g m^{-3} h^{-1}						
Cattle	Farm-scale	lagoon	3	0.27	0.29	0.30	0.77	1.0	1.7	0.83
Cattle	Farm-scale	tank	7	< 0.01	0.26	0.75	0.83	1.3	1.9	0.71
Cattle	Pilot-scale		46	0.01	0.07	0.42	0.56	0.75	3.6	0.69
Cattle	Laboratory-scale		15	< 0.01	0.15	0.64	10	16	51	16
Pig	Farm-scale	lagoon	2	< 0.01	0.88	1.8	1.8	2.6	3.5	2.5
Pig	Farm-scale	tank	10	0.02	0.25	0.55	1.6	3.1	5.0	1.8
Pig	Pilot-scale		21	0.01	0.13	0.18	0.77	1.0	3.4	1.1
Pig	Laboratory-scale		18	0.02	1.3	2.9	7.4	6.6	33	10
				CO_2 g m^{-2} h^{-1}						
Cattle	Farm-scale	lagoon	18	0.27	1.9	2.3	4.7	5.3	27	6.4
Cattle	Farm-scale	tank	3	11	11	11	16	18	25	8.1
Cattle	Pilot-scale		15	0.17	2.8	4.3	5.6	6.3	21	5.2
Cattle	Laboratory-scale		14	0.45	2.4	8.0	86	189	332	120
Pig	Farm-scale	lagoon	7	< 0.01	< 0.01	0.03	0.89	0.74	4.7	1.8
Pig	Farm-scale	tank	1	5.7	5.7	5.7	5.7	5.7	5.7	–
Pig	Pilot-scale		7	3.2	3.6	4.4	6.6	9.0	13	4.1
Pig	Laboratory-scale		14	1.0	6.3	9.1	52	80	217	75
				H_2S g m^{-2} h^{-1}						
Cattle	Farm-scale	lagoon	3	0.02	0.04	0.06	0.05	0.07	0.07	0.03
Cattle	Laboratory-scale		3	< 0.01	< 0.01	0.01	0.01	0.01	0.02	0.01
Pig	Farm-scale	lagoon	14	< 0.01	< 0.01	< 0.01	0.01	0.03	0.08	0.02
Pig	Laboratory-scale		6	< 0.01	< 0.01	< 0.01	0.47	0.02	2.8	1.1

Table 8
Emissions on an area or volume basis from cattle and pig slurry stored uncovered in tanks at pilot-scale and at farm-scale without slurry treatment and in lagoons with solid-liquid separation and biological treatment. Baseline emissions for storage in tanks and lagoons given in g m^{-2} h^{-1} / kg m^{-2} y^{-1} for NH_3, N_2O and CO_2 and in g CH_4 m^{-3} h^{-1} / kg CH_4 m^{-3} y^{-1}. n: number of records after aggregation; Avg: average; l95, u95: lower and upper 95% confidence bounds; cells denoted with "-": value is not available; #: values denoted with different letters are significantly different ($p < 0.05$). Detailed information is provided in Supplementary data 4.

Slurry type	Study type/baseline emissions		n	Avg	l95	u95	#	Avg yearly amount
				NH_3 g m^{-2} h^{-1}				NH_3 kg m^{-2} y^{-1}
Cattle	Pilot-scale studies		34	0.08	0.07	0.09	a	–
Cattle	Farm-scale studies	tank	11	0.09	0.05	0.13	ab	–
Cattle	**Baseline emissions***	**lagoon**	**28**	**0.12**	0.10	0.15	**bc**	**1.1**
Cattle	**Baseline emissions****	**tank**	**45**	**0.08**	0.07	0.09	**a**	**0.67**
Pig	Pilot-scale studies		15	0.24	0.15	0.38	def	–
Pig	Farm-scale studies	tank	8	0.23	0.13	0.37	cdef	–
Pig	**Baseline emissions***	**lagoon**	**40**	**0.15**	0.12	0.19	**ce**	**1.3**
Pig	**Baseline emissions****	**tank**	**23**	**0.24**	0.17	0.34	**f**	**2.1**
				N_2O g m^{-2} h^{-1}				N_2O kg m^{-2} y^{-1}
Cattle	Pilot-scale studies		33	0.002	0.001	0.002	a	–
Cattle	Farm-scale studies	tank	–	–	–	–	–	–
Cattle	**Baseline emissions***	**lagoon**	**11**	**< 0.001**	–	–	–	**< 0.01**
Cattle	**Baseline emissions****	**tank**	**35**	**0.002**	**0.001**	**0.002**	**a**	**0.02**
Pig	Pilot-scale studies		12	0.002	< 0.001	0.005	a	–
Pig	Farm-scale studies	tank	2	< 0.001	–	–	–	–
Pig	**Baseline emissions***	**lagoon**	–	–	–	–	–	–
Pig	**Baseline emissions****	**tank**	**14**	**0.002**	**< 0.001**	**0.005**	**a**	**0.01**
				CH_4 g m^{-3} h^{-1}				CH_4 kg m^{-3} y^{-1}
Cattle	Pilot-scale studies		35	0.49	0.38	0.70	a	–
Cattle	Farm-scale studies	tank	6	1.2	0.88	1.5	b	–
Cattle	**Baseline emissions***	**lagoon**	**3**	**0.95**	**0.40**	**1.5**	ab	**8.3**
Cattle	**Baseline emissions****	**tank**	**41**	**0.58**	**0.46**	**0.76**	a	**5.1**
Pig	Pilot-scale studies		16	0.67	0.38	1.1	a	–
Pig	Farm-scale studies	tank	3	0.76	–	–	–	–
Pig	**Baseline emissions***	**lagoon**	**1**	**3.5**	–	–	–	**31**
Pig	**Baseline emissions****	**tank**	**19**	**0.68**	**0.41**	**1.1**	a	**6.0**
				CO_2 g m^{-2} h^{-1}				CO_2 kg m^{-2} y^{-1}
Cattle	Pilot-scale studies		6	7.0	–	–	–	–
Cattle	Farm-scale studies	tank	–	–	–	–	–	–
Cattle	**Baseline emissions***	**lagoon**	**14**	**6.6**	**2.6**	**17**	–	**58**
Cattle	**Baseline emissions****	**tank**	**8**	**8.0**	–	–	–	**70**
Pig	Pilot-scale studies		4	8.8	–	–	–	–
Pig	Farm-scale studies	tank	1	5.7	–	–	–	–
Pig	**Baseline emissions***	**lagoon**	**3**	**0.30**	–	–	–	**2.7**
Pig	**Baseline emissions****	**tank**	**5**	**8.0**	–	–	–	**70**

Cells denoted with "-": value is not available.
* Baseline emissions lagoon are entirely based on values from farm-scale studies lagoon.
** Based on the average from studies at farm-scale tank and pilot-scale.

3.2. Baseline emissions

3.2.1. Emissions on an area or volume basis

Table 8 shows emissions on an area or volume basis from cattle and pig slurry stored uncovered in tanks at farm-scale and at pilot-scale without slurry treatment and in lagoons with solid-liquid separation and biological treatment for NH_3, N_2O, CH_4 and CO_2. Average NH_3 emissions from farm-scale studies conducted at lagoons are higher than those from tanks for cattle slurry but lower for pig slurry. Pilot-scale studies exhibit similar emissions as farm-scale studies conducted at tanks, but they differ when compared to measurements from lagoons. The range between the lower and upper 95% confidence bounds is relatively small for cattle slurry but large for pig slurry with the greatest range for farm-scale studies from tanks (0.13 to 0.37 g NH_3 m^{-2} h^{-1}). The baseline emission for lagoons is 0.12 g NH_3 m^{-2} h^{-1} and 0.15 g NH_3 m^{-2} h^{-1} for cattle and pig slurry, and for tanks 0.08 g NH_3 m^{-2} h^{-1} and 0.24 g NH_3 m^{-2} h^{-1} for cattle and pig slurry, respectively. Baseline emissions given as a yearly average emitted amount for lagoons are 1.1 kg NH_3 m^{-2} y^{-1} and 1.3 kg NH_3 m^{-2} y^{-1} for cattle and pig slurry, and for tanks 0.67 kg NH_3 m^{-2} y^{-1} and 2.1 kg NH_3 m^{-2} y^{-1} for cattle and pig slurry, respectively. The differences between baseline emissions for cattle slurry and pig slurry, and the difference between lagoons and tanks are both statistically significant ($p < 0.05$).

Values for N_2O emissions mostly originate from pilot-scale studies. The data from the three studies which exhibit high values mentioned in section 3.1.2 were excluded for the calculation of baseline emissions. The N_2O losses shown in Table 8 are very low and often close to the limit of detection. Negative fluxes are reported e.g. in VanderZaag et al. (2009) or values lower than the limit of detection in Misselbrook et al. (2016). Pig slurry exhibits a large range between the lower and upper 95% confidence bounds (< 0.001-0.005 g N_2O m^{-2} h^{-1}). Baseline emissions are 0.002 g N_2O m^{-2} h^{-1} for cattle and pig slurry stored in tanks. Storage in lagoons for cattle slurry is 0.0003 g N_2O m^{-2} h^{-1} while for pig slurry no baseline value is available. Statistically significant differences were not found for N_2O.

Farm-scale studies exhibit higher CH_4 emissions than pilot-scale studies (Table 8). For both study types, pig slurry has a higher emission level as compared to cattle slurry. The baseline emission values for lagoons are 0.95 g CH_4 m^{-3} h^{-1} (cattle slurry) and 3.5 g CH_4 m^{-3} h^{-1} (pig slurry), and for tanks 0.58 g CH_4 m^{-3} h^{-1} (cattle slurry) and 0.68 g CH_4 m^{-3} h^{-1} (pig slurry), respectively. The baseline emission for lagoon storage of pig slurry is based on one record only. But its distinctly higher emission level as compared to the baseline for tank storage and relative to the baseline emissions of cattle slurry stored in lagoons and tanks is confirmed by the area based CH_4 emissions where the data basis is much larger and statistically significant differences ($p < 0.05$) were found (Supplementary data 4).

For CO_2, the number of observations is relatively small. Some studies exhibit high values for cattle slurry which are greater than 20 g CO_2 m^{-2} h^{-1} (Leytem et al., 2011; Minato et al., 2013; Misselbrook

Table 9
Flow based baseline emissions for tanks from untreated cattle and pig slurry stored uncovered for NH_3 given in percent of total ammoniacal nitrogen (TAN), N_2O in percent of nitrogen (N), CH_4 and CO_2 in percent of volatile solids (VS). The average (Avg) and the lower and upper 95% confidence bounds (l95, u95) are shown. The numbers are mainly based on pilot-scale studies. Cells denoted with "-": value is not available; #: values denoted with different letters are significantly different ($p < 0.05$). Detailed information is provided in Supplementary data 4.

	n	Avg	l95	u95	#
		NH_3% TAN			
Cattle	31	16%	14%	19%	a
Pig	17	15%	9.2%	23%	a
		N_2O% N			
Cattle	16	0.13%	0.08%	0.18%	a
Pig	8	0.10%	0.01%	0.18%	a
		CH_4% VS			
Cattle	27	2.9%	2.3%	3.7%	a
Pig	14	4.7%	2.1%	10%	a
		CO_2% VS			
Cattle	4	11%	–	–	–
Pig	3	9.2%	–	–	–

Cells denoted with "-": value is not available.

et al., 2016). The baseline emissions for lagoon storage are 6.6 g CO_2 m^{-2} h^{-1} and 0.30 g CO_2 m^{-2} h^{-1} for cattle and pig slurry, respectively, and for tank storage, 8.0 g CO_2 m^{-2} h^{-1} for both slurry types. Data on H_2S emission are sparse and a calculation of baseline emissions is only feasible for lagoon storage which are 0.04 g H_2S m^{-2} h^{-1} for cattle slurry and 0.01 g H_2S m^{-2} h^{-1} for pig slurry (Supplementary data 4).

3.2.2. Flow-based emissions

Flow-based emissions, i.e. emissions given in percent of TAN, N or VS present in the store are shown for NH_3, N_2O, CH_4 and CO_2 in Table 9. Almost all data originate from pilot-scale studies (Supplementary data 4) which can be used for baseline emissions for tanks but not for lagoons. Baseline emission values for NH_3 are 16% of TAN for cattle slurry and 15% of TAN for pig slurry, respectively. N_2O emissions are 0.13% of N for cattle slurry and 0.10% of N for pig slurry. Baseline emissions for CH_4 are 2.9% of VS for cattle slurry and 4.7% of VS for pig slurry. Emissions for CO_2 reach 11% of VS and 9.2% of VS for cattle and pig slurry, respectively, but the data basis is limited. The ranges between the lower and upper 95% confidence bounds are large in most cases and are partially skewed to high values, especially for N_2O and CH_4 from pig slurry. There were no statistically significant differences.

3.3. Emission changes due to slurry treatments

Acidification clearly reduces NH_3 emissions by ca. 70% during storage compared to untreated cattle and pig slurry (Table 10). The effect is even higher for CH_4 (61%–96%) but lower for CO_2. For NH_3 and CH_4, the differences are statistically significant ($p < 0.05$). An emission reduction also occurs for digested slurries and slurries after solid-liquid separation combined with acidification for all gases except for N_2O (Supplementary data 6). In contrast, the emissions are enhanced for N_2O emissions compared to untreated cattle and pig slurry although limited data are available and the differences not statistically significant. Data on H_2S emissions are sparse. Fangueiro et al. (2015) state in their review that H_2S emissions were either unaffected or decreased following acidification.

The number of studies on emission changes due to anaerobic digestion is limited. Where more than one observation is available, both an increase and a decrease in emissions occur for storage after anaerobic digestion as compared to untreated slurry (Supplementary data 6). NH_3 and N_2O exhibit on average greater emissions from anaerobically digested slurry. Most studies comparing anaerobically digested and untreated slurry exhibit lower emissions of CH_4 for the former. An emission increase is observed for N_2O and CO_2 for pig slurry, although this is based on only one observation for both gases. Statistically significant differences do not occur for anaerobic digestion.

Average NH_3 emissions during storage from the liquid fraction are significantly ($p < 0.05$) higher as compared to untreated cattle slurry (Table 10). But for pig slurry, only a slight effect of solid-liquid separation on NH_3 release can be observed which is statistically insignificant. CH_4 and CO_2 exhibit lower emissions from the liquid fraction as compared to untreated slurry with a statistically significant difference for CH_4. A statistically significant reduction ($p < 0.05$) in N_2O emissions occurs for cattle slurry. But the release of N_2O is greater for pig slurry compared to untreated slurry where the difference is statistically not significant.

Five studies examined the effect of slurry dilution with water and found an average reduction of all investigated gases in the range of approximately 30–50%. Statistically significant effects occurred for cattle slurry for NH_3 and N_2O. Maximum abatement effects of 88% and 86% were found for N_2O and CH_4, respectively (Supplementary data 6).

3.4. Emission changes due to covering of slurry stores

The average NH_3 emission percent reduction due to covers ranges between approximately 50% up to ca. 90% for most cover types (Table 11). However, the variability of values is large. Minimum values can be around 15% and maximums higher than 95% (Supplementary data 7). The emission mitigation does not systematically differ between cattle and pig slurry on a percentage basis. Emission reductions lie in a similar range for structural covers, impermeable floating covers, permeable floating covers and the other cover materials. The differences are statistically significant ($p < 0.05$) for the following covers and

Table 10
Percentage emission change (i.e. % change of emissions on an area or volume basis) during storage due to acidification, anaerobic digestion, solid-liquid separation and dilution of cattle and pig slurry for NH_3, N_2O, CH_4 and CO_2 relative to untreated slurry. Positive figures indicate a decline, negative numbers an increase in emissions. n: number of records, Avg: average emission change; Std: standard deviation; cells denoted with "-": value is not available. Detailed information is provided in Supplementary data 6.

		NH_3			N_2O			CH_4			CO_2		
		n	Avg	Std	n	Avg	Std	n	Avg	Std	n	Avg	Std
Acidification	Cattle	5	71%*	17%	1	−4%	–	5	61%*	36%	5	7%	23%
	Pig	3	77%*	22%	1	−39%	–	3	96%*	3%	1	67%	–
Anaerobic digestion	Cattle	3	−59%	64%	3	−16%	29%	5	−2%	129%	1	53%	–
	Pig	1	45%	–	1	−363%	–	1	99%	–	1	−22%	–
Solid-liquid separation	Cattle	12	−23%*	21%	6	43%*	36%	10	32%*	27%	7	18%	24%
	Pig	7	−1%	18%	1	−258%	–	7	39%*	39%	5	13%	12%
Dilution	Cattle	5	48%*	29%	5	57%*	38%	5	39%	33%	–	–	–
	Pig	–	–	–	–	–	–	2	47%	15%	2	30%	11%

Cells denoted with "-": value is not available.
* Numbers with an asterisk indicate a statistically significant difference ($p < 0.05$) between the treated and the untreated slurry.

Table 11
Percentage emission change (i.e. % change of emissions on an area or volume basis) from storage of cattle and pig slurry due to different types of covers relative to uncovered storage for NH_3, N_2O, CH_4, CO_2 and H_2S. Positive figures indicate a decline, negative numbers an increase in emissions. n: number of records, Avg: average emission change; Std: standard deviation; cells denoted with "-": value is not available. Detailed information is provided in Supplementary data 7.

		Slurry type	NH_3			N_2O			CH_4			CO_2			H_2S		
			n	Avg	Std	n	Avg	Std	n	Avg	Std	n	Avg	Std	n	Avg	Std
Impermeable structural covers	Lid (wood or concrete)	Cattle	6	73%*	29%	2	−4%	23%	2	15%	2%	–	–	–	–	–	–
		Pig	7	64%*	35%	4	31%	56%	4	45%*	17%	–	–	–	–	–	–
	Tent covering	Cattle	2	77%	9%	–	–	–	–	–	–	–	–	–	–	–	–
		Pig	2	89%	7%	–	–	–	–	–	–	–	–	–	–	–	–
Impermeable synthetic floating covers	Plastic film	Cattle	4	66%*	22%	–	–	–	–	–	–	–	–	–	–	–	–
		Pig	6	88%*	18%	2	100%	0%	2	62%	54%	–	–	–	–	–	–
Permeable synthetic floating covers	Plastic fabrics	Cattle	1	89%	–	1	68%	–	1	−2%	–	1	15%	–	–	–	–
		Pig	5	39%*	15%	–	–	–	3	−17%	18%	–	–	–	4	50%*	20%
	Expanded clay	Cattle	4	59%	39%	–	–	–	2	11%	7%	2	0.1%	1%	–	–	–
		Pig	12	74%*	20%	1	−8%	–	6	8%	17%	5	29%*	8%	–	–	–
	Expanded polystyrene	Cattle	2	79%	2%	–	–	–	–	–	–	–	–	–	–	–	–
		Pig	4	64%*	32%	–	–	–	2	−26%	41%	2	26%	35%	–	–	–
	Plastic tiles	Cattle	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
		P	2	88%	11%	1	−7%	–	1	25%	–	–	–	–	–	–	–
Permeable natural floating covers	Peat	Cattle	2	90%	13%	–	–	–	–	–	–	–	–	–	–	–	–
		Pig	3	59%	31%	–	–	–	1	−33%	–	1	−31%	–	–	–	–
	Straw cover	Cattle	8	71%*	19%	2	−79%	30%	4	3%	30%	4	−6%	10%	–	–	–
		Pig	8	73%*	22%	–	–	–	7	0.2%	36%	2	13%	9%	–	–	–
	Other organic material#	Cattle	4	51%*	32%	–	–	–	4	−13%	37%	4	−46%	71%	–	–	–
		Pig	4	45%	44%	–	–	–	4	−9%	37%	4	20%	17%	–	–	–
	Vegetable oil	Cattle	4	71%*	16%	–	–	–	2	39%	6%	2	27%	9%	–	–	–
		Pig	4	94%*	10%	–	–	–	2	11%	2%	–	–	–	–	–	–

Cells denoted with "-": value is not available; # materials like maize stalks or wood chips; cells denoted with "-": value is not available.
* Numbers with an asterisk indicate a statistically significant difference ($p < 0.05$) between storage with a cover and uncovered storage.

both slurry types: lid, plastic film, straw cover, vegetable oil; other organic materials for cattle slurry; plastic fabrics, expanded clay, expanded polystyrene for pig slurry.

For N_2O, an increase in emissions is observed in many cases. But reduced emissions occur as well (Supplementary data 7). However, the number of records providing emission changes from slurry storage due to store covers is sparse and the effects are statistically insignificant. CH_4 emissions being lower by approximately 10% to 60% occur for impermeable covers (lid and plastic film), plastic tiles and vegetable oil compared to uncovered storage (Table 11). For plastic fabrics, expanded polystyrene and peat, the emissions are higher by 2% to 33%. The other cover types (expanded clay, straw and organic materials such as corn stalks or wood chips) show both increases and reductions in CH_4 emission (Supplementary data 7). On average, CH_4 emissions from slurry stores covered with permeable materials moderately differ in emission levels as compared to uncovered storage. The differences in CH_4 emissions are statistically not significant ($p < 0.05$) except for pig slurry covered with a lid. Stores covered with plastic fabrics, expanded clay and expanded polystyrene emit less CO_2 while higher emissions are observed for peat and straw covers than for the uncovered controls, but the differences are statistically not significant. Plastic fabrics induce a significant ($p < 0.05$) emission reduction for pig slurry by 50% for H_2S. Data on both CO_2 and H_2S emissions are sparse.

4. Discussion

4.1. Variability in emissions

The high variability of emission levels as shown by descriptive statistics (Table 7) may be due to different meteorological conditions, disturbance of the slurry surface induced by operations at the stores and slurry characteristics. The enhanced variability in laboratory-scale studies compared to the other study types is striking. In laboratory-scale studies, the environment is expected to be largely uniform since the experiments were mostly conducted in a temperature-controlled room with ambient temperatures lying in a narrow range and the slurry being undisturbed. As most of the laboratory-scale studies aimed at a comparison of different techniques or systems, the representativeness of the resulting emission rates for real-world conditions was not the primary focus and discrepancies between different approaches are very likely present. A thorough evaluation of potential biases of the laboratory studies is not possible due to missing information on the measuring systems and is beyond the scope of this paper (see Liu et al. (2020) and the related discussion). Also, for other study types, the occurrence of methodological biases cannot be ruled out which may lead to implausible results. Detection of striking values might be hampered due to the multitude in units used in the papers. Therefore, a standardization as used here and providing guide values are important issues. For this, a favorable option is the unit g m^{-2} h^{-1} or g m^{-3} h^{-1} of a molecule. It is equally suitable to illustrate an emission pattern within one day, also in combination with important influencing factors such as temperature or wind speed which can change over short time periods and to compare them with e.g. average emissions over one year. If a yearly amount of a gas release is required, data can be obtained from Table 8. Alternatively, the unit mol m^{-2} h^{-1} could be used to facilitate the comparability between different molecules, even if to date, it is generally not used in the context of emission inventories.

4.2. Important factors influencing emissions

The relevance of important influencing factors on emissions from slurry stores is discussed in this section in order to support interpretation and understanding of the data used to determine baseline emissions and emission changes due to slurry treatment and coverage of slurry stores. It should be noted that a part of these influencing factors could not be included in the data processing such as the weighting or the statistical analysis of emission data due to insufficient information in the records. This data limitation applied for operations at stores, the meteorological parameters rain and wind speed and the natural crust.

4.2.1. Type of slurry

Records from the same study where both cattle and pig slurry have been investigated using the same approach were compared. Eight studies (De Bode, 1991; Sommer et al., 1993; Husted, 1994; Kaharabata

et al., 1998; Balsari et al., 2007; Dinuccio et al., 2008; Mosquera et al., 2010; Misselbrook et al., 2016; Baral et al., 2018) with a total of 14, 2, 8 and 3 pairs of records on NH_3, N_2O, CH_4 and CO_2 emissions, respectively, were available. For NH_3, 85% of data pairs, exhibited higher emissions for pig slurry than for cattle slurry. Similar for N_2O, CH_4 and CO_2, pig slurry exceeds emissions of cattle slurry in most cases. These findings agree with the data reported in Table 8 (except for CO_2) and with data previously published by Sommer et al. (2006) and VanderZaag et al. (2015).

4.2.2. Operations at stores

Operations at the storage tank, such as agitation, filling and removing of slurry are necessarily related to real-world storage systems. Their effects are usually reflected in farm-scale measurements using non-intrusive methods but rarely included in pilot studies or farm-scale studies using chamber systems. A series of studies specifically investigated such processes (see Supplementary data 10). They showed consistent results and provided evidence that disturbance of the manure surface due to slurry agitation, filling and discharging of the stores induces large episodic emissions for NH_3, CH_4, CO_2 but not for N_2O. While emissions of CH_4 and CO_2 rapidly decline after cessation of the operations and can even drop to levels below the previously undisturbed stores, increased emission levels persist for NH_3. Due to the relatively short time duration of agitation over the year and the subsequent drop below average levels for CH_4, this operation per se does not substantially contribute to annual NH_3 and GHG emissions from slurry (VanderZaag et al., 2009). A more detailed overview on emissions during and following operations at stores is given in the Supplementary data 10.

4.2.3. Meteorological conditions

Increasing air temperature and wind speed enhance the emissions since they directly affect diffusion and convection of gases near the emitting surfaces (Sommer et al., 2013). The relationship between the temperature as represented by the season of measurements and the emission level could be demonstrated in the present study (Supplementary data 5). It must be considered however, that the air temperature is a simplistic surrogate for the slurry temperature which is a determinant factor for GHG emissions. Rennie et al. (2018) demonstrated that slurry store design and operations (i.e. filling level, agitation) influence the slurry temperature and the emission level of gases such as CH_4. In 25 studies, slurry temperatures during different seasons are available. Slurry temperatures increase as expected in the order cold < temperate < warm for 94% of the cases. The effects of temperature and wind speed are not discussed further in the present study because this topic has been previously covered by e.g. Ni (1999) or Sommer et al. (2006). In contrast, emission changes related to the influence of rain events and thawing of the slurry surface are summarized here since they have been less frequently addressed in the literature. Petersen et al. (2013) found lower NH_3 emission from uncovered storage of pig slurry with precipitation than from the treatment without rain although the differences are not statistically significant. It was shown that ammonia emissions can decline towards zero during rain events after slurry spreading (Hafner et al., 2019) due to sorption of NH_3 onto wet surfaces. Moreover, the TAN-concentration at the emitting surface may decrease with precipitation due to dilution or transport of TAN from a crusted slurry surface into the bulk liquid. Overall, it can thus be assumed that NH_3 emissions from slurry storage during rain events are low. In contrast, an increase in emissions of CH_4 has been observed. Balde et al. (2016b) reported average emissions of 1.8 g CH_4 m^{-2} h^{-1} for digested slurry while peak emissions during rain events reached 10 g CH_4 m^{-2} h^{-1}. This was likely due to bursting of bubbles at or near the surface. Elevated emissions were also observed by Balde et al. (2016a) from storage of the liquid fraction of cattle slurry which confirms earlier findings from Kaharabata et al. (1998) and Minato et al. (2013) on slurry stored in open tanks or lagoons. Kaharabata et al. (1998) suggested that the emission increase is due to more disturbance at the slurry surface induced by rain and thus enhancement of the CH_4 exchange through the liquid surface area and of incidental outburst of gas bubbles (ebullition). Petersen et al. (2013) found a drop of N_2O emissions to zero as a result of rewetting of the crust after rainfall inducing a shift towards anaerobic conditions. Grant and Boehm (2015) did not find a relationship between H_2S emissions and rain events.

VanderZaag et al. (2011) observed important bubble flux events in late winter/early spring that coincided with surface thawing which were probably due to a release of previously produced CH_4 that was trapped under the frozen slurry surface. In the study of VanderZaag et al. (2010a) which encompassed winter and spring, N_2O release was only recorded during spring thaw. A moderate increase in CH_4 emissions was observed during the same period at slurry temperatures above 0 °C while NH_3 and CO_2 flows were unaffected by spring thaw. Elevated CH_4 emissions due to thawing of the manure store were also reported by Leytem et al. (2017).

4.2.4. Natural crust

There is agreement that crusting impacts the gas release in many ways: enhanced resistance to mass transfer (Olesen and Sommer, 1993), oxidation of NH_3 (Nielsen et al., 2010) and CH_4 (Petersen et al., 2005) and formation of N_2O related to nitrification and denitrification occurring in liquid–air interfaces near air-filled pores present in crusts (Petersen and Miller, 2006). Several studies investigated the effect of a natural crust on the emission level (Sommer et al., 1993; Misselbrook et al., 2005; Aguerre et al., 2012; Wood et al., 2012). All studies showed that a natural crust provided an efficient barrier leading to an emission reduction for NH_3. Baldé et al. (2018) confirmed these findings by measurements conducted under farm conditions at tanks and earthen basins containing slurries with differing ability to form natural crusts (i.e. raw cattle slurry, the liquid fraction of cattle slurry produced by solid-liquid separation, digested slurry with and without solid-liquid separation). They confirmed that slurry stored with a thick surface had lower NH_3 losses. Grant and Boehm (2015) found that crusting of a lagoon surface containing dairy cow slurry reduced NH_3 but not H_2S emissions. Nielsen et al. (2010) showed that NH_3-oxidizing bacteria may contribute to a significant reduction of NH_3 emissions if a natural crust is present on a slurry store. Grant and Boehm (2018) found emissions from a tank containing pig slurry to be greater by 10% when the surface was covered with a crust than without crusting (difference not statistically significant). They explained their findings by the higher TAN content of the crusted slurry surface as compared to a non-crusted one. Sommer et al. (2000) and Husted (1994) found higher emissions of CH_4 from slurry without than from slurry with a natural surface crust. Wood et al. (2012) investigated the emissions from dairy slurry with varying DM contents and thus natural crusts with different thicknesses and coverage of the storage surfaces. They were not able to relate the CH_4 fluxes to the presence of a natural crust. N_2O production was found to be enhanced after build-up of a natural crust (VanderZaag et al., 2009).

In the literature (e.g. Vanderzaag et al., 2015), a natural crust is often classified as abatement measure for NH_3 similar as slurry store covers. However, crust formation can only be controlled to a limited extent. Crusts are of variable thickness, coverage of the store and durability. Their effectiveness for emission abatement has therefore be considered as inconsistent (Vanderzaag et al., 2015). Crusts only develop for slurry types with a high content of fibrous material (Bittman et al., 2014). This applies mainly for cattle slurry (Smith et al., 2007) and less for pig slurry (Sommer et al., 2006). Crusting is likely to occur at a slurry DM content of more than 20 g L^{-1} (Sommer et al., 2006; Wood et al., 2012) which mostly does not apply for slurry stored in lagoons (Table 6). Consequently, they have much less ability to form a natural crust as shown by e.g. Balde et al. (2018).

We therefore did not consider crusting as an emission mitigation technique equivalent to slurry store covers but rather as a parameter

influencing emissions from stored slurry and thus excluded it from the analysis of emission changes due to covering of stores. But we stress that if a natural crust is present, it is likely to significantly contribute to an emission reduction and, therefore, should be preserved by e.g. reducing slurry agitation and addition of manure below the surface.

The limited information in the data impedes our ability to clearly distinguish between crusted and non-crusted stores. This may be relevant for (i) the calculation of baseline emissions and (ii) emissions changes due to slurry treatments and covering of stores: (i) baseline emissions determined here may include stores with variable occurrence of a natural crust. For lagoons, information on crusting was available for 45% (cattle slurry) and 19% (pig slurry) of the records, respectively. Among these, 62% of the lagoons containing cattle slurry were fully or partly covered by a crust during the emission measurements. For pig slurry, this applies for 21% only. Among records used for the determination of baseline emissions for tanks, 78% and 50% included information regarding crusting for cattle and pig slurry, respectively. Of these, 83% (cattle slurry) and 48% (pig slurry) had a fully or partly crusted surface. This complies with findings that crusting occurs less on lagoon surfaces and stores containing pig slurry. The proportion of crust occurrence for cattle slurry stored in tanks is in line with earlier findings (Smith et al., 2007). We thus suggest that the baseline emissions determined here are based on studies which appropriately reflect the range of store surface crusts occurring at farms. (ii) A natural crust may occur in combination with a storage cover and thereby be enhanced (Chadwick et al., 2011) since the slurry surface is less exposed to wind turbulence. In experiments comparing uncovered and covered storage, it is thus difficult to stringently distinguish between the effect of covering and of crusting. Moreover, this information is not always available: only 60% of the records used to determine the emission change due to covering included information on crusting. From these, about half had crusted surfaces and the other half not. This might partly explain the variability of emission changes due to covering found here. These considerations should be taken into account for the discussion in the Sections 4.4 and 4.6.

4.3. Study types to be included for baseline emissions

Data should only be included for the calculation of baseline emissions if they can be considered as representative or typical for gas flows occurring at farm conditions. In principle, this applies for farm-scale studies. Pilot-scale studies imply some aspects of farm-scale studies due to measurements conducted in outdoor facilities and a slurry volume in the order of several cubic meters. But there are concerns extrapolating data from pilot-scale studies to real-world systems. VanderZaag et al. (2009, 2010a, 2010b) who performed pilot-scale studies state that although measured fluxes were reported, emission trends and treatment differences or temporal trends were the focus of their analysis. Moreover, almost all pilot-scale studies are based on flux chambers. VanderZaag et al. (2010b) argued that steady-state chambers alter the enclosed environment and concluded that absolute fluxes measured might deviate from emissions that would occur without chambers. Nevertheless, several studies conducted in pilot-scale facilities similar to that of VanderZaag et al. (2009, 2010a, 2010b) quantified emissions of NH_3 and GHGs and derived emission factors for slurry storage (e.g. Amon et al., 2006, 2007; Rodhe et al., 2012). Petersen et al. (2009) presented a pilot-scale facility and suggested to use the obtained results for better documentation of emission data for GHG and ammonia inventories. Pilot-scale studies have occasionally been conducted with simulation of real-world conditions by including mixing of the slurry or filling of tanks during the experiment (VanderZaag et al., 2009; Rodhe et al., 2012).

Emission peaks for CH_4 were observed in several studies (VanderZaag et al., 2011; Balde et al., 2016a) due to ebullition. They may remain unrecorded (Rodhe et al., 2012) unless the gas measurements are continuous with a high temporal resolution. This shortcoming may apply for pilot-scale studies where e.g. a flow chamber is used which is moved between several experimental tanks (e.g. Amon et al., 2006). Intermittent gas sampling can hamper measurements at a farm-scale as well. Grant et al. (2015) assumed differences in emission levels between two locations due to under-sampling of ebullition events given the short measurement periods. Sampling large storage areas using chambers might be hampered if the sampled surface areas are not representative for the entire store. Balde et al. (2016b) found average emissions of CH_4 measured at an earthen storage containing liquid digestate with a floating chamber which were about four-fold greater than measured at the same time with a non-intrusive bLS technique. The authors explained this by the limited area covered by the chamber and by disturbances induced by the chamber causing bubble formation and bursting thereby increasing emissions.

To summarize, it can be hypothesized that farm-scale measurements using non-intrusive methods are a preferential option. Still, data from such studies are limited at present time. Therefore, inclusion of records from pilot-scale and farm-scale studies appears to be the best opportunity for the determination of baseline emissions. This approach provides a larger data basis as if only farm-scale studies were included. Moreover, Table 8 shows that emissions from pilot-scale studies comply with farm-scale studies tank for NH_3 but less for CH_4. On the other hand, we excluded laboratory-scale studies for the determination of baseline emissions. They are mostly not designed for generating emission rates. Their experimental conditions strongly deviate from an environment that occurs under practical conditions. The enhanced variability found in emissions level from laboratory-scale studies (section 3.1.2) points to severe methodological shortcomings which might bias baseline values.

4.4. Baseline emissions

4.4.1. Emissions on an area or volume basis

NH_3 emissions from pig slurry are higher as expected due to its higher TAN content and its lower ability to form a natural crust compared to cattle slurry. Sommer et al. (2006) and VanderZaag et al. (2015) suggested lower emissions on an area basis from pig slurry stored in lagoons than from storage in tanks. This complies with the results of this study (Table 8). Lagoons are the prevailing system for slurry storage in the US (Sorensen et al., 2013). They usually have a greater surface area than tanks which would imply more exposure to the ambient air turbulence suggesting a higher emission potential. Slurries from lagoons have on average a lower dry matter and TAN content as compared to tanks. This might be due to a stronger dilution with water: e.g. five out of six lagoons investigated by Leytem et al. (2017) collected parlor wash water and not slurry from a pit of a livestock housing. We assume that solid-liquid-separation was applied at the farms studied which have lagoons although this was not always clearly defined in the papers. This is supported by the low contents in DM and TAN in slurry from lagoons as shown in Table 6. The lower solids content would enhance the emission potential due to less ability for formation of a natural crust at the slurry surface (Wood et al., 2012). But the lower TAN content induces the opposite effect on NH_3 emissions (Sommer et al., 2006). The overall impact of these effects combined on the emission level is difficult to assess. The present data suggest higher emissions from lagoons than from tanks containing cattle slurry but the opposite for pig slurry.

The baseline emissions (lagoons: 0.12 g NH_3 m^{-2} h^{-1} and 0.15 g NH_3 m^{-2} h^{-1} for cattle and pig slurry, tanks: 0.08 g NH_3 m^{-2} h^{-1} and 0.24 g NH_3 m^{-2} h^{-1} for cattle and pig slurry, respectively), are mostly lower than numbers given by VanderZaag et al. (2015), Sommer et al. (2006) and Bittman et al. (2014). VanderZaag et al. (2015) suggested emissions for crusted and non-crusted cattle slurry of 0.11 and 0.19 g NH_3 m^{-2} h^{-1}, respectively, from tanks or lagoons. For pig slurry stored in a lagoon, they give 0.12 g NH_3 m^{-2} h^{-1}, and stored in a tank, 0.40 g NH_3 m^{-2} h^{-1}. Sommer et al. (2006) provided similar values. Bittman

et al. (2014) gave baseline emissions between 0.19 and 0.40 g NH_3 m^{-2} h^{-1}. They attributed the lower value to slurry which is frozen in the store for several months, and the higher value applies to warm countries. For N_2O, most studies exhibit emissions clearly below 0.01 g N_2O m^{-2} h^{-1} (Supplementary data 8). In contrast, three papers reach values from 0.02 to 0.06 g N_2O m^{-2} h^{-1} and N_2O losses ranging between 25% and 160% of the NH_3 emissions determined concomitantly (Clemens et al., 2006; Amon et al., 2007; Leytem et al., 2011). Unless at very low levels of NH_3 emissions, flows of both NH_3 and N_2O in the same order of magnitude do not occur in other records and have not been reported in the livestock sector (e.g. EEA, 2016). Therefore, the data from the three studies were excluded for the calculation of baseline emissions. If they were kept, the baseline emissions for N_2O would be higher by a factor of two and three for cattle and pig slurry stored in tanks, respectively. Chadwick et al. (2011) stated in their review that N_2O emission from slurry stores without a surface cover are negligible which supports the baseline emissions shown in Table 8.

For CH_4, higher emissions occur for farm-scale studies than for pilot-scale studies (Table 8; statistically significant differences for emissions on an area basis; $p < 0.05$; Supplementary data 4). This could be due to the temperature dependency of methanogenesis (Elsgaard et al., 2016). Pilot-scale studies exhibit lower slurry volumes as compared to farm-scale stores which suggests faster cooling of the slurry and therefore a lower methane conversion rate. Another reason could be the batch-filling of vessels used for pilot-scale studies which differs from continuous filling and incomplete removal of slurry at farm-scale stores. Under such conditions, aged slurry may act as inoculum which was shown to enhance emissions of CH_4 (Wood et al., 2014). Overall, the lower emission level for CH_4 measured at pilot-scale included for the determination of baseline emissions tank could lead to an underestimation thereof.

The review of Owen and Silver (2015) reported CH_4 emission data from lagoons and tanks of dairy systems being 2.3 and 2.7 g CH_4 m^{-2} h^{-1}, respectively. This is higher than data from farm-scale studies reported here which are 1.2 and 1.3 g CH_4 m^{-2} h^{-1} for cattle slurry stored in lagoons and tanks, respectively (Supplementary data 4). However, the data basis of Owen and Silver (2015) is smaller and measurements carried out in the warm season tend to be overrepresented. The higher CH_4 emissions from pig slurry as compared to cattle slurry are expected due to the higher methane production potential of pig slurry (Triolo et al., 2011). Both cattle and pig slurry exhibit lower losses from tanks than from lagoons. Moreover, lagoon storage produces a solid fraction which includes a large proportion of the slurry VS generating additional emissions. According to VanderZaag et al. (2010b), a CO_2-C:CH_4-C ratio of 50:50 is expected from stores. Looking at records which include emission data of both CH_4 and CO_2, a large variation occurs. The average CO_2-C:CH_4-C ratio is approximately 65:35 which also differs from the CH_4 to CO_2 relationship expected from anaerobic digestion of livestock slurries (ca. 55%–70% CH_4 content of dry biogas; Triolo et al., 2011). This could be due to a tendency for greater CO_2-C:CH_4-C ratios in pilot-scale studies which increases the average CO_2-C:CH_4-C ratio of all records included. The greater ratios were also linked to studies with low CH_4 fluxes. This is likely because pilot-scale studies had less ability to provide appropriate conditions for CH_4 production as mentioned above. On the other hand, CO_2 seems to be emitted more consistently in all studies.

As the aim of all studies considered for the calculation of baseline values in the present paper was the determination of emission rates we think that the baseline emissions are robust and reflect the current state of knowledge. But the confidence intervals shown in Table 8 may be substantial. This suggests an inherent variability in the systems which can be due to differing conditions regarding meteorological conditions, operations at stores and occurrence of a natural crust. Baseline values must be considered as average numbers. In a specific situation and e.g. for representative regional values, deviations from the presented baseline values can occur. Moreover, methodological biases cannot be ruled out and different experimental approaches might entail systematic differences in results (e.g. possibly CH_4 emissions from pilot-scale studies). Such effects have been observed for experimental data on NH_3 emissions from slurry application (Hafner et al., 2018).

4.4.2. Flow-based emissions

The determined baseline emission values for NH_3 of 16% of TAN and 15% of TAN for cattle and pig slurry, respectively, which are mostly based on pilot-scale studies exhibit similar values as the emission factors of EEA (2016) which give 20% of TAN and 14% of TAN as Tier 2 default values for cattle and pig slurry. Data from farm-scale studies have comparable numbers for storage in tanks for cattle slurry: 16% of TAN (Baldé et al., 2018) and 13% of TAN (McGinn et al., 2008) but lower emissions for pig slurry (Dinuccio et al., 2012) with 2% and 5% of TAN. Flow-based emissions are not available for lagoons. IPCC (2006) and EEA (2016) suggest an N_2O emission factor being zero for slurry storage without a natural crust. For a crusted store, IPCC (2006) and EEA (2016) give EFs of 0.5% of N and 1% of TAN entering the store, respectively. These values are higher than the values determined in this study which are 0.13% of N and 0.10% of N for cattle and pig slurry, respectively (Table 9). The eight highest values for flow-based N_2O emissions originate from records that include slurry stores with a crust which supports the occurrence of N_2O emissions with crusted store surfaces. This complies with Sommer et al. (2000) who suggest that N_2O is produced in drying of natural crusts where aerobic and anaerobic zones exist. Drying enhances convection of liquid upward through the cover, where dissolved ammonium can be oxidized by nitrifying bacteria in an aerobic environment and under such conditions, molecules produced from nitrification can be denitrified. During ammonium oxidation and denitrification, N_2O is released as an intermediate or final product. At limited oxygen availability, formation of N_2O is enhanced.

For CH_4, a direct comparison between the suggested baseline emissions with default emission factors used in models for emission inventories is not possible. A simplified application of the approach of Mangino et al. (2001) and IPCC (2006) using the methane conversion factor (MCF) for slurry in a cool climate with an annual average temperature of 14 °C results in a CH_4 emission of ca. 4.0% of VS and 7.5% of VS for cattle slurry and pig slurry, respectively. These figures are somewhat higher than the baseline emissions suggested (Table 9) which are 2.9% of VS and 4.7% of VS for cattle and pig slurry, respectively. It should be noted that emission values for CH_4 derived from such model approaches can strongly deviate from measured values as shown by several studies (e.g. Kariyapperuma et al., 2018).

For the determination of flow-based emissions, analytical data of the slurry, the flow volume of slurry into storage and its residence time in the store must be known. Determining these three parameters is not straightforward which might explain the high degree of absence regarding flow-based emissions in farm-scale studies. This particularly applies for lagoons where extended slurry residence times, accumulation of solids over long time periods and repeated recycling of liquids used for flushing or recharging pits of livestock housings represent additional challenges. Generally, lagoons have a greater surface to volume ratio and longer slurry residence times as compared to tanks. These two factors will lead to higher flow-based emissions for lagoons as compared to tanks if identical emissions on an area basis are assumed for both storage systems.

For inventory purposes, emission factors could be calculated using the baseline emissions on an area or volume basis and an assumption of the surface or volume of the storage system, the average values for the residence time of the slurry in the store and the slurry contents of TAN, N or VS. These values are specific for different countries and production systems. A further assessment thereof is outside the scope of this paper. The calculation of flow-based emissions (and emission factors) is subject to additional uncertainties as compared to emissions on an area basis due to the requirement of further parameters.

4.5. Emission changes due to slurry treatments

The pH value has a strong effect on gaseous emissions from slurry stores (Sommer et al., 2013). This is appropriately reflected by the data on emission changes due to slurry acidification through addition of inorganic acids shown in Table 10. The variability in the achieved reduction is likely related to the degree of acidification and the different pH values in slurry (Dai and Blanes-Vidal, 2013). The emission reductions found for NH_3 and CH_4 are in line with the review of Fangueiro et al. (2015). Similarly, Petersen et al. (2012) observed significant reduction effects for NH_3 and CH_4 due to acidification. The data point at an increase in N_2O emission but this is based on limited data. Bastami et al. (2016) concluded that self-acidification of slurry induced by addition of substrates rich in carbon may be a promising alternative to slurry acidification using concentrated acids for abatement of CH_4 emissions. Additives other than acids to reduce gaseous emissions or odor nuisance from manure storage have been investigated in some studies (Martinez et al., 2003; Sun et al., 2014; Owusu-Twum et al., 2017). A clear emission reduction due to other additives did not occur. Similarly, Van der Stelt et al. (2007); Wheeler et al. (2011) and Holly and Larson (2017a) found little evidence that manure additives other than acids have a clear influence on the release of ammonia and GHGs. Still, individual investigations have shown an emission reduction potential for certain additives (Bastami et al., 2016).

The number of studies allowing a direct comparison of emissions from storage of untreated slurry and anaerobically digested slurry is limited since biogas plants are mostly fed with manure and off-farm organic feedstock material which hampers a direct comparison with unamended untreated slurry. The increase of NH_3 emissions due to anaerobic digestion complies with studies which include anaerobic digestion with addition of organic feedstock material. Baldé et al. (2018) measured NH_3 emissions from two stores at different farms containing untreated livestock slurry and liquid digestate obtained from livestock slurry and organic feedstock materials under farm conditions. Emissions from the untreated slurry were lower. Koirala et al. (2013) suggested that anaerobic digestion of dairy slurry significantly increased the NH_3 volatilization potential. The most important factor was the enhanced ammonium dissociation. Anaerobic digestion seems to reduce CH_4 emissions during slurry storage. Maldaner et al. (2018) found lower CH_4 losses from the liquid fraction of anaerobically digested slurry amended with organic feedstock material compared to unamended raw slurry from the same farm before the installation of anaerobic digestion. This is likely due to the reduction of the VS load after digestion but also a consequence of solids removal with solid-liquid separation of the major part of the digestate. Furthermore, Maldaner et al. (2018) suggested that VS remaining in the digestate was less degradable which leads to a reduced CH_4 production. VanderZaag et al. (2018) showed the CH_4 emission potential (B_0) from digestate was 35% lower than the B_0 of untreated manure. In contrast, Sommer et al. (2000) and Rodhe et al. (2015) measured higher emissions from anaerobically digested slurry as compared to untreated cattle slurry. They explained this by the presence of a larger and more active microbial community in digested slurry. However, most storage tanks are never completely empty. Residual aged slurry may act as inoculum and enhance the production of CH_4 (Sommer et al., 2007; Ngwabie et al., 2016). Although, the microbial population in aged slurry may be less efficient for methane production as compared to microbes present in anaerobically digested slurry, the higher amount of degradable organic carbon available in untreated slurry might compensate this. It can therefore be hypothesized that untreated slurries as occurring in real-world stores imply a higher potential for CH_4 emissions than anaerobically digested slurry.

Solid-liquid separation reduces the solids content of the slurry and thus the potential to develop a natural crust. This enhances NH_3 emissions during storage which complies with the increasing emissions of cattle slurry due to solid-liquid separation. Pig slurry exhibits a lower ability to form a natural crust which could explain why almost no effect of solid-liquid separation on NH_3 emissions can be observed (Table 10). Baldé et al. (2018) investigated the NH_3 emissions from two stores situated at different dairy farms containing untreated slurry and separated liquids under farm conditions. They measured higher emissions from the liquid fraction than from the untreated slurry and reported similar findings for the separated liquids from digestate derived from livestock slurry and organic feedstock materials. In contrast, Hjorth et al. (2009) found significantly higher NH_3 emissions from raw and digested slurries than from the corresponding liquid fractions. They explained their findings by the higher ammonium and N contents of the unseparated raw and pre-digested slurries compared with the liquid fractions, which increased the potential for NH_3 volatilization. The lower N_2O storage emissions of the liquid fraction for cattle slurry as compared to raw slurry is in line with the conclusions of the review paper published by Chadwick et al. (2011). The reduced emissions of CH_4 due to solid-liquid separation results from the reduction of the total solids content in the slurry which can be considered as a surrogate for the available VS pool. This leads to a lower amount of organic matter which can be degraded to CH_4 and CO_2 (Wood et al., 2012). However, yearly average CH_4 emissions of 1.4 g CH m^{-3} h^{-1} and 2.2 g CH m^{-3} h^{-1} for the first and second year of measurements were reported for dairy slurry from a farm-scale study conducted at a tank (Balde et al., 2016a). These numbers exceed the baseline emission and emissions from farm-scale studies from tanks for cattle slurry given in Table 8. Balde et al. (2016a) explained the elevated emission levels by the high biodegradability of the liquid fraction and the limited crust development. VanderZaag et al. (2018) showed that the speed of CH_4 production was much higher for the separated liquid fraction, compared to untreated slurry. Grant et al. (2015) found CH_4 emissions on an area basis from the liquid fraction of cattle slurry stored in a lagoon which are similar to the baseline emission for cattle slurry (Supplementary data 4). The discrepancy between the emission changes given in Table 10 and the high emissions found in these two studies is difficult to explain.

Dilution of slurry with water changes its DM content. DM of slurry can be considered as an indicator for the N/TAN- and VS-content which influences the potential production of NH_3, N_2O, CH_4 and CO_2, respectively (Wood et al., 2012). However, DM affects the formation of a natural crust as well (section 4.2.4). Overall, dilution leads to a reduction of all investigated gases which complies with the findings of Ni et al. (2010) for NH_3 and CO_2 and of Habetwold et al. (2017) for CH_4. But this conclusion is based on pilot-scale studies where the slurry volume is identical for the diluted and untreated slurry. Under practical conditions, addition of water leads to a higher amount of slurry. If the area of manure stores is thereby increased due to requiring larger storage capacities, the reduction might be overcompensated due to a rise in emitting surface (Ni et al., 2010).

Aeration of slurry is a technique which is used to remove excess N from slurries. It induces nitrification and denitrification that converts TAN in the slurry to nitrite/nitrate with the aim of a complete denitrification to N_2. If the process is not properly controlled aeration can produce substantial amounts of NH_3 and N_2O (Loyon et al., 2007). The effect of aeration was investigated in several laboratory- and pilot-scale studies. Amon et al. (2006) found a strong increase of NH_3 emissions by up to a factor of five. Molodovskaya et al. (2008) reported NH_3 emissions of up to 50% of total slurry N. Losses were increased at greater aeration rates. Many studies found a strong increase in emissions for N_2O with aeration (Beline et al., 1999; Beline and Martinez, 2002; Amon et al., 2006; Loyon et al., 2007). Low emissions for both NH_3 and N_2O were achieved from low flow phased oxic/anoxic treatment (Molodovskaya et al., 2008). A reduction of CH_4 by ca. 50% to almost 100% emissions was observed by Martinez et al. (2003) and Amon et al. (2006) if slurry aeration was applied. Concomitantly, CO_2 emissions were reduced (Martinez et al., 2003).

An increase in emissions of a specific gas during slurry storage due to a treatment technique does not necessarily indicate a conflict related

to emission mitigation. Enhanced losses during storage can be reduced by e.g. storage covering and might be overcompensated by reduced emissions during subsequent field application. The overarching goal of manure management is the reduction of gaseous losses between the excretion by livestock and uptake by arable and fodder crops. Therefore, the discussion on effects of slurry treatments on emissions from slurry storage must consider the context of good management practices along the whole manure management chain (Sajeev et al., 2018).

4.6. Emission changes due to coverage of slurry stores

Almost all types of covers induce a substantial emission reduction for NH_3 which complies with the review of VanderZaag et al. (2008). Emission reductions lie in a similar range for all categories of covers and for both cattle and pig slurry. This contrasts to Bittman et al. (2014) who give distinct values for the different cover types and lower values for "Low technology" floating covers such as permeable natural floating covers. VanderZaag et al. (2015) give an emission reduction of 80% for impermeable structural covers and for impermeable synthetic floating covers which is in the range of the values given in Table 11. A larger layer thickness of natural floating covers leads to a higher emission reduction (Guarino et al., 2006; VanderZaag et al., 2009). This is probably due to a more efficient barrier for the gas transport between the slurry and the ambient air (VanderZaag et al., 2009). Other cover types not included in the data analysis according to section 2.4.3 also efficiently reduce NH_3 emissions. Organic materials such as steam-treated wood or biochar were shown to exhibit similar effects as floating covers consisting of straw or peat (Holly and Larson, 2017b). Minerals like perlite or zeolite were also found to be efficient in NH_3 emission reduction (Hörnig et al., 1999; Portejoie et al., 2003).

The increase in emissions observed for N_2O in many cases agrees with the previously published literature (VanderZaag et al., 2008; Chadwick et al., 2011). Petersen et al. (2013) observed lower N_2O flows with a straw cover exposed to precipitation as compared to straw covers where wetting by precipitation was excluded. Sommer et al. (2000) suggested that N_2O is only produced in periods with drying surface layers. Storage covers can influence the formation of a natural crust (Chadwick et al., 2011). A natural surface crust on slurry can provide sites with aerobic conditions where nitrification occurs which produces N_2O (Sommer et al., 2000). Therefore, the variability in emission changes due to slurry storage covering could be driven by differing moisture contents of the manure surfaces and differing formation of a natural crust due to covering. However, the number of records related to emission changes for N_2O due to store covers is sparse and these findings can be uncertain.

The observed increase in CH_4 emissions for plastic fabrics, expanded polystyrene and peat complies with the review of VanderZaag et al. (2008). Straw covers provide additional carbon but might reduce ebullition and increase aerobic microbial activity at the upper storage layer (VanderZaag et al., 2009). This induces contrasting effects on CH_4 net emissions. VanderZaag et al. (2009) suggested that the reduction of CH_4 emissions due to a straw cover is related to areas in a crust where microbial breakdown of CH_4 might occur. It can be assumed that the enhanced CH_4 consumption overcompensates the increased potential for CH_4 production due to the additional carbon supply with straw. An opposite effect can occur if straw is incorporated into the bulk slurry during storage due to e.g. agitation. Petersen et al. (2013) found that an elevated CH_4 concentration in the gas phase above the slurry surface is required for a significant stimulation of methane oxidation. This would support the preponderant emission reduction found for impermeable covers. For other cover types, the CH_4 concentration above the emitting surface might have been inconsistent in the experiments which could explain the contrasting emission changes for CH_4 due to storage covering. Similar to NH_3, a larger layer thickness of straw covers leads to a higher emission reduction for CH_4 although the differences of the emissions are low (Guarino et al., 2006; VanderZaag et al., 2009).

The contribution of the different gases to the total of GHG emissions is largest for CH_4 with a proportion of ca. 80% (VanderZaag et al., 2009; Petersen et al., 2013). Therefore, the changes of GHG equivalents due to effects of covers is moderate with a slight trend towards lower total GHG emissions.

VanderZaag et al. (2010b) have shown that a permeable synthetic floating cover was more efficient regarding emission reduction of NH_3 and CH_4 when slurry is agitated as compared to undisturbed slurry. VanderZaag et al. (2009) found that agitation increased NH_3 losses from straw covered tanks less than from the uncovered reference. CH_4 emissions from covered and control tanks were similarly changed.

Although found efficient in emission reduction, low cost floating covers such as straw covers are probably not efficient for emission mitigation in practice since they may be destroyed when the slurry surface is disturbed due to strong winds or operations at a store. Therefore, we consider impermeable structural covers or synthetic floating covers as most reliable for emission mitigation.

4.7. Recommendations for further research

The emission data provided in records from different studies range over several orders of magnitude even for the same slurry type, the same type of study and identical seasons of measurement. This may be partly due to varying conditions related to manure management and meteorological conditions occurring during the measurements. In addition, different study designs and measuring methods are likely to contribute to the variability in emissions. An important issue in future research should thus focus to identify and quantify potential experimental biases. This aspect requires the simultaneous use of independent approaches to determine emissions.

Farm-scale studies using non-intrusive methods such as micrometeorological mass balance (Wagner-Riddle et al., 2006) or dispersion modeling (Flesch et al., 2009) are likely to be a preferential option. Such approaches avoid interactions with emitting processes and determined emission rates best reflect the emissions occurring under conditions at farm-scale. They have the ability to cover large area sources (Gao et al., 2008) and can thus integrate the large inhomogeneity of emissions over space and time. For dispersion modeling, the limiting factor is the requirement of a simple topography allowing for representative turbulence measurements. Most of the micrometeorological methods require a minimum wind speed. Many sensors, e.g. for NH_3, have a minimum detection limit which may be higher than gas concentrations occurring under conditions with low emissions (Balde et al., 2019). Consequently, farm-scale studies using non-intrusive methods have a risk to overestimate the true average emissions (Baldé et al., 2018). This risk can be minimized by using recently developed sensors such as DOAS systems (Volten et al., 2012; Bell et al., 2017). Moreover, it would be important to quantify such potential biases by an assessment of gap filling procedures used for missing data due to e.g. non-detection at low concentration levels as done by Voglmeier et al. (2018). For reliable results from farm-scale studies, extended measurement periods are required covering all seasons of a year. Moreover, recent research has demonstrated that the history of the storage may play an important role for CH_4 emissions (Kariyapperuma et al., 2018) pointing at the necessity of measurement campaigns over several years for an adequate determination of representative emission rates. This implies a large effort in labor and costs. In addition, thorough recording of the operations at the storage facilities (agitation, filling, discharging of the stores by using e.g. a webcam, continuous measuring of the slurry volume stored), of crusting at the stores surface (thickness, structure, coverage of the surface), of slurry temperature at several depths, of meteorological conditions as well as slurry sampling and analyses are required. A few studies comply with these requirements (e.g. Baldé et al., 2018; Kariyapperuma et al., 2018). Still, collection of such data can be challenging or even hardly

feasible (e.g. representative slurry sampling at large lagoons). Also, operations at stores can largely differ between individual farms and consequently, it is difficult to select an experimental site at farm-scale which is appropriate to generate baseline emissions. Therefore, several measurement campaigns that consider the variety of different conditions occurring at slurry stores are required.

Pilot-scale studies are indispensable for studying principal mechanisms and influencing factors driving emissions or to evaluate the effectiveness of emission mitigation techniques. Facilities allowing for continuous measurements e.g. as presented by Petersen et al. (2009) are probably the best option. Further advantages of pilot-scale studies are the possibility to conduct experiments in replicates and a better control of the experimental conditions. There is also a potential to generate bases for modeling which could be used to complement data from farm-scale studies. Further progress for the quantification of emissions from slurry storage could be achieved by an analysis of individual measurement intervals from several experiments and model construction on this basis as e.g. done for slurry application by Hafner et al. (2019). The measurement intervals should include the relevant information regarding influencing factors. For this, we recommend that the researchers provide the emission data along with parameters as given in the Supplementary data 2. For indistinct parameters such as crusting, we suggest the elaboration of a standardized procedure to achieve a definition which reliably reflects its influence on the emission level.

5. Conclusions

The present article provides a comprehensive overview on published emission data from slurry storage which serves as a basis to determine guide values and baseline emissions for NH_3, GHGs and H_2S. Standardization of the emission data is an important issue in the present study due to the use of a large variety of units in the studies. Accompanying parameters (e.g. data on slurry analyses) were only partly available in the papers and could thus not be used for a more advanced data analysis. However, the season of the experimental period which served as a surrogate for the temperature was provided in most studies. Descriptive statistics of the emission data revealed a large variability for all gases. Data generated during warm, temperate and cold seasons are unevenly distributed over all records. Therefore, the calculation of an average annual value completed with a confidence range based on a weighting of the emission data according to the season and measurements duration was done. The baseline emissions on an area or volume basis determined for cattle and pig slurry stored in lagoons and tanks (Table 8) are mostly lower than existing reference values. NH_3 baseline emissions for tanks related to TAN are 16% of TAN (range: 14%–19% of TAN) and 15% TAN (range: 9.2%–23% of TAN) for cattle slurry and for pig slurry, respectively, and thus similar to emission factors used in emission inventory models. The flow-based baseline emissions for N_2O and CH_4 are lower than current emission factors. Total GHG emissions from slurry stores based on the global warming potential using a 100-year time horizon are dominated by CH_4.

Techniques for slurry treatment exhibit contrasting effects on emission levels during storage. Acidification was found to be efficient in reducing the emissions of NH_3 and CH_4 but less for CO_2 while the release of N_2O was enhanced in few studies. Solid-liquid separation causes higher losses for NH_3 and a reduction in CH_4, N_2O and CO_2 emissions. Anaerobic digestion promoted NH_3 emissions in most studies. In contrast, emission changes during slurry storage were less explicit for CH_4, although there is evidence toward an emission reduction. The effect of anaerobic digestion on N_2O and CO_2 emissions is unclear. It is essential to consider the context of good management practices along the whole manure management chain when the effect of slurry treatments on emissions from slurry storage is assessed.

All storage cover types reduce emissions of NH_3 while the effect is small for CH_4 and CO_2 with a trend toward a reduction. Permeable covers increase emissions of N_2O. Total GHG emissions tend to be lower with coverage of slurry stores. Overall, coverage of slurry is efficient to abate NH_3 emissions involving a minimum risk of pollution swapping.

The present study provides a robust data basis for the determination of baseline emissions except for flow-based baseline emissions for lagoons which could not be calculated. The emission data in the records from different studies may vary over several orders of magnitude even for the same slurry type, the same type of study and identical seasons of measurement. For future research, appropriate study designs are required to generate baseline emissions appropriate to improve emission inventories. For this, farm-scale studies using non-intrusive methods are likely to be a preferential option. Pilot-scale studies are important to complement results from farm-scale studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.106963.

References

Aguerre, M.J., Wattiaux, M.A., Powell, J.M., 2012. Emissions of ammonia, nitrous oxide, methane, and carbon dioxide during storage of dairy cow manure as affected by dietary forage-to-concentrate ratio and crust formation. J. Dairy Sci. 95, 7409–7416.
Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric. Ecosyst. Environ. 112, 153–162.
Amon, B., Kryvoruchko, V., Frohlich, M., Amon, T., Pollinger, A., Mosenbacher, I., Hausleitner, A., 2007. Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: housing and manure storage. Livest. Sci. 112, 199–207.
ASAE, 2005. ASAE Standard D384.2: Manure Production and Characteristics. ASAE Standards. American Society of Agricultural Engineering, St. Joseph, MI.
Balde, H., VanderZaag, A., Smith, W., Desjardins, R.L., 2019. Ammonia emissions measured using two different GasFinder open-path lasers. Atmosphere 10.
Balde, H., VanderZaag, A.C., Burtt, S., Evans, L., Wagner-Riddle, C., Desjardins, R.L., MacDonald, J.D., 2016a. Measured versus modeled methane emissions from separated liquid dairy manure show large model underestimates. Agric. Ecosyst. Environ. 230, 261–270.
Balde, H., VanderZaag, A.C., Burtt, S.D., Wagner-Riddle, C., Crolla, A., Desjardins, R.L., MacDonald, D.J., 2016b. Methane emissions from digestate at an agricultural biogas plant. Bioresour. Technol. Rep. 216, 914–922.
Baldé, H., VanderZaag, A.C., Burtt, S.D., Wagner-Riddle, C., Evans, L., Gordon, R., Desjardins, R.L., MacDonald, J.D., 2018. Ammonia emissions from liquid manure storages are affected by anaerobic digestion and solid-liquid separation. Agric. Forest Meteorol. 258, 80–88.
Balsari, P., Airoldi, G., Dinuccio, E., Gioelli, F., 2007. Emissions from farmyard manure heaps and slurry stores - effect of environmental conditions and measuring methods. Biosys. Eng. 97, 456–463.
Baral, K.R., Jego, G., Amon, B., Bol, R., Chantigny, M.H., Olesen, J.E., Petersen, S.O., 2018. Greenhouse gas emissions during storage of manure and digestates: key role of methane for prediction and mitigation. J. Agric. Food Syst. Community Dev. 166, 26–35.
Bastami, M.S.B., Jones, D.L., Chadwick, D.R., 2016. Reduction of methane emission during slurry storage by the addition of effective microorganisms and excessive carbon source from brewing sugar. J. Environ. Qual. 45, 2016–2022.
Beline, F., Martinez, J., 2002. Nitrogen transformations during biological aerobic treatment of pig slurry: effect of intermittent aeration on nitrous oxide emissions. Bioresour. Technol. Rep. 83, 225–228.

Beline, F., Martinez, J., Chadwick, D., Guiziou, F., Coste, C.M., 1999. Factors affecting nitrogen transformations and related nitrous oxide emissions from aerobically treated piggery slurry. J. Agr. Eng. Res. 73, 235–243.
Bell, M., Flechard, C., Fauvel, Y., Häni, C., Sintermann, J., Jocher, M., Menzi, H., Hensen, A., Neftel, A., 2017. Ammonia emissions from a grazed field estimated by miniDOAS measurements and inverse dispersion modelling. Atmos. Meas. Tech. 10, 1875–1892.
Bittman, S., Dedina, M., Oenema, O., Sutton, M.A., 2014. Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen. Centre for Ecology and Hydrology, Edinburgh, UK.
Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., Misselbrook, T., 2011. Manure management: implications for greenhouse gas emissions. Anim. Feed Sci. Tech. 166–167, 514–531.
Clemens, J., Trimborn, M., Weiland, P., Amon, B., 2006. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. Agric. Ecosyst. Environ. 112, 171–177.
Dai, X.R., Blanes-Vidal, V., 2013. Emissions of ammonia, carbon dioxide, and hydrogen sulfide from swine wastewater during and after acidification treatment: effect of pH, mixing and aeration. J. Environ. Manage. 115, 147–154.
De Bode, M.J.C., 1991. Odour and ammonia emissions from manure storage. In: Nielsen, V.C., Voorburg, J.H., L'Hermite, P. (Eds.), Odour and Ammonia Emissions from Livestock Farming. Elsevier Applied Science, London, England, pp. 69–76.
Dinuccio, E., Berg, W., Balsari, P., 2008. Gaseous emissions from the storage of untreated slurries and the fractions obtained after mechanical separation. Atmos. Environ. 42, 2448–2459.
Dinuccio, E., Gioelli, F., Balsari, P., Dorno, N., 2012. Ammonia losses from the storage and application of raw and chemo-mechanically separated slurry. Agric. Ecosyst. Environ. 153, 16–23.
EEA, 2016. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016. Technical Guidance to Prepare National Emission Inventories. European Environment Agency, Luxembourg.
Efron, B., 1987. Better bootstrap confidence-intervals. J. Am. Stat. Assoc. 82, 171–185.
Elsgaard, L., Olsen, A.B., Petersen, S.O., 2016. Temperature response of methane production in liquid manures and co-digestates. Sci. Total Environ. 539, 78–84.
Fangueiro, D., Hjorth, M., Gioelli, F., 2015. Acidification of animal slurry– a review. J. Environ. Manage. 149, 46–56.
Flesch, T.K., Harper, L.A., Powell, J.M., Wilson, J.D., 2009. Inverse-dispersion calculation of ammonia emissions from Wisconsin dairy farms. Trans. ASABE 52, 253–265.
Gao, Z.L., Desjardins, R.L., van Haarlem, R.P., Flesch, T.K., 2008. Estimating gas emissions from multiple sources using a backward Lagrangian stochastic model. J. Air Waste Manage. Assoc. 58, 1415–1421.
Grant, R.H., Boehm, M.T., 2015. Manure ammonia and hydrogen sulfide emissions from a Western dairy storage basin. J. Environ. Qual. 44, 127–136.
Grant, R.H., Boehm, M.T., 2018. Ammonia emissions from an in-ground finisher hog manure tank. Atmos. Environ. 190, 43–52.
Grant, R.H., Boehm, M.T., Bogan, B.W., 2015. Methane and carbon dioxide emissions from manure storage facilities at two free-stall dairies. Agric. Forest Meteorol. 213, 102–113.
Guarino, M., Fabbri, C., Brambilla, M., Valli, L., Navarotto, P., 2006. Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. Trans. ASABE 49, 737–747.
Habetwold, J., Gordon, R.J., Wood, J.D., Wagner-Riddle, C., VanderZaag, A.C., Dunfield, K.E., 2017. Dairy manure total solid levels impact CH4 flux and abundance of methanogenic archaeal communities. J. Environ. Qual. 46, 232–236.
Hafner, S.D., Pacholski, A., Bittman, S., Burchill, W., Bussink, W., Chantigny, M., Carozzi, M., Genermont, S., Häni, C., Hansen, M.N., Huijsmans, J., Hunt, D., Kupper, T., Lanigan, G., Loubet, B., Misselbrook, T., Meisinger, J.J., Neftel, A., Nyord, T., Pedersen, S.V., Rochette, P., Sintermann, J., Vermeulen, B., Vestergaard, A., Voylokov, P., Williams, J.R., Sommer, S.G., 2018. The ALFAM2 database on ammonia emission from field-applied manure: description and illustrative analysis. Agric. Forest Meteorol. 258, 66–78.
Hafner, S.D., Pacholski, A., Bittman, S., Carozzi, M., Chantigny, M., Genermont, S., Häni, C., Hansen, M.N., Huijsmans, J., Kupper, T., Misselbrook, T., Neftel, A., Nyord, T., Sommer, S.G., 2019. A flexible semi-empirical model for estimating ammonia volatilization from field-applied slurry. Atmos. Environ. 199, 474–484.
Hamilton, D.W., Fulhage, C.D., Clarkson, W., Lalman, J., 2001. Treatment lagoons for animal agriculture. In: J.M, Rice, Humenik, F.J. (Eds.), Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers. American Society of Agricultural and Biological Engineers, St. Joseph, Michigan, USA, pp. 547–574.
Hill, R.A., Smith, K., Russell, K., Misselbrook, T., Brookman, S., 2008. Emissions of ammonia from weeping wall stores and earth-banked lagoons determined using passive sampling and atmospheric dispersion modelling. J. Atmos. Chem. 59, 83–98.
Hjorth, M., Nielsen, A.M., Nyord, T., Hansen, M.N., Nissen, P., Sommer, S.G., 2009. Nutrient value, odour emission and energy production of manure as influenced by anaerobic digestion and separation. Agron. Sustain. Dev. 29, 329–338.
Hobbs, P.J., Misselbrook, T.H., Cumby, T.R., 1999. Production and emission of odours and gases from ageing pig waste. J. Agr. Eng. Res. 72, 291–298.
Holly, M.A., Larson, R.A., 2017a. Effects of manure storage additives on manure composition and greenhouse gas and ammonia emissions. Trans. ASABE 60, 449–456.
Holly, M.A., Larson, R.A., 2017b. Thermochemical conversion of biomass storage covers to reduce ammonia emissions from dairy manure. Water Air Soil Pollut. Focus. 228.
Hörnig, G., Turk, M., Wanka, U., 1999. Slurry covers to reduce ammonia emission and odour nuisance. J. Agr. Eng. Res. 73, 151–157.
Husted, S., 1994. Seasonal-variation in methane emission from stored slurry and solid manures. J. Environ. Qual. 23, 585–592.
IPCC, 2006. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan.
IPCC, 2007. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Kaharabata, S.K., Schuepp, P.H., Desjardins, R.L., 1998. Methane emissions from aboveground open manure slurry tanks. Global Biogeochem. Cy. 12, 545–554.
Kariyapperuma, K.A., Johannesson, G., Maldaner, L., VanderZaag, A., Gordon, R., Wagner-Riddle, C., 2018. Year-round methane emissions from liquid dairy manure in a cold climate reveal hysteretic pattern. Agric. Forest Meteorol. 258, 56–65.
Koirala, K., Ndegwa, P.M., Joo, H.S., Frear, C., Stockle, C.O., Harrison, J.H., 2013. Impact of anaerobic digestion of liquid dairy manure on ammonia volatilization process. Trans. ASABE 56, 1959–1966.
Leytem, A.B., Bjorneberg, D.L., Koehn, A.C., Moraes, L.E., Kebreab, E., Dungan, R.S., 2017. Methane emissions from dairy lagoons in the western United States. J. Dairy Sci. 100, 6785–6803.
Leytem, A.B., Dungan, R.S., Bjorneberg, D.L., Koehn, A.C., 2011. Emissions of ammonia, methane, carbon dioxide, and nitrous oxide from dairy cattle housing and manure management systems. J. Environ. Qual. 40, 1383–1394.
Liu, D., Rong, L., Kamp, J., Kong, X., Adamsen, A.P.S., Chowdhury, A., Feilberg, A., 2020. Photoacoustic measurement with infrared band-pass filters significantly overestimates NH3 emissions from cattle houses due to volatile organic compound (VOC) interferences. Atmos. Meas. Tech. 13, 259–272.
Loyon, L., Guiziou, F., Beline, E., Peu, P., 2007. Gaseous emissions (NH_3, N_2O, CH_4 and CO_2) from the aerobic treatment of piggery slurry - comparison with a conventional storage system. Biosys. Eng. 97, 472–480.
Maldaner, L., Wagner-Riddle, C., VanderZaag, A.C., Gordon, R., Duke, C., 2018. Methane emissions from storage of digestate at a dairy manure biogas facility. Agric. Forest Meteorol. 258, 96–107.
Mangino, J., Bartram, D., Brazy, A., 2001. Development of a Methane Conversion Factor to Estimate Emissions from Animal Waste Lagoons. Technical Report. pp. 14. (Accessed 30 January 2020). https://www.epa.gov/ttn/chief/conference/ei11/ammonia/mangino.pdf2001.
Martinez, J., Guiziou, F., Peu, P., Gueutier, V., 2003. Influence of treatment techniques for pig slurry on methane emissions during subsequent storage. Biosys. Eng. 85, 347–354.
McGinn, S.M., Coates, T., Flesch, T.K., Crenna, B., 2008. Ammonia emission from dairy cow manure stored in a lagoon over summer. Can. J. Soil Sci. 88, 611–615.
Minato, K., Kouda, Y., Yamakawa, M., Hara, S., Tamura, T., Osada, T., 2013. Determination of GHG and ammonia emissions from stored dairy cattle slurry by using a floating dynamic chamber. Anim. Sci. J. 84, 165–177.
Misselbrook, T., Hunt, J., Perazzolo, F., Provolo, G., 2016. Greenhouse gas and ammonia emissions from slurry storage: impacts of temperature and potential mitigation through covering (pig slurry) or acidification (cattle slurry). J. Environ. Qual. 45, 1520–1530.
Misselbrook, T.H., Brookman, S.K.E., Smith, K.A., Cumby, T., Williams, A.G., McCrory, D.F., 2005. Crusting of stored dairy slurry to abate ammonia emissions: pilot-scale studies. J. Environ. Qual. 34, 411–419.
Molodovskaya, M., Singurindy, O., Richards, B.K., Steenhuis, T.S., 2008. Nitrous oxide from aerated dairy manure slurries: effects of aeration rates and oxic/anoxic phasing. Bioresour. Technol. Rep. 99, 8643–8648.
Mosquera, J., Schils, R.L.M., Groenestein, C.M., Hoeksma, P., Velthof, G., Hummelink, E., 2010. Emissions of Nitrous Oxide, Methane and Ammonia From Manure After Separation. Rapport 427, Lelystad..RApport 387 (in Dutch). Livestock Research, Wageningen UR, Wageningen, The Netherlands.
Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659–740.
Ngwabie, N.M., Gordon, R.J., VanderZaag, A., Dunfield, K., Sissoko, A., Wagner-Riddle, C., 2016. The extent of manure removal from storages and its impact on gaseous emissions. J. Environ. Qual. 45, 2023–2029.
Ni, J.Q., 1999. Mechanistic models of ammonia release from liquid manure: a review. J. Agr. Eng. Res. 72, 1–17.
Ni, J.Q., Heber, A.J., Sutton, A.L., Kelly, D.T., Patterson, J.A., Kim, S.T., 2010. Effect of swine manure dilution on ammonia, hydrogen sulfide, carbon dioxide, and sulfur dioxide releases. Sci. Total Environ. 408, 5917–5923.
Nielsen, D.A., Nielsen, L.P., Schramm, A., Revsbech, N.P., 2010. Oxygen distribution and potential ammonia oxidation in floating, liquid manure crusts. J. Environ. Qual. 39, 1813–1820.
Olesen, J.E., Sommer, S.G., 1993. Modelling effects of wind speed and surface cover on ammonia volatilization from stored pig slurry. Atmos. Environ. Part A Gen. Topics 27A, 2567–2574.
Owen, J.J., Silver, W.L., 2015. Greenhouse gas emissions from dairy manure management: a review of field-based studies. Glob. Change Biol. Bioenergy 21, 550–565.
Owusu-Twum, M.Y., Polastre, A., Subedi, R., Santos, A.S., Ferreira, L.M.M., Coutinho, J., Trindade, H., 2017. Gaseous emissions and modification of slurry composition during storage and after field application: effect of slurry additives and mechanical separation. J. Environ. Manage. 200, 416–422.
Pain, B., Menzi, H., 2011. Glossary of Terms on Livestock and Manure Management, second edition. Ramiran, pp. 80.

Petersen, S.O., Ambus, P., 2006. Methane oxidation in pig and cattle slurry storages, and effects of surface crust moisture and methane availability. Nutr. Cycl. Agroecosys. 74, 1–11.
Petersen, S.O., Amon, B., Gattinger, A., 2005. Methane oxidation in slurry storage surface crusts. J. Environ. Qual. 34, 455–461.
Petersen, S.O., Andersen, A.J., Eriksen, J., 2012. Effects of cattle slurry acidification on ammonia and methane evolution during storage. J. Environ. Qual. 41, 88–94.
Petersen, S.O., Dorno, N., Lindholst, S., Feilberg, A., Eriksen, J., 2013. Emissions of CH4, N2O, NH3 and odorants from pig slurry during winter and summer storage. Nutr. Cycl. Agroecosys. 95, 103–113.
Petersen, S.O., Miller, D.N., 2006. Greenhouse gas mitigation by covers on livestock slurry tanks and lagoons? J. Environ. Sci. Health B 86, 1407–1411.
Petersen, S.O., Skov, M., Droscher, P., Adamsen, A.P.S., 2009. Pilot scale facility to determine gaseous emissions from livestock slurry during storage. J. Environ. Qual. 38, 1560–1568.
Portejoie, S., Martinez, J., Guiziou, F., Coste, C.M., 2003. Effect of covering pig slurry stores on the ammonia emission processes. Bioresour. Technol. Rep. 87, 199–207.
Rennie, T.J., Gordon, R.J., Smith, W.N., VanderZaag, A.C., 2018. Liquid manure storage temperature is affected by storage design and management practices-A modelling assessment. Agric. Ecosyst. Environ. 260, 47–57.
Richner, W., Flisch, R., Mayer, J., Schlegel, P., Zähner, M., Menzi, H., 2017. 4/ Eigenschaften und Anwendung von Düngern. In: Richner, W., Sinaj, S. (Eds.), Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz / GRUD 2017. Agrarforschung Schweiz, Spezialpublikation 8, 4/1-4/23.
Rodhe, L.K.K., Abubaker, J., Ascue, J., Pell, M., Nordberg, A., 2012. Greenhouse gas emissions from pig slurry during storage and after field application in northern European conditions. Biosys. Eng. 113, 379–394.
Rodhe, L.K.K., Ascue, J., Willén, A., Persson, B.V., Nordberg, Å, 2015. Greenhouse gas emissions from storage and field application of anaerobically digested and non-digested cattle slurry. Agric. Ecosyst. Environ. 199, 358–368.
Sajeev, E.P.M., Winiwarter, W., Amon, B., 2018. Greenhouse gas and Ammonia emissions from different stages of liquid manure management chains: abatement options and emission interactions. J. Environ. Qual. 47, 30–41.
Smith, K., Cumby, T., Lapworth, J., Misselbrook, T., Williams, A., 2007. Natural crusting of slurry storage as an abatement measure for ammonia emissions on dairy farms. Biosys. Eng. 97, 464–471.
Sommer, S.G., Christensen, B.T., Nielsen, N.E., Schjorring, J.K., 1993. Ammonia volatilization during storage of cattle and pig slurry - effect of surface cover. J. Agr. Sci. 121, 63–71.
Sommer, S.G., Christensen, M.L., Schmidt, T., Jensen, L.S., 2013. Animal Manure Recycling: Treatment and Management. John Wiley Sons Ltd, West Sussex, UK.
Sommer, S.G., Petersen, S.O., Sogaard, H.T., 2000. Greenhouse gas emission from stored livestock slurry. J. Environ. Qual. 29, 744–751.
Sommer, S.G., Petersen, S.O., Sorensen, P., Poulsen, H.D., Moller, H.B., 2007. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. Nutr. Cycl. Agroecosys. 78, 27–36.
Sommer, S.G., Zhang, G.Q., Bannink, A., Chadwick, D., Misselbrook, T., Harrison, R., Hutchings, N.J., Menzi, H., Monteny, G.J., Ni, J.Q., Oenema, O., Webb, J., 2006. Algorithms determining ammonia emission from buildings housing cattle and pigs and from manure stores. Adv. Agron. 89, 261–335.
Sorensen, C.A.G., Sommer, S.G., Bochtis, D., Rotz, A., 2013. Technologies and logistics for handling, transport and distribution of animal manures. In: Sommer, S.G., Christensen, M.L., Schmidt, T., Jensen, L.S. (Eds.), Animal Manure Recycling: Treatment and Management. John Wiley Sons Ltd, West Sussex, UK, pp. 211–236.
Sun, F., Harrison, J.H., Ndegwa, P.M., Johnson, K., 2014. Effect of manure treatment on ammonia emission during storage under ambient environment. Water Air Soil Pollut. Focus. 225.
Sutton, M.A., Oenema, O., Erisman, J.W., Leip, A., van Grinsven, H., Winiwarter, W., 2011. Too much of a good thing. Nature 472, 159–161.
Triolo, J.M., Sommer, S.G., Moller, H.B., Weisbjerg, M.R., Jiang, X.Y., 2011. A new algorithm to characterize biodegradability of biomass during anaerobic digestion: influence of lignin concentration on methane production potential. Bioresour. Technol. Rep. 102, 9395–9402.
UN, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. New York NY. .
UNECE, 2015. Guidelines for reporting emissions and projections data under the Convention on Long-range Transboundary Air Pollution. Paper ECE/EB.AIR/128. United Nations Economic Commission for Europe (UNECE), Geneva, Switzerland.
UNECE, 1999. Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long-range Transboundary Air Pollution. (Accessed 30 January 2020). http://www.unece.org/env/ lrtap/multi_h1.html.
UNECE, 2014. Guidance Document for Preventing and Abating Ammonia Emissions from Agricultural Sources. Paper ECE/EB.AIR/120, February 7, 2014. United Nations Economic Commission for Europe (UNECE), Geneva, Switzerland.
Van der Stelt, B., Temminghoff, E.J.M., Van Vliet, P.C.J., Van Riemsdijk, W.H., 2007. Volatilization of ammonia from manure as affected by manure additives, temperature and mixing. Bioresour. Technol. Rep. 98, 3449–3455.
VanderZaag, A., Amon, B., Bittman, S., Kuczynski, T., 2015. Ammonia abatement with manure storage and processing techniques. In: Reis, S., Howard, C., Sutton, M.A. (Eds.), Costs of Ammonia Abatement and the Climate Co-Benefits. Springer, Netherlands, pp. 75–112.
VanderZaag, A.C., Baldé, H., Crolla, A., Gordon, R.J., Ngwabie, N.M., Wagner-Riddle, C., Desjardins, R., MacDonald, J.D., 2018. Potential methane emission reductions for two manure treatment technologies. Environ. Technol. 39, 851–858.
VanderZaag, A.C., Gordon, R.J., Glass, V.M., Jamieson, R.C., 2008. Floating covers to reduce gas emissions from liquid manure storages: a review. Appl. Eng. Agric. 24, 657–671.
VanderZaag, A.C., Gordon, R.J., Jamieson, R.C., Burton, D.L., Stratton, G.W., 2009. Gas emissions from straw covered liquid dairy manure during summer storage and autumn agitation. Trans. ASABE 52, 599–608.
VanderZaag, A.C., Gordon, R.J., Jamieson, R.C., Burton, D.L., Stratton, G.W., 2010a. Effects of winter storage conditions and subsequent agitation on gaseous emissions from liquid dairy manure. Can. J. Soil Sci. 90, 229–239.
VanderZaag, A.C., Gordon, R.J., Jamieson, R.C., Burton, D.L., Stratton, G.W., 2010b. Permeable synthetic covers for controlling emissions from liquid dairy manure. Appl. Eng. Agric. 26, 287–297.
VanderZaag, A.C., Wagner-Riddle, C., Park, K.H., Gordon, R.J., 2011. Methane emissions from stored liquid dairy manure in a cold climate. Anim. Feed Sci. Tech. 166-67, 581–589.
Voglmeier, K., Jocher, M., Häni, C., Ammann, C., 2018. Ammonia emission measurements of an intensively grazed pasture. Biogeosciences 15, 4593–4608.
Volten, H., Bergwerff, J.B., Haaima, M., Lolkema, D.E., Berkhout, A.J.C., van der Hoff, G.R., Potma, C.J.M., Kruit, R.J.W., van Pul, W.A.J., Swart, D.P.J., 2012. Two instruments based on differential optical absorption spectroscopy (DOAS) to measure accurate ammonia concentrations in the atmosphere. Atmos. Meas. Tech. 5, 413–427.
Wagner-Riddle, C., Park, K.H., Thurtell, G.W., 2006. A micrometeorological mass balance approach for greenhouse gas flux measurements from stored animal manure. Agric. Forest Meteorol. 136, 175–187.
Wheeler, E.F., Adviento-Borbe, A.A., Brandt, R.C., Topper, P.A., Topper, D.A., Elliott, H.A., Graves, R.E., Hristov, A.N., Ishler, V.A., Bruns, M.V., 2011. Amendments for mitigation of dairy manure ammonia and greenhouse gas emissions: preliminary screening. Agric. Eng. Int. CIGR J. 13, 1–14.
Wood, J.D., Gordon, R.J., Wagner-Riddle, C., Dunfield, K.E., Madani, A., 2012. Relationships between dairy slurry total solids, gas emissions, and surface crusts. J. Environ. Qual. 41, 694–704.
Wood, J.D., VanderZaag, A.C., Wagner-Riddle, C., Smith, E.L., Gordon, R.J., 2014. Gas emissions from liquid dairy manure: complete versus partial storage emptying. Nutr Cycl Agroecosys 99, 95–105.

RETHINKING MANURE BIOGAS

Policy Considerations to Promote Equity and Protect the Climate and Environment

Ruthie Lazenby

VERMONT LAW & GRADUATE SCHOOL
CENTER FOR AGRICULTURE & FOOD SYSTEMS

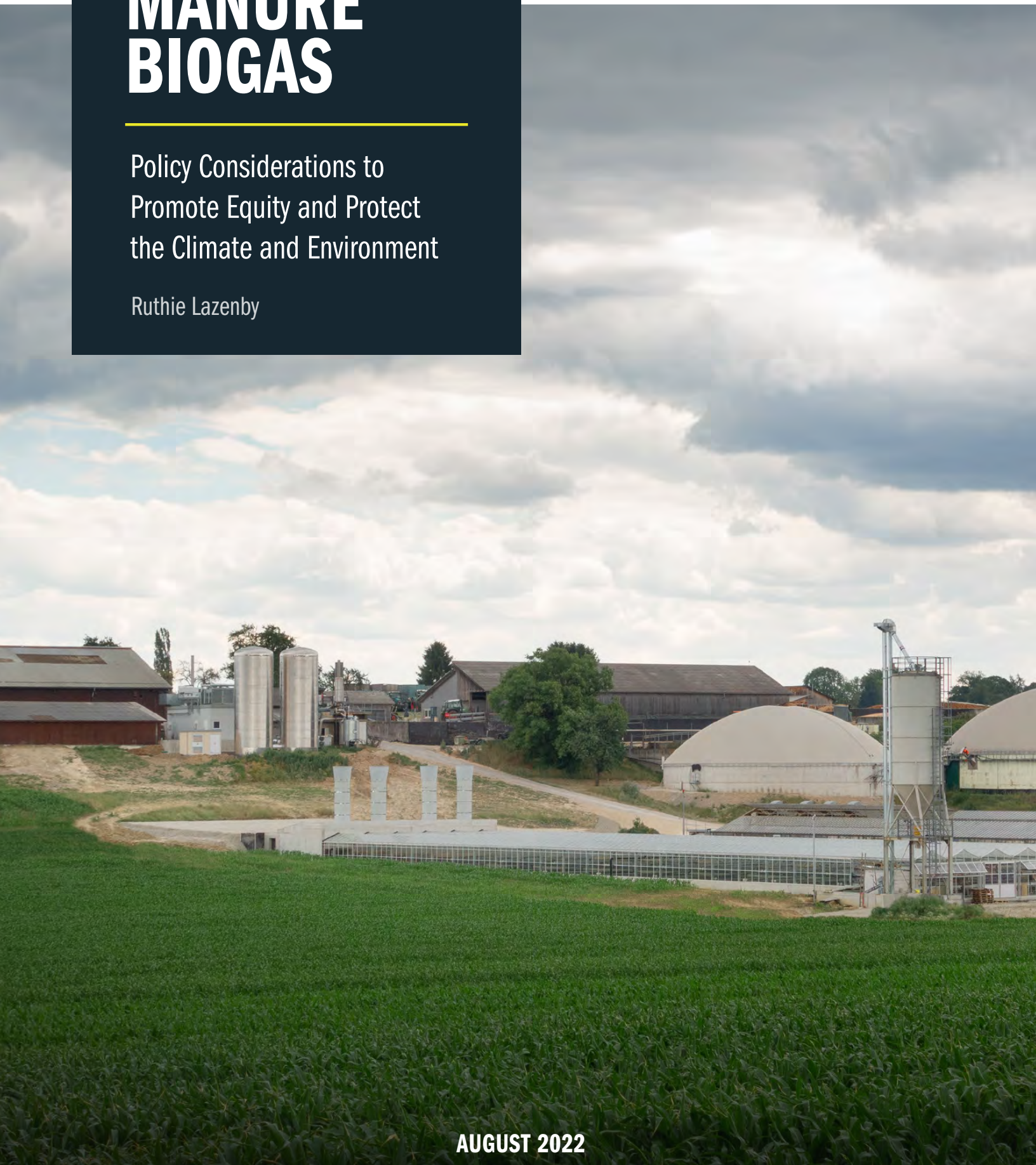

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Vermont Law and Graduate School's Center for Agriculture and Food Systems (CAFS) uses law and policy to build a more sustainable and just food system. In partnership with local, regional, national, and international partners, CAFS addresses food system challenges related to food justice, food security, farmland access, animal welfare, worker protections, the environment, and public health, among others. CAFS works closely with its partners to provide legal services that respond to their needs and develop resources that empower the communities they serve. Through CAFS' Food and Agriculture Clinic and Research Assistant program, students work directly on projects alongside partners nationwide, engaging in innovative work that spans the food system. Please visit www.vermontlaw.edu/cafs to learn more.

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INTRODUCTION

THE WORLD IS ON TRACK TO EXCEED A 2° C INCREASE DURING THE 21ST CENTURY, an outcome scientists have described as catastrophic.[1] Direct impacts on the food and agriculture sectors will be far-reaching.[2] Already, climate-related impacts to farming include "observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones."[3] These changes impact both crop and livestock production. Experts predict that further warming will continue to dramatically affect the "global water cycle and its variability, global monsoon precipitation and the severity of wet and dry events."[4]

In regions like eastern North Carolina, home to the United States' top two pork producing counties,[5] producers will experience more regular hurricanes of greater magnitude.[6] California's Central Valley, which provides cropland for over 250 different crops[7] and houses 80 percent of the state's milk cows,[8] already relies on the second most over-pumped aquifer in the nation while facing substantially drier conditions as a result of climate change.[9] These impacts will disproportionately harm vulnerable populations[10] in addition to historically marginalized farmers, who will be the first to lose their livelihoods.[11] Climate change will force agriculture to adapt—either now, through innovation to mitigate increased warming, or later, as regional climates become incompatible with existing models of food production.[12]

It is clear that the food and agriculture sector will bear significant impacts from climate change, but this sector is also a major contributor of greenhouse gas (GHG) emissions. Animal agriculture, in particular, is responsible for approximately 20 percent of global GHG emissions and 57 percent of food related emissions.[13] Animal agriculture's primary contributions to climate change result from methane and nitrous oxide emissions. Methane has a global warming potential 28 to 36 times that of carbon dioxide on a 100-year timescale and nitrous oxide has a global warming potential 265 to 298 times that that of carbon dioxide on a 100-year timescale.[14] Moreover, while emissions from the energy sector have decreased as a result of emission reduction policies, GHG emissions from agriculture have increased over recent decades with this trend projected to continue.[15] Consequently, addressing emissions from agriculture is increasingly critical.

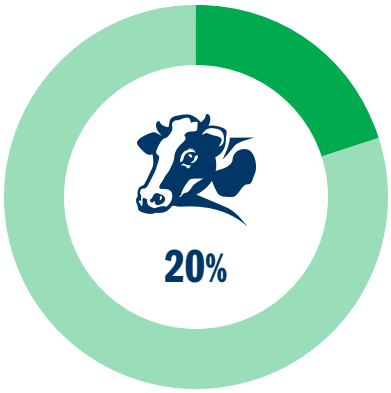

Percent of global greenhouse gas emissions caused by animal agriculture

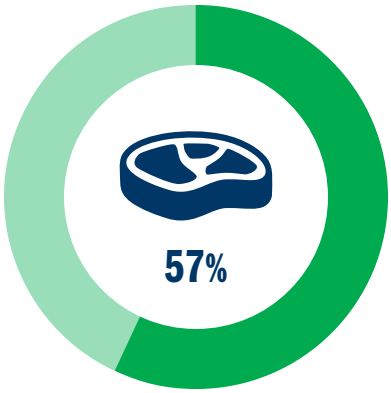

Percent of global food-based emissions caused by animal agriculture

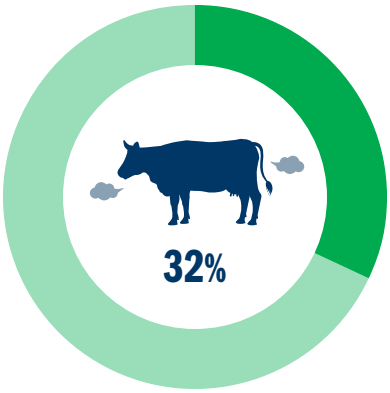

Percent of global methane emissions caused by livestock manure and enteric fermentation

Source: Food in the Anthropocene: the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems, THE LANCET

One approach to reducing atmospheric GHGs from livestock involves capturing emissions from manure through the use of anaerobic digesters.[16] Proponents of this approach herald it as a win-win. Manure biogas systems reduce GHG emissions by capturing GHGs that would otherwise be emitted and can displace the use of fossil fuels. Additionally, this new fuel source (biogas) creates a new revenue stream from a former waste product. In a 2017 press release announcing federal funding to help farmers construct biogas systems, the United States Department of Agriculture (USDA) articulated the conventional wisdom of the emissions reduction claim, stating:

> "Anaerobic digesters actually provide two-fold greenhouse gas reduction. First, they capture methane that otherwise would be emitted from the manure into the atmosphere. . . . Second, by utilizing the trapped biogas as a renewable energy source, digesters displace the need for additional fossil fuels."[17]
>
> **– LAURA MELLING**

While these claims sound promising, they omit important nuance. **Animal agriculture generates emissions throughout the operation—from land conversion to enteric fermentation (the emissions generated from ruminant burps), to transportation.** It is imperative that policymakers and others recognize that manure biogas systems reduce emissions from only one part of this system—manure management. At the same time, manure biogas systems rely on the ongoing production of large quantities of livestock manure—the source of manure management emissions—to function. Espousing these systems to the exclusion of other emissions mitigation measures can foreclose the potential to make important modifications throughout the livestock life cycle. Ultimately, this reinforces current conventional models of livestock production at the expense of farmers using more sustainable production models.

Currently, policymakers are dedicating increasing amounts of public funding and attention to manure biogas as compared to other policy interventions that can reduce livestock emissions. Recently, the American Biogas Council suggested that the US could support at least another 13,740 potential new biogas systems, including 8,300 on farms, in addition to 4,000



What is Methane?

"Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes."

Source: Inventory of US Greenhouse Gas Emissions and Sinks (1990-2020), Environmental Protection Agency

What is Enteric Fermentation?

"Enteric fermentation is fermentation that takes place in the digestive systems of animals. In particular, ruminant animals (cattle, buffalo, sheep, goats, and camels) have a large "fore-stomach," or rumen, within which microbial fermentation breaks down food into soluble products that can be utilized by the animal."

Source: AP-42: Compilation of Air Emissions Factors, Environmental Protection Agency

What are Biosolids?

"Biosolids are a product of the wastewater treatment process. During wastewater treatment the liquids are separated from the solids. Those solids are then treated physically and chemically to produce a semisolid, nutrient-rich product known as biosolids. The terms 'biosolids' and 'sewage sludge' are often used interchangeably."

Source: Environmental Protection Agency

for wastewater, 1,000 for food scraps, and 440 for landfills.[18] Biogas systems are expensive to construct and operate. They require substantial investment into long-lasting, durable infrastructure such as pipeline interconnections and facilities upgrades. As more public and private resources are dedicated to this infrastructure, the incentives to continuing using these systems will increase.

To date, many discussions on the benefits of manure biogas fail to account for the concerning and negative implications associated with widespread adoption of manure biogas systems. For example, the climate implications resulting from the need for these systems to engage in long-term production of massive quantities of livestock manure (or other biosolids) to recoup the fixed upfront costs of installation and continued revenue generation is rarely addressed. To illustrate this point, the public programs subsidizing production and sale of biomethane from these operations provide incentives for the ongoing production of the core input—livestock manure—even as climate scientists warn that greater reductions from animal agriculture are necessary.[19] Promoting widespread investment in and adoption of manure biogas systems will inevitably impact livestock agriculture for years, if not decades, into the future, creating potential barriers for more substantial and systemic climate mitigation measures for the sector.

Moreover, because manure digesters are typically feasible only for industrial-scale livestock operations, the largest confined animal feeding operations will reap the financial and public relations benefits that accompany the installation of digesters. This is not a new trend: today and historically, large-scale commercial operations have benefited from the lion's share of federal funding for agriculture. Due to decades of discriminatory lending by USDA,[20] the majority of these operations are owned by white farmers.[21] Racism and discriminatory lending by the federal government over the past century has resulted in a dramatic loss of Black-owned land and farms across the board (one recent analysis calculated this dispossession to total $326 billion).[22] This disparity is even more pronounced for larger agricultural operations.[23] However, in some parts of the country, the substantial environmental impacts generated by these larger agricultural operations disproportionately harm Black, Indigenous, and communities of color.[24]

The share of Black farmers has declined significantly over the last century. Today just 1.4 percent of farmers identify as Black.

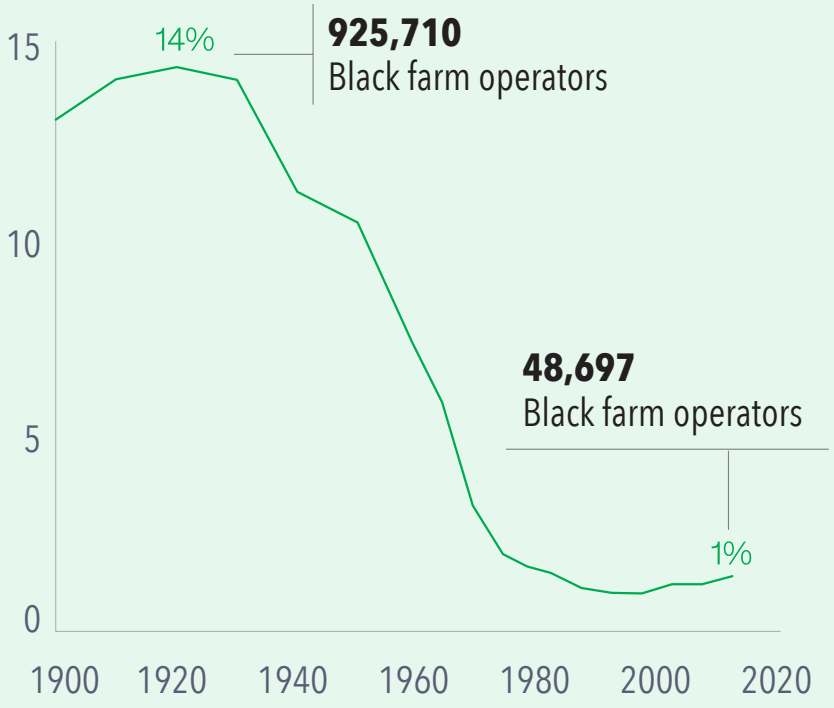

Source: Black farmers in the US: The opportunity for addressing racial disparities in farming, McKinsey & Company

Anaerobic digesters, in contrast to alternative mitigation measures, are an appealing means to reduce livestock emissions in industrial animal agriculture because they require no change to the structure of conventional livestock operations and manure management. On the contrary, these systems function by ensuring the continuity of both the existing system and its beneficiaries. This fails to consider and plan for the systemic changes needed in conventional operations and manure management due to the current, near, and long-term impacts of climate change.[25] Consequently, policymakers should immediately begin to proactively plan for the future by assessing the full range of suitable mitigation measures and supporting those that will provide for long-term sustainability and climate mitigation. As part of this process, policymakers must also critically evaluate the environmental justice impacts to neighboring communities and equity implications of elevating biogas systems over other mitigation measures.

This report analyzes and evaluates the extensive adoption and support of manure anaerobic digesters with a specific focus on the resulting equity implications, a goal explicitly aligned with two executive orders issued by the Biden Administration—Executive Order 14008: Tackling the Climate Crisis at Home and Abroad[26] and Executive Order 13985: Advancing Racial Equity and Support for Underserved Communities Through the Federal Government.[27] The report begins by surveying existing funding opportunities for manure biogas systems and the fuels they produce. It then addresses the direct environmental impacts of installing and operating these systems, including a brief discussion about the methodology used to account for life cycle emissions. The next section evaluates alternative methods to reduce livestock emissions, indirect environmental impacts of adopting manure biogas as the primary means to reduce GHG emissions from livestock operations, and the equity impacts. The report concludes with a set of recommendations for policymakers and regulators as they consider the role this technology should play in shifting livestock agriculture toward a more equitable, just, and climate-smart model.

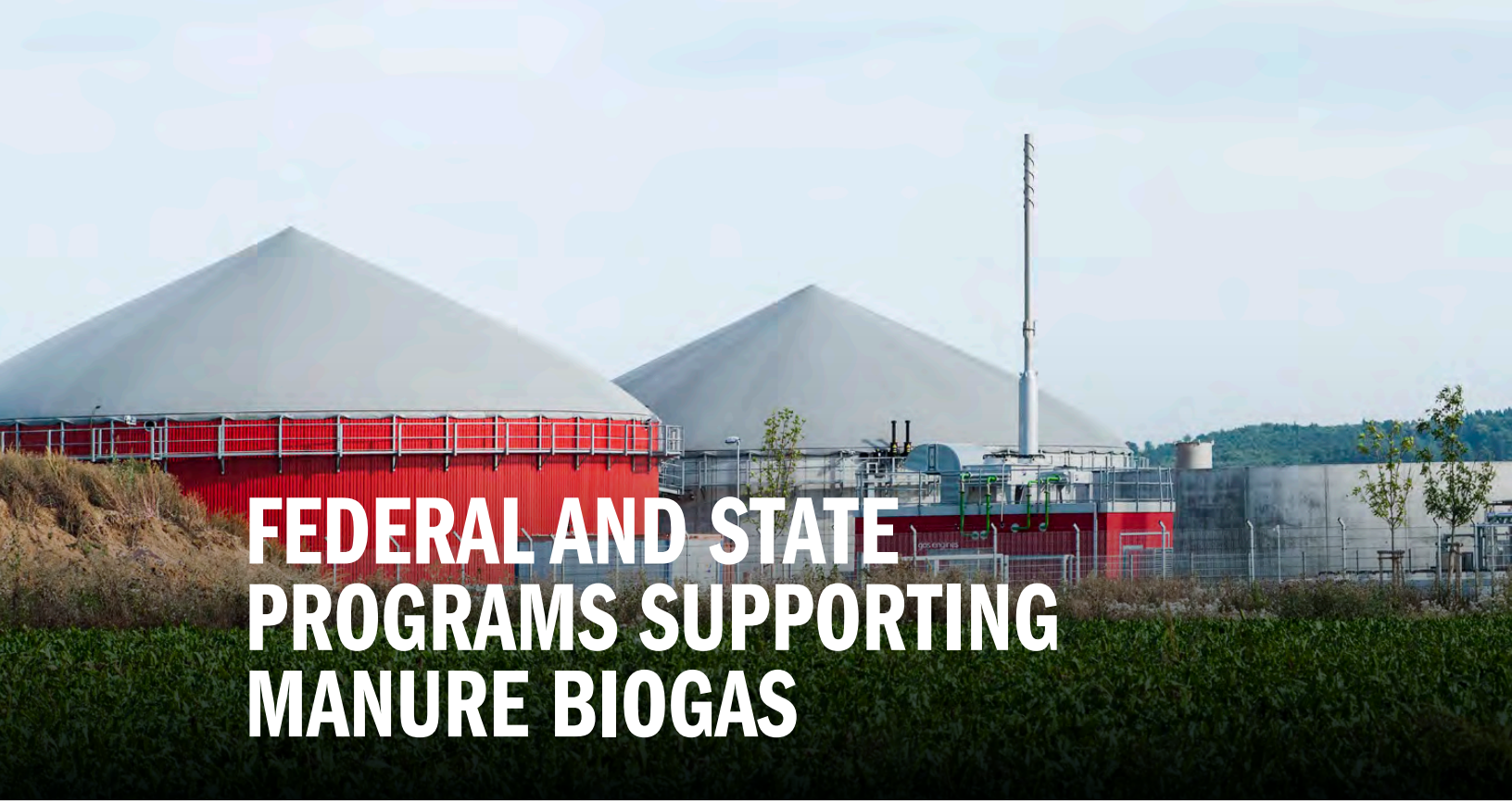

FEDERAL AND STATE PROGRAMS SUPPORTING MANURE BIOGAS

THE BIDEN ADMINISTRATION HAS CONSISTENTLY EMPHASIZED ITS COMMITMENT TO CLIMATE-SMART AGRICULTURE and tasked a number of federal agencies with collecting input from stakeholders and developing plans to address the climate crisis.[28] USDA was directed to submit a report to the administration laying out an "agricultural and forestry strategy."[29] In USDA's 90-Day Progress Report on Climate-Smart Agriculture and Forestry,[30] the agency embraced the president's "focus on developing a climate-smart agriculture and forestry strategy that employs proven conservation practices," announced plans to reduce methane from livestock,[31] and significantly funded research efforts targeted at these reductions.[32] With this new momentum, policy attention and interest in manure biogas has never been greater due to the perception that it provides an easy solution to reduce atmospheric emissions without requiring significant changes to the conventional industrial livestock model. This section surveys many of the existing and overlapping funding sources and incentive programs for manure biogas.

Grants & Loans Covering Start-Up Costs

Direct financial support for anaerobic digester systems is available to livestock facilities in the form of grants and loans. At the federal level, the Rural Energy for America Program (REAP) provides guaranteed loan financing and grant funding for the construction of biogas systems.[33] Federal funds for biogas systems can also be obtained through USDA's conservation programs—the Environmental Quality Incentives Program (EQIP), the Conservation Stewardship Program (CSP), and the newer Conservation Loan Program (CLP).[34] While these conservation and energy programs are the most important sources of federal funds for manure biogas, many other programs support the development of the industry. The 2018 Farm Bill's Energy Title alone includes the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program;[35] the Bioenergy Program for Advanced Biofuels;[36] Biomass Research and Development Program;[37] the Biodiesel Fuel Education Program;[38] and the Carbon Utilization and Biogas Education Program.[39]

USDA encourages livestock operations to "stack" multiple programs. In 2015, USDA stated:

> To coordinate and maximize the potential assistance programs, Rural Development (RD) and Natural Resources Conservation Service (NRCS) met and developed a working partnership to deliver USDA services to producers interested in getting an anaerobic digester for their farming operation…. When "stacking," both RD and NRCS funding mechanisms can be used to assist in funding a project but each has limitations; for instance, the $450,000 cap on EQIP encompasses financial assistance for any practice that the producer wants to implement during the life of the Farm Bill.[40]

The report encourages the 50-50 use of EQIP and REAP funds and provides a detailed breakdown of estimated costs, where the two programs cover the total $1,778,950 required to construct the digester system.

Some states provide a similar suite of programs to fund the installation of manure biogas systems. In California, for example, the Dairy Digester Research & Development Program (DDRDP) provides funding for the installation of dairy digesters.[41] There are many smaller programs that offer grants, such as the Minnesota Department of Agriculture's Methane Digester Loan Program.[42]

The federal 1603 program, "Payments for Specified Energy Property in Lieu of Tax Credits,"[43] provides grants to reimburse businesses for a portion of the cost of installing certain energy projects, including anaerobic digesters on farms.[44] The 1603 program's creation as part of the American Recovery and Reinvestment Act in 2009 was "motivated by difficult economic conditions and the perceived lack of tax-equity capacity to support renewable energy projects" eligible for the tax credits discussed below.[45] While most 1603 funding has gone to wind and solar projects,[46] the program has provided funding for at least 98 projects designated "biomass (open loop, livestock)" for a total of $119,133,949.00 or an average of $1,215,652.54 per operation.[47]

1603 PROGRAM:
Payments for Specified Energy Property in Lieu of Tax Credits

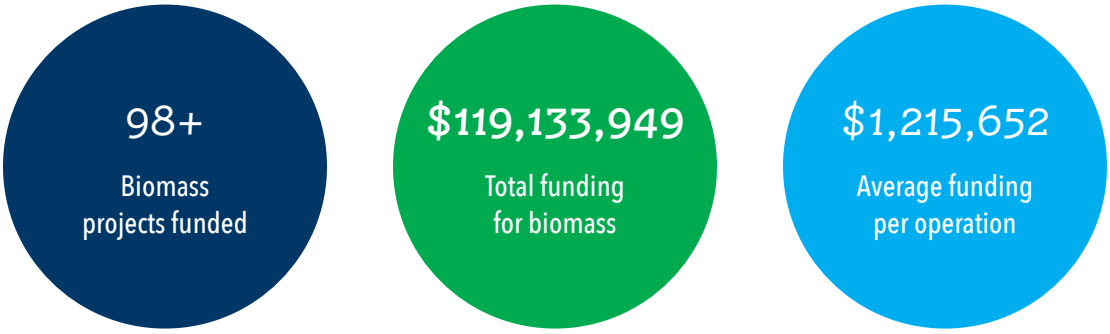

Private investment is also available to livestock operations seeking funding to install digester systems. As public programs to subsidize manure biogas production proliferate, the industry has become increasingly appealing to private investors. A March 2021 report by Stifel Equity Research laid out the prospects for manure biogas as follows:

> We are bullish on the fundamentals of renewable natural gas (RNG) as it is positive for the environment (net negative carbon form of energy post-combustion), it is economic today (10-60 percent project IRRs), and offers immense growth potential (IEA projects an 18x increase in supply by 2040).[48]

The report noted that the current optimistic forecast for investors is closely linked to the enormous policy supports for this technology:[49]

> The combination of policy ([CA] Senate Bill 1383, requiring reductions in short-lived climate pollutants) and regulatory incentives (both federal and state) have driven the recent inflection in RNG growth. In our view, producers are not in the business of producing RNG; they are in the business of monetizing RNG's environmental attributes through various federal and state programs.[50]



Subsidies & Other Programs That Enhance Revenue from Biogas Sales

In addition to funding sources intended to help livestock operators cover the fixed costs of biogas system construction, state and federal programs subsidize the revenue from biogas production on an ongoing basis.

The Federal Renewable Fuel Standard (RFS), which requires transportation fuels sold in the United States to contain a minimum amount of renewable fuel (a "Renewable Volume Obligation"), is a key source of potential revenue for manure biogas operations. The RFS is a market-based program intended to reduce overall emissions from transportation fuels in the United States. It is structured like a cap-and-trade program, but rather than cap net GHG emissions, the RFS mandates a quota for the amount of renewable fuel that must be incorporated into conventional transportation fuels.

EPA measures the emissions impact of each eligible renewable fuel through the evaluation of fuel "pathways."[51] The pathway for each renewable fuel describes the inputs and processes required, as well as the life cycle GHGs.[52] Renewable fuel producers then apply to EPA for the specific pathways to which their fuel product corresponds. Once approved, these fuel producers can generate renewable identification numbers (RINs), which allow EPA to track and monitor these fuels.[53] Renewable fuels and their corresponding RINs can be sold to producers of conventional fuels so they can meet the quota required by the RFS. Biogas from manure digesters can be used to generate advanced biofuel RINs, coded D5 in the RFS regulation.[54] (77,000 British thermal units are equal to one gallon equivalent or one RIN.[55]) RINs are explicitly allowed to be layered on top of other analogous credits, such as those from California's Low Carbon Fuel Standard.[56]

Meeting the Federal Renewable Fuel Standard (RFS)

EPA measures the emissions impact of renewable fuels by evaluating their fuel "pathway," or the processes required to produce them. Biogas from manure digesters can be used to generate advanced biofuel renewable identification numbers (RINs).



Renewable fuel producers apply to EPA for their product's specific pathway.



Approved fuel producers generate RINs so EPA can track and monitor their fuels.



RINs can be sold to conventional fuel producers, allowing them to meet the Renewable Fuel Standard.

The federal Advanced Biofuel Payment Program also subsidizes biogas revenue. The program provides quarterly payments "for the actual quantity of eligible advanced biofuel produced during that quarter" to biofuel producers, including refined biogas from farms.[57] Entities that produce and sell biofuels, as defined in 7 CFR § 4288.102, can apply to participate in the program.[58] This program was granted $322,000,000 in mandatory funding between 2009 and 2023, in addition to $80,000,000 of discretionary funding authorized to be appropriated for the program between 2019 and 2023.[59]

In addition to direct payments, the federal government provides tax credits through the Electricity Production Credit and the Investment Tax Credit. Both corporate tax credits reduce energy producers' tax burdens, but while the Electricity Production Credit compensates producers on a per kilowatt-hour basis for renewable energy (including "open-loop biomass"), the Investment Tax Credit reimburses a set percentage of installation costs.[60] Importantly, taxpayers must choose either the Electricity Production Credit or the Investment Tax Credit—they cannot apply for both.

TYPES OF PROJECT REVENUES

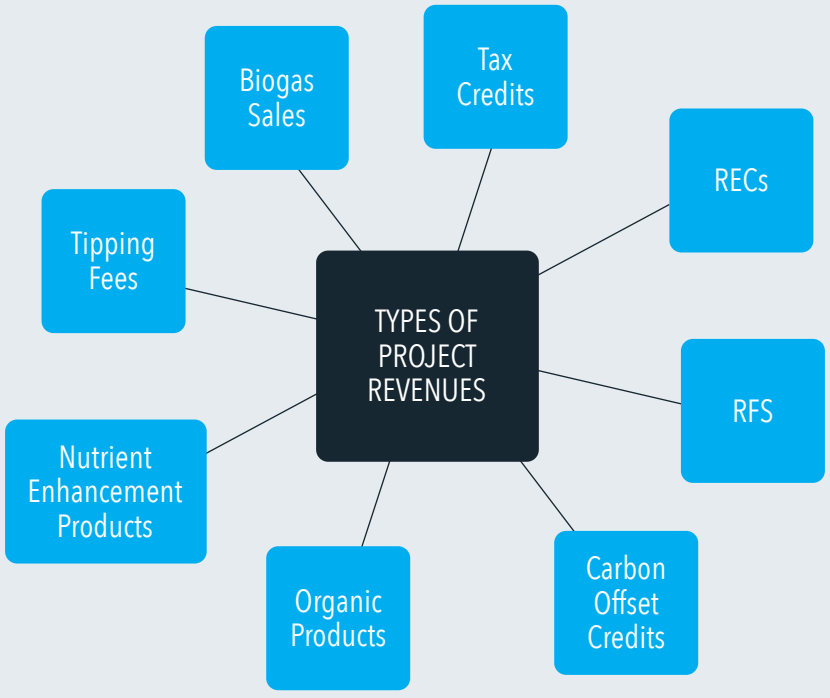

Source: AgSTAR Project Development Handbook, Environmental Protection Agency

[61]

At the state level, the Biofuels Investment Tax Credit also allowed companies in Florida to recoup "75% of all capital, operation, maintenance, and research and development costs incurred in connection with an investment in the production, storage, and distribution of biodiesel (B10-B100), ethanol (E10-E100), or other renewable fuel" through 2016.[62] Additionally, industry groups tout California's Low Carbon Fuel Standard (LCFS) as a boon to the biogas industry's profitability.[63] The program creates a tradeable market for credits and deficits, which are allocated to transportation fuel producers based on the carbon intensity of the fuels they produce. Low carbon intensity fuels receive credits, while high carbon intensity fuels receive deficits. Like the federal RFS, California's LCFS program currently designates manure biogas as a negative emissions fuel and, consequently, awards profitable credits for its production.[64] This revenue is allocated to producers on an ongoing basis in proportion to the quantity of fuel they produce. Biogas producers that participate in the LCFS are also explicitly allowed to participate in California's cap-and-trade program, as well as the federal RFS. Like the stacking of USDA and DOE funds described above, layering multiple credits is explicitly described as a benefit.

Ultimately, however, the layering of credits from multiple market-based programs can undermine the additionality of emissions reductions claimed by those programs. Additionality is a term of art used to evaluate whether the policy intervention in question is in fact the cause of a given real-world behavior change. A behavior is not additional if it would have happened with or without the policy intervention. Compensating or crediting nonadditional behaviors, like the production of manure biogas, risks over-incentivizing them and even increasing rather than decreasing overall emissions. While California's LCFS is the most well-developed credit trading program for transportation fuels, other states are developing similarly structured programs, including Oregon's Clean Fuels Initiative program.

Finally, some states are creating reliable markets for these fuels as a source of "renewable energy" through utilities. Where renewable fuels standards like the programs described above focus on transportation fuels, renewable portfolio standards or renewable electricity standards focus on the use of renewable energy sources for electricity generation. These programs typically mandate that a certain amount of energy be derived from renewable sources and define what constitutes renewable sources for the purposes of the program. Much like the RINs in the federal renewable fuel standard, many renewable portfolio standards at the state level implement trading programs using renewable electricity certificates (RECs). State programs vary, but they usually include manure biogas as a renewable energy source.[65]

Considered collectively, these funds represent potential windfalls for operations well suited to the installation of manure biogas systems. But, smaller, less established operations, or operations that use dry manure management systems or grazing systems are unlikely to benefit from these funds, even though their models may be more climate smart overall in accord with the Biden Administration's stated goals and objectives.

More Information on Funding for Manure Biogas

- *Federal and State Laws and Incentives*, Alternative Fuels Data Center, https://afdc.energy.gov/laws/search
- U.S. Env't Protection Agency, AgStar Handbook, https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf#page=81
- Cal. Dep't of Food and Agriculture, *Dairy Digester Research and Development Program Report of Funded Projects (2015-2019)* (April 2020), https://www.cdfa.ca.gov/oefi/ddrdp/docs/DDRDP_Report_April2020.pdf
- Cal. Public Utilities Comm'n., *Bioenergy Feed-In Tariff Program* (SB 1122), https://www.cpuc.ca.gov/SB_1122/





ANAEROBIC DIGESTERS CAN IMPOSE NEW ENVIRONMENTAL HARMS

TO PRODUCE BIOGAS FROM MANURE, farming operations must install an anaerobic digester, typically by capping or covering an existing manure lagoon to create an oxygen-free environment in which bacteria can break down organic matter. Biogas is a byproduct of this process. These systems offer some climate benefits (namely capturing methane and converting it to carbon dioxide during combustion) but their installation and use can also add new environmental harms. Such harms depend on a range of factors, including:

- the scale of the operations;
- the geography of the site;
- existing cumulative impacts to air and water;
- the end use of the biomethane; and
- the management of digestate (a byproduct of anaerobic digestion).

Through the process of anaerobic digestion, animal manure undergoes chemical changes that result in the production of a mix of gases, solid digestate, and liquid effluent. Biogas can be combusted to generate electricity on-site or exported as electricity and sold to the grid or at wholesale rates. The gases can be further "upgraded" to biomethane, which has a range of potential uses. Biomethane can be used on-site, injected into a pipeline, or used as a transportation fuel (when compressed to produce compressed natural gas).[66]

Through the process of anaerobic digestion, animal manure undergoes chemical changes that result in the production of a mix of gases, solid digestate, and liquid effluent.

Photo source: 20120717-OSEC-RBN-8338 by US Department of Agriculture is licensed under CC BY 2.0.

Anaerobic System Design & Technology

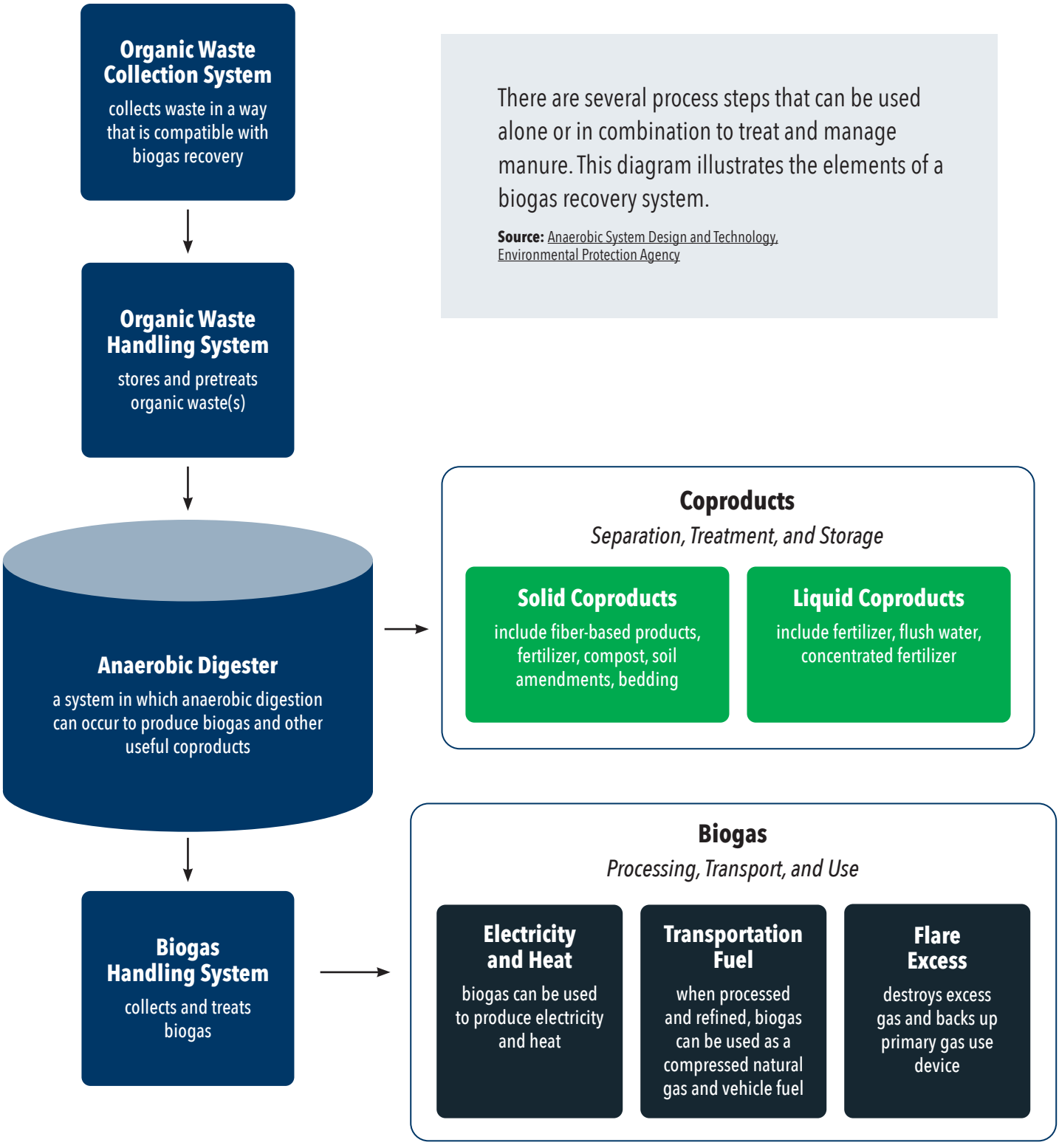

There are several process steps that can be used alone or in combination to treat and manage manure. This diagram illustrates the elements of a biogas recovery system.

Source: Anaerobic System Design and Technology, Environmental Protection Agency

Biogas Systems Primarily Benefit Large Operations Using Liquid Manure Management Systems

Two of EPA's screening questions to evaluate a livestock facility's potential for anaerobic digester systems ask whether the operation is "large" and whether it uses a liquid manure management system.[67] To be financially viable, biogas recovery systems typically require manure from at least 2,000 hogs or at least 500 cows.[68] According to EPA, manure biogas projects are "most likely to succeed where manure is collected as a liquid, slurry, or semi-solid and stored in open pits, ponds, or lagoons" because liquid manure can be easily flushed into lagoons.[69] Dry manure management is more common on pasture-based operations, where there is no easy manure collection system. Industrial scale operations and liquid manure management tend to go hand-in-hand because very large facilities often cannot dispose of all of their manure safely through land application without exceeding the amount of nutrients the land can take up. Additionally, liquefaction makes manure management less costly where livestock is confined.[70] A major downside to the liquefaction of manure, however, is that it generates more GHG emissions, since the anaerobic conditions in manure lagoons produce additional methane.[71] A 2022 EPA report explains:

To be financially viable, biogas recovery systems typically require manure from at least 2,000 hogs or at least 500 cows.

> When livestock manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH4 (methane). When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO2 and little or no CH4.[72]

The same report tied growth in industrial animal agriculture operations that liquefy manure to the broader increase in manure-related methane and nitrous oxide emissions since 1990.[73] EPA concluded:

> In many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems… The shift toward larger dairy cattle and swine facilities since 1990 has translated into an increasing use of liquid manure management systems, which have higher potential CH4 emissions than dry systems.[74]

Biogas Systems Require New Infrastructure

Depending on the desired end use of the refined biomethane produced by anaerobic digestion and subsequent refining, operations require a range of additional infrastructure. New infrastructure can introduce additional truck traffic or pipeline interconnections and result in significant wear to common infrastructure such as roads. Depending on how the biogas is to be used, on-site gas treatment systems may be necessary to process the gas accordingly. Temporary storage systems for biogas may also be required and excess biogas may need to be flared, or burned off, in some cases.

Biogas Systems Produce New Co-Pollutants & Exacerbate Existing Co-Pollutants

Anaerobic digestion creates a byproduct called digestate, which can be used as animal bedding or as fertilizer. Digestate is chemically different from the original manure. Digestate contains "more soluble plant nutrients due to mineralization and has less degradable biomass than the original substrate resulting in changes in GHG and NH3 emissions."[75] The method of storage and treatment of digestate can significantly impact the total GHG emissions from the biogas system, as well as co-pollutants like volatile organic compounds (VOCs) and hydrogen sulfide.

A 2017 study seeking to provide clarity on the emissions impact of anaerobic digestion (versus solid-liquid separation versus a combination of the two methods) found that anaerobic digestion alone resulted in an 81 percent increase in ammonia emissions during storage.[76] The authors concluded that anaerobic digestion could "significantly increase NH3 emissions from manure storage if manure covers are not implemented."[77] While ammonia is not a greenhouse gas, it



creates serious public health harms and degrades air quality.[78] The study also found that the nitrous oxide from digested separated solids "was much higher than separated solids without digestion," canceling out net GHG reductions.[79] This indicates that the simple adoption of manure biogas systems is not enough to ensure a net reduction in emissions from a given operation.

One study at a swine biogas facility in China took digestate to a research facility, stored it under controlled conditions, and then measured resulting emissions. The study identified 49 VOCs, 22 of which have been described as hazardous air pollutants by EPA. Of these 22 hazardous VOCs, "11 of these had relatively high concentrations . . . 8 were identified to be or likely to be carcinogenic, and 14 were identified to be harmful to other human organs or systems."[80] While most studies on VOCs from manure focus on the odor-causing compounds, the "proportion of hazardous air pollutants (32.77 percent) was shown to be considerably higher than that of odorous pollutants (5.15 percent)."[81]

Another study looked at manure under anaerobic conditions from two different dairy farms in Japan and found that hydrogen sulfide emissions vary considerably based on the mixing speed and frequency of disturbance of the stored manure as well as the manure's total solid content, temperature, and pH. For example, when stored at 18 degrees Celsius (64 degrees Fahrenheit), there was a sudden increase in the concentration of hydrogen sulfide (H_2S).[82] Additionally, "[the highest H_2S emissions were achieved at the fastest speed and longest duration of manure mixing."[83] Given that exposure to hydrogen sulfide is extremely dangerous and has been linked to death, the storage and treatment of manure and digestate is critical.[84]

New Impacts Must Be Evaluated in Analyses of Biogas Systems

These new impacts must be incorporated into analyses intended to evaluate the potential benefits of manure biogas systems. Unfortunately, such analyses often omit key considerations regarding co-pollutants, new infrastructure, and the environmental justice and equity implications associated with manure biogas systems. As stated above, the conventionally cited environmental benefit of manure biogas systems is a net reduction in atmospheric GHG emissions. Policy support for biogas systems rests on this reduction and as a result, life cycle analyses of manure biogas systems typically focus their impact evaluation on GHG emissions specifically and do not always address harms from co-pollutants or new infrastructure.

The metric typically used to quantify the environmental sustainability of a product or service is life cycle analysis (LCA). The goal of LCA is to provide a comprehensive view of environmental impacts to help decision-makers identify the effect of a given good or service. LCAs estimate

To properly account for the full life cycle emissions, any manure biogas LCA should include the storage and disposal of digestate, as well as the emissions generated in the production of manure, that is, the emissions resulting from raising the livestock in question.



the cumulative environmental impacts resulting from all stages of a product, process, or service through the life cycle, from raw material acquisition, manufacturing, use/reuse/maintenance, to recycling/waste management.[85] Programs like the Federal Renewable Fuel Standard and California's Low Carbon Fuel Standard, described above in part II, rely on life cycle assessments to determine the life cycle GHG emissions of participant fuels, including those derived from manure biogas systems. Both EPA and the California Air Resources Board use versions of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) life cycle analysis model which is designed for transportation fuels.[86]

System boundaries mark the beginning and end of the process or life cycle in question. Consequently, the boundaries and assumptions used in the LCA model are critical. For example, an LCA that excluded emissions related to digestate would not fully account for life cycle emissions of manure biogas. To properly account for the full life cycle emissions, any manure biogas LCA should include the storage and disposal of digestate, as well as the emissions generated in the production of manure, that is, the emissions resulting from raising the livestock in question.

When produced at an industrial scale, animal manure can create severe environmental harms and adverse impacts to public health. The impacts of manure include water contamination, air pollution, and foul odor (which can degrade quality of life for neighboring communities and decrease property values), in addition to GHG emissions. Manure biogas systems capture some of the emissions from livestock facilities, but fail to address the co-pollutants associated with manure production while also producing new co-pollutants from the processing and storage of the resulting digestate, as discussed above. Multiple toxic pollutants, including VOCs, ammonia, endotoxins, particulate matter, and bioaerosols are linked to large-scale industrial confined animal feeding operations.[87] To the extent that anaerobic digestion technology maintains or even expands the model of concentrated industrial animal agriculture, it can perpetuate and even increase resulting public health harms.

In many parts of the country, these impacts disproportionately harm Black, Indigenous, and low-income communities. Multiple disparity analyses (and resulting civil rights complaints submitted to regulators) have challenged states' approaches to the regulation of industrial animal agriculture. One recent complaint filed with EPA's External Civil Rights Compliance

"These harms disproportionately affect Black and Latinx people living near the Hog Operations, and it is these communities who will suffer most if pollution from the Hog Operations worsens, as is expected with the Permits. Decades of research–including research reviewed by this office–demonstrate how the lagoon and sprayfield waste management system authorized by the Permits pollute rivers, streams, and air quality throughout eastern North Carolina. Despite this, and despite evidence indicating the increased risk of pollution and adverse health impacts to nearby residents from the increases to harmful hog waste pollutants resulting from biogas production, DEQ issued the Permits without addressing these harms. This is unacceptable and a violation of federal law." – SELC complaint to EPA, 2021

Source: Southern Environmental Law Center

Office under Title VI of the Civil Rights Act alleged that North Carolina's new general permit for manure biogas exacerbated existing discriminatory impacts of the livestock industry in the state.[88] The complaint alleges that the North Carolina Department of Environmental Quality's new general permit for biogas systems on confined animal feeding operations "authorizes not only the continued use of the discriminatory lagoon and sprayfield system, but also the use of anerobic digesters and uncovered 'secondary' lagoons, which will exacerbate the underlying system's impacts on communities of color."[89] This complaint follows another civil rights complaint addressing the discriminatory harms of the hog industry in North Carolina, to which EPA responded with a letter expressing "deep concern."[90]

Typical Pollutants Found in Air Surrounding CAFOs

CAFO EMISSIONS	SOURCE	TRAITS	HEALTH RISKS
Ammonia	Formed when microbes decompose undigested organic nitrogen compounds in manure	Colorless, sharp pungent odor	Respiratory irritant, chemical burns to the respiratory tract, skin, and eyes, severe cough, chronic lung disease
Hydrogen Sulfide	Anaerobic bacterial decomposition of protein and other sulfur containing organic matter	Odor of rotten eggs	Inflammation of the moist membranes of eye and respiratory tract, olfactory neuron loss, death
Methane	Microbial degradation of organic matter under anaerobic conditions	Colorless, odorless, highly flammable	No health risks. Is a greenhouse gas and contributes to climate change
Particulate Matter	Feed, bedding materials, dry manure, unpaved soil surfaces, animal dander, poultry feathers	Comprised of fecal matter, feed materials, pollen, bacteria, fungi, skin cells, silicates	Chronic bronchitis, chronic respiratory symptoms, declines in lung function, organic dust toxic syndrome

Source: Understanding Concentrated Animal Feeding Operations and Their Impact on Communities

More Information on the Impacts of Manure Biogas

- Michael A. Holly, Rebecca A. Larson, J. Mark Powell, Matthew D. Ruark, & Horacio Aguirre Villegas, *Greenhouse Gas and Ammonia Emissions from Digested and Separated Dairy Manure During Storage and After Land Application*, Agriculture, Ecosystems and Env't 239 410–419 (2017), http://dx.doi.org/10.1016/j.agee.2017.02.007
- Valerio Paolini, Francesco Petracchini, Marco Segreto, Laura Tomasetti, Nour Naja, & Angelo Cecinato, *Environmental Impact of Biogas: A Short Review of Current Knowledge*, 53 J. Env't Sci. Health Pt. A 899-906 (2018), https://doi.org/10.1080/10934529.2018.1459076
- C. Alan Rotz, *Modeling Greenhouse Gas Emissions from Dairy Farms,* 101 J. Dairy Sci. 6675-6690 (2018), https://www.sciencedirect.com/science/article/pii/S002203021731069X
- F. Montes, R. Meinen, C. Dell, A. Rotz, A. N. Hristov, J. Oh, et al., *SPECIAL TOPICS-Mitigation of Methane and Nitrous Oxide Emissions From Animal Operations: II. A Review of Manure Management Mitigation Options*, J. Anim. Sci. 91 5070–5094 (2013), https://doi.org/10.2527/jas.2013-6584
- Emily Grubert, *At Scale, Renewable Natural Gas Systems Could Be Climate Intensive: The Influence of Methane Feedstock and Leakage Rates*, Env't Research Letters 15 084041, 5 (August 2020), https://doi.org/10.1088/1748-9326/ab9335
- Hannah Rigby, *A Critical Review of Nitrogen Mineralization in Biosolids-Amended Soil, the Associated Fertilizer Value for Crop Production and Potential for Emissions to the Environment*, 541 Sci. of the Total Env't 1310, 1310 (Jan. 2016), https://www.sciencedirect.com/science/article/abs/pii/S0048969715305921



Photo source: Anaerobic Digester Fenville, MI by eXtension Farm Energy Community of Practice is licensed under CC BY-NC 2.0.

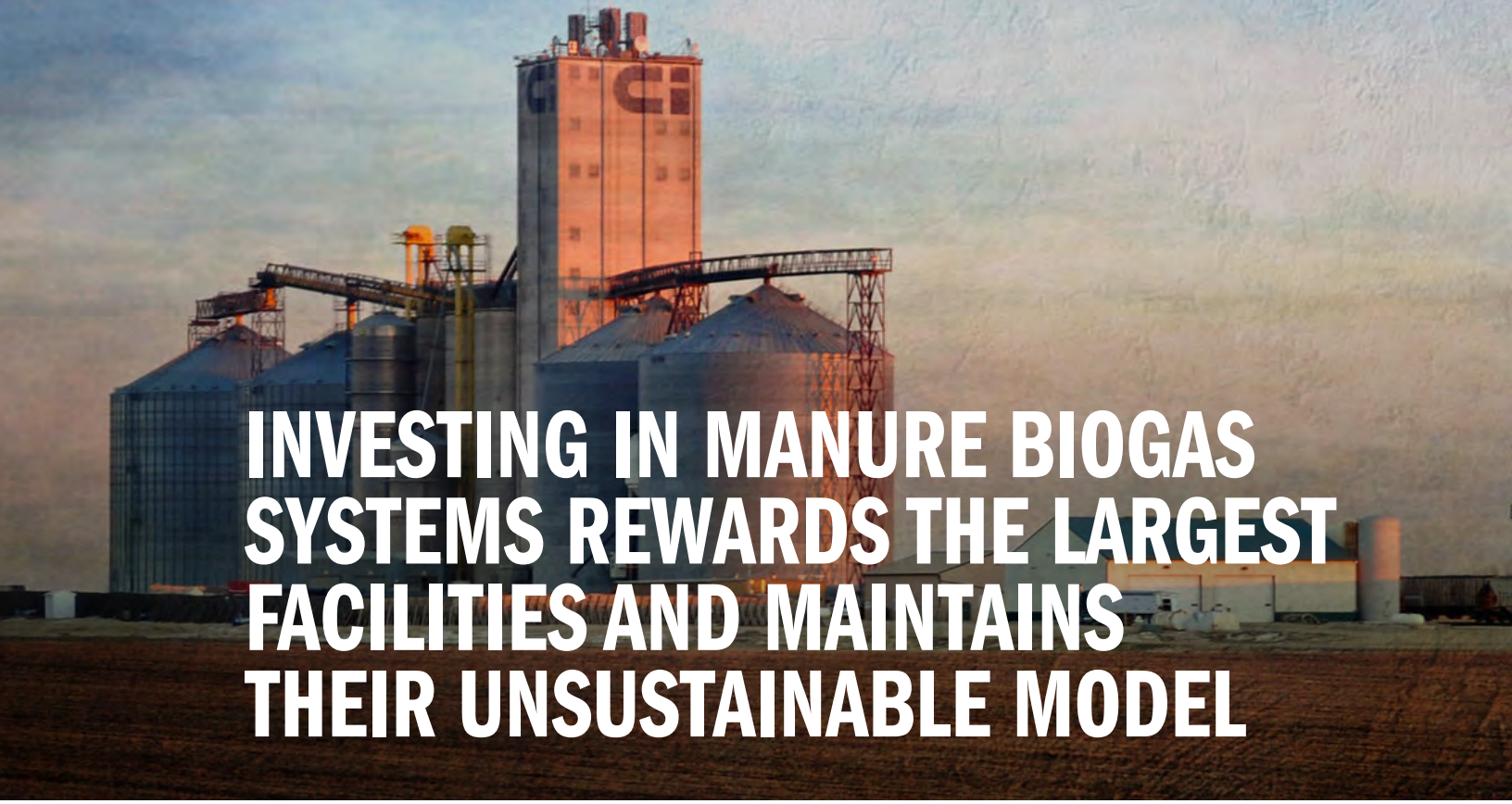

INVESTING IN MANURE BIOGAS SYSTEMS REWARDS THE LARGEST FACILITIES AND MAINTAINS THEIR UNSUSTAINABLE MODEL

THE SHEER NUMBER OF PROGRAMS designed to support the installation and operation of manure biogas systems on livestock operations presents two important questions. First, are these programs necessary to obtain the intended climate benefits of biogas systems and to what extent do they contribute to an overall emissions reduction? Second, what are the opportunity costs of the intense focus on this one method of reducing livestock emissions, given the range of alternatives? The fact that alternatives exist, coupled with the requirement that manure production continue at staggering rates to ensure the productivity of manure biogas systems calls into question whether it is prudent to focus policy efforts on a single solution.

Biogas Systems May Not Reduce Overall Emissions

Anaerobic digesters are designed to capture (and monetize) methane and other gases that would otherwise be emitted into the air from manure lagoons. However, *capturing* emissions does not avoid or reduce emissions at the source. Reducing emissions at the source would entail significant changes in livestock production systems. Digester systems are sometimes described as stopgap measures—a means to reduce emissions quickly in the absence of developing or implementing alternative measures. However, climate science demonstrates that significant reductions at the source are required in the next decade. Investing in expensive durable infrastructure that requires ongoing manure production at current rates without emissions reductions fails to meet this imperative.

Because manure biogas systems capture rather than reduce emissions, these systems **require the ongoing generation of GHG emissions** to be financially viable. The digester's function is to capture the emissions, so the system breaks down if emissions are reduced at the source. Producers must continue to generate manure at scale for the facilities to remain financially sustainable. The large upfront investment in these systems then fixes the current numbers and concentration of livestock at facilities where they are installed, despite the range of harms

Photo source: Ag Partners, Hartley, Iowa by TumblingRun is licensed under CC BY-NC-ND 2.0.

generated by such concentrated operations. Simultaneously, the new subsidized revenue streams support the ongoing generation of manure at scale. This outcome is sharply at odds with the prescriptions of climate scientists and the Biden Administration's stated climate goals.

Additionally, while anaerobic digesters capture manure methane from lagoons, they do not capture greenhouse gas emissions before or after this point. The emissions from manure management that can be targeted by digesters make up 9.2 percent of total methane emissions from anthropogenic activities, while emissions from enteric fermentation, which remain untouched by digester systems, make up 26.9 percent.[91] In contrast, other interventions in the industrial animal agriculture system, including alternative methods of manure management and changes to animals' diet, address emissions throughout or at various points in the process of raising livestock. Importantly, a significant portion of livestock GHG emissions result from the decision to liquefy manure.[92] Some manure management emissions can be avoided by using dry manure management systems, as many farmers do. Capturing GHG emissions should be a last resort option after other alternatives have been pursued to avoid

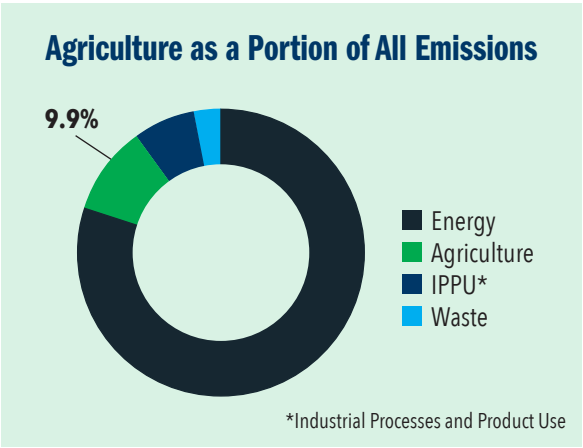

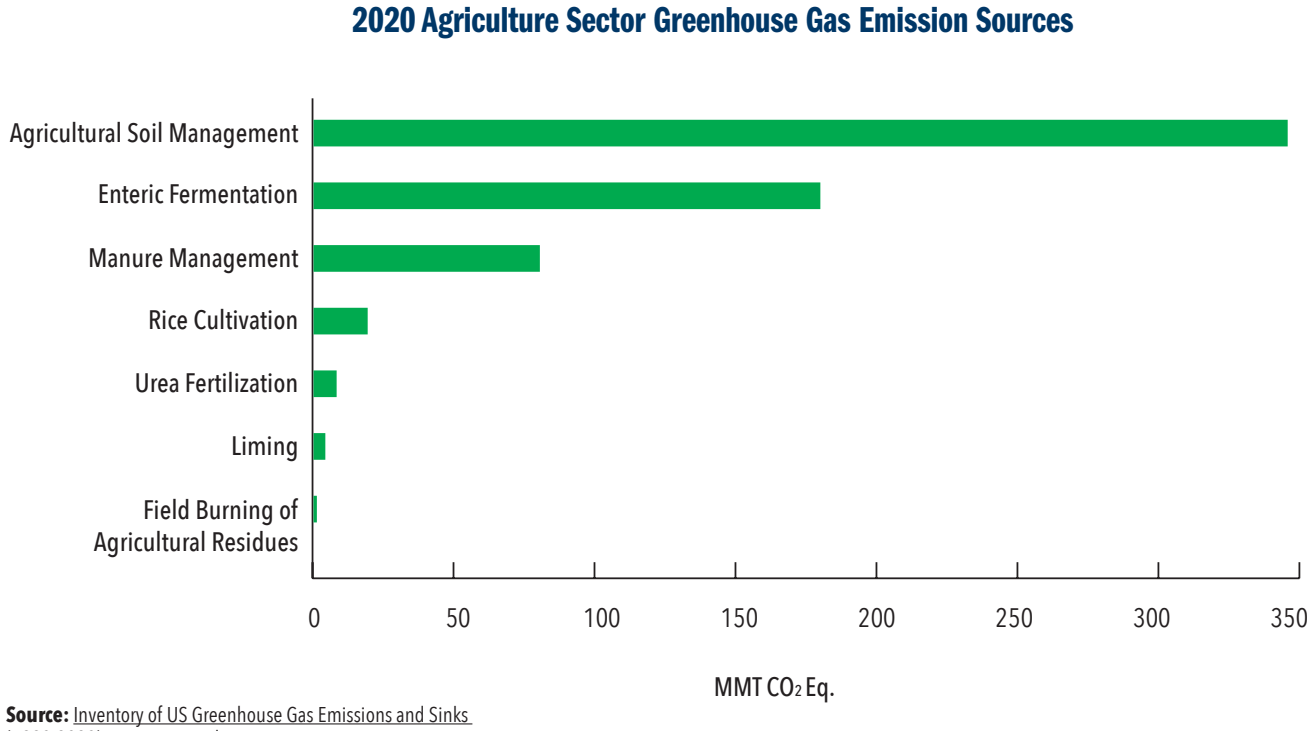

Source: Inventory of US Greenhouse Gas Emissions and Sinks (1990-2020), Environmental Protection Agency

Waste Management Hierarchy

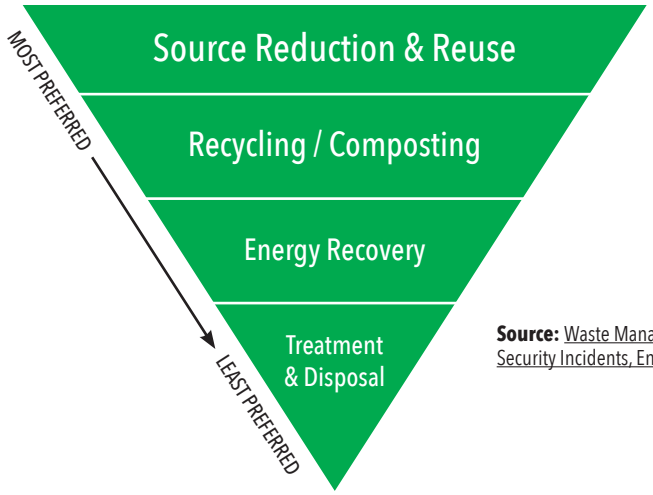

Source: Waste Management Hierarchy and Homeland Security Incidents, Environmental Protection Agency

or reduce emissions. This tracks with other federal policy efforts and priorities, as reduction is the management method at the top of EPA's waste management hierarchy for decision-making (organized from least to most detrimental to human and animal health and the environment).[93]

Alternative measures to reduce methane emissions from animal agriculture are available and feasible. Manure management systems generally include processes for the collection, transfer, storage, and sometimes treatment and end-use of manure.[94] Alternatives are available at each point along the way. At the initial collection stage, operations can opt for dry-scrape systems, rather than the flush systems typically used for lagoons. Dry scrape systems use mechanical scrapers to move manure into holding pits.

Livestock operations can also be designed as pasture-based, rather than confinement. On pasture-based operations, manure is typically left on pasture and produces minimal methane.[95] Pasture-based operations that rely primarily on grazing for animals' nutrition can also avoid emissions associated with the production and transportation of the feed used on confinement operations[96] and can potentially provide carbon sequestration benefits if grasslands and grazing are properly managed.[97] At the storage stage, operations can employ solid-liquid separation rather than flushing all liquefied manure directly into a lagoon. Once liquids have been separated out, manure solids can be composted.[98] A technical report prepared for the California Air Resources Board concluded that, in addition to manure biogas system installation:

> Methane emissions from lagoon storage systems can be decreased by reducing the amount or modifying anaerobic storage (i.e. solids separation and diversion from lagoon, modifying dominant flush collection to manure scraping with drying/composting or other lagoon diversion, etc.), aerating the lagoon (to reduce or eliminate anaerobic conditions).[99]

These are viable methods of manure management that would avoid, rather than simply capture, at least some emissions associated with open-air lagoons of liquid manure.[100] Many livestock operations already employ these lower-emissions practices. Unfortunately for them, however, smaller operations, pasture-based operations, or operations that have a more sustainable business model of dry manure management will not benefit from the significant public funds currently being channeled to biogas-eligible facilities. This sets a perverse precedent of neglecting historically good actors while rewarding the worst polluters in the livestock industry with new revenue and fodder for positive public relations.

Tied to the claim that biogas systems reduce emissions is the argument that the use of manure systems displaces the use of fossil fuels. An empirical analysis of this claim is beyond the scope of this report. However, regulators and policymakers should carefully consider the climate value of replacing fossil fuels with the combustion of biomethane, especially for the magnitude of public funds invested in this displacement. Renewability does not necessarily mean that a fuel is sustainable or climate friendly.[101]

Biogas Systems May Not Generate Revenue & "Design Out Waste"

Another important consideration is whether manure biogas systems really generate revenue and "design out" waste. This reflects a broader trend in policy prescriptions, sometimes referred to as the "circular economy," that seeks to "design out" waste from various industrial life cycles.[102] Proponents of the circular economy use the phrase "designing out" manure or any other waste product to mean that the waste is made profitable through other industrial processes. Unlocking new profits from waste,[103] however, does not necessarily entail any changes to the processes of waste generation or to any environmental or public health harms that arise from these processes.

In the case of manure biogas systems, manure is still produced, liquefied, and transported to manure lagoons—it must be for the biogas system to function. Anaerobic digestion does not make the manure vanish, it produces digestate. As discussed above, digestate has industrial uses, as fertilizer, for example, but also carries many of the same potential environmental harms as manure. Therefore, while it is correct to say that manure biogas systems access the potential economic value of manure as a fuel source, the waste does not disappear and can continue to cause environmental and public health harms, before, during, and after (as digestate) the process of anaerobic digestion.

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The massive quantities of manure produced at industrial scale livestock facilities can and do cause serious environmental, quality of life, and public health harms to neighboring communities. These harms do not cease to exist upon the addition of an anaerobic digester. In fact, while proponents of biogas systems sometimes argue that capping lagoons can address these issues, impacted environmental justice communities around the country have organized against the proliferation of biogas because it is viewed as maintaining and supporting a harmful system.[104]

Beyond the Baseline: Evaluating Mitigation Measures Against Policy Alternatives

The climate benefits associated with greater public resources devoted to expanding manure biogas production can only be evaluated relative to other available policy options. Such policy options cannot be limited to a business-as-usual scenario, which the scientific community has made clear is untenable. Regulators currently consider the displacement of fossil fuels when evaluating the benefits associated with these systems, but they must also consider the alternative emissions reduction strategies that are displaced now and into the future upon investment in large-scale manure biogas systems.

Unfortunately, conventional win-win claims break down when framed in the broader context of policy mechanisms available to address emissions from livestock. This is attributable to the many alternative approaches to reducing emissions from livestock facilities, some of which could reduce emissions throughout the life cycle, instead of those emitted only from



manure lagoons. The Biden Administration's plan to reduce methane names several of these alternatives, including installing "solid separators that reduce methane-producing slurries; providing conservation assistance for transitions to alternative manure management systems, such as deep pits, composting, transitions to pasture, or other practices that have a lower greenhouse gas profile."[105] Despite the administration's support of reducing methane-producing slurries on paper, funding for manure biogas systems that require methane-producing slurries to function continues to dwarf alternatives.

While it is unreasonable to expect a single policy mechanism or technology to solve all problems, there are viable alternative manure management practices and policy mechanisms to decrease emissions as well as co-pollutants in a more equitable manner. Currently, however, these programs are not being funded at nearly the same rate as manure biogas. In California, for example, the Alternative Manure Management Program (AAMP) has been funded at roughly half the rate of the Dairy Digester Research & Development Program (DDRDP) in recent years.[106]

In addition to a broad evaluation of each of these alternative mechanisms and potential policy mechanisms to promote them, it is essential to note the reason policy incentives are strictly necessary in this case—industrial livestock operations have historically been essentially exempt from any regulation of GHG emissions. It is, in fact, only this absence of regulation that makes the calculation of emissions reductions from the addition of digesters so high. The primary alternative policy mechanism should be to treat industrial livestock operations like every other industry in the country and regulate the emissions they externalize to the detriment of the public—the primary funders of manure biogas systems. Regulators should actively support farmers that engage in climate-friendly practices less likely to harm neighboring communities.

In the United States, livestock agriculture has dramatically shifted toward "large scale industrialized production systems."[107] As a result, livestock operations are producing more manure in centralized regions.[108] The storage, transportation, and land application[109] of this waste poses serious environmental risks, in addition to the GHG emissions from other parts of the livestock life cycle. Methane emissions from livestock manure are significant, but experts note that the trade-offs associated with manure management options, including the use of biodigesters, are not well studied and have not been proven to be "climate smarter."[110]

While it is unreasonable to expect a single policy mechanism or technology to solve all problems, there are viable alternative manure management practices and policy mechanisms to decrease emissions and co-pollutants in a more equitable manner.



POLICY RECOMMENDATIONS AND CONCLUSION

LIVESTOCK OPERATIONS' IMPACT ON CLIMATE CHANGE presents an opportunity for a real win-win: the US can develop policies that reduce GHG emissions from these facilities—as is required in order to mitigate the substantial impact of livestock agriculture on the climate—while simultaneously reducing the additional environmental harms many such facilities externalize into local communities. In many cases, have a discriminatory impact on the basis of race. These prerogatives are well aligned with the Biden Administration's Climate Smart Agriculture policy, Executive Order 14008, and Executive Order 13985.[111] Specifically, policymakers should consider the following:

USDA must ensure that recipients of its funding are in compliance with Title VI of the Civil Rights Act of 1964. This includes ensuring that state agencies that receive USDA funding and implement programs supporting manure biogas are developing such policies in a manner that does not disproportionately benefit white operators or disproportionately harm nearby communities on the basis of race, national origin, or color.

Evaluate USDA's programs to ensure that they do not have a disproportionate impact on the basis of race, national origin, or other protected class.

Properly account for the full climate impacts of manure biogas and ensure that emissions life cycle analyses consider the full range of upstream and downstream emissions in the manure biogas life cycle.

Move beyond business-as-usual as a point of comparison for manure biogas, which does not ensure a viable climate-smart future. The point of comparison should be the range of policy alternatives to biogas promotion, including the regulation of methane from agricultural operations.

Properly account for the full impacts of policies supporting manure biogas, including environmental, public health, and quality of life impacts from co-pollutants caused by manure.

Ensure a just transition for all, including for livestock farmers. Policy should ensure that farmers and farmworkers can make viable livelihoods while transitioning to more sustainable models.

Evaluate the efficacy of overlapping programs to ensure that public funds for manure biogas are effectively promoting new emissions reductions.

Endnotes

1 *Why Did the IPCC Choose 2° C As the Goal for Limiting Global Warming*, MIT Climate Portal (June 22, 2021), https://climate.mit.edu/ask-mit/why-did-ipcc-choose-2deg-c-goal-limiting-global-warming/.

2 *See generally* U.S. Climate Change Science Program, The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States (May 2008), https://www.usda.gov/sites/default/files/documents/CCSPFinalReport.pdf.

3 IPCC, *Sixth Assessment Report Headline Statement from the Summary for Policymakers* at A.3 (August 9, 2021).

4 *Id.* at B.3.

5 Jennifer Shike, *Residents in Top Pork-Producing Counties Reveal Their Perspective on Ag*, Farm Journal's Pork (January 12, 2022), https://www.porkbusiness.com/news/industry/nc-residents-top-pork-producing-counties-reveal-their-perspective-ag.

6 Kendra Pierre-Louis, *Lagoons of Pig Waste Are Overflowing After Florence. Yes, That's as Nasty as It Sounds*, N.Y. Times (September 19, 2018), https://www.nytimes.com/2018/09/19/climate/florence-hog-farms.html; James Bruggers, *After Back-to-Back Hurricanes, North Carolina Reconsiders Climate Change*, Inside Climate News (December 27, 2018), https://insideclimatenews.org/news/27122018/hurricane-damage-north-carolina-climate-change-2018-year-review-florence-michael-matthew/.

7 *California's Central Valley*, U.S. Geol. Survey, https://ca.water.usgs.gov/projects/central-valley/about-central-valley.html.

8 *California is the Leading Farm State*, Cal. Legislative Analyst's Office (December 4, 2014), https://lao.ca.gov/LAOEconTax/Article/Detail/13#:~:text=Over%2080%20percent%20of%20California's,surpassed%20Wisconsin%20in%20milk%20production.

9 The Central Valley is predicted to be "substantially drier (10 to 15 percent) during the mid-late 21st century." *Conjunctive Use in Response to Potential Climate Changes in the Central Valley, California*, USGS, https://ca.water.usgs.gov/projects/central-valley/climate.html; Bettina Boxall, *Overpumping of Central Valley Groundwater Creating a Crisis, Experts Say*, L.A. Times (March 18, 2015), https://www.latimes.com/local/california/la-me-groundwater-20150318-story.html.

10 *See generally* U.S. EPA, Climate Change and Social Vulnerability in the United States, https://www.epa.gov/system/files/documents/2021-09/climate-vulnerability_september-2021_508.pdf. Leah Campbell, *North Carolina Hurricanes Linked to Increases in Gastrointestinal Illnesses in Marginalized Communities*, Inside Climate News (March 7, 2022), https://insideclimatenews.org/news/07032022/north-carolina-hurricanes-gastrointestinal-illnesses/.

11 Huanjia Zhang, *For Black Farmers, Climate Change Magnifies Existing Inequality*, ScienceLine (January 19, 2021), https://scienceline.org/2021/01/for-black-farmers-climate-change-magnifies-existing-inequality/. Internationally, "the negative impacts [of climate change] on [farmer] income are hitting the poorest countries and farmers most due to both higher exposure to climate risks as well as lower adaptation capacity." Food and Agriculture Organization of the United Nationals, Climate Change and Food Security: Risks and Responses (2015) at 21, https://www.fao.org/3/i5188e/I5188E.pdf.

12 Sabri Ben-Achour, *Farmers Need to Adapt Crops to Climate Change to Stay Profitable, Experts Say*, Marketplace (October 20, 2020), https://www.marketplace.org/2020/10/20/many-farmers-need-swap-crops-stay-profitable-climate-change-continues/.

13 Walter Willett, MD *et al.*, *Food in the Anthropocene: the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems,* The Lancet (January 16, 2019), https://doi.org/10.1016/S0140-6736(18)31788-4; Gidon Eshel *et al.*, *Land, Irrigation Water, Greenhouse Gas, and Reactive Nitrogen Burdens of Meat, Eggs, and Dairy Production in the United States*, PNAS (July 21, 2014), https://www.pnas.org/doi/10.1073/pnas.1402183111; Henry Fountain, *Cutting Greenhouse Gases From Food Production Is Urgent, Scientists Say*, N.Y. Times (October 26, 2021), https://www.nytimes.com/2020/11/05/climate/climate-change-food-production.html; Andrea Thompson, *Here's How Much Food Contributes to Climate Change*, Scientific American (September 13, 2021), https://www.scientificamerican.com/article/heres-how-much-food-contributes-to-climate-change/. It has recently been argued that estimates of methane emissions from U.S. livestock operations have routinely been underestimated. *See* Matthew N. Hayek and Scot M. Miller, *Underestimates of Methane from Intensively Raised Animals Could Undermine Goals of Sustainable Development*, Env't Res. Lett. *16 (June 4, 2021),* https://iopscience.iop.org/article/10.1088/1748-9326/ac02ef.

14 Understanding Global Warming Potential, U.S. Env't Protection Agency, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

15 *Burps in Merps: Addressing Agricultural Methane Emissions in the U.S. Methane Emission Reduction Plan (MERAP),* https://storymaps.arcgis.com/stories/be03fd94bbfb4586bf7ccf5627aa4afb. Not only are overall emissions from agriculture increasing, but per head emissions from enteric fermentation are also increasing. U.S. Greenhouse Gas Inventory Agriculture at 5-5, U.S. Env't Protection Agency, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf. .

16 *See, e.g.,* Sustainia, *Win-Win Scheme Turns Pig Waste into Power*, Global Opportunity Explore (March 14, 2019), https://goexplorer.org/win-win-scheme-turns-pig-waste-into-power/; *Using Methane from Waste Streams for Energy: A Win-Win Solution*, Environmental and Energy Study Institute (March 9, 2010), https://www.eesi.org/articles/view/using-methane-from-waste-streams-for-energy-a-win-win-solution.

17 Laura Melling, *USDA Offers Funding to Help Farmers Turn Manure into Energy*, U.S. Dep't of Ag. (February 21, 2017), https://www.usda.gov/media/blog/2010/11/18/usda-offers-funding-help-farmers-turn-manure-energy.

18 American Biogas Council, *How to Maximize USDA Funds Webinar* (January 30, 2020), *available at* https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiG3YaUrtz1AhXmIEQIHbk7B0cQFnoECAMQAQ&url=https%3A%2F%2Famericanbiogascouncil.org%2Fwp-content%2Fuploads%2F2020%2F01%2FHow-to-Maximize-USDA-Grant-Dollars-from-REAP.pdf&usg=AOvVaw3u_9Ola0x9SiHDF3spSqC1.

19 Michael Clark *et al., Global Food System Emissions Could Preclude Achieving the 1.5 and 2 C Climate Change Targets,* 370 Science 6517 (November 6, 2020), https://www.science.org/doi/10.1126/science.aba7357.

20 Ximena Bustillo, *'Rampant Issues': Black Farmers Are Still Left Out at USDA*, Politico (July 5, 2021), https://www.politico.com/news/2021/07/05/black-farmers-left-out-usda-497876; Nathan Rosenberg and Bryce Wilson Stucki, *How USDA Distorted Data to Conceal Decades of Discrimination Against Black Farmers*, The Counter (June 26, 2019), https://thecounter.org/usda-black-farmers-discrimination-tom-vilsack-reparations-civil-rights/.

21 *Who Is the American Farmer?,* USA Facts, https://usafacts.org/articles/farmer-demographics/ (95.4% of American farmers are white).

22 Dania Francis, Darrick Hamilton, Thomas Mitchell, Nathan Rosenberg, and Bryce Wilson Stucki, *How the Government Helped White Farmers Steal Black Farmland*, The New Republic (May 5, 2020), https://newrepublic.com/article/166276/black-farm-land-lost-20th-century-billions.

23 Today the average size of farms owned by Black farmers is 132 acres, as compared to 441 acres for white farmers. 15% of Black farmers own farms larger than 180 acres, as compared to 32% of white farmers. *2017 Agricultural Census,* U.S. Dep't. of Ag., https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Race,_Ethnicity_and_Gender_Profiles/cpd99000.pdf.

24 *See, e.g.* Ji-Young Son *et al.*, *Distribution of Environmental Justice Metric for Exposure to CAFOs in North Carolina*, USA, Env't Research 195 (April 2021), https://doi.org/10.1016/j.envres.2021.110862.

25 For example, heat stress due to climate change has already significantly impacted dairy production in the United States and is expected to further contribute to economic losses for that sector. More broadly, the "U.S. Global Change Research Program (USGCRP) recognizes that increased heat stress will increase livestock production costs, lower feed efficiency, and compromise livestock health." *Climate Change, Heat Stress, and US Dairy Production,* U.S. Dep't. of Ag. Econ. Research Serv. at 1-2 (2014), https://www.ers.usda.gov/webdocs/publications/45279/49164_err175.pdf?v=2463.8.

26 Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg. 7619 (2021).

27 Exec. Order 13985, Advancing Racial Equity and Support for Underserved Communities Through the Federal Government, 86 Fed. Reg. 7009 (2021).

28 *See generally* Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg. 7619 (2021).

29 *See generally* Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg. 7619 (2021).

30 U.S. Dep't of Ag., Climate-Smart Agriculture and Forestry St5rategy: 90-Day Progress Report (May 2021), https://www.agri-pulse.com/ext/resources/pdfs/Embargoed-climate-smart-ag-forestry-strategy-90-day-progress-report.pdf.

31 Lisa Friedman, *Biden Administration Moves to Limit Methane, a Potent Greenhouse Gas*, N.Y. Times (November 2, 2021), https://www.nytimes.com/2021/11/02/climate/biden-methane-climate.html.

32 Jared Strong, *USDA Pledges $1B for 'Climate Smart' Ag Products*, Missouri Independent (February 7, 2022), https://missouriindependent.com/briefs/usda-pledges-1b-for-climate-smart-ag-products/.

33 *Rural Energy for America Program Renewable Energy Systems & Energy Efficiency Improvement Guaranteed Loans & Grants*, U.S. Dep't of Ag. Rural Development, https://www.rd.usda.gov/programs-services/energy-programs/rural-energy-america-program-renewable-energy-systems-energy-efficiency-improvement-guaranteed-loans.

34 *Conservation Programs*, U.S. Dep't of Ag. Rural Development, https://www.fsa.usda.gov/programs-and-services/conservation-programs/index.

35 7 U.S.C.A. § 8103 ("The purpose of this section is to assist in the development of new and emerging technologies for the development of advanced biofuels, renewable chemicals, and biobased product manufacturing…")

36 7 U.S.C.A. § 8105 ("The Secretary shall make payments to eligible producers to support and ensure an expanding production of advanced biofuel.")

37 7 U.S.C.A. § 8108.

38 7 U.S.C.A. § 8106 "…make competitive grants to eligible entities to educate governmental and private entities that operate vehicle fleets, other interested entities (as determined by the Secretary), and the public about the benefits of biodiesel fuel use.")

39 7 U.S.C.A. § 8115. This program provides grants to educate agricultural producers and other stakeholders about the collection of organic waste from multiple sources to be used in a single biogas system.

40 *Biogas Opportunities Roadmap Progress Report*, U.S. Dep't of Ag., Env't Protection Agency & Dep't of Energy (December 2015) at 2, https://www.energy.gov/sites/prod/files/2015/12/f27/biogas_opportunites_roadmap_progress_report_0.pdf.

41 *Dairy Digester Research & Development Program*, Cal.

Dep't Food & Ag., https://www.cdfa.ca.gov/oefi/ddrdp/.

42 *Methane Digester Loan Program*, Minn. Dep't of Ag., https://www.mda.state.mn.us/methane-digester-loan-program.

43 Referring to Section 1603 of the 2009 American Recovery and Reinvestment Act (ARRA).

44 *1603 Program: Payments for Specified Energy Property in Lieu of Tax Credits*, U.S. Dep't of the Treasury, https://home.treasury.gov/policy-issues/financial-markets-financial-institutions-and-fiscal-service/1603-program-payments-for-specified-energy-property-in-lieu-of-tax-credits.

45 *ARRA Section 1603 Grants in Lieu of Tax Credits for Renewable Energy: Overview, Analysis, and Policy Options*, Congressional Research Service (November 9, 2011), https://www.everycrsreport.com/files/20111109_R41635_f042092b5c65021d792f0ccb79634694bd9aeea8.pdf.

46 *Id.* at 5, Figure 1.

47 *1603 Program List of Awards*, U.S. Dep't of the Treasury, *available at* https://home.treasury.gov/policy-issues/financial-markets-financial-institutions-and-fiscal-service/1603-program-payments-for-specified-energy-property-in-lieu-of-tax-credits.

48 Stifel Equity Research, Energy & Power – Biofuels: Renewable Natural Gas (March 8, 2021) at 4.

49 *See also*, *Chevron's Energy Transition Spotlight Edited Transcript,* Chevron Corp. (September 14, 2021), *available at* https://chevroncorp.gcs-web.com/static-files/f9d402c6-22e2-4c00-ad45-3a61fde9ff73 ("For roughly half a billion dollars committed to date, we're building an RNG business expected to produce about 10,000 million BTUs per day in less than five years, with expected double-digit returns and an average carbon intensity feedstock score of around negative 250 under California's Low Carbon Fuel Standard.")

50 Stifel Equity Research, Energy & Power – Biofuels: Renewable Natural Gas (March 8, 2021) at 5.

51 For general information on fuel pathways, *see What is a Fuel Pathway?,* U.S. Env't Protection Agency, https://www.epa.gov/renewable-fuel-standard-program/what-fuel-pathway.

52 40 C.F.R. § 80 subpart M. EPA also provides a list of fuel pathways online at *Approved Pathways for Renewable Fuel*, U.S. Env't Prot. Agency, https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel.

53 *Renewable Identification Numbers*, Alternative Fuels Data Center, U.S. Dep't of Energy, https://afdc.energy.gov/laws/RIN.html.

54 40 C.F.R. § 80.1426; *Renewable Fuel Standard*, Alternative Fuels Data Center, U.S. Dep't of Energy, https://afdc.energy.gov/laws/RFS; *Approved Pathways for Renewable Fuel*, U.S. Env't Protection Agency, https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel.

55 U.S. Env't Protection Agency, *Information About Renewable Fuel Standard for Landfill Gas Energy Project,* https://www.epa.gov/lmop/information-about-renewable-fuel-standard-landfill-gas-energy-projects.

56 "The federal RFS and state LCFS incentives are additive, meaning both incentives can be earned for a specific project." *Renewable Natural Gas from Agricultural-Based AD/Biogas Systems*, U.S. Env't Protection Agency, https://www.epa.gov/agstar/renewable-natural-gas-agricultural-based-adbiogas-systems.

57 *Advanced Biofuel Payment Program*, U.S. Dep't of Ag. Rural Development, https://www.rd.usda.gov/programs-services/energy-programs/advanced-biofuel-payment-program.

58 7 C.F.R Part 4288, Advanced Biofuel Payment Program Final Rule, *available at* https://www.rd.usda.gov/sites/default/files/AdvancedBiofuel_9005_FinalRule122719.pdf; *Advanced Biofuel Payment Program in California,* U.S. Dep't of Ag. Rural Development, https://www.rd.usda.gov/programs-services/energy-programs/advanced-biofuel-payment-program/ca.

59 7 U.S.C. § 8105(g).

60 *Renewable Electricity Production Tax Credit Information*, U.S. Env't Protection Agency, https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information; *Form 8835*, Dep't of the Treasury Internal Revenue Service, *available at* https://www.irs.gov/pub/irs-pdf/f8835.pdf.

61 U.S. Env't Protection Agency, AgStar, Project Development Handbook: A Handbook for Developing Anaerobic Digestion/Biogas Systems on Farms in the United States 3rd Edition, *available at* https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf#page=81.

62 *Biofuels Investment Tax*, Alternative Fuels Data Center, U.S. Dep't. of Energy, https://afdc.energy.gov/laws/6074.

63 Cal. Code of Regs Tit. 17 § 95480.

64 *See* Jessica Fu, *Is California Giving Its Methane Digesters Too Much Credit?,* Grist (May 19, 2022), https://grist.org/accountability/california-methane-digesters-low-carbon-fuel-standard/; Evan Halper, *California Set Off a Biofuel Boom–But Can It Manage the Fallout?,* L.A. Times (March 24, 2022), https://www.latimes.com/politics/story/2022-03-24/california-set-off-a-biofuel-boom-but-can-it-manage-the-fallout.

65 *State Renewable Portfolio Standards and Goals*, National Conference of State Legislatures, https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx.

66 U.S. Env't Protection Agency, AgStar, Project Development Handbook: A Handbook for Developing Anaerobic Digestion/Biogas Systems on Farms in the United States 3rd Edition at 6.3.2., *available at* https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf#page=81.

67 *Is Anaerobic Digestion Right for Your Farm*, U.S. Env't Protection Agency, Ag Star, https://www.epa.gov/agstar/anaerobic-digestion-right-your-farm#q2.

68 *Id.*

69 U.S. Env't Protection Agency, AgStar, Market Opportunities for Biogas Recovery Systems at US Livestock Facilities (June 2018), *available at* https://www.epa.gov/sites/default/files/2018-06/documents/epa430r18006agstar-marketreport2018.pdf.

70 Horacio A. Aguirre-Villegas, Rebecca A. Larson, and Mahmoud A. Sharara, *Anaerobic Digestion, Solid-Liquid Separation, and Drying of Dairy Manure: Measuring Constituents and Modeling Emission*, Sci. of the Total Env't 696 (December 2019), https://www.sciencedirect.com/science/article/pii/S0048969719340367.

71 S.O. Peterson et al., *Manure Management for Greenhouse Gas Mitigation*, Animal 7 at 2 (2013), https://doi.org/10.1017/S1751731113000736 ("CH4 emissions may occur from all manure environments, but is mainly associated with liquid or compacted manure.")

72 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture at 5-11, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf.

73 Ben Lilliston, *EPA Data Confirms Role of Factory Farms in Rising Agriculture Emissions*, Inst. for Ag. and Trade Policy, https://www.iatp.org/new-epa-data-confirms-role-factory-farms-rising-agriculture-emissions.

74 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture at 5-12, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf.

75 Holly, et al., *Greenhouse gas and ammonia emissions from digested and separated dairy manure during storage and after land disposal*, AG., Ecosystems and Env't 239 at 411 (2017), https://doi.org/10.1016/j.agee.2017.02.007.

76 *Id.* at 413. This increase was attributed to the "mineralization of organic N through the digestion process which increased NH4 + NH3 concentrations in manure."

77 *Id.* at 418.

78 *See* Ma, R., Li, K., Guo, Y. *et al. Mitigation potential of global ammonia emissions and related health impacts in the trade network*, Nat Commun 12 at 6308 (2021), https://doi.org/10.1038/s41467-021-25854-3 (""NH_3 emissions contribute to $PM_{2.5}$ pollution through the chemical formation of particulate ammonium sulfate and ammonium nitrate, and lead to tens of thousands of deaths annually.")

79 Holly, et al. at 418 ("…anaerobically stacking digested solids increase emissions of N20 negating abatement of total GHG.")

80 Y. Zhang et al., *Characterization of Volatile Organic Compound (VOC) Emissions from Swine Manure Biogas Digestate Storage*, Atmosphere 10(7):411 at 8 (2019). https://doi.org/10.3390/atmos10070411.

81 *Id.* at 9.

82 Fetra J. Andriamanohiarisoamanana, et al., *Effects of handling parameters on hydrogen sulfide emission from stored dairy manure*, J. of Env't Management, Vol. 154 at 112 (2015), https://doi.org/10.1016/j.jenvman.2015.02.003.

83 *Id.* at 115.

84 Wendee Nicole, *CAFOs and Environmental Justice*, Env't Health Perspectives (June 2013), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3672924/A ("As one pair of investigators explained, '[P]eople of color and the poor living in rural communities lacking the political capacity to resist are said to shoulder the adverse socio-economic, environmental, or health related effects of swine waste externalities without sharing in the economic benefits brought by industrialized pork production.'")

85 Scientific Applications International Corp., *Life Cycle Assessment: Principles and Practice*, prepared for U.S. Env't Protection Agency, *available at* https://www.epa.gov/nscep. Life cycle studies can be conducted within different scopes, including "cradle to gate" (from raw materials to factory gate), gate to gate (only focusing on the manufacturing processes), cradle to grave (from raw materials until disposal), or cradle to cradle (a specific cradle to grave assessment, in which the disposal process is actually a recycling process). Life cycle assessments which are not conducted for a full life cycle from "cradle to grave" are called partial life cycle assessments.

86 Meltem Urgun-Demirtas, *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*, U.S. Dep't of Energy (May 16, 2019), https://www.energy.gov/eere/bioenergy/articles/greet-greenhouse-gases-regulated-emissions-and-energy-use-transportation.

87 Christine Loftus et al., *Estimated time-varying exposures to air emissions from animal feeding operations and childhood asthma*, International J. of Hygiene and Env't Health, Vol. 223: 1 (2020), https://doi.org/10.1016/j.ijheh.2019.09.003; B. Yuan et al., *Emissions of volatile organic compounds (VOCs) from concentrated animal feeding operations (CAFOs): chemical compositions and separation of source*s, Atmos. Chem. Phys. 17 (2017), https://doi.org/10.5194/acp-17-4945-2017.

88 SELC Complaint to EPA, 2021, https://www.southernenvironment.org/wp-content/uploads/2021/09/2021-09-27-Title-VI-Complaint-Index-DEQ-Biogas-Permits.pdf.

89 *Id.* at 3.

90 *Letter to Secretary Ross re: EPA File No. 11R-14-R4* (November 12, 2017), *available at* https://www.epa.gov/sites/default/files/2018-05/documents/letter_of_concern_to_william_g_ross_nc_deq_re_admin_complaint_11r-14-r4_.pdf.

91 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture , https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf.

92 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture , https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf.

93 *Waste Management Hierarchy and Homeland Security Incidents*, U.S. Env't Protection Agency, https://www.epa.gov/homeland-security-waste/waste-management-hierarchy-and-homeland-security-incidents (last updated May 31, 2018).

94 Randall James et al., *Ohio Livestock Management Guide*, Ohio State Univ. Extension at 18 (2006), *available at* https://agcrops.osu.edu/sites/agcrops/files/imce/fertility/bulletin_604.pdf.

95 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture , https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf ("When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO2 and little or no CH4.")

96 Feed production can generate nitrous oxide emissions from the application of synthetic N or manure to crops, while energy use in field operations, feed transport, fertilizer manufacturing, feed blending, etc. can contribute more nitrous oxide as well as carbon dioxide and methane emissions. Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G., *Tackling Climate Change Through Livestock – A Global Assessment of Emissions and Mitigation Opportunities*, Food and Agriculture Organization of the United Nations (2013) Table 1 at 7, https://www.fao.org/3/i3437e/i3437e.pdf.

97 *Id.* at 12.

98 Randall James et al., *Ohio Livestock Management Guide*, Ohio State Univ. Extension at 31 (2006), https://agcrops.osu.edu/sites/agcrops/files/imce/fertility/bulletin_604.pdf.

99 Stephen Kaffka, Tyler Barzee, Hamed El-Mashad, Rob Williams, Steve Zicari, and Ruihong Zhang, *Evaluation of Dairy Manure Management Practices for Greenhouse Gas Emissions Mitigation in California, FINAL TECHNICAL REPORT to the State of California Air Resources Board Contract # 14□456 (*February 26, 2016), https://biomass.ucdavis.edu/wp-content/uploads/ARB-Report-Final-Draft-Transmittal-Feb-26-2016.pdf.

100 *See Alternative Manure Management Program*, Cal. Dep't Food and Ag., https://www.cdfa.ca.gov/oefi/AMMP/.

101 Renewability describes an energy source that is replenished over time. However, even renewable sources can contribute to climate change or impose environmental harms. For example, wood pellets used as biomass may technically be renewable but the . Similarly, a solar array may provide renewable energy and climate benefits but cause other environmental harms by destroying habitat. Policymakers evaluating a given energy source should be vigilant to avoid the all-too-common slippage between "renewable" and "climate-friendly" in order to properly identify the costs and benefits of a given intervention.

102 *The Circular Economy in Detail*, Ellen Macarthur Foundation, https://archive.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail.

103 An Ellen Macarthur Foundation report doesn't mince words: "The circular economy presents a multi-trillion-dollar economic opportunity… More and more companies across industries are adopting circular principles to reduce costs, increase revenues, and manage risks." Ellen MacArthur Foundation, Financing the Circular Economy, Executive Summary, *available at* https://ellenmacarthurfoundation.org/financing-the-circular-economy-capturing-the-opportunity.

104 *See, e.g.,* Phoebe Gittelson et al., *The False Promises of Biogas: Why Biogas Is an Environmental Justice Issue*, Mary Ann Liebert, Inc., https://doi.org/10.1089/env.2021.0025.

105 White House Office of Domestic Climate Policy, U.S. Methane Emission Reduction Act Plan at 11 (November 2021), https://www.whitehouse.gov/wp-content/uploads/2021/11/US-Methane-Emissions-Reduction-Action-Plan-1.pdf.

106 *See* Cal. Dep't Food and Ag., AMMP Program-Level Data of Executed and Funded Grant Projects (updated December 23, 2021), https://www.cdfa.ca.gov/oefi/AMMP/docs/AMMP_Program_Level_Data.pdf; and Cal. Dep't Food and Ag., DDRDP Program-Level Data of Executed and Funded Grant Projects (updated December 23, 2021), https://www.cdfa.ca.gov/oefi/DDRDP/docs/DDRDP_Program_Level_Data.pdf.

107 U.S. Dep't of Ag. Econ. Research Service, The Transformation of U.S. Livestock Agriculture: Scale, Efficiency, and Risks (2009), https://www.ers.usda.gov/webdocs/publications/44292/10992_eib43.pdf?v=0 (2009).

108 *Id.* at iv ("Livestock wastes are becoming more geographically concentrated in the United States, and excessive applications of the nutrients contained in manure pose risks to air and water resources.")

109 *Id.* at 29 ("Large livestock operations store substantial quantities of manure onsite. The manure is generally applied to cropland much more intensely than on smaller farms, and large volumes of manure must still be removed from the operation. High concentrations of manure–whether stored in lagoons, pits, or ponds prior to transport or application–raise the likelihood of leaching or volatilization, threatening groundwater and air quality. And farms that intensively apply manure to cropland and pasture may apply it at rates that exceed the ability of crops to absorb nutrients, with the excess nutrients transmitted to water and air resources.").

110 Leslie Lipper et al., *Climate Smart Agriculture*, Food and Ag. Org. of the United Nations at 397-398, https://link.springer.com/content/pdf/10.1007/978-3-319-61194-5.pdf.

111 Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg. 7619; Exec. Order No. 13985, Advancing Racial Equity and Support for Underserved Communities Through the Federal Government, 86 Fed. Reg. 7009.


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Advancing Climate-Neutral Agriculture in New York

Viewpoint

Peter H. Lehner and Nathan A. Rosenberg

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In every state, New York included, the realities of climate change are becoming ever more tangible—more frequent floods, droughts, heat waves, and more. Agricultural producers are facing some of the most immediate impacts as these extreme and changed weather events, as well as increased pests and more challenging working conditions, profoundly affect producers' ability to grow plants and raise animals. As a result, federal and state officials are now looking at how we can reform our agriculture system both to reduce its contribution to climate change and to be more resilient to climate change's impacts. Our new book, *Farming for Our Future: The Science, Law, and Policy of Climate-Neutral Agriculture*,[1] aims to provide the foundation that policymakers need for making sound decisions.

Fortunately, New York is ahead of the pack and enacted a strong climate change law in 2019. The Climate Leadership and Community Protection Act (CLCPA) requires New York to reduce overall emissions by 40% below 1990 emissions by 2030 and by 85% by 2050.[2] The law also requires the state to achieve 100% emission-free electricity by 2040, but has no goals or targets for agriculture or other sectors.

Agriculture's contribution to climate change differs from what is normally discussed—the emission of carbon dioxide from the burning of fossil fuels. Agriculture's contributions, by contrast, come largely from methane from the exhalations of dairy and beef cows (ruminant animals whose guts produce methane) and liquid manure management; nitrous oxide that derives primarily from excess fertilization of crops; and carbon stripped from soils by agricultural activities. Over 20 years, methane is about 85 times stronger than carbon dioxide in global warming, and nitrous oxide is about 265 times stronger.[3]

In New York, the 2021 greenhouse gas (GHG) emissions report by the State Department of Environmental Conservation (DEC) indicates that agriculture is responsible for 6% of total statewide GHG emissions, and that 92% of those emissions come from livestock.[4] Unlike other sectors in New York where emissions have already decreased, livestock management emissions have increased 44% since 1990. Overall, about two-thirds of these emissions statewide are from cows exhaling methane and

[1] PETER H. LEHNER & NATHAN A. ROSENBERG, FARMING FOR OUR FUTURE: THE SCIENCE, LAW, AND POLICY OF CLIMATE-NEUTRAL AGRICULTURE (2021).
[2] N.Y. ENV'T CONSERV. LAW § 75-0107(1).
[3] *Understanding Global Warming Potentials*, EPA, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials (last updated Oct. 18, 2021); *see also* LEHNER & ROSENBERG, *supra* note 1, at 47–57.
[4] *Statewide Greenhouse Gas Emissions Report*, N.Y. STATE DEPT. OF ENV'T CONSERV., https://www.dec.ny.gov/energy/99223.html#Report (last visited Mar. 10, 2022).

one-third from liquid manure management (although actual measurements of methane emissions suggest that the models on which these emission figures are based significantly understate actual manure emissions).[5]

This statewide figure is highly concentrated, with a small number of large facilities contributing the vast majority of emissions.[6] According to the U.S. Department of Agriculture (USDA) Census of Agriculture (the most recent from 2017), New York has about 625,000 dairy cows and a total of approximately 1.5 million cows and calves, including the beef herd.[7] All release enteric methane, although dairy cows release more per cow than beef cows. The state also has about 4,500 dairies and 7,300 beef operations. Most are small with cows on pasture, but New York also has about 500 "concentrated animal feeding operations" (CAFOs)—which in New York are mostly dairies with an average of over 800 cows where the animals are kept in confined spaces and feed is brought to them. These relatively few facilities hold about 70% of the state's dairy cows. These CAFOs generate a large amount of waste and under State law must have manure storage systems, mostly large liquid lagoons, that hold the waste until it can be spread on fields. The anaerobic conditions in these lagoons generate (per unit of waste) about 20 times or more methane than manure deposited on pasture. Thus, these facilities are not only responsible for the bulk of enteric emissions in New York, but also the majority of manure emissions which are exacerbated by storage conditions—an important consideration for State policymakers.

DEC's report considers only the direct emissions of agricultural activities and thus somewhat understates the real impact of agricultural operations on climate change—and thus the potential of farm policy reform. For example, while the CLCPA requires inclusion of the embedded GHG gas emissions of energy and fuel produced out of state and imported into New York (about 17% of total state GHG emissions),[8] it does not similarly require inclusion of the GHG emissions from the production of other energy-intensive projects such as fertilizer or pesticide imported into the state. (Nor does it require consideration of the embedded GHG from the food imported into the state, which is likely significant.) Thus, for example, policies that could reduce fertilizer use in the state would have a larger climate impact than analyses focused entirely on New York would suggest, and policies that reduce on-farm energy would help the State meet its overall goals, if not agriculture sector goals. Moreover, DEC assigns all energy-related emissions to the energy sector rather than to where the energy is used and thus does not include the impact of on-farm energy in the agriculture climate footprint. Perhaps for this reason, the draft scoping plan has no discussion of eliminating emissions from farm vehicles and equipment.

Perhaps more important, DEC's report discusses separately the climate impact of annual land conversions (which in New York is largely a function of the 19 million acres of forest), and does not include at all the lost carbon sequestration potential of prior land conversion of New York's almost 7 million acres in farms.[9] This farmland takes the place of native vegetation, which generally would otherwise sequester more carbon. However, this land offers great potential to regain and restore its lost carbon through more climate-friendly agricultural practices.

Supplementing DEC's report with all these considerations indicates that agriculture's true contribution to climate change in New York far exceeds the modest 6% figure given. Indeed, many analyses find that agriculture and food systems (which often include emissions from food processing and other after-farm steps) contribute about one-third of all U.S. (or global) emissions[10] and that countries cannot reach their climate goals without addressing the agriculture and food production sector.[11] Policymakers must recognize the importance and opportunities of this sector.

Unfortunately, thus far, ambition for the agriculture sector has been overly modest. The CLCPA created a Climate Action Council (CAC) to develop a specific plan for climate change mitigation. The statute also established several advisory committees to the CAC, including one on agriculture and forestry. That advisory committee recommended measures that would achieve only a 30% reduction from current levels by 2050 in agriculture's contribution to climate change (i.e., a return to 1990 levels), even though the CLCPA's overall goal is an 85% reduction below 1990 levels of emissions statewide.[12] The draft scoping plan adopts these recommendations and proposes actions that would result in a 15% GHG reduction by 2030 and a 30% reduction by

[5] *See, e.g.*, Matthew N. Hayek & Scot M. Miller, *Underestimates of Methane from Intensively Raised Animals Could Undermine Goals of Sustainable Development*, ENV'T RSCH. LETTERS 16 063006 (2021), https://doi.org/10.1088/1748-9326/ac02ef.

[6] *See* Earthjustice, Visualizing USDA 2017 Census of Agriculture Livestock Inventory Concentrations, https://sustainablefoodfarming.shinyapps.io/CAFOINVENTORY/ (last visited Mar. 28, 2022).

[7] *See Census of Agriculture*, U.S. DEPT. OF AGRIC., https://www.nass.usda.gov/Publications/AgCensus/2017/index.php (last modified Jan. 12, 2022).

[8] *See* N.Y. STATE CLIMATE ACTION COUNCIL, DRAFT SCOPING PLAN 25–26 (Dec. 30, 2021) [hereinafter CLCPA DRAFT SCOPING PLAN], https://climate.ny.gov/-/media/Project/Climate/Files/Draft-Scoping-Plan.ashx.

[9] *See, e.g.*, Matthew N. Hayek et al., *The Carbon Opportunity Cost of Animal-Sourced Food Production on Land*, 4 NATURE SUSTAINABILITY 21 (2021), https://doi.org/10.1038/s41893-020-00603-4.

[10] *See, e.g.*, M. Crippa et al., *Food Systems Are Responsible for a Third of Global Anthropogenic GHG Emissions*, 2 NATURE FOOD 198 (2021), https://doi.org/10.1038/s43016-021-00225-9.

[11] Michael A. Clark et al., *Global Food System Emissions Could Preclude Achieving the 1.5° and 2°C Climate Change Targets*, 370 SCI. 705 (2020), https://doi.org/10.1126/science.aba7357.

[12] *Appendix A: Advisory Panel Recommendations*, *in* CLCPA DRAFT SCOPING PLAN, *supra* note 8, https://climate.ny.gov/-/media/Project/Climate/Files/Draft-Scopping-Plan-Appendix-A.ashx.

2050.[13] The CAC should explore and develop additional and more aggressive abatement opportunities. To date, however, the CAC and the agencies drafting the scoping plan appear to be continuing to downplay agriculture's role, even noting that "Climate Act policies typically affect only combustion sources."[14]

There is still time for the CAC to develop a more ambitious plan. There are many opportunities to change agricultural practices that would significantly reduce GHG emissions. It has been well demonstrated that farmers and ranchers can reduce net GHG emissions through improved grazing and animal feeding practices, better manure management, more efficient irrigation, and climate-friendly crop and soil management.[15] For instance, aggressive agricultural tillage of soil and pesticide application reduce soil organic carbon and nutrients. Farmers seek to compensate for this with heavy doses of fertilizer—often synthetic fertilizer, the manufacture of which itself creates significant GHG emissions. Indeed, studies show that on average about twice as much fertilizer is applied to U.S. cropland than the plants can use. The fertilizer not taken up by plants runs off into waterways (contributing to harmful algae blooms) or converts into nitrous oxide driving climate change. Yet soil can be restored to biological health and greater natural fertility. Reduced tillage that disturbs the soil less and cover crops that keep soil covered all year can restore nutrients to the soil. This reduces the need for fertilizers—saving farmers money—and the amount of nitrous oxide released into the atmosphere, as well as increasing the carbon stored in the soil and plants.

The challenge is that these climate-friendly practices are employed on just a small fraction of New York agricultural land. In 2017, cover crops were used on only about 14% of New York cropland, no-till on 18%, and certified organic practices on a mere 4%. There is no accessible data on how widespread managed rotational grazing practices are; these practices can significantly reduce erosion and increase soil carbon sequestration. Liquid manure management practices that increase methane emissions have actually increased in recent years, causing the emissions growth noted above. Policy change is needed to accelerate the development and adoption of climate-friendly practices. Widespread implementation of these practices could make New York's agriculture close to or even beyond climate neutral.

New York has several tools in addition to the CLCPA to accelerate adoption of these policies. Much of the State's technical outreach to farmers and ranchers is through the Agricultural Environmental Management (AEM) program overseen by the Department of Agriculture and Markets and the New York Soil and Water Conservation Committee and Districts. The draft scoping plan appropriately proposes to expand this program, providing site-specific climate-specific assistance.[16] However, much of this work is not shared and is held confidential, inhibiting the ability of farmers to learn from others and to build greater public support for these changes on farms. In addition to expanding this program, it would be helpful to increase its transparency.

Most of these climate-friendly practices will also reduce nutrient and pesticide runoff from fields and animal operations and can make farms more resilient to extreme weather. Thus, the state Agricultural Non-Point Source program, which funds projects to reduce farm runoff, can be expanded and focused on particularly climate-friendly practices. The Climate Resilient Farming program has provided about $20 million since 2015, some for soil management practices and most to cover manure lagoons at dairies and flaring the methane to convert it to carbon dioxide, thereby reducing the warming potential of these emissions (but not addressing many other polluting aspects of CAFOs). In 2021, the Legislature passed and Governor Hochul signed the Soil Health and Climate Resiliency Act,[17] which codifies the Climate Resilient Farming program; creates a soil health initiative that will, among other things, establish soil health standards; and increases research and development funding authority. In her proposed budget (S. 8004/A. 9004), Governor Hochul proposed to increase funding to $15 million for Soil and Water Conservation Districts and $17.5 million for the Climate Resilient Farming program, tripling past funding. Viewing all of agriculture and its impacts holistically opens the door to more system-level approaches that can benefit both farmers and the landscape.

As the State implements the CLCPA, it can augment and accelerate these efforts. One of its main tools to drive policy is to set targets that agencies must then figure out how to meet. As noted, the law has specific targets for electricity generation but none for the agriculture or land use sector. Before it is finalized, the scoping plan must include additional specific practice-based targets to be achieved by 2030 and 2050 to enable the sector to achieve more significant reductions and to guide further policy. Even trying to develop such goals—or other adaptive management system of accountable continuous improvement—would lead to important policy advances. (Indeed, one of the specific recommendations is to monitor and benchmark agricultural GHG emissions, noting that it is "central to the success of all other agricultural mitigation efforts."[18]) There is currently a woeful lack of accurate information about agricultural practices employed in New York (and elsewhere). New York does not collect its own data but relies

[13] *See* CLCPA Draft Scoping Plan, *supra* note 8. Appendix G of the scoping plan shows different reductions associated with different scenarios in the integration analysis for agriculture (see page 54). This shows about a 13–15% reduction by 2030 and a 30–34% reduction by 2050 under the primary scenario. This also shows a greater 20% reduction by 2030 for all other scenarios, and a 38–63% reduction by 2050 under other scenarios.

[14] N.Y. State Climate Action Council, Integration Analysis: Benefits and Costs with Sensitivity Analysis (updated Nov. 18, 2021), https://climate.ny.gov/-/media/Project/Climate/Files/2021-11-18-Integration-Analysis-Benefits-Costs-Presentation.ashx.

[15] *See, e.g.*, Natalie D. Hunt et al., *Fossil Energy Use, Climate Change Impacts, and Air Quality-Related Human Health Damages of Conventional and Diversified Cropping Systems in Iowa, USA*, 54 Env't Sci. & Tech. 10977 (2020), https://doi.org/10.1021/acs.est.9b06929.

[16] *See* CLCPA Draft Scoping Plan, *supra* note 8, at 195, 220–21.

[17] 2021 N.Y. Laws ch. 735.

[18] CLCPA Draft Scoping Plan, *supra* note 8, at 221.

on the Census of Agriculture done by the USDA every five years. For several reasons, this data is incomplete and often inaccurate. At the federal level, there has been great resistance to increasing reporting of GHG emissions from CAFOs; New York policy makers should not succumb to similar pressure here. The effort to set targets and monitor progress toward them would itself provide valuable information to New York policymakers and better allow farmers to learn from each other.

The Agriculture Resilience Act, first introduced by U.S. Representative Chellie Pingree (ME) in 2020,[19] offers several possible targets that could be adopted in New York:

- Overall reduce agriculture's GHG footprint 50% below 2010 levels by 2030 and achieve net-zero emissions by 2040 (a far more ambitious target than proposed in the draft scoping plan);
- Triple agricultural research and development funding by 2030 and quadruple it by 2040 (offsetting a long-term reduction in such funding and critical to achieving the other goals);
- Maintain year-round living plant cover on at least 50% of cropland acres by 2030 and 75% by 2040;
- Expand soil health practices to increase soil carbon by at least 0.4% per year (consistent with an international effort to offset much of the world's fossil fuel GHG emissions);
- Establish advanced rotational grazing management (which increases soil carbon and decreases manure emissions) on 50% of grazing land by 2030 and 100% by 2040;
- Increase agroforestry and silvicultural practices onto 15% of applicable land by 2030 and 30% by 2040;
- Increase crop-livestock integration by at least 100% over 2017 levels by 2040;
- Convert at least half of wet manure handling and storage to dry or alternative management systems that generate far less methane by 2040; and
- Reduce GHG emissions related to the feeding of ruminants by at least 50% below 2010 levels by reducing non-grazing of ruminants, growing feed grains and forages with soil health and nutrient practices that minimize net GHG from cropland, and utilizing livestock feed mixtures and supplements to mitigate enteric methane emissions.

New York could of course also establish additional targets, such as dramatically increasing the amount of organic farmland, both certified and non-certified, in the state (rough estimates suggest that total organically managed farmland in the state may be double the certified acreage). Similarly, it should add equity-focused goals, such as significantly increasing the amount of farmland owned and operated by farmers of color (now less than one percent of New York farmland) and ensuring that these farmers get a major share of the State's financial and technical support.

Livestock methane comprises the bulk of the state's agricultural GHG emissions, and the draft scoping plan includes two strategies for livestock emissions—improved manure management and feed management.[20] However, the draft scoping plan integration analysis shows only partial reduction of manure methane (far less than the statewide 85% goal) and little reduction in enteric methane in all but the last (less likely) scenario. But the plan notes that "additional innovation in methane mitigation" is necessary to attain the CLCPA goals and even acknowledges that this "will require transformative solutions."[21]

Despite this acknowledgment, the current recommendations are modest. They focus largely on technological measures such as destroying manure methane and should focus more on reducing methane generation. Known feed additives that slightly reduce methane emissions are used on much of the dairy herd, but relatively little research or effort is yet underway to tackle enteric emissions[22] or find alternatives to products with unavoidably high emissions. The recommendations could also put more emphasis on shifting to dry management and pasture systems, which generate a tiny fraction of the methane generated by liquid systems, or reducing herd size.[23] The draft scoping plan does not consider alternative plant-based milk products as an option, even though this could significantly decrease methane emissions and be a major growth industry for New York agriculture.[24] This omission is akin to looking only at reducing emissions from coal-fired power plants but not looking at energy efficiency or renewable energy.

The draft scoping plan then offers several soil health and nutrient management recommendations.[25] These generally seek to increase education and outreach, as well as financial and technical assistance for better soil health practices and to ensure programs are reaching all—and especially previously

[19] H.R. 5861, 116th Cong. (2020). Representative Pingree reintroduced the bill in 2021. *See* H.R. 2803, 117th Cong. (2021).

[20] CLCPA DRAFT SCOPING PLAN, *supra* note 8, at 208–13.

[21] *See* Climate Action Council, Draft Scoping Plan Overview 8, 12 (Jan. 2022) [hereinafter Draft Scoping Plan Overview], https://climate.ny.gov/-/media/Project/Climate/Files/Draft-Scoping-Plan-Overview.ashx; CLCPA DRAFT SCOPING PLAN, *supra* note 8, at 74.

[22] The draft scoping plan acknowledges the need for research to address enteric emissions. CLCPA DRAFT SCOPING PLAN, *supra* note 8, at 75. The various State budget proposals included some additional research and development (R&D) funds. Along with more R&D, there should be a commitment to transparency about the studies and results.

[23] *See* LEHNER & ROSENBERG, *supra* note 1, at 94–102.

[24] *See, e.g.*, *The Dairy That Gave Up Dairy*, ELMHURST, https://elmhurst1925.com/pages/our-story (last visited Mar. 29, 2022).

[25] *See* CLCPA DRAFT SCOPING PLAN, *supra* note 8, at 213–23.

underserved—producers.[26] These sound voluntary measures would be well supported by some of the other measures suggested here.

One of the most powerful tools to reduce net GHG emissions is shifting to more perennial crops,[27] and the draft scoping plan proposes increasing agroforestry.[28] Perennial plants produce more biomass than shorter-lived annuals, and this additional biomass stores dramatically more carbon. This effectively pulls carbon dioxide from the atmosphere and helps restore lost and declining soil carbon stocks. Even conservative estimates find that perennial practices sequester two to five times more carbon per acre than the most effective annual practices.[29] New York is already one of the largest producers of apples, grapes, and other perennials. We can further expand the number of trees, shrubs, and other perennial plants on farms and ranches by intercropping annual plants between rows of tree crops, introducing riparian and field buffers of trees with marketable crops, and adding trees to pasture. The plan recommends programs to expand these practices through incentives, financial support, and technical assistance; it would do well to also consider making adoption of some of these practices (e.g., riparian buffers) a "best management practice" that must be followed in order to receive general financial support.[30]

While the CAC is considering imposition of some form of price on carbon dioxide emissions (or "polluter pays"), the State could also develop a similar approach regarding agricultural GHGs. Nitrous oxide is a powerful GHG that also depletes the ozone layer, and is emitted almost entirely by agricultural soil management. It accounts for about 10% of the state's agricultural GHG emissions. New York could impose a modest fee on synthetic fertilizer that could both directly encourage fertilizer use efficiency and shifts to organic fertilizer and provide funds to assist this transition (although it may not be appropriate until the current price spike driven by Russia's invasion of the Ukraine abates). More sophisticated fee schemes could provide a base rate with discounts for enhanced-efficiency fertilizers that convert less to nitrous oxide. Recent studies by Cornell and others suggest that great improvements in fertilizer management are possible—and profitable—with similar reductions in nitrous oxide emissions.[31] Similarly a fee on methane would internalize the pollution cost (primarily pollution cost associated with beef and dairy along with oil and gas and food waste), and could fund efforts to accelerate feed and manure management changes.

In addition to policies directed at farmers, governments at all levels can use their enormous procurement power to support the production of climate-friendly food.[32] The scoping plan appropriately encourages purchasing of and education about climate-friendly products, but so far without many specifics.[33] Several bills pending in the State Legislature (S. 740, S. 7534) would mandate agencies or encourage municipalities to use their purchasing power for foods with a lower climate footprint. Governor Hochul in her State of the State address proposed to create green procurement standards for State agencies and authorities. The Cool Food Pledge, which establishes a methodology for calculating the GHG impact of foods and proposes a reduction target of at least 25% by 2030 relative to a 2015 baseline,[34] and the Good Food Purchasing Program, which commits governments to purchase food that meets five values including environmental sustainability,[35] offer good models for this approach. New York City has recently adopted these programs; other cities in New York State as well as the State itself could do the same.

While the draft scoping plan notes that "consumer … decision-making is key," it then only mentions the purchase of "new passenger vehicles and heating systems."[36] Thus, the scoping plan unfortunately misses an important opportunity to include consumer dietary decisions among actions individuals can make to help curb climate change. These can be some of the most significant opportunities for individuals to reduce their personal carbon footprint.[37]

Finally, New York should consider combining financial and other incentives with regulation. As noted above, a small percentage of New York dairies account for nearly 70% of New York's dairy cow population and are responsible for the vast majority of associated methane emissions. Most of these CAFOs

[26] *See* CLCPA Draft Scoping Plan, *supra* note 8, at 214–22 (Strategies AF11, AF12, AF14, AF16).

[27] Ranjith P. Udawatta & Shibu Jose, *Agroforestry Strategies to Sequester Carbon in Temperate North America*, 86 Agroforestry Sys. 225 (2012), https://doi.org/10.1007/s10457-012-9561-1.

[28] *See* CLCPA Draft Scoping Plan, *supra* note 8, at 218–20 (Strategy AF13).

[29] *See* Lehner & Rosenberg, *supra* note 1, at 67–68.

[30] *See* Lehner & Rosenberg, *supra* note 1, at 156–59.

[31] *See, e.g.*, Fred Magdoff & Harold Van Es, Building Soils for Better Crops: Ecological Management for Healthy Soils (4th ed. 2021), https://www.sare.org/wp-content/uploads/Building-Soils-for-Better-Crops.pdf; Lehner & Rosenberg, *supra* note 1, at 84–87.

[32] *See* Lehner & Rosenberg, *supra* note 1, at 229–39; *see also, e.g.*, Press Release, U.S. Dept. of Agric., USDA Announces $3 Billion Investment in Agriculture, Animal Health, and Nutrition; Unveils New Climate Partnership Initiative, Requests Public Input (Sept. 29, 2021), https://www.usda.gov/media/press-releases/2021/09/29/usda-announces-3-billion-investment-agriculture-animal-health-and.

[33] CLCPA Draft Scoping Plan, *supra* note 8, at 222–23 (Strategy AF17).

[34] *The Cool Food Pledge*, Cool Food, https://coolfood.org/ (last visited Mar. 11, 2022).

[35] Ctr. for Good Food Purchasing, https://goodfoodpurchasing.org/ (last visited Mar. 11, 2022).

[36] Draft Scoping Plan Overview, *supra* note 21, at 11.

[37] *See* Lehner & Rosenberg, *supra* note 1, at 237–39; World Res. Inst., Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050 (July 2019), https://research.wri.org/sites/default/files/2019-07/WRR_Food_Full_Report_0.pdf; J. Poore & T Nemecek, *Reducing Food's Environmental Impacts Through Producers and Consumers*, 360 Science 987 (2018), https://doi.org/10.1126/science.aaq0216.

already operate under a water pollution permit issued by DEC under the Environmental Conservation Law; this permit could include provisions regarding manure handling that could reduce methane as well as water pollution. DEC also has authority to address air pollution under the Environmental Conservation Law. Manure lagoons at large dairies, in addition to releasing methane, generally emit two toxic gases, ammonia and hydrogen sulfide, over the standard air toxics regulatory threshold of 10 tons per year. The State could focus its financial support on the smaller dairies and use its regulatory authority to speed change in these few largest facilities. (The CLCPA provides that regulations must "include legally enforceable emissions limits, performance standards, or measures or other requirements to control emissions from greenhouse gas emission sources, with the exception of agricultural emissions from livestock," but this only means that DEC is not required to impose such limits under the CLCPA; it does not apply to GHG emissions from manure or limit DEC's pre-existing air pollution mitigation authority.)

The food system affects many other aspects of our economy and GHG emissions. In our homes, restaurants, and stores, we waste about one-third of the food produced, and most of that is dumped in landfills where it rots and releases methane. DEC indicates that landfill methane accounts for about 9% of New York's total GHG emissions. The State's new Food Donation and Food Scraps Recycling Law, effective January 2022, requires that businesses and institutions that generate an annual average of two tons of wasted food per week donate excess edible food to the maximum extent practicable and recycle all remaining food scraps if they are within 25 miles of an organics recycler.[38] The effectiveness of this law is compromised by the unreasonably low distance limit (garbage is often trucked far further to landfills) and dearth of organics recycling facilities (which seems to be in part a result of the small catchment areas created by the distance limit). It also exempts several large food waste generators and it does not apply in New York City, where Mayor Adams recently proposed to suspend the expansion of the City's composting program.[39] By increasing the number of composting and other organics recycling facilities around the state, especially near cities where the food waste is largely generated, and increasing efforts to reduce food waste, the State can make additional progress in reducing methane emissions and, indeed, the plan relies on the complete diversion of organic waste from landfills and incinerators to achieve its goals.

At a time when the President's efforts to tackle the climate crisis are becoming bogged down in politics and may be undercut by the Supreme Court, and Congress's ability to act is thwarted by entrenched interests of industrial agriculture and agrochemical companies, all Americans—not just those in New York—could benefit from New York's leadership enacting policies to help make agriculture more just and a climate solution. New York's policymakers must answer that call.

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LEGAL DEVELOPMENTS

ENERGY

State Supreme Court Rejected Challenge to Easement for Offshore Wind Transmission Cable

The Supreme Court, Suffolk County dismissed a challenge to an easement granted by the Town of East Hampton Town Board for the landing site of a transmission cable from a proposed offshore wind facility. The petitioners argued that the Town Board acted arbitrarily and capriciously by granting the easement prior to Public Service Commission (PSC) approval of the Certificate of Environmental Compatibility and Public Need under Article VII of the Public Service Law in order to "do something" about climate change. The court first concluded that three of the individual petitioners established standing because they were residents along the route of the easement who alleged "dangers and disruptions" from use of the easement. Other petitioners, however, failed to establish standing, including a petitioner described as "a local community organization devoted to preserving the natural beauty and bucolic character of Wainscott." The court found that the organization's "speculative statements about disruptions to the neighborhood" did not constitute an injury different from that experienced by the public at large. In addition, individuals who did not reside on property near the easement did not have standing; the court found that their alleged harm—that digging for the transmission cable could cause a known contaminant plume to migrate toward their property and wells—was not connected simply to use of the easement but to the way the project was connected, an issue considered by the PSC that should have been raised in those proceedings. The court also found that a property owners association and individual residents did not establish standing because alleged harms related to a new substation were conclusory and speculative. After addressing standing, the court proceeded to conclude that granting the easement did not constitute site preparation activity that could only be undertaken after the PSC approved the certificate. The court also rejected the claim that the Town Board was required to comply with New York's State Environmental Quality Review Act (SEQRA) before granting the easement. The court concluded that SEQRA did not apply to the project because the project was subject to environmental review pursuant to the Article VII process. In addition, the court found that the petitioners failed to state a claim under New York's General Municipal Law § 51 for fraudulent

[38] N.Y. ENV'T CONSERV. LAW §§ 27-2201–27-2219.

[39] Anne Barnard, *New York Was Set to Expand Composting. Now It's on the Chopping Block.*, N.Y. TIMES (Feb. 23, 2022), https://www.nytimes.com/2022/02/17/nyregion/nyc-budget-composting-adams.html.

or illegal use of public property. *Citizens for the Preservation of Wainscott, Inc. v. Town Board of East Hampton*, No. 601847/2021 (Sup. Ct. Suffolk County Feb. 24, 2022).

State Supreme Court Upheld Schoharie Town Board's Determination That Solar Energy System Was Inconsistent with Comprehensive Plan

The Supreme Court, Schoharie County upheld the Town of Schoharie Town Board's denial of a special use permit for construction of a solar energy system. The court described its review of the Town Board's determination as "quite deferential," given that the Town's Solar Energy Systems law gave the Board discretion to grant or deny the permit for the type of solar energy system at issue and did not limit the Town Board to consideration of certain factors. The court also rejected, as a preliminary matter, the petitioner's contention that the Town Board erred by considering the project's consistency with the Comprehensive Plan. The court noted that consideration of the Comprehensive Plan was required by both the Solar Energy Systems law and the Town's general zoning law. The court then found that the record "firmly" supported the finding that the location, size, and character of the proposed project was inconsistent with the Comprehensive Plan. The court cited the Comprehensive Plan's goal to maintain the Town's "rural, small town character"; its emphasis on the Town's "scenic beauty," including its "agricultural landscape"; and its specific identification of the road on which the project would be located as an important scenic location. The court further found that record evidence supported the Board's finding that solar panels would be visible from some locations, even with mitigation, and found that under the circumstances there was no error in the finding that "this new, large-scale commercial development would be out of place and inconsistent with the character of the area where it is proposed to be located." The court also found that petitioner did not establish that the Town Board was "unduly influenced by, or relied entirely on, community pressure." *Matter of Bliss Solar 1, LLC v. Town of Schoharie Town Board*, Index No. 2021-320 (Sup. Ct. Schoharie County Feb. 2, 2022).

HAZARDOUS SUBSTANCES

Federal Court Rejected Counterclaims Against Town of Islip in Park Waste Dumping Case

The federal district court for the Eastern District of New York dismissed counterclaims asserted by four defendants in the Town of Islip's lawsuit seeking to recover costs for the cleanup of Roberto Clemente Park in connection with illegal dumping of hazardous materials. The Town asserted claims under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); the Racketeer Influenced and Corrupt Organizations Act (RICO); and State law. The four defendants—who allegedly transported construction waste to the park—asserted First Amendment retaliation, Fourteenth Amendment substantive and procedural due process, and conspiracy claims under 42 U.S.C. § 1983, as well as claims for indemnification/contribution. They alleged that the Town named them as defendants "solely to punish them for filing and pursuing" a lawsuit against the Town. The court found that the *Noerr-Pennington* doctrine protected the Town from the alleged violations of the First and Fourteenth Amendments because no reasonable jury could find that the Town's lawsuit fell within the "sham exception" to the doctrine since the Town had "an objectively reasonable reason to commence litigation," given CERCLA's broad imposition of strict liability and evidence connecting the four defendants with the person they asserted was responsible for the waste dumping (the son of two of the four defendants). The court also found that the absence of an underlying constitutional violation prevented a finding of conspiracy or, alternatively, that the intracorporate conspiracy doctrine would bar the conspiracy counterclaims since the individual counterclaim defendants were part of, or agents of, the Town and were not "motivated by an independent personal stake." The court concluded that the four defendants were barred by CERCLA from seeking indemnification or contribution for CERCLA liability because the Town had resolved its liability to New York State in an administrative settlement. The court also concluded the four defendants could not seek indemnification and contribution against the Town for non-CERCLA liability because they did not have liability exposure to other co-defendants and alleged tortfeasors may not seek contribution or indemnification from a claimant in the absence of a direct tort claim against the tortfeasor by another party. *Town of Islip v. Datre*, 2022 U.S. Dist. LEXIS 26044 (E.D.N.Y. Feb. 14, 2022). [*Editor's Note:* This case was previously covered in the June 2017 issue of *Environmental Law in New York*.]

LAND USE

Court of Appeals Said State Law Authorizing Town Regulation of Firearm Discharges Did Not Authorize Bow Restrictions

The New York Court of Appeals ruled that Town Law § 130(27)—which authorizes certain towns to regulate discharge of "firearms"—did not authorize the Town of Smithtown to regulate discharge of bows. The Court of Appeals concluded that when construed in accordance with its usual and commonly understood meaning, the term "firearm" did not encompass a "bow." The court noted that it was not considering the question of whether a town would have other authority to regulate the setback distance for discharge of bows under its municipal home rule authority or whether the Environmental Conservation Law would preempt such regulations. (The court said the Town of Smithtown had conceded that its Town Code provision would be invalid absent specific authority under Town Law § 130(27) and could not assert a contrary argument at this point.) *Hunters for Deer, Inc. v. Town of Smithtown*, 2022 N.Y. LEXIS 66 (N.Y. Feb. 10, 2022). [*Editor's Note:* This case was previously covered in the December 2020 issue of *Environmental Law in New York*.]

Appellate Division Found That Adjacent Property Owners Had Standing to Challenge Zoning Determination That Allowed Continued Concrete Manufacturing

Reversing the Supreme Court, Putnam County, the Appellate Division, Second Department held that owners of property adjacent to property where a concrete batch plant had operated had standing to challenge a Town of Kent Zoning Board of Appeals (ZBA) determination that vacated the Town Building Inspector's determination that the property could no longer be used for concrete manufacturing. The Building Inspector issued the determination in May 2017, finding that a 1948 variance permitting employment of more than five people in operating a concrete manufacturing plant was not a use variance that ran with the land and that concrete manufacturing was no longer permitted due to an extended discontinuance of the nonconforming use after an accident during renovations at the plant. The Second Department found that all petitioners had standing to challenge the ZBA decision vacating this determination. In one proceeding, the petitioners had alleged environmental injuries to a private lake owned by the lead petitioner that was directly across from the subject property. They also alleged other injuries different from those suffered by the public at large and within the zone of interests of zoning laws such as interference with recreational activities in and around the lake and property impacts such as noise, truck traffic, dust, and pollutants. The Second Department said the other set of petitioners similarly had sufficiently alleged injuries within the zone of interests protected by zoning laws. The court also found that the lead petitioner did not have to establish organizational standing, given its ownership of the lake. The Second Department affirmed the Supreme Court's rejection of petitioners' motion to compel the ZBA to include in the record documents from appeals of earlier determinations by the Building Inspector. The Second Department found that those earlier appeals were not part of the "proceedings under consideration" and that materials concerning the earlier appeals had not been presented to the ZBA in connection with the current proceeding. *Matter of Veteri v. Zoning Board of Appeals of Town of Kent*, 2022 N.Y. App. Div. LEXIS 1004 (2d Dept. Feb. 16, 2022).

Appellate Division Affirmed Decision That Town Supervisor's Conflict of Interest Rendered Concrete Manufacturing Restrictions Invalid

In a related proceeding concerning the continued operation of a concrete batch plant in the Town of Kent, the Appellate Division, Second Department agreed with the Supreme Court, Putnam County that the Town Supervisor's conflict of interest and incomplete recusal invalidated a local law restricting concrete manufacturing in the Town. The law at issue prohibited production and manufacture of concrete and operation of a concrete products plant in all but one zoning district and required such activities in other zoning districts to terminate by amortization within two years, with the possibility of limited extensions. The Town Supervisor was a member of the lead petitioner (the owner of the private lake) in the related proceeding. She recused herself from voting on the local law but continued to preside over public hearings, engaged in discussions with the concrete manufacturer's representative and the public, participated in executive session, and voted on certain motions related to the law. The Second Department found that as a member of a petitioner in a proceeding seeking the plant's closure in its current location, the Town Supervisor "had an interest in the local law which went beyond mere expressions of personal opinion or an interest shared by the majority of property owners in the town." The Second Department further found that her limited recusal was "insufficient to remedy the appearance of impropriety which arose from her participation in the public hearings." The Second Department also noted that the Town Supervisor had not obtained an advisory opinion from a local ethics board concluding that her participation was appropriate. *Matter of Titan Concrete, Inc. v. Town of Kent*, 2022 N.Y. App. Div. LEXIS 991 (2d Dept. Feb. 16, 2022). [*Editor's Note:* This case was previously covered in the June 2019 issue of *Environmental Law in New York*.]

Appellate Division Reinstated Private and Public Nuisance Claims in Connection with Daytime Beach Driving Regulation by Village and Town of Southampton

The Appellate Division, Second Department found that the Supreme Court, Suffolk County should not have granted summary judgment to the Village of Southampton on private nuisance and public nuisance claims brought by a residential property owner in connection with regulation by the Village of Southampton that allowed exceptions to the general prohibition on summer daytime beach driving and parking. The Second Department also reinstated a private nuisance claim for damages against the Trustees of the Freeholders and Commonalty of the Town of Southampton (Town Trustees) in connection with a similar (but now repealed) regulation. The Second Department found that photographs of the beach area and the affidavits of the plaintiff and her family raised triable issues of fact as to whether the driving and parking "was of an unreasonable character" so as to constitute a private nuisance. In addition, the Second Department found there were triable issues of fact as to whether these activities endangered the health and safety of the public or the beach itself so as to constitute a public nuisance. (The Second Department concluded, however, that the Town Trustees' repeal of their regulation rendered the public nuisance claim and certain other claims against the Town Trustees academic.) In addition, the Second Department found that the Supreme Court "improvidently exercised its discretion" to search the record and award the Village summary judgment on the plaintiff's claim that the Village Code provision was void because it violated State regulations on coastal erosion management. The Second Department affirmed other aspects of the Supreme Court's decision, including the dismissal of a mandamus claim that improperly sought to direct how the New York State Department of Environmental Conservation regulated coastal areas. In addition, the Second Department found that equal protection claims against the Village and an unconstitutional taking claim against the Village and Town Trustees were barred by the doctrine of res judicata based on decisions in lawsuits filed in 1988 and 2005. *Thomas v. Trustees of Freeholders & Commonalty of Town of Southampton*, 2022 N.Y. App. Div. LEXIS 872 (2d Dept. Feb. 9, 2022).

OIL SPILLS & STORAGE

Boy Scout Camp Found to Be in Violation of Petroleum Bulk Storage Regulations

New York State Department of Environmental Conservation (DEC) Commissioner Basil Seggos granted DEC staff's motion for default judgment and found that a Boy Scouts of America council had violated the petroleum bulk storage regulations at a camp owned by the council in the Town of Long Lake, Hamilton County. The violations included failures to comply with registration requirements, failure to have a surface coating on two aboveground storage tanks to prevent corrosion and deterioration, failures to mark tanks properly, and failures to conduct monthly inspections and maintain inspection records. The Commissioner assessed a civil penalty of $16,200 but suspended $11,200 of the penalty contingent upon the respondent's compliance with the order. Among the steps the respondent must take is to submit documentation of its compliance with the regulations, including by either submitting photographs showing that corrosion areas on the tanks had been coated or by providing documentation that the tanks had been closed in accordance with DEC regulations. *In re Patriots' Path Council, Inc.*, 2022 N.Y. ENV LEXIS 11 (DEC Feb. 10, 2022).

SEQRA/NEPA

Third Department Found Impermissible Segmentation in SEQRA Review of Zoning Map Amendments

The Appellate Division, Third Department found that the City of Saratoga Springs improperly segmented its environmental review of a zoning map amendment from a hospital's future plans to develop the affected parcel with a medical office building and parking. The court noted that the zoning map amendment "would be the green light to reignite development plans" and found that the hospital's potential redevelopment of the parcel "was not so attenuated from the zoning map amendment" that segmentation would be permissible. The Third Department therefore reversed the portion of judgment of the Supreme Court, Saratoga County that dismissed the petitioners' cause of action asserting SEQRA violations. The Third Department affirmed, however, the Supreme Court's determinations that the zoning map amendments were aligned with the comprehensive plan and did not constitute illegal spot zoning. The Third Department also rejected the petitioners' contention that City Council members' receipt of campaign contributions from representatives of the hospital constituted a conflict of interest requiring annulment of the zoning map amendments. *Matter of Evans v. City of Saratoga Springs*, 2022 N.Y. App. Div. LEXIS 1086 (3d Dept. Feb. 17, 2022).

Appellate Division Dismissed Fire District's Challenges to Assisted Living Facility Zoning Approvals

The Appellate Division, Second Department affirmed the dismissal of two Article 78 proceedings brought by the Greenville Fire District to challenge area variances, a special permit, and a SEQRA conditioned negative declaration for an assisted living facility in the Town of Greenburgh. In the first proceeding, the Second Department agreed with the Supreme Court, Westchester County that claims challenging the area variances and conditioned negative declaration were time-barred. The appellate court found that the Supreme Court properly determined that the challenge to the conditioned negative declaration became ripe for review when the Town of Greenburgh Zoning Board of Appeals (ZBA) granted the area variances and that the 30-day limitations period began to run upon the filing of the ZBA meeting results with the Town Clerk (and not on a later date when the ZBA filed a certification of the decision setting forth its findings). In the second proceeding, the Second Department found that the Fire District's second challenge to the conditioned negative declaration was barred by the doctrine of res judicata. The Second Department also found that the Fire District did not have standing to challenge the special permit granted by the Town Board for the assisted living facility because the alleged injury—the need for additional personnel and equipment due to an anticipated increase in the number of emergency calls related to the facility—was outside the zone of interests protected by the zoning ordinance. The Second Department further found that allegations regarding road safety hazards for emergency vehicles were conclusory and speculative and thus insufficient to establish standing. *Matter of Greenville Fire District v. Zoning Board of Appeals of Town of Greenburgh*, 2022 N.Y. App. Div. LEXIS 1040 (2d Dept. Feb. 16, 2022); *Matter of Greenville Fire District v. Town Board of Greenburgh*, 2022 N.Y. App. Div. LEXIS 1031 (2d Dept. Feb. 16, 2022).

Organizations and Nearby Residents Lacked Standing to Challenge Assisted Living Facility Special Permit

In a separate proceeding brought by the Council of Greenburgh Civic Associations, Edgemont Community Council, and individual petitioners to challenge the special permit for the assisted living facility, the Appellate Division, Second Department agreed that the petitioners failed to establish standing. The Second Department found that the individual petitioners failed to establish that their properties were sufficiently close to the proposed development to give rise to an inference of damage or injury. The appellate court also found that the petitioners' "generalized allegations" of a potential public safety hazard "failed to set forth an actual injury distinct from that suffered by the public at large." The court further found that the organizational petitioners lacked standing because their standing was dependent on the standing of the individual petitioners. *Matter of Council of Greenburgh Civic Associations v. Town Board of Greenburgh*, 2022 N.Y. App. Div. LEXIS 1015 (2d Dept. Feb. 16, 2022).

State Supreme Court Said Challenge to Negative Declaration for Open Restaurant Program Was Ripe

The Supreme Court, New York County denied New York City's motion to dismiss an Article 78 proceeding challenging the negative declaration issued under SEQRA and City Environmental Quality Review for a proposed permanent version of the program that allowed restaurants and bars to expand to certain outdoor areas during the COVID-19 pandemic. The court rejected the City's contention that the petition was not ripe for review. The court found that the petitioners alleged "concrete injuries, environmental impacts including vermin, noise, and garbage, currently occurring," and concluded that while the City Council might review the permanent open restaurant proposal, there was no guarantee that the Council would act and the temporary open restaurant program was continuing in the interim. The court found that in this case, it was the SEQRA process, and not the zoning action, that inflicted the alleged injuries. The court therefore concluded that dismissal on ripeness grounds was not appropriate. *Matter of Arntzen v. City of New York*, 2022 N.Y. Misc. LEXIS 461 (Sup. Ct. New York County Feb. 1, 2022).

SOLID WASTE

Solid Waste Management Company and President/ CEO Ordered to Pay $25,000 Penalty

DEC Commissioner Seggos found that the operator of a solid waste management facility in Mount Vernon and its president and chief executive officer (CEO) had violated the facility's permit by failing to submit annual monitor fees in the amount of $37,800 for fiscal year 2020-2021. A processing and transfer station for acceptance and storage of yellow grease was operated at the facility. The Commissioner ordered that the respondents were jointly and severally liable for a civil penalty of $25,000. The Commissioner noted that it was "well-settled law" that officers of corporations could be held liable for environmental violations without piercing the corporate veil where their actions or omissions result in or contribute to the violations. In this case, the president and CEO "had direct responsibility for compliance with the monitor fee requirement" of the solid waste management facility permit. *In re NYC Oil Corp.*, 2022 N.Y. ENV LEXIS 5 (DEC Jan. 31, 2022).

DEC Commissioner Ordered Trucking Company to Pay $50,000 Penalty, Denying Staff Request for Higher Penalty

DEC Commissioner Basil Seggos imposed a $50,000 civil penalty on a freight shipping and trucking company that disposed of solid waste at an unauthorized facility in Earlton, Greene County. The respondent hauled 161 loads of "overs"—topsoil, rocks, bricks, processed paint wood, electrical wiring, piping, foam, tiles, metals, and plastics—at the site over the course of five months in 2017. The respondent did not answer or appear in the proceeding, but the Commissioner agreed with the administrative law judge (ALJ) that the pleadings and papers provided sufficient facts to enable a determination that the DEC staff had a viable claim and that default judgment was warranted. The Commissioner declined, however, to impose the $122,000 civil penalty that DEC staff requested in their motion papers. The Commissioner noted that the complaint itself sought a civil penalty of "no less than" $50,000 and that the penalty assessed in a default judgment could not exceed the amount demanded in a complaint, absent notice to the respondent. The Commissioner concluded that the use of the phrase "no less than" in the complaint did not provide adequate notice since the complaint could refer to any penalty amount between $50,000 and the maximum penalty of more than $1 million calculated by the ALJ. *In re Merrick Trucking Corp.*, 2022 N.Y. ENV LEXIS 2 (DEC Jan. 31, 2022).

TOXIC TORTS

Federal Court Approved Settlement in Hoosick Falls PFOA Class Action

The federal district court for the Northern District of New York granted final approval of a settlement agreement in a class action in which plaintiffs asserted claims based on the alleged presence of perfluorooctanoic acid (PFOA) in the Village of Hoosick Falls municipal water system, in private wells, and/or in the plaintiffs' blood. The settlement provided that the three settling defendants would pay $65,250,000 into a settlement fund, with the funds allocated to four classes: (1) a Municipal Water Property Settlement Class; (2) a Private Well Water Property Settlement Class; (3) a Nuisance Settlement Class; and (4) a Medical Monitoring Settlement Class. The court found the settlement agreement to be fair, reasonable, and adequate pursuant to Federal Rules of Civil Procedure (FRCP) 23(e), noting that "the reaction of the Settlement Classes has been overwhelmingly positive, which weighs strongly in favor of the Settlement's fairness." In reaching its determination that the settlement's method of distributing benefits to the settlement classes was fair, reasonable, adequate, and efficient, the court said more than 2300 claims had been filed during the enrollment period; the court found that this "substantial" claims rate was "a testament to the fairness" of the settlement. The court also certified the four settlement classes for purposes of settlement only, finding that they met the requirements for class certification under FRCP 23(a) and (b)(3). In addition, the court approved the requested attorneys' fee award of $12,397,500 and reimbursement of $1,040,817 for expenses incurred in connection with the litigation. The court found that the attorneys' fees were reasonable considering the magnitude and complexity of the litigation, the risk of the litigation, and the quality of representation on both sides. The court also found that the 19% fee award compared favorably with class counsel fees in other Second Circuit cases. In addition, the court awarded each of 10 class representative plaintiffs $25,000 for their "commendable work" in achieving the settlement. The court found that the settlement agreement's release was valid and enforceable and enjoined the assertion of contribution or

similar claims against the released parties. The court dismissed all released claims with prejudice, including all claims asserted against the settling defendants in the Second Amended Complaint. *Baker v. Saint-Gobain Performance Plastics Corp.*, No. 1:16-cv-00917 (N.D.N.Y. Feb. 4, 2022). [*Editor's Note:* This case was previously covered in the May 2017 and October 2021 issues of *Environmental Law in New York*.]

WATERS

Federal Magistrate Again Recommended Dismissal of Safe Drinking Water Act Endangerment Claim in Connection with Septic Systems in Long Island Parks

A magistrate judge in the federal district court for the Eastern District of New York recommended denial of reconsideration of the court's decision to dismiss a Safe Drinking Water Act (SDWA) claim in a citizen suit alleging that septic systems operated by the New York State Office of Parks, Recreation, and Historic Preservation at parks on Long Island violated the endangerment standard under the SDWA and the U.S. Environmental Protection Agency's (EPA's) implementing regulations. The magistrate issued reports and recommendations (R&Rs) in 2019 and 2021 recommending the SDWA claim be dismissed; after the 2021 R&R, EPA filed a Statement of Interest that objected to the R&Rs' interpretation that the SDWA's endangerment standard did not apply to the "Upper Glacial Aquifer" underlying Long Island because the aquifer was not a drinking water system since no drinking water wells existed downgradient from the parks' septic systems. The district court construed EPA's Statement of Interest as a motion for reconsideration. In its report and recommendation on the motion for reconsideration, the magistrate found that EPA's position did not meet the standard for reconsideration because it was the same interpretation that the plaintiffs articulated, and EPA did not present controlling case law or new evidence the court overlooked. The magistrate noted that EPA conceded the SDWA might leave "'some ambiguity' as to whether the endangerment requires a showing of a possible effect on a public water system." The magistrate also found that EPA's argument regarding EPA's implementing regulations did not meet the standard for reconsideration. *Peconic Baykeeper, Inc. v. Kulleseid*, 2022 U.S. Dist. LEXIS 18384 (E.D.N.Y. Feb. 1, 2022). [*Editor's Note:* This case was previously covered in the July 2019 and January 2022 issues of *Environmental Law in New York*.]

$6,840 Penalty Assessed for Failure to Submit Discharge Monitoring Reports for Mid-2019 Through End of 2020

DEC Commissioner Seggos granted DEC staff's motion for default judgment and found that a respondent violated DEC regulations and the State Pollutant Discharge Elimination System (SPDES) Multi-Sector General Permit (MSGP) for Stormwater Discharges Associated with Industrial Activity (GP-0-17-004) by failing to file complete semiannual discharge monitoring reports for three reporting periods extending from July 1, 2019 through December 31, 2020. The respondent obtained coverage under the SPDES MSGP in 2018 for its land transportation and/or warehousing facility in Bay Shore on Long Island, where it conducted repair, maintenance, and storage of vehicles and trailers. The Commissioner assessed a $6,840 civil penalty, declining to assess a higher penalty requested by DEC staff in their motion papers. (The Commissioner noted that a penalty assessed in a default judgment cannot exceed the amount demanded in the complaint, absent notice to the respondent that a greater penalty would be sought.) *In re XPO Logistics Freight, Inc.*, 2022 N.Y. ENV LEXIS 4 (DEC Feb. 9, 2022).

NEW YORK NEWSNOTES

Chapter Amendments Made Changes to Environmental Laws Enacted in 2021

In January and February 2022, Governor Kathy Hochul signed chapter amendments modifying a number of environmental laws enacted in 2021:

- **Bioheating fuel mandate:** An Environmental Conservation Law provision establishing statewide mandates for use of bioheating fuel was amended to provide that "Renewable Hydrocarbon Diesel" could be produced anywhere in North America, not just domestically. The amendments also eliminated a requirement for DEC to promulgate regulations to enforce assurances that bioheating fuel will not void manufacturers' warranties unless the bioheat provider provides its own warranty. (Chapter 5)
- **Effluent limitations in Nassau and Suffolk Counties:** Chapter amendments modified the standard applied to establishing effluent limitations in special ground water protection areas or in Nassau or Suffolk Counties where discharges will impact marine waters within 10 years. Amendments in 2021 required application of "best available technology," and the chapter amendments added an economic feasibility and cost effectiveness requirement. (Chapter 8)
- **Flame retardant chemicals in furniture, mattresses, and electronic casings:** In December 2021, New York enacted the Family and Fire Fighter Protection Act, which will prohibit sales of upholstered furniture, mattresses, and electronic displays containing certain flame retardant chemicals that are halogenated, organophosphorus, organonitrogen, or nanoscale chemicals. The law also will bar custom upholsterers from using components that contain the regulated chemicals. The chapter amendments extended the sales prohibitions' effective date from January 1, 2024 to December 1, 2024 and the upholsterer prohibition

effective date from January 1, 2023 to December 1, 2025. As amended, the prohibitions apply where the regulated chemicals are present "[a]t or above levels set by [DEC] in regulation" or are "intentionally added." The amendments also add a new section that provides that sellers of covered products will not be found to have violated the law if they can show good-faith reliance on a manufacturer's certificate of compliance. (Chapter 11)

- **Pesticide data compilation:** A 2022 law further amended requirements for DEC to compile data on pesticide applications. DEC must compile and report data by EPA registration number and active ingredient and post annual reports on its website by December 31. (Chapter 30)
- **State geological trail:** Amendments to a 2021 law regarding the establishment of a State geological trail gave the DEC Commissioner more discretion regarding the designation of sites of geological significance and the establishment of the State geological trail. The amendments also pushed back the effective date of the law by one year. (Chapter 31)
- **Glass recycling study:** A 2022 law expanded the scope of a study on alternative municipal uses for recycled glass to include glass collection, processing, and recycling. The law also gave DEC additional time—until December 31, 2023—to complete the study. (Chapter 32)
- **Small plastic bottle hospitality personal care products:** The compliance dates for the prohibition on large hotels providing small plastic bottles containing a hospitality personal care product was extended from January 1, 2024 to January 1, 2025. The deadline for small hotels was extended from January 1, 2025 to January 1, 2026. (Chapter 33)
- **Seaweed cultivation in Suffolk County:** A 2021 law establishing kelp cultivation in Gardiner's and Peconic Bays in Suffolk County was amended to expand the authorized cultivation to include other types of seaweed. The permitting process was also revised. (Chapter 34)
- **Lead warnings for seasonal and decorative lighting cord casing:** The chapter amendments moved the warning requirement from Section 1376-b of the Public Health Law to Section 389-s of the General Business Law. The amendments also reduced the penalty to $500 for a violation (from $1,000) and limited the penalty provision to manufacturers. (Chapter 40)
- **Supermarket excess food donation:** The amendments to the Food Donation and Food Scraps Recycling Law clarified that large supermarkets (more than 10,000 square feet) that do not meet the scrap generation weight threshold to qualify as "food scrap generators" are subject to a separate provision that provides that they "shall from time to time make excess food available to food relief organizations."
- **Storm hardening and system resiliency plans for utilities:** A 2021 law required that electric utilities submit climate change vulnerability studies to the Public Service Commission. The chapter amendments modified and clarified the process for submission and review of the plans, as well as the cost recovery provisions. (Chapter 45)
- **Emerging contaminants:** The chapter amendments extended by 90 days the required timeframe for adopting a "first list" of emerging contaminants. The amendments also removed 17 substances from the list of substances required to be on the "first list" of emerging contaminants. Instead, the law established a longer timeline (to January 1, 2024) for the Health Commissioner to determine whether to include 14 of the chemicals as emerging contaminants. The amendments also provided that the Commissioner could determine not to include two of the substances as emerging contaminants (but without a specified timeframe) and removed a substance (chlorate) from the law's scope. (Chapter 69)
- **Pesticide use at children's camps:** The amendments modified the 2021 law prohibiting application of pesticides on playgrounds or athletic or playing fields at overnight and day camps. The changes included eliminating the authority of the Health Commissioner to exempt camps for which use of a pesticide alternative is not practicable and eliminating a provision to allow an emergency application of a pesticide if a camp does not receive a response to a request for emergency application within 24 hours. (Chapter 71)
- **Airport health impacts study:** The chapter amendments gave the New York State Department of Health (instead of DEC) the lead role in conducting a study describing the impacts of JFK and LaGuardia airports on noise and human health. The amendments also modified the law to focus on noise and human health—asthma, in particular—and added a requirement that the report on the study's findings include all raw and aggregate data. (Chapter 92)
- **Soil Health and Climate Resiliency Act:** The chapter amendments grant the Commissioner of the Department of Agriculture and Markets and the Soil and Water Conservation Committee the authority to adopt regulations to implement the 2021 Soil Health and Climate Resiliency Act. (Chapter 102)
- **Zero-emission passenger cars and trucks:** The 2021 law set a goal for 100% of new passenger cars and trucks to be zero-emissions by 2035. The amendments made the New York State Energy Research and Development Authority (instead of DEC) responsible for development of a market development strategy. (Chapter 109)
- **State Administrative Procedure Act public hearings:** The amendments increased the number of persons that must join a petition to trigger a requirement for a public hearing

on a proposed rule. For DEC, the number was increased from 125 to 750. Amendments also exempted rules adopted on an emergency basis from the public hearing requirement and made the hearing optional if the petition is received less than 30 days before the comment deadline. In addition, the law will take effect January 1, 2023 (instead of January 1, 2022), and agencies may require that agency-generated forms be used to submit petitions for hearings. (Chapter 116)

- **Access to locally produced, healthy foods:** In response to the governor's concerns about the potentially duplicative role of a task force created by a 2021 law to make recommendations on improving urban and rural consumer access to locally produced, healthy foods, the chapter amendments modified the law to establish instead an "advisory group" that will identify strategies and opportunities to expand access for underserved, nutritionally deficient urban and rural communities to healthy, locally produced food in New York State. (Chapter 124)
- **MTA strategic action plan for improving bicycle and pedestrian access:** Changes included requiring the Metro-North Rail Commuter Council, the Long Island Rail Road Commuter's Council, and the New York City Transit Advisory Council to submit their recommendations on improving bicycle and pedestrian access to the Metropolitan Transportation Authority by June 1, 2022 and every five years thereafter. (Chapter 125)
- **Aquatic invasive species inspection stations in the Adirondack Park:** Changes to the law authorizing DEC to establish the inspection stations included clarification that owners or operators of motorized watercraft are required to obtain a certification or certificate to ensure compliance with requirements to prevent spread of aquatic invasive species only when the stations are open for operation. The amendments also require DEC to annually review data from the inspection stations to identify improvements to reduce the spread of aquatic invasive species. (Chapter 126)
- **Potable water testing for lead in schools:** The amendments authorize the Health Commissioner to grant waivers from lead testing requirements for school buildings if the school district "has substantially complied with the testing requirements and has been found to be below lead levels as determined by regulations … for such buildings." The amendments also require that schools use other state and federal funding sources for testing and remediation prior to using funds allocated to a school district by the Board of Cooperative Educational Services under Education Law § 1950 or apportionments to school districts for school building purposes and testing and filtering of potable water systems under Education Law § 3602. (Chapter 130)

Requirements for Conditional Adult-Use Cannabis Licenses Include Environmental Sustainability

On February 22, 2022, Governor Hochul signed legislation establishing temporary conditional licenses for adult-use cannabis cultivators and processors (Chapter 18). The law directed the Office of Cannabis Management to set out terms and conditions for the awarding and maintenance of such licenses, which must include a requirement that licensees agree to participate in an environmental sustainability program. The provisions establishing the conditional licenses are codified at Sections 68-c and 69-a of the Cannabis Law.

DEC Issued Guidance on Operational Requirements for L3 Landfills Permitted Before November 2017

In the February 23, 2022 issue of the *Environmental Notice Bulletin*, DEC announced that it had finalized a program policy on "Guidance for Renewing or Modifying an Existing Part 360 Permit for Construction and Demolition Debris Landfills Three Acres or Less in Area." The guidance applies to existing construction and demolition debris landfills that are three acres or less in area and were permitted under the 6 N.Y.C.R.R. Part 360 regulations in effect before November 4, 2017. The policy sets forth options for such "L3 Landfills" at the time of permit expiration, renewal, or modification. Until an L3 Landfill's current permit expires or is renewed or modified, the landfill can operate with the existing low permeability liner system. There are three options for an L3 Landfill at the time of permit expiration, renewal, or modification: (1) it may continue to operate with the existing low permeability liner system if waste accepted for disposal is limited to tree debris; uncontaminated soil and rock from land clearing, utility line maintenance, and seasonal or storm-related cleanups; and recognizable uncontaminated concrete and concrete products, asphalt pavement, brick, glass, soil, and rock; (2) the facility can construct a liner system that meets the requirements of the current Part 363 and can continue to accept a mixed construction and demolition debris waste stream; or (3) the facility can initiate closure of the facility. The policy is available at https://www.dec.ny.gov/regulations/124062.html.

DEC Finalized Methane and VOC Regulations for Oil and Gas Sector

In the February 16, 2022 issue of the *NYS Register*, DEC published notice of its adoption of regulations to control emissions of methane and volatile organic compounds (VOCs) from the oil and natural gas sector. The regulations are primarily codified in a new Part 203 of DEC's regulations. The regulations—which have a compliance date of January 1, 2023—impose requirements on new and existing oil and natural gas well activities, natural gas gathering lines, natural gas transmission pipelines and compressor stations, natural gas underground storage facilities, and the "city gate" (a transfer point between a natural gas transmission system pipeline company/operator and a distribution system company/operator). The new Part 203 does not apply to distributing gas

utilities or equipment and components located downstream of a city gate. The regulations prohibit venting natural gas to the atmosphere from some components and include leak detection and repair (LDAR) requirements, with the frequency of required inspections varying from bimonthly to semiannually depending on the type of activity, with less frequent inspections required if an alternative method offering continuous monitoring is used. The regulations generally require that leaks be repaired within 30 days and reinspected within 15 days of repair. The regulations provide, however, for delays of repairs and replacements if certain conditions are met. Blowdown activity (releases of natural gas from pipelines or compressor stations) requires notification if the amount is greater than 10,000 cubic feet, whether the blowdown is planned or unplanned. Baseline component inventories from regulated sources are due to DEC by March 31, 2023, or by March 31 of the year following initiation of operation. Records must be maintained for five years. DEC said the regulations would serve three functions: reducing methane emissions in support of the goals and requirements of the Climate Leadership and Community Protection Act; reducing VOC emissions, an ozone precursor; and fulfilling the requirements of the EPA's 2016 Control Techniques Guidelines for the oil and gas industry.

New York State Common Retirement Fund to Divest from Certain Shale Oil and Gas Companies

On February 9, 2022, New York State Comptroller Thomas P. DiNapoli announced that the New York State Common Retirement Fund would restrict investments in 21 shale oil- and gas-producing companies (out of 42 companies reviewed) that the Fund determined had failed to show viable strategies to transition to a low-carbon company. The fund will sell more than $238 million in public equity and debt securities issued by the 21 companies in a manner consistent with fiduciary obligations. The Fund previously divested from 34 oil sands and coal companies that the Fund determined had failed to demonstrate transition readiness. The Fund next will evaluate integrated oil and gas companies. The announcement of the divestment from the shale oil and gas companies said the restrictions were part of the Comptroller's Climate Action Plan and commitment to transition the Fund's investment portfolio to net zero greenhouse gas emissions by 2040.

Audit Found that NYPA Electric Vehicle Programs Failed to Achieve Goals

On February 4, 2022, Comptroller DiNapoli released an audit of the Charge NY, Charge NY 2.0 and Evolve NY programs that found that the New York Power Authority (NYPA) had failed to install electric vehicle (EV) chargers where they were most needed. The audit found that NYPA placed public charging ports in only 32 of the State's 62 counties, and that counties with a high number of EVs have relatively few public charging ports. For instance, Suffolk County has 17% of registered EVs in New York State but only 1.1% of the public charging ports. The audit also found that NEPA did not review and analyze usage data for charger placement or use outreach efforts to encourage its customers to install EV chargers. In addition, NEPA had only installed 29 high-speed chargers as of March 5, 2021, though the EVolve NY program had a deadline of the end of 2019 for stalling 200 high-speed chargers. The report said installation of such chargers was as much as two years behind schedule. The audit report's recommendations included development of a formal process for evaluating new initiatives and programs; development of a formal marketing strategy to increase awareness of the features and benefits of EVs; incorporation of analysis of usage data into NYPA's current EV program; and work with the NYPA customer base to roll out EV charging stations. The audit report is available at https://bit.ly/3tZp9if.

Amendments to New York City Stormwater Rule Established Citywide Construction/ Post-Construction Permitting Requirements

Amendments to New York City's stormwater rule took effect on February 15, 2022. The amended rules apply to discharges from industrial stormwater sources within portions of New York City served by the municipal separate storm sewer system (MS4) as well as discharges of stormwater from "covered development projects" regardless of whether they are in the MS4 area. Covered development projects encompass private or public development activity involving or resulting in an amount of soil disturbance of at least 20,000 square feet or creation of at least 5,000 square feet of impervious surface or roadway maintenance involving 20,000 square feet or more. The New York City Department of Environmental Protection (DEP) described the amendments as part of a unified citywide stormwater policy that will align the construction/post-construction permitting program water quality requirements (15 R.C.N.Y. Chapter 19.1) with stormwater quantity and flow rate requirements in the sewer connection regulations (15 R.C.N.Y. Chapter 31). DEC said the amended stormwater rule would allow for reduction in combined sewer overflows and flooding, increase in green space, greater consistency across stormwater programs, flexibility in design options, and improvements in water quality. DEP also added a NYC Stormwater Manual as an appendix to Chapter 19.1 to provide additional procedural and technical guidance to owners, developers, and applicants.

WORTH READING

Michael B. Gerrard & Edward McTiernan, *Regulation of Polyfluoroalkyl Chemicals in New York*, N.Y.L.J. (Mar. 9, 2022), https://bit.ly/3CvIVG0

Meredith Mandell, *Placing an Emphasis on the "S" in ESG*, NYSBA Journal, Mar./Apr. 2022, at 24, https://nysba.org/nysba-journal-march-april-2022/

Office of the N.Y. State Comptroller, *Green and Growing: Employment Opportunities in New York's Sustainable Economy* (Feb. 2022), https://www.osc.state.ny.us/files/reports/pdf/green-jobs-in-new-york.pdf

Jack Rusk, *Across Currents*, Urb. Omnibus (Feb. 3, 2022), https://urbanomnibus.net/2022/02/across-currents/

David E. Schwartz & Emily D. Safko, *Employment Law Considerations for ESG in Upcoming Proxy Season*, N.Y.L.J. (Feb. 18, 2022), https://bit.ly/36BjB5F

Jared Woollacott et al., State of New York, U.S. Climate Alliance, & RTI Int'l, *Economic Impacts of Investing in Climate Mitigation in New York State Forests and Agriculture: Afforestation, Reforestation, and Manure Methane Capture* (Feb. 2022), https://on.ny.gov/3CHUQ3K

UPCOMING EVENTS

May 2–6, 2022

The RPA Centennial Assembly. For information, see https://rpa.org/events/assembly/2022.

May 2–8, 2022

Circular City Week New York. For information, see https://www.circularcityweek.com/.

May 18, 2022

Independent Power Producers of New York Annual Conference, Albany Capital Center, Albany. For information, see https://www.ippny.org/page/events-3.html.

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FARMING FOR OUR FUTURE

THE SCIENCE, LAW, AND POLICY OF CLIMATE-NEUTRAL AGRICULTURE

Peter H. Lehner & Nathan A. Rosenberg

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Figure 3. Industrial Agriculture Contributes to Climate Change

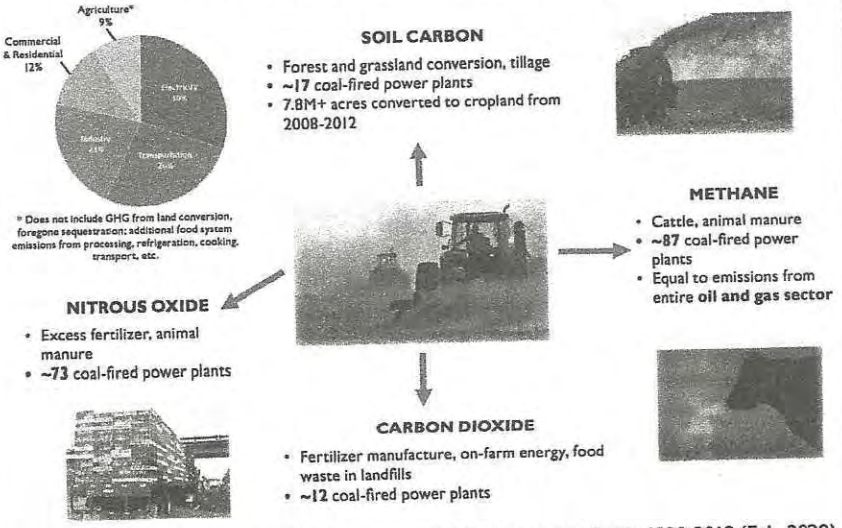

Source: U.S. EPA, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2018 (Feb. 2020), https://www.epa.gov/sites/production/files/2020-02/documents/us-ghg-inventory-2020-main-text.pdf (tables 2-1 & 2-2, trends in U.S. greenhouse gas emissions; 2-4, energy; 2-5, combustion; 2-10, industrial; 5-1, agriculture; 6-1, land use and land use change; and 7-1, 7-3 & 7-6, waste & landfills); coal-fired power plants equivalencies from U.S. EPA, *Greenhouse Gas Equivalencies Calculator*, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator. Percentages are of total gross U.S. anthropogenic GHG emissions.

countries are already investing significant sums into agroforestry research and production, yet the United States has lagged, despite robust research demonstrating its significant potential to sequester carbon while producing ample food. Moreover, food production needs will increase as the global population continues to grow. Thus, perhaps even more than agriculture's current contribution, its long-term determinative factor in climate stability demands careful policy attention.

2. U.S. Agricultural Greenhouse Gas Emissions

The U.S. Environmental Protection Agency (EPA) estimates that 2019 emissions from agricultural activities—growing crops and raising livestock and poultry—totaled about 629 million metric tons of carbon dioxide equiva-

lent (MMT CO_2 eq.), accounting for more than 10% of total U.S. greenhouse gas emissions.[12]

These agricultural emissions are at a minimum roughly equivalent to that produced by 136 million automobiles in a typical year.[13] However, unlike the greenhouse gas emissions of most other sectors of the economy, which consist of CO_2 released from the burning of fossil fuels, agriculture greenhouse gas emissions consist largely of nitrous oxide (N_2O) from soils and manure and methane (CH_4) from livestock and manure (as shown in Figure 3 on page 40). Agriculture also produces CO_2 from fossil fuel combustion (both on farms and off-site for on-farm electricity) and CO_2 from land conversion, neither of which are included in the EPA sector total. Agriculture is responsible for approximately 80% of U.S. N_2O emissions and 40% of U.S. CH_4 emissions—the same as the entire oil and gas sector's production emissions.[14]

The largest source of U.S. agricultural greenhouse gas emissions according to EPA is agricultural soil management. Activities by microorganisms in soil naturally result in emissions of N_2O, while agricultural practices, management, and land use can stimulate and accelerate these emissions by increasing the availability of nitrogen. Agricultural greenhouse gas emissions are dominated by emissions resulting from application of fertilizer as well as emissions associated with the breakdown of soil organic matter.[15] Soil management generates approximately half of all U.S. agricultural emissions and 93% of all U.S. N_2O emissions from agriculture.[16] Seventy-three percent of N_2O emissions from agricultural soil management come from cropland and 27% come from grazed grasslands.[17]

The next largest source of agricultural emissions is enteric fermentation, which results from the digestive process of ruminants (largely cows and sheep in the United States) (see Figure 4, page 42). Enteric fermentation creates CH_4, which animals subsequently release into the atmosphere through

12. U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019, at 5-1 (2021), https://www.epa.gov/sites/production/files/2020-02/documents/us-ghg-inventory-2020-main-text.pdf. The 2019 emissions are more than 1% higher than those from just the prior year, 2018.
13. *Compare id., with* U.S. EPA, Greenhouse Gas Emissions From a Typical Passenger Vehicle (2018) (a typical passenger vehicle emits 4.6 metric tons of CO_2 annually).
14. *See* U.S. EPA, *Overview of Greenhouse Gases*, https://www.epa.gov/ghgemissions/overview-greenhouse-gases (last updated Sept. 8, 2020).
15. U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018, Box 5-3 at 5-36 (2020) (EPA 430-R-20-002), https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf). In the methodology used by EPA to calculate nitrous oxide emissions, microorganisms in soil produce nitrous oxide at rates dependent on the availability of nitrogen, land use and management, weather, soil types, and other environmental conditions.
16. *See* U.S. EPA, *supra* note 15, at 5-2 tbl.5-1.
17. *See id.* at 5-25 tbl.5-15.

Figure 4. Major Sources of Agricultural Greenhouse Gas Emissions in the United States

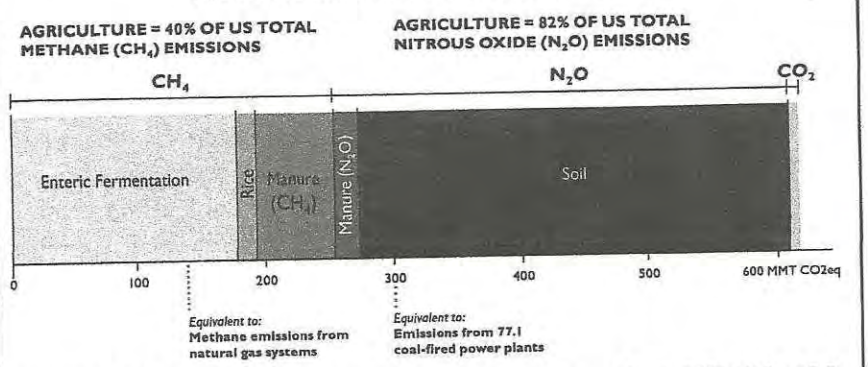

Source: U.S. EPA, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2018, at 5-2 tbl.5-1 (Feb. 2020), https://www.epa.gov/sites/production/files/2020-02/documents/us-ghg-inventory-2020-main-text.pdf.

belching and exhalation.[18] Enteric fermentation is responsible for 32% of all agricultural emissions and 27% of CH_4 emissions in the United States.[19] (As discussed below, the relative impact of bovine exhalation would be much greater using more appropriate approaches for calculating CH_4 emissions.)

Manure management activities are the third major category of U.S. agricultural emissions, releasing N_2O and CH_4 in quantities that total 13% of total U.S. agricultural emissions.[20] The largest animal facilities—those with over 1,000 cattle on feed, 1,000 dairy cows, 2,000 finishing hogs, 100,000 turkeys sold, 300,000 broilers sold, or over 50,000 laying hens —generate the substantial majority of these emissions. Greenhouse gas emissions from enteric fermentation and manure are largely dependent on the number of animals raised in these facilities, which are heavily concentrated in a small proportion of the largest operations: over 50% of dairy cows in the United States are in the 4% of operations that stock 1,000 or more dairy cows.[21]

18. Andy Thorpe, *Enteric Fermentation and Ruminant Eructation: The Role (and Control?) of Methane in the Climate Change Debate*, 93 CLIMATE CHANGE 407, 411 (2009).
19. *See* U.S. EPA, *supra* note 15, at ES-7 tbl.ES-2, 5-2 tbl.5-1.
20. *See id.* at 5-2 tbl.5-1.
21. *See* NATIONAL AGRICULTURAL STATISTICS SERVICE, USDA, 2017 CENSUS OF AGRICULTURE, U.S. NATIONAL LEVEL DATA tbl.12 (2019). NASS uses different class sizes than does EPA in its definition of a "concentrated animal feeding operation" under the Clean Water Act. Pursuant to EPA rules, a large concentrated animal feeding operation (CAFO) is one with more than 1,000 animal units. An animal unit is defined as an animal equivalent of 1,000 pounds live weight and equates to 1,000 head of beef cattle, 700 dairy cows, 2,500 swine weighing more than 55 pounds, 125,000 broiler chickens, or 82,000 laying hens or pullets. *See* 40 C.F.R. §122.23(b)(4).

More than 90% of hogs in the United States are in the 12% of facilities that stock 2,000 or more hogs,[22] and more than three-quarters of all cattle on feed in the United States are in the 5% of facilities that stock 1,000 or more cattle.[23] As shown in Figures 5 and 6 (see page 44), the climate footprint of animal agriculture is directly correlated to this concentration of inventory, with a few large facilities responsible for the majority of greenhouse gas emissions.

Methane emissions released from soils flooded for rice cultivation and the field burning of crop residues make up more than 2% of total U.S. greenhouse gas emissions from agriculture.[24] In addition, CO_2 emissions from urea fertilization and liming—included by EPA in its estimate of agricultural emissions for the first time in 2015[25]—account for just under 2% of agricultural emissions.[26] We compare emissions of various agricultural activities in Figure 4.

The vast majority of agricultural emissions are from animal production, particularly beef and dairy. In the United States, meat and dairy production—including emissions related to production of their feed (which is about half of U.S. crop production), grazing, enteric fermentation, and manure—accounts for almost 80% of agriculture's greenhouse gas emissions.[27] If the global cattle population were a country, it would constitute the second largest greenhouse gas emitter after China.[28] Both the grazing stage for cows and the feedlot stage for beef, dairy, swine, and poultry production, as practiced now, produce substantial greenhouse gas emissions.[29] Because cows produce only one calf at a time, which nurse for months and then must graze until their bodies can take a grain diet in a feedlot, there are about five cows grazing for each of the close to 30 million cows in feedlots.[30] This requires vast amounts of land—almost 800 million acres or about 40% of the contiguous United States is devoted to grazing.[31]

22. *See* National Agricultural Statistics Service, *supra* note 21, at tbl.25.
23. *See id.* at tbl.12.
24. *See id.*
25. *See id.*
26. *See id.*
27. These sources were responsible for 421.8 MMT CO_2 eq. or 78% of agricultural emissions in 2017. *Compare* U.S. EPA, *supra* note 15, at 5-2 tbl.5-1 (showing annual emissions from agriculture by source), *with infra* note 35 (calculating emissions from agricultural soils devoted to feed crop production or grazing).
28. Justin Ahmed et al., McKinsey & Co., Agriculture and Climate Change: Reducing Emissions Through Improved Farming Practices 5 (2020).
29. *See* C. Alan Rotz et al., *Environmental Footprints of Beef Cattle Production in the United States*, 169 Agric. Systems 1 (2019).
30. Matthew N. Hayek & Rachael D. Garrett, *Nationwide Shift to Grass-Fed Beef Requires Larger Cattle Population*, 13 Env't Res. Letters 0845005 (2018).
31. *See* Bigelow & Borchers, *supra* note 6.

Figure 5. Concentration and Production of Largest Animal Producton Operations

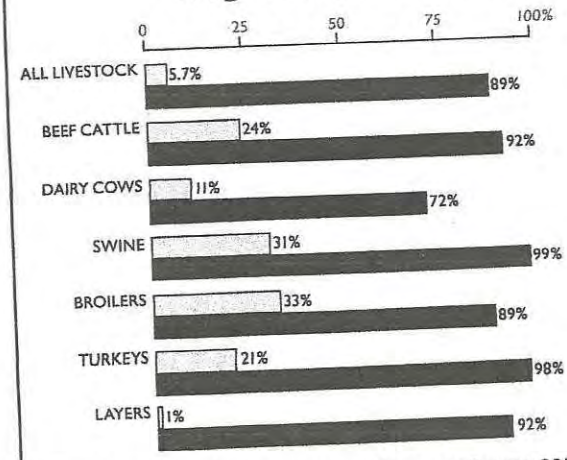

Source: USDA, National Agriculture Statistics Service, 2017 Census of Agriculture, United States Summary and State Data, tbls.12-30 (April 2019); Claire Huang, Earthjustice, Air and GHG Emissions CAFOs: Quantifying a National Estimate 25 (Aug. 19, 2020). For purposes here, the largest facilities are those with over 1,000 cattle on feed, 1,000 dairy cows, 2,000 finishing hogs, 100,000 turkeys sold, 300,000 broilers sold, or over 50,000 laying hens.

Figure 6. Share of Manure Emissions From Largest Animal Production Operations

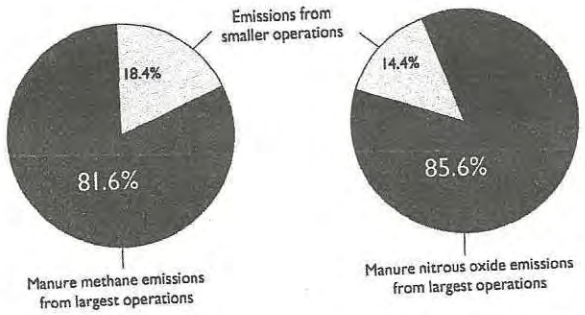

Sources: USDA, National Agriculture Statistics Service, 2017 Census of Agriculture, United States Summary and State Data, tbls.12-30 (April 2019); Claire Huang, Earthjustice, Air and GHG Emissions CAFOs: Quantifying a National Estimate 23 (Aug. 19, 2020).

Figure 7. Annual Greenhouse Gas Emissions From Largest Animal Facilities

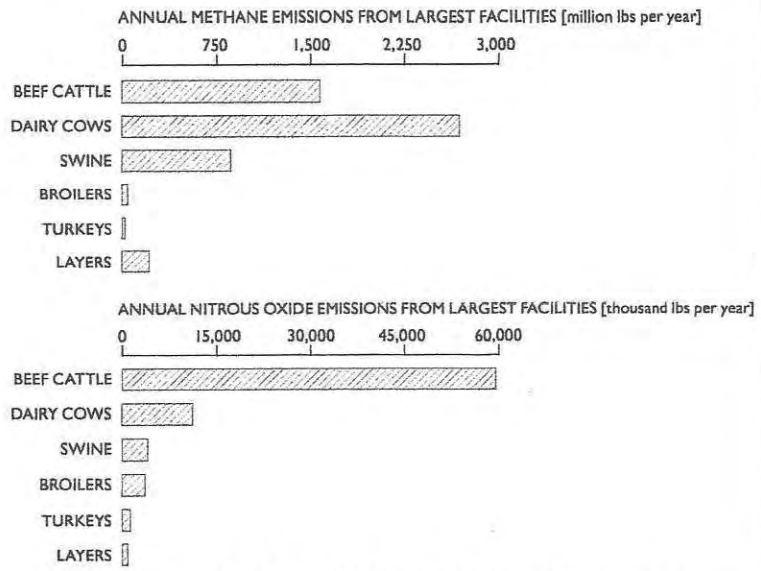

Source: CLAIRE HUANG, EARTHJUSTICE, AIR AND GHG EMISSIONS CAFOS: QUANTIFYING A NATIONAL ESTIMATE 25 (Aug. 19, 2020).

In addition, approximately half of all harvested cropland is devoted to animal feed crop production, adding to animal agriculture's already capacious footprint.[32] This cropland is often cultivated more intensely than cropland growing human food and often emits more nitrous oxide per acre than the production of crops for human consumption.[33] However, only a fraction of those crop calories is delivered to humans because the feed-to-meat ratio is so inefficient. For example, the production of one pound of beef from feedlot

32. There were approximately 310 million acres of harvested cropland in 2007 according to the Census of Agriculture. NATIONAL AGRICULTURAL STATISTICS SERVICE, U.S. DEPARTMENT OF AGRICULTURE, 2007 CENSUS OF AGRICULTURE: U.S. NATIONAL LEVEL DATA 16 tbl.8 (2009). The U.S. Department of Agriculture (USDA) estimates that approximately 165 million of those acres were devoted to feed crops; however, up to 10% of the feed was diverted to biofuels. CYNTHIA NICKERSON ET AL., USDA, MAJOR USES OF LAND IN THE UNITED STATES, 2007, at 20 (2011) (EIB-89). This total does not include soybeans, which USDA considers a "food crop," despite the fact that soybean meal is typically used as animal feed. TANI LEE ET AL., USDA, MAJOR FACTORS AFFECTING GLOBAL SOYBEAN AND PRODUCTS TRADE PROJECTIONS (2016).

33. Conventionally grown feed crops, such as corn, soybean, and hay, generally result in high N_2O emissions. *See* EPA, *supra* note 15, at 5-23.

cattle requires 15 pounds of grain.[34] As a result, grazing and feed crop production contribute almost two-thirds of N_2O emissions from agricultural soils.[35]

Not only does animal agriculture overall have an outsized impact on climate change, but this impact is—under current production methods—particularly influenced by beef, dairy, and to a lesser extent, swine production. This impact is all the more striking given that Americans receive only 30% of their calories from animal products.[36]

3. State-Level Agricultural Greenhouse Gas Emissions

While virtually all U.S. states have important agricultural sectors, their agricultural emission rates vary significantly due to climate differences and the type and intensity of agriculture within the state. A major factor is the amount of livestock. The top 10 highest overall greenhouse gas emitters (including fossil fuel emissions) account for nearly 50% of national emissions, with Texas and California in the lead. (See total emissions listed below state names in Figures 8 and 9 on pages 47 and 48.) However, the states with the largest total agricultural greenhouse gas emissions are Iowa (63 MMT CO_2 eq./yr.) with more than 10% of all U.S. agricultural greenhouse gas emissions, Texas (38 MMT CO_2 eq./yr.), Nebraska (33 MMT CO_2 eq./yr.), and California (29 MMT CO_2 eq./yr.). All of these states have both very high numbers of livestock and extensive cropland.

States also vary in the significance of agricultural emissions, accounting for more than 50% of total state emissions in South Dakota, and more than 30% of state emissions in Idaho, Nebraska, and Iowa. Finally, agricultural greenhouse gas emissions also vary when scaled by total cropland acres, indicating the relative intensity of the agricultural practices and the portion of

34. The feed conversion ratio expresses the number of pounds of grain necessary to increase the "live weight" of a head of cattle by one pound. At industrial feedlots, a feed conversion ratio of 6:1 is common. Dan W. Shike, Beef Cattle Feed Efficiency 3 (2013). About 40% of the live weight of a head of cattle is sold as beef, which means that 15 pounds of grain is necessary to yield one pound of beef. *See* Rob Holland et al., University of Tennessee Institute of Agriculture, How Much Meat to Expect From a Beef Carcass 9 (2016) (PB-1822).

35. This includes grassland emissions, which account for 73.3 MMT CO_2 eq., as well as 48% of cropland emissions—the approximate percentage of harvested cropland devoted to feed crop production in 2007—which adds an additional 92.7 MMT CO_2 eq. *Compare* U.S. EPA, *supra* note 15, at 5-2 tbl.5-1, 5-25 tbl.5-15 (showing annual emissions from agriculture by source), *with supra* note 32(explaining how the percentage of harvested cropland devoted to feed crop production was calculated). Together, they were responsible for 166 MMT CO_2 eq. or 62% of all emissions from agricultural soils in 2016. This total does not include the approximately 16.5 million acres devoted to the production of biofuel feedstock. *See supra* note 32.

36. USDA Economic Research Service, *Seventy Percent of U.S. Calories Consumed in 2010 Were From Plant-Based Foods*, https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=81864 (last updated Jan. 6, 2017).



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Methane emissions from dairy lagoons in the western United States

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ABSTRACT

Methane generation from dairy liquid storage systems is a major source of agricultural greenhouse gas emissions. However, little on-farm research has been conducted to estimate and determine the factors that may affect these emissions. Six lagoons in south-central Idaho were monitored for 1 yr, with CH_4 emissions estimated by inverse dispersion modeling. Lagoon characteristics thought to contribute to CH_4 emissions were also monitored over this time period. Average emissions from the lagoons ranged from 30 to 126 kg/ha per day or 22 to 517 kg/d. Whereas we found a general trend for greater emissions during the summer, when temperatures were greater, events such as pumping, rainfall, freeze or thaw of lagoon surfaces, and wind significantly increased CH_4 emissions irrespective of temperature. Lagoon physicochemical characteristics, such as total solids, chemical oxygen demand, and volatile solids, were highly correlated with emission. Methane prediction models were developed using volatile solids, wind speed, air temperature, and pH as independent variables. The US Environmental Protection Agency methodology for estimating CH_4 emissions from manure storage was used for comparison of on-farm CH_4 emissions from 1 of the lagoon systems. The US Environmental Protection Agency method underestimated CH_4 emissions by 48%. An alternative methodology, using volatile solids degradation factor, provided a more accurate estimate of annual emissions from the lagoon system and may hold promise for applicability across a range of dairy lagoon systems in the United States.
Key words: emission, methane, manure, inverse dispersion

INTRODUCTION

The latest US Environmental Protection Agency (**USEPA**) greenhouse gas (**GHG**) inventory (USEPA, 2016b) estimates that agriculture accounts for 9% of total GHG emissions in the United States. The percentage of agricultural GHG emissions from enteric CH_4 production and manure management are 28.6 and 13.7%, respectively. The majority of enteric CH_4 produced is estimated to be from beef cattle (71%), whereas dairy cattle contributed 26%; however, CH_4 production from dairy manure management is estimated to be the largest fraction of CH_4 produced from manure at 53%, followed by swine at 37%. The majority of these manure emissions are generated from the storage of liquid manures in anaerobic lagoons.

A large body of work exists related to estimation of enteric CH_4 production by cattle and potential mitigation strategies (e.g., Kebreab et al., 2008; Sejian et al., 2011; Powers et al., 2014); however, CH_4 production from manure storage is not well studied and there may be large discrepancies between inventory estimates and actual on-farm emissions. Some research indicates that the USEPA and Intergovernmental Panel on Climate Change methodologies may be underestimating CH_4 contributions from liquid dairy manure storage by up to 130% (Lory et al., 2010; Baldé et al., 2016). One of the reasons for these large discrepancies is that the emission factors developed for inventory purposes were based on limited data that may not represent the variety of manure storage conditions found on US dairies (Bryant et al., 1976; Morris 1976; Mangino et al., 2001).

Approximately 17 on-farm studies (21 lagoons) have been published related to CH_4 production from dairy liquid manure storage (Table 1). Only 8 of these studies were conducted on dairies located in the United States, and another 4 were on Canadian dairies, which could represent both weather characteristics and management practices in certain regions of US dairy production. Approximately half of the studies have provided an annual average CH_4 emission factor, whereas the remaining studies only looked at emissions during shorter intervals. The emission rates reported in the literature vary widely, with a range of 12 to 2,030 kg of CH_4/ha per day and 4.7 to 1,028 g/head per day. This range in values indicates the diversity of the different manure-management systems that can be found in dairy

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production and originates from factors such as fraction of manure stored as a liquid, effects of enhanced solid separation, length of storage, temperature, agitation, and crust formation. In addition, the influence of cattle diets, the addition of materials such as spilled feed, milk, and cleaning agents that are washed into storage areas, and the amount of inoculum remaining in storage may have an effect.

The goal of the current study was to add to the body of knowledge related to CH_4 emissions from storage of liquid manure on dairy production facilities in the western United States. In particular, we aimed to study seasonal trends in emissions, relate emissions measured on the farm with lagoon liquid characteristics, and compare these emissions with estimates derived with current inventory methodology.

MATERIALS AND METHODS

Farm Descriptions

During September 2010 to November 2015, 6 dairy lagoons were selected for monitoring of CH_4 emissions (Table 2). These farms were selected to represent manure-handling techniques typically found on a western US dairy and based on farm layout and the ability to separate the lagoon emissions from the rest of the farm. They were also situated in areas where no other upwind CH_4 sources could contribute to measured CH_4 concentrations. This enabled us to select lagoons that would not have any interference from internal or external CH_4 sources. In addition, farms were selected to represent a variety of sizes, ranging from less than 1,000 cows to greater than 5,000 cows. Five of the dairies were dry lot dairies where cows were housed in pens and the majority of manure was stored as a solid. In these systems, manure from the milking parlor and holding areas flowed into a lagoon system, which typically consisted of 1 or more settling basins to separate out some of the solids followed by a larger lagoon. These lagoons were typically pumped out in the spring and fall onto the surrounding cropland; however, the sludge remaining in the ponds was typically not removed. The settling basins were cleaned out on an infrequent basis, but in many cases they were not cleaned out more than once a year at the most. One dairy was a freestall dairy where the lactating cows were housed in naturally ventilated barns and the manure from the barns was cleaned out by flushing the alleyways behind the freestalls. The wash water from the milking parlor and holding area on this dairy also flowed into the lagoon system. The dairy manure-handling systems varied by farm and are described below.

- D1: A dry lot dairy with manure storage comprised of 3 settling basins and a main lagoon. The main lagoon was monitored.
- D2: A dry lot dairy with manure storage comprised of 4 settling basins and a main lagoon. The main lagoon was monitored.
- D3: A dry lot dairy that was recently converted to a heifer operation; however, during the last quarter of the study lactating animals were on the farm. The lagoon system consisted of 5 settling basins and a main lagoon. The main lagoon and settling basins were monitored.
- D4: A freestall dairy utilizing a flush system with the manure-storage system consisting of a screen separator, 3 settling basins, 3 main lagoons, and a satellite lagoon. The satellite lagoon was monitored.
- D5: A dry lot dairy composed of a concrete settling cell and 3 lagoons. The final lagoon in the series was monitored.
- D6: A dry lot dairy comprised of 1 settling basin and a main lagoon. The main lagoon and settling basin were monitored.

Methane Concentration and Wind Measurements

Initially, lagoons were monitored seasonally (D1 and D2), but as more resources became available monitoring times were increased to better capture annual variations in emissions (D3–D6). The concentration of CH_4 was measured using open-path Fourier transform infrared spectrometry (**OP/FTIR**; Griffiths et al., 2009; Shao et al., 2010). One OP/FTIR (Air Sentry, Cerex Monitoring Solutions, Atlanta, GA, or ABB-Bomem MB-100, MDA, Atlanta, GA) was located either across the downwind edge/corner (D1, D3, D4) or on the downwind bank (D2, D5, D6) of the lagoon, with a sensor height at 1.7 m and path lengths ranging from 130 to 240 m. On D3 and D6, the position of the OP/FTIR enabled monitoring of either the settling basins or the lagoons depending on wind direction. Spectra were acquired continuously and averaged over 5-min intervals. Background concentrations were measured at each dairy for several days at the onset of the study as well as at a remote (nonagricultural affected) location for comparison. Experiments performed with the OP/FTIR units demonstrated that background concentrations were very stable and did not fluctuate daily (CV = 4% over a 4-d period with 1,049 measurements and a change in background concentration of $\leq$0.3 ppm). In addition, the on-farm concentration data at each location was filtered for wind directions to isolate times when no upwind source of CH_4 was present to verify

Table 1. Summary of on-farm CH_4 emissions from dairy wastewater storage reported in the literature

Reference	Country	Method	Season	Type of storage	CH_4 (kg/ha per day)	CH_4 (g/head per day)
Safley and Westerman, 1992	United States	Floating cover	Annual	Slurry tank	970	
Husted, 1994	Denmark	Dynamic chamber	Annual	Slurry tank		42
Khan et al., 1997	New Zealand	Micrometeorological mass balance	Winter	Slurry pond	12–14	
Kaharabata and Schuepp, 1998	Canada	Tracer	Summer/fall	Slurry tank	2,030	833
Su et al., 2003	Taiwan	Mass balance	Annual	Covered basin		13
Craggs et al., 2008	New Zealand	Floating cover	Annual	Lagoon	170	42
Bjorneberg et al., 2009	United States	Inverse dispersion	Annual	Lagoon	23.7	325
Borhan et al., 2011a	United States	Flux chamber	Summer	Settling basin		14.2
			Summer	Primary lagoon		666
			Summer	Secondary lagoon		141
Borhan et al., 2011b	United States	Flux chamber	Summer	Settling basin		166
			Summer	Primary lagoon		85
			Winter	Settling basin		4.7
			Winter	Primary lagoon		31
			Winter	Secondary lagoon		10
Leytem et al., 2011	United States	Inverse dispersion	Annual	Lagoon	1,030	1,028
Todd et al., 2011	United States	Inverse dispersion	Summer	Lagoon	400	211
VanderZaag et al., 2011	Canada	Micrometeorological mass balance	Winter–summer	Slurry tank	43	19
Leytem et al., 2013	United States	Inverse dispersion	Annual	Lagoon	220	361
Minato et al., 2013	Japan	Floating chamber	Annual	Slurry tank	340–550	94–152
VanderZaag et al., 2014	Canada	Inverse dispersion	Spring/fall	Slurry tank	130–340	249–673
Grant et al., 2015	United States	Inverse dispersion	Fall/winter	Lagoon		12–295
Baldé et al., 2016	Canada	Inverse dispersion	Annual	Slurry tank	580–740	400–510

that background concentrations were consistent over time. Quantitative determinations of CH_4 concentrations were performed by partial least squares regression of the OP/FTIR spectra (Griffiths et al., 2009; Shao et al., 2011, 2013), and the detection limit of CH_4 was less than 0.01 ppm. Concentration data were processed to produce 15-min average mixing-ratio concentrations at the source areas ($\boldsymbol{C}$).

The wind environment at the dairy was described by simple Monin-Obukhov similarity theory relationships defined by u^*, L, z_0, and β, as provided by 3-dimensional sonic anemometers (RM Young Model 81000 ultrasonic anemometer, Traverse City, MI), where u^* is the friction velocity, L is the Obukhov stability length, z_0 is the surface roughness length, and β is wind direction. Flesch et al. (2004) details how these parameters were calculated from a sonic anemometer. The sonic anemometer was located on a 3-m tower at each lagoon, where there were minimal flow disturbances from structures upwind, to capture a more idealized wind flow of the area, as suggested by Flesch et al. (2005a). Wind parameters were calculated for each 15-min period (corresponding to C observations). A meteorological station was also located at each lagoon to record barometric pressure, air temperature, wind direction, and wind speed (all at 2 m) during the experimental period.

Emissions Calculations

We used WindTrax 2.0 software (Thunder Beach Scientific, Nanaimo, Canada) to determine lagoon emission rates, which combines the backward Lagrangian stochastic inverse-dispersion technique described by Flesch et al. (2004), with an interface allowing sources and sensors to be conveniently mapped. This technique has been used in several controlled-release studies to determine emissions from barn and lagoon source areas and was shown to provide estimates of emissions within 15% of actual emissions (McGinn et al., 2009; Gao et al., 2010; Ro et al., 2013). For a detailed description of the backward Lagrangian stochastic technique, see Flesch et al. (2005a,b, 2007). The lagoons and settling basins were mapped using available satellite imagery and on-farm global positioning system data. Emission estimates (kg/ha per day and kg/d) were calculated using n = 50,000 trajectories and fixed background concentrations. Emissions from the settling basins were determined using the method stated above; however, the lagoons at both dairies (D3 and D6) and the cattle housing at D6 were also included as source areas in the model and set at an average emission rate to account for any CH_4 contributions from those sources (Flesch et al., 2009). The lagoon emission rates were determined from the data generated during the same time periods, and the emission rates from the housing, which would be mainly enteric CH_4 production from the cattle, were calculated using the approach of Rotz and Chianese (2009) and set at 100 kg/d for the housing area.

As good emissions estimates are dependent on utilizing data that do not violate the Monin-Obukhov similarity theory assumptions (i.e., low winds, extreme stabilities, wind profile errors), data were filtered. We (1) removed periods where $u^* \leq 0.10$ m/s (low wind conditions), (2) removed periods where $|L| \leq 5$ m (strongly stable/unstable atmosphere;), and (3) removed periods where $z_0 \geq 1$ m (associated with errors in wind profile; Ro et al., 2013; Flesch et al., 2014).

Due to the location of the concentration sensors and other source areas on the site, for some wind directions, measurements of the downwind concentrations may not sample enough of the farm plume, which can lead to uncertainty in emission estimates (Flesch et al. 2005b). Additionally, cross contamination might occur due to emissions from other source areas on the farm. Therefore, we filtered out data when the wind was either not within $\pm 40^\circ$ perpendicular to the OP/FTIR path length or from areas where there could be other CH_4 sources (such as cattle pens, manure piles) to ensure that the concentration sensors were measuring gases from the source areas of interest only. The 15-min emission estimates were then averaged for each hour, with hourly values averaged over a day. Monthly averages

Table 2. Characteristics of the dairies used to determine on-farm lagoon methane emissions in south-central Idaho

Dairy	Housing	Size class of operation (no. of cattle)	Lagoon water source	Surface area (m^2)	Depth (m)	Monitoring periods (mo/d)
D1	Dry lot	1,000–5,000	Parlor wash water	26,628	2.4–2.7	9/10–6/11
D2	Dry lot	5,000–10,000	Parlor wash water	47,398	1.5	12/10–6/11
D3	Dry lot	1,000–5,000	Parlor wash water	19,621–23,237	1.2–1.9	6/12–5/13
D4	Freestall	5,000–10,000	Flush system from barn and parlor wash water	4,005–13,220	0.9–1.6	5/12–5/13
D5	Dry lot	1,000–5,000	Parlor wash water	1,300–3,373	0.3–1.3	7/13–11/14
D6	Dry lot	<1,000	Parlor wash water and runoff	2,101	0.3–0.9	11/14–11/15

were determined by averaging all available daily emission values collected during that month.

Lagoon Sampling and Analyses

An intensive lagoon sampling campaign was conducted simultaneously with the emissions monitoring to determine spatial and temporal changes in lagoon properties that could be associated with CH_4 emissions. Measurements included chemical oxygen demand (**COD**), TS, volatile solids (**VS**), pH, temperature, dissolved oxygen (**DO**), and specific conductivity. A detailed description of the study can be found in Leytem et al. (2017), a brief description follows.

Lagoons were sampled (500 mL) every 2 to 3 wk on a grid with the number of sampling points (4 to 10) related to the size of the lagoon and distributed as evenly as possible across the lagoon surface. Lagoon depth was determined with a sampling rod that was marked for depth. The rod was allowed to sit on the top of the sludge layer at the bottom of the lagoon to determine the depth of the water column. This rod was connected to a container with a retractable lid to collect samples at specific depths. When lagoons were deeper than 1 m (D1–D4), samples were collected from the surface (0.15 m below surface) and 0.3 m above the top of the sludge layer at each sampling location; otherwise only surface samples were collected.

Immediately after collection, a 125-mL subsample was taken and mixed with 1 mL of concentrated sulfuric acid to stabilize the sample for COD analysis. All samples were transferred to the laboratory in coolers, then stored under refrigeration at 5°C and processed within 36 h. In addition to collecting samples for analysis, the lagoon temperature, pH, DO, and specific conductivity were determined in situ with a YSI 556 Multiprobe System (YSI Inc., Yellow Springs, OH) at each sampling location and depth; these measurements were typically made in late morning or early afternoon. All samples were allowed to come to room temperature and thoroughly mixed before subsampling and analysis. Analyses were performed for TS and VS according to standard methods 2540B and 2540E, respectively (Eaton et al., 2005), and COD according to USEPA method 410.4 (USEPA, 1993). As we found no significant differences spatially or with depth at each lagoon (Leytem et al., 2017), the data were averaged (across location and depth) to produce 1 daily value. The coefficient of variation in COD at each sampling time ranged from 1 to 110, with 62% of values being less than 10% and only 1 value over 40%. The coefficient of variation of TS ranged from 1 to 46%, with 87% being less than 10%; for VS the coefficient of variation ranged from 1 to 49%, with 90% being less than 10%. The higher coefficient of variation values were association with time periods when the lagoons were being pumped out or agitated in some other way (filling, irrigation, and so on).

USEPA CH_4 Emissions Estimates

We calculated the USEPA estimated emissions for D6 based on the "Methodology for estimating CH_4 and N_2O emissions from manure management" (USEPA, 2016a) to determine how well on-farm measurements compared with calculated inventory estimates. This was done only for D6, as we had the most continuous emissions data from this dairy and we were able to obtain measurements from all of the stored liquid generated on the farm. The CH_4 generated each month was calculated as

$$CH_4 = VS \times B_o \times MCF \times 0.662 \times MDP, \quad [1]$$

where CH_4 is emissions in kilograms per month, VS is the amount of VS entering the lagoon each month (kg), B_o is the maximum CH_4-producing capacity of the manure (m^3 of CH_4/kg of VS), MCF is the methane conversion factor, 0.662 is the density of CH_4 at 25°C (kg of CH_4/m^3 of CH_4), and the MDP is the management and design practices factor (0.8). The estimated VS excreted for dairy cows in Idaho were obtained from Table A-206 (USEPA, 2016a; 2,902 kg/cow per year) and B_o for dairy cows was obtained from Table A-204 (USEPA, 2016a; 0.24 m^3 of CH_4/kg of VS). The MCF was calculated each month based on average ambient air temperature measured at the lagoon for the month with the equation:

$$MCF = \exp[E(T_2 - T_1)/RT_1T_2], \quad [2]$$

where E is the activation energy constant (15,175 cal/mol), T_2 is the average ambient air temperature (K) for the month, T_1 is 303.15 K, and R is the ideal gas constant (1.987 cal/K per mole). A minimum temperature of 5°C was used due to the biological activity in the lagoon which keeps the temperature above freezing.

The USEPA calculation assumes that lagoons are fully emptied in October of each year and start accumulating VS in November; thus, we started the calculation in November and ran it through the following November and compared this with on-farm data from December through November. The VS consumed during each month were subtracted from total available VS for the next month's calculation according to Mangino et al. (2001). We assumed that 10% of VS

generated by the lactating cattle on the farm went to the lagoon, based on estimates of Saggar et al. (2004), along with an estimate of the time that the cattle spent in the holding area and milking parlor each day. As the USEPA does not account for the use of settling basins, all the liquid was assumed to go into the lagoon for calculation purposes, and this was compared with the combined measured emissions from the settling basin and lagoon. We also calculated an annual CH_4 emission estimate based on equation 1 and using the values stated above with the exception of the MCF, which we obtained from Table A-210 (USEPA, 2016a) for an anaerobic lagoon in Idaho (69%).

Emissions Estimate Using Lory et al. (2010) Methodology

Lory et al. (2010) argued that the USEPA method would likely underestimate actual emissions from uncovered anaerobic dairy lagoons, particularly in colder climates. Those authors concluded that a large part of the discrepancy would be related to the B_o factor that had been derived from anaerobic digesters, which would not necessarily reflect the VS degradation found in uncovered anaerobic lagoons, coupled with a flawed MCF calculation. They instead proposed using a volatile solids degradation factor (**VSDF**) that was based on published research from uncovered anaerobic dairy lagoons coupled with a factor estimating the amount of CH_4 produced from the VS destroyed. We estimated CH_4 emissions from D6 based on this methodology as

$$CH_4 = VS \times VSDF \times B' \times 0.662, \quad [3]$$

where CH_4 is the emissions in kilograms per year, VS is the total volatile solids excreted going to the lagoon (kg), VSDF is the fraction of VS broken down in storage (kg of VS destroyed/kg of VS added; 0.57), B' is the volume of CH_4 generated on a VS destroyed basis for the lagoon (m^3 of CH_4/kg of VS destroyed; 0.45–0.85), and 0.662 is the density of CH_4 at 25°C (kg of CH_4/m^3 of CH_4). The estimated VS excreted for dairy cows in Idaho were obtained from Table A-206 (USEPA, 2016a), as described above (2,902 kg/cow per year), and we assumed 10% of excreted VS went to the lagoon system.

Statistical Analysis

Linear regression was performed with SAS (ver. 9.3; SAS Institute Inc., Cary, NC) to relate daily CH_4 emissions estimates to both meteorological parameters and lagoon physicochemical characteristics. As lagoon characteristics changed predictably and slowly over time (Leytem et al., 2017), daily lagoon physicochemical characteristics were calculated by linear interpolation between sampled days.

Mixed effects models were developed to predict CH_4 emissions (kg/ha per day) using independent variables describing lagoon and meteorological characteristics: lagoon-specific conductivity (mS/cm), VS (mg/L), TS (mg/L), COD (mg/L), lagoon pH, wind speed (m/s), and mean air temperature (°C). To avoid multicollinearity, 4 pools of independent variables were created for which the correlation of any pair of independent variables, within a pool, was smaller than 0.5. For each of the 4 pools, all possible models (i.e., models resulting from all combinations of independent variables) were fitted and the model with the smallest Akaike information criterion (**AIC**; Sakamoto et al., 1986) was selected. The final selected models (the best model from each pool) were subjected to a 10-fold cross validation for the determination of the mean square prediction error (**MSPE**) with independent data (Hastie et al., 2009). In short, the data were randomly divided into 10 folds of similar size. Ten training sets were created by leaving each 1 of the 10 folds out. The 10 testing sets were the folds that were left out of each of the 10 training sets. The following linear mixed effects model was used as the framework:

$$y_{ij} = \mathbf{x}_{ij}^T\boldsymbol{\beta} + \alpha_i + \varepsilon_{ij}, \quad [4]$$

where y_{ij} is the jth record ($j = 1, \ldots, m_i$) of CH_4 emissions in the ith dairy ($i = 1, \ldots, 6$), $\mathbf{x}_{ij}$ is the corresponding vector of independent variables to be selected, $\boldsymbol{\beta}$ is the vector of fixed regression coefficients, α_i is the random effect of the ith dairy [assumed $N(0,\tau)$], and ε_{ij} is the error [assumed $N(0,\sigma^2)$] with N denoting the normal distribution, τ and σ^2 variance components. Random effects were assumed to be mutually independent and independent of errors. All models were fitted with the lme4 package in the R statistical software (Bates et al., 2015). Predictions used to calculate the MSPE, in each fold of the 10-fold cross validation, were computed only with the fixed regression coefficients, that is,

$$\hat{\mathbf{y}}_\mathbf{f} = \mathbf{X}_\mathbf{f}\hat{\boldsymbol{\beta}}_{-\mathbf{f}},$$

where $\hat{\mathbf{y}}_\mathbf{f}$ is a vector of predictions in the fth fold, $\mathbf{X}_\mathbf{f}$ is corresponding matrix of independent variables in the fth fold and $\hat{\boldsymbol{\beta}}_{-\mathbf{f}}$ is the vector of regression coefficients estimated with a data set without the fth fold.

Table 3. Average wind speed, air temperature, and emission rates (±SD) from 6 lagoons located in south-central Idaho[1]

Dairy	Wind speed (m/s)	Air temperature (°C)	Number of 15-min data points[1]	Average CH_4 emissions (kg/ha per day)	Average CH_4 emissions (kg/d)
D1	4.3 ± 2.3	7.9 ± 13.9	346	36 ± 44	96 ± 118
D2	5.3 ± 1.4	14.2 ± 7.1	575	109 ± 31	517 ± 146
D3	4.0 ± 1.8	18.3 ± 7.4	1,060	30 ± 13	66 ± 28
D4	4.3 ± 2.4	16.0 ± 6.0	1,342	126 ± 62	160 ± 83
D5	4.3 ± 1.5	15.7 ± 7.9	4,382	68 ± 19	24 ± 7
D6	3.6 ± 2.0	14.5 ± 6.9	7,219	103 ± 51	22 ± 11

[1]The number of valid 15-min emissions values used to calculate the average emission rate for each lagoon.

RESULTS AND DISCUSSION

Average Lagoon Emissions and Temporal Variation in Emissions

The 6 lagoons ranged in size from 1,300 to 47,398 m^2, with depths ranging from 0.3 to 2.7 m (Table 2). The average wind speed ranged from 3.6 to 5.3 m/s, whereas the overall range in wind speed at the dairies was from 1.4 to 10.9 m/s (Table 3). Average ambient air temperatures ranged from 7.9 to 18.3°C, with an overall range of −1.4 to 31.5°C. The lagoons had a fairly wide range of physicochemical characteristics expected to drive CH_4 emissions, which are presented in Table 4. Average COD, TS, and VS ranged from 1,456 to 11,171, 3,400 to 11,892, and 1,581 to 6,224 mg/L, respectively. Average pH ranged from 7.7 to 8.3, whereas average lagoon temperatures ranged from 15 to 17°C. None of the lagoons had crust formation during any time of the year, whereas settling basins typically had a crust over the surface.

Figures 1 and 2 present the CH_4 emissions and ambient air temperature over time for each lagoon. In general, emissions from lagoons D1 to D4 had greater emissions during summer months when temperatures were greater. This overall trend has been documented in the literature (Borhan et al., 2011b; Minato et al., 2013; Baldé et al., 2016); however, there were time periods, particularly at D5 and D6, when we saw large emissions spikes at times of the year when temperatures were cooler (early spring and late fall to winter). At D5, we saw spikes at or around d 118, 305, and 354. On d 118, we noted a very strong wind event with an average wind speed of 8.3 m/s; these high winds tend to agitate the lagoons similar to a pumping or rainfall event and, therefore, could cause an enhanced release of CH_4. We also saw this same effect on D4 at d 94, when a spike in emissions was noted on a day with a very high wind event (11.1 m/s). Around d 305 at D5, the lagoon was being pumped out, which not only causes agitation of the lagoon waters but also exposes the sludge at the bottom of the lagoon that could enhance transfer of CH_4 to the atmosphere. Days 352 to 354 at D5 had very cold temperatures, and the surface of the lagoon was freezing and thawing; we suspect that this freeze/thaw action also enhanced the release of built up CH_4 (trapped under the ice sheets) to the atmosphere when the surface would thaw.

At D6, we noted spikes in emissions during the spring peaking on d 104 as well as spikes in the fall and winter centered on d 304 and 345. In the spring at D6, several factors that, when combined, likely caused high emission rates. We observed a large number of windy days between d 77 and 105, with several days of wind speeds that were above 5 m/s. In addition, some rain fell during this time period, which would cause perturbation of the lagoon surface. In addition, during this time period we found a 60% increase in COD (compared with previous sampling date) with a concomitant 56% decrease in DO (Figure 3). These changes in chemical characteristics of the lagoon suggest that not only was there greater substrate present, but there were greater reducing conditions as well, which combined would enhance

Table 4. Average concentrations (±SD) of lagoon characteristics measured over time at 6 dairies monitored for methane in southern Idaho[1]

Dairy	COD (mg/L)	TS (mg/L)	VS (mg/L)	pH	Temp (°C)
D1	3,868 ± 745	5,410 ± 529	2,648 ± 299	7.7 ± 0.3	16 ± 2
D2	6,057 ± 1,111	8,941 ± 1,063	4,419 ± 522	7.9 ± 0.1	16 ± 2
D3	1,456 ± 411	3,400 ± 429	1,581 ± 468	8.2 ± 0.2	15 ± 5
D4	11,171 ± 1,124	11,892 ± 1,223	6,224 ± 767	7.9 ± 0.2	17 ± 3
D5	4,711 ± 1,353	8,756 ± 2,843	3,349 ± 720	8.3 ± 0.3	16 ± 4
D6	5,758 ± 910	9,855 ± 1,964	4,050 ± 680	8.2 ± 0.4	15 ± 4

[1]COD = chemical oxygen demand; VS = volatile solids; Temp = lagoon water temperature.

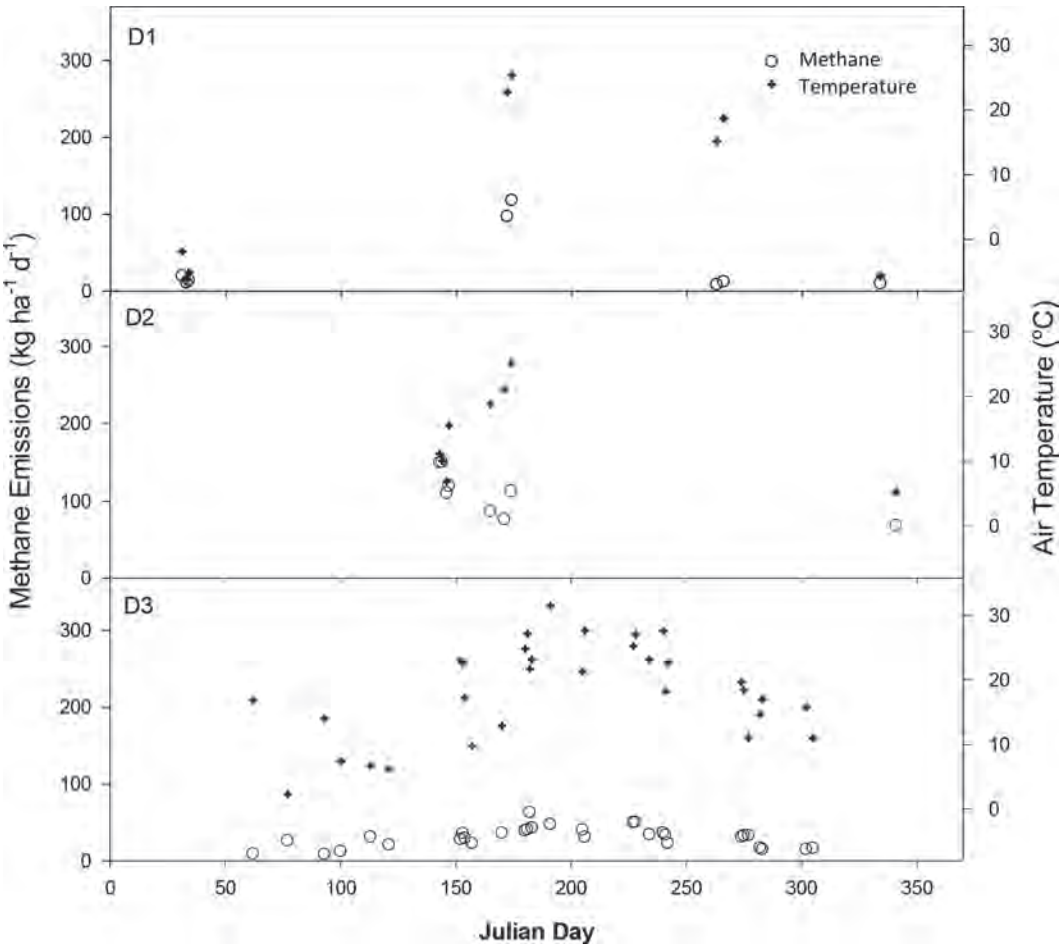

Figure 1. Measured on-farm methane emissions and air temperature over time from farms D1 to D3 located in south-central Idaho.

CH_4 production. Later in the year, the D6 lagoon was being pumped out around d 304 and 345 along with some freezing and thawing of the lagoon surface around d 345. We suspect that these factors are responsible for the spikes that were seen in emissions during these time periods.

Methane fluxes were strongly influenced by short-term events, similar to those which have been noted previously in the literature (Husted, 1994; Kaharabata and Schuepp, 1998; VanderZaag et al., 2009). VanderZaag et al. (2010b) reported that CH_4 flux trends from dairy slurry in tanks consisted of 2 main components: baseline fluxes due to diffusion and intermittent bursts due to bubble flux (ebullition). Therefore, events that either promote or interfere with these processes are likely to affect emission rates. Agitation of slurry tanks, with and without crusts or covers, has been shown to generate spikes in CH_4 emissions, caused by the enhanced diffusion of CH_4 and the release of trapped CH_4 bubbles (Kaharabata and Schuepp, 1998; VanderZaag et al., 2014; Baldé et al., 2016). Rainfall events have also been shown to generate spikes in CH_4 emissions due to surface disturbances (VanderZaag et al., 2010a; Minato et al., 2013; Baldé et al., 2016). In fact, Kaharabata and Schuepp (1998) reported that two-thirds of rainy days showed concentration increases by factors of 1.2 to 4 during the sampling interval compared with the surrounding days. Those authors surmised that the mechanical agitation of the slurry surface increased the exchange of CH_4 through increased liquid surface area via the creation of ripples and through the augmentation of the ebullition process. Ice formation occurring at the surface of a lagoon or slurry tank can inhibit loss of CH_4 via diffusion or ebullition, and upon thawing this trapped gas can be released, causing increased trends in emissions (VanderZaag et al., 2010b, 2011). VanderZaag et al. (2011) reported that spring thaw of a dairy slurry tank coincided with the highest CH_4 flux measured during the entire study. A second spring thaw coincided with the second highest CH_4 flux rate, sug-

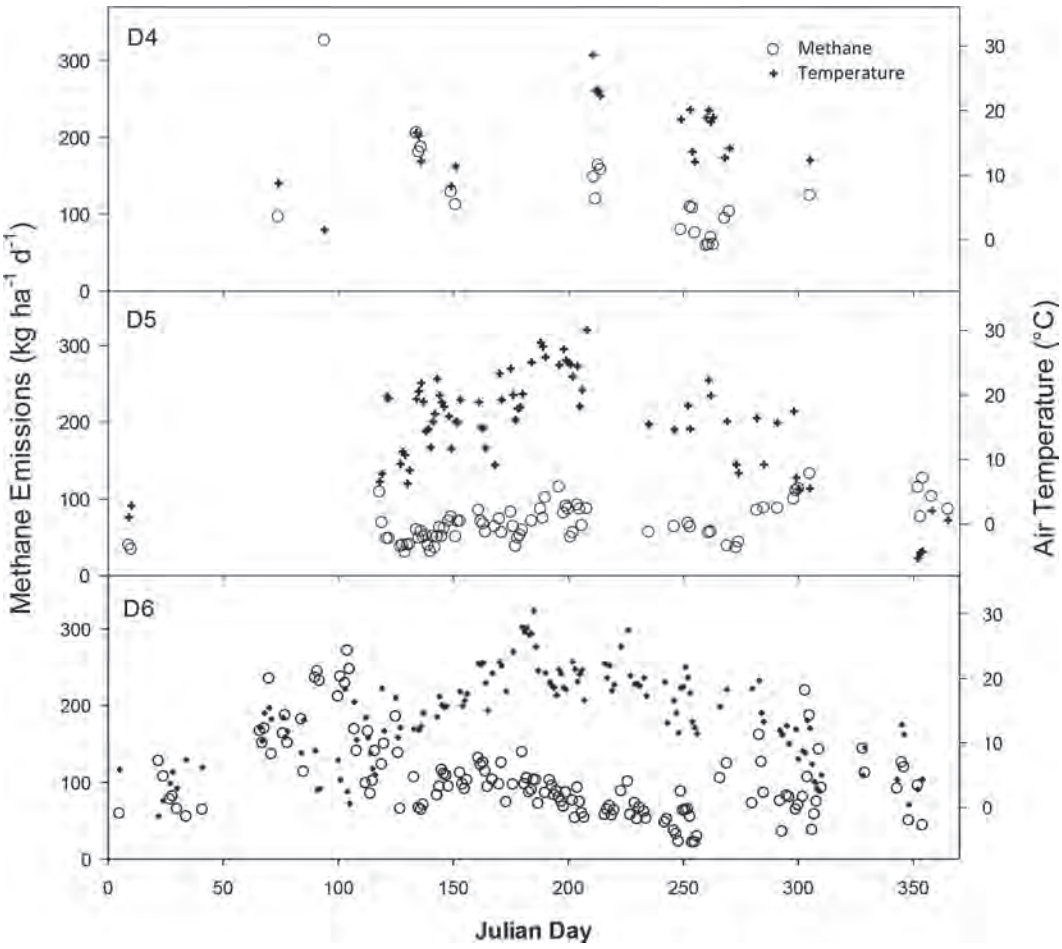

Figure 2. Measured on-farm methane emissions and air temperature over time from farms D4 to D6 located in south-central Idaho.

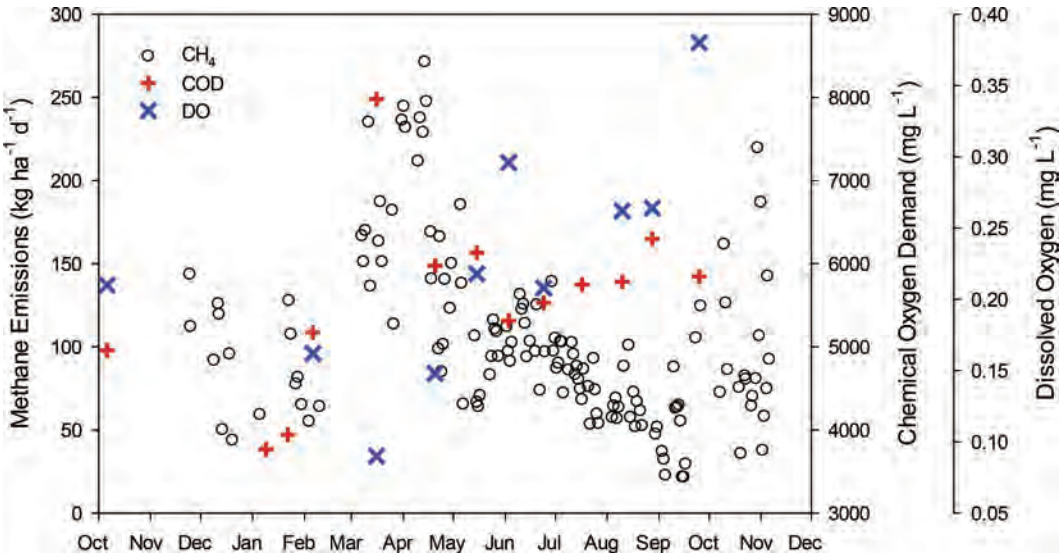

Figure 3. Methane emissions and lagoon characteristics (D6) measured over time at a dairy lagoon in south-central Idaho. Color version available online.

gesting that the quantity of dissolved CH_4 and bubbles were decreasing with each thaw. Following these flux events, CH_4 emissions tended to decrease significantly until more CH_4 built up in the system. Grant et al. (2015) reported a positive relationship between wind speed and CH_4 flux at dairy lagoons during certain times of the year. It is thought that wind shear at the surface promotes the emission of CH_4 through turbulent diffusion of the gases released from solution at the surface (Ro and Hunt, 2006).

We binned the hourly data together by season; an example is seen in Figure 4 for D6, to look for diel patterns in emissions. The daily variability in emissions was larger than diel trends in emissions. This is contrary to the diel trend found by Todd et al. (2011), who reported a spike in CH_4 flux early in the morning each day, corresponding to the formation and dissipation of a bubble scum on the surface of the lagoon. However, the Todd et al. (2011) study was only conducted for 7 d in the summer and, therefore, less daily variation was captured in that study compared with the present study. Baldé et al. (2016) also reported the same increases in CH_4 flux from a dairy slurry tank in the early morning during July and August. Although, in the present study, the variability in emissions each hour is quite large, in the spring and summer there appeared to be a peak in emissions in the early morning at D2 to D6 (not all data shown); in some cases this was followed by a second peak later in the day as temperatures increased.

As the variation in emissions over a 24-h period appeared to be less than the daily variation in emissions, annual emissions were calculated by averaging all of the available data from each lagoon. The number of 15-min data points that went into each average ranged from 346 to 7,219 (Table 3). When compared on an area basis, average CH_4 emissions ranged from 30 to 126 kg/ha per day. The greatest emissions were from D4, which was expected, as this lagoon system received all of the manure solids from the lactating herd and had the highest COD, TS, and VS concentrations. The lowest average emissions were from D3, which received very few inputs into the system as the dairy switched from a lactating to a heifer operation. However, even with little added manure, this lagoon still produced significant quantities of CH_4, which was similar to one of the active dairies. The areal emissions in our study fall within the range reported in the literature (Table 1). On a daily basis, CH_4 production ranged from 22 to 517 kg/d, with the greatest emissions from D2. As the lagoons monitored did not capture emissions from the entire liquid storage, in many cases it is not possible to make meaningful comparisons of daily emissions between the different manure storage systems.

Correlation of CH_4 with Meteorological Conditions and Lagoon Characteristics

Linear regression revealed very weak trends between CH_4 emissions and meteorological conditions (Figure 5). We observed little relationship between CH_4 emissions and ambient air temperature ($R^2 = 0.02$; $P = 0.02$). This demonstrates that, although temperature certainly drives the chemical and biological activity that generates CH_4, other conditions can have a large effect on these emissions, such as agitation of the surface, pumping, and freezing and thawing. We found a strong relationship between wind speed and CH_4 emissions ($R^2 = 0.13$, $P < 0.001$). The effect of high wind events on mixing of the lagoons and agitation of lagoon surfaces seemed to drive high flux events in addition to enhancing CH_4 transport. No significant relationship was ob-

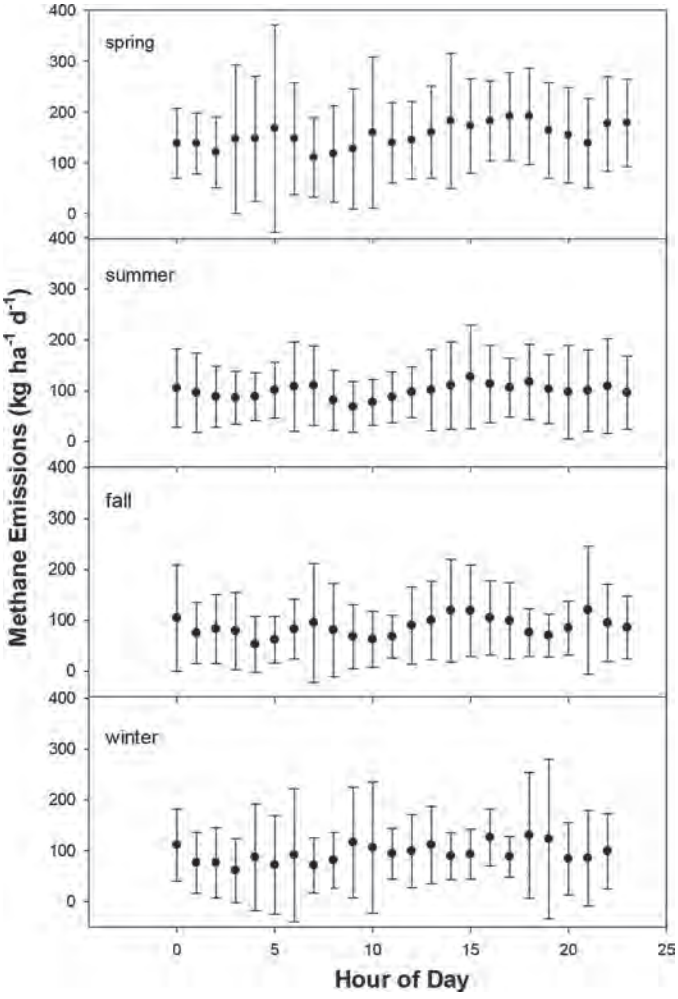

Figure 4. Hourly emissions of methane binned over each season (spring, summer, fall, winter) at a dairy lagoon (D6) in south-central Idaho. Error bars represent the SD of the mean hourly average over the season.

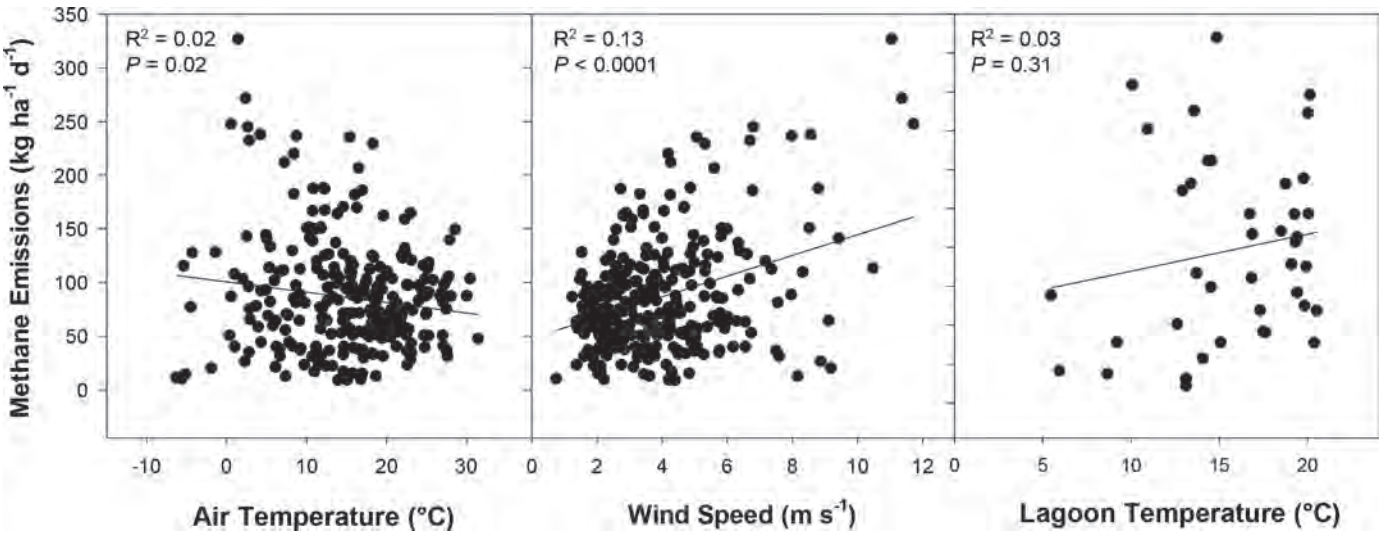

Figure 5. Linear regression of average daily emissions measured at dairy lagoons in south-central Idaho with meteorological conditions.

served between lagoon temperature and emissions ($R^2 = 0.03$, $P = 0.31$). Safley and Westerman (1992) also found weak relationships between CH_4 generation and temperature in a dairy lagoon, and in fact reported a negative relationship between sludge temperature and CH_4 concentration.

Because of large range in the physicochemical properties of the lagoons in our study, the effects of temperature were likely confounded by other lagoon characteristics as well as other events that affected CH_4 emissions. The relationships between lagoon physicochemical properties and CH_4 emissions were much stronger than those with meteorological conditions (Figure 6). Methane emissions were positively related to TS, COD, and VS, with R^2 ranging from 0.47 to 0.52 ($P < 0.0001$) and COD having the highest R^2 value. This suggests that, overall, lagoon properties may be a larger factor in determining emissions than temperature.

One additional factor that could be affecting emissions on these dairies is the presence of purple sulfur bacteria (**PSB**) and other microorganisms in the lagoons. All but D2 and D4 had a strong pink coloration of the lagoon, indicating the presence of PSB, which is common for lagoons in this region (Dungan and Leytem, 2015). The proliferation of the PSB tend to increase with temperature; therefore, the ponds tend to

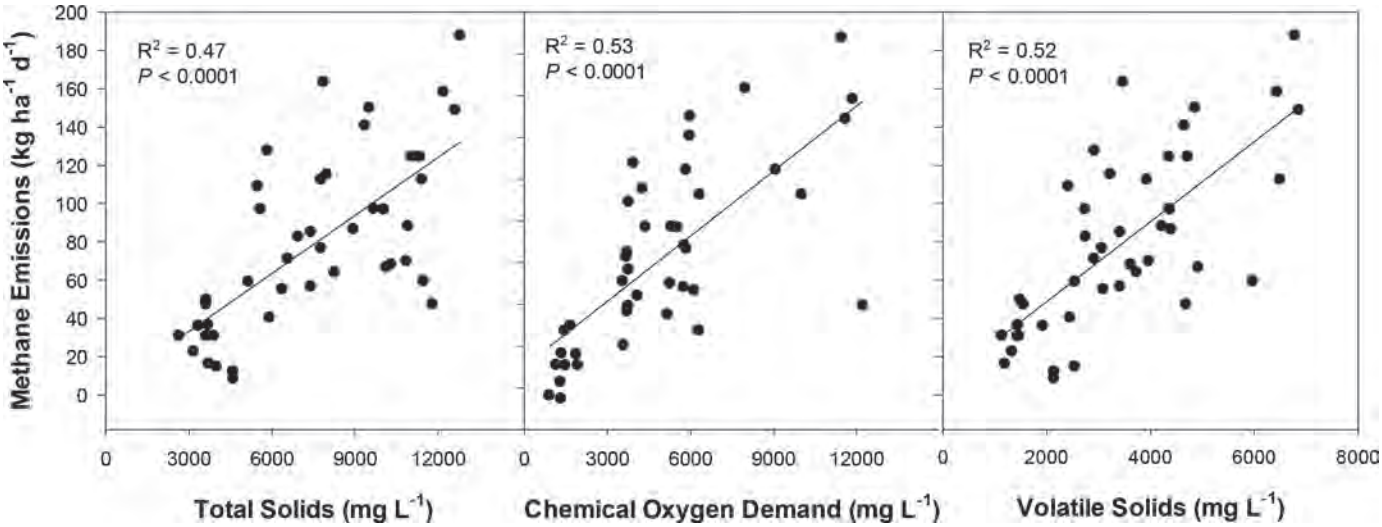

Figure 6. Linear regression of average daily emissions measured at dairy lagoons in south-central Idaho with lagoon physicochemical characteristics.

not express signs of the presence of PSB in early spring and winter but will become a pink/purple color starting in late April to early May and reach peak color by July. Holm and Vennes (1970) also found that PSB in sewage treatment lagoons reached maximal concentrations in the warmest part of the summer, with laboratory studies indicating that the bacteria grew over the temperature range of 16 to 30°C, with optimal temperature at 25 to 30°C. As CH_4 is a good electron donor, some sulfate-reducing bacteria may play a role in the anaerobic oxidation of CH_4 (Barton and Fauque, 2009) via the following reaction:

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O. \quad [5]$$

Barton and Fauque (2009) also noted that the biological oxygen demand in a wastewater lagoon decreased with PSB growth. It is possible that, as lagoon temperature increases in the summer and PSB populations increase, they oxidize some CH_4 in the lagoons; therefore, the peak emissions expected during high temperatures in the summer could be counteracted by the utilization of CH_4 by the PSB population. The presence of purple nonsulfur bacteria has also been detected in swine lagoons (Okubo et al., 2006); purple nonsulfur bacteria also have the capacity to reduce CH_4 emissions (Nunkaew et al., 2015). More research would need to be done to test this hypothesis.

Predicting CH_4 Based on Meteorological Conditions and Lagoon Properties

As it may be difficult to determine actual VS loading rates at any given lagoon and several meteorological and management factors appear to be driving emissions, we wanted to determine if there was a way to estimate emissions from these lagoons using simple characteristics that would either be publically available (meteorological) or could be easily measured. Whereas we fully understand that the lagoon samples themselves do not measure the total amount of COD, TS, and VS in the lagoon system, we wanted to test if they could be used as a proxy for estimating the CH_4 emissions from the lagoons. Therefore, we tested models that included ambient air temperature, wind speed, lagoon specific conductivity, VS, TS, COD, and pH to determine if we could estimate lagoon CH_4 emissions.

The selected models (i.e., the models with smallest AIC in each 1 of the 4 pools of independent variables) are presented in Table 5. The square root of the MSPE for each model, determined through a 10-fold cross validation, are also presented in Table 5. The model with the smallest prediction error (Model 2) included VS, wind speed, mean air temperature, and pH as independent variables. The model with the second smallest prediction error (Model 3) included TS instead of VS as an independent variable. A third model (Model 4) with similar prediction error had COD, wind speed, mean air temperature, and pH as independent variables (Table 5). Model 4 had the smallest AIC, although the AIC of the 3 previously described models were very similar (Table 5). These results suggest that lagoon TS, VS, COD, and pH, as well as mean air temperature and wind speed, may be useful for estimating lagoon CH_4 emissions.

The prediction errors were substantially large when compared with the mean of the CH_4 emissions. In particular, the square root of the MSPE ranged from 48.7 to 58.4% of the observed CH_4 emission mean. Diagnostic plots (Figure A1) suggested considerable variation in the predictions, especially in predictions of high CH_4 emission rates. In particular, analysis of residuals suggested large variation in predictions and possible heterogeneity in the data (i.e., a variance that increases with the predicted values). Therefore, the same models described in the previous section were fitted with CH_4 emissions transformed with a natural logarithm operation (Kutner at al., 2004). In essence, the dependent variable is now $y' = \log(y)$, and the model selection, fitting, and cross-validation procedures were reconducted with CH_4 in the natural logarithmic scale. The fitted models, with associated AIC and MSPE are presented in Table 5. The selection of variables was unchanged and the ranking of models, based on both AIC and prediction error, were also the same as when using CH_4 in the original scale (i.e., in kg/ha per day). Model 2 had the smallest prediction error and had lagoon VS, pH, mean air temperature, and wind speed as independent variables. The prediction error, obtained through cross validation, ranged from 9.66 to 13.1% of the mean of the calculated natural logarithm of CH_4 emissions. Analysis of residuals suggested a better ability of the model in describing the data when compared with the models fitted in the original scale, especially for predictions of large CH_4 emissions (Figure A2). The predicted versus on-farm measurements using model 2 (Table 5) are presented in Figure 7. Even given the large range in weather conditions and lagoon characteristics, the model did a good job of predicting emissions across farms; however, these equations may only be useful for farms in this region.

CH_4 Emissions from the Settling Basins

The emissions from the settling basins on 2 dairies (D3, D6) were also estimated to determine the con-

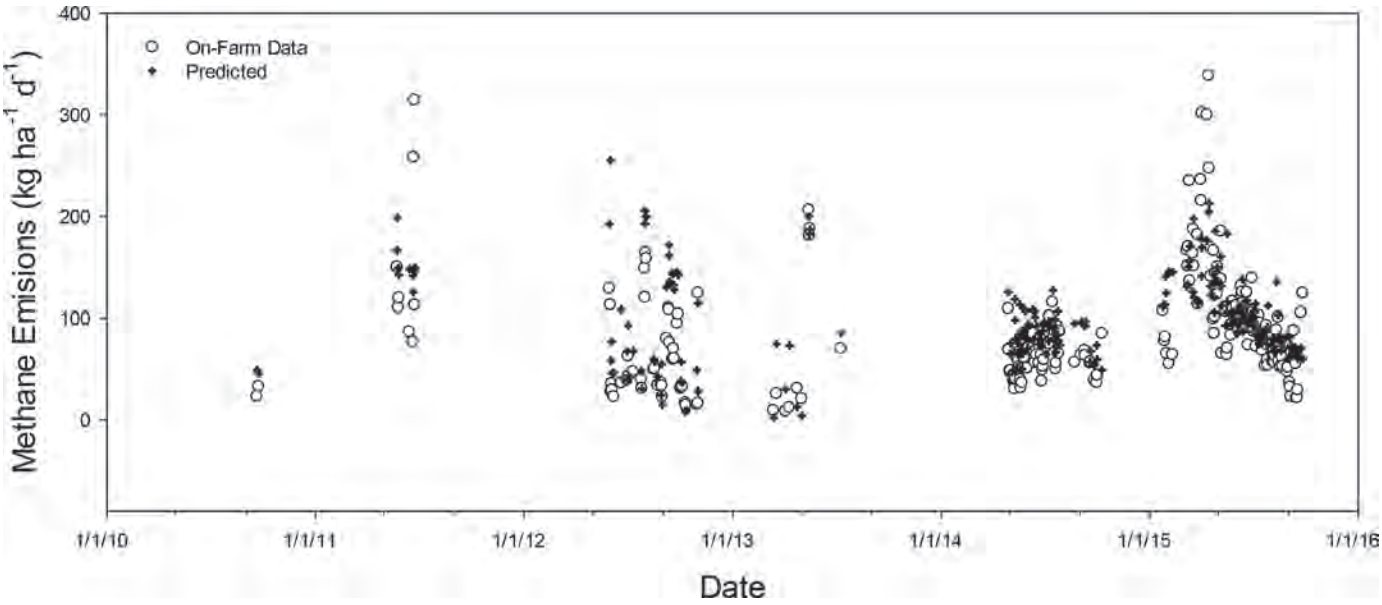

Figure 7. On-farm methane emissions for all lagoons monitored in the study compared with estimated emissions predicted using model 2 (Table 5).

tribution of these basins to the overall lagoon system emissions. These dairies had either one (D6) or a series of settling basins (D3) in addition to a primary lagoon, which allowed us to examine the relative contribution of the settling basins to the overall liquid-storage system (Figure 8). We did not expect to observe high levels of CH_4 emissions from the settling basins, as they are smaller than the lagoons and tend to be covered by a thick crust, which has been shown to inhibit CH_4 emissions (Husted, 1994; Sommer et al., 2000). At D3 the proportion of total CH_4 emissions originating from the settling basin ranged from 0.34 to 0.71 with an average of 0.52, whereas at D6 the proportion ranged from 0.13 to 0.65 with an average of 0.44. The CH_4 emissions from the settling basins seemed to be more affected by air temperature than the lagoons, and we noted a strong relationship between fraction of CH_4 generated from the settling basins versus ambient air temperature ($R^2 = 0.40$; Figure A3). This sensitivity to temperature is likely due to the smaller size of the basins, which

Table 5. Methane prediction models and associated Akaike information criteria (AIC) and square root of the mean square prediction error (RMSPE) obtained through cross validation[1]

Model[2]	Prediction equation[3]	AIC	RMSPE[4] (kg/ha per day)	RMSPE[4] (% of mean)
Original scale				
1	$CH_4 = 479.3 + 14.5 \times Wind + 1.78 \times Tm - 57.2 \times pH$	2,361	50.7	58.4
2	$CH_4 = 556.6 + 0.023 \times VS + 13.6 \times Wind + 1.31 \times Tm - 76.1 \times pH$	2,354	42.3	48.7
3	$CH_4 = 593.4 + 0.006 \times TS + 14.6 \times Wind + 1.48 \times Tm - 77.2 \times pH$	2,360	43.5	50.1
4	$CH_4 = 365.5 + 0.014 \times COD + 13.8 \times Wind + 1.51 \times Tm - 51.7 \times pH$	2,349	45.3	52.2
Log scale				
1	$\log(CH_4) = 9.19 + 0.138 \times Wind + 0.034 \times Tm - 0.743 \times pH$	206.3	0.56	13.1
2	$\log(CH_4) = 10.1 + 0.0003 \times VS + 0.128 \times Wind + 0.029 \times Tm - 0.966 \times pH$	193.2	0.41	9.66
3	$\log(CH_4) = 10.8 + 0.0001 \times TS + 0.139 \times Wind + 0.031 \times Tm - 1.031 \times pH$	203.9	0.42	9.74
4	$\log(CH_4) = 8.51 + 0.0001 \times COD + 0.134 \times Wind + 0.033 \times Tm - 0.719 \times pH$	200.8	0.46	10.7

[1]Emissions are either expressed in kg/ha per day or in a natural logarithm scale.

[2]Models 1, 2, 3, and 4 are the models with smallest AIC in pools of independent variables 1, 2, 3, and 4.

[3]Wind is the wind speed (m/s), Tm is the mean air temperature (°C), VS is the volatile solids (mg/L), TS is the total solids (mg/L), COD is the chemical oxygen demand (mg/L), TKN is the total Kjeldahl nitrogen (mg/L), and the TAN is the total ammonia nitrogen (mg/L).

[4]With a 10-fold cross-validation and using only fixed regression coefficients.

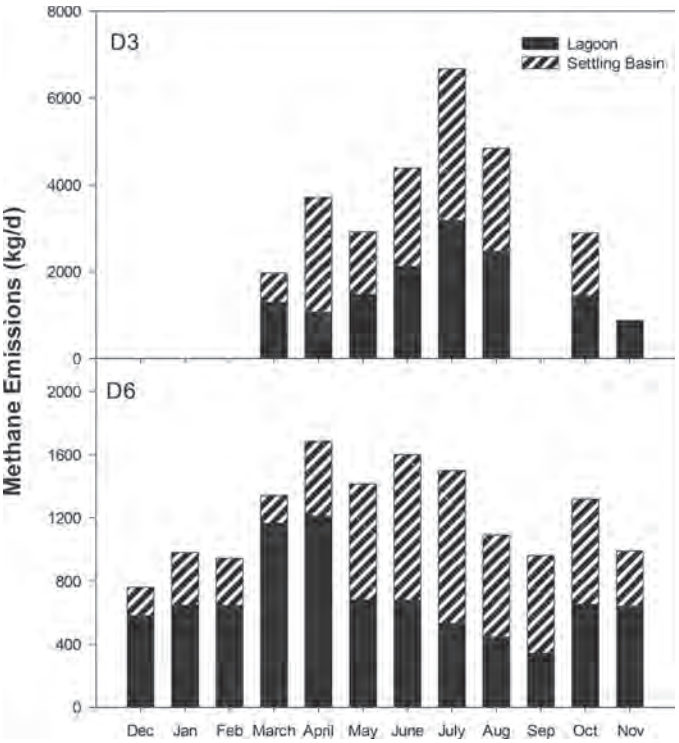

Figure 8. Emissions of methane from the primary lagoons and settling basins of 2 dairies (D3, D6) in south-central Idaho.

could inhibit their ability to buffer against temperature changes as well as the crusting. As temperatures increase and the crusts dry out, the crust permeability likely increased along with crust porosity, which could reduce the effectiveness of the crusts to inhibit CH_4 emissions during warmer temperatures (Husted, 1994). Borhan et al. (2011b) also found that the settling basin of a dairy was producing nearly twice as much CH_4 as the primary lagoon in the summer, yet in the winter the primary lagoon was producing 6.5 times as much CH_4 as the settling basin.

On-Farm Versus Predicted Emissions

We estimated the monthly and annual emissions from the lagoon system at D6 using the USEPA inventory methodology to see how closely they compared (Figure 9). The cumulative emissions estimated with the USEPA inventory method were 48% lower than the actual measured on-farm emissions (combining the lagoon and settling basin emissions). Baldé et al. (2016) reported that the USEPA estimate for a dairy slurry tank was 48 to 59% lower than measured emissions. As seen in Figure 9, the inventory model appears to be highly dependent on temperature (Figure 9b), with a large peak in July and low emissions in late fall through spring. The emissions from the settling basin tended to follow this trend with temperature, although the model underestimated CH_4 emissions in late fall. This trend of higher fall emissions has also been reported by VanderZaag et al. (2009). In contrast, the emissions from the primary lagoon were much higher throughout the late fall through spring, with peak emissions in the spring. This led to total CH_4 emissions (lagoon + settling basins) that were greater than estimated with the USEPA model for all but 2 mo (July and August).

Several factors could account for these large discrepancies between estimated and measured emissions. The inventory method assumes a complete cleanout of the lagoon systems in October; however, the water in lagoon D6 (and all of the lagoons studied) was regularly pumped out in late fall and spring, but the sludge at the bottom was not removed. In addition, the settling basins may be cleaned out very infrequently, with the settling basin at D6 not having been cleaned out during the 2-yr period that we worked at this dairy. Therefore, there is likely unaccounted VS remaining in the system available for breakdown over time as well as serving as a constant inoculum, which maintains high levels of CH_4 generation even after the lagoons are pumped out. A lag phase in CH_4 emissions of up to 50 d has been noted in the literature when manure is stored in clean tanks, after which CH_4 emissions increase exponentially (VanderZaag et al., 2010a).

The B_o values used in the USEPA emissions estimates were derived from research on the biological activity of CH_4 digesters (Bryant et al., 1976; Morris, 1976; Hashimoto et al., 1981; Hashimoto, 1983), which may not represent the lagoons monitored in our study. The broader microbial community, longer residence times, and lower loading rates of uncovered anaerobic lagoons may lead to higher VS degradation rates than those found in anaerobic digesters (Lory et al., 2010). The B_o value only estimates the CH_4 production based on VS added, it does not estimate the total amount of VS that can be degraded in a digester or lagoon. According to a review of the literature, Lory et al. (2010) surmised that a properly operating uncovered anaerobic lagoon can break down solids to a higher degree than is predicted using anaerobic digester models. Therefore, B_o may underestimate the potential amount of CH_4 generated from these lagoons and thus underestimate overall CH_4 emissions.

We estimated the annual CH_4 emissions from the lagoon at D6 using the methodology of Lory et al. (2010) to see how closely they compared (Table 6). This method uses a VSDF to estimate the potential VS degradation from uncovered anaerobic dairy lagoons coupled with the amount of CH_4 generated from the destruction of these VS (B') to estimate an annual CH_4 emission

factor. The value of VSDF (0.57) was calculated as an average of reported literature values, whereas a range of B′ (0.45–0.85) was used because of uncertainty in the correct estimate of this parameter. Utilizing this equation, the range in estimated emissions at D6 was 10,495 to 19,824 kg of CH_4/yr, which encompassed the value measured on the farm (14,594 kg of CH_4/yr). Using the on-farm measured CH_4 emissions, we calculated a value of 0.63 for B′.

As we were only able to make this comparison on 1 dairy lagoon, we used the data of Baldé et al. (2016), who monitored annual emissions from a dairy slurry tank to calculate the annual emissions using the Lory et al. (2010) methodology. In this comparison, we used the reported annual VS loading rate of 294,000 kg/yr and the VSDF and B′ values stated above. This estimate provided a range in emissions of 49,922 to 94,297 kg of CH_4/yr, whereas the measured on-farm emissions were 42,000 kg of CH_4/yr (Table 6). The estimates generated from the Lory et al. (2010) methodology were much closer than that estimated using the USEPA methodology (17,000 kg of CH_4/yr). Baldé et al. (2016) reported emissions from a slurry tank that, due to the frequency of cleanouts, may operate more like a batch reactor than a typical anaerobic lagoon where the sludge is rarely removed from the system. Therefore, we might expect less CH_4 produced from these systems than from an anaerobic lagoon system and perhaps perform more like an anaerobic digester. We repeated the calculation above, but used the VSDF factor for anaerobic digesters (0.42) reported by Lory et al. (2010). This provided an estimate of 36,784 to 69,482 kg of CH_4/yr, encompassing the on-farm measured value. Using this value for VSDF (0.42) we calculated a B′ value of 0.51 for this slurry tank. Craggs et al. (2008) also reported a VS removal rate of 59% from an anaerobic dairy lagoon in

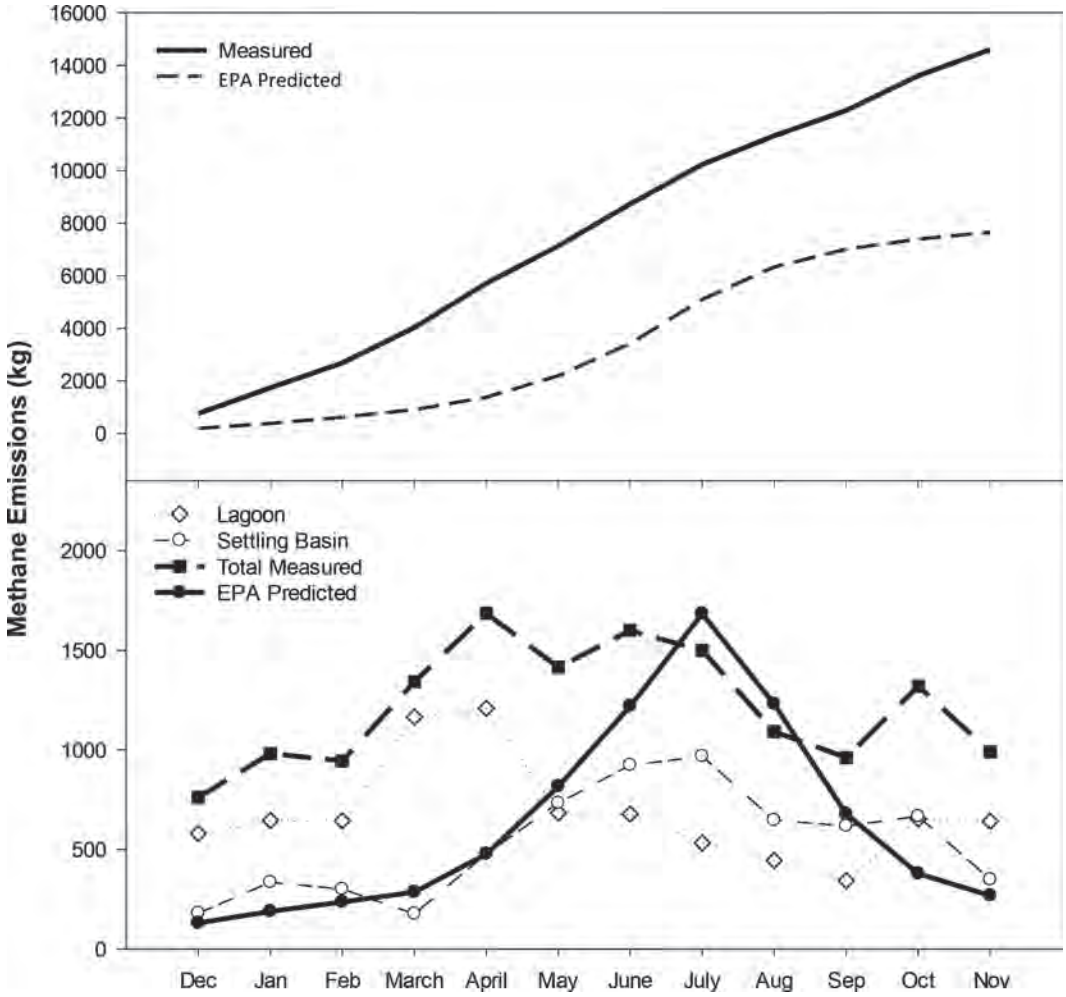

Figure 9. Cumulative on-farm emissions of methane from a dairy lagoon in south-central Idaho (D6) and emissions estimates calculated using the US Environmental Protection Agency (EPA) methodology (USEPA, 2016a) for estimating methane emissions from manure storage.

Table 6. On-farm and estimated methane (CH_4) emissions calculated for lagoon D6 and data from Baldé et al. (2016) using the USEPA methodology and the methodology proposed by Lory et al. (2010)

Data set	Methodology	VSDF[1]	B′[2]	Annual CH_4 emissions (kg of CH_4/yr)
Present study	On-farm measurement			14,594
	USEPA – monthly[3]			8,187
	USEPA – annual[4]			6,776
	Lory et al. (2010)	0.57	0.45	10,495
	Lory et al. (2010)	0.57	0.85	19,824
Baldé et al., 2016	On-farm measurement			42,000
	USEPA – monthly			17,000
	Lory et al. (2010)	0.57	0.45	49,922
	Lory et al. (2010)	0.57	0.85	94,297
	Lory et al. (2010)	0.42	0.45	36,784
	Lory et al. (2010)	0.42	0.85	69,482

[1]VSDF = volatile solids destroyed during storage, based on literature value of 0.57 for uncovered anaerobic lagoons and 0.42 for anaerobic digesters.

[2]B′ = conversion of destroyed volatile solids to methane, with values ranging from 0.45 to 0.85.

[3]Emissions calculated using a monthly time step, with monthly average air temperature accounting for volatile solids added and destroyed each month.

[4]Emissiosn calculated using the annual volatile solids produced and an annual reported methane conversion factor.

New Zealand and a biogas production rate of 0.44 (m^3/kg of VS removed), which is very similar to those estimated by Lory et al. (2010) and determined with the present data. Although these are only 2 comparisons, it appears that the methodology proposed by Lory et al. (2010) may provide better estimates of CH_4 emissions from stored dairy liquid than the current USEPA inventory methods, at least in regions with colder climates.

CONCLUSIONS

Average CH_4 emissions measured from lagoons in southern Idaho ranged from 30 to 126 kg/ha per d (22–517 kg/d). The factors having the greatest effects on emissions were lagoon physicochemical characteristics, such as VS, pH, and COD, along with events such as pumping, rainfall, high winds, and freezing and thawing, which affected both the rates of diffusion as well as ebullition of CH_4 from the lagoons. It was demonstrated that CH_4 emissions from these lagoons could be predicted using easily obtained weather data (temperature, wind speed) along with easily determined lagoon characteristics (VS and pH), which could enable producers in the region to estimate CH_4 emissions from their lagoons. Settling basins, which are commonly used in dairy manure management systems, may produce 50% of the total lagoon system CH_4 emissions and should be accounted for in overall CH_4 emissions estimates. The USEPA methodology for estimating CH_4 emissions from manure storage underestimated on-farm emissions by 48%. We believe that this is likely due to an underestimation of VS destruction in uncovered anaerobic lagoons. The pattern of seasonal variation in emissions also differed significantly from that estimated with the USEPA methodology; in particular, spring and fall emissions were underestimated with the USEPA method. This seasonality in emissions also underlines the importance of obtaining yearlong data to determine annual emissions estimates and for comparison with inventory methods, as there were times where the USEPA methodology both over- and underestimated emissions. Alternatively, the proposed estimation methodology of Lory et al. (2010) provided a better estimate of on-farm emissions. More work with this alternative methodology should be performed to determine its applicability across a larger range of dairy liquid-storage systems.

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REFERENCES

Baldé, H., A. C. Vander Zaag, S. Burtt, L. Evans, C. Wagner-Riddle, R. L. Desjardins, and J. D. MacDonald. 2016. Measured versus modeled methane emissions from separated liquid dairy manure show large model underestimates. Agric. Ecosyst. Environ. 230:261–270.

Barton, L. L., and G. D. Fauque. 2009. Biochemistry, physiology and biotechnology of sulfate reducing bacteria. Adv. Appl. Microbiol. 68:41–98.

Bates, D. B., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67:1–48.

Bjorneberg, D. L., A. B. Leytem, D. T. Westermann, P. R. Griffiths, L. Shao, and M. J. Pollard. 2009. Measurement of atmospheric ammonia, methane, and nitrous oxide at a concentrated dairy pro-

duction facility in southern Idaho using open-path FITR spectrometry. Trans. ASABE 52:1749–1756.
Borhan, M. S., S. C. Capareda, S. Mukhtar, W. B. Faulkner, R. McGee, and C. B. Parnell. 2011a. Greenhouse gas emissions from ground level area sources in dairy and cattle feedyard operations. Atmosphere 2:303–329.
Borhan, M. S., S. C. Capareda, S. Mukhtar, W. B. Faulkner, R. McGee, and C. B. Parnell. 2011b. Determining seasonal greenhouse gas emissions from ground-level area sources in a dairy operation in Central Texas. J. Air Waste Manag. Assoc. 61:786–795.
Bryant, M. P., V. H. Varel, R. A. Frobish, and H. R. Isaacson. 1976. Biological potential of thermophilic methanogenesis from cattle wastes. In Seminar on Microbial Energy Conversion. H. G. Schlegel, ed. E. Goltze KG, Gottingen, Germany.
Craggs, R., J. Park, and S. Heubeck. 2008. Methane emissions from anaerobic ponds on a piggery and a dairy farm in New Zealand. Aust. J. Exp. Agric. 48:142–146.
Dungan, R. S., and A. B. Leytem. 2015. Detection of purple sulfur bacteria in purple and non-purple dairy wastewaters. J. Environ. Qual. 44:1550–1555. https://doi.org/10.2134/jeq2015.03.0128.
Eaton, A. D., L. S. Clesceri, E. W. Rice, and A. E. Greenberg, ed. 2005. Standard Methods for the Examination of Water & Wastewater. 21st ed. American Public Health Association, American Water Works Association, Water Environment Federation. Port City Press, Baltimore, MD.
Flesch, T. K., L. A. Harper, J. M. Powell, and J. D. Wilson. 2009. Inverse-dispersion calculation of ammonia emissions from Wisconsin dairy farms. Trans. ASAE 52:253–265.
Flesch, T. K., S. M. McGinn, D. Chen, J. D. Wilson, and R. L. Desjardins. 2014. Data filtering for inverse dispersion emission calculations. Agric. For. Meteorol. 198–199:1–6.
Flesch, T. K., J. D. Wilson, and L. A. Harper. 2005a. Deducing ground-to-air emissions from observed trace gas concentrations: A field trial with wind disturbances. J. Appl. Meteorol. 44:475–484. https://doi.org/10.1175/JAM2214.1.
Flesch, T. K., J. D. Wilson, L. A. Harper, and B. P. Crenna. 2005b. Estimating gas emissions from a farm with an inverse-dispersion technique. Atmos. Environ. 39:4863–4874. https://doi.org/10.1016/j.atmosenv.2005.04.032.
Flesch, T. K., J. D. Wilson, L. A. Harper, B. P. Crenna, and R. R. Sharpe. 2004. Deducing ground-to-air emissions from observed trace gas concentrations: A field trial. J. Appl. Meteorol. 43:487–502.
Flesch, T. K., J. D. Wilson, L. A. Harper, R. W. Todd, and N. A. Cole. 2007. Determining ammonia emissions from a cattle feedlot with an inversion dispersion technique. Agric. For. Meteorol. 144:139–155. https://doi.org/10.1016/j.agrformet.2007.02.006.
Gao, Z., R. L. Desjardins, and T. K. Flesch. 2010. Assessment of the uncertainty of using an inverse-dispersion technique to measure methane emissions from animals in a barn and in a small pen. Atmos. Environ. 44:3128–3134. https://doi.org/10.1016/j.atmosenv.2010.05.032.
Grant, R. H., M. T. Boehm, and B. W. Bogan. 2015. Methane and carbon dioxide emissions from storage facilities at two free-stall dairies. Agric. For. Meteorol. 213:102–113.
Griffiths, P. R., L. Shao, and A. B. Leytem. 2009. Completely automated open path FT-IR spectrometry. Anal. Bioanal. Chem. 393:45–50. https://doi.org/10.1007/s00216-008-2429-6.
Hashimoto, A. G. 1983. Thermophilic and mesophilic anaerobic fermentation of swine manure. Agric. Wastes 6:175–191.
Hashimoto, A. G., Y. R. Chen, and V. H. Varel. 1981. Theoretical aspects of methane production: State of the art. Pages 86–91, 95 in Livestock Waste: A Renewable Resource. Proc. Int. Symp. Livest. Wastes, 4th ed. Amarillo, TX. Apr. 15–17, 1980. ASAE, St. Joseph, MI.
Hastie, T., R. Tibshirani, and J. Friedman. 2009. Elements of Statistical Learning: Data Mining, Inference, and Prediction. 2nd. ed. Springer-Verlag, New York, NY.
Holm, H. W., and J. W. Vennes. 1970. Occurrence of purple sulfur bacteria in a sewage treatment lagoon. Appl. Microbiol. 19:988–996.
Husted, S. 1994. Seasonal variation in methane emission from stored slurry and solid manures. J. Environ. Qual. 23:585–592.
Kaharabata, S. K., and P. H. Schuepp. 1998. Methane emissions from aboveground open manure slurry tanks. Global Biogeochem. Cycles 12:545–554.
Kebreab, E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth. 2008. Model for estimating enteric methane emissions from United States dairy and feedlot cattle. J. Anim. Sci. 86:2738–2748.
Khan, R. Z., C. Müller, and S. G. Sommer. 1997. Micrometeorological mass balance technique for measuring CH_4 emissions from stored cattle slurry. Biol. Fertil. Soils 24:442–444.
Kutner, M., C. Nachtsheim, J. Neter, and W. Li. 2004. Applied Linear Statistical Models. 5th ed. McGraw Hill/Irwin, Chicago, IL.
Leytem, A. B., R. S. Dungan, and D. L. Bjorneberg. 2017. Spatial and temporal variation in physicochemical properties of dairy lagoons in south-central Idaho. Trans. ASABE. In press.
Leytem, A. B., R. S. Dungan, D. L. Bjorneberg, and A. C. Koehn. 2011. Emissions of ammonia, methane, carbon dioxide and nitrous oxide from dairy cattle housing and manure management systems. J. Environ. Qual. 40:1383–1394.
Leytem, A. B., R. S. Dungan, D. L. Bjorneberg, and A. C. Koehn. 2013. Greenhouse gas and ammonia emissions from an open-freestall dairy in southern Idaho. J. Environ. Qual. 42:10–20.
Lory, J. A., R. E. Massey, and J. M. Zulovich. 2010. An evaluation of the USEPA calculations of greenhouse gas emissions from anaerobic lagoons. J. Environ. Qual. 39:776–783.
Mangino, J., D. Bartram, and A. Brazy. 2001. Development of a methane conversion factor to estimate emissions from animal waste lagoons. Technical Report. Accessed Jan. 2017. https://www3.epa.gov/ttnchie1/conference/ei11/ammonia/mangino.pdf.
McGinn, S. M., K. A. Beuchemin, and T. K. Flesch. 2009. Performance of a dispersion model to estimate methane loss from cattle in pens. J. Environ. Qual. 38:1796–1802.
Minato, K., Y. Kouda, M. Yamakawa, S. Hara, T. Tamura, and T. Osada. 2013. Determination of GHG and ammonia emissions from stored dairy cattle slurry by using a floating dynamic chamber. Anim. Sci. J. 84:165–177.
Morris, G. R. 1976. Anaerobic fermentation of animal wastes. MS Thesis. Cornell University, Ithaca, NY.
Nunkaew, T., D. Kantachote, T. Nitoda, and H. Kanzaki. 2015. Selection of salt tolerant purple nonsulfur bacteria producing 5-aminolevulinic acid (ALA) and reducing methane emissions from microbial rice straw degradation. Appl. Soil Ecol. 86:113–120.
Okubo, Y., H. Futamata, and A. Hiraishi. 2006. Characterization of phototrophic purple nonsulfur bacteria forming colored microbial mats in a swine wastewater ditch. Appl. Environ. Microbiol. 72:6225–6233.
Powers, W., B. Auvermann, N. A. Cole, C. Gooch, R. Grant, J. Hatfield, P. Hunt, K. Johnson, A. Leytem, W. Liao, and J. M. Powell. 2014. Chapter 5: Quantifying greenhouse gas sources and sinks in animal production systems. In Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory. Technical Bulletin Number 1939. M. Eve, D. Pape, M. Flugge, R. Steele, D. Man, M. Riley-Gilbert, and S. Biggar, ed. Office of the Chief Economist, USDA, Washington, DC.
Ro, K. S., and P. G. Hunt. 2006. A new unified equation for wind-driven surficial oxygen transfer into stationary water bodies. Trans. ASABE 49:1615–1622.
Ro, K. S., M. H. Johnson, K. C. Stone, P. G. Hunt, T. Flesch, and R. W. Todd. 2013. Measuring gas emissions from animal waste lagoons with an inverse dispersion technique. Atmos. Environ. 66:101–106.
Rotz, C. A., and D. S. Chianese. 2009. The Dairy Greenhouse Gas Model: Reference Manual. Ver. 1.2. Pasture Systems and Watershed Management Research Unit, Agricultural Research Service, USDA, Washington, DC.
Safley, L. M., Jr., and P. W. Westerman. 1992. Performance of a diary manure anaerobic lagoon. Bioresour. Technol. 42:43–52.
Saggar, S., N. S. Bolan, R. Bhandral, C. B. Hedley, and J. Luo. 2004. A review of emissions of methane, ammonia, and nitrous oxide

from animal excreta deposition and farm effluent application in grazed pastures. N. Z. J. Agric. Res. 47:513–544.
Sakamoto, Y., M. Ishiguro, and G. Kitagawa. 1986. Akaike Information Criterion Statistics. KTK Scientific Publishers, Tokyo, Japan.
Sejian, V., R. Lal, J. Larkritz, and T. Ezeji. 2011. Measurement and prediction of enteric methane emission. Int. J. Biometeorol. 55:1–16.
Shao, L., P. R. Griffiths, and A. B. Leytem. 2010. Advances in data processing for open-path fourier transform infrared spectrometry of greenhouse gases. Anal. Chem. 82:8027–8033. https://doi.org/10.1021/ac101711r.
Shao, L., B. Liu, P. R. Griffiths, and A. B. Leytem. 2011. Using multiple calibration sets to improve the quantitative accuracy of partial least squares (PLS) regression on open-path fourier transform infrared (OP/FT-IR) spectra of ammonia over wide concentration ranges. Appl. Spectrosc. 65:820–824.
Shao, L., W. Wang, P. R. Griffiths, and A. B. Leytem. 2013. Increasing the quantitative credibility of open-path Fourier transform infrared (FT-IR) spectroscopic data, with focus on several properties of the background spectrum. Appl. Spectrosc. 67:335–341.
Sommer, S. G., S. O. Petersen, and H. T. Sogaard. 2000. Greenhouse gas emissions from stored livestock slurry. J. Environ. Qual. 29:744–751.
Su, J. J., B. Y. Liu, and Y. C. Chang. 2003. Emission of greenhouse gas from livestock waste and wastewater treatment in Taiwan. Agric. Ecosyst. Environ. 95:253–263.
Todd, R. W., N. A. Cole, K. D. Casey, R. Hagevoort, and B. W. Auvermann. 2011. Methane emissions from southern High Plains dairy wastewater lagoons in the summer. Anim. Feed Sci. Technol. 166–167:575–580.
USEPA. 1993. Method 410.4, Revision 2.0: The determination of chemical oxygen demand by semi-automated colorimetry. Accessed Mar. 2017. https://www.epa.gov/sites/production/files/2015-08/documents/method_410-4_1993.pdf.
USEPA. 2016a. Annex 3.11. Methodology for estimating CH_4 and N_2O emissions from manure management. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2014. USEPA, Washington, DC, April 2016. Accessed Jan. 2017. https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-annex-3-additional-source-or-sink-categories-part-b.pdf.
USEPA. 2016b. Inventory of US Greenhouse Gas Emissions and Sinks 1990–2014. Accessed Sep. 1, 2016. https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014.
VanderZaag, A. C., T. K. Flesch, R. L. Desjardins, H. Balde, and T. Wright. 2014. Measuring methane emissions from two dairy farms: Seasonal and manure-management effects. Agric. For. Meteorol. 194:259–267.
VanderZaag, A. C., R. J. Gordon, R. C. Jamieson, D. L. Burton, and G. W. Stratton. 2009. Gas emissions from straw covered liquid dairy manure during summer storage and autum agitation. Trans. ASABE 52:599–608.
VanderZaag, A. C., R. J. Gordon, R. C. Jamieson, D. L. Burton, and G. W. Stratton. 2010a. Permeable synthetic covers for controlling emissions from liquid dairy manure. Appl. Eng. Agric. 26:287–297.
VanderZaag, A. C., R. J. Gordon, R. C. Jamieson, D. L. Burton, and G. W. Stratton. 2010b. Effects of winter storage conditions and subsequent agitation on gaseous emissions from liquid dairy manure. Can. J. Soil Sci. 90:229–239.
VanderZaag, A. C., C. Wagner-Riddle, K. H. Park, and R. J. Gordon. 2011. Methane emissions from stored liquid dairy manure in a cold climate. Anim. Feed Sci. Technol. 166–167:581–589.

Appendix

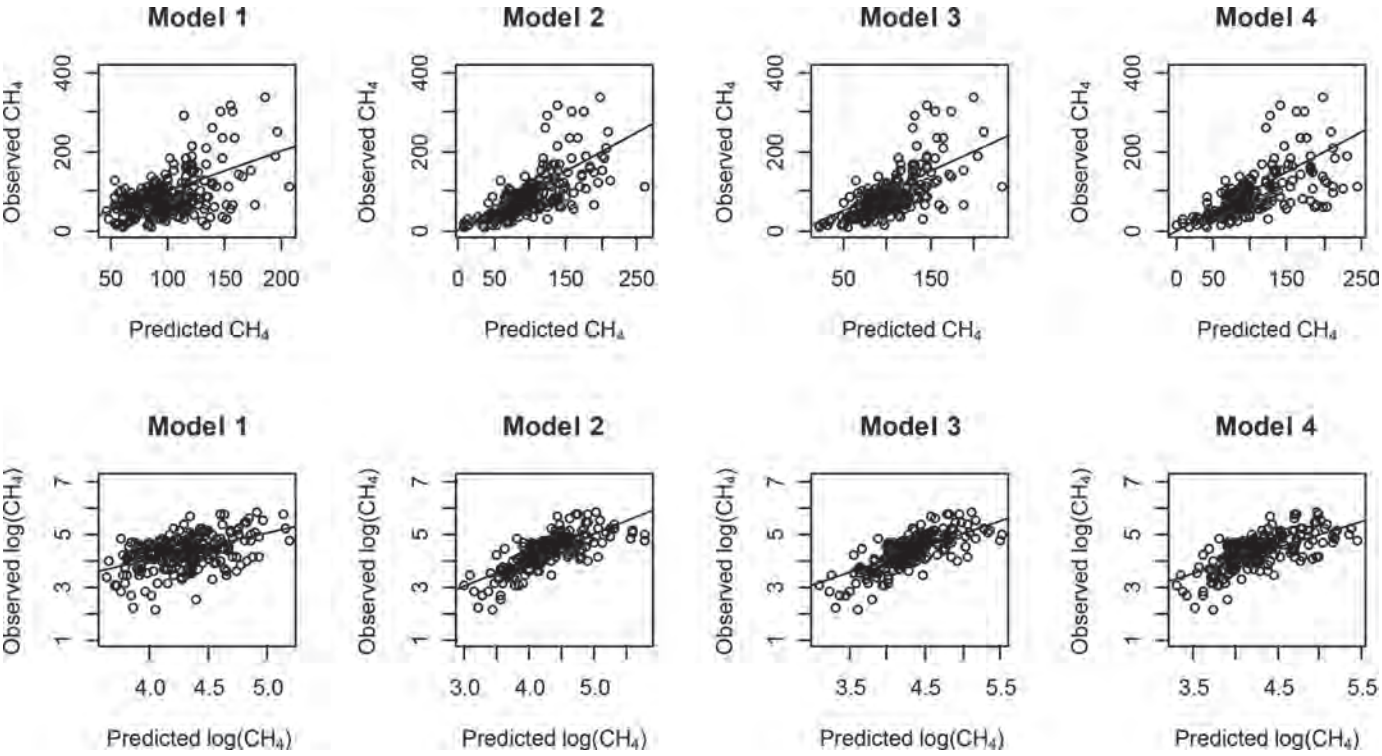

Figure A1. Observed versus predicted values for the selected methane prediction models in each of the 4 pools of independent variables. The first row has models in the original scale (methane emissions expressed in kg/ha × d) and the second row has models fitted with methane emissions in a natural logarithm scale.

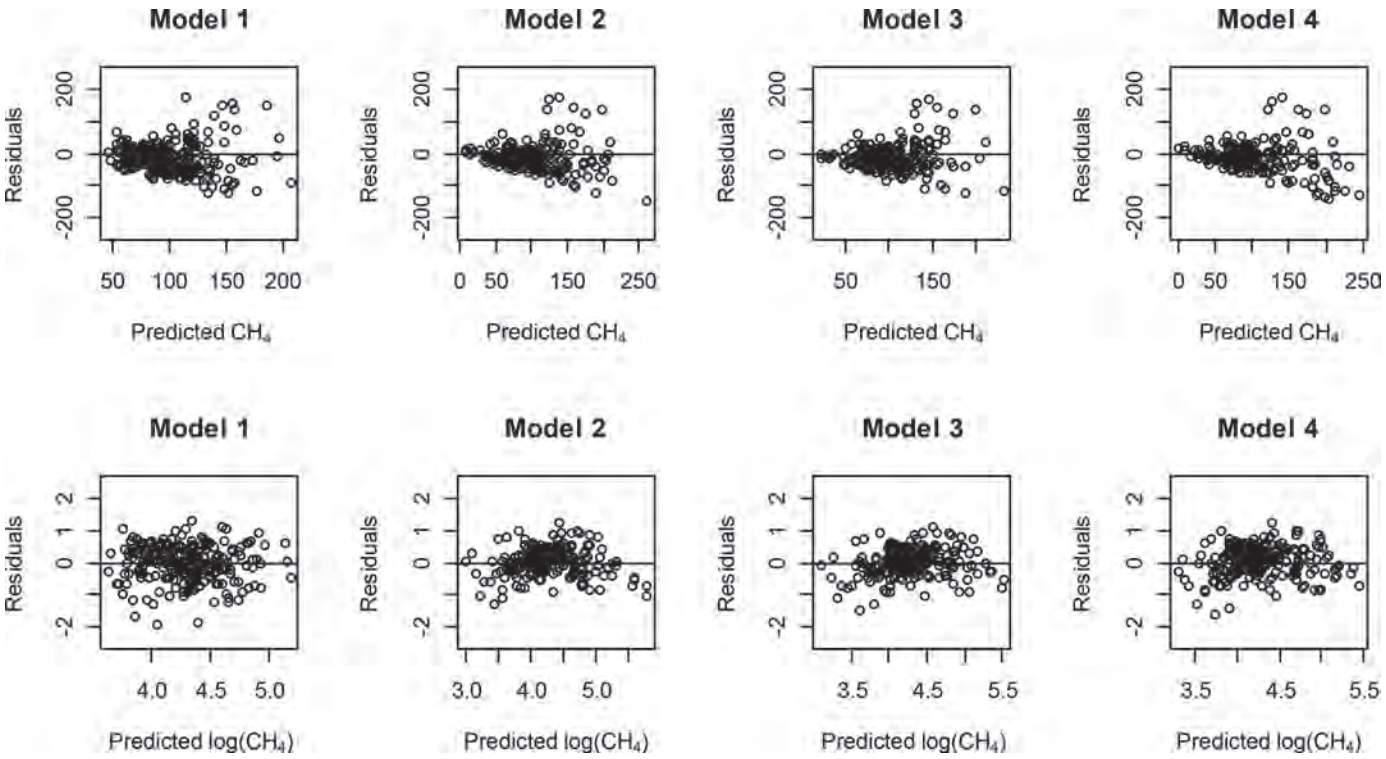

Figure A2. Residuals versus predicted values for the selected methane prediction models in each of the 4 pools of independent variables. The first row has models in the original scale (methane emissions expressed in kg/ha × d) and the second row the models fitted with methane emissions in a natural logarithm scale.

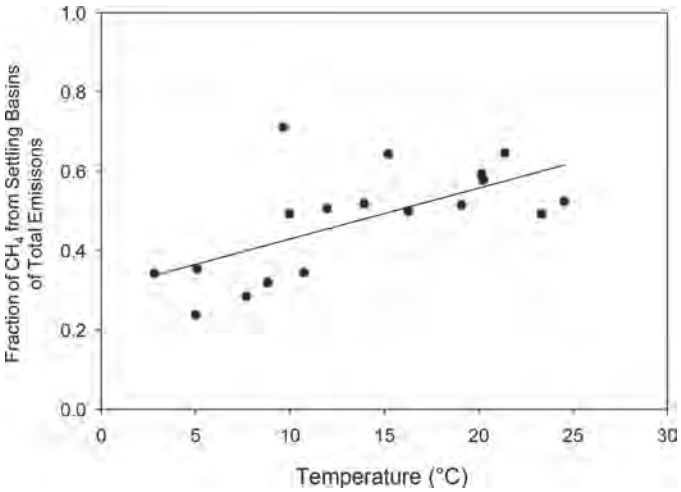

Figure A3. The relationship between the fraction of total methane (CH_4) produced by the liquid handling system originating from the settling basins and temperature for D3 and D6.



MINNESOTA AGRICULTURE EMISSIONS: THE CAFO CHALLENGE

Summary

The latest biennial greenhouse gas (GHG) emissions data from the Minnesota Pollution Control Agency (MPCA) shows major emission reductions since the last report, finding a 23% reduction in overall emissions from 2005-2020.[1] While the state is now on track to meet its GHG emission reduction goals, the MPCA cautions that the pandemic-related shutdown was likely a significant factor in the recent sharp decline and that emissions may return to pre-pandemic levels. The new data show that the agriculture sector is the state's largest source of emissions, with emissions slowly rising. A major share of the agriculture sector's emissions is tied to large-scale concentrated animal feeding operations (CAFOs) for dairy, hogs and beef. Agriculture is the state's largest source of the potent GHGs methane and nitrous oxide. Governor Tim Walz's climate framework supports more climate-friendly, less-emitting farming systems, particularly those focused on regenerative agriculture practices that enhance soil health. However, it will be difficult to reduce agriculture emissions significantly without addressing the state's continued reliance on and expansion of CAFOs.

Minnesota's Agriculture Emissions

Minnesota's Next Generation Energy Act (passed in 2007) used 2005 as a baseline to set targets to reduce emissions in the state by 15% by 2015, 30% by 2025 and ultimately 80% by 2050. Minnesota did not meet the 2015 target but due to a pandemic-aided drop in emissions (see below) is on track to meet the 2025 target. Since 2005, Minnesota's emissions have declined 23%. It is possible emissions will rise again when future data includes the re-opening of businesses, schools and other institutions in the state that were closed during the height of the pandemic shutdown. Governor Walz's Climate Action Framework (CAF) targets a 50% reduction in 2005 level emissions by 2030, to reach net zero by 2050.

Minnesota's GHG emissions 2005-2020 and goals from the Next Generation Energy Act and Climate Action Framework

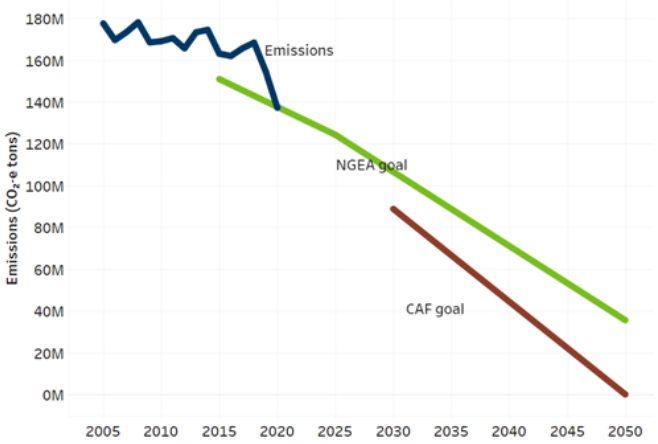

Source: MPCA Data Services, "Greenhouse gas emissions inventory," https://public.tableau.com/app/profile/mpca.data.services/viz/GHGemissioninventory/GHGsummarystory (accessed March 2023).

While emissions in other sectors, such as electrical generation (down 54%) and transportation (down 18%), have declined since 2005, agriculture emissions have been

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slowly rising. Agriculture is responsible for nearly one-quarter of the state's emissions and is the highest source of two potent GHGs, methane and nitrous oxide. Methane is a short-lived but extremely potent gas: It has around 80 times more warming potential than carbon dioxide over a 20-year timespan but only lives in the atmosphere for around a decade.[2] Nitrous oxide is 273 times more potent than carbon dioxide over a 100-year period.[3]

The state has elected to combine agriculture and forestry into one land-based sector, unlike at the federal level where the Environmental Protection Agency separates the two sectors. Forests, including re-growth and new plantings, can act as a carbon sink. While that sink does not sequester carbon from any emitting sector in particular, MPCA has tied it to agriculture.

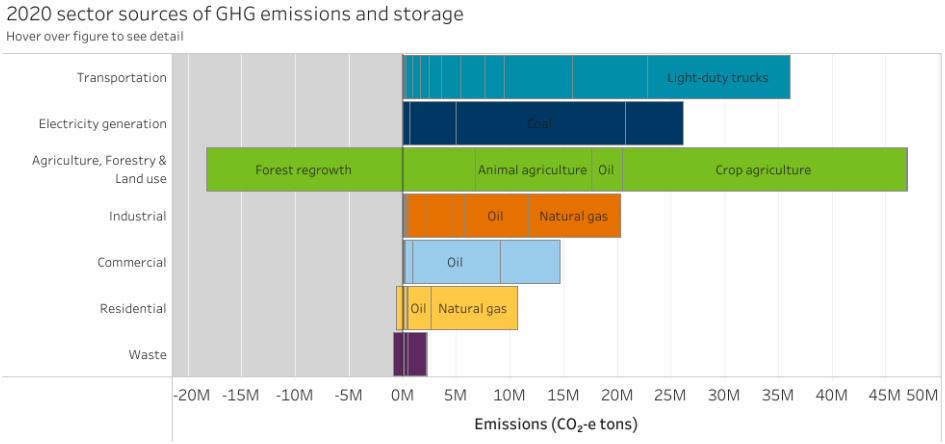

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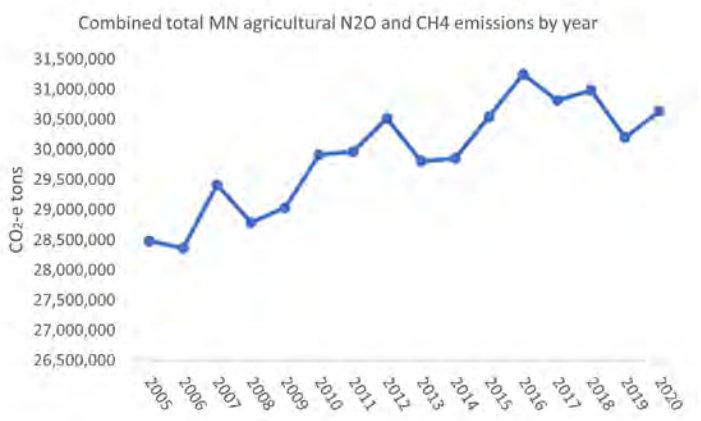

Source: Created by IATP using MPCA Data Services, "Greenhouse gas emissions inventory," https://public.tableau.com/app/profile/mpca.data.services/viz/GHGemissioninventory/GHGsummarystory (accessed March 2023).

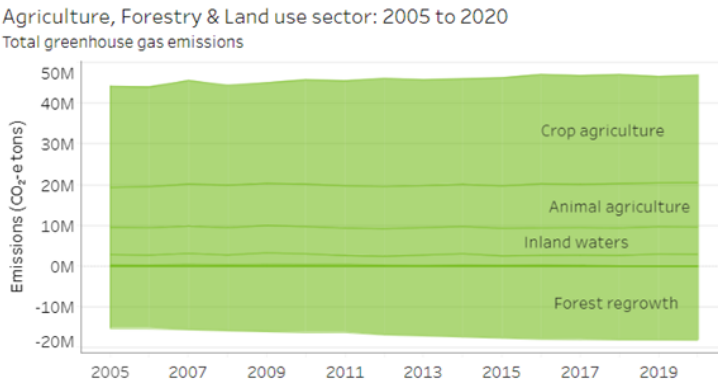

Source: MPCA Data Services, "Greenhouse gas emissions inventory," https://public.tableau.com/app/profile/mpca.data.services/viz/GHGemissioninventory/GHGsummarystory (accessed March 2023).

Agriculture-related emissions within the state have risen steadily since 1990, including emissions from animal agriculture (primarily methane from cows, and methane and nitrous oxide from manure) and crop agriculture linked to growing nitrogen fertilizer use (tied to expanded corn acres).

According to the MPCA, since 2005, methane emissions from animal agriculture have increased 10% in the state, and nitrous oxide emissions related to both manure and synthetic fertilizer use have increased 9%.[4] MPCA reports that "Animal agriculture is Minnesota's largest source of methane emissions, specifically from manure management and cattle digestion." Rising nitrous oxide emissions, according to MPCA, are linked to "a variety of agricultural sources, including nutrient application, crop residues, and runoff. Animal agriculture also produces nitrous oxide from manure."

Ruminant animals like cows naturally emit methane through their digestive process, mostly through burps. Minnesota's shift toward more large-scale CAFOs for dairy, beef and hog production over the last several decades has required more capacity to store the massive amounts of concentrated manure under those systems. That type of concentrated manure storage emits both methane and nitrous oxide, particularly when that manure is liquified and sprayed on fields. The shift toward a CAFO systems explains why methane emissions from animals (ruminants) have remained relatively flat since 2005, while emissions

from manure have risen. The CAFO system contrasts with well-managed grazing-based systems that emit fewer GHGs and in which manure is spread more appropriately on fields with long-rooted, perennial pasture.[5]

Table 1: MN livestock methane emissions, 2005-2020[6]

Sources	GHGs	2005	2010	2015	2017	2018	2020
Manure	CH_4	2,655,597	3,030,879	3,079,583	3,174,756	3,396,291	3,064,240
Ruminants	CH_4	5,373,991	5,563,424	5,518,560	5,550,030	5,533,421	5,742,391

The updated data (Table 1) shows a long-term increase in methane from manure and ruminants since 2005, with an increase from ruminants and a slight decline from manure from 2018-2020.

Similarly, emissions are rising from nitrous oxide, linked to high nitrogen fertilizer use on crops (primarily corn), increases in feedlot-related nitrous oxide emissions, with slight declines in manure and runoff-related emissions.[7]

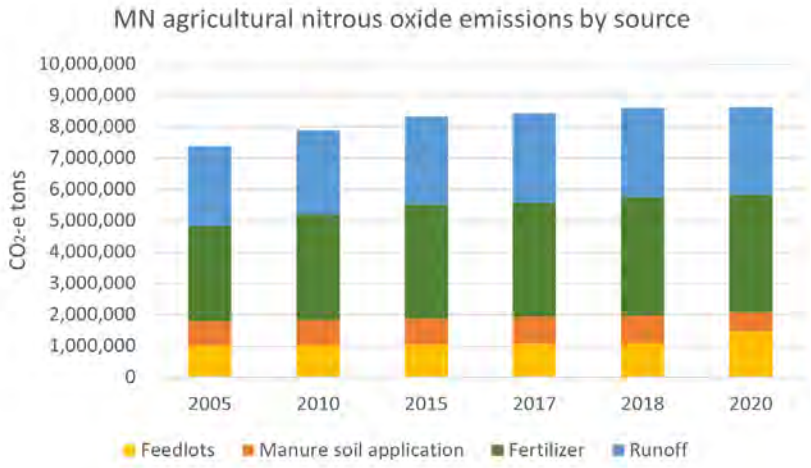

Source: Created by IATP using MPCA Data Services, "Greenhouse gas emissions inventory," https://public.tableau.com/app/profile/mpca.data.services/viz/GHGemissioninventory/GHGsummarystory (accessed March 2023).

The CAFO Connection

Since the 1980s, Minnesota and much of the United States have undergone a transition toward CAFOs to raise animals. CAFOs raise large numbers of animals in smaller spaces, often indoors, and rely on feed crops (such as corn and soybeans) rather than pasture to feed animals. CAFOs produce an enormous amount of waste, which is often stored in manure lagoons. The MPCA estimates that the amount of manure generated by livestock in Minnesota would be equivalent to that of a human population of about 50 million.[8] While the state has lost tens of thousands of farmers over the last several decades, the number of animals (particularly hogs) has risen dramatically. We now have fewer, larger farms raising more animals. Linked to the growth in CAFOs is a rise in acres for corn and soybeans used to feed animals.

In the latest U.S. Department of Agriculture Census, Minnesota lost 130 hog producers from 2012-2017, but the number of hogs in the state grew by 850,000.[9] The state lost 16% of its dairy farms from 2016-2019, while dairy herd size grew 16% over the same period, according to the Minnesota Department of Agriculture (MDA).[10] As more farmland has shifted toward animal feed, Minnesota has lost valuable pastureland, including long-rooted grasses that can sequester carbon. Since 2012, Minnesota experienced a 27% loss of pastureland.[11]

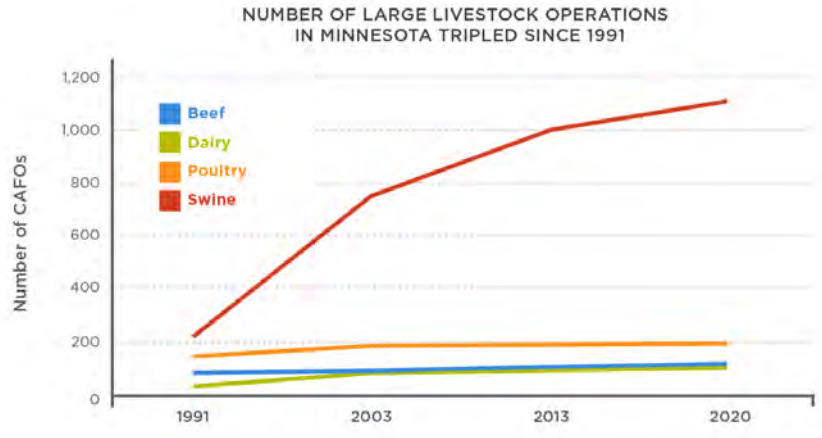

Source: Porter, Sarah and Craig Cox. "Manure Overload: Manure Plus Fertilizer Overwhelms Minnesota's Land and Water," Environmental Working Group, https://www.ewg.org/interactive-maps/2020-manure-overload/ (accessed March 2023).

Rising Fertilizer Use

The rise in CAFOs and corn ethanol production has propelled an increase in corn acres in Minnesota and associated nitrogen-based fertilizer sales in the state since 2010.

Nitrogen-based fertilizers are a major source of the potent GHG nitrous oxide.

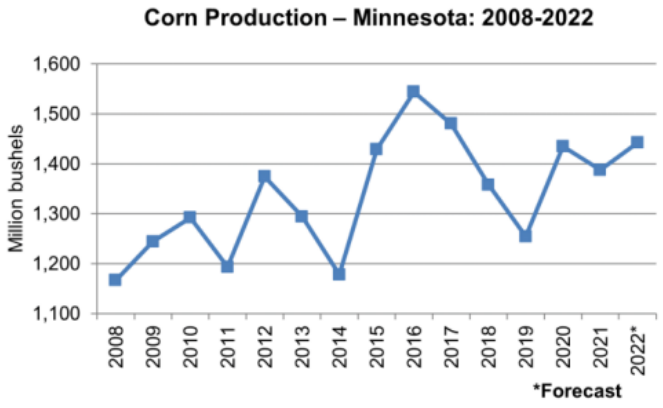

Source: USDA National Agriculture Statistics Service, "Minnesota Ag News — Crop Production," USDA press release, November 9, 2022, https://www.nass.usda.gov/Statistics_by_State/Minnesota/Publications/Crops_Press_Releases/2022/MN-Crop-Production-11-22.pdf, (accessed March 2023).

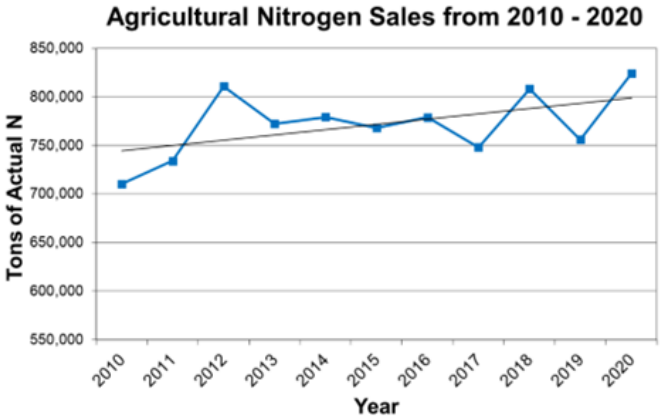

Source: Minnesota Dept. of Agriculture, 2020 Crop Year Fertilizer Sales Report, November 4, 2022, https://www.mda.state.mn.us/sites/default/files/docs/2022-12/2020fertsalesreport.pdf, (accessed March2023).

CAFOs and GHG Reporting

Currently, feedlots with 50 or more animal units in Minnesota must be permitted with the Minnesota Pollution Control Agency. There are an estimated 18,000 registered feedlots in the state.[12] New or expanding feedlots that exceed 1,000 animal units (714 dairy cows, 1,000 beef cows, 3,334 hogs) are required to complete an environmental assessment worksheet (EAW) on the impact of the proposed operation on the air, water and land, and how the project will mitigate those impacts. Last year, the state's Environmental Quality Board approved new requirements for projects undergoing an EAW,including the reporting of potential greenhouse gas emissions and how the project will adapt to expected climate impacts, such as extreme weather events.[13] The new requirements will provide additional information on how new or expanding CAFOs may impact the climate, but the requirements are anticipatory, without monitoring or a review on accuracy in the years to come. Additionally, the state has not set any limits on emissions per project or accumulative emissions per year, so the new CAFO reporting requirements are limited to informational purposes.

What's Next?

Governor Walz's climate action framework, announced in 2022, sets new emissions reduction targets aligned with the Intergovernmental Panel on Climate Change (IPCC) and the U.S. climate commitment as part of the Paris Agreement.[14] These goals include reducing the state's GHG emissions by 50% (from 2005 levels) by 2030, achieving net-zero emissions by 2050 and prioritizing investments in climate resilience over the next 10 years.

The framework includes a climate-smart natural and working lands plan with immediate and long-term strategies, guided by two goals:

- **Increase by 25% the amount of carbon sequestered and stored annually in natural and working lands, compared to 2014-2018 average levels.**
- **Reduce annual GHG emissions in the working lands sector by 25% from 2018 levels.**

The framework assigns multiple agencies to work on calculating carbon sequestration on natural lands and to set resilience and adaptation metrics. It prioritizes greater technical assistance for farmers to improve soil health and support for emerging farmers. It hopes to accelerate forest, wetland, grassland restoration and species diversity, as well as to promote local and community-based agriculture to reduce transportation needs and increase food

access. The framework would also promote and expand the use of cover crops and perennial crops that can better hold water and limit nitrogen pollution.

Significant scientific uncertainty raises questions about the state's reliance on carbon sequestration in the agriculture and land sector. Scientists have not yet answered important questions about how much carbon can be sequestered in dynamic natural systems and for how long by various practices. The latest IPCC report concluded that there is not a one-to-one relationship between precisely measured industrial sources of emissions and less scientifically certain (and less permanent) land-based carbon sequestration, including farmland sequestration.[15] The scientists found that climate change itself, through rising temperatures and the increasing frequency of extreme weather events, will slow or disrupt the soil's ability to sequester carbon on farms and forests over time.[16] An emerging body of research is highlighting the complexities of measuring soil carbon in the short and long term.[17] Parts of the U.S. have already seen extreme weather events literally burn through forest-based carbon sequestration projects.[18]

It will be challenging to reach the Walz framework goal of a 25% reduction in emissions on working lands without addressing the continued expansion of the CAFO system in the state. The framework targets the challenge of reducing methane and nitrous oxide emissions but focuses primarily on better nutrient and manure management, rather than the need to place limits on the CAFO system.

Conclusion

In the early 1970s, President Nixon's Agriculture Secretary Earl Butz told farmers to "get big or get out." Since then, but particularly accelerating after the 1996 Farm Bill, the North American Free Trade Agreement and the U.S. entry into the World Trade Organization, U.S. agriculture has become more concentrated and more globalized. Many agriculture markets are controlled by global companies, such as Smithfield/WH Group, JBS, Tyson Foods and Cargill. Minnesota farmers operate within this global system of production and markets. Several U.S. Farm Bill programs, from commodity supports to crop insurance to government-backed loans, support the production of cheap animal feed for CAFO production to feed this global market. Renewable Fuel Standards and other policies have driven the expansion of the corn ethanol industry. This is the challenging playing field many of the state's farmers are operating in.

Minnesota can leverage the influx of federal resources coming into the state from the Inflation Reduction Act to expand conservation spending (including to prioritize climate benefits) and the Infrastructure Bill to build out local infrastructure for meat and food processing to better support pasture-based systems and community food systems. IATP's analysis of conservation spending in the state finds that in 2022 only 8% of farmers who apply for assistance through the conservation stewardship program (CSP) were awarded contracts.[19] While the numbers are better (26.5%) for Minnesota farmers applying for the Environmental Quality Incentives Program (EQIP), three out of every four farmers who apply are turned down. These numbers show there is enormous interest from the state's farmers to implement conservation practices and whole farm systems that could both reduce emissions and build climate resilience.

The EQB's new reporting requirements for greenhouse gas emissions on new or expanding CAFOs is welcome and will aid in tracking some of the sector's emissions. However, to achieve the reductions necessary to respond to the climate crisis and meet the Governor's targets, the state must begin the challenging conversation about how to stem the continued expansion of CAFOs, identify limits to growth (not only to reduce GHGs, but also water pollution and biodiversity) and work with farmers in the state on a transition strategy toward less-emitting, more climate-resilient farming systems.

Endnotes

1. Minnesota Pollution Control Agency. Greenhouse gas emissions in Minnesota: 2005-2020. January 2023. https://www.pca.state.mn.us/sites/default/files/lraq-2sy23.pdf

2. Intergovernmental Panel on Climate Change. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2013. https://www.ipcc.ch/report/ar5/wg1/

3. U.S. Environmental Protection Agency. Understanding Global Warming Potentials. May 5, 2022. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

4. MPCA. Greenhouse gas emissions in Minnesota: 2005-2020. January 2023. https://www.pca.state.mn.us/sites/default/files/lraq-2sy23.pdf

5. Stanley, P., Rowntree, J. Beede, D. DeLong, M. Hamm, M. Impacts of soil carbon sequestration on lifecycle greenhouse gas emissions in Midwestern USA beef finishing systems. Agricultural Systems. V. 162. May 2018. https://doi.org/10.1016/j.agsy.2018.02.003

6. MPCA Greenhouse gas emissions in Minnesota: 2005-2020. January 2023. https://www.pca.state.mn.us/sites/default/files/lraq-2sy23.pdf

7. Ibid.

8. Minnesota Pollution Control Agency. Livestock and the Environment: MPCA Feedlot Program Overview. January 2021. https://www.pca.state.mn.us/sites/default/files/wq-f1-01.pdf

9. U.S. Department of Agriculture. Agriculture Census. Hogs and Pigs Inventory and Sales. 2017. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_2_US_State_Level/st99_2_0012_0012.pdf

10. Minnesota Department of Agriculture. Vegetative Cover in Minnesota: Prospects and Challenges. July 2020. https://wrl.mnpals.net/islandora/object/WRLrepository%3A3609/datastream/PDF/view

11. Ibid.

12. Minnesota Pollution Control Agency. Livestock and the Environment: MPCA Feedlot Program Overview. January 2021. https://www.pca.state.mn.us/sites/default/files/wq-f1-01.pdf

13. Minnesota Environmental Quality Board. Climate Assessment and Environmental Review. December 2022. https://www.eqb.state.mn.us/content/climate-assessments-and-environmental-review

14. State of Minnesota. Climate Action Framework. September 2022. https://climate.state.mn.us/sites/climate-action/files/Climate%20Action%20Framework.pdf

15. Intergovernmental Panel on Climate Change. Climate Change 2021: The Physical Science. Working Group I Contribution to the Sixth Assessment Report. 2021. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/

16. Ibid.

17. Slessarev. E. Zelikova, J. Hamman, J. Cullenward, D. Freeman, J. Soil Depth Matters for Soil Carbon Accounting. Carbon Plan June 17, 2021. https://carbonplan.org/research/soil-depth-sampling

18. Fires and Forest Offsets. Carbon Plan. 2022. https://carbonplan.org/research/forest-offsets-fires

19. Happ, Michael. Still Closed Out. Institute for Agriculture and Trade Policy. March 2023. https://www.iatp.org/still-closed-out

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Author Manuscript

Author Manuscript

HHS Public Access

Author manuscript

Int J Hyg Environ Health. Author manuscript; available in PMC 2021 January 01.

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Estimated time-varying exposures to air emissions from animal feeding operations and childhood asthma

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Abstract

Background/Aim: Industrial-scale animal feeding operations (AFOs) have adverse impacts on regional air quality. Air emissions include endotoxins and other pro-inflammatory components, and exposure may cause airway inflammation and respiratory effects in susceptible individuals residing nearby. We aimed to develop and validate metrics for estimating time-varying exposure to AFO air pollution in surrounding communities and, secondly, to determine whether exposure is associated with health effects in children with asthma.

Methods: We conducted a longitudinal panel study of N=58 children with asthma in an agricultural region of Washington State with a high density of dairy AFOs. Children were followed for up to 26 months with repeated measures of respiratory health (N=2023 interviews; N=3853 lung function measurements); urine was collected in a subcohort (N=16) at biweekly intervals over three months and analyzed for leukotriene E4 (LTE4), a biomarker of systemic inflammation (N=138 measurements). We developed an approach to estimate daily exposure to AFO airborne emissions based on distance to AFOs, AFO size, and daily wind speed and direction, and validated the estimates against direct measurements of ammonia, a chemical marker of AFO emissions, measured biweekly at 18 sites across the region for 14 months. Short-term relationships between AFO pollutant exposure and outcomes were assessed using regression models accounting for within-participant correlation and several potential confounders.

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Results: Estimates of daily AFO air pollution correlated moderately well with outdoor ammonia measurements (N=842; r=0.62). Forced expiratory volume in one second (FEV_1) as percent of predicted was 2.0% (95% CI: 0.5, 3.5) lower with each interquartile increase in previous day exposure, but no associations with asthma symptoms were observed. There was suggestive evidence that LTE4 concentrations were higher following days of elevated exposure to AFO emissions (p=0.07).

Conclusions: A simple metric of time-varying exposure to AFO emissions was correlated with daily outdoor ammonia levels. Children with asthma may be adversely affected by exposure to AFO emissions.

Keywords

air pollution; agriculture; animal feeding operations; industrial food production; dairy farms; pediatric asthma

INTRODUCTION

The rise of industrial-scale agriculture in the United States threatens environmental quality in a number of ways, including pollution of regional airsheds (Aneja et al., 2009). Large-scale facilities where livestock and poultry are raised for food production, called animal feeding operations (AFOs)[1], emit numerous biological and chemical pollutants to the surrounding atmosphere. Previous studies have documented elevated concentrations of hydrogen sulfide (Feilberg et al., 2017 Pavilonis et al., 2013; Thorne et al., 2009;), ammonia (Donham et al., 2006; Schulze et al., 2011; Williams et al., 2009), endotoxins (Dungan et al., 2012; Ko et al., 2010; Williams et al., 2016), bioaerosols (Thorne et al., 2009), odors (Thorne et al., 2009; Wing et al., 2008), and total dust (Purdy et al., 2009; Williams et al., 2009) in the vicinity of AFOs. Many components of AFO emissions are toxic to the respiratory system (Heederik et al., 2007; May et al., 2012). Increased risks of respiratory diseases for AFO workers are well-documented (Arteaga et al., 2015; Donham et al., 1993; Douglas et al., 2018; Reynolds et al., 2013;Von Essen et al., 2010); in contrast, impacts on community health are less certain. Previous epidemiologic studies have described associations between community-level AFO exposures and health effects (Hooiveld et al., 2016; Horton et al., 2009; Kalkowska et al., 2018; Loftus et al., 2015a; Merchant et al., 2015; Mirabelli et al., 2006; Pavilonis et al., 2013; Radon et al., 2007; Rasmussen et al., 2017; Schinasi et al., 2011; Schulze et al. 2011; Sigurdarson et al., 2006; Wing et al., 2013), but most were cross-sectional in design and dependent on time-invariant exposure estimates such as distance to nearest AFO (Kalkowska et al., 2018; Merchant et al., 2015; Mirabelli et al., 2006; Schinasi et al., 2011), count of AFOs within a certain distance (Hooiveld et al., 2016; Pavilonis et al., 2013; Radon et al., 2007) or modeled ambient concentrations of an AFO-related pollutant (Sigurdarson et al., 2006).

[1]**Abbreviations and definitions:** AFARE – Aggravating Factors of Asthma in a Rural Environment; AFO – animal feeding operation; ATS – American Thoracic Society; BMI – body mass index; CI – confidence interval; DNMP – Dairy Nutrient Management Program; FEV_1–forced expiratory volume in 1 second; FEV_1% – forced expiratory volume in 1 second as a percentage of predicted value; GEE – generalized estimating equations; ICC – intraclass correlation coefficient; IQR – interquartile range; LMM – linear mixed models; LOD – limit of detection; LTE4 – leukotriene E4; NH3 – ammonia; PFM – peak flow meter; uLTE4 – urinary leukotriene E4; YVFWC – Yakima Valley Farmworkers Clinic

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To date, a small number of longitudinal, repeated measures studies of health effects utilizing time-varying AFO exposures have been conducted (Horton et al., 2009; Loftus et al., 2015a; Schinasi et al., 2011; Wing et al., 2013). This study design, also referred to as a "panel study," is especially well-suited to assess time-varying exposures that result in short-term, reversible health effects. Since each participant is observed repeatedly during periods of varying exposure, within-participant associations between exposure and health can be analyzed and the influence of between-participant confounding is mitigated (Janes et al., 2008). Estimating individual, time-varying exposures in a panel study can be challenging. Personal exposure modeling is often prohibitively expensive and difficult, and there are limited options for estimating individual exposure to airborne emissions from point sources of pollution, like AFOs (Brender et al., 2011; Cordioli et al., 2013; Hoek et al., 2018; Pascal et al., 2013). Relying on simple distance to sources of air pollution as proxy of exposure can lead to substantial exposure measurement error (Hodgson et al., 2007; White et al., 2009).

We previously conducted pediatric asthma panel studies in the Aggravating Factors of Asthma in a Rural Environment (AFARE) study, a community-based participatory research project set in an agricultural region of Washington State. We found that lung function of children with asthma was poorer on days following higher concentrations of outdoor ammonia (Loftus et al., 2015a). Here, we extend this research by first developing and validating a measure of daily exposure to airborne AFO pollutants that accounts for distance to nearby AFOs, AFO size, and wind direction and speed. Secondly, we demonstrate use of this metric and repeat our previous panel study of AFO air pollution exposure and asthma morbidity with a substantially larger sample size. Finally, we evaluate whether modeled AFO emissions are associated with a biomarker of systemic inflammation, urinary leukotriene E4 (uLTE4), measured repeatedly in a subset of the AFARE cohort. uLTE4 is a measure of total body cysteinyl leukotrienes, key mediators in airway inflammation that may play an important role in inflammatory-mediated responses to environmental pollutants (Hoffman et al., 2018).

We hypothesized that children with asthma experience short-term increases in inflammation, more asthma symptoms and poorer lung function following days of elevated exposure to AFO air pollutants.

MATERIALS AND METHODS

The AFARE Study

AFARE was conducted within El Proyecto Bienestar, a community-based participatory research partnership between the University of Washington Pacific Northwest Center for Agricultural Safety and Health; the Yakima Valley Farm Worker Clinics (YVFWC), a network of federally-qualified health clinics serving migrant and seasonal farmworker families as well as other underserved populations in the region; and the Northwest Community Education Center, which provides support and education for the Latino community in the Yakima Valley. Details of AFARE have been described previously (Armstrong et al., 2013; Loftus et al., 2015a; Loftus et al., 2015b); this is a secondary analysis of previously-collected data that expands on previous work by incorporating analysis of a urinary biomarker, described below. The study was conducted from 2010 to

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2013 in the Yakima Valley of Washington State, a region spanning from the city of Yakima in the northwest to Prosser in the southeast and roughly 42 miles in length from corner to corner. Approximately 70-80% of the region is used for agriculture, including a high density of animal feeding operations -- predominantly large dairies -- located in the southeastern half of the valley. In 2012 there were 65 dairies in the Lower Yakima Valley licensed through the Washington State Department of Agriculture, housing over 150,000 cows in total (WA State Dept of Agriculture, 2014).

As described previously, AFARE participant recruitment started in August 2010 and spanned one year. Families actively involved in the YVFWC Asthma Program were invited to enroll if children were of school age (6 to 16 years old), had no other serious illnesses and intended to stay in the region during the two-year duration of the study. All research was approved by the University of Washington Institutional Review Board, and consent or assent was obtained from all participants prior to participation. In total, 58 participants were enrolled and 9 (16%) dropped out prior to the end of AFARE data collection in October 2012. Data from participants who left the study were retained in analysis because the choice to end participation was unrelated to health or exposure status (e.g., moved out of region).

Asthma health assessment

Longitudinal asthma health assessments in the AFARE cohort are described in detail in previous papers (Loftus et al., 2015a and 2015b). See Figure 1 for a timeline of health and environmental data collection. Two methods were used to repeatedly assess participants' respiratory health across the study period: 1) biweekly phone surveys regarding child asthma symptoms and medication use and 2) daily home lung function tests.

Biweekly Asthma Symptom Surveys: Approximately every two weeks, phone interviews with either the child or an adult family member were conducted to assess the presence of recent asthma symptoms and medication use. Interviewees were asked five questions about asthma symptoms (shortness of breath, nighttime waking, limitation of activities, wheezing, and morning asthma symptoms) in reference to the week prior. A sixth question pertained to short-acting bronchodilator use over the past week, estimated as average number of "puffs" per day. Our survey is not validated but comprised of questions on asthma symptom occurrence and rescue medication use which are commonly assessed in combination or independently to determine asthma control in clinical practice and in research studies.

In analysis, we analyzed each symptom and medication use separately as a binary value: any reported experience of the symptom (or use of medication) use in the week prior versus no experience of symptom (or use of medication).

Daily home lung function tests: Each child was trained in proper use of a PikoNET PiKo-1 handheld peak flow meter (PFM) with digital memory (nSpire Health, Inc; Longmont, CO) according to American Thoracic Society (ATS) guidelines and instructed to use it every day prior to any short-acting bronchodilator medication. Stored data were downloaded by YVFWC staff at approximately six-week intervals. During a 12-month AFARE follow-up visit, clinical staff observed each child's technique and retrained

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participants if necessary. The PFMs produced a value of FEV_1 with each blow, which was converted into the percent of predicted value (FEV_1%) based on standard reference equations (Hankinson et al., 1999). Values of FEV_1% that were implausibly high (above 150%) or low (below 30%) as well as measurements that were flagged by the device as potential errors were omitted from analysis. If multiple FEV_1 values were available on a given day, the highest FEV_1% was chosen to represent daily FEV_1%.

Urinary LTE4 measurements

In the final three months of the AFARE study, we collected urine samples from a subset of the cohort (n=16), chosen based on residential proximity to air monitors. They provided "spot" morning urine samples every six days over 14 weeks. Study field staff picked up the urine samples and kept the samples at 0 degrees C until return to the field office, after which samples were stored at −20 degrees C until time of analysis.

Quantitative analysis of uLTE4 was performed in the UW Department of Environmental and Occupational Health Studies Functional Genomic Lab. First urine samples were purified using Cayman's Cysteinyl Leukotriene Affinity Columns (Item No. 400068 for samples with low volume and Item No. 400069 for samples with higher volume) according to manufacturer's protocol. Then uLTE4 levels of the purified samples were quantified using Leukotriene E4 EIA kit (Cayman Item No. 520411) according to manufacturer's protocol.

Urinary creatinine was analyzed by a modified Jaffe procedure (Beckman Coulter AU System Creatinine [Beckman Coulter Inc.; Brea, CA]). All uLTE4 measurements were adjusted for creatinine and log transformed before statistical analyses.

Ammonia monitoring

Air monitoring was conducted during the second year of the AFARE study. We have described the design, deployment and performance of AFARE air sampling devices elsewhere (Armstrong et al., 2013). In brief, fourteen devices were placed outside the homes of a subset of the AFARE participants selected based on accessibility, security and overall spatial variability across the study region. Four monitors were moved to a new location during the air monitoring period because families changed residences (n=3) or the participant dropped out of the study (n=1), and one monitor was destroyed in a home fire three months prior to the end of the study. As a result, there were 18 monitoring sites during the course of the study. Every six days, devices actively sampled outdoor air for 24 hours using a silica bead sampling tube (SKC Inc; Eighty Four, PA), and flow rates were calibrated once a month. Sampling tubes were transported the University of Washington Environmental Health Laboratory at 0°C, where they were desorbed with deionized water and analyzed for ammonium using ion chromatography. Ammonia masses below the limit of detection (LOD) (either 1 or 0.5 μg, depending on the date of analysis) were replaced by LOD/2 for the calculation of concentration. In sensitivity analyses, we substituted $\mathrm{LOD}/\sqrt{2}$ for values below the LOD and repeated all analyses; all of the results were the same. Average ammonia concentration over the sampling period was calculated as the mass divided by total volume of air sampled over the period. A total of 814 ammonia concentrations were measured during the study period.

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Calculation of daily plume exposure (E_{plume})

We developed an approach to estimating daily AFO airborne "plume" exposure at specific locations in the study region based on simple principles of atmospheric plume dispersion from point sources (Curtiss and Rabl, 1996). Four equations were used to calculate daily exposure to AFO plumes at participant locations (Table 1). The first two versions, $E_{plume,1}$ and $E_{plume,2}$, were time-invariant and were calculated based upon characteristics of regional AFOs. $E_{plume,1}$ was calculated using distance to regional AFOs alone, and $E_{plume,2}$ incorporated facility size, a proxy measure for number of animals, in addition to distance. $E_{plume,3}$ and $E_{plume,4}$ were time-dependent quantities calculated with daily resolution based on wind conditions measured at each AFO location during a 24-hour period: $E_{plume,3}$ included a term to account for changing hourly wind directions and the bearing from AFO to participant location, and $E_{plume,4}$ additionally included a term to account for wind speed during the hours when wind was blowing in the direction from AFO to participant location.

To estimate locations and sizes of all AFOs in the study region, we started with the WA State Department of Agriculture database of dairy operations registered through the Dairy Nutrient Management Program (DNMP) in 2012, because the majority of animal operations in the Yakima Valley are dairies. Then we inspected aerial photography images of the entire study region available online via Google Earth for characteristic features of AFOs such as large dirt areas containing cattle, feeding and milking shelters, and animal waste storage ponds. We confirmed or corrected the location of the dairy operations in the region registered with the DNMP (N=65) and, further, identified facilities not in the DNMP database (N=32). We estimated the area of each facility in units of m^2 and approximated the geographic location as the center of the facility. The distance and bearing (360°) from each AFO to every participant location were determined using the "geosphere" package in R (version 2.14.2, The R Foundation for Statistical Computing).

Hourly meteorological conditions (wind speed and direction) at each AFO on every day of the study were obtained from the Washington State University AgWeatherNet database (http://weather.wsu.edu/awn.php [Accessed June 21, 2014]), which maintains historical meteorology data for ten weather stations within the region. For each AFO, the nearest weather station was identified and used as the source of hourly wind measurements. The term in equations for $E_{plume,3}$ and $E_{plume,4}$ pertaining to wind direction, $f(t, s, a)$, was calculated as the proportion of hours when the wind was blowing from the AFO to the participant location based on an eight-point wind rose. Finally, the term describing daily wind speed in $E_{plume,4}$, $u(t, s, a)$, was calculated as the average wind speed only during the hours of the day in which the wind was blowing in the direction from the AFO to participant location. Hourly wind speeds lower than 0.5 m/s were considered to be "calm conditions" and replaced by 0.5 m/s (Hanna et al., 1982).

We utilized $E_{plume,4}$ as our primary exposure metric for all epidemiological analyses. We estimated exposures for each participant's home and school address, and accounted for exposure at both locations by applying simple assumptions about time-activity patterns. For weekends and days outside the regular school year, exposure was assigned based on home location. For weekdays during the school year, a time-weighted average of home- and

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school-based values was calculated assuming seven hours spent at school and 17 hours at home.

Statistical analysis

All statistical analyses were performed using Stata 12.0 IC (StataCorp LP; College Station, TX) or R (version 2.14.2, The R Foundation for Statistical Computing). We performed descriptive analyses of all outcomes, exposures and covariates. Relationships between log-transformed ammonia concentrations and E_{plume} estimates were summarized using Pearson correlation coefficients (r). Univariate associations between participant-specific mean uLTE4 concentrations and child characteristics were compared using t-tests with unequal variances with the exception of child age of enrollment, which was compared to participant-specific mean uLTE4 by linear regression with robust standard errors.

Statistical methods for epidemiologic analysis varied by outcome. To models associations between AFO exposure and asthma symptoms and lung function (in separate models), we used linear regression with generalized estimating equations (GEE) and an exchangeable correlation matrix (Diggle et al., 2002). Reported asthma symptoms were based on surveys referring to the week prior to the interview; therefore, we calculated average AFO plume exposure across the seven days prior to the interview date for the primary exposure in analyses of these outcomes. For analyses of daily lung function (FEV_1%), we investigated lagged daily exposures ranging from 0 (same day) to 5 days prior to lung function measurement. Covariates included as potential confounders in analyses of asthma symptoms and lung function were selected *a priori* based on existing scientific evidence of relationships with respiratory health and/or exposure. Our final model included several time-varying factors: temperature, relative humidity (both as cubic splines), elapsed week of study, and seasonality (calendar month). We additionally controlled for participant-specific characteristics likely associated with asthma morbidity: sex, age, atopy, use of inhaled corticosteroids at baseline, BMI at baseline and presence of adult smoker in household.

We also measured associations between estimated AFO exposure and uLTE4. We investigated lagged daily exposure to estimated AFO air pollution ranging from 0 (same day) to 4 days prior to the day of urine collection. We used linear mixed models (LMM) instead of GEE for these analyses because GEE performs best with larger numbers of clusters, and there were only 14 participants in the LTE4 substudy. In addition, we also selected covariates differently due to a much smaller sample size available for LTE4 analyses. For a more parsimonious model, we only included participant characteristics associated with uLTE4 in univariate analyses: child age, use of inhaled corticosteroids at baseline, and atopy status.

In all epidemiologic models, the mean outcome was modeled to be linear in response to the primary exposure of interest, and we present results as effect sizes per interquartile range (IQR) increase in exposure.

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RESULTS

Study population and setting

AFARE children ranged in age from 6 to 16 years old at the time of enrollment and were split evenly by gender (Table 2). The majority of participants self-identified as Latino/Hispanic in ethnicity, and half reported that one or more parents were employed in farm work. 24 (41%) children were from families with an annual household income of $15,000 or less. Two thirds (n=38) had been hospitalized for asthma at one point in their lives, and 46 (n=79%) had visited an urgent care clinic or the emergency department for asthma in the 12 months prior to enrollment. The majority of children were taking daily maintenance medications (i.e., “controller” medications) for asthma at baseline, of which the most common was inhaled corticosteroids. 42 (71%) tested positive to at least one aeroallergen in skin prick testing, and 8 (14%) lived with at least one adult smoker. The N=16 children who participated in the urinary LTE4 sub-study were representative of the full cohort (Table 2).

In the AFARE study region there were N=65 dairy operations licensed by the Washington DNMP in 2012, N=5 of which (7.7%) were classified as small, with up to 199 mature animals each; N=16 (25%) as medium, with 200-699 animals; and N=44 (68%) as large, with over 700 animals. Our review of aerial images of the region identified an additional N=32 potential animal facilities. The N=97 total facilities in the region ranged in size from 6500 to 900,000 m^2 in estimated surface area (mean=190,000 m^2).

Longitudinal asthma health

N=2,023 biweekly interviews were conducted over 26 months; the respondent was the child in 35% of the interviews and a parent in 65%. Participant-specific frequencies of report for each symptom were calculated and then averaged to give a mean and standard deviation across the population. Woken by asthma was reported most frequently and shortness of breath was the least frequent symptom, on average (mean of 45% and 19% of surveys, across participants; Table 3). N=3852 lung function measurements were collected, and the participant-average FEV_1 as percent of predicted (FEV_1%) averaged 75% (s.d. = 15%). FEV_1 increased for the cohort across the study period, at an average rate of 0.26 L per year. Participants’ PFM data completeness rates (i.e., percent of days with at least one PFM measurement) ranged from 12 to 80% (mean = 35%). We assessed patterns in PFM missingness and detected no statistically significant relationships between participant-specific completeness rates and symptom reports, average FEV_1%, atopy status, or use of inhaled corticosteroids at baseline. We also found no evidence that the odds of FEV_1 missingness on a specific day of the study was related to average lung function during the same time period (week average FEV_1%). In our previous analyses of lung function data, we imputed missing values and observed no differences in results when analyses were conducted in multiple imputed datasets (Loftus et al., 2015a and 2015b); for the current analysis, we conducted complete case analysis.

Urinary LTE4

Children who participated in the LTE4 substudy (n=16) contributed an average of 9 urine samples each (range = 1 to 15). A total of 138 samples were analyzed for LTE4. The

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geometric mean (geometric standard deviation) of creatinine-adjusted uLTE4 concentration was 85 (1.9) pg/mg creatinine. We observed substantial within-participant temporal variability in uLTE4 (Figure A.1). The intraclass correlation coefficient (ICC) of log (adjusted uLTE4) was 0.34, indicating that within participant variability was greater than between participant variability.

In univariate analyses of participant-averaged uLTE4 measurements, uLTE4 was higher for children with atopic asthma ($p = 0.09$) and for children taking inhaled corticosteroids at baseline ($p = 0.028$; Figure 2). Boys had higher uLTE4 than girls, but the difference was small and imprecise. uLTE4 was significantly lower with older age; log (adjusted uTLE4) averaged 0.12 points lower (95% CI: 0.05, 0.19) per each year older.

Estimated AFO air pollution exposure and comparison to outdoor ammonia

All four metrics of plume exposure were moderately-to-highly correlated with directly measured outdoor ammonia concentrations across the region (Figure 3). Ammonia concentrations estimated from ammonia mass below the laboratory LOD are more uncertain than those calculated from higher ammonia masses; these two categories of ammonia concentrations are distinguished in the plots. In general, weaker relationships between ammonia and estimated AFO exposure were observed when ammonia mass was below the LOD. Both time-invariant estimates of exposure ($E_{plume,1}$ and $E_{plume,2}$) displayed a moderate degree of positive correlation with measured ammonia concentrations ($r=0.54$ in both cases).

Adding a variable reflecting wind direction (i.e., the difference between $E_{plume,2}$ and $E_{plume,3}$) increases the correlation to 0.61. That is, accounting for wind direction increased the model R^2 from 0.29 to 0.37, indicating that the wind direction term alone accounts for 8% of the variability in daily ammonia at monitoring sites. Addition of the wind speed term with $E_{plume,4}$ increased correlation from 0.61 to 0.62 (an increase in R^2 from 0.37 to 0.38), a very minor improvement. We examined site-specific relationships between ammonia and $E_{plume,4}$ and observed a consistently positive relationship at all 14 sites (Figure A.2).

Associations between AFO air pollution and asthma health

Analysis of daily FEV_1% and estimated AFO air pollution exposure on various lag days indicated that decrements in lung function occurred following elevated exposures to AFO plumes (Figure 4). Statistically significant decrements were observed one day after exposure: −2.0% (95%CI: −3.5, −0.5) per IQR increase in predicted exposure, while associations with other lag days were smaller in magnitude and null. We observed no associations between reported asthma symptom and medication use and average AFO pollution exposure in the week prior (Table 4).

Associations between AFO air pollution and urinary LTE4

Higher uLTE4 concentrations occurred on days of higher estimated AFO plume exposure, both for the subcohort overall (N=16 children; 134 urine analyses) as well as for most individual participants (Figure 5). In multivariable regression, we found a marginally

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significant elevation of uLTE4 associated with same day exposure and nonsignificant elevations of uLTE4 on one or more days after exposure assessment (Table 5).

DISCUSSION

We developed an easy-to-implement approach for modeling spatiotemporal variations in exposure to airborne emissions from AFOs and validated the model against measurements of outdoor ammonia, a chemical marker of AFO-related air pollution, monitored at several sites across the study region over a year (N=814 measurements). This method was then applied to estimate personal daily exposures for a panel study of lung function, asthma symptoms and biological markers of inflammation in children with asthma residing near AFOs. We found that children's lung function was lower in the days following increased exposure to AFO emissions. Note that the effect size was small in magnitude. For comparison, the standard deviation in participant-averaged FEV_1 in this study was 15%, and the ATS classifies a 20% change of FEV_1 as being a mild exacerbation (Reddel et al., 2009). A study of children with asthma in urban Windsor observed a more modest effect size of approximately 0.5% reduction in predicted FEV_1 per interquartile increase in PM2.5 (6 mcg/m3). However, as noted in that study, such modest effects may have public health importance as these ambient exposures are experienced by children across the community. The 2% in FEV_1% associated with an IQR increase in plume exposure we observed is the average difference across the entire cohort and all occurrences of exposure; the decrease in FEV_1 for a specific child on a given day of exposure could be much larger in magnitude. Because child living in close proximity to AFOs may be repeatedly exposed to elevated emissions over time, the impact on asthma health could be substantial.

In general, our findings of increased respiratory morbidity associated with AFO air exposures were in line with findings from our previous, smaller study of lung function and monitored ammonia (Loftus et al., 2015a), as well as those of other recent studies of pediatric asthma in communities impacted by AFO-related pollution (Merchant et al., 2015; Mirabelli et al., 2006; Pavilonis et al., 2013; Radon et al., 2007; Rasmussen et al., 2017). Our finding that systemic inflammation may increase following higher exposures to AFO air pollution are novel, and further strengthens the hypothesis that these exposures contribute to community asthma morbidity. We were not able to conduct statistical tests of mediation or to assess whether uLTE4 predicts asthma symptoms or poorer lung function, however, because timing of biomarker and asthma outcome data did not align well enough.

One contribution of the current work is the development and validation of a simple, time-varying metric of air emissions from point sources for use in epidemiological investigations of short-term health effects. Epidemiological studies of community exposures to air pollution from industrial point sources typically utilize distance to source or number of sources within a circular buffer to estimate exposure (De Sario et al., 2018; Hoek et al. 2018; Pascal et al., 2013). The exposure measurement error introduced by assuming that exposure depends only on distance can bias epidemiological associations. A number of health effects studies have accounted for meteorological factors that affect environmental transport of pollutants emanating from point sources like waste incinerators, refineries, and other industrial facilities (Coudon et al., 2019; Ghannam et al., 2013; Hoek et al., 2018; Micheli et

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al., 2014; White et al., 2009; Yu et al., 2005); some have utilized sophisticated dispersion models that additionally incorporate stack height, variations in emissions rate, chemical transformations, and other determinants of pollutant concentration (Ghannam et al., 2013). Most of these modeled long-term exposure and evaluated associations with cancer, birth outcomes and chronic conditions (Brender et al., 2011; Coudon et al., 2019; Coudon et al., 2018; Micheli et al., 2014; Yu et al., 2005;). Few studies of asthma exacerbations or morbidity have utilized time-varying individual exposure to point-source air pollution in a panel or case-crossover study (Lewin et al., 2013; Loyo-Berrios et al., 2007; Smargiassi et al., 2009).

We conducted our modeling approach in stages to evaluate the relative contributions of components of the model. The simplest metric of plume exposure ($E_{plume,1}$), which was calculated solely upon distances to regional AFOs, had a moderate degree of correlation with daily ammonia concentrations (r=0.54). The addition of facility size ($E_{plume,2}$) did not improve correlation with ammonia by a meaningful amount, indicating that the surface area of AFOs in this region might not be an accurate proxy for number of animals, an important determinant of ammonia emissions (Hristov et al., 2011). To address temporal variations in AFO exposure, we incorporated daily wind direction and wind speed. With $E_{plume,3}$ we accounted for changing wind directions at AFO locations; this addition explained an additional 8% of the daily variation in ammonia beyond that of the two simpler, time-invariant metrics of plume exposure. For $E_{plume,4}$ an additional term in the denominator was included to attenuate the estimated exposure with increased wind speeds, because pollutants in plumes should become more dispersed at increased wind speed (Hanna et al., 1982). Counter to our expectations, correlation with $E_{plume,4}$ was not better than with $E_{plume,3}$, reflecting possible increased volatilization rates of ammonia with wind speed (Moore et al., 2014). The relationship between ambient ammonia concentrations and wind speed may be nonmonotonic if faster winds increase the amount of ammonia emitted from an AFO but also decrease the resultant downwind concentrations by dilution. One investigation of swine AFO odor in residential communities found that odor intensity increased at both low speeds and high speeds relative to moderate wind speeds (Wing et al., 2008), implying a nonlinear relationship between wind speed and AFO exposures.

Our findings in this study were similar to those of our earlier smaller longitudinal study of childhood and ambient ammonia (Loftus et al., 2015a). This is not surprising because ammonia is a component of the complex mixture of air pollutants comprising AFO air emissions. From this analysis we are unable to determine whether observed associations with health are due to any specific component of AFO air pollution or a combination of one or more contaminants, many of which have been associated with respiratory effects. The current analysis expands upon the previous one by employing a substantially larger sample size and by focusing on exposure to AFO plumes as a mixture of potential toxicants rather than on a single chemical component. We also report suggestive evidence that increased exposure to AFO air pollution leads to short-term increases uLTE4, a biomarker of short-term immunological changes that increases with asthma exacerbations (Hoffman et al., 2018; Rabinovitch et al., 2012). Urinary LTE_4 is an emerging biomarker of asthma severity and exacerbation, and has been recommended for research on short term asthma morbidity (Hoffman et al., 2018; Rabinovitch et al., 2012). In a separate analysis of the AFARE cohort,

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higher LTE4 levels occurred with concurrent elevations in criteria pollutants and pesticides (Benda-Coker et al., 2019). Our current findings provide further evidence of the utility of LTE4 as a sensitive biomarker of asthma morbidity associated with environmental exposures.

Strengths of our study include the panel study design, which mitigates between-participant confounding by leveraging within-participant contrasts in exposure and outcome over time. Another important strength is that we validated our modeled AFO plume exposures with comparisons to ambient concentrations of ammonia, a component of AFO plumes, measured repeatedly at 18 sites across the region. We accounted for exposure at both home and school by modeling exposure at both locations for each child and time-averaging based on school schedules.

There are methodological limitations that should be considered when interpreting our results. The approach to modeling AFO pollution was informed by principles of pollutant dispersion from a point source, but AFOs are area sources rather than true point sources. Violations of this assumption would affect exposure estimates at locations closest to AFOs (Hanna et al., 1982). Another potential limitation is that our calculations of E_{plume} assumed constant pollutant emission rates from each AFO. This is a reasonable assumption considering that most toxic components of AFO plumes are emitted by animal waste, and animals produce waste daily. However, our exposure estimates do not account for the fact that emission rates from individual AFOs can differ substantially by facility-specific characteristics, such as the type and age of animals confined, manure treatment practices, duration of manure storage in waste lagoons, and protein content of animal feed (Hristov et al., 2011). Also, our time-varying exposure estimates did not account for applications of manure slurry or fertilizer to nearby fields, an event likely to significantly increase local concentrations of ammonia, hydrogen sulfide, and other pollutants (Bussink et al., 1998). Our plume modeling did not include occurrence of inversions or other meteorological events that could substantially affect spatial dispersion of AFO emissions, nor did we factor in local topography or nearby buildings. The study region is relatively flat, so regional topography may have had minimal influence on short-range pollutant dispersion, though the mountains that bound the valley could impact long-range dispersion. Further limitations in exposure assessment include crude and unvalidated assumptions about time spent at home versus school in order to calculate time-weighted exposure estimates. In addition, we cannot rule out the possibility that avoidance of intense AFO malodors affected children's behavior and, in turn, outdoor exposures to AFO plumes.

Limitations specific to our epidemiologic analyses include possible outcome misclassification and measurement error. Both reported asthma symptoms and home lung function tests can be inaccurate in pediatric populations (Fritz et al., 1996; Redline et al., 1996). Asthma symptoms were reported by child or parents, and misclassification could vary by reporter. We did not account for time of day of home lung function tests, though diurnal patterns could affect this outcome. Quantification of uLTE4 by immunoassay may overestimate LTE4 concentrations compared to other methods (Armstrong et al., 2009). However, because results of a panel study are driven by within-participant contrasts in exposures, biases due to systematic errors in outcome assessment would be reduced in

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comparison to a cross-sectional design. Additionally, children were asked to use peak flow meters on a daily basis, but we had missing FEV_1 data due to imperfect compliance and data loss. As described in our previous analyses of lung function measurements collected in AFARE (Loftus et al., 2015a and 2015b), we assessed likelihood of FEV_1 missingness in association with participant characteristics and did not see evidence of differential missingness; further, re-analysis with multiple imputation of FEV_1 values did not affect results. Because we previously detected no evidence of differential missingness and results were very similar to complete case analyses, we did not conduct multiple imputation for the current work. Finally, it should be noted that despite the large number of repeated measurements collected, the number of children in our cohort was rather small, which may limit generalizability of results to other pediatric populations.

Our findings add to accumulating evidence that exposure to AFO air emissions causes adverse short-term health effects in children with asthma residing nearby (Loftus et al., 2015a; Merchant et al., 2015; Mirabelli et al., 2006; Pavilonis et al., 2013; Radon et al., 2007; Rasmussen et al., 2017) and, further, suggest that health effects may be mediated by increases in inflammation. Emissions from AFOs are a complex mixture of numerous potential respiratory system toxicants. Based on our data collection we cannot identify the toxic agents responsible for adverse effects. AFO emissions are a complex mixture of contaminants with potential respiratory effects, all highly correlated in the exposure scenarios in this study. Ammonia is a respiratory system irritant but evidence linking environmental exposures to asthma exacerbations is scarce; it may serve as a proxy for correlated, established respiratory toxicants, including particulate matter, endotoxins, and hydrogen sulfide. A careful study of emission source contributions would be needed to understand how to mitigate the health effects, if they were confirmed; for example, regulations related to manure management and spraying could reduce community exposures. This research topic is important because pediatric asthma poses a significant public health burden for rural communities in the United States. Families in rural areas tend to be lower in socioeconomic status and have more limited access to quality health care compared to urban and suburban counterparts, increasing risk of respiratory morbidity for children with asthma (Ownby, 2005; Perry et al., 2008; Ungar et al., 2011). Furthermore, environmental pollution associated with industrial agricultural disproportionately impacts lower income and minority populations in the United States (Wing et al., 2000).

CONCLUSIONS

We developed a method for estimating daily exposure to AFO and validated estimates with direct measurements of ammonia, a chemical marker of AFO emissions. We utilized this metric in epidemiologic analyses of short-term changes in asthma outcomes in children with asthma; the results strengthen existing evidence that one or more pollutants emitted by AFOs may compromise community health. These findings motivate further work to identify the most toxic agents in AFO emissions and identify strategies for minimizing exposure, especially for children with asthma and other sensitive individuals.

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APPENDIX A

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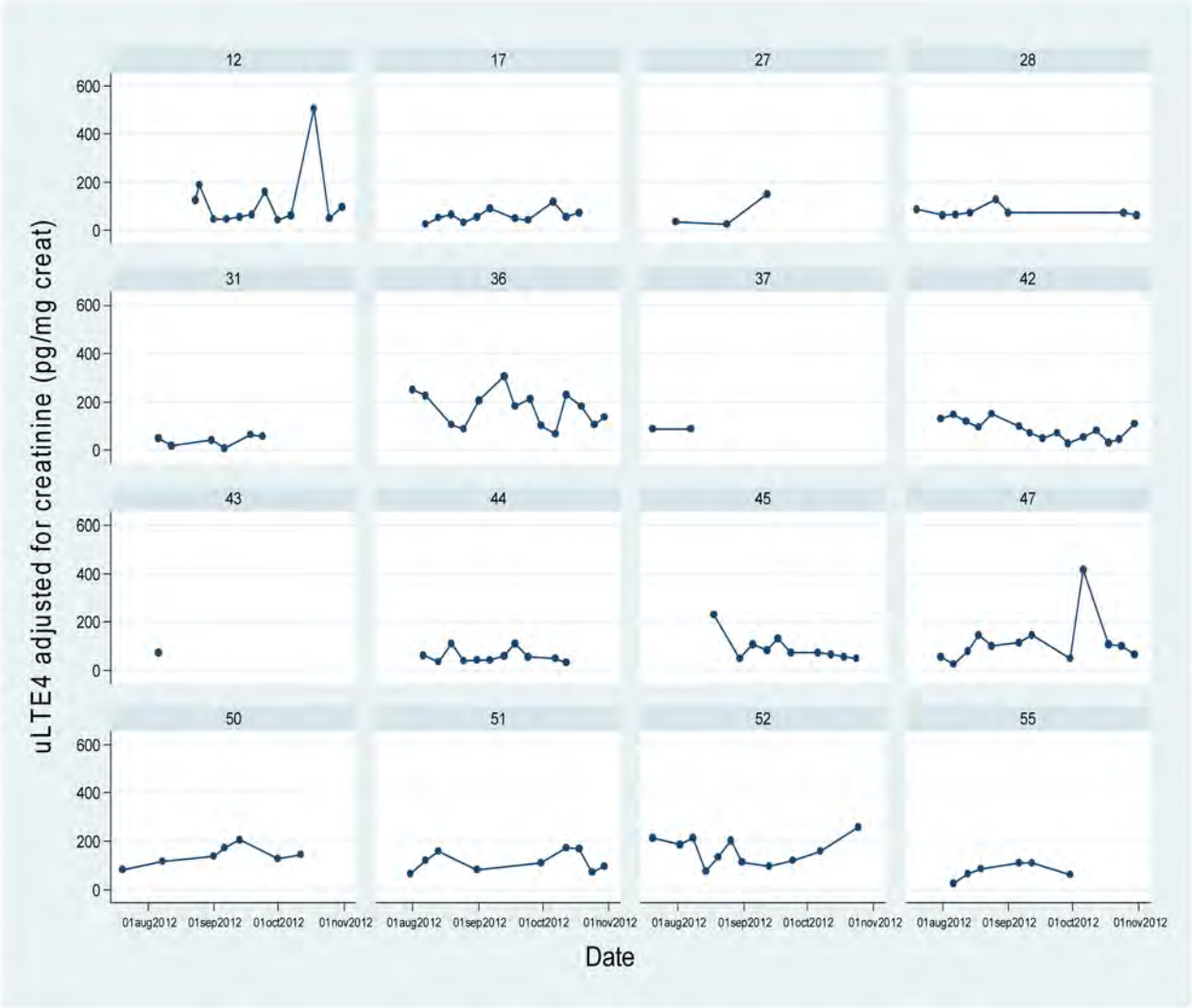

Figure A.1: Repeated measures of urinary LTE4 concentrations for AFARE participants.
Time series plots of uLTE4 (N=16) for all children participating in the LTE4 substudy. uLTE4 concentrations were adjusted for creatinine and log transformed.

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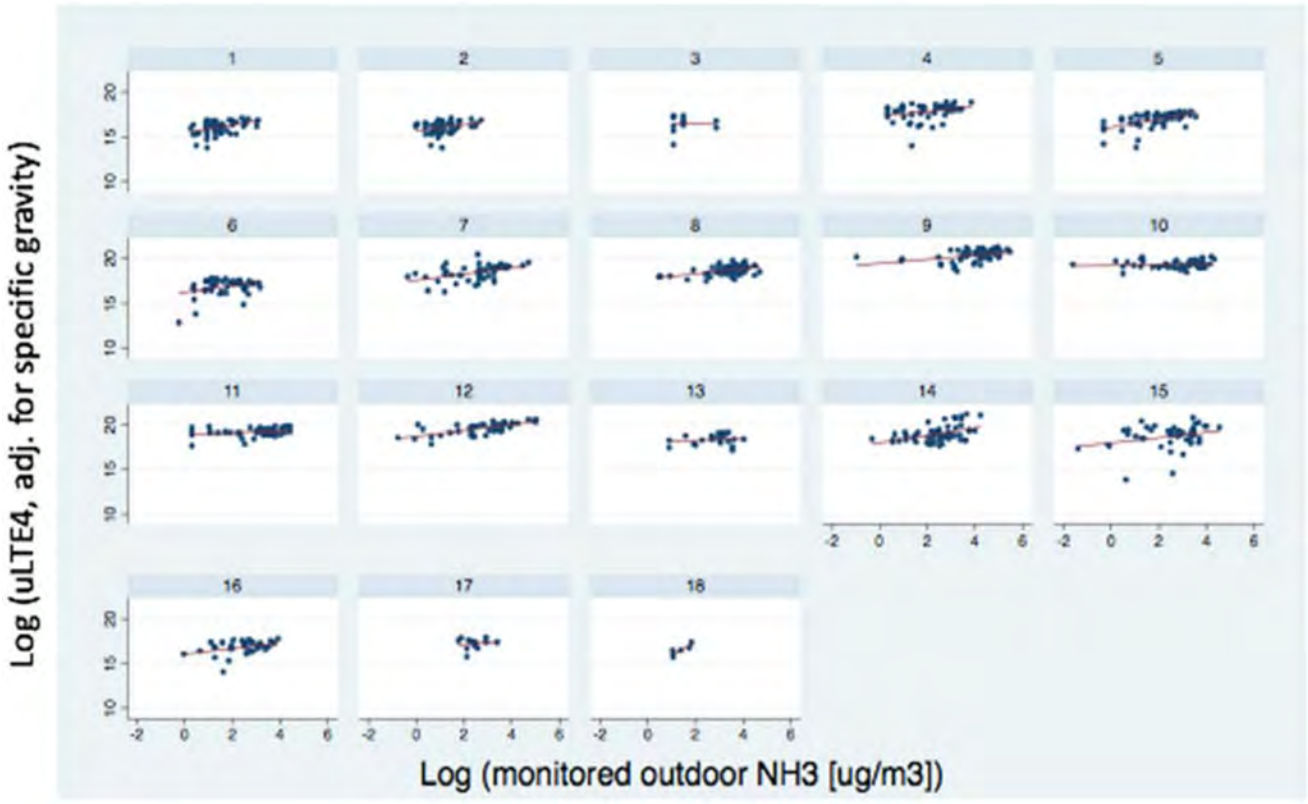

Figure A.2: Site-specific comparisons between outdoor ammonia and estimated ARO-related air pollution exposure.

Outdoor ammonia was measured at 18 sites at six-day intervals over a year (N=834).

REFERENCES

Adams PJ, Seinfeld JH, Koch DM. Global concentrations of tropospheric sulfate, nitrate, and ammonium aerosol simulated in a general circulation model. Journal of Geophysical Research-Atmospheres 1999;104(D11):13791–13823.

Aneja VP, Schlesinger WH, Erisman JW. Effects of Agriculture upon the Air Quality and Climate: Research, Policy, and Regulations. Environmental Science & Technology 2009;43(12):4234–4240. [PubMed: 19603628]

Armstrong JL, Fitzpatrick CF, Loftus CT, Yost MG, Tchong-French M, Karr CJ. Development of a unique multi-contaminant air sampling device for a childhood asthma cohort in an agricultural environment. Environ Sci Process Impacts. 2013: 15(9):1760–7. [PubMed: 23896655]

Armstrong M, Liu AH, Harbeck R, Reisdorph R, Rabinovitch N, Reisdorph N. Leukotriene-E4 in human urine: Comparison of on-line purification and liquid chromatography-tandem mass spectrometry to affinity purification followed by enzyme immunoassay. J Chromatogr B Analyt Technol Biomed Life Sci. 2009; 877: 3169–3174

Arteaga V, Mitchell D, Matt G, Quintana P, Schaeffer J, Reynolds S, Schenker M, Mitloehner F. Occupational Exposure to Endotoxin in PM2.5 and Pre- and Post-Shift Lung Function in California Dairy Workers. Journal of Environmental Protection. 2015; 6, 552–565.

Benka-Coker W, Loftus C, Karr C, Magzamen S. Association of Organophosphate Pesticide Exposure and a Marker of Asthma Morbidity in an Agricultural Community. J Agromedicine. 2019 5 25:1–9. [PubMed: 31766983]

Brender JD, Maantay JA, Chakraborty J. Residential proximity to environmental hazards and adverse health outcomes. Am J Public Health. 2011 12;101 Suppl 1:S37–52. [PubMed: 22028451]

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

Bussink D & Oenema O Ammonia volatilization from dairy farming systems in temperate areas: a review. Nutrient Cycling in Agroecosystems. 1998; 51: 19.

Cordioli M, Ranzi A, De Leo GA, Lauriola P. A review of exposure assessment methods in epidemiological studies on incinerators. J Environ Public Health. 2013;2013:129470. [PubMed: 23840228]

Coudon T, Hourani H, Nguyen C, Faure E, Mancini FR, Fervers B, Salizzoni P. Assessment of long-term exposure to airborne dioxin and cadmium concentrations in the Lyon metropolitan area (France). Environ Int. 2018 2;111:177–190. [PubMed: 29220728]

Coudon T, Danjou AMN, Faure E, Praud D, Severi G, Mancini FR, Salizzoni P, Fervers B. Development and performance evaluation of a GIS-based metric to assess exposure to airborne pollutant emissions from industrial sources. Environ Health. 2019 1 25;18(1):8. [PubMed: 30683108]

Curtiss PS, Rabl A. Impacts of air pollution: general relationships and site dependence. Atmos Environ 1996;30: 3331–47.

Dales R, Chen L, Frescura AM, Liu L, Villeneuve PJ. Acute effects of outdoor air pollution on forced expiratory volume in 1 s: a panel study of schoolchildren with asthma. Eur Respir J. 2009 8;34(2): 316–23 [PubMed: 19251781]

De Sario M, Pasetto R, Vecchi S, Zeka A, Hoek G, Michelozzi P, Iavarone I, Fletcher T, Bauleo L, Ancona C. A scoping review of the epidemiological methods used to investigate the health effects of industrially contaminated sites. Epidemiol Prev. 2018 Sep-Dec;42(5-6S1):59–68. [PubMed: 30322236]

Diggle Peter J.; Patrick Heagerty, Kung-Yee Liang, Zeger Scott L.. Analysis of Longitudinal Data. Oxford: Oxford University press; 2002.

Donham KJ. Respiratory disease hazards to workers in livestock and poultry confinement structures. Semin Respir Med 14:49–59 (1993).

Donham KJ, Lee JA, Thu K, Reynolds SJ. Assessment of air quality at neighbor residences in the vicinity of swine production facilities. Journal of Agromedicine 2006;11(3/4):15–24. [PubMed: 19274894]

Douglas P, Robertson S, Gay R, Hansell AL, Gant TW. A systematic review of the public health risks of bioaerosols from intensive farming. Int J Hyg Environ Health. 2018 3;221(2):134–173. [PubMed: 29133137]

Dungan RS, Leytem AB. Ambient Endotoxin Concentrations and Assessment of Offsite Transport at Open-Lot and Open-Freestall Dairies (vol 40, pg 462, 2011). Journal of Environmental Quality 2012;41(5):1702–1702.

Feilberg A, Hansen MJ, Liu D, Nyord T. Contribution of livestock H(2)S to total sulfur emissions in a region with intensive animal production. Nat Commun. 2017 10 20;8(1):1069. [PubMed: 29051487]

Fritz GK, McQuaid EL, Spirito A, Klein RB. Symptom perception in pediatric asthma: relationship to functional morbidity and psychological factors. J Am Acad Child Adolesc Psychiatry. 1996 8;35(8):1033–41. [PubMed: 8755800]

Ghannam K, El-Fadel M. Emissions characterization and regulatory compliance at an industrial complex: an integrated MM5/CALPUFF approach. Atmos Environ. 2013;69:156–169.

Hankinson JL, Odencrantz JR, Fedan KB. Spirometric reference values from a sample of the general US population. Am J Respir Crit Care Med. 1999;159(1):179–187. [PubMed: 9872837]

Hanna SR, Briggs GA, Hosker RP. Handbook on atmospheric diffusion. United States Department of Energy. Office of Energy Research.; United States Department of Energy. Office of Health and Environmental Research 1982.

Heederik D, Sigsgaard T, Thorne PS, et al. Health effects of airborne exposures from concentrated animal feeding operations. Environ Health Perspect. 2007;115(2):298–302. [PubMed: 17384782]

Hodgson S, Nieuwenhuijsen MJ, Colvile R, Jarup L. Assessment of exposure to mercury from industrial emissions: comparing "distance as a proxy" and dispersion modelling approaches. Occup Environ Med. 2007 6;64(6):380–8. Epub 2006 Dec 20. [PubMed: 17182645]

Hoek G, Ranzi A, Alimehmeti I, Ardeleanu ER, Arrebola JP, Ávila P, Candeias C, Colles A, Crişan GC, Dack S, Demeter Z, Fazzo L, Fierens T, Flückiger B, Gaengler S, Hänninen O, Harzia H,

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

Hough R, Iantovics BL, Kalantzi OI, Karakitsios SP, Markis KC, Martin-Olmedo P, Nechita E, Nicoli T, Orru H, Pasetto R, Pérez-Carrascosa FM, Pestana D, Rocha F, Sarigiannis DA, Teixeira JP, Tsadilas C, Tasic V, Vaccari L, Iavarone I, de Hoogh K. A review of exposure assessment methods for epidemiological studies of health effects related to industrially contaminated sites. Epidemiol Prev. 2018 Sep-Dec;42(5-6S1):21–36. [PubMed: 30322233]

Hoffman BC, Rabinovitch N. Urinary Leukotriene E_4 as a Biomarker of Exposure, Susceptibility, and Risk in Asthma: An Update. Immunol Allergy Clin North Am. 2018 11;38(4):599–610. [PubMed: 30342582]

Hooiveld M, Smit LAM, van der Sman-de Beer F, Wouters IM, van Dijk CE, Spreeuwenberg P, Heederik DJJ, Yzermans CJ. Doctor-diagnosed health problems in a region with a high density of concentrated animal feeding operations: a cross-sectional study. Environ Health. 2016 2 17;15:24. [PubMed: 26888643]

Horton RA, Wing S, Marshall SW, Brownley KA. Malodor as a trigger of stress and negative mood in neighbors of industrial hog operations. Am J Public Health. 2009;99:S610–S615. [PubMed: 19890165]

Hristov AN, Hanigan M, Cole A, et al. Review: Ammonia emissions from dairy farms and beef feedlots. Can J Anim Sci. 2011;91(1):1–35.

Janes H, Sheppard L, Shepherd K. Statistical analysis of air pollution panel studies: an illustration. Ann Epidemiol. 2008 10;18(10):792–802. [PubMed: 18922395]

Kalkowska DA, Boender GJ, Smit LAM, Baliatsas C, Yzermans J, Heederik DJJ, Hagenaars TJ. Associations between pneumonia and residential distance to livestock farms over a five-year period in a large population-based study. PLoS One. 2018 7 17;13(7):e0200813. [PubMed: 30016348]

Ko G, Simmons OD III, Likirdopulos CA, Worley-Davis L, Williams CM, Sobsey MD. Endotoxin Levels at Swine Farms Using Different Waste Treatment and Management Technologies. Environmental Science & Technology 2010;44(9):3442–3448. [PubMed: 20356077]

Lewin A, Buteau S, Brand A, Kosatsky T, Smargiassi A. Short-term risk of hospitalization for asthma or bronchiolitis in children living near an aluminum smelter. J Expo Sci Environ Epidemiol. 2013 Sep-Oct;23(5):474–80. [PubMed: 23695491]

Loftus C, Yost M, Sampson P, Torres E, Arias G, Breckwich Vasquez V, Hartin K, Armstrong J, Tchong-French M, Vedal S, Bhatti P, Karr C. Ambient Ammonia Exposures in an Agricultural Community and Pediatric Asthma Morbidity. Epidemiology. 2015a;26(6):794–801. [PubMed: 26352250]

Loftus C, Yost M, Sampson P, Arias G, Torres E, Vasquez VB, Bhatti P, Karr C. Regional PM2.5 and asthma morbidity in an agricultural community: a panel study. Environ Res. 2015b;136:505–12. doi: 10.1016/j.envres.2014.10.030. [PubMed: 25460673]

Loyo-Berríos NI, Irizarry R, Hennessey JG, Tao XG, Matanoski G. Air pollution sources and childhood asthma attacks in Catano, Puerto Rico. Am J Epidemiol. 2007 4 15;165(8):927–35. [PubMed: 17308332]

May S, Romberger DJ, Poole JA. Respiratory Health Effects of Large Animal Farming Environments. Journal of Toxicology and Environmental Health-Part B-Critical Reviews 2012;15(8):524–541.

Merchant JA, Naleway AL, Svendsen ER, Kelly KM, Burmeister LF, Stromquist AM, Taylor CD, Thorne PS, Reynolds SJ, Sanderson WT, Chrischilles EA. Asthma and farm exposures in a cohort of rural Iowa children. Environ Health Perspect. 2005 3;113(3):350–6. [PubMed: 15743727]

Micheli A, Meneghini E, Mariottini M, Baldini M, Baili P, Di Salvo F, Sant M. Risk of death for hematological malignancies for residents close to an Italian petrochemical refinery: a population-based case-control study. Cancer Causes Control. 2014 12;25(12):1635–44. [PubMed: 25281327]

Mirabelli MC, Wing S, Marshall SW, Wilcosky TC. Asthma symp- toms among adolescents who attend public schools that are located near confined swine feeding operations. Pediatrics. 2006;118:e66–e75. [PubMed: 16818539]

Moore KD, Young E, Gurell C, Wojcik MD, Martin RS, Bingham GE, Pfeiffer RL, Praeger JH, Hatfield JL. AMMONIA MEASUREMENTS AND EMISSIONS FROM A CALIFORNIA DAIRY USING POINT AND REMOTE SENSORS. Transactions of the ASABE 2014;57(1):181–198.

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

Ownby DR. Asthma in rural America. Ann Allergy Asthma Immunol. 2005 11;95(5 Suppl 1):S17–22. [PubMed: 16312158]

Partridge MR, van der Molen T, Myrseth SE, Busse WW. Attitudes and actions of asthma patients on regular maintenance therapy: The INSPIRE study. BMC Pulm Med. 2006;6:13. [PubMed: 16772035]

Pascal M, Pascal L, Bidondo ML, Cochet A, Sarter H, Stempfelet M, Wagner V. A review of the epidemiological methods used to investigate the health impacts of air pollution around major industrial areas. J Environ Public Health. 2013;2013:737926. [PubMed: 23818910]

Pavilonis BT, Sanderson WT, Merchant JA. Relative exposure to swine animal feeding operations and childhood asthma prevalence in an agricultural cohort. Environmental Research 2013;122:74–80. [PubMed: 23332647]

Pavilonis BT, O'Shaughnessy PT, Altmaier R, Metwali N, Thorne PS. Passive monitors to measure hydrogen sulfide near concentrated animal feeding operations. Environmental Science-Processes & Impacts 2013;15(6):1271–1278. [PubMed: 23681048]

Perry TT, Vargas PA, McCracken A, Jones SM. Underdiagnosed and uncontrolled asthma: findings in rural schoolchildren from the Delta region of Arkansas. Ann Allergy Asthma Immunol. 2008 10;101(4):375–81. [PubMed: 18939725]

Postma JM, Smalley K, Ybarra V, Kieckhefer G. The Feasibility and Acceptability of a Home-Visitation, Asthma Education Program in a Rural, Latino/a Population. J Asthma. 2011 ;48(2): 139–146. [PubMed: 21043988]

Purdy CW, Clark RN, Straus DC. Ambient and indoor particulate aerosols generated by dairies in the southern High Plains. J Dairy Sci. 2009 12;92(12):6033–45. [PubMed: 19923606]

Rabinovitch N Urinary leukotriene E4 as a biomarker of exposure, susceptibility and risk in asthma. Immunol Allergy Clin North Am. 2012 8;32(3):433–45. [PubMed: 22877620]

Radon K, Schulze A, Ehrenstein V, van Strien RT, Praml G, Nowak D. Environmental exposure to confined animal feeding operations and respiratory health of neighboring residents. Epidemiology 2007;18(3):300–308. [PubMed: 17435437]

Rasmussen SG, Casey JA, Bandeen-Roche K, Schwartz BS. Proximity to Industrial Food Animal Production and Asthma Exacerbations in Pennsylvania, 2005-2012. Int J Environ Res Public Health. 2017 3 31;14(4).

Reddel HK, Taylor DR, Bateman ED, Boulet LP, Boushey HA, Busse WW, Casale TB, Chanez P, Enright PL, Gibson PG, de Jongste JC, Kerstjens HA, Lazarus SC, Levy ML, O'Byrne PM, Partridge MR, Pavord ID, Sears MR, Sterk PJ, Stoloff SW, Sullivan SD, Szefler SJ, Thomas MD, Wenzel SE; American Thoracic Society/European Respiratory Society Task Force on Asthma Control and Exacerbations. An official American Thoracic Society/European Respiratory Society statement: asthma control and exacerbations: standardizing endpoints for clinical asthma trials and clinical practice. Am J Respir Crit Care Med. 2009 7 1;180(1):59–99. [PubMed: 19535666]

Redline S, Wright EC, Kattan M, Kercsmar C, Weiss K. Short-term compliance with peak flow monitoring: results from a study of inner city children with asthma. Pediatr Pulmonol. 1996;21(4): 203–10. [PubMed: 9121848]

Reynolds SJ, Nonnenmann MW, Basinas I, Davidson M, Elfman L, Gordon J, Kirychuck S, Reed S, Schaeffer JW, Schenker MB, Schlünssen V, Sigsgaard T. Systematic review of respiratory health among dairy workers. J Agromedicine. 2013;18(3):219–43. [PubMed: 23844790]

Schinasi L, Horton RA, Guidry VT, Wing S, Marshall SW, Morland KB. Air Pollution, Lung Function, and Physical Symptoms in Communities Near Concentrated Swine Feeding Operations. Epidemiology 2011;22(2):208–215. [PubMed: 21228696]

Schulze A, Roemmelt H, Ehrenstein V, van Strien R, Praml G, Kuechenhoff H, Nowak D, Radon K. Effects on Pulmonary Health of Neighboring Residents of Concentrated Animal Feeding Operations: Exposure Assessed Using Optimized Estimation Technique. Archives of Environmental & Occupational Health 2011;66(3):146–154. [PubMed: 21864103]

Sigurdarson ST, Kline JN. School proximity to concentrated animal feeding operations and prevalence of asthma in students. Chest 2006;129(6):1486–1491. [PubMed: 16778265]

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Smargiassi A, Kosatsky T, Hicks J, Plante C, Armstrong B, Villeneuve PJ, Goudreau S. Risk of asthmatic episodes in children exposed to sulfur dioxide stack emissions from a refinery point source in Montreal, Canada. Environ Health Perspect. 2009 4;117(4):653–9. [PubMed: 19440507]

Thorne PS, Ansley AC, Perry SS. Concentrations of Bioaerosols, Odors, and Hydrogen Sulfide Inside and Downwind from Two Types of Swine Livestock Operations. Journal of Occupational and Environmental Hygiene 2009;6(4):211–220. [PubMed: 19177273]

Ungar WJ, Paterson JM, Gomes T, Bikangaga P, Gold M, To T, Kozyrskyj AL. Relationship of asthma management, socioeconomic status, and medication insurance characteristics to exacerbation frequency in children with asthma. Ann Allergy Asthma Immunol. 2011 1;106(1):17–23. [PubMed: 21195940]

Von Essen S, Moore G, Gibbs S, et al. Respiratory issues in beef and pork production: recommendations from an expert panel. J Agromedicine 2010;15:216–25. [PubMed: 20665307]

Washington State Department of Agriculture. Chapter RCW 90.64, Dairy Nutrient Management Act. http://agr.wa.gov/foodanimal/livestock-nutrient/ [Accessed June 23, 2014]

White N, WaterNaude J, van der Walt A, Ravenscroft G, Roberts W, Ehrlich R. Meteorologically estimated exposure but not distance predicts asthma symptoms in schoolchildren in the environs of a petrochemical refinery: a cross-sectional study. Environ Health. 2009 9 25;8:45. [PubMed: 19781087]

Williams DL, Breysse PN, McCormack MC, Diette GB, McKenzie S, Geyh AS. Airborne cow allergen, ammonia and particulate matter at homes vary with distance to industrial scale dairy operations: an exposure assessment. Environ Health. 2011 8 12;10:72. [PubMed: 21838896]

Williams DA, McCormack MC, Matsui EC, Diette GB, McKenzie SE, Geyh AS, Breysse PN. Cow allergen (Bos d2) and endotoxin concentrations are higher in the settled dust of homes proximate to industrial-scale dairy operations. J Expo Sci Environ Epidemiol. 2016 Jan-Feb;26(1):42–7. [PubMed: 25138294]

Wing S, Cole D, Grant G. Environmental injustice in North Carolina's hog industry. Environ Health Perspect. 2000;108(3):225–231

Wing S, Horton RA, Marshall SW, Thu K, Tajik M, Schinasi L, Schiffman SS. Air pollution and odor in communities near industrial swine operations. Environ Health Perspect. 2008 10;116(10):1362–8. [PubMed: 18941579]

Wing S, Horton RA, Rose KM. Air Pollution from Industrial Swine Operations and Blood Pressure of Neighboring Residents. Environmental Health Perspectives 2013;121(1):92–96. [PubMed: 23111006]

Yu CL, Wang SF, Pan PC, Wu MT, Ho CK, Smith TJ, Li Y, Pothier L, Christiani DC; Kaohsiung Leukemia Research Group. Residential exposure to petrochemicals and the risk of leukemia: using geographic information system tools to estimate individual-level residential exposure. Am J Epidemiol. 2006 8 1;164(3):200–7. [PubMed: 16754633]

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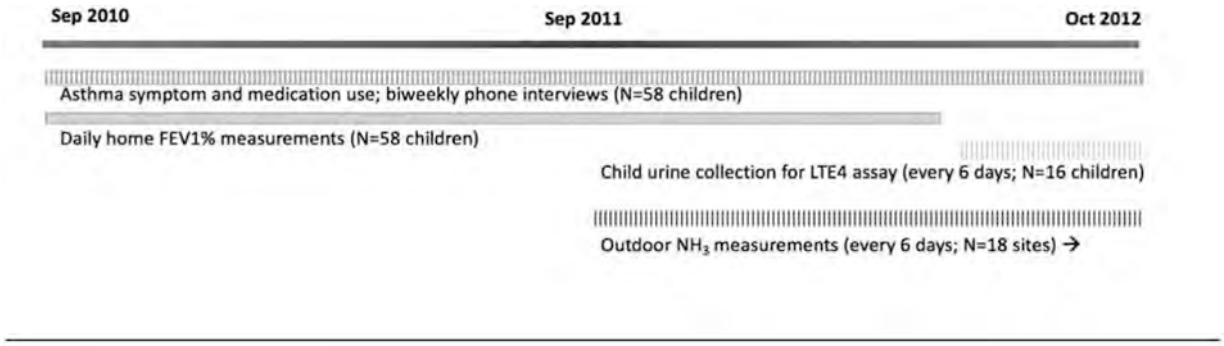

Figure 1: Timeline of health and exposure data collection.

Repeated collection of longitudinal health and exposure data across the span of the AFARE study.

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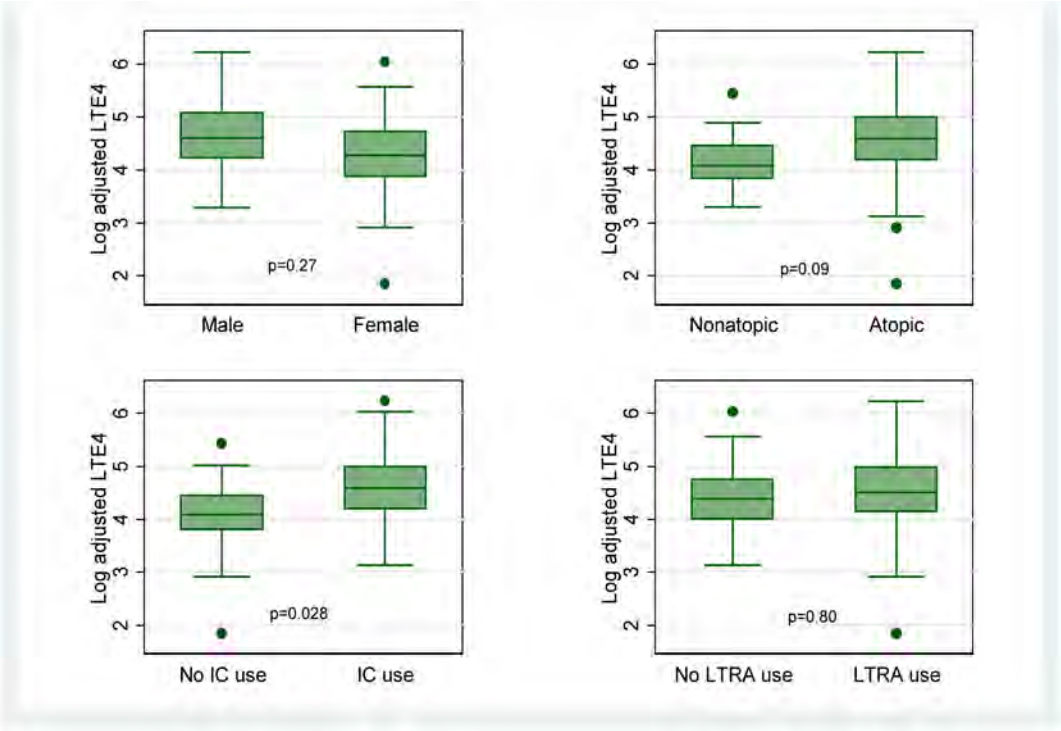

Figure 2: Univariate associations between subject-mean urinary LTE4 and child characteristics.
Average subject-specific mean uLTE4 (N=16) was compared to child characteristics using t-tests with unequal variances. uLTE4 concentrations were adjusted for creatinine and log transformed. Abbreviations: IC = inhaled corticosteroid use reported at baseline; LTRA = leukotriene receptor agonist use reported at baseline; LTE4 = leukotriene E4

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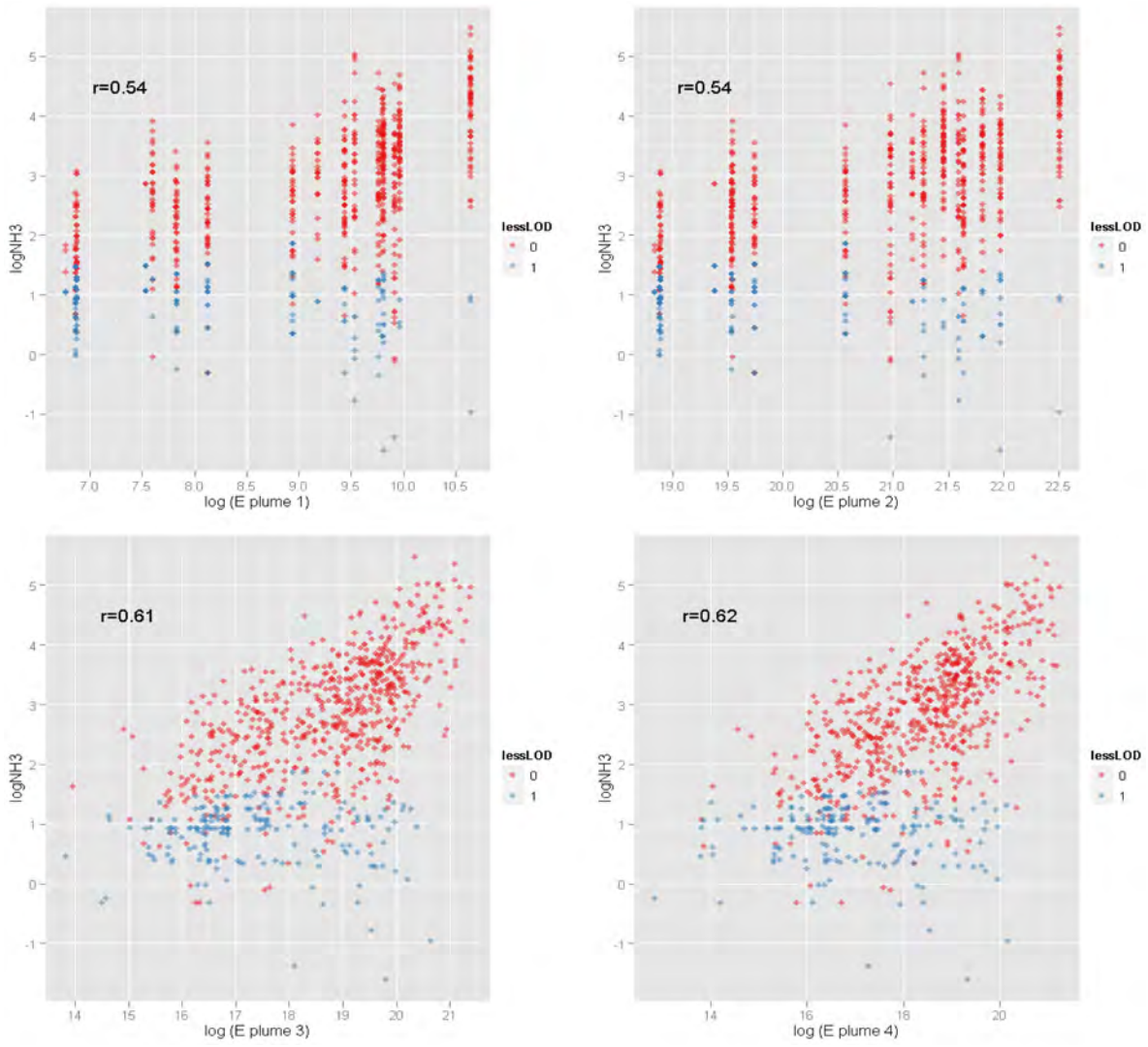

Figure 3: Comparison between outdoor ammonia and estimated ARO-related air pollution exposure at AFARE monitoring sites.

Outdoor ammonia was measured at 18 sites at six-day intervals over a year (N=834). Concentrations estimated from an ammonia mass below the LOD are highlighted in blue.

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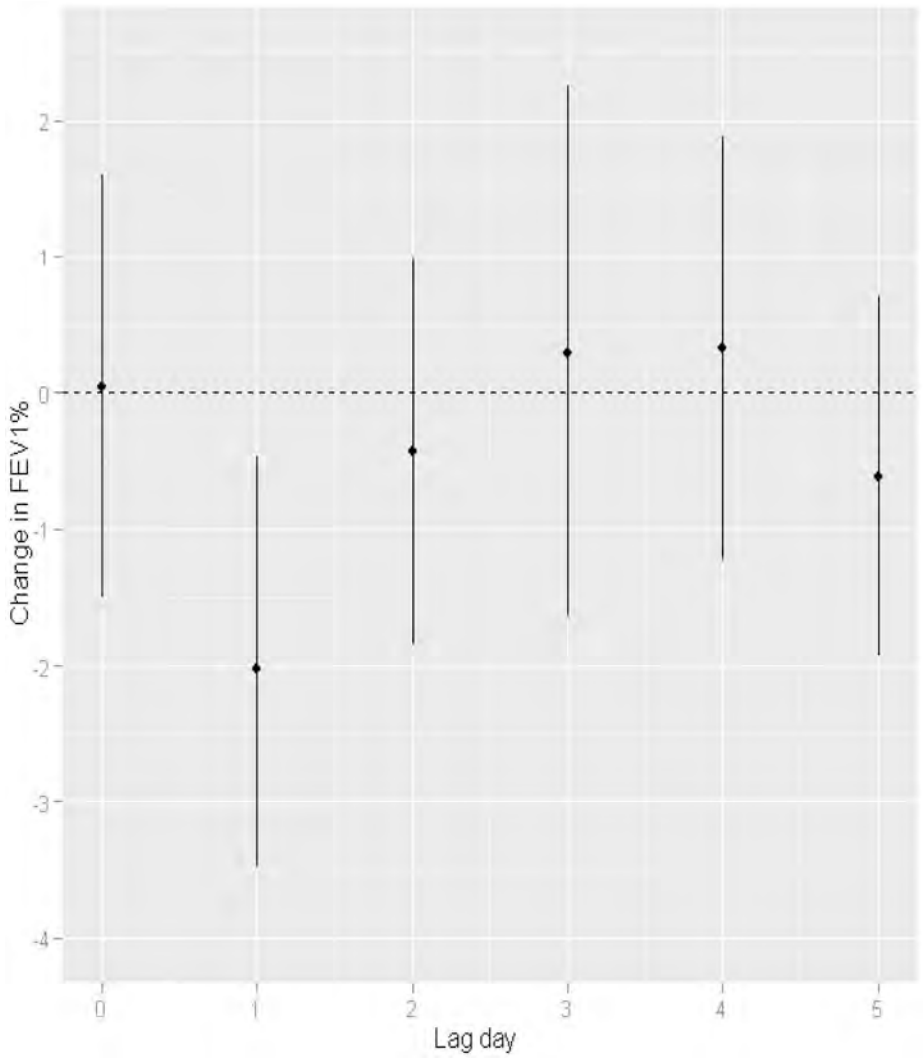

Figure 4: Associations between estimated daily AFO exposure and child lung function (FEV1, % predicted).

Associations between AFO exposure and daily lung function (FEV1, % predicted; N=3853 measurements) were estimated using generalized estimating equations, with adjustment for time-varying factors, each modeled using cubic splines (temperature, relative humidity, elapsed week of study, and seasonality (calendar month)) as well as subject-specific characteristics (sex, age, atopy, use of inhaled corticosteroids at baseline, BMI at baseline and presence of adult smoker in household.) Effect sizes are scaled to an IQR increase in AFO exposure, estimated using E plume 4.

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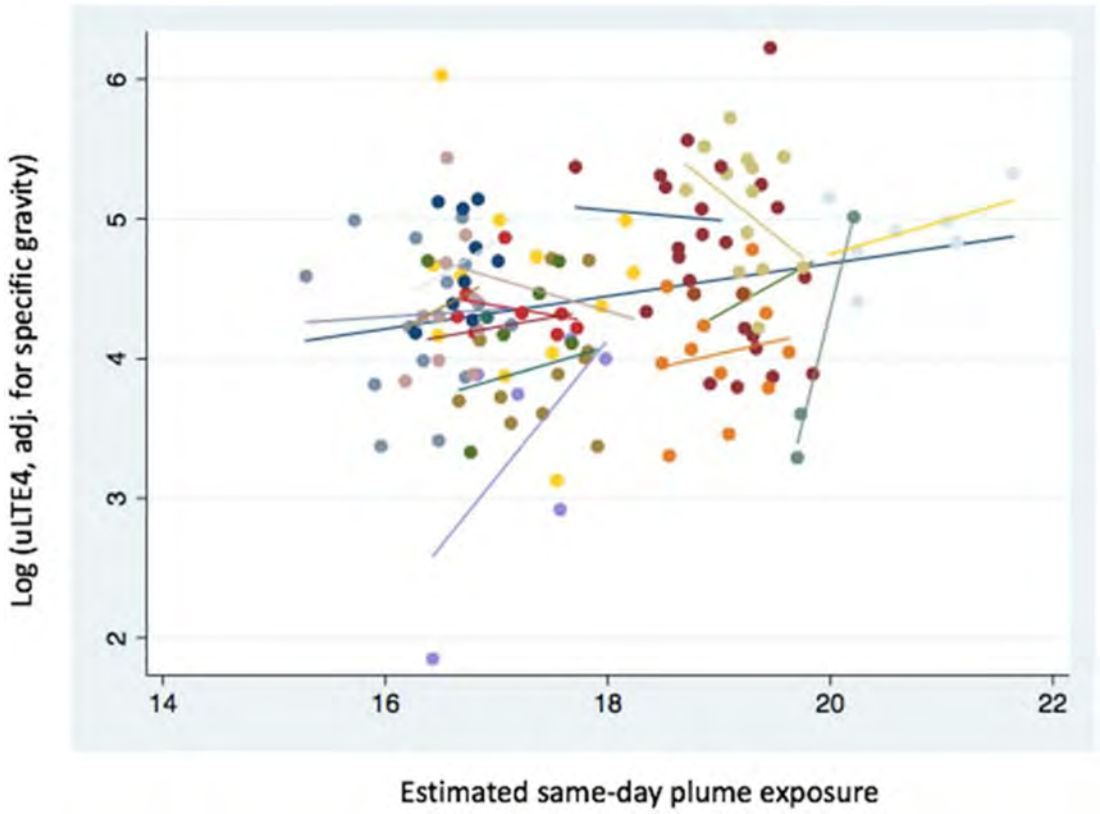

Figure 5: Urinary LTE4 and estimated AFO pollution exposure on the same day.

Participant urinary LTE4 (adjusted for creatinine and log-transformed) and estimated AFO plume exposure on the same day is plotted. Shorter lines show subject-specific slopes and the longer line shows the trend for the entire sample.

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Table 1:

Metrics to estimate daily AFO plume exposure

E_{plume}	Formula	Description
1	$E_{plume,1}(s,a) = log\sum_{a=1}^{97} \frac{1}{d_{a,s}^2}$	Exposure depends on proximity to AFOs alone (time invariant)
2	$E_{plume,2}(s,a) = log\sum_{a=1}^{97} \frac{A_a}{d_{a,s}^2}$	Exposure depends on proximity to AFOs and estimated size of facility (time invariant)
3	$E_{plume,3}(t,s,a) = log\sum_{a=1}^{97} \frac{A_a f(t,s,a)}{d_{a,s}^2}$	Exposure depends on distance, size and the percent of time on that day when wind was blowing towards subject location (time varying)
4	$E_{plume,4}(t,s,a) = log\sum_{a=1}^{97} \frac{A_a f(t,s,a)}{d_{a,s}^2 * u(t,s,a)}$	Same as (3) but with an additional term in denominator for average wind speed (time varying)

Abbreviations:

s = subject location (home or school)

a = animal operation (AFO)

t = day of study

A_a = estimated size of AFO facility (in m^2)

$d_{a,s}$ = AFO to subject distance

f (t, s, a) = fraction of hours in day when wind is blowing from AFO to home on 8-point wind rose

u (t, s, a) = average wind speed during the hours when wind is blowing from AFO to home

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Table 2:

Characteristics of participants in analytic sample

	All participants (N=58) N (%) or mean +/− s.d.	LTE4 substudy (N=16) N (%) or mean +/− s.d.
Child demographics		
Female	29 (50%)	7 (44%)
Age at baseline (years)	10.4 +/− 2.7	9.7 +/− 2.5
Born outside US	10 (17%)	4 (25%)
Hispanic/Latino ethnicity	54 (93%)	15 (94%)
Household characteristics		
Household income <$15k/year	24 (41%)	8 (50%)
Parent(s) employed as farmworker	29 (50%)	9 (56%)
At least one adult smoker in household	8 (14%)	0 (0%)
Baseline asthma health		
Reported controller medication use		
Inhaled corticosteroids (IC)	41 (71%)	11 (69%)
Leukotriene antagonist (LTRA)	17 (29%)	6 (38%)
Both IC and LTRA	14 (24%)	5 (31%)
Ever hospitalized with asthma	38 (66%)	8 (50%)
Unscheduled visit for asthma in previous 12 months	46 (79%)	14 (88%)
Atopic asthma[a]	42 (71%)	12 (75%)

Abbreviations: s.d., standard deviation; US, United States; ED, emergency department; BMI, body mass index; IC, inhaled corticosteroids; LTRA, leukotriene antagonist.

[a]Indicated by positive skin prick test to at least one of 22 common inhalant allergens.

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Table 3:

Summary of participant-specific asthma outcomes[1]

	mean +/− s.d.
Percentage of interviews in which symptom reported in week prior	
Woken by asthma	45 +/− 25%
Limited in daily activities	35 +/− 23%
Shortness of breath	19 +/− 14%
Symptoms in morning	39 +/− 22%
Wheezing	25 +/− 19%
Percentage of interviews in which short-acting medication use reported in week prior	49 +/− 27%
Participant-average FEV_1%	75 +/− 15%

[1] For every outcome, an average value for each participant across all time points was determined. The average and s.d. across all participant-specific means are presented here.

Abbreviations: FEV_1%, forced expiratory volume in 1 second as a percent of predicted value; s.d., standard deviation

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Table 4:

Associations between weekly AFO air pollution exposure and reported asthma symptoms and medication use.

Odds ratios for report vs. no report of symptoms or medication use on biweekly surveys (N=2023) were estimated using generalized estimating equations, with adjustment for time-varying factors, each modeled using cubic splines (temperature, relative humidity, elapsed week of study, and seasonality (calendar month)) as well as subject-specific characteristics (sex, age, atopy, use of inhaled corticosteroids at baseline, BMI at baseline and presence of adult smoker in household.) Odds ratios are scaled to an IQR increase in AFO exposure (1.89), estimated using E plume 4, averaged over the week prior.

Reported symptom or medication use in week prior	OR for report vs. no report of symptom	95% CI		p-value
Woken by asthma	0.90	0.75	1.08	0.27
Limited in daily activities	0.93	0.76	1.14	0.29
Shortness of breath	0.93	0.77	1.13	0.48
Symptoms in morning	0.93	0.79	1.12	0.45
Wheezing	0.90	0.75	1.08	0.27
Use of short-acting bronchodilator	1.00	0.78	1.13	0.49

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Table 5:

Associations between AFO air pollution exposure at various lag days and urinary LTE4.

Average differences in uLTE4 were calculated for an IQR increase in AFO plume exposure on varying lag days using linear mixed models, adjusted for child age, atopy status, and reported inhaled corticosteroid use at baseline.

Exposure lag	Difference in log pLTE4 (ug/mg creatinine)	95% CI	p-value
0 (same day)	0.17	−0.01, 0.35	0.059
1	0.12	−0.02, 0.26	0.09
2	0.11	−0.07, 0.28	0.23
3	0.13	−0.04, 0.31	0.14

The Death of the Duty to Apply: Limitations to CAFO Oversight Following Waterkeeper & National Pork Producers

William M. McLaren*

I. Introduction

For approximately fifty years, concentrated animal feeding operations[1] (CAFOs) have been the method of choice for the large-scale livestock "farming" industry.[2] CAFOs are facilities designed to house and cultivate livestock in which common feeding practices are mechanized for efficiency. CAFOs are designed to maximize livestock density, and the yields of resulting animal products are thereby increased compared to traditional feeding operations.[3] Through technological improvements and cost-saving methods, CAFO owners can reduce the traditionally required capital to sustain large-scale livestock operations and thereby substantially increase long-term profits.[4]

While CAFOs are often criticized for compromising human health,[5] another significant area of critical focus is their detrimental impacts on surface and groundwater quality caused by incidental

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[1] Note that "concentrated" and "confined" may be used interchangeably, depending on the authority employing the term. *Compare* 33 U.S.C. § 1362(14) (2006) (including "concentrated animal feeding operations" in the definition of a "point source") *with* Or. Admin. R. 603-074-0010(3)(a) (2012) (defining "confined animal feeding operation" to mean "the concentrated confined holding of animals or poultry"). Regardless of this fact, CAFO overwhelmingly carries the same definition.

[2] *See* David Fraser, Food And Agriculture Organization Of The United Nations, Animal Welfare and The Intensification Of Animal Production: An Alternative Interpretation 4, 6 (2005).

[3] The Pew Comm'n on Indus. Farm Animal Prod., Putting Meat on the Table: Industrial Farm Animal Production In America 2 (2008), *available at* http://perma.cc/CC9T-YSBX.

[4] Doug Gurian-Sherman, CAFOs Uncovered: The Untold Costs of Confined Animal Feeding Operations 19 (2008) , *available at* http://perma.cc/6Z4N-JK7R.

[5] *See generally* Carrie Hribar, Nat'l Ass'n of Local Boards of Health, Understanding Concentrated Animal Feeding Operations and Their Impacts on Communities 2–11 (Mark Schultz ed., 2010) (providing a concise summary of the prominent environmental and health impacts of CAFOs).

animal waste runoff, or "effluent."[6] To address this, the definition of "point source" in the Clean Water Act (CWA) includes CAFOs,[7] and the CWA is the primary tool used by federal and state governments in regulating effects on the nation's waters resulting from CAFO-produced effluent. Importantly, the Environmental Protection Agency (EPA) entered into a consent decree in which the agency proposed to issue a rule to address and limit CAFO pollutants entering federal waters, thereby expanding on previously relaxed enforcement of the industry.[8] After extensive planning, a federal rule was promulgated and adopted in 2003 that imposed permit requirements on CAFOs under the CWA's National Pollutant Discharge Elimination System (NPDES).[9] The NPDES permitting program operates to set and maintain allowable levels of pollutant discharge to protect the waters of the United States and concurrently seeks to meet the concerns of an industry whose progress can be stifled by over-regulation.[10] The adopted rule brought CAFOs under the broad NPDES regulatory scheme, requiring CAFO owners to apply for NPDES permits unless they could proffer evidence showing no potential discharge from their facility.[11] This requirement is broadly referred to as the strict "duty to apply" because it imposes an affirmative duty upon CAFO owners to secure NPDES permits regardless of whether EPA or an affiliate regulatory body affirmatively shows the facility actually discharges in violation of the CWA. For the purposes of this article, the strict duty to apply will be simply referred to as the "duty to apply." When this rule was in effect, CAFO owners who failed to apply were subject to action in response to CWA violations.[12]

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[6] *Cf.* U.S. GEN. ACCOUNTING OFFICE, GAO/RCED-95-200BR, ANIMAL AGRICULTURE: INFORMATION ON WASTE MANAGEMENT WATER QUALITY ISSUES 1-2 (1995) (indicating, in in the early era of the CAFO water quality regulating regime, that the number of regulated operations was nearly two thousand), *available at* http://perma.cc/3CEB-2Z4Z.

[7] 33 U.S.C. § 1362(14) (2006).

[8] Terrence J. Centner, *Courts and EPA Interpret NPDES General Permit Requirements for CAFOs*, 38 ENVTL. L. 1215, 1219 (2008).

[9] National Pollution Discharge Elimination System Permit Regulation and Effluent Guidelines and Standards for Concentrated Animal Feeding Operations, 68 Fed. Reg. 7176 (Feb. 12, 2003) (codified at 40 C.F.R. pt. 122) [hereinafter "the 2003 Rule"].

[10] *See generally id.* at 7179 (explaining that "[a]mong its core provisions, the Act prohibits the discharge of pollutants to the waters of the United States *except as authorized* by an NPDES permit," insinuating that the purpose of NPDES permits is to allow a controlled pollutant discharge within the confines of measured safe levels).

[11] *Id.* at 7202–03 ("[A]n unpermitted CAFO that does in fact discharge pollutants to waters of the U.S., *with or without a determination of 'no potential to discharge,'* would be in violation of the Clean Water Act).

[12] *Id.*

a. Waterkeeper and the Death of the Duty to Apply

In recent years, two pivotal cases have significantly altered the regulatory regime that EPA employs to monitor and police CAFOs. Decided in 2005, *Waterkeeper Alliance, Inc. v. U.S. Environmental Protection Agency* ("*Waterkeeper*") was brought by two primary interest groups classified by the court as the "Environmental Petitioners" and the "Farm Petitioners."[13] These two groups challenged the Final CAFO Rule ("the 2003 Rule") based on three general categories.[14] For the purposes of this article, the most important challenge was that directed against the 2003 Rule's permitting scheme. The petitioners specifically targeted the "mandatory duty to apply for an NPDES permit"[15] that the 2003 Rule imposed on all CAFOs, save for those with "no potential to discharge." Those CAFOs were specifically required to "make such a demonstration in lieu of obtaining a permit."[16]

In *Waterkeeper*, the Farm Petitioners argued that the mandatory permit requirement of the 2003 Rule (also called the "duty to apply")[17] was legally inconsistent with the CWA.[18] The *Waterkeeper* court agreed, declaring that the CWA only authorizes EPA to regulate "the discharge of pollutants," and does not create "a statutory obligation of point sources to seek or obtain an NPDES permit in the first instance."[19] Because of this perceived disparity between the 2003 Rule and the CWA itself, the court determined that the duty to apply, as required by the 2003 Rule, was inconsistent with the intent of Congress and failed the deference test applied by the court.[20] Some commenters argue that the court's application of *Chevron* was in direct contradiction with its ruling

[13] Waterkeeper Alliance, Inc. v. EPA, 399 F.3d 486 (2d Cir. 2005) [hereinafter "*Waterkeeper*"] (both of these groups were composed of interests that favored change to EPA's regulatory scheme, but for widely different purposes).

[14] *Id.* at 497 ("(1) challenges to the permitting scheme established by the CAFO Rule; (2) challenges to the types of discharges subject to regulation under the CAFO Rule; and (3) challenges to the effluent limitation guidelines established by the CAFO Rule.").

[15] The 2003 Rule, *supra* note 9, at 7182.

[16] *Id.*

[17] *Waterkeeper*, *supra* note 13, at 504.

[18] *Id.*

[19] *Id.* at 505 (citing National Resources Defense Council v. EPA, 859 F.2d 156, 170 (D.C. Cir. 1988).

[20] *Id.* at 506 ("[T]he Clean Water Act, on its face, prevents EPA from imposing, upon CAFOs, the obligation to seek an NPDES permit or otherwise demonstrate that they have no potential to discharge.") (citing Chevron U.S.A. Inc. v. Natural Resources Defense Council, Inc., 467 U.S. 837, 842–43 (1984) (noting "where Congress has directly spoken to the precise question at issue and the intent of Congress is clear, that is the end of the matter; for the court, as well as the agency, must give effect to the unambiguously expressed intent of Congress." (internal quotations omitted)).

on other related matters.[21] However, the court clearly declared that the CWA "prevents EPA from imposing upon CAFOs the obligation to seek an NPDES permit."[22] This pivotal decision marked the first in a series of integral blows to EPA's ability to regulate CAFOs using NPDES permits.

b. National Pork Producers and the Invalidation of "Proposes to Discharge"

The validity of NPDES permit requirements under the CWA was revisited in *National Pork Producers Council v. United States Environmental Protection Agency* ("*National Pork Producers*"), a 2011 case in which several of *Waterkeeper's* petitioners reprised their roles[23] to challenge yet another rule relating to the regulation of CAFOs.[24] The breadth of disagreement with EPA's new rule was vast, as the *National Pork Producers* court was by the Judicial Panel on Multi-District Litigation[25] to review an array of challenges filed in *six* different districts.[26] The rule at issue in *National Pork Producers* ("the 2008 Rule") was promulgated by EPA in response to the *Waterkeeper* decision.[27] Specifically, the 2008 Rule included a provision that replaced the 2003 Rule's duty to apply[28] with a seemingly more lenient requirement: "that a CAFO owner or operator [must] apply for a permit only if the CAFO discharges or *proposes to discharge* pollutants."[29] Unsurprisingly, this requirement met opposition from Farm interests once again, who proceeded to challenge it on several grounds.[30]

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[21] Christopher Brown, *When the "Plain Text" Isn't So Plain: How* National Pork Producers Council *Restricts The Clean Water Act's Purpose and Impairs its Enforcement Against Factory Farms*, 16 DRAKE J. AGRIC. L. 375, 383 (2011) [hereinafter "Brown"].

[22] *Waterkeeper*, *supra* note 13, at 506 (citing Chevron U.S.A. Inc. v. Nat'l. Res. Def. Council, Inc., 467 U.S. 837, 842–43 (1984)) (internal punctuation omitted).

[23] The petitioners common to both cases are the National Pork Producers Council, the National Chicken Council, and the American Farm Bureau Federation. Nat'l. Pork Producers Council v. U.S. E.P.A., 635 F.3d 738 (5th Cir. 2011) [hereinafter "*Nat'l Pork Producers*"].

[24] *Id.* at 741.

[25] *Nat'l Pork Producers*, 635 F.3d at 741. The random selection requirement was pursuant to 28 U.S.C. § 2112(a)(3) (2006).

[26] *Nat'l Pork Producers*, 635 F.3d at 741.

[27] *See* Revised National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines for Concentrated Animal Feeding Operations in Response to Waterkeeper Decision, 71 Fed. Reg. 37744 (June 30, 2006) (codified at 40 C.F.R. pt. 122) [hereinafter "the 2008 Rule"].

[28] The 2003 Rule, *supra* note 9, at 7181–82.

[29] *Nat'l Pork Producers*, 635 F.3d at 746 (citing 71 Fed. Reg. 37744, 37747 (June 30, 2006)) (emphases added) (internal quotation marks omitted).

[30] *Id.* at 749–50.

With the argument against any duty to apply bolstered by the *Waterkeeper* decision, the 2008 Rule proved susceptible to the Farm Petitioners' challenge, and ultimately fell in a way similar to of the 2003 Rule.[31] The *National Pork Producers* court also addressed the duty to apply with respect to CAFOs that "propose[] to discharge." The court rejected the notion that "proposes to discharge" means "wants to discharge" or "intends to discharge."[32] Instead, the court identified that a CAFO that "proposes to discharge" means "a CAFO[] designed, constructed, operated, and maintained in a manner such that the CAFO *will* discharge." In a puzzling analysis of the phrase "proposes to discharge," the court declared that the duty to apply would effectively require permits both from CAFOs that are presently discharging pollutants, which is an legically sound outcome, and CAFOs whose operators "*want* to discharge,"[33] which, according to the court, is outside of EPA's statutory authority.[34] Because this particular definition was deemed by the court to require facilities that are not actually discharging to apply for a permit, the court determined that it "runs afoul of *Waterkeeper*."[35] Therefore, the duty to apply, even in a form so innocuous as to require permits from CAFOs that *want* to discharge pollutants, was once again stripped from the NPDES program. This marked the second substantial blow to the CAFO-related NPDES permitting requirements, and led EPA to vacate the duty to apply aspects of the 2008 Rule.[36]

While it is inarguable that the *Waterkeeper* and *National Pork Producers* decisions imposed limitations upon EPA's jurisdiction over CAFOs regarding their potential to discharge pollutants,[37] some commenters posit that artifice led to those outcomes.[38] The reasoning

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[31] *Id.* at 750.

[32] *Id.* (citing WEBSTER'S THIRD NEW INTERNATIONAL DICTIONARY 1819 (8th ed. 1993)).

[33] *See id.* (emphasis added).

[34] *Id.* at 751.

[35] *Id.* at 750.

[36] *See* National Pollutant Discharge Elimination System Permit Regulation for Concentrated Animal Feeding Operations: Removal of Vacated Elements in Response to 2011 Court Decision, 77 Fed. Reg. 44494 (July 30, 2012) (to be codified at 40 C.F.R. § 122).

[37] *See id.* ("remov[ing] from the Code of Federal Regulations (CFR) the specific "propose to discharge" requirement in 40 CFR 122.23(d)" because the *Nat'l Pork Producers* court "issued an opinion that, among other things, vacated those portions of the 2008 CAFO Rule requiring CAFOs that propose to discharge to apply for an NPDES permit").

[38] Brown, *supra* note 21, at 376–77 (arguing that courts should interpret the CWA in light of its ultimate purpose, "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" and asserting that "pre-discharge permitting and monitoring would appear to further, rather than violate the purposes of the CWA," as the *Waterkeeper* and *Nat'l Pork Producers* courts seem to suggest).

employed by the courts warrants analysis,[39] but the importance of regulating CAFOs and the regulatory structure itself must first be considered.

II. The Effects of CAFOs on Waters

The shift in farming methods away from spacious, decentralized family farms to compact, high-yield factory farms has not come without consequence. The incorporation of CAFOs into rural communities—which, for obvious reasons, are often the locale of choice for CAFO owners[40]—results in a veritable cacophony of impacts that lead to environmental, health, economic, and humanitarian concerns. These impacts include, but are by no means limited to, groundwater contamination,[41] surface water contamination,[42] air quality degradation,[43] proliferation of antibiotic-resistant pathogens,[44] increases in localized insect vectors,[45] inhumane and injurious treatment of animals,[46] shifts towards oligopolies in the agricultural market,[47] reductions in property values based on proximity to CAFOs,[48] and the production of significant

[39] *Infra* Part IV.A–B.

[40] *See* The Pew Comm'n on Indus. Farm Animal Prod., *supra* note 3, at 17.

[41] Hribar, *supra* note 5, at 3; *infra* Part II.A.

[42] *Id.* at 4; *infra* Part II.B.

[43] *Id.* at 5 (explaining that CAFOs "produce... air emissions, including gaseous and particulate substances," proportionate to the size of the CAFO, and "[t]he primary cause of gaseous emissions is the decomposition of animal manure, while particulate substances are caused by the movement of animals").

[44] Gurian-Sherman, *supra* note 4, at 5 (observing that "the massive use of antibiotics in CAFOs, especially for non-therapeutic purposes such as growth promotion," can contribute to "the development of antibiotic-resistant pathogens [such as Salmonella, Escherichia coli, and Campylobacter] that are more difficult to treat").

[45] Hribar, *supra* note 5, at 8 (describing the production of these vectors, namely those of "Houseflies, stable flies, and Mosquitoes," the most common insects associated with CAFOs, continuing by stating "[h]ouseflies breed in manure, while stable and other flies breed in decaying organic material, such as livestock bedding. Mosquitoes breed in standing water, and water on the edges of manure lagoons can cause mosquito infestations to rise").

[46] The Pew Comm'n on Indus. Farm Animal Prod., *supra* note 3, at 13 (explaining the connection between the intensive confinement practices common to CAFOs and the severe restriction of animal movement and natural behaviors such that animals are unable to walk. The resulting stress from these situations can promote immunodeficiency.).

[47] *Id.* at 17 (finding that "[t]he family-owned farm producing a diverse mix of... food animals is largely gone as an economic entity, replaced by larger farm factories that produce just one animal species" and rural communities have fared poorly.).

[48] Ind. Bus. Research Ctr., The Effect of Regulated Livestock Operations on Property Values in Selected Indiana Counties 3 (2008), *available at* http://perma.cc/5SLK-4WKL.

greenhouse gases (GHGs).[49] For the purposes of this article, the most important of these issues are those of ground- and surface water contamination.

a. Groundwater Contamination Caused by CAFO-Produced Effluent

Groundwater is the subject of extensive quality analysis and maintenance by governmental and private interests alike, due in part to its high value and multiple functions, and the benefits of groundwater are shared by citizens, businesses, agricultural interests, and municipalities, among others.[50] Waste runoff from mismanaged CAFOs has the propensity to detrimentally effect groundwater nutrient concentrations and contaminate groundwater resources.[51] Liquid effluent from CAFOs percolates into soils by flowing through their naturally porous infrastructure.[52] Excess percolation can occur in any number of ways, the most prominent of which is over-application of waste runoff to "farmland" immediately adjacent to CAFOs.[53]

In modern practice, the predominant method of disposing of the effluent produced by CAFOs is "land application." Land application redistributes animal waste in the form of solid or liquid effluent over agricultural plots connected to CAFOs.[54] This method spurs increased agricultural yields due to the arguable similarity between effluent nutrient contents and commercial manure.[55] Land application may be performed using direct-soil injection methods or through airborne distribution. Airborne distribution uses "tankers," which are specialized vehicles outfitted with large arms that deploy effluent onto fields in a

[49] GURIAN-SHERMAN, *supra* note 4, at 52, 54–56.

[50] *See generally* STATE OF OR. DEP'T OF ENVTL. QUALITY, GROUNDWATER PROTECTION IN OREGON 2 (January 2011) (explaining the values and functions of groundwater in Oregon and listing as examples, among others, "[g]roundwater makes up approximately 95 percent of [] freshwater resources[,]... Oregon's businesses require clean groundwater for industries such as food processing, dairies, manufacturing, and computer chip production[.] . . . [g]roundwater provides irrigation water for Oregon agriculture and water for livestock[,] . . . [g]roundwater supplies base flow for most of the state's rivers, lakes, streams, and wetlands").

[51] *See* IND. DEP'T OF ENVTL. MGMT., CONFINED FEEDING OPERATIONS (CFOs/CAFOs), http://perma.cc/QW49-VY3V (last visited Jan. 27, 2013).

[52] *See* ANDRÉS ALCOLEA & AGUSTÍN MEDINA, UNIVERSITAT POLITECNICA DE CATALUNYA, GROUNDWATER FLOW IN POROUS MEDIA 18 (2012) (explaining how soil porosity results in "groundwater flow rules" which "control the quantity and the quality of the groundwater"), *available at* http://perma.cc/6VV9-EP8H.

[53] IND. DEP'T OF ENVTL. MGMT., *supra* note 51.

[54] U.S. ENVTL. PROT. AGENCY, UNIFIED NATIONAL AFO STRATEGY EXECUTIVE SUMMARY § 4.4 (1999).

[55] *Id.*

method comparable to an enormous version of a lawn sprinkler.[56] If land application is performed incorrectly or in excess, the chemicals and nutrients contained in the re-applied wastewater may contaminate sub-surface streams, rivers, and aquifers, as explained above.[57]

Groundwater problems and the effects of land application have been recognized and addressed in existing regulatory schemes.[58] To combat these problems, "[i]ndividual [NPDES] permits can allow for the evaluation and accounting of the suitability of the [permitted] land for the application of manure."[59] Therefore, application for and enforcement of NPDES permits may result in a concrete source of information, available to CAFO owners and regulating bodies alike, to help check groundwater contamination.[60] Examples of the data to be gained from site-specific NPDES permits include: measurements of "the soil and subsoil permeability, the presence of aquifers, the vulnerability of groundwater resources, ... surrounding land uses, and the existence of water withdrawals downstream of the proposed disposal site."[61] All of this data enable informed decision-making and promote management practices that benefit not only CAFO properties but also surrounding land uses. Thus, site-specific NPDES permits have the capacity to encourage CAFO owners to select methods of effluent application and efficient effluent storage facility locations that account for the site-specific conditions of the property containing the CAFO.[62] Requiring CAFO owners to take account for hydrological and ecological realities of individual properties when executing management and construction decisions can potentially promote groundwater protection.[63]

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[56] U.S. ENVTL. PROT. AGENCY, BIOSOLIDS TECHNOLOGY FACT SHEET: LAND APPLICATION OF BIOSOLIDS (2000), *available at* http://perma.cc/NN9E-HGDB.

[57] *See generally* JORDE BATTLE-AGUILAR, UNIVERSITÉ DE LIÈGE, GROUNDWATER FLOW AND CONTAMINANT TRANSPORT IN AN ALLUVIAL AQUIFER: IN-SITU INVESTIGATION AND MODELING OF A BROWNFIELD WITH STRONG GROUNDWATER—SURFACE WATER INTERACTIONS 28 (2008) (explaining, via a study directed towards brownfield contamination mitigation, "ground- and surface water are not independent systems[,] ... [c]hanges in surface water [contaminant] levels ... are likely to cause changes on groundwater levels ... in the adjacent aquifer (or river/stream), as well as water fluxes from one system to the other").

[58] *See* U.S. ENVTL. PROT. AGENCY, AMENDMENTS TO THE STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE (1995); 40 C.F.R. § 503.10 (2007).

[59] Michael Steeves, *EPA's Proposed CAFO Regulations Fall Short of Ensuring the Integrity of Our Nation's Waters*, 22 J. LAND RES. & ENVTL. L. 367, 378–79 (2002).

[60] *See generally* National Pollutant Discharge Elimination System (NPDES) Concentrated Animal Feeding Operation (CAFO) Reporting Rule, 77 Fed. Reg. 42679 (July 20, 2012) (to be codified at 40 C.F.R. § 9) (proposing to collect information about existing CAFOs from NPDES programs that have officiated permits to those CAFOs in the past).

[61] Steeves, *supra* note 59, at 378–79

[62] *Id.* at 379.

[63] *See* A. Dennis McBride, N.C. Dep't of Health and Human Services, *The Association of Health Effects With Exposure to Odors from Hog Farm Operations*,

b. Surface Water Contamination Caused by CAFO-Produced Effluent

As with groundwater contamination, surface water contamination caused by CAFO-borne effluent byproducts is a near constant source of environmental concern.[64] Surface water is more susceptible to contamination than groundwater simply because there are fewer natural, pollutant arresting barriers (e.g., soil, vegetation) between surface-level contamination sources and surface water bodies.[65] Depending on a CAFO's specific design and structure, runoff from storm events or light rain is a common means by which CAFO-produced animal effluent is conveyed into surface water.[66] When animal waste, whether in solid or liquid state, is kept near waterways that run through or are adjacent to CAFOs, severe weather or poor storage facility design may cause spills directly into surface water.[67] Two representative examples of large-scale failures of CAFO waste storage provide context for the concept of effluent runoff, and were the subject of a major monitoring project on the effects of large effluent spills on surrounding habitats.[68] First, in 1995, due to massive structural failure of a *single* "waste treatment lagoon,"[69] 25 million gallons of swine effluent were released into North Carolina's New River and its estuaries. The effluent polluted approximately 22 miles of river, causing fish kills, algal blooms, and E. coli bacterial contamination throughout.[70] A second event befell Duplin, North Carolina in 1995, when 8.6 million gallons of chicken effluent burst from another ruptured waste lagoon and ultimately flowed into the

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http://perma.cc/65XB-LQCB (1998) (last accessed Jan. 27, 2013); *see also* William Ritter & Anastasia Chirnside, *The Impact of Land Use on Groundwater Quality in Southern Delaware*, 22 Ground Water 38, 41 (1984) (a Delaware study of a sampling of wells associated with a high water table aquifer in which more than 30 percent of the subjects had nitrate levels that exceeded EPA's designated drinking water standards).

[64] Hannah Connor, *Comprehensive Regulatory Review: Concentrated Animal Feeding Operations Under The Clean Water Act From 1972 To The Present*, 12 VT. J. ENVTL. L. 275, 280 (2011).

[65] Steeves, *supra* note 59, at 374.

[66] *See* U.S. ENVTL. PROT. AGENCY, CAFOs—LIVESTOCK OPERATION INSPECTION: WHAT TO EXPECT WHEN EPA INSPECTS YOUR LIVESTOCK 1 (2003), *available at* http://perma.cc/Z686-G7YL.

[67] GURIAN-SHERMAN, *supra* note 4, at 51.

[68] JoAnn Burkholder, et al., *Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality*, 115 ENVTL. HEALTH PERSPECTIVES 308, 309 (2007).

[69] A "waste treatment lagoon" is an "impoundment made by constructing an embankment and/or excavating a pit or dugout" employed to "biologically treat waste . . . and thereby reduce pollution." NATURAL RES. CONSERVATION SERV., CONSERVATION PRACTICE STANDARD: WASTE TREATMENT LAGOON 359-1 (2003).

[70] GURIAN-SHERMAN, *supra* note 4, at 51.

Northeast Cape Fear River.[71] These events merely serve as snapshots of the many instances of surface water contamination resulting from common failures of CAFOs.[72]

Much like groundwater contamination,[73] surface water contamination by CAFOs usually takes the form of increased nutrient concentrations and a resulting propagation of existing bacterial communities which can negatively affect human health. Studies have shown that increased levels of microorganisms spawned by pollutants from CAFOs, specifically cyanobacteria, "may be especially harmful to people with depressed or immature immune systems."[74] Further, eutrophication serves as another example of a frequent and severe surface water impairment resulting from CAFO pollution. Eutrophication is a process that results when CAFO runoff emits high concentrations of nutrient pollutants that reduce oxygen levels in receiving streams and lakes and thereby accelerate the development of naturally occurring algae.[75] Increased algal bloom results in even greater net positive feedback to this process and promotes oxygen depletion in the host water body, both by algal respiration[76] and reduction in sunlight penetration.[77] This process can culminate in massive fish kills, sometimes in the hundreds of thousands,[78] as well as the death of shellfish and other invertebrates in similar magnitudes.[79] To mitigate the effects of these problems, CAFO owners occasionally employ vegetative buffers, composed of densely placed regional, perennial vegetation or other constructed barriers. These buffers decrease effluent runoff rates, lower nutrient pollution in nearby streams and rivers, and tend to increase vegetation-based soil infiltration.[80]

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[71] Michael Mallin & JoAnn Burkholder, *Comparative Effects of Poultry and Swine Waste Lagoon Spills on the Quality of Receiving Streamwaters*, 26 J. ENVTL. QUAL. 1622, 1631 (1997).

[72] *See* ROBBIN MARKS, CESSPOOLS OF SHAME: HOW FACTORY FARM LAGOONS AND SPRAYFIELDS THREATEN ENVIRONMENTAL AND PUBLIC HEALTH 36 (2001) (offering a compendium of CAFO spills and detrimental environmental effects from throughout the 1990s); *see generally* NATURAL RESOURCES DEFENSE COUNCIL, *Facts About Pollution from Livestock Farms*, http://perma.cc/XNA5-DVE5 (last visited Jan. 27, 2013) (listing specific and generalized concerns over nationwide surface water pollution resulting from CAFOs).

[73] *See infra* Part II.A.

[74] THE PEW COMM'N ON INDUS. FARM ANIMAL PROD., *supra* note 3, at 25 (citing Rao PV et al., *Toxicity Evaluation of In Vitro Cultures of Freshwater Cyanobacterium Microcystis Aeruginosa*, 8 BIOMED. ENVTL. SCI. 254 (1995)).

[75] Connor, *supra* note 64, at 287.

[76] Archie McDonnell & Rupert Kountz, *Algal Respiration in a Eutrophic Environment*, 38 J. WATER POLL. CONTROL FED'N 841 (1966).

[77] CLAUDIA COPELAND, SPECIALIST IN RESOURCES AND ENVIRONMENTAL POLICY, ANIMAL WASTE AND WATER QUALITY: EPA REGULATION OF CONCENTRATED ANIMAL FEEDING OPERATIONS, CONG. RESEARCH SERVICE 4 (2010).

[78] MARKS, *supra* note 72, at 36.

[79] COPELAND, *supra* note 77, at 4.

[80] GURIAN-SHERMAN, *supra* note 4, at 51.

As significant as these CAFO-based environmental maladies may be, a regulatory structure that offers both flexibility and consistency can make significant strides toward thorough mitigation of their detrimental effects on the nation's waters. While the NPDES permitting regime, implemented under the CWA and enforced by EPA, has been met with complete acceptance in the private sector, it remains the principal line of environmental defense against the externalities borne of unregulated CAFOs. Because this limited regulatory structure is unlikely to change, these realities will continue affect not only environmental and public interests, but also members of the CAFO industry who tend to play by the regulatory book.

III. The Regulatory Framework

General federal environmental regulation in the United States has a storied past, and the regulation of pollutants entering the nation's waters is no exception. With many of the nation's waterways still impaired, the importance of a stable and evenhanded regulatory regime is immeasurable.[81] The CWA and the NPDES program were not the first federal attempts to implement water quality requirements and control pollutant discharge into the nation's waters, but they have undoubtedly been the most persistent and successful.[82] Effectively, the CWA assures that the amount of pollution that CAFOs, among others, are permitted to produce is bridled by a set of uniform standards.[83] These standards may be generalized or individually tailored, based on the regulating body and the regulated entity.[84] However, this was not always the case.

a. Early Federal Water Pollution Regulation

In their infant stages, federal water pollution control programs were enacted based on the protection of human health, rather than environmental protection or conservation.[85] The first in a litany of varying regimes leading to the current iteration of the CWA was the 1948 Water Pollution Control Act,[86] which "allocated funds to state and

[81] *See* U.S. Envtl. Prot. Agency, Office of Wastewater Mgmt., Water Permitting 101 (1999) [hereinafter U.S. Envtl. Prot. Agency].

[82] David H. Moreau, *The Clean Water Act Revisited: Accomplishments and Issues for Reauthorization, Water Pollution Control in the United States: Policies, Planning, and Criteria*, 94 J. Contemp. Water Res. & Educ. 4, 20 (1994).

[83] *See* 40 C.F.R. 122.45(b) (2000).

[84] U.S. Envtl. Prot. Agency, Types of NPDES Permits: Individual Versus General Permits, http://perma.cc/6PMY-9XKV (last accessed February 1, 2013) (explaining "[a]n NPDES permit can be written to address discharges either from an individual point source or from a number of similar dischargers").

[85] U.S. Envtl. Prot. Agency, *supra* note 81.

[86] Pub. L. No. 80-845, 62 Stat. 1155 (1948).

local governments for pollution control" in general, but had "few, if any, federal goals, objectives, limits, or guidelines."[87]

The role of the federal government in curtailing water pollution increased in the fifties and sixties, during which Congress passed the Water Pollution Control Act Amendments of 1956[88] and the Federal Water Pollution Control Act Amendments of 1961.[89] Both "focused on giving additional funding to municipalities for constructing wastewater treatment works."[90] Then, in 1965, the concept of setting water quality standards for the nation's waters was formally introduced via the Water Quality Act,[91] which required individual states to develop water quality standards that would protect their waterways within a two-year period following the Act's passage.[92] This attempt suffered from limited enforcement because it placed a large burden on the federal government to "prove that pollutant loadings had an impact on human health or violated water quality standards" prior to carrying out enforcement procedures.[93] It became apparent that the loftiness of this goal destined the Act for failure. In addition to those shortcomings, the Water Quality Act attached no substantial penalties to states that violated its requirements,[94] reducing it to a toothless beast.[95]

Although the enacted legislation was largely ineffective, after the passage of the Water Quality Act in 1965, the "view that water quality was deteriorating became an 'uncontested truth' in Washington [D.C.], despite the absence of facts and documentation to back up that position."[96] The movement toward legislative change in the area of water quality culminated in the passage of the Federal Water Pollution Control Act Amendments of 1972.[97] These amendments, along with "modest changes" in the seventies and eighties,[98] have become collectively referred to as the Clean Water Act. These amendments "mark[ed] a distinct change in the philosophy of water pollution control in the United

[87] U.S. ENVTL. PROT. AGENCY, *supra* note 81.

[88] Pub. L. No. 84-660, 70 Stat. 498 (1956).

[89] Pub. L. No. 87-88, 75 Stat. 204 (1961).

[90] U.S. ENVTL. PROT. AGENCY, *supra* note 81.

[91] John H. Minan, *Municipal Separate Storm Sewer System (Ms4) Regulation Under The Federal Clean Water Act: The Role Of Water Quality Standards?*, 42 SAN DIEGO L. REV. 1215, 1230 (2005).

[92] U.S. ENVTL. PROT. AGENCY, *supra* note 81.

[93] *Id.*

[94] *Id.* at 2.

[95] *See* Pub. L. No. 89-234, 70 Stat. 498 (1965); *see also* Andrew P. Morris et al., *The Failure of EPA's Water Quality Reforms: From Environment-Enhancing Competition to Uniformity and Polluter Profits*, 20 UCLA J. ENVTL. L. & POL'Y 25, 27 n.9 (2001).

[96] Moreau, *supra* note 82, at 13.

[97] *Id.*

[98] *Id.*

States" by setting ambitious goals to not only maintain the quality-based controls established by prior regulatory system, but to place equal emphasis on "technology-based, or end-of-pipe, control strategies."[99] The system established by the CWA has become the framework for water pollution control in the United States, and has remained that way for over thirty years.[100]

b. Federal Enforcement of Water Pollution Regulations

As Congress learned through past attempts at water quality regulation, effective and enforceable regulations must necessarily attach to pollution control standards for standards to operate as intended and policy goals to be met.[101] In order to meet its lofty goal of "[r]estoration and maintenance of [the] chemical, physical and biological integrity of [the] Nation's waters,"[102] Congress included the NPDES program in the CWA—a large step towards filling the enforcement void that plagued prior legislation.[103] The CWA's revolutionary regulatory scheme, which established uniform water quality standards, best management practices, and best-use technology, would be rendered useless legislation without the NPDES program.[104] The Supreme Court has acknowledged the importance of the NPDES program and described the purpose of a permit as "serv[ing] to transform generally applicable effluent limitations and other standards including those based on water quality into the obligations . . . of the individual discharger."[105] The Court also noted that "with few exceptions, for enforcement purposes a discharger in compliance with the terms and conditions of an NPDES permit is deemed to be in compliance with those sections of the [CWA] on which the permit conditions are based."[106]

Prior to the CWA, similar attempts were made to regulate the quality of the nation's waters but were unsuccessful due to a lack of effective enforcement mechanisms.[107] An interesting historical parallel

[99] U.S. ENVTL. PROT. AGENCY, *supra* note 81, at 2.

[100] Moreau, *supra* note 82, at 13.

[101] *See* U.S. ENVTL. PROT. AGENCY, REPORT NO. 12-P-0113, EPA MUST IMPROVE OVERSIGHT OF STATE ENFORCEMENT 1 (2011), *available at* http://perma.cc/G79F-EHS8.

[102] Connor, *supra* note 64, at 284 (citing 33 U.S.C. § 1251(a) (2006)).

[103] 33 U.S.C. §§ 1342, 1362 (2006). *See also supra* Part III.A.

[104] *See* EPA v. California ex rel. State Water Res. Control Bd., 426 U.S. 200, 204–05 (1976) (calling the NPDES program "a means of achieving and enforcing the effluent limitations" set forth by the CWA).

[105] *Id.* at 205.

[106] *Id.*

[107] *See* Pub. L. No. 89-234, 70 Stat. 498 (1965); *see generally* Morris, *supra* note 95, at 27 n.9 (explaining that the "Water Quality Act direct[ed] states to develop water quality standards that set water quality goals for interstate waters" but "left quality issues to the states.").

to the controversial "duty to apply" issues of *Waterkeeper* and *National Pork Producers*[108] is embodied by the tumult surrounding the Refuse Act Permit Program (RAPP).[109] RAPP was promulgated by the Army Corps of Engineers (the Corps),[110] acting pursuant to Executive Order 11574.[111] It "required any facility discharging wastes into public waterways to obtain a federal permit."[112] Permits under RAPP specified abatement requirements as designated by the Army Corps of Engineers. [113] These requirements outlined the amount of acceptable refuse discharges given the capabilities of the permit-holder.[114] In an even-handed, though somewhat nepotistic manner, RAPP attempted to regulate the discharge of pollutants directly into the nation's waters.[115] RAPP made it unlawful to "discharge ... refuse matter of any kind," including industrial waste but excluding liquid sewage,[116] "into any navigable water of the United States, or into any tributary of any navigable water from which the same shall float or be washed into such navigable water."[117] RAPP famously introduced an early form of the "duty to apply," in that it added an enforcement mechanism to the Rivers and Harbors Act of 1899 prohibiting "discharge or deposit of [refuse] in any navigable water ... without a permit."[118] A RAPP permit, much like a NPDES permit, was the enforcement mechanism of choice for the RAPP system.

As is clearly illustrated by its wording, RAPP imposed a tacit duty to apply on polluters when it rendered discharge without a permit inherently illegal.[119] Moreover, as noted above, the creation and implementation of RAPP's permitting requirement may be considered a parallel to the implementation of the duty to apply under the CWA's NPDES permitting program, particularly the 2003 Rule.[120] However,

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[108] *See supra*, Part I.A–B.

[109] 33 U.S.C. § 407 (1970).

[110] Kalur v. Resor, 335 F. Supp. 1, 4 (D.D.C. 1971).

[111] Exec. Order No. 11574, 35 C.F.R. 19627 (1970).

[112] U.S. ENVTL. PROT. AGENCY, *supra* note 81, at 2.

[113] Richard G. Hildreth, *Federal Control of Water Pollution: The Refuse Act Permit Program*, 27 BUS. LAW 567, 569–70 (1971).

[114] *Id.*

[115] *See id.* at 567 (explaining that RAPP, "by its terms . . . does not apply to "operations in connection with the improvement of navigable waters or construction of public works, considered necessary and proper by the United States officers supervising such improvement or public work.")

[116] Deposit of Refuse in Navigable Waters Generally, 33 U.S.C. § 407 (1970); *see* United States v. Republic Steel Corp., 362 U.S. 482, 485 (1960) (differentiating industrial deposits and liquid sewage and concluding that "industrial deposits" are "discharges not exempt under" the Rivers and Harbors Act of 1899, of which RAPP is an extension).

[117] 33 U.S.C. § 407 (1970).

[118] Hildreth, *supra* note 113, at 570 (internal quotations omitted).

[119] *Supra* text accompanying note 118.

[120] *See supra* text accompanying note 9.

RAPP's ultimate failure is where that parallel ends and a stark historical contrast begins. To elaborate, RAPP was challenged in *Kalur v. Resor*[121] and the court determined that the promulgation of RAPP was beyond the authority of the Corps and was stripped of effect by the court.[122] This challenge came on the heels of the enactment of RAPP itself, just one year after the Executive Order recommending its inception and implementation.[123] The court's reasoning did not consider the implications of imposing permit requirements on those who "propose to discharge"[124] or "want to discharge"[125] pollutants, which were the pillars of the *Waterkeeper* and *National Pork Producers* decisions to vacate the duty to apply. Instead, the *Kalur* court struck down RAPP partly because it *allowed* discharge in the first place.[126]

The reasoning of the *Kalur* court and that of the *Waterkeeper* and *National Pork Producers* courts is vastly divergent. The *Kalur* court impugned the Corps' authority to issue permits under RAPP based on the environmental harms that the court believed were attached to the activity being permitted.[127] In contrast, the *Waterkeeper* and *National Pork Producers* courts struck the duty to apply for NPDES permits based on the perceived overreach of EPA requiring industrial polluters, like CAFOs, to actively secure permits when they propose to discharge pollutants.[128] While the difference in the courts' collective opinions is likely a result of the disparities in jurisprudential and legislative philosophy concerning support of environmental regulations between the 1970's and today,[129]

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[121] *Kalur*, 335 F. Supp. at 10.

[122] *Id.* at 10.

[123] *Id.* at 20.

[124] *See Nat'l Pork Producers,* 635 F.3d at 746 (citing 71 Fed. Reg. 37, 744, 747 (June 30, 2006)) (internal citations omitted).

[125] *See Nat'l Pork Producers,* 635 F.3d at 750.

[126] *See Kalur*, 335 F. Supp. at 11 (explaining that "[o]nce a polluter has received a permit from the Corps of Engineers to dump "refuse" into a non-navigable waterway, the polluter is shielded from prosecution so long as he stays within the permit's terms. Shields from prosecution for otherwise criminal offenses should not be broadly distributed"). Additionally, the *Kalur* court found that the limitation of discharges into non-navigable waterways, more specifically "into any tributary of any navigable water from which the same shall float or be washed into such navigable water," was beyond the authority of the Corps and was another contributor to the lack of validity of RAPP. *Id.* at 10 (citing 33 U.S.C. § 407 (1971)) (alteration in original).

[127] *Id.* at 11.

[128] *Nat'l Pork Producers*, 635 F.3d at 751; *Waterkeeper Alliance, Inc.*, 399 F.3d at 505.

[129] *See* Moreau, *supra* note 82, at 13 (describing how the passage of the CWA occurred "in the still bright afterglow of Earth Day," after commenting that, in 1965, "[t]he view that water quality was deteriorating had become an 'uncontested truth' in Washington"); *see also* William H. Rodgers, *The Environmental Laws of the 1970's: They Looked Good on Paper*, 12 VT. J. ENVTL. L. 1, 32 (2009) (asserting that "the more significant and more dramatic changes [of statutory construction] occurred because the

the *Waterkeeper* and *National Pork Producers* courts desperately tried to think of another, more legally sound, reason to justify their decisions. Ultimately, they found one, however tenuous, in the CWA.[130]

c. *The Clean Water Act and the National Pollution Discharge Elimination System*

As described above,[131] the CWA is a key component of the federal government's pollution prevention toolbox.[132] By its basic operating terms, the CWA renders it illegal for a person[133] to discharge pollutants from a "point source"[134] into the waters of the United States[135] without first obtaining a permit issued in accordance with the NPDES system.[136] CAFOs were initially brought under the scope of the CWA in 1972[137] and only the larger of them fell into the regulatory requirements at the time.[138] Later considerations resulted in smaller CAFOs falling into the definition of "point source" if they discharged in violation of the CWA.[139] Following the passage of the CWA, using the NPDES permit regime to restrain the massive effluent runoff capacities of CAFOs became a

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Supreme Court was able to lay its hands repeatedly and directly upon all sentiments bound up with a 1970s understanding of 'effective judicial review.'").

[130] *Nat'l Pork Producers*, 635 F.3d at 750-51; *Waterkeeper Alliance, Inc.*, 399 F.3d at 505.

[131] *See supra* notes 101–06 and accompanying text.

[132] *See generally Water is Worth It*, U.S. ENVTL. PROT. AGENCY, http://water.epa.gov/action/cleanwater40/ (last visited February 3, 2013) (celebrating the fortieth anniversary of the CWA and touching on milestones of the Act, similar activities performed by other entities, and the basics of the CWA).

133 33 U.S.C. § 1362(5) (2006) (defining "'person'" as an "individual, corporation, partnership, association, State, municipality, commission, or political subdivision of a State, or any interstate body.").

[134] § 1362(14) (defining "'point source'" as "any discernible, confined and discrete conveyance, including ... any pipe, ditch, channel ... concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture.").

[135] § 1362(7). The statutory equivalent to "the waters of the United States" is "navigable waters," this term includes "territorial seas." *Id.*

[136] *See* 33 U.S.C. § 1342 (2006).

[137] *Environmental Protection Agency Regulations*, 119 CONG. REC. 34811 (1973) (statement of Sen. Gaylord Nelson).

[138] *Id.* (citing regulations excluding CAFOs with "less than 1,000 beef cattle, 700 dairy cows, 290,000 broilers, 180,000 laying hens, 55,000 turkeys, 4,500 hogs, 35,000 feeder pigs, 12,000 sheep and lambs and 145,000 ducks from compliance with sections 301 and 402" of the CWA).

[139] *Id.* (referring to Senator Edmund Muskie's findings and statement that "'if a man-made drainage ditch ... is involved and if any measurable waste results and is discharged into water, it is considered a 'point source' ... [therefore] [a]ny feedlot operations which result in the direct discharge of waste in a stream that transverses the feedlot are considered point sources without regard to number of animals involved.'").

regulatory focus, as evinced by the inclusion of CAFOs in the definition of point source.[140] The NPDES program, of course, is the premiere water quality permitting system in the United States, making it the obvious tool for the job.[141] The terms of the CWA are efficiently effectuated by NPDES permits, as they allow each permit to be individualized to its accompanying CAFO so that a CAFO's individual needs and capabilities may be taken into account when setting limitations.[142]

NPDES permits rely on effluent standards[143] that are formulated in accordance with a set of common guidelines.[144] NPDES standards differ based on the industry in question in terms of stringency. NPDES standards employ four general categories: (1) "best conventional pollutant control technology," which is based on a "cost reasonableness" test that "compares the cost for an industry to reduce its pollutant discharge with the cost to a publicly owned treatment works facility for similar levels of" pollutant reduction;[145] (2) "best practicable control technology currently available," which sets a standard "generally based on the average of the best existing performance by plants within an industrial category or subcategory";[146] (3) "best available technology economically achievable," which standardizes the "most appropriate means available on a national basis for controlling the direct discharge of toxic and nonconventional pollutants to navigable waters";[147] and (4) "new source performance standards," which apply to facilities qualifying as new sources under applicable federal regulations[148] and "consider that the new source facility has an opportunity to design operations to

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[140] § 1362(14).

[141] *See generally* U.S. ENVTL. PROT. AGENCY, PROTECTING THE NATION'S WATERS THROUGH EFFECTIVE NPDES PERMITS, 4 (2001) (providing an overview of the structure of the NPDES water quality permit divisions—illustrating the national efficacy of the program and showing its state, municipal, industrial, and rural viability), *available at* http://perma.cc/AC97-DE2N.

[142] U.S. ENVTL. PROT. AGENCY, *supra* note 84.

[143] 40 C.F.R. §§ 423.12–15 (1983).

[144] Clean Water Act of 1977, Pub. L. No. 95-217, § 53, 91 Stat. 1566 (1977) (explaining that each specific pollutant's effluent standard must "take into account toxicity of the pollutant, its persistence, degradability, the usual or potential presence of the affected organisms in any waters, the importance of the affected organisms and the nature and extent of the effect of the toxic pollutant on such organisms, and the extent to which effective control is being or may be achieved under other regulatory authority.").

[145] U.S. ENVTL. PROT. AGENCY, NPDES PERMIT WRITER TRAINING MANUAL G-2 (1996), *available at* http://perma.cc/RTE5-LT9M.

[146] *Id.*

[147] *Id.*

[148] *See* 40 C.F.R. § 122.2 (2000) (defining "[n]ew discharger" as "any ... facility ... [f]rom which there is or may be a discharge of pollutants ... [t]hat did not commence the discharge of pollutants ... prior to August 13, 1979" (internal quotations omitted); *see also* 40 C.F.R. § 122.29 (2000).

more effectively control pollutant discharges."[149] Using these categories to tailor permits to individual facilities ideally results in a set of permit requirements that is both restrictive enough to limit water pollution to an acceptable amount and permissive enough to avoid obstruction of industry activity. The NPDES program has been the subject of criticism from a broad spectrum of commentators. Some argue that it stifles industrial actors, in that NPDES implementation and enforcement create a "bad business climate."[150] Others complain that NPDES permits, specifically generalized permits, ineffectively enforce water quality standards because they allow permitting authorities to over-generalize permits.[151] However, the most celebrated aspects of NPDES permits are the perceived environmental benefits, such as water pollution control, protection of drinking water, and wildlife protection.[152]

While the precedent set by *Waterkeeper* is now considered textbook by most measures, and has obviously found footing in subsequent decisions on the duty to apply;[153] the binding nature of the opinion does not apply to all agencies implementing NPDES permits. To elaborate, EPA may authorize state implementation of the CWA and enforcement of NPDES permits, and it has done so to a great degree. EPA has enabled forty-six states to impose state-specific permitting regulations under a cooperative federalism regime.[154] In states that are not qualified to administer the CWA or issue and enforce NPDES permits—Idaho, Massachusetts, New Hampshire, and New Mexico—EPA remains responsible for administration and issuance.[155] In qualifying states, this near-universal delegation allows state regulatory agencies to carry out some of the responsibilities otherwise relegated to EPA.

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[149] U.S. ENVTL. PROT. AGENCY, *supra* note 145.

[150] *See* David R. Hodas, *Enforcement of Environmental Law in a Triangular Federal System: Can Three Not be a Crowd When Enforcement Authority is Shared by the United States, the States, and Their Citizens?*, 54 MD. L. REV. 1552, 1615 (1995).

[151] *See* Jeffrey M. Gaba, *Generally Illegal: NPDES General Permits Under The Clean Water Act*, 31 HARV. ENVTL L. REV. 410, 473 (2007) (arguing the "most troubling aspect of the broad use of general permits is EPA's failure to adequately assure compliance with water quality standards").

[152] *See* 33 U.S.C. § 1342 (2006); *see also* U.S. ENVTL. PROT. AGENCY, BENEFITS DERIVED FROM TAKING A WATERSHED APPROACH, http://perma.cc/396P-RW6J (last accessed Feb. 9, 2013) (explaining that "coordinating programs on a watershed basis," including the implementation of NPDES permits, results in "joint[] review[] . . . of assessment efforts for drinking water protection, pollution control, [and] fish and wildlife habitat protection." Further, "[u]sing this information to set priorities for action allows public and private managers from all levels to allocate limited financial and human resources to address the most critical needs").

[153] *Nat'l Pork Producers*, 635 F.3d at 749–50.

[154] CLAUDIA COPELAND, SPECIALIST IN RESOURCES AND ENVIRONMENTAL POLICY, CLEAN WATER ACT: A SUMMARY OF THE LAW, CONG. RESEARCH SERV. ii (2010).

[155] *Id.* at 4.

Aspects of the CWA that may be assigned to qualified states include the authority to issue discharge permits to industries and municipalities, the ability to enforce those permits, and the ability to establish water quality standards.[156]

d. Rounding Up CAFOs

The movement toward stricter regulation of CAFOs mentioned above[157] was a deliberate process that culminated in a call to action in 1998.[158] The Clean Water Action Plan, a legislative blueprint proffered by President Bill Clinton, called for a coordinated effort to initiate a series of strategic decisions to reduce polluted runoff in the waters of the United States.[159] In response to this appeal, EPA and the United States Department of Agriculture (USDA) developed "a Unified National Strategy to minimize the water quality and public health impacts of animal feeding operations."[160] In their unified plan to curb egregious effluent output and bring many unregulated CAFOs into compliance, the Strategy anticipated the inclusion of states, among others, in a grand scheme to diversify the sources of CWA and NPDES regulation and enforcement.[161] The Unified National Strategy led to the development and promulgation of the 2003 Rule,[162] which, as explained above, was subsequently dismantled by the *Waterkeeper* court.[163]

Due to the diversity in regulatory bodies charged with carrying out the CWA's requirements, the *Waterkeeper* and *National Pork Producers* decisions do not effect full-scale change upon existing enforcement regimes. However, this does not mean those decisions are devoid of significant consequences.[164] Even though they are not universally binding, important questions still loom over those decisions and their aftermath; what was the statutory basis upon which the courts prevented EPA from imposing a duty upon CAFOs to apply for NPDES permits? Did congress *truly* intend, when devising the NPDES program,

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[156] *Id.*

[157] *See supra*, text accompanying note 8.

[158] U.S. ENVTL. PROT. AGENCY, *supra* note 54, at 1.

[159] *Id.*

[160] *Id.*

[161] *Id.* at 2.

[162] *Supra* note 9 and accompanying text.

[163] *See supra*, Part I.A.

[164] *See* National Pollutant Discharge Elimination System Permit Regulation for Concentrated Animal Feeding Operations: Removal of Vacated Elements in Response to 2011 Court Decision, 77 Fed. Reg. 44494, 44495 (July 30, 2012) (to be codified at 40 C.F.R. § 122) (incorporating the decision of National Pork Producers into the regulatory regime used by EPA to enforce NPDES permits and requirements against CAFOs).

such limits on the authority of agencies charged with implementation? The logical answers to these questions seem to contravene the answers provided by the *Waterkeeper* and *National Pork Producers* courts and present an important parable with a subtle lesson: the duty to apply, at least with respect to CAFOs that "propose to discharge," may have suffered a wrongful death.

IV. The Progeny of Waterkeeper and National Pork Producers

For better or worse, after Waterkeeper, unpermitted CAFOs enjoy freedom from required permitting unless EPA can show that they are discharging into the nation's waters.[165] The benefit of this, of course, is that non-discharging CAFOs are not faced with burdensome NPDES permit requirements.[166] A perceived drawback of the Waterkeeper outcome, though, is that even when CAFOs are discharging, they need not actively seek permits unless EPA affirmatively finds them in violation.[167] This burden of proof brings with it the administrative costs that EPA must bear when making individual site determinations—costs that EPA traditionally cannot afford to bear.[168]

Of course, given its limited resources, EPA must delegate its permitting authority to meet its goals of bringing discharging CAFOs into compliance.[169] The freedom of complete delegation has led to states, in some cases, negligently implementing and enforcing their CAFO permitting regulations, leading to intense criticism and objection by members of the public and EPA.[170] Illinois is one such state. In response

[165] 40 C.F.R. § 122.23 (2011); *See also Brown*, *supra* note 21, at 423.

[166] *See* David J. Salmonsen et al., *Regulatory And Incentive Based Approaches To CAFOs*, SJ028 ALI-ABA 357, 359-60 (2003).

[167] *See generally* National Resource Defense Council v. Environmental Protection Agency, Settlement Agrmt., 2 (No. 09-60510), *available at* http://perma.cc/HS3M-3L78 (settling that EPA will specify a duty to apply for CAFOs discharging or proposing to discharge, and requiring information from those facilities and failing to include other CAFOs in the agreement); *see also* Brown, *supra* note 21, at 424–25.

[168] U.S. Envtl. Prot. Agency, Final Action on the Proposed National Pollutant Discharge Elimination System (NPDES) Concentrated Animal Feeding Operation (CAFO) Reporting Rule—

> Questions and Answers 1 (2012) (explaining *why* EPA is seeking to implement an information collection system regarding CAFOs and noting that "[l]imited agency resources warrant a targeted approach" on collecting such information about CAFOs).

[169] *See supra* text accompanying notes 154–56.

[170] U.S. Envtl Prot. Agency, Initial Results of an Informal Investigation of the National Pollutant Discharge Elimination System Program for Concentrated Animal Feeding Operations in the State of Illinois 3 (2010), *available at* http://perma.cc/PE33-AQBT.

to a citizen petition for review of the Illinois Environmental Protection Agency's ("Illinois EPA") CAFO permitting program, EPA conducted an extensive investigation of the practices and programs that the Illinois EPA had implemented.[171] Most importantly, EPA found that the "Illinois EPA does not maintain a program capable of making a comprehensive survey of CAFOs subject to NPDES permit requirements."[172] In response to such a finding, EPA can require and recommend suitable actions.[173] The onus then falls on the state to implement such actions, and failure to do so may result in a disqualification of the state's self-regulation privileges under the CWA.[174] Illinois EPA's failure to implement a proper CAFO regulation scheme is not an isolated incident,[175] and the existence of such failures provides evidence for the argument that EPA is overburdened with similar administrative and regulatory responsibilities in the context of CAFO enforcement, without having the affirmative duty to investigate each individual CAFO to determine whether it actually discharges pollutants into the nation's waters.

Further, EPA maintained that the strict duty to apply provision was necessary based on a sound presumption that all large CAFOs have the potential to discharge pollutants.[176] That argument was met with fervent disagreement by many industry interests, who generally posited that EPA's presumption of universal CAFO discharge was baseless.[177]

a. Before and After Waterkeeper

The Waterkeeper decision shifted the paradigm of CAFO regulation. Before it issued the 2003 Rule, creating the duty to apply, EPA estimated that approximately 4,500 CAFOs were covered by NPDES permits but that another 11,000 would be required to secure permits

[171] *Id.*

[172] *Id.* at 36.

[173] *See id.* at 35–41 (listing all of the federal EPA's required and recommended actions in response to its findings).

[174] *See* 40 C.F.R. § 123.27 (1993); 40 C.F.R. § 123.63 (1998).

[175] *See, e.g.*, U.S. Envtl. Prot. Agency, Preliminary Results of an Informal Investigation of the National Pollutant Discharge Elimination System Program for Concentrated Animal Feeding Operations in the State of Iowa 37–40 (2012), *available at* http://perma.cc/564F-75YP.

[176] The 2003 Rule, *supra* note 9, at 7202 (explaining that "there is a sound basis in the administrative record for the presumption that all CAFOs have a potential to discharge to the waters of the United States such that they should be required to apply for a permit, unless they can show no potential to discharge."). *Id.* at 7201.

[177] Nat'l Pork Producers Council, et al., "Comments on Proposed Post-Waterkeeper CAFO NPDES Regulations," August 29, 2006, p. 38 71 Fed. Reg. 37,744 (June 30, 2006) (arguing "the record demonstrates that CAFOs as a class cannot be presumed to be discharging, and that the probability that most of these CAFOs will not have a discharge in the future under the CWA regulatory provisions as amended by this proposal, is extremely high.").

based on the 2003 Rule's requirements.[178] This disparity in regulation of a highly polluting industry's[179] compliance with the CWA illustrated the problems that informed the inclusion of many of the 2003 Rule's additional provisions.[180] After the 2003 Rule, CAFOs found themselves without a choice in determining whether permits were necessary or beneficial for their operation.[181] The legal implications of not securing a permit outweighed the costs of permit procurement and compliance—however costly NPDES permit compliance actually was.[182] Further, unless an individual CAFO was situated in such a way that there was "no potential to discharge,"[183] all CAFOs were brought in under the broad terms of the 2003 Rule.[184]

After the Waterkeeper deceision vacated the provisions of the 2003 Rule with which the court disagreed, the general approach to permit requirements changed.[185] Even though the strict "duty to

[178] LEONARD H. DOUGAL, AMERICAN BAR ASSOCIATION SECTION OF ENVIRONMENT, ENERGY, AND RESOURCES, CAFOs & MORE: AGRICULTURAL POLICY MEETS ENVIRONMENTAL LAW—EMERGING LEGAL ISSUES IN THE REGULATION AND OPERATION OF CAFOs 4 (2005).

[179] U.S. ENVTL PROT. AGENCY, NATIONAL WATER QUALITY INVENTORY REPORT 52 (2002) (charting fertilizer application, underground storage tanks, septic systems, and runoff from animal feedlots as four of the primary pollutants responsible for groundwater contamination).

[180] *See, e.g., id.* at 3.

[181] The 2003 Rule, *supra* note 9, at 7176.

[182] *See* OR. REV. STAT. § 468B.220 (2011) (an Oregon state statute imposing $500 in civil penalties on CAFO owners who fail to apply for and secure a permit for their operation). *See also* ILL. ENVTL. PROT. AGENCY, ILLINOIS EPA LIVESTOCK PROGRAM 2003 LIVESTOCK FACILITY INVESTIGATION ANNUAL REPORT 14–17, 21–24 (2003) (showing an annual summary of the results of CAFO NPDES permit violations and the accompanying site visits, letters of non-compliance, and penalties imposed based on complaints received by the Illinois EPA). *But see* U.S. ENVTL. PROT. AGENCY, ECONOMIC ANALYSIS OF THE FINAL REVISIONS TO THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM REGULATION AND THE EFFLUENT GUIDELINES FOR CONCENTRATED ANIMAL FEEDING OPERATIONS ES-8–9 (2002) (listing the estimated total costs of compliance for CAFOs under the NPDES permit requirements imposed by the 2003 Rule).

[183] An example of such a situation would be a CAFO located a great distance from any water of the United States and designed in a way such that rainfall events would not disturb the constitution of the CAFOs waste storage mechanisms or facilities. The 2003 Rule, *supra* note 9, at 7202.

[184] *See id.* at 7181-82 ("In general, all CAFOs have a mandatory duty to apply for an NPDES permit and must comply with the technology and water quality-based limitations in the permit as defined by the permitting authority. Only CAFOs that have successfully demonstrated no potential to discharge may avoid a permit.").

[185] *See* Ellen Steen et al., *EPA Weighs Competing Arguments—And Likely Litigation—On Proposed CAFO Requirements*, 11 NO. 1 ABA AGRIC. MGMT. COMM. NEWSL. 2 (Am. Bar Ass'n, Chicago, Ill.) Apr. 2007, at 8 (explaining that the *Waterkeeper* "decision calls for careful consideration of the benefits and burdens of permit coverage, as well as site-specific factors and operational history that may shed light on the risk of a regulated discharge from production areas and from land application areas," and declaring it "certain . . . that, for CAFOs not already operating

apply" was no more, CAFO owners still considered their potential to discharge in deciding whether to secure a NPDES permit.[186] While this new structure—which renewed the ability of some CAFOs to operate without a permit—was more forgiving of potentially polluting CAFOs than the 2003 Rule, the post-Waterkeeper model mirrored many similar permit regimes facing other industries.[187] CAFO owners no longer met a binding requirement when determining whether to come into compliance. Instead, they had a choice of operating without a permit and risking a violation if caught by EPA, or paying the costs associated with the permit.[188] However, the fact that the Waterkeeper ruling "upheld major parts of the rule, vacated other parts, and remanded still other parts to EPA for clarification, [left] all parties unsatisfied to at least some extent."[189] Some commenters argue that the Waterkeeper court's striking of provisions from the 2003 Rule was misguided because the court's actions were contradictory to "the fundamental principle" that "CAFO permit coverage [must increase] if pollutant discharges from CAFOs were to be reduced."[190] In light of some of these perceived problems, the 2008 Rule was promulgated.[191]

Upon the promulgation of the 2008 Rule, which "modif[ied] the requirement to apply for a permit by specifying that an owner or

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under an NPDES permit, a decision will be required; and operators would be well advised to begin the process—if possible—now, rather than after publication of [the 2008 Rule]").

[186] *See generally*, Ellen Steen et al., *Waterkeeper Alliance, Inc. v. EPA: A View From the Farm Groups' Perspective*, 6 No. 2 ABA Water Quality & Wetlands Comm. Newsl. 9 (Am. Bar Ass'n, Chicago, Ill.) Aug. 2005 (explaining that "CAFO operators should . . . evaluate the potential for regulated stormwater discharges from their operations[,]" and such assessments "should include an assessment of: (1) whether stormwater runoff from the production area or from land application areas will enter navigable waters (which can be very broadly defined to include small streams, wetland areas and even ditches that ultimately connect to rivers or streams); and (2) whether any such discharge would be regulated (subject to NPDES permitting) under the CWA.").

[187] The common practice of trading pollution permits evidences this decision process; when a polluting firm can afford to pay for the additional costs of more volumes of permitted pollution, the firm is effectively making the decision based on a cost-benefit analysis. Further, the firm selling the pollution permit is making a similar decision by forfeiting the permit and foregoing the additional pollution volumes that firm would otherwise be able to emit. While this is a more efficient process that simply deciding whether to operate under a permitting structure in the first place, it still reflects a similar decision-making model. For more on permit trading, *see* Lisa Heinzerling, *Selling Pollution, Forcing Democracy*, 14 Stan. Envtl. L.J. 300, 301 (1995).

[188] *See* Steen, *supra* note 186, at 9; *but cf.* Heinzerling, *supra* note 187, at 334.

[189] Claudia Copeland, Animal Waste and water quality: EPA's Response to the Waterkeeper Alliance Court Decision on Regulation of CAFOs, 2 (2008).

[190] Brown, *supra* note 21, at 379.

[191] *Id.*

operator of a CAFO that discharges or proposes to discharge must apply for an NPDES permit," the permit requirements were pulled back towards the center of the spectrum of regulatory flexibility.[192] The 2008 Rule arguably struck the closest between leniency and stringency since the inception of the Unified National Strategy, described above.[193]

After the 2008 Rule, though, any CAFO proposing to discharge once again fell into the regulatory scope.[194] EPA, after receiving extensive critical comments on the 2008 Rule,[195] clarified that its NPDES permit requirement for CAFOs proposing to discharge was not contrary to the Waterkeeper court's mandate that permits could be required only from CAFOs that actually discharge.[196] EPA explained,

> Unlike the 2003 rule, which categorically required a permit for any CAFO with a "potential to discharge," this final rule calls for a case-by-case evaluation by the CAFO owner or operator as to whether the CAFO discharges or proposes to discharge from its production area or land application area based on actual design, construction, operation, and maintenance.[197]

It is notable here that EPA intended to place the burden of evaluation on the CAFO owner, rather than offer to oversee each individual facility's permitting necessities.[198]

Arguably, this normalization of the previously skewed picture was the high point of CAFO regulation in that it was comprised of an equitable regulatory structure that served regulators, industry, and the public alike.

b. Not "Just Right," According to National Pork Producers

While the duty to apply introduced in the 2003 Rule, tempered by the Waterkeeper court, and restructured by the 2008 Rule was the proverbial third bowl of porridge, it met a large contingent of opposition that ultimately culminated in National Pork Producers.[199]

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[192] *See* the 2008 Rule, *supra* note 27, at 70419.

[193] *Supra* Part III.D.

[194] *See* the 2008 Rule, *supra* note 27, at 70422.

[195] *See id.* at 70423 (noting that "some commenters thought that "propose to discharge" and "potential to discharge" were not sufficiently distinguishable, and that "proposed" discharges could be understood as contrary to the *Waterkeeper* court's holding that only "actual" discharges are subject to CWA requirements).

[196] The 2008 Rule, *supra* note 27 at 70423 ("[i]ncluding a duty to apply for CAFOs that "propose to discharge" is not the same as requiring a permit for CAFOs with only a "potential to discharge").

[197] *Id.*

[198] *See id.*

[199] *E.g.*, Nat'l Pork Producers Council, et al., "Comments on Proposed Post-

In its opinion, the National Pork Producers court reached its conclusions on the 2008 Rule and imposed far-reaching consequences on some of the provisions therein. The court based its findings largely on a simple differentiation between "wanting to discharge pollutants" and "actually discharging pollutants," and by citing precedent only tenuously related to its point. To elaborate, the court relied on *Natural Resources Defense Council, Inc. v. Environmental Protection Agency*[200] when it stated,

> The D.C. Circuit explained more than 20 years ago that the CWA "does not empower the agency to regulate point sources themselves; rather, EPA's jurisdiction under the operative statute is limited to regulating the discharge of pollutants.[201]

This assertion, however astute, is unrelated to the question that was at issue in National Pork Producers: whether EPA may regulate sources that want to discharge pollutants. Instead, the cited case was differentiating between "regulating the discharge of pollutants," which is allowable,[202] and "banning the construction of new sources pending permit issuance" or "impos[ing] permit conditions unrelated to the discharge itself,"[203] which are both beyond the scope of EPA's authority.[204] The "seminal case"[205] so eagerly quoted by the court dealt with issues in a significantly starker contrast than the question facing the National Pork Producers court. To elaborate, supporting a decision as to whether EPA is limited to regulating CAFOs actually discharging pollutants rather than those wanting to discharge pollutants with precedent that determined whether EPA is authorized to ban the construction of buildings seems inherently problematic. These cases are irreconcilably distinguishable. Nonetheless, the court proceeded to disband the "proposes to discharge" provision of the 2008 Rule.[206]

The National Pork Producers decision prompted EPA to initiate a current rulemaking initiative;[207] one that will remove the

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Waterkeeper CAFO NPDES Regulations," August 29, 2006, p. 38, 71 Fed. Reg. 37,744 (June 30, 2006); *See generally* Brown, *supra* note 21.

[200] Natural Res. Def. Council, Inc. v. E.P.A., 859 F.2d 156 (D.C. Cir. 1988).

[201] Nat'l Pork Producers v. U.S. E.P.A, 635 F.3d 738, 750 (5th Cir. 2011) (citing Nat'l. Res. Def. Council v. EPA, 859 F.2d 156, 170 (D.C. Cir. 1988)).

[202] 33 U.S.C. § 1342 (2006).

[203] Nat'l. Res. Def. Council, 859 F.2d at 170.

[204] *Id.*

[205] Nat'l Pork Producers, 635 F.3d at 750.

[206] *Id.* at 756.

[207] National Pollutant Discharge Elimination System Permit Regulation for Concentrated Animal Feeding Operations: Removal of Vacated Elements in Response to 2011 Court Decision, 77 Fed. Reg. 44494 (July 30, 2012) (to be codified at 40 C.F.R. § 122).

vacated provisions of the 2008 Rule and effectively return the CAFO regulatory regime to the post-Waterkeeper, pre-2008 Rule era.[208] Some commenters laud this as a move in the right direction because, notionally, CAFOs that have curtailed all of their discharges should not be required to secure NPDES permits.[209] Others argue that the total shift away from pre-discharge enforcement can operate to lower permitting and enforcement standards because states with pre-discharge statutes may suffer challenges to their validity.[210] Theoretically, this would seem to be the case. In practice, however, such challenges have already been attempted and met with failure.[211]

V. Conclusion

The death of the duty to apply and the end of pre-discharge CAFO permit requirements under the CWA has resulted, and will continue to result, in spectrum-wide effects. Those CAFOs that are not discharging, whether because of well-designed facilities or ideal geographic location,[212] will not suffer costly permit requirements—which would be imposed only on a presumption that discharge is inevitable.[213] On the other hand, CAFOs without NPDES permits but with inherent structural deficiencies or poor locations relative to waterways will enjoy unchecked discharge until a regulatory body finds occasion for testing and proving that effluent discharge is indeed taking place.[214] To determine which of these effects is more cost-efficient would require years of study and resources simply unavailable to existing regulatory

[208] *Id.* at 44494 (explaining that the rule promulgation is in response to the *Nat'l Pork Producers* court, which "vacated those portions of the 2008 CAFO Rule requiring CAFOs that propose to discharge to apply for an NPDES permit . . . This action removes from the Code of Federal Regulations (CFR) the specific "propose to discharge" requirement in 40 CFR 122.23(d).")

[209] Delmar R. Ehrich & Ann E. Prouty, *Federal Courts Limits EPA Jurisdiction Over CAFOs That Do Not Discharge Pollutants*, FAEGRE BANKS DANIELS, http://perma.cc/8L95-W5QX (last visited Mar. 17, 2011).

[210] *See* Agricultural Management: 2011 Annual Report, *Concentrated Animal Feeding Operations,* 2011 ABA SEC. Env't Energy, & Res. L.: The Year in Review 1, 2.

[211] *See* Michigan Farm Bureau v. Dep't of Envtl. Quality, 807 N.W.2d 866 (Mich. Ct. App. 2011).

[212] *Kalur,* 335 F. Supp. at 10.

[213] *Supra* text accompanying notes 175–76.

[214] U.S. Gov't Accountability Office, Concentrated Animal Feeding Operations: EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality 12 (2008); *See* Catherine Groves, *To Promote Compliance with the Clean Water Act, EPA Should Pursue a National Enforcement Initiative to Regulate Concentrated Animal Feeding Operations*, 39 Ecology L.Q. 321, 326 (2012).

bodies, not to mention the costs associated with the perpetual discharges of the latter group.[215]

To remedy the current circumstances, broad disclosure requirements should be implemented against CAFOs.[216] Such requirements would streamline the process of distinguishing between unpermitted CAFOs potentially taking advantage of the freedom to pollute and those operating efficiently and without the perceived environmental impacts commonly associated with the industry. As it is, though, regulatory bodies face significant hurdles even when attempting to determine the existence of CAFOs.[217] An information-forcing rule would likely address these hurdles and assist in normalizing the regulation of those CAFOs that need regulation, while promoting the continued and only mildly interrupted operation of those CAFOs that choose to comply with relevant regulations. Importantly, a disclosure requirement has been proposed by EPA in a previous settlement agreement and may be implemented, but definitive steps must still be taken.[218]

Whether *Waterkeeper* and *National Pork Producers* are subjectively considered victories or defeats, the reality remains that efforts to protect waters from degradation—the clear purpose of the CWA and its NPDES program—are significantly undercut if permitting requirements cannot be implemented until *after* discharge is already known to be occurring.[219] For that reason, *Waterkeeper* and *National Pork Producers* have established an untenable precedent. Had the courts provided sound legal qualifications for their interpreting the CWA—an act designed to eliminate discharge into the nation's waters—to require discharges to occur before permits may be used to enforce its prohibitions on discharge, then this analysis would be unnecessary. However, because the courts' opinions rested on unrelated precedent[220] and an improper application of *Chevron's* deference test,[221] a second look must be taken at their validity and accompanying results.

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[215] *See* Christopher Brown, *Uncooperative Federalism, Misguided Textualism: The Federal Courts' Mistaken Hostility Toward Pre-Discharge Regulation Of Confined Animal Feeding Operations Under The Clean Water Act*, 30 TEMP. J. SCI. TECH. & ENVTL. L. 175, 216–18 (2011).

[216] *Id.* at 216.

[217] *See id.* (arguing that "EPA's lack of information on the existence of CAFOs and their characteristics led the agency to use extraordinary means").

[218] *See* National Resource Defense Council v. Environmental Protection Agency, *supra* note 167, at 2–3.

[219] Brown, *supra* note 21, at 381.

[220] Nat'l. Res. Def. Council, 859 F.2d at 170

[221] *Supra* text accompanying notes 20.

MINNESOTA
ENVIRONMENTAL QUALITY BOARD

Environmental assessment worksheet (EAW) guidance

Developing a carbon footprint and incorporating climate adaptation and resilience

June 2024

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Section 1 – Developing a carbon footprint

In 2007, the Minnesota Legislature passed the Next Generation Energy Act (Minn. Stat. § 216H) into law, which requires the tracking of certain greenhouse gas (GHG) emissions. The statute also includes statewide GHG emission reduction goals, from a 2005 baseline.

It is important that environmental documents required by the Minnesota Environmental Policy Act (MEPA) include usable information about the potential effects of a proposed project on GHG emissions and climate change.

Estimation of GHG emissions is a useful way to measure the potential climate impacts of a proposed project. It also helps track progress in meeting state and local GHG reduction goals and supports efforts to reduce emissions, mitigate, and adapt to the impacts of climate change.

The purpose of this section of the guidance is to help project proposers and responsible governmental units (RGU) estimate GHG emissions by developing a carbon footprint in response to item 18 of the Environmental Assessment Worksheet (EAW) Form. This guidance document is meant to support an RGU as they develop climate related information on the EAW form.

This guidance section should serve as a starting point for information to help answer item 18 of the EAW form, but it does not limit the use of other reliable and relevant tools for quantifying and assessing GHG emissions. This guidance is not exhaustive and RGUs are encouraged to use any relevant tools beyond those listed below. An RGU has discretion for identifying what information is needed and how much information is required to respond to item 18 on the EAW Form, based on the nature and location of the project.

What is a carbon footprint?

In general, a carbon footprint is the total greenhouse gas emissions associated with a project. This includes greenhouse gas emissions from direct use of fuel, such as providing heat to a building or fuel in a car. It also includes greenhouse gases that come from producing the goods or services necessary to complete a project, including emissions from power plants that make electricity or factories that make the products used in the project. It also encompasses the emissions associated with any involved products' disposal.

A carbon footprint generally includes any upstream and downstream emissions from a project. Upstream emissions include those related to the production, acquisition, or transportation of goods or services required for the project. Downstream emissions include those related to the handling and disposal of any resultant products at the end of their life.

At a minimum, a proposed project's carbon footprint includes, but is not limited to, identification and assessment of:

- Sources of GHG emissions associated with the proposed project
- Types of GHG emissions

- Amount of GHG emissions from those sources
- Reduction of GHG emissions from planned mitigation

Steps to assemble a carbon footprint

Step 1: Identify sources of GHG emissions

Specific to item 18 of the EAW Form, GHG emission sources include all project sources of GHG emissions by source, type, and phase. Common phases include pre-purchase, transportation, production, operation/use, and disposal.

Emissions can be categorized as either direct or indirect. Direct emissions are emissions released directly from properties owned or under the control of the project proposer. These are also commonly referred to as "Scope 1" emissions. This includes emissions from on-site energy use and mobile equipment during construction.

Indirect emissions originate either upstream or downstream of the project. They are also commonly referred to as "Scope 2" and "Scope 3" emissions. Scope 2 emissions are emissions associated most often with the offsite generation of purchased electricity, steam, and heating and cooling.

Scope 3 emissions are from the offsite provision of waste management services, including land disposal (landfilling), recycling, and solid waste composting, use of sold products, and transportation and distribution for waste management. According to the Environmental Protection Agency, "Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly affects in its value chain. Scope 3 emissions include all sources not within an organization's scope 1 and 2 boundary. The scope 3 emissions for one organization are the scope 1 and 2 emissions of another organization. Scope 3 emissions, also referred to as value chain emissions, often represent the majority of an organization's total greenhouse gas (GHG) emissions. Scope 3 emission sources include emissions both upstream and downstream of the organization's activities."

The U.S. Environmental Protection Agency (EPA) annually prepares a detailed analysis of GHG emissions by source and type. A list of these sources is shown in Table 1, arranged by type of greenhouse gas emitted. GHG sources in Minnesota are assessed biennially by the Minnesota Pollution Control Agency (MPCA). Environmental review documents generally include sources shown in Table 1 that are potentially associated with, and may result in, GHG emissions from the proposed project.

The GHG types most commonly included in project GHG reporting are:

- carbon dioxide (CO2)
- nitrous oxide (N2O)
- methane (CH4)
- sulfur hexafluoride (SF6)
- two families of gases known as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)

Table 1. Sources of greenhouse gases

Source	Gas Type
Stationary fossil fuel combustion	CO_2, CH_4, N_2O
Mobile source fossil fuel combustion	CO_2, CH_4, N_2O
Biomass and biofuels fuels combustion	CH_4, N_2O
Purchased electricity or steam (emitted offsite at generation)	CO_2, CH_4, N_2O
Nonfuel use of fossil fuels[1]	CO_2
Natural gas transmission/distribution	CH_4, CO_2, N_2O
Petroleum refining	CO_2, CH_4
Electricity transmission & distribution	SF_6
Ammonia, nitric acid, caprolactam, adipic acid manufacture	CO_2, N_2O
Cement, lime, glass manufacture	CO_2
Copper/nickel mining/processing	CO_2
Fire suppression	PFCs
Industrial solvent use (electronics, precision cleaning)	PFCs, HFCs
Petrochemicals, other chemical manufacture[2]	CO_2, CH_4
Metallurgy	CO_2
Polyurethane, polystyrene, phenolic, polyolefin foam manufacture	HFC-134a, HFC-152a, HFC-245fa
Refrigeration and cooling	HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a
Secondary lead production	CO_2
Semiconductor manufacture	PFCs, SF_6, HFC-134a
Silicon carbon consumption as abrasives in manufacturing	CO_2
Taconite and DRI pellet production, steel production	CO_2, CH_4
Titanium dioxide production	CO_2
Waste incineration	CO_2[3], CH_4, N_2O
Solid waste landfilling	CH_4
Solid waste composting	N_2O, CH_4
Biosolids land application	N_2O
Wastewater treatment	N_2O, CH_4
Effluent nitrogen discharges	N_2O

[1] Lubricants, waxes

[2] Adhesives, binders, chemical intermediates, fillers, humectants, paint and coating additives, reagent catalysts, resins, sealants, solvents, surface treatment agents

[3] CO_2 from combustion of petrochemical part of solid and hazardous waste

Table 1. Sources of greenhouse gases (continued)

Source	Gas Type
Feedlot manure storage/land application	CH_4, N_2O
Feedlot livestock	CH_4
Soil nutrient management	N_2O, CO_2
Wetland drainage	CO_2, CH_4, N_2O
Grassland conversion to cultivation or pasture	CO_2, CH_4
Forest harvesting	CO_2, N_2O
Atmospheric GHG removal	Gas
Solid waste landfilling	biogenic CO_2
Wood products manufacture	biogenic CO_2

Step 2: Identify types of GHGs emitted

In response to item 18 of the EAW Form for a project's carbon footprint, it is typical for reporting to include emissions of:

- carbon dioxide (CO2)
- nitrous oxide (N2O)
- methane (CH4)
- sulfur hexafluoride (SF6)
- two families of gases known as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)

State-level reporting of GHG emissions to the Minnesota Legislature under the Next Generation Energy Act is limited to this set of gases. Other GHGs and their precursors not commonly reported in GHG inventories but may be relevant to consider, include:

- chlorofluorocarbons (CFCs)
- hydrochlorofluorocarbons (HCFCs)
- hydrofluoroethers (HFEs)
- sulfuryl fluoride (SO2F2)
- ozone
- various idiocarbons and chlorocarbons

For more information on these GHG types, see "Section 2: Sources and Sinks of Greenhouse Gases" in the MPCA's Greenhouse Gas Emissions in Minnesota: 1970-2006 report.

Step 3: How to report GHG emissions

GHG emissions should be reported in CO_2-equivalent short tons (English units). GHG emissions are converted to CO_2-equivalent units by multiplying nominal estimated emissions of each gas, in short tons, by its global warming potential (GWP). A GWP is a factor that converts emissions of any one GHG to its equivalent in tons of emitted CO_2.

It is conventional in emissions reporting, whether at the national, state or facility level, to use the 2007 version of the GWPs developed by the Intergovernmental Panel on Climate Change. These are shown in Table 2.

Table 2. Greenhouse gas global warming potentials

Greenhouse gas	Chemical formula	Global warming potential
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Sulfur hexafluoride	SF_6	22,800
Nitrogen trifluoride	NF_3	17,200
Hydrofluorocarbons		
HFC-23	CHF_3	14,800
HFC-32	CH_2F_2	675
HFC-125	C_2HF_5	3,500
HFC-134a	CH_2FCF_3	1,430
HFC-143a	$C_2H_3F_3$	4,470
HFC-152a	CH_3CHF_2	124
HFC-227ea	C_3HF_7	3,220
HFC-236fa	$C_3H_2F_6$	9,810
HFC-245fa	$C_3H_3F_5$	1,030
HFC-365mfc	$C_4H_5F_5$	794
HFC-4310mee	$CF_3CFHCFHCF_2CF_3$	1,640
Perfluorocarbons		
PFC-14 (Perfluoromethane)	CF_4	7,390
PFC-116 (Perfluoroethane)	C_2F_6	12,200
PFC-218 (Perfluoropropane)	C_3F_8	8,830
PFC-31-10 (Perfluorobutane)	C_4F_{10}	8,860
PFC-51-14 (Perfluorohexane, FC-72)	C_6F_{14}	9,300

Projected GHG emissions are conventionally developed on an average annual basis and include the proposer's best estimate of average annual emissions over the proposed life or design service life of the project. As noted above, the estimates should include emissions from the operating phase of the project plus emissions from

project construction and any materials' end of life. To include construction emissions in the footprint, emissions should be annualized by dividing total construction GHG releases to the atmosphere by project life.

In project GHG accounting, it is conventional to report GHG emissions by source, type, and project phase (i.e., construction, operations), and then sum emissions to a project total. It is recommended that emissions be reported using the reporting framework and categories shown in Table 3, which additionally breaks out emissions by type and subtype of emission and gas.

Table 3. Emission categories for project carbon footprint

Category	Scope	Project phase	Type of emission	Emissions Sub-type	Chemical Emitted
Direct emissions	Scope 1-emissions	Operations	combustion	stationary; area; mobile	CO_2,[4] N_2O, CH_4
	Scope 1-emissions	Operations	non-combustion process[5]	stationary[6]	CO_2, CH_4, N_2O, HFCs, PFCs, other fully fluorinated GHGs
	Scope 1-emissions	Construction	combustion	mobile	CO_2, N_2O, CH_4
	Scope 1-emissions	Construction	land-use	area	CO_2, N_2O, CH_4
Indirect Emissions	Scope 2-emissions	Operations	off-site electricity/steam production	grid-based	CO_2, CH_4, N_2O
	Scope 3-emissions	Operations	off-site waste management	stationary; area	CO_2, CH_4
Atmospheric Removals of GHGs	Scope 1-sinks	Construction/ operations	land-use	area	CO_2 removals to terrestrial storage

A sink is a reduction in atmospheric GHGs by storing carbon in another form. Carbon removals from the atmosphere act to offset emissions of CO_2 to the atmosphere. CO_2 removals from the atmosphere through afforestation and other forms of terrestrial carbon sequestration may be included in the carbon footprint, though this is not required. Given the atmosphere's continued retention of CO_2 after emission, to fully offset a ton of emitted CO_2, carbon removed from the atmosphere through terrestrial sequestration must remain in terrestrial storage for about 50 years. For projects with shorter lifetimes, terrestrial carbon sequestration may only partially offset CO_2 emissions.

Total Emissions plus Sinks = Direct Emissions + Indirect Emissions + Sinks

[4] Fossil CO_2; see discussion in subsection 'Treatment of Emitted Biomass CO_2' below

[5] Noncombustion industrial process emissions are often chemical in nature, but can involve evaporative or other noncombustion processes

[6] Process emissions usually are from stationary sources. If they derive from area or mobile sources, they should be reported as area or mobile noncombustion process emissions

Treatment of emitted biomass CO_2

Biogenic CO_2 emissions should be included in the proposed facility's carbon footprint if they result from permanent land-use change. Permanent land-use changes may include:

- forestland converted to cropland, pastureland, or urban uses
- grassland converted to cropland, pastureland, or urban uses
- all wetland conversions

Beyond emissions from permanent land use change, other emissions of CO_2 from biomass combustion sources or ecosystem or animal respiration generally are not included in project accounting. Unless released as a result of permanent land use change, CO_2 emitted to the atmosphere from biomass combustion or ecosystem or animal respiration is often rapidly removed from the atmosphere through subsequent photosynthesis and returned to storage in living biomass and soils. Table 4 includes a list of common biogenic sources of CO_2 for which carbon neutrality is often assumed in carbon footprint development.

Table 4. Common Biomass CO_2 Sources[7]

Type	State	Source
Common Biomass Fuels	Solid fuels	sawdust, hogged bark, waste wood, other papermill and sawmill residuals, some types of refuse-derived fuel (RDF), paper mill sludge, wastewater treatment sludge, urban tree removal wastes, residential firewood, dedicated whole tree or perennial grasses for bioenergy
Common Biomass Fuels	Liquid fuels	ethanol, biodiesel
Common Biomass Fuels	Gaseous fuels	landfill gas (LFG), digester gas, biomethane for pipeline uses
Other common Biogenic Sources of CO_2 Emissions		organics composting, municipal wastewater and industrial treatment, biosolids land application, industrial grain fermentation, manure storage, grain storage, prescribed burning of grassland/brushland, residential recreational burning, cropland cultivation, forest harvest residuals (slash)

Table 5 summarizes the recommended reporting requirements under this guidance. They do not include requirements related to documentation of data sources, assumptions made, or methods used. At its discretion, the RGU may wish to establish requirements for documentation of information sources that are used in carbon footprint development.

For emissions related to materials management, the EPA's Waste Reduction Model (WARM) is commonly used. According to the EPA website, "EPA created the Waste Reduction Model (WARM) to provide high-level estimates of potential greenhouse gas (GHG) emissions reductions, energy savings, and economic impacts from several different waste management practices. WARM estimates these impacts from baseline and alternative waste management

[7] This listing should not be considered to be exhaustive, but rather broadly indicative of biomass fuels and biogenic CO_2 sources that, in carbon footprint development, may sometimes (on a case-by-case basis) be treated as carbon neutral

practices—source reduction, recycling, anaerobic digestion, combustion, composting and landfilling."

Table 5. Summary of potential reporting elements for a carbon footprint

Reporting element	Detail
Units to report in	CO_2-equivalent (CO_2-e) short tons
Greenhouse gas (GHG) emissions to report	CO_2, CH_4, N_2O, SF6, HFCs, PFCs (see Table 2 above)
How to calculate CO_2-e tons	nominal tons * global warming potential (GWP)
Version of IPCC GWPs to use in calculating CO_2-e emissions	2007 Fourth IPCC Assessment version
What to report	Total project emissions over the life of the project and emissions disaggregated by source and project phase
Averaging period for emissions estimate	One-year, e.g., average annual emissions
Project phases over which to report emissions	Operating phase, construction phase
How to include construction emissions in annual totals	Annualize by spreading construction emissions over projected life or design service life of the project
Types of emissions to report	Stationary, mobile, and area sources, including land-use
Specific sources to report	See Table 1 above
Project boundaries for emissions estimation	• All sources within project fence-line or under contractual control of project proposer • Emissions from purchased electricity/steam • Off-site emissions from purchased waste disposal services • Upstream and downstream sources
How to treat emissions of CO_2 from wood burning, and the combustion of other solid, liquid or gaseous biofuels	Exclude all CO_2 emissions from biomass sources except those from permanent forest clearing, or wetlands or grasslands conversion to other uses
Treatment of sequestration removals of atmospheric CO_2	Recommended

Step 4: How to quantify GHGs emitted

Simplified methods to quantify GHG emissions from a wide variety of sources have been developed by the Intergovernmental Panel on Climate Change (IPCC).[8] The simplified IPCC methods usually take the form of linear equations involving emission factors and activity factors. The Environmental Protection Agency's Center for Corporate Climate Leadership (CCCL) provides easy-to-use default emission factors for creating GHG inventories on the GHG Emission Factors Hub.

Simplified example formulas and references are listed below as one example for each scope and emission type outlined in Table 3 above.

[8] Intergovernmental Panel on Climate Change (IPCC), 2006 IPCC Guidelines for National Greenhouse Gas Inventories; IPCC, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Scope 1 combustion emissions

For stationary combustion sources, emissions of CO_2 from fossil fuel production are typically calculated using the equation:

*tons CO_2 = fuel use in physical units * MMBtu per physical fuel unit * tons of CO_2/MMBtu of fuel use*

While emissions of N_2O from fuel of stationary sources use would be calculated similarly, albeit with the addition of GWP as an additional term, so:

*tons CO_2-e = fuel use in physical units * MMBtu per physical fuel unit * tons of N_2O/MMBtu of fuel use * GWP*

For mobile combustion sources, emissions of CO_2 from fossil fuel combustion are calculated using the equation:

*tons CO_2 = fuel use in physical units *CO_2 Emission Factor (kg CO_2/physical unit of fuel use) * Conversion of kg to tons*

while for CH_4 and N_2O, the equation is:

*tons CO_2-e = Vehicle Miles Traveled * CH_4/N_2O Emission Factor (g/mile) * Conversion of g to tons * GWP*

Scope 1 non-combustion emissions

Scope 1 non-combustion emissions may vary depending on the project type. Table 6, below, provides some pre-existing tools that may be helpful in calculating emissions from non-combustion sources. Furthermore, Appendix B provides references to other methodological sources that can be used for calculating emissions from non-combustion sources.

Scope 1 land use emissions

Simplified formulas used for emissions from land use changes use carbon flux estimates from Chapter 6: Land Use, Land-Use Change, and Forestry in the EPA's *Inventory of Sources and Sinks of Greenhouse Gases.*[9] The simplified formula is:

*tons CO_2-e = Emission Factor Based on Land Type Carbon Flux (tons CO_2e/area) * area of land use change*

where the emission factor is calculated as:

*Emission Factor Based on Land Type Carbon Flux (tons CO_2e/area) = net CO_2 flux from land conversion * total area of land use change in U.S.*[10]

Terrestrial carbon sequestration (TCS) is the process of carbon being absorbed by plants through photosynthesis and stored as carbon in soils and biomass. The offsets value of TCS for projects with lifetimes of 50 years or more is generally assessed at full value, while projects with lifetimes of 20 years and 25 to 49 years are assessed at 40% and 75% offsets values,[11] respectively. In practice, offsets value may be calculated by multiplying total tons of CO_2

[9] EPA's Inventory of Sources and Sinks of Greenhouse Gases

[10] Section 6.1. Ibid.

[11] 40% offsets valuation is the valuation at 20-years of continuous storage, while 75% is the valuation at 40 years of continuous storage. For the schedule of atmospheric CO_2 retention upon emission of CO_2 from combustion, see: F. Joos, et al., "Carbon Dioxide and climate Impulse

removed from the atmosphere by 1, 0.75 or 0.4, depending on project lifetime.

Scope 2 off-site electricity/steam/heat emissions

The simplified formula for calculating GHG emissions from off-site purchased electricity is:

*tons CO_2-e = purchased electricity (MWh) * Emission Factor * GWP*

Regional emission factors published by the EPA's Emission & Generation Resource Integrated Database (eGRID) for off-site electrical generation can be found in Table 6 of EPA's CCCL GHG Emission Factor Hub.[12]

For off-site purchased steam and heat, the formula is:

*tons CO_2-e = purchased steam/heat (MMBtu) * Emission Factor * GWP*

Emission Factors can be found in Table 7 of EPA's CCCL GHG Emission Factor Hub.

Scope 3 off-site waste management emissions

Similar to the equations used for Scope 2, the simplified formula for calculating GHG emissions from waste generation is:

*tons CO_2-e = mass of waste material (tons) * Emission Factor * GWP*

Emission Factors can be found in Table 9 of EPA's CCCL GHG Emission Factor Hub.

More highly developed methods exist of greater complexity, including some developed by the IPCC. A more complete list of methodological sources that might be consulted is included in Appendix B. For specific sources, these may provide an additional approach to the estimation of emissions.

A number of pre-existing tools also are available. These may prove helpful in calculating emissions from one or more GHG emission sources. Table 6 includes a list of some of the more helpful tools available at time of publication. This is not an exhaustive list. These may be used by project proposers to estimate emissions from individual or multiple GHG sources.

Table 6. Tools for estimating GHG emissions from different sources

Tool name	GHG sources covered
SGEC Tool "Simplified GHG Emissions Calculator"	"Simplified GHG Emissions Calculator" stationary source combustion, mobile source combustion, biomass and biofuels combustion, refrigerant and cooling, fire suppression, electricity and steam purchases, off-site solid waste management

Response Functions for the Computation of Greenhouse Gas Metrics: A Multi-Model Analysis," Atmospheric Chemistry and Physics 13 (2013): 2,793-2,825. At 100-years, the usual integration period for analysis, for a one-ton emission of CO_2, the atmosphere retains roughly 50 ton-years of emissions. For comparison, one ton of CO_2 continuously stored in soils and biomass for 50 years would result in similar degree of offsetting storage, about 50 ton-years of storage. At 20 and 40 years, CO_2 storage in soils and biomass resulting from one ton stored, assuming no leakage, would be 38 and 76 ton-years, respectively. Offsets value is derived by dividing, for one ton of CO_2 storage, total tons-years of terrestrial storage by total 100-year ton-years of atmospheric retention resulting from a 1 ton emission of CO_2.

[12] EPA's CCCL GHG Emission Factor Hub.

MPCA feedlot tool[13]	Feedlot livestock, manure storage and treatment, manure land application
Minnesota Infrastructure Carbon Estimator (MICE)	Highway mobile combustion sources, highway construction
Federal HFC Emissions Accounting Tool	Refrigeration and space cooling
Clear Path: Local Government Action Climate Tool	Stationary source combustion, mobile source combustion, electricity purchases, solid waste management, biosolids land application, natural gas distribution and services
Cool Farm Tool	On-farm mobile source combustion, cropland nutrient management, livestock, manure storage and treatment, land use change
Virtual (Dairy) Farm	Crop production, enteric methane (dairy cows), on-farm energy use, manure management
EPA Waste Reduction Model (WARM)	Solid waste reuse, recycling, composting, incineration, landfilling
COMET-Planner	Conservation and nutrient management practices in crop production and grazing

Project proposers should provide sufficient background and technical information so that the emissions calculations are replicable. Once calculated in nominal tons of emissions, emissions should be converted to CO_2-equivalent short tons and sum to a project total. For tools that estimate emissions in metric units, a conversion factor of 1.102 can be used to convert from metric tons to short tons.

Section 2 – Climate mitigation

This section provides guidance and resources to help respond to EAW item 18b. There are many ways to mitigate a project's impact on the climate by reducing its GHG emissions, and new mitigation options are rapidly emerging. Many of these mitigations can also reduce costs and make compliance with future climate regulation easier and more affordable.

EAW item 18b(i): How to identify and assess reasonably available mitigation options

There are many existing resources that identify GHG mitigation measures that can be used to reduce project emissions. Moreover, projects implementing these mitigations can often benefit from tax credits, rebates, or other financial subsidies provided through federal, state, or local governments or through utility-run programs. Many future GHG mitigations can be more easily and cost-effectively implemented by anticipating them in the project's original design. For example, if a project anticipates replacing gas-fired furnaces or other appliances with electric heat pumps in the future, it could reduce the cost of that future replacement by including upgraded electrical wiring and circuit boxes at the time of construction. Similarly, if a project anticipates adding solar panels in the future it could orient its rooftops with that in mind, or design landscaping to avoid shading future solar panels. Electrical systems can also be designed with future electric vehicle charging needs in mind, even if charging stations are not part of the original project design.

[13] Available by request from the MPCA

See various categories below with links to resources that give additional technical and available financial assistance information.

(1) **Energy efficiency**: Increasing energy efficiency reduces a project's emissions. Common mitigation measures in this category include:

   a. Designing and constructing energy efficient buildings along with installing energy-efficient appliances, equipment, and lighting

   b. Utilizing process efficiencies for extraction and production to reduce energy and water consumption

Additional technical information on energy efficiency and financial subsidies is available in Appendix C.

(2) **Electrifying appliances and equipment**: Projects can usually reduce GHG emissions by using electric appliances and equipment in lieu of fossil-fuel burning appliances and equipment. For example, heat pumps can replace gas-fired appliances. While electrification of project appliances increases electricity use, electrification typically reduces on-site emissions even more, and GHG benefits will increase over the years as the power grid continues to decarbonize. Additional technical information on electrifying appliances and equipment and financial subsidies for electrification is available in Appendix D.

(3) **Distributed electricity generation:** Projects can reduce their emissions by generating electricity on-site, such as through the installation of solar panels on rooftops or elsewhere at a facility. Considerable financial support is available for solar power and storage through tax credits and rebates. Additional technical and financial assistance information on electricity generation is available in Appendix E.

(4) **Transportation**: Projects that involve mobile sources can reduce GHGs by electrifying their fleets or on-site mobile equipment and by providing electric vehicle charging stations. Additional technical and financial assistance information on transportation electrification is available in Appendix F.

(5) **Land Use:** Projects can reduce GHG emissions associated with land use, and even create GHG sinks through best practices in land-use management, nutrient and sediment run-off control, on-site terrestrial biogenic carbon sequestration, and wetland mitigation, among others. Additional technical and financial assistance information on land use GHG emissions is available in Appendix G.

EAW item 18b(ii): Quantifying GHG reductions from mitigations

Environmental review documents generally include complete descriptions, quantifications, and a detailed assessment of the planned mitigation activity as a part of the proposed project. Resources provided in the previous section and in Part I of this guidance can help quantify the emission reductions expected from various mitigations. The assessment should also explain why the selected mitigation for the project was preferred over other mitigation options.

In quantifying potential emission reductions or emission offsets, project proposers should provide sufficient background technical information to enable the reader to replicate the calculations.

EAW item 18b(iii): Quantifying net lifetime emissions and effects on GHG reduction goals

Project proposers and RGUs should be aware that projects proposed today face the prospect of needing to greatly reduce, and even eliminate their GHG emissions in the years ahead as national, state, and local governments are setting increasingly more ambitious GHG reduction goals and policies. Achieving these reductions will affect virtually all projects with GHG emissions during their operating lifetime.

For example, Minnesota's Climate Action Framework, published in 2022, sets forth the goal of reducing the state's GHG emissions by 50% by 2030 and of achieving "net-zero" emissions by 2050.[14] These are more ambitious targets than those enacted by the state in 2007 via the Next Generation Energy Act,[15] reflecting advances in the climate science and the growing global response. The Minnesota Framework's goals are consistent with the United States' pledge to reduce GHG emissions to achieve net-zero GHG emissions by 2050. They are also aligned with the international agreements to take steps to limit global warming to 1.5 degrees Celsius.

Many Minnesota cities and other local units of government have similarly issued plans to achieve reductions in GHG emissions, and some are updating plans adopted years ago.[16] Local units of government should be contacted to obtain the latest local climate plans.

To calculate a project's net lifetime GHG emissions, multiply its annual emissions by its predicted years of operational life. Then, the project's net lifetime emissions can be compared to the Next Generation Energy Act goals[17] and any other more stringent state or local GHG reduction goals and Minnesota's Climate Action Framework.[18] Responses to this question should discuss how the project aligns with the Next Generation Energy Act and other GHG reduction goals by achieving a similar scale and timing of GHG emission reductions.

Many future GHG mitigations can be more easily and cost-effectively implemented by anticipating them in the project's original design. The answer to item 18b(iii) should list any project design features the project plans to implement that would facilitate future GHG reductions for the project (e.g., upgraded electrical to support potential future HVAC and appliance electrification and renewable energy installation).

[14] Minnesota's Climate Action Framework, https://climate.state.mn.us/sites/climate-action/files/Climate%20Action%20Framework.pdf
[15] Minn. Stat. § 216J.02, subd. 1.
[16] City Climate Action Plans in Minnesota: Overview and Review, 2022, https://www.house.leg.state.mn.us/comm/docs/DvlEmiU0SE23Iao3b_Qv8g.pdf
[17] The Next Generation Energy Act goals are listed at Minn. Stat. § 216H.02, subd. 1.
[18] Available at https://climate.state.mn.us/sites/climate-action/files/Climate%20Action%20Framework.pdf

Section 3 – Climate adaptation and resilience

The purpose of this section is to help project proposers and responsible governmental units (RGU) respond to the specific climate adaptation and resilience questions of the EAW Form. This guidance supports the development of climate related information but does not limit the use of other reliable and relevant guidance for discussing how current Minnesota climate trends and anticipated climate change may interact with a project and its development.

EAW item 7a: Climate trends

Establish a description of climate change specific to the most representative geographic unit or location of the project using readily available information. Look at historical climate trends data for conditions at the start of the project and projected (future) climate data for conditions during the life of the project.

This item is intended to lay the groundwork for understanding how climate change is likely to affect the area where the project is located throughout the life of the project. This groundwork is important for several reasons:

- Facilities, infrastructure, and other assets constructed as part of the project may be subjected to increasingly extreme conditions over time. Anticipating and adapting to these projected conditions will provide greater resilience for the project throughout its expected life.
- Environmental effects may change over time as climate conditions become more extreme.
- Design decisions for the project may affect the surrounding area in positive or negative ways as the climate continues to warm and with greater precipitation extremes. Examples include mitigating or contributing to urban heat island effects, localized flooding, stress on the local electric grid and/or water resources.

As described by the Minnesota Department of Natural Resources webpage, Minnesota's climate shows the following trends:

- Warmer and wetter
- Cold weather warming
- More damaging rains

These three trends are expected to continue in the future in Minnesota along with two additional projected changes:

- Increasing risk of heat waves
- Increasing risk of drought

This description of current climate trends and how climate change is anticipated to affect the general location of the project during the life of the project will be used in answering subsequent climate related questions in the EAW. The extent and scale of readily available information may vary depending on when the EAW is completed and the nature and location of the project.

When establishing a description of climate change specific to the most representative geographic unit or location of the project, keep these things in mind:

- Depending on the data source, model, or tool used, you might be able to type in a specific address, click on a specific location in a map tool, or select the applicable census tract, county, major watershed, state forest, state park, or other geography – choosing whatever is consistent with how you justified the geographic scale for the rest of your project analysis.
- Look at historical climate trends data to establish current project conditions. Historical climate information will be based on actual data from specific reporting stations. Discuss the time frame options and trend years you selected for this data, and why it fairly represents your project.
- Explore projected (future) climate data to anticipate conditions during the life of the project. Projected climate data is modeled, so data from different sources may be based on models with somewhat differing methodologies, assumptions about the factors that affect climate change, and resolution / scale (e.g., downscaled global data to a 25km grid vs. 10km vs. 4km, special treatment of lakes, CMIP5 climate models vs. CMIP6). Typically, smaller grid sizes are more specific to local climatic conditions if a "downscaling" process is applied that is based on physical relationships and atmospheric processes (dynamical), rather than on statistical techniques.
- Many sources offer projected data for multiple future time periods, so be sure to select the period that best aligns with the life of the effects of the project.
- Many sources offer projected data for multiple model scenarios. It can be helpful to review and discuss multiple models.

Current climate trends

An available Minnesota source for determining location-specific ***current*** climate trends for temperature ranges and total precipitation based on historical data is the Minnesota Climate Trends tool.

The Minnesota Climate Trends tool shows historical data for one or multiple adjacent selected climate divisions, counties, deer permit areas, ecological subsections, major watersheds, state forests, state parks, tribal governments, wildlife management areas, and the entire state. It allows comparisons, trend lines, and smoothed time series for warming (average, minimum, and maximum temperature) and for total precipitation. The time scale for data is from 1 month to 60 months ending in any month – or annual – going back to 1895. This tool allows the user to look at historical data and trends annually, for individual months or for seasons relevant to the project. Use the tool to explore each of the project-relevant climate variables and associated time frames. See an example from the tool immediately below (subject to change). *(Source: Minnesota Department of Natural Resources)*

Image 1. Minnesota Climate Trends tool

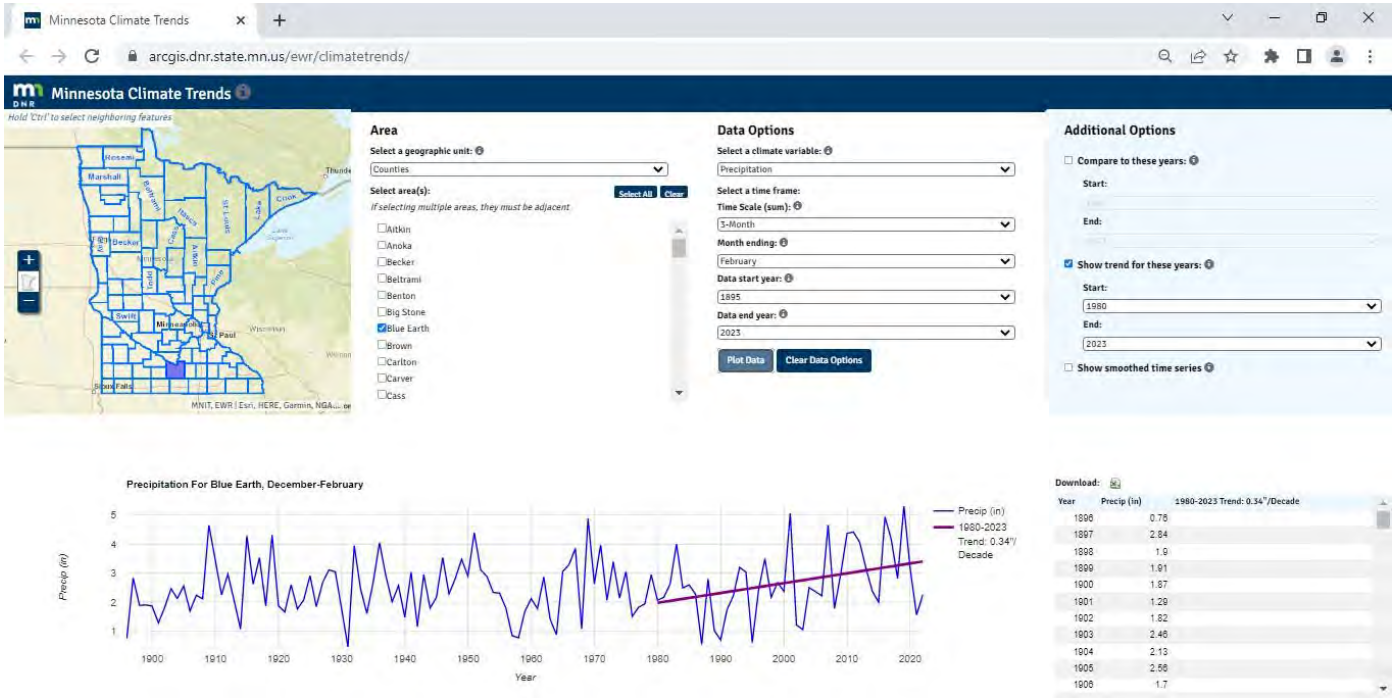

Directions for the Minnesota Climate Trends tool:

Step 1: Open the tool and under “Area,” select an appropriate geographic unit (i.e., watershed, county, etc.) and specific area(s) consistent with your project analysis.

Step 2: Under “Data Options” select a climate variable (precipitation, temperature, etc.) and a time frame which includes the time scale, month ending, data start year, and data end year. For example, it may be helpful to evaluate your project only in terms of winter climate trends if your project will only be operating in the winter. Additionally, construction schedules, C&D waste disposal, or other project specific details may call for month-specific analysis.

Step 3: Under Additional Options, click “Show trend for these years” and pick whatever start and end dates are desired for the trend line. Setting the trend line from 1980 to the most recent year with complete data is an approach often used.

Step 4: Click “Plot Data” back under “Data Options” Scroll down for a graphical representation of the data and a data table. To open/save an Excel spreadsheet of the data, click the icon next to “Download” in the upper left of the data table.

Anticipated climate changes – projections for climate variables

Minnesota CliMAT - Climate Mapping and Analysis Tool (CMIP6) is an interactive online tool that provides highly localized climate projections for Minnesota. Users can view climate projections down to the 4km/2.6mile scale across the state, visualizing even how specific towns will likely be impacted in the coming decades. MN CliMAT uses the latest generation of global climate models, called CMIP6 (used for the Fifth National Climate Assessment).

"Create Map" allows users to define an Area of Interest (AOI) within Minnesota to view what the future climate might look like for a chosen emissions scenario, variable, and time period. AOIs can be selected on the map from predefined options such as counties or watersheds, drawn by hand, or uploaded in a geographic data file. See an example immediately below (subject to change). *(Source: University of Minnesota Climate Adaptation Partnership)*

Image 2. Minnesota CliMAT – Climate Mapping and Analysis Tool

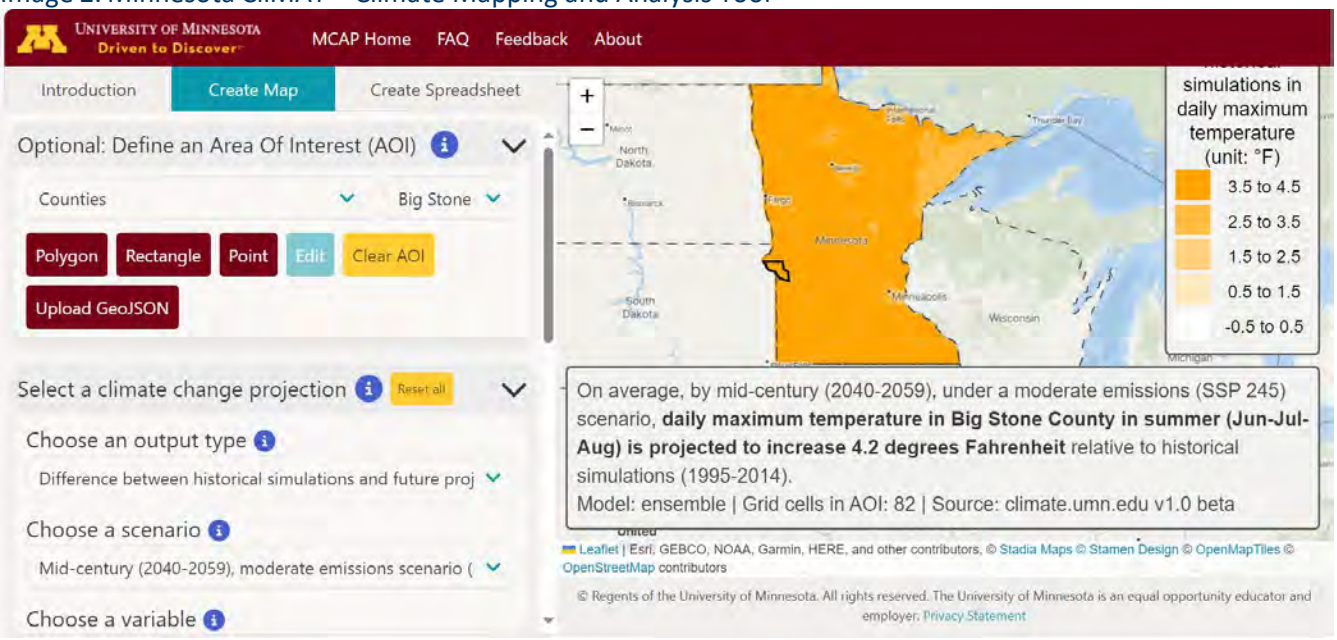

Directions for Minnesota CliMAT:

Step 1: Click on “Launch the tool” and select the “Create Map” tab.

Step 2: “Define an Area of Interest (AOI)”. Choose from three options for defining the geographic area consistent with your project analysis: (1) select a pre-made AOI from the drop-down menu (i.e., counties, climate divisions, state boundary, state parks, state forests, One Watershed One Plan units, HUC 8 watersheds, tribal governments, ceded territory boundaries, electric service areas), or (2) draw an AOI on the map by selecting the polygon, rectangle, or point tool to define a geographic area that incorporates at least one grid cell, or (3) upload a GeoJSON file to define the geography.

Step 3: “Choose an output type”. Use the drop-down menu to select projected future conditions or the change from that geographical area’s historical climate (i.e., modeled values, difference between historical simulations and future projections, percent difference).

Step 4: “Choose a scenario”. Use the drop-down menu to select from either the moderate or high-emissions scenario for the appropriate period – mid-century (2040-2059), late-century (2060-2079), or end-of-century (2080-2099). Explore multiple scenarios and appropriate periods to help anticipate conditions during the life of the project, and also to assess conditions during the period that best aligns with the life of the effects of the project.

Step 5: “Choose a variable”. Use the drop-down menu to select from the multiple options under each of the headings (i.e., precipitation values and thresholds, precipitation intensity, snow, humidity, temperature averages, minimum temperature thresholds, maximum temperature thresholds, soil, lakes). Each option shows the time

frames for which the data is available, and clicking on that option does not work if an unavailable time frame is selected (Step 6 drop-down menu). Explore all the variables which might have bearing on the project during the life of the project and the life of the effects of the project.

Step 6: “Choose a time frame”. Use the drop-down menu to select from multiple time frame options which include the year (Y), the growing season (GS), one of the meteorological seasons (S), or a specific month (M). The time frame allows the user to view projected climate changes for portions of the year that might specifically affect project or facility design, operations, or effects. Explore various time frames to get a complete picture because averages may obscure important seasonal or monthly differences. Be sure the time frame fits with the availability of data for the selected variable.

Step 7: “Map options”. If drawing the AOI on the map, make it easier by using the drop-down menu to “Choose a basemap” type that will be the most helpful to identify the appropriate area of interest. Click applicable “Show / Hide / Round” options (e.g., roads). Use the slider to “Set transparency of climate data” at a level that shows the features of the basemap and options selected.

Anticipated climate changes – climate hazard projections

Available national sources for location-specific data related to anticipated climate change hazards including extreme heat, drought, wildfire, flooding, and storm intensity include the following.

Climate Mapping for Resilience and Adaptation (CMRA) Assessment Tool: This tool explores current and anticipated extreme heat, drought, wildfire, and flooding hazards by tract, county, or tribal land for two emissions scenarios in any of three time periods – Early Century (2015-2044), Mid Century (2035-2064), and Late Century (2070-2099). It includes climate projections for numerous variables related to each climate hazard. [CMRA is scheduled to be updated in September 2024 with CMIP6 climate model data replacing (older) CMIP5 data.] See an example of the tool immediately below (subject to change). *(Source: U.S. Global Change Research Program)*

Image 3. Climate Mapping for Resilience and Adaptation tool

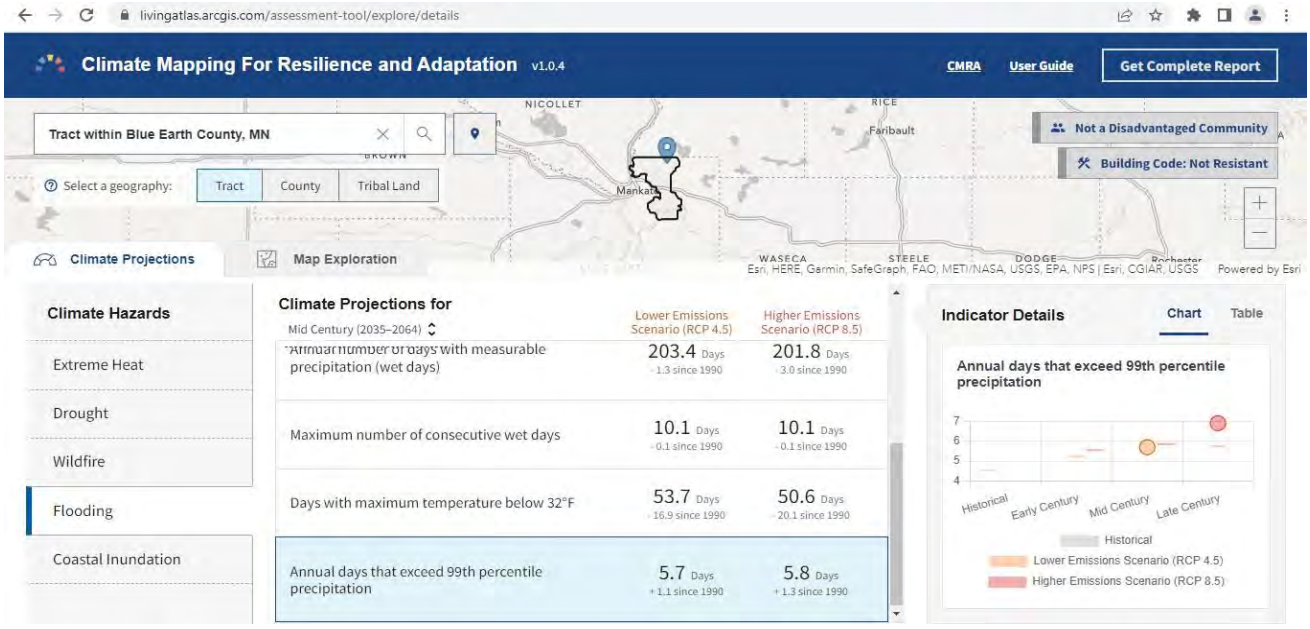

Directions for the CMRA Assessment Tool:

Step 1: Open the tool and click on the "Launch" button.

Step 2: "Find address or place". In the address bar, type in a specific address or a more general location such as a city or county name to see options and select the most relevant. Then to get a more exact location, repeatedly click the "+" icon on the map to the needed scale and drag the map around to the right place. Then, next to the address bar, click on the location icon. Click again on the desired place on the map.

Step 3: "Select a geography". Click on whichever geography (i.e., Census Track, County, Tribal Area) is most consistent with your project analysis.

Step 4: In the "Climate Projections" tab, click on one of the "Climate Hazards" listed in the left menu bar (i.e., Extreme Heat, Drought, Wildfire, Flooding). Explore each of the climate hazards relevant to the project.

Step 5: "Climate Projections for". Use the up/down arrows to see the menu of time periods (i.e., Early Century, Mid Century, Late Century) and select the most relevant to the life of the project. Then scroll through the related climate projections shown and select any of interest to see the associated "Indicator Details" Chart (or Table) on the righthand side.

Step 6: "Get Complete Report". To download printable images (landscape presentation format) of the climate projection data for that location for each of the five hazards, first select the "County" geography and then click on the "Get Complete Report" button at the top right-hand corner of the page.

Anticipated climate changes – climate scenarios projections

CREAT Climate Change Scenarios Projection Map. This tool provides projections of storm intensification, which differ from those of average conditions. Unlike changes in annual precipitation, more intense storms present a more acute challenge in water resource management and infrastructure protection. The range of future climate conditions is defined by two scenarios – a "Stormy" future and a "Not as Stormy" future. The two time periods, centered on 2035 and 2060, are provided as short- and long-term infrastructure and water resource planning horizons. Climate models used were drawn from the (older) CMIP5 dataset. *(Source: U.S. Environmental Protection Agency)*

Image 4. CREAT Climate Change Scenarios Projection Map

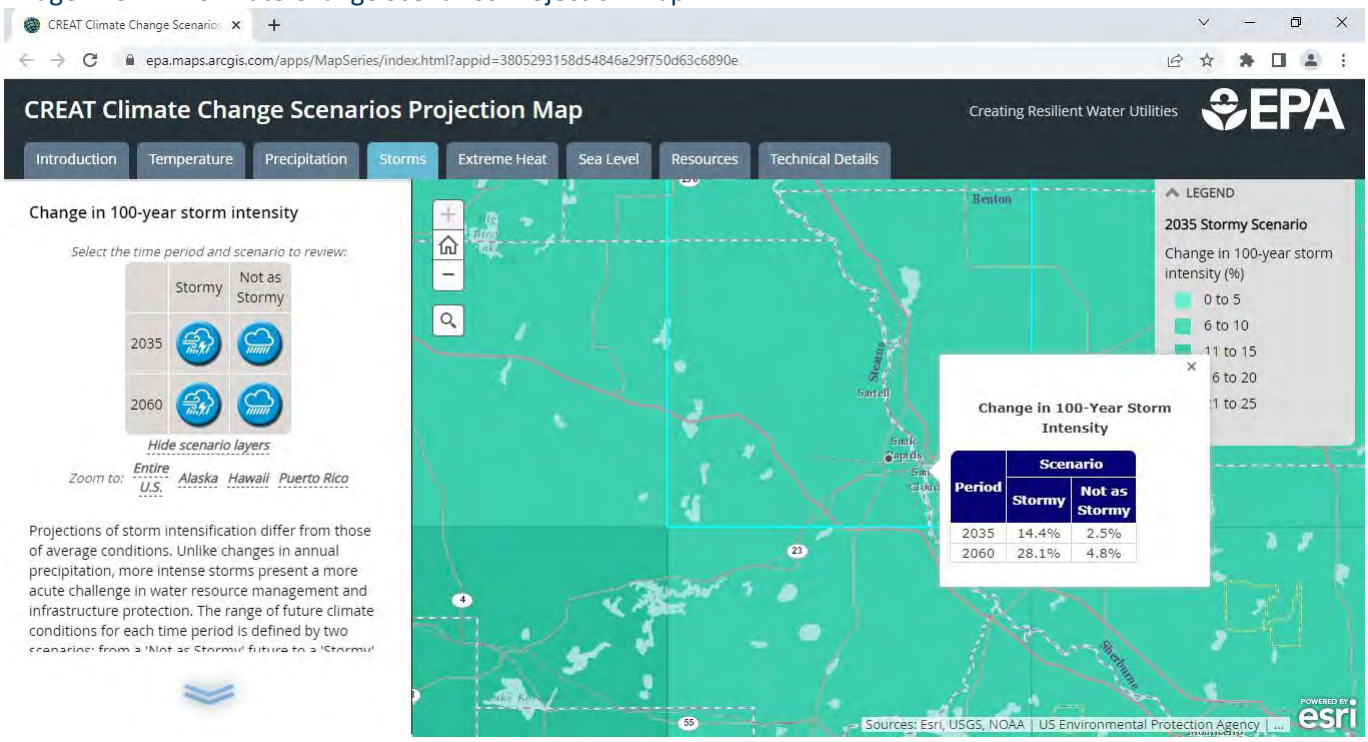

Directions for the CREAT Climate Change Scenarios Projection Map:

Step 1: Click on the "Storms" tab to see data for projected change in 100-year storm intensity.

Step 2: Use the "+" icon and drag the map to zoom in to the specific location.

Step 3: Click on the location on the map to see a pop-up with specific projected (future) percentage changes for each of the time periods and scenarios.

Anticipated climate changes – additional information sources

Fifth National Climate Assessment, especially Chapter 24: Midwest, or more current version if available: The NCA report is an official U.S. Government report about climate change vetted by 13 federal agencies. It relies on the climate-related scenarios that are generated for the IPCC assessments (see bullet below). NCA5 contains useful information in Chapter 31: Adaptation about what is needed to make adaptation strategies successful. *(Source: U.S. Global Change Research Program)*

Explore the NCA5 Interactive Atlas, based on CMIP6 climate models. To access a variety of temperature and precipitation climate projection maps in the Atlas follow these steps: click on Climate Maps, click Open the Explorer, click Open Map, select your preferred map, use +/- to locate area of interest on the map, click on the county of interest to get a popup and then on Select Feature in upper right corner of the popup to toggle between data for three climate scenarios). *(Source: U.S. Global Change Research Program)*

Intergovernmental Panel on Climate Change Assessment Report (IPCC 6, or more current version if available): Through its assessments, the IPCC determines the international state of knowledge on climate change. It

identifies where there is agreement in the scientific community and where further research is needed. The modeled climate scenarios generated by scientists from around the world used in the IPCC assessment are the basis for all local sources of projected (future) climate data. Use this source for general context about the most up-to-date assessment of global and regional climate trends. The Summary for Policymakers discusses the Shared Socioeconomic Pathways (SSPs) scenarios and modelled pathways used for the assessment (based on CMIP6 climate models). *(Source: Intergovernmental Panel on Climate Change)*

National Oceanic and Atmospheric Administration (NOAA): NOAA Climate.gov is an additional source of timely and authoritative scientific data and information about climate, coordinated with many of the other sources listed. The dataset on Future Climate Projections – Graphs & Maps is based on (older) CMIP5 climate models. *(Source: National Oceanic and Atmospheric Administration)*

Caveats and definitions

It is important to note that readily available data may or may not (depending on project location) include projections for future years showing the type of intense precipitation events Minnesota currently experiences, and which are anticipated to increase.

In responding to this item, the following are helpful explanations of terms:

- General location of the project: the specific project location plus its environs, including the nearby and encompassing local governmental jurisdictions, and the major watershed(s) it affects.
- Life of the project: (options relevant to different project types)
- Proposed life: the period of time the project is proposed to operate or last.
- Design service life: expected period of use as intended by the designer, after which it may need to be replaced.
- For project definition and interpretation consistency, consider using the same project life assumptions as the greenhouse gas emissions calculations.
- Default: the anticipated impact of climate change on the proposed project over the next 30 years, such as for conservation or restoration projects that may continue indefinitely into the future if properly maintained.
- Vulnerability: a function of exposure to climate hazards and associated impacts, sensitivity to these hazards, and capacity of a system or community to adapt or cope with the adverse effects. A hazard has the potential to disrupt or damage a project or system.

- Risk: the probability of a climate hazard exploiting a vulnerability and the magnitude of associated impacts and consequences. Significant risks share both a likelihood of occurrence and degree of impact to the project or system if they occur.

EAW item 7b: Project interaction with climate trends

Using the description of the climate trends in the project vicinity (item 7a), to the best extent practicable, describe how the project's proposed activities will interact with those climate trends. Identify the risk of long-term impacts that climate trends might pose to the proposed activities throughout the project life, considering how conditions may continue to change throughout that time. Identify climate change hazards, threats, and the proposed activities' vulnerabilities to them. Identify the risk of key project assumptions and design parameters becoming outdated or insufficiently defined if the future climate reality aligns with trends and projections.

Project design

Aspects or features to consider that may amplify or interact with how climate change is anticipated to affect the design of the project include, but are not limited to:

- Changes to land cover, such as impervious surfaces:
    - During intense rainfall events, increases in the amount of impervious surface on a site (from table in Q7) may result in more localized flooding in the immediate area of the project, in addition to other stormwater effects, especially when vegetative buffers are absent.
    - Impermeable pavement (concrete or asphalt) without the benefit of vegetative cover absorbs heat during the day and radiates it at night, increasing surface temperatures and urban heat island (UHI) effect in the area.
- Construction materials:
    - Dark roofing and siding materials absorb heat during the day and radiate it at night, which increases the UHI effect and amplifies the warming temperatures of climate change.
- Site design:
    - Retaining mature trees can provide shading of structures to reduce energy use and many ecosystem services, including air quality and stormwater benefits.
    - Siting and orientation of buildings has ramifications for energy use, flood risk, and more.

Available sources for information on causes and mitigations of urban heat:

- Information about the UHI effect including definitions, risks and strategies is available on EPA's Heat Island Effect webpage.
- In-depth information about mitigation strategies using green infrastructure practices is available on EPA's Heat Island Compendium webpage.
- Specifically for the Twin Cities metropolitan area, see Metropolitan Council's Keeping Our Cool: Extreme Heat in the Twin Cities Region, including an Extreme Heat Map Tool.

Land use

Discuss the compatibility of the project's activities with land use, planning, and zoning as it relates primarily to the development and the projected climate changes for the project location.

For purposes of describing existing and planned land uses, open space is any natural space, public or private, that is used primarily for passive recreation (passive recreation uses are those that require little to no landscape modifications, e.g., birdwatching), animal habitat, and/or for maintaining ecological services and/or rural character. Open space may or may not be protected by federal, state, or local entities. Examples could include woodlands, prairie, groundwater recharge areas, or greenways.

Actions or features to consider that may amplify or interact with how climate change is anticipated to affect land use include, but are not limited to:

- Reduction or loss of tree cover may lead to the loss of many climate resilience benefits, leading to more intense stormwater runoff, increased urban heat island effect, loss of shade for protection during extreme heat, potential reduction in air quality, and more. Information about benefit-cost considerations of tree canopy in the urban landscapes is available in the EPA's "Reducing Urban Heat Islands: Compendium of Strategies".
- Increased heat and longer growing seasons can increase or reduce crop production, causing producers to modify land use and cropland management to adapt. Longer growing seasons enable additional pest and weed growth, likely increasing application of pesticides and herbicides, which may impact local plant and animal communities.
- Cropland and rangeland productivity is reduced by prolonged extreme flooding, topsoil loss, drought, or groundwater depletion.
- Prolonged groundwater rise can result in the expansion of wetlands, ponds, and lakes, resulting in habitat loss.
- Prolonged drought can result in habitat loss from constriction of wetlands, ponds, and lakes, and may also affect area wells and groundwater resources.
- The removal of wetlands and other low-lying areas eliminates the ability for the land to retain and absorb stormwater, leading to more intense stormwater runoff, nutrient loading, and more effects. See stormwater guidance below for related information.
- Extreme storm events erode topsoil, which results in decreased crop productivity and nutrients washed into natural waterbodies.
- Heat stress can kill vegetation, leaving soils open to erosion.
- Landslides can occur on steep slopes where soils are saturated.
- Increased freeze/thaw can result in increased icing of roadways, trails, sidewalks, and parking lots, requiring increased salting. Chlorides from salting can degrade lake water quality, impact aquatic life, degrade soil, and kill landscape plantings.

Consider the risk potential for critical facilities proposed to be sited in floodplains or other areas identified as at risk for localized flooding considering changing precipitation and event intensity. Critical facilities are facilities necessary to a community's public health and safety.

In further considering land use, also discuss the compatibility with land use, planning, and zoning as it relates primarily to development and the projected climate changes for the project location.

Available sources for identifying locations that are more vulnerable to extreme heat and/or localized flooding due to land use:

- Heat Vulnerability in Minnesota Tool: Use this tool to assess community vulnerability to extreme heat. The tool provides recent historical data on excessive heat warnings and heat advisories, as well as projections for cooling degree days. Select the study area (HSEM Region, County). In the "Sensitivity" menu, select "% impervious surface". Select your preferred variable for historical or projected heat data in the "Exposure" menu. Zoom in on the maps using the "+" icon to locate your project site. See more resources about specific climate change in Minnesota on the Climate & Health website. *(Source: University of Minnesota)*
- Climate Vulnerability Assessment Regional Risks and Opportunities for the Twin Cities Region: This website includes tools, resources and mitigation actions for current regional climate hazards including Extreme Heat (Story Map and Extreme Heat Map Tool) and Localized Flooding (Story Map and Localized Flood Map Screening Tool) related to existing land use. This data is a comprehensive resource for the seven-county region (Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington counties) governed under the Metropolitan Council. *(Source: Metropolitan Council)*
- The Growing Shade Mapping Tool for projects located in the Twin Cities metropolitan area provides a customized report showing tree canopy and other data for the specific geography (cities/townships, neighborhoods in Minneapolis and St. Paul, or census block group). *(Source: Metropolitan Council)*

Contamination/hazardous materials/wastes

Warmer, wetter weather with more frequent extreme rainfall events and localized flooding could pose operational concerns which may result in either more frequent or more severe environmental effects. Examples include:

- Increased leaching from disposed wastes of contaminants into the groundwater
- Increased erosion of exposed soil and other earthen materials
- Increase in contact water volumes that may require collection and treatment
- Increased erosion on the working face of waste storage or containment
- Increased moisture added to the waste material or debris, which will in turn increase methane gas production and add to greenhouse gasses
- Lack of capacity for holding and managing the leachate, stormwater, and wastewater volume generated because the system was designed based on smaller precipitation events
- Increased stormwater sediments or solids that need proper disposal
- Increases in leachate and contact water needing treatment; options for treatment may be affected by additional limitations on land application due to changing precipitation and temperature patterns, and on limitations at wastewater treatment plants due to treatment system capacity strained by heavy rain

events, leading to additional potential water quality effects

- Increased extreme heat and humidity, making environmental effects such as odors more likely and may increase their severity
- Increased freeze/thaw cycles and more "unseasonal" weather making operational issues, which may result in environmental effects – such as frost heave of cover materials – more likely and may increase the severity of the environmental effects
- Increased flooding events can mobilize contamination and transport pathogens and environmental contaminants that are dangerous to people and livestock
- Decreased air quality due to temperature inversions, wildfires, and atmospheric reactions driven by heat. Poor air quality can increase stresses to people, livestock, and wildlife

Changes in Minnesota's climate include rainfall events of greater intensity and more localized flooding, more frequent freeze/thaw cycles, lack of snow cover, extreme heat, and more. This may damage infrastructure and create situations that result in accidental spills and releases. Include these anticipated consequences of climate change in the spill prevention plan contingency plans as relevant.

EAW item 8: Cover types

Minnesota is already facing wetter weather conditions, more intense precipitation events, and an increase in average temperatures due to climate change. The result will be an increase in stormwater runoff, especially in areas with more extreme land cover changes (e.g., higher percentage loss of tree canopy or changes from natural vegetated areas to impervious surfaces like parking lots, roofs, and sidewalks). One approach for consideration in minimizing climate change effects is green infrastructure. Green infrastructure is an approach to manage wet weather impacts in a way that mimics, restores and maintains natural hydrology. The fundamental concept behind green infrastructure is to retain precipitation where it falls. Green infrastructure includes a wide array of practices that manage stormwater and reduce stormwater runoff, but also provide other benefits including carbon sequestration, wildlife habitat, recreation, and increased property values. Green infrastructure practices can reduce adverse impacts of climate change when designed, constructed, and maintained properly. Green infrastructure does not include stormwater pond wet sedimentation basins. Stormwater ponds are not constructed infiltration systems.

To determine the acreage for the "green infrastructure" category, calculate the acreage of each green infrastructure practice to be installed for the project, based on the surface area (length multiplied by width) of the footprint for that installment (not the area that drains into the installment). Make sure not to double count any of the green infrastructure acreage in the "lawn/landscaping" category, nor in the "stormwater pond (wet sedimentation basin)" category, nor in the "impervious surface" category (for green roofs).

The infrastructure installments included in the "green infrastructure" category are described below:

- **Constructed infiltration systems** – Examples of such infiltration systems include, but are not limited to:
    - **Raingardens** - Raingardens utilize soil (typically engineered media or mixed soil) and native vegetation (including those that attract pollinators) to capture runoff and remove pollutants. Both the media and underlying soil typically have high infiltration rates. More information is

available on the Minnesota Pollution Control Agency's Green Infrastructure benefits of bioretention webpage.

  - **Bioswales** - Bioswales are vegetated channels used primarily to transport runoff and filter sediment from the runoff. Although their primary effect is on removing pollutants associated with sediment, they can be designed to infiltrate water. More information is available on the Minnesota Pollution Control Agency's Overview for filtration webpage.

- **Constructed tree trenches and tree boxes** – Tree trenches and tree boxes are engineered structural practices that behave like a raingarden. Water is captured and delivered to a storage area (engineered media), where the water can infiltrate and be taken up by trees. More information is available on the Minnesota Pollution Control Agency's Green Infrastructure benefits of tree trenches and tree boxes webpage.
- **Constructed wetlands** - Stormwater wetlands differ from stormwater ponds (wet sedimentation basins) by their variety of water depths and associated vegetation. Stormwater wetlands are constructed stormwater management practices, not natural wetlands (including wetland restoration/enhancement/creation for compensatory mitigation required under state and/or federal requirements). More information is available on the Minnesota Pollution Control Agency's Green Infrastructure benefits of constructed wetlands webpage.
- **Constructed green roofs** – Green roofs consist of a series of layers that create an environment suitable for plant growth without damaging the underlying roof system. Green roofs provide both volume and rate control, thus decreasing the stormwater volume being delivered to downstream best management practices. Green roofs also provide filtering of suspended solids and pollutants associated with those solids. More information is available on the Minnesota Pollution Control Agency's Green roofs webpage.
- **Constructed permeable pavements** – Permeable pavements allow stormwater runoff to filter through surface voids into an underlying stone reservoir for temporary storage and/or infiltration. The most commonly used permeable pavement surfaces are pervious concrete, porous asphalt, and permeable interlocking concrete pavers. More information is available on the Minnesota Pollution Control Agency's Permeable pavement webpage.
- **Other** – Implementing natural systems that promote infiltration of rainfall where it falls, mimic predevelopment hydrology and provide ecosystem services may include a variety of unique, project-specific measures, such as:
  - riparian habitat
  - shoreline restorations
  - stream restorations
  - aquatic bench restoration
  - upland native plant community restorations
  - soil loosening
  - soil compost amendments and soil life enhancements
  - some types of on-site rainwater reuse

Percent tree canopy (cover) for a given area can be estimated utilizing GIS or, if that is not available, another tool option is i-Tree Canopy, which also provides an estimate of the benefits of those existing trees. For the Twin Cities Region, the Growing Shade Mapping Tool provides a customized report showing tree canopy and other

data for the specific geography (cities/townships, neighborhoods in Minneapolis and St. Paul, or census block group). *(Source: Metropolitan Council)*

Tree size and maturity will vary based on species, but research cited by EPA in Reducing Urban Heat Islands: Compendium of Strategies Trees and Vegetation has found that after 15 years, an average tree usually has matured enough to provide the full range of benefits. Cities and counties often have tree inventories, which estimate the age of trees and can be a useful resource. In general, a mature tree is one that can take care of itself without aid (e.g., stakes, water). They typically have a well-developed tree canopy, are even-aged stands capable of sexual reproduction (i.e., fruits, flowers, nuts, cones) and have attained most of their potential height growth. For tree and forestry definitions, please refer to USDA's Forest Service Glossary (USDA, 2010).

EAW item 12: Water resources

Include a qualitative overview of how effects from project activities on water resources may be affected by, unaffected by, or mitigated due to current climate trends and anticipated climate change, including the following as relevant to environmental effects and the general location of the project:

- Rainfall frequency, intensity, and amount
- Higher daytime temperatures and winter low temperatures affecting surface and waterbody temperatures
- Increases in extreme heat affecting surface and waterbody temperatures
- Increases in extended drought and/or periods of flooding
- Changes in streamflow highs and lows
- Increases in the frequency of freeze-thaw cycles
- Later ice in and earlier ice out
- Longer growing season

Climate change may amplify environmental impacts of a project. For example:

- If discharges of warm water are added to surface water already warmer than historical norms due to higher nighttime lows and more daytime heat and humidity, it could lead to the water becoming even less hospitable for native aquatic species.
- Additional runoff may add contaminants to surface waters already more polluted by increased extreme precipitation and flooding from climate change.
- Increased use of groundwater added to greater frequency of drought may affect area wells and groundwater resources for multiple uses.

An available source for streamflow data projected for late century:

- Streamflow Projections Map: The tool provides historical streamflow observations and projected changes (ratio of projected future flows divided by baseline historical flows) for the late 21st century (2071-2100). Separate tabs are provided for future projected average flow, projected high flow, and projected low flow for both the “Wetter Projection” (90th percentile) and the “Drier Projection” (10th percentile). *(Source: Environmental Protection Agency)*

In the Projected Low Flow tab, three types of ratios are displayed - annual low, 2-yr low, and 10-year low. Zoom in

to see colors on the map that provide a range for the annual low projected streamflow ratio for wetter or drier. Click on the table to the left of the map to select a specific period of time and projection scenario for all the grid cells with colors explained on the map legend. Click a grid cell on the map to get the specific projected low ratios for that general location for both wetter and drier and for the three ratio types.

In the Projected High Flow tab, zoom in to see colors on the map that provide a range for the annual high projected streamflow ratio for wetter or drier. Click on the table to the left of the map to select a scenario for all the grid cells with colors explained on the map legend. Click a grid cell on the map to get the specific projected high ratio for that general location for wetter and drier.

The Projected Average Flow tab is structured the same as the Projected High Flow tab. *(Source: Environmental Protection Agency)*

Wastewater

Include a characterization of potential climate-driven elements that may influence long-term wastewater disposal and to provide ideas on possible mitigation measures for these potential effects on wastewater.

An available source to assess climate change risk and explore mitigation measures:

- Climate Resilience Evaluation and Awareness Tool (CREAT) Risk Assessment Application for Water Utilities: This tool assists water sector utilities in assessing climate-related risks to utility assets and operations. Throughout CREAT's five modules, users consider climate impacts and identify adaptation options to increase resilience. *(Source: Environmental Protection Agency)*

Possible mitigations for septic system installation and ongoing use related to anticipated changes in Minnesota's climate include, but are not limited to:

- Self-impose larger setbacks for SSTS within the development from wetlands, rivers, and lakes to reduce risk of flooding from extreme precipitation events, unless compliance with an established regulatory flood elevation is required.
- Keep in mind that some fields are available for land application of septage only during certain times of the year. Consider whether the project as designed will have sufficient storage flexibility and proximate land availability to protect against changing precipitation patterns and increasing concerns about air and water quality.
- As applicable, explore whether mitigations such as setting up a regular septage-pumping schedule or spreading out the schedule over multiple months or years for a project with many septic systems will help provide sufficient protection.

Stormwater

Include a characterization of the effect of the project on the amounts and the composition of stormwater runoff from the site and the techniques planned to minimize adverse impacts from stormwater quantity and quality.

Discuss the changes in land cover caused by the project and the effects on existing site surface hydrology. These

may include changes such as loss of tree canopy or other vegetative cover, wetland losses, and an increase in impervious surfaces.

Discuss the effects of the cumulative increase in impervious surfaces in the immediate watershed of the project location and its effect on downstream waterbodies within the project watershed along with efforts to mitigate these effects. Examples of potential stormwater impacts may include increases in receiving water flows and base flow, increase in downstream flood risk, channel erosion, thermal changes to trout streams and/or an increase or change in the generation of pollutants in runoff.

Discuss how additional stormwater flows resulting from more frequent and intense rainfall, increases in runoff from winter snowmelt, and the impacts of warmer temperatures may intensify the effects on water quality and quantity. Examples include:

- Climate change trends toward more frequent and intense extreme precipitation, riverine flooding, localized flash flooding at streams, stormwater management facilities, and in upland areas lacking overflow and conveyance capacity.
- Winter warming leads to increased frequency and intensity of freeze/thaw cycles, which increases deicing chemical, salt, and sand application; these materials are eventually carried by runoff to downstream water bodies if unmanaged.
- Extreme storm events erode topsoil, which results in decreased crop productivity and nutrients washed into natural waterbodies.
- Floodwaters can mobilize pollutants, including pathogens and environmental contaminants dangerous to people and livestock.
- With increased precipitation, stormwater management features become overwhelmed and have reduced effectiveness for controlling the rate of runoff or pollutant capture, leading to increased sediment and contaminants entering natural waterbodies.
- Warming leads to increased algal blooms and pathogen growth, which can be detrimental for humans, wildlife, and aquatic communities.
- Climate change trends may result in local and regional surface-water/groundwater interactions. Prolonged groundwater rise can result in the expansion of wetlands, ponds, and lakes, leading to habitat loss or impacts to cropland and rangeland. Fluctuating water levels in wetlands from very wet to very dry periods are amplified through climate change. Wetland plants and animal life cycles are interrupted, and their survival may become threatened.

Describe specific erosion and sedimentation control BMPs during and after construction, including additional BMPs needed to protect surface waters. For projects resulting in one or more acres of new impervious surfaces, identify methods of permanent stormwater management, including a volume reduction practice (required by the MPCA stormwater permit, if applicable to a project). Volume reduction includes infiltration, harvest and reuse, or other green infrastructure practices (see Green Infrastructure Practices Guidance for EAW Item 8) designed to restore or maintain the natural hydrology of the site, promote groundwater recharge, and decrease discharges and potential impacts to area waters.

An available source for projected precipitation depths:

- Equipping Municipalities with Climate Change Data to Inform Stormwater Management: Read the Final Report and use the Minnesota county-level reports for more specificity about projected precipitation amounts over a range of durations and recurrence intervals (e.g., 100-year 24-hour storms) based on a high emissions scenario for the end-of-century time frame 2080-2097. This Atlas-14 replication for Minnesota's future climate utilizes the same downscaled 10km grid data from CMIP5 climate models as the Minnesota Climate Explorer. See example county report with data tables immediately below. The authors intend to update this Atlas-14 replication soon using Minnesota CliMAT dynamically downscaled 4km grid data which is based on CMIP6 climate models. *(Source: University of Minnesota Center for Science, Technology, and Environmental Policy)*

Image 6. Projected precipitation depths example from U of M Atlas-14 replication (CMIP5)

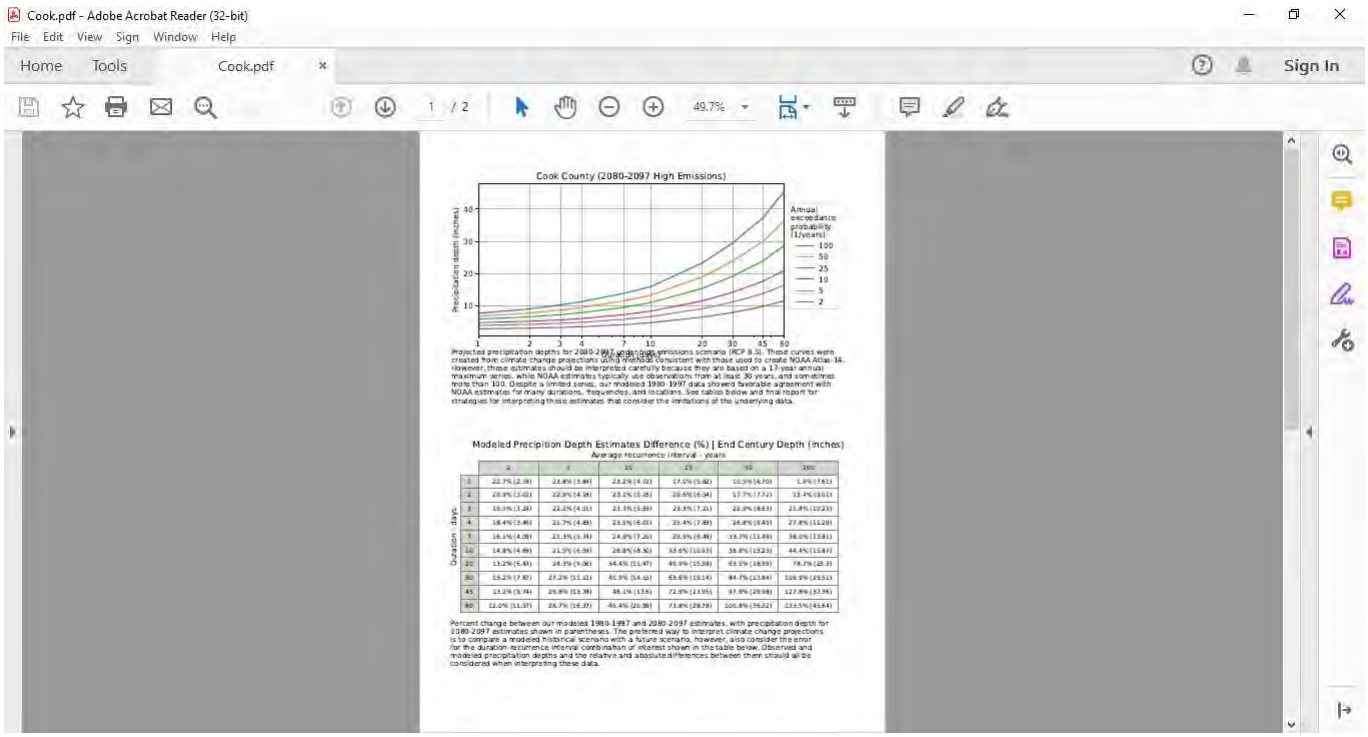

Image 7. Validation modeling of historic precipitation depths example from U of M Atlas-14 replication (CMIP5)

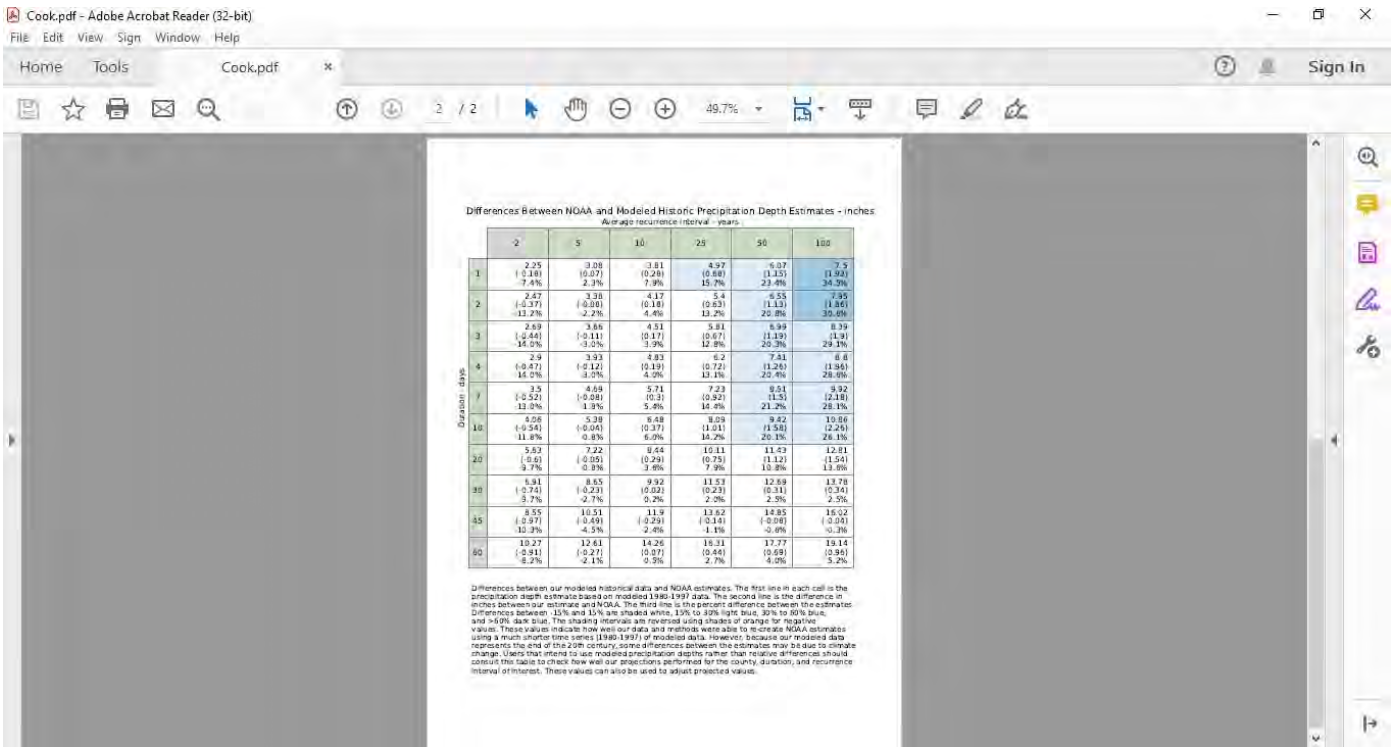

Water appropriation

Climate change trends may result in local and regional surface-water/groundwater interactions that create long-term uncertainty related to surface water and groundwater levels. This may create risk of conditions that reduce or inhibit surface-water and groundwater supply availability, quality and quantity. Include an evaluation of how climate trends can impact the long-term sustainability of water appropriations needed for a project and how proposed water use is resilient, including at least the following:

- How the water use demand can be met with diversified sources of water to reduce short-term and long-term risks.
- Whether the demand for water use has been reduced through conservation and efficiency.
- Can some supply be met through water recycling and reuse, rainwater and stormwater harvesting, and/or other methods?
- If appropriations are restricted in times of short water supply due to climate change impacts such as drought, the feasibility of ceasing water appropriations as a contingency.

EAW item 14: Fish, wildlife, plant communities, and sensitive ecological resources

Include an assessment of how fish, wildlife, plant communities, and sensitive ecological resources interact with climate trends and predictions for the proposed project.

Available resources to consider:

- The 2015-2025 Minnesota Wildlife Action Plan (MNWAP) took a habitat and landscape approach to address climate change. Chapter 1 describes the landscape approach via the Wildlife Action Network, and Chapter 3 identifies target habitat/ecosystems most sensitive to climate change. The Wildlife Action Network includes concepts such as, providing movement corridors along climate gradients and building-out protected habitat to provide ecotonal shifts. See also scientific references on page 36.
- Audubon's 2019 MN Climate Change report: "Survival by Degrees: 389 bird species on the brink": The webpage shows Audubon's report for Minnesota species. It breaks Minnesota bird species into high, moderate, and low vulnerability, and stable species. You can then click on an individual species and get more details. It also allows you to adjust the warming scenario and chose a season (summer or winter) to see how those conditions are expected to impact that species.
- USGS climate adaptation centers develop data and tools to address the informational needs of natural and cultural resource managers. Topics include the impacts of climate change on fish, wildlife, and ecosystems.

Aspects or features to consider that may amplify or interact with how climate change is anticipated to affect fish, wildlife, plant communities and sensitive ecological resources include:

- Warming winters lead to increased survival of invasive species and tree-destructive insects which can result in extensive tree death such as eastern larch beetle, pine bark beetle, and eastern spruce budworm.
    - Increased survival of terrestrial and aquatic invasive species may alter ecosystem functions. New invasive species encroach because they can survive through warmer winters. Additional expense is incurred for their control and pesticide use increases. Shift of species (especially plants) resulting in extinction of some plant species from Minnesota areas and the introduction of invasive species.
- Warming leads to increased algal blooms and pathogen growth, which can be detrimental for humans, wildlife, and aquatic communities.
- Longer growing season allows for additional weed growth, requiring control.
- Lack of snow stresses some vegetation and wildlife species because of lack of cover and protection from cold.
- Trend of earlier ice-out on lakes affects fish spawning.
- Warming waters are shifting the fish species components of natural waterbodies from cool water species such as walleye to warm-water species such as small mouth bass in some regions.

Appendix A. Default fuel heat content and stationary source emission factors

Source: EPA Center for Corporate Climate Leadership (CCCL), GHG Emission Factors Hub, stationary combustion (2020), all factors except those listed in footnotes t-v.

Table 7. Solid fossil fuels, mixed fuels, and peat

Fuel type	Heat Content (MMBtu per short ton)	CO_2 Factor (lb CO_2/MMBtu)	CH_4 Factor (lb CH_4/MMBtu)	N_2O Factor (lb N_2O/MMBtu)
Anthracite coal	25.09	228.59	0.0243	0.0035
Bituminous coal	24.93	205.65	0.0243	0.0035
Subbituminous coal	17.25	214.22	0.0243	0.0035
Lignite	14.21	215.43	0.0243	0.0035
Coal coke	24.80	250.60	0.0243	0.0035
Municipal solid waste	9.95	199.96	0.0705	0.0093
Petroleum coke	30.00	225.77	0.0705	0.0093
Plastics	38.00	165.35	0.0705	0.0093
Tire-derived fuel	28.00	189.53	0.0705	0.0093
Peat	8.00	246.56	0.0705	0.0093

Table 8. Gaseous fossil fuels

Fuel type	Heat content (MMBtu/MMcf)	CO_2 Factor (lb CO_2/MMBtu)	CH_4 Factor (lb CH_4/MMBtu)	N_2O Factor (lb N_2O/MMBtu)
Natural gas	1,026	116.98	0.0022	0.0002
Refinery gas	1,388	130.07	0.0066	0.0013
Coke oven gas	599	103.29	0.0011	0.0002
Blast furnace gas	92	604.77	0.0000	0.0002

Table 9. Fossil fuel liquid fuels: crude oil and refined petroleum products

Fuel type	Heat Content (MMBtu per short ton)	CO_2 Factor (lb CO_2/MMBtu)	CH_4 Factor (lb CH_4/MMBtu)	N_2O Factor (lb N_2O/MMBtu)
Crude oil	0.138	164.33	0.0066	0.0013
Asphalt and road oil	0.158	166.14	0.0066	0.0013
Aviation gasoline	0.120	152.67	0.0066	0.0013

Butane	0.103	142.79	0.0066	0.0013
Distillate fuel oil #1	0.139	161.49	0.0066	0.0013
Distillate fuel oil #2	0.138	163.05	0.0066	0.0013
Distillate fuel oil #4	0.146	165.43	0.0066	0.0013
Ethane	0.068	131.84	0.0066	0.0013
Heavy gas oils	0.148	165.17	0.0066	0.0013
Isobutane	0.990	143.17	0.0066	0.0013
Jet fuel – kerosene type	0.135	159.22	0.0066	0.0013
Kerosene	0.135	165.79	0.0066	0.0013
Liquefied petroleum gases (LPG)	0.092	136.05	0.0066	0.0013
Lubricants	0.144	163.74	0.0066	0.0013
Motor gasoline	0.125	174.65	0.0066	0.0013
Naphtha <401 deg F)	0.125	149.96	0.0066	0.0013
Natural gasoline	0.110	151.85	0.0066	0.0013
Oil >4091 deg F	0.139	168.03	0.0066	0.0013
Pentanes plus	0.110	154.37	0.0066	0.0013
Petrochemical feedstocks	0.125	156.57	0.0066	0.0013
Petroleum coke	0.143	225.77	0.0066	0.0013
Propane	0.091	138.60	0.0066	0.0013
Residual fuel oil #5	0.140	160.78	0.0066	0.0013
Residual fuel oil #6	0.150	165.57	0.0066	0.0013
Special naphtha	0.125	159.48	0.0066	0.0013
Unfinished oil	0.139	164.33	0.0066	0.0013
E10 [19]	0.126	138.57	0.0066	0.0013
B10 [20]	0.137	147.91	0.0066	0.0013

[19] Calculated from fuel heat content and fuel fossil carbon content by volume for motor gasoline, diesel fuel oil, ethanol and biodiesel given in EPA Center for Corporate Climate Leadership (2020) and EIA State Energy Data System (2020)

[20] Calculated from fuel heat content and fuel fossil carbon content by volume for motor gasoline, diesel fuel oil, ethanol and biodiesel given in EPA Center for Corporate Climate Leadership (2020) and EIA State Energy Data System (2020)

Table 10. Solid biomass fuels

Fuel type	**Heat Content** (MMBtu per short ton)	**CO_2 Factor** (lb CO_2/MMBtu)	**CH_4 Factor** (lb CH_4/MMBtu)	**N_2O Factor** (lb N_2O/MMBtu)
Agricultural byproducts	8.25	Not relevant	0.0705	0.0093
Black liquor	11.76[21]	Not relevant	0.0042	0.0009
Manufacturing residues	10.39	Not relevant	0.0705	0.0093
Wood and wood waste	8.6 to 17.2 (depending on moisture content)[22]	Not relevant	0.0159	0.0079

Table 11. Biogas fuels

Fuel type	**Heat content** (MMBtu/MMcf)	**CO_2 Factor** (lb CO_2/MMBtu)	**CH_4 Factor** (lb CH_4/MMBtu)	**N_2O Factor** (lb N_2O/MMBtu)
Landfill gas	485	Not relevant	0.0071	0.0014
Other biogases	655	Not relevant	0.0071	0.0014

[21] EIA, Renewable Energy Annual (2009)

[22] USFS Forest Products laboratory, Fuel Value Calculator

Appendix B. Protocols and methods for calculating GHG emissions

- American Petroleum Council, Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Gas Industry (2009)
- American Public Transportation Association, Quantifying Greenhouse Gas Emissions from Transit, APTA SUDS CC-RP-001-09, Rev. 1, 2018
- California Air Resources Board, et al., Local Government Operations Protocol, version 1.1, May 2010
- Environmental Protection Agency (EPA), Inventory of US Sources and Sinks of Greenhouse Gases 1990-2019, EPA-430-R-21-005 (2021)
- EPA, 40 CFR Part 98—Mandatory Greenhouse Gas Reporting (2009)
- EPA Center for Corporate Climate Leadership (CCCL), GHG Inventory Guidance: Stationary Combustion Guidance (2020)
- EPA CCCL, GHG Inventory Guidance: Mobile Combustion Guidance (2020)
- EPA CCCL, GHG Inventory Guidance: Indirect Emissions from Purchased Electricity (2020)
- EPA CCCL, GHG Inventory Guidance: Direct Fugitive Emissions from Refrigeration, Air Conditioning, Fire Suppression, and Industrial Gases (2020)
- EPA CCCL, Scope 3 Inventory Guidance
- ICLEI, U.S. Community Protocol for Accounting and Reporting of Greenhouse Gas Emissions, version 1.2, 2019
- Intergovernmental Panel on Climate Change (IPCC), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol. 1-5 (2006)
- IPCC, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (2013)
- IPCC, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol 1-5 (2019)
- IPCC, Good Practice Guidance for Land Use, Land-Use Change and Forestry (2003)
- Minnesota Department of Transportation (MnDOT), Minnesota Infrastructure Carbon Estimator tool (MICE)
- National Council for Air and Stream Improvement, Inc. (NCASI), Calculation Tools for Estimating Greenhouse Gas Emissions from Pulp and Paper Mills V.1.1, 2005
- The Climate Registry, General Reporting Protocol, V 3.0 (2019)
- J. Smith, et al., Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States, U.S. Department of Agriculture, Forest Service, Northeastern Research Station, 2006, DOI: 10.2737/ne-gtr-343.
- The Climate Registry, Electric Sector Protocol: Annex to the General Reporting Protocol, V. 1.0. (2009)
- USDA, Office of the Chief Economist, Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory, Technical Bulletin 1939, 2014
- USDA, Office of the Chief Economist, US Agriculture and Forest Greenhouse Gas Inventory 1990-2013 Technical Bulletin 1943, 2016

- World Business Council for Sustainable Development, and World Resources Institute, The GHG Protocol: A corporate reporting and accounting standard (revised edition) (2020)
- World Business Council for Sustainable Development, and World Resources Institute, Calculating Greenhouse Gas Emissions from Iron and Steel Production: A component tool of the Greenhouse Gas Protocol Initiative (2009)

Appendix C – Sources for technical information on energy efficiency and financial subsidies

Information on energy efficiency and financial subsidies is available from many sources, including, but not limited to the following:

Technical resources
Energy efficiency technical and financial information, Minnesota Department of Commerce: https://mn.gov/commerce/energy/conserving-energy/
Home energy efficiency, Minnesota Department of Commerce: https://mn.gov/commerce/energy/conserving-energy/efficiency/
Efficient home building, Minnesota Department of Commerce: https://mn.gov/commerce/energy/conserving-energy/efficient-buildings/
Home energy guide, Minnesota Department of Commerce: https://mn.gov/commerce-stat/pdfs/home-energy-guide.pdf
Energy efficiency consulting for single and multi-family new construction, Center for Energy and Environment (CEE): https://www.mncee.org/new-construction-services
Energy saving equipment on the farm, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/energy-saving-equipment-farm
Xcel Energy efficient buildings program, Xcel Energy: https://mn.my.xcelenergy.com/s/business/new-building-programs/energy-efficient-buildings
Energy efficiency strategies and upgrades, American Council for an Energy-Efficient Economy (ACEEE): https://www.aceee.org/topic/ee-strategies-and-upgrades
Design guides for energy efficient commercial buildings (including office buildings, K-12, big box retail, hospitals, and grocery stores), Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy: https://www.energy.gov/eere/buildings/advanced-energy-design-guides
Zero energy buildings resource hub, Office of Energy Efficiency and Renewable Energy, US Department of Energy: https://www.energy.gov/eere/buildings/zero-energy-buildings-resource-hub
Energy efficiency guidance for commercial new construction, Energy Star: https://www.energystar.gov/buildings/resources_audience/service_product_providers/commercial_new_construction
Save energy, commercial buildings, Energy Star: https://www.energystar.gov/buildings/save_energy_commercial_buildings?s=mega
Resources for residential new construction, Energy Star: https://www.energystar.gov/partner_resources/residential_new

Energy efficiency education and trainings, Building Science Corporation: https://buildingscience.com/service/education-and-training
Builder's guide to cold climates, Building Science Corporation: https://buildingscience.com/bookstore/books/builders-guide-cold-climates
Tools and guides, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/tools-guides
Resource for builders on zero-energy homes, Getting to Zero: https://gettingtozeroforum.org/residential-resources/
Advanced energy design guides for buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): https://www.ashrae.org/technical-resources/aedgs
Financial resources
Opportunity for businesses to save on efficiency improvements, Center for Energy and Environment (CEE): https://www.mncee.org/179d-expansion-provides-another-opportunity-businesses-save-efficiency-improvements
Evaluate the economics of energy efficiency projects, Energy Star: https://www.energystar.gov/buildings/save_energy_commercial_buildings/economics_efficiency_projects
Tax incentives for energy-efficiency upgrades in commercial buildings, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, https://www.energy.gov/eere/buildings/tax-incentives-energy-efficiency-upgrades-commercial-buildings
Federal tax credits for builders of energy efficient homes, Energy Star: https://www.energystar.gov/about/federal_tax_credits/federal_tax_credit_archives/tax_credits_home_builders
Tax deductions for commercial buildings, Energy Star: https://www.energystar.gov/about/federal_tax_credits/tax_credits_commercial_buildings
Database of state incentives for renewables & efficiency, DSIRE: https://www.dsireusa.org/
Federal energy efficiency tax incentives, SmarterHouse: https://smarterhouse.org/resources/federal-tax-incentives
Grants for farmers and rural businesses, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/grants-farmers-rural-businesses

Appendix D - Sources for technical and financial information on electrifying appliances and equipment

Information on electrifying appliances and equipment, as well as on financial subsidies for electrification, is available, but not limited to, the following:

Technical resources
Ground source heat pumps, Minnesota Department of Commerce: https://mn.gov/commerce/energy/conserving-energy/ground-source/
Electrify Everything Minnesota, Minnesota Center for Energy and Environment (CEE): https://www.mncee.org/electrifyeverythingmn?home
Geothermal in Minnesota, Clean Energy Resource Teams (CERTS): https://www.cleanenergyresourceteams.org/geothermal-minnesota
Electrification resources, Getting to Zero: https://gettingtozeroforum.org/electrification/
Electrify everything in your home, Rewiring America: https://www.rewiringamerica.org/electrify-home-guide
Heat pump systems, Office of Energy Efficiency and Renewable Energy, U.S Department of Energy: https://www.energy.gov/energysaver/heat-pump-systems
Cold climate air source heat pump technical information, Northeast Energy Efficiency Partnerships: https://neep.org/high-performance-air-source-heat-pumps/air-source-heat-pump-installer-and-consumer-resources
Industrial heat pumps: electrifying industry's process heat supply, American Council on an Energy Efficient Economy (ACEEE): https://www.aceee.org/research-report/ie2201
Electrifying space heating in existing commercial buildings, American Council on an Energy Efficient Economy (ACEEE): https://www.aceee.org/research-report/b2004
Air-source heat pumps, Energy Star: https://www.energystar.gov/products/air_source_heat_pumps
Electrification, U.S. Green Building Council: https://www.usgbc.org/about/priorities/electrification
Financial information
Federal rebates, tax credits, energy efficiency programs, Minnesota Department of Commerce: https://mn.gov/commerce/energy/federal-rebates/
Federal energy efficiency tax incentives, SmarterHouse: https://smarterhouse.org/resources/federal-tax-incentives
Guide to the inflation reduction act, Rewiring America: https://www.rewiringamerica.org/IRAguide

IRA savings calculator, Rewiring America: https://www.rewiringamerica.org/app/ira-calculator
The Inflation Reduction Act: What you need to know (scroll down to "Residents + Energy Efficiency Rebates" and "Residents + Heat Pumps"), Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/inflation-reduction-act-what-you-need-know

Appendix E - Sources for technical and financial assistance information on electricity generation

Considerable financial support is available for solar power and storage through tax credits and rebates. Additional technical and financial assistance information is available, but not limited to, the following:

Technical Resources
Solar energy for homes, Minnesota Department of Commerce: https://mn.gov/commerce/energy/solar-wind/solar-for-homes/
Minnesota solar guide, Minnesota Department of Commerce: https://mn.gov/commerce-stat/pdfs/solar-directory.pdf
Minnesota solar pathways solar guide, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/minnesota-solar-guide
Community solar gardens, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/solargardens
Powering K-12 education with solar energy, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/solarschools
Homeowner's guide to going solar, Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy: https://www.energy.gov/eere/solar/homeowners-guide-going-solar
Wind energy for homes, Minnesota Department of Commerce: https://mn.gov/commerce/energy/solar-wind/wind-energy-homes/
Small wind energy systems, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/small-wind-energy-systems
Renewable energy for businesses and organizations, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/businesses-organizations
Buy renewable energy from your utility, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/green-pricing
Renewable opportunities, Xcel Energy: https://mn.my.xcelenergy.com/s/renewable
Renewable choices, Minnesota Power: https://www.mnpower.com/ProgramsRebates/RenewableChoices
Renewable energy, Otter Tail Power: https://www.otpco.com/ways-to-save/renewable-energy-residential/
Lease your land for solar or wind, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/lease-your-land-solar-or-wind
Renewable energy for greater Minnesota, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/greatrenewables
Financial Information
Grants for farmers and rural businesses, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/grants-farmers-rural-businesses
Federal Solar Tax Credits for Businesses, Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy: https://www.energy.gov/eere/solar/federal-solar-tax-credits-businesses
Questions about the inflation reduction act guide, Clean Energy Resource Teams (CERTs):

https://www.cleanenergyresourceteams.org/tools-guides
The inflation reduction act: What you need to know (scroll down to "Commercial"), Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/inflation-reduction-act-what-you-need-know
Model RFP for third-party solar, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/3rdpartyrfp
Database of state incentives for renewables & efficiency, DSIRE: https://w ww.dsireusa.org/

Appendix F – Sources for technical and financial assistance information on transportation electrification

Projects that involve mobile sources can reduce GHG emissions by electrifying their fleets or on-site mobile equipment and by providing electric vehicle charging stations. Additional technical and financial assistance information is available, but not limited to, the following:

Technical resources
Finding the best options to electrify your fleet, Drive Electric Minnesota: https://driveelectricmn.org/electrify-your-fleet/
Adding EV chargers to homes and workplaces, Drive Electric Minnesota: https://driveelectricmn.org/electric-vehicles/businesses-and-employers/
Electrify fleets & support charging, Clean Energy Resource Teams (CERTs): https://www.cleanenergyresourceteams.org/cities-charging-ahead
90 minute course on EVs and charging for architects, developers & real estate professionals, Shift2Electric: https://www.shift2electric.com//realestatepro
Workplace charging for electric vehicles, Office of Energy Efficiency & Renewable Energy, U.S Department of Energy: https://afdc.energy.gov/fuels/electricity_charging_workplace.html
Smartway heavy-duty truck electrification resources, U.S. Environmental Protection Agency: https://www.epa.gov/smartway/smartway-heavy-duty-truck-electrification-resources
Financial information
Clean vehicle credit for commercial use of EVs, Internal Revenue Service: https://www.irs.gov/credits-deductions/commercial-clean-vehicle-credit

Appendix G - Sources for technical and financial assistance information on land use GHG emissions

Projects can reduce GHG emissions associated with land use, and even create GHG sinks, such as through best practices in land-use management, nutrient and sediment run-off control, on-site terrestrial biogenic carbon sequestration, and wetland mitigation, among others. Additional technical and financial assistance information is available at:

Technical resources
Greenhouse gas reduction potential of agricultural best management practices, Minnesota Pollution Control Agency: https://www.pca.state.mn.us/sites/default/files/p-gen4-19.pdf
Climate change trends and action plan, Minnesota Board of Water and Soil Resources: Climate Change Trends + Action Plan 2022.pdf (state.mn.us)
Nature and climate solutions for Minnesota, The Nature Conservancy: https://www.nature.org/content/dam/tnc/nature/en/documents/NCSinMinnesotaReport_01.11.2021.pdf
Climate-smart agriculture and forestry mitigations (includes eligible financial support through EQIP, CSP, and other programs), Natural Resources Conservation Service of the U.S. Department of Agriculture: https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/climate/climate-smart-mitigation-activities
Virtual farm, Carbon calculator tool from Penn State's College of Agricultural Sciences and Penn State Extension, in collaboration with the University of Wisconsin-Madison: https://www.virtualfarm.psu.edu/virtual-farm/

Environmental Assessment Worksheet

Alternative EAW Form for Animal Feedlots

December 2024 version

This form is authorized to prepare Environmental Assessment Worksheets (EAWs) for **animal feedlots.** This most recent Environmental Assessment Worksheet (EAW) Alternative Form for Animal Feedlots (and guidance) is available at the Environmental Quality Board's (EQB) website. This form provides information about a project that may have the potential for significant environmental effects. Guidance documents provide additional detail and links to resources for completing the EAW form.

Cumulative potential effects can be addressed under each applicable EAW Item or collectively under EAW Item 21.

Note to reviewers

Comments must be submitted to the Responsible Governmental Unit (RGU) during the 30-day comment period following notice of the EAW in the *EQB Monitor*. Comments should address the accuracy and completeness of information, potential impacts that warrant further investigation, and the need for an EIS.

1. Feedlot Project Title:

2. Proposer:	**2a. Consultant assisting in EAW completion (if applicable):**	**3. Responsible Governmental Unit (RGU):**
Company	*Company*	*Government Body*
Contact Name	*Contact Name*	*Contact Name*
Title	*Title*	*Title*
Address	*Address*	*Address*
City, State, Zip	*City, State, Zip*	*City, State, Zip*
Phone	*Phone*	*Phone*
Email	*Email*	*Email*

4. Reason for EAW Preparation: *Choose an item.*

a. MN Rule 4410.4300 subp. 29. – Animal Feedlots. If EAW is mandatory, does subpart A or B apply? *Choose an item.*

5. Project Location:

a. County:
b. City or Township:
c. Legal Description (¼, ¼, Section, Township, Range):
d. Watershed in 81 major watershed scale, Hydrologic Unit Code (HUC) 8:
e. GPS Coordinates:
f. Tax Parcel Number:
g. At a minimum, attach each of the following to the EAW:

- County map showing the general location of the project

- U.S. Geological Survey 7.5 minute, 1:24,000 scale map indicating project boundaries
- Site plan showing all significant project and natural features for pre- and post-construction
- Map showing manure application sites, manure storage, permanent manure stockpiles, and setback buffers
- Map showing all wells, tile inlets, residences, and sensitive receptors within a one-mile radius of the feedlot or on manure land application sites
- Feedlot Permit Application (SDS, NPDES)
- Map of Tribal boundaries within 10 miles
- List of data sources, models, and other resources (from the Item-by-Item Guidance: *Climate Adaptation and Resilience* or other) used for information about current Minnesota climate trends and how climate change is anticipated to affect the general location of the project during the life of the project (as detailed below in item 7. Climate Adaptation and Resilience)

6. Project Description:

a. Provide the brief project summary to be published in the *EQB Monitor* (approximately 50 words).

b. Give a complete description of the proposed project and related new construction, including infrastructure needs. If the project is an expansion, include a description of the existing facility; emphasize:
- purpose of the project,
- construction, operation methods, and features that will cause physical manipulation of the environment or will produce waste,
- modifications to existing equipment or industrial processes,
- significant demolition, removal, or remodeling of existing structures,
- timing and duration of construction activities,
- any future plans/stages for this project including an anticipated timeline and plans for environmental review, and
- any past stages of this project, including timeframe and environmental review proceedings.

c. Provide facility information.

Facility components (show on site map)			
Animal holding areas	**Existing/Proposed**	**Total quantity**	**Total area (sq ft)/volume (gal)**
• Total confinement barns			
• Partial confinement barns			
• Open lots			
• Individual animal housing areas			
Manure storage areas	**Existing/Proposed**	**Total quantity**	**Total area (sq ft)/volume (gal)**
• Liquid manure storage areas			
• Solid manure storage areas			
Other components	**Existing/Proposed**	**Total quantity**	**Total area (sq ft)/volume (gal)**
• Feed storage areas			

• Mortality management areas			
• *Etc.*			

d. Provide animal information.

Animal type	Number existing	Animal units existing	Number after project	Animal units after project
Swine				
Dairy cattle				
Beef cattle				
Turkeys				
Chickens				
Other (Identify species)				
TOTAL	N/A		N/A	

e. Provide annual manure generation information.

Animal type	Existing annual generation		After project annual generation	
	liquid (gal)	solid (ton)	liquid (gal)	solid (ton)
Swine				
Dairy cattle				
Beef cattle				
Turkeys				
Chickens				
Other (Identify species)				
TOTAL				

f. Check any of the items below that are part of the manure management system proposed for this feedlot.

☐ Stockpiling

☐ Liquid storage under barns

☐ Liquid storage outside of barns

☐ Dry manure/litter pack

☐ Dry manure/litter under barn storage

☐ Manure composting system

☐ Anaerobic digestion

☐ Manure solids separation

i. Manure storage capacity (number of months/days):

ii. Land available for manure application (acres):

iii. Land needed for manure application (acres):

g. Are future stages of this development including development on any other property planned or likely to happen? If yes, briefly describe future stages, relationship to the present project, timeline, and plans for environmental review.

h. Is this project a subsequent stage of an earlier project? If yes, briefly describe the past development, timeline, and any past environmental review.

7. Climate Adaptation and Resilience:

a. Describe the climate trends in the general location of the project and how climate change is anticipated to affect that location during the life of the project. See guidance: EQB Climate Adaptation and Resilience, Section 2, and the Feedlot EAW Guidance document. Examples are shown in italics, below. List which climate trends and projections resource tool(s) was used in completing the EAW and describe how it was used.

State of Minnesota historic climate trends (data-driven) and projected climate changes (model-driven)	**County/local trends**	**Project impacts (climate effects on project location)**
Average annual temperature increasing		*e.g., Site may be subject to increased air conditioning loads to grid, interior and exterior infrastructure.*
Average annual precipitation increasing		*e.g., Increased run-off and erosion may affect soil/site stability.*
Cold weather warming		*e.g., Decreased snow cover may affect vegetation cover that leads to increased soil erosion.*
Heavier, more damaging rains		*e.g., Vegetation changes, stressors, more exposed soils in winter.*
Increasing heat waves		*e.g., Construction materials may break down quicker in high heat conditions.*
Increasing risks of drought		*e.g., Limitations on groundwater, surface water for use in dust reduction.*
Optional: Additional relevant climate variables		

b. For each Resource Category in the table below, describe how the project's proposed activities and how the project's design will interact with those climate trends. Describe proposed adaptations to address the project effects identified. Refer to Feedlot Guidance and EQB EAW Guidance and complete the table below using the information from those guidance documents. Examples are shown in italics, below.



Refer to Feedlot EAW Guidance, Section 7, to help complete the table below.

Resource category	Climate trends and climate projections	Project components	Potential environmental effects Identify climate change risks & vulnerabilities to the project component. Identify long-term impacts that climate conditions pose to proposed activities.	Adaptation strategies (with applicable timeframe – construction to end of expected lifespan)
Project design	**Average annual temperature increasing**	*e.g., Increased impervious surfaces.*	*e.g., Environmental impact not foreseen with interaction between impervious surfaces and average temperature increasing.*	*e.g., Decrease impervious surfaces where possible.*
		e.g. , Increased constructed surfaces, such as dark roofing and asphalt.	*e.g., Increased heat absorption during the day that is radiated at night, which increases heat island effect and amplifies warming temperatures of climate change.*	*e.g., Use of light-colored building materials and surfaces to reduce heat absorption. Regular maintenance and updates to infrastructures, as needed, for life of project.*
		e.g., Increased quantity of concrete and building construction materials, and infrastructure.	*e.g., Infrastructure more vulnerable to damage and deterioration from elevated temperatures.*	*e.g., Use of construction materials that are resilient to increasing temperatures for the life of the project.*
	Average annual precipitation increasing	***Repeat all project components** for each climate trend and projection↓*	*Discuss potential environmental effects with each project component↓*	*List adaptation strategies for each project component↓*
	Cold weather warming			
	Heavier, more damaging rains			

Resource category	Climate trends and climate projections	Project components	Potential environmental effects Identify climate change risks & vulnerabilities to the project component. Identify long-term impacts that climate conditions pose to proposed activities.	Adaptation strategies (with applicable timeframe – construction to end of expected lifespan)
	Increasing risk of heatwaves			
	Increasing risk of drought			
Land use	Address in item 10	Address in item 10	Address in item 10	Address in item 10
Water resources	Address in item 12	Address in item 12	Address in item 12	Address in item 12
Contamination/Hazardous Materials/Wastes	Address in item 13	Address in item 13	Address in item 13	Address in item 13
Fish, wildlife, plant communities, and sensitive ecological resources (rare features)	Address in item 14	Address in item 14	Address in item 14	Address in item 14

8. Cover Types:

Estimate the acreage of the site with each of the following cover types before and after development:

Cover types	Before (acres)	After (acres)
Wetlands and shallow lakes (<2 meters deep)		
Deep lakes (>2 meters deep)		
Wooded/forest		
Rivers/streams		
Brush/grassland		
Cropland		
Livestock rangeland/pastureland		
Lawn/landscaping		
Green infrastructure TOTAL (from table below*)		
Impervious surface		
Stormwater pond (wet sedimentation basin)		
Other (describe)		
TOTAL		

Green infrastructure*	Before (acres)	After (acres)
Constructed infiltration systems (infiltration basins/infiltration trenches/ rainwater		
Gardens/bioretention areas without underdrains/swales with impermeable check dams)		
Constructed tree trenches and tree boxes		
Constructed wetlands		
Constructed green roofs		
Constructed permeable pavements		
Other (describe)		
TOTAL*		

Trees	Percent	Number
Percent tree canopy removed, or number of mature trees removed during development		
Number of new trees planted	N/A	

9. Permits and Approvals Required: List all known local, state, and federal permits, approvals, certifications, and financial assistance for the project. Include modifications of any existing permits, governmental

review of plans, and all direct and indirect forms of public financial assistance, including bond guarantees, Tax Increment Financing, and infrastructure. ***All of these final decisions are prohibited until all appropriate environmental review has been completed****. See Minnesota Rules, Chapter 4410.3100.*

a. MPCA

i. **Feedlot permit**

☐ Planned ☐ Submitted ☐ Denied ☐ Not required

ii. **Construction stormwater permit**

☐ Planned ☐ Submitted ☐ Denied ☐ Not required

b. DNR

i. **Water appropriations**

☐ Planned ☐ Submitted ☐ Denied ☐ Not required

c. City/Township/County

i. ☐ Planned ☐ Submitted ☐ Denied ☐ Not required

d. Tribe

i. ☐ Planned ☐ Submitted ☐ Denied ☐ Not required

e. Other (Feedlot permit, rezoning, variance): *Please note permit here.*

☐ Planned ☐ Submitted ☐ Denied ☐ Not required

Cumulative potential effects may be considered and addressed in response to individual EAW Item Nos. 10-20, or the RGU can address all cumulative potential effects in response to EAW Item No. 22. If addressing cumulative effect under individual items, make sure to include information requested in EAW Item No. 21.

10. Land Uses:

a. Describe:

i. Existing uses of the site as well as adjacent lands to and near the site, and give the distances and directions to nearby residences, schools, daycare facilities, senior citizen housing, places of worship, open space, cemeteries, trails, prime or unique farmlands, tribal lands, and other places accessible to the public (including roads) within one mile of the feedlot and within or adjacent to the boundaries of the manure application sites.

ii. Planned land use as identified in a comprehensive plan (if available) and any other applicable plan for land use, water, or resources management by a local, regional, state, or federal agency.

iii. Zoning, including special districts or overlays such as shoreland, floodplain, wild and scenic river, critical area, agricultural preserve, etc.

iv. If any critical facilities (i.e. facilities necessary for public health and safety, those storing hazardous materials, or those with housing occupants who may be insufficiently mobile) are proposed in floodplain areas and other areas identified as at risk for localized flooding, describe the risk potential considering changing precipitation and event intensity.

b. Discuss the project's compatibility with nearby land uses, zoning, and plans listed in Item 10a above, concentrating on implications for environmental effects.

c. Identify measures incorporated into the proposed project to mitigate any potential incompatibility as discussed in Item 10b above and any risk potential.

11. Geology, Soils and Topography / Landforms:

a. Geology – Describe the geology of the underlying project area and identify and map any susceptible geologic features such as sinkholes, shallow limestone formations, unconfined/shallow aquifers, or karst conditions. Discuss any limitations of these features for the project and any effects the project could have on these features. Identify any project designs or mitigation measures to address effects to geologic features.

Geologic features	Project site	Manure application site
Unconfined or shallow aquifer?	☐ Yes ☐ No	☐ Yes ☐ No
Less than 50 ft of soil cover over karst susceptible bedrock?	☐ Yes ☐ No	☐ Yes ☐ No
Less than 40 inches of soil cover over karst susceptible bedrock?	☐ Yes ☐ No	☐ Yes ☐ No
Karst features [a] within 300 ft?	☐ Yes ☐ No	☐ Yes ☐ No

[a] *Karst features include sinkholes, caves, resurgent springs, disappearing springs, karst windows, blind/dry valleys*

b. Soils and topography – Describe the soils on the site, giving Natural Resources Conservation Service (NRCS) classifications and descriptions, including limitations of soils. Describe topography, any special site conditions relating to erosion potential, soil stability or other soils limitations, such as steep slopes or highly permeable soils. Provide estimated volume and acreage of soil excavation and/or grading. Discuss impacts from project activities (distinguish between construction and operational activities) related to soils and topography. Identify measures during and after project construction to address soil limitations including stabilization, soil corrections or other measures. Erosion/sedimentation control related to stormwater runoff should be addressed in response to Item 12, b. ii. Soils information for the manure land application sites will be addressed in Item 12, b., V.

NRCS soil	Feedlot	Manure storage area
List classifications	*x*	*x*

12. Water Resources:

a. Describe surface water and groundwater features on or near the site and manure application areas below and on attached maps**.**

i. **Surface water** – lakes, streams, wetlands, intermittent streams, and county/judicial ditches. Include any special designations such as public waters, shoreland classification and floodway/floodplain, trout stream/lake, wildlife lakes, migratory waterfowl feeding/resting lake, and outstanding resource value water. Include the presence of aquatic invasive species and the water quality impairments or special designations listed on the current MPCA 303(d) Impaired Waters List that are within 1 mile of the project. Include DNR Public Waters Inventory number(s) if any.

ii. **Groundwater** – aquifers, springs, seeps. Include: 1) depth to groundwater; 2) if project is within a MDH wellhead protection area; 3) federal equivalent to wellhead protection areas or drinking water supply management areas found near/within tribal boundaries; 4) identification of any onsite and/or nearby wells, including unique numbers and well logs if available. If there are no wells on site or nearby, explain the methodology used to determine this.

iii. **Risks to Groundwater** – Indicate ***Yes or No*** whether any of the following **geologic site risks to ground water** are present at the feedlot, manure storage area, or manure application sites. If yes, describe the features, show them on a map, and discuss proposed design and mitigation measures to avoid or minimize potential impacts.

Geologic site risks to groundwater	**Feedlot**	**Manure storage area**	**Manure application sites**
Karst features (sinkhole, cave, resurgent spring, disappearing spring, karst window, blind valley, or dry valley)			
Exposed bedrock and /or limited unconsolidated cover soils			
Soils developed in bedrock (as shown on soils maps)			
Sandy soils and/or sand plain			

b. Describe effects from project activities on water resources and measures to minimize or mitigate the effects in items below.

i. **Wastewater** – All sewage produced in Minnesota must be disposed of in accordance with Minn. R 7080.2450 Subp. 6. This rule requires that "Septage or any waste mixed with septage must be disposed of in accordance with state, federal, and local requirements for septage and other wastes." As such, anyone wishing to co-mix sewage with animal manure is allowed to do so provided all state, federal, and local regulations are met. Currently, state regulations require adherence with the federal regulations found within 40 C.F.R. § 503. Additionally, local units of government within Minnesota may have supplementary ordinance requirements that must be followed. All material that comes into contact with sewage must be treated to the same requirements as sewage alone. Furthermore, any other regulations which apply to the material the sewage is mixed with must also be followed.

For each of the following, describe the sources, quantities and composition of all sanitary, municipal/domestic, and industrial wastewater produced or treated at the site.

(1) If the wastewater discharge is to a publicly owned treatment facility, identify any pretreatment measures and the ability of the facility to handle the added water and waste loadings, including any effects on, or required expansion of, municipal wastewater infrastructure.

(2) If the wastewater discharge is to a subsurface sewage treatment system (SSTS), describe the system used, the design flow, and suitability of site conditions for such a system. If septic systems are part of the project, describe the availability of septage disposal options within the region to handle the ongoing amounts generated as a result of the project. Consider the effects of current Minnesota climate trends and anticipated changes in rainfall frequency, intensity, and amount with this discussion.

(3) If the wastewater discharge is to surface water, identify the wastewater treatment methods and identify discharge points and proposed effluent limitations to mitigate impacts. Discuss any effects to surface or groundwater from wastewater discharges, taking into consideration how current Minnesota climate trends and anticipated climate change in the general location of the project may influence the effects.

ii. **Stormwater** – Describe the following:
(1) changes in surface hydrology resulting from change of land cover;
(2) routes and receiving water bodies for runoff from the project site (immediate receiving waters and major downstream water bodies);
(3) environmental effects from stormwater discharges on receiving waters post-construction including affected runoff volume, discharge rate, and change in pollutants,
(4) effects of current Minnesota climate trends and anticipated changes in rainfall frequency, intensity;
(5) total number of acres that will be disturbed and describe the stormwater pollution prevention plan (SWPPP) (for projects requiring NPDES/SDS Construction Stormwater permit coverage), include best management practices to address soil erosion and sedimentation during and after project construction;
(6) permanent stormwater management plans, including methods of achieving volume reduction to restore or maintain the natural hydrology of the site using green infrastructure practices or other stormwater management practices;
(7) any receiving waters that have construction-related water impairments or are classified as special as defined in the Construction Stormwater permit;
(8) additional requirements for special and/or impaired waters.

iii. **Water appropriation** – Describe the following:
(1) if the project proposes to appropriate surface or groundwater (including dewatering);
(2) the source, quantity, duration, use and purpose of the water use and if a DNR water appropriation permit is required;
(3) any well abandonment. If connecting to an existing municipal water supply, identify the wells to be used as a water source and any effects on, or required expansion of, municipal water infrastructure;
(4) environmental effects from water appropriation, including an assessment of the water resources available for appropriation;
(5) how the proposed water use is resilient in the event of changes in total precipitation, large precipitation events, drought, increased temperatures, variable surface water flows and elevations, and longer growing seasons;
(6) any measures to avoid, minimize, or mitigate environmental effects from the water appropriation;
(7) contingency plans should the appropriation volume increase beyond infrastructure capacity or water supply for the project diminish in quantity or quality, such as reuse of water, connections with another water source, or emergency connections.
(a) Current water use (gal/yr):
☐ Not applicable
(b) Proposed water use (gal/yr):
(c) Water supply source:
☐ Existing well
☐ New well

☐ Public supply
☐ Other:

(d) Aquifer test required by DNR? ☐ Yes ☐ No

iv. **Surface Waters**

(1) **Wetlands** – Describe the following:
(a) any anticipated physical effects or alterations to wetland features such as draining, filling, permanent inundation, dredging and vegetative removal;
(b) direct and indirect environmental effects from physical modification of wetlands, (include anticipated effects to the host watershed, taking into consideration how current Minnesota climate trends may be affected);
(c) measures to avoid (e.g., available alternatives that were considered), minimize, or mitigate environmental effects to wetlands;
(d) required compensatory wetland mitigation for unavoidable wetland impacts that will occur in the same minor or major watershed and identify those probable locations.

(2) **Other surface waters** – Describe the following:
(a) anticipated physical effects or alterations to surface water features (lakes, streams, ponds, intermittent streams, county/judicial ditches) such as draining, filling, permanent inundation, dredging, diking, stream diversion, impoundment, aquatic plant removal, riparian alteration, drain tiling, and tile inlets or outlets. Show these features on maps;
(b) direct and indirect environmental effects from physical modification of water features, taking into consideration how current Minnesota climate trends and anticipated climate change in the general location of the project may influence the effects;
(c) measures to avoid, minimize, or mitigate environmental effects to surface water features, including in-water best management practices that are proposed to avoid or minimize turbidity/sedimentation while physically altering the water features;
(d) how the project will change the number or type of watercraft on any water body, including current and projected watercraft usage;
(e) quantity and quality of site runoff before and after the project;
(f) permanent controls to manage or treat runoff. Identify water resource affected and give the DNR Protected Waters Inventory (PWI) number(s) if the water resources affected are on the PWI;
(g) proposed mitigation measures to avoid or minimize impacts.

v. **Manure management.** Describe how manure will be collected and stored at this facility. Include a description of any manure processing activities such as liquid solid separation and anaerobic digestion. Attach a copy of the Manure Management Plan (MMP). If an anaerobic digester will process manure, list any other feedstocks used in the digester.

(1) **Manure removal activities.**
(a) Manure removal frequency:
☐ Once per year
☐ Twice per year
☐ Other:

(b) Time required for manure removal (days/year):

(2) **Manure transfer.** Will any amount of manure be transferred to a third party for land

application?

☐ Yes – complete a-c below ☐ No – skip a-c below

(a) Estimated amount of manure transferred throughout the year:

Transfer timeframe (months)	Liquid (gal)	Solid (ton)
• *e.g. October 1-14*		
•		
TOTAL		

(b) Describe the protocols used to ensure information about nutrient content, nitrogen and phosphorus rate requirements, and setback requirements are made available to the recipient.

(c) Describe efforts to limit the potential for application of transferred manure to fields without actively growing crops during the summer and during frozen or snow-covered conditions.

(3) **Manure Land Application (non-transfer).** Will any amount of manure be applied to fields owned, leased, rented, or otherwise controlled by any member of the ownership entity of the feedlot?

☐ Yes – complete a-e below ☐ No – skip a-e below

(a) Estimated amount of manure applied throughout the year:

Application timeframe	Liquid (gal)	Solid (ton)
• *e.g. October 1-14*		
•		
TOTAL		

(b) Describe anticipated manure application technologies and methods of application and incorporation. Include measures to limit the potential for runoff, especially for manure applied in winter conditions.

(c) Describe measures used to manage field soil phosphorous levels to prevent excessive phosphorus build-up.

(d) Describe any measures (Best Management Practices) used to limit the potential for nitrate impacts to water resources.

(e) If land application acres drain to a waterbody with an impairment, describe the measures used to limit land application effects on the impairment.

(4) **Manure application fields.**

(a) **General description.** Describe each land application field with the following:

(i) Field name/ID, location (Township-Range-Section), tillable acres, predominant soil type, field tiling system, irrigation system, description of bordering lands/roads, waters (within 2 miles) receiving runoff or tile line flow, etc.… Include DNR Public Waters

Inventory numbers (if available) and any special designations such as public waters, shoreland classification and floodway/floodplain, trout stream/lake, wildlife lakes, migratory waterfowl feeding/resting lake, and outstanding resource value water.

(b) Map the manure application fields. Show on a map the following within or near (300 ft) land application fields:
  (i) Lakes, rivers, streams, intermittent streams, wetlands, county/judicial ditches, open tile intakes, wells, springs, Karst features (Sinkholes, caves, resurgent springs, disappearing springs, karst windows, blind/dry valleys)

(c) Additional field sensitivity information. Below each of the following items list any fields that meet the criteria described.
  (i) Fields within Drinking Water Supply Management Areas (DWSMAs) or Source Water Protection Areas (SWPAs) with medium to high vulnerability, including tribal drinking water supply areas.
  (ii) Fields planned for winter manure applications.
  (iii) Fields with soil phosphorous tests levels above 21 ppm Bray 1 or 16 ppm Olson and have surface water within 300 feet.
  (iv) Fields with soil phosphorous tests levels above 75 ppm Bray 1 or 60 ppm Olson.
  (v) Fields that could receive broadcast manure (not immediately incorporated) that have slopes at 6% or greater.

(d) Using Web Soil Survey data, list any fields with at least 33% of the acreage that meets the following:
  (i) sensitive aquifer assessment rating
  (ii) soil texture of sand, loamy sand, loamy coarse sand, fine sand, loamy fine sand, coarse sand, or very fine sand
  (iii) depth to bedrock of 40 inches or less
  (iv) soil erosion ("T factor") rating of 5 or more tons/acre/year
  (v) frequently flooded

(5) **Manure application setbacks.** Describe any required township/county/state setbacks for land application systems. Show as a buffer on maps.

(6) **Other methods of manure utilization.** If the project will utilize manure other than by land application, please describe the methods. If the project includes an anaerobic digester or one exists on-site include that information here.

13. Contamination/Hazardous Materials/Wastes:

a. Pre-project site conditions — Describe existing contamination or potential environmental hazards on or in close proximity to the project site such as soil or ground water contamination, abandoned dumps, closed landfills, existing or abandoned storage tanks, and hazardous liquid or gas pipelines. Discuss any potential environmental effects from pre-project site conditions that would be caused or exacerbated by project construction and operation. Identify measures to avoid, minimize or mitigate adverse effects from existing contamination or potential environmental hazards. Include development of a Contingency Plan or Response Action Plan.

b. Project related generation/storage of solid wastes — Describe solid wastes generated/stored during construction and/or operation of the project. Indicate method of disposal. Discuss potential

environmental effects from solid waste handling, storage, and disposal. Identify measures to avoid, minimize or mitigate adverse effects from the generation/storage of solid waste including source reduction and recycling.

c. Project related use/storage of hazardous materials — Describe chemicals/hazardous materials used/stored during construction and/or operation of the project including method of storage. Indicate the number, location, and size of any new above or below ground tanks to store petroleum or other materials. Indicate the number, location, size, and age of existing tanks on the property that the project will use. Discuss potential environmental effects from accidental spill or release of hazardous materials. Identify measures to avoid, minimize or mitigate adverse effects from the use/storage of chemicals/hazardous materials including source reduction and recycling. Include development of a spill prevention plan.

d. Project related generation/storage of hazardous wastes — Describe hazardous wastes generated/stored during construction and/or operation of the project. Indicate method of disposal. Discuss potential environmental effects from hazardous waste handling, storage, and disposal. Identify measures to avoid, minimize or mitigate adverse effects from the generation/storage of hazardous waste including source reduction and recycling.

e. Dead animal disposal — Describe the quantities of dead animals anticipated, the method for storing and disposing of carcasses, and frequency of disposal. What is the response to a major disease or death event? Identify local ordinance restrictions for animal disposal, composting, etc.

14. Fish, Wildlife, Plant Communities, and Sensitive Ecological Resources (Rare Features):

a. Describe fish and wildlife resources as well as habitats and vegetation on or near the site.

b. Describe rare features such as state-listed (endangered, threatened, or special concern) species, native plant communities, Minnesota County Biological Survey Sites of Biodiversity Significance, and other sensitive ecological resources on or within close proximity to the site. Provide the license agreement number (LA-____) and/or correspondence number (ERDB ____) from which the data were obtained and attach the Natural Heritage letter from the DNR. Indicate if any additional habitat or species survey work has been conducted within the site and describe the results.

c. Discuss how the identified fish, wildlife, plant communities, rare features and ecosystems may be affected by the project including how current Minnesota climate trends and anticipated climate change in the general location of the project may influence the effects. Include a discussion on introduction and spread of invasive species from the project construction and operation. Separately discuss effects to known threatened and endangered species.

d. Identify measures that will be taken to avoid, minimize, or mitigate the adverse effects to fish, wildlife, plant communities, ecosystems, and sensitive ecological resources.

15. Historic and Cultural Resources: Describe any historic structures, archeological sites, and/or traditional cultural properties on or in close proximity to the site. Include 1) historic designations, 2) known artifact areas, 3) architectural features, 4) Tribal connections to the site. Attach any comment letters received from the state, Tribal, or other governmental organizations. Discuss anticipated effects to historic properties and cultural resources during project construction and operation. Identify measures that will be taken to avoid, minimize, or mitigate adverse effects to historic properties and cultural resources.

16. Visual: Describe any scenic views or vistas on or near the project site. Describe any project-related visual effects such as vapor plumes or glare from intense lights. Discuss the potential visual effects from the project. Identify any measures to avoid, minimize, or mitigate visual effects.

17. Air/Odor Emissions: Describe the following.

a. Stationary source emissions –

i. type, sources, quantities, and compositions of any hazardous air pollutants and criteria pollutants emissions from stationary sources;

ii. effects on air quality including any sensitive receptors, human health, or applicable regulatory criteria. Include a discussion of any methods used to assess the project's effect on air quality and the results of that assessment;

iii. Identify pollution control equipment and other measures that will be taken to avoid, minimize, or mitigate adverse effects from stationary source emissions**;**

iv. proposed feedlot design features or air or odor emission mitigation measures to be implemented to avoid or minimize potential adverse impacts and discuss their anticipated effectiveness.

If no feedlot design features or mitigations were proposed, provide a summary of the results of an air emissions modeling study designed to compare predicted emissions at the property boundaries with state standards, health risk values, or odor threshold concentrations. The modeling must incorporate an appropriate background concentration for hydrogen sulfide to account for potential cumulative air quality impacts.

b. Vehicle emissions – Describe the effect of the project's traffic generation on air emissions. Discuss the project's vehicle-related emissions effect on air quality. Identify measures (e.g. traffic operational improvements, diesel idling minimization plan) that will be taken to minimize or mitigate vehicle-related emissions.

c. Dust and odors – Describe sources, characteristics, duration, quantities, and intensity of dust and odors generated during project construction and operation, and any proposed measures to mitigate adverse impacts. (Fugitive dust may be discussed under item 17a). Discuss the effect of dust and odors in the vicinity of the project including nearby sensitive receptors and quality of life. Identify measures that will be taken to minimize or mitigate the effects of dust and odors. Describe any plans to notify neighbors of operational events (such as manure storage agitation and pump out) that may result in higher-than-usual levels of air or odor emissions.

18. Greenhouse Gas (GHG) Emissions/Carbon Footprint:

a. GHG Quantification: For all proposed projects, provide quantification and discussion of project GHG emissions. Include additional rows in the tables as necessary to provide project-specific emission sources. Describe the methods used to quantify emissions. If calculation methods are not readily available to quantify GHG emissions for a source, describe the process used to come to that conclusion and any GHG emission sources not included in the total calculation. Refer to EAW Guidance, Section 18 and GHG calculator tools.

The following tables list some examples, but the user must complete tables based on their project components; other layouts are acceptable for providing GHG quantification results.

Construction emissions

Scope	Type of emission	Emission sub-type	Project-related CO_2e emissions (tons/year)	Calculation method(s)
Scope 1	*Combustion*	*Mobile equipment*		
Scope 1	*Land use*	*Conversion*		
Scope 1	*Land use*	*Carbon sink*		
TOTAL				

Operational emissions

Scope	Type of emission	Emission sub-type	Existing facility CO_2e emissions (tons/year)	Project related CO_2e emissions (tons/year)	Total CO_2e emissions (tons/year)	Calculation method(s)
Scope 1	*Combustion*	*Mobile equipment*				
Scope 1	*Combustion*	*Stationary equipment*				
Scope 1	*Combustion*	*Area*				
Scope 1	*Non-combustion*	*Stationary equipment*				
Scope 1	*Land Use*	*Carbon Sink*				
Scope 2	*Off-site electricity*	*Grid-based*				
Scope 2	*Off-site steam production*	*Not applicable*				
Scope 3	*Off-site waste management*	*Area*				
TOTAL						

b. GHG assessment

i. Describe any mitigation considered to reduce the project's GHG emissions.

ii. Describe and quantify reductions from selected mitigation, if proposed to reduce the project's GHG emissions. Explain why the selected mitigation was preferred.

iii. Quantify the proposed project's predicted net lifetime GHG emissions (total tons/# of years) and how those predicted emissions may affect the achievement of the Minnesota Next Generation Energy Act goals and/or other more stringent state or local GHG reduction goals.

19. Noise:

Describe sources, characteristics, duration, quantities, and intensity of noise generated during project construction and operation. Discuss the effect of noise in the vicinity of the project including 1) existing noise levels/sources in the area, 2) nearby sensitive receptors, 3) conformance to state noise standards, and 4) quality of life. Identify measures taken to minimize or mitigate the effects of noise.

20. Transportation:

a. Describe traffic-related aspects of project construction and operation. Include:

i. existing and proposed additional parking spaces,

ii. estimated total average daily traffic generated,

(1) Estimate the number of heavy truck trips generated per week and describe their routing over local roads. Describe any road improvements to be made.

(2) Identify manure application routes and crossings, types of hauling equipment, impacts to road surface, and impacts to traffic. Identify use and road crossings of drag hoses.

iii. estimated maximum peak hour traffic generated and time of occurrence,

iv. source of trip generation rates used in the estimates, and

v. availability of transit and/or other alternative transportation modes.

b. Discuss the effect on traffic congestion on affected roads and describe any traffic improvements necessary. Discuss the project's impact on the regional transportation system. *If the peak hour traffic generated exceeds 250 vehicles or the total daily trips exceeds 2,500, a traffic impact study must be prepared as part of the EAW.* Use the format and procedures described in the Minnesota Department of Transportation's Access Management Manual, Chapter 5 *(available at: http://www.dot.state.mn.us/accessmanagement/resources.html)* or a similar local guidance.

c. Identify measures that will be taken to minimize or mitigate project-related transportation effects.

d. Will new or expanded utilities, roads, other infrastructure, or public services be required to serve the project?

☐ Yes ☐ No

If yes, please describe.

21. Cumulative Potential Effects: (Preparers can leave this item blank if cumulative potential effects are addressed under the applicable EAW Items)

a. Describe the geographic scales and timeframes of the project-related environmental effects that could combine with other environmental effects resulting in cumulative potential effects.

b. Describe any reasonably foreseeable future projects (for which a basis of expectation has been laid) that may interact with the environmental effects of the proposed project within the geographic scales and timeframes identified above.

c. Discuss the nature of the cumulative potential effects and summarize any other available information relevant to determining whether there is potential for significant environmental effects due to these cumulative effects.

22. Other Potential Environmental Effects: If the project may cause any additional environmental effects not addressed by items 1 to 20, describe the effects here, discuss how the environment will be affected, and identify measures that will be taken to minimize and mitigate these effects.

RGU CERTIFICATION.

I hereby certify that:

- The information contained in this document is accurate and complete to the best of my knowledge.
- The EAW describes the complete project; there are no other projects, stages, or components other than those described in this document, which are related to the project as "phased actions," pursuant to Minn. R. 4410.0200, subp. 60, 4410.1000, subp. 4, and 4410.4300, subp. 1.
- Copies of this EAW are being sent to the entire EQB distribution list.

Signature_____ Date _____

Title _____

The format for the alternative Environmental Assessment Worksheet form has been approved by the Chair of the Environmental Quality Board pursuant to Minn. R. 4410.1300 for use for animal feedlot projects (Minn. Rule 4410.4300 subp. 29.). For additional information contact: Environmental Quality Board, 520 Lafayette Road, St. Paul, Minnesota, 551554194, 651-296-6300, or visit the Environmental Review Program website.

Office of the Legislative Auditor - Program Evaluation Division

Animal Feedlot Regulation

Summary

During the 1990s, Minnesota has experienced a significant growth in the number of large animal feedlots, particularly swine facilities. There has also been an increasing tendency for owners of large feedlots to live offsite. Neighbors of these facilities have become increasingly concerned about the potential environmental impacts of animal feedlots on the air they breathe, the water they drink, and the lakes and streams they use for recreational purposes. Concerns have also been raised about the economic impact of large feedlots on existing producers.

As a result of the growing controversy over feedlots, the 1998 Legislature authorized the preparation of a generic environmental impact statement (GEIS) by the Environmental Quality Board. The GEIS will examine the long-term effects of the livestock industry on Minnesota's environment and economy. Because the GEIS is expected to take at least two years to complete, the Legislative Audit Commission directed our office to conduct a shorter and more focused study of animal feedlots. Our evaluation focuses on the adequacy of the environmental regulation of feedlots by the Minnesota Pollution Control Agency (MPCA) and the counties that have chosen to participate in the feedlot regulation program. In particular, our evaluation addresses the following issues:

- **Does MPCA review feedlot permit applications in a thorough and timely manner? Does MPCA conduct appropriate inspections of feedlots prior to issuing permits and during construction?**
- **Do MPCA and counties provide adequate oversight of feedlots on an ongoing basis, including taking appropriate actions to ensure that feedlots, when closed, are not pollution hazards?**
- **Does MPCA adequately analyze pollution risks for large feedlots that require preparation of an environmental assessment worksheet (EAW)?**
- **Does MPCA adequately respond to complaints about feedlot pollution and adequately enforce existing laws, rules, and permit conditions?**
- **What are the strengths and weaknesses of county feedlot programs? Does MPCA provide sufficient oversight of county feedlot programs?**
- **What are the deficiencies in MPCA's current administrative rules regulating feedlots and will MPCA's proposed rules adequately address the problems?**
- **Do MPCA and the counties have adequate resources to operate feedlot regulatory programs? If additional resources became available, where should they be targeted?**

In conducting this study, we interviewed MPCA management and staff, county regulatory staff, other state and local agency staff, livestock producers, environmental groups, concerned citizens, and other state and national experts. We reviewed MPCA permit, enforcement, and environmental review files in detail. We surveyed county regulatory officials and personally visited with some of them. We also reviewed existing reports and literature on feedlot pollution and regulation and examined information on the regulatory activities of other states. Finally, we visited feedlots in rural Minnesota to see firsthand the steps being taken to address water and air pollution concerns.

Overall, we found that MPCA's feedlot program has several strengths, including the design standards applied to new or expanded feedlots, the monitoring of water quality at certain large feedlots, and the relatively new monitoring of air quality. However, the program also has numerous weaknesses. These weaknesses include a lack of timeliness in reviewing and approving permit applications, insufficient review of some permit applications, limited follow-up on expired interim permits, insufficient resources devoted to visiting sites prior to permit approval or during construction, insufficient oversight of

feedlots once they are in operation except in response to complaints, poor tracking of staff responses to citizen complaints, a weak but improving enforcement program, little or no meaningful oversight of delegated county feedlot programs, and the failure to update rules since the late 1970s.

Background

The livestock industry is a significant component of the state's agricultural economy. Livestock and related products such as milk and eggs bring in almost as much cash revenue as crop production in Minnesota. In 1997, cash receipts from the livestock industry totaled $4.1 billion, with the dairy sector accounting for 30 percent of cash revenue. Other large components of the industry include hogs (29 percent), cattle and calves (24 percent), and poultry and eggs (15 percent). Turkeys dominate the poultry and egg sector, accounting for more than 60 percent of poultry and egg cash receipts.

Minnesota ranks high nationally in a number of livestock categories. Minnesota is the second highest among the 50 states in turkey production after North Carolina. Minnesota trails only Iowa and North Carolina in the number of hogs and pigs. In terms of the number of milk cows and milk production, Minnesota ranks fifth among the 50 states. Minnesota is also third in cheese production, fifth in butter production, fifth in ice cream production, and ninth in egg production.

MPCA is the principal agency responsible for regulating animal feedlots in Minnesota. A feedlot is any lot, building, or combination of lots and buildings in which animals are confined and manure may accumulate. State officials do not know exactly how many feedlots there are in Minnesota. In 1997, MPCA estimated that Minnesota had about 45,000 farms with animal feedlots, but there are probably fewer feedlots today.

The main purpose of feedlot regulation is to protect Minnesota citizens from pollution caused by animal manure. Manure is a valuable resource that can provide beneficial nutrients to the soil and thus help in the production of crops. However—if improperly stored, transported, or disposed—manure may pollute lakes and streams or drinking water sources. Manure can also produce unpleasant and annoying odors and emissions, possibly affecting the health of nearby residents. In addition, emissions from manure may contribute to acid rain and greenhouse gas effects.

MPCA's regulation of feedlots takes many forms. The agency requires any feedlot owner with 50 or more animal units to apply for a feedlot permit if a new feedlot is proposed, an existing feedlot is expanded or its operation is changed, or the ownership of a feedlot is changed. <FN - Within shoreland areas, a permit is required under similar circumstances for feedlots with more than ten animal units. An "animal unit" is a measure that attempts to rate animals based on the volume and nutrient content of the manure they produce. For example, a mature dairy cow is considered to be 1.4 animal units, a slaughter steer or heifer is 1.0 animal unit, a hog over 55 pounds is 0.4 animal units, a hog under 55 pounds is 0.05 animal units, a turkey is 0.018 animal units, and a chicken is 0.01 animal units.> MPCA is also responsible for adopting rules on feedlots, conducting environmental reviews of large feedlots, overseeing compliance with feedlot rules and permit conditions, investigating complaints about feedlots, and taking enforcement action against feedlot owners who violate state pollution laws, agency rules, or permit conditions. Funding for feedlot regulation by MPCA for the 1998-99 biennium was $3.2 million. The base level of staffing for feedlot regulation is 24 full-time equivalent positions, which includes 15 staff in MPCA's St. Paul office, 5 staff in regional offices around the state, and 4 vacant positions. This base level does not include MPCA managers or environmental review staff.

Minnesota law allows MPCA to delegate some of its feedlot regulation responsibilities to counties. To become a delegated county, the county board must pass a resolution stating that it assumes responsibility for processing permit applications, accompanied by a statement describing permitting procedures. It must also receive written approval from MPCA and appoint a county feedlot officer who is responsible for distributing feedlot permit application forms, helping farmers complete the applications, inspecting feedlots to ensure that they comply with agency rules and local feedlot ordinances, and maintaining feedlot permit records. In 1998, 47 counties had delegation agreements with MPCA. Counties received $2.1 million in state aid for feedlot regulation in the 1998-99 biennium.

A delegated county does not issue all of the permits for feedlots within its county boundaries. Delegated counties are responsible for issuing permits for feedlots with less than 300 animal units, provided that all potential pollution hazards at these feedlots have been corrected, and for feedlots between 300 and 1,000 animal units that do not have a potential pollution hazard. The county must forward all other feedlot permit applications to MPCA.

Permitting

Most of the permits MPCA issues are either "interim permits" or "certificates of compliance." An interim permit is issued for new construction or for a feedlot that poses a potential pollution hazard to the environment. An interim permit expires after ten months and should be replaced with a certificate of compliance once construction has been completed satisfactorily or corrective action has been taken to eliminate the pollution hazard. A certificate of compliance has no expiration date and indicates that a feedlot meets agency standards. MPCA also issues National Pollution Discharge Elimination System (NPDES) permits to certain large feedlots (over 1,000 animal units) that have the potential to discharge to waters of the state. Roughly 16,000 feedlots in the state have state or county feedlot permits, and about 23 of these are NPDES permits. Currently, MPCA charges permit fees only for NPDES permits.

Before MPCA issues permits, the agency usually reviews plans and specifications for all proposed manure storage structures to ensure that the structures are designed in a manner that will not degrade ground or surface water quality. In general, we found that:

- **MPCA has adequate design standards for structures that store manure.**

For example, MPCA's design standards for earthen basins tend to be more stringent than those in other states. Additionally, MPCA has guidelines for the construction of concrete pits that help to minimize the chance that these structures will leak or collapse. MPCA is monitoring about a dozen earthen basins that have been constructed since the agency toughened its standards in 1993 to gather information on the long-term adequacy of these basins. MPCA is also considering alternative ways of addressing concerns about potential leakage from unlined earthen basins installed before the standards were changed.

Plans and specifications for proposed manure storage systems are just one piece of information submitted with a feedlot permit application. Applicants must also provide information on proposed construction, site location, and manure management. Based on a random sample of permits we reviewed, we found that:

- **MPCA staff review permit applications and document their review in an inconsistent manner.**

For example, we found that some certificates of compliance were issued without MPCA receiving the necessary documentation required in the permits. Sometimes important documents had not been received such as a consulting engineer's certification that construction occurred in accordance with design specifications and permit requirements. We also found that often no written record of required karst reviews were on file for feedlots built in southeastern Minnesota's geologically sensitive karst region.

One particular area of concern is manure management plans. Current MPCA rules require feedlot permit applicants to submit a manure management plan that describes manure handling and application techniques and acreage available for manure application. MPCA uses this information to ensure that there are enough acres to spread the manure and that the method of spreading manure is appropriate. However, we found that:

- **Manure management information currently required by MPCA is inadequate.**

Manure management plans do not normally require a nutrient analysis of the manure generated or soil tests of the land on which manure will be applied. Manure nutrient analysis is essential to precise manure management since there can be wide variability in the nutrient value of manure. Without nutrient analysis, manure could be overapplied and could negatively affect the quality of ground or surface water. Soil analysis of phosphorus is particularly useful in certain environmentally sensitive locations to avoid excess application of phosphorus and potential negative impacts on surface water.

We also found that MPCA does not always verify the acreage information provided by the feedlot owner on the number of acres available for land application of manure. For example, we found discrepancies in some files between the number of acres the feedlot owner noted as available for land application of manure and the number available according to aerial photographs. The discrepancies sometimes were not noted in the permit files by MPCA staff.

Site inspections prior to construction are useful to verify information on the permit application and to evaluate the site's potential for pollution. For example, it is useful to inspect the site to gain a better understanding of the geological conditions and the presence of environmentally sensitive areas such as wells and sinkholes. Inspections during and after construction are useful to ensure that facilities, such as underground concrete pits, are constructed according to design specifications. We found that:

- **MPCA permitting staff do not normally conduct a site visit when they review a permit application or when a facility is being constructed.**

Eighteen percent of the permit files we reviewed contained evidence that MPCA conducted a site visit. MPCA staff told us that the agency has not normally conducted a site visit when reviewing a permit application. In the past, they have felt that their limited resources could be used more effectively to review construction plans, topographic maps, aerial photographs of the site, manure management plans, and information provided by the permit applicant to determine whether the proposed feedlot poses a potential for environmental harm. If the permitting staff have concerns about the site, they may visit the site or ask someone from the regional office to visit the site. In lieu of site visits during and after construction, MPCA has sometimes relied on certification by a feedlot owner's consulting engineer that structures were built according to the specifications on file with the agency. However, these certifications have not been required or enforced on all permits.

We also found that MPCA does not regularly track how long it takes to issue an interim permit or certificate of compliance. Based on our review, MPCA took a median of 113 days to issue an interim permit and 61 days to issue a certificate of compliance. Although there are many reasons for delays in feedlot permit issuance, such as local opposition to the feedlot or incomplete application information, we believe that:

- **The main cause of delay in issuing permits was the backlog of permits at MPCA.**

Our sample of permit applications suggests that it takes about one to two months between the time MPCA receives a complete application and the time an MPCA engineer begins to review the application.

MPCA typically issues interim permits for ten months, after which they expire. Once an applicant completes construction and provides verification to MPCA that the interim permit conditions have been satisfactorily met, MPCA can convert the interim permit to a certificate of compliance. We found that:

- **MPCA does not adequately follow up on expired interim permits.**

MPCA has several file cabinets full of interim permits, many of which have expired. Our sample of interim permits revealed that more than two-thirds had expired at some point. Nearly half had expired and to date had not been converted to certificates of compliance.

Overall, we found that because its staff is concentrated in St. Paul, MPCA has focused too many of its permitting efforts on reviewing engineering plans. Even though the agency has made efforts in recent years to inspect more facilities, we do not think that MPCA devotes sufficient attention to visiting feedlot sites prior to permit approval as well as during and after construction. Counties with the resources to do inspections have told us that field visits help ensure that the site is suitable for locating a feedlot and that manure storage facilities are constructed according to specifications. MPCA management also has told us that they would like to shift some of their emphasis from document reviews in St. Paul to more inspections of construction work. We recommend that:

- **MPCA should conduct more site visits prior to issuing feedlot permits, particularly for feedlots in environmentally sensitive areas.**
- **MPCA should conduct more site visits of feedlots during and after construction work, particularly when the feedlot is in an environmentally sensitive location or the construction involves contractors or engineers that MPCA is unfamiliar with or has had problems with on previous feedlot projects.**
- **MPCA should strive to provide a thorough review of all permit applications and ensure that required documents are filed with the agency in a timely manner.**

- **MPCA should develop a tracking system to make sure that feedlot owners follow through on permit requirements and should notify feedlot owners with expired interim permits and consider appropriate actions.**

- **MPCA should track the timeliness of its performance in issuing feedlot permits and strive to reduce its permitting backlog and the time producers wait for their applications to be reviewed.**

Environmental Review

Another important function performed by MPCA and sometimes by counties is the environmental review of certain proposed feedlots. According to rules established by the Minnesota Environmental Quality Board (EQB), an environmental assessment worksheet (EAW) must be prepared for any proposed new total confinement feedlot with a capacity of 2,000 or more animal units or an expansion of an existing total confinement feedlot resulting in an increase in capacity of 2,000 or more animal units. For partial confinement facilities, an increase in capacity of 1,000 or more animal units requires an EAW.

An EAW may also be prepared for a smaller project if the governmental unit responsible for permitting the facility decides that the project, because of its nature or location, may have the potential for significant environmental effects. The responsible governmental unit, which may be either MPCA or a county, may make this decision based on its own knowledge or upon evidence presented to it in a petition signed by at least 25 citizens.

During calendar year 1998, MPCA experienced a dramatic increase in its environmental review workload. The number of environmental assessment worksheets assigned to MPCA grew from an annual average of 10 for the period 1995-97 to 22 in 1998. There has also been an increase in the number of citizen petitions for EAWs assigned to MPCA. As of the middle of October, the number of petitions had grown from an annual average of 8 in 1996 and 1997 to 12 in 1998. The result of the dramatic growth in MPCA's environmental review workload has been an increase in the time it takes MPCA to complete a routine EAW, from about three to four months to five to nine months. MPCA's ability to promptly respond to citizen petitions has also been affected.

We reviewed a sample of EAWs done by MPCA and a number of citizen petitions decided by MPCA. Overall, we think that:

- **MPCA has improved its environmental review of feedlot projects.**

This improvement has largely occurred in the last year as MPCA has become more knowledgeable about hydrogen sulfide and ammonia emissions from feedlots. As a result, the agency has been able to more effectively respond to citizen concerns about odors.

In general, we think that the environmental review process has been useful in providing needed citizen input into MPCA's permitting and regulatory practices. Environmental review has resulted in MPCA imposing special permit conditions on particular feedlots when citizen input or other information has demonstrated the environmental need for such conditions. The process has also helped bring about changes in how MPCA handles permits for other facilities not undergoing environmental review.

There has been some dissatisfaction with EQB's "connected action rule" that requires multi-site feedlot projects to undergo a mandatory EAW if their combined increase in animal units exceeds 2,000 for total confinement projects or 1,000 for partial confinement projects. The rule may cause two "connected" sites to undergo an environmental review even though the sites are far enough apart that their environmental impacts are not cumulative. In response to such concerns, the 1998 Legislature directed the EQB to reconsider its connected action rule as it pertains to feedlots and to propose changes in the rule if appropriate. The EQB has drafted a proposed rule change that would eliminate the connected action provision for feedlots but instead lower the increase in capacity triggering a mandatory EAW for a total confinement facility from 2,000 to 1,000 animal units. The proposal would also require a mandatory EAW for new or expanding feedlots of any size in certain environmentally sensitive areas.

We are concerned that the proposed rule could increase MPCA's environmental review workload. MPCA had difficulties coping with an increased workload in 1998 and had estimated that the EQB rule change would increase the number of EAWs by 10 to 15 per year. The proposed rule change could require MPCA to shift more resources to environmental review activities unless market conditions cause fewer large feedlot expansions to be proposed or the livestock industry downscales

expansion plans to under 1,000 animal units to avoid mandatory EAWs. While we are supportive of the environmental review process, we are also aware of the many other needed improvements in feedlot regulation such as increased site visits, more timely enforcement actions, and increased review of manure management practices. We think that these improvements, if implemented, have the potential to affect more feedlots than environmental review is likely to affect and thus should be given higher priority than increasing the number of EAWs conducted by MPCA. We recommend that:

- **The Legislature should review the need for, and the potential cost of, the Environmental Quality Board's proposed rule on the environmental review of feedlots.**

Oversight

Feedlot regulation should not focus entirely on the issuance of permits. There is a need for ongoing oversight of permitted facilities and scrutiny of unpermitted feedlots as well. A detailed feedlot inventory can help identify facilities needing permits as well as facilities with previously unknown pollution problems. In addition, a regulatory agency should periodically inspect all permitted facilities on an ongoing basis to ensure that facilities are being operated in accordance with the permits and that pollution problems are not occurring. It is also important for a regulatory agency to ensure that appropriate steps are taken to protect the environment from water pollution when a feedlot closes and is no longer in operation.

We found that there are significant deficiencies in MPCA's oversight of feedlots on an ongoing basis. For example:

- **There is no statewide inventory of feedlots.**

Only a limited number of counties have done detailed feedlot inventories enabling them to identify where pollution problems exist. MPCA does not attempt to identify feedlots needing permits that have failed to apply for and obtain them. In addition, due to staffing constraints:

- **MPCA does not conduct periodic inspections of feedlots once they are in operation.**

A facility is likely to be inspected only if it is the subject of a complaint or enforcement action. We also found that:

- **MPCA has no way to track when feedlots are closed and has insufficient staff resources to check on whether closed feedlots are cleaned up in a timely manner.**

As part of an effective regulatory program, MPCA must ensure that its rules and regulations are followed by feedlot owners. Because it does not do routine inspections of feedlots, MPCA relies primarily on the public to inform the agency when a producer violates feedlot rules or engages in practices that endanger the environment. When it receives a complaint that a producer may have violated environmental laws, feedlot rules, or permit requirements, MPCA generally investigates the complaint. If it finds that the complaint is valid and a pollution hazard exists, MPCA considers taking steps to ensure that the feedlot owner corrects the problem and minimizes the threat of pollution. We found that:

- **MPCA does not adequately keep records of water quality complaints relating to feedlots, so we were unable to systematically analyze the agency's timeliness and thoroughness of complaint investigations.**

In some cases, MPCA also pursues sanctions against violators. Enforcement is important both to correct the immediate environmental threat and to deter the violator and other feedlot owners from committing future violations. MPCA has several enforcement tools at its disposal, including a notice of violation, an administrative order, an administrative penalty order, a stipulated settlement, a civil court action, and criminal prosecution. We found that:

- **MPCA has taken several significant enforcement actions that have resulted in penalizing feedlot owners and correcting conditions and practices that posed a threat to water quality.**

However,

- **MPCA takes a long time to complete enforcement actions, and some uncooperative feedlot owners have been able to avoid enforcement for several years.**

For the most part, MPCA relies on its regional staff to pursue enforcement action when warranted. We found that some regional staff are more aggressive in pursuing enforcement actions while others generally choose not to pursue enforcement. At least one regional office has not been undertaking enforcement efforts involving feedlots. As a result, enforcement caseloads are uneven and those staff with large caseloads have trouble keeping up, resulting in delays. We found other reasons for delays, including the reluctance of some county attorneys to file criminal charges and the reluctance of MPCA to take formal court action when feedlot owners fail to comply with their orders.

In response to a governor's budget proposal resulting from growing concerns about air pollutants emitted from feedlots, the 1997 Legislature required MPCA to develop a protocol for measuring hydrogen sulfide levels, monitor feedlots with suspected odor problems, and take appropriate actions to bring feedlots into compliance with hydrogen sulfide standards. Overall, we think that:

- **MPCA has developed a good initial program to respond to citizen complaints about feedlot odors.**

As of September 1998, MPCA staff had monitored 82 feedlots and found 26 to have potential violations of the standard for hydrogen sulfide. MPCA is working with those facilities identified as having potential violations to identify corrective or preventive measures that will reduce hydrogen sulfide emissions and perhaps odor complaints as well. In contrast to its handling of water pollution complaints, MPCA has done a good job of documenting complaints about feedlot odors and air emissions over the last year. MPCA has also responded appropriately to complaints by monitoring air emissions in a generally timely manner. However:

- **MPCA's air quality monitoring and compliance program for feedlots will face a number of challenges as it attempts to develop a policy on what mitigation steps various types of feedlots need to follow.**

The basic challenge that MPCA faces is that research into feedlot emissions and odor control does not yet have the answers to many of the relevant questions, such as how well technologies will work under various conditions or how long particular remedies will last. Because of these and other uncertainties, MPCA must be careful not to order excessively costly remedies if less costly remedies are available. MPCA also needs to make sure that it prescribes remedies that address the true source of odors and emissions. Additional research efforts by MPCA and others are needed to achieve these goals.

To address the shortcomings in the oversight of existing feedlots, we recommend that:

- **The Legislature should carefully consider the need for additional county feedlot inventories along with the budget request it will receive for the Generic Environmental Impact Statement on Animal Agriculture.**

- **MPCA should require its staff to record all complaints received about feedlots and briefly document how each complaint was resolved.**
- **MPCA should require regular status reports from investigators to ensure that progress is being made on water quality enforcement cases.**

- **MPCA should assign more staff to water quality enforcement activities in order to reduce the backlog and speed up resolution of cases.**
- **MPCA should ensure that regional offices are consistent in their willingness to investigate potential water quality violations.**

County Feedlot Programs

MPCA's feedlot program depends on delegated counties to issue feedlot permits, oversee feedlot operations, and minimize environmental pollution from feedlots. Ideally, a good county feedlot program should have an inventory of feedlots in the county, know which feedlots pose environmental problems, and have a plan to address the pollution problems. County officials should also thoroughly review new and expanded feedlot permit applications and ensure that feedlots are constructed in accordance with MPCA rules and guidelines, local zoning ordinances, and sound engineering practices. We found that county programs vary considerably in the degree to which they are funded and have the desired regulatory

practices in place. Counties also vary in the type and extent of environmental risks that result from their geographical and geological features. Minnesota has programs in some counties that are less than adequate and has programs in other counties that are exemplary and more advanced than MPCA's own regulatory efforts.

In particular, we found that:

- **Counties vary considerably in the amount of resources they devote to feedlot regulation. Only part of this variation is due to county differences in the number of feedlots.**

County feedlot budgets in 1998 ranged from $3,540 to $125,000. The number of full-time equivalent staff devoted to feedlot regulation in delegated counties ranged from 0 to 3. Sixteen counties reported that less than 0.5 FTE staff worked on feedlot regulation. Some of this variation is expected due to differences in the number of feedlots. However, there is also considerable variation among counties that have similar numbers of feedlots. We also found that:

- **Counties vary considerably in the level of feedlot inventory they have completed.**

There are three levels of feedlot inventories. A Level 1 inventory is the most basic, and indicates all sites where livestock are present. A Level 2 inventory identifies sites where a potential for pollution exists, and a Level 3 inventory identifies sites where an actual pollution hazard exists. Based on our survey of county feedlot officers and other information we received from MPCA, we estimate that about 51 of the state's 87 counties have completed or are working on a feedlot inventory. Thirteen counties have completed or are working on a Level 3 inventory, 28 have completed or are working on a Level 2 inventory, and 10 counties have completed or are working on a Level 1 inventory. We estimate that statewide, about 36 counties (including 6 delegated counties) do not have a feedlot inventory completed or in progress.

We also found that:

- **There are wide differences among delegated counties in the extent to which they visit proposed new feedlots, existing feedlots, or abandoned feedlots.**

Most delegated counties visit all proposed feedlots before construction of new facilities begins, but only one-third of the counties visit all feedlots during or after construction to ensure the facilities are built according to design specifications and are environmentally sound. Additionally, few counties do routine inspections of existing feedlots to ensure that they are operating in accordance with permit requirements and feedlot rules, and few counties visit abandoned feedlots to ensure that they are closed properly.

Although MPCA delegates authority to counties with feedlot programs, we found that:

- **MPCA has provided little oversight of county feedlot programs, although it has recently made efforts to require delegated counties to meet some minimal requirements as a condition of remaining in the feedlot program.**

Unless a county requests assistance, MPCA does little to check on the thoroughness of county site inspections and does not verify the information that counties submit on their county feedlot officer reports. In particular, MPCA does not appear to check whether counties are matching the state aid they receive with cash or in-kind contributions from non-state sources. Oversight is important because county programs can be affected by local politics, which may sometimes cause programs to lack necessary environmental safeguards.

There is also a need for improved training and technical assistance for counties. County feedlot officers expressed concern to us about the adequacy of training provided by MPCA. Only 30 percent of those responding to our survey of county feedlot officers thought that MPCA training was "good" or "very good." Some counties want better technical training, while others want more on-the-job training. We recommend that:

- **MPCA should provide more effective oversight of county feedlot programs. The agency should establish expectations and standards for county feedlot programs and ensure that counties are meeting their financial obligations set forth in law.**

- **MPCA should attempt to ensure that county feedlot officers receive adequate training.**

Despite our concerns about some county programs and MPCA's lack of oversight, we think that:

- **MPCA should encourage, and the Legislature should support, the participation of additional counties in the feedlot program.**

With adequate technical support and proper oversight, counties can provide a valuable regulatory service. County staff will always be located closer to regulated facilities than MPCA and thus be able to more efficiently visit the sites of proposed feedlots, check on construction, and follow up on complaints. Increasing the number of counties in the feedlot program would also help to reduce MPCA's permitting workload and enable the agency to improve its performance in a number of areas. Adding more counties would also leverage county funds and make it less costly to the state to improve feedlot regulation than appropriating funds for more MPCA staff.

We have also noticed that, even in counties with good inventories and adequate regulatory budgets, it can often be difficult to get owners of small existing feedlots to correct potential water pollution problems. Owners of small facilities lack adequate resources and may not be able to borrow money at a reasonable interest rate. In addition, public funds available for assisting feedlot owners are limited. As a result, some counties do not even bring these feedlots to MPCA's attention, since MPCA will generally not accept anything less than a perfect solution in which the pollution potential is reduced to zero. An alternative approach in some cases might be for MPCA to accept a less than perfect, but more cost-effective, solution to pollution abatement. Such an approach could be more effective in reducing manure runoff from open lot feedlots than the current policy and should probably be applied only to existing feedlots under 300 animal units due to restrictions in federal rules. Consequently, we recommend that:

- **The Legislature, MPCA, and other policy makers should consider alternative ways of reducing water pollution emanating from small existing feedlots, including the need for additional public funds as well as more cost-effective ways of achieving a reduction in water pollution.**

Feedlot Rules

One of the key reasons why there have been problems with animal feedlot regulation is that:

- **MPCA's administrative rules for feedlots are outdated.**

There are numerous problems with the existing rules, which have not been revised since 1978. They do not adequately address land application of manure, manure stockpiling, manure storage structures, and the proper closure of feedlots. In addition, the rules do not sufficiently spell out the responsibilities of counties in the delegated county program. The existing rules do not establish the responsibilities of consultant engineers working for feedlot owners in inspecting construction to make certain that work is done according to design specifications and MPCA permit requirements. The rules also fail to address feedlot siting issues such as whether new construction or expansion should be allowed in environmentally sensitive areas.

As a result of these and other concerns, MPCA began working on new feedlot rules in early 1995. Due to concerns that MPCA has taken too long to develop new rules, the 1998 Legislature set a deadline of June 1, 1999 for MPCA to adopt new rules. However:

- **It is unlikely that MPCA will meet the legislative deadline for completing the rulemaking process.**

As of mid-January 1999, MPCA staff had still not finished drafting rule changes. While the bulk of the drafting work is done, staff have yet to coordinate how some of sections of the draft affect others and they are still seeking comments from outside parties on the draft. The agency may be able to issue proposed rules by sometime in March 1999, but is unlikely to complete the rulemaking process until late in the year. Despite the length of time it will have taken to draft and adopt rule changes, we think that:

- **MPCA has put much thought and effort into the drafting process, has aggressively sought outside comments, and appears to be pursuing changes that will address many of the concerns we have about existing rules.**

We are hesitant to provide a more specific endorsement of MPCA's work at this time, since the drafts have changed over time and may continue to change. Furthermore, we do not know exactly what rules MPCA will propose and take to hearings. We have some concerns about the direction the drafts have taken. For example, we are concerned that some of the proposed permit requirements may create a large workload for MPCA which its resources are inadequate to handle. We are also concerned that proposed permitting changes, such as the elimination of interim permits and the use of "short form" permits, may not allow MPCA to assure that a site is appropriate for use as a feedlot or that the design complies with agency requirements. The agency believes these changes will help streamline the permitting system so that some resources can be moved from permit application and design review to inspection of construction work and existing feedlot operations. In addition, streamlining may help MPCA provide a more timely response to permit applicants. MPCA management thinks, and we tend to agree, that resources should be shifted from an area of relative strength to areas of weakness in its feedlot program. Our concern is that the draft rules, as well as MPCA's regulatory and staffing practices, need to be designed so as to minimize the environmental risks of reducing MPCA's review of permit applications. We think that there are still some important issues to be worked out.

MPCA Resources

We think that there are two fundamental resource problems adversely affecting MPCA's performance:

- **Until recently, MPCA has not had enough staff working on feedlot regulation, and**
- **Too few of MPCA's feedlot staff are located outside of St. Paul.**

MPCA has not been able to perform its regulatory functions in a timely and thorough manner. The agency has been unable to keep up with its workload in permitting, enforcement, and environmental review. In addition, MPCA has not been sufficiently thorough in its review of permits and lacks an adequate presence in the field for the purpose of reviewing proposed feedlot sites, inspecting construction work, and overseeing existing feedlots. Furthermore, the agency needs to provide much better oversight of counties in the feedlot program. Finally, MPCA has not done a good job of tracking its own performance in responding to complaints or processing permits.

Only about 25 percent of existing feedlot staff are located outside of St. Paul. MPCA's centralization makes it difficult for the agency to visit the sites of proposed new feedlots or feedlot expansions, inspect construction work, periodically visit existing facilities, and carry out its complaint handling and enforcement responsibilities. While MPCA has five to six feedlot staff located in regional offices around the state, attempting to manage these staff from St. Paul has been a cumbersome and inefficient arrangement.

In September 1998, MPCA management attempted to address some of these staffing and management concerns by assigning a new manager to bring focus and direction to feedlot regulation and temporarily reassigning eight full-time equivalent staff to feedlot related activities during fiscal year 1999. The agency also plans to use four vacant positions in the feedlot program to increase its staffing in MPCA offices outside of St. Paul.

In general, we think that:

- **MPCA can implement some of the recommendations in this report by using existing resources.**

Even without increased resources, MPCA could do a better job of reviewing permit applications, tracking interim permits, tracking complaint investigations, managing enforcement cases, and providing a basic level of county program oversight. MPCA could also develop cost-effective strategies for addressing water pollution problems at small feedlots as well as policies for addressing hydrogen sulfide and other air emission problems.

In addition, the four vacant positions in the feedlot program could be used to increase the number of site visits conducted prior to issuing permits, during feedlot construction, or after feedlots are in operation. The positions could also be used for complaint investigations, enforcement activities, or technical assistance to feedlot owners who need to correct potential pollution hazards. MPCA could also consider moving some of its existing feedlot staff to decentralized locations to assist in these functions.

However, we also think that:

- **MPCA and counties will probably need additional resources to address certain problems in feedlot regulation.**

The temporary reassignment of staff to feedlot activities is scheduled to end on June 30, 1999. Without additional resources, MPCA is unlikely to be able to monitor whether feedlots have been properly closed. The agency will also be unable to conduct periodic inspections of operating feedlots except by either selecting a small sample of feedlots for compliance reviews or focusing on a few watersheds each year. We also think that progress in identifying and addressing long-standing pollution problems with small feedlots could be slow. Some delegated counties have made progress in addressing pollution problems and MPCA may be able to develop strategies to help other delegated counties make progress. However, MPCA does not have the resources to effectively run programs in non-delegated counties or to take over programs in delegated counties that are not doing an adequate job.

A better way of addressing some of these concerns would be for MPCA to encourage more counties to participate in the feedlot program, have clear expectations about their responsibilities, and provide greater technical support and oversight. However, that approach will require additional funding for county programs, including more funding for detailed county feedlot inventories, technical assistance to feedlot owners, and possibly more financial assistance to feedlot owners if policy makers want to speed up progress in addressing pollution problems.

We also find that:

- **It is difficult to assess how much of an increase in resources MPCA may need to improve its feedlot program.**

It is difficult to estimate how market forces may affect the agency's workload in the future. Declining hog prices, for example, could reduce the number of permit applications for new or expanded swine feedlots. In addition, regulatory changes being considered by MPCA and EQB or in the process of being implemented may affect MPCA's workload. MPCA's new feedlot rules might require the agency to issue new five-year renewable permits to all existing feedlots and EQB's proposed "connected action" rule may increase MPCA's environmental review workload. In addition, MPCA needs to meet legislative deadlines for issuing NPDES permits to existing feedlots with 1,000 or more animal units. On the other hand, MPCA is considering possible ways of streamlining its permitting system, and these changes may reduce the impact of other changes on the agency's workload. Finally, MPCA's future workload will depend on how many more counties choose to participate in the feedlot program. While increased participation may require more resources for MPCA oversight and technical assistance, it would also reduce MPCA resources devoted to issuing permits in the newly participating counties.

In addition to economic and regulatory uncertainties, it is difficult to quantify MPCA's staffing needs because the agency does not have data on the average amount of staff time needed to perform certain tasks such as permit review. Internally, MPCA staff have estimated that the feedlot program, including related functions such as environmental review and air quality monitoring, needs twice the current number of staff to adequately perform its duties. We are skeptical of such estimates because they are not based on workload estimates and the number of hours needed to complete major tasks. In our view:

- **If MPCA requests an appropriation for additional feedlot staff, it should provide the Legislature with detailed information on its estimated workload and the average amount of time it takes to complete major tasks.**

We also recommend that:

- **Before appropriating additional funds for more MPCA staff, the Legislature should consider whether funds from other MPCA activities could be permanently reallocated to feedlot regulation.**

MPCA has already temporarily reallocated staff from other programs to feedlot regulation. However, funding for some of those staff came from fees collected from non-feedlot facilities regulated by the agency. MPCA may not be able to use these funds for feedlot regulation on a permanent basis. Nevertheless, MPCA and the Legislature should consider whether there are funds within the agency that could be permanently reallocated to feedlot regulation without impairing the programs currently receiving those funds.

If the Legislature determines that additional funding for feedlot staff is justified, it could consider using fee revenue as an alternative to general fund appropriations. Currently, the general taxpayer finances most of the cost of feedlot regulation. The only existing feedlot fees are for NPDES permits. Revenue from NPDES permit fees will be increasing as more feedlots are

required to obtain an NPDES permit. These additional revenues and funds from new fees being considered by MPCA could be used to provide additional support for the feedlot regulation program. However, MPCA and the Legislature should consider the impact of a fee-based approach on the livestock industry. More than other regulated industries, the livestock industry operates in very competitive markets that do not ordinarily allow producers to raise their prices if local fees are raised. It would be particularly difficult to justify new fees in the hog industry if the current low prices continue.

More Information

The Program Evaluation Division was directed to conduct this study by the Legislative Audit Commission in April 1998. For a copy of the full report, entitled "Animal Feedlot Regulation," (99-04), 96 pp., published on January 28, 1999, please call 651/296-4708, e-mail Legislative.Auditor@state.mn.us, or write to Office of the Legislative Auditor, 658 Cedar St., St. Paul, MN 55155.

Staff who worked on this project were John Yunker (project manager), David Chein, and Jennifer Moenck Feige.

More Information

Brief Summary (PDF)
Summary (PDF)
Full Report (PDF)
[Text Only]
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Minnesota Issue Guide

Feedlots

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Large livestock feedlots, also known as concentrated animal feeding operations (CAFO), have been controversial in Minnesota as in other states. Environmental concerns include air pollution, ground water contamination, surface water contamination, and the long-term reliability of waste containment facilities. The social and economic impacts of these large operations on rural communities have been questioned as well.

During the 1998 session of the Minnesota Legislature the feedlot issue sparked heated debate. The House passed a moratorium on new construction or expansion of feedlots at the level of 750 animal units. The Senate and the Governor did not support a moratorium. The final language, passed as part of the Environment, Natural Resources, and Agriculture spending bill did not include a moratorium (*Laws of Minnesota 1998*, chapter 401). Several provisions of this law affected feedlots. One such change was that counties were allowed to adopt feedlot ordinances calling for standards more stringent than Minnesota Pollution Control Agency rules. The Minnesota Pollution Control Agency (MPCA) regulates animal feedlots in Minnesota, according to *Minnesota Rules*, chapter 7020.

Recognizing the need for further study of animal agriculture, the Legislature appropriated $1.2 million to the Office of Strategic and Long-Range Planning for the first year of a three-year study of the effects of the livestock industry on the state's economy and environment (*Laws of Minnesota 1998*, chapter 366, section 86). Staff at the Environmental Quality Board produced a *Generic Environmental Impact Statement on Animal Agriculture*, advised by a citizen committee. Detailed information about Minnesota's 1998 legislation is outlined in a House Research Department Information Brief, *1998 Law Changes Affecting Minnesota Animal Feedlots*.

In May 1999, a bill was passed that eased restrictions on feedlot operators (House File 1235/Senate File 692). One provision exempted feedlots from compliance with standards for ambient hydrogen sulfide for the days when manure is being removed from barns or storage facilities and handled for application or disposal. The bill was vetoed by Governor Ventura on May 25, 1999.

A new law in 2000 relaxed feedlot rules (*Laws of Minnesota 2000*, chapter 435). The law gave legislative direction to the Minnesota Pollution Control Agency (MPCA) on how the rules should be amended before final adoption. The MPCA Citizens' Board passed revised rules on August 22, 2000. On October 23, 2000 those feedlot rule changes took effect.

On May 17, 2002, the governor signed the omnibus agriculture policy law which bars the Minnesota Pollution Control Agency or a county board from approving permits for the construction of open-air swine manure basins (*Laws of Minnesota 2002*, chapter 373). For exceptions to this prohibition, see the House Research Bill Summary for H.F. 3183. The moratorium was originally effective May 18, 2002 through June 30, 2007, but has been extended several times (*Minnesota Statutes*, section 116.0714).

In 2005, the Minnesota Legislature allocated funds to the Minnesota Department of Agriculture to develop a program to assist local units of government with agricultural planning and zoning issues and livestock siting issues. As a result of this legislative action, the Local Land Use and Livestock Siting Program was formed.

In May of 2014, revised rules went into effect regarding three areas: (1) the storage, transportation, disposal and use of animal manure and process wastewaters; (2) the application for and issuance of permits for construction and operation of animal manure management; and (3) disposal or utilization systems for the protection of the environment (*Minnesota Rules*, chapter 7020, *Minnesota Rules*, chapter 7002, and *Minnesota Rules*, chapter 7001).

Although the National Pollutant Discharge Elimination System (NPDES) general permit expired on January 31, 2021, the agency allowed permit coverage to continue while the agency completes the online permit application system. The current NPDES general permit is set to expire on January 31, 2026. Minnesota currently issues both the NPDES permit and the State Disposal System (SDS) permit for larger feedlot construction and/or operation. Some local ordinances regarding zoning, setbacks, stormwater, or feedlots may also impact construction and operation of feedlots. More details are available on the MPCA feedlot program permit webpage.

The new NPDES general permit (which expires in 2026) includes changes to the application of manure and sowing of cover crops. Restrictions specific to MPCA permitting of these processes had been under discussion in the 2021 Legislature (SF566 and SF814, sec. 86). Some of the language regarding permitting, manure, and cover crops from these bills were included in *Laws of Minnesota 2021*, 1st special session, chapter 6. Much of this language significantly changed feedlot permitting at the MPCA. However, the federal Environmental Protection Agency reinstated the original permit stating that this session law conflicts with the federal clean water law.

Significant Books and Reports

(books in reverse chronological order)

Trom Eayrs, Sonja. *Dodge County, Incorporated: Big Ag and the Undoing of Rural America*. Lincoln: University of Nebraska Press, 2024. (HD9007.M6 E29 2024)

Notable Changes to the Feedlot NPDES General Permit. Saint Paul, MN: Minnesota Pollution Control Agency, 2021.

Livestock and the Environment: Feedlot Program Overview. St. Paul: Minnesota Pollution Control Agency, January 2021. (TD930.2 .L58 2021)

Zimmerman, Curt. *2015 Livestock Industry Study*. St. Paul: Minnesota Department of Agriculture, 2016. (HD9417.M53 L58 2016) (Required by Laws of Minnesota 2015 First Special Session, chapter 4, article 2, section 83.)

Sullivan, Colbey. *A Minnesota Lawmaker's Guide to the Agri-Environmental Policy Landscape.* St. Paul: Minnesota House of Representatives, Research Department, 2015. (S589.757.M6 S85)

Oie, Michelle. *County Feedlot Program Report*. Saint Paul, MN: Minnesota Pollution Control Agency, 2015. (TD930.2 .C68 2015) (Required Laws of Minnesota 2013, chapter 114, article 3, section 3, subdivision 2.)

Industrial Food Animal Production in America: Examining the Impact of the Pew Commission's Priority Recommendations. Baltimore, MD: Johns Hopkins Center for a Livable Future, 2013. (SF140.L58 I53)

Feedlot Financial Needs Assessment Report for Feedlots with Less Than 300 Animal Units to Comply with Applicable State Rules and Statutes by October 1, 2010. Minnesota Board of Water and Soil Resources, January 2008. (TD930.2 .F432 2008) (Required by *Laws of Minnesota 2007*, chapter 57, article 1, section 2.)

The Minnesota Livestock Producer's Guide to Feedlot Rules: Overview of the Feedlot Rules, Minnesota Rules, Chapter 7020. St. Paul: Minnesota Department of Agriculture, March 2008. (KFM5646.A35 M56 2008)

Hendrick, Scott & Farquhar, Doug. *Concentrated Animal Feeding Operations: A Survey of State Policies.* Denver, CO: National Conference of State Legislatures, 2008. (KF1730.H46 2008)

Putting Meat on the Table: Industrial Farm Animal Production in America. Pew Commission on Industrial Farm Animal Production, 2008. (SF140.L58 P87 2008)

Feedlot Rules Overview: Minnesota Rules Chapter 7020. St. Paul: Minnesota Pollution Control Agency, 2004.

Livestock, Local Governments, and Land Use: A Guide for Local Officials. St. Paul: Minnesota Department of Agriculture, 2006. (HD256 .L58 2006)

Feedlot Program: Report to the Legislature. St. Paul: Minnesota Pollution Control Agency, 2004. (TD930.2 .T86 2004) (Required by *Laws of Minnesota 2001 First Special Session*, chapter 2, section 2.)

Report to the Legislature: Public Participation in Permitting of Animal Feedlots for Feedlots under 1,000 Animal Units. St. Paul: Minnesota Environmental Quality Board, 2004. (GE185.M6 R47 2004) (Required by *Laws of Minnesota 2003*, chapter 128, article 3, section 46.)

2002 Feedlot Program: Report to the Legislature. St. Paul: Minnesota Pollution Control Agency, 2002. (TD930.2.T86 2003) (Required by *Laws of Minnesota 2001 First Special Session*, chapter 2, section 2.)

Generic Environmental Impact Statement on Animal Agriculture. St. Paul: Minnesota Planning Agency, Environmental Quality Board, 2002. (TD428.A37 G50 2002) (Required by *Laws of Minnesota* 1998, chapter 366, section 86.)

Report to the Legislature on the Minnesota Pollution Control Agency's Ability to Meet 60-day Issuance Deadline for Feedlot Permits. St. Paul: Minnesota Environmental Quality Board, 2000. (TD524.M6 R37 2000) (Required by *Laws of Minnesota 2000*, chapter 435, section 9.)

Animal Feedlot Regulation. St. Paul: Minnesota Office of the Legislative Auditor, Program Evaluation Division, 1999. (KFM5646.A65 1999)

Feedlot Issues: Animal Waste Liability Account, Incident Reporting and Contingency Action Plan. St. Paul: Minnesota Pollution Control Agency, 1999. (TD524.M6 F33 1999) (Required by *Laws of Minnesota 1998*, chapter 401, section 56.)

Helland, John. *1998 Law Changes Affecting Minnesota Animal Feedlots*. St. Paul: Minnesota House of Representatives, Research Department, 1998. (KFM5646 .A3 1998)

Legislative Report of the Feedlot Hydrogen Sulfide Program. St. Paul: Minnesota Pollution Control Agency, February 1998. (TD885.5.H9 L44 1998) (Required by *Laws of Minnesota 1997*, chapter 216, section 159.)

Significant Articles

(articles in reverse chronological order)

Johnson, Michael. "Comment Period Marks the Beginning of Minnesota's Animal Feedlot Rules Update." *Agweek*, June 9, 2025, P. A6.

Vondracek, Christopher. "Driftless-area Dairy Farm Loses Appeal to Add Cows." *The Minnesota Star Tribune*, December 12, 2024, P. A11.

Root, Kaitlyn. "New Feedlot Regs Near." *The Farmer*, November 2024, p. 32.

Vondracek, Christopher. "Stinky Reception for Manure Rules in Minnesota Farm Country." *Star Tribune*, July 26, 2024.

McVan, Madison. "In Winona County, the Tension Between Agriculture and Water Quality Gets Personal." *Minnesota Reformer,* April 30, 2024.

Stevens, Margaret. "Large Dairy Farms Would Face Additional Environmental Scrutiny Under Proposed Bill." *Session Daily*, March 20, 2024.

Vondracek, Christopher and Brooks Johnson. "Minnesota Hog Farmers Shoulder Weight of Adapting to California's Law." *Star Tribune*, January 9, 2024.

Bjorhus, Jennifer and Christopher Vondracek. "State Groups Sue to Pressure EPA to Regulate Feedlots." *Star Tribune*, September 18, 2023.

Marohn, Kirsti. "Digesters Make Renewable Energy from Manure, but Face Hurdles." *MPR News*, September 12, 2023.

Radelat, Ana. "Minnesota Farmers Press Congress to Block California Ban on Pork Produced Through 'Inhumane' Gestation Pens." *MinnPost*, August 31, 2023.

Fish, Noah. "The Changing World of Raising Livestock." *AgWeek*, March 14, 2022.

Bjorhus, Jennifer. "Dairy Farm Expansion Rejected." *Star Tribune*, December 3, 2021.

Orenstein, Walker. "EPA nixes Minnesota Legislature’s bid to relax feedlot regulations." *MinnPost*, September 2, 2021.

Orenstein, Walker. "New Rules for Minnesota's Large Animal Feedlots to be Relaxed Under Compromise Legislation." *MinnPost*, June 24, 2021.

Orenstein, Walker. "Why Republicans at the Minnesota Legislature are Determined to Kill the State's Latest Feedlot Regulations." *MinnPost*, May 11, 2021.

Ramstad, Evan. "Judge Finds Winona County Board of Adjustment was Biased in Denial of Dairy Farm Expansion." *Star Tribune*, December 22, 2020.

Belz, Adam. "Battle Over Southeast Minnesota Dairy Expansion Drags On: The Land Stewardship Project Must Hand Internal Documents to a Judge in the Lewiston Case." *Star Tribune*, October 6, 2020.

Mohr, Paula. "MPCA Proposes New Manure Application Rules." *The Farmer*, June 2020, p. 1.

Bjorhus, Jennifer. "State Rejects In-Depth Study on Greenhouse Gases at Winona County Dairy: State Says Deeper Look at 3,000-Cow Expansion Plan at Dairy Unnecessary." *Star Tribune*, April 29, 2020.

Belz, Adam. "Moratorium on Large Dairies Proposed at Minnesota Legislature." *Star Tribune*, March 12, 2020.

Belz, Adam. "Greenhouse gas readout for dairy expansion near Winona Heightens Scrutiny of Methane." *Star Tribune*, January 23, 2020.

Associated Press. "Court of Appeals Orders State to Reconsider Dairy Expansion." *Minnesota Lawyer*, October 16, 2019.

Bjorhus, Jennifer. "Farmer Drops 'Karst Country' Swine Feedlot Plan: Proposal Drew Opposition in Southeastern Minnesota, Where Many Wells are Contaminated." *Star Tribune*, Februrary 12, 2019.

Phaneuf, Taryn. "Feedlot Dilemma: Local Entities Consider Whether to Set Caps on Size." *MinnPost*, February 6, 2019.

Todd, Brian. "Daley Farm Gets Approval from MPCA for Expansion." *Rochester Post Bulletin*, January 9, 2019.

Dunbar, Elizabeth. "Pollution Agency Denies Permit for Huge Hog Feedlot in SE Minnesota." *MPR News*, December 18, 2018.

Bjorhus, Jennifer. "In Southeastern Minnesota's Karst Country, Feedlot Proposal has Neighbors Riled: Water Worries Prompt Rare Second Hearing for SE. Minn. Hog Farm." *Star Tribune*, November 26, 2018.

Marcotty, Josephine. "Ag Industry Sues State over Public Review of Winona County Megafarm." *Star Tribune*, October 31, 2018.

Marcotty, Josephine. "As Hog Feedlots Grow, Neighbors Ask: What About Our Rights? In Todd County and at Legislature, a Showdown Looms Over Rural Quality of Life." *Star Tribune*, April 17, 2017.

Mohr, Jonathan. "From Home Cooks to Fences and Feedlots, Omnibus Ag Policy Bill Passes House." *Session Daily*, April 5, 2017.

Mohr, Jonathan. "Stink Over Farm Odors Has Some Doing More than Plugging Their Nose." *Session Daily*, February 21, 2017.

Mosedale, Mike. "Raising a Stink: Return of the Feedlot Wars." *Minnesota Lawyer*, August 6, 2015.

Clement, Douglas. "Knee Deep in Feedlot Feuds." *FedGazette*, July 1, 2001.

deFiebre, Conrad. "Audit: MPCA Lags Badly on Feedlots." *Star Tribune*, January 29, 1999.

Lien, Dennis & Egerstrom, Lee. "Feedlot Debate Muddies Future of Proposed Farm/State and Federal Scrutiny Increases with Farms' Scale of Operations" *St. Paul Pioneer Press*, March 8, 1998.

Rigert, Joe & Ison, Chris. "Diluted Enforcement: State Watchdog Lags in Policing Water Polluters." *Star Tribune*, December 13, 1998.

Significant Internet Resources

Animal Feeding Operations Overview – Learn about U.S. Federal Rules and Regulations relating to feedlots from the National Pollutant Discharge Elimination System (NPDES), a division of the U.S. Environmental Protection Agency.

Manure Management - The University of Minnesota Extension Service provides information about storage, air quality, pathogens, treatment, wastewater, and application of manure.

Minnesota Department of Agriculture – Feedlot Information including Feedlot Permitting in Minnesota: A Checklist for Producers, and the Local Ordinances Regulating Livestock in Minnesota.

Minnesota Pollution Control Agency – Feedlots, which includes the option to subscribe to the Agriculture Stewardship newsletter.

Additional Library Resources

For historical information, check the following codes in the Newspaper Clipping File and the Vertical File:
A12.22 (Agriculture - Livestock), A12.45 (Agriculture - Pollution), A12.6 (Agriculture - Corporate Farms)

For additional reports at the Legislative Reference Library, use these Library catalog searches:
Feedlots; Animal Industry; Farm Manure.

Minnesota's Climate Action Framework



MINNESOTA

cc-mn4-01

From the Governor

Climate change is an existential threat for all people in Minnesota. That's why Lieutenant Governor Flanagan and I created the Climate Change Subcabinet and Advisory Council on Climate Change — to seek input from thousands of Minnesotans across the state and help us take action together. Through these partnerships, we can protect the things we love about Minnesota — our clean air and water, our health, our outdoor traditions, and our four seasons.

This Climate Action Framework includes ambitious goals that will harness the power of Minnesota's innovative spirit and small businesses to create thousands of well-paying jobs and develop the next generation of climate-smart technologies.

We can do this together while ensuring that everyone — including neighborhoods that have been historically marginalized — can thrive in Minnesota.

This framework is Minnesota's next step in responding to climate change, but it will not be our last. We will use the Climate Action Framework to work with tribal nations, the legislature, cities, counties, and communities to build ambitious solutions that reflect the urgency of the issue and ensure all Minnesotans benefit. We will not be moving forward alone.

We know this framework will guide us to a cleaner, safer future for all Minnesotans. I invite you to join us in making that future possible.

In solidarity,

Governor Tim Walz



ACKNOWLEDGEMENTS

The Climate Change Subcabinet is grateful to the 11 tribal sovereign nations in the state of Minnesota and their respective staff and to the Governor's Advisory Council on Climate Change for their review and input on the framework.

Thanks also to the thousands of Minnesotans who participated in the process by writing comments and participating in surveys to share what is most important to them.

The subcabinet also thanks the members of six working groups for their important contributions to each goal chapter. Teams of staff and leadership from each of the 15 subcabinet agencies wrote this framework based on their expertise and the critical input from Minnesotans. Working group members and agency staff are listed at the end of the framework.

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Supporting documents

- Summary of climate actions
- Greenhouse gas analysis
- Summary of input
- Acronyms and glossary

These are available at **mn.gov/framework**

The climate vision for our state

The vision for our state embodied in this framework is:



Carbon-neutral

By 2050, Minnesota substantially reduces greenhouse gas (GHG) emissions and balances any GHG emissions with carbon storage, especially in our landscapes.



Resilient

Minnesota communities, businesses, and the natural environment can prepare, respond to, and recover from the impacts of climate change so all Minnesotans can thrive in the face of these challenges.



Equitable

Minnesotans acknowledge and address inequitable and inaccessible systems that contribute to some communities experiencing disproportionate climate change impacts; ensure fair distribution of the costs and benefits of action now and to future generations; and ensure meaningful participation in planning.

To get there, we all have a role to play.
This Climate Action Framework outlines priorities and next steps to help Minnesota achieve this vision. The framework also invites you, your organization, and your community to join us to achieve a shared vision.

Executive summary

Climate change is happening now, and we are on course for more frequent, widespread, and intense weather events with cascading and complex effects. Communities, businesses, and individuals across Minnesota are acting to reduce our climate-changing pollution and build resilience against future changes. However, there is more work to do.

We must act now. The international body that assesses the science of climate change, called the Intergovernmental Panel on Climate Change (IPCC), issued "a code red for humanity" last year, saying that urgent action is required if we are to ward off the worst consequences of a warming climate and keep global temperature increases below 1.5 degrees Celsius (about 2.7 degrees Fahrenheit). Scientists warn that exceeding this temperature increase will result in long-lasting, irreversible changes and make parts of the planet uninhabitable. In addition, once we exceed those temperature thresholds, opportunities for successful adaptation rapidly diminish.

A guide for the years ahead. The Climate Action Framework sets a vision for how Minnesota will address and prepare for climate change. It identifies immediate, near-term actions we must take to achieve our long-term vision of a carbon-neutral, resilient, and equitable future for our state. The framework is a foundational document designed to broadly guide the direction of climate action in the state for many years.

Many people and groups weighed in. The Climate Change Subcabinet is publishing this framework to advance our conversation with Minnesotans on the work we all must do to reduce greenhouse gas emissions and build resilient communities across our state. The framework is informed by public input received as a part of previous climate work, as well as specific input received throughout the framework development process beginning in 2021. The document was shaped by input from the 11 tribal nations who share Minnesota's geography and the Governor's Advisory Council on Climate Change. Through the winter and spring of 2022, the subcabinet convened workgroups to provide detailed input on each of the framework chapters. The subcabinet also shared its proposals broadly and received more than 130 written comments and nearly 3,000 responses to online surveys. (See Appendix 3 for more information.) All this input contributed to the final document.



The framework is organized around six goals

1. **Clean transportation:** Connect and serve all people through a safe, equitable, and sustainable transportation system.
2. **Climate-smart natural and working lands:** Enhance climate benefits by absorbing and storing carbon, reducing emissions, and sustaining resilient landscapes.
3. **Resilient communities:** Provide each Minnesota community with tools to plan for and become resilient to its unique climate impacts.
4. **Clean energy and efficient buildings:** Expand the use of carbon-free energy and create healthy, comfortable buildings that are cheaper to operate and pollute less.
5. **Healthy lives and communities:** Protect the health and wellbeing of all Minnesotans in the face of climate change.
6. **Clean economy:** Build a thriving carbon-neutral economy that produces goods and services with environmental benefit and equitably provides family-sustaining job opportunities.

Within each goal

- **A summary** of the challenges
- **Priority actions** and larger initiatives needed to achieve the goal
- **Measures** to help gauge our progress
- **Equity considerations** and opportunities for addressing them

Moving forward, the subcabinet will continue to seek input, report on our progress, and revisit and refine action steps as we implement the framework. Next steps include identifying lead agencies and setting priorities for the action steps in Appendix 1 and seeking authorities and funding as needed.



Interconnected goals and collaboration

The framework goals are interconnected: Work in one area of our lives may create opportunities — or challenges — in another. We must collaborate across sectors to ensure that all outcomes are considered.

What effect will electric vehicles have on demand for renewable energy? If we adopt newer, less polluting technologies, how do we manage the waste from the old technologies? Are the newer technologies being manufactured sustainably or are they creating new environmental challenges?

We need a diversity of people and perspectives to ensure thoughtful and effective action. By working together we can address trade-offs and build solutions that work for all Minnesotans.

Goals and their related initiatives

Clean transportation	**Connected communities:** Maintain and improve multimodal transportation connections to reduce emissions and congestion.
	Clean and efficient vehicles: Accelerate the transition to electric vehicles, alternative fuels, and greater fuel efficiency.
Climate-smart natural and working lands	**Carbon sequestration and storage in forested lands, grasslands, and wetlands:** Manage forests, grasslands and wetlands for increased carbon sequestration and storage.
	Resilient landscapes and ecosystems: Enhance the ability of plants and animals, including crops, to adapt to the effects of climate change.
	Healthy farmland: Accelerate soil health and nitrogen and manure management practices that reduce emissions and enhance carbon storage, water quality, and habitat.
	Sustainable landscapes and water management: Reduce GHGs and improve landscape resiliency through multipurpose water storage and management practices that protect farmland, water supplies, and infrastructure.
	Investments in emerging crops, products, and local economies: Support emerging agricultural and forest technologies and products that reduce waste, create jobs, and expand economic opportunities.
Resilient communities	**Climate-smart communities:** Build the capacity of Minnesota communities to protect against and withstand the effects of climate change.
	Healthy community green spaces and water resources: Expand and protect tree canopies; parks and other green spaces; and lakes, rivers, and wetlands that provide community resilience benefits.
	Resilient buildings, infrastructure, and business: Help the built environment and local economies become more resilient to climate change.
Clean energy and efficient buildings	**Clean energy:** Transition to 100% carbon-free, reliable, and affordable electrical power and heat through policies, investments, and partnerships.
	Smarter buildings and construction: Reduce GHG emissions in the building sector by promoting conservation, efficiency, and lower-carbon design, materials, and fuels.
Healthy lives and communities	**Healthy communities:** Protect communities from the direct and indirect health effects of climate change.
	Climate-smart public health and healthcare systems: Bolster public health resources and promote strategies to reduce GHGs from health care facilities.
Clean economy	**Business innovation and entrepreneurship:** Invest in research and development, innovation, and partnerships.
	Equitable access to jobs and a just transition: Support workers to adapt and evolve their skills through inclusive strategies, ensuring family-sustaining jobs.

Minnesota is changing

Minnesota's climate has changed and will continue to change, affecting the health and economy of our communities. Frequent and intense storms — now occurring more often than at any time on record — are damaging homes, businesses, infrastructure, farms, and natural resources, and the trend is projected to continue. Record-breaking floods, like those in Duluth in 2012 and Faribault in 2010 and 2016, have damaged streets, wastewater facilities, businesses, and homes, costing local governments, business owners, and residents millions of dollars in cleanup and repairs.

Huge wildfires in Canada and the western U.S., brought on by changing conditions, have caused unhealthy air quality in our state. Minnesota lakes have lost an average of 10 to 14 days of ice cover in the past 50 years, affecting lake and fish health, outdoor recreation opportunities, and business owners. Climate change effects are harming wildlife habitat, like those of trout and walleye. Beloved northern tree species such as spruce, aspen, black ash, and birch are expected to decline. Minnesota's state grain, wild rice (manoomin, psíŋ), and the habitats it supports are also affected. In addition, our health is threatened by more floods, longer allergy seasons, warmer temperatures, and expanded tick ranges.

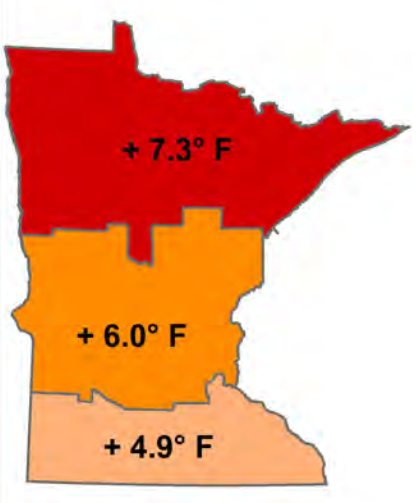

Minnesota is getting warmer, especially winter nights in the northern parts of the state.

Change in daily average minimum temperature during winter (Dec-Feb), 1895-2021.

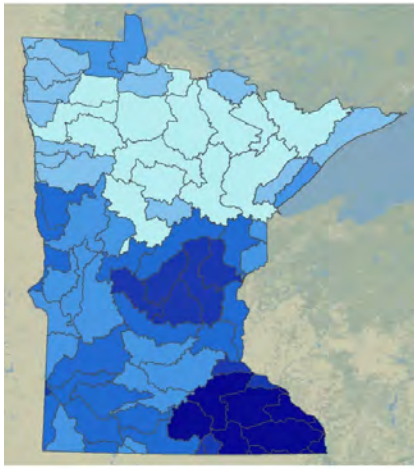

Minnesota is getting wetter, especially the southern parts of the state.



Annual precipitation change by watershed for 2000-2019, compared to 20th century averages.

Leading with action

We can build climate solutions that work for Minnesota.

The Climate Action Framework identifies immediate actions to help both avoid the worst impacts of climate change and become resilient to the changes ahead. To reduce the severity of future climate-change impacts, we must reduce GHG emissions in every sector of our economy by:

- Accelerating our transition to clean energy
- Improving energy efficiency and using clean energy in buildings and industrial processes
- Developing more efficient modes of transportation and producing cleaner fuels
- Reducing emissions from activities on natural and working lands
- Building carbon storage in forests and soils

Technological tools, such as electric vehicles, wind and solar energy, and better battery storage, are helping us limit climate change, while creating jobs and boosting the economy. But technology alone won't solve our climate change challenges. We also need smart planning and new ways of working and collaborating. Investments in job training, grants to organizations to build expertise, and peer-to-peer learning among businesses are just some examples of how we build skills and create opportunities across the state. We also need to support communities planning for and implementing new technologies, so they are prepared to capitalize on innovations.



Partners across Minnesota are already leading with action. Local and tribal governments are prioritizing climate adaptation planning, expanding urban and community forests, and transitioning to clean energy. Our utilities are taking bold steps to phase out coal plants and increase investments in renewable energy. Large and small businesses have committed to reducing their emissions and developing the technology that will help others worldwide reduce their emissions.

Climate change affects everyone, but some are hit harder.

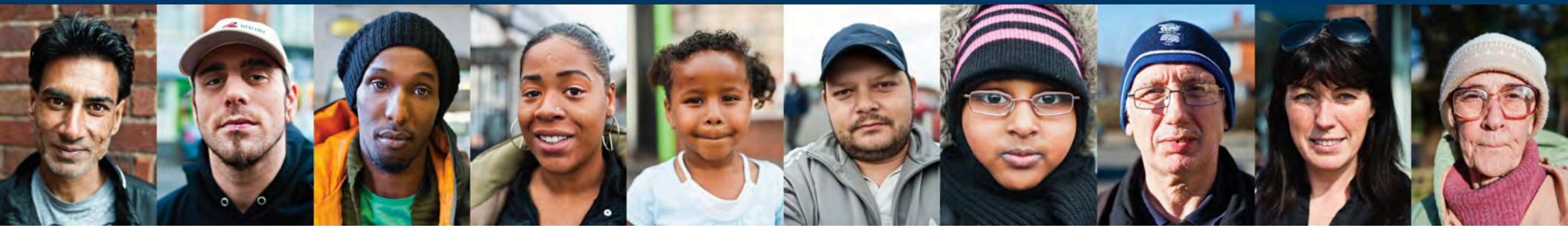

Let's acknowledge: Some people carry a bigger burden.

People at higher risk from climate change due to social, economic, historical, and political factors have less ability to prepare for, cope with, and recover from climate change impacts. Groups at greater risk from the effects of climate change include:

- People of color
- Indigenous people and tribal nations
- Older adults and children
- People with disabilities and chronic illnesses
- People in rural areas
- People without housing
- People who are socially and economically disadvantaged
- Pregnant people
- People who are incarcerated
- Future generations

For instance, people with lower incomes; Black, Indigenous, and people of color; and tribal nations are exposed to higher levels of pollution due to ongoing structural racism and inequitable policies and decision-making processes. Conversely, some Minnesotans will benefit from economic opportunities related to climate change and have greater access to climate-change decision-making. Addressing these inequities and understanding the experiences of high-risk communities is essential to making Minnesota more resilient and prosperous.

Inequalities & climate change



Unequal exposure to pollution: Black, Indigenous, people of color, and residents with low incomes are more likely to live near industrial sites and highways, with elevated exposure to air pollution that increases their vulnerability to climate-related health impacts. Children, older adults, and people with underlying health conditions may also see poor health outcomes from degraded air quality, excessive heat, increased pollen, and wildfire smoke.

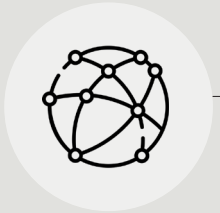

Technology deficits: Rural communities may lack access to broadband and other technologies, impeding their full participation in the economy, education, and decision-making.



Barriers to energy-efficient housing and improvements: Long-term discrimination against Minnesotans of color in home buying has limited their access to money-saving home weatherization programs and energy-efficiency upgrades. Rental property owners have little incentive to invest in these upgrades that benefit tenants.



Uncertain access to resources: Climate change threatens many of the natural resources and landscapes that Indigenous communities, recent immigrant groups, and others depend on for subsistence foods and deep cultural connections.



Higher costs: Higher home energy bills during very hot summers disproportionately affect people with low incomes.

Working together to meet global goals

Along with many other states and countries, Minnesota will work to meet the Intergovernmental Panel on Climate Change (IPCC) greenhouse gas reduction goals. This includes:

- Reducing GHG emissions by 50% by 2030
- Achieving net-zero emissions by 2050

The IPCC also recognizes that climate adaptation reduces risk, enhances resilience, and provides co-benefits. The next 10 years is the most effective timespan to get this done. Once temperatures escalate over 1.5 degrees Celsius, opportunities for successful adaptation rapidly diminish.

These global goals are ambitious. Meeting them will require Minnesota to increase efforts to better understand current conditions, improve data on GHG emissions and storage, implement the Framework's action steps, and identify new approaches, technologies, and partnerships. The framework lays the foundation to meet these targets, but will not get Minnesota all the way there. To achieve these reductions, we will need the efforts of federal, tribal, state, and local governments, businesses, nonprofits, and individuals all working together to rapidly cut climate pollution.



The opportunity

Acting to prevent and prepare for climate change is a chance to make Minnesota a better place to live for all. It is a once-in-a-generation opportunity to create new jobs for Minnesotans, support innovation, and protect our health and environment.

We have already seen our state economy grow while decreasing GHG emissions. We know that investing in clean energy and a sustainable future will help Minnesota continue to grow and become more resilient and equitable for all Minnesotans. Climate action can help create well-paying jobs and save consumers, businesses, and taxpayers money.

- **Weatherizing homes and buildings** will employ workers, reduce energy use, and lower Minnesotans' energy costs.
- **Increasing wind production** could lower property taxes and provide additional revenue for rural Minnesota counties.
- Installing and maintaining thousands of new **electric vehicle charging stations** will bring more jobs to communities across Minnesota.
- **Expanding our forests and urban tree canopy** to reduce the impacts of rising temperatures will require the expertise of foresters.

The farms, forests, grasslands, and wetlands that stretch across our state are natural parts of our climate solutions. Expanding sustainability initiatives, voluntary action incentives, and emerging





markets provide opportunities to strengthen rural economies, build climate resilience, deliver ecosystem benefits, protect water quality, improve soil health, and help our farmers and forest landowners continue to meet the demand for food and natural resources. We can't meet our goals without climate-smart land management practices. Storing more carbon in both natural and working lands can help us slow the carbon buildup in our atmosphere.

There will be many jobs in sectors commonly considered part of the growing clean economy, such as electric vehicles, energy efficiency, and sustainability, and expanded job opportunities in more traditional areas of Minnesota's economy, such as agriculture, forest products, manufacturing, natural resource management, and construction. Across these sectors, workers will be needed to develop new products, implement new land management practices, grow and maintain trees, improve our heating and cooling systems, retrofit our existing buildings, engineer interconnected alternative energy systems and efficiency improvements, upgrade our electricity transmission grid, and more.

Acting on climate change is also an opportunity to protect our environment and improve our health. Preserving and growing our forestland will store carbon and improve access to the outdoors for all Minnesotans. Reducing pollution from our cars can help reduce asthma rates and other illnesses. Building local food systems will decrease the climate impact of making meals while providing healthier food options for our communities.

Integrating policies across all levels of government, coordinating public and private efforts, and including people across diverse communities will amplify the impact of our actions. Making progress towards our carbon-neutral, resilient, and equitable future is critical and depends on everyone making choices that meet our economic goals while reducing emissions and prioritizing risk reduction.

More benefits of climate action

- Reducing the number of fossil-fuel vehicles on the road will have an immediate impact on air quality, especially in urban areas.
- Incentivizing regenerative agricultural helps farmers meet consumer demands and protects water quality.
- Growing native plants and shade trees reduces heat islands and improves air quality.
- Developing our clean economy, especially in underserved communities, helps bridge long-standing wealth gaps.



Minnesota today

Reclaiming our role as climate leaders.

In 2007, Minnesota was a national leader in climate action with the adoption of the bipartisan Next Generation Energy Act, setting statutory goals to reduce GHG emissions by 15% from 2005 levels by 2015, 30% by 2025, and 80% by 2050. Minnesota missed its goal in 2015 and is not on track to meet future goals. Since 2005, overall GHG emissions have declined by just 8%.

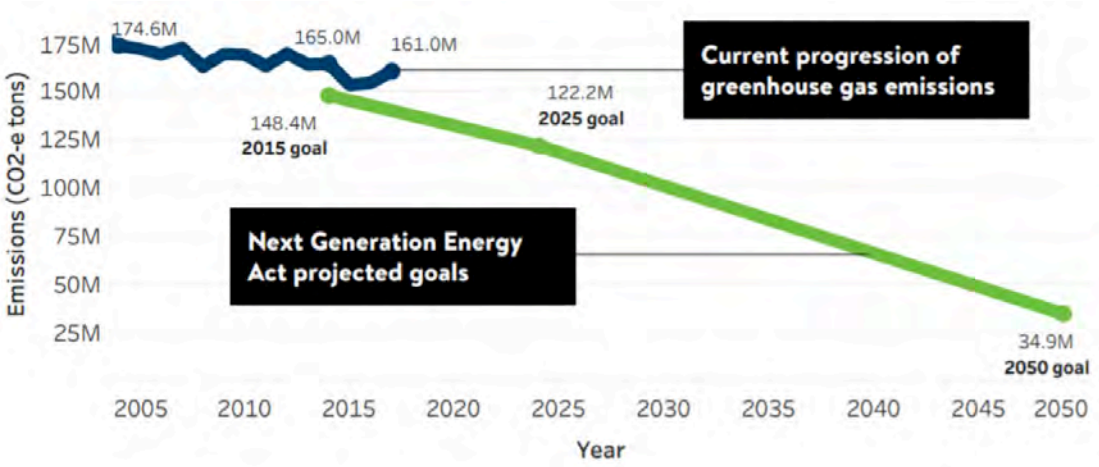

In Minnesota, the largest sources of GHG emissions are transportation, electricity generation, and agriculture. While Minnesota has made important progress towards these goals in some sectors, we must do more to achieve our Next Generation Energy Act goals and reduce our contribution to global climate change.

The Next Generation Energy Act also launched Minnesota's efforts to track and analyze GHG emissions across all parts of our economy. Understanding emissions sources and trends helps the state identify priorities and challenges in reducing GHGs.

Minnesota was once a leader on climate solutions, and by taking the actions included in this framework, we will be again.

Each sector has its own challenges and opportunities for reducing emissions, and each is at a very different place in planning and implementing strategies. Electricity producers have made important progress towards the Next Generation Energy Act goals. In contrast, other sectors are just now beginning to understand and implement opportunities for reductions.

20 years of climate action in Minnesota

Minnesota has a strong foundation for climate action, and now is the time for our state to accelerate our work.

- **2003:** Minnesota Climate Change Action Plan: A Framework for Climate Action published.
- **2007:** Next Generation Energy Act created GHG emission reduction goals for the state.
- **2008:** Minnesota Climate Change Advisory Group publishes its final report recommending a comprehensive set of state-level climate policies.
- **2016:** Climate Solutions and Economic Opportunity report identifies near-term emission reduction opportunities between 2016 and 2030.
- **2017:** Adapting to Climate Change in Minnesota 2017 report identifies efforts by Minnesota state agencies to address climate change impacts. Minnesota hosts the National Adaptation Forum biennial conference.
- **2019:** Climate Change Subcabinet and Governor's Advisory Council on Climate Change established. Governor Walz directs state agencies to engage communities and identify policies to reduce emissions and build resiliency. In addition, Executive Order 19-27 affirmed the State of Minnesota's goals to reduce greenhouse gas emissions, waste, energy and fuel consumption, water usage, and the sustainable procurement of goods and services in government operations.
- **2021:** Legislature passes the ECO Act, a critical update to Minnesota's Conservation Improvement Program, creating additional energy efficiency opportunities. Legislature also funds climate adaptation planning grants for local stormwater, wastewater, and other community-focused resilience projects.
- **2021:** Clean Cars Minnesota rule adopted, preserving access for Minnesotans to the cleanest, most efficient vehicles and increasing access to EVs.

What's next

The framework will continue to accelerate climate action in Minnesota. The conversations and collaboration in developing the framework have helped identify key priorities and critical next steps in Minnesota's climate work.

The framework will guide the state agencies' priorities in the coming years. From the actions identified in the document, we will develop legislative proposals for new policies, programs, and grants. We will identify new data and analyses that must be developed and more conversations we need to have with Minnesotans.

The following are some of the initial priorities for action from the state agencies as we begin implementing the framework.

Building momentum

The Climate Change Subcabinet is charged with ensuring meaningful public engagement, collaboration, and involvement in policy and strategy development and implementation. To build momentum for climate action, we need all Minnesotans to be informed, invested, and involved in the effort. Together, we must:

- Foster a better understanding of climate change and its effects, and develop skills for addressing it
- Harness the potential economic, environmental, and social benefits that come from taking climate action
- Seek climate solutions informed by the creativity and knowledge of people of all ages and walks of life

To get there, we need to:

- Build capacity at the state, local, and individual levels for climate action through education and training opportunities
- Raise public awareness about the urgency of climate change and ways to respond
- Provide access to information and resources
- Ensure consistent and meaningful opportunities for participation in decision-making and implementation especially for communities who are often left out of decisions that impact them
- Strengthen opportunities for partnerships and knowledge exchange to maximize our impact
- Ensure information, opportunities for participation and decision-making, resources, and training are equitably distributed and actively include disproportionately impacted communities

The good news is that these efforts can be great or small. They can happen at the State Capitol, city halls, boardrooms, or at the dinner table. Building momentum for climate action will require a diversity of skills, where everyone has something to contribute.

Moving forward, the state agencies will continue to engage Minnesotans to drive progress on the framework as well as look for ways to deepen and improve engagement and partnerships to ensure that climate action in Minnesota is collaborative, equitable, and effective.

Measuring progress

Achieving our vision will require that we track and report on our progress. The state agencies have identified key progress indicators with measurable targets associated with each goal chapter that will help us understand in real time whether our efforts are making a difference.

We will also report on the outcomes of our proposed action. Which actions are being implemented and what progress is being made? What results did we achieve?

As part of its annual update required under Executive Order 19-37, the subcabinet will report progress on implementing the framework to inform our action planning, demonstrate success, and identify areas that need greater investment and leadership. As we tackle the complexities of mitigating and adapting to climate change, we will continue to develop the data and information streams that best describe the work.

Guiding action

The framework is a foundational document designed to broadly guide the direction of climate action in the state for many years to come. The The state agencies will use the Framework to prioritize legislative proposals, administrative actions, and engagement efforts to advance our climate goals. We will use our measures of progress as well as public input to guide action planning.

As the subcabinet identifies priorities and state agencies begin implementation of the Framework, we will weigh critical elements of our climate effort, including:

Impact: We will use analysis and the best science to identify actions with substantial GHG reduction potential and that address the greatest resiliency needs.

Equity: We will review policies and strategies with an equity lens, seek input and collaboration from disproportionately impacted communities, and prioritize actions with the greatest opportunity for improving equity.

Economy: We will seek opportunities to grow our clean economy, support a just transition for workers and communities impacted by this transition, and expand well-paying jobs.

Health and environment: We will prioritize actions that address climate change while also reducing other harmful pollutants that damage our environment and our health.

How the state agencies will approach our work

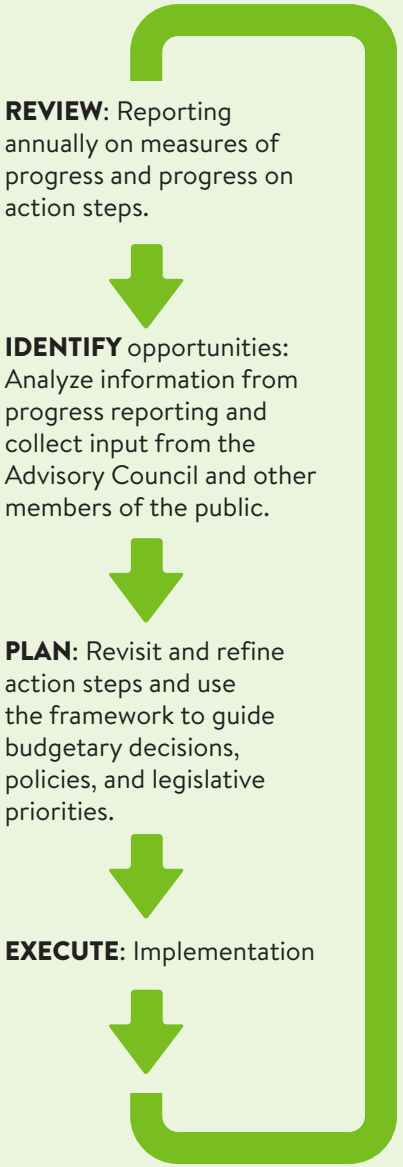

Ongoing priorities

The subcabinet has been leading on climate action over the past several years by advancing policy and budget priorities in the Legislature and integrating climate action into the operations of state government. These priorities will continue in the upcoming year and beyond:

Carbon-free electricity by 2040: It is an ongoing priority for Walz-Flanagan Administration to achieve 100% carbon-free electricity and 55% renewable electricity by 2040.

Stormwater management: The state agencies, led by the Pollution Control Agency (MPCA), will continue to prioritize support for local governments and tribal nations as they adapt to major rainfall events by providing funding for stormwater planning and infrastructure investments.

Electric vehicle adoption: The MPCA and Department of Transportation (MnDOT) will continue to help expand EV adoption through grants to electrify heavy- and medium-duty vehicles and equipment, installation of EV charging infrastructure, and implementation of the Clean Cars Minnesota rule.

Enterprise sustainability: The state agencies lead by example and aim to reduce GHG emissions by 30% by 2025 from a 2005 baseline. Priorities include purchasing EVs, installing solar on state properties, and improving energy efficiency of state buildings.

Transportation options: MnDOT will finalize and implement the Statewide Multimodal Transportation Plan to expand options for Minnesotans to bike, walk, roll, and take transit.

Sustainable land management: Continue to manage state-owned lands and provide technical and financial assistance to other landowners to promote sustainable land management practices, which enhance climate mitigation and resiliency while providing additional benefits.

Foundational steps

There are key areas where the subcabinet agencies will work to further their understanding of the current baseline, opportunities for action, and potential costs and benefits of action. Improving our understanding in these areas will provide critical foundational understanding for future action. The following are priorities for further exploration:

Natural and working lands data: The MPCA, Department of Natural Resources (DNR), Department of Agriculture (MDA), and the Board of Water and Soil Resources (BWSR) will work to refine and standardize methodologies for tracking GHG emissions and carbon sequestration and storage on our landscapes. This is an emerging field of understanding and Minnesota has an opportunity to be a leader.

Measures of resiliency: The state, with leadership from the MPCA, DNR, and the University of Minnesota Climate Adaptation Partnership, is working to further develop metrics to measure success of adaptation and resiliency strategies, which will help the state and local communities understand the impacts of adaptation actions and guide future implementation.

Setting goals for our landscapes: In collaboration with partners and stakeholders, the DNR, BWSR, MDA, and other state agencies must establish landscape-level goals for strategic restoration and management of our forests, grasslands, wetlands, and peatlands to maximize benefits to the climate, our environment, and our economy. Working with tribes, local governments, landowners, and others will be a critical part of setting goals.

Leveraging federal action

The federal government has recently adopted major climate-related statutes, namely the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act. These critical climate actions direct substantial new funds towards both reducing GHG emissions and adapting to our changing climate. These new investments are in addition to existing federal funding — such as Farm Bill programs, Pittman-Robertson Act funding, and the Land and Water Conservation Fund – that support conservation activities with multiple climate benefits. The subcabinet will use the framework to guide us as we develop plans and direct funds from the federal government. Some of the major federal policy and funding activities occurring in the near term include:

National Electric Vehicle Infrastructure Program (IIJA): MnDOT developed and will begin implementing a plan that will direct $68 million of federal funds over the next five years to develop a long-distance EV fast charging network across the state.

Transportation resiliency and emissions (IIJA): MnDOT will be developing plans for the Carbon Reduction Program and the Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation Program to increase resiliency and reduce emissions from transportation, especially through multimodal transportation options.

Community forestry (IIJA): The federal government is providing increased funding to the DNR to expand community tree canopy, as well as partner training and engagement.

Advancing critical policy and programs

The state agencies continue to enhance existing policies and programs, as well as explore, analyze, and engage on possible new policies and programs. Some of these critical state actions include:

Sustainability in affordable housing: Minnesota Housing will enhance the Qualified Allocation Plan and existing sustainability standards for buildings the agency finances to improve energy efficiency and access to renewables, while reducing utility bills for residents and providing a healthier place to live.

Building codes: The Department of Labor and Industry is conducting a rulemaking process to adopt the most current building codes for commercial and large multi-family residential dwellings, which will improve the energy efficiency of these buildings.

Soil health: MDA and BWSR are increasing technical and equipment assistance to farmers to implement practices that improve soil health and support a healthy climate.

Support emerging farmers: MDA will explore opportunities to expand and strengthen existing programs that support access to suitable farmland for emerging farmers.

Assistance to local and tribal governments: The MPCA plans to increase opportunities to develop and share resiliency and adaptation strategies, as well as best practices and expand community capacity through programs such as GreenStep Cities and Minnesota GreenCorps.

Clean fuels standard: The subcabinet, with leadership from MnDOT and MDA, continues to analyze and discuss with stakeholders the opportunities and challenges of possibly adopting a clean fuels standard to support the use of cleaner transportation fuels.

Next generation highways: MnDOT will explore the opportunities and challenges of possibly locating transmission lines in highway right of ways to efficiently expand the transmission of clean energy.

The important role and leadership of Minnesota tribal nations



Mni Sota Maḳoce

Minnesota comes from the Daḳota name for this region, Mni Sota Maḳoce — "the land where the waters reflect the clouds."

The Daḳota and Anishinaabe, whose cultural, spiritual, and economic practices are intrinsically woven into this landscape, hold this land sacred. The relationship that the Anishinaabe and Daḳota people have with the natural environment is interwoven in cultural identity and traditional practices. The State of Minnesota recognizes tribal nations as original stewards of this land and all the relatives within it, who had thriving and vibrant communities prior to European settlement.

A shared climate fate

Today, the State of Minnesota shares geography with 11 tribal nations: Bois Forte Band of Chippewa, Fond du Lac Band of Lake Superior Chippewa, Grand Portage Band of Lake Superior Chippewa, Leech Lake Band of Ojibwe, Lower Sioux Indian Community, Mille Lacs Band of Ojibwe, Prairie Island Indian Community, Red Lake Band of Chippewa, Shakopee Mdewakanton Sioux Community, Upper Sioux Community, and the White Earth Nation. In addition, the Ho-Chunk, Cheyenne, Oto, Iowa, Hidatsa, Arikara, A'aninin, Cree, Blackfeet, Assiniboine, and the Sac and Fox Tribes all also acknowledge Minnesota as important to their tribal histories. The State recognizes and respects tribal sovereignty and holds itself accountable to counter the historical and contemporary injustices that continue to impact Indigenous people.

Due to shared geography, history, and people, the climate fate of the State of Minnesota and tribal nations are deeply intertwined. Treaties are nation-to-nation agreements among sovereign entities — political groups with the ability to set rules for their own communities, determine their own membership, care for their own territory, and enter agreements with other sovereign entities. Dakota and Anishinaabe are inherently sovereign as Indigenous people of this land; sovereignty isn't given, nor can it be taken away. As sovereign governments, tribal nations have a unique relationship with the State of Minnesota and each tribal nation in Minnesota has their own individual priorities, practices, and histories. The State recognizes and respects the need to consult and coordinate with each individual tribal nation on climate actions.

Honoring our responsibility

Tribal nations and their communities cannot remove themselves from their homeland and move to another location due to impacts from climate change. Most of the land in what is now Minnesota was ceded by the Anishinaabe and Dakota people to the United States through treaties that allowed the United States to remove Indigenous people from their original homelands and move them to smaller land bases. These land bases are federally and state recognized to this day, but the connection that Anishinaabe and Dakota people have to their original homelands remains. As part of these treaties, the Anishinaabe and Dakota people reserved rights to hunt, fish, and harvest from ceded lands and waters. The ability to exercise those treaty rights depends on clean water, air, and healthy ecosystems. The State of Minnesota must uphold treaty responsibilities in all State decisions, public processes, and policies by protecting the land, native foods, and the cultural heritage of Indigenous Minnesotans, including from the ravages of climate change.

Indigenous knowledge about the interconnectedness of place, subsistence lifeways, and the natural world has been passed on for generations. In Anishinaabe and Dakota knowledge systems, the earth is sacred and all living beings — plants, animals, land, and water — are relatives and ancestors. Actions and decisions made by tribal nations are based on this holistic knowledge and also consider potential impacts to the next seven generations. The interconnectedness that tribal nations have with everything that surrounds them and the related teachings passed down from generation to generation, can be found in the principles of science, sustainability, resiliency, resource protection, and environmental health. The state respects and acknowledges these principles from Indigenous knowledge and will work with tribal nations on how to apply this knowledge to address climate change.

Consultation and collaboration

State policies have impacts on tribal nations and their members living within and outside of reservation and community boundaries. The State of Minnesota is committed to working with tribal governments both though formal consultation between government leaders and informal coordination and collaboration. Consultation is required by Minnesota Statutes 10.65, Government-to-Government Relationship with tribal governments, and informal coordination between tribal and state government staff is founded on those same principles.

Climate change policies have the potential to impact tribal nations, and timely and meaningful consultation at the beginning of policy or program development, along with ongoing collaboration, establishes mutually beneficial outcomes. State and tribal governments both develop, review, and implement their own policies, programs, rules, and laws related to climate change with their jurisdiction. Consultation helps improve interactions across these interconnected regulatory structures.

Supporting tribal priorities

Each tribal nation has its own climate, environmental, health, and economic priorities. Often these priorities may be shared with the state government and are an opportunity to collaborate. In addition, as the State prioritizes its climate actions, it can elevate those that align with the priorities of tribal nations.

Tribal governments also often pursue environmental, energy, housing, and other policy priorities that reduce emissions and build resiliency, even when climate change may not be the primary purpose of the policy. Some tribal environmental, energy, housing, or other policy priorities may not be pursued explicitly to address climate change, but contribute to reducing emissions and building resiliency. Supporting tribal-led efforts across all sectors including energy, waste management, air quality, forestry, wildlife, carbon sequestration, fisheries, and others contributes to mitigating impacts of climate change and benefits all residents of Minnesota.

Through coordination meetings with tribal environmental staff, review of tribal climate assessments and plans, and formal tribal comments on the framework and other of State actions, the State recognizesseveral priorities of many tribal nations where there are particular opportunities for collaboration:

Water quality is a shared priority of all tribal nations. Water supports and connects all life, including culturally significant wild rice, aquatic species, and others that support subsistence lifeways.

Ensuring affordable housing and renewable energy access for all tribal communities and members.

Protecting and restoring native ecosystems and important habitats and species where they are threatened, degraded, or have been lost due to climate change.

Funding is necessary for both the state and tribes to minimize the impacts of climate change. The state and tribes have the opportunity to collaborate and support each other in pursuit of funding. In addition, when the state creates a grant opportunity, it will work to ensure tribal governments are eligible to apply, and that the requirements for reporting, matching funds, and eligibility consider Tribal needs and constraints.

Collaborative data gathering, analyzing, and sharing can improve outcomes for both state and tribal governments. The state also recognizes the importance of tribal data sovereignty, protection, and respectful data collection processes which will be determined in consultation with each respective tribal nation.

Memorandums of agreement are an important tool to formalize collaboration between state and tribal governments that recognize and respect tribal sovereignty.

The state recognizes the value of the time and energy that tribal nations and their respective tribal staff spend working on climate change strategies. The state will continue to share information with tribal nations early and often regarding climate actions and will continue to strive for just and equitable outcomes while recognizing and respecting tribes' sovereign status. Climate change directly impacts tribal nations and communities, their members, and their lifeways. As the State of Minnesota works toward solutions to limit the impacts of climate change, these solutions must include the knowledge and voices of tribal nations.

Clean transportation

Connect and serve all people through a safe, equitable, and sustainable transportation system



SHORT FORM

The challenges Transportation is the number one source of greenhouse gases in Minnesota. Land use patterns and unsafe, inconvenient, and unaffordable alternatives to driving alone make car travel the first choice for many. Most cars are powered by fossil fuels and produce health-harming air pollution with disproportionate effects on communities close to traffic corridors. Climate change impacts are also damaging transportation infrastructure.

The vision Minnesota's transportation system is sustainable, resilient to a changing climate, and supports equitable transportation options for all Minnesotans. Air pollution is reduced, especially in communities most affected by it. Walking, biking, rolling, and transit options are accessible, safe, and plentiful.

Priority actions

Increase funding for non-motorized transportation. Direct resources towards a statewide pedestrian and bicycle network.

Increase transit services. Create more reliable and convenient transit networks, prioritize services in communities where transit is essential and residents are disproportionately affected by air pollution.

Plan land use and transportation together. Prioritize land use that facilitates multimodal transportation options.

Priority actions

Continue exploring opportunities for a clean fuels standard. Incentivize investment and create markets for cleaner fuels, such as advanced biofuels, renewable natural gas, sustainable aviation fuels, and electricity.

Expand regional charging. Coordinate with neighboring states, tribes, and other partners to establish a Midwest regional EV charging network.

Develop a Minnesota EV plan. Create a strategy to increase EV-charging infrastructure and EV access and availability. Educate communities about the benefits of EVs.

Measures of progress



Reduce GHG emissions from the transportation sector 80% by 2040.



Decrease vehicle miles traveled 20% per capita by 2050.*

*This target was proposed as part of the Statewide Multimodal Transportation Plan and will be finalized after public input on that plan.



Reach 20% EVs on Minnesota roads by 2030.

CONTEXT

The largest sector

The transportation sector is the largest source of GHGs in Minnesota, accounting for about a quarter of total emissions. GHG emissions from transportation have decreased by about seven percent since 2005, but have leveled off since 2016.

Within transportation, more than 70% of emissions come from passenger vehicles. More stringent tailpipe emissions standards helped lower vehicle GHG emissions, but consumers increasingly own larger vehicles and drive them more miles, hampering emission-reduction efforts.

Transportation sector 2018
by source of GHGs

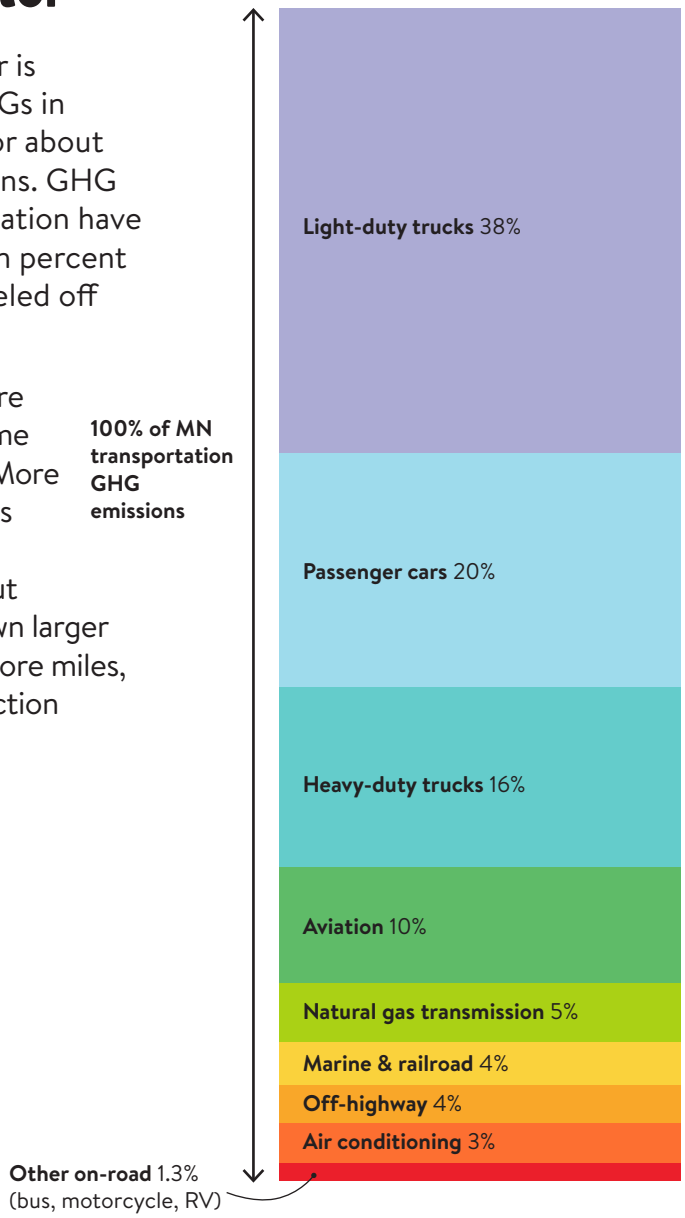

Multimodal transportation options

Supporting different modes of transportation, like walking, biking, and transit, as well as access to high-quality broadband can reduce emissions. Increased access to diverse types of transportation facilities and networks supports those who rely on driving alternatives due to disability, age, economics, or personal preference. We can add new and complete existing walking, biking, and transit networks in our state.

Electric vehicles

Replacing vehicles with electric versions will reduce carbon pollution. EV sales will increase as more manufacturers transition to producing only EVs. Minnesota has more than 1,300 EV chargers, but more are needed for a fast and reliable charging network that supports EV users in all parts of the state. We must also explore ways to power EVs with clean energy and recycle EV batteries, to further reduce their impact on the environment.

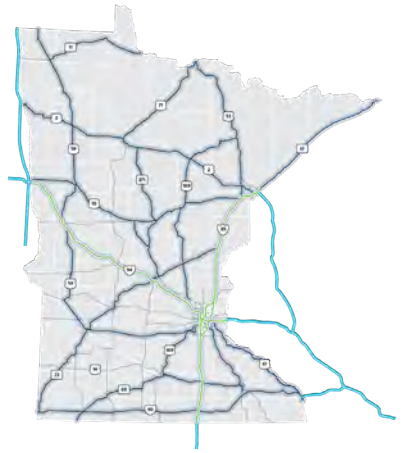

Minnesota is building out a network of EV fast chargers along highway corridors.

WHAT WE WILL DO TOGETHER

Make a cleaner, low-carbon transportation future
Minnesota's future transportation system will be safer, cleaner, and more comfortable, affordable, and convenient for all users, whether they drive, bike, walk, roll, or meet their needs virtually without transportation.

Initiative 1.1 Connected communities

Maintain and improve multimodal transportation connections to reduce emissions and congestion.

- **Create more opportunities for biking, walking, transit, and telecommuting**



Improving infrastructure for biking, walking, transit, and telecommuting will make these options more reliable, safe, convenient, and affordable. For example, building bike lanes with increased separation from vehicles make them safer and more comfortable for riders of all skill levels. Expanding high-speed internet coverage can enable telecommuting and less driving. Safe walking environments and expanded transit networks with increased service will benefit everyone. To successfully encourage multimodal transportation, we must understand Minnesotans' needs and preferences, provide education, and demonstrate success.

- **Plan land use that supports multimodal transportation**



Climate-smart land use can make both communities and transportation safe, pleasant, convenient, and affordable to bikers, pedestrians, and transit riders.

- **Maximize resiliency and GHG mitigation in infrastructure projects**



Choosing the right materials, equipment, and work practices can minimize the carbon footprint of transportation construction projects. Coordinating other improvements, such as broadband expansion and stormwater management, with those projects provides added benefits.

Initiative 1.2 Clean and efficient vehicles

Accelerate the transition to electric vehicles, alternative fuels, and greater fuel efficiency.



▸ **Increase the use of clean fuels, including lower-carbon biofuels**

Cleaner fuels such as electricity, hydrogen, and advanced biofuels, can reduce GHGs and other emissions from vehicles. Hydrogen and advanced biofuels may be particularly helpful in reducing emissions from heavy-duty vehicles and other hard to electrify modes, such as air travel. Both electricity and biofuels can get cleaner with investments in renewable energy and advanced industrial technology.



▸ **Expand EV charging infrastructure**

To enable all Minnesotans to drive electric, we need to expand the network of EV charging stations across the state using public and private investments.



▸ **Increase EV availability and access**

EVs must be widely available and affordable to encourage consumers to make the switch. Providing incentives and supporting dealerships in supplying a wide variety of EVs will encourage EV adoption.



▸ **Accelerate the transition to EVs and clean transportation**

Opportunities for EV ownership, EV-related jobs, and clean transportation investment are expanding. Supporting the transition will require educating consumers about EVs in partnership with auto dealers, especially in underserved communities, training the clean transportation workforce, and attracting transportation investment.



▸ **Improve vehicle efficiency and emissions standards**

State and federal rules can require improved vehicle efficiency and reduced emissions from new vehicles. GHG emissions go down over time as older vehicles are replaced with new, cleaner ones. Programs can encourage more rapid replacement of older vehicles.

We all have a role



Transportation touches all Minnesotans and all parts of our economy. We all have a role to play in achieving a cleaner transportation system.

- Federal, state, tribal, and local governments must work together to plan, fund, and build a resilient transportation system that prioritizes safe, affordable, and clean multimodal transportation options.
- Governments, businesses, and non-profits must invest in expanding the infrastructure needed to support active transportation, low-carbon fuels and electric vehicles.
- Organizations can use education and incentives to encourage employees and visitors to choose cleaner transportation options.
- Individuals can walk, roll, bike, take transit, telecommute, consolidate short trips, rideshare, and prioritize electric options. Individuals can also call on government bodies to implement infrastructure improvements.

Benefits of shared action



Connected communities, low-carbon fuels, and clean vehicles support many additional benefits:

- Jobs in clean fuel infrastructure and clean transportation manufacturing
- Healthier communities from more active transportation and reduced pollution
- Safer communities with fewer traffic crashes
- More accessible transportation that supports people of all physical abilities
- Cleaner air and water
- Economic growth in rural communities

Big impacts

Which actions will achieve the largest GHG reductions?

- Transitioning to cleaner fuels, including electricity and biofuels, through incentives and policies such as a low carbon fuel standard
- Increasing EV adoption by making EVs more affordable, requiring and incentivizing manufacturers to sell EVs in Minnesota, and expanding charging infrastructure
- Increasing efficiency of vehicles fueled by traditional fuels, such as gasoline and diesel, so they pollute less

EQUITY

Transportation is critical for Minnesotans to access jobs, education, healthcare, recreation, family, and more. An equitable transportation system would fairly and justly distribute the benefits and burdens of transportation spending and services, and ensure that all Minnesotans can travel safely, conveniently, and affordably. Understanding how transportation services and decision-making help or hinder people in underserved communities is necessary to create equitable clean transportation strategies.



Rural areas have fewer reliable, safe, and practical options for transportation, such as public transit and non-motorized transport. More older adults and those with lower incomes live in rural areas, and they need reliable and affordable transportation options. Investments in cleaner fuels, EV infrastructure, and alternative modes of transportation, where feasible, can help rural communities thrive and transition away from internal combustion engines. Supporting cleaner-fuel development can ignite new businesses in rural areas and create new jobs.

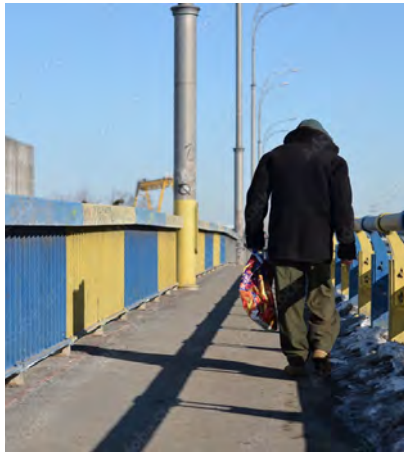

Historically and today, low-income communities and communities of color disproportionately bear the burdens of our transportation system without having fair and just access to its benefits. In Minnesota, Black, Indigenous, people of color, and lower-income individuals are exposed to higher levels of air pollution as a result of an ongoing history of structural racism. Inequitable policies such as racial covenants, redlining, the destruction and division of Black neighborhoods to build Interstates 94 and 35W, and zoning and permitting decisions that concentrate pollution sources in marginalized communities continue to cause harm. As a result, the health of residents in these communities is at risk from traffic pollution, noise, and physical hazards, such as crashes.

As Minnesota plans for climate action, we must address these inequities and redress past harms by prioritizing investments in infrastructure and improved transportation options for populations that have historically been underserved or harmed by our transportation system.

Climate-smart natural and working lands

Enhance climate benefits by absorbing and storing carbon, reducing emissions, and sustaining resilient landscapes



SHORT FORM

The challenges Long-term trends in climate and weather patterns, such as increasing temperatures and more extreme rain events, present formidable challenges to management of natural and working lands. Certain activities on our working lands, as well as conversion of our native landscapes to more intensive uses are also significant sources of GHGs.

The vision Healthy natural and working lands absorb and store more carbon, produce food and other products, sustain local economies, enhance climate resiliency, and improve the quality of life for Minnesotans.

Priority actions

Accelerate forest, grassland and wetland restoration to store more carbon in our landscapes, and avoid conversion to other land uses that reduce carbon storage.

Store more carbon. Promote actions that store more carbon on croplands, in yards and open spaces, and on public lands.

Restore and expand habitat complexes and corridors. Increase species diversity to promote climate resiliency and adaptation of natural landscapes.

Priority actions

Expand climate-resilient agriculture and forestry. Incentivize beneficial practices and assist in implementation, including increased access to technologies, equipment, and seed and plant material.

Manage agricultural lands in a way that reduces GHG emissions, particularly potent gases such as methane and nitrous oxide.

Increase water storage and infiltration, and manage drainage. Reduce runoff and minimize downstream flooding, erosion, and habitat loss.

Prioritize groundwater and drinking water protection in vulnerable areas.

Invest in new markets and supply chains for crops and that keep soil covered year-round, and for wood products that increase carbon storage and substitute for more fossil fuel-intensive materials.

Promote local and community-based agriculture to reduce transportation needs and increase food access, especially in underserved communities.

Measures of progress



By 2035, increase by 25% the amount of carbon sequestered and stored annually in natural and working lands, compared to 2014-2018 average levels.



By 2035, reduce annual GHG emissions in the working lands sector by 25% from 2018 levels.



By 2030, all state-funded or sponsored land, water, and species management plans identify actions to increase adaptation.

CONTEXT

Storing carbon and reducing emissions

Minnesota's varied landscapes — croplands, pastures, forests, woodlands, prairies, wetlands, and our more than 10,000 lakes — are part of our identity. They are also an essential part of our climate solution. An acre of grassland can hold as much as 78 tons of carbon while an acre of mature evergreen forest can hold up to 140 tons. Harvested forest products store carbon — sometimes for long periods of time — and can replace fossil-fuel-intensive products. We also have opportunities to reduce GHG emissions on agricultural lands from fertilizer, livestock, and energy use, while storing carbon in healthy soils.

Economically viable solutions

The expense of changing land management practices and adopting new technologies can be prohibitive, particularly for family-owned farms. We must identify innovations that benefit the climate and avoid undue financial risks for landowners. We must also choose the best solutions for all types of landscapes, based on site conditions, climate vulnerability, market conditions (for timber and agricultural lands), and government policies and practices.

Additional research

Our understanding of how land use practices affect climate change is rapidly evolving, though we have a solid basis for immediate actions. We need further research to explain how GHGs flow into and out of landscapes, and to identify effective ways to make natural and working lands more resilient to climate change. Filling these gaps in our knowledge will help support strategic decision-making, investments, policy development, and goal setting.



Land and water stewardship

The actions we take to reduce GHG emissions and sequester carbon on natural and working lands — such as soil health initiatives, water retention projects, and certain forestry practices — also enhance our ongoing land and water protection efforts. The added benefits include improving habitat for wildlife, pollinators, and endangered species; protecting food production; and safeguarding water quality.

Many landscapes are both "working" and "natural." Natural lands may provide critical fishing, hunting, and gathering resources, especially for tribal nations and Indigenous communities. Agricultural and other developed landscapes, including yards, can support native plant and animal species. Integrating tribal perspectives, traditional ecological knowledge, and culturally important species and foodways into our efforts to address climate change will ensure that we consider both the needs of people and the needs of landscapes and ecosystems.

WHAT WE WILL DO TOGETHER

Innovative approaches to create a more resilient landscape
Minnesota's agricultural and natural lands will increasingly absorb and store more carbon while producing food and other products, sustaining local economies, and improving quality of life around the state.

Initiative 2.1 Carbon sequestration and storage in forested lands, grasslands, and wetlands

Manage forests, grasslands, and wetlands for increased carbon sequestration and storage.

- **Maintain, expand, and actively manage forestlands**
  Active forest management promotes carbon uptake, adapts forests to current and future climate stressors such as pests and diseases, and reduces emissions from wildfires. Maintaining existing forests and expanding forest cover where appropriate strengthens the carbon sink.



- **Protect, restore, and manage peatlands and other wetlands**
  Peatlands (bogs and fens) hold some of Minnesota's largest carbon reserves, but emit large quantities of carbon when ditched and drained. Protecting existing peatlands and other wetlands, and restoring drained, farmed or pastured peatlands and wetlands will increase carbon storage.



- **Protect, restore, and manage grasslands**
  Grasslands with high native plant diversity are more beneficial for wildlife and pollinators, and store more carbon, than low-diversity grasslands. Grasslands are important to ecosystems and to livestock production.



- **Encourage individual actions that increase carbon storage**
  Most landowners and managers can take steps to store more carbon and boost climate resilience, with pollinator plantings, neighborhood gardens, community boulevard trees, woodland stewardship projects, and more. The improvements can be accomplished almost anywhere, from residential and commercial landscaping to small woodlots or city parks.



Initiative 2.2 Resilient landscapes and ecosystems

Enhance the ability of plants and animals, including crops, to adapt to the effects of climate change.



▸ **Conserve and enhance biodiversity**
Landscapes with high native plant diversity provide the best wildlife and pollinator habitat, the most resistance to invasive species, and the greatest adaptability to climate change.



▸ **Use land management practices that enhance climate resilience**
Certain timber harvest, soil health, grazing, and other land management practices can enhance climate resiliency, create wildlife habitats, and contribute to the economy. Strategic habitat restoration helps connect plant and wildlife populations.



▸ **Promote the benefits of natural lands in climate adaptation**
Natural landscapes that effectively store and filter water, reduce erosion, and support habitats also provide economic and cultural benefits to the state, including livestock, timber, recreation, and tourism.

Initiative 2.3 Healthy farmland

Accelerate soil health and nitrogen and manure management practices that reduce emissions and enhance carbon storage, water quality, and habitat.



▸ **Increase organic carbon content and reduce erosion**
Practices such as cover crops, conservation tillage, diverse crop rotations, buffers, shelterbelts, and hedgerows can help to store carbon in soils, reduce use of nitrogen fertilizers, and improve resilience to precipitation fluctuations. Emerging practices such as the use of green fertilizers and biochar on cropland and pastureland are promising options.



▸ **Manage fertilizer and manure to reduce emissions**
The nitrous oxide produced from nitrogen fertilizer and manure is about 300 times more powerful as a GHG than carbon dioxide. The methane in manure is about 30 times more powerful. Precision agriculture, plant selection, and breeding, soil amendment technologies, nitrification inhibitors, split nitrogen fertilizer applications, and similar nutrient management practices can reduce nitrous oxide emissions. Advanced technologies for manure management,

such as acidification and anaerobic digestion, can reduce methane emissions. Proper nutrient management also provides agronomic benefits and improves profitably.

- **Manage land for multiple benefits**

Helping farmers combine climate-resilient best management practices through programs such as the Minnesota Agricultural Water Quality Certification Program and various state and USDA conservation programs can improve profitability while decreasing emissions and improving soil health, water quality, and wildlife habitat.



Initiative 2.4 Sustainable landscapes and water management

Reduce GHGs and improve landscape resiliency through multi-purpose water storage and management practices that protect farmland, water supplies and infrastructure.

- **Manage agricultural landscapes to hold nitrogen and retain rainfall and snow melt**

Planting native vegetation, cover crops, and perennial crops in source water protection areas can promote infiltration, store more carbon, reduce nitrous oxide emissions, and protect drinking water supplies.



- **Manage agricultural landscapes to hold water and reduce runoff**

Climate change is making Minnesota's climate wetter, with more frequent and higher-intensity storms. Water storage and treatment in targeted areas can reduce downstream flooding and erosion. Practices such as wetland and floodplain restoration, drainage water management, and buffer establishment can build resiliency by reducing flow rates and velocities, improving stream stability, and enhancing wildlife habitat.



Initiative 2.5

Investments in emerging crops, products, and local economies

Support emerging agricultural and forest technologies and products that reduce waste, create jobs, and expand economic opportunities.



▸ **Invest in climate-smart agriculture and develop markets for climate-benefitting products**
Supporting end markets for cover crops and perennial crops that keep soil covered in spring and fall, increase carbon storage, and decrease use of nitrogen fertilizer can encourage farmers to plant them and boost local economies. Minnesota can be a leader in developing technologies and products for climate-smart agriculture, such as plant and soil amendments that decrease nitrous oxide while increasing nitrogen use efficiency; manure management practices that decrease methane emissions; and fuel, fertilizer, and fiber products that capture, repurpose, or sequester carbon.



▸ **Promote forest products that store carbon and reduce GHG emissions**
Long-lived wood products, such as building materials, store carbon for the life of the product. Many emerging forests products — engineered wood, biochemicals, biofuels, and environmental remediation products — are low-carbon substitutes for fossil-fuel-intensive products. Extracting energy from waste wood and wood residuals can diversify forest-product markets and reduce the need for energy from other sources.



▸ **Support local food markets, urban agriculture, and emerging farmers**
Food produced and consumed locally can reduce emissions from transportation of goods. It can also support local farmers and entrepreneurs, promote economic vitality, and provide underserved communities with access to healthy, fresh food, and economic opportunities.



▸ **Reduce waste and promote beneficial use of materials**
Increasing composting as an agricultural practice will enhance soil health. Supporting local and regional composting programs, zero waste challenges, and beneficial uses of waste wood will contribute to emission reductions.

Big impacts

Which actions will achieve the largest GHG reductions?

- Applying agricultural practices to reduce emissions and sequester carbon.
- Protecting, restoring, and managing grasslands and wetlands to sequester more carbon.
- Increasing carbon sequestration and storage in forests and harvested wood products.

We all have a role



How our parks, yards, agricultural lands, forests, wetlands, and grasslands are managed affects our climate and our quality of life. We all have a role to play in managing, protecting, and restoring our natural and working lands.

- Businesses, educational institutions, and governments must fund research to find and develop climate-smart land practices, educate landowners on their use and benefits, and support workforce training and development in these areas.
- Governments and organizations can protect key natural lands and implement best practices such as green infrastructure on developed lands.
- Individuals can purchase locally produced food and consumer goods, reduce food waste, and plant and tend trees and native plants.

Benefits of shared action



Climate-smart natural and working land management supports a broad array of additional benefits, including:

- Reduced surface and groundwater pollution, which helps protect drinking water and keeps lakes and rivers swimmable and fishable
- Stronger agricultural, forest, recreation, and tourism economies, especially in rural communities
- A more resilient food supply that supports healthy lives, especially in underserved communities
- Healthy native plant and animal communities
- Natural lands that serve our cultural, recreational, health, and spiritual needs

EQUITY

Opportunities to benefit from Minnesota's natural and working lands are not equitably distributed. Structural injustices have historically influenced land access, ownership, management, and protection. Tribal nations have lost treaty-protected resources and rights due to inequitable policies such as the 1889 Nelson Act. Underserved racial and ethnic populations have also been disproportionately affected by limited access to nature, exposure to pollution, lack of shared decision-making, and inequitable land ownership and land use laws and practices. Agricultural opportunity has not been equally accessible to all Minnesotans due in part to laws and programs, such as the 1862 Homestead Act, which distributed essentially free land to mostly white Americans and immigrants, and 20th-century U.S. Department of Agriculture grant and loan programs, which had documented racial bias in their distribution. Challenges continue today, including access to capital, government programs, and land.





While acting to address climate change, we must also address these inequities by:

- Removing barriers to participation in sustainable farming and timber production, such as lack of access to capital and land.
- Developing career paths and employment programs for urban populations who are underrepresented in agriculture, forestry, and natural resource conservation professions.
- Increasing access to healthy food, especially in underserved communities, to improve community health, reduce emissions, and support local economies.
- Ensuring all Minnesotans have access to, and feel welcome in, natural lands and open spaces, especially publicly owned lands.
- Preserving and protecting traditional cultural resources and outdoor spaces.

Resilient communities

Provide each Minnesota community with tools to plan for and become resilient to its unique climate impacts



SHORT FORM

The challenges Communities experience a variety of climate-change effects, including wastewater releases, stormwater flooding, shoreline erosion, drought, and more. Solutions must be tailored to each community's needs.

The vision Communities across Minnesota have the resources and support to plan for and implement projects to build a more resilient future for themselves. Physical infrastructure, natural systems, and communities are more prepared for climate impacts and can recover from extreme events.

Priority actions

Provide more resources for adaptation. Expand funding, staff capacity, technical support, and training for planning and implementation of adaptation and resiliency projects.

Increase capacity of the GreenStep Cities program. Share resilience best practices and adaptation resources and expand pilot programs that include tribal nations, schools, counties, and townships.

Plant climate-ready trees and preserve mature trees. Climate-ready tree species are well-adapted to challenges such as heat, drought, extreme weather, and pests. Along with mature trees, they decrease energy use in homes and buildings and mitigate heat islands. They should be used to replace diseased trees.

Priority actions

Expand green infrastructure and stormwater management control flooding, restore lost habitat, and improve water quality.

Adopt resilient building policies. Adopt provisions in construction and remodeling codes that prioritize adaptive reuse, and create resilient design standards.

Assess vulnerabilities at critical facilities. Use climate projections to predict future hazards and make plans to ensure continuity of operation.

Combat heat islands. Provide funding and technical assistance to help communities reduce their urban heat island effect.

Measures of progress



By 2030, 100% of Minnesotans live in communities with plans that identify climate risks and actions to build resiliency.



By 2026, at least 25 adaptation projects that increase community resiliency are fully funded.



Achieve 30% overall tree canopy cover in Minnesota communities by 2030 and 40% by 2050.



CONTEXT



Extreme weather effects

Communities must manage the cleanup and repair of the flood damage, infrastructure failure, downed trees, and other destruction that comes with increasingly frequent and intense storms. Climate adaptation strategies can be implemented at the individual and community levels. Collective adaptation action protects and sustains local assets and services that are fundamental to a community's prosperity.



Aging infrastructure

Many communities have aging and inadequate water infrastructure (stormwater systems, sewers, septic systems, and wastewater treatment plants) that can't handle this extreme precipitation. The result is flooded streets, sewage backing up into homes and businesses, wastewater treatment system overflows, and millions of dollars in damages to public and private property. Development of resilient design standards can help communities build and upgrade infrastructure to better handle current and future climate impacts.

Urban heat

In urban space, hard surfaces and buildings absorb and radiate heat, which can increase temperatures significantly. This is called the heat island effect. Green infrastructure, including growing and maintaining trees and making smart land use decisions, can help offset and lower temperatures and reduce the heat island effect.

Land surface temperature
Twin Cities Metro

July 22, 2016, 12 p.m.

High: 125F

Low: 74F

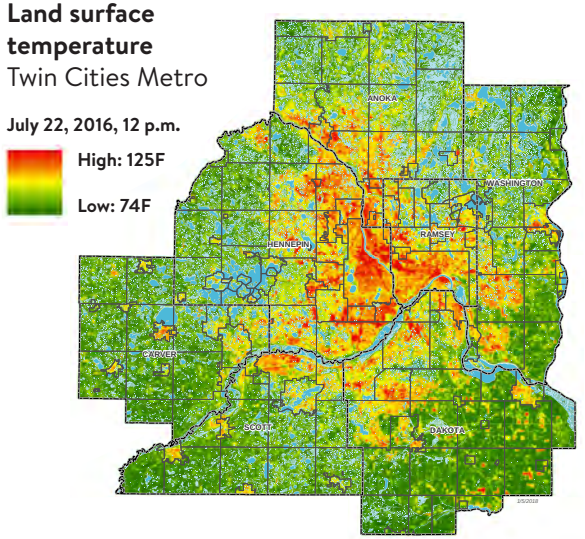

Support for communities

Cities, towns, and residents need support to assess vulnerabilities and identify, plan, and implement climate resiliency projects. We must provide data, resources, and technical assistance.

WHAT WE WILL DO TOGETHER

Minnesota communities will be prepared for the effects of climate change
Local planners will have the data, tools, and technical expertise they need to implement community-specific adaptation actions and increase resilience, including equity-based solutions.

Initiative 3.1 Climate-smart communities

Build the capacity of Minnesota communities to protect against and withstand the effects of climate change.

- **Provide needed technical assistance, tools, maps, and data**



Communities need resources and support for asset management, risk assessment, adaptation, and resilient metrics and performance measurements. Adaptation technical assistance and tools provide communities with access to expertise, enable them to evaluate and implement strategies, and expand their capacity to pursue funding. Maps show flood-prone areas, key infrastructure, community assets like hospitals and parks, and areas most vulnerable to climate change. High quality climate-projection data, along with data on past and current temperature, humidity, precipitation, air quality, and drought, also help communities with resilience planning.

- **Deliver necessary funding**



Federal, state, and local funds will be invested in building community resilience, and supplemented by private funding sources.

- **Share best practices through learning networks**



Create community connections to circulate successful adaptation strategies and project results. Build community capacity through GreenStep Cities, Minnesota GreenCorps, and the University of Minnesota Climate Adaptation Partnership. Expand pilot programs with tribal nations, schools, counties, and townships.

Initiative 3.2 Healthy community green spaces and water resources

Expand and protect tree canopies; parks and other green spaces; and lakes, rivers, and wetlands that provide community resilience benefits.



▸ **Expand tree planting and preservation**

Planting and preserving shade trees in urban areas is a remedy for heat island effects that helps decrease energy use in homes and buildings. Increasing tree canopy — and engaging residents in planning and decision-making — is especially important in low-income and marginalized communities. Planting climate-ready trees and managing tree stressors, such as emerald ash borer, are important parts of the overall strategy.



▸ **Plant beneficial vegetation on urban land**

Parks, community gardens, yards, and other public and private green spaces have underused potential for lowering temperatures, providing habitat, and managing stormwater. Growing native and climate-adapted species in these areas can also support pollinators, protect biodiversity, and boost ecosystem resiliency and the food web.



▸ **Protect and improve water quality and quantity**

Minnesota's groundwater and our many lakes, rivers, and wetlands support ecosystems, provide drinking water, offer recreation, sustain industries and food producers, and bear important cultural and spiritual significance for us. We must take action to counteract the precipitation and temperature changes and other climate change effects that threaten water quality and quantity.

Initiative 3.3 Resilient buildings, infrastructure, and business

Help the built environment and local economies become more resilient to climate change.



▸ **Plan for climate adaptation in residential and commercial development**

Buildings must be able to withstand the extreme precipitation, flooding, extended heat waves, urban heat islands, and grid failures caused by climate change. Building codes, permits, and policies for land use, new construction, and rehabilitation should encourage or require adaptive planning. New research, innovation, and design standards are needed to ensure buildings are climate resilient.

▸ **Fund resilient infrastructure and critical facilities**

We must support the building and maintenance of climate-ready water and wastewater treatment facilities, hospitals, energy infrastructure, roadways, and other critical facilities and infrastructure, to ensure they are accessible and continue to operate during and after extreme weather.



▸ **Expand green infrastructure and stormwater management**

Using plants, soils, and permeable surfaces to reduce runoff and divert it from storm drains can help restore lost habitat, control flooding and manage intense rain events, improve water quality and watershed health, protect infrastructure, and provide other benefits to vulnerable people.



▸ **Reduce the urban heat island effects**

Cities and towns of all sizes need funding and technical assistance to reduce urban heat island effects. Replacing or limiting hard surfaces, adding green infrastructure, and preserving mature trees will significantly lower temperatures and reduce the impacts of excessive heat. Investments should be prioritized to address local vulnerabilities, equity, and impact.



▸ **Support adaptation for local businesses**

Providing better access to capital and technical expertise will help small businesses plan for effects such as unseasonable conditions, flooding, or supply chain disruptions due to extreme weather. Some industries, such as construction and remodeling, may see opportunities in building climate-resiliency knowledge and skills and supporting community adaptation efforts.



We all have a role



Building resiliency will require localized planning, and action and expertise from federal, state, tribal, and local governments, researchers, businesses, and community members.

- Federal, state, tribal, and local governments need to collaborate to develop, share, and use the data necessary for analyzing and planning for climate impacts.
- Educational institutions and organizations can provide training and technical expertise to help communities understand their vulnerabilities to climate change and implement strategies to build resilience.

Benefits of shared action



Action to build resilience and adapt to climate change can also support:

- Resilient ecosystems that provide habitat, protect water quality, promote the inherent value of wildlife and plants and their right to exist, and support tribal hunting and gathering.
- Jobs in emergency preparedness, community resource and asset management, and planning and implementing resilience projects, particularly for stormwater and wastewater systems.
- Parks, natural areas, and community forests that nurture community well-being and require less energy to maintain.
- Well-designed buildings, critical facilities, and infrastructure that require less ongoing funding and repair.
- Residents feeling safe and healthy in their communities.

EQUITY

Communities of color and lower income communities are often least able to invest in adaptive strategies. Historical policies of housing segregation, such as redlining and mortgage discrimination, have caused housing insecurity in these communities, which are often located on land vulnerable to flooding, erosion, and other climate change impacts. Minnesotans with fewer financial resources and renters are less able to make home upgrades, maintain their indoor air quality, and safely and affordably heat and cool their homes.

Under-investment in these communities means that they often have fewer trees and parks and are more vulnerable to urban heat islands. We must prioritize the needs of climate-vulnerable communities and ensure their meaningful involvement and fair treatment at all stages of adaptation planning and implementation.





An equitable transition to a more resilient Minnesota will:

- Prioritize engagement of front-line communities in work to assess climate risks and identify priority actions to mitigate risks.
- Fund resiliency planning and infrastructure improvements in communities that have been under invested in historically through use of a climate & equity index and other resources.
- Prioritize clean-up strategies and climate adaptation investments in neighborhoods with fewer resources and that are disproportionately affected by unhealthy water, soil, and air.

Clean energy and efficient buildings

Expand the use of carbon-free electricity and create healthy, comfortable buildings that are cheaper to operate and pollute less



SHORT FORM

The challenges Electrical utilities are producing less carbon and more renewable energy, yet we still must address the energy burdens of low-income households, energy grid inadequacies, and equitable access to clean energy. Most existing buildings pre-date the current efficiency standards, and buildings' GHG emissions are rising. Reducing emissions from electricity and heating will drive reductions from buildings.

The vision Minnesotans have reliable, clean, and lower-cost energy through equitable investments in energy efficiency, clean energy, and low-carbon technology. The transition creates more jobs and more comfortable homes and businesses.

Priority actions

Establish a standard to achieve 100% carbon-free electricity and 55% renewable electricity by 2040.

Adapt the grid. Promote electrical grid and transmission upgrades and research and development to enable greater reliability and renewable energy access and integration.

Priority actions

Reduce emissions related to heating and cooling homes and businesses. Explore and evaluate new regulatory and policy options such as, but not limited to, a clean thermal standard and incentive programs. Maximize emission reductions through implementation of the Energy Conservation Optimization Act and the Natural Gas Innovation Act.

Reduce energy use and waste. Support opportunities for additional incentives, loans, and policies for existing homes, businesses, government, and schools in order to reduce energy use for all Minnesotans as well as to improve health through better air quality. Investigate supply-side supports, or pricing supports, for energy-efficient appliances, heating and air conditioning equipment, and domestic water heaters so that the low-cost-choice is also an energy-efficient choice.

Improve codes and standard for all new commercial and large multi-family buildings to achieve net-zero by 2036.

Measures of progress



By 2040, all of Minnesota's electricity is carbon-free.



By 2030, weatherize a quarter of dwellings where occupants earn 50% or less of the state median income.



By 2035, reduce GHG emissions from existing buildings by 50% compared to 2005 levels.



By 2030, reduce thermal GHG emissions by at least 20%, compared to 2005 levels.



By 2030, reduce energy use by 10% and total waste heat and waste electricity by 15%, compared to 2005 levels.



By 2030, reduce the energy burden so at least 80% of Minnesotans spend less than 5% of their household income on energy costs.



By 2030, reduce statewide primary energy usage by 10%, compared to 2005 levels.

CONTEXT

Making strides in electricity generation and distribution

Electricity generation in Minnesota is getting cleaner as coal plants retire and renewable energy grows, and we need to continue the trend. Tribal nations and many other communities need better access to energy conservation opportunities and renewable energy. We must also address energy-grid reliability, transmission, and distribution costs and barriers.

Rising GHG emissions from buildings

Since 2005, GHG emissions from commercial buildings have risen 15%, and 32% from residential buildings. Reversing this trend will require low-carbon and energy-efficient building technology, investing in building electrification, and retrofitting existing buildings.



Projected electricity generation by source Minnesota, 2020-2034

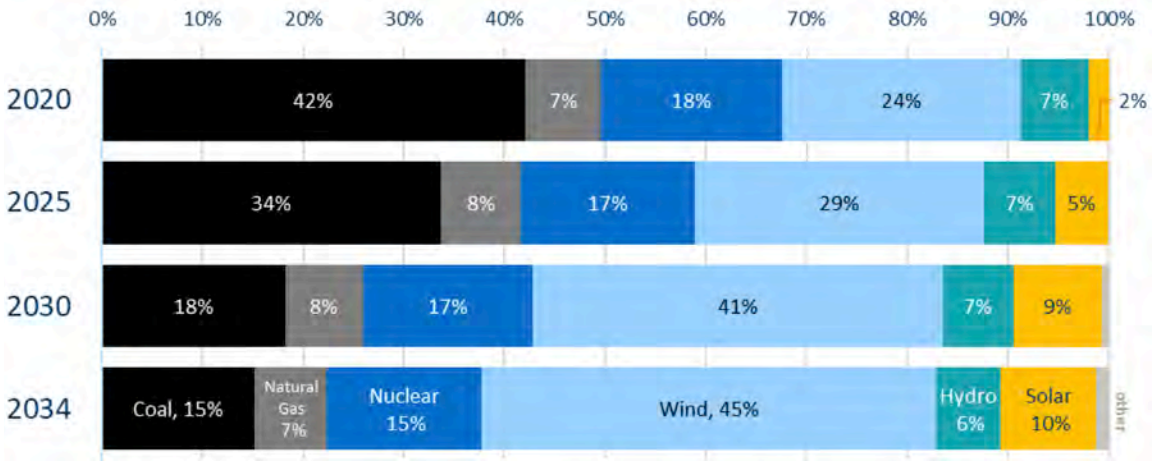

Utilities are already planning to transition to an energy mix that is over 75% carbon-free by 2034.

WHAT WE WILL DO TOGETHER

Transitioning to clean energy and more efficient buildings
Investments in renewable energy, electrification, energy efficiency, lower-emitting technologies and materials, and building resiliency will help mitigate climate change, create jobs, and improve our quality of life.

Initiative 4.1 Clean energy

Transition to 100% carbon-free, reliable, and affordable electrical power and heat through policies, investments, and partnerships.

▸ **Transition to 100% carbon-free electricity**
By 2040, Minnesota's electricity generation will add no carbon to the atmosphere. The transition will lay the groundwork for emission reductions in other sectors as they move towards electric vehicles and other electric alternatives. We must also ensure the power grid is reliable and affordable and has adequate capacity, and that all Minnesotans have equitable access to renewable energy and energy efficiency opportunities.



▸ **Utilize waste heat**
The machines used to produce electricity and the systems that heat and cool buildings generate by-product "waste heat" that can be captured and utilized. Currently, more than half of this energy is not captured. Introducing new mechanisms to trap and use the heat can lower costs, improve efficiency, and reduce GHG emissions.



Initiative 4.2 Smarter buildings and construction

Reduce GHG emissions in the building sector by promoting conservation, efficiency, and lower-carbon design, materials, and fuels.

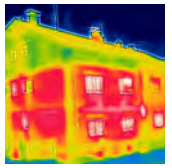

▸ **Increase efficiency and reduce emissions in existing buildings**

Support opportunities for energy-efficient upgrades by providing tools to assess building performance and promoting energy and emissions benchmarking. Target investments in lower-income communities that are challenged by older buildings and a lack of resources. Train building professionals on energy-efficient and low-carbon equipment and strategies.



▸ **Design and build climate-smart new buildings**

Ensure new buildings are energy efficient, climate-resilient, and powered by renewable energy. We must also update building codes and construction standards to mandate net-zero energy construction; incorporating energy efficiency in new buildings is much less expensive than retrofitting existing structures.



▸ **Building reuse and preventing waste**

Incentivize the rehabilitation of existing buildings that include energy, resilience, and efficiency upgrades. Provide tools to assess buildings' adaptive reuse potential. Promote the reuse and recycling of demolition materials.

Big impacts

Which actions will achieve the largest GHG reductions?

Electricity generation:

- Producing only carbon-free electricity in Minnesota by 2040
- Increasing the renewable energy standard

Buildings sector:

- Updating building codes to ensure the highest possible efficiency and lowest possible emissions in new buildings
- Providing tools and incentives to improve the efficiency and reduce emissions from existing buildings

We all have a role



Many partners must contribute to the efforts to advance energy efficiency, increase the availability of renewables, and make buildings more efficient and resilient.

- Individuals can lower their energy use though new technologies, behavior changes, and home upgrades using utility and government-offered weatherization programs.
- Government units can provide weatherization and energy-efficiency education, funding, and implementation assistance for homeowners and renters.
- Businesses, nonprofits, governments, and utilities can work together to improve energy efficiency and reduce GHG emissions in their existing and new buildings.

Benefits of shared action



Actions to reduce emissions and improve efficiency in the power sector and buildings have other benefits:

- Cost savings for businesses and residents from lowered energy use.
- Improved health from less indoor and outdoor air pollution and from home-weatherization efforts, and lower medical costs, along with fewer missed school and work days.
- New jobs in energy efficiency and clean energy industries.

EQUITY

Power generation and building efficiency affect everyone, but not all Minnesotans are able to access the available benefits. People with lower incomes pay a larger portion of their income on energy and housing than those earning more. Due to decades of housing segregation, redlining, and other harmful policies, Minnesotans of color are more likely to rent homes rather than own them, which limits their access to energy efficiency and renewable energy opportunities. These communities also suffer disproportionate rates of utility disconnection, which can be life-threatening during extreme weather.



Renewable Energy Partners in Minneapolis does solar installation and skill training in an underserved part of the city.

An equitable transition to our clean energy future would include:

- Expanding incentives and other mechanisms for businesses in overburdened communities to transition to renewable energy.
- Invest in energy efficiency programs, and ensure that communities of color, tribal nations, and lower-income communities have access to them. Eliminate inequities by fuel used or area of the state.
- Help lower-income households access local and affordable renewable energy, with options such as community and rooftop solar.
- Support job training in rural and low-income communities for work in energy-efficiency retrofits of current housing stock.
- Promote community-driven solutions to affordable housing that incorporate energy efficiency, address gentrification, and prevent climate-related displacement.

Healthy lives and communities

Protect the health and wellbeing of Minnesotans in the face of climate change



SHORT FORM

The challenges Changes in Minnesota's climate threaten the health of all our communities, but not everyone contributes to nor experiences these impacts equally. Existing inequities based on race, age, gender, geography, economic status, and more place some communities at greater risk.

The vision Minnesotans are healthy, safe, and resilient in the face of climate change, especially those that live in the communities that are most affected.

Priority actions

Raise awareness of health impacts. Build partnerships to improve education and raise awareness of the health impacts of climate change.

Fund and support community-led initiatives across Minnesota that address health risks from climate change and improve health outcomes.

Prepare for diseases. Build the capacity of public health agencies and communities to prepare for and respond to new and current diseases that are increasing due to climate change.

Priority actions

Track, monitor, and compile a regular report on the health impacts of climate change in diverse populations in Minnesota.

Adapt outdoor recreation on public lands for a changing climate and to serve changing demographics.

Assess healthcare resilience. Ensure hospitals and other facilities can withstand extreme weather and other hazards. Plan and implement adaptation projects.

Provide proactive health services. Deliver culturally-appropriate, affordable, and responsive healthcare and mental health services to protect public health and create a foundation for climate resiliency.

Measures of progress



By 2030, reduce the age-adjusted rate of heat-related ER visits to 10 per 100,000.



By 2025, ensure at least 40% of the benefits of certain state and federal climate investments are in disadvantaged communities.



Increase the diversity of state agencies' leadership to reflect the state's changing demographics.

CONTEXT

Our greatest health challenge

Climate change has been called the greatest health challenge because it threatens the very basics we depend upon for life, including safe and available drinking water, clean air, and a reliable food supply. Some of the known direct health impacts of climate change:

- More heat-related illnesses due to extreme heat waves
- Injuries and death from extreme precipitation and flooding
- Increasing societal and healthcare costs from more emergency department visits, hospitalizations, and premature deaths
- Increase in diseases transmitted by animals to humans that may then spread from humans to humans and diseases transmitted by ticks and mosquitoes
- Respiratory and cardiovascular impacts from increased wildfire smoke and pollen
- Mental health impacts from experiencing extreme weather events, climate-related instability, and other changes



Impacting things that support our health

Climate change also impacts our health indirectly, by affecting the many things that create our health, such as safe housing, reliable transportation, nutritious and affordable foods, and job stability. Indirect impacts can make other health conditions worse. For example, if increased precipitation creates problems with mold in a family's home, this could increase their child's allergies. Other indirect health impacts include:

- Disruptions to transportation systems from extreme weather making it more difficult to access grocery stores, jobs, and medical care.
- Loss of neighborhood tree canopy from invasive pests making extreme heat worse.
- Loss of income to families when businesses and farms are impacted by drought or extreme weather.





Health is affected by all parts of our society

All parts of our economy and society affect our health, including transportation, jobs, energy, housing, and agriculture. The rest of the actions in the framework will support healthier communities as we address climate change and build resiliency across Minnesota. It is also necessary to specifically focus on supporting community health, public health infrastructure, healthcare systems, and other ways climate change impacts our health.

WHAT WE WILL DO TOGETHER

Protect health and improve health equity
Minnesota will invest resources and implement policies and strategies that address the health impacts of climate change on individuals and communities.

Initiative 5.1 Healthy communities

Protect communities from the direct and indirect health effects of climate change.

- **Support healthy communities and workplaces**

Help workplaces protect employees who are vulnerable to climate-related health risks, such as those working outdoors in extreme heat. Ensure communities have access to safe places during climate-related disasters. Educate Minnesotans on the health effects of climate change, and help communities address them.



- **Protect culturally important activities**

Conserve species and habitats that are critical to tribal nations and other communities. Safeguard outdoor recreation opportunities, such as ice fishing, hunting, ricing, swimming, hiking, biking, and skiing, that are important to Minnesotans' health and wellbeing.



Initiative 5.2 Climate-smart public health and healthcare systems

Bolster public health resources and promote strategies to reduce GHGs from healthcare facilities.

- **Increase public health capacity and adaptation resources**

Increase capacity of public health agencies to prepare for and respond to changing and novel diseases and illnesses related to climate change, collect and develop climate-related data, track the health impacts of climate change, implement health-protection strategies, and ensure healthcare and mental health services are available through climate-related disasters.



- **Support climate-smart healthcare systems**

Encourage healthcare facilities and organizations to lower their GHG emissions and reduce waste.



We all have a role



Working together with climate-vulnerable communities, businesses, nonprofits, faith-based organizations, educational agencies and institutions, public health, healthcare systems, and others, we can build resiliency while reducing health disparities for those most impacted by climate change.

- Local governments and organizations can create resiliency hubs to protect people during extreme weather events.
- Employers can protect workers from extreme weather and offer telecommuting options that reduce greenhouse gas emissions and support families.
- Public health organizations can track the health impacts of climate change and partner with communities in implementing health-protective strategies.
- Educational institutions and universities can prepare future generations by raising awareness of climate change and resiliency strategies and researching the health effects of climate change.
- Healthcare systems can reduce their carbon footprint and prepare for extreme weather to ensure delivery of services.

Benefits of shared action



Addressing the health impacts of climate change through mitigation and adaptation actions serves to:

- Protect public health and reduce health disparities
- Protect the environment and culturally important places
- Improve community climate resiliency

EQUITY

Many Minnesota communities have demonstrably poorer health due to unequal access to health care, biased housing practices that placed them closer to sources of pollution, and other factors. These health disparities are made worse by climate change. For example, American Indian and African American middle and high school-aged kids are more likely than other students to have been diagnosed with asthma. Asthma is exacerbated by poor air quality and wildfire smoke. Historically racist housing policies (such as redlining) are associated with urban heat islands and lack of tree canopy in low-income neighborhoods of color, which suffer more from extreme heat as a result. Communities that already lack resources are burdened by the costs of increased healthcare and of withstanding or recovering from climate-related events.

Climate change amplifies existing health and economic inequities. Protecting the health of our communities requires protecting communities at the greatest risk of health burdens.





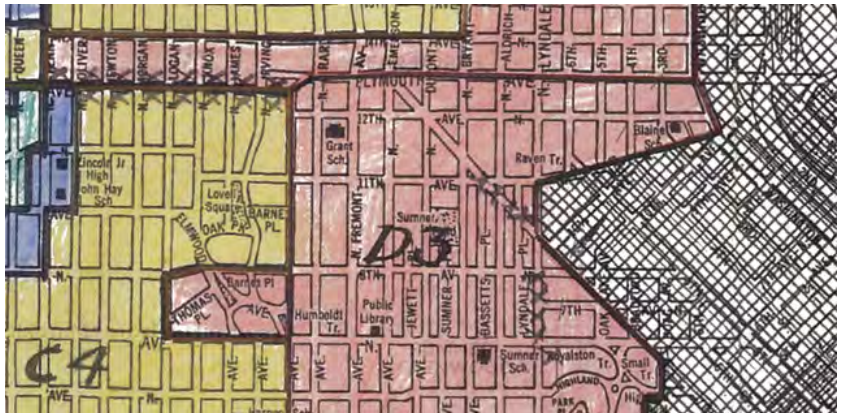

Clean economy

Build a thriving carbon-neutral economy that produces goods and services with environmental benefit and equitably provides family-sustaining job opportunities



SHORT FORM

The challenges Minnesota's economic activity produces GHG emissions and other air pollutants, while climate change is threatening jobs and our economy. Some Minnesotans have limited access to well-paying careers and the training that allows entry to career paths that help mitigate and adapt to climate change. The clean economy future will require workers, communities, and businesses to acquire new skills and build resiliency.

The vision Minnesota has a strong economy, aided by public and private investments in emerging research, technology, and businesses. Tens of thousands of people are employed in mitigating and adapting to climate change. Minnesota companies sell sustainable products made with green processes. Labor, businesses, and educational institutions collaborate to support skills training for in-demand jobs.

Priority actions

Complete a clean economy workforce and economic development plan. Assess high-growth sectors, potential job losses, and workforce and skill set needs, using an inclusive definition of clean jobs.

Encourage innovation. Work with tribal nations, universities, commercial consortiums, and private labs to nurture new technologies and clean economy businesses.

Develop worker skills. Create workforce strategies that train, upskill, and reskill workers to adapt to changing technologies and job needs.

Priority actions

Support power-plant host communities. Assist communities with aging fossil fuel-run power plants to ensure a successful transition. Provide long-term planning and support to retrain workers and promote economic development.

Identify and remove barriers to employment and training for women, people of color and individuals with disabilities. In addition, diversify the clean economy workforce in both leadership positions and frontline careers.

Assist businesses moving toward sustainability. Identify supply chain needs and support environmental goals.

Measures of progress



In 2023, create a clean economy workforce and economic development plan with trackable metrics.



Increase the number of apprentices in the construction trades' registered apprenticeship programs and the percentages of people of color and women who enroll in and complete the programs.



Increase jobs in all sectors of the clean economy, including new and emerging sectors such as land management, transportation, long-lived wood products, etc.



Increase the number of clean technology businesses and the number of jobs they provide.

CONTEXT

An economy in transition



Climate change is negatively affecting jobs, natural environments, and our economy. Customers and businesses are increasingly asking for energy efficient, lower-carbon products, and building owners want options to reduce their carbon footprint and save money. Businesses need help adapting to remain competitive. Workers also need support to transition or retrain to successfully adapt to new technologies and in-demand job skills. Several communities host large electric-generating power facilities that are retiring in the coming years, which will impact jobs, tax base, and community prosperity.

Clean economy opportunities



Existing careers will be the foundation of a carbon-neutral economy, many requiring new skills or functions as they become more sustainable. Blue-collar work and the construction industry will be major components. In energy efficiency, renewable energy, clean transportation, power grid, and clean fuels alone Minnesota boasts more than 55,000 jobs — more than a third of which are in Greater Minnesota —and there are many jobs beyond the energy sectors that contribute to sustainability. People of color and women are largely underrepresented in these careers, and employers must address this lack of diversity. Workforce training for the clean economy should ensure access by communities disproportionately impacted by climate change and workers disadvantaged by systemic racism and other barriers.



Adaptation and growth

Minnesota businesses and workers will need more economic development and training assistance to power the transition to a clean economy. Business innovation and entrepreneurship spurs job growth, and a well-trained workforce is needed to fill those jobs. The movement towards an inclusive clean economy is a win-win-win for employees, consumers, and businesses.

WHAT WE WILL DO TOGETHER

Grow clean economy jobs and businesses that provide equitable opportunities for all Minnesotans
Minnesota will support the businesses and workers that are part of the clean economy with training, research, incentives, and partnerships.

Initiative 6.1 Business innovation and entrepreneurship

Invest in research and development, innovation, and partnerships.

▸ **Become a national leader in clean innovation**
Attract new industries and innovative thinkers through multi-sector partnerships and technical and financial support for entrepreneurs. Invest in research and development. Support businesses owned by women, people of color, veterans, people with disabilities, and others who have historically been left out of investment opportunities.



Initiative 6.2 Equitable access to jobs and a just transition

Support workers to adapt and evolve their skills through inclusive strategies, ensuring family-sustaining careers.

▸ **Support transitions as industries evolve**
Plan how to connect people with workforce training and apprenticeship opportunities to prepare them for the carbon-neutral economy, and gain skills that will adapt to new, cleaner technologies as they develop. Help workers in declining industries adapt and redevelop their skills. Assist communities where large power plants will be retired to plan for a prosperous future. Ensure training and work opportunities are accessible to all. Transition planning and support should be long-term and take into account the amount of time it may take to train workers, execute economic development strategies, and other considerations.



▸ **Develop career pathways**
Outreach, education, and training should lead to employment in clean economy jobs that pay a family-sustaining wage with skills that can be adapted to new and cleaner technologies as they develop.



▸ **Ensure good wages and benefits for workers and address systemic barriers**
Engage with businesses, educational institutions and policymakers to develop strategies to ensure jobs provide family-sustaining wages and benefits. Make job opportunities and training accessible for communities that have faced structural bias and discrimination that are disproportionately impacted by climate change.



We all have a role



Helping Minnesota's workforce and businesses to succeed and transition to a clean economy will require partnerships across government, unions, industry, trades, colleges and universities, training programs, and businesses of all sizes.

- Local governments offer incentives for economic development — and can help link businesses with communities to retain and create homegrown jobs.
- Businesses and industry will develop and seek clean technologies, participate in energy efficiency programs, and optimize supply chain and production proficiencies.
- Educational institutions and labor training programs can work with governments and businesses to train Minnesotans for clean economy jobs that pay family-sustaining wages.

Benefits of shared action

Growing clean economy jobs and businesses and ensuring a just transition have other benefits:

- Vibrant and healthy communities across the state
- Reduced income disparities
- More innovative business practices
- More Minnesota workers with adaptable skills to meet workforce demand



EQUITY

Many clean economy jobs are and will continue to be in the construction trades. While overall construction jobs tend to provide good wages and benefits, the industry continues to be dominated by white men. Attracting and retaining women and people of color in the trades — such as through outreach in schools career guidance programs to align education and training; safe, hands-on learning opportunities; mentoring; and financial support during seasonal layoffs — will be critical to achieving an inclusive and equitable clean economy.

We know that health, environmental, and economic crises disproportionately affect overburdened communities and can displace workers. Job training and job placement efforts should focus on reaching communities disproportionately impacted by climate change and communities that have faced structural bias and discrimination.





Other key activities will include:

- Ensuring unique regional needs are addressed and there is equitable access to training.
- Identifying potential high-demand clean economy sectors, and training resources and needs by region. Targeting training to populations that are underrepresented in the trades.
- Consulting and coordinating with tribal nations, to support and learn from their workforce development efforts and clean economy initiatives.
- Exploring the multifaceted opportunities to grow a clean economy with strategies such as educating consumers on sustainable options.

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Climate Action Framework

climate.state.mn.us/minnesotas-climate-action-framework



Minnesota's plan to address and prepare for climate change.

Minnesota is updating the Climate Action Framework in 2024 and 2025.

Check out the update process and how you can participate.

Climate change is no longer a far-off possibility. Minnesotans across our state are suffering its devastating effects right now — and it will get worse. Luckily, we can all be a part of the solution. Addressing climate change presents us with a historic opportunity to strengthen our economy, improve our health, and create a more equitable Minnesota for everyone.

To guide this work, the State of Minnesota has developed a Climate Action Framework. This plan sets a vision for how our state will address and prepare for climate change. It identifies immediate, near-term actions we must take to achieve our long-term goal of a carbon-neutral, resilient, and equitable future for Minnesota.



Explore the documents:

Climate Action Framework.pdf7.1 MB
State action steps.pdf484.48 KB
Greenhouse gas emissions analysis.pdf218.99 KB
Glossary and list of acronyms.pdf81.51 KB
Summary of input.pdf302.46 KB

Read more about the framework goals

Select the links below to read more about Minnesotans' experiences with climate change and the solutions included in the Climate Action Framework.



Connect all people through a safe, equitable, and sustainable transportation system.



Manage our lands to reduce GHG emissions and sustain resilient landscapes.



Prepare communities with resources to build a more resilient future for themselves.



Expand the use of carbon-free energy and create healthy, comfortable buildings that are cheaper to operate and pollute less.



Protect the health and wellbeing of all Minnesotans in the face of climate change.



Build an economy that addresses climate change and creates equitable opportunities.

Questions?

Email climate.mn@state.mn.us with your questions about Minnesota's Climate Action Framework.

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MPCA







MINNESOTA POLLUTION CONTROL AGENCY

1967 — 1987

TWENTY YEARS ECTING THE ENVIRONMENT

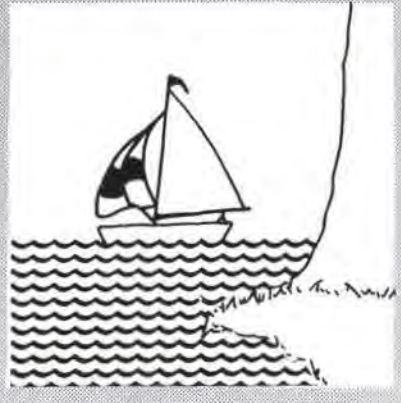

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INTRODUCTION

"To meet the variety and complexity of problems relating to water, air and land pollution in the areas of the state affected thereby, and to achieve a reasonable degree of purity of water, air and land resources of the state consistent with the maximum enjoyment and use thereof in the furtherance of the welfare of the people of the state, it is in the public interest that there be established a pollution control agency."

Minnesota Statutes, Chapter 116

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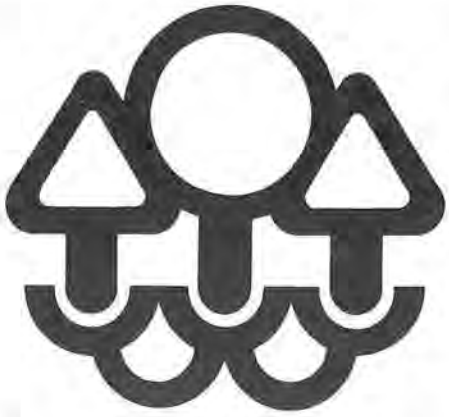

Twenty years have passed since public concerns over the declining quality of Minnesota's environment led the Legislature to create the Minnesota Pollution Control Agency (MPCA). It was 1967 — three years before a federal counterpart known as the U.S. Environmental Protection Agency (EPA) would be established and three years before environmentalists would observe the first annual Earth Day.

Rising from the former Water Pollution Control Commission and retaining all of its duties and authorities, the MPCA immediately received additional powers to deal with the emerging problems of air pollution and solid waste disposal. Other legislation followed rapidly in succeeding years, providing the MPCA with supplemental authorities and programs in order to respond to new demands for action.

Undoubtedly the state's most visible regulatory agency, the MPCA has often found itself embroiled in controversy as it considered its decisions. Environmentalists have cried out for more and increasingly restrictive environmental protections as those targeted by regulations have declared their opposing needs for less stringent standards. Over the years, the Agency's policy has been to attempt to work out the differences to satisfy all parties; when that has not been possible, however, the MPCA has not avoided confrontation in the interests of protecting the environment.

The results are obvious: the air and water are cleaner now than they were 20 years ago, in spite of a growing population and rising industrialization. As new issues have come to the fore, the Agency has tackled the problems and found solutions.

This booklet reviews the 20 years of MPCA history, relating the stories of hurdles surmounted and progress achieved. It also looks at directions for the future and some ways that you, the citizen, can help it in the pursuit of a cleaner, healthier environment.

The MPCA carries out the Legislature's mandate

Environmental protection begins and ends with monitoring. To determine what kind of pollution control is necessary and how effective it is, the MPCA regularly monitors the status of the environment, sampling air and water quality and collecting information on disposal of solid and hazardous wastes.

Lakes, rivers, fish tissue and the water underground are routinely analyzed at hundreds of sites to indicate safe uses for the water and to indicate trends and chronic pollution problems. The MPCA monitors air

quality for major pollutants at 50 sites throughout the state, and the program to detect the effect of acid rain includes data from rain and snowmelt acid-monitoring devices in ten locations and on several thousand lakes. Landfills are monitored regularly by means of water and soil tests.

With this information in hand, the MPCA has been able to set standards to protect the environment and to establish Agency rules. When monitoring indicates current rules do not effectively eliminate stubborn pollution problems or when problems are newly discovered, MPCA rules are altered in response to the information. In addition, the Agency reviews plans for major development projects with possible environmental effects, in order to foresee and prevent environmental damage by incorporating pollution control measures at the outset.

The primary tool in controlling pollution is the environmental permit. Facilities that might discharge pollutants into the air or water, or those which generate, treat or store hazardous wastes, or are disposal sites for solid wastes are required to have MPCA permits for their activities. Unlike other permits and licenses, these are expressly written for the individual activity being permitted. The permits contain details of specific enforceable conditions under which the facilities may operate, and include monitoring and reporting requirements. They often compel remedies for pre-existing pollution problems.

Some pollution emergencies require immediate action. MPCA staff is on-call 24 hours a day to respond to oil leaks, chemical spills or serious air pollution emergencies to be sure that adequate cleanup or containment measures begin without delay.

Checking for pollution problems throughout the state is a big job. Fortunately, the MPCA is not alone in caring for the environment. Concerned citizens frequently provide valuable assistance, bringing suspected violations to the Agency's attention. The MPCA also cooperates with other Minnesota departments and agencies, and works with the U.S. EPA in carrying out its environmental programs.

"The MPCA was a dream of the scientific fraternity of the area. I was one of four city engineers who served on the committee that came up with the idea of a single agency dealing with the three areas of pollution: water, air and solid waste. We came up with the idea and gave it to Governor Levander, and he and Senator Rosenmeier and Representative Frenzel carried the ball. At the time, we were one of only one or two agencies in the country of this type, so we established a pattern for other states to follow."

John Badalich
Executive Director 1967-1971



Minnesota's famous quality of life is largely due to abundant and unblemished natural resources. The MPCA and the people of Minnesota are proud of the results of 20 years of environmental leadership which have made our state a great place to live, work and enjoy the outdoors.

JUL 31 1990

THE MPCA CITIZENS BOARD

"A pollution control agency, designated as the Minnesota pollution control agency, is hereby created. The agency shall consist of nine members appointed by the governor, by and with the advice and consent of the senate. One of such members shall be a person knowledgeable in the field of agriculture."

Minnesota Statutes 116.02

"The sensitivity or awareness of Minnesotans to the environment increased rapidly in the first years of the Agency's existence. When I was on the Water Pollution Control Commission, for example, we had an application from Reserve Mining to increase the deposition of tailings into Lake Superior by a considerable amount. No one seemed to be interested in it. At the same time, we had an application from Northern States Power for a nuclear energy plant, and no one showed up. Then, when the MPCA had hearings on those issues, hundreds of people attended. Feelings ran high. During the first few years, we lived in a goldfish bowl because of all the interest in what we were doing."

Bob Tuveson
Member, MPCA Board 1967-1971

In establishing the MPCA, the Legislature empowered a body of selected citizens to make the difficult policy decisions in a public forum. The MPCA is the Citizens Board, supported by Agency staff. Originally seven members, the Board was increased in the MPCA's early years to nine members, and a later requirement added that one member should represent agriculture.

Board members serve four-year, staggered terms. They come from all parts of the state, with diverse backgrounds. The Board meets regularly each fourth Tuesday of the month at MPCA headquarters in St. Paul, and in special meetings as necessary. In these meetings, affected citizens, environmentalists, industry spokespersons and representatives from local governments are heard and their concerns considered as decisions are made.

Over the years, the Board has made countless decisions. For many, public attention has been moderate, as the Agency has gone about its business protecting the environment. At times, however, the MPCA board room has filled to overflowing with various factions and interests trying to persuade the Board to decide in their favor on some issue. Sometimes the 9:00 a.m. meeting continues well into the evening hours, as the Board ensures that it has heard all the arguments on each side of the topic.



The MPCA Citizens Board sets major environmental policy for Minnesota. Any citizen may testify at board meetings, held the 4th Tuesday of each month at MPCA headquarters in St. Paul.

Board members

Howard Anderson	1967-1982
Carol Baudler	1985-1986
John Borchert	1967-1970
Carol Buckmann	1975-1979
Duane Dahlberg	1982-
Russell Domino	1982-
Art Englebrecht	1973-1981
Ruth Ericson	1986-
Edward Fairbanks	1983-1987
Jim Fellows	1969-1972
Hal Field	1971-1979
Dan Foley	1985-
Steve Gadler	1967-1981, 1983-1985
Marcia Gelpe	1984-
Burt Genis	1973-1981
Janet Green	1983-
Joe Grinnell	1973-1980
Mace Harris	1967-1973
Virgil Herrick	1979-1983
Cynthia Jepsen	1981-1985
Curtis Johnson	1982-1983
Keith Langmo	1982-
Homer Luick	1967-1972
Dorothy Nelson	1969-1970
Wally Nelson	1980-1982
Dale Olson	1971-1974
Arnold Onstad	1986-
Wayne Packard	1967-1971
Duane Rappana	1979-1983
Bob Tucker	1972
Bob Tuveson	1967-1971
Marion Watson	1972-1981
Bill Walker	1985
Lois West	1981-1985
David Zentner	1974-1978

Progress

The next 15 pages summarize progress achieved in the Agency's 20 years of effort. By necessity, the summaries are short. Much remains to be accomplished, and the Agency cannot relax its vigilance. However, even the casual reader will note that the progress is real and quantifiable, in air quality, in water quality, and in dealing with the disposal of solid and hazardous wastes.

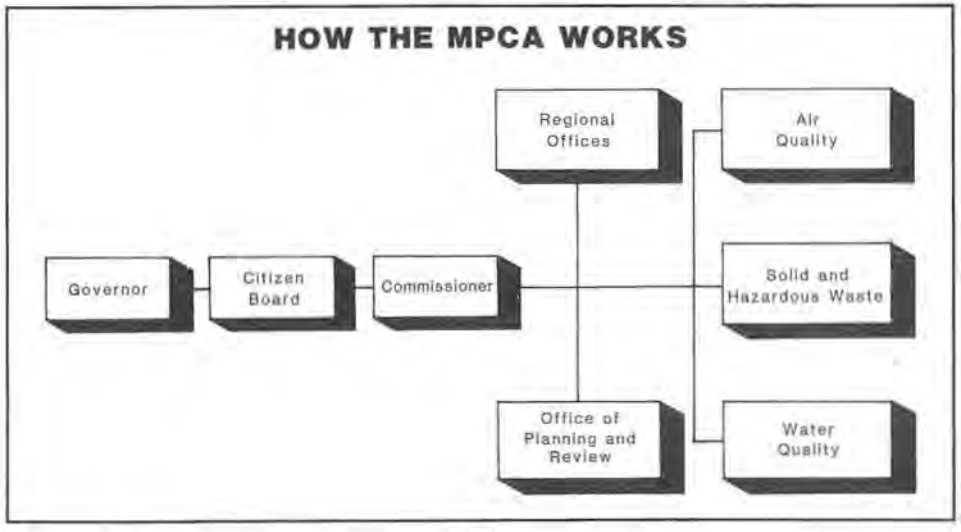

"The two outstanding presentations I recall were not by eloquent lawyers or other professionals. One was by a Finnish fisherman on Lake Superior, who knew what the situation had been before Reserve Mining discharged tailings and what it was at that time. The other was a trash hauler. He knew his business inside and out, and he talked very simply and very, very well. If a person knows his stuff and is sincere, it doesn't matter. He doesn't have to hire a lawyer to represent him. I think those presentations by people who were not professionals were much more impressive than from some professionals."

Dr. Howard Anderson
Member, MPCA Board 1967-1982

"We were required to balance environmental issues versus economic issues, but the Agency always put protection of the environment first. Balancing those sometimes got to be a difficult thing. It's hard to quantify, but you know it is out there, and you're thinking about it, sure. On the other hand, I am not much of a proponent of the economists who try to solve environmental problems with cost-benefit ratios. The Agency has a basic responsibility to protect the environment."

David Zentner
Member, MPCA Board 1974-1979

"I think we always felt a sense of mission, and it seemed at times that we were protecting people against themselves. We had to go out and sell — convince municipalities and industries that there was a problem that had to be corrected. We were competing at the time. Municipalities would rather have had paved streets, or better sidewalks, or new city halls. But it was satisfying."

Lyle Smith
Acting Executive Director 1967

Trends in the quality of water in Minnesota's lakes and rivers reflect the MPCA's efforts to combat water pollution, building on the work begun by the Water Pollution Control Commission. The national effort accelerated with the passage of the federal Clean Water Act in 1972. The goal of the act was to "restore and maintain the chemical, physical, and biological integrity of the nation's waters," and it created a variety of programs to study and regulate sources of water pollution, with most of the responsibility for carrying out the programs delegated to the states, under EPA supervision.

Considerable effort has been focused on so-called "point sources" of pollution: discharges of wastewater from municipal sewage treatment systems and industrial or commercial operations. At the heart of these efforts has been a program to require MPCA permits for such sources and a grant program to cover much of the cost of upgrading or building new municipal sewage treatment plants.

The last 20 years have seen continuous growth in construction of new wastewater treatment plants and MPCA training and certification of their operators to ensure the plants are properly maintained and operated. A dramatic increase in federal funding began with the passage of the 1972 Clean Water Act. Since 1967, more than $1 billion in state and federal funds has been granted to municipalities by the MPCA for wastewater treatment construction.



"Point-source" discharges are no longer the main threat to our waters. Polluted runoff from city streets, farm fields and other nonpoint sources is now the leading contributor to violations of water-quality standards.



Figure 1

In 1971 the Minnesota Legislature authorized a mandatory certification program for treatment plant operators (certification previously had been optional), and the program began the following year. Figure 1 shows the increase in certified treatment plant operators, and in the number of operators receiving MPCA training.

Figure 2 demonstrates the result of these increases. Just a few small municipalities remain that do not now have at least secondary wastewater treatment, although several hundred need to upgrade these systems.

Government, citizens and industry have worked together to achieve significant progress in eliminating pollution from point sources. Analysis of trends in stream water quality in Minnesota from 1973 to 1985 indicates that improved wastewater treatment has reversed the adverse effects of municipal and industrial discharges. Currently, about 95 percent of industrial dischargers and 75 percent of municipal dischargers are in compliance with their permit limits.

The effects from nonpoint sources, however, are increasing in some parts of the state. These sources are the land-management or land-use practices which allow polluted water to run off the surface of the ground, percolate into ground water or seep from underground into surface water.

To help define trends in stream water quality in Minnesota, the state has been divided into seven aquatic ecoregions, based on land use, soils, land surface forms and potential natural vegetation, as shown in Figure 3.

"Minnesota is a national leader in the operator training program, so it has been used as a model for other states. We've developed a lot of top-notch operating personnel, and many of the staff within our unit have moved on to bigger and better positions in the country. It's been rewarding to see the growth."

Bill Sexauer
Water Quality Division 1967-

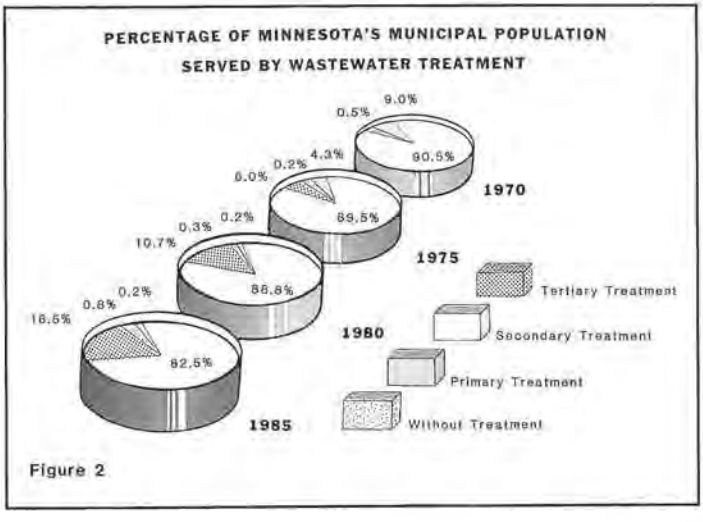

Figure 2

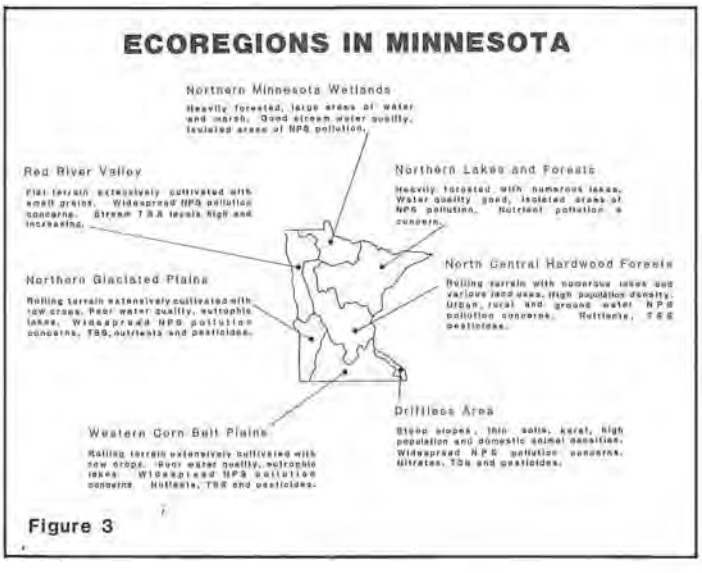

Figure 3

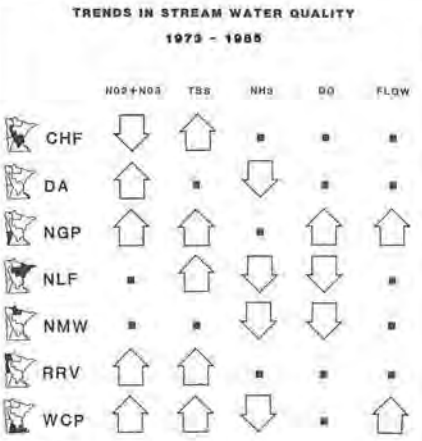

Figure 4

The elements included in the trend analysis include nitrate-nitrite concentrations (NO2 + NO3), total suspended solids (TSS), ammonia (NH3), dissolved oxygen (DO), and flow, factors that affect how well the water can support fish or encourage the growth of algae. Many regions experienced decreases in the ammonia concentrations and all regions except the Northern Lakes and Forests showed small changes in dissolved oxygen values, a direct result of improved control of point sources of pollution. Measurements most affected by nonpoint-source pollution (nitrite-nitrate concentration and total suspended solids) were more likely to indicate degraded water quality. The 1987 Legislature created the Clean Water Partnership Program to provide interested local units of government with resources with resources to establish water-quality projects which will protect and improve lakes, streams and aquifers degraded by nonpoint sources of pollution.

Water quality improvements by Minnesota's major wastewater dischargers

St. Louis Bay in Duluth

A major step was taken in improving the quality of water in the St. Louis River and Lake Superior when a new regional wastewater treatment facility called the Western Lake Superior Sanitary District began operating in November 1978. The district brought together seven cities and 10 townships, serving a population of approximately 135,000 and four major industries, to provide improved wastewater treatment, with the help of $96 million in EPA and MPCA grants.

The treatment plant discharges to St. Louis Bay, and monitoring and compliance reports show the treatment to be excellent. Both the St. Louis River and the Bay have responded with dramatic improvements in several pollution indicators. Figure 5 depicts the progress in reducing pollution in the St. Louis Bay. The residents have detected the change as well, and, perceiving the improved quality, have returned to fishing the area. The fish had been plagued with a tainted taste, but are now considerably better in flavor, and the long-term outlook is one of optimism for continued improvement.

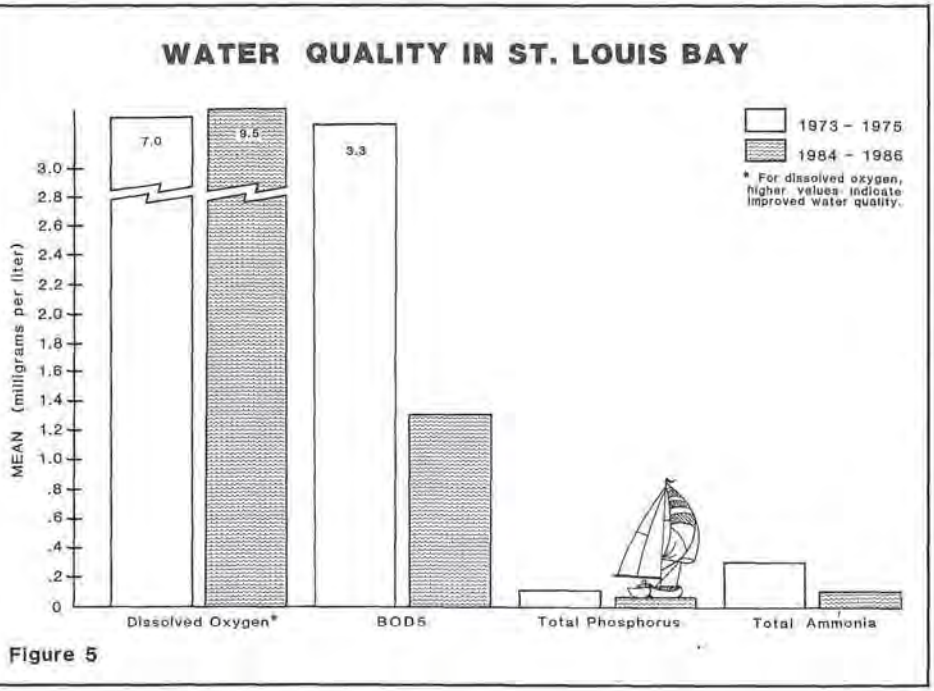

Figure 5

Mississippi River in the Twin Cities metropolitan area

The Mississippi River plays a crucial role in the vitality of the Twin Cities of Minneapolis and St. Paul. It supplies drinking water to its citizens, cooling water for its utilities and industries, efficient transportation for barges hauling its grain, and recreation for its residents. It also provides a site for convenient sewage and waste disposal, and concern arises as to whether the river can satisfy all these uses.

The Metropolitan Wastewater Treatment Plant treats approximately 85 percent of the wastewater in the Twin Cities system. Located on the Mississippi River in St. Paul, the Metro Plant treats an average wastewater flow of 231 million gallons a day produced by industry and more than 1.5 million people in the Twin Cities and 60 adjoining municipalities. It treats wastewater from nearly half the people in the state who are served by sewers.

Constructed in 1937, the Metro Plant initially provided only primary treatment: removal of large solids and settleable organic matter. Much of the original facility is still in operation. By 1986 it had expanded, however, to provide secondary and advanced treatment, funded by $300 million in EPA and MPCA grants.

The result is a discharge that meets MPCA standards, and it is now possible to fish in the Mississippi River downstream from the plant. The following table compares water quality indicators in the Mississippi downstream of the Metro Plant for 1973-75 and 1984-86 summer months, when water-quality problems are most likely. Continued improvements are likely in the future, now that the expansion is complete.

The primary obstacle to achieving the Clean Water Act's goal of making it safe to swim in the river is the existence of sewers designed to carry both storm water and sanitary sewage. Due to the limited flow capacity of these old sewers, as many as 87 overflow points discharge untreated combined sewage when it rains. The main effect of the overflows is the probable discharge of disease-causing organisms, which can pose a health threat to any swimmers. The overflows account for 98 percent of the summer loading of fecal coliform bacteria to the river, an indication that untreated sewage is reaching the river.

"In the time that I have headed up the MPCA, the single thing that has impressed me the most is the zeal and dedication of Agency staff. These men and women come to the MPCA with a genuine concern for the environment, and they work long and hard hours, giving extra from their personal time and energy. They truly care about the important job they're doing."

Thomas Kalitowski
Commissioner

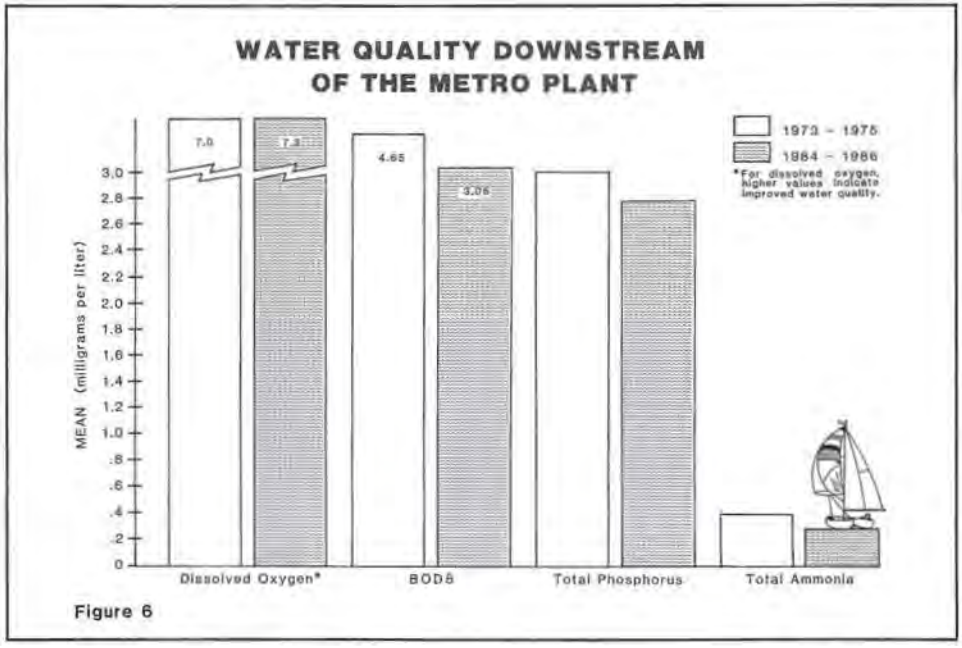

Figure 6

"I think of the Agency as a technical agency. It has to look at the issues that are out there and address the problems. Ultimately, the MPCA Board has to deal with policy. It has to determine the economic impact and balance that with the standards necessary to deal with the problem."

Lou Breimhurst
MPCA Staff 1975-1983
Director, Water Quality Division
Acting Director, Solid Waste Division
Deputy Executive Director
Executive Director 1981-1983

A study of the problem concluded that a sewer separation program at an estimated cost of $349 million would be the preferred solution. The Cities of St. Paul, Minneapolis and South St. Paul are now involved in an intensive ten-year project to separate the sewers and correct the problem, assisted by the MPCA's construction grants program.



Clean rivers are important for drinking water, commerce, wildlife and recreation.

Lake Superior near Reserve Mining Company

The Reserve Mining Company long operated a taconite processing plant in Silver Bay, Minnesota. At full production, the plant processed approximately 90,000 long tons a day into iron ore pellets and discharged some 67,000 tons of waste tailings into Lake Superior.

During the early 1970s, a controversy arose among Reserve, the State of Minnesota and the federal government regarding the disposal of these tailings. Litigation was initiated on the basis that Reserve's discharge violated state and federal law and the common law of nuisance. In addition, it was discovered that mineral fibers in Duluth's drinking-water supply originated from a unique geological deposit in one of Reserve's mines, and federal courts ruled that the fibers were indistinguishable from asbestos fibers known to be carcinogenic.

In April 1977, the controversy was resolved when the Minnesota Supreme Court ordered construction of an on-land disposal basin at a site referred to as Mile Post 7. The site included an approximately six-square-mile area about five miles northwest of the plant. Total cost to Reserve was estimated to be in excess of $370 million. In 1980, use of the on-land disposal site began, and the discharge into Lake Superior ceased.

In 1967, air pollution control in Minnesota was largely a function of local governments, some of which had received federal grants to begin their programs. The first federal Clean Air Act had been enacted in 1963, establishing air quality standards. The same year that the MPCA was created also saw the passage of a federal Air Quality Act requiring the states to set standards and plan control strategies to meet them.

As the MPCA's Air Quality Division developed, local programs were largely phased out, with many staff from local programs in the Twin Cities joining MPCA staff. During the last 20 years, substantial progress has been made in improving air quality at the same time as population and industrial growth have resulted in an ever-increasing need to control emission sources.

One of the more dramatic improvements in air quality during the 20-year period has been reduction of sulfur dioxide, a colorless gas which affects our respiratory tracts, vegetation and building materials. As shown in Figure 7, annual arithmetic means (the midpoints between highs and lows of sulfur dioxide each year) of sulfur dioxide in Minneapolis and St. Paul have declined to one-fourth

"We had one of the first metropolitan-area air monitoring systems with continuous analysis, with data being telemetered into our headquarters. When we had regional meetings with the EPA, often we would be the only state that would have all the data, out of the six states in the region. We did have one air quality alert, in 1972. We were able to stay on top of it because we were getting readouts every hour."

Ed Wiik
Director, Air Quality Division
1968-1980

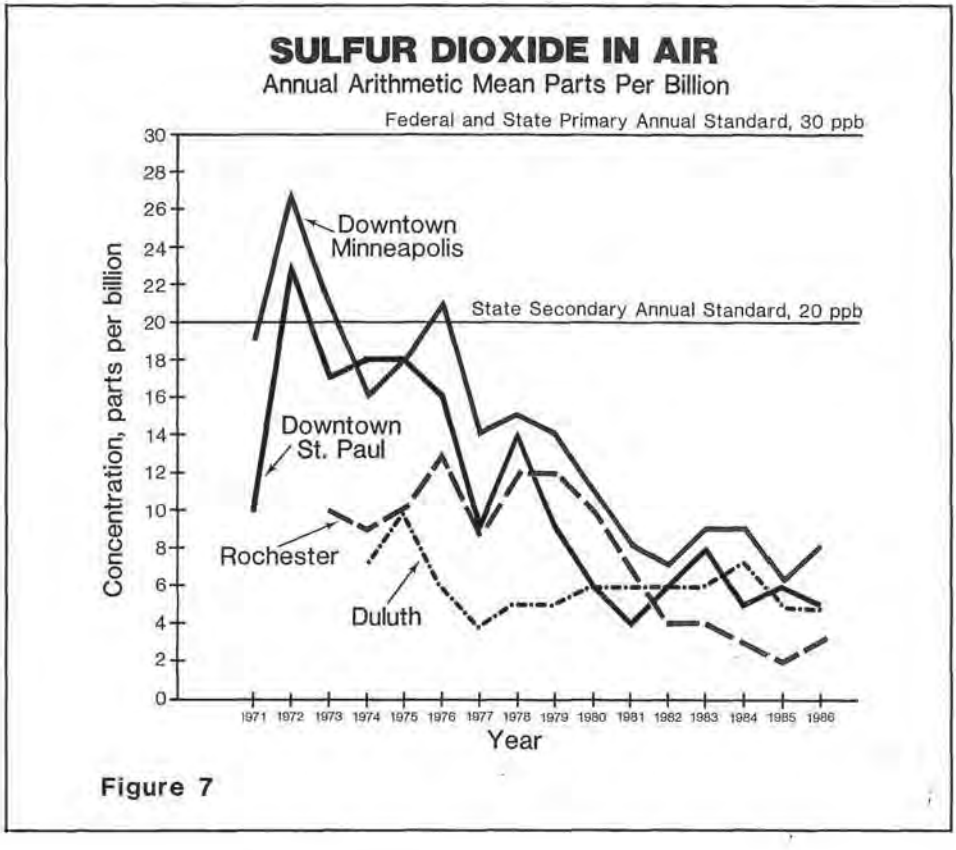

Figure 7



Industrial air pollution has decreased significantly in 20 years, making such scenes extremely rare. Other less visible air pollutants from vehicles and toxic pollutants from industrial processes will challenge the state as our population and economy expands.

the 1967 level. This is consistent with the reductions of sulfur dioxide emitted into the air during the same time, as shown in Figure 13 (page 14). Annual sulfur dioxide levels in Rochester and Duluth also declined during the period, although not nearly as dramatically. These levels are now in compliance with all state and federal standards. This can be attributed directly to the MPCA's emission standards used to regulate power plants, boilers, refiners, and other industries.

Similar improvement is seen in the lowering of the lead levels in the air. Figure 8 shows the decline of lead levels at several key monitoring locations. Airborne lead is significant because chronic exposures to lead can lead to anemia, weakness and brain damage. The I-35W and Nicollet Mall monitors measure the amount of lead in the air caused by vehicles. The Berry Street monitor is placed near a company handling lead materials. The reduced lead in air is due to several general control strategies. Traffic-generated airborne lead has been controlled largely by reducing lead additives in gasoline. The MPCA's tight emission standards have reduced the lead in air near manufacturing sources. While lead in air has been significantly reduced, the accumulation of lead in soil remains a concern owing to the many years that lead was added to gasoline and subsequently emitted into the environment, as well as the contribution of lead from lead-based paints.

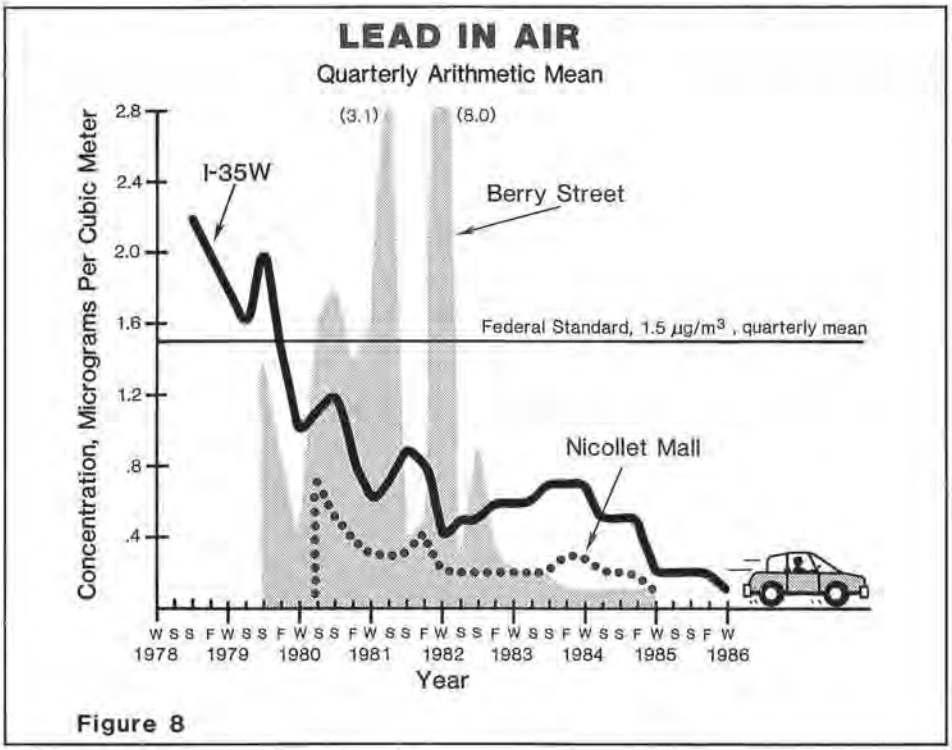

Figure 8

Another pollutant, carbon monoxide, is a highly toxic gas which in small amounts can impair alertness and cause fatigue and headaches. In larger amounts, of course, it can kill. Reducing carbon monoxide levels in the metropolitan areas has been difficult, as it is largely due to traffic congestion and appears to concentrate at busy intersections where traffic backs up.

The federal approach to reducing carbon monoxide levels has been requiring pollution-control devices on automobiles. This federal plan, along with state planning to promote better traffic flow, has accounted for some improvements. Although carbon monoxide varies from place to place, Figure 9 indicates some overall improvement in the Twin Cities metropolitan area.

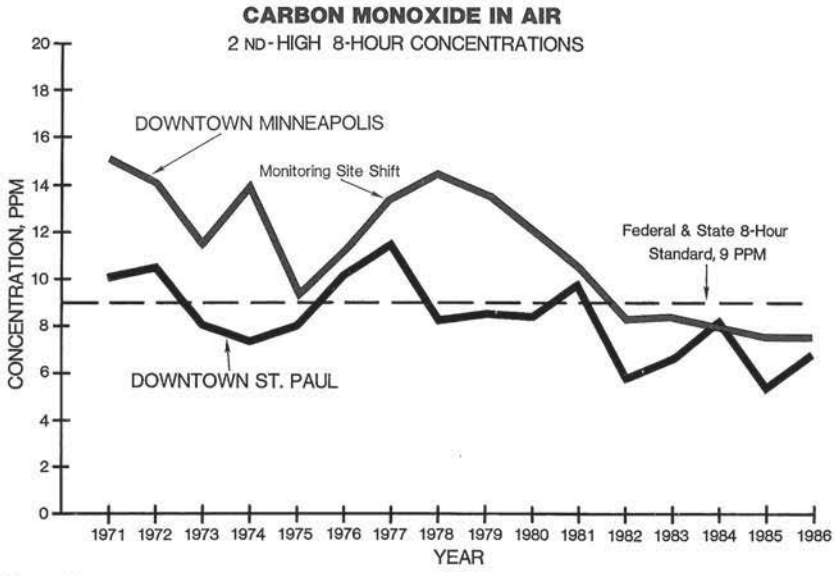

Figure 9

Elevated carbon monoxide levels also occur in smaller cities, as shown in Figure 10.

Currently only a few monitored locations do not meet standards, the most notable being the Snelling and University complex in St. Paul. However, recent and planned development projects in the downtown areas and suburbs, coupled with overall growth in the Twin Cities, will likely increase carbon monoxide levels in the future, requiring additional steps to protect public health.

Ozone, formed by the reactions of nitrogen oxides and hydrocarbons in sunlight, high humidity and high temperatures, is basically a summer pollutant which can cause eye, nose and throat irritation. Emissions resulting in ozone are

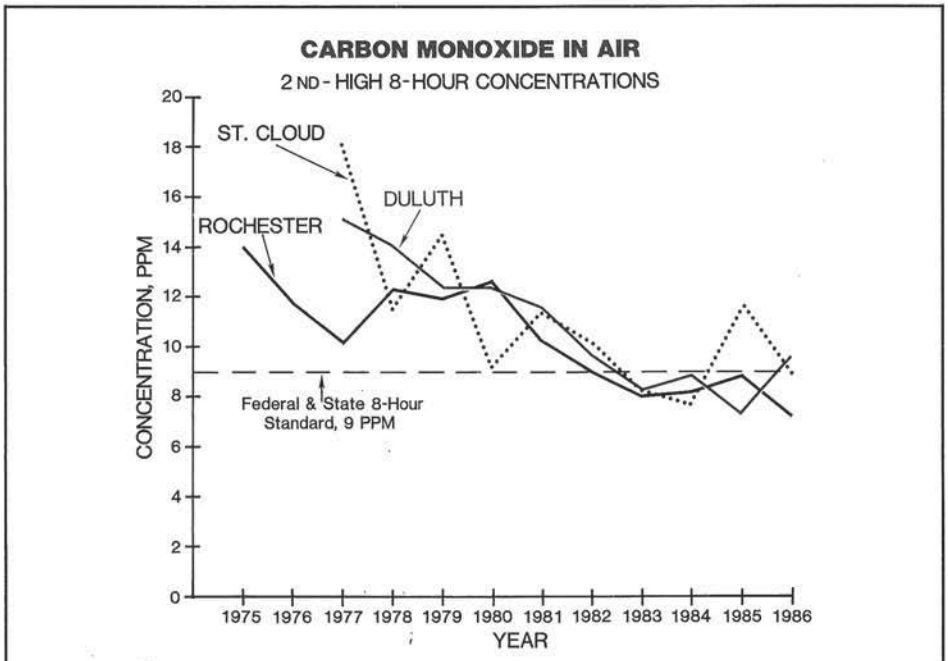

Figure 10

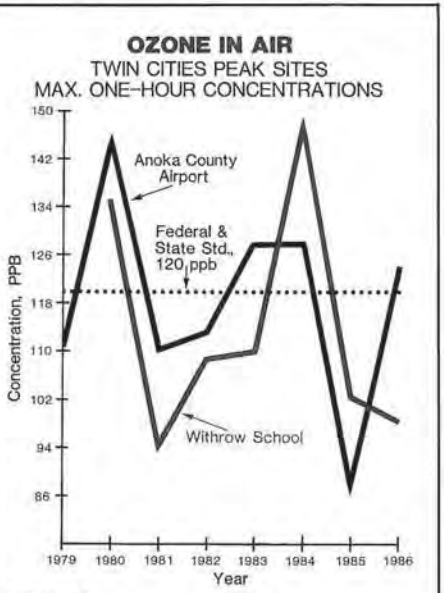

Figure 11

from traffic and industrial sources, and maximum concentrations in Minnesota are measured generally north of the Twin Cities metropolitan area under southerly wind conditions.

Figure 11 shows maximum one-hour concentrations at the two most significant monitoring sites over an eight-year period, demonstrating the cyclic nature of ozone generation. Minnesota is now one of only a few states in the country entirely in compliance with federal ozone standards. As with carbon monoxide, however, continued development and population growth may well dictate additional ozone control measures to prevent unhealthy concentrations.


Clean air is vital to our health and economy.

Airborne particles such as dust or soot are also regulated pollutants, as they can aggravate respiratory diseases, reduce sunlight and damage plants. Particulate matter can come from both natural and man-made sources. In general, particulates originating from stacks or chimneys have been well controlled, but wind-blown dust from sources such as roads and construction sites remain a problem in some areas. In dry conditions, natural sources of wind-blown dust such as open fields contribute significantly to airborne concentrations of particulates. As with carbon monoxide, particulate levels can depend upon local conditions, and it is very difficult to discern trends or to depict concentrations in an area-wide sense. A new fine-particulate standard recently promulgated by the EPA is aimed more at the man-made particulates that are likely to threaten human health.

Nitrogen dioxide is the only federal criteria pollutant for which compliance with ambient standards has always been achieved. Nitrogen dioxide comes from fossil fuel combustion in vehicle exhausts and industrial boilers, and it reacts with hydrocarbons to form ozone. The MPCA has two monitoring locations in the Twin Cities, and data from these monitors are used to help predict the role of Twin Cities-generated nitrogen dioxide in the formation of ozone downwind of the metropolitan area. Nitrogen dioxide levels have been consistently 50-60 percent below the annual arithmetic mean standard, a national standard which allows 40 parts per billion.

The 1982 Legislature passed the Minnesota Acid Deposition Control Act, the first act of its kind in the world, which directed the MPCA to develop a standard and control plan to protect sensitive Minnesota resources from the harmful effects of acid rain. After considerable study and debate, the MPCA adopted rules in 1986 which set the standard at 11 kilograms of wet sulfate deposited by rain or snow per hectare per year, or about 10 lbs. per acre. This standard is the amount of acid fallout that the most sensitive lakes can withstand before damage occurs.

The control plan which will help keep acid rain within this limit caps emissions from the two largest utilities in the state and limits emissions from large, coal-fired boilers. Although the MPCA is controlling the state's sulfur dioxide emissions through this control plan, other states and Canadian provinces contribute about 90 percent of the sulfate depositions in Minnesota (see Figure 12). Since the MPCA cannot regulate emissions in other states, the Agency supports the goal of a national program to reduce those emissions which contribute to acid rain.

Figure 13 shows the historical trend in Minnesota's sulfur dioxide emissions, along with the sulfate deposition measured at the Marcell Experimental Forest in north-central Minnesota. As emissions have declined, the sulfate deposition rate has evidenced a similar decrease. The acid deposition standard and control plan will help to keep these deposits at levels safe for Minnesota's lakes.

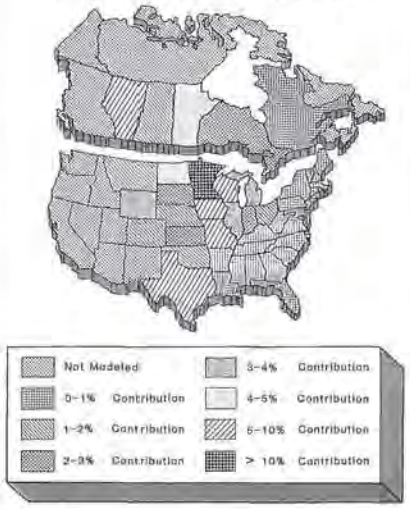

Figure 12

"I cannot say enough about MPCA staff. I think the people in Minnesota are very, very well served by their agency staffs, in general. But the PCA staff was bright, dedicated, hard working and honest. I took a lot of pride in their quality. I think in general, civil servants in Minnesota are vastly underrated."

Marion Watson
MPCA Board Member 1972-1981

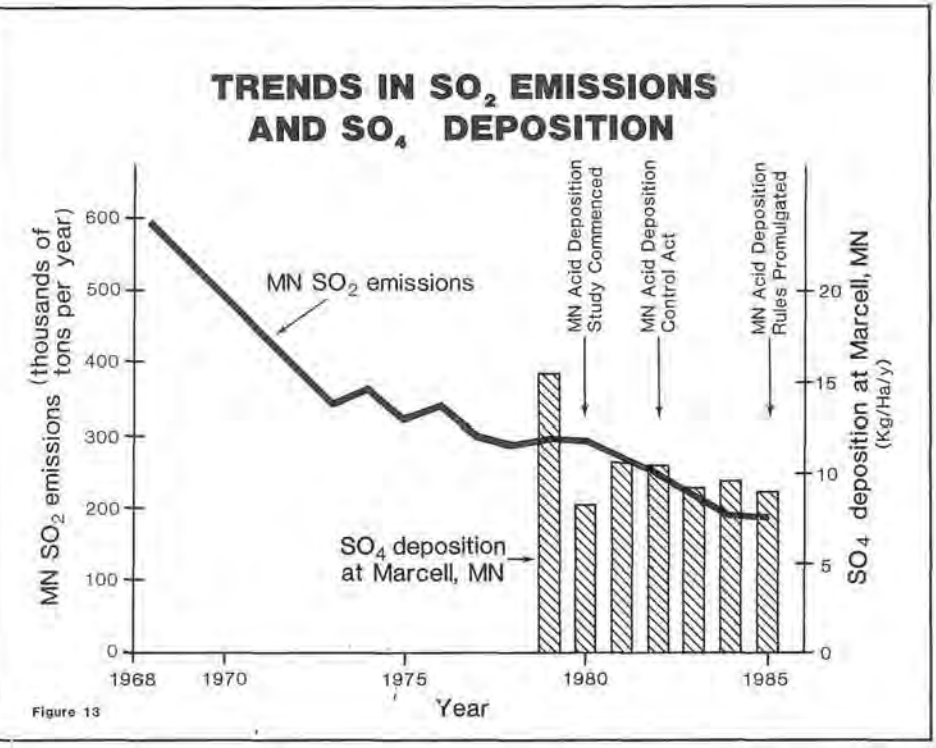

Figure 13

"Executive Director John Badalich approached me in 1968 to organize the solid waste division. Initially, I had two people, and our thrust was to develop land disposal regulations. They were adopted in January 1970. Minnesota was one of the first states to pursue this kind of regulation. A lot of other states later took our regulations as a basis for their own."

Floyd Forsberg
Director, Solid Waste Division
1968-1973

Minnesotans generate enough refuse each year to fill five lanes of garbage trucks stretching from the Iowa border to the Canadian border. In 1969 when the first solid waste rules became effective, Minnesota probably generated three and one-half lanes of waste which was disposed of in 1,500 open dumps and one landfill. That first landfill is now on the list of sites where hazardous wastes pose a threat to human health and the environment, the Superfund list.

During the early 1970s, emphasis of the Solid Waste Division's four staff members and a few student workers was to close open dumps and establish low-cost sanitary landfills as a replacement. The concept was to create earthen cells around the waste to keep out insects and rodents and prevent odors, blowing litter, water pollution and fires. Early solid waste rules also required each county to develop a disposal plan designating locations for all wastes generated in the county. Within a few years, MPCA staff had helped cities and counties to close the vast majority of open dumps and establish county or regional sanitary landfills, vastly enlarging the private solid waste industry serving the public.



Open dumps like this one have been closed around the state, but our own solid waste continues to plague us at a rate of more than four million tons per year, nearly one ton per person.

THE MAKEUP OF THE MINNESOTA SOLID WASTE STREAM

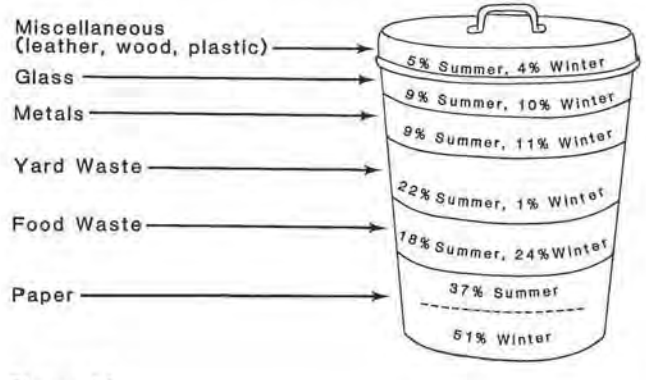

Figure 14

By 1975, 125 landfills with MPCA permits served more than 90 percent of the population. Landfill design standards, enforcement practices and staff expertise had become increasingly sophisticated to deal with the growing evidence of the environmental hazards caused by improper solid-waste disposal. During the mid-1970s, the movement to consider alternatives to disposal such as recycling and waste-to-energy incineration began, driven by energy costs, petroleum shortages and rising concern about ground-water contamination at landfills.

The Waste Management Act of 1980 and later amendments specifically required an equitable comparison of all alternatives to land disposal and a movement toward implementing those alternatives. MPCA review of existing solid-waste programs and issues encouraged counties to prepare action-oriented plans for solid-waste management, while at the same time Agency staff provided technical assistance to the counties and drafted more stringent requirements for solid-waste facilities.

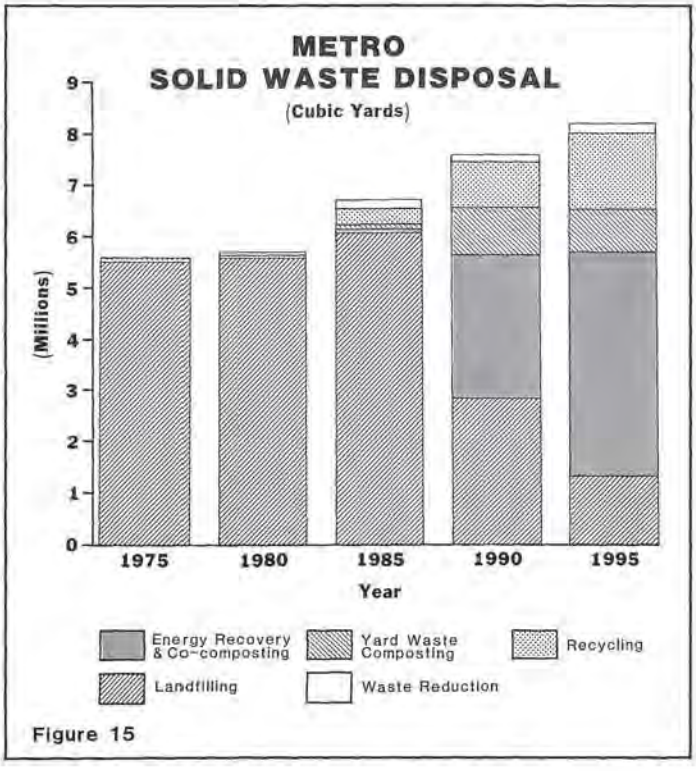

Figure 15

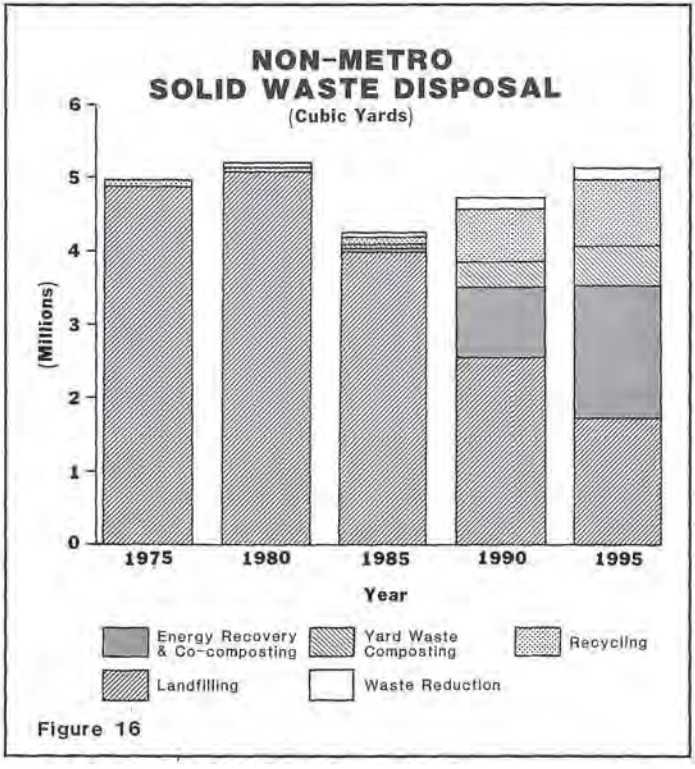

Figure 16

"Something that threaded its way through the Agency both times I served as executive director was the changing approach to the management of solid waste. Over a fairly short period of time, we moved from essentially nonregulated dumping to more regulated land disposal and then, finally, to an approach which emphasized alternatives to land disposal and recycling our materials or using the energy recovery approach."

Sandra Gardebring
Executive Director 1977-1979,
1983-1984

County planning at work

Officials in Olmsted County discovered in the early 1980s that their landfill was rapidly running out of room and could not be expanded. Because the geology in the area made it difficult to find a safe site for a new landfill, the county embarked on an ambitious schedule to implement alternatives.

Today the Olmsted County Landfill no longer accepts mixed-municipal waste and is in the process of being properly closed. The county has developed a multi-faceted waste management program. An incinerator burns much of the refuse from Olmsted County and neighboring Dodge County and a portion of Wabasha and Goodhue Counties. The incinerator represents one of the best technologies currently available and is well run and well managed.

A recycling center adjacent to the incinerator receives recyclable wastes, shredding newspaper and selling it for livestock bedding. Leaves and other yard waste are composted at three sites. Collection boxes for newspapers can be found in shopping centers and towns throughout Olmsted and Dodge Counties. Several special tire collection days have been held, and the county solid-waste advisory board is currently planning programs for household hazardous wastes and special wastes such as automobile batteries. Olmsted County continues to work on modifications and improvements for its solid-waste management system.

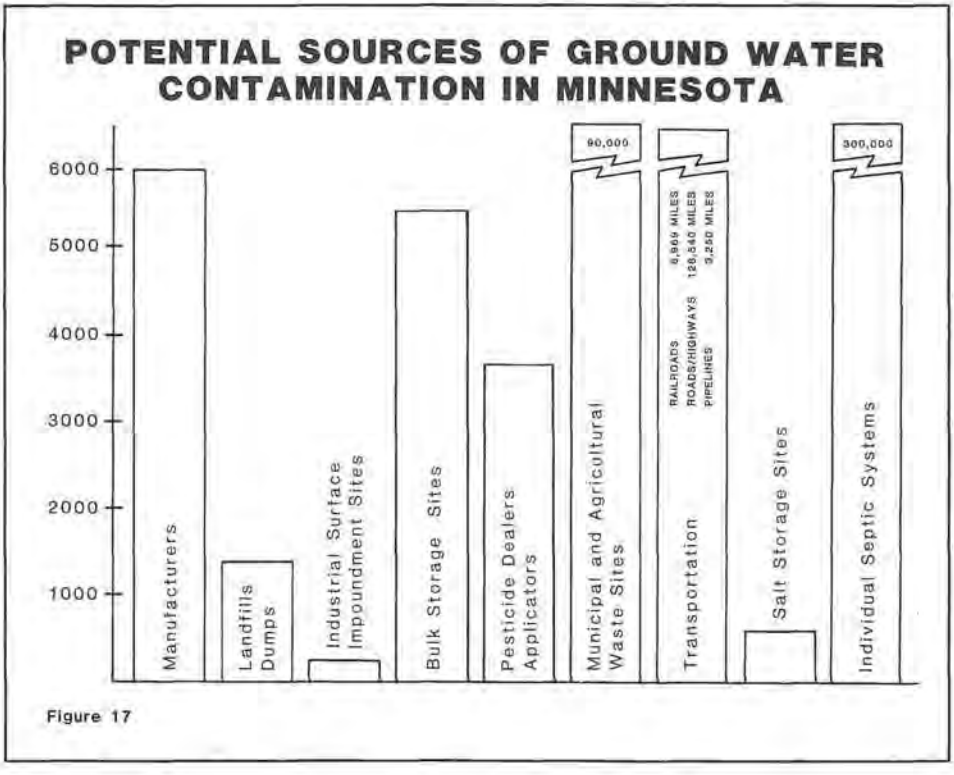

Figure 17

Ground water is an abundant, valuable and vulnerable resource in Minnesota. Two-thirds of the state's population rely on ground water for drinking water. Though its importance has long been recognized, the full effects of above-ground activities on the resource continue to become evident in the 1980s. Current MPCA activities cover a wide range of ground-water protection issues, including coordinating the development of a comprehensive ground-water protection strategy through a multi-agency work group.

The MPCA's hazardous waste program began in 1974 when the legislature passed the first laws requiring proper management of hazardous wastes. In 1979, the Agency

published the hazardous waste rules containing the cradle-to-grave regulatory system. The national program was just a step behind. Congress passed the first hazardous waste regulatory act in 1976, and in 1980 the EPA published its own version of the hazardous waste rules.

Numerous rule revisions followed, aimed at making Minnesota's rules equivalent to the changing federal regulations. The state's current hazardous waste rules became effective in 1984; and in 1985 Minnesota became the first state in the Great Lakes region to be formally authorized to regulate hazardous waste in lieu of the federal government. This milestone was welcomed by industry, which until then had to comply with two sets of hazardous waste rules.

The MPCA's hazardous-waste regulatory system requires those who handle hazardous waste to report their activities to the MPCA and develop plans for proper hazardous-waste management. The agency reviews the plans and provides assistance when necessary. Hazardous-waste handlers must also receive MPCA permits, which are enforced by regular inspections.

The manifest is the key element in keeping track of hazardous wastes. This document accompanies wastes from the point at which they are generated to their final destination. It is signed by the generator, the transporter and the receiving facility, and copies are sent to the MPCA by both the generator and the facility accepting the wastes. A computer system tracks the shipments

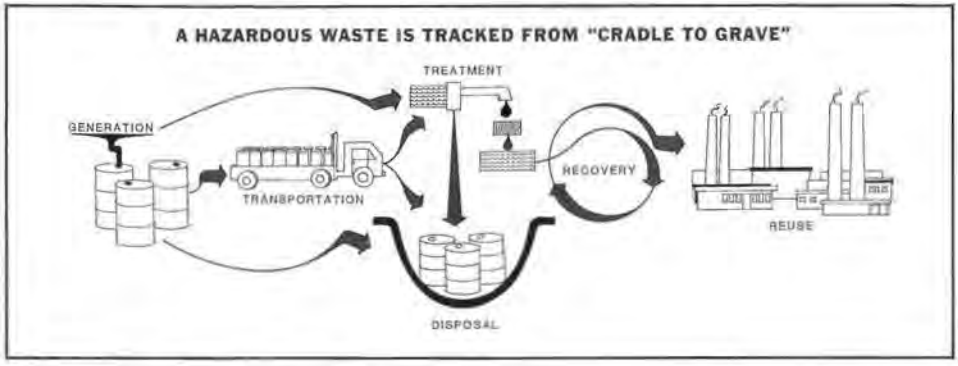

to be sure they are received by the facility named.

The state Superfund was enacted by the legislature in 1983. The law's objectives are to protect the people of Minnesota from exposure to improperly disposed of hazardous waste and, equally important, to

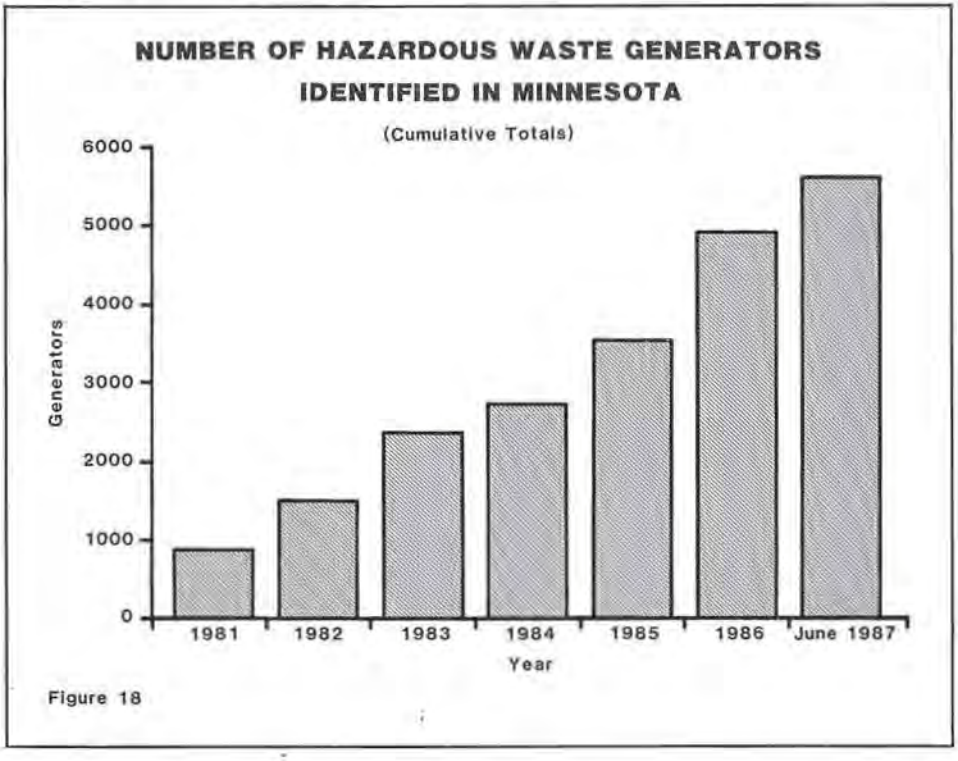

Figure 18

preserve and restore the important ground-water resources of the state. Emphasis is placed on giving responsible parties the opportunity to clean up.

The state Superfund law gives the MPCA authority and resources to compel those who are responsible for environmental or human health-threatening hazardous wastes to clean up the site. If they cannot or will not, the Agency can remedy the problem itself and collect its costs from the responsible parties later.

The Minnesota Superfund has achieved remarkable results in its four years. Safe drinking water has been supplied to residents of 12 communities, and 250 above-ground arsenic caches have been cleaned up. At 50 sites responsible parties are undertaking investigations leading toward cleanup, and the MPCA is investigating 23 sites under the state or federal Superfund programs.



Drums of hazardous waste excavated from an illegal dump site await shipment to a permitted facility outside Minnesota. This expensive cleanup could have been avoided with careful "cradle-to-grave" hazardous-waste management.

More than 25 major cleanups are either completed or in place. More than $100 million of private-sector funds have been committed to cleanup. The program has also allowed the Agency to follow up on suspected sites, resulting in a priority list of 130 confirmed hazardous waste sites as compared to 60 in 1983.

State Superfund arsenic projects

Arsenic was used in the 1930s and 1940s to control a serious grasshopper infestation in the Upper Midwest, but at that time no provision was made for proper disposal of the leftover arsenic and arsenic-laced bait. In many cases it was kept in deteriorating containers and decaying outbuildings. In some cases, it had been buried. The Minnesota Superfund has enabled the MPCA to clean up buried arsenic that had created a threat to human health and the environment in Perham and near Wadena, excavating the contaminated soil and shipping it to a secure out-of-state hazardous-waste landfill.

The MPCA also conducted a statewide campaign to encourage people who knew of stored or buried arsenic to report it to the Agency. After confirming that stored materials were arsenic, the MPCA collected approximately 75,000 lbs. of arsenic from 250 locations for safe disposal outside Minnesota. Reports of buried arsenic were followed up at once to ensure that no immediate hazard existed, and the MPCA will investigate the sites further in the future.



Realizing the diverse nature of Minnesota's economy, natural resources and population, the Agency established five regional offices in its early years in order to provide access to MPCA programs in each area of the state. Their locations in greater Minnesota make it readily possible for Agency staff in regional offices to meet face-to-face with the public they serve. Regional staff also inspect operations that have MPCA permits and respond to spills and other local pollution issues.

Regional office addresses and telephone numbers are listed on the back cover.

"Our real role is to maintain interaction between the clientele the Agency affects and the Agency itself. That person-to-person linkage is vital to ensure that the programs we acquire through legislation accomplish what is intended and meet the specific needs of each part of the state."

Larry Shaw
Director of Regional Operations



MPCA staff listen to concerns of officials in southwestern Minnesota. The Agency's regional office staff help citizens with local pollution issues and provide access to programs and services in the St. Paul office.

HISTORY AT-A-GLANCE

"The nature of the business is such that we cost certain people money they would rather keep, and we never satisfy the blue-sky idealists. If we are performing our task responsibly, we are probably making everyone equally mad at us. What a way to be a success! However, if we ever get to the point where we were being praised by any one segment, it's time to inventory the program, because the balance is gone."

Lovell Richie
MPCA staff 1967-1987
Deputy Executive Director
Senior Executive Officer

1967-1968	1969-1970
MPCA established; given authority formerly held by the Water Pollution Control Commission, added authority for air-quality control and solid-waste management. Twenty-six people transfer from Minnesota Department of Health to MPCA. MPCA director given seat on Soil and Water Conservation Commission. MPCA authorized to grant pollution control investment tax credits. Air monitoring begins, June 1968.	Law enacted requiring persons to notify MPCA of discharges and to recover pollutants. Water-quality standards adopted. Agency authorized to enforce orders and permits and to direct immediate discontinuance if imminent and substantial danger results. U.S. Environmental Protection Agency created. First air-quality standards adopted in 1969; first continuous air-monitoring station established 1970. Open-burning of garbage banned, by law, August 1970. Federal Clean Air Act enacted, 1970. First national Earth Day observed April 2, 1970. Reserve Mining ordered to comply with MPCA water-quality standards. Solid-waste rules become effective — 1,500 open dumps identified.

1971-1972	1973-1974	1975-1976
Agency authorized to adopt noise pollution standards and regulations. Municipal wastewater treatment construction grants program established. Agency authorized to regulate cleaning agents and chemical water conditioners. Minnesota Environmental Rights Act enacted. Agency given authority over disposal of abandoned motor vehicles; auto hulk program established. Feedlot regulations approved March 1971. Air pollution alert announced in Twin Cities metro area. Federal Water Pollution Control Act enacted. Five MPCA regional offices established. 250 bills in Minnesota Senate deal with environmental issues in 1971.	Legislature establishes Minnesota's environmental policies and goals. Grant program authorized to encourage solid waste recycling, resource recovery. Agency authorized to review packaging and ban over-packaged products; packaging rules adopted. Agency authorized to regulate hazardous waste management. Regulations established for NPDES and SDS water quality permits; EPA delegates permitting program to MPCA. Phosphorous limits set for detergents. MPCA monitors dismantling of Elk River Reactor, begins monitoring radioactive releases from Monticello and Prairie Island nuclear plants. Noise rules established. MPCA studies periphyton growth in Lake Superior relative to Reserve Mining tailings discharge. MPCA sues for wastewater treatment grant funds impounded by President Nixon. Spills Unit established in Water Quality Division. EPA announces Duluth drinking water contaminated by asbestiform fibers, June 1973. Reserve Mining trial begins in August, leading to 1974 federal shutdown order. Order appealed successfully; Court of Appeals affirms health hazard, orders Duluth water supply filtration, sets dumping time limits.	MPCA adds Hazardous Waste Section to Solid Waste Division. MPCA receives EPA grant to study land disposal of hazardous waste. Air Quality rules amended to allow diseased shade-tree burning sites. MPCA and Department of Natural Resources draft Environmental Impact Statement on Reserve Mining's Mile Post 7 disposal basin. Active open dumps now total 255. PCBs found in Mississippi and Minnesota River fish; MPCA Board calls for federal ban on sale and use of PCBs. Natural gas cut-off to industrial and commercial users forces switch to coal, degrading Twin Cities air quality. Industry lawsuit prevents enforcement of packaging rules. PCI incinerator in Shakopee closes down.

HISTORY AT-A-GLANCE

"I really haven't been unfairly tough on industry. I've just tried to convince industry people that they, too, are citizens of this state and ought to clean up their act. Some of them have, and I congratulate them on that."

The late Steve Gadler
Member, MPCA Board 1967-1981, 1983-1985

1977-1978	1979-1980
MPCA participates in study of environmental impacts of copper-nickel mining. Western Lake Superior Sanitary District begins operating. Noise barriers erected along freeways. Reserve Mining adds control equipment for airborne emissions. Solid Waste Division reviews chemical waste land-disposal project; candidate sites rejected. MPCA Board revokes first landfill permit, due to ground-water contamination. Water Quality Division begins new emphasis on controlling toxic pollutants. MPCA drafts hazardous-waste rules. Minnesota Supreme Court orders construction of on-land disposal basin for Reserve Mining tailings.	Reserve stops discharging taconite tailings into Lake Superior, March 1980. Agency adopts "208" nonpoint-source program. MPCA conducts demonstration vehicle-inspection and maintenance program in Metro Area; 44 percent of vehicles fail emission inspection. MPCA adopts "cradle to grave" hazardous-waste rules. Waste Management Act passed. MPCA acid-rain investigation authorized. Federal Superfund enacted. MPCA establishes Hazardous Waste Strike Force; 25 dump sites identified.

1981-1982	1983-1984	1985-1987
Agency revises air-quality rules, holds 59 days of formal public hearings, the longest administrative hearing ever. Pinhole-sized leak in Williams Pipeline in Maplewood loses 100,000 gallons of gasoline. Bemidji wastewater treatment issues resolved; permit issued. Hazardous waste cleanup in Isanti County first such use of federal Superfund by any state; PCI cleanup under way in Shakopee. Investigations begin of contaminated soil and ground water from former Reilly Tar and Chemical Corp. site in St. Louis Park. Acid Deposition Control Act passed.	MPCA begins program to identify toxic air pollutants. State Superfund law enacted. Cleanup begins on two major hazardous waste sites, FMC Fridley and the 3M-Oakdale dump. MPCA begins study of underground storage tanks. MPCA encourages reporting of arsenic caches; pickup and disposal follows. MPCA authorized to eliminate waste tire dumps. Ambient ground-water monitoring begins. Legislature requires MPCA certificates of need for new solid waste landfills. Conservation Foundation ranks Minnesota first in nation in environmental effort.	Agency adopts plan to control acid rain, a national first. Permits issued requiring separated storm and sanitary sewers in Twin Cities by end of 10 years. MPCA authorized to conduct hazardous-waste regulatory program in lieu of EPA. Cleanup agreement reached regarding former Reilly Tar and Chemical Corp. hazardous waste site in St. Louis Park. Pilot household hazardous-waste collection programs conducted. MPCA investigates extent and risk of lead contamination of soils. Williams Pipeline explodes in Mounds View; two people die in fire. State enacts new laws to control pipelines, underground tanks, polluted runoff, household hazardous waste; replenishes funds for wastewater treatment grants, state superfund.

THE MPCA FUTURE

"We, the people, are the polluters. As a society, we can determine quality of life we want to maintain. After deciding, we must individually act to maintain that quality of life, and we must also be willing to pay the cost and to be involved."

Duane Dahlberg
Member, MPCA Board 1982-

As the MPCA moves beyond its second decade, it is clear that much progress has been made. A Conservation Foundation study report in 1984 indicated that its staff had found Minnesota ranking first among the states in its effort to provide a high-quality environment for its citizens.

But we today are very much aware of what yet needs to be done, and concern is great because the problems are less obvious. We fear what we cannot see — the invisible parts-per-billion in the air and water that could affect public health, the water pollution resulting not from the discharge at the end of a pipe but from the natural runoff of precipitation heedlessly allowed to carry pollution to our lakes and streams, and the acid rain that falls long distances from the source of air pollutants.

The MPCA must now extend its efforts to newly emerging problems while continuing its traditional pollution control programs. In many cases, these new problems are more difficult to solve, involving complex political, economic and cultural considerations as well as the technical. Information, advice and cooperation from all sectors of society will be necessary if the solutions are to be equitable and effective.

Minnesota residents care about their environment. Public support created the Agency and citizen support for its programs has enabled it to tackle new problems as they became evident. Survey results in a recent First Banks "Quality of Life Report" indicate that the public overwhelmingly opposes relaxing environmental standards.

That enduring public concern demands that the MPCA be unrelenting in its protection of Minnesota's environment. It has become increasingly apparent, however, that much pollution can be prevented best by the individual decisions of Minnesota residents. These decisions include how we will handle our wastes, how we travel, whether we use disposables or reusables and whether we care enough about our lakes and rivers to limit runoff pollution. The following page includes some suggestions on how you can help to combat pollution. With your assistance, we can help protect Minnesota's environment and the quality of life we enjoy.



Photo courtesy of Ramsey/Washington County Resource Recovery Project.

Household sorting of garbage into recyclable items is key to breaking the landfill habit.

Reduce your solid waste output

- Recycle your cans, bottles, paper and motor oil.
- Make a soil-enriching compost pile for leaves, clippings and kitchen scraps.
- Reduce your use of disposable products.
- Don't buy products in wasteful packaging. Buy returnable beverage containers, and fight litter.

Protect water resources

- Don't waste water. Fix leaky faucets promptly and run washers only with full loads. Don't water lawns and gardens wastefully.
- Go easy on fertilizers. Overapplied fertilizers can fertilize algae and weeds when they get into lakes and streams. Use a fertilizer low in phosphorous.
- Make sure your septic system is working properly and not polluting your own well or a nearby lake.
- Join the MPCA's Citizen Lake-Monitoring Program and help collect water quality information on your favorite lake. Call (612) 296-6300.
- Avoid placing hazardous wastes in your trash. Use them up, give them away, or save them for a household hazardous waste collection program.

Keep the air clean

- Avoid unnecessary driving and keep your car tuned — the car is still our worst air polluter. Walk, ride the bus, bike, form car pools.
- Conserve electricity. Even the best power plants are potential polluters.
- If you have a wood-burning stove, be sure you admit enough air for it to burn at a high temperature. Don't burn garbage or trash.

Be a watchdog

- Report pollution problems and suspected violations to the MPCA or your local officials. Call the MPCA at 296-6300 in the Twin Cities metropolitan area or toll-free 1-800-652-9747 outside the metro area, or call your regional MPCA office.

Support strong pollution control laws

- Lawmakers need to know that you care about a clean environment.



Some 400 Minnesotans help the MPCA measure water quality in their favorite lakes through the Citizen Lake-Monitoring Program.

Minnesota Pollution Control Agency
520 Lafayette Road North
St. Paul, Minnesota 55155
(612) 296-6300
Toll-free, 1-800-652-9747

Region I — Duluth
Duluth Government Service Center, Room 704
320 West Second Street
Duluth, MN 55802
(218) 723-4660

Region II — Brainerd
1601 Minnesota Street
Brainerd, MN 56401
(218) 828-2492

Region III — Detroit Lakes
Lake Avenue Plaza
714 Lake Avenue, Suite 220
Detroit Lakes, MN 56501
(218) 847-1519

Region IV — Marshall
RLC Building
109 South Fifth Street
Marshall, MN 56258
(507) 537-7146

Region V — Rochester
2116 Campus Drive S.E.
Rochester, MN 55904
(507) 285-7343

Clean Cars Minnesota

MPCA proposed new air quality rules to reduce greenhouse gas emissions from passenger vehicles, Minnesota Rules, 7023 – rules concepts

Introduction

This document provides an overview of what the Minnesota Pollution Control Agency (MPCA) is considering for the Clean Cars Minnesota rulemaking. Clean Cars Minnesota is intended to reduce greenhouse gas (GHG) and other harmful air pollutant emissions from passenger vehicles by adopting the Low Emission Vehicles (LEV) and Zero Emission Vehicles (ZEV) standards adopted by the California Air Resources Board, as allowed under section 177 of the Clean Air Act (CAA).

The MPCA is at the initial stage of the rulemaking process and is sharing proposed concepts for a new rule. This document will help readers understand the potential rules being considered and the reasons for those rules so that people may provide comments. Topics where input is specifically requested are highlighted, but comments are welcomed on any or all of this rule concept. Instructions on how to submit comments are provided at www.pca.state.mn.us/air/clean-cars-mn-rulemaking.

Purpose of the rulemaking

The main focus of the Clean Cars Minnesota rulemaking is to reduce GHG emissions from passenger vehicles. Minnesota statute 116.07 directs the MPCA to "adopt standards of air quality, including maximum allowable standards of emission of air contaminants from motor vehicles" and more broadly, standards "relevant to the prevention, abatement, or control of air pollution." GHGs are harmful air pollutants that contribute to global climate change. MPCA therefore has the authority under Minnesota statute to regulate emissions of GHGs from motor vehicles.

In addition, the Next Generation Energy Act (NGEA), Minnesota statute 216H.02, subd. 1 establishes a statewide goal "to reduce statewide greenhouse gas emissions across all sectors producing those emissions to a level at least 15 percent below 2005 levels by 2015, to a level at least 30 percent below 2005 levels by 2025, and to a level at least 80 percent below 2005 levels by 2050." Minnesota did not meet its 2015 goal and is not on track to achieve the 2025 or 2050 goals. Transportation is the largest emitter of GHGs in Minnesota and passenger vehicles are the largest source of GHG emissions within that sector. State-level regulation is needed in order to achieve the necessary emission reductions in this sector. The Clean Cars Minnesota rulemaking would help get the state on track to achieve its statutory goals.

This rulemaking would reduce tailpipe emissions of not just GHGs, but also other harmful air pollutants, including fine particles and the pollutants that form ground-level ozone. MPCA and the Minnesota Department of Health recently released the "Life and Breath" report that showed that fine particles and ground-level ozone contributed to roughly 2,000-4,000 deaths in Minnesota in 2013 as well as hundreds of increased hospital visits. Reducing emissions of these pollutants is therefore critical for protecting the health of Minnesotans. Reducing air pollution from vehicles is especially critical for addressing environmental justice. MPCA research shows that communities of color and lower-income communities are disproportionately exposed to pollution from vehicles because those communities are disproportionately located near busy roadways. Adopting this rule is necessary to help reduce exposures to these vulnerable and overburdened communities.

Clean Cars Minnesota is also about consumer choice and ensuring Minnesotans have more and better options for cleaner vehicles. The rule is intended to ensure that Minnesotans in all parts of the state can drive the cleanest vehicles, whether they drive a truck, an SUV, or a car. In addition, there are more electric vehicle (EV) models available in other states than can be easily acquired in Minnesota. Adopting Clean Cars Minnesota would mean that Minnesotans who wish to purchase and EV would have more options to choose from to meet their preferences and needs. Increasing the supply of EVs in the market may also help lead to more used EVs available in Minnesota, further increasing EV options for consumers, particularly people who are interested in used vehicles.

Background

The CAA gives the federal government responsibility for setting vehicle emissions standards for the country and bars states from setting their own standards. However, section 209 of the CAA allows California to set air emissions standards for motor vehicles that are more stringent than federal standards and section 177 allows other states to adopt those standards. California developed the LEV standard and the ZEV standard to reduce emissions of GHGs and other air pollutants. The Clean Cars Minnesota proposal would adopt both of these standards.

The LEV standard would require automobile manufacturers to deliver for sale in Minnesota only vehicles that meet the more stringent GHG and other air pollutant emissions standards established by California. The LEV standard applies to emissions of GHGs and other air pollutants for all passenger vehicles and gets more stringent every year. The LEV standard does not establish any requirements directly for vehicle owners and does not require a personal vehicle inspection program. LEV matches the current federal GHG emissions standards; however, the U.S. Environmental Protection Agency has proposed to weaken those standards starting in model year 2021. Adopting LEV would preserve the standards and protections that Minnesotans have been expecting.

The ZEV standard would require automobile manufacturers to deliver for sale in Minnesota a certain number of vehicles with ultra-low or zero tailpipe emissions each year, including battery electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen-fueled vehicles. These vehicles are collectively considered "zero emission vehicles" (ZEVs). Manufacturers are given ZEV credit quotas based on their average annual sales (i.e. big manufacturers must earn more credits annually than smaller ones), and the quotas get more stringent every year. Manufacturers generate different numbers of credits for delivering different types of vehicles for sale, based on vehicle technology and maximum range per charge. For instance, long-range full battery EVs receive the most credits while PHEVs with short electric ranges receive the least. Regular (non-plug-in) hybrids and highly efficient gas vehicles do not receive credits. Manufacturers can bank credits to meet requirements in future years and are able to buy and sell them from other manufacturers. The ZEV standard would result in additional ZEVs sold in Minnesota, but does not require any individual to purchase a ZEV.

The MPCA may consider adopting the LEV standard, the ZEV standard, both, or neither. Section 177 requires that implementation of California standards in another state can only begin after a minimum of two model years after the final adoption of the rules into state code. Since the CAA requires states wishing to adopt California's standards to do so exactly, Minnesota has no flexibility within the rules to adopt Minnesota-specific changes. To date, 13 states and the District of Columbia have adopted the LEV standard and 10 states have adopted both the LEV and ZEV standards.

State	LEV	ZEV
Colorado	X	X
Connecticut	X	X
Delaware	X	
Maine	X	X
Maryland	X	X
Massachusetts	X	X
New Jersey	X	X
New York	X	X
Oregon	X	X
Pennsylvania	X	
Rhode Island	X	X
Vermont	X	X
Washington	X	
District of Columbia	X	

Rulemaking concept and questions

The concepts described in this document are preliminary and may or may not occur. The MPCA will provide additional opportunity for review and comment if and/or when any rules are formally proposed.

Structure of the rules

The MPCA is considering adopting both the LEV and ZEV standards as part of the Clean Cars Minnesota rulemaking. Colorado is the most recent state to have adopted these standards. The MPCA is considering using Colorado's rule language as a model from which to develop our own. The following questions refer to Colorado's final rules (5 Code of Colorado Regulations 1001-24) (available under "Rulemaking Documents" at www.pca.state.mn.us/air/clean-cars-mn-rulemaking).

1. Generally, does the structure of Colorado's rule serve as a good model for Minnesota? What, if any, changes would you recommend to the language and structure of the rule to make it more straightforward?
2. The rule essentially incorporates the California regulations by reference (Part D – Incorporations by Reference, pages 10-13). The rest of the rule language at 5 CRR 1001-24 provides context to the incorporation by reference. Should Minnesota provide similar contextual rule language? If yes, what purpose would it serve? Or should Minnesota minimize rule language and simply adopt the rules by reference?

Initial credit bank

The one area of flexibility for implementing the ZEV standard is if or how Minnesota might allow manufacturers to establish an initial bank of ZEV credits prior to the first year of implementation. Since Minnesota would be adopting the ZEV standard much later than other states, manufacturers would be required to increase delivery of ZEVs much more quickly than they have in other states to meet their annual quotas. There are many more ZEV models available for sale around the country than there were when the ZEV standard was first adopted by most other states. This larger number of available models would assist the manufacturers in more rapidly increasing their delivery in Minnesota. Even with the number of available vehicles, it is possible some manufacturers may find it challenging to reach their quotas in the first years of the program. States that adopt the ZEV standard can develop mechanisms for manufacturers to start the program with some ZEV credits already in the bank, which would help ease them into the early years of the program. The MPCA has several questions about this potential flexibility:

3. Should Minnesota develop a mechanism to help manufacturers meet their quotas in the early years of the program? Why or why not?
4. Should Minnesota decide whether or not to develop such a mechanism based on an analysis? If so, what should Minnesota consider in such an analysis?
5. Colorado's ZEV rule includes a mechanism for manufacturers to bank EV credits prior to the start of the program (Subparts V.B-V.C., page 9 – see link above). It allows manufacturers to begin the program with an established bank of credits based on (1) a proportional number of credits to what they have in the bank in California and (2) sales of ZEVs for each manufacturer between the finalization of the rule and the beginning of implementation (2 years). Should Minnesota adopt the same strategy as Colorado? Are there changes we should make to it to adapt it for the Minnesota context?
6. Are there other mechanisms to ease into implementation of ZEV that the MPCA should consider?

Rulemaking analysis

The MPCA will analyze this rule for potential impacts and benefits, including health and cost impacts for all Minnesotans. The MPCA is also committed to analyzing this rule and addressing any potential disproportionate negative impacts on communities of color and/or lower income, as well as ensuring these communities benefit from this rulemaking.

Below is a list of potential topics the MPCA is considering analyzing to better understand the potential impacts of this rule on all Minnesotans, and especially on communities of color and lower income communities. Is this an appropriate list of areas to analyze? Are there other areas the MPCA should consider analyzing?

- Air pollution emissions and where these emissions occur
- Health co-benefits and where these occur
- Cost of purchasing and owning a vehicle
- Economic effects, including employment, economic output, and secondary impacts on other sectors of Minnesota's economy

The MPCA is considering using Colorado's regulatory analysis methodologies as a model from which to develop our analysis of costs and benefits. The following questions refer to Colorado's regulatory analysis documents (available under "Rulemaking Documents" at www.pca.state.mn.us/air/clean-cars-mn-rulemaking).

- Do you have any recommended changes to the methodology Colorado used for its regulatory analysis?
- Are there different data sources or models that the MPCA should use?
- Did Colorado use appropriate methods for calculating emissions and cost impacts?
- Are there additional topics, issues, or impacts that the MPCA should address in its analysis?

Extension
University of Missouri

Nitrogen in the Environment: Nitrate Poisoning

Reviewed March 2022

Reviewed by David Brune
Department of Agricultural Engineering

Scott C. Killpack and Daryl Buchholz
Department of Agronomy

Nitrate (NO^-) is a naturally occurring form of nitrogen found in soils. Nitrates result from the biological decay of plants, animals and organic matter. Nitrates in the soil can also result from nitrogen fertilizers and animal manure. Some nitrates in the soil come from the atmosphere through rain or snow. Nitrates are essential to plants for proper growth and development.

Nitrates are not held by soil particles and are easily moved by water. If soil and/or bedrock conditions allow, nitrates can be moved into groundwater. As a result, nitrates can sometimes be found in water at concentrations that can pose serious problems.

How does nitrate poisoning happen?

The greatest danger is for babies less than one year old. Small babies have a bacteria in their digestive tract that converts nitrate into nitrite, which is toxic. Nitrite reacts with a substance in the blood called hemoglobin. Hemoglobin is part of the red blood cell that transports oxygen to all parts of the body. When nitrites are present, hemoglobin will preferentially combine with nitrite instead of oxygen. The new substance formed is called methemoglobin and does not carry oxygen. As the amount of methemoglobin increases, the amount of oxygen in the blood decreases, eventually causing internal suffocation.

The most common symptom of nitrate poisoning is a bluish color to the skin, particularly around the eyes and mouth. The blood will also turn a chocolate-brown color, which reflects the lack of oxygen.

After six months to one year, the digestive system no longer contains the nitrate-converting bacteria. In older children and adults, nitrate is not changed to the toxic nitrite. It is absorbed and excreted by the body.

People are also exposed to nitrates in their diets. The average dietary intake of nitrate is 75 to 100 milligrams per day. Nitrate is mainly taken in through vegetables because it is a natural substance found in plants. Some common vegetables with high nitrate content include beets, celery, lettuce and spinach.

Nitrate water standards

Nitrates become a concern when they exceed the maximum safe standards established by public health agencies for safe drinking water by humans. The maximum standard for nitrate, when it is reported as **nitrate-nitrogen,** represents the proportion of nitrogen in the nitrate molecule and is set at 10 ppm. These two values are equivalent. They do not reflect more, or less, nitrate in water, but simply a difference in how nitrate is reported. Therefore, when interpreting a water analysis for nitrate, you must determine how the nitrate concentration is being reported so that the correct health standard can be applied.

Table 1
Maximum safe levels for nitrate in drinking water

Reported as	Maximum value in parts per million[1]
Nitrate-Nitrogen	10
Nitrate	45

[1]Example
One ppm of sugar in water would be equivalent to one ounce of sugar in 7,813 gallons of water.

The initial draft of this publication was written by Karen DeFelice, former associate extension agronomist; Nyle Wollenhaupt, former state extension agronomist; and Daryl Buchholz, state extension agronomist. This material is based upon work supported by the United States Department of Agriculture, Extension Service, under special project number 89-EWQI-1-9203.

An official website of the State of North Carolina How you know

NORTH CAROLINA
Department of Environmental Quality

Program Summary

Facts about North Carolina's Animal Feeding Operations Program:

The N.C. Department of Environmental Quality's Animal Feeding Operations Program has regulated animal operations (swine, cattle, horses and liquid waste treatment system poultry) and established siting requirements for application setbacks from property boundaries and perennial streams since 1992.

Animal operations are defined by General Statute 143-215.10B as feedlots involving more than 250 swine, 100 confined cattle, 75 horses, 1,000 sheep, or 30,000 poultry with a liquid waste management system.

North Carolina has the strongest permit program for concentrated animal feeding operations in the country and is one of the only states that requires annual inspections of every facility. The state's permitting requirements for animal feeding operations in North Carolina can be found here (/about/divisions/water-resources/permitting/animal-feeding-operations/permits-applications-and-reporting). Nearly all of the permitted swine facilities are covered by the N.C. Swine Waste Management System General Permit, which is valid for five years and was renewed in 2014 following extensive public involvement. The general permit contains the required performance standards, operation and maintenance requirements, monitoring and reporting requirements, policy for

inspections and entry to the farms, general conditions and the penalty policy. Each general permit is issued with a Certificate of Coverage that is permittee-specific and designates the permitted number and type of animals.

All permitted animal operations are required to have a Certified Animal Waste Management Plan (CAWMP) that has been developed by a Certified Technical Specialist. The CAWMP is incorporated into the permit by reference and defines the fields to which the waste is applied, the crops to be grown and other details of the operation. All waste must be applied at no greater than agronomic rates – an amount that can be used productively by the crops planted.

In 1997, North Carolina implemented a moratorium on new and expanded swine farms. That moratorium was made permanent in 2007 for farms that use anaerobic waste lagoons as primary waste treatment. Currently, any new or expanding swine farm must meet five performance standards. These standards are further detailed in the North Carolina Administrative Code, 15A NCAC 02T .1307-.1308 and 15A NCAC 02D .1808. Therefore, the 2014 General Permit for swine are renewal permits for previously existing operations only.

For more Information click here (/water-animal-waste-state-permit/download)

USGS Study

The North Carolina Division of Water Resources (DWR) partnered with the U.S. Geologic Survey to design and implement a study of nitrogen profiles in watersheds adjacent to animal operations in Eastern North Carolina. DWR used grant money to help fund half of the study, in which USGS scientists took water samples from 54 agricultural sites in the Coastal Plain area in order to assess water-quality differences among streams draining watersheds with and without concentrated animal feeding operations, or CAFOs.

The study did not find any evidence that water quality standards were violated as a result of concentrated animal feeding operations (CAFOs) in the area. However, it serves to provide additional scientific information on how CAFOS impact water quality. DEQ is taking the findings of the report under consideration as the CAFO program moves forward and evolves.

Results of the study were released June 23, 2015. A full copy of the report, “Surface-Water Quality in Agricultural Watersheds of the North Carolina Coastal Plain Associated with Concentrated Animal

Feeding Operations," is available online at http://pubs.usgs.gov/sir/2015/5080/ (http://pubs.usgs.gov/sir/2015/5080/).

North Carolina's general statutes for animal operations:

- 143-215.10B defines the threshold for facilities requiring a permit.
- 143-215.10C establishes applications and permitting requirements.
- 143-215.10D addresses operation reviews to be conducted by Division of Soil & Water Conservation.
- 143-215.10E establishes violations that require immediate notification.
- 143-215.10F establishes the requirement for annual inspections on all permitted animal operations.
- 143-215.10G establishes permit fees.
- 143-215.10H requires facilities to register the name of the integrator with which they are affiliated.
- 143-215.10I establishes the performance standards for new/expanding swine farms.

Documents

- Water Animal Waste State Permit (/water-animal-waste-state-permit/open)

Cases, Causes, and Impacts of Safety Incidents at AD Systems

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Workshop of Manure Management and Utilization Technologies (6)
– Anaerobic Digestion Topics Part 3
Bio Town Ag. Reynolds, IN 47980, USA
March 10, 2023

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Introduction

- Anaerobic digestion (AD) offers many benefits:
  - Generate energy
  - Reduce environmental pollution
  - Produce organic fertilizer
  - Increase revenue
  - …
  - BUT AD can also pose serious risks to health, life, and property.



- Objectives of this study:
  - NOT to paint a negative image of AD
  - BUT to
    - Raise awareness
    - Understand causes and impacts
    - Promote a safe and sustainable use of AD



www.chemtrack.org/News-Detail.asp?TID=2&ID=37

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Methods

- Data collection:
  - Literature review
  - Internet search: Google ™, Google Scholar ™, Web of Science ™
  - Conversations with AD extension workers
- Database building:
  - Software: MS Excel, EndNote ™
  - Data coding: Dates, locations, circumstances, fatalities, injuries, damages, victims' genders and ages, etc.
- Data analysis:
  - Sources of event reporting
  - Geographical distribution
  - Chronological distribution
  - Causes and impacts
  - Measures to mitigate the risks

???...



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Case Sources in 3 Continents

Europe
- Scholarly publications
- News media

North America
- News media

Asia
- News media
- Scholarly publications
- Final project report & personal communication



Maps from Wikipedia.com

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Cases in Europe



Map from Wikipedia.com

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169 Cases in Europe (1995–2014)

12% (20 cases) of the 169 were major accidents (*major emission, fire, or explosion leading to serious danger to human health or the environment*).

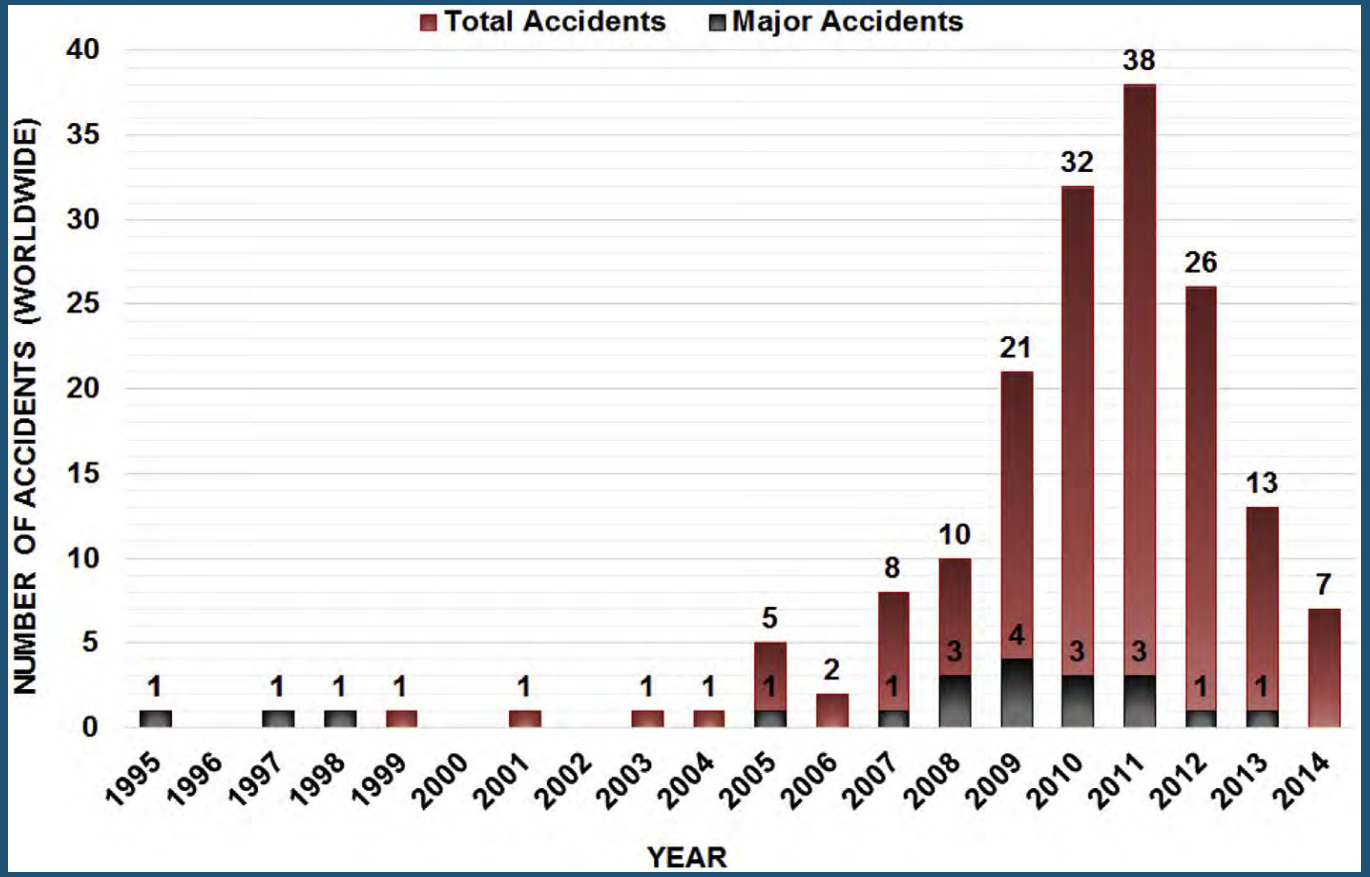

Casson Moreno et al. 2016. Renewable Energy. 96, 1127-1134.

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169 Cases in Different Countries

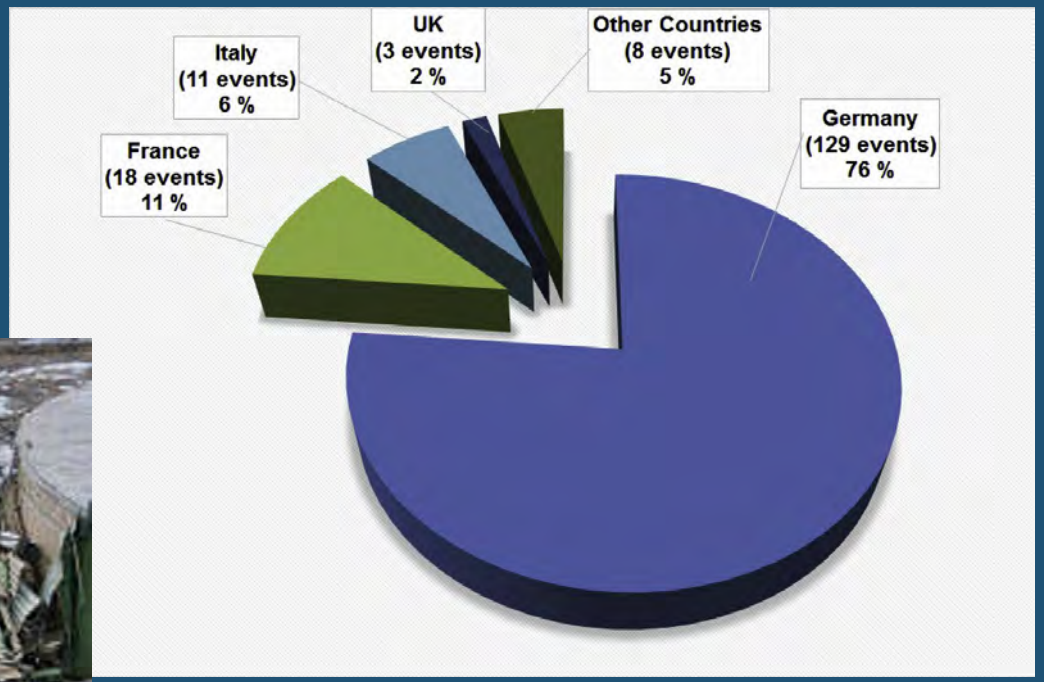

Countries of the 169 cases

Casson Moreno et al. 2016. Renewable Energy. 96, 1127-1134.



Damage in an AD incident

Jenkins et al., 2013. Loss Prevention Bulletin (229), 19-24.

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208 Cases in Europe (2006–2016)

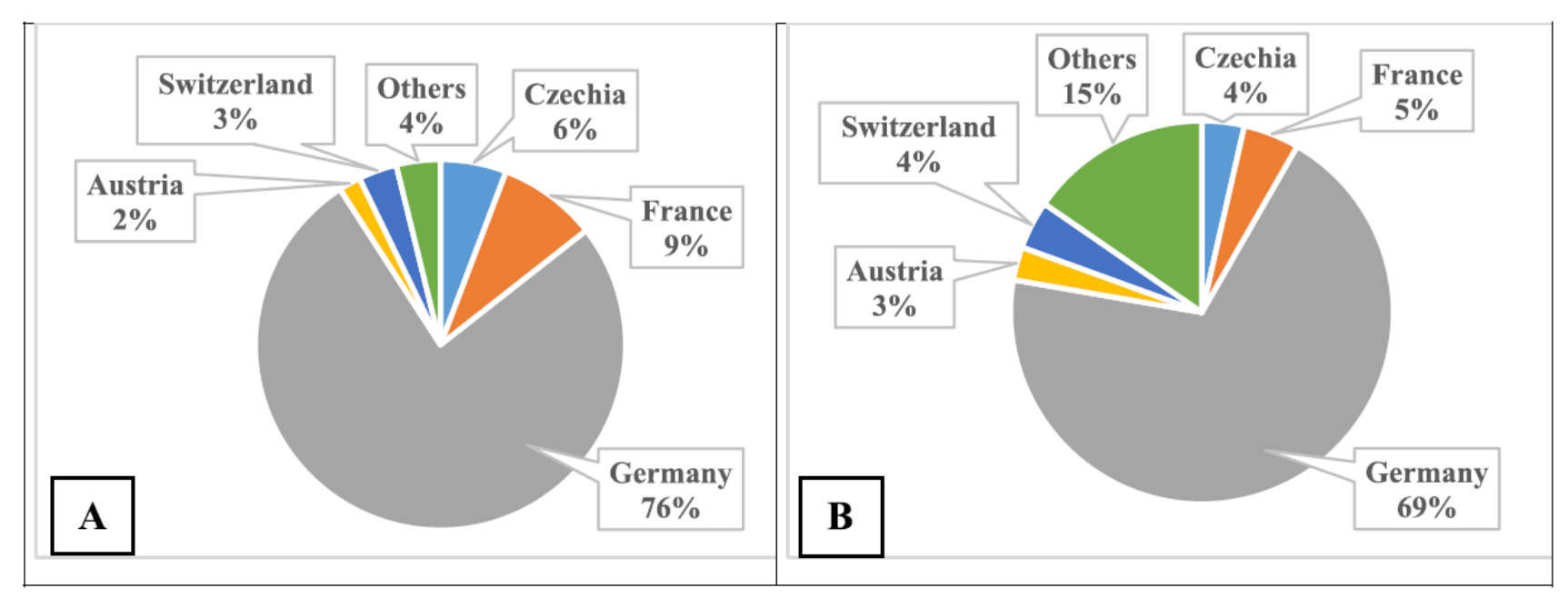

Share of accidents in individual countries of 208 events (A). Share of individual countries in the total number of biogas stations in 2015 (B).

Travnicek et al. 2018. Renewable Energy. 122, 89-97

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2 Additional Cases Before 1995

1. In 1976 a concrete biogas digester exploded in Åkeshov (Sweden).
2. Aug. 22, 1990, a biogas digester exploded at Vejle WWTP (Denmark).





Aftermath of the accident on August 22, 1990, in Denmark.

Hedlund, 2017. 25th Eur. Biomass Conf. pp. 1804-1814.

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2 More 2015 Cases in Denmark

1. Aug. 6, 2015, several people were overcome by hydrogen sulfide at Hashøj Biogas while unloading food waste.
2. Nov. 29, 2015, a storm severely damaged the exterior insulation on digesters at Holsted biogas.



In the facility of Hashøj Biogas where several people were injured on Aug. 6, 2015.

Hedlund, 2017. 25th Eur. Biomass Conf. pp. 1804-1814.
Hedlund and Madsen, 2018. J. Chem. Health & Safety. 25 (6), 13-21.

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7 Other Cases in Denmark

1. Dec. 2, 1999, at Ribe, a severe storm caused a digester to collapse. The digester damaged a neighboring tank, probably another digester, and partly crushed to buildings.
2. Late Jul. 2002, a lightning strike had damaged the flare at Blåbjerg biogas causing leaked foul biogas for at least 1½ weeks.
3. Sep. 2, 2005, a covered tank with degassed manure from a biogas digester "exploded“ at Hemmet.
4. Mar. 20, 2007, the outer protective membrane of a double membrane gas storage holder collapsed in a storm at Hashøj biogas .
5. May 20, 2009, a biogas powered public transportation bus caught fire at Jernbane Allé, Vanløse.
6. Early Sep. 2013 a silo with dried sludge exploded at Bjergmarken WWTP.
7. May 25, 2014, a biogas storage “burned down” in Thorsø.

Hedlund, 2017. 25th Eur. Biomass Conf. pp. 1804-1814.

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2 Cases in England and Hungary

Dec. 3, 2020, Avonmouth, Bristol, England. Wesset Water's anaerobic digester explosion killed four people.

https://www.industrytap.com/what-may-have-caused-the-avonmouth-anaerobic-digester-explosion/55634



2021, Hungary: Explosion in the Nyírbátor Biogas Plant - three people died.

Daily News Hungary · Bátor Média · Oct 14, 2021

Cases in USA (North America)



Map from Wikipedia.com

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4 Cases in USA (2011–2016)

1 April 17, 2011, Linwood, New York. Noblehurst Farms lost its digester, in an early morning fire.
https://www.manuremanager.com/noblehurst-farms-loses-digester-in-fire-3731/

2 July 2012, Oakley Farm in Aumsville, Oregon. An explosion at the anaerobic manure digester.
https://www.oregonlive.com/pacific-northwest-news/2012/07/methane_fueled_explosion_at_au.html

3 Aug. 6, 2014, Town of Vienna, Wisconsin. An explosion destroyed the roof of a 1.25-million-gallon manure digester.
https://www.manuremanager.com/manure-digester-explosion-in-wisconsin-sparks-fire-15850/

4 Nov. 2016, Lowell, Michigan. Lowell Energy AD digester exploded due to a buildup of methane gas, resulted in a ruptured tank cover, a lingering odor and spilled waste.
https://www.waste360.com/safety/michigan-biodigester-explodes-methane-gas-buildup

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3 Cases in USA in 2017 & 2018

5 Jan. 22, 2017, International Paper in Cantonment, Florida. An explosion caused significant structural damage to the largest pulp digester as well as the power house at the mill.
http://www.northescambia.com/2017/01/my-heart-sank-mill-manager-speaks-out-about-explosion-future-of-ip

6 Jan. 2018, Missouri. Gas build-up leads to explosion at Blue River Wastewater Treatment Plant, Part of the building collapsed.
https://www.kshb.com/news/local-news/gas-build-up-leads-to-explosion-at-blue-river-wastewater-treatment-plant

7 Aug. 30, 2018, Chicago. An explosion at a water reclamation plant in appears to have been caused by methane gas ignited by a worker's welding torch.
https://www.wateronline.com/doc/explosion-at-chicago-water-reclamation-plant-injures-0001

2 Cases in USA in 2020 & 2021

8 April 2020. Jay, Maine.
A paper mill disabled by a dramatic explosion.

No one was injured but 230 workers were left without jobs.

The mill will close in the first quarter of 2023.

https://apnews.com/article/explosions-maine-susan-collins-angus-king-4dfd183575a0f364a4545bec0e1132e6



Photo from AP News.
https://apnews.com/article/391dfff9b3768186d3ad318fa30f11fb/gallery/8139f20f69904163b8ebe9756ecea959

9 June 8, 2021, Stockton, Iowa. Bob Baenziger Jr., 54, died while performing a dive to repair a broken cable at the bottom of a million-gallon anaerobic digester tank at Sievers Family. *(From multiple source, including https://www.desmoinesregister.com/story/news/2021/07/30/diver-robert-baenziger-jr-drowns-iowa-farm-accident/5427513001/)*

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Cases in Asia



Map from Wikipedia.com

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143 Cases in Asia (1958–2022)

Cases and losses

- Total cases: 143 (all “major accidents”)
- Fatalities: 266
- Injuries: 219
- Total property damages: unknown, but huge

Victims

- Male : female = 5.5 : 1
- Minimum age: 3-year-old
- Maximum age: 75-year-old

Cases in two digester types:

- ~73.2% at household digesters
- ~26.8% at industrial digesters

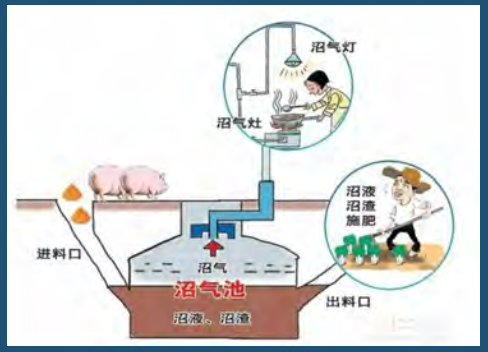

Household digester

https://www.sohu.com/a/323140642_120034261



Industrial digesters

Ni, Unpublished data. Do not cite.

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Geographical Distribution

Cases in five countries and one region

- China: 111 (77.6%)
- Vietnam: 12 (8.4%)
- Thailand: 11 (7.9%)
- India: 7 (4.9%)
- Malaysia: 1 (0.7%)
- Taiwan: 1 (0.7%)

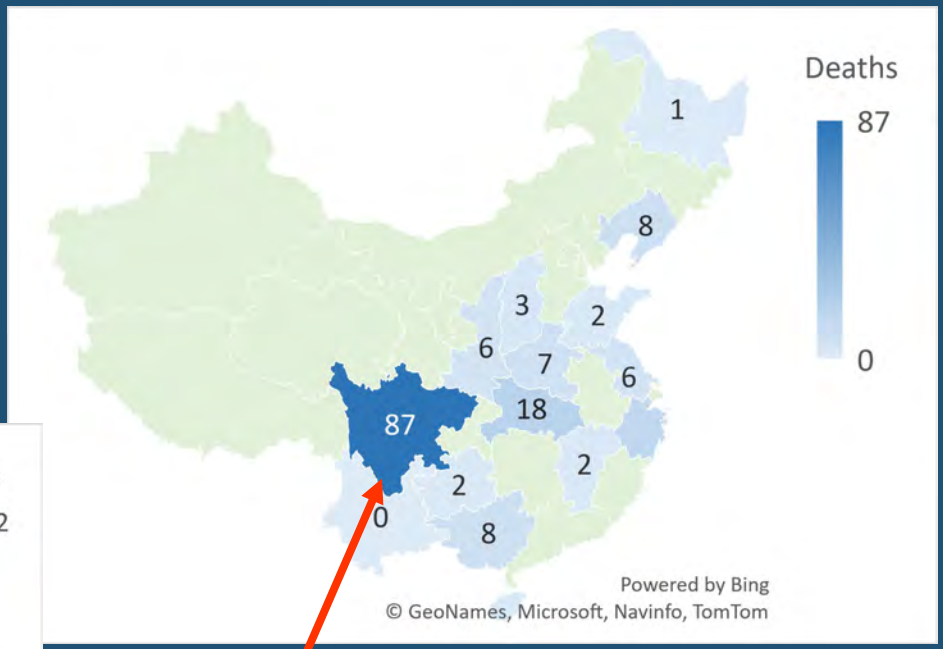

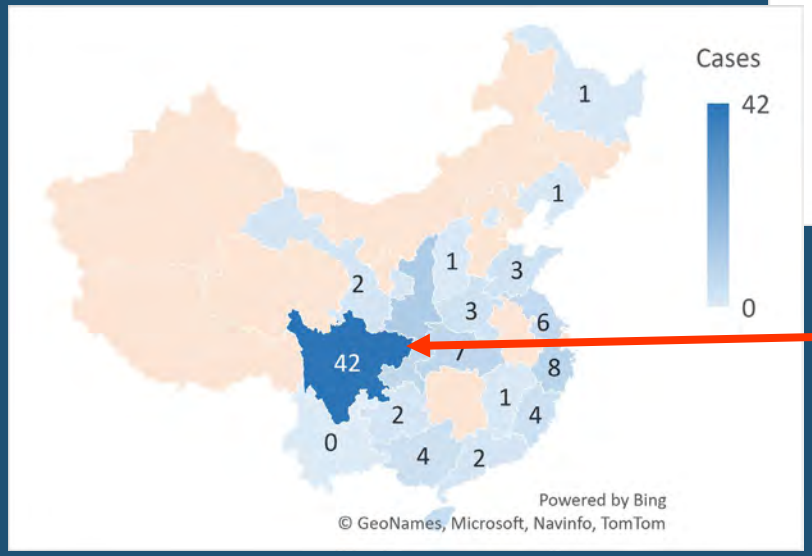

Sichuan Province in China had the largest numbers of cases and deaths.

Ni, Unpublished data.

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Chronological Distribution

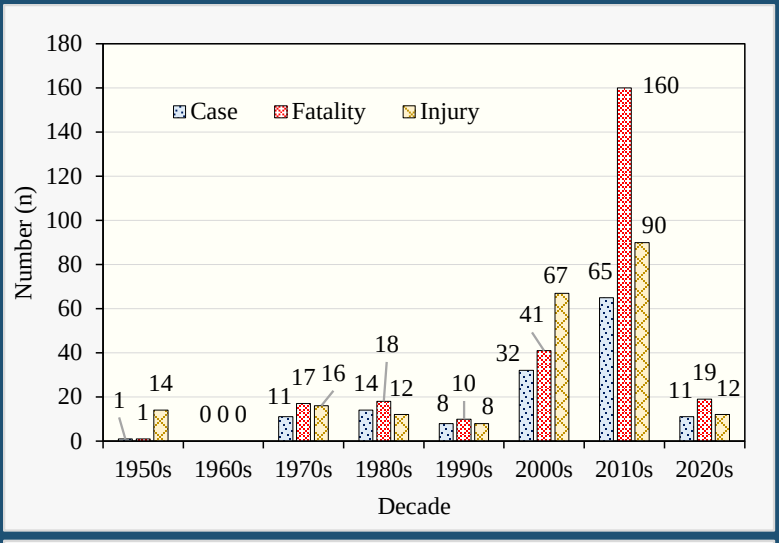

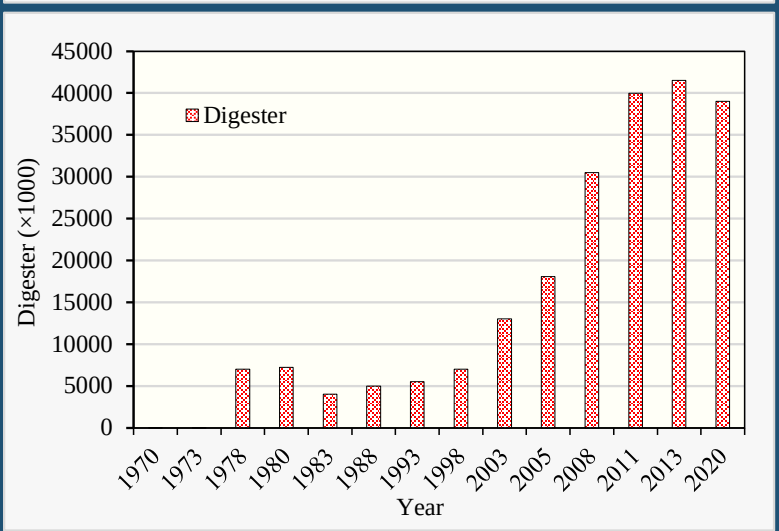

Cases & damages in 8 decades.

- An increasing trend.
- Highest in the 2010s.
- 11 cases in recent <3 years.

Number of digesters in China.

- Shows some similar patters with Asian cases.

Ni, Unpublished data.

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Acute Poisoning and Explosion

- Poisoning by inhaling hydrogen sulfide (H_2S), 80.6% of all cases.
- Explosions by welding or other work at digesters, and fires by inappropriate use of biogas for cooking, and a lightning strike, 19.4% of all cases.



Poisoning in 2018, China.
https://www.sohu.com/a/233521492_420076

Incidents occurred while:

- Maintaining and repairing digester systems.
- Rescuing other victims in digesters.
- Rescuing animals fallen into digesters.
- Recovering lost items (such as cell phones) from digesters.



Explosion in 2013, India.
https://www.indiatvnews.com/news/india/

Ni, Unpublished data.

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Status of Digesters at Incidents

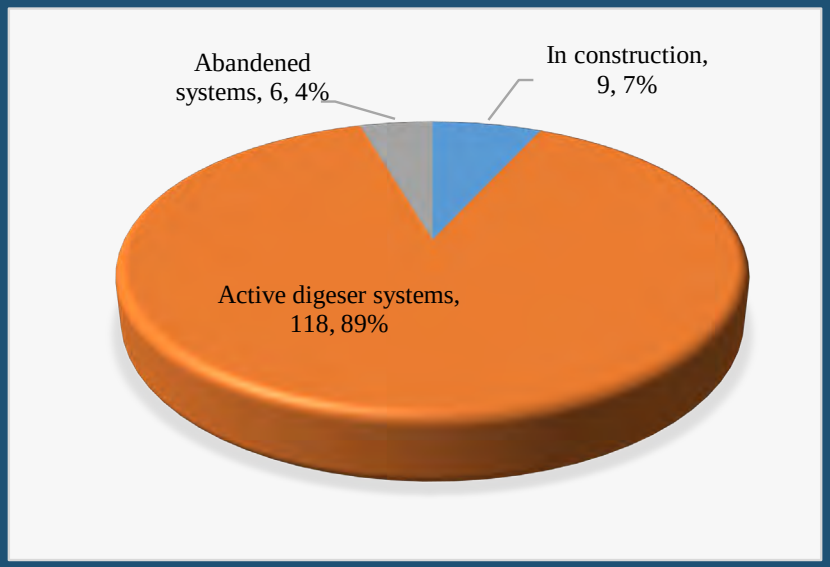

Ni, Unpublished data.

Incidents occurred:

- 89% at active digester systems.
- 7% at digesters in construction.
- 4% at abandoned digesters.



An abandoned household digester in China that claimed 3 lives

Chen, 2015. Deyang Evening News.

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Summarized Causes

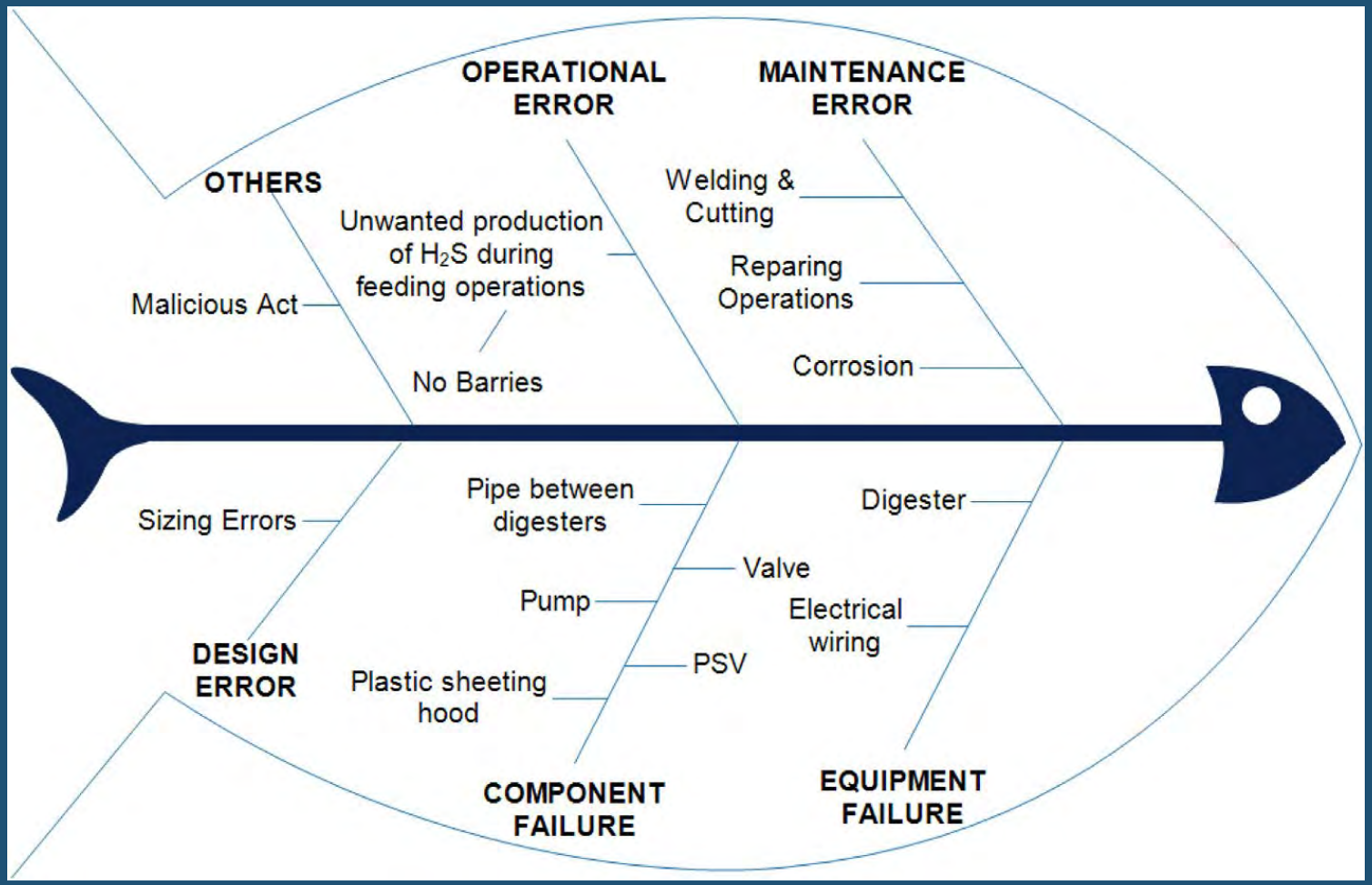

Casson Moreno et al. 2016. Renewable Energy. 96, 1127-1134.

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Economic Impact

- Property damage
- Medical expense
- Loss due to death, burial costs
- Loss of earnings or business
- Loss of employment and benefits
- Replacement service loss
- …

Two examples

- An incident in Thailand (2/25/2011 Chaiyaphum Province): ~ US$ 670,000.
- An explosion in China (2018): US$ 584,495, but not clear if the deaths of three workers were included.



Three people in a family died in this covered lagoon digester in 2019 in Thailand.

https://www.thairath.co.th/news/local/south/1580255?fbclid=IwAR3wGctDO7UxZxeY3_IPkBRTwwK9krGoxGAF18qrW532YAn7whIm41eBs_I

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Individual and Family Impact

Death and/or injury causes:

- Emotional trauma and mental health problem.
- Suffering from injuries.
- Loss of family supporter and social welfare.
- Decrease in quality of life.
- Altered family dynamics and relationships.

- No systematic study was found.

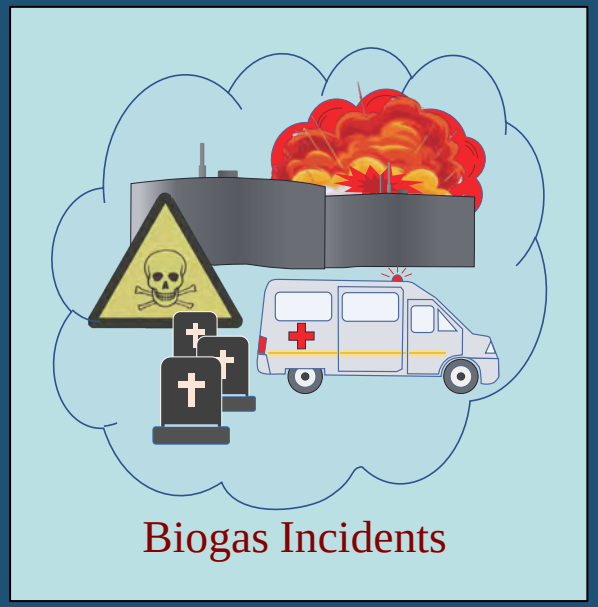

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Social Impact

- Shock waves in local community and beyond.
- Negative images of biogas technology.
- Depression of employees and work fellows.
- Political turmoil.
- Follow-up safety measures.

- No systematic study was found.



https://www.lcasp.org.vn/vi/news/phong-tranh-su-co-tu-ham-biogas-314.htmlhttps://www.lcasp.org.vn/vi/news/phong-tranh-su-co-tu-ham-biogas-314.html

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Key Recommendations

- A high level of safety is built into the processes.
- Ventilation systems are fit for purpose.
- Take account of potential for biogas accumulation.
- Process control systems in biogas handling areas are fit for purpose.
- Safe vehicle movements are factored.
- Give more attention to integrating and optimizing design and control systems.

Jenkins et al., 2013. Loss Prevention Bulletin (229), 19-24.

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AgSTAR – AD Safety Practices

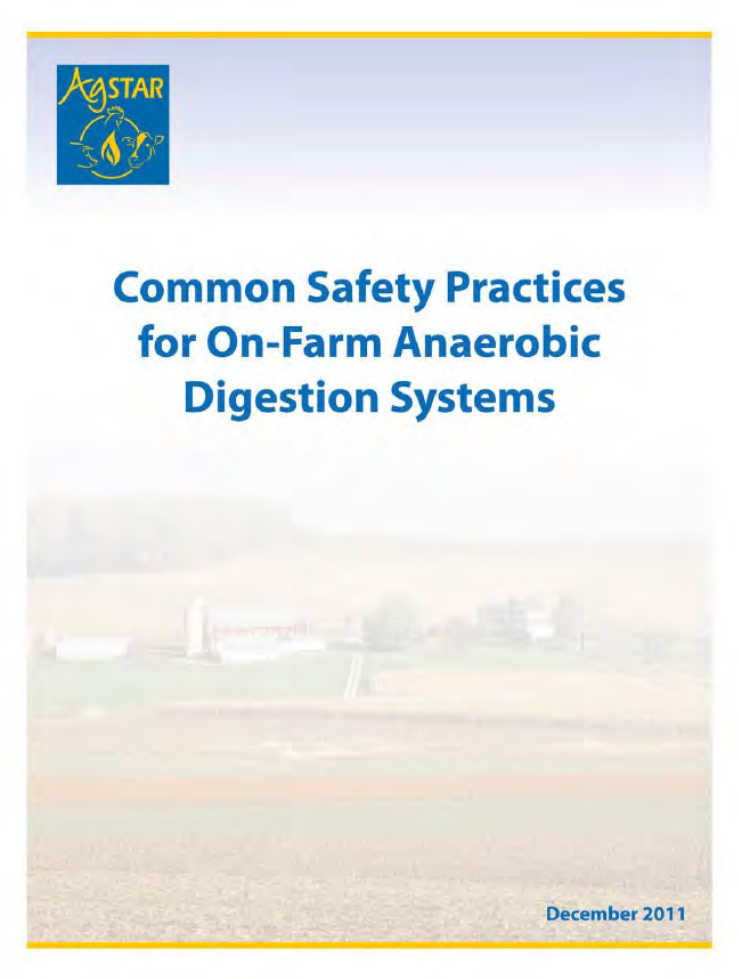

AgSTAR Biogas Toolkit

The U.S. Environmental Protection Agency (EPA) Biogas Toolkit serves as a centralized knowledge hub for biogas project stakeholders. The toolkit is designed to allow stakeholders to search and browse for information and resources that meet their specific project needs.

https://www.epa.gov/agstar/biogas-toolkit

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Conclusions

- Actual cases are believed more than what were reported.
- Cases in Europe, USA, and Asia had their own characteristics.
- Most of the cases in Europe and USA were explosion and fire.
- No much detail is available for the U.S. cases.
- Acute hydrogen sulfide poisoning caused most of the deaths and injuries in Asia.
- Most accidents occurred during maintenance and repair of digesters.
- The accidents resulted in large impacts, which need more studies.
- Safety practices are critical to mitigate the risks.

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CAFOs *and* Environmental Justice

The Case *of* North Carolina

The home of a minority family in Kenansville, North Carolina, situated next to a concentrated animal feeding operation, or CAFO. Dust, odors, and manure from CAFOs can reach nearby residents' homes, including their laundry.
©2013 Donn Young Photography

On the coastal plain of eastern North Carolina, families in certain rural communities daily must deal with the piercing, acrid odor of hog manure—reminiscent of rotten eggs and ammonia—wafting from nearby industrial hog farms. On bad days, the odor invades homes, and people are often forced to cover their mouths and noses when stepping outside. Sometimes, residents say, a fine mist of manure sprinkles nearby homes, cars, and even laundry left on the line to dry.[1]

Today's industrial-scale farms—called concentrated animal feeding operations (CAFOs)—house thousands of animals whose waste is periodically applied to "spray fields" of Bermuda grass or feed crops.[2,3] The waste can contain pathogens, heavy metals, and antibiotic-resistant bacteria,[4,5] and the spray can reach nearby homes and drinking water sources. The odor plume, which often pervades nearby communities, contains respiratory and eye irritants including hydrogen sulfide and ammonia.[6,7,8] A growing body of research suggests these emissions may contribute not only to mucosal irritation[9] and respiratory ailments[10] in nearby residents but also decreased quality of life,[11] mental stress,[12,13] and elevated blood pressure.[14]

Although the Midwest is the traditional home for hogs, with Iowa still the top-producing state, North Carolina went from fifteenth to second in hog production between the mid-1980s and mid-1990s.[15] This explosive growth resulted in thousands of CAFOs located in the eastern half of the state—squarely in the so-called Black Belt, a crescent-shaped band throughout the South where slaves worked on plantations.[16,17] After emancipation many freed slaves continued to work as sharecroppers and tenant farmers. A century later, black residents of this region still experience high rates of poverty, poor health care, low educational attainment, unemployment, and substandard housing.[18,19]

The clustering of North Carolina's hog CAFOs in low-income, minority communities—and the health impacts that accompany them—has raised concerns of environmental injustice and environmental racism.[20] As one pair of investigators explained, "[P]eople of color and the poor living in rural communities lacking the political capacity to resist are said to shoulder the adverse socio-economic, environmental, or health related effects of swine waste externalities without sharing in the economic benefits brought by industrialized pork production."[21] Although North Carolina is not the only area with environmental justice concerns vis-à-vis CAFOs, it has become one of the best studied.

Environmental Injustice?

One of the misunderstandings about environmental racism, in particular, is that the term suggests malicious or at least discriminatory intent in terms of locating hazards. Although that may exist in some cases, several studies have argued that industry or government simply followed the "path of least resistance" in choosing sites where people were less likely to object or land was cheap.[22,23] The situation nevertheless results in environmental injustice if minority populations are disproportionately affected, no matter the reason.[24]

From a scientific perspective, hundreds of studies have documented disparities in the location of environmental hazards relative to race and class, and, further, in the extent and timeliness of remediative actions.[25,26,27,28] "Environmental justice science [seeks to] understand how burden disparities lead to exposure, risk, and health disparities," says Sacoby Wilson, a University of Maryland environmental health professor.

Debates still exist over the relative importance of race versus socioeconomic status[29] and whether hazards are disproportionately sited in regions where minorities and impoverished people live, or whether communities change after polluting facilities move in. Most studies suggest the former.[22,30] However, research also suggests that people who can afford to move away from environmental hazards often do, increasing disparities.[30]

East Carolina University sociology professor Bob Edwards says he had heard environmental justice groups claiming disparities in the siting of hog farms and industry



This resident of Kenansville usually wears a facemask when he's in his yard because of the dust from the neighboring CAFO. Most studies suggest that communities already have high levels of poverty and large percentages of minority residents when CAFOs are built there. People who can afford to move away often do.
© 2013 Donn Young Photography



Another Kenansville resident stands in his front yard, feet from the CAFO across the street. Donn Young, the North Carolina–based photographer who took these images, says of his time in Kenansville, "I encountered problems with my eyes—itchy, watering, something akin to allergies." To the people who live there, CAFOs are simply a fact of everyday life.
© 2013 Donn Young Photography

proponents denying them when he realized it was an empirical question. "There was no real research at the time," he says. So in 2000 he began a study with collaborator Anthony E. Ladd of the Loyola University Department of Sociology. They found that even when controlling for regional differences, urbanization level, property value, and attributes of the labor force, eastern North Carolina counties with larger minority populations were home to greater concentrations of hog waste, a function of hog population density, compared with more urbanized counties with a higher percentage of white residents.[21] Another North Carolina study later reported

What Is Environmental Justice?

Environmental justice refers to both a social movement and a field of scientific research. As a movement, it is a marriage of civil rights and environmentalism, emerging in 1982 when black citizens lay down on the road to stop the government from dumping 120 million pounds of soil contaminated with polychlorinated biphenyls in Warren County, North Carolina.[74] Although the Warren County waste site ultimately was established,[75,76] the protests captured the nation's attention.

The study of environmental justice began in earnest in 1983, when the Government Accountability Office (then known as the General Accounting Office) investigated the racial composition of communities near four hazardous waste sites in the Southeast, three of which were located in predominantly black communities where at least 26% of the population lived below the poverty level.[77] In 1987 the first national study to analyze the issue with multivariate statistics found that even after controlling for household income, housing values, amount of hazardous waste generated in an area, and other factors, the percentage of minority residents in a zip code proved the greatest predictor of hazardous waste facility siting. Zip codes with hazardous waste sites had double the percentage of minority residents compared with those with none, and zip codes with more than one facility had triple the percentage of minority residents.[74]

By the early 1990s, the federal government first acknowledged environmental justice with a working group that published the report *Environmental Equity: Reducing Risks for All Communities*.[78] Soon after, the Environmental Protection Agency created the Office of Environmental Equity, since renamed the Office of Environmental Justice. The agency defines environmental justice as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies."[79]

nine times more hog CAFOs in areas where there was more poverty and higher percentages of nonwhite people even after adjusting for population density as a measure of rural location and cheaper land.[20]

Edwards has also reported that large hog operations forced small farmers out of business.[31] As the industry consolidated, the primary slaughterhouse in North Carolina refused to accept hogs in lots of fewer than 1,000.[32] With the exception of the slaughterhouse, the industry does not create many working-class jobs and sometimes creates major rifts in the social fabric of communities between proponents and opponents of local CAFOs.[31,33,34,35]

A Brief History of Swine

For centuries, animal husbandry operated much like a farm in a cartoon: pigs wallowing in mud, chickens wandering about pecking the ground, and cows grazing on grass, with a barn to store hay and feed. Farms were largely sustainable; they generally did not deplete the soil, water, or land resources needed to maintain the farm for the next generation. The waste from the animals helped grow the next year's crops.

Today, the vast majority of America's 1 billion–plus food animals slaughtered annually[36] are raised in CAFOs.[37] John Ikerd, professor emeritus of agricultural economics at the University of Missouri, says farms have changed over his long career in three main ways. First, today's farms specialize in growing one crop or in one phase of production; in the hog industry there are facilities for breeding sows, raising piglets to about 40 pounds, and finishing operations, where animals are raised to the point of slaughter. Second, large corporations ("integrators") contract with individual farmers to raise animals and set precise standards for what the animals eat, their housing conditions, and the antibiotics and hormones they receive. Finally, there's been a consolidation of control and ownership that, as mentioned, has forced small farmers out of business and altered local economies and communities.[31,32]

The hog industry in North Carolina changed rapidly starting in the 1970s, when Wendell Murphy applied the CAFO model, already used for poultry, to swine.[38] As a successful hog farmer, Murphy was elected to the North Carolina House of Representatives in 1983 and to the state Senate in 1988, where he sponsored and helped to pass legislation—dubbed "Murphy's laws"—that eliminated sales tax on hog farm equipment and prevented local authorities from using zoning authority to deal with odor issues.[39,40]

The industry's rapid growth in the state followed the passage of these bills, causing a major shift in the state's hog farming. In 1982

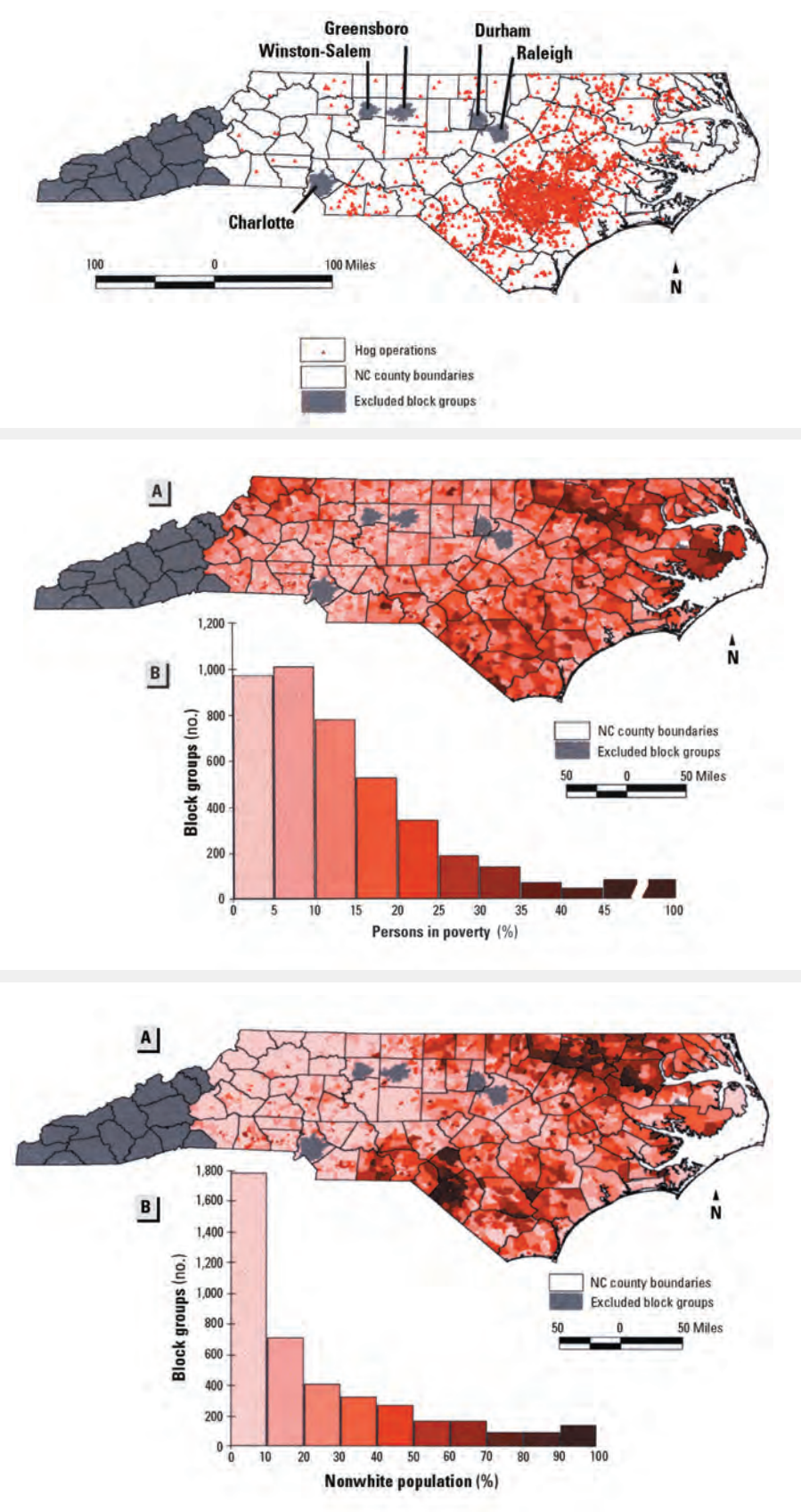

Maps from an older study show distributions of poverty, minority residents, and hog CAFOs in North Carolina as of 1998–2000. Little has changed appreciably since then.
Source: Wing et al. (2000)[20]

every county in North Carolina but one had a commercial hog farm; by 1997, 95% of hog farms were located in the eastern counties of the coastal plain.[32]

Today the North Carolina hog herd, all told, numbers around 9–10 million animals annually, according to the state Department of Agriculture and Consumer Services.[41] This results in an enormous amount of manure, with each hog producing an estimated four to eight times as much feces as a human.[32,42] In 2008 the Government Accountability Office reported that some 7.5 million hogs in five eastern North Carolina counties produced an estimated 15.5 million tons of waste per year, and that in one year a single 80,000-head facility could create 1.5 times the waste of the city of Philadelphia.[43]

The lagoons in which this waste is stored contain pathogens such as *Salmonella*, insecticides, antimicrobial agents and other pharmaceuticals, and nutrients that cause widespread pollution and impairment of watersheds across the coastal plain.[44,45,46] Much concern has been raised over antibiotic-resistant bacteria that result from CAFO animals' near-continual exposure to subtherapeutic doses of antibiotics as an inexpensive means to prevent disease and promote growth.[47,48]





Upper: CAFOs apply accumulated animal waste to spray fields of Bermuda grass or field crops located around the barns and lagoons. Lower: Hogs are packed tightly inside CAFOs like this one in Princeton, North Carolina.

© 2013 Donn Young Photography

Whereas human sewage is treated with chemical and mechanical filtration before being released into the environment, CAFOs channel waste from hog houses into pits or lagoons, where it is stored untreated until it is applied to land. All lagoons leach to some degree,[49,50,51] and during hurricanes and storms they can overflow or burst, spilling raw sewage onto the landscape and into waterways. In 1995 an eight-acre lagoon ruptured, spilling 22 million gallons of manure into North Carolina's New River, killing millions of fish and other organisms; other spills followed that summer.[52,53] Even without spills, ammonia and nitrates may seep into groundwater, especially in the coastal plain where the water table is near the surface.[32,54]

Odors, Plumes, and Toxics

Although more research is needed on the impact of CAFO emissions on susceptible groups of people,[10] studies have linked hog odors and air pollution from the associated odor plume with adverse effects on health and quality of life.[55] Wilson, who has documented environmental justice issues surrounding hog farms in North Carolina and Mississippi, explains that CAFO emissions go beyond bad smells. "It's much more complex than that," he says. "You have exposures through air, water, and soil. You have … inhalation, ingestion, and dermal exposures. People have been exposed to multiple chemicals: hydrogen sulfide, particulate matter, endotoxins, nitrogenous compounds. Then you have a plume that moves; what gets into the air gets into the water. You have runoff from spray fields. These are complex exposure profiles."

University of North Carolina epidemiology professor Steve



Hog waste being applied to sprayfields near Warsaw, North Carolina. Nutrients, pathogens, heavy metals, and other potentially toxic agents in the waste can make their way into local watersheds, with implications for drinking water and aquatic ecosystems.
© 2013 Donn Young Photography

Wing and colleagues have reported that waste odor frequently prevents local residents from spending time outdoors, opening windows, putting laundry out to dry, or inviting visitors over.[9,56] In the Community Health Effects of Industrial Hog Operations study, a repeated-measures, community-driven project, Wing and colleagues enrolled 102 individuals in 16 communities to sit outside twice a day, recording odor strength and symptoms such as eye irritation and difficulty breathing. Participants self-monitored aspects of their physical health, including blood pressure and lung function, and also used mobile air pollution monitors to collect data on levels of hydrogen sulfide, endotoxin, coarse particulate matter (PM_{10}), and semivolatile compounds in particle phase within each neighborhood.

The researchers found that hydrogen sulfide levels were strongly related to odor.[57] Furthermore, measures of odor, endotoxin, hydrogen sulfide, and PM_{10} were associated, variously, with increased respiratory difficulty, sore throat, chest tightness, nausea, and eye irritation,[58] whereas hydrogen sulfide and semivolatile particles were linked to reports of feeling stressed, annoyed, nervous, and anxious.[13]

Most recently, Wing reported associations between blood pressure increases and increased odor and hydrogen sulfide.[14] "In this primarily African-American population, in a region that is known historically as the Stroke Belt because of very high rates of death from cerebrovascular disease, we don't need environmental exposures that are leading to additional blood pressure increases," Wing says.

Because these communities are typically impoverished and lack political clout, they often have little means to fight back.[59] "It creates a major burden on communities when they have few legal protections," says Wilson. However, getting communities involved in data collection has empowered citizens.[59] "When we train residents to do sampling, they understand the science of the process," says Wilson. "They can go to the town council, they can go to the media, they can explain it. That's powerful. It helps build up a community's ability to be more involved in decision making."

Who Looks After Residents' Health?

The shift to CAFOs happened so fast that regulations and laws protecting human health and the environment have not caught up with the changing face of animal husbandry. A 2013 report revealed that despite the highly localized health impacts associated with CAFOs, local and state health departments generally do not have jurisdiction over them; instead, that responsibility is typically held by state environmental or natural resource agencies.[60] Jillian Fry, a researcher at the Johns Hopkins Center for a Livable Future who was lead author on that report, says, "The agencies responsible for regulating CAFOs—their mission is not to protect human health."

Fry says the study was inspired by a CAFO expansion meeting she attended with a colleague. A proponent of the expansion stood up at the meeting and stated that if hog farms caused health concerns, the health department would make the community aware; therefore, there was nothing to worry about. "I knew … that the health department was not involved, so we wanted to see what the situation was in other parts of the country," Fry says.

She and her colleagues interviewed health department staff in eight states and found that most health departments did not deal with CAFO issues. Either they lacked the jurisdiction, had no budget or expertise, or were dealing with political pressure. Fry says, "Even if a health department thinks this is a really important issue, we're hearing from a lot of them, 'We're aware of the science, we



Piles of what is believed to be poultry litter in a field near New Bern, North Carolina. A state moratorium on new hog CAFOs has resulted in the construction of more poultry CAFOs, according to researcher Steve Wing.
© 2013 Donn Young Photography

know of the problem, but it's the political barriers.'"

The survey also found that community members did not get very far with inquiries. "We asked community members, 'Was there ever a time you contacted a health department and they addressed your complaint?' They all said no," says Fry. "They were almost always referred to another agency, or maybe they would look into it and hit a barrier."

An Eye to the Future

With accumulating scientific evidence over the environmental and community health impacts of hog CAFOs and extensive media coverage of ruptured lagoons, opposition crescendoed in the mid-1990s. In 1997 North Carolina passed a law prohibiting the expansion of existing hog operations and placing a temporary moratorium on new hog CAFOs,[61] although permits in the hopper were approved. The moratorium became permanent in 2007 with the Swine Farm Environmental Performance Standards Act, which banned new lagoons and mandated that any new or expanded CAFOs must use environmentally superior technologies (ESTs) to substantially reduce emissions and prevent waste discharges into surface and ground waters.[62] The 2007 law provided for a substantial cost-share for operators to upgrade their lagoons and implement ESTs, yet only 11 of 2,200 have applied, and only 8 have participated.[63,64]

Although the act limited growth of new hog facilities, it didn't clean up existing ones, says Wing. Local residents still deal daily with odor and pollutants in the vicinity of hog farms. The moratorium also catalyzed other changes whose impact is yet to be fully realized. "More poultry facilities have been built," Wing says. "That brings up other issues such as the spread of microbes between species."

Another milestone occurred when Smithfield Foods, Inc., entered into an agreement with the state Attorney General in 2000 after dozens of lagoons ruptured during Hurricane Floyd, resulting in Clean Water Act violations.[65] Smithfield Foods agreed to pay $15 million toward research on ESTs and $50 million toward environmental enhancement.[66,67] Premium Standard Farms, a subsidiary of Smithfield Foods, later voluntarily added $2.1 million toward the agreement for EST research and development.[68] If an EST were found to be both economically feasible and environmentally superior in five categories, the companies agreed to implement it at each of the farms they owned, although not at farms they subcontracted. (Mike Williams, director of the Animal and Poultry Waste Management Center at North Carolina State University and supervisor of the agreement, says an estimated 5–10% of North Carolina hog farms are company-owned.)

After phase 1 of development, only one of the new technologies examined—the Super Soil System (since renamed Terra Blue)—met all five environmental standards, but it was deemed uneconomical. Improvements made during phase 2 reduced the cost but not enough to meet the economic criteria. The project is now in the final weeks of phase 3. "If the process shows that it does meet bona fide EST status and economic criteria, then the agreement states [farms have a certain] amount of time to implement," Williams says.

In 2011 the state passed a bill that allows hog CAFOs to upgrade their buildings without needing to upgrade their waste management systems or use ESTs, counter to the previous decade's mandates.[69] Some critics have called this a loophole, given that the 2007 law stipulated hog farmers were supposed to implement ESTs if they wanted to increase herd size or install new buildings.[70]

At the same time, the handful of pioneers who are implementing ESTs are creating what could be the future of hog farming.[71] In one of those projects, Google has partnered with Duke University and Duke Energy to turn Yadkin County's Loyd Ray Farms into a sustainable operation that generates renewable energy and carbon offsets.[72] The 8,600-head finishing farm captures methane from its hog waste using an anaerobic digester. The methane provides fuel to run a microturbine that powers part of the farm and supports components that reduce odors, nutrients, pathogens, and heavy metals. Google and Duke University

share the carbon credits, while Duke Energy receives renewable energy certificates (credits for generating renewable energy that are sold separately from the actual electricity produced[73]). Although projects like these so far make up only a tiny fraction of the market, their experimental approach could lead the way toward hog farms becoming better neighbors.

Wendee Nicole, based in Houston, TX, has written for *Nature*, *Scientific American*, *National Wildlife*, and other magazines.

REFERENCES AND NOTES

1. Wing S. Social responsibility and research ethics in community-driven studies of industrialized hog production. Environ Health Perspect 110(5):437–444 (2002); http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1240831/.
2. Zublena JP, et al. Soil Facts: Swine Manure as a Fertilizer Source. Publication AG-439-4. Raleigh, NC:North Carolina Cooperative Extension Service (updated Dec 1997). Available: http://goo.gl/BmEvj [accessed 22 May 2013].
3. EPA. Managing Manure Nutrients at Concentrated Animal Feeding Operations. Washington, DC:U.S. Environmental Protection Agency (Aug 2004). Available: http://tammi.tamu.edu/final-manure-guidance.pdf [accessed 22 May 2013].
4. Lowman A, et al. Land application of treated sewage sludge: community health and environmental justice. Environ Health Perspect 121(5):537–542 (2013); http://dx.doi.org/10.1289/ehp.1205470.
5. Marks R. Cesspools of Shame: How Factory Farm Lagoons and Sprayfields Threaten Environmental and Public Health. Washington, DC:Natural Resources Defense Council and Clean Water Network (2001). Available: http://goo.gl/o0lhr [accessed 22 May 2013].
6. Wilson SM, Serre ML. Examination of atmospheric ammonia levels near hog CAFOs, homes, and schools in eastern North Carolina. Atmos Environ 41(23):4977–4987 (2007); http://dx.doi.org/10.1016/j.atmosenv.2006.12.055.
7. NRC. The Scientific Basis for Estimating Air Emissions from Animal Feeding Operations: Interim Report. Washington, DC:Committee on Animal Nutrition, National Research Council (2002). Available: http://goo.gl/oX1hD [accessed 22 May 2013].
8. Ciganek M, Neca J. Chemical characterization of volatile organic compounds on animal farms. Veterinarni Medicina 53(12):641–651 (2008); http://www.vri.cz/en/publications/+dt-73.
9. Wing S, Wolf S. Intensive livestock operations, health, and quality of life among eastern North Carolina residents. Environ Health Perspect 108(3):233–238 (2000); http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1637983/.
10. Thorne PS. Environmental health impacts of concentrated animal feeding operations: anticipating hazards—searching for solutions. Environ Health Perspect 115(2):296–297 (2007); http://dx.doi.org/10.1289/ehp.8831.
11. Schiffman SS, et al. The effect of environmental odors emanating from commercial swine operations on the mood of nearby residents. Brain Res Bull 37(4):369–375 (1995); http://www.ncbi.nlm.nih.gov/pubmed/7620910.
12. Bullers S. Environmental stressors, perceived control, and health: the case of residents near large-scale hog farms in eastern North Carolina. Hum Ecol 33(1):1–16 (2005); http://dx.doi.org/10.1007/s10745-005-1653-3.
13. Horton RA, et al. Malodor as a trigger of stress and negative mood in neighbors of industrial hog operations. Am J Public Health 99(suppl 3):S610–S615 (2009); http://dx.doi.org/10.2105/AJPH.2008.148924.
14. Wing S, et al. Air pollution from industrial swine operations and blood pressure of neighboring residents. Environ Health Perspect 121(1):92–96 (2013); http://dx.doi.org/10.1289/ehp.1205109.
15. Furuseth OJ. Restructuring of hog farming in North Carolina: explosion and implosion. Prof Geogr 49(4):391–403 (1997); http://dx.doi.org/10.1111/0033-0124.00086.
16. Baharanyi N, et al., eds. Focus on Black Belt Counties: Life Conditions and Opportunities. Proceedings of a Preconference of the 50th Annual Professional Agricultural Workers Conference, Tuskegee, AL, 5–6 Dec 1992. Tuskegee, AL and Mississippi State, MS:Tuskegee University and the Southern Rural Development Center (1993). Available: http://goo.gl/4iCrN [accessed 22 May 2013].
17. Wimberley DW. Quality of life trends in the southern Black Belt, 1980–2005: a research note. J Rural Soc Sci 25(1):103–118 (2010); http://goo.gl/crUCJ.
18. Calhoun SD, et al. Federal funds in the Black Belt. Rural Am 15(1):20–27 (2000); http://goo.gl/IMVmY.
19. Wimberley RC, Morris LV. The regionalization of poverty: assistance for the Black Belt South? South Rural Soc 18(1):294–306 (2002); http://goo.gl/9fxMz.
20. Wing S, et al. Environmental injustice in North Carolina's hog industry. Environ Health Perspect 108(3):225–231 (2000); http://www.ncbi.nlm.nih.gov/pmc/articles/79837958/.
21. Edwards B, Ladd AE. Race, poverty, political capacity and the spatial distribution of swine waste in North Carolina, 1982–1997. North Carolina Geogr (9):55–77 (2001); http://goo.gl/v6YyJ.
22. Mohai P, et al. Environmental justice. Annu Rev Environ Resour 34:405–430 (2009); http://dx.doi.org/10.1146/annurev-environ-082508-094348.
23. Pulido L. Rethinking environmental racism: white privilege and urban development in Southern California. Ann Assoc Am Geogr 90(1):12–40 (2000); http://dx.doi.org/10.1111/0004-5608.00182.
24. Attempts to get comment from the National Pork Producers Council and the North Carolina Pork Council on this question were not answered.
25. Brown P. Race, class, and environmental health: a review and systematization of the literature. Environ Res 69(1):15-30 (1995); http://dx.doi.org/10.1006/enrs.1995.1021.
26. Bryant B, Mohai P, eds. Race and the Incidence of Environmental Hazards: A Time for Discourse. Boulder, CO:Westview Press (1992).
27. Ringquist EJ. Assessing evidence of environmental inequities: a meta-analysis. J Policy Anal Manage 24(2):223–247 (2005); http://dx.doi.org/10.1002/pam.20088.
28. Anderton DL, et al. Environmental equity: the demographics of dumping. Demography 31(2):229–248 (1994); http://dx.doi.org/10.2307/2061884.
29. Evans GW, Kantrowitz E. Socioeconomic status and health: the potential role of environmental risk exposure. Annu Rev Public Health 23:303–331 (2002); http://dx.doi.org/10.1146/annurev.publhealth.23.112001.112349.
30. Brulle RJ, Pellow DN. Environmental justice: human health and environmental inequalities. Annu Rev Public Health 27:103–124 (2006); http://dx.doi.org/10.1146/annurev.publhealth.27.021405.102124.
31. Edwards B, Ladd AE. Environmental justice, swine production and farm loss in North Carolina. Sociol Spectr 20(3):263–290 (2000); http://dx.doi.org/10.1080/027321700405054.
32. Edwards B, Driscoll A. From farms to factories: the environmental consequences of swine industrialization in North Carolina, 1982–2007. In: Twenty Lessons in Environmental Sociology (Gould K, Lewis T, eds.). New York, NY:Oxford University Press (2008).
33. Pew Commission on Industrial Farm Animal Production. Putting Meat on the Table: Industrial Farm Animal Production in America. Philadelphia, PA and Washington, DC:The Pew Charitable Trusts (2008). Available: http://goo.gl/us9XR [accessed 22 May 2013].
34. DeLind LB. Social consequences of intensive swine production: some effects of community conflict. Culture Agric 26(1–2):80–89 (2004); http://dx.doi.org/10.1525/cag.2004.26.1-2.80.
35. LeDuff C. At a slaughterhouse, some things never die: who kills, who cuts, who bosses can depend on race. How Race Is Lived in America [special series]. The New York Times, online edition (16 Jun 2000). Available: http://goo.gl/ME4lH [accessed 22 May 2013].
36. USDA. Livestock Slaughter [website]. Washington, DC:National Agricultural Statistics Service, U.S. Department of Agriculture (updated 25 Apr 2013). Available: http://goo.gl/L3swQ [accessed 22 May 2013].
37. Farm Forward. Factory Farming [website]. Portland, OR:Farm Forward (2013). Available: http://goo.gl/CqQxM [accessed 22 May 2013].
38. Starmer E, Wise TA. Living High on the Hog: Factory Farms, Federal Policy, and the Structural Transformation of Swine Production. Medford, MA:Global Development and Environment Institute, Tufts University (Dec 2007). Available: http://goo.gl/MIBNh [accessed 22 May 2013].
39. Stith P, Warrick J. Murphy's laws: for Murphy, good government means good business. Raleigh News & Observer (22 Feb 1995). Available: http://www.pulitzer.org/archives/5897 [accessed 22 May 2013].
40. McKown AM. Hog Farms and Nuisance Law in *Parker v. Barefoot*: Has North Carolina Become a Hog Heaven and Waste Lagoon? Agriculture Law Research Article. Fayetteville, AR:The National Agricultural Law Center. Available: http://goo.gl/IQ5V5 [accessed 22 May 2103].
41. NCDACS. 2012 North Carolina Agricultural Statistics. Raleigh, NC:North Carolina Department of Agriculture and Consumer Services/National Agricultural Statistics Service, U.S. Department of Agriculture (2012). Available: http://goo.gl/s3TXX [accessed 22 May 2013].
42. Thu KM, Durrenberger EP. Pigs, Profits and Rural Communities. Albany, NY:State University of New York Press (1998). Available: http://goo.gl/u0khB [accessed 22 May 2013].
43. GAO. Concentrated Animal Feeding Operations. EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern. GAO-08-944. Washington, DC:U.S. Government Accountability Office (Sep 2008). Available: http://www.gao.gov/new.items/d08944.pdf [accessed 22 May 2013].
44. Burkholder JM, et al. Impacts of waste from concentrated animal feeding operations on water quality. Environ Health Perspect 115(2):308–312 (2007); http://dx.doi.org/10.1289/ehp.8839.
45. Burkholder JM, et al. Impacts to a coastal river and estuary from rupture of a large swine waste holding lagoon. J Environ Qual 26(6):1451–1466 (1997); http://dx.doi.org/10.2134/jeq1997.00472425002600060003x.
46. Gerba CP, Smith JE Jr. Sources of pathogenic microorganisms and their fate during land application of wastes. J Environ Qual 34(1):42–48 (2005); http://goo.gl/zWjhW.
47. Silbergeld EK, et al. Industrial food animal production, antimicrobial resistance, and human health. Annu Rev Public Health 29:151–169 (2008); http://dx.doi.org/10.1146/annurev.publhealth.29.020907.090904.
48. Gibbs SG, et al. Isolation of antibiotic-resistant bacteria from the air plume downwind of a swine confined or concentrated animal feeding operation. Environ Health Perspect 114(7):1032–1037 (2006); http://dx.doi.org/10.1289/ehp.8910.
49. Huffman RL, Westerman PW. Estimated seepage losses from established swine waste lagoons in the lower coastal plain of North Carolina. Trans ASAE 38(2):449–453 (1995).
50. Westerman PW, et al. Swine-lagoon seepage in sandy soils. Trans ASAE 38(6):1749–1760 (1995).
51. Huffman RL. Seepage evaluation of older swine lagoons in North Carolina. Trans ASAE 47(5):1507–1512 (2004); http://goo.gl/hhZgH.
52. Burns JD. The Eight Million Little Pigs—A Cautionary Tale: Statutory and Regulatory Responses to Concentrated Hog Farming. Fayetteville, AR:The National Agricultural Law Center, University of Arkansas (1996). Available: http://goo.gl/bA6LJ [accessed 22 May 2013].
53. EPA. Animal Waste Disposal Issues. Washington, DC:Office of Inspector General, U.S. Environmental Protection Agency (1997). Available: http://www.epa.gov/oig/reports/1997/hogexsm.pdf [accessed 22 May 2013].
54. Warrick J, Stith P. New studies show that lagoons are leaking: groundwater, rivers affected by waste. Raleigh News & Observer (19 Feb 1995). Available: http://www.pulitzer.org/archives/5893. [accessed 22 May 2013].
55. Cole D, et al. Concentrated swine feeding operations and public health: a review of occupational and community health effects. Environ Health Perspect 108(8):685–699 (2000); http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1638284/.
56. Tajik M, et al. Impact of odor from industrial hog operations on daily living activities. New Solut 18(2):193–205 (2008); http://dx.doi.org/10.2190/NS.18.2.i.
57. Wing S, et al. Air pollution and odor in communities near industrial swine operations. Environ Health Perspect 116(10):1362–1368 (2008); http://dx.doi.org/10.1289/ehp.11250.
58. Schinasi L, et al. Air pollution, lung function, and physical symptoms in communities near concentrated swine feeding operations. Epidemiology 22(2):208–215 (2011); http://dx.doi.org/10.1097/EDE.0b013e3182093c8b.
59. Wing S, et al. Community based collaboration for environmental justice: south-east Halifax environmental reawakening. Environ Urban 8(2):129–140 (1996); http://dx.doi.org/10.1177/095624789600800214.
60. Fry JP, et al. Investigating the role of state and local health departments in addressing public health concerns related to industrial food animal production sites. PLoS ONE 8(1):e54720 (2013); http://dx.doi.org/10.1371/journal.pone.0054720.
61. General Assembly of North Carolina. S.L. 1997-458. HB 515: Clean Water Responsibility Act. Effective 27 Aug 1997. Available: http://goo.gl/rkl9C [accessed 22 May 2013].
62. General Assembly of North Carolina. House DRH30306-SB-6: Swine Farm Env. Performance Standards/Funds. Effective 1 Jul 2007 and 1 Sept 2007. Available: http://goo.gl/6Eyc8 [accessed 22 May 2013].
63. NCDACS. 2012 Annual Report on the Implementation of the Lagoon Conversion Program. 2012 Semi-annual Report on the Pilot Program for the Inspection of Animal Waste Management Systems. Raleigh, NC:Division of Soil and Water Conservation, North Carolina Department of Agriculture and Consumer Services (9 Oct 2012). Available: http://goo.gl/kuK94 [accessed 22 May 2013].
64. Karan A. Pigs, Profit, Planet: North Carolina Farmers' Perspectives on Waste Lagoon Conversion [undergraduate honors thesis]. Durham, NC:Sanford School of Public Policy, Duke University (Dec 2011). Available: http://goo.gl/fzf4Y [accessed 22 May 2013].
65. Wing S, et al. The potential impact of flooding on confined animal feeding operations in eastern North Carolina. Environ Health Perspect 110(4):387–391 (2002); http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1240801/.
66. Development of Environmentally Superior Technologies for Swine Waste Management per Agreements Between the Attorney General of North Carolina, Smithfield Foods, Premium Standard Farms and Frontline Farmers [website]. Raleigh, NC:Animal and Poultry Waste Management Center, College of Agriculture and Life Sciences, North Carolina State University. Available: http://goo.gl/ObcEn [accessed 22 May 2013].
67. Attorney General of the State of North Carolina. Agreement between the Attorney General of North Carolina; Smithfield Foods, Inc.; Brown's of Carolina, Inc.; Carroll's Foods, Inc.; Murphy Farms, Inc.; Carroll's Foods of Virginia, Inc.; and Quarter M Farms, Inc. Raleigh, NC:Office of the Attorney General, State of North Carolina (25 Jul 2000). Available: http://goo.gl/5s68N [accessed 22 May 2013].
68. Premium Standard Farms, Inc. Annual Report, Filed 5/16/2005 for Period Ending 3/26/2005. Kansas City, MO:Premium Standard Farms, Inc. (2005). Available: http://www.psfarms.com/PSF_FY_2005_10K.pdf [accessed 22 May 2013].
69. General Assembly of North Carolina. S.L. 2011-118. SB 501: An Act to Facilitate Improved Operations and Conditions at Certain Preexisting Swine Farms by Providing for the Construction or Renovation of Swine Houses at Those Farms. Effective 13 Jun 2011. Available: http://goo.gl/J5RMN [accessed 22 May 2013].
70. Bindell R. Hog Waste Is Dragging North Carolina Through the Manure [weblog entry]. http://www.foodandwaterwatch.org (11 May 2011). Available: http://goo.gl/TlK83 [accessed 22 May 2013].
71. Prasodjo D, et al. A Spatial-Economic Optimization Study of Swine-Waste Derived Biogas Infrastructure Design in North Carolina. Durham, NC:Duke University, Duke Carbon Offsets Initiative (April 2013). Available: http://goo.gl/cxFT7 [accessed 22 May 2013].
72. The Loyd Ray Farms Swine Waste-to-Energy Offsets Project [website]. Durham, NC:Duke University (2013). Available: http://goo.gl/Swyxw [accessed 22 May 2013].
73. EPA. Renewable Energy Certificates (RECs) [website]. Washington, DC:U.S. Environmental Protection Agency (updated 16 Oct 2012). Available: http://www.epa.gov/greenpower/gpmarket/rec.htm [accessed 22 May 2013].
74. United Church of Christ Commission for Racial Justice. Toxic Wastes and Race at Twenty: 1987–2007: A Report Prepared for the United Church of Christ Justice and Witness Ministries. Cleveland, OH:Justice and Witness Ministries, United Church of Christ (2007). Available: http://goo.gl/4AqvD [accessed 22 May 2013].
75. Bullard RD, ed. Unequal Protection: Environmental Justice and Communities of Color. San Francisco, CA:Sierra Club Books (1994).
76. The PCB dump was remediated in 2004. See: Bullard RD. Environmental Racism PCB Landfill Finally Remedied But No Reparations for Residents. Atlanta, GA:Environmental Justice Resource Center, Clark Atlanta University (12 Jan 2004). Available: http://goo.gl/Djih5 [accessed 22 May 2013].
77. GAO. Siting of Hazardous Waste Landfills and Their Correlation with Racial and Economic Status of Surrounding Communities. RCED-83-168. Washington, DC:U.S. General Accounting Office (1983). Available: http://www.gao.gov/assets/150/140159.pdf [accessed 22 May 2013].
78. EPA. Environmental Equity: Reducing Risks for All Communities. Washington, DC:U.S. Environmental Protection Agency (Jun 1992). Available: http://goo.gl/gey0u [accessed 22 May 2013].
79. EPA. Environmental Justice [website]. Washington, DC:U.S. Environmental Protection Agency (updated 20 May 2013) Available: http://goo.gl/lWgdL [accessed 22 May 2013].

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Erratum: "CAFOs and Environmental Justice: The Case of North Carolina"

The June 2013 News article "CAFOs and Environmental Justice: The Case of North Carolina" [Environ Health Perspect 121:A182–A189 (2013)] referred to farms that companies "co-own with farmers." These farms should have been referred to as "company-owned." *EHP* regrets the error.

2017 News & Events

Characterizing Emissions From Animal Feedlots

20 April 2017



A feedlot in northeastern Colorado. Photo: D. Bon

A team of scientists from CSD and the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder published a paper in *Atmospheric Chemistry and Physics* that characterizes the emissions from animal feedlots.

Scientists have long known that animal feedlots emit volatile organic compounds (VOCs) into the atmosphere. This is problematic because VOCs can react to form ozone and fine particles, affecting air quality and human health. Furthermore, these VOCs are responsible for the unpleasant odor from animal feedlots.

However, it wasn't well-understood how different activities within the feedlots contribute to VOC emissions – for example, to what extent emissions come from the animals and their waste, or from the storage and use of the feed. CSD scientists also looked to characterize the chemical composition of those VOCs specific to animal feedlots, which included a broad category of chemicals such as alcohols, carboxylic acids, and sulfur compounds.



The CSD van, outfitted with instruments to take measurements of methane, nitrous oxide and ammonia. Photo: J. Peischl, NOAA / CIRES

To better understand the sources and chemical compositions of the VOC emissions, CSD scientists made measurements from both their mobile laboratory and the NOAA WP-3D research aircraft. A new instrument on the aircraft and mobile laboratory allowed the scientists to get fast, high-resolution measurements of many different VOC chemicals as they sampled downwind from the feedlots.

The researchers looked at different kind of facilities and examined the chemical signatures of the VOCs and ammonia they emitted. The results show that VOC emissions mainly come from two sources: animals and their waste or feed storage and handling. However, the composition of what each source emits is different. For example, animals and their waste emit phenols and nitrogen-containing compounds such as ammonia, while the feed emits alcohols, carboxylic acids, and sulfur-containing compounds.

The researchers found that the same animals (cows) give off different VOCs depending on their diet and other practices. For example, across the Front Range, beef cattle had higher levels of emissions than dairy cattle. Also, there are sometimes complaints of unpleasant smells near large animal feedlots. The researchers found that sulfur-based compounds were the primary source of feedlot

odor for all types of animal feedlots, and these sulfur compounds are largely emitted by animal waste.

Industry practices (e.g. feed additives) affect odor and atmospheric chemistry in and around feedlots. These results suggest that a better understanding of these processes – the sources and chemical composition of VOCs – could help industry target specific compounds and mitigate the impacts of emissions on air quality and human health, without affecting the productivity of the industry.

Yuan, B., M.M. Coggon, A.R. Koss, C. Warneke, S. Eilerman, J. Peischl, K.C. Aikin, T.B. Ryerson, and J.A. de Gouw, Emissions of volatile organic compounds (VOCs) from concentrated animal feeding operations (CAFOs): chemical compositions and separation of sources, *Atmospheric Chemistry and Physics*, doi:10.5194/acp-17-4945-2017, 2017.

Abstract

Concentrated animal feeding operations (CAFOs) emit a large number of volatile organic compounds (VOCs) to the atmosphere. In this study, we conducted mobile laboratory measurements of VOCs, methane (CH_4) and ammonia (NH_3) downwind of dairy cattle, beef cattle, sheep and chicken CAFO facilities in northeastern Colorado using a hydronium ion time-of-flight chemical-ionization mass spectrometer (H_3O^+ ToF-CIMS), which can detect numerous VOCs. Regional measurements of CAFO emissions in northeastern Colorado were also performed using the NOAA WP-3D aircraft during the Shale Oil and Natural Gas Nexus (SONGNEX) campaign. Alcohols and carboxylic acids dominate VOC concentrations and the reactivity of the VOCs with hydroxyl (OH) radicals. Sulfur-containing and phenolic species provide the largest contributions to the odor activity values and the nitrate radical (NO_3) reactivity of VOC emissions, respectively. VOC compositions determined from mobile laboratory and aircraft measurements generally agree well with each other. The high time-resolution mobile measurements allow for the separation of the sources of VOCs from different parts of the operations occurring within the facilities. We show that the emissions of ethanol are primarily associated with feed storage and handling. Based on mobile laboratory measurements, we apply a multivariate regression analysis using NH_3 and ethanol as tracers to determine the relative importance of animal-related emissions (animal exhalation and waste) and feed-related emissions (feed storage and handling) for different VOC species. Feed storage and handling contribute significantly to emissions of alcohols, carbonyls, carboxylic acids and sulfur-containing species. Emissions of phenolic species and nitrogen-containing species are predominantly associated with animals and their waste.

References, Resources & More information:

Shale Oil and Natural Gas Nexus (SONGNEX) »

Agricultural Emissions Studies »

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REPORT

CAFOS: WHAT WE DON'T KNOW IS HURTING US



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Introduction

Corporate livestock facilities, known as concentrated animal feeding operations (CAFOs), threaten the health of communities and pollute the air and water.[1] CAFO-related pollution is more than a nuisance; it is dangerous. Manure from CAFOs contains more than 150 pathogens that have the potential to contaminate water supplies, while fumes and particulate matter elevate rates of asthma, lung disease, and bronchitis among farm workers and people living nearby.[2,3] Nitrates from animal manure poison drinking water sources and contribute to epic dead zones in sensitive aquatic habitats.[4] Confining large numbers of animals in close proximity requires routine antibiotic regimens, and this, in turn, exacerbates the global crisis of antibiotic resistance.[5]

The animal agriculture industry comprises hundreds of thousands of individual animal feeding operations (AFOs)—facilities that raise animals in confinement.[6] CAFOs are a subset of AFOs distinguished by their large size or their designation as significant polluters of surface waters.[7] CAFOs have become more prevalent as part of a decades-long trend of corporate consolidation and vertical integration across the livestock industry. Today the pork, broiler chicken, and beef sectors are all "highly concentrated" in the hands of three or four companies that exercise enormous market power—and control the practices used across these facilities.[8]

This power extends to the regulatory sphere as well. Although the Clean Water Act requires the U.S. Environmental Protection Agency (EPA) to regulate CAFOs, pressure from the corporate livestock industry led to a series of dubious administrative and court decisions in the 2000s that raised serious concerns about the EPA's willingness and capacity to effectively carry out this responsibility.[9]

A decade ago, the nonpartisan Government Accountability Office concluded that the EPA could not fulfill its regulatory duties under the Clean Water Act without accurate and facility-specific information about CAFOs.[10] The EPA, for its part, has admitted that "unlike many other point source industries, the EPA does not have facility-specific information for all CAFOs in the United States."[11]

This report and the accompanying resources are the culmination of NRDC's decadelong effort to understand just how much—or how little—the EPA knows about the



animal agriculture industry that it is supposed to regulate. Fearing that the EPA lacked even basic information about CAFOs—their location, how many animals they confine, how much waste they produce, and how they dispose of that waste—in 2010 NRDC and other environmental organizations reached an agreement with the EPA, which was designed to collect the missing data needed to start cleaning up our waterways and protecting public health from CAFO pollution.[12] When that effort stalled under industry pressure in 2012, NRDC turned to compiling available data using Freedom of Information Act requests and public databases (see "The Search for CAFO Data").

THE SEARCH FOR CAFO DATA

When the EPA's effort to survey CAFOs stalled under industry pressure in 2012, the agency claimed it could get the information it needed from existing sources.[13] Skeptical of this claim, NRDC filed Freedom of Information Act (FOIA) requests to discover how much information regulators actually had.

To comply with NRDC's FOIA request, in early 2013 the EPA released records to NRDC on CAFOs, including information that the EPA had collected from individual states.[14] After the EPA's compliance, industrial livestock interests went on the attack. A lawsuit filed by the American Farm Bureau Federation and the National Pork Producers Council in the summer of 2013 challenged the EPA's decision to release this public information.[15] The corporate livestock industry also sought to shut down the release of any state-gathered information received by the EPA since its initial response, and to prevent the EPA from releasing data in response to future FOIA requests for updated information.

A federal district court dismissed the case in 2015 after ruling that the industry groups did not have standing.[16] On appeal in 2016, however, the Eighth Circuit sided with agribusiness, the court finding that certain information about animal agriculture facility operators fell under a FOIA provision exempting the release of "personnel and medical files and similar files" if disclosure "would constitute a clearly unwarranted invasion of personal privacy."[17] The circuit court sent the case back to the district court to decide whether the EPA had the authority to release this information at its own discretion. The parties settled before the case was resolved, as discussed below.[18]

While the livestock industry was fighting to keep important information under wraps, NRDC undertook the monumental task of compiling and organizing the revised data it had received from the EPA and supplementing that information with additional information gleaned from publicly available databases on state websites.[19] The process of developing the database ran from 2013 until 2016, spanning the same period as the litigation over the FOIA requests. Although the database was completed in 2016, NRDC held out hope that it would be able to update the database using more recent and complete data released by the EPA after the litigation concluded. However, in 2017, under former EPA administrator Scott Pruitt, the EPA signed a settlement agreement with industry groups severely limiting the scope of any future information releases.

As a result, some of the data used in this report date to 2013 or even earlier, depending on when they were gathered. In many cases they are old and incomplete, but they are the best that NRDC is aware of—and that is exactly the problem. Unfortunately, given the Eighth Circuit's decision and the subsequent settlement agreement, the data from the EPA, despite their numerous limitations, are likely more comprehensive than anything the agency will release in the foreseeable future. After years of uncertainty about the EPA's intentions, NRDC decided to move forward in the knowledge that it already had the best data it could get.

Analysis of these records shows pervasive gaps in the data about the size, type, and location of CAFOs and the pollution control measures they are using. NRDC found at least some data on 7,595 CAFOs in 40 states. That leaves more than half of the 17,000-plus CAFOs the EPA estimated to exist in 2012 completely unaccounted for in the agency's own data.[20] Further clouding the situation, NRDC's analysis suggests that the EPA may have significantly underestimated the number of CAFOs and that the true number of undocumented operations is even higher.

Drilling into the existing data reveals stark disparities among the states. NRDC found no information for nine states that the EPA determined housed CAFOs. Where data were available, both the quantity and nature of the data were highly variable from state to state. States are responsible for collecting information and reporting it to the EPA, but there is no standardized collection or reporting requirement. Moreover, many states that appear to have an accurate count of the number of CAFOs nonetheless lack critical data about operations' size, permit status, location, method of storing manure, animal type, and ownership. Regulators and the public need this information to protect communities from CAFO pollution and hold the agriculture industry accountable for its impacts under the law.

States have the opportunity to fill the CAFO data void. Toward that end, NRDC has created a Clean Water Act permit based on some of the better approaches in several states and lessons learned from developing this report. The permit would allow states to collect and share critical data on the CAFOs within their borders. The permit would also improve public accountability by making information more available. It would require all but the smallest AFO facilities to obtain a permit, inform neighbors about their operations, and disclose their location and nutrient management plans to the state, the EPA, and the public. NRDC's permit would clarify that every CAFO's nutrient management plan—which enumerates the permit holder's responsibilities for handling animal waste—is a public record that communities have a right to understand and enforce. Finally, the permit would expand notice requirements so that neighbors are fully informed when a new CAFO wants to open down the road, or when existing operations are planning to expand, thereby increasing their production of waste.

It is time for states to step up where the federal government has failed. This report shows how the EPA's acquiescence to industry demands leaves the agency in the position of knowing little about the facilities it is supposed to hold accountable. Given the dangers posed by CAFO pollution, what the EPA doesn't know can hurt all of us.

WHAT IS A CAFO?

CAFOs are livestock farms distinguished by their large animal population or their significant contribution to water pollution, or both. CAFOs are a subset of Animal Feeding Operations (AFOs) as defined by the Clean Water Act. An AFO is a "lot or facility" where animals are confined and fed for at least 45 days per year, and where the confinement takes place on a surface other than pasture or vegetated ground.[2] Whether an individual facility is designated as a CAFO is often at the discretion of individual state regulators. CAFO status can be determined purely by size, if the number of animals meets specific thresholds set out in federal regulations, with the number depending on the type of animal being confined—e.g. hogs, cattle, or chickens.[22] However, an AFO can also be designated as a CAFO if it is discharging animal waste into surface waters, either directly or via a man-made channel, to the extent that regulators determine it is "a significant contributor of pollutants to waters of the United States."[23]

THE EXISTING REGULATORY REGIME

The Clean Water Act (CWA) is the primary law regulating the pollution of U.S. waters, including rivers, lakes, and wetlands.[24] The law, passed in 1972, requires that all "point sources" discharging pollutants be subject to permitting requirements under the National Pollutant Discharge Elimination System (NPDES).[25] These permitting requirements set strict discharge limits intended to help eliminate pollution in waterways by 1985.[26] The Act is enforced primarily by the EPA and through cooperative federalism with the states.[27]

Since the original Act, the definition of "point source" has included "concentrated animal feeding operation[s]."[28] Despite this very clear language, actual regulation of CAFOs under the CWA started slowly. In 1974, the EPA issued water-quality protection rules called effluent limitation guidelines (ELGs) for feedlots, which are a specific subset of AFOs used for finishing livestock prior to slaughter.[29] Substantial exemptions excluded smaller facilities, those that discharged only under extreme storm conditions, and chicken operations with dry-manure handling systems.[30] Though all exemptions for point sources were struck down soon after in federal court, the newly formed EPA designated CAFOs as a "low enforcement priority" in light of other pressing environmental challenges facing the new agency; regulation was largely left to the states, with limited federal oversight.[31] This arrangement left certain states with standards that fell well below the requirements imposed by federal law. With little oversight from the EPA, some states with high numbers of CAFOs simply ignored their duty to issue permits well into the 2000s.[32]

Congress exacerbated this passive regulatory approach when, in 1987, it amended the CWA to exempt "agricultural stormwater discharges" from the statutory definition of a point source.[33] A stormwater discharge occurs when rain washes contaminants off a surface and into waterways. Since it is common to apply CAFO manure directly to the surface of agricultural fields, the amendment made it harder to regulate industrial livestock operations. Despite evidence that the amendment was not intended to impact how preexisting regulations applied to CAFOs, these operations began claiming coverage under the exemption.[34]

The EPA addressed this and other issues in 2003 when, in response to a lawsuit brought by NRDC and Public Citizen, the agency finalized its first comprehensive rule governing CAFO regulation under the CWA.[35] This rule—the high-water mark in federal CAFO regulation—obligated all CAFOs to apply for an NPDES permit unless they could demonstrate that they had "no potential to discharge" pollution. However, a federal court disagreed that the CWA supported such an obligation and struck down that element of the rule.[36] (The rule also included standards relating to manure handling, nutrient management plans, and facility design.) In response, the EPA released a new rule in 2008 that limited the permitting obligation to CAFOs that "propose to discharge," but even that circumscribed requirement was struck down.[37] The EPA's 2012 CAFO rule then cemented the loophole by officially exempting from permitting requirements any CAFO that was not actively discharging.[38]

The 2003 rule contained an important additional loophole as well. It specified that discharges from CAFOs qualified as exempt "agricultural stormwater" if they were precipitation-related discharges from the land application area (rather than the production area) and if manure had been "properly" applied.[39] A 2013 district court decision made matters worse. It held that even discharges from the production area were covered by the exemption, contradicting decades of case law.[40] Such discharges include manure, litter, and feathers blown out of poultry houses by a ventilation system. The EPA appealed the decision but later dropped its appeal while maintaining the position that it could require a permit for such discharges in the future.[41]

CAFOs AND THEIR POLLUTION

A relentless tide of consolidation has swept across animal agriculture over the past half century.[42] As technological advances allowed farmers to raise huge numbers of fast-growing animals in close quarters, large industrial operations proliferated while small farms struggled and generally failed to compete on the industry's new terms.[43] This rise in consolidation and the growth of CAFOs go hand in hand.[44]

CAFOs are tailored to produce vast quantities of meat, eggs, and dairy that can be sold to consumers at low prices. For example, Americans pay only about $1.50 for a pound

of fresh chicken, something made possible by facilities that raise tens of thousands of birds in a single building and take advantage of breeding and feeding refinements that allow chickens to reach slaughter weight in about six weeks.[45,46] However, these low consumer prices hide the true costs of production.[47] Supermarket prices do not account for the fact that the public heavily subsidizes CAFOs, including manure management and feed costs, through the United States' vast system of agricultural price supports and subsidies.[48] And supermarket prices do not reflect the environmental and human health costs of CAFOs, which can threaten neighboring communities, pollute waterways, and exacerbate antibiotic resistance. Neither the market nor existing safeguards compel CAFOs or the big businesses that operate them to cover those costs.[49]

MANURE MANAGEMENT

A CAFO raising 82,000 laying hens can produce 2,800 tons of manure in a year, and a single CAFO raising 10,000-head of beef cattle can produce up to 117,000 tons of manure annually.[50] How animal manure is handled, stored, and disposed of affects human and environmental health, but practices vary widely across facilities. "Handling" is the process of getting manure from the facility floor into some kind of storage container, where it sits until it is "disposed." Dry manure handling systems, which are commonly used in poultry operations, release substantial amounts of nitrous oxide and particulate matter into the air.[51] In contrast, wet handling systems, most commonly found on swine and dairy farms, use water to wash manure into storage structures or lagoons, where it releases methane and hydrogen sulfide as it is anaerobically digested.[52] Wet systems can also attract and breed insects, contributing to mosquito and fly problems in communities, and research indicates that leakage from wet storage lagoons can contribute to increased concentrations of nitrate, ammonium, bacteria, and other contaminants in groundwater.[53]

Storing such vast quantities of manure presents one set of problems; disposing of it is another matter entirely. There are no sewage treatment requirements for animal manure, in stark contrast to the requirements that apply to human waste management, and the majority of manure from CAFOs is never treated.[54] Instead, CAFO waste is generally disposed of on land in solid, slurry, or liquid form, depending on the type of animal and the practices of the individual facility.[55] There are several ways to dispose of manure on land, but among the least expensive and most common is applying it directly on top of soil as fertilizer.[56] Manure is an important source of natural fertilizer, but given the immense volumes of manure generated at CAFOs, facilities often apply it in concentrations that far exceed the nutrient requirement of their crops or the holding capacity of the underlying soil.[57] This nutrient overloading commonly causes contaminants to leach from manure into groundwater, or to run off into streams and rivers after a heavy rain.[58]

Although Clean Water Act regulations place some restrictions on manure application within the boundaries of the CAFOs themselves, these do not extend to the application of manure that is shipped off-site.[59] And in some areas of intensive CAFO farming, like Maryland's Eastern Shore, facilities ship up to 85 percent of their manure off-site where federal rules no longer regulate its application to open fields.[60]

MARYLAND'S MANURE PROBLEM

A 2014 analysis by the Environmental Integrity Project found that poultry operations on Maryland's Eastern Shore spread three times more manure on agricultural land than crops planted there could reasonably use.[6l] The study examined records from 62 poultry operations across five counties—a fraction of the 404 poultry operations that raised nearly 218 million chickens in those counties in 2012.[62] These 62 operations alone applied 482,000 pounds of phosphorus, contained in chicken manure, in a single year.[63] The excess nutrients run off into nearby streams and then into the ecologically fragile Chesapeake Bay, where the phosphorus and nitrogen fuel algal outbreaks that can make the water uninhabitable for fish and blue crabs.[64] Outbreaks of cyanobacteria, in particular, have increased in the Chesapeake Bay, and these can damage not only ecosystems but also human health.[65]

The pollution, from CAFOs as well as other point sources, grew so bad that in 2010, after decades of failed efforts to clean up the bay and the surface waters that feed into it, the EPA put the Chesapeake Bay on a "historic and comprehensive 'pollution diet.' "66 The plan set pollution limits, known as a total maximum daily loads (TMDLs), on nitrogen, phosphorus, and sediment within the Chesapeake Bay Watershed.67 There are signs that the diet is working: The overall health of the Chesapeake Bay ecosystem is the best it has been in decades, improving from "moderately poor" in 2010 to "moderate" in 2017.68 However, meeting the EPA's goal of restoring full ecosystem health by 2025 will require further steps to rein in CAFO pollution across the Chesapeake Bay Watershed.

IMPACT ON COMMUNITIES

From what we know, CAFOs tend to be located near populations that lack the political clout to successfully oppose their construction.[69] Thus, low-income and minority populations suffer disproportionately from proximity to CAFO pollution and waste.[70] Localized harms include impaired drinking water, antibiotic resistance, air pollution, and waste spills and associated fish kills.

IMPAIRED DRINKING WATER

CAFOs can pollute local water on a massive scale. According to an analysis of EPA records, "the drinking water of millions of Americans living in or near farming communities across the country is contaminated by dangerous amounts of nitrates and coliform bacteria from fertilizer and manure widely used in agriculture."[71] Tens of thousands of times, nitrate and coliform levels have exceeded the federal limits on contaminants in public water systems set by the Safe Drinking Water Act (SDWA).[72] CAFOs contribute much of this contamination: Both the EPA and the National Cancer Institute trace human health hazards associated with elevated nitrate levels in drinking water to animal waste.[73]

SDWA regulations limit nitrate concentrations to 10 parts per million in municipal drinking water.[74] Regulators chose this limit to protect infants from blue baby syndrome, a potentially fatal condition that prevents blood from carrying sufficient oxygen.[75] However, nitrate levels at even half the legal limit increase risk for colon, kidney, ovarian, and bladder cancers in otherwise healthy adults.[76] Rural residents located near CAFOs are particularly vulnerable because many rural residents draw water from private wells, which are not covered by the SDWA.[77] About 4 percent of private wells in the United States have nitrate levels above the SDWA standards, and that number is much higher in farming communities.[78]

In addition to nitrates, animal manure is a significant source of pathogens that flow or leach into drinking water sources. More than 150 pathogens are found in animal manure.[79] Six of these, *Campylobacter*, *Salmonella*, *Listeria*, *E. coli 0157:H7*, *Cryptosporidium*, and *Giardia*, account for 90 percent of all human foodborne and waterborne diseases.[80] Though healthy people who are exposed to these pathogens often recover after a bout of diarrhea, more vulnerable groups like infants, pregnant women, the elderly, and those with weak immune systems are at risk of severe illness and death.[81]

ANTIBIOTIC RESISTANCE

As industrial animal facilities increasingly rely on antibiotic drugs to suppress disease in their facilities, microbes begin to develop immunity—meaning that the drugs that we depend on to treat serious human infections become less effective. Experts from the World Health Organization (WHO) and the Centers for Disease Control and Prevention (CDC) identify antibiotic resistance as one of the top public health threats in the world.[90] According to the WHO, "Antimicrobial resistance threatens the effective prevention and treatment of an ever-increasing range of infections caused by bacteria, parasites, viruses and fungi."[91]

In 2017, producers fed their cattle, pigs, and poultry over 12.3 million pounds of antibiotics that are "medically important," meaning they are extremely similar or identical to antibiotics that humans depend on to combat infection.[92] CAFOs routinely feed low doses of antibiotics to animals that are not yet sick in order to prevent disease, a need that arises from the dirty and stressful conditions of close confinement.[93] While the antibiotics will kill some bacteria, resistant bacteria remain in the gut, multiply, and are excreted in manure—along with substantial amounts of the antibiotics themselves—and enter the surrounding community's air, soil, and water.[94] When antibiotics-laden runoff from CAFOs spills into the surrounding environment, these drugs further promote antibiotic resistance and can also be toxic to soil microflora and fauna.[95] The problem stretches to meat products as well: A 2015 analysis found that antibiotic-resistant bacteria were present in approximately 35 to 80 percent of raw meat from the supermarket.[96]

AIR POLLUTION

CAFOs can also threaten local air quality by releasing ammonia, hydrogen sulfide, and other gases and particulate material into the atmosphere.[97] For instance,

GROUNDWATER IN KEWAUNEE COUNTY, WISCONSIN

In Kewaunee County, Wisconsin, which has experienced a substantial increase in the number of CAFOs over the past two decades, a 2017 study found fecal microbes in 60 percent of sampled wells.[82] Researchers estimated that one of those microbes, *cryptosporidium*, was infecting 140 county residents each year.[83] *Cryptosporidium* symptoms include diarrhea, dehydration, stomach cramps, and vomiting.[84] In October 2014, local environmental groups petitioned the EPA to use its powers under the Safe Drinking Water Act to investigate the sources of the groundwater contamination—which in some cases was turning people's tap water brown—and to order alternative water supplies be made available to Kewaunee County residents.[85,86] In May 2017, under continuous pressure from residents and advocates, the state began supplying bottled water to residents whose wells tested positive for bacteria from livestock manure.[87] In a ruling on a separate petition filed by local residents opposing removal of certain clean water protections from a state permit issued to a dairy CAFO, Administrative Law Judge Jeffrey Boldt noted that "the proliferation of contaminated wells represents a massive regulatory failure to protect groundwater" by the Wisconsin Department of Natural Resources, the state permitting authority.[88] Since the ruling, the petition has been wending its way through the appeals process; in January 2019 the case reached the Wisconsin Supreme Court, which must now decide whether to consider the state's claim that it lacks authority to implement commonsense requirements such as groundwater monitoring at manure-spreading sites.[89]



it has been estimated that the average broiler chicken emits between 0.27 and 0.54 grams of ammonia each day in its manure.[98] These seemingly small numbers add up: An average broiler facility raising 90,000 birds at a time may release more than 15 tons of ammonia a year, causing respiratory problems and chronic lung disease as well as chemical burns to the respiratory tract, skin, and eyes of nearby residents.[99,100] Ammonia, in particular, also contributes to algal outbreaks in nearby bodies of water.[101] Algae outbreaks disrupt oxygen availability, creating dead zones devoid of aquatic and marine life.[102] In some cases, the algal blooms are themselves toxic.[103]

The release of hydrogen sulfide and toxic particulate matter can be equally damaging, with devastating impacts on workers and neighboring residents, particularly children.[104] As many as 30 percent of industrial livestock farmworkers experience occupation-related asthma and chronic bronchitis.[105] Asthma rates are higher among children living near animal operations: One study found that 46 percent of children living on large swine farms (500-plus swine) had asthma, compared with 26 percent of those living on farms without livestock.[106] Beyond asthma, lengthy exposure to the particulate matter and gases can have other deleterious effects including lung disease and heart attacks.[107] Odors from these emissions can also harm a community's quality of life, preventing people from spending time outside and even, according to some studies, impacting mental health.[108]

SMITHFIELD FOODS AND NORTH CAROLINA

The CAFO construction boom began in North Carolina in the 1970s and took off in the 1980s after a series of state laws eliminated sales tax on swine farm equipment and preempted local officials from using zoning powers to limit swine facility construction.[109] Today, North Carolina's approximately 2,500 permitted swine operations raise about nine million animals at any given time, with some individual facilities capable of housing up to 60,000.[110] A series of cases brought by neighbors against Smithfield Foods, a swine producer with operations in North Carolina, allege that the facilities' excessive odors, flies, and noise from truck traffic interfere with nearby residents' use and enjoyment of their property.[111] The CAFOs at the center of the lawsuit are disproportionately located in low-income black communities that lacked the political power to resist their construction.[112] Thus far, juries in four trials have awarded 26 plaintiffs more than half a billion dollars in combined damages, and 22 suits involving another 500 or so residents are still pending.[113] However, this important moment in holding facilities accountable looks to be short-lived: A judge has already substantially decreased several of the awards based on a state law limiting punitive damages.[114] To further shield Smithfield, the North Carolina legislature recently passed legislation—over the governor's veto—limiting plaintiffs' ability to bring similar suits in the future.[115]

SPILLS AND FISH KILLS

Although CAFOs can cause significant environmental risks even when all goes according to plan, unforeseen events or errors can compound the problems, causing manure to leak or spill into surrounding ecosystems. These leaks and spills can have a number of causes, including accidents during transport of manure, willful discharges made in an effort to avoid regulatory requirements, leaking lagoons, and rainstorms that cause storage containers or lagoons to overflow or burst. The sheer scope of the spillage can be staggering: The Wisconsin Department of Natural Resources determined that more than three million gallons of manure were spilled in the state in 2013 and 2014.[116] With so much waste in one place, a single mistake or a single unethical operator can wreak havoc on neighboring communities.

CAFO spills are a common cause of fish kills. In 2017, three large spills killed close to 67,000 fish in Ohio.[117] Other states have dealt with similar issues: In Minnesota, which experiences an average of 20 manure spills each year, approximately 700,000 fish died in a single incident when hog waste washed into Beaver Creek.[118] Spilled manure from a dairy CAFO in Lewis County, New York, killed 375,000 fish.[119] These events can devastate local wildlife and ecosystems.

FISH KILLS IN ILLINOIS

In July 2012, manure from a hog confinement facility in Illinois leaked from fields into a creek, where it reportedly polluted more than 20 miles of the waterway and killed nearly 150,000 fish and 18,000 freshwater mussels.[120] Two years later, biologists could not locate any examples of nine fish species that had been in the creek prior to the discharge.[121] According to one man whose family fished in the creek, "It looked like ink, the water. It had fish all over the place, dead. It wasn't fit for nothing. Not even a wild animal could drink out of it."[122]

MONITORING

As described in more detail below, CAFOs are formally regulated for their environmental impact by the EPA, which generally delegates its responsibilities to state and local environmental agencies.[123] The EPA and state regulators conduct facility inspections, which serve as the primary monitoring mechanism to uncover violations. If a facility is out of compliance, regulators can initiate an enforcement action. However, inspections and enforcement actions occur remarkably infrequently. In the 2017 fiscal year, the EPA conducted 125 inspections and concluded 18 enforcement actions.[124] For context, the EPA estimated in 2017 that there were 19,961 CAFOs in the United States, which means that the EPA inspected 0.6 percent of all facilities.[125] Between 2008 and 2013, the EPA averaged about 260 inspections annually with an average of 60 enforcement actions across a similar number of CAFOs; remarkably, this still-low figure reflects a period of time when CAFOs were identified as a national enforcement priority.[126]

These figures do not account for inspections conducted by state agencies, which run their own inspection programs.[127] However, the lack of consistent and complete data at the state level raises serious questions about how comprehensively states are keeping tabs on the CAFOs within their borders. The nonpartisan Government Accountability Office (GAO) attributes these state failures, at least in part, to poor oversight by the EPA.[128] Although states must submit annual updates to the EPA on their CAFO permitting programs, reporting standards are insufficient to ensure that the EPA has site-specific data to hold facilities or their state regulators accountable. The GAO concluded that the EPA cannot fulfill its regulatory duties under the Clean Water Act without accurate and facility-specific information about CAFOs.[129] The EPA, for its part, admits that in contrast to its oversight of other major emitting industries, it does not have comprehensive, facility-level information for CAFOs.[130]

THE CAFO DATA VOID

Despite the ongoing harms caused by CAFO pollution, no federal agency collects and maintains the kind of comprehensive data about CAFO size, location, and operations that would be prerequisite to an effective environmental enforcement strategy.[131] Instead, regulators must rely on the patchwork of state-level information that forms the basis for this report. Moreover, regulators rely heavily on self-reporting: Although some proactive states impose a stricter duty on operators to apply for permits, under federal law CAFOs are obligated to apply for a permit only if they discharge.[132] This means the government must demonstrate that a CAFO is discharging into waters if it wants to compel the facility to apply for a permit—a difficult task, especially if the EPA does not even know that the CAFO exists. Given the costs of permitting and the relatively low likelihood of an enforcement action, it is not surprising that many CAFOs operate without a NPDES permit.[133] And even where permits are formally requested, permit standards in some states lag well behind those of the EPA.[134]

NRDC and other groups have repeatedly pressed the EPA to take steps to fill gaps in their information. In 2008, federal officials acknowledged that:

> ...[the] EPA does not have data on the number and location of CAFOs nationwide and the amount of discharges from these operations. Without this information and data on how pollutant concentrations vary by type of operation, it is difficult to estimate the actual discharges occurring and to assess the extent to which CAFOs may be contributing to water pollution.[135]

The EPA cannot currently execute its congressionally imposed duty to protect human health and the environment. Specifically, the EPA's blind spots make it difficult or impossible to evaluate the effectiveness of the NPDES program, identify and permit CAFOs that discharge, promote best management practices, locate and address sources of water quality impairment, estimate the amount of pollution entering water bodies, and efficiently target resources at areas of concern.[136]

The EPA initially responded to these findings, along with pressure from NRDC and other groups, by agreeing to circumvent the states and directly survey the industry. In 2011 the agency proposed the "CAFO Reporting Rule" or "308 Rule."[137] The proposed rule would have leveraged the EPA's authority under Section 308 of the Clean Water Act to require all CAFOs to report certain data.[138] Specifically, the EPA proposed to collect the following basic information about animal operations:

- Name and address of the owner/operator
- Facility location
- NPDES permit status
- Animal type and number
- Location and total number of acres under control of the owner available for land application of manure

The proposed inventory would have replaced the EPA's inconsistent and patchy information with a much-needed national database of animal facilities. At the same time, the proposed information collection was extremely modest; the EPA decided not to collect numerous pieces of data urged by environmental and public health advocates—including the type and capacity of available manure storage, the presence of a nutrient management plan (or lack thereof), and information on off-site transfer of manure.[139] The agency also proposed to limit data collection to once every 10 years. However, under industry pressure, the EPA withdrew the proposed rule in 2012.[140] Instead of collecting the information directly, the EPA stated it would pursue "an approach that relies on a range of existing sources of information, other regulations, and other programs at the federal, state, and local level to gather basic information about CAFOs."[141]

In scuttling the survey, the EPA claimed that it could obtain the missing data by working more closely with states, erroneously asserting that the states and other government entities already have that data.[142] Unfortunately, this approach failed to produce the information that the EPA needs to assess and regulate CAFOs nationwide. Rather, the quantity and quality of data on industrial livestock operations has historically varied widely across states, with some states leading and other lagging.[143] Concerned that the EPA's new approach would fail to address data gaps and inconsistencies, NRDC set out to assess what information was in fact available about these operations across the country.

RESEARCH METHODOLOGY

Following the EPA's failure to act, NRDC attempted to collect publicly available data to better understand just how much (or how little) information the EPA had about CAFOs in the United States. By recreating the EPA's database and then comparing it with the EPA and USDA estimates of the total number of industrial animal facilities, NRDC sought to determine whether existing facility-specific data were sufficient for informing and protecting communities or holding the agriculture industry accountable for its pollution impacts.

NRDC created a database using facility-specific CAFO data obtained from four sources between 2012 and 2015. First, we obtained data from the EPA after filing FOIA requests in 2012. In response to these requests, the EPA provided the CAFO data it had collected directly from the states.[144] Second, NRDC searched the EPA's Permit Compliance System (PCS) and Integrated Compliance Information System (ICIS) for all animal facilities.[145] Data were collected for all animal agricultural facilities in every state with active NPDES permits. Facilities that did not meet the regulatory definition of a CAFO (such as aquaculture operations) were excluded. Third, we conducted an independent search of publicly available data on state permitting websites.[146] These searches took place in the spring of 2015. NRDC extracted all readily available information from these websites on AFOs, regardless of whether they were NPDES permitted, and added this information to the database.[147] Finally, we added data for all NPDES-permitted CAFOs from the EPA's Enforcement and Compliance History Online (ECHO) database in the spring of 2015.[148]

Once we added all the information we could find to the database, we took additional steps to improve the data quality. First, facilities with inactive or expired permits were removed, along with facilities whose permit status indicated they were no longer operational. Second, duplicates were identified and consolidated into a single entry. Where duplicate entries contained different types of data, the information in both fields was retained, and where duplicate entries contained information that conflicted across the same field, NRDC prioritized the most recently collected data.

WHAT WE FOUND (AND DIDN'T FIND)

Overall, NRDC identified 7,595 CAFOs in 40 states. By comparison, the EPA estimated in 2012 that there were 17,329 CAFOs in the United States.[149] This means that we—and, by extension, the public regulators from which NRDC obtained the data—have information for fewer than half of the CAFOs that the EPA estimated to exist. Moreover, the EPA's estimate should be viewed cautiously; in nine states, NRDC found *more* facilities than the EPA estimated. In Maryland, for example, the agency estimated that there were 150 CAFOs, but NRDC's data indicate that there were



at least 789.[150] The problems and inconsistencies in the EPA's data make it impossible to know when the agency is overestimating or, more likely, underestimating the number of CAFOs in a state.

The most defining characteristic of the information we gathered is perhaps the inconsistency among the states in terms of data availability. NRDC found no data for nine states that the EPA determined housed CAFOs. These include Idaho, South Carolina, and Washington, each of which, according to EPA estimates, has more than 100 CAFOs within its borders. Even more striking, California has an EPA-estimated 1,028 CAFOs, but NRDC found data on only a single CAFO.

When data on CAFOs were available, both the quantity and nature of the data were highly variable from state to state. For some states, like Texas, Florida, and Iowa, a wide range of data was available about a limited number of CAFOs, including operations' permit status, location, method of storing manure, size, animal type, and ownership, but there were no data at all for many of the CAFOs that the EPA estimated are located in these states. In other states, such as Arizona, Montana, New York, Pennsylvania, South Dakota, and Utah, it appears likely that all or almost all CAFOs were accounted for, but only a very limited amount of data was available about each.

On balance, the state for which data appeared to be the most complete was, by a fairly wide margin, Tennessee. No other state had data available on permit status, location, method of storing manure, size, animal type, and ownership of more than 5 percent of EPA-estimated operations. For Tennessee, NRDC was able to obtain each of these data points for more than 70 percent of all estimated operations. Other states with relatively high numbers of CAFOs that did relatively well in terms of both the breadth and depth of available data included Alabama, Colorado, Indiana, and Maryland. The section below describes how the states lined up in terms of the particular types of data that were collected.

PERMIT STATUS

Overall, NRDC could identify the permit status of 4,234 CAFOs. This makes up about 24 percent of the EPA's estimate of total CAFOs in the country (and 56 percent of the CAFOs NRDC could identify). The data are skewed heavily toward several states. In 13 states—Colorado, Florida, Kansas, Maryland, Montana, New York, North Dakota, Oregon, Pennsylvania, Tennessee, Texas, Wisconsin, and Wyoming—NRDC found data on permitting for 50 percent or more of estimated CAFOs. These states contain 3,180 of those 4,234 CAFOs for which NRDC has data—more than 75 percent. On the other hand, for 18 states NRDC could find permitting data on less than 1 percent of estimated CAFOs. Several of these states—Arkansas, Arizona, California, Idaho, Louisiana, Nebraska, South Dakota, and Washington—have more than 100 CAFOs, according to EPA estimates.

OWNER/OPERATOR

NRDC found information identifying the owner or operator of 4,248 CAFOs, or roughly 25 percent of the EPA's overall estimate (and 56 percent of the CAFOs NRDC could identify). Though the total number of CAFOs for which NRDC has ownership data is nearly identical to that for permitting status, the list of states for which substantial ownership data are available is quite different. In 16 states—Alabama, Arizona, Delaware, Florida, Georgia, Indiana, Maryland, Michigan, Montana, Nebraska, New Jersey, North Dakota, Pennsylvania, Tennessee, Utah, and Wyoming—NRDC found data for 50 percent or more of estimated CAFOs. For 25 states, NRDC could find no data on ownership.

TYPE AND NUMBER OF ANIMALS

The data point that was most commonly available was information on the type of animal confined at a facility. Since, for example, a single hog produces far more manure than a single chicken, knowing the type of animal in confinement is necessary in order to assess the pollution potential of a CAFO. NRDC was able to determine this for 37 percent of the EPA's estimated number of CAFOs (and 84 percent of the CAFOs NRDC could identify). Knowing the number of animals confined is equally important, but NRDC could determine this for only 29 percent of the EPA's estimated number of CAFOs. This data void is particularly troubling; without knowing a CAFO's size, it is impossible to assess its impact on the community.

States that provided the most complete data on animal type and animal numbers included Alabama, Delaware, Georgia, Indiana, Maryland, North Dakota, South Dakota, Tennessee, and Utah. NRDC found data about the type and number of animals for more than 70 percent of estimated CAFOs in each of these states. Perhaps the most notable

laggard in animal type/number reporting is Pennsylvania. Although there are some data available for 356 CAFOs in the state, the type of animal is reported for only 51 of these, and there is no information about facility size. This is particularly concerning given that Pennsylvania is known to be a diverse CAFO state, housing cattle, dairy, hog, broiler, and egg layer operations.[151]

LOCATION

NRDC's database includes the location of 34 percent of CAFOs the EPA estimates exist (and 77 percent of the CAFOs NRDC could identify). Location is a crucial data point as it informs regulators and the public where concentrations of animals have become sufficiently high to warrant increased scrutiny, greater monitoring, or development of individualized permit conditions. Geographic data serves other important purposes, such as advancing our understanding of how CAFOs create disparate impacts on communities of color. For example, facility location data informed a complaint to the EPA under Title VI of the Civil Rights Act alleging that North Carolina's Department of Environmental Quality's permitting process had a racially discriminatory impact.[152] (see "Smithfield Foods and North Carolina.")

The states where NRDC could find location data for 80 percent or more of estimated CAFOs were New Jersey, Indiana, Colorado, Delaware, Montana, Michigan, Oregon, New York, and Maryland. While the southeastern United States generally performed well in terms of data availability, it lagged in facility location information. Across this region, NRDC found location data for more than half of all estimated CAFOs only in Georgia, Tennessee, and Alabama.

WASTE MANAGEMENT PRACTICES

Despite the crucial importance of waste management for the impact of CAFOs on neighboring communities, NRDC could find less information about waste management practices than for any other data category included in this report. Our database contains waste management information for 5.6 percent of the EPA's estimated number of CAFOs (and 13 percent of the operations NRDC could identify). NRDC could find this data for more than 2 percent of CAFOs in only seven states: Alabama, Florida, Iowa, North Carolina, Tennessee, Texas, and Wyoming. Some of the states with the most troubling records on waste management are notably absent from this list.

CONCLUSION

The fight for clean water and breathable air in communities neighboring industrial animal facilities stands at a crossroads. Efforts to improve how CAFOs are regulated have stagnated over the past decade, and the current administration has attacked federal environmental protections across the board, including the CWA. Yet in the absence of federal leadership, some states are seizing the opportunity to step up.

Recent developments suggest two directions in which regulators could move in the years to come. On the one hand, the current administration has pursued a path that weakens clean water protections and could allow more CAFO pollution to enter streams and other bodies of water. In this connection, the EPA recently reversed its longstanding interpretation that some subsurface discharges might trigger permitting under the CWA.[153] For decades, the EPA has maintained that point source discharges to subsurface waters with a direct connection to surface waters are subject to CWA permitting requirements.[154] In these circumstances, contamination from manure lagoons, especially unlined lagoons, can leak into subsurface water and then migrate to surface waters. The EPA's interest in reopening this issue signals its intent to exempt even more facilities from scrutiny and enforcement under the law. Weakening the interpretation discounts one of the primary routes by which CAFOs pollute bodies of water. Ultimately, this move will leave the EPA and the public with even less information about polluting facilities.

On the other hand, some states are taking a different path toward better regulation, more data collection, better transparency, and healthier communities. For example, the New York Supreme Court recently ruled that the state's dairy CAFO permit must be revised to reflect the CWA's rule that pollution-handling practices at permitted facilities are a matter of public record.[155] In the CAFO context, this means nutrient management plans must be available for public review, which is critical to holding facilities accountable and ensuring that the best management practices are used when and where they are required.

The CWA provides minimum regulatory standards for New York and the 45 other states that currently run their own CAFO permitting program.[156] States are free, however, to go above CWA standards to protect their local waters and the health of their local communities, and NRDC is working to empower states to do so.[157] To facilitate the process, NRDC scoured state permitting programs from across the nation to identify best practices and synthesize them into a permit that states can adopt under their existing powers.

NRDC's CAFO permit goes above and beyond the current federal minimum NPDES requirements in some ways. For example, many facilities avoid their duty to obtain a CWA permit by claiming not to discharge. The permit expands coverage to all confined animal operations within a state, so that every facility above a certain size threshold has a duty to obtain a permit. It requires that basic information on each facility, like location, size, and waste management practices, be available in a public database, as well as reported directly to the state and the EPA. It is important for regulators and the public to have this information in order to understand how CAFOs are distributed over the landscape and which water bodies are threatened by high concentrations of polluting facilities. The permit addresses the data collection void that has hobbled the EPA and the states in meeting their regulatory duties. The permit also improves transparency and accountability more generally.

Collecting and sharing basic information on facilities is only part of the battle. Communities deserve to know the conditions and standards that apply to nearby facilities, and those same communities need the power to hold facilities accountable when they violate the terms of their permit. In order to obtain a permit, CAFO operators currently must develop a nutrient management plan that specifies how the facility will live up to its obligations under the permit. NRDC's permit clarifies that the nutrient management plan must be public information. It also expands notice requirements so that nearby residents are fully informed when a CAFO wants to expand its facility or open a new one, or when existing operations are making changes that will increase the production of waste. To further empower communities to hold neighboring CAFOs accountable, the permit affirms the right of individual citizens to bring a civil action against any person found to be in violation of CWA standards or limitations.

There is a long road ahead in the fight to clean up industrial animal operations and hold them accountable for their pollution. As a first step, the EPA, states, and communities must understand the true scope and scale of the agriculture industry. That understanding requires comprehensive and reliable CAFO data that are currently not available. To remedy this, federal policymakers should reintroduce the reporting requirements they dropped under industry pressure in 2012. In the absence of federal action, states must use their existing authority to demand transparency and accountability of the CAFOs within their borders. Citizens concerned with the environmental and health threats that CAFOs pose to their communities must demand much more from their representatives at both the state and federal levels.

TRANSPARENCY OF CAFO DATA

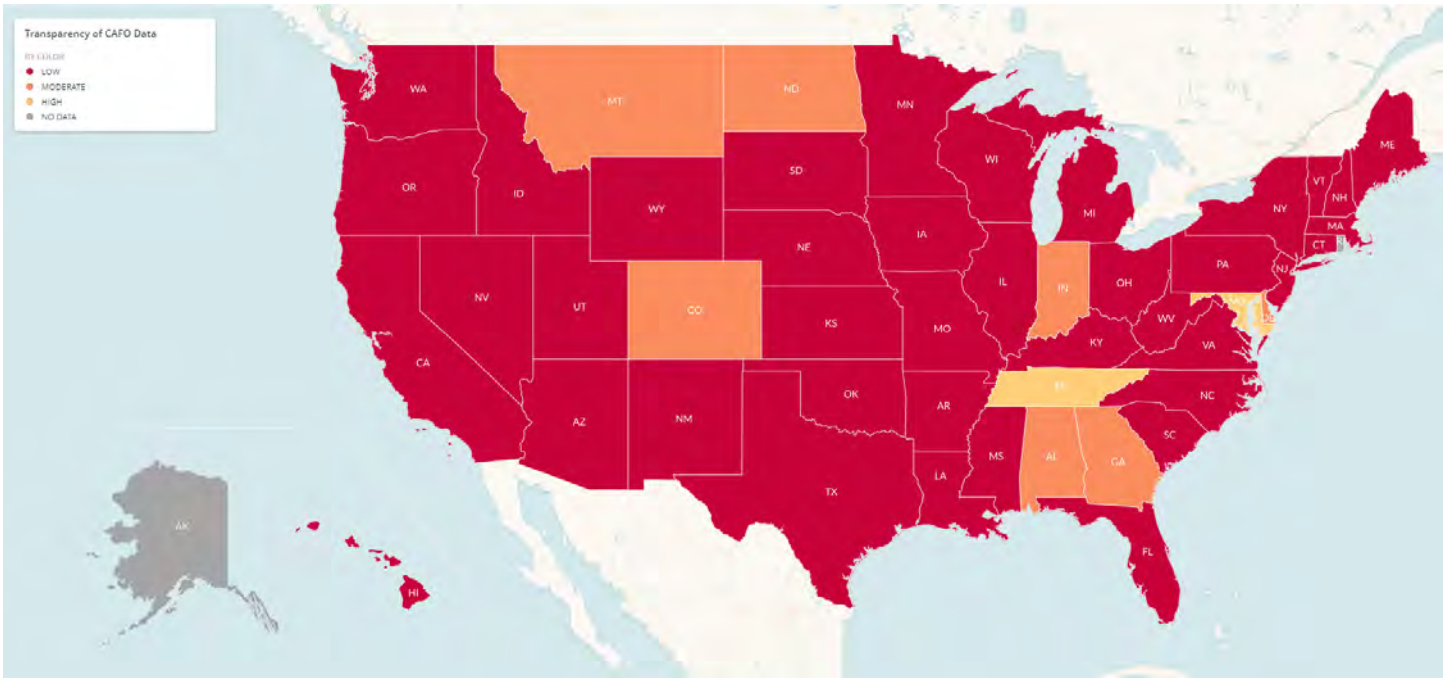

STATE TRANSPARENCY RATINGS							
State	Overall Transparency Rating	Transparency of Permit status	Transparency of Location	Transparency of Manure storage	Transparency of Type of Animal	Transparency of Count of Animal	Transparency of Owner Information
Alabama	Moderate	Low	Moderate	Moderate	Moderate	Moderate	Moderate
Alaska	No Data	No Data	No Data	No Data	No Data	No Data	No Data
Arizona	Low	Low	Low	Low	High	Low	High
Arkansas	Low	Low	Low	Low	Low	Low	Low
California	Low	Low	Low	Low	Low	Low	Low
Colorado	Moderate	High	High	Low	High	Low	Low
Connecticut	Low	Low	Low	Low	Low	Low	Low
Delaware	Moderate	Low	High	Low	High	High	High
Florida	Low	Low	Low	Low	Low	Low	Low
Georgia	Moderate	Low	Moderate	Low	Moderate	Moderate	Moderate
Hawaii	Low	Low	Low	Low	Low	Low	Low
Idaho	Low	Low	Low	Low	Low	Low	Low
Illinois	Low	Low	Low	Low	Low	Low	Low
Indiana	Moderate	Low	High	Low	High	High	High
Iowa	Low	Low	Low	Low	Low	Low	Low
Kansas	Low	Moderate	Low	Low	Moderate	Low	Low
Kentucky	Low	Low	Low	Low	Low	Low	Low
Louisiana	Low	Low	Low	Low	Low	Low	Low
Maine	Low	Low	Low	Low	Low	Low	Low
Maryland	High	High	High	Low	High	High	High
Massachusetts	Low	Low	Low	Low	Low	Low	Low
Michigan	Low	Low	High	Low	Moderate	Low	High
Minnesota	Low	Low	Low	Low	Low	Low	Low
Mississippi	Low	Low	Low	Low	Low	Low	Low
Missouri	Low	Low	Low	Low	Low	Low	Low
Montana	Moderate	High	High	Low	Moderate	Low	Low
Nebraska	Low	Low	Low	Low	Low	Low	Low
Nevada	Low	Low	Low	Low	Low	Low	Low
New Hampshire	Low	Low	Low	Low	Low	Low	Low
New Jersey	Low	Low	High	Low	Low	Low	High
New Mexico	Low	Low	Low	Low	Low	Low	Low
New York	Low	Low	High	Low	Low	Moderate	Low
North Carolina	Low	Low	Low	Low	Low	Low	Low
North Dakota	Moderate	Moderate	Moderate	Low	Moderate	Moderate	Moderate
Ohio	Low	Low	Moderate	Low	Moderate	Moderate	Low
Oklahoma	Low	Low	Low	Low	Low	Low	Low
Oregon	Low	High	High	Low	Low	High	Low
Pennsylvania	Low	High	Low	Low	Low	Low	High
Rhode Island	No Data	No Data	No Data	No Data	No Data	No Data	No Data
South Carolina	Low	Low	Low	Low	Low	Low	Low
South Dakota	Low	Low	Low	Low	High	High	Low
Tennessee	High	High	Moderate	High	High	High	High
Texas	Low	Low	Low	Low	Low	Low	Low
Utah	Low	Low	Low	Low	Moderate	Moderate	Moderate
Vermont	Low	Low	Low	Low	Low	Low	Low
Virginia	Low	Low	Low	Low	Low	Low	Low
Washington	Low	Low	Low	Low	Low	Low	Low
West Virginia	Low	Low	Low	Low	Low	Low	Low
Wisconsin	Low	High	Moderate	Low	High	Low	Low
Wyoming	Low	Moderate	Low	Low	Low	Low	Moderate

Methodology

DATA SOURCES

We obtained the data on the CAFOs that we used for our analysis, map, and Table 1 from four sources:

SPREADSHEETS OF DATA ON CAFOS OBTAINED FROM THE U.S. ENVIRONMENTAL PROTECTION AGENCY (EPA)

Pursuant to a Freedom of Information Act (FOIA) request filed by NRDC in 2012, we obtained spreadsheets containing data on CAFOs that had been supplied by states to the EPA, as well as a few spreadsheets containing information about CAFOs gathered by the EPA from publicly available sources. Although the EPA initially provided us with unredacted data from states, we returned those documents and based our analysis on subsequent, redacted versions of the EPA's data.

We did not use spreadsheets produced by the FOIA request that contained data gathered from the EPA's own PCS/ICIS systems in order to avoid duplication; we gathered updated versions of those data from the EPA's Envirofacts and ECHO databases later. We also did not use most of the data that were compiled by the EPA from publicly available state web sources, again to avoid duplication; we later gathered updated versions of publicly available information from state CAFO permitting websites.

PCS/ICIS SEARCHES ON THE EPA ENVIROFACTS WEBSITE

On the EPA Envirofacts website, we conducted searches of the Permit Compliance System (PCS) and Integrated Compliance Information System (ICIS) databases at http://www3.epa.gov/enviro/facts/pcs-icis/search.html. We searched in every state for animal agricultural facilities with Standard Industrial Classification codes starting with "02," the code for Agricultural Production—Livestock. These searches were conducted in April and May 2014.

From our searches in Envirofacts, we added to our database those facilities that had active National Pollutant Discharge Elimination System (NPDES) permits. We excluded facilities that had NPDES permits but did not appear to be CAFOs, based on their animal types. For example, we excluded aquaculture facilities from our list.

STATE CAFO PERMITTING WEBSITES CONTAINING INFORMATION ABOUT CAFOS WITHIN THE STATE

In April 2015, we conducted searches of state websites that contained publicly available information about CAFOs. We extracted all readily available information from these websites on AFOs regardless of whether they were NPDES-permitted, and we added this information to our database.

We considered information about CAFOs to be "readily available" if it was downloadable in a batch CSV or Excel file, or if we were otherwise able to copy and paste it from the website en masse. Some state websites contained additional pieces of information about CAFOs on separate pages for each facility, or linked to PDFs of permitting documents for facilities. We did not consider this type of information to be readily available due to the substantial amount of time it would have taken to manually extract information about each facility, one by one. We did not include information that was not readily available in our database, except in the cases of Iowa and Texas. The websites for these states had a substantial amount of important information about CAFOs on separate sub-pages for each facility. Our web contractor was able to write code to extract this information about the facilities from the separate sub-pages.

The state websites from which we gathered data for our database were these:

- Alabama Department of Environmental Management, "Animal Feeding Operations," http://www.adem.state.al.us/programs/water/cafo.cnt.
- Arkansas Department of Environmental Quality, "ADEQ Facility and Permit Summary," https://www.adeq.state.ar.us/home/pdssql/pds.aspx.
- California Environmental Protection Agency, State Water Resources Control Board, "Regulated Facility Report," https://ciwqs.waterboards.ca.gov/ciwqs/readOnly/CiwqsReportServlet?inCommand=reset&reportName=RegulatedFacility.
- Florida Department of Environmental Protection, "Wastewater Facility Information," http://www.dep.state.fl.us/water/wastewater/facinfo.htm.

- Indiana Department of Environmental Management, "Confined Feeding Operations," http://www.in.gov/idem/landquality/2349.htm.
- Iowa Department of Natural Resources, "Animal Feeding Operation," https://programs.iowadnr.gov/animalfeedingoperations/FacilitySearch.aspx.
- Maryland Department of the Environment, "Permit Application Database Search," https://mde.maryland.gov/programs/permits/pages/sb47.aspx.
- Mississippi Department of Environmental Quality, OPC Environmental Permits Division, "Active Permit & Coverage Search," http://opc.deq.state.ms.us/search_ai_alt.aspx#grid.
- New Jersey Department of Environmental Protection, "NJPDES Excel Reports," http://datamine2.state.nj.us/dep/DEP_OPRA/NJDEPexcel.htm.
- North Carolina Department of Environmental Quality, "Animal Feeding Operations: Permits," http://portal.ncdenr.org/web/wq/aps/afo/perm.
- Tennessee Department of Environment and Conservation, "Heritage WPC Permits in Tennessee," http://environment-online.tn.gov:8080/pls/enf_reports/f?p=9034:34001:0: .
- Texas Commission on Environmental Quality, "Water Quality General Permits & Registration Search," http://www2.tceq.texas.gov/wq_dpa/index.cfm. .
- State of Washington Department of Ecology, "Facility/Site Search," https://fortress.wa.gov/ecy/facilitysite/SearchData/ShowSearch.aspx?ModuleType=FacilitySite&RecordSearchMode=New.
- Wisconsin Department of Natural Resources, "CAFO Permittees," http://dnr.wi.gov/topic/AgBusiness/data/CAFO/cafo_all.asp?FULL=1.

THE EPA ENFORCEMENT AND COMPLIANCE HISTORY ONLINE WEBSITE

We conducted a search on April 9, 2015, of all NPDES-permitted CAFOs in the EPA Enforcement and Compliance History Online (ECHO) website, http://echo.epa.gov/?redirect=echo. We added this data to our database by state and included all NPDES-permitted facilities, regardless of their permit status. We later filtered out facilities whose permit status indicated that they were no longer operational, as discussed below.

For a complete listing of each source of data collected for each state, please see our Source List [link to source attribution].

TYPES OF DATA COLLECTED

From the sources listed above, we compiled data about AFOs across 24 categories:

- State
- Permit type
- Permit number
- Permit status
- CAFO name
- CAFO address
- Name of the owner and operator
- Address of the owner and operator
- If contract operation, name and address of the integrator
- Longitude of the operation
- Latitude of the operation
- Type of facility
- Type of animals

- Number of animals (or range)
- Number of animal units
- Type and capacity of manure storage
- Available acreage for land application
- Quantity of manure, process wastewater, and litter generated annually by the CAFO
- Whether the CAFO land-applies (Y/N)
- If the CAFO land-applies, whether it implements a nutrient management plan for land application
- If the CAFO land-applies, whether it employs nutrient management practices and keeps records on site consistent with 40 CFR 122.23(e)
- If the CAFO does not land-apply, alternative uses of manure, litter, and/or wastewater
- Whether the CAFO transfers manure off site
- If the CAFO transfers manure off site, quantity transferred to recipient(s)

ELIMINATING DUPLICATION OF DATA

We took steps to limit the amount of duplication in our database. However, given our multiple sources, there were duplicate entries for many facilities in our database when our collection was complete. To accurately analyze "readily available" data about CAFOs, we had to eliminate this duplication. First, we identified duplicate facilities using the following metrics independently:

- Latitude and longitude to four decimal places
- Permit number
- CAFO name within a state
- CAFO address
- CAFO owner within a state

After duplicates were identified, we consolidated information for those CAFOs across duplicate entries instead of eliminating duplicates entirely, because different entries contained different pieces of information. Thus, where duplicate entries contained information in different fields, the information in both fields was retained. Where duplicate entries contained information that conflicted within the same field, we chose which information to retain on the basis of the source. We created a hierarchy of sources according to how recent their data were and whether they were state or federal sources. We prioritized the latter because federal sources contained consistent and reliable information on NPDES permits that we wanted to retain. This hierarchy was as follows:

1. ECHO (more recently gathered than Envirofacts)
2. Envirofacts
3. State public databases (more recently gathered than FOIA)
4. State data from FOIA request

We used this hierarchy as our default and diverged from it only for a few states in order to ensure that we were capturing the most precise information on animal types, which was contained in the state sources.

Finally, we did a manual review of our data to identify any remaining duplicate entries and consolidated their information as described above.

REFINEMENT OF DATA

After ensuring that there was just one entry for each facility, we limited the facilities that appear in the database to CAFOs that either had a NPDES permit or contained enough animals to qualify as a Large CAFO per federal regulations.

We reviewed state permitting schemes to determine which permits were NPDES permits and included all NPDES-permitted facilities for which we had information in the database.

For facilities without NPDES permit information, we reviewed our data on the number of animals (or range) at each facility to determine whether the facility would qualify as a Large CAFO. We possessed information from a few states on the animal units at each facility rather than the number of animals, but we did not use animal unit data in our analysis because current federal CAFO regulations categorize facilities on the basis of animal numbers, not units. Further, we did not attempt to convert animal unit data to animal numbers because of a lack of information on the specific types of animals contained. We included in our database only those facilities that would qualify as Large CAFOs and did not include facilities that might qualify as a Medium or Small CAFO. We made this decision because in order for a facility to be a Medium or Small CAFO per federal regulations, it must also meet other conditions relating to its pollution or be specifically designated as such by an appropriate authority. Because Large CAFOs are the only category of CAFO defined as such on the basis of animal numbers alone, we could confidently categorize as CAFOs only those facilities with enough animals to be considered Large CAFOs. Therefore, we only included facilities in our CAFO database on the basis of animal numbers alone that would qualify as Large CAFOs.

We used the following definitions of Large CAFOs from the federal regulations:

An AFO is defined as a Large CAFO if it stables or confines as many as or more than the numbers of animals specified in any of the following categories:

- 700 mature dairy cows, whether milked or dry
- 1,000 veal calves
- 1,000 cattle other than mature dairy cows or veal calves. Cattle includes but is not limited to heifers, steers, bulls, and cow/calf pairs
- 2,500 swine each weighing 55 pounds or more
- 10,000 swine each weighing less than 55 pounds
- 500 horses
- 10,000 sheep or lambs
- 55,000 turkeys
- 30,000 laying hens or broilers, if the AFO uses a liquid manure handling system
- 125,000 chickens (other than laying hens), if the AFO uses other than a liquid manure handling system
- 82,000 laying hens, if the AFO uses other than a liquid manure handling system
- 30,000 ducks, if the AFO uses other than a liquid manure handling system
- 5,000 ducks, if the AFO uses a liquid manure handling system

We assigned the animal types that were described in our data to the animal categories in the federal CAFO regulations. When we did not have enough information about the type of animal contained at a CAFO to assign it to an animal category under the federal definitions, we were conservative in assigning it to a category. For example, if we knew that a facility contained swine but did not know the size of the swine, we would assign the swine at that facility to the category "swine each weighing less than 55 pounds." Similarly, if we did not have information on a poultry facility's manure handling system, we would conservatively assume that it used something "other than a liquid manure handling system." By doing so, we avoided designating facilities as large CAFOs when they actually were not.

Using this conservative approach, we classified the following animal types that were present in our data as the following animal types under the CAFO regulations for the purpose of determining whether the number of animals the facility contained put it over the threshold for Large CAFOs.

ANIMAL TYPE IN CAFO REGULATIONS	ANIMAL TYPE FROM DATA
Mature dairy cows, whether milked or dry	Cattle–Milk Cow; Dairy; DAIRY; dairy; Dairy Cattle; dairy cattle; Dairy Cattle (Mature); Dairy Cow, Dry; Dairy Cow, Milking; DAIRY FARMS; Dairy Farms; Mature Dairy; Mature Dairy Cattle; milking; milking/dry
Veal calves	Calves; Cattle - veal; Veal Calves
Cattle other than mature dairy cows or veal calves. Cattle includes but is not limited to heifers, steers, bulls, and cow/calf pairs.	Beef; Beef calf; Beef calves; Beef Cattle; beef cattle; Beef cattle; Beef Cattle Feedlots; BEEF CATTLE FEEDLOTS; Beef Cow; Beef Feeder; Calves; calves and heifers; Cattle; CATTLE; cattle; Cattle – Beef Brood Cow; Cattle – Beef Feeder; Cattle – Beef Stocker Calf; Cattle – Dairy Calf; Cattle – Dairy Heifer; Cattle – Dry Cow; Cattle – includes heifers; Cattle (All except Mature Dairy Cattle and Veal Calves); Cattle (includes heifers); Cattle (Not Mature Dairy/Veal); cows; Dairy calf; Dairy Calves; Dairy Heifer; Dairy Heifers; Dairy Heifers/Calves; heifer; heifers; Heifers; Heifers/Calves
Swine each weighing 55 pounds or more	Boars; finisher swine; Finishers; Finishers-pigs; Pigs, Boar; Pigs, Finishing; Pigs, Gestating; Pigs, Lactating; Sows; sows; Swine – Boar/Stud; Swine (Greater than 55 Lbs.); Swine >= 55 lbs; Swine >= 55 pounds; Swine – Large; Swine Lg; SWINE LG; Swine over 55 lbs.
Swine each weighing less than 55 pounds	farrow to finish swine; grow to finish swine; HOGS; Hogs; Nursery Pigs; nursery swine; nursery swine, finisher swine; Piglets; Pigs, Grower; Pigs, Nursery; production swine; production, finisher swine; Swine; swine; Swine – Farrow to Feeder; Swine – Farrow to Finish; Swine – Farrow to Wean; Swine – Feeder to Finish; Swine – Gilts; Swine – Med; Swine – Other; Swine – Wean to Feeder; Swine – Wean to Finish; Swine (Less than 55 Lbs.); Swine < 55 lbs; Swine < 55 pounds; SWINE LG/MD; Swine Md; SWINE MD; Swine Sm; SWINE SM; Swine under 55 lbs
Horses	Horse; Horses; horses; Horses – Horses; Horses – Other; Horses And Other Equines; Horses and other equines
Sheep or lambs	Sheep; Sheep or Lambs
Turkeys	Turkey; turkey; Turkeys; turkeys; Turkeys and Turkey Eggs
Laying hens or broilers, if the AFO uses a liquid manure handling system	Chickens with liquid manure handling; Layer (Wet); Wet Poultry – Layers; Wet Poultry – Non Laying Pullets; Wet Poultry – Other
Chickens (other than laying hens), if the AFO uses other than a liquid manure handling system	Breeder; Broiler; BROILER; broiler; BROILER FRYER ROAST CHICKENS; Broiler, fryer, and roaster chickens; Broiler, Fryer and Roaster Chickens; Broilers; chicken; Chickens; chickens; Chickens (All except Layers); Chickens (other than laying hens) with dry manure handling; Chickens-not laying hens-dry; Poultry; poultry; Poultry and Eggs; POULTRY AND EGGS NEC; Poultry Hatcheries; Poultry – Breeders; Poultry – Broilers; Poultry – Pullets; Poulty; Pullet; PULLET; Pullet Poultry; Pullets
Laying hens, if the AFO uses other than a liquid manure handling system	Chicken Eggs; CHICKEN EGGS; Chicken Eggs, Poultry and Eggs; Chicken, Layer; Chickens (Layers); Dry Poultry – Laying Chickens; Layer; Layers; layers; Laying Hens; Laying hens – dry manure; Laying Hens (dry); Laying hens with dry manure handling; Poultry – Breeder layers; Poultry – Layers; Poultry, layers
Ducks, if the AFO uses other than a liquid manure handling system	Duck; Ducks
Ducks, if the AFO uses a liquid manure handling system	Ducks – liquid manure

Any listed animal types other than those in the table above were logged as either "other" or "unknown," and their animal numbers, to the extent they were provided, were not used to qualify a facility as a Large CAFO.

FILTERING OF PERMIT STATUSES

We further limited the data in our final data set of CAFOs by filtering out facilities whose permit status clearly indicated that it was no longer operational. We filtered out facilities with the following permit statuses:

- Expired
- Closed
- Termination
- Voided
- App Terminated
- CFO Approval Expiration - Date Issued 03/13/2015
- CFO Approval Expiration - Pending
- CFO Approval Voidance - Date Issued 03/27/2015
- CFO Approval Voidance - Pending
- Historical
- Inactive
- Number was skipped
- Permit Terminated
- REVOK

We encountered other permit statuses indicating that a facility was potentially no longer permitted, and we excluded these facilities as well under the following conditions: 1) if the facility was in the database only because it had an NPDES permit, and 2) if we did not have information indicating that the number of animals the facility contained met the threshold to qualify it as a Large CAFO. We filtered out facilities that met those conditions and had the following permit statuses:

- Incomplete
- No
- NOT
- Not given
- Not issued
- not permitted
- sold
- Transferred
- UNPERMITTED
- WITH
- Withdrawn

FILTERING OF ANIMAL TYPES

We also filtered out of the database facilities that were NPDES-permitted but had the following animal types that indicated they were not CAFOs. These animal types were:

- ANIMAL AQUACULTURE
- Animal aquaculture
- BEEF CATTLE EXCEPT FEEDLOTS
- Beef Cattle, Except Feedlots
- Beef cattle, except feedlots
- Beef Cattle, Except Feedlots
- Beef Cattle, Except Feedlots, Livestock
- Beef; Beef cattle, except feedlots
- Fish hatcheries
- FISHFARM
- Fishing preserves
- LOCAL TRUCKING WITHOUT STORAGE
- Tropical fish farm
- Trout farm

CREATION OF CAFO MAP AND TABLE 1

In the map and Table 1, "Level of Transparency" was determined based on the amount of "readily available" data.

SCORING

The following six categories of information were chosen to assess the transparency of CAFO data in each state. NRDC considers this information to be necessary to protect communities from CAFO pollution and hold industry accountable if they fail to meet their responsibilities under the law:

- Location
- Permit status
- Type of manure storage
- Count of animals
- Type of animal
- Owner information

For each of these six categories for each state, percentages were calculated using the number of CAFOs for which we have the relevant information, divided by the EPA's estimate of the total number of CAFOs in the state at the time the information was gathered.[a] Each category received a score of 0 to 5 points, based on the percentages:

- 0% = 0 points
- Less than 20% = 1 point
- 20% to <40% = 2 points
- 40% to <60% = 3 points
- 60% to <80% = 4 points
- 80% and above = 5 points

a U.S. Environmental Protection Agency, *NPDES CAFO Rule Implementation Status—National Summary, Midyear 2012*, June 30, 2012, https://www3.epa.gov/npdes/pubs/tracksum%20midyear2012_publish.pdf (accessed July 22, 2018).

The points from each of the six categories were added for the final score. The maximum score was 30. The final score determined the final transparency rating, based on the following ranges:

High Transparency = 24–30 points.
80% or more of all CAFO sites in the state are accounted for with readily available data.

Moderate Transparency = 18–23 points.
About 60% to 80% of all CAFO sites in the state are accounted for with readily available data.

Low Transparency = 1–17 points.
60% or fewer of all CAFO sites in the state are accounted for with readily available data.

No Data = No data were readily available for CAFO sites in the state.

DISCREPANCY IN DATA

For the following states, NRDC found data for more sites than the EPA estimated to be present in the state, which we used as our denominator when calculating percentages. Due to the discrepancy in data, we will make a note of this in the map and table for the following states: Delaware, Maryland, Michigan, Montana, New York, Oregon, Pennsylvania, Utah, and Wisconsin.

ENDNOTES

1 *See* "CAFOs and Their Pollution," *infra*.

2 Chris Augustin, Charles Stoltenow, and Ron Wiederholt, "Biosecure Nutrient Management Practices," 1, North Dakota State University, reprinted January 2017, https://www.ag.ndsu.edu/publications/livestock/biosecure-nutrient-management-practices.

3 Carrie Hribar, *Understanding Concentrated Animal Feeding Operations and Their Impact on Communities*, 6, National Association of Local Boards of Health, 2010, https://www.cdc.gov/nceh/ehs/docs/understanding_cafos_nalboh.pdf.

4 Carol M. Browner, et al., *Environmental Assessment of Proposed Revisions to the National Pollutant Discharge Elimination System Regulation and Effluent Limitations Guidelines for Concentrated Animal Feeding Operations*, 3-1, U.S. Environmental Protection Agency (hereinafter EPA), January 2001, https://www3.epa.gov/npdes/pubs/cafo_proposed_env_assess_ch1-3.pdf.

5 Union of Concerned Scientists, "Prescription for Trouble: Using Antibiotics to Fatten Livestock," last revised August 11, 2009, https://www.ucsusa.org/food_and_agriculture/our-failing-food-system/industrial-agriculture/prescription-for-trouble.html#.XEI5SM9KjaY; Carrie Hribar, *Understanding Concentrated Animal Feeding Operations*, 10.

6 40 CFR § 122.23(b)(1); U.S. Department of Agriculture, Natural Resources Conservation Service, "Animal Feeding Operations," https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/plantsanimals/livestock/afo/.

7 EPA, Office of Water, *NPDES Permit Writers' Manual for Concentrated Animal Feeding Operations*, EPA 833-F-12-001, § 2.2, February 2012, https://www3.epa.gov/npdes/pubs/cafo_permitmanual_chapter2.pdf. 40 CFR § 122.23(b), (c).

8 Angela Huffman, Joe Maxwell, and Andres Salerno, *Consolidation, Globalization, and the American Family Farm*, 1-2, Organization for Competitive Markets, August 2017, https://competitivemarkets.com/wp-content/uploads/2017/08/Consolidation-Globalization-and-the-American-Family-Farm.pdf.

9 *See* "The Existing Regulatory Regime," *infra*.

10 U.S. Government Accountability Office (hereinafter GAO), *Concentrated Animal Feeding Operations: EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern*, GAO-08-944, 4-5, September 2008, https://www.gao.gov/products/GAO-08-944.

11 76 Fed. Reg. 65436.

12 See "The CAFO Data Void," *infra*.

13 Withdrawal CAFO Reporting Rule, 77 Fed. Reg. 42,679-81 (withdrawn July 20, 2012).

14 Several months after their provision, EPA asked the Natural Resources Defense Council (hereinafter NRDC) to return some of these data because they contained information that EPA determined was private, such as personal telephone numbers. Because NRDC was interested in information about these facilities' environmental footprints, NRDC returned the requested information and allowed EPA to update the scope of its release.

15 *Am. Farm Bureau Fed'n v. EPA,* 0:13–cv–01751–ADM–TNL (D.Minn.2013).

16 *Am. Farm Bureau Fed'n v. EPA*, No. CIV. 13-1751 ADM/TNL, 2015 WL 364667 (D. Minn. Jan. 27, 2015).

17 *Am. Farm Bureau Fed'n v. EPA*, 836 F.3d 963 (8th Cir. 2016).

18 *Am. Farm Bureau Fed'n v. EPA*, 836 F.3d 963 (8th Cir. 2016).

19 *See* "Research Methodology," *infra*.

20 EPA, *NPDES CAFO Rule Implementation Status—National Summary, Midyear 2012*, June 30, 2012, https://www3.epa.gov/npdes/pubs/tracksum%20midyear2012_publish.pdf.

21 40 CFR § 122.23(b)(1-2).

22 40 CFR § 122.23(b)(4),(6).

23 EPA, Office of Water, *NPDES Permit Writers' Manual.*

24 EPA, "History of the Clean Water Act," https://www.epa.gov/laws-regulations/history-clean-water-act (accessed January 18, 2019); 33 U.S.C. §§ 1251 et seq. (2012).

25 EPA, "NPDES Permit Basics," https://www.epa.gov/npdes/npdes-permit-basics (accessed January 18, 2019); 33 U.S.C. §§ 1311(a), 1342(a), 1362(12).

26 EPA, Office of Water, *NPDES Permit Writers' Manual,* § 1-2, September 2010, https://www.epa.gov/sites/production/files/2015-09/documents/pwm_chapt_01.pdf. 33 U.S.C. § 1251(a)(1).

27 EPA, "Clean Water Act (CWA) Compliance Monitoring," https://www.epa.gov/compliance/clean-water-act-cwa-compliance-monitoring (accessed July 22, 2018).

28 EPA, "Clean Water Act (CWA) Compliance Monitoring."

29 EPA, "*Effluent Limitations Guidelines*," 39 Fed. Reg. 5704 (Feb. 14, 1974) (codified at 40 C.F.R. pt. 412).

30 EPA, *Pollutant Discharge Elimination: Form and Guidelines Regarding Agricultural and Silvicultural Activities*, 38 Fed. Reg. 18,000-18,001 (July 5, 1973).

31 *NRDC v. Costle*, 568 F.2d 1369, 1383 (D.C. Cir. 1977). GAO, *Livestock Agriculture: Increased EPA Oversight Will Improve Environmental Program for Concentrated Animal Feeding Operations*, GAO-03-285, 3, January 2003, https://www.gao.gov/new.items/d03285.pdf.

32 GAO, *Livestock Agriculture: Increased EPA Oversight*, 11, January 2003.

33 Water Quality Act of 1987, Pub. L. No. 100-4, § 503, 101 Stat. 7 (1987).

34 Emily Kenyon, "Enough of This Manure: Why the EPA Needs to Define the Agricultural Stormwater Exemption to Limit the 'Runoff' From the *Alt* Court," *New York University Law Review* 92 (October 2017): 1187, 1197.

35 EPA, *National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feed Operations (CAFOs)*, 68 Fed. Reg. 7176 (Feb. 12, 2003). *Natural Res. Def. Council v. Reilly*, Civ. No. 89-2980, 1991 U.S. Dist. LEXIS 5334, at *12, *30 (D.C. Cir. Apr. 21, 1991).

36 *Waterkeeper All., Inc. v. EPA*, 399 F.3d 486, 524 (2d Cir. 2005).

37 *Nat'l Pork Producers Council v. EPA*, 635 F.3d 738, 756 (5th Cir. 2011).

38 EPA, *National Pollutant Discharge Elimination System Permit Regulation for Concentrated Animal Feeding Operations: Removal of Vacated Elements in Response to 2011 Court Decision*, 77 Fed. Reg. 44,494, 44,494 (July 30, 2012) (codified at 40 C.F.R. pt. 122).

39 40 C.F.R. § 122.23(e) (2011).

40 *Alt v. EPA*, 979 F. Supp. 2d 701, 711 (N.D. W. Va. 2013). This finding contradicted decades of case law in which courts found that over-application of animal waste to agricultural fields may be a "solid waste" under the Resource Conservation and Recovery Act. *See, e.g.*, *Water Keeper All., Inc. v. Smithfield Foods, Inc.*, No. 4:01-CV-27-H(3), 2001 WL 1715730, at *5 (E.D.N.C. Sept. 20, 2001) (animal waste may be a "solid waste" under RCRA when applied "in such large quantities that its usefulness as organic fertilizer is eliminated"); *Cmty. Ass'n for Restoration of the Env't, Inc. v. R & M Haak, LLC*, No. 13-CV-3026-TOR, 2013 WL 3188855, at *5 (E.D. Wash. June 21, 2013) (". . . Defendants over-applied and improperly applied manure to their fields, and allowed liquid manure to leak from lagoons, thereby 'discarding' the manure and qualifying it as 'solid waste' under RCRA").

41 Motion to Voluntarily Dismiss Appeal, *Alt v. EPA*, No. 13-2527 (L) (4th Cir. Sept. 22, 2014); Order, *Alt v. EPA*, No. 13-2527 (L) (4th Cir. Sept. 24, 2014) (granting EPA motion to dismiss appeal). Cynthia Giles, "A Commitment to Keep Our Waters Clean and Safe," *EPA Connect*, September 19, 2014, http://blog.epa.gov/blog/2014/09/a-commitment-to-keep-our-watersclean-and-safe/.

42 James M. MacDonald and Robert A. Hoppe, "Examining Consolidation in U.S. Agriculture," *USDA Economic Research Service*, March 14, 2018, https://www.ers.usda.gov/amber-waves/2018/march/examining-consolidation-in-us-agriculture/.

43 Ibid.

44 GAO, *Concentrated Animal Feeding Operations: EPA Needs More Information*, 4.

45 U.S. Department of Labor, Bureau of Labor Statistics, "Consumer Price Index—Average Price Data: Chicken, fresh, whole, per lb." https://data.bls.gov/PDQWeb/ap (accessed September 21, 2018).

46 Christopher Leonard, "The Ugly Economics of Chicken," *The Week*, April 13, 2014, http://theweek.com/articles/447911/ugly-economics-chicken.

47 *See generally*, Michelle B. Nowlin, "Sustainable Production of Swine: Putting Lipstick on a Pig?" *Vt. L. Rev.* 37 (2013): 1079.

48 Ibid. at 1096-1101.

49 *See generally*, Erin M. Tegtmeier and Michael D. Duffy, "External Costs of Agricultural Production in the United States," *Int'l J. Agric. Sustainability* 2, no. 1 (2004).

50 GAO, *Concentrated Animal Feeding Operations: EPA Needs More Information*, 5.

51 EPA, Emission Standards Division, Office of Air Quality Planning and Standards, *Emissions From Animal Feeding Operations*, preliminary draft report 2-15 (Aug. 15, 2001), www.epa.gov/ttn/chief/ap42/ch09/draft/draftanimalfeed.pdf.

52 EPA, *Emissions From Animal Feeding Operations*.

53 Carrie Hribar, *Understanding Concentrated Animal Feeding Operations*, 8. Melanie Redding, *Manure and Groundwater Quality: Literature Review*, 26-29, State of Washington, Department of Ecology, June 2016, https://fortress.wa.gov/ecy/publications/documents/1603026.pdf.

54 Amira Oun et al., "Effects of Biosolids and Manure Application on Microbial Water Quality in Rural Areas in the US," *Water* 6, no. 12 (2014): 3701-23, www.mdpi.com/2073-4441/6/12/3701/pdf.

55 Carrie Hribar, *Understanding Concentrated Animal Feeding Operations*, 7.

56 Ibid. at 2.

57 Ibid. at 3.

58 Ibid.

59 Pew Environmental Group, "Animal Agriculture and the Clean Water Act," 3, 2010, http://www.pewtrusts.org/~/media/assets/2010/12/01/animal-agriculture-and-the-clean-water-act.pdf.

60 Environmental Integrity Project, *Manure Overload on Maryland's Eastern Shore*, 1, December 8, 2014, http://www.environmentalintegrity.org/wp-content/uploads/2016/11/Manure-Overload1.pdf.

61 Ibid.

62 Ibid. at 3.

63 Ibid. at 6.

64 Ibid. at 2.

65 University of Maryland Center for Environmental Science, "Harmful Algal Blooms in the Chesapeake Bay Are Becoming More Frequent," *ScienceDaily*, May 11, 2015, www.sciencedaily.com/releases/2015/05/150511125219.htm.

66 EPA, "Chesapeake Bay Total Maximum Daily Load," https://www.epa.gov/sites/production/files/2015-07/documents/bay_tmdl_fact_sheet.pdf (accessed November 7, 2018).

67 Ibid.

68 University of Maryland Center for Environmental Science, "Eco Health Report Cards: Chesapeake Bay," https://ecoreportcard.org/report-cards/chesapeake-bay/health/ (accessed February 5, 2019).

69 *See, e.g.*, Steve Wing and Jill Johnston, "Industrial Hog Operations in North Carolina Disproportionately Impact African-Americans, Hispanics and American Indians," NC Policy Watch, 2014, http://www.ncpolicywatch.com/wp-content/uploads/2014/09/UNC-Report.pdf; Wendee Nicole, "CAFOs and Environmental Justice: The Case of North Carolina," 121 *Environ. Health Perspect.* 121 (2013): A182–A189, https://www.ncbi.nlm.nih.gov/pubmed/23732659, citing Bob Edwards and Anthony E. Ladd, "Race, Poverty, Political Capacity and the Spatial Distribution of Swine Waste in North Carolina, 1982–1997," *North Carolina Geographer* 9 (2001): 55–77.

70 Wendee Nicole, "CAFOs and Environmental Justice."

71 Jackie Wang, Nicole Tyau, and Chelsea Rae Ybanez, "Farming Activity Contaminates Water Despite Best Practices," *The Californian*, August 15, 2017, https://www.thecalifornian.com/story/news/2017/08/15/water-near-farms-often-contaminated-nitrates-coliform-bacteria/571000001/.

72 Ibid. EPA, "Drinking Water Contaminants—Standards and Regulations," https://www.epa.gov/dwstandardsregulations (accessed September 18, 2018).

73 EPA, Office of Water, *Environmental Assessment of Proposed Revisions to the National Pollutant Discharge Elimination System Regulation and Effluent Limitations Guidelines for Concentrated Animal Feeding Operations*, January 2001, https://www3.epa.gov/npdes/pubs/cafo_proposed_env_assess_ch1-3.pdf. National Cancer Institute, "Nitrate," February 2018, progressreport.cancer.gov/prevention/nitrate.

74 EPA, "National Primary Drinking Water Regulations," https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations#Inorganic.

75 Environmental Working Group, "Nitrate," Tap Water Database, July 2017, www.ewg.org/tapwater/reviewed-nitrate.php#.WsJdr4hzaUk.

76 Anne W. Schechinger and Craig Cox, "America's Nitrate Habit Is Costly and Dangerous," Environmental Working Group, October 2, 2018, https://www.ewg.org/research/nitratecost/.

77 Leslie A. DeSimone et al., "Quality of Water From Domestic Wells in Principal Aquifers of the United States, 1991–2004," U.S. Geological Survey, March 2009, pubs.usgs.gov/circ/circ1332/.

78 Ibid. at 2, 25-27.

79 Chris Augustin, Charles Stoltenow, and Ron Wiederholt, "Biosecure Nutrient Management Practices, 1."

80 Brown, Vence & Associates, *Task 2 Report: Title 27 Effectiveness to Protect Groundwater Quality*, 22, https://www.waterboards.ca.gov/rwqcb5/water_issues/confined_animal_facilities/library/bva_final_task2_rpt_ess_ctns1_6.pdf (accessed July 20, 2018).

81 Carrie Hribar, *Understanding Concentrated Animal Feeding Operations*, 9.

82 Coburn Dukehart, "Fecal Microbes Found in 60 Percent of Sampled Wells, Raising Concerns About Dairy Manure, Septic Waste," WisconsinWatch, June 8, 2017, https://www.wisconsinwatch.org/2017/06/fecal-microbes-found-in-60-percent-of-sampled-wells-raising-concerns-about-dairy-manure-septic-waste/.

83 Ibid.

84 Centers for Disease Control and Prevention, Parasites: "Cryptosporidium," https://www.cdc.gov/parasites/crypto/illness.html (accessed February 5, 2019).

85 Coburn Dukehart, "Fecal Microbes Found in 60 Percent of Sampled Wells."

86 Midwest Environmental Advocates, "Safe Drinking Water Act Petition to EPA," http://midwestadvocates.org/issues-actions/actions/safe-drinking-water-act-petition-to-epa-1/.

87 Chuck Quirmbach, "DNR Offers Bottled Drinking Water to Residents With Contaminated Wells," Wisconsin Public Radio, May 10, 2017, https://www.wpr.org/dnr-offers-bottled-drinking-water-residents-contaminated-wells.

88 "In the Matter of the Wisconsin Pollutant Discharge Elimination System Permit No. WI-0059536-03-0 (WPDES Permit) Issued to Kinnard Farms, Inc., Town of Lincoln, Kewaunee County," 2014 WL 5797722, at 12.

89 State ex rel. *Dep't. of Nat. Res. v. Wisconsin Court of Appeals*, District IV, 2018 WI 25, 380 Wis. 2d 354, 909 N.W.2d 114.

90 Centers for Disease Control and Prevention, *Antibiotic Resistance Threats in the United States, 2013*, 5, April 23, 2013, https://www.cdc.gov/drugresistance/threat-report-2013/pdf/ar-threats-2013-508.pdf#page=5. World Health Organization, "Antimicrobial Resistance," February 15, 2018, http://www.who.int/mediacentre/factsheets/fs194/en/.

91 World Health Organization, "Antimicrobial Resistance."

92 US Food and Grug Administration, 2017 Summary Report on Antimicrobials Sold or Distributed for Use in Food-Producing Animals (Dec. 2018) 19, https://www.fda.gov/downloads/ForIndustry/UserFees/AnimalDrugUserFeeActADUFA/UCM628538.pdf

93 Carrie Hribar, Understanding Concentrated Animal Feeding Operations, 10, https://www.cdc.gov/nceh/ehs/docs/understanding_cafos_nalboh.pdf.

94 K. Kumar et al., "Antibiotic Uptake by Plants from Soil Fertilized With Animal Manure," *Journal of Environmental Quality* 34, no. 6 (Nov.–Dec.2005): 2082-85. US Environmental Protection Agency, *National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitations Guidelines and Standards for CAFOs*, 43-44, 50, December 2000, https://www3.epa.gov/npdes/pubs/cafo_ch5.pdf.

95 K. Kumar et al., "Antibiotic Uptake by Plants."

96 Dawn Undurraga, "Supermarket Meat Still Superbugged, Federal Data Show," Environmental Working Group, June 28, 2018, https://www.ewg.org/research/superbugs/. EWG calculations based on data from U.S. Food and Drug Administration, "National Antimicrobial Resistance Monitoring System 2015 Integrated Report," October 23, 2017, https://www.fda.gov/AnimalVeterinary/SafetyHealth/AntimicrobialResistance/NationalAntimicrobialResistanceMonitoringSystem/ucm059103.htm.

97 Carrie Hribar, *Understanding Concentrated Animal Feeding Operations*, 5.

98 Abel Russ and Eric Schaeffer, *Ammonia Emissions From Broiler Operations Higher Than Previously Thought*, 2, Environmental Integrity Project, January 2018, http://www.environmentalintegrity.org/wp-content/uploads/2017/02/Ammonia-Report.pdf.

99 James M. MacDonald, "Financial Risks and Incomes in Contract Broiler Production," U.S. Department of Agriculture Economic Research Service, August 2014), https://www.ers.usda.gov/amber-waves/2014/august/financial-risks-and-incomes-in-contract-broiler-production/.

100 Carrie Hribar, *Understanding Concentrated Animal Feeding Operations*, 5. Robert T. Burns et al., *Tyson Broiler Ammonia Emission Monitoring Project: Final Report*, 32, May 1, 2007, https://lib.dr.iastate.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1014&context=abe_eng_reports.

101 Robert T. Burns et al., *Tyson Broiler Ammonia Emission Monitoring Project*.

102 Carrie Hribar, *Understanding Concentrated Animal Feeding Operations*, 4-5.

103 Ibid.

104 Ibid. at 5-6.

105 Ibid. at 6-7.

106 James A. Merchant et al. "Asthma and Farm Exposures in a Cohort of Rural Iowa Children," *Environmental Health Perspectives* 113, no. 3 (March 2005): 350, 355 (Figure 1), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1253764/.

107 Carrie Hribar, *Understanding Concentrated Animal Feeding Operations*, 6.

108 Steve Wing and Susanne Wolf, "Intensive Livestock Operations, Health, and Quality of Life Among Eastern North Carolina Residents," *Environmental Health Perspectives* 108, no. 3 (March 2000). Kendall Thu et al., "A Control Study of the Physical and Mental Health of Residents Living Near a Large-Scale Swine Operation," *Journal of Agricultural Safety and Health* 3, no. 1 (1997): 13-26. Susan Schiffman et al., "The Effect of Environmental Odors Emanating From Commercial Swine Operations on the Mood of Nearby Residents," *Brain Research Bulletin* 37, no. 4 (1995): 369-75.

109 Wendee Nicole, "CAFOs and Environmental Justice."

110 The vast majority of industrial swine facilities in North Carolina operate under a state swine permit; approximately one dozen have obtained a federal NPDES permit. North Carolina Department of Environmental Quality, "Animal Facility Map—List of Permitted Animal Facilities," https://files.nc.gov/ncdeq/List_O_fPermitted_Animal_Facilities%201-26-2018.xls?SdODtHdc46AxmsgSZ0z_o0dLzRFbNgZs (accessed January 18, 2019). According to North Carolina's permit database, at their full permitted capacity, the state's swine operations could house more than 15 million swine. However, farms may not always have swine present or may not operate at their permitted capacity. The latest U.S. Census of Agriculture estimates that there are approximately nine million swine being raised in North Carolina at any given time. *See* USDA, National Agricultural Statistics Service, Quick Stats, 2012, https://quickstats.nass.usda.gov/#BBCF08EB-60FA- 3108-AEEC-8B4B0D143668.

111 Anne Blythe, "Jury Awards More Than $25 Million to Duplin County Couple in Hog-Farm Case," *News & Observer*, June 29, 2018, https://www.newsobserver.com/news/local/article214096384.html.

112 Wendee Nicole, "CAFOs and Environmental Justice."

113 Craig Jarvis, "Hog Farm's Neighbors Not Entitled to Punitive Damages, Judge Rules," *News & Observer*, December 13, 2018, https://www.newsobserver.com/news/politics-government/state-politics/article223044710.html.

114 Ibid.

115 Sara Brown, "N.C. Legislators Override Veto of Hog Farm Nuisance Protection Bill," *AgPro*, June 28, 2018, https://www.agprofessional.com/article/nc-legislators-override-veto-hog-farm-nuisance-protection-bill.

116 Associated Press, "Environmentalists: Manure Spills Endangering Wisconsin Water," *AgWeb*, https://www.agweb.com/article/environmentalists-manure-spills-endangering-wisconsin-water-naa-associated-press/ (accessed July 20, 2018).

117 Associated Press, "Ohio Hands Out Fines Over Fish Kills Caused by Farm Manure," WTOP, October 11, 2017, https://www.apnews.com/a90c9dcdc7e64164939ef465cdd8cf08. "Crews Cleaning Up Manure Spill; Fish Kill Reported in Nearby Creek," WGAL, October 20, 2017, http://www.wgal.com/article/crews-cleaning-up-manure-spill-fish-kill-reported-in-nearby-creek/13059548.

118 Brian DeVore, "Manure Matters," *Minnesota Conservation Volunteer*, Minnesota Department of Natural Resources, July-August 2002, https://webapps8.dnr.state.mn.us/volunteer_index/past_issues/issue_pdf?issue_id=66.

119 EPA, *Literature Review of Contaminants in Livestock and Poultry Manure and Implications for Water Quality*, 49, July 2013, https://nepis.epa.gov/EPA/html/DLwait.htm?url=/Exe/ZyPDF.cgi/P100H2NI.PDF?Dockey=P100H2NI.PDF.

120 David Jackson and Gary Marx, "Spills of Pig Waste Kill Hundreds of Thousands of Fish in Illinois," *Chicago Tribune*, August 5, 2016, http://www.chicagotribune.com/news/watchdog/pork/ct-pig-farms-pollution-met-20160802-story.html.

121 Ibid.

122 Ibid.

123 EPA, "State Compliance Monitoring Expectations," https://echo.epa.gov/trends/comparative-maps-dashboards/state-compliance-monitoring-expectations (accessed July 18, 2018).

124 EPA, "National Enforcement Initiative: Preventing Animal Waste From Contaminating Surface and Ground Water," https://www.epa.gov/enforcement/national-enforcement-initiative-preventing-animal-waste-contaminating-surface-and-ground (accessed July 18, 2018).

125 EPA, "*NPDES CAFO Permitting Status Report—National Summary, Endyear 2017,*" December 31, 2016, https://www.epa.gov/sites/production/files/2018-05/documents/tracksum_endyear_2017.pdf (accessed September 22, 2018).

126 EPA, "National Enforcement Initiative." Christopher Ball, "EPA Announces Triennial Enforcement Priorities," Manko Gold Katcher Fox LLP, January 16, 2008, https://www.mankogold.com/publications-365.html. "EPA Announces 2012 National Enforcement Initiatives and Regional Priorities," Bingham Greenbaum Doll LLP, December 1, 2011, https://www.bgdlegal.com/newsroom-news-epa-announces-2012-national-enforcement-initiatives-and-regional-priorities.

127 EPA, "EPA Targets Clean Water Act Crimes—Illegal Pollution by Animal Feeding Operations Punished by Fines and Incarceration," *Criminal Enforcement Alert* 1, no. 3 (July 2013): 2, https://www.epa.gov/sites/production/files/documents/cr-cafo-06-13.pdf.

128 GAO, *Livestock Agriculture: Increased EPA Oversight Will Improve Environmental Program for Concentrated Animal Feeding Operations*, GAO-03-285, 3, January 2003, https://www.gao.gov/new.items/d03285.pdf. Food & Water Watch et al., *Petition to Revise the Clean Water Act Regulations for Concentrated Animal Feeding Operations*, 12–13, https://www.foodandwaterwatch.org/sites/default/files/citizens_cafo_cwa_petition.pdf (accessed July 22, 2018).

129 GAO, *Concentrated Animal Feeding Operations: EPA Needs More Information*, 4-5.

130 76 Fed. Reg. 65436.

131 GAO, *Concentrated Animal Feeding Operations: EPA Needs More Information*, 2.

132 EPA, *National Pollutant Discharge Elimination System Permit Regulation for Concentrated Animal Feeding Operations: Removal of Vacated Elements in Response to 2011 Court Decision*, 77 Fed. Reg. 44,494, 44,494, July 30, 2012 (codified at 40 C.F.R. pt. 122).

133 William M. McLaren, "The Death of the Duty to Apply: Limitations to CAFO Oversight Following Waterkeeper & National Pork Producers," *Journal of Animal & Natural Resource Law* 11 (2015): 87, 106. Terence J. Centner, "Clarifying NPDES Requirements for Concentrated Animal Feeding Operations," *Penn State Environmental Law Review* (2006): 361, 362. Food & Water Watch, "The EPA's Failure to Track Factory Farms," 1, August 2013, https://www.foodandwaterwatch.org/sites/default/files/EPA%20Factory%20Farms%20IB%20Aug%202013_0.pdf (stating that "as of 2011, the EPA estimated that only 41 percent of NPDES-defined CAFOs actually had NPDES permits").

134 EPA, "NPDES State Program Information," https://www.epa.gov/npdes/npdes-state-program-information (accessed July 22, 2018). Food & Water Watch et al., *Petition to Revise the Clean Water Act Regulations*, 12–13.

135 GAO, *Concentrated Animal Feeding Operations: EPA Needs More Information*, 31.

136 EPA, "Proposed National Pollutant Discharge Elimination System Concentrated Animal Feeding Operation Reporting Rule," Questions and Answers, October 2011, http://www.epa.gov/npdes/pubs/2011_npdes_cafo_qa.pdf.

137 EPA, "*National Pollutant Discharge Elimination System (NPDES) Concentrated Animal Feeding Operation (CAFO) Reporting Rule*," 76 Fed. Reg. 65,431, 65,435-37 (proposed Oct. 21, 2011) (to be codified at 40 C.F.R. pts. 9, 122).

138 76 Fed. Reg. 65,437 (October 21, 2011).

139 76 Fed. Reg. 65,435 (October 21, 2011).

140 EPA, "*National Pollutant Discharge Elimination System (NPDES) Concentrated Animal Feeding Operation (CAFO) Reporting Rule*," 77 Fed. Reg. 42,679, 42,679 (withdrawn July 20, 2012).

141 Ibid. at 42,681.

142 Ibid.

143 Jon Devine, "Seeking Industrial Livestock Information Is Not 'Extreme.' It's Needed to Protect U.S. Waterways and Human Health," *NRDC Expert Blog*, February 21, 2013, https://www.nrdc.org/experts/jon-devine/seeking-industrial-livestock-information-not-extreme-its-needed-protect-us.

144 In addition to the data collected from states, EPA provided spreadsheets containing information that it had compiled from two publicly available sources: online state databases and EPA's own PCS/ICIS system. Instead of using EPA's data from these publicly available sources, NRDC relied on its own more recent searches of the same sources.

145 EPA, "PCS-ISIS Search," https://www.epa.gov/enviro/pcs-icis-search (accessed July 22, 2018).

146 Alabama Department of Environmental Management, "Animal Feeding Operations," http://www.adem.state.al.us/programs/water/cafo.cnt (accessed July 22, 2018). Arkansas Department of Environmental Quality, "ADEQ Facility and Permit Summary," https://www.adeq.state.ar.us/home/pdssql/pds.aspx (accessed July 22, 2018). California Environmental Protection Agency, State Water Resources Control Board, "Regulated Facility Report," https://ciwqs.waterboards.ca.gov/ciwqs/readOnly/CiwqsReportServlet?inCommand=reset&reportName=RegulatedFacility (accessed July 22, 2018). Florida Department of Environmental Protection, "Wastewater Facility Information," http://www.dep.state.fl.us/water/wastewater/facinfo.htm (accessed July 22, 2018). Indiana Department of Environmental Management, "Confined Feeding Operations," https://vfc.idem.in.gov/DocumentSearch.aspx (accessed July 22, 2018). Iowa Department of Natural Resources, "Animal Feeding Operation," https://programs.iowadnr.gov/animalfeedingoperations/FacilitySearch.aspx (accessed July 22, 2018). Maryland Department of the Environment, "Permit Application Database Search," http://www.mde.state.md.us/programs/Permits/Pages/SB47.aspx (accessed July 22, 2018). Mississippi Department of Environmental Quality, OPC Environmental Permits Division, "Active Permit & Coverage Search," http://opc.deq.state.ms.us/search_ai_alt.aspx#grid (accessed July 22, 2018). New Jersey Department of Environmental Protection, "NJPDES Active Permit List," https://www13.state.nj.us/DataMiner (accessed July 22, 2018). North Carolina Department of Environmental Quality, "List of Permitted Animal Facilities," https://deq.nc.gov/about/divisions/water-resources/water-resources-permits/wastewater-branch/animal-feeding-operation-permits/animal-facility-map (accessed July 22, 2018). Tennessee Department of Environment and Conservation, "DWR Permits in Tennessee," http://environment-online.tn.gov:8080/pls/enf_reports/f?p=9034:34001:0 (accessed July 22, 2018). Texas Commission on Environmental Quality, "Water Quality General Permits & Registration Search," http://www2.tceq.texas.gov/wq_dpa/index.cfm (accessed July 22, 2018). State of Washington Department of Ecology, "Facility/Site Search," https://fortress.wa.gov/ecy/facilitysite/SearchData/ShowSearch.aspx?ModuleType=FacilitySite&RecordSearchMode=New (accessed July 22, 2018). Wisconsin Department of Natural Resources, "CAFO Permittees," http://dnr.wi.gov/topic/AgBusiness/data/CAFO/cafo_all.asp?FULL=1 (accessed July 22, 2018).

147 By "readily available," we mean that a user could download information in a batch (.csv or excel) file or otherwise copy and paste it from the website in batches. Some state websites contained additional pieces of information about CAFOs on separate pages for each facility, or linked to individual PDFs of permitting documents for each facility. This type of information was not considered readily available. In the cases of Iowa and Texas, it was possible to write a program to obtain information from separate pages, and this information was included in the database.

148 EPA, "Enforcement and Compliance History Online (ECHO)," http://echo.epa.gov/?redirect=echo (accessed July 22, 2018).

149 EPA, "*NPDES CAFO Rule Implementation Status—National Summary, Midyear 2012*," June 30, 2012, https://www3.epa.gov/npdes/pubs/tracksum%20midyear2012_publish.pdf (accessed July 22, 2018).

150 Ibid.

151 Food & Water Watch, "Factory Farm Map," Pennsylvania, https://www.factoryfarmmap.org/#animal:all;location:PA;year:2012 (accessed July 22, 2018).

152 Earthjustice, *Re: Complaint Under Title VI of the Civil Rights Act of 1964, 42 U.S.C. § 2000d, 40 C.F.R. Part 7*, letter to Gina McCarthy, EPA administrator, and Velveta Golightly-Howell, director, EPA Office of Civil Rights, September 3, 2014, http://blogs.law.unc.edu/documents/civilrights/20140902complaint.pdf.

153 Interpretive Statement on Application of the Clean Water Act National Pollutant Discharge Elimination System Program to Releases of Pollutants From a Point Source to Groundwater, 84 Fed. Reg. 16,810 (Apr. 23, 2019).

154 Ibid. at 7127. EPA, *National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitations Guidelines and Standards for Concentrated Animal Feeding Operations*, 66 Fed. Reg. 2,960, 3,017 (Jan. 12, 2001) (stating, "As a legal and factual matter, EPA has made a determination that, in general, collected or channeled pollutants conveyed to surface waters via groundwater can constitute a discharge subject to the Clean Water Act").

155 *Riverkeeper, Inc. v. Seggos*, No. 902103-17, Decision and Order (N.Y. Sup. Ct. Apr. 23, 2018), https://waterkeeper.org/wp-content/uploads/2018/04/Riverkeeper-v.-Seggos-DO.4.24.2018.pdf.

156 EPA, "NPDES CAFO Permitting Status Report, National Summary, Endyear 2017," (December 31, 2017), https://www.epa.gov/sites/production/files/2018-05/documents/tracksum_endyear_2017.pdf.

157 Environmental Law Institute, "State Constraints: State-Imposed Limitations on the Authority of Agencies to Regulate Waters Beyond the Scope of the Federal Clean Water Act," 2, May 2013, https://www.eli.org/sites/default/files/eli-pubs/d23-04.pdf. (stating, "The Clean Water Act establishes national minimum standards—essentially, a stringency 'floor'—beneath which states are not allowed to fall in their protection of water quality. States may, however, protect their waters more rigorously").

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Subpart 253-1 General Provisions

253-1.1 Purpose

The purpose of this Part is to establish a mandatory greenhouse gas (GHG) reporting program to provide information about GHG emissions from GHG emission sources.

253-1.2 Applicability

(a) This Part applies to greenhouse gases from GHG emission sources as set forth in this section.

(b) Reporting Categories. This Part applies to GHG emission sources, specifically the following persons that meet or exceed the thresholds established under subdivision (c) of this section. GHG emission sources may fall into multiple reporting entity categories.

(1) Owners and Operators of Facilities. The owner and operator of a facility within New York.

(2) Fuel suppliers.

(i) Suppliers of Natural Gas.

(ii) Suppliers of Liquid Fuels and Petroleum Products.

(iii) Suppliers of Liquefied Natural Gas and Compressed Natural Gas.

(iv) Suppliers of Coal.

(3) Waste Haulers and Transporters.

(4) Electric Power Entities.

(5) Suppliers of Agricultural Lime and Fertilizer.

(6) Anaerobic Digestion and Liquid Storage of Waste.

(c) Applicability Thresholds. The following applicability thresholds apply for Reporting

Entities:

(1) If a GHG emission source's annual emissions or activity in any emissions year from 2023 through 2025 meets or exceeds the thresholds identified in paragraph (3) of this subdivision, that person is a reporting entity as of January 1, 2026, and for all future years until the requirements for cessation set forth in subdivisions (n) or (o) of this section are met.

(2) If a GHG emission source's annual emissions or activity in any emissions year after January 1, 2026, meets or exceeds the thresholds identified below, that person is a reporting entity for that year and for all future years until the requirements for cessation set forth in subdivisions (n) or (o) of this section are met.

(3) The applicability threshold for each type of GHG emission source identified in this subdivision shall apply for emissions or activity categories as specified following the emission years set forth in paragraph (1) or (2) of this subdivision as follows:

(i) Owners and Operators of Facilities. The applicability threshold for owners and operators of facilities is 10,000 metric tons or more of CO_2e emissions per year, or a facility with budget unit(s) pursuant to Part 242 of this Title.

(ii) Fuel suppliers.

('a') Suppliers of Natural Gas. The applicability threshold for suppliers of natural gas is the cubic feet of natural gas necessary to generate any GHG emissions per emission year.

('b') Suppliers of Liquid Fuels and Petroleum Products. The applicability threshold for suppliers of liquid fuels and petroleum products is the gallons of

affected liquid fuel necessary to generate any GHG emissions per emission year.

('c') Suppliers of Liquefied Natural Gas and Compressed Natural Gas. The applicability threshold for suppliers of liquefied natural gas and compressed natural gas is the cubic feet of liquified natural gas and/or compressed natural gas to generate any GHG emissions per emission year.

('d') Suppliers of Coal. The applicability threshold for suppliers of coal is the tonnage of coal necessary to generate any GHG emissions per emission year.

(iii) Waste haulers and transporters. The applicability threshold for waste haulers and transporters is as described in section 2.19 of this Part.

(iv) Electric power entities. The applicability threshold for electric power entities is any GHG emissions or imported Mwh.

(v) Suppliers of Agricultural Lime and Fertilizer. The applicability threshold for Suppliers of Agricultural Lime and Fertilizer is the quantity of agricultural lime and fertilizer necessary to generate any GHG emissions per emission year.

(vi) Anaerobic Digestion and Liquid Storage of Waste. The applicability threshold for facilities reporting emissions from anaerobic digesters or liquid storage of waste is as described in section 2.2 of this Part.

(d) Emissions Reported by Category. Persons that own or operate GHG emission sources that fall into the categories listed in subdivision (b) of this section, and meet the threshold listed in subdivision (c) of this section shall report as provided below:

(1) Facilities operators shall report emissions separately for each facility, and the applicability threshold shall apply to each facility separately.

(2) Fuel suppliers shall report emissions for all types of fuels that are owned in New York. A fuel supplier for multiple categories of fuel (liquid, gas, coal, LNG, or CNG) shall report annual emissions for these categories separately in one emissions report.

(3) Electric power entities shall report emissions separately for each facility or for each importer or exporter of electricity or retail provider.

(4) The applicability threshold for a waste transporter shall apply to the sum of emissions from all waste transported out of State by this person's waste transporters. The applicability thresholds apply to the person's emissions from all waste transporters operated by that person.

(e) Emissions Data Report. Any GHG emission source meeting the criteria in subdivisions (b) and (c) of this section must submit an annual emissions data report, except as provided in the cessation provisions of subdivisions (n) and (o) of this section. An emission source submitting annual data reports shall be known as a reporting entity. The emissions data report must cover all source categories and GHGs for which calculation methods are provided or referenced in this Part for the reporting source. Except as otherwise specified in this Part, the report must be compiled using the methods specified by source category in 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(1) The department may request information from emission sources not identified in this Part to ascertain compliance or noncompliance with this Part.

(2) Emission sources reporting after January 1, 2026, under 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) shall notify the

department under which subpart of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) they are reporting and provide the department with the emissions reported if those emissions are not otherwise reported pursuant to this Part.

(3) The department is authorized to access any real property at which an emission source exists during normal business hours (7 a.m. to 7 p.m. Monday through Friday). Department representatives may inspect the real property unaccompanied by property representatives. Department representatives may traverse the property, inspect facilities, take measurements, analyze physical site characteristics, take environmental samples, sketch and photograph the property, and conduct other activities necessary to evaluate emissions and compliance with applicable statutory or regulatory requirements. The department may make reasonable efforts to share with the property owner or operator data collected during any access of real property. Establishment of a reporting account pursuant to section 1.6 of this Part may be considered written permission from the owner(s) of the real property on which an emission source is located for the department to access such property.

(f) Large Emission Sources. Emission sources meeting the thresholds identified in paragraphs (1) through (3) of this subdivision are considered large emission sources.

(1) Owners and Operators of Facilities. The applicability threshold for owners and operators of facilities is 25,000 metric tons or more of CO_2e per emissions year.

(2) Fuel suppliers.

(i) Suppliers of Natural Gas. The applicability threshold for suppliers of natural gas is 15,000,000 cubic feet or more of natural gas per emission year.

(ii) Suppliers of Liquid Fuels and Petroleum Products. The applicability threshold for suppliers of liquid fuels and petroleum products is 100,000 gallons or more of affected liquid fuels per emission year.

(iii) Suppliers of Liquefied Natural Gas and Compressed Natural Gas. The applicability threshold for suppliers of liquefied natural gas and compressed natural gas is 15,000,000 cubic feet or more of liquefied natural gas and/or compressed natural gas per emission year.

(iv) Suppliers of Coal. The applicability threshold for suppliers of coal is 500 U.S. short tons of coal per emission year.

(3) Waste Haulers and Transporters. The applicability threshold for waste haulers and transporters is 25,000 metric tons CO_2e per emission year. This applies to the sum of emissions reported for out-of-state landfill facilities and out of state combustion facilities for all of the waste exported out of New York by a waste transporter or a person operating multiple waste transporters.

(g) Calculating Facility GHG Emissions Relative to Thresholds. For emission sources specified in subdivision (b) of this section, the owner and operator must calculate, and report emissions as directed in section 1.4 and Subpart 2 of this Part.

(h) Hydrogen Fuel Cells. Operators of a hydrogen fuel cell unit must include emissions from the hydrogen fuel cell unit in calculating emissions for comparison to applicability thresholds.

(i) Fuel Suppliers. Liquid and gaseous fuel suppliers listed in this subdivision, as defined pursuant to this Part, are required to report under this Part when they own and

distribute for sale any affected liquid or gaseous fuel in any quantity;

(1) position holders at terminals owning affected liquid fuels, as described in section 2.16 of this Part;

(2) enterers that own affected liquid fuels as described in section 2.16 of this Part;

(3) downstream owners, including below-the-rack distributors, of affected liquid fuels have reporting requirements pursuant to section 2.16 of this Part;

(4) owners of LPG that have reporting requirements pursuant to sections 2.16 and 2.17 of this Part;

(5) Energy Service Companies who provide gaseous fuels to end users in New York, as described in section 2.17 of this Part;

(6) operators of interstate pipelines delivering gaseous fuels, as described in section 2.17 of this Part;

(7) importers of compressed natural gas or liquefied natural gas into New York, as described in section 2.17 of this Part;

(8) local distribution companies who are public utility gas corporations or publicly-owned natural gas utilities delivering gaseous fuels, as described in section 2.17 of this Part;

(9) operators of intrastate pipelines delivering gaseous fuels as described in section 2.17 of this Part;

(10) all natural gas liquid fractionators, without regard to quantities produced, as described in section 2.17 of this Part;

(11) facilities that make liquefied natural gas products or compressed natural gas products by liquefying or compressing natural gas received from interstate pipelines, as described in section 2.17 of this Part.

(j) Electric Power Entities. The entities listed below are required to report under this Part:

(1) electricity importers and exporters, as defined pursuant to this Part;

(2) retail providers as defined pursuant to this Part.

(k) Petroleum and Natural Gas Systems. The facility types listed in this subdivision, as further specified in section 2.12 of this Part, are required to report emissions from stationary combustion, upstream out of state, fugitive, process, and vented:

(1) onshore petroleum and natural gas production facilities;

(2) onshore natural gas processing plants;

(3) onshore natural gas transmission compression facilities;

(4) onshore natural gas transmission pipelines;

(5) underground natural gas storage facilities;

(6) liquefied natural gas storage facilities;

(7) liquefied natural gas import and export facilities; and

(8) natural gas distribution facilities.

(l) Exemptions.

(1) GHG emissions reporting is not required for:

(i) fire suppression systems and equipment;

(ii) portable equipment at a facility when the fuel used in the equipment

has been purchased at a retail location;

(iii) retailers of fuel unless the retailer is otherwise a facility or fuel supplier.

(2) Verification under this Part does not apply to the following:

(i) GHG emissions and facilities regulated pursuant to Part 242 of this Title.

(ii) GHG emissions associated with the fuel supplied by a fuel supplier to facilities regulated pursuant to Part 242 of this Title.

(iii) This exemption from verification does not apply to CO_2 budget units that have received a limited exemption pursuant to section 242-1.4(b) or (c) of this Title and whose primary NAICS code is not electricity generation. The primary NAICS code will be based on the one that most accurately describes the person's primary activity for its principal source of revenue, at the six-digit NAICS code level. The determination of which NAICS codes apply for the purposes of this subparagraph will be made by the department.

(iv) Owners and Operators of facilities in which the floor area dedicated to residential use accounts for 60 percent or more of its total floor area are exempted from the verification requirements under this Part if they submit to the department a certification that shall include:

('a') the total floor area of all buildings and structures associated with the facility, the uses of the facility, and the floor area associated with each use; and

('b') an attestation as follows: "I certify under penalty under the laws of the State of New York that I have personally examined, and am familiar with, the

statements and information submitted in this document and all its attachments. I certify under penalty under the laws of the State of New York that the statement of information submitted to the department is true, accurate, and complete."

(v) N_2O emissions associated with the reporting requirements under section 2.2 of this Part. This exemption does not apply to N_2O emissions from the utilization of fuels at such reporting facilities.

(vi) GHG emissions associated with the reporting requirements for electric power entities under section 2.4 of this Part.

(vii) GHG emissions associated with the reporting requirements under subdivision 2.21(b) of this Part.

(m) Demonstration of Non-applicability. The department may request a demonstration from the owners and operators of an emission source that the emission source does not meet one or more of the applicability criteria specified in this Part. Such demonstration must be provided to the department within 30 days of receipt of a written request.

(n) Cessation of Reporting and Verification for Reduced Emissions. The requirements for the owners and operators of emission sources whose emissions are reduced below applicable reporting and verification thresholds are as follows for ceasing reporting and verification.

(1) Reporting for Large Emission Sources.

(i) Large emission sources pursuant to subdivision (f) of this section, must report and verify emissions until they are less than the thresholds specified in subdivision (f) of this section for three consecutive years, except as specified in this

subparagraph. If annual emissions for an emission source exceed the thresholds specified in subdivision (f) of this section in any year after cessation requirements have been met, then the emission source is a large emission source and must resume verification as required pursuant to this Part.

(‘a’) If an emission source’s emissions drop below the threshold specified in subdivision (f) of this section in meeting the requirements for cessation in subparagraph (i) of this paragraph, but the emission source’s total emissions remain above the threshold specified in subdivision (c) of this section, the emission source must continue to report under this Part until emissions drop below the threshold specified in subdivision (c) of this section for three consecutive years, and in this case the owner or operator of an emission source must meet the requirements in paragraph (2) of this subdivision to cease reporting under this Part.

(‘b’) Fuel suppliers that cease to supply fuel in New York and whose emissions drop to zero for a consecutive three-year period. Pursuant to section 1.4(j)(2)(iv) of this Part, entities that cease to have a reporting obligation or qualify as a large emission source pursuant to subdivision (f) of this section as a fuel supplier due to a change in ownership or sale or relinquishment of an inventory position at a terminal must continue to report and verify emissions from the reportable fuel transactions that occurred prior to the change. Fuel suppliers that cease to supply fuel in New York and no longer have any reportable emissions must verify their emissions data report in the first year in which they report zero emissions. Any reporting year thereafter with zero reportable emissions is not subject to verification.

(ii) An emission source that meets the cessation requirements for reporting, and verification if applicable, pursuant to subparagraph (i) of this paragraph must notify the department in writing that it is ceasing to report, and ceasing to verify if applicable, pursuant to this Part and provide the reason(s) for the reduction of emissions. The notification must be submitted no later than the applicable reporting deadline for the year following the last emission year that the emission source is required to submit an emissions data report. Emission sources must provide the cessation notification to the address indicated in section 1.4(k) of this Part.

(2) Reporting Entities that are not Large Emission Sources.

(i) Facility operators and suppliers. The owners and operators of emission sources whose total reported emissions are below the reporting thresholds specified in subdivision (c) of this section in each reporting year must report under this Part until emissions are less than the reporting thresholds for three consecutive years. If total reported emissions for an emission source exceeds the reporting thresholds in any year after cessation requirements have been met, the owner or operator must resume reporting as required under this Part.

('a') Emission sources that have total reported emissions or fuel throughputs that exceed the thresholds in subdivision (f) of this section in a reporting year must have their emissions data report verified for three consecutive years, are a large emission source, and must follow cessation requirements in paragraph (1) of this subdivision.

('b') If in meeting the cessation requirements in this subparagraph a fuel supplier ceases to supply fuel in New York and emissions drop to zero, the person

must continue to report until emissions are zero for a consecutive three-year period. Pursuant to section 1.4(j)(2)(iv) of this Part, entities that cease to have a reporting obligation as a fuel supplier due to a change in ownership or sale or relinquishment of an inventory position at a terminal must continue to report and verify emissions from the reportable fuel transactions that occurred prior to the change.

(ii) Electric power entities that import or export electricity from New York must report until there are zero imports or exports to report for a consecutive three-year period.

(iii) An emission source that meets the cessation requirements for reporting, and verification if applicable, pursuant to subparagraphs (i) and (ii) of this paragraph must notify the department in writing that it is ceasing to report, or verify if applicable, pursuant to this Part and provide the reason(s) for cessation of reporting, or verification if applicable. The notification must be submitted no later than the applicable reporting deadline for the year following the last emission year that the emission source is required to submit an emissions data report. Emission sources must provide the cessation notification to the address indicated in section 1.4(k) of this Part.

(iv) Owners and operators of emission sources that fully exit reporting pursuant to this paragraph must maintain the corresponding records required under section 1.7 of this Part and retain such records for five years following the submission of the final emissions data report to the department.

(o) Cessation of Reporting and Verification for Shutdown Facilities. The requirements for owners and operators of an emission source that cease to operate or permanently shut

down as defined in this subdivision are as follows for ceasing reporting and verification.

(1) If the operations of an emission source are changed such that all applicable GHG-emitting processes and operations cease to operate or are permanently shut down, the owner or operator must submit an emissions data report for the year in which the facility's GHG-emitting processes and operations ceased to operate, and for the three years of non-operation that follow. The owner or operator must submit a notification to the department that announces the cessation of reporting and certifies to the cessation of all GHG-emitting processes and operations no later than the reporting deadline of the year following the cessation of operations or permanent shutdown.

(2) For the purposes of this provision, "cease to operate" means the facility did not operate any GHG-emitting processes for an entire calendar year. Continued operation of space heaters and water heaters as necessary until operations are restarted in a subsequent year does not preclude a facility from meeting the definition of "cease to operate" provided that the reporting entity's emissions from the space heaters and water heaters are below the applicable threshold pursuant to this section. If the emissions from the operation of space heaters and water heaters is greater than the reporting threshold pursuant to this section, the facility is subject to the reporting requirements of this Part. The owner or operator must resume reporting for any future calendar year during which any of the GHG-emitting processes or operations resume operation and are subject to reporting.

(3) For the purposes of this paragraph, permanently "shut down" means the emission source has objective evidence that operations are permanently shut down, including but not limited to, decommissioning, and cancelling air permits or other operating

permits. For this provision, permanent shutdown may include continued operation of space heaters and water heaters as necessary to support decommissioning activities. If the emissions from the operation of space heaters and or water heaters is greater than the applicable reporting threshold pursuant to this section, the facility is subject to the reporting requirements of this Part.

(4) Paragraph (1) of this subdivision does not apply to seasonal or other temporary cessation of operations.

(5) The owner or operator of an emission source must resume reporting for any future calendar year during which any of the GHG-emitting processes or operations resume operation and are subject to reporting.

(p) Emission Factor Adjustments. For reporting year 2031 and beyond, Reporting Entities shall use the updated emission factors specified by the department as published on the department website and used within the reporting mechanism pursuant to section 1.6 of this Part.

(1) Six months before the start of the 2031 reporting year and six months before the start of any reporting year thereafter, the department will issue a report updating the emission factors for use in this Part. The department will publicly post the report and invite public comment for 30 calendar days from the date the report is posted. The report will include:

(i) for the first report, previously reported emissions and activity data submitted under this Part and from other reliable sources will be compared to the existing emission factors and the methodologies used to establish those factors. For each

subsequent report, emissions and activity data reported in the previous three years under this Part and from other reliable sources will be compared to established emission factors and methodologies;

(ii) the reports will highlight the difference in emission factors and data trends from the start of the reporting program up to the most recently issued report.

253-1.3 Definitions

(a) To the extent that they are not inconsistent with the specific definitions in subdivision (b) of this section, the general definitions in Part 200 of this Title and 40 CFR § 98.6 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) apply to this Part.

(b) General Definitions.

For the purposes of this Part, the following specific definitions apply:

(1) ‘Absorbent Circulation Pump’. A pump commonly powered by natural pressure that circulates the absorbent liquid between the absorbent regenerator and natural gas contactor.

(2) ‘Accuracy’. The closeness of the agreement between the result of the measurement and the true value of the particular quantity (or a reference value determined empirically using internationally accepted and traceable calibration materials and standard methods), taking into account both random and systematic factors.

(3) ‘Acid Gas’. Hydrogen sulfide (H2S) and/or carbon dioxide (CO_2) contaminants that are separated from sour natural gas by an acid gas removal.

(4) ‘Acid Gas Removal Unit (AGR)’. A process unit that separates hydrogen sulfide and/or carbon dioxide from sour natural gas using liquid or solid absorbents or membrane separators.

(5) ‘Adverse Emissions Data Verification Statement’. A verification statement rendered by a verification body attesting that the verification body cannot say with reasonable assurance that the submitted emissions data report is free of material misstatement, or that the emissions data submitted in the emissions data report contains correctable errors as defined pursuant to this section and thus is not in conformance with the requirement to fix such errors pursuant to section 4.2(b)(8) of this Part, or both.

(6) ‘Adverse Product Data Verification Statement’. A verification statement rendered by a verification body attesting that the verification body cannot say with reasonable assurance that the submitted emissions data report is free of material misstatement, or that the industrial product data submitted in the emissions data report contains correctable errors as defined pursuant to this section and thus is not in conformance with the requirements to fix such errors pursuant to section 4.2(b)(8) of this Part, or both.

(7) ‘Adverse Verification Statement’. An adverse emissions data verification statement or adverse product data verification statement.

(8) ‘Affected Liquid Fuels’. Liquid fuels or petroleum products owned in New York and destined for, or resulting in, final sale in New York.

(9) ‘Agricultural Liming Material’. All materials and all calcium and magnesium products in the oxide, hydrate, carbonate or silicate form or combinations thereof and intended for use in the correction of soil acidity, including such forms of material designated

as burned lime, hydrated lime, carbonate of lime, agricultural limestone, slag, and marl.

(10) ‘Agricultural Waste’. Manure, crop residue, animal carcasses, and other similar waste that is generated on a farm.

(11) ‘Aluminum Alloy’. An alloy in which aluminum is the predominant metal and the alloying elements may typically be copper, magnesium, manganese, zinc, or other elemental additives or any combination of elements added.

(12) ‘Aluminum and Aluminum Alloy Billet’. A solid bar of nonferrous metal produced by casting molten aluminum alloys that is suitable for subsequent rolling, casting, or extrusion.

(13) ‘Anaerobic Digester’. The system where wastes are collected and anaerobically digested in large containment vessels or covered lagoons. Anaerobic digesters stabilize waste by the microbial reduction of complex organic compounds to CO_2 and CH_4, which is captured and may be flared or used as fuel. Anaerobic digestion systems include but are not limited to covered storages, complete mix, plug flow, and fixed film digesters.

(14) ‘Anaerobic Reactor’. An enclosed vessel used for anaerobic wastewater treatment (e.g., upflow anaerobic sludge blanket, fixed film).

(15) ‘Anaerobic Treatment’. The biochemical decomposition of organic matter primarily into stabilized solids, CH_4, and CO_2 by microorganisms in the absence of O_2. For purposes of section 2.2 of this Part, anaerobic treatment does not include depositing waste in landfills.

(16) ‘Annual’. With a frequency of once a year; unless otherwise noted, annual events such as reporting requirements will be based on the calendar year.

(17) ‘API’. The American Petroleum Institute or API.

(18) ‘API Gravity’. A scale used to reflect the specific gravity (SG) of a fluid such as crude oil, or water. The API gravity is calculated as [(141.5/SG) - 131.5], where SG is the specific gravity of the fluid at 60°F.

(19) ‘Asphalt’. The dark brown to black cementitious material (solid, semisolid or liquid in consistency) of which the main constituents are bitumens that occur naturally or as a residue of petroleum refining.

(20) ‘Asset-Controlling Supplier’. Any person that owns or operates inter-connected electricity generating facilities or serves as an exclusive marketer for these facilities even though it does not own them and is assigned a supplier-specific identification number and system emission factor by the department for the wholesale electricity procured from its system and imported into New York. Asset controlling suppliers are considered specified sources.

(21) ‘Assigned Emissions Level’. An amount of GHG emissions, in CO_2e, assigned to the reporting entity by the department under the requirements of section 4.2(c)(5) of this Part.

(22) ‘Associated Gas’. A natural gas that is produced in association with the production of crude oil.

(23) ‘ASTM’. The American Society of Testing and Materials.

(24) ‘Atomic Hydrogen Content’. The mass fraction of all hydrogen atoms in a gas, mixture of gases, or a mixture of other materials.

(25) ‘Aviation Gasoline’. A complex mixture of volatile hydrocarbons, with or

without additives, suitably blended to be used in aviation reciprocating engines. Specifications can be found in ASTM D910–24, “Standard Specification for Aviation Gasolines” (2024) (see Table 1, section 200.9 of this Title).

(26) ‘Balancing Authority’. The responsible person that integrates resource plans ahead of time, maintains load-interchange-generation balance within a balancing authority area and supports interconnection frequency in real time.

(27) ‘Balancing Authority Area’. The collection of generation, transmission, and loads within the metered boundaries of a balancing authority. A balancing authority maintains load-resource balance within this area.

(28) ‘Barrel’. A volume equal to 42 U.S. gallons.

(29) ‘Basin’. Geological provinces as defined by the American Association of Petroleum Geologists (AAPG) Geologic Note: AAPG-CSD Geological Provinces Code Map: AAPG Bulletin, Prepared by Richard F. Meyer, Laurie G. Wallace, and Fred J. Wagner, Jr., Volume 75, Number 10 (October 1991) (see Table 1, section 200.9 of this Title).

(30) ‘Below-The-Rack Distributor’. An owner of affected liquid fuels at the time such fuel is delivered for final sale or to the end user in New York.

(31) ‘Best Available Data and Methods’. Methods described by the department for emissions calculations set forth in this Part where reasonably feasible, or facility fuel use and other facility process data used in conjunction with department provided emission factors and other data, or other industry standard methods for calculating GHG emissions.

(32) ‘Bias’. Systematic error resulting in measurements that will be either consistently low or high relative to the reference value.

(33) ‘Bigeneration Unit’. A unit that simultaneously generates electricity and useful thermal energy from the same fuel source but without waste heat recovery. An example of bigeneration includes a boiler generating steam that is split into two streams, and one stream powers a steam turbine to generate electricity, while the other stream is used for other industrial, commercial, heating, and cooling purposes that are not in support of or a part of the electricity generation system.

(34) ‘Biodiesel’. A diesel fuel substitute produced from nonpetroleum renewable resources that meet the registration requirements for fuels and fuel additives established by the U.S. Environmental Protection Agency under section 211 of the Clean Air Act (42 U.S.C. 7545) (January 3, 2024) (see Table 1, section 200.9 of this Title). It includes biodiesel that is all of the following:

(i) registered as a motor vehicle fuel or fuel additive under 40 CFR part 79 (July 1, 2024) (see Table 1, section 200.9 of this Title);

(ii) a mono-alkyl ester;

(iii) meets American Society for Testing and Material designation ASTM D6751- 24 “Standard Specification for Biodiesel Fuel Blendstock (B100) for Middle Distillate Fuels” (2024) (see Table 1, section 200.9 of this Title);

(iv) intended for use in engines that are designated to run on conventional diesel fuel; and

(v) derived from non-petroleum renewable resources.

(35) ‘Biogas’. The combination of CO_2, CH_4, and other gases produced by the biological breakdown of organic matter in the absence of oxygen. Gas that is produced from

the breakdown of organic material in the absence of oxygen. Biogas is produced in processes including anaerobic digestion, anaerobic decomposition, and thermochemical decomposition. These processes are applied to biodegradable biomass materials, such as manure, sewage, municipal solid waste, green waste, and waste from energy crops, to produce landfill gas, digester gas, and other forms of biogas.

(36) ‘Biomass’. Non-fossilized and biodegradable organic material originating from plants, animals and micro-organisms, including products, by-products, residues and waste from agriculture, forestry and related industries, as well as the non-fossilized and biodegradable organic fractions of industrial and municipal wastes, including gases and liquids recovered from the decomposition of non-fossilized and biodegradable organic material.

(37) ‘Biomass-Derived Fuels or Biomass Fuels or Biofuels or Biomass-Based Fuels’. Fuels derived from biomass; includes but is not limited to biodiesel and ethanol.

(38) ‘Biosolids’. the accumulated semi-solids or solids resulting from treatment of municipal or industrial wastewater. Biosolids do not include grit, fixed solids, or screenings or ash generated from the incineration of biosolids.

(39) ‘Blendstock’. Any liquid compound or mixture of compounds (not including fuel or fuel additive) that is used or intended for use as a component of a fuel.

(40) ‘Blowdown’. The act of emptying or depressurizing a vessel. This may also refer to the discarded material such as blowdown water from a boiler or cooling tower.

(41) ‘Boiler’. An enclosed fossil or other fuel-fired combustion device, or other heat source, used to produce heat and to transfer heat to recirculating water, steam or other

medium.

(42) ‘Bone Dry Short Ton’. An amount of material that weighs 2,000 pounds at zero percent moisture content.

(43) ‘Bottom Ash’. Ash that collects at the bottom of a combustion chamber.

(44) ‘Bottoming Cycle’. A type of cogeneration system in which the energy input to the system is first applied to a useful thermal energy application or process, and at least some of the reject heat emerging from the application or process is then used for electricity production.

(45) ‘British Thermal Unit or Btu’. The quantity of heat required to raise the temperature of one pound of water by 1°F at about 39.2°F.

(46) ‘BTEX’. Gaseous compounds of benzene, toluene, ethyl benzene, and xylenes.

(47) ‘Bubble Point Pressure’. The pressure, at the pressurized sample collection temperature, at which the first bubble of gas comes out of solution.

(48) ‘Bulk Transfer/Terminal System’. A fuel distribution system consisting of refineries, pipelines, vessels, and terminals. Fuel storage and blending facilities that are not fed by pipeline or vessel are considered outside the bulk transfer system.

(49) ‘Busbar’. A power conduit of a facility with electricity generating units that serves as the starting point for the electricity transmission system.

(50) ‘Butane or n-Butane’. A paraffinic straight-chain hydrocarbon with molecular formula C_4H_{10}.

(51) ‘Butylene or n-Butylene’. An olefinic straight-chain hydrocarbon with

molecular formula C_4H_8.

(52) ‘Bypass Dust’. Discarded dust from the bypass system dedusting unit of suspension preheater, precalciner and grate preheater kilns, consisting of fully calcined kiln feed material.

(53) ‘Calcination’. The thermal decomposition of carbonate minerals, such as calcium carbonate (the principal mineral in limestone) to form calcium oxide in a cement kiln.

(54) ‘Calcine’. To heat a substance so that it oxidizes or reduces.

(55) ‘Calendar Year’. Refers to a period of time based upon a calendar year commencing January 1 and terminating midnight December 31.

(56) ‘Calibrated Bag’. A flexible, non-elastic, anti-static bag of a calibrated volume that can be affixed to an emitting source such that the emissions inflate the bag to its calibrated volume.

(57) ‘Carbon Dioxide or CO_2’. A GHG, consisting of a molecular level of a single carbon atom and two oxygen atoms.

(58) ‘Carbon Dioxide Equivalent or CO_2 Equivalent or CO_2e’. The amount of carbon dioxide by mass that would produce the same global warming impact as a given mass of another GHG over an integrated 20-year time frame after emission. CO_2e shall be calculated using the CO_2e values in section 496.5 of this Title. For values not listed in section 496.5 of this Title, CO_2e shall be calculated using GWP20 values consistent with the Intergovernmental Panel on Climate Change (IPCC) Assessment Report, Table 7.SM.7 from Smith, C., Z.R.J. Nicholls, K. Armour, W. Collins, P. Forster, M. Meinshausen, M.D. Palmer, and M. Watanabe, 2021: The Earth’s Energy Budget, Climate Feedbacks, and Climate

Sensitivity Supplementary Material. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.), pp 16-27 (see Table 1, section 200.9 of this Title).

(59) ‘Carbonate’. Compounds containing the ion CO_3^{-2}. Upon calcination, the carbonate radical decomposes to evolve carbon dioxide (CO_2). Common carbonates consumed in the mineral industry include calcium carbonate ($CaCO_3$) or calcite; magnesium carbonate ($MgCO_3$) or magnesite; and calcium-magnesium carbonate ($CaMg(CO_3)_2$) or dolomite.

(60) ‘Carbonate-Based Raw Material’. Any of the following materials used in the manufacture of glass: Limestone, dolomite, soda ash, barium carbonate, potassium carbonate, lithium carbonate, and strontium carbonate.

(61) ‘Catalyst’. A substance added to a chemical reaction, which facilitates or causes the reaction, and is not consumed by the reaction.

(62) ‘CBOB’. Conventional blendstock for oxygenate blending. A petroleum product that, when blended with a specified type and percentage of oxygenate, is motor gasoline that is not certified to meet the requirements for reformulated gasoline in regulations promulgated by the U.S. EPA under 40 CFR § 1090.220 (July 1, 2024) (see Table 1, section 200.9 of this Title).

(63) ‘Cement’. A building material that is produced by heating mixtures of

limestone and other minerals or additives at high temperatures in a rotary kiln to form clinker, followed by cooling and grinding with blended additives. Finished cement is a powder used with water, sand and gravel to make concrete and mortar.

(64) ‘Cement Kiln Dust or CKD’. The fine-grained, solid, highly alkaline waste removed from cement kiln exhaust gas by air pollution control devices. CKD consists of partly calcined kiln feed material and includes all dust from cement kilns and bypass systems including bottom ash and bypass dust.

(65) ‘Centrifugal Compressor’. Any equipment that increases the pressure of a process natural gas or CO_2 by centrifugal action, employing rotating movement of the driven shaft.

(66) ‘Centrifugal Compressor Dry Seals’. A series of rings around the compressor shaft where it exits the compressor case that operate mechanically under the opposing forces to prevent natural gas or CO_2 from escaping to the atmosphere.

(67) ‘Certification or Certify’. Refers to the procedure in 40 CFR § 98.4(e) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), as required for reports submitted to the department under this Part.

(68) ‘CFR’. Code of Federal Regulations

(69) ‘Chain of Title’. The sequence of historical transfers of title to a fuel or product from the producer to the reporting entity, which may include bills of lading.

(70) ‘City Gate’. Is a point or measuring where custody transfer occurs between a natural gas transmission system pipeline company/operator and a distribution system company/operator.

(71) ‘Clinker’. The mass of fused material produced in a cement kiln from which finished cement is manufactured by milling and grinding.

(72) ‘Coal’. All solid fuels classified as anthracite, bituminous, sub-bituminous, or lignite by the American Society for Testing and Materials Designation ASTM D388–23 “Standard Classification of Coals by Rank” (2023) (see Table 1, section 200.9 of this Title).

(73) ‘Coal Supplier or Supplier of Coal’. A person producing, importing, supplying, distributing, or selling coal.

(74) ‘Cogeneration’. An integrated system that produces electric energy and useful thermal energy for industrial, commercial, or heating and cooling purposes, through the sequential or simultaneous use of the original fuel energy. Cogeneration must involve generation of electricity and useful thermal energy and some form of waste heat recovery. Some examples of cogeneration include: (i) a gas turbine or reciprocating engine generating electricity by combusting fuel, which then uses a heat recovery unit to capture useful heat from the exhaust stream of the turbine or engine; (ii) steam turbines generating electricity as a by-product of steam generation through a fired boiler; (iii) cogeneration systems in which the fuel input is first applied to a thermal process such as a furnace and at least some of the heat rejected from the process is then used for power production. For the purposes of this Part, a combined-cycle power generation unit, where none of the generated thermal energy is used for industrial, commercial, or heating and cooling purposes (these purposes exclude any thermal energy use that is either in support of or a part of the electricity generation system), is not considered a cogeneration unit.

(75) ‘Cogeneration System’. Individual cogeneration components including the

prime mover (heat engine), generator, heat recovery, and electrical interconnection, configured into an integrated system that provides sequential or simultaneous generation of multiple forms of useful energy (usually mechanical and thermal), at least one form of which the facility consumes on-site or makes available to other users for an end-use other than electricity generation.

(76) ‘Cogeneration Unit’. A unit that produces electric energy as an electricity generating unit and useful thermal energy for industrial, commercial, or heating and cooling purposes, through the sequential or simultaneous use of the original fuel energy and waste heat recovery.

(77) ‘Combustion Emissions’. GHG emissions occurring during the exothermic reaction of a fuel with oxygen.

(78) ‘Combustion Source’. A source of emissions resulting from combustion.

(79) ‘Commercial Fertilizer’. Any substances containing one or more recognized plant nutrients which is used for its plant nutrient content, and which is designed for use or claimed to have value in promoting plant growth, except unmanipulated animal and vegetable manures, agricultural liming material, wood ashes, gypsum, and other products exempted by regulation of the commissioner.

(80) ‘Community Choice Aggregator’. A municipality or group of municipalities that acts as an aggregator and broker for the sale of energy and other services to residents.

(81) ‘Component’. For the purposes of section 2.12 of this Part, each metal-to-metal joint or seal of non-welded connection separated by a compression gasket, screwed thread (with or without thread sealing compound), metal to metal compression, or fluid barrier

through which natural gas or liquid can escape to the atmosphere.

(82) ‘Composting and Other Organics Processing Facility’. A facility that treats the readily biodegradable organic components in waste to produce a mature product for use as a source of nutrients, organic matter, liming value, or other essential constituent for a soil or to help sustain plant growth. The processes include, but are not limited to, composting, vermiculture, anaerobic digestion, fermentation, and class A processes. An organics waste processing facility also includes processes to convert biodegradable organic components in food scraps into animal feed including pet food.

(83) ‘Compressed Natural Gas or CNG’. Natural gas in high-pressure containers that is highly compressed (though not to the point of liquefaction), typically to pressures ranging from 2900 to 3600 psi.

(84) ‘Compressor’. Any machine for raising the pressure of a natural gas or CO_2 by drawing in low pressure natural gas and discharging significantly higher-pressure natural gas or CO_2.

(85) ‘Condensate’. Liquid hydrocarbons that were originally in the gaseous phase in the reservoir and liquids recovered by surface separation from natural gas.

(86) ‘Conflict-of-interest’. A situation in which, because of financial or other activities or relationships with other persons, a person is unable or potentially unable to render an impartial verification statement of an existing or potential client’s GHG emissions data report, or the person’s objectivity in performing verification services is or might be otherwise compromised.

(87) ‘Construction and Demolition Debris or C&D Debris’. Means waste

resulting from construction, remodeling, repair and demolition of structures, buildings and roads. C&D debris includes fill material, demolition wastes, and construction wastes. Materials that are not C&D debris (even if generated from construction, remodeling, repair and demolition activities) include municipal solid waste, friable asbestos-containing waste, corrugated container board, electrical fixtures containing hazardous liquids such as fluorescent light ballasts or transformers, fluorescent lights, furniture, appliances, tires, drums, fuel tanks, containers greater than 10 gallons in size, and any containers having more than one inch of residue remaining on the bottom.

(88) ‘Continuous Bleed’. The continuous venting of natural gas from a gas actuated pneumatic device to the atmosphere by design.

(89) ‘Continuous Emissions Monitoring System or CEMS’. The total equipment required to obtain a continuous measurement of a gas concentration or emission rate from combustion or industrial processes.

(90) ‘Continuous Physical Transmission Path’. The full transmission path shown in the physical path table of a single NERC e-tag from the first point of receipt closest to the generation source to the final point of delivery closest to the final sink.

(91) ‘Corn’ The kernels of the dent corn plant (Zea mays var. indentata.) that have been shelled and contain no more than 10 percent of other grains.

(92) ‘Correctable Errors’. Errors identified by the verification team that affect emission source data or industrial product data in the submitted emissions data report that result from a nonconformance with this Part. Differences that, in the professional judgment of the verification team, are the result of differing but reasonable methods of truncation or

rounding or averaging, where a specific procedure is not prescribed by this Part, are not considered errors and therefore do not require correction.

(93) ‘Cracking’. The process of breaking down larger molecules into smaller molecules, using catalysts and/or elevated temperatures and pressures.

(94) ‘Crude Oil’. A mixture of hydrocarbons that exists in the liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities. Depending upon the characteristics of the crude stream, it may also include any of the following:

(i) small amounts of hydrocarbons that exist in gaseous phase in natural underground reservoirs but are liquid at atmospheric conditions (temperature and pressure) after being recovered from oil well (casing-head) gas in lease separators and are subsequently commingled with the crude stream without being separately measured. Lease condensate recovered as a liquid from natural gas wells in lease or field separation facilities and later mixed into the crude stream is also included;

(ii) small amounts of non-hydrocarbons, such as sulfur and various metals;

(iii) drip gases, and liquid hydrocarbons produced from tar sands, oil sands, gilsonite, and oil shale;

(iv) petroleum products that are received or produced at a refinery and subsequently injected into a crude supply or reservoir by the same refinery owner or operator; and

(v) liquids produced at natural gas processing plants and natural gas

fractionating facilities are excluded, unless the produced natural gas liquids are extracted from produced gas, associated gas, and waste gas at a facility and re-injected into barrels of crude oil produced by the same facility.

(95) ‘Customer’. A purchaser of electricity not for the purposes of retransmission or resale.

(96) ‘Customer Meter’. The meter that measures the transfer of gas from an operator to a consumer, including the riser, and fittings at residential, commercial, or industrial premise(s).

(97) ‘Degradable Organic Carbon (DOC)’ the fraction of waste (kg C/kg-dry mass of waste) that can be biologically degraded. This may include but is not limited to volatile solids in animal manure, biosolids and sources of biological oxygen demand in municipal and industrial wastewater.

(98) ‘Dehydrator’. A device in which an absorbent (including desiccant, ethylene glycol, diethylene glycol, or triethylene glycol) directly contacts a natural gas stream to absorb water vapor.

(99) ‘Dehydrator Vent Emissions’. Natural gas and CO_2 release from a natural gas dehydrator system absorbent (typically glycol) reboiler or regenerator to the atmosphere or a flare, including stripping natural gas and motive natural gas used in absorbent circulation pumps.

(100) ‘Delayed Coking’. A process by which heavier crude oil fractions are thermally decomposed under conditions of elevated temperature and pressure to produce a mixture of lighter oils and petroleum coke.

(101) ‘Delivered Electricity’. Electricity that was distributed from a purchasing-selling entity (PSE) and received by a PSE or electricity that was generated, transmitted, and consumed.

(102) ‘Desiccant’. A material used in dehydrators to remove water from raw natural gas by adsorption or absorption. Desiccants include activated alumina, palletized calcium chloride, lithium chloride and granular silica gel material. Wet natural gas is passed through a bed of the granular or pelletized solid adsorbent or absorbent in these dehydrators. As the wet gas contacts the surface of the particles of desiccant material, water is adsorbed on the surface or absorbed and dissolves the surface of these desiccant particles. Passing through the entire desiccant bed, almost all of the water is adsorbed onto or absorbed into the desiccant material, leaving the dry gas to exit the contactor.

(103) ‘Designated Representative’. The person responsible for certifying, signing, and submitting the GHG emissions data report.

(104) ‘Destruction Device’. Means a flare, thermal oxidizer, boiler, turbine, internal combustion engine, or any other CH_4 destroying unit.

(105) ‘Diesel Fuel’. Distillate Fuel No. 1 and Distillate Fuel No. 2, including dyed and nontaxed fuels.

(106) ‘Digestate’. The solid and liquid material removed from an anaerobic digester once it has undergone anaerobic treatment.

(107) ‘Direct Delivery of Electricity or Directly Delivered’. Electricity that meets any of the following criteria:

(i) the facility has a first point of interconnection with transmission

facilities within the NYCA;

(ii) the facility has a first point of interconnection with distribution facilities used to serve end users within NYCA;

(iii) the electricity is scheduled for delivery from the specified source to NYCA via a continuous physical transmission path from interconnection of the facility in the balancing authority in which the facility is located to a sink located in New York; or

(iv) there is a private agreement from the facility to a person within New York State.

(108) ‘Disburse’. With respect to a position holder, to cause the physical transfer of liquid fuels or petroleum products from a terminal at a rack.

(109) ‘Disbursed for final sale or to an end user in New York.’ Disburse affected liquid fuels as reflected in the records of the terminal operator on in the shipping documents issued at the time of disbursement. If in the records or shipping document the destination of the fuel or product is in New York, then the fuel or product shall be treated as disbursed for final sale or to an end user in New York and be an affected liquid fuel unless a subsequent shipping document for this fuel contains corrected destination for diversion or a subsequent fuel owner (below the rack distributor) reports this fuel as being diverted.

(110) ‘Distillate Fuel Oil’. A classification for one of the petroleum fractions produced in conventional distillation operations and from crackers and hydrotreating process units. The generic term “distillate fuel oil” includes kerosene, kerosene-type jet fuel, diesel fuels (Diesel Fuels No. 1, No. 2, and No. 4), and fuel oils (Fuel Oils No. 1, No. 2, and No. 4).

(111) ‘Distribution Pipeline’. A pipeline that is designated as such by the

Pipeline and Hazardous Material Safety Administration (PHMSA) in 49 CFR § 192.3 (October 1, 2023) (see Table 1, section 200.9 of this Title).

(112) ‘District Heating Facility’. A facility that, at a central plant, produces hot water, steam and/or chilled water that is distributed through underground pipes to buildings and facilities connected to the system that are not part of the same facility. District Heating Facility does not include a facility that produces electricity.

(113) ‘Diversion or Diverted’. An owner of affected liquid fuels changing the destination for final sale to a jurisdiction that is not New York.

(114) ‘Double Valve Cylinder’. Means a metal cylinder equipped with valves on either side for collecting crude oil, condensate, or produced water samples.

(115) ‘Dry Gas or Dry Natural Gas’. Natural gas which remains after:

(i) the liquefiable hydrocarbon portion has been removed from the gas stream (i.e., gas after lease, field, and/or plant separation); and

(ii) any volumes of nonhydrocarbon gases have been removed where they occur in sufficient quantity to render the gas unmarketable.

Dry natural gas is also known as consumer-grade natural gas. The parameters for measurement are cubic feet at 60°F and 14.73 pounds per square inch absolute.

(116) ‘Dry Mass’. Mass of material that has been dried at 105°C until reaching a constant mass or 100 percent solids content.

(117) ‘EIA’. The Energy Information Administration. The Energy Information Administration (EIA) is a statistical agency of the U.S. Department of Energy.

(118) ‘Electrical Distribution Utility(ies) or EDU’. A person that owns and/or

operates an electrical distribution system, including:

(i) a public utility corporation as defined in section 2 of the Public Service Law;

(ii) a public utility company owned or operated by a municipality as those terms are defined in section 2 of the Public Service Law; or

(iii) an Electrical Cooperative as defined as a Cooperative in section 2 of the Rural Electric Cooperative Law, that provides electricity to retail end users in New York.

(119) ‘Electric Power Entity or EPE’. An electricity importer, electricity exporter or a retail provider.

(120) ‘Electricity Exporter’. A person that delivers exported electricity. The person that exports electricity is identified on the NERC e-Tag as the PSE on the last segment of the tag’s physical path, with the point of receipt located inside New York and the point of delivery located outside New York.

(121) ‘Electricity Generating Facility’. A facility that generates electricity and includes one or more generating units at the same location.

(122) ‘Electricity Generation Provider’. A provider of the energy or generation component of electricity services, as distinguished from the provider of transmission and/or distribution service that provides the wires for the transport of electricity. Electricity generation providers may include electricity service providers, community choice aggregators, cogeneration facilities, and other entities in addition to electrical distribution utilities that may provide both generation and transmission/distribution service.

(123) ‘Electricity Generating Unit or EGU’. Any combination of physically

connected generator(s), reactor(s), boiler(s), combustion turbine(s), or other prime mover(s) operated together to produce electric power. An EGU may include a unit that generates electricity from fuel combustion or from other renewable energy sources, such as solar and wind.

(124) ‘Electricity Generation System’. A cogeneration system, a bigeneration system, a combined cycle electricity generation system, or a system with boilers and steam turbine generators.

(125) ‘Electricity Importers’. A person that delivers imported electricity. For electricity that is scheduled with a NERC e-Tag to a final point of delivery inside New York, the electricity importer is identified on the NERC e-Tag as the PSE on the last segment of the tag’s physical path with the point of receipt located outside New York and the point of delivery located inside New York. For facilities physically located outside New York with the first point of interconnection to the New York State electric transmission system when the electricity is not scheduled on a NERC e-Tag, the importer is the facility operator or scheduling coordinator.

(126) ‘Electricity Transaction’. The purchase, sale, import, export or exchange of electric power.

(127) ‘Electricity wheeled through New York or wheeled electricity’. Electricity that is generated outside New York and delivered into New York with the final point of delivery outside New York. Electricity wheeled through New York is documented on a single NERC e-Tag showing the first point of receipt located outside New York, an intermediate point of delivery located inside New York, and the final point of delivery located outside New

York.

(128) ‘Emission Factor’. A unique value for determining an amount of a GHG emitted for a given quantity of activity (e.g., metric tons of carbon dioxide emitted per barrel of fossil fuel burned.)

(129) ‘Emissions or Greenhouse Gas Emissions’. Gaseous constituents of the atmosphere that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the earth’s surface, the atmosphere itself, and by clouds. GHG emissions include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and any other substance emitted into the air that may be reasonably anticipated to cause or contribute to anthropogenic climate change.

(130) ‘Emissions Data Report or Greenhouse Gas Emissions Data Report or Report’. The report prepared by an owner or operator or supplier each year and submitted as prescribed by the department that provides the information required by this Part. The emissions data report is for the submission of required data for the calendar year prior to the year in which the report is due. For example, a 2026 emissions data report would cover emissions and product data for the 2026 calendar year and would be reported in 2027.

(131) ‘Emissions Data Verification Statement’. The final statement rendered by a verification body attesting whether an emission source’s emissions data in its emissions data report is free of material misstatement, and whether the emissions data conforms to the requirements of this Part.

(132) ‘Emission Year’. The calendar year in which emissions occurred, were caused to occur, or an activity that causes or may cause emissions to occur, including the

calendar year in which the final sale or consumption of the fuel or product to an end user occurred in New York.

(133) ‘Emulsion’. Any mixture of crude oil, condensate, or produced water with varying quantities of natural gas entrained in the liquids.

(134) ‘End User’. A final purchaser or consumer of a product, such as fuels, thermal energy, or natural gas not for the purposes of retransmission or resale. In the context of fuels and natural gas consumption, an end user is the point to which natural gas is delivered for consumption. In the context of final sale or consumption of affected liquid fuels, an end user may take possession of the fuel at a filling station.

(135) ‘Energy Services Company or ESCO’. A person eligible to sell energy services to end-use customers using the transmission or distribution system of a utility.

(136) ‘Engineering Estimation’. For the purposes of sections 2.12 of this Part, means an estimate of emissions based on engineering principles applied to measured and/or approximated physical parameters such as dimensions of containment, actual pressures, actual temperatures, and compositions.

(137) ‘Enhanced Oil Recovery or EOR’. The use of certain methods such as steam (thermal EOR), water flooding or gas injection into new or existing wells to increase the recovery of crude oil from a reservoir. In the context of this rule, EOR also applies to injection of critical phase CO_2 into a crude oil reservoir to enhance the recovery of oil.

(138) ‘Enterer’. A person who imports into New York affected liquid fuels or petroleum products outside the bulk transfer/terminal system and who is the owner of affected liquid fuels or petroleum product upon import into New York.

(139) ‘Equipment’. Any stationary article, machine, or other contrivance, or combination thereof, which may cause the issuance or control the issuance of air contaminants; equipment shall not mean portable equipment, tactical support equipment, or electricity generators designated as backup generators in a permit issued by the department.

(140) ‘Equipment Leak’. Those emissions from equipment, components, and other point sources that could not reasonably pass through a stack, chimney, vent, or other functionally equivalent opening.

(141) ‘Ethane’. A paraffinic hydrocarbon with molecular formula C_2H_6.

(142) ‘Ethanol’. An anhydrous alcohol with molecular formula C_2H

(143) ‘Ethylene’. An olefinic hydrocarbon with molecular formula C_2H_4.

(144) ‘Exchange Agreement’. A commitment between electricity market participants to swap energy for energy. Exchange transactions do not involve transfers of payment or receipts of money for the full market value of the energy being exchanged but may include payment for net differences due to market price differences between the two parts of the transaction or to settle minor imbalances.

(145) ‘Exclusive Marketer’. A marketer that has exclusive rights to market electricity for a generating facility or group of generating facilities.

(146) ‘Exported Electricity’. Electricity generated inside New York and delivered to serve load located outside New York. This includes electricity delivered from a first point of receipt inside New York, to the first point of delivery outside New York, with a final point of delivery outside New York. Exported electricity delivered across balancing authority areas is documented on NERC e-Tags with the first point of receipt located inside New York and the

final point of delivery located outside New York. Exported electricity does not include electricity generated inside New York then transmitted outside of New York, but with a final point of delivery inside New York.

(147) ‘External Combustion’. Fired combustion in which the flame and products are separated from contact with the process fluid to which the energy is delivered. Process fluids may be air, hot water, or hydrocarbons. External combustion equipment may include fired heaters, industrial boilers, and commercial and domestic combustion units.

(148) ‘Facility’. Unless otherwise specified in relation to natural gas distribution facilities and onshore petroleum and natural gas production facilities as defined pursuant to this Part, means:

(i) Any physical property, plant, building, structure, source, or stationary equipment located on one or more contiguous or adjacent properties in actual physical contact or separated solely by a public roadway or other public right- of-way and under common ownership or common control, that emits, may emit, or may cause to emit any GHG. Operators of military installations may classify such installations as more than a single facility based on distinct and independent functional groupings within contiguous military properties.

(ii) With respect to natural gas distribution, Facility includes the collection of all distribution pipelines and metering-regulating stations that are operated by a local distribution company within the State of New York.

(149) ‘Farm Taps’. Pressure regulation stations that deliver gas directly from transmission pipelines to rural customers. In some cases, a nearby LDC may handle the billing of the gas to the customer(s).

(150) ‘Feedstock’. The raw material supplied to a process.

(151) ‘Field’. In the context of oil and gas systems, means the general area underlaid by one or more pools, or underground reservoirs containing a common accumulation of oil or gas or both.

(152) ‘Field Accuracy Assessment’. A test, check, or engineering analysis intended to confirm that a flow meter or other mass or volume measurement device is operating within an acceptable accuracy range. A field accuracy assessment should be conducted in a manner that does not interrupt operations or require removal of the meter or require primary element inspection. The selected method for field accuracy assessment will vary based on meter type and piping system design, and may be performed by the facility operator, a third-party meter servicing firm, or the original equipment manufacturer.

(153) ‘Filling Station’. Any facility, portion of a facility, or vehicle from which affected liquid fuels are transferred as the final sale or consumption into the fuel tank of a motor vehicle or other portable fuel tank. A filling station includes any temporary storage (at the facility or portion of the facility or in the vehicle) dedicated to holding that liquid fuel or petroleum product before such transfer.

(154) ‘Final Point of Delivery’. The sink specified on the NERC e-Tag, where defined points have been established through the NERC Registry. When NERC e-Tags are not used to document electricity deliveries, as may be the case within a balancing authority, the final point of delivery is the location of the load. Exported electricity is disaggregated by the final point of delivery on the NERC e-Tag.

(155) ‘Final Sale’. The transfer of affected liquid fuels through a filling station to

a vehicle's tank or other receptacle for temporary storage and later combustion used in the operation of an engine. Or the transfer of liquid fuels or petroleum products to a storage vessel for later utilization in facility processes, products, space heating, equipment, portable equipment, or mechanisms. Includes transfer to storage for later use in non-road engines or equipment or fleet owned vehicles. Includes transfer to storage for later combustion in emergency generators or to create electricity in distributed generation units.

(156) 'First Deliverer of Electricity or First Deliverer'. The owner or operator of an electricity generating facility in New York or an electricity importer.

(157) 'First Point of Delivery in New York'. The first defined point on the transmission system located inside New York at which imported electricity and electricity wheeled through New York may be measured, consistent with defined points that have been established through the NERC Registry.

(158) 'First Point of Receipt'. The generation source specified on the NERC e-Tag, where defined points have been established through the NERC Registry. When NERC e-Tags are not used to document electricity deliveries, as may be the case within a balancing authority, the first point of receipt is the location of the individual generating facility or unit, or group of generating facilities or units. Imported electricity and wheeled electricity are disaggregated by the first point of receipt on the NERC e-Tag.

(159) 'Fixed Solids'. The solids in waste that are not degradable organic carbon. They are the portion of total solids that are not converted to gases after being brought to 600°C for at least 1 hour plus any petroleum-based plastics that are converted to gases by heating to 600°C for at least 1 hour.

(160) ‘Flare’. A combustion device, whether at ground level or elevated, that uses an open flame to burn combustible gases with combustion air provided by uncontrolled ambient air around the flame.

(161) ‘Flare Combustion Efficiency’. The fraction of liquid and gases sent to the flare, on a volume or mole basis, that is combusted at the flare burner tip.

(162) ‘Flare Stack Emissions’. CO_2, N_2O and CH_4 emissions resulting from the incomplete combustion of hydrocarbon gas in the flare.

(163) ‘Flash Analysis’. For purposes of section 2.12 of this Part, means laboratory methodologies for measuring the volume and composition of gases released from liquids, including the molecular weight of the total gaseous sample, the weight percent of individual compounds, and a Gas-Oil Ratio or Gas-Water Ratio required to calculate the specified emission rates as described in section 2.12 of this Part.

(164) ‘Flash Point’. The lowest temperature at which a volatile liquid can vaporize to form an ignitable mixture in air.

(165) ‘Flashing’. A process during which gas dissolved in crude oil, condensate, or produced water under pressure is released when subject to a decrease in pressure, such as when liquids are transferred from an underground reservoir to a tank on the earth’s surface or from a pressure vessel to an atmospheric tank. For purposes of section 2.12 of this Part, means the release of hydrocarbons and carbon dioxide from liquid to surrounding air when the liquid changes temperature and pressure, also known as phase change.

(166) ‘Floating-Piston Cylinder’. A metal cylinder containing an internal pressurized piston for collecting crude oil, condensate or produced water samples. For

purposes of section 2.12 of this Part, means a cylinder used for gathering produced water. The cylinder contains an internal piston controlled by gas pressure. The piston prevents sample liquid from flashing within the sampling cylinder and provides a means of extracting the sample liquid.

(167) ‘Flow Meter’. A measurement device consisting of one or more individual components that is designed to measure the bulk fluid movement of liquid or gas through a piped system at a designated point. Bulk fluid movement can be measured with a variety of devices in units of mass flow or volume.

(168) ‘Flow Monitor’. A component of the continuous emission monitoring system that measures the volumetric flow of exhaust gas.

(169) ‘Fluorinated Greenhouse Gas or Fluorinated GHG’. Greenhouse gases that contain fluorine including sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluoroolefin, and any fluorocarbon that includes but is not limited to any hydrofluorocarbon, any perfluorocarbon, any fully fluorinated linear, branched or cyclic alkane, ether, tertiary amine or aminoether, any perfluoropolyether, and any hydrofluoropolyether.

(170) ‘Food Waste’. The organic residues generated by the handling, storage, sale, preparation, cooking, and serving of foods.

(171) ‘Fractionates’. The process of separating natural gas liquids into their constituent liquid products.

(172) ‘Fractionator’. Plants that produce fractionated natural gas liquids (NGLs) extracted from produced natural gas and separate the NGLs individual component products:

ethane, propane, butanes and pentane-plus (C5+). Plants that only process natural gas but do not fractionate NGLs further into component products are not considered fractionators. Some fractionators do not process production gas but instead fractionate bulk NGLs received from natural gas processors. Some fractionators both process natural gas and fractionate bulk NGLs received from other plants.

(173) ‘Fuel’. A solid, liquid, or gaseous combustible material.

(174) ‘Fuel Analytical Data’. Data collected about fuel usage (including mass, volume, and flow rate) and fuel characteristics (including heating value, carbon content, and molecular weight) to support emissions calculation.

(175) ‘Fuel Cell’. A device that converts the chemical energy of a fuel and an oxidant directly into electrical energy without using combustion. Fuel cells require a continuous source of fuel and oxidant to operate.

(176) ‘Fuel Characteristic Data’. For the purpose of this Part, properties of a fuel used for calculating GHG emissions including carbon content, high heat value, and molecular weight.

(177) ‘Fuel Ethanol’. Ethanol that meets ASTM D4806-21A “Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel” (2021) (see Table 1, section 200.9 of this Title), specifications, for blending with gasolines for use as automotive spark-ignition engine fuel.

(178) ‘Fuel Flowmeter System’. A monitoring system which provides a continuous record of the flow rate of fuel oil or gaseous fuel. A fuel flowmeter system consists of one or more fuel flowmeter components, all necessary auxiliary components (e.g.,

transmitters, transducers, etc.), and a data acquisition and handling system (DAHS).

(179) ‘Fuel Production Facility’. A facility, other than a refinery, in which motor vehicle fuel, diesel fuel or biomass-based fuel is produced.

(180) ‘Fuel Supplier’. A supplier of natural gas, a supplier of coal, a supplier of affected liquid fuels, and/or a supplier of Liquefied Natural Gas and Compressed Natural Gas.

(181) ‘Fuel Transaction’. The record of the exchange of fuel possession, ownership, or title from one person to another.

(182) ‘Fugitive Emissions’. Those emissions which are unintentional and could not reasonably pass through a stack, chimney, vent, or other functionally equivalent opening.

(183) ‘Full Verification’. All verification services as provided in section 4.2 of this Part.

(184) ‘Gas’. The state of matter distinguished from the solid and liquid states by: relatively low density and viscosity; relatively great expansion and contraction with changes in pressure and temperature; the ability to diffuse readily; and the spontaneous tendency to become distributed uniformly throughout any container.

(185) ‘Gas Gathering/Booster Stations’. Centralized stations where produced natural gas from individual wells is co-mingled, compressed for transport to processing plants, transmission and distribution systems, and other gathering/booster stations which co-mingle gas from multiple production gathering/booster stations. Such stations may include gas dehydration, gravity separation of liquids (both hydrocarbon and water), pipeline pig launchers and receivers, and gas-powered pneumatic devices.

(186) ‘Gas-to-oil Ratio or GOR’. The ratio of the volume of gas produced in standard cubic feet to each barrel of oil produced concurrently during any stated period.

(187) ‘Gas-to-water Ratio or GWR’. The ratio of gas produced from a barrel of produced water when cooling and depressurizing produced water to standard conditions, expressed in terms of standard cubic feet of gas per barrel of water.

(188) ‘Generated Electricity’. Electricity generated by an electricity generating unit at the emission source. Generated electricity does not include any electricity that is generated outside the facility and delivered into the facility with final destination outside of the facility.

(189) ‘Generated Energy’. Electricity or thermal energy generated by the electricity generating, cogeneration, or bigeneration units included in the emission source.

(190) ‘Generated Thermal Energy’. The thermal energy generated by a cogeneration unit or district heating facility that is sold to particular end-users and reported pursuant to section 2.5(a)(5)(i) of this Part, and the thermal energy used on-site by industrial processes or operations and heating and cooling operations that is not in support of or a part of the electricity generation or cogeneration system and is reported pursuant to section 2.5(a)(5)(iii) of this Part. Generated thermal energy does not include thermal energy that is vented, radiated, wasted, or discharged before it is used at industrial processes or operations, or, for a facility with a cogeneration unit, any thermal energy generated by equipment that is not an integral part of the cogeneration unit.

(191) ‘Generating Unit’. Any combination of physically connected generator(s), reactor(s), boiler(s), combustion turbine(s), or other prime mover(s) operated together

to produce electric power.

(192) ‘Generation Providing Entity or GPE’. A facility or generating unit operator, full or partial owner, party to a contract for a fixed percentage of net generation from the facility or generating unit, party to a tolling agreement with the owner, or exclusive marketer recognized by the department that is either the electricity importer or exporter with prevailing rights to claim electricity from the specified source.

(193) ‘Geothermal’. Heat or other associated energy derived from the natural heat of the earth.

(194) ‘Graduated Cylinder’. For purposes of section 2.12 of this Part, means a measuring instrument for measuring fluid volume, such as a glass container (cup or cylinder or flask) which has sides marked with or divided into amounts.

(195) ‘Greenhouse Gas or GHG’. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and other fluorinated greenhouse gases.

(196) ‘Greenhouse Gas Emission Reduction or GHG Emission Reduction or Greenhouse Gas Reduction or GHG Reduction’. A calculated decrease in GHG emissions relative to a project baseline or source baseline over a specified period of time.

(197) ‘Greenhouse Gas Emission Source or Emission Source’. Any type of anthropogenic activity that releases, causes the release of, may cause the release of, or contributes to the release of greenhouse gases into the atmosphere.

(198) ‘Grid or Electric Power Grid’. A system of synchronized power providers and consumers connected by transmission and distribution lines and operated by one or

more control centers.

(199) ‘Grit’. Any solid material that does not include degradable organic carbon such as sand, most plastics, or metal.

(200) ‘Gross Generation or Gross Power Generated’. The total electrical output of the generating facility or unit, expressed in megawatt hours (MWh) per year.

(201) ‘GWP20.’ An assessment of the Global Warming Potential of greenhouse gases over an integrated 20-year time frame.

(202) ‘Gypsum’. A mineral with the chemical formula $CaSO_4 \cdot 2H_2O$.

(203) ‘Hazardous Waste’. A material that is defined in Part 371 of this Title to be both a solid waste and a hazardous waste.

(204) ‘Heat Input Rate’. The product (expressed in MMBtu/hr) of the gross calorific value of the fuel (expressed in MMBtu/mass of fuel) and the fuel feed rate into the combustion device (expressed in mass of fuel/hr) and does not include the heat derived from preheated combustion air, recirculated flue gases, or exhaust from other sources.

(205) ‘Heavy Crude Oil or Heavy Crude’. A category of crude oil characterized by relatively high viscosity, a higher carbon-to-hydrogen ratio, and a relatively higher density having an API gravity of less than 20.

(206) ‘High Bleed Pneumatic Devices’. Automatic, continuous or intermittent bleed flow control devices powered by pressurized natural gas and used for maintaining a process condition such as liquid level, pressure, delta-pressure and temperature.
Part of the gas power stream that is regulated by the process condition flows to a valve actuator controller where it vents continuously or intermittently (bleeds) to the atmosphere at

a rate in excess of six standard cubic feet per hour.

(207) ‘High Heat Value or HHV’. The high or gross heat content of the fuel with the heat of vaporization included. The water vapor is assumed to be in a liquid state.

(208) ‘Horsepower Tested’. The total horsepower of all turbine and generator set units tested prior to sale.

(209) ‘Hydraulic Retention Time’. The average time in days that liquid is present in an anaerobic digester or reactor. The hydraulic retention time is equivalent to the average liquid volume held by the equipment divided by the average rate of removal.

(210) ‘Hydrocarbons’. Chemical compounds containing predominantly carbon and hydrogen.

(211) ‘Hydrofluorocarbons or HFCs’. A class of GHGs consisting of hydrogen, fluorine, and carbon.

(212) ‘Hydrogen’. Diatomic molecular hydrogen.

(213) ‘Hydrogen Plant’. A facility that produces hydrogen with steam hydrocarbon reforming, partial oxidation of hydrocarbons, or other processes.

(214) ‘Imported Electricity’. Electricity generated outside New York and delivered to serve load located inside New York.

(i) Imported electricity includes:

(‘a’) Electricity delivered across balancing authority areas from a first point of receipt located outside New York, to the first point of delivery located inside New York, having a final point of delivery in New York.

(’b’) Electricity imported into New York from a facility or unit

physically located outside New York with the first point of interconnection located inside New York State.

(‘c’) Electricity that is a result of cogeneration located outside New York.

(ii) Imported electricity does not include:

(’a’) Electricity wheeled through New York, defined pursuant to this section.

(’b’) Electricity imported into New York by an Independent System Operator to obtain or provide emergency assistance under applicable emergency preparedness and operations reliability standards of the North American Electric Reliability Corporation or NPCC.

(215) ‘Importer of Fuel’. A person that imports fuel into New York and who is the importer of record under Federal customs law. For imported fuel not subject to Federal customs law, the importer of fuel is the owner of the fuel upon its entering into New York if the eventual transfer of ownership of the product to an end user or marketer located in New York occurs at a location inside New York. However, where the transfer of ownership of the fuel to a New York end user or marketer occurs at a location outside of New York, the “importer of fuel” is the producer, marketer, or distributor that is the seller of the fuel to the end user or marketer located inside New York. Only importers of liquefied petroleum gas, compressed natural gas, and liquefied natural gas are subject to reporting as an importer of fuel.

(216) ‘Importer of Record’. The owner or purchaser of the goods that are

imported into New York.

(217) ‘Independently Operated and Sited Cogeneration or Bigeneration Facility’. A cogeneration or bigeneration facility that is not located on the same facility footprint as its thermal host and has different operational control and different ownership than the thermal host.

(218) ‘Independently Operated Cogeneration or Bigeneration Facility Co-Located with the Thermal Host’. A cogeneration or bigeneration facility that is located on the same property footprint as its thermal host but has different operational control and different ownership than the thermal host.

(219) ‘Industrial, Institutional, Commercial Facility with Electricity Generation Capacity’. A facility whose primary business is not electricity generation and includes one or more electricity generating, cogeneration, or bigeneration units.

(220) ‘Industrial Product Data’. All product data or annual production data as required under section 2.22 of this Part.

(221) ‘Industrial Wastewater’. Water containing wastes from an industrial process. Industrial wastewater includes water that comes into direct contact with or results from the storage, production, or use of any raw material, intermediate product, finished product, by-product, or waste product. Examples of industrial wastewater include, but are not limited to, paper mill white water, wastewater from equipment cleaning, wastewater from air pollution control devices, rinse water, contaminated stormwater, and contaminated cooling water.

(222) ‘Intermittent Bleed Pneumatic Devices’. Automated flow control devices

powered by pressurized natural gas and used for automatically maintaining a process condition such as liquid level, pressure, delta-pressure and temperature. These are snap-acting or throttling devices that discharge all or a portion of the full volume of the actuator intermittently when control action is necessary, but do not bleed continuously. Intermittent bleed devices which bleed at a cumulative rate of six standard cubic feet per hour or greater are considered high bleed devices for the purposes of this regulation.

(223) ‘Internal Combustion’. The combustion of a fuel that occurs with an oxidizer (usually air) in a combustion chamber. In an internal combustion engine, the expansion of the high-temperature and high-pressure gases produced by combustion, applies direct force to a component of the engine, such as pistons, turbine blades, or a nozzle. This force moves the component over a distance, generating useful mechanical energy. Internal combustion equipment may include gasoline and diesel industrial engines, natural gas-fired reciprocating engines, and gas turbines.

(224) Interstate Pipeline’. A pipeline or that part of a pipeline that is used in the transportation of fuel or carbon dioxide in interstate or foreign commerce.

(225) ‘Intrastate Pipeline’. A gas pipeline facility and transportation of gas within a State not subject to the jurisdiction of the Federal Energy Regulatory Commission under the Natural Gas Act (15 U.S.C. 717 et seq.) (2023) (see Table 1, section 200.9 of this Title). For purposes of this Part, only intrastate pipeline operators that physically deliver gas to end users in New York are subject to reporting under this Part. This definition includes onshore petroleum and natural gas production facilities and natural gas processing facilities, as defined pursuant to this Part, that deliver pipeline and/or non-pipeline quality natural gas to

one or more end users. Facility operators that operate an interconnection pipeline that connects their facility to an interstate pipeline, or that share an interconnection pipeline to an interstate pipeline with other nearby facilities, are not considered intrastate pipeline operators. Facilities that receive gas from an upstream LDC and redeliver a portion of the gas to one or more adjacent facilities are not considered intrastate pipelines.

(226) ‘Inventory Position’. A contractual agreement with the terminal operator for the use of the storage facilities and terminaling services for the fuel.

(227) ‘ISO’. The International Organization for Standardization.

(228) ‘Isobutane’. A paraffinic branch chain hydrocarbon with molecular formula C_4H_{10}.

(229) ‘Isobutylene’. An olefinic branch chain hydrocarbon with molecular formula C_4H_8.

(230) ‘Isopentane’. The methylbutane or 2-methylbutane, branched chain, isomer of C_5H_{12}.

(231) ‘Jurisdiction’. A U.S. state or Canadian province. For purposes of this Part, U.S. state means U.S. State, the District of Columbia, the Commonwealth of Puerto Rico, the Virgin Islands, Guam, and American Samoa and includes the Commonwealth of the Northern Mariana Islands. For purposes of this Part, province means any Canadian province or territory.

(232) ‘Kerosene’. A light petroleum distillate with a maximum distillation temperature of 400°F at the 10 percent recovery point, a final maximum boiling point of 572°F, a minimum flash point of 100°F, and a maximum freezing point of -22°F. Includes No.

1-K and No. 2-K, distinguished by maximum sulfur content (0.04 and 0.30 percent of total mass, respectively), as well as all other grades of kerosene called range or stove oil. “Kerosene” does not include kerosene-type jet fuel.

(233) ‘Kerosene-type Jet Fuel’. A kerosene-based product used in commercial and military turbojet and turboprop aircraft. The product has a maximum distillation temperature of 400°F at the 10 percent recovery point and a final maximum boiling point of 572 °F. Includes Jet A, Jet A–1, JP–5, and JP–8.

(234) ‘Kiln’. An oven, furnace, or heated enclosure used for thermally processing a mineral or mineral-based substance.

(235) ‘Landfill’. A facility where waste is intentionally placed and intended to remain and which is designed, constructed, operated and closed to minimize adverse environmental impacts.

(236) ‘Large Emission Sources’. Emission sources meeting the thresholds identified in section 1.2(f) of this Part.

(237) ‘Last Point of Delivery in New York’. The last defined point on the transmission system located inside New York at which exported electricity may be measured, consistent with defined points that have been established through the NERC Registry.

(238) ‘Lead and lead alloys’. Lead or the metal alloy that combines lead and other elements such as antimony, selenium, arsenic, copper, tin, or calcium.

(239) ‘Lead Verifier’. A person that has met all of the requirements in sections 4.3(b) or 4.3(c)(2) of this Part, and who may act as the lead verifier of a verification team providing verification services or as a lead verifier providing an independent review of

verification services rendered.

(240) ‘Lead Verifier Independent Reviewer or Independent Reviewer’. A lead verifier within a verification body who has not participated in conducting verification services for a reporting entity, or authorized project designee for the current reporting year who provides an independent review of verification services rendered to the reporting entity as required in section 4.2 of this Part.

(241) ‘Leak Detection’. The process of identifying equipment leaks or fugitive emissions.

(242) ‘Less Intensive Verification’. The verification services provided in interim years between full verifications; less intensive verification of an emission source’s emissions data report only requires data checks and document reviews of an emission source’s emissions data report based on the analysis and risk assessment in the most current sampling plan developed as part of the most current full verification services. This level of verification may only be used if the verifier can provide findings with a reasonable level of assurance.

(243) ‘Light Crude Oil’. A category of crude oil characterized by relatively low viscosity, a lower carbon-to-hydrogen ratio, and a relatively lower density having an API gravity of greater than or equal to 20.

(244) ‘Limestone’. A sedimentary rock composed largely of the minerals calcite and aragonite, which are different crystal forms of calcium carbonate ($CaCO_3$).

(245) ‘Limited Alternative Emissions’. Those emissions reported for an emission source or sources that are calculated using alternative methods selected by the operator,

subject to the limits specified in section 1.4(e) of this Part.

(246) ‘Liquefied Natural Gas or LNG’ means natural gas (primarily methane) that has been liquefied by reducing its temperature to -260°F at atmospheric pressure.

(247) ‘Liquefied Petroleum Gas or LP-Gas or LPG’. A petroleum hydrocarbon, such as propane, butane or isobutane which is normally a gas but which has been compressed and condensed to a liquid.

(248) 'Liquid Fuel or Petroleum Product’. Fuels or products typically delivered in a liquid form including, but not limited to, Gasoline RBOB; Distillate Fuel Oils; Renewable Diesel; Residual Fuel Oils; Liquified Petroleum Gas, L.P. gas and propane; Kerosene; Jet fuel; Aviation gasoline; Biomass-derived fuels or products; Lubricants; Asphalt and Road Oil; and Petroleum coke.

(249) ‘Liquid Hydrogen’. Hydrogen in a liquid state.

(250) ‘Liquid or Slurry Waste Storage’. A container for waste that is less than or equal to 15 percent solids by mass (kg-dry mass/kg) and is not equipped with surface aerators. The average residence time of waste in a container must be more than two days in order for that container to be considered a storage.

(251) ‘Local Distribution Company or LDC’. For purposes of this Part, means a company that owns or operates distribution pipelines, not interstate pipelines, that physically deliver natural gas to end users and includes public utility gas corporations, publicly owned natural gas utilities and intrastate pipelines that are delivering natural gas to end users.

(252) ‘Lookback Period’. The specified time period of historical data that the operators must use for missing data substitution as required by the regulation.

(253) ‘Low Bleed Pneumatic Devices’. Automated flow control devices powered by pressurized natural gas and used for maintaining a process condition such as liquid level, pressure, delta-pressure and temperature. Part of the gas power stream that is regulated by the process condition flows to a valve actuator controller where it vents continuously or intermittently bleeds to the atmosphere at a rate equal to or less than six standard cubic feet per hour.

(254) ‘Marketer’. A purchasing-selling entity that delivers electricity and is not a retail provider.

(255) ‘Material Misstatement’. Any discrepancy, omission, or misreporting, or aggregation of the three, identified in the course of verification services that leads a verification team to believe that the total reported emissions (metric tons of CO_2e) or reported industrial product data contains errors greater than five percent, as applicable, in an emissions data report. Material misstatement is calculated separately for emissions and industrial product data, as specified in section 4.2(b)(11)(i) of this Part.

(256) ‘Maximum Potential Fuel Flow Rate or Maximum Fuel Consumption Rate’. The maximum fuel use rate the source is capable of combusting, measured in physical unit of the fuel (e.g. million standard cubic feet for gases, gallons for liquids, short tons for non-biomass solids, and bone-dry short tons for biomass-derived solids). When the source consists of multiple units, the maximum potential fuel use rate is the sum of the maximum potential fuel use rates of all the units aggregated as a source.

(257) ‘Megawatt Hour or MWh’. The electrical energy unit of measure equal to one million watts of power supplied to, or taken from, an electric circuit steadily for one hour.

(258) ‘Meter/Regulator Run’. A series of components used in regulating pressure or metering natural gas flow or both.

(259) ‘Metering/Regulating Station’. A station that meters the flow rate, regulates the pressure, or both, of natural gas. This does not include customer meters, customer regulators, or farm taps.

(260) ‘Methane or CH_4’. A GHG consisting of a single carbon atom and four hydrogen atoms.

(261) ‘Metric Ton or MT’. A common international measurement for mass, equivalent to 2204.6 pounds.

(262) ‘Missing Data Period’. A period of time during which a piece of data is not collected, is invalid, or is collected while the measurement device is not in compliance with the applicable quality-assurance requirements. In the context of periodic fuel sampling, missing data period is the entire sampling period (e.g. week, month, or quarter) for which corresponding fuel characteristic data are not obtained. In the context of periodic fuel consumption monitoring and recording, a missing data period consists of the consecutive time intervals (e.g. hours, days, weeks, or months) for which fuel consumption during the time period is not monitored and recorded.

(263) ‘MMBtu’. A million British thermal units.

(264) ‘Motor Vehicle Fuel’. Gasoline. It does not include aviation gasoline, jet fuel, diesel fuel, kerosene, liquefied petroleum gas, natural gas in liquid or gaseous form, or racing fuel.

(265) ‘Mscf’. One thousand standard cubic feet.

(266) ‘Municipal Solid Waste or MSW’. Municipal solid waste as defined in Part 360 of this Title.

(267) ‘Municipal Wastewater’. Wastewater from domestic, business, and industrial sources that is collected in city sewers and transported to a centralized wastewater treatment system such as a publicly owned treatment works.

(268) ‘Nameplate Generating Capacity’. The maximum electrical output (in MWe) that a generator can sustain over a specified period of time when not restricted by seasonal or other deratings as measured in accordance with the U.S. Department of Energy standards.

(269) ‘Naphthas’. Is a generic term applied to a petroleum fraction with an approximate boiling range between 122°F and 400°F. The naphtha fraction of crude oil is the raw material for gasoline and is composed largely of paraffinic hydrocarbons.

(270) ‘Natural Gas’. A naturally occurring mixture or process derivative of hydrocarbon and non-hydrocarbon gases. Its constituents include the greenhouse gases CH_4 and carbon dioxide and may include natural gas liquids.

(271) ‘Natural Gas Distribution Facility’. The collection of all distribution pipelines, metering stations, and regulating stations that are operated by a local distribution company (LDC) that is regulated as a separate operating company by a public service commission or that are operated as an independent municipally owned distribution system.

(272) ‘Natural Gas Driven Pneumatic Pump’. A pump that uses pressurized natural gas to move a piston or diaphragm, which pumps liquids on the opposite side of the piston or diaphragm.

(273) ‘Natural Gas Liquids or NGLs’. Those hydrocarbons in natural gas that are separated from the gas as liquids through the process of absorption, condensation, adsorption, or other methods. Natural gas liquids can be classified according to their vapor pressures as low (condensate), intermediate (natural gasoline), and high (liquefied petroleum gas) vapor pressure. Generally, such liquids consist of ethane, propane, butanes, pentanes, and higher molecular weight hydrocarbons. Bulk NGLs refers to mixtures of NGLs that are sold or delivered as undifferentiated product from natural gas processing plants.

(274) ‘Natural Gas Liquid Fractionator’. An installation that fractionates natural gas liquids (NGLs) into their constituent liquid products (ethane, propane, normal butane, isobutene or pentanes plus) for supply to downstream facilities.

(275) ‘Natural Gas Supplier or Supplier of Natural Gas’. A person that distributes, supplies, or sells natural gas, renewable natural gas, biogas, biomethane, or blends thereof, to end users in New York, including the following:

(i) a public utility gas corporation operating in New York;

(ii) the owner and operator of an intrastate pipeline that distributes, supplies, or sells natural gas, renewable natural gas, biogas, biomethane, or blends thereof to end users in New York;

(iii) interstate pipeline operator who distributes, supplies, or sells natural gas, renewable natural gas, biogas, biomethane, or blends thereof to end users in New York; and

(iv) an energy services company who distributes, supplies, or sells natural gas, renewable natural gas, biogas, biomethane, or blends thereof to end users in New York.

(276) ‘Natural Gasoline’. A mixture of liquid hydrocarbons (mostly pentanes and heavier hydrocarbons) extracted from natural gas. It includes isopentane. Natural gasoline is a natural gas liquid of intermediate vapor pressure.

(277) ‘NERC e-Tag’. The North American Electric Reliability Corporation (NERC) energy tag representing transactions on the North American bulk electricity market scheduled to flow between or across balancing authority areas.

(278) ‘Net Generation or Net Power Generated’. The gross generation minus station service or unit service power requirements and parasitic load, expressed in megawatt hours (MWh) per year. In the case of cogeneration, this value is intended to include internal consumption of electricity for the purposes of a production process, as well as power put on the grid.

(279) ‘New York’. The State of New York.

(280) ‘New York Control Area or NYCA’. The area under the electrical control of the NYISO.

(281) ‘New York Independent System Operator or NYISO’. The not-for-profit organization responsible for the efficient and non-discriminatory administration of the wholesale electricity markets in New York State and for the safe and reliable operation of the New York Control Area.

(282) ‘Nitric Acid’. HNO_3 of 100 percent purity.

(283) ‘Nitrous Oxide or N_2O’. A GHG consisting at the molecular level of two nitrogen atoms and a single oxygen atom.

(284) ‘Nonconformance’. The failure to use the methods or emission factors specified in this Part to calculate emissions, or the failure to meet any other requirements of the regulation.

(285) ‘Non-Submitted/Non-Verified Emissions Data Report’. An emissions data report that is not submitted to the department by the applicable reporting deadline, or for which a verification statement has not been issued by the applicable verification deadline.

(286) ‘Non-Thermal Enhanced Oil Recovery or Non-Thermal EOR’. The process of using methods other than thermal EOR, which may include water flooding or CO_2 injection, to increase the recovery of crude oil from a reservoir.

(287) ‘North American Industry Classification System (NAICS) code(s)’. The six- digit code(s) that represent the product(s)/activity(s)/service(s) at a facility or supplier as defined in North American Industrial Classification System Manual 2022 (see Table 1, section 200.9 of this Title).

(288) ‘Oil’. Crude petroleum oil and all other hydrocarbons, regardless of API gravity, that are produced at the wellhead in liquid form by ordinary production methods and that are not the result of condensation of gas.

(289) ‘Oil and Gas Systems Specialist’. A verifier accredited to meet the requirements of section 4.2(a)(2) of this Part for providing verification services to operators of petroleum refineries, hydrogen production units or facilities, and petroleum and natural gas systems listed in section 1.2(k) of this Part.

(290) ‘Onshore Petroleum and Natural Gas Production Facility’. All petroleum or natural gas equipment on a well pad, or associated with a well pad or to which emulsion is transferred and EOR operations that are under common ownership or common control including leased, rented, or contracted activities by an onshore petroleum and natural gas production owner or operator that are located in a single basin as defined in 40 CFR § 98.238 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title). When a commonly owned cogeneration plant is within the basin, the cogeneration plant is only considered part of the onshore petroleum and natural gas production facility if the onshore petroleum and natural gas production facility operator or owner has a greater than 50 percent ownership share in the cogeneration plant. Where a person owns or operates more than one well in a basin, then all onshore petroleum and natural gas production equipment associated with all wells that the person owns or operates in the basin would be considered one facility.

(291) ‘On-site or Onsite’. In the context of GHG reporting means within the facility boundary.

(292) ‘Open-ended Valve or Line’. Any valve, except pressure relief valves, having one side of the valve seat in contact with process fluid and one side open to atmosphere, either directly or through open piping.

(293) ‘Operational Control’. For a facility subject to this Part, means the authority to introduce and implement operating, environmental, health and safety policies. In any circumstance where this authority is shared among multiple persons and one such person holds a permit to operate from the department, that person is considered to have operational control for purposes of this Part.

(294) ‘Operator’. The person, including an owner, having operational control of a facility. Where petroleum and natural gas wells operate without a drilling or operating permit to identify them as an owner or operator, the person that pays the State or Federal business income taxes is considered the owner or operator for the purposes of this Part.

(295) ‘Organics Recycling Facility’. A facility that processes the organic components in waste to produce a mature product for use as a source of nutrients, animal feed, organic matter, liming value, or other essential constituent for a soil to help sustain plant growth. The processes include, but are not limited to, composting, vermiculture, anaerobic digestion, fermentation, and class A processes. An organics waste processing facility also includes processes to convert biodegradable organic components in waste to produce animal feed. The product no longer has the visual appearance of the waste from which it was produced.

(296) ‘Outside of the Facility Boundary’. Not within the physical boundary of the facility (regardless of ownership or operational control), or not in the same operational control of the reporting entity if within the same physical boundary of the facility. For example, a person outside of the facility boundary may include another facility not in the reporting entity’s operational control, another facility under the same operational control but considered a separate facility according to the definition of facility in this section, or an on-site industrial operation (e.g. a cogeneration system) within the facility fence line but that is operated by another operator and for which the on-site industrial operation has not been included in the reporting entity’s GHG report.

(297) ‘Parasitic Load’. The amount of electricity consumed by auxiliary

equipment that supports the electricity generation or cogeneration process. The equipment may include fans, pumps, drive motors, pollution control equipment, lighting, computer, CEMS, and other equipment.

(298) ‘Particular End-User’. A final purchaser of an energy product (e.g., electricity or thermal energy) for whom the energy product is delivered for final consumption and not for the purposes of retransmission or resale.

(299) ‘Pentane’. The n-pentane, straight chain, isomer of C_5H_{12} under the International Union of Pure and Applied Chemistry (IUPAC) nomenclature.

(300) ‘Pentanes Plus or C5+’. A mixture of hydrocarbons that is a liquid at ambient temperature and pressure and consists mostly of pentanes (five carbon chain) and higher carbon number hydrocarbons. Pentanes plus includes normal pentane, isopentane, hexanes-plus (natural gasoline), and plant condensate.

(301) ‘Percent Water Cut’. For purposes of section 2.12 of this Part, means the percentage of water by volume, of the total emulsion throughput as measured using ASTM D4007-22 (2022) (see Table 1, section 200.9 of this Title). The percent water cut is expressed as a percentage.

(302) ‘Perfluorocarbons or PFCs’. A class of greenhouse gases consisting, on the molecular level, of carbon and fluorine.

(303) ‘Performance Review’. An assessment conducted by department of an applicant seeking to become accredited as a verification body, verifier, lead verifier, or sector-specific verifier pursuant to section 4.3 of this Part. Such an assessment may include a review of applicable past sampling plans, verification reports, verification statements, conflict-

of-interest submittals, and additional information or documentation regarding the applicant's fitness for qualification.

(304) 'Person'. Any individual, organization, business entity, limited liability company, company, public or private corporation, political subdivision, government agency, department or bureau of the State, municipality, industry, public district, partnership or co-partnership, association, firm, trust, estate, or any other legal entity.

(305) 'Petroleum'. Oil removed from the earth and the oil derived from tar sands and shale.

(306) 'Petroleum Coke'. A black solid residue, obtained mainly by cracking and carbonizing of petroleum derived feedstocks, vacuum bottoms, tar and pitches in processes such as delayed coking or fluid coking. It consists mainly of carbon (90 to 95 percent), has low ash content, and may be used as a feedstock in coke ovens. This product is also known as marketable coke.

(307) 'Petroleum Refinery or Refinery'. Any facility engaged in producing gasoline, gasoline blending stocks, naphtha, kerosene, distillate fuel oils, residual fuel oils, lubricants, or asphalt (bitumen) through distillation of petroleum or through redistillation, cracking, or reforming of unfinished petroleum derivatives. Facilities that distill only pipeline transmix (off-spec material created when different specification products mix during pipeline transportation) are not petroleum refineries, regardless of the products produced.

(308) 'Physical Address'. With respect to a United States parent company as defined in this section, means the street address, city, state, and zip code of that company's physical location.

(309) ‘Pipeline Dig-in’. Unintentional puncture or rupture to a buried natural gas transmission and distribution pipeline during excavation activities.

(310) ‘Pipeline Quality Natural Gas’. For the purpose of calculating emissions under this Part, natural gas having a high heat value greater than 970 Btu/scf and equal to or less than 1,100 Btu/scf, and which is at least 90 percent methane by volume, and which is less than five percent carbon dioxide by volume.

(311) ‘Point of Delivery or POD’. The point on an electricity transmission or distribution system where a deliverer makes electricity available to a receiver, or available to serve load. This point can be an interconnection with another system or a substation where the transmission provider’s transmission and distribution systems are connected to another system.

(312) ‘Point of Receipt or POR’. The point on an electricity transmission or distribution system where an electricity receiver receives electricity from a deliverer. This point can be an interconnection with another system or a substation where the transmission provider’s transmission and distribution systems are connected to another system.

(313) ‘Point Source’. Any separately identifiable stationary point from which greenhouse gases are emitted.

(314) ‘Portable’. Designed and capable of being carried or moved. Indications of portability include, but are not limited to, wheels, skids, carrying handles, dolly, or trailer. Equipment is not portable if any one of the following conditions exists: the equipment is attached to a foundation; the equipment or a replacement resides at the same location or facility for 12 or more consecutive months; the equipment is located at a seasonal facility and

operates during the full annual operating period of the seasonal facility, remains at the facility for at least two years, and operates at that facility for at least three months each year; or the equipment is moved from one location to another in an attempt to circumvent the portable residence time requirements of this definition.

(315) ‘Portable Pressurized Separator’. A sealed vessel that can be moved from one location to another by attachment to a motor vehicle without having to be dismantled and is used for separating and sampling crude oil, condensate, or produced water at the temperature and pressure of the separator and tank system required for sampling.

(316) ‘Position Holder’. A person that holds an inventory position in motor vehicle fuel, ethanol, distillate fuel, biodiesel, or renewable diesel as reflected in the records of the terminal operator or a terminal operator that owns motor vehicle fuel or diesel fuel in its terminal. Position holder does not include inventory held outside of a terminal, fuel jobbers (unless directly holding inventory at the terminal), retail establishments, or other fuel suppliers not holding inventory at a fuel terminal.

(317) ‘Positive Emissions Data Verification Statement’. A verification statement rendered by a verification body attesting that the verification body can say with reasonable assurance that the emissions data in the submitted emissions data report is free of material misstatement and that the emissions data conforms to the requirements of this Part.

(318) ‘Positive Product Data Verification Statement’. A verification statement rendered by a verification body attesting that the verification body can say with reasonable assurance that the industrial product data in the submitted emissions data report is free of material misstatement and that the industrial product data conforms to the requirements of

this Part.

(319) ‘Positive Verification Statement’. A verification statement rendered by a verification body attesting that the verification body can say with reasonable assurance that the submitted emissions data report is free of material misstatement and that the emissions data report conforms to the requirements of this Part. This definition applies to the emissions data verification statement and the product data verification statement.

(320) ‘Power’. Electricity, except where the context makes clear that another meaning is intended.

(321) ‘Power Contract or Written Power Contract’. As used for the purposes of documenting specified versus unspecified sources of imported and exported electricity, means a written document, including associated verbal or electronic records if included as part of the written power contract, arranging for the procurement of electricity. Power contracts may be, but are not limited to, power purchase agreements, enabling agreements, electricity transactions, and tariff provisions, without regard to duration, or written agreements to import or export on behalf of another person, as long as that other person also reports to the department the same imported or exported electricity. A power contract for a specified source is a contract that is contingent upon delivery of power from a particular facility, unit, or asset-controlling supplier’s system that is designated at the time the transaction is executed.

(322) ‘Pressure Relief Valve or Device’. A valve, rupture disk, or similar device used only to release an unplanned, nonroutine discharge of gas from process equipment in order to avoid safety hazards or equipment damage.

(323) ‘Pressure Separator’. A pressure vessel used for the primary purpose of

separating crude oil and produced water or for separating natural gas and produced water.

(324) ‘Pressure Vessel’. Any vessel rated, as indicated by an American Society of Mechanical Engineers (ASME) pressure rating stamp and operated to contain normal working pressures of at least 15 psig without vapor loss to the atmosphere and may be used for the separation of crude oil, condensate, produced water, or natural gas.

(325) ‘Primary Fuel’. The fuel that provides the greatest percentage of the annual heat input to a stationary fuel combustion unit.

(326) ‘Prime Mover’. The type of equipment such as an engine or water wheel that drives an electric generator, including but not limited to reciprocating engines, combustion or gas turbines, steam turbines, microturbines, and fuel cells.

(327) ‘Process’. The intentional or unintentional reactions between substances or their transformation, including, but not limited to, the chemical or electrolytic reduction of metal ores, the thermal decomposition of substances, and the formation of substances for use as product or feedstock.

(328) ‘Process Emissions’. The emissions from industrial processes involving chemical or physical transformations other than fuel combustion. For example, the calcination of carbonates in a kiln during cement production or the oxidation of methane in an ammonia process results in the release of process CO_2 emissions to the atmosphere. Emissions from fuel combustion to provide process heat are not part of process emissions, whether the combustion is internal or external to the process equipment.

(329) ‘Process Emissions Specialist’. A verifier accredited to meet the requirements of section 4.2(a)(2) of this Part for providing verification services to operators of

facilities engaged in cement production, glass production, lime manufacturing, pulp and paper manufacturing, iron and steel production, nitric acid production, and lead production.

(330) ‘Process Gas’. Any gas generated by an industrial process.

(331) ‘Process Heater’. Equipment for the heating of process streams (gases, liquids, or solids) other than water through heat provided by fuel combustion.

(332) ‘Process Unit’. The equipment assembled and connected by pipes and ducts to process raw materials and to manufacture either a final or an intermediate product used in the onsite production of other products. The process unit also includes the purification of recovered by products.

(333) ‘Process Vent’. An opening where a gas stream is continuously or periodically discharged during normal operation.

(334) ‘Produced Water’. The resulting brine that is produced as a byproduct of crude oil or natural gas production.

(335) ‘Producer’. A person who owns, leases, operates, controls, or supervises a New York production facility.

(336) ‘Product’. An item or category of items manufactured from raw or recycled materials which performs a function or task and is functional upon completion of manufacturing.

(337) ‘Product Data’. The sector-specific data specified in Subparts 2 and 5 of this Part, including requirements in 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(338) ‘Product Data Verification Statement’. The final statement rendered by a

verification body attesting whether an emission source's industrial product data in its emissions data report is free of material misstatement, and whether the product data conforms to the requirements of this Part.

(339) 'Professional Judgment'. The ability to render sound decisions based on professional qualifications and relevant GHG accounting and auditing experience.

(340) 'Propane'. A paraffinic hydrocarbon with molecular formula C_3H_8.

(341) 'Propylene'. An olefinic hydrocarbon with molecular formula C_3H_6.

(342) 'Public Utility Gas Corporation'. A gas corporation defined in New York Public Service Law section 2 that is also a public utility company or public utility corporation as defined in New York Public Service Law section 2.

(343) 'Publicly Owned Natural Gas Utility'. A municipality or municipal corporation, a municipal utility district, a public utility district, or a joint powers authority that includes one or more of these agencies that furnishes natural gas services to end users.

(344) 'Pump'. A device used to raise pressure, drive, or increase flow of liquid streams in closed or open conduits.

(345) 'Pump Seals'. Any seal on a pump drive shaft used to keep methane and/or carbon dioxide containing light liquids from escaping the inside of a pump case to the atmosphere.

(346) 'Purchasing-Selling Entity or PSE'. The person that is identified on a NERC e- Tag for each physical path segment.

(347) 'PURPA Qualifying Facility'. A facility that has acquired a "qualifying facility (QF)" certification pursuant to 18 CFR § 292.207 (April 1, 2024) (see Table 1, section

200.9 of this Title) under the Public Utility Regulatory Policies Act of 1978 (PURPA) (August 9, 2013) (see Table 1, section 200.9 of this Title).

(348) ‘QA/QC’. Quality assurance and quality control.

(349) ‘Qualified Positive Emissions Data Verification Statement’. A statement rendered by a verification body attesting that the verification body can say with reasonable assurance that the emission source data in the submitted emissions data report is free of material misstatement and is in conformance with section 4.2(b)(8) of this Part, but the emissions data may include one or more other nonconformances with the requirements of this Part that do not result in a material misstatement.

(350) ‘Qualified Positive Product Data Verification Statement’. A statement rendered by a verification body attesting that the verification body can say with reasonable assurance that the industrial product data in the submitted emissions data report is free of material misstatement and is in conformance with section 4.2(b)(8) of this Part, but the product data may include one or more other nonconformance(s) with the requirements of this Part that do not result in a material misstatement.

(351) ‘Qualified Positive Verification Statement’. A qualified positive emissions data verification statement or qualified positive product data verification statement.

(352) ‘Quality-Assured Data or Quality-Assured Value’. The data obtained from a monitoring system that is operating within the performance specifications and the quality assurance/quality control procedures set forth in the applicable rules, for example 40 CFR part 60 (July 1, 2024) or part 75, (July 1, 2023) (see Table 1, section 200.9 of this Title), without unscheduled maintenance, repair, or adjustment.

(353) ‘Rack’ A mechanism for delivering motor vehicle fuel, diesel, or other liquid fuels or products from a refinery or terminal into a truck, trailer, railroad car, or other means of non-bulk transfer.

(354) ‘Reasonable Assurance’. A high degree of confidence that submitted data and statements are valid.

(355) ‘Reciprocating Compressor’. Equipment that increases the pressure of natural gas by positive displacement of a piston in a compression cylinder that is powered by an internal combustion engine or electric motor.

(356) ‘Reciprocating Compressors Rod Packing’. A seal comprised of a series of flexible rings in machined metal cups that fit around the reciprocating compressor piston rod to limit the amount of compressed natural gas that vents into the atmosphere.

(357) ‘Reciprocating Internal Combustion Engine or RICE or Piston Engine’. A reciprocating engine in which power, produced by heat and/or pressure that is developed in the engine combustion chambers by the burning of a mixture of air and fuel, is subsequently converted to mechanical work.

(358) ‘Recyclables Handling and Recovery Facility’. A facility that processes source-separated non-putrescible recyclables.

(359) ‘Recycled’. Refers to a material that is reused or reclaimed.

(360) ‘Refiner’. For purposes of this Part, a person that delivers transportation fuels to end users in New York that were produced by petroleum refineries owned by that person or a subsidiary of that person.

(361) ‘Refinery Fuel Gas or Still Gas’. Gas generated at a petroleum refinery, or

any gas generated by a refinery process unit, and that is combusted separately or in any combination with any type of gas or used as a chemical feedstock.

(362) ‘Reformulated Gasoline Blendstock for Oxygenate Blending or RBOB’. The same meaning as defined in 40 CFR § 1090.80 (July 1, 2024) (see Table 1, section 200.9 of this Title).

(363) ‘Relative Accuracy Test Audit or RATA’. A method of determining the correlation of continuous emissions monitoring system data to simultaneously collected reference method test data, for example as required in 40 CFR part 60 (July 1, 2024) (see Table 1, section 200.9 of this Title) and 40 CFR part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title).

(364) ‘Rendered Animal Fat or Tallow’. Fats extracted from animals which are generally used as a feedstock in making biodiesel.

(365) ‘Renewable Diesel’. A motor vehicle fuel or fuel additive that is all of the following:

(i) registered as a motor vehicle fuel or fuel additive under 40 CFR part 79 (July 1, 2024) (see Table 1, section 200.9 of this Title);

(ii) not a mono-alkyl ester;

(iii) intended for use in engines that are designed to run on conventional diesel fuel; and

(iv) derived from nonpetroleum renewable resources.

(366) ‘Renewable Energy’. Electrical energy produced by a system that generates electricity or thermal energy through use of the following technologies: solar

thermal, photovoltaics, on land and offshore wind, hydroelectric, geothermal electric, geothermal ground source heat, tidal energy, wave energy, ocean thermal, and fuel cells that do not use a fossil fuel resource in the process of generating electricity.

(367) ‘Renewable Natural Gas’. Biogas that meets pipeline quality natural gas standards.

(368) ‘Reporting Entity’. A facility owner, operator, supplier, or electric power entity subject to the requirements of this Part.

(369) ‘Reporting Period’. The calendar year that coincides with the emission year for the GHG report.

(370) ‘Reporting Year or Report Year’. Emission year.

(371) ‘Reservoir’. Any underground reservoir, natural or artificial cavern or geologic dome, sand or stratigraphic trap whether or not it was previously occupied by or containing oil or gas.

(372) ‘Residue Gas and Residue Gas Compression’. Respectively, production lease natural gas from which gas liquid products and, in some cases, non-hydrocarbon components have been extracted such that it meets the specifications set by a pipeline transmission company, and/or a distribution company; and the compressors operated by the processing facility, whether inside the processing facility boundary fence or outside the fence-line, that deliver the residue gas from the processing facility to a transmission pipeline.

(373) ‘Retail End-Use Customer or Retail End User’. A residential, commercial, agricultural, or industrial electric customer who buys electricity to be consumed as a final product and not for resale.

(374) ‘Retail Outlet or Retail Location’. Any establishment at which liquid fuels are sold or offered for final sale for use in motor vehicles, nonroad engines, nonroad vehicles, or nonroad equipment, including locomotive or marine engines.

(375) ‘Retail Provider’. A person that provides electricity to retail end users in New York and is an EDU, a community choice aggregator, or an ESCO.

(376) ‘Retail Sales’. Means electricity sold to retail end users.

(377) ‘Retailer’. Any person who owns, leases, operates, controls, or supervises a retail outlet.

(378) ‘Sector’. A broad industrial categorization such as specified in section 1.2 of this Part. Sector-specific verifier means a verifier accredited pursuant to section 4.3(c)(5)(i) of this Part, as one or more of the following types of specialists defined pursuant to this section: a transactions specialist, an oil and gas systems specialist, or a process emissions specialist.

(379) ‘Separator’. A sump or vessel used to separate crude oil, condensate, natural gas, produced water, emulsion or solids.

(380) ‘Separator and Tank System’. The first separator in a crude oil or natural gas production system and any tank or sump connected directly to the first separator.

(381) ‘Shale’. A very fine-grained, clastic sedimentary rock that forms when mud, silt, and clay-size mineral particles are consolidated and compacted into relatively impermeable layers. Shale is characterized by a finely laminated or stratified structure and is the most abundant sedimentary rock. Shale can contain varying amounts of organic matter, so it has the potential to become a hydrocarbon source rock. The pore size of shale

reservoirs ranges from nanometers to micrometers. Hydrocarbons in some shale reservoirs can be extracted using hydraulic fracturing.

(382) ‘Shale Gas’. Natural gas produced from wells that are completed in shale formations.

(383) ‘Short Ton’. A common international measurement for mass, equivalent to 2,000 pounds.

(384) ‘Shutdown’. The cessation of operation of an emission source for any purpose.

(385) ‘Simplified Block Diagram’. A diagram consisting of boxes, shapes, lines, arrows, and labels that meets the requirements of section 2.5(a)(6) or section 1.7(c) of this Part. A simplified block diagram is not an architectural drawing or an engineering drawing that shows the likeness of the physical objects being depicted and their actual locations and sizes in scale; it is a simplified graphical representation of the objects being depicted, their relative locations, and how they are connected through flows of energy or energy carrier (e.g. steam, water, electricity, or fuel).

(386) ‘Sink or Sink to Load or Load Sink’. The sink identified on the physical path of NERC e-Tags, where defined points have been established through the NERC Registry. Exported electricity is disaggregated by the sink on the NERC e-Tag, also referred to as the final point of delivery on the NERC e-Tag.

(387) ‘Solid Waste or Waste’. Solid waste or waste as defined in Part 360 of this Title, except as described in section 360.2(a)(3) of this Title.

(388) ‘Solids Retention Time’. The average time in days that solids are held in

an anaerobic digester or reactor. The solids retention time is equivalent to the average mass of solids present in the equipment divided by the average rate at which solids are removed.

(389) ‘Sorbent’. A material used to absorb or adsorb liquids or gases.

(390) ‘Sour Natural Gas’. Natural gas that contains significant concentrations of hydrogen sulfide (H2S) and/or carbon dioxide that exceed the concentrations specified for commercially saleable natural gas delivered from transmission and distribution pipelines.

(391) ‘Source Category’. Categories of emission sources as defined by tables A-3, A-4, and A-5 of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(392) ‘Source of Generation or Generation Source’. The generation source identified on the physical path of NERC e-Tags, where defined points have been established through the NERC Registry. Imported electricity and wheels are disaggregated by the source on the NERC e-Tag, also referred to as the first point of receipt.

(393) ‘Specified Source’. A facility or unit which is permitted to be claimed as the source of electricity delivered. The reporting entity must have either full or partial ownership in the facility/unit or a written power contract to procure electricity generated by that facility/unit. Specified facilities/units include cogeneration systems. Specified source also means electricity procured from an asset-controlling supplier recognized by the department.

(394) ‘Stand-Alone Electricity Generating Facility’. An electricity generating facility whose primary business and sole industrial operation is electricity generation and is not a cogeneration or bigeneration facility.

(395) ‘Standard Conditions or Standard Temperature and Pressure (STP)’.

60°F and 14.7 pounds per square inch absolute.

(396) ‘Standard Cubic Foot or SCF’. A measure of quantity of gas, equal to a cubic foot of volume at 60°F and either 14.696 pounds per square inch (1 atm) or 14.73 PSI (30 inches Hg) of pressure.

(397) ‘Stationary’. Neither portable nor self-propelled, and operated at a single facility.

(398) ‘Station Service’. Electricity that is used to operate an electric generating facility. It includes energy consumed for plant lighting, power, and auxiliary facilities, regardless of whether the electricity is produced at the plant or comes from another source.

(399) ‘Steam Generator’. Equipment that produces steam using an external heat source.

(400) ‘Storage Tank’. Any tank, other container, or reservoir used for the storage of organic liquids, excluding tanks that are permanently affixed to mobile vehicles such as railroad tank cars, tanker trucks or ocean vessels.

(401) ‘Substitute Power or Substitute Electricity’. Electricity that is provided to meet the terms of a power purchase contract with a specified facility or unit when that facility or unit is not generating electricity.

(402) ‘Sulfur Hexafluoride or SF_6‘. A GHG consisting of a single sulfur atom and six fluorine atoms.

(403) ‘Sump’. For purposes of section 2.12 of this Part means a lined surface impoundment or pit in the ground that, during normal operations, is used to temporarily store produced water.

(404) ‘Supplemental Firing’. An energy input to the cogeneration facility used only in the thermal process of a topping cycle plant, or in the electricity generating or manufacturing process of a bottoming cycle cogeneration facility.

(405) ‘Supplier’. A producer, importer, exporter, enterer, position holder, interstate pipeline operator, intrastate pipeline operator, energy service company, or local distribution company of a fossil fuel, fuel, petroleum product, agricultural lime or fertilizer, a fluorinated GHG, or products and systems.

(406) ‘Supplier of Affected Liquid Fuels or Supplier of Liquid Fuels or Petroleum Products’. A person that distributes, sells, transfers, delivers, or supplies affected liquid fuels or blends thereof, including position holders, enterers, and below-the-rack distributors.

(407) ‘Suppliers of Liquefied Natural Gas and Compressed Natural Gas’. A person producing, importing, supplying, distributing, or selling LNG and/or CNG and blends thereof, including:

(i) owners and operators of facilities in New York that make liquefied natural gas products or compressed natural gas products by liquefying or compressing natural gas received from interstate pipelines; and

(ii) importers of liquefied natural gas and compressed natural gas for sale or consumption to end users in New York.

(408) ‘System’. An assemblage of separate components that typically are connected and charged in the field with a fluorinated GHG to perform a function or task.

(409) ‘Tank’. Any container constructed primarily of non-earthen materials used for the purpose of storing, holding, or separating emulsion, crude oil, condensate, or

produced water and that is designed to operate below 15 psig normal operating pressure. For the purposes of section 2.12 of this Part, means a container, constructed primarily of non-earthen materials, used for holding or storing crude oil, condensate, produced water, or emulsion.

(410) ‘Target Temperature’. The temperature at which a pressurized hydrocarbon liquid is flashed and is therefore the temperature of the first atmospheric separator or tank.

(411) ‘Terminal’. A liquid fuel or petroleum product storage and distribution facility that is supplied by pipeline or vessel, and from which liquid fuels and petroleum products may be removed at a rack. Terminal includes a fuel production facility where fuels and products are produced and stored and from which fuel may be removed at a rack. Fuels and products that are not suitable for pipeline transport or supplied in small volumes may be delivered to a terminal by other means.

(412) ‘Terminal Operator’. Any person that owns, operates or otherwise controls a terminal that is supplied by pipeline or vessel and from which accountable fuel products may be removed at a rack.

(413) ‘Thermal Energy’. The thermal output produced by a combustion source used directly as part of a manufacturing process, industrial/commercial process, or heating/cooling application, but not used to produce electricity.

(414) ‘Thermal Enhanced Oil Recovery or Thermal EOR’. The process of using injected steam to increase the recovery of crude oil from a reservoir.

(415) ‘Thermal Host’. The user of the steam or heat output of a cogeneration or

bigeneration facility.

(416) ‘Throughput’. For natural gas, the average volume of gas such as mcf/day or mcf/year. For crude oil, the average volume of liquid processed by a vessel over a period of time, such as barrels per day. The throughput of crude oil or condensate may need to be calculated using the Percent Water Cut. The throughput of crude oil or condensate is calculated as the difference in volume between these liquids and the produced water. For cement, the maximum short tons of raw material put through the kiln. For iron/steel, the maximum capacity of carbon containing inputs and outputs put through the system.

(417) ‘Tier’. The level of calculation method from 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) that is required for a stationary combustion source in section 2.7 of this Part.

(418) ‘Tier 1’. A stationary combustion calculation method that applies default values for emission factors and high heat value to generate an emissions estimate, as specified in 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(419) ‘Tier 2’. A stationary combustion calculation method that applies a default value for an emission factor and a fuel’s measured high heat value (or a boiler efficiency for steam-generating solid fuels) to generate an emissions estimate, as specified in 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(420) ‘Tier 3’. A stationary combustion calculation method that uses a fuel’s measured carbon content to generate an emissions estimate, as specified in 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(421) ‘Tier 4’. A stationary combustion calculation method that uses quality assured data from a continuous emission monitoring system to generate an emissions estimate, as specified in 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title). This method may also capture process emissions from a common stack.

(422) ‘Tight Gas’. Natural gas produced from low-permeability sandstone and carbonate reservoirs.

(423) ‘Tolling Agreement’. An agreement whereby a person rents a power plant from the owner. The rent is generally in the form of a fixed monthly payment plus a charge for every MW generated, generally referred to as a variable payment.

(424) ‘Topping Cycle’. A type of cogeneration system in which the energy input to the plant is first used to produce electricity, and at least some of the reject heat from the electricity production process is then used to provide useful thermal output.

(425) ‘Total Solids’. The mass of the material that remains after water is removed from waste by drying at 105°C until a constant mass is reached. Total solids in a sample equal the sum of volatile and fixed solids.

(426) ‘Total Thermal Output’. The total amount of usable thermal energy generated by a cogeneration or bigeneration unit that can potentially be made available for use in any industrial or commercial processes, heating, or cooling applications, or delivered to other end users. This quantity excludes the heat content of returned condensate and makeup water, but includes the thermal energy used for supporting (but not directly used for) power generation, thermal energy used in other on-site processes or applications that are not in support of or a part of the electricity generation system, thermal energy provided or sold to

a particular end-user, and thermal energy that is otherwise not used. Thermal energy directly used for power generation (e.g., steam used to drive a steam turbine generator for electricity generation) is not included in total thermal output.

(427) ‘Traceable’. That a standard used to calibrate a device has an unbroken chain of comparisons to a stated reference (such as a standard set by the National Institute of Standards and Technology), with each comparison having a stated uncertainty.

(428) ‘Transactions Specialist’. A verifier accredited to meet the requirements of section 4.2(a)(2) of this Part for providing verification services to electric power entities; suppliers of petroleum products and biofuels; suppliers of natural gas, natural gas liquids, and liquefied petroleum gas; and suppliers of CO_2.

(429) ‘Transmission-Distribution (T-D) Transfer Station’. A metering-regulating station where a local distribution company takes part or all of the natural gas from a transmission pipeline and puts it into a distribution pipeline.

(430) ‘Transmission Pipeline’. A high-pressure cross-country pipeline transporting saleable quality natural gas from production or natural gas from processing to natural gas distribution pressure let-down, metering, regulating stations, where the natural gas is typically odorized before delivery to customers.

(431) ‘Transporter or Solid Waste Transporter’. A person engaged in the off-site transportation of waste by means of air, rail, highway, or water conveyance.

(432) ‘Turbine’. Any of various types of machines in which the kinetic energy of a moving fluid is converted into mechanical energy by causing a bladed rotor to rotate.

(433) ‘Turbine Meter’. A flow meter in which a gas or liquid flow rate through the

calibrated tube spins a turbine from which the spin rate is detected and calibrated to measure the fluid flow rate.

(434) ‘Type of Thermal Energy Product’. The form in which energy is transferred from a facility producing thermal energy to another facility, or if not transferred, the form in which the energy is used. Types of thermal energy products include steam, hot water, chilled water, and distilled water.

(435) ‘Uncertainty’. The degree to which data or a data system is deemed to be indefinite or unreliable.

(436) ‘United States Parent Company(s)’. The highest-level United States company(s) with an ownership interest in the reporting entity as of December 31 of the reporting year.

(437) ‘Unspecified Source of Electricity or Unspecified Source’. A source of electricity that is not a specified source at the time of entry into the transaction to procure the electricity.

(438) ‘Unspecified Waste’. Solid waste transported outside of New York for which the ultimate destination or location is unknown or is not a hazardous waste, combustion, composting, organics processing, organics recycling, or recyclables handling and recovery facility.

(439) ‘Upstream Entity’. The last person in the chain of title prior to the fuel being received by the reporting entity.

(440) ‘Upstream Out of State Emissions'. Greenhouse gases produced outside of the state that are associated with the generation of electricity imported into the state and

the extraction and transmission of fossil fuels imported into the state.

(441) ‘U.S. EPA or EPA’. The U.S. Environmental Protection Agency.

(442) ‘Vapor Recovery System’. Any equipment located at the source of potential gas emissions to the atmosphere or to a flare, that is composed of piping, connections, and, if necessary, flow-inducing devices, and that is used for routing the gas back into the process as a product and/or fuel.

(443) ‘Vegetable Oil’. Oils extracted from vegetation that are generally used as a feedstock in making biodiesel.

(444) ‘Vented Emissions’. CH_4, CO_2, or other greenhouse gases released to the atmosphere through seals or vent pipes, components, equipment, equipment blowdown, or direct venting of gas used to power equipment (such as pneumatic devices). Such emissions are typically associated with natural gas or hydrocarbon gas, not including stationary combustion flue gas.

(445) ‘Verification’. A systematic, independent and documented process for evaluation of a reporting entity’s emissions data report against the department’s reporting procedures and methods for calculation and reporting GHG emissions and product data as contained in this Part.

(446) ‘Verification Body’. A firm with accreditation from or accepted by the department that is able to render a verification statement and provide verification services for Reporting Entities subject to reporting under this Part.

(447) ‘Verification Services’. Services provided during verification as specified in section 4.2 of this Part.

(448) ‘Verification Statement’. The final statement rendered by a verification body attesting whether a reporting entity’s emissions data report is free of material misstatement, and whether it conforms to the requirements of this Part.

(449) ‘Verification Team’. All of those working for a verification body, including all subcontractors, to provide verification services for a reporting entity.

(450) ‘Verified Emissions Data Report’. An emissions data report that has been reviewed by a third-party verifier and has a verification statement, or statements, if applicable, submitted to the department.

(451) ‘Verifier’. A natural person accredited by the department to carry out verification services as specified in section 4.2 of this Part.

(452) ‘Verifier Review’. A verifier conducts all reviews and services in section 4.2 of this Part, except the material misstatement assessment pursuant to section 4.2(b)(11) of this Part.

(453) ‘Vessel’. For the purposes of section 2.12 of this Part, means any container constructed primarily of non-earthen materials used for the purpose of storing, holding, or separating emulsion, crude oil, condensate, or produced water and that is designed to operate below a normal operating pressure of 15 psig.

(454) ‘Volatile Solids or VS’. The portion of total solids in waste that can be converted to gases when brought to 600°C for at least 1 hour exclusive of any petroleum-based plastics.

(455) ‘Well’. A boring in the earth for the purpose of the following:

(i) Exploring for or producing oil or gas.

(ii) Injecting fluids or gas for stimulating oil or gas recovery.

(iii) Re-pressuring or pressure maintenance of oil or gas reservoirs.

(iv) Disposing of oil field waste gas or liquids.

(v) Injection or withdrawal of gas from an underground storage facility.

(456) ‘Waste Gas’. A natural gas that contains a greater percentage of gaseous chemical impurities than the percentage of methane. For purposes of this definition, gaseous chemical impurities may include carbon dioxide, nitrogen, helium, or hydrogen sulfide.

(457) ‘Well Completions’. The process that allows for the flow of petroleum or natural gas from newly drilled wells to expel drilling and reservoir fluids and test the reservoir flow characteristics, steps which may vent produced gas to the atmosphere via an open pit or tank. Well completion also involves connecting the well bore to the reservoir, which may include treating the formation or installing tubing, packer(s), or lifting equipment, steps that do not significantly vent natural gas to the atmosphere. This process may also include high rate flowback of injected gas, water, oil, and proppant used to fracture or re-fracture and prop open new fractures in existing lower permeability gas reservoirs, steps that may vent large quantities of produced gas to the atmosphere.

(458) ‘Well Testing Venting and Flaring’. Venting and/or flaring of natural gas at the time the production rate of a well is determined for regulatory, commercial, or technical purposes. If well testing is conducted immediately after a well completion or workover, then it is considered part of well completion or workover.

(459) ‘Well Workover’. The process(es) of performing one or more of a variety of maintenance or remedial operations on existing petroleum and natural gas wells to

increase or restore production. This process also includes high-rate flowback of injected gas, water, oil, and proppant used to re-fracture and prop-open new fractures in existing low permeability gas reservoirs, steps that may vent large quantities of produced gas to the atmosphere.

(460) ‘Wellhead’. The piping, casing, tubing and connected valves protruding above the earth’s surface for an oil and/or natural gas well. The wellhead ends where the flow line connects to a wellhead valve. Wellhead equipment includes all equipment, permanent and portable, located on the improved land area (i.e. well pad) surrounding one or multiple wellheads.

(461) ‘Wet Natural Gas’. Natural gas in which water vapor exceeds the concentration specified for commercially saleable natural gas delivered from transmission and distribution pipelines. This input stream to a natural gas dehydrator is referred to as “wet gas”.

(462) ‘Wood Residuals’. Materials recovered from three principal sources: Municipal solid waste (MSW); construction and demolition debris; and primary timber processing. Wood residuals recovered from MSW include wooden furniture, cabinets, pallets and containers, scrap lumber (from sources other than construction and demolition activities), and urban tree and landscape residues. Wood residuals from construction and demolition debris originate from the construction, repair, remodeling and demolition of houses and non-residential structures. Wood residuals from primary timber processing include bark, sawmill slabs and edgings, sawdust, and peeler log cores. Other sources of wood residuals include, but are not limited to, railroad ties, telephone and utility poles, pier and dock timbers,

wastewater process sludge from paper mills, trim, sander dust, and sawdust from wood products manufacturing (including resinated wood product residuals), and logging residues.

253-1.4 Greenhouse Gas Reporting Requirements

(a) Emissions Monitoring and Reporting. Owners or operators of emission sources specified in section 1.2 of this Part must monitor emissions and submit emissions data reports to the department, except as otherwise provided in this Part, following the requirements specified in 40 CFR § 98.3 through .4 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) and, as applicable, section 2.21(b) of this Part.

(b) Reporting Deadlines. Each reporting entity must submit an emissions data report no later than June 1 of each emission year.

(c) Verification Requirement and Deadlines. The requirements of this subdivision apply to each reporting entity that has met any of the applicability requirements pursuant to section 1.2(f) of this Part in any year. These requirements also apply to each reporting entity that has not met the requirements for cessation of verification in section 1.2(n) or section 1.2(o) of this Part. Each reporting entity subject to verification must obtain third-party verification services for that report from a verification body that meets the requirements specified in Subpart 4 of this Part. Such services must be completed, and separate verification statements for emissions data and for product data, as applicable, must be submitted by the verification body to the department, by August 10 each year. Each reporting entity must ensure that these verification statements are submitted by this deadline. Contracting with a verification body without providing sufficient time to complete the verification statements by the

applicable deadline will not excuse the reporting entity from this responsibility. These requirements are additional to the requirements in 40 CFR § 98.3(f) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(d) Non-submitted/Non-verified Emissions Data Reports. The department may develop and assign an emissions level for an emission source that fails to submit an emissions data report or fails to obtain a positive emissions data verification statement or qualified positive emissions data verification statement by the applicable deadline. The department shall develop an assigned emissions level for the emission source as set forth in section 4.2(c)(5)(i) through (iii) of this Part.

(e) Calculation and Reporting of Limited Alternative Emissions. A facility operator may represent no more than three percent of a facility's total CO_2 equivalent emissions (including emissions from biomass-derived fuels and feedstocks), not to exceed 20,000 metric tons of CO_2e as limited alternative emissions. The reporting entity may estimate limited alternative emissions using methods of the operator's choosing, subject to the concurrence of the verification body that the methods used are reasonable, not biased toward significant under estimation or over estimation of emissions, and unlikely to exceed three percent of the reported emissions or 20,000 metric tons CO_2e. The reporting entity must separately identify and include in the emissions data report the emissions designated as limited alternative emissions. The reporting entity must determine CO_2 equivalence according to the CO_2 equivalence definition of this Part.

(f) Calculating, Reporting, and Verifying Emissions from Biomass-Derived Fuels. The reporting entity must separately identify and report all biomass-derived fuels. Except for a

reporting entity that uses the methods of 40 CFR § 98.33(a)(2)(iii) or § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), the reporting entity must separately identify, calculate, and report all direct emissions of CO_2 resulting from the combustion of biomass-derived fuels as specified in sections 2.5 and 2.7 of this Part for facilities, and sections 2.16 and 2.17 of this Part for suppliers. The reporting entity must meet the verification requirements in section 4.2(i) of this Part for biomass-derived fuels. Carbon dioxide combustion emissions from biomass-derived fuel will be identified as biomass-derived CO_2.

(1) When reporting solid waste, the reporting entity must separately report the mass, in short tons, of wood residuals recovered from construction and demolition (C&D) debris, agricultural waste, and municipal solid waste (MSW).

(2) When reporting the use of wood residuals from primary timber processing as a fuel, the reporting entity must report: the bone-dry mass received; information about the supplier, including the name, physical address, mailing address, contact person with phone number and e-mail address; and the corresponding identification number under which the wood was removed.

(3) When reporting biomethane, the reporting entity that is reporting biomass emissions from biomethane fuel must also report the following information for each contracted delivery:

(i) name and address of the biomethane vendor from which biomethane is purchased;

(ii) annual MMBtu delivered by each biomethane vendor.

(4) The reporting entity must also report the name, address, and facility type of the facility from which the biomethane is produced. In addition, relevant documentation including invoices, shipping reports, allocation and balancing reports, storage reports, in-kind nomination reports, and contracts must be made available for verifier or departmental review to demonstrate the receipt of eligible biomethane.

(5) Reporting of fuel consumption from biomass-derived fuel is subject to the requirements of subdivision (g) of this section and reporting of emissions from biomass-derived fuels is subject to the requirements of this Part.

(g) Measurement Accuracy Requirement. A reporting entity that does not meet the thresholds specified in section 1.2(f) of this Part, that is subject to the requirements of 40 CFR § 98.3(i) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) must meet those requirements for data used for calculating emissions or product data, except as otherwise specified in this subdivision. In addition, the following accuracy requirements apply to data used for calculating emissions and industrial product data for emission sources as specified in section 1.2(f) of this Part. A reporting entity that meets the requirements of section 1.2(f) in any reporting year must meet the requirements of paragraphs (1) through (10) of this subdivision for calibration and measurement device accuracy. Inventory measurement, stock measurement, or tank drop measurement methods are subject to paragraph (11) of this subdivision. The requirements of paragraphs (1) through (11) of this subdivision apply to fuel consumption monitoring devices, feedstock consumption monitoring devices, process stream flow monitoring devices, steam flow devices, product data measuring devices, mass and fluid flow meters, weigh scales, conveyer scales, gas

chromatographs, mass spectrometers, calorimeters, and devices for determining density, specific gravity, and molecular weight. The provisions of paragraphs (1) through (11) of this subdivision do not apply to: stationary fuel combustion units that use the methods in 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) to calculate CO_2 mass emissions; emissions reported as limited alternative emissions under subdivision (e) of this section; and devices that are solely used to measure parameters used to calculate emissions or product data from Reporting Entities that do not meet the thresholds specified in section 1.2(f) of this Part. Provisions of paragraphs (1) through (9) and (11) of this subdivision do not apply to stationary fuel combustion units that use the methods in 40 CFR part 75 appendix G § 2.3 (July 1, 2023) (see Table 1, section 200.9 of this Title) to calculate CO_2 mass emissions, but the provisions in paragraph (10) of this subdivision are applicable to such units.

(1) Except as otherwise provided in paragraphs (7) through (9) of this subdivision, all flow meter and other measurement devices used to provide data for the GHG emissions calculations or industrial product data must be calibrated prior to the year data collection is required to begin using the procedures specified in this section, and subsequently recalibrated according to the frequency specified in paragraph (4) of this subdivision. Each meter or measurement device must meet the applicable accuracy specification in paragraph (6) of this subdivision; however, each individual component of a flow meter device is not required to meet the accuracy specifications. The procedures and methods used to quality assure the data from each measurement device must be documented in the written monitoring plan required by section 1.7(e) of this Part.

(2) All flow meters and other measurement devices that provide data used to calculate GHG emissions or product data must be calibrated according to either the manufacturer's recommended procedures or a method specified in an applicable subpart of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title). The calibration method(s) used must be documented in the monitoring plan required under section 1.7(e) of this Part and are subject to verification under this Part and review by the department to ensure that measurements used to calculate GHG emissions or product data have met the accuracy requirements of this section.

(3) For facilities and suppliers that become subject to this Part after January 1, 2025, all flow meters and other measurement devices that provide data used to calculate GHG emissions or product data must be installed and calibrated no later than the date on which data collection is required to begin under this Part.

(4) Except as otherwise provided in paragraphs (7) through (9) of this subdivision, subsequent recalibrations of the flow meter and other measurement devices subject to the requirements of this section must be performed no less frequently than at one of the following time intervals, whichever is shortest:

(i) the frequency specified in a subpart of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) that is applicable under this Part;

(ii) the frequency recommended by the manufacturer;

(iii) once every 36 months;

(iv) immediately upon replacement of a previously calibrated meter.

(v) immediately upon replacement or repair of a device that is deemed out of calibration as determined in paragraph (6) of this subdivision; or

(vi) if the device manufacturer explicitly states in the product documentation that calibration is required at a period exceeding three years, the operator may follow the procedures in paragraph (9) of this subdivision to obtain department approval to relieve the operator from having to comply with subparagraphs (i) and (iii) of this paragraph.

(5) All standards used for calibration must be traceable to the National Institute of Standards and Technology or other similar national government body responsible for measurement standards.

(6) In addition to the specific calibration requirements specified in subparagraph (i) of this paragraph, and, if applicable, the field accuracy assessment requirements specified in subparagraph (ii) of this paragraph, all flow meter and other measurement devices covered by this section, regardless of type, must be selected, installed, operated, and maintained in a manner to ensure accuracy within ±5 percent.

(i) Perform all mass and volume measurement device calibration as specified in the original equipment manufacturers (OEM) documentation. If OEM documentation is unavailable, calibrate as specified in 40 CFR § 98.3(i)(2) through (3) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), except that a minimum of three calibration points must be used spanning the normal operating conditions. When using the three calibration points, one point must be at or near the zero-point, one point must be at or near the upscale point, and one point at or near the mid- point of the

device's operating range. If OEM documentation does not specify a method or is unavailable, and calibration methods specified in 40 CFR §98.3(i)(2) through (3) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) are not possible for a particular device, the procedures in section 1.11(b) of this Part must be followed to obtain approval for an alternative calibration procedure. Additionally:

('a') Pressure differential devices must be inspected at a frequency specified in paragraph (4) of this subdivision unless the device is located at a refinery or hydrogen plant that operates continuously with infrequent outages. In such cases, the owner or operator of the refinery or hydrogen plant must inspect each device at a frequency of at least once every six years. The inspection must be conducted as described in the appropriate part of ISO 5167-2: 2022 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full Part 2: Orifice plates (see Table 1, section 200.9 of this Title), or American Gas Association Report No. 3 Part 2 (2003) (see Table 1, section 200.9 of this Title), or a method published by an organization listed in 40 CFR § 98.7 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) applicable to the analysis being conducted. If the device fails any one of the tests, then the meter shall be deemed out of calibration. If OEM guidance for a particular pressure differential device recommends against disassembly and inspection of the device, disassembly and inspection requirements in this paragraph do not apply. Documentation of OEM guidance must be made available to verifiers and the department upon request.

('1') Records of all tests, including an as-found condition, must be preserved pursuant to section 1.7 of this Part and made available to verifiers and the

department upon request.

('2') Where inspection requirements apply, the primary element must also be photographed on both sides prior to any treatment or cleanup of the element to clearly show the condition of the element as it existed in the pipe.

('b') Devices used to measure total pressure and temperature must be calibrated using methods specified in paragraph (2) of this subdivision and at a frequency specified in paragraph (4) of this subdivision.

('c') If temperature and/or total pressure measurements are not available or are taken at a remote location, the uncertainty caused by this must be factored into the evaluation of the overall measurement accuracy required under paragraph (6) of this subdivision.

(ii) Operators and suppliers may conduct an annual field accuracy assessment of mass and volume measurement devices to test for field accuracy in years between successive calibrations to ensure the device is maintaining measurement accuracy within ±five percent. When performing a field accuracy assessment, the as-found condition must be recorded to ensure the device is measuring with accuracy within ±five percent. Should a device be found to be operating outside the ±five percent accuracy bounds, the device shall be deemed out of calibration. Records of all field accuracy assessments must clearly indicate the assessment procedure and the as-found condition, be preserved pursuant to section 1.7 of this Part, and be made available to verifiers and the department upon request. Device accuracy may be assessed using one of the following options:

('a') engineering analysis;

(‘b’) OEM calibration guidance or other OEM recommended methods;

(‘c’) standard industry practices; or

(‘d’) portable instruments.

(iii) Pursuant to paragraph (10) of this subdivision, in the event of a failed calibration or recalibration, operators or suppliers who choose not to perform the annual field accuracy assessment specified in subparagraph (ii) of this paragraph for one or more mass or volume measurement devices must demonstrate data accuracy going back multiple years to the most recent successful calibration. Multiple years of data may be deemed invalid if accuracy cannot be demonstrated by other means, including strap-on meters or engineering methods. For operators and suppliers who conduct the annual field accuracy assessment, and a device is found to be out of calibration, accuracy must be demonstrated back to the most recent successful calibration or the most recent successful field accuracy assessment, whichever is most recent.

(7) The requirements of this subdivision do not apply under the following circumstances:

(i) Financial transaction meters are exempted from the calibration requirements of this subdivision if the supplier and purchaser do not have any common owners and are not owned by subsidiaries or affiliates of the same company. Financial transaction meters where the supplier and the purchaser do have common owners or are owned by subsidiaries or affiliates of the same company are exempt from the calibration requirements of this subdivision if one of the following is true:

('a') the financial transaction meter is also used by other companies that do not share common ownership with the fuel supplier; or

('b') the financial transaction meter is sealed with a valid seal from the county sealer of weights and measures or from a county certified designee; or

('c') the financial transaction meter is operated by a third-party.

(ii) Upstream ethanol and additive meters used to ensure proper blendstock percentage for finished gasoline are exempted from the calibration requirements of this subdivision.

(iii) Non-financial transaction meters used by Public Utility Gas Corporations for purposes of reporting natural gas supplier emissions are exempt from the calibration requirements in paragraphs (1) through (6) of this subdivision if the supplier can demonstrate that the meters are operated and maintained in conformance with a standard that meets the measurement accuracy requirements of Chapter III of Title 16.

(8) For units and processes that operate continuously with infrequent outages, it may not be possible to meet deadlines for the initial or subsequent calibrations of a flow meter or other fuel measurement or sampling device, or inspection of orifice plates without disrupting normal process operation. In such cases, the owner or operator may submit a written request to the department to postpone calibration or inspection until the next scheduled maintenance outage. Such postponements are subject to the procedures of paragraph (9) of this subdivision and must be documented in the monitoring plan that is required under section 1.7(e) of this Part.

(9) In cases of continuously operating units and processes where calibration or

inspection is not possible without operational disruption, the operator must demonstrate by other means to the satisfaction of the department that measurements used to calculate GHG emissions and product data still meet the accuracy requirements of paragraph (6) of this subdivision. The department must approve any postponement of calibration or required recalibration beyond January 1, 2026.

(i) A written request for postponement must be submitted to the department not less than 30 days before the required calibration, recalibration, or inspection date. The department may request additional documentation to validate the operator's claim that the device meets the accuracy requirements of this section. The operator shall provide any additional documentation to the department within 10 working days of a request by the department.

(ii) The request must include:

('a') the date of the required calibration, recalibration, or inspection;

('b') the date of the last calibration or inspection;

('c') the date of the most recent field accuracy assessment, if applicable;

('d') the results of the most recent field accuracy assessment, if applicable, clearly indicating a pass/fail status;

('e') the proposed date for the next field accuracy assessment, if applicable;

('f') the proposed date for calibration, recalibration, or inspection

which must be during the time period of the next scheduled shutdown. If the next shutdown will not occur within three years, this must be noted and a new request must be received every three years until the shutdown occurs and the calibration, recalibration or inspection is completed.

(‘g’) a description of the meter or other device, including at a minimum:

(‘1’) make;

(‘2’) model;

(‘3’) install date;

(‘4’) location;

(‘5’) annual emissions calculated or annual product data reported using data from the device;

(‘6’) sources for which the device is used to calculate emissions or product data;

(‘7’) calibration or inspection procedure;

(‘8’) reason for delaying calibration or inspection;

(‘9’) proposed method to assure the accuracy requirements of paragraph (6) of this subdivision are met; and

(‘10’) name, title, phone number and e-mail of contact person capable of responding to questions regarding the device.

(10) If the results of an initial calibration, recalibration, or field accuracy assessment fail to meet the required accuracy specification, and the emissions or product

data estimated using the data provided by the device represent more than five percent of total facility emissions or product data on an annual basis, the operator must demonstrate by other means to the satisfaction of the verifier or the department that measurements used to calculate GHG emissions and product data still meet the ±five percent accuracy requirements going back to the last instance of successful field accuracy assessment or calibration of the device. Where the results of an initial calibration, recalibration, or field accuracy assessment fail to meet the accuracy specifications, the verifier shall note at a minimum a nonconformance as part of the emissions data verification statement.

(11) When using an inventory measurement, stock measurement, or tank drop measurement method to calculate volumes and masses, the method must be accurate to ±five percent for the time periods required by this Part, including annually for industrial product data. Techniques used to quantify amounts stored at the beginning and end of these time periods are not subject to the calibration requirements of this section. Uncertainties in beginning and end amounts are subject to verifier review for material misstatement under section 4.2(b)(11) of this Part. If any devices used to measure inputs and outputs do not meet the requirements of paragraphs (1) through (10) of this subdivision, the verifier must account for this uncertainty when evaluating material misstatements. Reported values must be calculated using Equations 1.4-1 and 1.4-2 as provided in this paragraph:

Equation 1.4-1: Fuel consumed (volume or mass) = (inputs during time period – outputs during time period) + (amount stored at beginning of time period) – (amount stored at end of time period)

Equation 1.4-2: Product produced (volume or mass) = (outputs during time period - inputs during time period) + (amount stored at end of time period - amount stored at beginning of time period)

(h) Reporting and Verifying Product Data. The reporting entity must separately identify, quantify, and report all product data as specified in sections 2.3, 2.11, and 2.12 of this Part. It is the responsibility of the reporting entity to obtain verification services for the product data. Product data will be evaluated for conformance and material misstatement independent of GHG emissions data. Industrial product data is evaluated for material misstatement and conformance, while the remaining reported product data is evaluated for conformance only. Emission sources must exclude inaccurate industrial product data and may elect to exclude accurate industrial product data. Reporting Entities that exclude industrial product data must report a description of the excluded data and an estimated magnitude using best available methods. The excluded industrial product data will not be used for the material misstatement assessment or for the total industrial product data variable described in section 4.2(b)(11)(i) of this Part. Operators of cement plants may not exclude industrial product data.

(i) Changes in Methodology. Except as specified below, where this Part permits a choice between different methods for the monitoring and calculation of GHGs and product data, the reporting entity must use the method chosen for all future emissions data reports, except as provided pursuant to paragraphs (1) and (2) of this subdivision.

(1) Changes in Prescribed Methods.

(i) Permanent Improvement in Monitoring or Calculation Methodology for Emissions Data. The reporting entity is permitted to permanently improve the emissions or product data monitoring or calculation method to a higher-tier monitoring or calculation method specified in this Part, such as the addition of a continuous emissions monitoring system. Permanent improvements to emissions monitoring or calculation methods do not require approval in advance by the department; however, the reporting entity must notify the department by the reporting deadline for the applicable reporting year.

(ii) Permanent Change to a Lower-Tier Methodology for Emissions Data. The reporting entity is permitted to submit a request for approval of a permanent change to a lower tier monitoring or calculation method specified in this Part for emissions data. The request must be provided to the department prior to January 1 of the year for which the data will be reported and must be approved by the department and implemented pursuant to the timing requirements in paragraphs (2) through (3) of this subdivision. The request must include a description of why the change in method is being proposed, a detailed description of the data that are affected by the method change, and a demonstration of differences in estimated data under the current and proposed methods.

(iii) Permanent changes to all industrial product data monitoring or calculation methods must be submitted to the department pursuant to paragraph (2) of this subdivision, except in the circumstances described in paragraph (4) of this subdivision.

(2) Alternative Methods. If a reporting entity identifies a situation where conventional metering or methods are not feasible, the reporting entity may submit a request to the department for approval of an alternative measurement/monitoring method that

achieves accuracy at an equivalent level to the ±five percent required by paragraph (g)(6) of this section. The alternative method request must be provided to the department prior to January 1 of the year for which the new method would be implemented for data collection. The request must include a description of why the change in method is being proposed, include a detailed description of the data that are affected by the alternative measurement/monitoring method, and include a demonstration of differences in estimated data under the current and proposed methods. The department may also approve the use of the alternative method in the current reporting year provided the reporting entity makes that request and shows that it has collected the necessary data to apply the alternative method to the entire current year.

(3) When permitted under paragraphs (1) and (2) of this subdivision, a change in the calculation or monitoring method must be made for an entire emission year and apply to the start of an emission year, except in the circumstances described in paragraph (4) of this subdivision.

(4) Use of a Temporary Methodology. The reporting entity is permitted to temporarily modify the emissions or product data monitoring or calculation method when necessary for the avoidance of missing data or to comply with the missing data provisions of this Part. For emissions data, in the event of an unforeseen breakdown in fuel analytical data monitoring equipment or CEMS equipment, the reporting entity must use the procedures in sections 3.1(h) and (i) of this Part, respectively, for seeking approval of interim data collection procedures. For all other instances that temporary methods are used, the department must be notified by the reporting deadline of the following information: a description of the

temporary method, the affected data, and the duration that the temporary method was used. A temporary method may be used for a period not to exceed 365 days unless the method is concurrently or subsequently submitted and approved by the department as a permanent method pursuant to the requirements in subparagraph (i)(1)(ii) or paragraph (2) of this subdivision. A reporting entity must be able to demonstrate during verification that the temporary method provides data accuracy within ±five percent as specified in paragraph (g)(6) of this section. Industrial product data that does not meet the required accuracy specification must be excluded using the procedure in subdivision (h) of this section to avoid an adverse verification statement.

(5) When regulatory changes impose new or revised reporting requirements or calculation methods on a reporting entity, the monitoring and calculation method must be in place on January 1 of the year in which data is first required to be collected pursuant to the reporting requirements.

(j) Changes in Ownership or Operational Control. If a reporting entity undergoes a change of ownership or operational control, the following requirements apply regarding notifications to the department and reporting responsibilities.

(1) Notifications. Prior to the change of ownership or operational control, the previous owner or operator of the reporting entity and the new owner or operator of the reporting entity must provide the following information to the department in a manner and method approved by the department. Required information must be submitted to the electronic address designated by the department.

(i) The previous owner or operator must notify the department via email

of the ownership or operational control change including the name of the new owner or operator and the date of the ownership or operational control change.

(ii) The new owner or operator must notify the department via email of the ownership or operational control change, including the following information:

('a') previous owner or operator;

('b') new owner or operator;

('c') date of ownership or operator change; and

('d') name of a new Designated Representative pursuant to section 1.5(b) of this Part for the affected reporting entity's account in the New York State Greenhouse Gas Reporting Tool (NYS e-GGRT) specified in section 1.6 of this Part.

(2) Reporting Responsibilities. Except as specified in subparagraph (iv) of this paragraph, the owner or operator of record at the time of a reporting or verification deadline specified in this Part has the responsibility for complying with the requirements of this Part, including certifying that the emissions data report is accurate and complete, obtaining verification services, and completing verification.

(i) Except as specified in subparagraph (iv) of this paragraph, the owner or operator of record at the time of a reporting deadline is responsible for submitting the emissions data report covering the complete calendar year data.

(ii) Except as specified in subparagraph (iv) of this paragraph, if an ownership change takes place during the calendar year, reported data must not be split or subdivided for the year, based on ownership. A single annual data report must be submitted for the reporting entity by the current owner or operator. This report must represent required

data for the entire calendar year.

(iii) Previous owners or operators are required to provide data and records to new owners or operators that are necessary and required for preparing annual emissions data reports required by this Part.

(iv) Fuel suppliers that cease to have reportable emissions as a result of an ownership change that affects supplier operations retain the responsibility for complying with the requirements of this Part, including certifying that the emissions data report is accurate and complete, obtaining verification services, and completing verification, for the emissions from all fuel transactions that occurred prior to the date of the change of ownership.

(k) Addresses. The electronic address designated by the department shall be substituted for the addresses provided in 40 CFR § 98.9 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) and used for any necessary notifications or materials that are not submitted by other means.

253-1.5 Greenhouse Gas Reporting Content

The emission sources specified in section 1.2 of this Part must develop, submit, and certify pursuant to 40 CFR § 98.4(e) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), GHG emissions data reports to the department each year in accord with the following requirements.

(a) General Contents. In addition to the items specified at 40 CFR § 98.3(c) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), each reporting entity must

include in the emissions data report the following information:

(1) department identification number, including DECID and/or Public ID;

(2) county;

(3) geographic location;

(4) electricity generating units must also provide Energy Information Administration numbers including ORIS code;

(5) other business entity identifiers as required by the department.

(b) Designated Representative. Each reporting entity must designate a reporting representative and adhere to the requirements of 40 CFR § 98.4 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) for this representative and for any named alternate designated representatives. In addition to the text specified at 40 CFR § 98.4(e)(1) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the certification statement signed by the designated representative, or any alternate designated representative must certify that the department or an authorized representative shall be allowed upon presentation of credentials and other documents as may be required by law to:

(1) enter upon the reporting entity’s premises where a facility subject to the reporting requirements of this Part, is located or emissions-related activity is conducted, or where records subject to the reporting requirements of this Part;

(2) have access to and copy, at reasonable times, any records subject to the reporting requirements of this Part;

(3) inspect at reasonable times any emission sources, equipment (including monitoring and emission control equipment), practices, and operations regulated or required

pursuant to this Part; and

(4) sample or monitor at reasonable times substances or parameters for the purpose of assuring compliance with the requirements of this Part.

(c) Corporate Parent, NAICS Codes, and Cogeneration. Each reporting entity must submit information to meet the requirements specified in 40 CFR §§ 98.3(c)(10), (c)(11) and (c)(4)(v) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) on Reporting of Corporate Parent Information, NAICS Codes and Cogeneration.

(d) Facility Level Energy Input and Output. The reporting entity must include in the emissions data report information about the facility's energy acquisitions and energy provided or sold as specified in this subdivision. For the purpose of reporting under this subdivision, the reporting entity may exclude any electricity that is generated outside the facility and delivered into the facility with final destination outside of the facility. The reporting entity may also exclude electricity consumed by operations or activities that do not generate any emissions, energy outputs, or products that are covered by this Part and that are neither a part of nor in support of electricity generation or any industrial activities covered by this Part. The reporting entity must report this information for the calendar year covered by the emissions data report, pro-rating purchases as necessary to include information for the full months of January and December.

(1) Electricity purchases or acquisition from sources outside of the facility boundary (MWh) and the name and department identification number of each electricity provider, as applicable.

(2) Facilities with a NAICS code listed in Table 2-9 in section 2.22 of this Part

must report the MWh from each electrical distribution utility that provides transmission and/or distribution service and the MWh from each electricity generation provider.

(3) Thermal energy purchases or acquisitions from sources outside of the facility boundary (MMBtu) and the name and department identification number of each energy provider, as applicable. If the operator acquires thermal energy from a PURPA Qualifying Facility and vents, radiates, wastes, or discharges more than 10 percent of the acquired thermal energy before using the energy in any industrial process, operation, or heating/cooling application, the reporting entity must report the amount of thermal energy actually needed and used, in addition to the amount of thermal energy received from the provider.

(4) Electricity provided or sold, as specified in section 2.5(a)(4) of this Part, if applicable.

(5) Thermal energy provided or sold to entities outside of the facility boundary: the reporting entity must report the amount of thermal energy provided or sold (MMBtu), the names and department identification number of each end-user as applicable, and the type of unit that generates the thermal energy. If section 2.5 of this Part applies to the operator, the reporting entity must follow the requirements of section 2.5(a)(5) in reporting the thermal energy generated by cogeneration or bigeneration units, and, if applicable, also separately report the information required in paragraph (4) of this subdivision for the thermal energy provided or sold that is not generated by cogeneration or bigeneration units.

(6) If the facility boundary includes more than one cogeneration system, boiler, or steam generator, and each unit/system or each group of units produces thermal energy for

different particular end-users or on-site industrial processes and operations, the reporting entity must report the disposition of generated thermal energy by unit/system or by group of units with the same dispositions, and by the type of thermal energy product provided.

(e) Increases and Decreases in Facility Emissions**.** The operator of a facility that meets the thresholds in section 1.2(f) of this Part must include the following information in the emissions data report:

(1) Whether a change in the facility's operations or status resulted in an increase or decrease of more than five percent in emissions of greenhouse gases in relation to the previous emission year.

(2) If there is an increase or decrease of more than five percent in emissions of greenhouse gases in relation to the previous year, the operator must provide a brief narrative description of what caused the increase or decrease in emissions. Include in this description any changes in air permit status.

(3) Verifiers must ensure the information reported pursuant to paragraph (1) of this subdivision is reported in conformance with this Part. Paragraph (2) of this subdivision, the narrative description, is not subject to the third-party verification requirements of this Part.

(f) Prohibited Submissions. No person shall submit any record, information, or report required by this Part that:

(1) falsifies, conceals, or covers up by any trick, scheme or device a material fact;

(2) makes any false, fictitious or fraudulent statement or representation;

(3) makes or uses any false writing or document knowing the same to contain

any false, fictitious or fraudulent statement or entry; or

(4) omits material facts from a submittal or record.

(g) Computation of Time.

(1) Unless otherwise stated, any time period scheduled under this Part to begin on the occurrence of an act or event shall begin on the day the act or event occurs.

(2) Unless otherwise stated, any time period scheduled under this Part to begin before the occurrence of an act or event shall be computed so that the period ends the day before the act or event occurs.

(h) Holidays and Weekends. Unless otherwise stated, if the final day of any time period under this Part falls on a weekend or a State or Federal holiday, the time period shall be extended to the next business day.

253-1.6 Reporting Mechanism

Reporting Entities shall submit emissions data reports and any revisions to the reports through the NYS e-GGRT, or any other reporting tool approved by the department that will guarantee transmittal and receipt of data required by this Part.

253-1.7 Record Keeping

Each emission source that is required to report greenhouse gases under this Part must keep records as required by 40 CFR § 98.3(g) through (h) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) and as specified in this Subpart or as prescribed in the relevant section of Subpart 2 of this Part.

(a) Duration.

(1) Large emission sources as specified in section 1.2(f) of this Part, in any reporting year, must maintain all records specified in 40 CFR § 98.3(g) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), and records associated with revisions to emissions data reports as provided under 40 CFR § 98.3(h) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), for a period of 10 years from the date of emissions data report certification.

(2) An emission source that is required under Subpart 4 of this Part to verify its emissions must maintain all records for a period of 10 years from the date of emissions data report certification.

(3) Emission sources that do not meet the threshold requirements pursuant to section 1.2(f) of this Part or are not required to verify their emissions pursuant to Subpart 4 of this Part during any reporting year, must maintain required records for a period of five years from the date of certification.

(4) Large emission sources as specified in section 1.2(f) of this Part that fully exit reporting pursuant to section 1.2(n)(1) of this Part must maintain the corresponding records required under this section and retain such records for 10 years following the submission of the final emissions data report to the department.

(b) Requests for Records. Copies of any records or other materials maintained under the requirements of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) or this Part must be made available to the department upon request within 14 days of receipt of such request by the designated representative of the reporting entity,

unless a different schedule is agreed to by the department.

(c) Types of Records to Retain. Emission sources must maintain the following records, including but not limited to:

(1) Information used to quantify or report emissions and product data in the emissions data report, underlying monitoring and metering data, invoices of receipts or deliveries, sales transaction data, calculation methods, protocols used, analysis results, calibration records, electricity transaction data, and other relevant information.

(2) A list of units, operations, processes, and activities for which GHG emissions were calculated.

(3) The data used to calculate the GHG emissions for each unit, operation, process and activity categorized by fuel or material type. These data include but are not limited to:

(i) the GHG emissions calculations and methods used;

(ii) analytical results for the development of site-specific emission factors;

(iii) the results of all required analyses for high heat value, carbon content, and other required fuel or feedstock parameters;

(iv) emissions data and input data, industrial product data and associated inputs; data associated with thermal energy provided, sold, purchased, or acquired; and data associated with electricity provided, sold, purchased, or acquired must be sufficient to allow for verification of each emissions data report; and

(v) any facility operating data or process information used for the GHG calculations.

(4) The annual GHG reports.

(5) Missing data computations for each missing data event, the cause of each event and the corrective actions taken to restore malfunctioning monitoring equipment.

(6) Continuous Monitoring System Records. The results of all required certification and quality assurance tests for continuous monitoring systems, fuel flow meters, and other instrumentation used to provide data for the GHG emissions reported under this Part.

(d) Format for Retained Records. When possible, all records shall be kept in readable electronic format and must be recorded in a form that is suitable of expeditious inspection and review. Upon request by the department, the records required under this section must be made available as required in subdivision (b) of this section.

(e) GHG Monitoring Plan. Each facility operator or supplier that reports under section 1.2 of this Part, must complete and retain for review by a verifier or the department a written GHG monitoring plan that meets the requirements of this subdivision. Each facility operator or supplier that meets the thresholds in section 1.2(f) of this Part must submit to the department a GHG monitoring plan by December 31, 2026, or by the end of the first calendar in which the source first meets the thresholds in section 1.2(f) of this Part. Any source that is required to submit a GHG monitoring plan must resubmit that monitoring plan in any year in which a revision is made. Submissions of GHG monitoring plans should be sent to the electronic address designated by the department.

(1) The GHG monitoring plan shall include these elements:

(i) identification of positions of responsibility (i.e., job titles) for collection

of the emissions data;

(ii) explanation of the processes and methods used to collect the necessary data for the GHG calculations; and

(iii) description of the procedures and methods that are used for quality assurance, maintenance, and repair of all continuous monitoring systems, flow meters, and other instrumentation used to provide data for the GHGs reported under this Part.

(2) The GHG monitoring plan may rely on references to existing corporate documents provided that the elements of paragraph (1) of this subdivision are clearly recognizable.

(3) The owner or operator of the emission source shall revise the GHG monitoring plan as needed to reflect changes in production processes, monitoring instrumentation, and quality assurance procedures; or to improve procedures for the maintenance and repair of monitoring systems to reduce the frequency of monitoring equipment downtime.

(4) Upon request by the department, the owner or operator of the emission source shall make all information that is collected in conformance with the GHG monitoring plan available for review during an audit.

(f) GHG Inventory Program for Electric Power Entities that Import or Export Electricity. In lieu of a GHG Monitoring Plan, electric power entities that import or export electricity must prepare GHG Inventory Program documentation that is maintained and available for department audit pursuant to the recordkeeping requirements of this section. The following information is required:

(1) information to allow the department to develop a general understanding of reporting entity boundaries, operations, and electricity transactions;

(2) reference to management policies or practices applicable to reporting pursuant to section 2.4 of this Part;

(3) list of key personnel involved in compiling data and preparing the emissions data report;

(4) training practices for personnel involved in reporting delivered electricity pursuant to section 2.4 of this Part, and responsible for data report certification, including documented training procedures;

(5) query of NERC e-Tag source data to determine the quantity of electricity (MWh) imported, exported, and wheeled for transactions in which the EPE is the PSE on the last physical path segment that crosses the border of New York, access to review the raw e-Tag data, a tabulated summary, and query description;

(6) reference to other independent or internal data management systems and records, including written power contracts and associated verbal or electronic records, full or partial ownership, invoices, and settlements data used to document whether reported transactions are specified or unspecified;

(7) description of steps taken and calculations made to aggregate data into reporting categories required pursuant to section 2.4 of this Part;

(8) records of preventive and corrective actions taken to address department findings of past nonconformances and material misstatements;

(9) log of emissions data report modifications made after initial certification; and

(10) a written description of an internal audit program that includes emissions data report review and documents ongoing efforts to improve the GHG Inventory Program.

253-1.8 Confidentiality.

(a) Public Information. Emissions data submitted to the department under this Part is public information and shall not be designated as confidential. Data reported to U.S. EPA under 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) which has been released to the public by U.S. EPA shall be considered public information by the department.

(b) Claim of Confidentiality. Any person submitting information to the department pursuant to this Part may claim such information as “confidential” by clearly identifying such information as “confidential.” Any claim of confidentiality by a person submitting information must be based on the person’s belief that the information marked as confidential is either trade secret or otherwise exempt from public disclosure under the section 87 of the Public Officers Law. All such requests for confidentiality shall be handled in accordance with the procedures specified in section 616.7 of this Title.

253-1.9 Enforcement.

(a) Penalties. Penalties may be assessed for any violation of this Part pursuant to article 71 of the Environmental Conservation Law.

(b) Report Violations. Each day or portion thereof that any report required by this Part remains unsubmitted, is submitted late, or contains information that is incomplete or

inaccurate is a single, separate violation. For purposes of this section, “report” means any emissions data report, verification statement, or other document required to be submitted to the department by this Part.

(c) Each metric ton of CO_2e emitted but not reported as required by this Part is a separate violation.

(1) The department will not initiate enforcement action under this section until after any applicable verification deadline for the pertinent report.

(d) Each failure to measure, collect, record, or preserve information in the manner required by this Part constitutes a separate violation, except where the emission source can demonstrate that the failure results solely from maintenance or calibration required by this Part.

(e) Order On Consent. The department may revoke or modify any Order on Consent issued pursuant to this Part as a sanction for a violation of this Part.

(f) The violation of any condition of an Order on Consent that is issued pursuant to this Part is a separate violation.

(g) Any violation of this Part may be enjoined pursuant to article 71 of the Environmental Conservation Law.

(h) Access Rights. The department or an authorized representative shall be allowed upon presentation of credentials and other documents as may be required by law to:

(1) enter upon a reporting entity’s premises where a facility subject to the reporting requirements of this Part is located or emissions-related activity is conducted, or where records subject to the reporting requirements of this Part are kept;

(2) have access to and copy at reasonable times any records subject to the reporting requirements of this Part;

(3) inspect at reasonable times any emission sources, equipment (including monitoring and emission control equipment), practices, and operations regulated or required pursuant to this Part; and

(4) sample or monitor at reasonable times substances or parameters for the purpose of assuring compliance with the requirements of this Part.

253-1.10 Severability.

Each provision of this Part shall be deemed severable, and in the event that any provision of this Part is held to be invalid, the remainder of this Part shall continue in full force and effect.

253-1.11 Standardized Methods.

(a) Applicable Methods. Entities that are required to report GHG emissions pursuant to this Part must use either those standardized methods and materials listed in 40 CFR § 98.7 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), or another similar method published by an organization listed in 40 CFR § 98.7 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) that is applicable to the analysis being conducted. For gaseous fuels, fuel characteristics may be determined using chromatographic analysis as specified in 40 CFR § 98.34(a)(6) or (b)(4) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title). All methods used must be documented in the GHG Monitoring Plan that is as required

by section 1.7(e) of this Part.

(b) Alternative Test Methods. Alternative test methods that are demonstrated to the satisfaction of the department to be equally or more accurate than the methods in subdivision (a) of this section may be used upon written approval by the department.

Subpart 253-2 Requirements for the Mandatory Reporting of Greenhouse Gas Emissions from Specific Types of Facilities, Suppliers, and Entities

253-2.1 Aluminum Production

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart F of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) in reporting stationary combustion and process emissions and related data from aluminum production to the department, except as otherwise provided in this section.

(a) CO_2, CH_4, and N_2O from Fuel Combustion. Operators must calculate and report fuel high heat value (in units of MMBtu/kg, MMBtu/scf, or MMBtu/gallon for solid, gaseous, or liquid fuels respectively). When calculating GHG emissions from fuel combustion, the operator must use a method in 40 CFR § 98.33(a)(1) to § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) or 40 CFR § 98.33(c) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part.

(b) Monitoring, Data, and Records. For each emissions calculation method chosen

under subdivision (a) of this section, the operator must meet the applicable requirements for monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR § 98.34-.37 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), except as modified in subdivisions (c) and (d) of this section, and sections 2.7 and 3.1 of this Part.

(c) Missing Data Substitution Procedures. The operator must comply with 40 CFR § 98.65 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) when substituting for missing data, except as otherwise provided in paragraphs (1) through (2) of this subdivision.

(1) To substitute for missing data for emissions reported under section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems), the operator must follow the requirements of section 3.1 of this Part.

(2) For each missing value from paste or anode consumption, the operator must apply a substitute value according to the procedures in subparagraphs (i) through (ii) of this paragraph.

(i) If the data capture rate is at least 80 percent for the emission year, the operator must substitute for each missing value according to 40 CFR § 98.65(a) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(ii) If the data capture rate is less than 80 percent for the emission year, the operator must substitute for each missing value with the maximum capacity of the system and the number of days per month.

(3) The operator must document and retain records of the procedure used for

all missing data estimates pursuant to the recordkeeping requirements of section 1.7 of this Part.

(d) Additional Product Data. In addition to the information required by 40 CFR § 98.66 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator must report additional information as follows:

(1) annual production of aluminum products in short tons;

(2) a description of the product(s);

(3) the process used to produce the products, such as prebake or Soderberg electrolysis; and,

(4) if the facility is producing aluminum billets, the operator must report the production of aluminum and aluminum alloy billets in the emission year (short tons); and,

(5) facilities using a CEMS to report emissions from a combined flue stack are required to use the Tier 4 calculation method to report both combustion and total stack emissions under section 2.7 of this Part, pursuant to the provisions of section 2.7(g) of this Part. These facilities are also required to report process emissions under this section. To report process emissions, the operator must subtract the fuel combustion emissions value from the facility's total reported combined stack emissions value in order to calculate the facility's process emissions value, in metric tons, to be reported under this section. The operator must use Equation 2.1-1 as provided in this paragraph to calculate process emissions:

Equation 2.1-1: $E_{process} = E_{total} – E_{combustion}$

Where:

Eprocess = The annual process emissions from a facility's combined flue stack using a CEMS (metric tons)

Etotal = The total annual emissions from a facility's combined flue stack using a CEMS (metric tons)

Ecombustion = The annual combustion emissions from a facility's combined flue stack using a CEMS (metric tons)

253-2.2 Anaerobic Digestion and Liquid Storage of Waste

The operator of a facility who is required to report under section 1.2 of this Part and that exceeds an applicability threshold pursuant to subdivision (a) of this section must report annual emissions and other data as specified in this section. Applicable facilities may include anaerobic digesters or reactors and liquid or slurry waste storages that are operated at solid waste management facilities or Concentrated Animal Feeding Operations or CAFO under section 750-1.2(a)(23) of this Title but does not include commercial chemical fertilizers or solid waste landfills.

(a) Applicability.

(1) Operators that treat waste in anaerobic digesters or reactors or store waste that contains degradable organic carbon as a liquid or slurry in storages must comply with the reporting requirements in subdivision (d) of this section if wastes imported to the facility or generated at the facility during the reporting year were in excess of at least one of the

following thresholds.

(i) 1×10^6 gallons of aqueous industrial food waste;

(ii) 7×10^8 gallons of municipal wastewater;

(iii) 1500 metric tons (wet mass) of food scraps, commercial food waste, or industrial food waste;

(iv) 430 metric tons (dry mass) of food scraps, commercial food waste, or industrial food waste;

(v) 1100 metric tons of stover, yard trimmings, or other plant biomass;

(vi) 1100 metric tons of paper or paper pulp;

(vii) 290 metric tons of fats, oils, or grease;

(viii) 600 metric tons of any other waste that contains degradable organic carbon; or

(ix) a combination of different waste types in amounts such that the following sum exceeds 1: gallons of aqueous industrial wastewater/(1×10^6) + gallons of municipal wastewater/(7×10^8) + wet metric tons of food waste/1500 + dry metric tons of food waste/430 + metric tons of plant biomass/1100 + metric tons of paper or paper pulp/1100 + metric tons of fats oils or grease/290 + metric tons of other waste that contains degradable organic carbon/600.

(2) Operators may comply with this section by submitting an abbreviated report as set forth in subdivision (b) of this section if either of the following apply during the reporting year:

(i) the facility is a Concentrated Animal Feeding Operations or CAFO

under section 750-1.2(a)(23) of this Title with 2500 or fewer mature dairy cows present at any one time; or

(ii) the facility is a Concentrated Animal Feeding Operations or CAFO under section 750-1.2(a)(23) of this Title with more than 2500 mature dairy cows present at any one time, the facility imports less than 50 percent of any of the waste thresholds in paragraph (1) of this subdivision, and the facility does not heat waste in liquid or slurry storages or anaerobic digesters or reactors using fossil fuels.

(b) Abbreviated reporting. Abbreviated reports submitted by facilities that meet the criteria in paragraph (a)(2) of this section must include the following information for each liquid or slurry storage or anaerobic digester:

(1) the construction years and locations (decimal degrees longitude and latitude);

(2) operational volumes (gallons);

(3) the total amounts of waste (gallons) stored or treated;

(4) average solids and hydraulic retention times (days);

(5) whether flares or storage covers are used; and

(6) whether fossil fuels are consumed to assist in on-site biogas generation or combustion.

(c) Additional Emissions Data Collection. Operators that exceed the applicability threshold under section 2.20(a) of this Part are required to complete an Emissions Monitoring and Measurement Plan and report pursuant to section 2.20(a) of this Part in addition to the reporting requirements in this section.

(d) Reporting Requirements. Operators subject to reporting requirements under paragraph (a)(1) of this section must provide an annual report of the following operational information and activity data to the department.

(1) Operational information

(i) Annual reports for each anaerobic digester or reactor must include all of the following information:

('a') the year constructed;

('b') the location (decimal degrees latitude and longitude);

('c') the operational volume (gallons);

('d') the carryover masses (kg-dry mass) of grit or fixed solids in the equipment from the previous year; or an average accumulation rate (kg-dry mass/month) of grit or fixed solids which is defined as the mass (kg-dry mass) of these materials removed from the digester during the most recent clean out divided by the amount of time in months since the previous clean out;

('e') the total volume (gallons) of material treated in the equipment during the reporting year;

('f') the total volume (gallons) and source (e.g., stormwater, alley wash water) of water added to waste prior to treatment in the equipment during the reporting year;

('g') dates during the reporting year when waste was not present in the equipment (e.g., during clean outs or repairs);

('h') the approximate residual volume (gallons) of waste retained

in the equipment after routine emptying;

('i') the type and number of any operational CH_4 destruction devices connected to the equipment and their respective installation date(s) or most recent replacement date(s);

('j') the type and number of vents to the atmosphere, open-ended valves or lines, and pressure relief valves or devices that are connected to the equipment;

('k') the range of internal operating temperatures (°C);

('l') the type and number of boilers or other heaters used to raise or maintain the internal operating temperature of the anaerobic equipment. Identify the fuel type consumed by each heater (e.g., natural gas, propane, biogas, etc.);

('m') any method(s) used to dewater digestate after anaerobic treatment (e.g., none, sedimentation or settling, centrifuge, hydrocyclone, roller drum, belt press/screen, screw press, stationary screen, vibrating screen, rotating screen);

('n') if dewatering of digestate occurs, the approximate percent moisture of the dewatered digestate, where percent moisture = (1-dry mass/mass before drying) x 100%;

('o') the total volume (gallons) of any liquid extracted by dewatering digestate;

('p') the average and maximum amount of time (days or hours) between the exit of digestate from the anaerobic equipment and dewatering the digestate, if applicable;

('q') the approximate percentage by volume of digestate that

undergoes dewatering during the reporting year (e.g., 0 percent, 50 percent, 100 percent);

('r') whether digestate that exits the digester is open to the atmosphere or held and conveyed in a covered container, building, or pipeline prior to dewatering or final placement;

('s') whether any liquid extracted from the digestate is open to the atmosphere or held and conveyed in a covered container, building, or pipeline prior to subsequent treatment or final placement;

('t') any additional treatment steps other than dewatering that are performed on underwatered digestate;

('u') all final placement location types for underwatered digestate (e.g., landfilling, composting, land application) with the approximate percentages by volume going to each type;

('v') all final placement locations of solids from dewatered digestate (e.g., landfilling, composting, land application);

('w') any additional treatment steps that are performed on any liquid extracted from the digestate;

('x') all final placement locations of any liquid extracted from the digestate (e.g., return to the head of the wastewater treatment facility, wash water); and

('y') any coagulants or flocculants (e.g., ferrous sulfate, ferric sulfate, ferric chloride) that are added to waste prior to or after anaerobic treatment.

(ii) Each annual report that includes a liquid or slurry storage must

include all of the following information.

(‘a’) the year constructed;

(‘b’) the location (decimal degrees latitude and longitude);

(‘c’) the operational volume (gallons);

(‘d’) the annual maximum depth (feet) of accumulated liquid or slurry waste in the storage;

(‘e’) whether the storage is covered or uncovered and the cover material type and thickness (cm);

(‘f’) the carryover masses (kg-dry mass) of grit or fixed solids in the storage from the previous year; or an average accumulation rate (kg-dry mass/month) of grit or fixed solids which is defined as the mass (kg-dry mass) of these materials removed from the storage during the most recent clean out divided by the amount of time in months since the previous clean out;

(‘g’) the total volume (gallons) of liquid or slurry waste placed in the storage during the reporting year;

(‘h’) the total volume (gallons) and source (e.g., stormwater, alley wash water) of water added to waste prior to placement in the storage;

(‘i’) dates during the reporting year when waste was not present in the storage (e.g., during clean outs or repairs);

(‘j’) the approximate volume (gallons) of waste retained in the equipment after routine emptying; and

(‘k’) the type and number of any operational CH_4 destruction

devices that are connected to covered storages and their respective installation date(s) or most recent replacement date(s);

(‘l’) the type and number of any vents to the atmosphere, open-ended valves or lines, and pressure relief valves or devices that are connected to any covered storages;

(‘m’) whether the stored waste is heated above ambient temperatures;

(‘n’) any method(s) used to dewater waste once it is removed from the storage (e.g., none, sedimentation or settling, belt press/screen);

(‘o’) if dewatering of waste occurs after storage, the approximate percent moisture of the dewatered waste (percent moisture = (1- dry mass/mass before drying) x 100 percent);

(‘p’) the total volume (gallons) of any liquid extracted by dewatering waste after storage;

(‘q’) the approximate percentage by volume of stored waste that undergoes dewatering during the reporting year (e.g., 0 percent, 50 percent, 100 percent);

(‘r’) whether any liquid extracted by dewatering stored waste is held in containers open to the atmosphere or held and conveyed in buildings, covered containers, or pipelines prior to subsequent treatment or final placement;

(‘s’) all final placement locations of undewatered waste after removal from the storage (e.g., landfilling, composting, land application);

(‘t’) all final placement locations of solids that are dewatered after

storage (e.g., landfilling, composting, land application);

('u') all final placement locations or types of reuse of any liquid extracted by dewatering waste after storage (e.g., alley wash water);

('v') any additional treatment steps that are performed on any liquid extracted by dewatering waste after storage; and

('w') any coagulants or flocculants (e.g., ferrous sulfate, ferric sulfate, ferric chloride) that are added to waste prior to or after storage.

(2) Activity data

(i) The following methods should be used to report the total mass of nitrogen (N) present in waste that has been treated in each anaerobic digester or reactor during the reporting year.

('a') For waste that is dewatered within two days of exiting the anaerobic digester or reactor, measure the Kjeldahl N (mg N/liter) concentrations of the water extracted from the digestate using methods listed in 40 CFR § 136 table 1B (July 1, 2023) (see Table 1, section 200.9 of this Title). Measurements should be made at a frequency that corresponds to the average hydraulic retention time of the anaerobic digester or reactor, or whenever a batch of digestate has finished reacting and is removed and dewatered. Samples should be taken immediately after dewatering occurs. Calculate and report the total annual mass of N (Total $Mass_{N\_Kjeldahl}$) exiting the anaerobic equipment using Equation 2.2-1 as provided in this clause:

Equation 2.2-1: $Total\ Mass_{N\_Kjeldahl} = \sum Volume_{extracted\ water\_i} \times [N_{Kjeldahl\_i}] \times 1/10^6$

Where:

Total $Mass_{N\_Kjeldahl}$ = the total annual mass (kg-N) of Kjeldahl N present in water extracted by dewatering digestate immediately after it is removed from anaerobic equipment;

$Volume_{dewater\_i}$ = the ith volume of water (liters) extracted by dewatering a batch of digestate produced during the reporting year; and

$[N_{Kjeldahl\_i}]$ = the concentration of Kjeldahl N (mg N/liter) in the ith volume of water extracted by dewatering digestate immediately after anaerobic treatment during the reporting year.

$1/10^6$ = kg/mg

('b') For waste that is not dewatered within two days of exiting the anaerobic digester or reactor, measure the Kjeldahl N (mg N/liter) concentrations on the undewatered digestate using methods listed in 40 CFR § 136 table 1B (July 1, 2023) (see Table 200.9 of this Title). Measurements should be made at a frequency that corresponds to the average hydraulic retention time of the anaerobic digester or reactor, or whenever a batch of digestate has finished reacting and is removed from the digester or reactor. Samples should be taken immediately after the waste exits the digester or reactor. Calculate and report the total annual mass of N exiting the anaerobic equipment using Equation 2.2-2 as provided in this clause:

Equation 2.2-2: $\text{Total Mass}_{N\_Kjeldahl} = \sum \text{Volume}_{digestate\_i} \times [N_{Kjeldahl\_i}] \times 1/10^6$

Where:

$\text{Total Mass}_{N\_Kjeldahl}$ = the total annual mass (kg-N) of Kjeldahl N present in undewatered digestate exiting the anaerobic equipment during the reporting year;

$\text{Volume}_{digestate\_i}$ = the ith volume (liters) of undewatered digestate produced during the reporting year;

$[N_{Kjeldahl\_i}]$ = the concentration of Kjeldahl N (mg N/liter) in the ith volume of digestate produced during the reporting year; and

$1/10^6$ = kg/mg

(ii) For each anaerobic digester or reactor and liquid or slurry storage that is used to treat animal manure during the reporting year, report the following.

('a') the total number of animals of each type listed in Table 2-1 of this section, whose manure went into that digester, reactor or storage; and

('b') the average masses (lb) of the animals of each type listed in Table 2-1 of this section whose manure went into that digester, reactor, or storage; and

('c') the average number of days' worth of manure that went into that digester, reactor, or storage; and

('d') the estimated fraction of any volatile solids separated from the manure through dewatering or other physical processes before the manure went into the digester, reactor, or storage. This estimated fraction can either be taken from Table 2-2 of

this section for the appropriate separation method, or shall be specified by the manufacturer of the solids separation equipment; and

(‘e’) any methods used to dewater manure or remove volatile solids before the manure went into the digester, reactor, or storage.

Table 2-1: Animal Types
Dairy Cows
Dairy Heifers
Dairy Calves
Feedlot Steers
Feedlot Heifers
Market Swine <60 lbs
Market Swine 60-119 lbs
Market Swine 120-179 lbs
Market Swine >180 lbs
Breeding Swine
Feedlot Sheep
Goats
Horses
Hens ≥ 1 year
Pullets
Other Chickens
Broilers
Turkeys

Table 2-2: Solids Separation Processes	Estimated fraction of volatile solids removed
Gravity/sedimentation/settling	0.60
Mechanical:	
Stationary Screen	0.20
Vibrating Screen	0.15
Screw Press	0.25

Centrifuge	0.50
Roller Drum	0.25
Belt Press/Screen	0.50

(iii) For each anaerobic digester or reactor and liquid or slurry storage, report the total annual masses (kg-O_2) of the biochemical oxygen demand (BOD5), chemical oxygen demand (COD), or carbonaceous biochemical oxygen demand (CBOD5) entering the anaerobic equipment in domestic, business, and industrial wastewater streams. Measurements of individual wastewater streams should only be combined with other wastewater measurements that use the same type of oxygen demand measurement method. If measurements of different wastewater streams are made using different types of oxygen demand methods (e.g. BOD5 vs COD) they should be summed separately using the equations as provided in this subparagraph:

Equation 2.2-3: $\text{Total Mass}_{BOD5\_year} = \sum \text{Volume}_i \times BOD_{5\_i} \times 1/10^6$; or

Equation 2.2-4: $\text{Total Mass}_{COD\_year} = \sum \text{Volume}_j \times COD_j \times 1/10^6$; or

Equation 2.2-5: $\text{Total Mass}_{CBOD5\_year} = \sum \text{Volume}_k \times CBOD_{5k} \times 1/10^6$;

Where:

$\text{Total Mass}_{BOD5\_year}$, $\text{Total Mass}_{COD\_year}$, $\text{Total Mass}_{BOD5\_year}$ = the total mass (kg-O_2) of oxygen consumed during microbial respiration or chemical oxidation of organic matter present in wastewater streams treated during the reporting year;

$Volume_i$, $Volume_j$ $Volume_k$ = the volume (liters) of the ith, j^{th}, or k^{th} wastewater streams;

BOD_{5_i} = the 5-day biochemical oxygen demand (mg O_2/liter) of the ith wastewater stream measured using an appropriate method listed in 40 CFR § 136 table 1B (July 1, 2023) (see Table 200.9 of this Title);

COD_j = the chemical oxygen demand (mg O_2/liter) of the jth wastewater stream measured using the appropriate method listed in 40 CFR § 136 table 1B (July 1, 2023) (see Table 200.9 of this Title);

$CBOD_{5\_k}$ = the chemical oxygen demand (mg O_2/liter) of the kth wastewater stream measured using an appropriate method listed in 40 CFR § 136 table 1B (July 1, 2023) (see Table 200.9 of this Title); and

$1/10^6$ = kg/mg.

(iv) For each anaerobic digester or reactor and liquid or slurry waste storage, report the total masses (kg-dry mass or kg-wet mass) and sources of all other degradable organic carbon that is treated or stored during the reporting year and is not reported as animal manure in subparagraph (c)(2)(ii) of this paragraph or as sources of oxygen demand in subparagraph (c)(2)(iii) of this paragraph. This may include but is not limited to food scraps without packaging, food waste with packaging, bedding for animals, stover and other plant biomass, waste generated during ethanol production, yard trimmings, solids from treatment of wastewater from domestic, commercial or industrial sources, waste from industrial food and beverage processing, pulp and paper manufacturing waste, and

petroleum refining waste. Waste may be reported as either wet mass (kg-wet mass) or dry mass (kg-dry mass), but wet mass measurements should not be combined with dry mass measurements.

(3) Quantified biogas methane destruction, emission, export, and fossil fuel combustion.

(i) For each anaerobic digester or reactor and covered liquid or slurry storage, it is optional to report the quantified total mass of CH_4 (kg) in generated biogas that is destroyed each year through combustion by flares, thermal oxidizers, boilers, turbines, internal combustion engines, or any other methane destroying units. This requires either continuously monitoring both the CH_4 fraction in the biogas (volume of CH_4 per volume of biogas) and the biogas flow rate, temperature and pressure to each methane destruction device that is connected to the digester, reactor, or covered storage according to clause (c)(3)(i)(‘a’) or (‘b’) of this subparagraph or continuously monitoring the biogas flow rate and making weekly point measurements of the temperature, pressure, and CH_4 fraction of the biogas on route to each methane destruction device according to clause (c)(3)(i)(‘c’) of this subparagraph.

(‘a’) If a monitoring system fully integrates the flow rate, CH_4 fraction, temperature, and pressure of the biogas into a mass of CH_4 that is destroyed over a period of time, sum these masses over the reporting year and report the annual total mass in kg-CH4. Report the CH_4 destruction efficiency (mass of CH_4 destroyed/total mass of CH_4) of each methane destruction device connected to the digester, reactor, or covered storage. Report the destruction efficiency indicated by the device manufacturer if measurements are

not available.

(‘b’) If an integrated monitoring system reports a volume of CH_4 (e.g., liters, cf, m^3) that is destroyed over a period of time, then these volumes may be summed over the reporting year and reported as a total volume of CH_4 along with the system manufacturer’s indicated standard pressure and temperature to which the volume measurements are normalized. Report the CH_4 destruction efficiency (mass of CH_4 destroyed/total mass of CH_4) of each methane destruction device connected to the digester, reactor, or covered storage. Report the destruction efficiency indicated by the device manufacturer if measurements are not available.

(‘c’) If the CH_4 fraction, pressure, and temperature of the biogas are not continuously monitored by an integrated system, and the biogas flow rate to a methane destruction device is continuously monitored, then integrate and report the volume of biogas (e.g., liters, cf, m^3) that is produced each calendar week during the reporting year. Measure and report the temperature, pressure, and CH_4 fraction of the biogas at a location representative of conditions at the flow meter at least once during each calendar week that biogas is generated. If temperature, pressure, and CH_4 fraction measurements are made only once per week, there should be at least three days between consecutive measurements. Indicate whether the biogas flow rate, pressure, temperature, and CH_4 fraction are measured before or after water vapor is stripped out of the biogas. Report the CH_4 destruction efficiency (mass of CH_4 destroyed/total mass of CH_4) of each methane destruction device connected to the digester, reactor, or covered storage. Report the destruction efficiency indicated by the device manufacturer if measurements are not available.

(ii) For each anaerobic digester or reactor and covered liquid or slurry storage, report the number of days during the reporting year that an installed CH_4 destruction device was not operational while waste was present in the digester, reactor, or storage.

(iii) For each anaerobic digester or reactor and covered liquid or slurry storage, it is optional to report the quantified total mass of CH_4 (kg) that is generated in biogas and emitted to the atmosphere through open-ended valves or lines, including unlit flares, using one of the quantification methods indicated in clauses (c)(3)(i)('a'), ('b'), or ('c') of this section.

(iv) For each anaerobic digester or reactor and liquid or slurry storage, report the quantity of natural gas or other fossil fuels that are burned in order to heat or otherwise maintain operation of the digester, reactor, or storage according to section 2.7 of this Part.

(v) For each anaerobic digester or reactor and liquid or slurry storage, report the total volume of biogas (e.g., liters, cf, m^3) or total mass of CH_4 (kg-CH_4) in biogas that is exported from the operation site during the reporting year.

(4) Domestic wastewater treatment operational information. In addition to reporting required under subdivision (c) of this section, for each anaerobic digester that operates at a facility that treats municipal wastewater, report the population currently served by the facility and identify any specific nitrogen removal steps that operate at that facility.

(5) Contact information. Provide the name, title, address, email address, and phone number of a contact person capable of responding to questions about digester, reactor, or storage operations.

(e) Monitoring, Data, and Records. Operators subject to reporting requirements of this section must retain the following records for five years substantiating the volumes and masses of waste that they report.

(1) Invoices, electronic records of transfer, bills of lading, or any other records that can be used to determine or verify imported waste quantities and types.

(2) An electronic record of entities from which waste was received and to which any biogas or products of waste treatment were supplied during the reporting year.

253-2.3 Cement Production.

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart H of 40 CFR part 98 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) in reporting annual stationary combustion and process emissions and other data from cement production to the department, except as otherwise provided in this section.

(a) CO_2, CH_4, and N_2O from Fuel Combustion. Operators must calculate and report fuel high heat value (in units of MMBtu/kg, MMBtu/scf, or MMBtu/gallon for solid, gaseous, or liquid fuels respectively). When calculating GHG emissions from fuel combustion, the operator must use a method in 40 CFR § 98.33(a)(1) to § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part.

(b) Monitoring, Data, and Records. For each emissions calculation method chosen under subdivision (a) of this section, the operator must meet the applicable requirements for

monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR § 98.34 to § 98.37 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), except as modified in subdivisions (c) and(d) of this section and sections 2.7 and 3.1 of this Part.

(c) Missing Data Substitution Procedures. The operator must comply with 40 CFR § 98.85 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) when substituting for missing data, except as otherwise provided in paragraphs (1) through (4) of this subdivision.

(1) To substitute for missing data for emissions reported under section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems), the operator must follow the requirements of section 3.1 of this Part.

(2) If data for the carbonate content of clinker or cement kiln dust as required by 40 CFR § 98.83(d) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) are missing, and a new analysis cannot be undertaken, the operator must apply a substitute value according to the procedures in subparagraphs (i) through (iii) of this paragraph.

(i) If the data capture rate is at least 90 percent for the emission year, the operator must substitute for each missing value using the best available estimate of the parameter, based on all available process data.

(ii) If the data capture rate is at least 80 percent but not at least 90 percent for the emission year, the operator must substitute for each missing value with the highest quality assured value recorded for the parameter during the given emission year, as well as the two previous emission years.

(iii) If the data capture rate is less than 80 percent for the emission year, the operator must substitute for each missing value with the highest quality assured value recorded for the parameter in all records kept according to section 1.7(a) of this Part.

(3) For each missing value of the monthly raw material consumption or monthly clinker production used to calculate emissions, the operator must apply a substitute value according to subparagraphs (i) and (ii) of this paragraph.

(i) If the data capture rate is at least 80 percent for the emission year, the operator must substitute for each missing value according to 40 CFR § 98.85(c) or 40 CFR § 98.85(d) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), as applicable.

(ii) If the data capture rate is less than 80 percent for the emission year, the operator must substitute for each missing value with the maximum short tons of clinker per day capacity of the system or the maximum short tons per day raw material throughput of the kiln, as applicable, and the number of days per month.

(4) The operator must document and retain records of the procedure used for all missing data estimates pursuant to the recordkeeping requirements of section 1.7 of this Part.

(d) Additional Product Data. In addition to the information required by 40 CFR § 98.86 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must report the parameters provided in paragraphs (1) through (4) of this subdivision, whether or not a CEMS is used to measure CO_2 emissions.

(1) Annual quantity clinker produced (short tons).

(2) Annual quantity clinker consumed (short tons).

(3) Annual quantity of limestone and gypsum (including both natural and synthetic gypsum) consumed for blending (short tons).

(4) Annual quantity of cement substitute consumed, by type (short tons). This parameter is not subject to review for material misstatement under the requirements of section 4.2(b)(11) of this Part.

(5) Facilities using a CEMS to report emissions from a combined flue stack are required to use the Tier 4 calculation method to report both combustion and total stack emissions under section 2.7 of this Part, pursuant to the provisions of section 2.7(g) of this Part. These facilities are also required to report process emissions under this section. To report process emissions, the operator must subtract the fuel combustion emissions value from the facility's total reported combined stack emissions value in order to calculate the facility's process emissions value, in metric tons, to be reported under this section. The operator must use Equation 2.3-1 as provided in this paragraph to calculate process emissions:

Equation 2.3-1: Eprocess = Etotal – Ecombustion

Where:

Eprocess = The annual process emissions from a facility's combined flue stack using a CEMS (metric tons)

Etotal = The total annual emissions from a facility's combined flue stack

using a CEMS (metric tons)

Ecombustion = The annual combustion emissions from a facility's combined flue stack using a CEMS (metric tons)

253-2.4 Electric Power Entities

An electric power entity that is required to report under section 1.2 of this Part must comply with the following requirements.

(a) General Requirements and Content for GHG Emissions Data Reports for Electricity Importers and Exporters.

(1) Greenhouse Gas Emissions. An electric power entity must report GHG emissions separately for each category of delivered electricity required, in metric tons of CO_2 equivalent (MT of CO_2e), according to the calculation methods in subdivision (b) of this section.

(2) Delivered Electricity. An electric power entity must report imported, exported, and wheeled electricity in MWh disaggregated by first point of receipt (POR) or final point of delivery, as applicable, and must also separately report imported and exported electricity from unspecified sources and from each specified source. Substitute electricity defined pursuant to this Part must be separately reported for each specified source, as applicable. First points of receipt and final points of delivery (POD) must be reported using the standardized code used in NERC e-Tags, as well as the full name of the POR/POD.

(3) Imported Electricity from Unspecified Sources. When reporting imported electricity from unspecified sources, an electric power entity must report for each first point of

receipt the following information:

(i) the amount of electricity from unspecified sources as measured at the first point of delivery in New York; and

(ii) GHG emissions, including those associated with transmission losses, as required in subdivision (b) of this section.

(4) Imported Electricity from Specified Facilities or Units. An electric power entity must report all direct delivery of electricity as from a specified source for facilities or units in which they are a generation providing entity (GPE) or have a written power contract to procure electricity. A GPE must report imported electricity as from a specified source when the importer is a GPE of that facility. When reporting imported electricity from specified facilities or units, the electric power entity must disaggregate electricity deliveries and associated GHG emissions by facility or unit and by first point of receipt, as applicable. The electric power entity must also report total GHG emissions and MWh from specified sources. Seller Warranty: The sale or resale of specified source electricity is permitted among entities on the e-tag market path insofar as each sale or resale is for specified source electricity in which sellers have purchased and sold specified source electricity, such that each seller warrants the sale of specified source electricity from the source through the market path.

(i) Claims of specified sources of imported electricity, defined pursuant to this Part, are calculated pursuant to subdivision (b) of this section, must meet the requirements in subdivision (e) of this section, and must include the following information:

(‘a’) Measured at Busbar. The amount of imported electricity from specified facilities or units as measured at the busbar; and

('b') Not Measured at Busbar. If the amount of imported electricity deliveries from specified facilities or units as measured at the busbar is not provided, report the amount of imported electricity as measured at the first point of delivery in New York, including estimated transmission losses as required in subdivision (b) of this section, and the reason why measurement at the busbar is not known.

(5) Imported Electricity Supplied by Asset-Controlling Suppliers. The reporting entity must separately report imported electricity supplied by asset-controlling suppliers recognized by the department. The reporting entity must:

(i) report the asset-controlling supplier standardized purchasing-selling entity (PSE) acronym or code, full name, and the department identification number;

(ii) report asset-controlling supplier power that was not acquired as specified power, as unspecified power;

(iii) report delivered electricity from asset-controlling suppliers as measured at the first point of delivery in New York; and,

(iv) report GHG emissions calculated pursuant to subdivision (b) of this section, including transmission losses.

(v) tagging ACS Power. To claim power from an asset-controlling supplier, the asset-controlling supplier must be identified on the physical path of the NERC e-Tag as the PSE at the first point of receipt, or in the case of asset controlling suppliers that are exclusive marketers, as the PSE immediately following the associated generation owner.

(6) Exported Electricity. The electric power entity must report exported electricity in MWh and associated GHG emissions in MT of CO_2e for unspecified sources

disaggregated by each final point of delivery outside New York, and for each specified source disaggregated by each final point of delivery outside New York, as well as the following information:

(i) Exported electricity as measured at the last point of delivery located in New York, if known. If unknown, report as measured at the final point of delivery outside New York.

(ii) Do not report estimated transmission losses.

(iii) Report GHG emissions calculated pursuant to subdivision (b) of this section.

(7) Exchange Agreements. The electric power entity must report delivered electricity under power exchange agreements consistent with imported and exported electricity requirements of this section. Electricity delivered into New York under exchange agreements must be reported as imported electricity, and electricity delivered out of New York under exchange agreements must be reported as exported electricity.

(8) Electricity Wheeled Through New York. The electric power entity that is the PSE on the last physical path segment that crosses the border of New York on the NERC e-tag must separately report electricity wheeled through New York, aggregated by first point of receipt, and must exclude wheeled power transactions from reported imports and exports. When reporting electricity wheeled through New York, the electric power entity must include the quantities of electricity wheeled through New York as measured at the first point of delivery inside New York. Only an electric power entity, as defined pursuant to this Part, must report wheeled electricity through New York.

(9) Record Keeping. The electric power entity must retain NERC e-Tags, written power contracts, settlements data, and all other information required to confirm reported electricity procurements and deliveries pursuant to the recordkeeping requirements of section 1.7 of this Part.

(10) Electricity Generating Units and Cogeneration Units in New York. Electric power entities that also operate electricity generating units or cogeneration units located inside New York that meet the applicability requirements of this Part must report GHG emissions to the department under section 2.5 of this Part.

(11) Electricity Generating Units and Cogeneration Units Outside New York. Operators and owners of electricity generating units and cogeneration units located outside New York that elect to report to the department under section 2.5 of this Part must fully comply with the reporting requirements of this Part.

(b) Calculating GHG Emissions.

(1) Calculating GHG Emissions from Unspecified Sources. For electricity from unspecified sources, the electric power entity must calculate the annual CO_2 equivalent mass emissions using Equation 2.4-1 as provided in this paragraph:

Equation 2.4-1: $CO_2e = MWh \times TL\ EF_{unsp}$

Where:

CO_2e = Annual CO_2 equivalent mass emissions from the unspecified electricity deliveries at each point of receipt identified (MT of CO_2e).

MWh = Megawatt-hours of unspecified electricity deliveries at each point of receipt identified.

EFunsp = Default emission factor for unspecified electricity imports.

EFunsp = 0.772 MT of CO_2e/MWh

TL = Transmission loss correction factor.

TL = 1.02 to account for transmission losses between the bus bar and measurement at the first point of receipt in New York.

(2) Calculating GHG Emissions from Specified Facilities or Units. For electricity from specified facilities or units, the electric power entity must calculate emissions using Equation 2.4-2 as provided in this paragraph:

Equation 2.4-2: $CO_2e = MWh \times TL \times EF_{sp}$

Where:

CO_2e = Annual CO_2 equivalent mass emissions from the specified electricity deliveries from each facility or unit claimed (MT of CO_2e).

MWh = Megawatt-hours of specified electricity deliveries from each facility or unit claimed.

EFsp = Facility-specific or unit-specific emission factor and calculated using total emissions and transactions data as described below or published on the department's website. The emission factor is based on data from the year prior to the

reporting year.

TL = Transmission loss correction factor.

TL = 1.02 to account for transmission losses associated with generation outside of NYISO.

TL = 1.0 if the reporting entity provides documentation that demonstrates to the satisfaction of the department that transmission losses (1) have been accounted for, (2) are supported by NYISO, or (3) are compensated by using electricity sourced from within New York.

The department shall calculate facility-specific or unit-specific emission factors and publish them on the department's website using Equation 2.4-3 as provided in this paragraph:

Equation 2.4-3: $EF_{sp} = E_{sp} / EG$

Where:

Esp = CO_2e emissions for a specified facility or unit for the report year (MT of CO_2e).

EG = Net generation from a specified facility or unit for the report year shall be based on data reported to the Energy Information Administration (EIA).

To register a specified unit(s) source of power pursuant to paragraph (e)(1) of this section, the emission source must provide to the department unit-level GHG

emissions consistent with the data source requirements of this section and net generation data as reported to the EIA, along with contracts for delivery of power from the specified unit(s) to the reporting entity, and proof of direct delivery of the power by the reporting entity as an import to New York.

(i) For specified facilities or units whose operators are subject to this Part or whose owners or operators voluntarily report under this Part, Esp shall be equal to the sum of CO_2e emissions reported pursuant to section 2.5 of this Part.

(ii) For specified facilities or units whose operators are not subject to reporting under this Part or whose owners or operators do not voluntarily report under this Part, but are subject to the U.S. EPA GHG Mandatory Reporting Regulation 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), Esp shall be based on GHG emissions reported to U.S. EPA pursuant to 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title). For GHG emissions reported to U.S. EPA pursuant to 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), if it is not possible to isolate the emissions that are directly related to electricity production, the department may calculate Esp based on EIA data consistent with Form EIA-923 (2024) (see Table 1, section 200.9 of this Title). Emissions from combustion of biomass-derived fuels will be based on EIA data consistent with Form EIA-923 (2024) (see Table 1, section 200.9 of this Title) until such time the emissions are reported to U.S. EPA.

(iii) For specified facilities or units whose operators are not subject to reporting under this Part or whose owners or operators do not voluntarily report under this

Part, nor are subject to the U.S. EPA GHG Mandatory Reporting Regulation 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), Esp is calculated using heat of combustion data reported to the EIA using Equation 2.4-4 as provided in this subparagraph.

Equation 2.4-4: $Esp = 0.001 \times \Sigma(Q \times EF)$

Where:

0.001 = conversion factor kg to MT

Q = Heat of combustion for each specified fuel type from the specified facility or unit for the report year (MMBtu). For cogeneration, Q is the quantity of fuel allocated to electricity generation consistent with Form EIA-923 reporting (2024) (see Table 1, section 200.9 of this Title). For geothermal electricity, Q is the steam data reported to EIA consistent with Form EIA-923 (2024) (see Table 1, section 200.9 of this Title) (MMBtu).

EF = CO_2e emission factor for the specified fuel type as required by this Part (kg CO_2e /MMBtu). For geothermal electricity, EF shall be reported based on the fuel utilized at the facility and fuel consumed based on the information reported consistent with Form EIA-860 (2017) and EIA-923 (2024) (see Table 1, section 200.9 of this Title).

(iv) Facilities or units will be assigned an emission factor by the department based on the type of fuel combusted or the technology used when a U.S. EPA GHG Report or EIA fuel consumption report not available, including new facilities and

facilities located outside the U.S.

(v) Meter Data Requirement. Electric power entities shall retain meter generation data to document that the power claimed by the reporting entity was generated by the facility or unit at the time the power was directly delivered.

('a') A lesser of analysis is applicable to imports from specified sources for which the department has calculated an emission factor of zero, and for imports from a covered renewable energy system as defined in section 66-R of the Public Service Law excluding the following: (1) dynamically tagged power deliveries; (2) nuclear power; (3) asset controlling supplier power; and (4) imports from hydroelectric facilities for which a reporting entity's share of metered output on an hourly basis is not established by power contract. A lesser of analysis is required pursuant to Equation 2.4-5 as provided in this clause:

Equation 2.4-5: Sum of Lesser of MWh = ΣHM_{sp} min(MG_{sp}*S_{sp}, TG_{sp})

Where:

ΣHM_{sp} = Sum of the Hourly Minimum of MG_{sp} and TG_{sp} (MWh).

MG_{sp} = metered facility or unit net generation (MWh).

S_{sp} = reporting entity's share of metered output, if applicable.

TG_{sp} = tagged or transmitted energy at the transmission or sub-transmission level imported to New York (MWh).

(‘b’) An EPE may conduct the lesser of analysis voluntarily for those resources excluded in clause (‘a’) of this subparagraph.

(3) Calculating GHG Emissions of Imported Electricity Supplied by Asset-Controlling Suppliers. Based on annual reports submitted to the department pursuant to subdivision (d) of this section, the department will calculate and publish on the department’s website the system emission factor for all asset-controlling suppliers recognized by the department. The reporting entity must calculate emissions for electricity supplied using Equation 2.4-6 as provided in this paragraph:

Equation 2.4-6: $CO_2e = MWh \times TL \times EF_{ACS}$

Where:

CO_2e = Annual CO_2 equivalent mass emissions from the specified electricity deliveries from department-recognized asset-controlling suppliers (MT of CO_2e).

MWh = Megawatt-hours of specified electricity deliveries.

EFACS = Asset-Controlling Supplier system emission factor published on the department’s website (MT CO_2e/MWh). The department will assign the system emission factors for all asset-controlling suppliers based on a previous GHG report submitted to the department pursuant to subdivision (d) of this section. The supplier-specific system emission factor is calculated annually by the department. The calculation is derived from data contained in annual reports submitted pursuant to subdivision (d) of this section. The emission factor is based on data from two years prior to the reporting year.

TL = Transmission loss correction factor.

TL = 1.02 when deliveries are not reported as measured at a first point of receipt located within the balancing authority area of the asset-controlling supplier.

TL = 1.0 when deliveries are reported as measured at a first point of receipt located within the balancing authority area of the asset- controlling supplier.

The department shall calculate the system emission factor for asset-controlling suppliers using Equation 2.4-7 as provided in this paragraph:

Equation 2.4-7: EF_{ACS} = Sum of System Emissions MT of CO_2e / Sum of System MWh Sum of System Emissions, MT of CO_2e = $\Sigma Easp + \Sigma(PEsp * EFsp) + \Sigma(PEunsp * EFunsp) - \Sigma(SEsp * EFsp)$ Sum of System MWh = $\Sigma EGasp + \Sigma PEsp + \Sigma PEunsp - \Sigma SEsp$

Where:

$\Sigma Easp$ = Emissions from Owned Facilities. Sum of CO_2e emissions from each specified facility/unit in the asset-controlling supplier's fleet, consistent with paragraph (2) of this subdivision (MT of CO_2e).

$\Sigma EGasp$ = Net Generation from Owned Facilities. Sum of net generation for each specified facility/unit in the asset-controlling supplier's fleet for the emission year as reported to the department under this Part (MWh).

PEsp = Electricity Purchased from Specified Sources. Amount of electricity purchased wholesale and taken from specified sources by the asset-controlling supplier for the emission year as reported to the department under this Part (MWh).

PEunsp = Electricity Purchased from Unspecified Sources. Amount of electricity purchased wholesale from unspecified sources by the asset-controlling supplier for the emission year as reported to the department under this Part (MWh).

SEsp = Electricity Sold from Specified Sources. Amount of wholesale electricity sold from specified sources by the asset-controlling supplier for the emission year as reported to the department under this Part (MWh).

EFsp = CO_2e emission factor as defined for each specified facility or unit calculated consistent with paragraph (b)(2) of this section (MT CO_2e/MWh).

EFunsp = Default emission factor for unspecified sources calculated consistent with paragraph (b)(1) of this section (MT CO_2e/MWh).

(c) Additional Requirements for Retail Providers. Retail providers must include the following information in the GHG emissions data report for each report year, in addition to the information identified in subdivisions (a), (b) and (g) of this section.

(1) Retail providers must report New York retail sales.

(2) Retail providers may elect to report the subset of retail sales attributed to the electrification of shipping ports, truck stops, and motor vehicles if metering is available to separately track these sales from other retail sales.

(3) For facilities or units located outside of New York that are fully or partially

owned by a retail provider that have GHG emissions greater than the default emission factor for unspecified imported electricity based on the most recent GHG emissions data report submitted to the department or U.S. EPA, the retail provider must include:

(i) information required in paragraph (e)(1) of this section in emission years with no reported imported electricity from the facility or unit;

(ii) the quantity of electricity from the facility or unit sold by the retail provider or on behalf of the retail provider having a final point of delivery outside New York, as measured at the busbar.

(iii) high GHG-Emitting Facilities or Units. For facilities or units that are operated by a retail provider or fully or partially owned by a retail provider and that have emissions greater than the default emission factor for unspecified electricity based on the most recent GHG emissions data report submitted to the department or to U.S.EPA, the retail provider must report the following information:

('a') when the product of net generation (MWh) and ownership share is greater than imported electricity (MWh), emissions associated with electricity not imported into New York must be reported using Equation 2.4-8 as provided in this clause:

Equation 2.4-8: CO_2e not imported = (EGsp*OS – Isp)*EFsp.

Where:

EGsp = facility or unit net generation, MWh.

OS = fraction ownership share.

Isp = imported electricity, MWh.

EFsp. = facility or unit-specific emission factor, MT of CO_2e/MWh.

('b') list the replacement generation sources, locations, and whether they are new units when Isp< 90 percent of EGsp*OS and when a facility specified in the previous report year has no imported electricity in the current report year.

(iv) retail providers that report as electricity importers or exporters also must separately report electricity imported from specified and unspecified sources by other electric power entities to serve their load, designating the electricity importer. In addition, all imported electricity transactions documented by NERC e-Tags where the retail provider is the PSE at the sink must be reported.

(d) Additional Requirements for Asset-Controlling Suppliers. Owners or operators of electricity generating facilities or exclusive marketers for certain generating facilities may apply for an asset-controlling supplier designation from the department. Approved asset-controlling suppliers may request that the department calculate a supplier-specific emission factor pursuant to paragraph (b)(3) of this section. To apply for asset-controlling supplier designation, the applicant must:

(1) meet the requirements in this Part, including reporting pursuant to section 2.4 of this Part as applicable for each generating facility or unit in the supplier's fleet;

(2) include in its emissions data report wholesale power purchased and taken (MWh) from specified and unspecified sources and wholesale power sold from specified sources according to the specifications in this section, and as required for the department to

calculate a supplier-specific emission factor;

(3) retain documentation that the power sold by the supplier originated from the supplier's fleet of facilities and either that the fleet is under the supplier's operational control or that the supplier serves as the fleet's exclusive marketer;

(4) provide the supplier-specific department identification number to electric power entities who purchase electricity from the supplier's system.

(5) to apply for and maintain asset-controlling supplier status, the applicant shall submit as part of its emissions data report the following information, annually:

(i) general business information, including applicant's name and contact information;

(ii) list of officer names and titles;

(iii) data requirements under paragraph (b)(3) of this section;

(iv) data requirements under paragraph (e)(1) of this section;

(v) a list and description of electricity generating facilities for which the reporting entity is a generation providing entity pursuant to section 1.3(a) of this Part; and,

(vi) an attestation, in writing and signed by an authorized officer of the applicant, as follows:

"I certify under the laws of New York that I am duly authorized by [name of applicant] to sign this attestation on behalf of [name of applicant], that [name of applicant] meets the definition of an asset-controlling supplier as specified in section 1.3(b) of Part 253 of Title 6 of the New York Codes, Rules and Regulations, and that the information submitted herein is true, accurate, and complete."

(6) Asset-controlling suppliers must annually adhere to all reporting requirements of this Part or be removed from asset-controlling supplier designation.

(e) Requirements for Claims of Specified Sources of Electricity. Each reporting entity claiming specified facilities or units for imported or exported electricity must register its anticipated specified sources with the department pursuant to paragraph (1) of this subdivision by February 1 following each emission year to obtain associated emission factors calculated by the department for use in the emissions data report required to be submitted by June 1 of the same year. If an operator fails to register a specified source by the June 1 reporting deadline specified in section 1.4(d) of this Part, the operator must use the emission factor provided by the department for a specified facility or unit in the emissions data report required to be submitted by June 1 of the same year. Each reporting entity claiming specified facilities or units for imported or exported electricity must also meet requirements pursuant to paragraphs (2) through (5) of this subdivision in the emissions data report.

(1) Registration Information for Specified Sources. The following information is required:

(i) The facility names and, for specification to the unit level, the facility and unit names.

(ii) For sources with a previously assigned department identification number, the department facility or unit identification number or supplier number. For newly specified sources, the department will assign a unique identification number.

(iii) If applicable, the facility and unit identification numbers as used for reporting to the U.S. EPA Acid Rain Program, U.S. EPA pursuant to 40 CFR part 98

(Amended November 18, 2024) (see Table 1, section 200.9 of this Title), U.S. Energy Information Administration, Federal Energy Regulatory Commission's PURPA Qualifying Facility program, New York Public Service Commission, and NYISO, as applicable.

(iv) The physical address of each facility, including jurisdiction.

(v) Provide names of facility owner and operator.

(vi) The percent ownership share and whether the facility or unit is under the electricity importer's operational control.

(vii) Total facility or unit gross and net nameplate capacity when the electricity importer is a GPE.

(viii) Total facility or unit gross and net generation when the electricity importer is a GPE.

(ix) Start date of commercial operation and, when applicable, date of repowering.

(x) GPEs claiming additional capacity at an existing facility must include the implementation date, the expected increase in net generation (MWh), and a description of the actions taken to increase capacity.

(xi) Designate whether the facility or unit is a newly specified source, a continuing specified source, or was a specified source in the previous report year that will not be specified in the current report year.

(xii) Provide the primary technology or fuel type as listed below:

('a') variable renewable resources by type, defined for purposes of this Part as solar, wind, and run-of-river hydroelectricity;

(‘b’) hybrid facilities such as solar thermal;

(‘c’) hydroelectric facilities ≤ 30 MW, not run-of-river;

(‘d’) hydroelectric facilities > 30 MW;

(‘e’) geothermal binary cycle plant or closed loop system;

(‘f’) geothermal steam plant or open loop system;

(‘g’) units combusting biomass-derived fuel, by primary fuel type;

(‘h’) nuclear facilities;

(‘i’) cogeneration by primary fuel type;

(‘j’) fossil sources by primary fuel type;

(‘k’) co-fired fuels;

(‘l’) municipal solid waste combustion;

(‘m’) other.

(2) Emission Factors. The emission factor published on the department’s website, calculated by the department according to the methods in subdivision (b) of this section, must be used when reporting GHG emissions for a specified source of electricity.

(3) Delivery Tracking Conditions Required for Specified Electricity Imports. Electricity importers must claim a specified source when the electricity delivery meets any of the criteria for direct delivery of electricity defined pursuant to this Part, and one of the following sets of conditions:

(i) the electricity importer is a GPE; or

(ii) the electricity importer has a written power contract for electricity

generated by the facility or unit, subject to meeting all other specified source requirements.

(4) Additional Information for Specified Sources. For each claim to a specified source of electricity, the electricity importer must indicate whether one or more of the following descriptions applies:

(i) deliveries from specified sources previously reported as consumed in New York. Specified source of electricity has been reported in a 2026 emissions data report and is claimed for the current emission year by the same electricity importer, based on a written power contract or status as a GPE in effect prior to January 1, 2026 that remains in effect, or that has been renegotiated for the same facility or generating unit for up to the same share or quantity of net generation within 12 months following prior expiration; or a specified facility for which imported electricity was reported as greater than 80 percent of net generation in the 2026 emission year;

(ii) deliveries from existing federally owned hydroelectricity facilities by exclusive marketers. Electricity from specified federally owned hydroelectricity facility delivered by exclusive marketers;

(iii) deliveries from existing federally owned hydroelectricity facilities allocated by contract. Specified federally owned hydroelectricity source delivered by electricity importers with a written power contract in effect within 12 months after changes in rights due to Federal power allocation or redistribution policies, including acts of Congress, and not related to price bidding, that remains in effect or has been renegotiated for the same facility for up to the same share or quantity of net generation within 12 months following prior contract expiration;

(iv) deliveries from new facilities. Specified source of electricity is first registered pursuant to paragraph (1) of this subdivision and delivered by an electricity importer within 12 months of the start date of commercial operation and the electricity importer making a claim in the current emission year is either a GPE or purchaser of electricity under a written power contract;

(v) deliveries from existing facilities with additional capacity. Specified source of electricity is first registered pursuant to paragraph (e)(1) of this subdivision and delivered by a GPE within 12 months of the start date of an increase in the facility's generating capacity due to increased efficiencies or other capacity increasing actions.

(5) Substitute electricity. Report substitute electricity received from specified and unspecified sources pursuant to the requirements of this section.

253-2.5 Electricity Generation and Cogeneration Units

The operator of a facility who is required to report under section 1.2 of this Part must report as specified below and comply with subpart C of 40 CFR part 98 (Amended May 14, 2024) and subpart D of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), as applicable, in reporting emissions and other data from electricity generating and cogeneration units to the department, except as otherwise provided in this section. Notwithstanding the above, the operator of a facility with total facility nameplate generating capacity of less than 1 MW may elect to follow section 2.7 of this Part in reporting electricity generating units as general combustion sources, in lieu of the requirements of section 2.5 of this Part. If engineering estimation is used to report disposition of generated

energy or energy flow data that are not used directly to determine emissions, facility operators must demonstrate accuracy of the chosen engineering estimation method.

(a) Information About the Electricity Generating Facility. Notwithstanding any limitations in 40 CFR part 75 (July 1, 2023) or part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator of an electricity generating facility is required to include in the emissions data report the information listed in this subdivision, unless otherwise specified in subdivisions (e) and (g) of this section for geothermal facilities and facilities with renewable energy generation. Reporting of information specified in paragraphs (4) through (6) of this subdivision is optional for facilities that do not provide or sell any generated energy outside of the facility boundary.

(1) If applicable, facility identification numbers assigned by the New York Public Service Commission, U.S. Energy Information Administration, Federal Energy Regulatory Commission’s PURPA Qualifying Facility program, and New York Independent System Operator.

(2) Total facility nameplate generating capacity in megawatts (MW).

(3) Indicate whether the facility is a stand-alone electricity generating facility, an independently operated cogeneration/bigeneration facility co-located with the thermal host, an independently operated and sited cogeneration/bigeneration facility, or an industrial, institutional, commercial facility with electricity generation capacity, as applicable. Also indicate whether the facility is a facility that does not provide any generated energy outside of the facility boundary, as applicable.

(4) The disposition of generated electricity in MWh, reported at the facility-level,

including for each of the following disposition categories, if applicable:

(i) Generated Electricity for Grid. Generated electricity provided or sold to a retail provider or electricity marketer who distributes the electricity over the electric power grid for wholesale or retail customers of the grid. The operator must report the name of the retail provider or electricity marketer.

(ii) Generated Electricity for Other Users. Generated electricity provided or sold directly to particular end-users. A reportable end-user includes any person, under the same or different operational control, that is not a part of the facility. Report each end-user's facility name, NAICS code, and department ID if applicable.

('a') In addition to reporting the overall amount of electricity provided or sold directly to end users, separately quantify and report the subset of generated electricity used to produce cooling energy (e.g., chilled water) to end-users outside of the facility boundary.

(iii) Generated Electricity for On-Site Industrial Applications Not Related to Electricity Generation. If the facility includes industrial processes or operations that are neither in support of nor a part of the power generation system, report the total amount of generated electricity used by those on-site industrial processes or operations.

(iv) In addition to reporting the overall amount of electricity used for on-site industrial applications not related to electricity generation, also separately quantify and report the subset of generated electricity that is used to produce cooling energy used on-site that is neither in support of nor a part of the power generation system.

(v) If the facility includes equipment that uses generated electricity to

produce cooling (e.g., absorption chiller) for the sole purpose of maintaining temperature in the electricity generation or cogeneration system, account for such electricity as a part of the difference between gross generation and net generation (parasitic load) pursuant to paragraph (b)(2) of this section.

(vi) If a facility includes more than one electricity generating unit or cogeneration system, and each unit/system or each group of units generate electricity for different particular end-users or retail providers or electricity marketers, the operator must separately report the disposition of generated electricity by unit/system or by group of units. For the purpose of separate reporting of disposition, the operator may group similar units together if the generated electricity from the group of units is provided to the same destination.

(5) The operator of a cogeneration or bigeneration unit must report the disposition of the thermal energy (MMBtu) generated by the cogeneration unit or bigeneration unit ("generated thermal energy"), reported at the facility-level, including for each of the following disposition categories, if applicable:

(i) Generated Thermal Energy for Other Users. Thermal energy provided or sold to particular end-users (as defined in section 1.3 of this Part). A reportable end-user includes any person, under the same or different operational control, that is not a part of the facility. Report each end-user's facility name, NAICS code, department ID if applicable, and the types of thermal energy product provided. Exclude from this quantity the amount of thermal energy that is vented, radiated, wasted, or discharged before the energy is provided to the end-user.

(‘a’) In addition to reporting the overall amount of generated thermal energy for other users, separately quantify and report the subset of generated thermal energy that is used to produce cooling energy (e.g., chilled water) or distilled water for a particular end-user outside of the facility boundary.

(ii) Parasitic Steam Use. Thermal energy used for supporting power production that has been included in the quantity reported under paragraph (b)(3) of this section but that is not accounted for in the quantities reported under subparagraphs (i) and (iii) of this paragraph. This thermal energy quantity must not include steam directly used for power production, such as the steam used to drive a steam turbine generator to generate electricity. Activities for supporting power generation may include steam used for power augmentation, NOx control, sent to a de-aerator, or sent to a cooling tower.

(iii) Generated Thermal Energy for On-Site Industrial Applications Not Related to Electricity Generation. If the facility includes other industrial processes or operations that are neither in support of nor a part of the electricity generation or cogeneration system, report the total amount of generated thermal energy that is used by those on-site industrial processes or operations and heating or cooling applications. Exclude from this quantity the amount of thermal energy that is vented, radiated, wasted, or discharged before it is used at industrial processes or operations. This quantity does not include the amount of thermal energy generated by equipment that is not an integral part of the cogeneration unit.

(‘a’) In addition to reporting the overall amount of thermal energy for on-site industrial applications not related to electricity generation, also separately quantify

and report the subset of generated thermal energy that is used on-site to produce cooling energy or distilled water that is neither in support of nor a part of the power generation system.

(‘b’) If the facility includes equipment that uses generated thermal energy to produce cooling (e.g., absorption chiller) for the sole purpose of maintaining temperature in the electricity generation or cogeneration system, follow subparagraph (ii) of this paragraph in reporting such use of generated thermal energy.

(‘c’) If a facility includes more than one cogeneration or bigeneration unit/system, and each unit/system or each group of units generates thermal energy for different particular end-users or on-site industrial processes or operations, the operator must report the disposition of generated thermal energy by unit/system or by group of units with the same dispositions. For the purpose of separate reporting of disposition, the operator may group similar units together if the generated thermal energy from the group of units is provided to the same destination.

(6) For the first year of reporting, operators of cogeneration or bigeneration units must submit a simplified block diagram depicting the following, as applicable: individual equipment included in the generation system (e.g. turbine, engine, boiler, heat recovery steam generator); direction of flows of energy specified in paragraphs (4) through (5) of this subdivision, (b)(2) through (4) and (b)(7) through (8) of this section, with the forms of energy carrier (e.g. steam, water, fuel) labeled; and relative locations of fuel meters and other fuel quantity measurements. If the cogeneration or bigeneration system is modified after the initial submission of the diagram, the operator must resubmit an updated diagram to the

department.

(b) Information About Electricity Generating Units. Notwithstanding any limitations in 40 CFR part 75 (July 1, 2023) or part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator of an electricity generating unit must include in the emissions data report the information listed in this subdivision. For aggregation of electricity generating units, the operator must meet the applicable criteria in 40 CFR § 98.36(c)(1) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), unless otherwise specified in section 2.7(h) of this Part and this subdivision. For an electricity generation system, the operator may aggregate all the units that are integrated into the system for the purpose of reporting data to the department. Operators of 40 CFR part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title) units may also aggregate units to the system level according to this paragraph, notwithstanding the limitation in 40 CFR § 98.36(d)(1)(i) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title). If there is more than one system present at the facility, each system must be reported separately. For electricity generating units that are not part of an integrated generation system, aggregation of electricity generating units is limited to units of the same type, as specified in section 2.7(h) of this Part. Operators of geothermal facilities, hydrogen fuel cells, and renewable electricity generating units must follow subdivisions (e), (f), or (g) of this section, whichever is applicable, instead of subdivision (b) of this section. For bottoming cycle cogeneration units, the operator is not required to report the data specified in paragraphs (4) through (6) of this subdivision except for any fuels combusted for supplemental firing as specified in paragraph (7) of this subdivision.

(1) Basic information about the generating unit, including:

(i) nameplate generating capacity in megawatts (MW);

(ii) prime mover technology;

(iii) for aggregation of units, provide a description of the individual equipment included in the aggregation;

(iv) if the unit generates both electricity and thermal energy, indicate whether the unit is a cogeneration or a bigeneration unit. If the unit is a cogeneration unit, indicate whether it is topping or bottoming cycle.

(2) Net and gross power generated, in megawatt hours (MWh). The difference between net generation and gross generation is the parasitic load of electricity generation or cogeneration. The net generation quantity represents the amount of generated electricity that can be provided to the disposition categories in paragraph (a)(4) of this section.

(3) If the unit is a cogeneration or bigeneration unit, the operator must report the total thermal output (MMBtu), as defined pursuant to this Part, that was generated by the unit and can be potentially used in other industrial operations that are not electricity generation, including thermal energy that is vented, radiated, wasted, or discharged. Exclude from this quantity the heat content of returned condensate and makeup water and steam used to drive a steam turbine generator for electricity generation. The total thermal output quantity represents the amount of generated thermal energy that can be provided to the thermal energy disposition categories in paragraph (a)(5) of this section.

(4) Fuel consumption by fuel type, reported in units of million standard cubic feet for gases, gallons for liquids, short tons for non-biomass solids, and bone-dry short tons

for biomass-derived solids.

(5) If not already reported under the requirements of 40 CFR § 98.36(b) (Amended May 14, 2024) for subpart C units and 40 CFR § 98.46 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) for subpart D units, the operator must report annual CO_2, CH_4, and N_2O emissions from the unit, expressed in metric tons of each gas.

(6) If used to calculate CO_2 emissions, the operator must report weighted or arithmetic average carbon content and high heat value by fuel type, whichever is used in calculating emissions as specified in 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), unless already required to report under 40 CFR § 98.36(e)(2)(ii)(C) and (iv)(C) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(7) For cogeneration systems, where supplemental firing has been applied to support electricity generation or thermal output, report the information in paragraphs (4) through (6) of this subdivision. Indicate by fuel type the portion of the total fuel consumption (MMBtu) that is used for supplemental firing and indicate the purpose of the supplemental firing.

(8) Other Heat Input for Electricity Generation. If the electricity generation unit uses additional heat input that is not already accounted for in paragraphs (4) through (6) of this subdivision (for example, if steam or heat is acquired from outside of the electricity generation system boundary or acquired from another facility for the generation of electricity), report the amount of acquired steam or heat (MMBtu). For bottoming cycle cogeneration units only, also report the input steam to the steam turbine (MMBtu) and the output of the

heat recovery steam generator (MMBtu).

(c) Emissions from Fuel Combustion and Sorbent. When calculating CO_2, CH_4, and N_2O emissions from fuel combustion, the operator who is subject to subpart C of 40 CFR part 98 (Amended May 14, 2024) or subpart D of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) must use a method in 40 CFR § 98.33(a)(1) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part, except that for CO_2 emissions the operator who is subject to subpart D of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) may elect instead to follow the provisions in 40 CFR § 98.43 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), within the limitations of section 1.4(i) of this Part.

(1) The operator of a Subpart D unit must report emissions from fuels combusted within the emission year but not reported pursuant to 40 CFR part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title) requirements, such as prior to initial provisional or monitoring certification of CEMS. The operator must use a method in 40 CFR § 98.33(a)(1) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part, or if applicable, according to the limited alternative emissions provisions in section 1.4(e) of this Part.

(2) The operator of a Subpart D unit with contractual deliveries of biomethane or biogas is subject to the requirements in section 4.2(i) of this Part and must follow the procedure in section 2.7(e)(4) through (5) of this Part in calculating emissions from biomethane, biogas, and natural gas.

(3) The operator of a Subpart D unit who reports CO_2 emissions using emission calculation methods specified in 40 CFR part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title), and who operates a unit with a wet flue gas desulfurization system, must indicate the portion of the total reported CO_2 emissions that is generated from sorbent injection for acid gas removal.

(d) Monitoring, Data, and Records. For each emissions calculation method chosen under subdivision (c) of this section, the operator must meet the applicable requirements for monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR § 98.34-.37 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), except as modified in sections 2.5, 2.7, and 3.1 of this Part.

(e) CO_2 and CH_4 Emissions from Geothermal Facilities. Operators of geothermal generating facilities must report CO_2 and CH_4 emissions from geothermal energy sources, the amount of geothermal steam used (MMBtu) if steam quantity is used in calculating emissions, and applicable requirements in paragraphs (a)(1) through (4) of this section, subparagraphs (b)(1)(i) through (iii) of this section, and paragraph (b)(2) of this section. Operators of geothermal generating facilities must also report whether the source is, (1) a geothermal binary cycle plant or closed loop system, or (2) a geothermal steam plant or open loop system.

The operator must calculate annual emissions of CO_2 and CH_4 from geothermal energy sources using source specific emission factors derived from a measurement plan approved by the department. The operator must submit to the department a measurement plan at least 45 days prior to the first test date. The measurement plan must include testing at

least annually, and more frequently as needed. Upon approval of the measurement plan by the department, the test procedures in that plan must be performed as specified in the plan.

(f) Hydrogen Fuel Cells. Operators of stationary hydrogen fuel cell units must include the following information in the annual GHG emissions data report:

(1) basic information about the generating unit specified in paragraphs (b)(1) through (2) of this section;

(2) fuel or feedstock consumption by fuel/feedstock type, reporting in units of million standard cubic feet for gases, gallons for liquids, short tons for non- biomass solids, and bone-dry short tons for biomass-derived solids;

(3) the provider of each fuel or feedstock, and the user's customer account number;

(4) cogeneration information in paragraph (b)(3) of this section, if applicable.

(5) CO_2 emissions from the hydrogen fuel cell, calculated using one of the following methods:

(i) The fuel and feedstock mass balance approach in 40 CFR § 98.163(b) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title). If the fuel's carbon content is not known, the facility operator may use the default carbon content percentage value listed in Table 3-1 of section 3.1(c) of this Part.

(ii) For natural gas and biogas, if the fuel heat input is measured by the facility operator or by the fuel supplier, the operator may use Equation 2.5-1 as provided in this subparagraph to estimate emissions.

Equation 2.5-1: CO_2 (MT/year) = H (MMBtu/year) x EF (kg CO_2/MMBtu) x 0.001 (MT/kg)

Where:

CO_2 = Annual CO_2 emissions from fuel and feedstock consumption (metric tons/year)

H = Total fuel heat input for the year (MMBtu/year)

EF = Default CO_2 emission factor. Use 53.02 kg CO_2/ MMBtu for natural gas. Use 52.07 kg CO_2/MMBtu for biogas.

0.001 = Conversion factor from kg to metric tons.

(iii) For biogas fuels, the facility operator may elect to use the best available estimation and engineering estimation approach to calculate emissions.

(g) On-site Renewable Electricity Generation. The requirements in this subdivision apply to facilities that meet the applicability for reporting under section 1.2 of this Part and are not otherwise exempted from reporting under section 1.2(l) of this Part. If such facility includes non-fuel-based renewable electricity generating units with nameplate generating capacity of greater than 0.5 MW, the operator must report the nameplate generating capacity (MW), gross power generated (MWh) by the non-fuel-based renewable electricity generating units, and the applicable information in subdivision (a) of this section.

For facility operators that do not operate other electricity generating units that are subject to the requirements in subdivisions (a) through (f) of this section, reporting of information specified in subparagraph (a)(4)(iii) of this section and paragraphs (a)(5) through

(6) of this section is optional.

(h) Missing Data Substitution Procedures. To substitute for missing data for emissions reported under this section or section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems), the operator must follow the requirements of section 3.1 of this Part. Facilities reporting under 40 CFR part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title) must substitute for missing data under the requirements of that part, as specified in 40 CFR § 98.45 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

253-2.6 Electronics Manufacturing

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart I of 40 CFR part 98 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) in reporting stationary combustion and process emissions and related data from electronics manufacturing to the department, except as otherwise provided in this section.

(a) CO_2, CH_4, and N_2O from Fuel Combustion. Operators must calculate and report fuel high heat values ((in units of MMBtu/kg, MMBtu/scf, or MMBtu/gallon for solid, gaseous, or liquid fuels respectively). When calculating GHG emissions from fuel combustion, the operator must use a method in 40 CFR § 98.33(a)(1) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) or 40 CFR § 98.33(c) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part.

(b) Monitoring, Data, and Records. For each emissions calculation method chosen

under subdivision (a) of this section, the operator must meet the applicable requirements for monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR § 98.34-.37 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), except as modified in subdivisions (c) through (d) of this section, and sections 2.7 and 3.1 of this Part.

(c) Missing Data Substitution Procedures. The operator must comply with 40 CFR § 98.95 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) when estimating missing data, except as otherwise provided in paragraphs (1) through (3) of this subdivision.

(1) To substitute for missing data for emissions reported under section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems), the operator must follow the requirements of section 3.1 of this Part.

(2) For each missing value of the use of fluorinated heat transfer fluid, the operator must apply a substitute value according to the procedures in subparagraphs (i) through (ii) of this paragraph.

(i) If the data capture rate is at least 80 percent for the emission year, the operator must substitute for each missing value according to 40 CFR § 98.95(b) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title).

(ii) If the data capture rate is less than 80 percent for the emission year, the operator must substitute for each missing value with the maximum capacity of the system and the number of days per month.

(3) The operator must document and retain records of the procedure used for all missing data estimates pursuant to the recordkeeping requirements of section 1.7 of this

Part.

(d) Additional Product Data. In addition to the information required by 40 CFR § 98.96 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must report the additional parameters provided in paragraph (1) of this subdivision.

(1) Facilities using a CEMS to report emissions from a combined flue stack are required to use the Tier 4 calculation method to report both combustion and total stack emissions under section 2.7 of this Part, pursuant to the provisions of section 2.7(g). These facilities are also required to report process emissions under this section. To report process emissions, the operator must subtract the fuel combustion emissions value from the facility's total reported combined stack emissions value in order to calculate the facility's process emissions value, in metric tons, to be reported under this section. The operator must use Equation 2.6-1 as provided in this paragraph to calculate process emissions:

Equation 2.6-1: Eprocess = Etotal – Ecombustion

Where:

Eprocess = The annual process emissions from a facility's combined flue stack using a CEMS (metric tons)

Etotal = The total annual emissions from a facility's combined flue stack using a CEMS (metric tons)

Ecombustion = The annual combustion emissions from a facility's combined flue stack using a CEMS (metric tons)

253-2.7 Facility Fuel Utilization and Combustion Sources

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart C of 40 CFR part 98 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) in reporting stationary fuel combustion emissions and related data to the department, except as otherwise provided in this section.

(a) CO_2 from Steam Producing Units. The operator of a steam producing unit combusting municipal solid waste or solid biomass fuels may use Equation C-2c of 40 CFR § 98.33(a)(2)(B)(iii) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), unless required to use Tier 3 or 4 by subpart C of 40 CFR part 98 (Amended November 18, 2024) or part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title). Operators of steam producing units combusting fossil-based solid fuels must select applicable Tier 3 or Tier 4 pursuant to subpart C of 40 CFR part 98 (Amended November 18, 2024) or part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title) methods.

(b) CEMS CO_2 Monitoring. Notwithstanding the allowed use of oxygen concentration monitors in 40 CFR § 98.33(a)(4)(iv) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), an operator installing a continuous emissions monitoring system that includes a stack gas volumetric flow rate monitor after January 1, 2026, and who reports CO_2 emissions using this system, must install and use a CO_2 monitor. An operator without a CO_2 monitor who uses a CEMS and O_2 concentrations to calculate and report a unit's CO_2 emissions, and who conducts a RATA for the unit, must at least annually include in the RATA the direct monitoring of CO_2 concentration and flow, and the calculation of CO_2 mass per hour. The

operator must retain these results pursuant to the recordkeeping requirements of section 1.7 of this Part and make them available to the department upon request. The requirements of this subdivision do not apply to facilities for which pipeline natural gas is the only fuel consumed.

(c) Choice of Tier for Calculating CO_2 Emissions. Notwithstanding the provisions of 40 CFR § 98.33(b) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), the operator's selection of a method for calculation of CO_2 emissions from combustion sources is subject to the following limitations by fuel type and unit size. The operator is permitted to select a higher tier than that required for the fuel type or unit size as specified in this subdivision.

(1) The operator may select the Tier 1 or Tier 2 calculation method specified in 40 CFR § 98.33(a) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for any fuel listed in Table 2-3 of this section that is combusted in a unit with a maximum rated heat input capacity of 250 MMBtu/hr or less, subject to the limitation at 40 CFR § 98.33(b)(1)(iv) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(2) The operator may select the Tier 2 calculation method specified in 40 CFR § 98.33(a)(2) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for natural gas when it is pipeline quality, and for distillate fuels listed in Table 2-3 of this section. Tier 1 may be selected when the fuel supplier is providing pipeline quality natural gas measured in units of therms or million Btu. Equation C-2c of 40 CFR § 98.33(a) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) may be selected for the units specified in subdivision (a) of this section.

(3) The operator may select any calculation method specified in 40 CFR § 98.33(a) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) when calculating emissions that are shown to be limited alternative emissions under section 1.4(e) of this Part, or for a fuel providing less than 10 percent of the annual heat input to a unit with a maximum rated heat input capacity of 250 MMBtu/hr or less, unless not permitted under 40 CFR § 98.33(b) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(4) The operator must use either the Tier 3 or the Tier 4 calculation method specified under 40 CFR § 98.33(a)(3) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for any other fuel, including non-pipeline quality natural gas and fuel with emissions identified as biomass-derived CO_2, subject to the limitations of 40 CFR § 98.33(b)(4) through (5) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) requiring use of the Tier 4 method. The operator using Tier 3 must determine annual average carbon content with weighted fuel use values, as required by Equation C-2b of 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title). When fuel mass or volume is measured by lot, the term “n” in Equation C-2b is substituted as the number of lots received in the year.

(d) Source Test Option for N_2O and CH_4. In lieu of other methods specified in this Part, a facility operator may conduct site-specific source testing to derive emission factors and determine annual emissions of N_2O or CH_4 from any combustion source. Alternatively, the operator may use the results of an applicable test method specified in Title 17, California Code of Regulations, section 95471 (June 17, 2010) (see Table 1, section 200.9 of this Title). For source testing:

(1) The facility operator must submit to the department a test plan at least 45 days prior to the first test date. The test plan must provide for testing at least annually, and more frequently as needed to account for seasonal variations in fuels or processes.

(2) The plan must specify conduct of performance and stack tests consistent with the requirements of approved department or U.S. EPA test methods. Process rates during the test must be determined in a manner that is consistent with the procedures used for GHG report accounting purposes.

(3) Upon approval of the test plan by the department, the test procedures in that plan must be repeated as specified in the plan. The department must be notified at least 10 days in advance of subsequent tests.

(e) Procedures for Biomass CO_2 Determination. Emission sources must use the following procedures when calculating emissions from biomass-derived fuels that are intermixed with fossil fuels:

(1) When combusting municipal solid waste (MSW) or any other fuel for which the biomass fraction is not known, the operator must follow the procedures specified in 40 CFR § 98.33(e)(3) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) to specify a biomass fraction.

(2) For the analysis conducted under the requirements of 40 CFR § 98.34(e) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for partially biogenic fuels other than MSW, the operator may choose to analyze monthly fuel samples. The operator must collect such samples weekly and combine a portion of each weekly sample to form a monthly composite mixture. The monthly composite mixture must be homogenized and well

mixed prior to withdrawal of a sample for analysis.

(3) When calculating emissions from a biomethane and natural gas mixture using the annual MMBtu of fuel combusted in place of the product of Fuel and HHV in Equation C-2a as described in 40 CFR § 98.33(a)(2) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), the operator must calculate emissions based on contractual deliveries of biomethane subject to the requirements of section 4.2(i) of this Part, using the natural gas emission factor in Equation 2.7-1 as provided in this paragraph:

$$\text{Equation 2.7-1: } E_{biomass} = EF_{natural\ gas} \times MMBTu_{biomethane} \times 0.001$$

Where:

$E_{biomass}$ = The annual biomass CO_2, CH_4 or N_2O emissions from biomethane (metric tons)

$E_{natural\ gas}$ = The annual fossil CO_2, CH_4 or N_2O emissions from natural gas (metric tons)

$EF_{natural\ gas}$ = The natural gas emission factor from tables C-1 and C-2 of 40 CFR part 98 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) (kg/MMBtu)

$MMBtu_{annual}$ = The total delivered MMBtus for the reporting year based on utility bills or meters meeting the accuracy requirements of section 1.4(g) of this Part

$MMBtu_{biomethane}$ = The total biomethane deliveries subject to the requirements of section 4.2(i) of this Part for the reporting year based on contractual

deliveries

(4) When calculating emissions from a biomethane and natural gas mixture as described in 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) using a continuous emission monitoring system (CEMS), or when calculating those emissions according to subpart D of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the reporting entity must calculate the biomethane emissions as described in paragraph (3) of this subdivision, with the remainder of emission being natural gas emissions.

(5) When calculating emissions from a biogas and natural gas mixture using 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) or the carbon content method described in 40 CFR § 98.33(a)(3) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), or when calculating those emissions according to subpart D of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the reporting entity must calculate biogas emissions using a carbon content method as described in 40 CFR § 98.33(a)(3) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), with the remainder of emissions being natural gas emissions.

(f) Fuel Sampling Frequencies. The operator who collects and analyses fuel samples to conduct the monitoring analyses required under 40 CFR § 98.34 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) must sample at the frequencies specified in that section, except in the following cases.

(1) Natural gas that is outside the range of pipeline quality as defined in section

1.3 of this Part must be sampled and analyzed at least monthly by the reporting entity or the fuel supplier.

(2) Under 40 CFR § 98.34(b)(3)(ii)(E) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), in cases where equipment necessary to perform daily sampling and analysis of carbon content and molecular weight for refinery fuel gas is not in place, such equipment must be installed, and procedures established to implement daily sampling and analysis no later than January 1, 2026.

(3) The operator is estimating CO_2 emissions using a CEMS under 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(g) Fuel Use for CEMS Units. The operator who estimates and reports CO_2 emissions using a CEMS under 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) must also report the quantity of each type of fuel combusted in the unit or group of units (as applicable) during the reporting year, in standard cubic feet for gaseous fuels, gallons for liquid fuels, short tons for solid fuels, bone dry short tons for biomass-derived solids, and high heat value in MMbtus/unit for each quantity of fuel. Fuel use monitoring devices for units covered under this subdivision are exempt from the provisions of section 1.4(g) of this Part.

(h) Additional Reporting Requirements. Facility combustion processes may include but are not limited to furnaces, kilns, generators, boilers, engines, incinerators, combustion turbines, process heaters, or smelters used for producing electricity, generating steam, or providing useful heat or energy for industrial, commercial, or institutional use. All facilities are required to report individual fuel volumes as required by 40 CFR § 98.36(b) and (c)

(Amended May 14, 2024) (see Table 1, section 200.9 of this Title) under this section for fuel used in combustion processes at the facility, including the following additional information.

(1) Following the reporting requirements set forth by 40 CFR § 98.36 (c)(2)(x) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), the operator must supplementally report annual CO_2 mass emissions from units sharing a common stack or duct.

(2) Facilities using the Tier 4 methodology to report emissions from a combined flue stack must also indicate the use of a CEMS and must report total emissions and combustion emissions in metric tons from the combined stack under this section.

(i) Aggregation of Units. Facility operators may elect to aggregate units according to 40 CFR § 98.36(c) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), except as otherwise provided in this subdivision. Facility operators that are reporting under more than one source category in Subpart 2 of this Part and that elect to follow 40 CFR § 98.36(c)(1), (c)(3), (c)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), must not aggregate units that belong to different source categories. For the purpose of unit aggregation, units subject to subpart C of 40 CFR part 98 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) that are associated with one source category must not be grouped with other units associated with another source category, except when 40 CFR § 98.36(c)(2) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) applies. Aggregation of stationary fuel combustion units is limited to units of the same type, where the unit type categories are: boiler, reciprocating internal combustion engine, turbine, process heater, and other (none of the above). When reporting under the provisions of 40 CFR §

98.36(c)(1) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for an aggregation of units or 40 CFR § 98.36(c)(3) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for common pipe configurations, the requirements can be met by separately reporting the fuel use by fuel type as a percentage of the aggregated fuel consumption attributed to each individual unit or each group of units of the same type. Units subject to section 2.5 of this Part must use the criteria for aggregation in section 2.5(b). Facility operators that choose to aggregate units according to the common stack provision in 40 CFR § 98.36(c)(2) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) using CEMS may report emissions according to 40 CFR § 98.36(c)(2) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), but they must separately report the fuel use by fuel type as a percentage of the aggregated fuel consumption attributed to each individual unit or each group of units of the same type, such that the grouping of units still meets the limitations for unit aggregation specified elsewhere in this subdivision.

(j) Pilot Lights. The operator must include emissions from pilot lights in the emissions data report. The operator may apply appropriate methods from 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) or engineering methods to calculate these emissions when pilot lights are unmetered. Pilot lights fueled from a common fuel source may be aggregated for reporting. Emissions reported from pilot lights may be reported as limited alternative emissions consistent with the requirements of section 1.4(e) of this Part. Pilot lights are not subject to the measurement device calibration requirements of section 1.4 of this Part, but pilot light emissions calculations are subject to verification.

(k) Electricity Generating and Cogeneration Units. The operator of a facility that

includes electricity generating and cogeneration units meeting the applicability criteria of section 1.2 of this Part must meet the requirements specified in section 2.5 of this Part.

(l) Fuel Supplier Information. The operator who is reporting emissions from the combustion or use of fuels must report the name(s) of the supplier(s) of fuels to the facility, the operator's fuel supplier customer account number(s), fuels supplier service account identification number(s) or other primary account identifier(s), and the annual MMBtu delivered to each account according to billing statements, and what type of fuel supplier provided the fuel (e.g., a position holder, enterer, intrastate natural gas pipeline operator, ESCO). In the case that the fuel is purchased from a person other than a fuel supplier, the operator must report the supplier's name and customer or service account identification number but may report the annual MMBtu delivered based on the seller's billing statement.

(m) Information on Natural Gas Supplied to Downstream Users. The operator who is reporting emissions from the combustion of natural gas must report whether any of the natural gas reported pursuant to subdivision (l) of this section was supplied to downstream users outside of the operator's facility boundary. If so, the operator must report the name of the facility and the annual MMBtu delivered to each user according to billing statements or financial records.

(n) Procedures for Missing Data. To substitute for missing data for emissions reported under section 2.7 of this Part, the operator must follow the requirements of section 3.1 of this Part.

(o) Upstream Out of State Emissions. Facilities reporting in this section must also estimate CO_2e emissions from fossil fuels for the upstream out-of-state emissions associated

with the use of these fuels in New York pursuant to the emission factors specified in section 2.18 of this Part.

(p) Other combustion or fuel utilization sources within a facility boundary. Facility owners or operators must report emissions from the use of fuels purchased or delivered to that facility within the reporting year that have not been reported elsewhere in this section or Subpart. Emissions from the fuel must be reported regardless of the type of process that used the fuel. This includes reporting emissions from emergency generators, non-permanent equipment, non-road equipment, and other mechanisms at the facility, provided the owner or operator of the facility took delivery of the fuel for use onsite.

(1) Fuels purchased at an offsite retail location and used on site are not required to be reported by the facility.

(2) A facility owner or operator may report emissions for this subdivision as the difference between total annual fuel purchases or deliveries in a reporting year and the fuel consumed or used in metered processes or inventoried emission sources at the facility in the same reporting year as reported elsewhere in this section or Subpart.

(q) Facilities reporting in this section may make a demonstration to the department that the fuels or products supplied by a fuel supplier or otherwise utilized at the facility were used to make a durable product which is ultimately not combusted or used as fuel.

(i) Without a demonstration, fuel and products are assumed to be combusted or otherwise emitted as a fugitive or vented emission.

(ii) The demonstration must meet the requirements of the department.

(iii) Facilities making successful demonstrations for quantities of fuel or

product determined to be turned into durable products would be required to report the upstream out-of-state emissions associated with the fossil fuels in these products pursuant to section 2.18 of this Part.

Table 2-3: Petroleum Fuels for Which Tier 1 or Tier 2 Calculation Methodologies May Be Used Under Paragraph (c)(1) Of This Section		
Fuel Type	Default High Heat Value	Default CO_2 Emission Factor
	MMBtu/gallon	kg CO_2/MMBtu
Distillate Fuel Oil No. 1	0.139	73.25
Distillate Fuel Oil No. 2	0.138	73.96
Distillate Fuel Oil No. 4	0.146	75.04
Kerosene	0.135	75.20
Liquefied petroleum gases (LPG) *** or Propane	0.092	62.98
Propylene	0.091	65.95
Ethane	0.096	62.64
Ethylene	0.100	67.43
Isobutane	0.097	64.91
Isobutylene	0.103	67.74
Butane	0.101	65.15
Butylene	0.103	67.73
Natural Gasoline	0.110	66.83
Motor Gasoline (finished)	0.125	70.22
Aviation Gasoline	0.120	69.25
Kerosene-Type Jet Fuel	0.135	72.22
***Commercially sold as "propane" including grades such as HD5.		

253-2.8 Glass Production

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart N of 40 CFR part 98 (Amended April 25, 2024) (see Table 1, section

200.9 of this Title) in reporting stationary combustion and process emissions and related data from glass production to the department, except as otherwise provided in this section.

(a) CO_2, CH_4, and N_2O from Fuel Combustion. Operators must calculate and report high heat value (in units of MMBtu/kg, MMBtu/scf, or MMBtu/gallon for solid, gaseous, or liquid fuels respectively). When calculating GHG emissions from fuel combustion, the operator must use a method in 40 CFR § 98.33(a)(1) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) or 40 CFR § 98.33(c) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part.

(b) Monitoring, Data, and Records. For each emissions calculation method chosen under subdivision (a) of this section, the operator must meet the applicable requirements for monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR § 98.34-.37 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), except as modified in subdivisions (c) through (d) of this section, and sections 2.7 and 3.1 of this Part.

(c) Missing Data Substitution Procedures. The operator must comply with 40 CFR § 98.145 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) when estimating missing data, except as otherwise provided in paragraphs (1) through (3) of this subdivision.

(1) To substitute for missing data for emissions reported under section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems), the operator must follow the requirements of section 3.1 of this Part.

(2) For each missing value of the monthly amounts of carbonate-based raw materials charged to any continuous glass melting furnace, the operator must apply a

substitute value according to the procedures in subparagraphs (i) through (ii) of this paragraph.

(i) If the data capture rate is at least 80 percent for the emission year, the operator must substitute for each missing value according to 40 CFR § 98.145(a) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title).

(ii) If the data capture rate is less than 80 percent for the emission year, the operator must substitute for each missing value with the maximum short tons per day raw material capacity of the continuous glass melting furnace.

(3) The operator must document and retain records of the procedure used for all missing data estimates pursuant to the recordkeeping requirements of section 1.7 of this Part.

(d) Additional Product Data. In addition to the information required by 40 CFR § 98.146 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must report the additional parameters provided in paragraphs (1) through (6) of this subdivision whether or not a CEMS is used to measure CO_2 emissions.

(1) The operator of a flat glass manufacturing facility must report the annual quantity of glass pulled from the melting furnace (short tons).

(2) The operator of a container glass manufacturing facility must report the annual quantity of glass pulled from the melting furnace (short tons).

(3) The operator of a fiberglass manufacturing facility must report the annual quantity of glass pulled from the melting furnace (short tons).

(4) The operator of a specialty glass manufacturing facility must report the

annual quantity of glass pulled from the melting furnace (short tons).

(5) The operator of a glass manufacturing facility must report the cullet ratio used in glass production if applicable (percentage).

(6) Facilities using a CEMS to report emissions from a combined flue stack are required to use the Tier 4 calculation method to report both combustion and total stack emissions under section 2.7 of this Part, pursuant to the provisions of section 2.7(g) of this Part. These facilities are also required to report process emissions under this section. To report process emissions, the operator must subtract the fuel combustion emissions value from the facility's total reported combined stack emissions value in order to calculate the facility's process emissions value, in metric tons, to be reported under this section. The operator must use Equation 2.8-1 as provided in this paragraph to calculate process emissions:

Equation 2.8-1: $E_{process} = E_{total} - E_{combustion}$

Where:

$E_{process}$ = The annual process emissions from a facility's combined flue stack using a CEMS (metric tons)

E_{total} = The total annual emissions from a facility's combined flue stack using a CEMS (metric tons)

$E_{combustion}$ = The annual combustion emissions from a facility's combined flue stack using a CEMS (metric tons)

253-2.9 Hydrogen Production

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart P of 40 CFR part 98 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) in reporting emissions and other data from molecular hydrogen production to the department, except as otherwise provided in this section.

(a) Definition of Source Category. This source category is defined consistent with 40 CFR § 98.160(b) through (c) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title). This category is further defined as a hydrogen production source that produces molecular hydrogen whether sold to other entities or consumed on-site.

(b) CO_2, CH_4, and N_2O from Fuel Combustion. Operators must calculate and report fuel high heat value (in units of MMBtu/kg, MMBtu/scf, or MMBtu/gallon for solid, gaseous, or liquid fuels respectively). When calculating GHG emissions from fuel combustion under subpart C as specified at 40 CFR § 98.162(b) through (c) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must use a method in 40 CFR § 98.33(a)(1) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) or 40 CFR § 98.33(c) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part.

(c) Monitoring, Data, and Records. For each emissions calculation method chosen under subdivision (b) of this section, the operator must meet the applicable requirements for monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR §98.34-.37 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title),

except as modified in subdivision (h) of this section and sections 2.7 and 3.1 of this Part.

(d) CO_2 Emissions from Hydrogen Production Units. When calculating CO_2 emissions from hydrogen production units under the fuel and feedstock material balance approach specified at 40 CFR § 98.163(b) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must apply the weighted average carbon content values (the term CC_n in Equations P-1 through P-3) and, for gaseous fuels and feedstocks, the weighted average molecular weight values obtained according to the frequencies specified in paragraph (e)(2) of this section.

(e) Fuel and Feedstock Contents. For each hydrogen production unit, operators must report the following information:

(1) When monitoring GHG emissions with a CEMS as specified in 40 CFR § 98.163(a) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must report the monthly carbon content, atomic hydrogen content (excluding hydrogen atoms contained in steam), and molecular hydrogen content for each feedstock. The reported values must be weighted averages from the results of one or more analyses per month.

(2) When monitoring GHG emissions without a CEMS as specified in 40 CFR § 98.163(b) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must report the monthly weighted average atomic hydrogen content (excluding hydrogen atoms contained in steam) and weighted average molecular hydrogen content for each feedstock from the results of one or more analyses per month. The operator must also report the monthly carbon content for each fuel and feedstock, and the molecular weight for each gaseous fuel and feedstock as follows:

(i) The reported values must be weighted averages from the results of one or more analyses per month for natural gas or standardized materials specified in Table 2-3 in 253-2.7(q) of this Part.

(ii) The reported values must be weighted averages from the results of daily sampling for each month for nonstandard materials not specified in Table 2-3 in 253-2.7(q) of this Part. For liquid and solid fuels and feedstocks, daily samples may be combined to generate a monthly composite sample for carbon content analysis.

(f) Weighted Average Sampling. Where this section requires sampling of a parameter on a more frequent basis than subpart P of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator or supplier must comply with the following:

(1) The samples must be spaced apart as evenly as possible over time, taking into account the operating schedule of the relevant unit or facility.

(2) The operator or supplier must calculate and report a weighted average of the values derived from the samples by using Equation 2.9-1 as provided in this paragraph:

Equation 2.9-1:

$$V_E = \frac{\sum_{j=1}^{n} (V_j \times M_j)}{\sum_{j=1}^{n} M_j}$$

Where:

VE = The value of the parameter to be reported under subpart P 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) for period E.

j = Each period during period E for which a sample is required by this Part.

N = The number of periods j in period E.

Vj = The value of the sample for period j.

Mj = The mass of the sampled material processed or otherwise used by the relevant unit or facility in period j.

(3) The operator or supplier must keep records of the date and result for each sample or composite sample and mass measurement used in Equation 2.9-1 in paragraph (2) of this subdivision, and of the calculation of each weighted average included in the emissions data report, pursuant to the record keeping requirements of section 1.7 of this Part.

(g) Data Reporting Requirements. When reporting data as specified in 40 CFR § 98.166 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must also report the mass of carbon and methane for which GHG emissions are calculated and reported by the facility using other calculation methods provided in this regulation (e.g., carbon in waste diverted to a fuel system or flare, where the CO_2 and CH_4 emissions are calculated and reported using other methods specified in this Part). To avoid double-counting, these emissions must be subtracted from the total facility emissions.

(h) Missing Data Substitution Procedures. The operator must comply with paragraphs

(1) through (2) of this subdivision.

(1) To substitute for missing data for emissions reported under section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems); the operator must follow the requirements of section 3.1 of this Part.

(2) For all other data required for emissions calculations in this section, the operator must follow the requirements of subparagraphs (i) through (iii) of this paragraph.

(i) If the analytical data capture rate is at least 90 percent for the emission year, the operator must substitute for each missing value using the best available estimate of the parameter, based on all available process data.

(ii) If the analytical data capture rate is at least 80 percent but not at least 90 percent for the emission year, the operator must substitute for each missing value with the highest quality assured value recorded for the parameter during the given emission year, as well as the two previous emission years.

(iii) If the analytical data capture rate is less than 80 percent for the emission year, the operator must substitute for each missing value with the highest quality assured value recorded for the parameter in all records kept according to section 1.7(a) of this Part.

(i) Additional Product Data. Operators must report the total annual mass of on-purpose and by-product gaseous hydrogen produced (metric tons) and total annual mass of liquid hydrogen sold (metric tons). Operators must separately report all gaseous and all liquid hydrogen sold or otherwise transferred (metric tons) to hydrogen vehicle fueling stations and include the name of the purchaser (or receiver) and the quantity sold or transferred to each

facility or person.

(j) Hydrogen producers shall use the methodology found in 40 CFR § 98.253(b) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) to calculate and report CO_2, CH_4, and N_2O emissions from all flaring at their facility, except that emissions from flare pilots shall be included in facility reported emissions.

253-2.10 Iron and Steel Production

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart Q of 40 CFR part 98 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) and 40 CFR § 98.180-.188 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) in reporting stationary combustion and process emissions and related data from iron and steel production to the department, except as otherwise provided in this section.

(a) CO_2, CH_4, and N_2O from Fuel Combustion. Operators must calculate and report fuel high heat value (in units of MMBtu/kg, MMBtu/scf, or MMBtu/gallon for solid, gaseous, or liquid fuels respectively). When calculating GHG emissions from fuel combustion at a stationary combustion unit under 40 CFR § 98.172(a) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator must use a method in 40 CFR § 98.33(a)(1) through (4) or 98.33(c) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part.

(b) Monitoring, Data, and Records. For each emissions calculation method chosen under subdivision (a) of this section, the operator must meet the applicable requirements for

monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR § 98.34-.37 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), except as modified in subdivisions (c) through (d) of this section, section 2.7, and section 3.1 of this Part.

(c) Missing Data Substitution Procedures. The operator must comply with 40 CFR § 98.175 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) when substituting for missing data, except as otherwise provided in paragraphs (1) through (2) of this subdivision.

(1) To substitute for missing data for emissions reported under section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems), the operator must follow the requirements of section 3.1 of this Part.

(2) If monthly mass or volume of carbon-containing inputs and outputs are missing when using the carbon mass balance procedure in 40 CFR § 98.173(b)(1) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must apply substitute values according to the procedures in subparagraphs (i) through (ii) of this paragraph

(i) If the data capture rate is at least 80 percent for the emission year, the operator must substitute for each missing value based on the best available estimate based on information used for accounting purposes (such as purchase records).

(ii) If the data capture rate is less than 80 percent for the emission year, the operator must substitute for each missing value with the maximum throughput capacity of the system and the number of days per month.

(3) The operator must document and retain records of the procedure used for

all missing data estimates pursuant to the recordkeeping requirements of section 1.7 of this Part.

(d) Additional Product Data. In addition to the information required by 40 CFR § 98.176 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title), the operator must report the additional data as follows:

(1) annual production of iron and steel products in short tons;

(2) a description of the product(s); and,

(3) facilities using a CEMS to report emissions from a combined flue stack are required to use the Tier 4 calculation method to report both combustion and total stack emissions under section 2.7 of this Part, pursuant to the provisions of section 2.7(g). These facilities are also required to report process emissions under this section. To report process emissions, the operator must subtract the fuel combustion emissions value from the facility's total reported combined stack emissions value in order to calculate the facility's process emissions value, in metric tons, to be reported under this section. The operator must use Equation 2.10-1 as provided in this paragraph to calculate process emissions:

Equation 2.10-1: Eprocess = Etotal – Ecombustion

Where:

Eprocess = The annual process emissions from a facility's combined flue stack using a CEMS (metric tons)

Etotal = The total annual emissions from a facility's combined flue stack

using a CEMS (metric tons)

Ecombustion = The annual combustion emissions from a facility's combined flue stack using a CEMS (metric tons)

253-2.11 Lead Production

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart R of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) in reporting stationary combustion and process emissions and related data from lead production to the department, except as otherwise provided in this section.

(a) CO_2, CH_4, and N_2O from Fuel Combustion. Operators must calculate and report fuel high heat value (in units of MMBtu/kg, MMBtu/scf, or MMBtu/gallon for solid, gaseous, or liquid fuels respectively). When calculating GHG emissions from fuel combustion at a stationary combustion unit under 40 CFR § 98.182(d) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator must use a method in 40 CFR § 98.33(a)(1) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) or 40 CFR § 98.33(c) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part.

(b) Monitoring, Data, and Records. For each emissions calculation method chosen under subdivision (a) of this section, the operator must meet the applicable requirements for monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR §98.34-.37 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title),

except as modified in subdivisions (c) through (d) of this section, section 2.7, and section 3.1 of this Part.

(c) Missing Data Substitution Procedures. The operator must comply with 40 CFR § 98.185 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) when substituting for missing data, except as otherwise provided in paragraphs (1) through (3) of this subdivision.

(1) To substitute for missing data for emissions reported under section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems), the operator must follow the requirements of section 3.1 of this Part.

(2) If the annual mass or carbon content of carbon-containing inputs are missing when using the process emissions calculation procedure in 40 CFR § 98.183(b)(2) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator must apply substitute values according to the procedures in subparagraphs (i) through (ii) of this paragraph.

(i) If the analytical data capture rate is at least 80 percent for the emission year, the operator must substitute for each missing value according to 40 CFR § 98.185(a) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) and the number of days per month.

(ii) If the analytical data capture rate is less than 80 percent for the emission year, the operator must substitute for each missing value with the maximum capacity of the system and the number of days per month.

(3) The operator must document and keep records of the procedures used for

estimating missing data pursuant to the recordkeeping requirements of section 1.7 of this Part.

(d) Additional Product Data. The operator of a lead production, recycling, recovery, or manufacturing facility must report production of lead and lead alloys during the emission year (short tons) as well as the furnace type used in that production.

(1) Facilities using a CEMS to report emissions from a combined flue stack are required to use the Tier 4 calculation method to report both combustion and total stack emissions under section 2.7 of this Part, pursuant to the provisions of section 2.7(g). These facilities are also required to report process emissions under this section. To report process emissions, the operator must subtract the fuel combustion emissions value from the facility's total reported combined stack emissions value in order to calculate the facility's process emissions value, in metric tons, to be reported under this section. The operator must use Equation 2.11-1 as provided in this paragraph to calculate process emissions:

Equation 2.11-1: $E_{process} = E_{total} - E_{combustion}$

Where:

$E_{process}$ = The annual process emissions from a facility's combined flue stack using a CEMS (metric tons)

E_{total} = The total annual emissions from a facility's combined flue stack using a CEMS (metric tons)

$E_{combustion}$ = The annual combustion emissions from a facility's

combined flue stack using a CEMS (metric tons)

253-2.12 Oil and Gas Systems

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart W of 40 CFR part 98 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) and report GHG emissions to the department, except as otherwise provided in this section.

(a) Facilities must report emissions from onshore petroleum and natural gas production, onshore petroleum and natural gas gathering and boosting, onshore natural gas transmission compression, onshore natural gas transmission pipeline, underground gas storage, LNG storage and natural gas distribution segments if emission sources in this section emit collectively 10,000 metric tons CO_2e emissions or more per year.

(b) Facilities must report all emissions from natural gas distribution or natural gas transmission equipment if those facilities also report emissions under sections 2.1 through 2.11 and 2.13 of this Part.

(c) Additional data. In addition to the information required by subpart W of 40 CFR part 98 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) facilities shall supply the information in paragraphs (1) – (4) of this subdivision.

(1) Natural gas distribution facilities shall report county specific data from their service area including:

(i) miles of main and service pipeline by material;

(ii) number and type of customer meters;

(iii) number of metering and regulating stations;

(iv) number of pipeline dig-ins; and

(v) the leak detection rate for customer gas meters inspected by the owner or operator of the natural gas distribution facility, including LDCs or contractors acting on their behalf, during the reporting year. The rate shall be reported as the number of meters that had detectable leaks at the time of inspection divided by the number of meters inspected for leaks, as part of inspection programs or opportunistically.

(2) Natural gas distribution facilities shall report county specific emissions data from their service area including:

(i) Annual CO2 and CH4 emissions, in metric tons for each gas, from customer meters serving each type of customer meter using the following emission factors:

('a') Residential customer meters: 0.01582 scf/meter-hour.

('b') Commercial customer meters: 0.00547 scf/meter-hour.

('c') Industrial customer meters: 0.00547 scf/meter-hour.

(ii) Annual CO2 and CH4 emissions, in metric tons for each gas, from pipeline dig-ins.

(3) Facilities that are subject to Part 203 of this Title and have compliant emissions control mechanisms and reporting requirements must use Part 203 emissions reporting information for CH_4 emissions when reporting emissions under this Part.

(4) Facilities that are subject to Part 203 of this Title shall submit blowdown,

pigging and component data as required under that Part.

253-2.13 Solid Waste Management

The operator of a facility who is required to report under section 1.2 of this Part must comply with subpart HH of 40 CFR part 98 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) or subpart TT of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) in reporting stationary combustion and waste management emissions to the department, except as otherwise provided in this section.

(a) CH_4 from Municipal Solid Waste Landfills. When calculating CH_4 emissions, the operator must use equation HH-5 with a degradable organic carbon or DOC fraction of 0.22 and a k value of 0.038 for all wastes for all years. Operators of facilities with landfill gas capture systems may subtract the quantity of recovered methane calculated from equation HH-4 for the reporting year.

(b) CH_4 from Industrial Waste Landfills. When calculating CH_4 emissions, the operator must use equation TT-6 of 40 CFR § 98.463(b)(1) (November 29, 2013) (see Table 1, section 200.9 of this Title) using an appropriate DOC and k value for wet climates from table TT-1 of subpart TT of 40 CFR part 98 (December 9, 2016) (see Table 1, section 200.9 of this Title) and may subtract the quantity of recovered methane calculated from equation HH-4 of 40 CFR § 98.343(b)(1) (November 29, 2013) (see Table 1, section 200.9 of this Title).

(c) Stationary Combustion. Operators must calculate and report fuel high heat value (in units of MMBtu/kg, MMBtu/scf, or MMBtu/gallon for solid, gaseous, or liquid fuels respectively). When calculating CO_2, CH_4, and N_2O emissions from fuel, waste, or landfill gas

combustion, the operator must use a method in 40 CFR § 98.33(a)(1) through (4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) or 40 CFR § 98.33(c) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as specified by fuel type in section 2.7 of this Part.

(d) Operators that exceed the applicability threshold under section 2.20(a) of this Part are required to complete an Emissions Measurement and Monitoring Plan and report pursuant to section 2.20(a) of this Part in addition to the reporting requirements in this section. Operators may also apply to use a revised DOC following the solid waste composition verification procedures under section 2.20(b) of this Part.

(e) Monitoring, Data, and Records. For each emissions calculation method chosen under subdivisions (a) through (c) of this section, the operator must meet the applicable requirements for monitoring, missing data procedures, data reporting, and records retention that are specified in 40 CFR § 98.340-.348 (Amended April 25, 2024) and 40 CFR § 98.460-.468 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), except as modified in this section, section 2.7, and section 3.1 of this Part.

(f) Missing Data Substitution Procedures. The operator must comply with 40 CFR §§ 98.345 and 98.465 (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) when estimating missing data, except as otherwise provided in paragraph (1) of this subdivision.

(1) To substitute for missing data for emissions reported under section 2.7 of this Part (stationary combustion units and units using continuous emissions monitoring systems), the operator must follow the requirements of section 3.1 of this Part.

253-2.14 Suppliers of Agricultural Lime and Fertilizer

Any supplier who is required to report under section 1.2(b)(5) of this Part and that produces fertilizer or agricultural liming material products in New York, or that otherwise supplies fertilizers or agricultural liming material products for the purposes of application to soils in New York, must comply with the reporting requirements in this section.

(a) Distributors of Commercial Fertilizer. Any supplier who is licensed and distributes commercial fertilizer pursuant to Part 153 of Title 1 NYCRR shall report the annual quantity of nitrogen distributed to non-licensed persons and a resulting mass of N_2O emissions that would result from land application in New York, using Equation 2.14-1 as provided in this subdivision.

Equation 2.14-1: $N_2O_{direct\ SN} = (F_{sn} * EF_1) * 44/28$

Where:

$N_2O_{direct\ SN}$ = Annual direct N_2O emissions from commercial fertilizer inputs to managed soils in New York (kg N_2O-N yr^{-1} converted to N_2O)

F_{sn} = Annual amount of commercial fertilizer N supplied to New York (kg N yr^{-1})

EF_1= Emission factor for N_2O emissions from commercial fertilizer inputs to managed soils. Use the default factor of 0.016 kg N_2O-N kg N^{-1}

(b) Distributors of Lime. Any supplier that distributes limestone or dolomite products

shall report the annual quantity of each distributed in New York and a resulting mass of CO_2 emissions that would result from land application in New York, using Equation 2.14-2 as provided in this subdivision.

Equation 2.14-2: $CO_2\text{-}C = ((M_{Limestone} * EF) + (M_{Dolomite} * EF)) * 44/12$

Where:

CO_2-C = Annual CO_2 emissions from lime application (metric tons C yr^{-1} converted to CO_2)

M = Annual amount of limestone or dolomite (metric tons yr^{-1})

EF = Emission factor for CO_2 emissions from lime application to managed soils. Use the default factors of 0.12 CO_2-C $CaCO_3$ (for limestone) and 0.13 $CaMg(CO_3)_2$ (for dolomite)

(c) Monitoring, Data, and Records. Suppliers must retain the following records for five years substantiating each of the supplies that they report:

(1) Invoices, an electronic record of transfers, or any other records used to determine or that can verify the quantities reported under subdivisions (a) through (c) of this section.

(2) An electronic record of entities from which supplies were received or that the reporting entity supplied during each reporting year.

(d) Missing Data Substitution Procedures. A complete record of all measured

parameters used in tracking lime and fertilizer quantities is required.

253-2.15 Suppliers of Coal

Any coal supplier in New York who is required to report under section 1.2 of this Part, must comply with this section.

(a) Annual GHG emissions shall be reported based on the complete combustion of the coal and the emissions from the upstream out-of-state extraction and transmission of the tons of coal brought into New York for final sale to an end user in New York. These emissions shall be calculated from the high heating value of the coal as specified in subdivision (b) of this section and the emission factors as specified in Table 2-4 of this section (combustion) and Table 2-6 of section 2.18 (upstream out of state) of this Part, using Equation 2.15-1 as provided in this subdivision.

Equation 2.15-1: Emissions = HHV * tons of coal * (combustion EF + upstream EF)

Table 2-4: Coal Combustion Emission Factors	CO_2 Kg/mmbtu	CH_4 g/mmbtu	N_2O g/mmbtu
Anthracite	103.69	11	1.6
Bituminous	93.28	11	1.6
Subbituminous	97.17	11	1.6
Lignite	97.72	11	1.6
Coal Coke	113.67	11	1.6

(1) Fuel suppliers in this section must also estimate CO_2e emissions from fossil fuels for the upstream out of state emissions associated with the use of these fuels in New

York pursuant to the emission factors specified in section 2.18 of this Part.

(2) All fuel suppliers in this section may make a demonstration to the department that the fuels or products supplied to an end user or facility were used to make a durable product which is ultimately not combusted or used a fuel.

(i) Without a demonstration, fuel and products are assumed to be combusted or otherwise emitted as a fugitive or vented emission.

(ii) The demonstration must meet the requirements of the department.

(iii) Fuel suppliers making successful demonstrations for quantities of fuel or product determined to be turned into durable products are required to report the upstream out of state emissions associated with the fossil fuels in these products pursuant to section 18 of this Subpart.

(b) Coal suppliers must determine a monthly weighted average high heating value for each delivery of coal. Multiple deliveries within the same month from the same supply source require only one representative sample.

(1) The high heating value shall be determined using ASTM D5865/D5865M-19, ‘‘Standard Test Method for Gross Calorific Value of Coal and Coke” (2019) (see Table 1, section 200.9 of this Title)

(2) The same supply source shall only apply to coal of the same type (i.e., anthracite, bituminous, sub-bituminous, or lignite)

(3) The coal supplier shall report the supply source information including business address of coal producer, corporation name of coal producer, geographic origin of coal, and point of receipt of coal.

(c) The coal supplier shall maintain records necessary to support the calculation of emissions and records supporting the receipt and sale of coal to a natural person or retail location in New York.

(d) Missing data procedures shall be applied whenever a quality-assured value (e.g., the high heating value) of a required parameter is unavailable.

(1) For each missing value, substitute the arithmetic average of the quality-assured values of that parameter immediately preceding and immediately following the missing data incident. If the “after” value has not been obtained by the time that the GHG emissions report is due, the coal supplier may use the “before” value for missing data substitution or the best available estimate of the parameter, based on all available process data (e.g., sales or delivery schedule, source of coal). If, for a particular parameter, no quality-assured data are available prior to the missing data incident, the substitute data value shall be the first quality-assured value obtained after the missing data period.

(e) The coal supplier shall provide:

(1) the data used to calculate emissions from the utilization of the fuel delivered, transferred, or sold to large emission sources, pursuant to section 1.2(f) of this Part, and other Reporting Entities of this Part that are the end users of this fuel; and

(2) the name(s) of the facility, the customer account number(s), and the annual MMbtu delivered, transferred, or sold to large emission sources, pursuant to section 1.2(f) of this Part, and other Reporting Entities of this Part that are customers or end users of the fuel supplier to the department.

253-2.16 Suppliers of Liquid Fuels and Petroleum Products

Any liquid fuel supplier who is required to report under section 1.2 of this Part must comply with this section.

(a) GHGs to Report.

(1) The CO_2, CO_2 from biomass, CH_4, N_2O, and CO_2e emissions, as described in subdivision (b) of this section, from the affected liquid fuels and petroleum products in Table 2-5 of this section.

(2) The CO_2, CO_2 from biomass, CH_4, N_2O, and CO_2e emissions, as described in subdivision (b) of this section, from the volume of affected liquid fuels and petroleum products diverted to non-New York locations.

(i) Below-the-rack distributors shall report the CO_2, CO_2 from biomass, CH_4, N_2O, and CO_2e emissions, as described in subdivision (b) of this section, from the volumes of affected liquid fuels and petroleum products diverted to non-New York locations or transferred to facilities as reported by below-the-rack distributors that were not the Position Holder or Enterer for the affected liquid fuels before the point of final sale.

(3) The CO_2, CO_2 from biomass, CH_4, N_2O, and CO_2e emissions, as described in subdivision (b) of this section, from affected liquid fuels and petroleum products sold or transferred to large emission sources pursuant to section 1.2(f) of this Part or other Reporting Entities pursuant to this Part.

(4) The CO_2, CO_2 from biomass, CH_4, N_2O, and CO_2e emissions, as described in subdivision (b) of this section, from fuels used for aviation or in ocean going vessel where this can be demonstrated.

(5) Emissions reporting is not required for liquid fuel or petroleum product that is disbursed from a rack in New York that has a final destination outside New York, or for liquid fuels that can be demonstrated to have been previously delivered by a position holder or refiner out of an upstream New York terminal or refinery rack prior to delivery out of a second terminal rack.

(6) The GHG emissions from fuel use at facilities with budget units as described in Part 242 of this Title.

(7) The GHG emissions must be separately reported for each fuel or product component or blendstock of blended fuels or products separately.

(8) All importers of liquefied petroleum gas into New York must record composition, if provided by the supplier, and quantity in barrels, corrected to 60°F, for each shipment received

(b) Calculating GHG emissions.

(1) Liquid fuel and petroleum product suppliers must use Equation 2.16-1 as provided in paragraph (2) of this subdivision, to calculate the GHG emissions, CO_2, CH_4, N_2O of all liquid fuels and petroleum products as described in subdivision (a) of this section, based on the quantity and types of fuels reported as specified in subdivision (d) of this section. For fuels that are blended, emissions must be reported for each individual fuel component separately as listed in Table 2-5 of this section, and not as motor gasoline (finished), biofuel blends, or other similar finished fuel. Emissions from denatured fuel ethanol must be calculated as 100 percent ethanol only. The volume of denaturant is assumed to be zero and is not required to be reported. If a position holder in diesel or biodiesel fuel does not have

sealed or financial transaction meters at the rack, and the position holder is the sole position holder at the terminal, the position holder must calculate emissions based on the delivering person's invoiced volume of fuel or a meter that meets the requirements of section 1.4(g) of this section either at the rack or at a point prior to the fuel going into the terminal storage tanks.

(2) For calculating the emissions from liquefied petroleum gas, or biomass-derived fuels, the GHG emissions from the individual components must be summed. Emission factors must be taken from Table 2-5 of this section.

Equation 2.16-1: $GHGi = Producti * Emission\ Factori$

Where:

GHG_i=annual GHG emissions from product i reported by fuel supplier

$Product_i$ = annual quantity of liquid fuel or petroleum product reported by fuel supplier in an emission year

Emission $Factor_i$ = Emission factor for GHG per product as specified in Table 2-5 of this section.

(3) All fuel suppliers in this section must estimate CO_2e emissions using Equation 2.16-2 as provided in this paragraph:

Equation 2.16-2: $CO_2e = \sum_{i=1}^{n} GHGi\ x\ GWP20i$

Where:

CO_2e = Carbon dioxide equivalent, metric tons.

GHG_i = Mass emissions of CO_2, CH_4, N_2O from fuels utilization, metric tons.

GWP_{20i} = Global warming potential for each GHG as specified in the CO_2 equivalence definition of this Part.

n = Number of greenhouse gases emitted.

(4) All Position Holders and Enterers must calculate and report the upstream out-of-state emissions for affected liquid fuels or products pursuant to section 2.18 of this Part.

(5) Any fuel supplier intending to develop individualized product emission factors must follow the requirements in 40 CFR § 98.393(f)(2) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(6) All fuel suppliers in this section may make a demonstration to the department that the fuels or products supplied to an end user or facility were used to make a durable product that is ultimately not combusted or used as fuel.

(i) Without a demonstration, fuel and products are assumed to be combusted or otherwise emitted as a fugitive or vented emission.

(ii) The demonstration must meet the requirements of the department. Asphalt shall meet the demonstration requirement by being supplied to an Asphalt Pavement

Manufacturing Plant.

(iii) Fuel suppliers making successful demonstrations for quantities of fuel or product determined to be turned into durable products would be required to report the upstream out-of-state emissions associated with the fossil fuels in these products pursuant to section 2.18 of this Part.

(c) Monitoring and QA/QC Requirements. For the emissions calculation under subdivision (b) of this section, the fuel supplier must meet all the monitoring and QA/QC requirements as specified in 40 CFR § 98.394 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), and the requirements of 40 CFR § 98.3(i) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) as further specified in section 1.4 of this Part and this subdivision.

(1) Position holders are exempt from 40 CFR § 98.3(i) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) calibration requirements except when the position holder and person receiving the fuel have common ownership or are owned by subsidiaries or affiliates of the same company. In such cases the 40 CFR § 98.3(i) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) calibration requirements apply, unless:

(i) the fuel supplier does not operate the fuel billing meter;

(ii) the fuel billing meter is also used by companies that do not share common ownership with the fuel supplier; or

(iii) the fuel billing meter is sealed with a valid seal from the county sealer of weights and measures and the operator has no reason to suspect inaccuracies.

(2) As required by 40 CFR § 98.394(a)(1)(iii) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), for fuels that are liquid at 60°F and one standard atmosphere, the volume reported must be temperature and pressure adjusted to these conditions. For liquefied petroleum gas the volume reported must be temperature-adjusted to 60°F.

(d) Data Reporting Requirements. In addition to reporting the information required in 40 CFR § 98.3(c) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the following Reporting Entities must also report the information identified below:

(1) New York position holders must report the annual quantity in barrels, as reported by the terminal operator, of each liquid fuel or petroleum product listed in Table 2-5 of this section, that is delivered across the rack in New York, including separately reporting liquid fuel or petroleum product that is disbursed for final sale or to an end user in New York, for which a final destination outside New York has been determined, where liquid fuel use or petroleum product use in exclusively aviation or ocean going vessel can be demonstrated, or for liquid fuel or petroleum product that can be demonstrated to have been previously delivered by a position holder out of an upstream New York terminal rack prior to delivery out of a second terminal rack. Denatured fuel ethanol will be reported with the entire volume as 100 percent ethanol only. The volume of denaturant is assumed to be zero and is not required to be reported.

(2) New York position holders that are also terminal operators must report the annual quantity in barrels delivered across the rack of each liquid fuel or petroleum product listed in Table 2-5 of this section, including separately reporting for fuel or product that is

disbursed for final sale or to an end user in New York, that has a final destination outside New York, where a use in exclusively aviation or ocean going vessel can be demonstrated, or for fossil transportation fuels that can be demonstrated to have been previously delivered by a position holder or refiner out of an upstream New York terminal or refinery rack prior to delivery out of a second terminal rack. Denatured fuel ethanol will be reported with the entire volume as 100 percent ethanol only. The volume of denaturant is assumed to be zero and is not required to be reported. If there is only a single position holder at the terminal and only diesel or biodiesel is being dispensed at the rack, then the position holder must report the annual quantity of fuel using a meter meeting the requirements of section 1.4(g) of this Part, or billing invoices from the person delivering fuel to the terminal.

(3) Enterers delivering liquid fuel or petroleum product for distribution outside the bulk transfer/terminal system must report the annual quantity in barrels, as reported on the bill of lading or other shipping documents of each liquid fuel or petroleum product listed in Table 2-5 of this section that is imported as an affected liquid fuel, including affected liquid fuels when use in aviation or ocean going vessels can be demonstrated, except for fuel for which a final destination outside New York can be demonstrated. The denatured fuel ethanol component of a finished transportation fuel must be reported with the entire denatured ethanol volume as 100 percent ethanol only. The volume of denaturant is assumed to be zero and is not required to be reported. Biodiesel or renewable diesel blends containing no more than one percent petroleum diesel by volume are considered to be 100 percent biodiesel or renewable diesel.

(4) Below the rack distributors must report the affected liquid fuel or petroleum

product received from Position Holders and Enterers by reporting the volume of the fuel received and the previous owner of the fuel. Additionally, below the rack distributors must report to the previous owner any diversion or delivery to a reporting entity of affected liquid fuel.

(5) Upstream out of state emissions and supporting data used by the Position Holder or Enterer shall be shared with subsequent fuel owners if they are a reporting facility or below the rack distributor under this Part.

(6) All liquid fuel suppliers identified in this section must report the total quantity of blendstocks, New York Gasoline, New York diesel fuel, and biodiesel and/or renewable diesel that was imported from outside of New York for use in New York. In addition, for blendstocks imports, the designated percentage of oxygenate must be reported.

(7) Fuel suppliers identified in this section must report the total quantity of biodiesel and/or renewable diesel blended in New York diesel for use in New York.

(8) Fuel suppliers identified in this section must report the total quantity in barrels of each Blendstock, Distillate Fuel Oil, or biomass-derived fuel listed in Table 2-5 of this section that is excluded from emissions reporting due to demonstration of final destination outside New York or use in exclusively aviation or marine applications, or demonstration that the fuel was previously delivered by a position holder or refiner out of an upstream New York terminal or refinery rack prior to delivery out of a second terminal rack.

(9) All importers of liquefied petroleum gas into New York must record composition, if provided by the supplier, and quantity in barrels, corrected to 60°F, for each shipment received.

(10) In addition to the information required in 40 CFR § 98.3(c) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the importer of liquefied petroleum gas into New York must report the annual quantity of liquefied petroleum gas imported as the total volume in barrels as well as the volume of its individual components for all components listed in table MM-1 of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), if supplied by the producer.

(e) Procedures for Missing Data. For quantities of fuels that are purchased, sold, or transferred in any manner, fuel suppliers must follow the missing data procedures specified in 40 CFR § 98.395 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title). The supplier must document and retain records of the procedure used for all missing data estimates pursuant to the recordkeeping requirements of section 1.7 of this Part.

(f) The liquid fuel and petroleum products supplier shall provide:

(1) the data used to calculate emissions from the utilization of the fuel delivered, transferred, or sold to large emission sources, pursuant to section 1.2(f) of this Part, and other Reporting Entities of this Part that are the customers or end users of this fuel; and

(2) the name(s) of the facility, the customer account number(s), and the annual MMbtu delivered, transferred, or sold to large emission sources, pursuant to section 1.2(f) of this Part, and other Reporting Entities of this Part that are customers or end users of the fuel supplier to the department.

Table 2-5: Liquid Fuels and Petroleum Products Subject to Reporting Under Section 2.16 of this Part

Liquid fuels	Density (metric tons/bbl)	Carbon Share (% of Mass)	Emission Factor (Metric tons CO_2/bbl)	Emission Factor (g CH_4/bbl)	Emission Factor (g N_2O/bbl)
CBOB—Summer					
Regular	0.1181	86.66	0.3753	20	20
Midgrade	0.1183	86.63	0.3758	20	20
Premium	0.1185	86.61	0.3763	20	20
CBOB—Winter					
Regular	0.1155	86.50	0.3663	20	20
Midgrade	0.1161	86.55	0.3684	20	20
Premium	0.1167	86.59	0.3705	20	20
RBOB —Summer					
Regular	0.1167	86.13	0.3686	20	20
Midgrade	0.1165	86.07	0.3677	20	20
Premium	0.1164	86.00	0.3670	20	20
RBOB —Winter					
Regular	0.1165	85.05	0.3676	20	20
Midgrade	0.1165	86.06	0.3676	20	20
Premium	0.1166	86.06	0.3679	20	20
Distillate No. 1	0.1346	86.40	0.4264	18	3
Distillate No. 2	0.1342	87.30	0.4296	17	3
Distillate Fuel Oil No. 4	0.1452	86.47	0.4604	18	4
Residual Fuel Oil No. 5	0.1365	85.67	0.4288	18	3
Residual Fuel Oil No. 6	0.1528	84.67	0.4744	19	4
Kerosene-type Jet Fuel	0.1294	86.30	0.4095	17	3
Kerosene	0.1346	86.40	0.4604	17	3
Aviation Gasoline	0.1120	85.00	0.3490	15	3
Special Naphtha	0.1222	84.76	0.3798	16	3
Lubricants	0.1428	85.80	0.4492	18	4
Waxes	0.1285	85.30	0.4019	17	3
Asphalt and Road Oil	0.1634	83.47	0.5001	20	4
Liquefied Petroleum Gas (LPG)	0.0806	81.71	0.241	12	3

Ethane	0.0579	79.89	0.170	8	2
Ethylene	0.0492	85.63	0.154	7	1
Propane	0.0806	81.71	0.241	11	2
Propylene	0.0827	85.63	0.260	11	2
Butane	0.0928	82.66	0.281	13	3
Butylene	0.0972	85.63	0.305	13	3
Isobutane	0.0892	82.66	0.270	13	3
Isobutylene	0.0949	85.63	0.2939	13	3
Pentanes Plus	0.1055	83.63	0.3235	14	3
Ethanol (100%)	0.1267	52.14	0.2422	4	1
Biodiesel (≥99%, methyl ester)	0.1396	77.30	0.3957	6	1
Renewable Diesel (≥99%)	0.1342	87.30	0.4296	17	3
Rendered Animal Fat	0.1333	76.19	0.3724	6	1
Vegetable Oil	0.1460	76.77	0.4110	6	1

253-2.17 Suppliers of Natural Gas, Natural Gas Liquids, Compressed Natural Gas, and Liquified Natural Gas

Any supplier of natural gas or natural gas liquids who is required to report under section 1.2 of this Part must comply with subpart NN of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) in reporting emissions and related data to the department, except as otherwise provided in this section.

(a) GHGs to Report.

(1) In addition to the CO_2 emissions specified under 40 CFR § 98.402(a) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), natural gas liquid fractionators must report the CO_2, CH_4, N_2O, and CO_2e emissions that would result from the use of natural gas, natural gas liquids, or biomethane sold, transferred, or delivered to any end user in New York.

(2) In addition to the CO_2 emissions specified under 40 CFR § 98.402(b)

(Amended November 18, 2024) (see Table 1, section 200.9 of this Title), local distribution companies, energy service companies, interstate pipeline operators, and intrastate pipeline operators must report the CO_2, CO_2 from biomass-derived fuels, CH_4, N_2O, and CO_2e emissions from the use of natural gas, natural gas liquids, or biomethane sold, transferred, or delivered to any end-user in New York.

(3) The importer of compressed natural gas or liquefied natural gas into New York must report the CO_2, CH_4, N_2O, and CO_2e emissions that would result from the use of the annual quantity of compressed natural gas, and liquefied natural gas imported into the state, except for products for which a final destination outside New York can be demonstrated.

(4) Operators of facilities that make liquefied natural gas products or compressed natural gas products by liquefying or compressing natural gas received from interstate pipelines must report the CO_2, CH_4, N_2O, and CO_2e emissions that would result from the use of all liquefied natural gas sold or delivered to others, except for product for which a final destination outside New York can be demonstrated.

(b) Calculating GHG Emissions.

(1) Natural gas liquid fractionators must use calculation methodology 2 as specified in 40 CFR § 98.403(a)(2) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) to estimate the CO_2 emissions that would result from the complete combustion of all natural gas liquid products supplied except that table MM-1 of 40 CFR part 98 must be used in place of table NN-2 of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(2) For the calculation of CO_2i in paragraph (6) of this subdivision, local distribution companies must estimate CO_2 emissions at the state border or city gate for pipeline quality natural gas using calculation methodology 1 as specified in 40 CFR § 98.403(a)(1) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), except that the product of HHV and Fuel is replaced by the annual MMBtu of natural gas received.

(3) For the calculation of CO_2j in paragraph (6) of this subdivision, public utility gas corporations and publicly owned natural gas utilities must estimate annual CO_2 emissions from instate receipts of pipeline quality natural gas from other public utility gas corporations, interstate pipelines and intrastate transmission pipelines, and annual CO_2 emissions from all natural gas redelivered to other public utility gas corporations or interstate pipelines. Annual CO_2 emissions from redelivered natural gas to intrastate pipelines or publicly owned natural gas utilities must be estimated only if emissions from the redelivered natural gas equals or exceeds 1,000 MT CO_2e calculated according to paragraph (2) of this subdivision. Emissions are calculated according to Equation NN-3 of 40 CFR § 98.403(b)(1) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) except that CO_2j will be the product of MMBtuTotal and the default emission factor from table NN-1 of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) or the product of MMBtuTotal and the reporter specific emission factor. MMBtuTotal must be calculated using Equation 2.17-1 as provided in this paragraph:

$$\text{Equation 2.17-1: } MMBtu_{Total} = MMBtu_{redelivery} - MMBtu_{receipts}$$

Where:

$MMBtu_{Total}$ = Total annual MMBtu used in equation NN-3

$MMBtu_{redelivery}$ = Total annual MMBtu of natural gas delivered to other companies as specified above

$MMBtu_{receipts}$ = Total annual MMBtu of natural gas received from other companies as specified above

(4) For the calculation of CO_2l in paragraph (6) of this subdivision, emissions from receipts of pipeline quality natural gas from in-state natural gas producers and net volume of pipeline quality natural gas injected into storage are estimated according to Equation NN-5 of 40 CFR § 98.403(b)(3) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) except that CO_2l will be calculated as the product of the net annual MMBtu and a default emission factor from table NN-1 of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) or the product of the net annual MMBtu and a reporter specific emission factor.

(5) Determination of pipeline quality natural gas is based on the annual weighted average HHV, determined according to Equation C-2b of 40 CFR § 98.33(a)(2)(ii)(A) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), for natural gas from a single city gate, storage facility, or connection with an in-state producer, interstate pipeline, intrastate pipeline or local distribution company. If the HHV is outside the range of pipeline quality natural gas, emissions will be calculated using the appropriate subparagraph of subdivision (a) of this section replacing the default emission factor with

either a reporter specific emission factor as calculated in 40 CFR § 98.404(b)(2) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) or one determined as follows:

(i) For natural gas or biomethane with an annual weighted HHV below 970 Btu/scf and not exceeding three percent of total emissions estimated under this section, the local distribution company may use the reporter specific weighted yearly average higher heating value and the default emission factor, or an emission factor as determined in 40 CFR § 98.404(c)(3) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title). If emissions exceed three percent of the total, then the Tier 3 method specified in 40 CFR § 98.33(a)(3)(iii) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) must be used with monthly carbon content samples to calculate the annual emissions from the portion of natural gas that is below 970 Btu/scf.

(ii) For natural gas or biomethane with an annual HHV above 1100 Btu/scf and not exceeding three percent of total emissions estimated under this section, the local distribution company must use the reporter specific weighted yearly average higher heating value and a default emission factor of 54.67 kg CO_2/MMBtu or an emission factor as determined in 40 CFR § 98.404(c)(3) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title). If emissions exceed three percent of the total, then the Tier 3 method specified in 40 CFR § 98.33(a)(3)(iii) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) must be used with monthly carbon content samples to calculate the annual emissions from the portion of natural gas that is above 1100 Btu/scf.

(6) When calculating total CO_2 emissions for New York, use Equation 2.17-2 as provided in this paragraph:

Equation 2.17-2: $CO_2 = \sum CO_{2i} - \sum CO_{2j} - \sum CO_{2l}$

Where:

CO_2 = Total emissions.

CO_{2i} = Emissions from natural gas received at the state border or city gate, calculated pursuant to paragraph (2) of this subdivision.

CO_{2j} = Emissions from natural gas received for redistribution to or received from other natural gas transmission companies, calculated pursuant to paragraph (3) of this subdivision.

CO_{2l} = Emissions from storage and direct deliveries from producers calculated pursuant to paragraph (4) of this subdivision.

(7) Natural gas liquid fractionators, local distribution companies, and energy service companies must estimate and report CH_4 and N_2O emissions using Equation C-8 and table C-2 as described in 40 CFR § 98.33(c)(1) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for all fuels where annual CO_2 emissions are required to be reported by 40 CFR § 98.406 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) and this section. Local distribution companies must use the annual MMBtu determined in paragraphs (2) through (4) of this subdivision in place of the product of the Fuel and HHV in equation C-8 as described in 40 CFR § 98.33 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) when calculating emissions.

(8) Local distribution companies and energy service companies must separately

and individually calculate end-user emissions of CH_4, N_2O, CO_2 from biomass-derived fuels, and CO_2e by replacing CO_2 in Equation 2.17-2 as provided in paragraph (6) of this subdivision, with CH_4, N_2O, CO_2 from biomass-derived fuels, and CO_2e. CO_2 emissions from biomass-derived fuel are based on the fuel the LDC or an energy service company has contractually purchased on behalf of and delivered to end users. LDCs or energy service companies can elect to report biomethane directly purchased by an end user and delivered by the LDC or energy service company if the LDC or energy service company can provide the information required by section 1.4(f)(3) of this Part. Emissions from contractually purchased biomethane are calculated using the methods for natural gas required by this section, including the use of the emission factor for natural gas found in table NN-1 40 CFR § 98.408 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title). Biomass-derived fuels directly purchased by end users and delivered by the LDC or energy service company must be reported as natural gas by the LDC or energy service company, unless the LDC or energy service company has elected to report the delivery as biomethane and can provide the necessary documentation during verification to determine exemption status as stated above.

(9) The importer of compressed natural gas or liquefied natural gas into New York must estimate CO_2 using calculation methodology 1 as specified in 40 CFR § 98.403(a)(1) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), except that the product of HHV and Fuel is replaced by the annual MMBtu of the imported compressed natural gas and liquefied natural gas.

(10) The importer of compressed natural gas or liquefied natural gas into New

York must estimate and report CH_4 and N_2O emissions using Equation C-8 and table C-2 as described in 40 CFR § 98.33(c)(1) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(11) Operators of facilities that make liquefied natural gas products or compressed natural gas products as described in paragraph (a)(4) of this section must estimate CO_2 using calculation methodology 1 as specified in 40 CFR § 98.403(a)(1) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), except that the product of HHV and Fuel is replaced by the annual MMBtu of the liquefied natural gas sold or delivered in New York.

(12) Operators of facilities that make liquefied natural gas products or compressed natural gas products as described in paragraph (a)(4) of this section must estimate and report CH_4 and N_2O emissions based on the MMBtu of liquefied natural gas sold or delivered using Equation C-8 and table C-2 as described in 40 CFR § 98.33(c)(1) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(13) All fuel suppliers in this section must also estimate CO_2e emissions using equation 2.17-3 as provided in this paragraph:

Equation 2.17-3: $CO_2e = \sum_{i=1}^{n} GHG_i \times GWP20_i$

Where:

CO_2e = Carbon dioxide equivalent, metric tons/year.

GHGi = Mass emissions of CO_2, CH_4, N_2O from fuels or products.

GWP20i = Global warming potential for each GHG as specified in the CO_2 equivalence definition of this Part.

n = Number of greenhouse gases emitted.

(14) Fuel suppliers in this section must also estimate CO_2e emissions from fossil fuels for the upstream out-of-state emissions associated with the use of these fuels in New York pursuant to the emission factors specified in section 2.18 of this Part.

(15) All fuel suppliers in this section may make a demonstration to the department that the fuels or products supplied to an end user or facility were used to make a durable product which is ultimately not combusted or used as a fuel.

(i) Without a demonstration, fuel and products are assumed to be combusted or otherwise emitted as a fugitive or vented emission.

(ii) The demonstration must meet the requirements of the department.

(iii) Fuel suppliers making successful demonstrations for quantities of fuel or product determined to be turned into durable products are required to report the upstream out of state emissions associated with the fossil fuels in these products pursuant to section 2.18 of this Part.

(c) Monitoring and QA/QC Requirements. For each emissions calculation method chosen under this section, the supplier must meet all monitoring and QA/QC requirements specified in 40 CFR § 98.404 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), except as modified in this subdivision, and sections 1.4 and 2.7 of this Part.

(1) All natural gas suppliers must measure required values at least monthly.

(2) All natural gas suppliers must determine reporter specific HHV at least monthly, or if the local distribution company or energy service company does not make its own measurements according to standard business practices it must use the delivering pipeline measurement.

(3) All natural gas liquid fractionators must sample for composition at least monthly.

(d) Data Reporting Requirements.

(1) For the emissions calculation method selected under subdivision (b) of this section, natural gas liquid fractionators must report, in addition to the data required by 40 CFR § 98.406(a) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the annual volume of liquefied petroleum gas, corrected to 60°F, that was produced on-site and sold or delivered to others, except for products for which a final destination outside New York can be demonstrated. Natural gas liquid fractionators must report the annual quantity of liquefied petroleum gas produced and sold or delivered to others as the total volume in barrels as well as the volume of the individual components for all components listed in 40 CFR part 98 table MM-1 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title). Fractionators must also include the annual CO_2, CH_4, N_2O, and CO_2e mass emissions (metric tons) from the volume of liquefied petroleum gas reported in 40 CFR § 98.406(a)(5) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) as modified by this Part, calculated in accordance with subdivision (b) of this section.

(2) For the emissions calculation method selected under subdivision (b) of this

section, local distribution companies and energy service companies must report all the data required by 40 CFR § 98.406(b) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) subject to the following modifications:

(i) Publicly owned natural gas utilities that report in-state receipts at the city gate under 40 CFR § 98.406(b)(1) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) must also identify each delivering person by name and report the annual energy of natural gas received in MMBtu.

(ii) Local distribution companies that report under 40 CFR § 98.406(b)(1) through (b)(7) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) must also report the annual energy of natural gas in MMBtu associated with the volumes.

(iii) In addition to the requirements in 40 CFR § 98.406(b)(8) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), local distribution companies and energy service companies must also include CO_2, CO_2 from biomass-derived fuels, CH_4, N_2O, and CO_2e annual mass emissions in metric tons calculated in accordance with 40 CFR § 98.403(a) and (b)(1) through (4) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) as modified by subdivision (b) of this section.

(iv) In addition to the reporting requirements in 40 CFR § 98.406(b)(6) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), local distribution companies, energy service companies, and intrastate pipelines that deliver natural gas to downstream gas pipelines and other local distribution companies or energy service companies, must report the annual energy in MMBtu, and the information required in 40 CFR § 98.406(b)(12) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(v) In lieu of reporting the information specified in 40 CFR § 98.406(b)(7) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), local distribution companies, energy service companies, and intrastate pipelines must report the annual energy in MMBtu, customer information required in 40 CFR § 98.406(b)(12) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), and the department ID number if available for all end-users registering supply equal to or greater than 105,500 MMBtu during the calendar year. In addition to reporting the information specified in 40 CFR § 98.406(b)(13) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), local distribution companies, energy service companies, and intrastate pipelines that deliver to end users must report the annual energy in MMBtu delivered to the following end-use categories: residential consumers; commercial consumers; industrial consumers; electricity generating facilities; vehicle fuel; and other end-users not identified as residential, commercial, industrial, or electricity generating facilities as described by Form EIA-176 (2024) (see Table 1, section 200.9 of this Title). Local distribution companies and energy service companies must also report the total energy in MMBtu delivered to all New York end-users.

(vi) Local distribution companies that report under 40 CFR § 98.406(b)(9) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) must report annual CO_2, CO_2 from biomass-derived fuel, CH_4, N_2O, and CO_2e emissions (metric tons) that would result from the complete combustion or oxidation of the natural gas supplied to all entities calculated in accordance with subdivision (b) of this section.

(3) In addition to the information required in 40 CFR § 98.3(c) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator of an interstate

pipeline that is not a local distribution company must report the customer name, address, and the department ID along with the annual energy of natural gas in MMBtu for natural gas delivered to each customer, including themselves.

(4) In addition to the information required in 40 CFR § 98.3(c) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator of an intrastate pipeline that delivers natural gas directly to end users must follow the reporting requirements described under subpart NN of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) and this section for local distribution companies. In lieu of the city gate information specified by paragraph (b)(2) of this section, the intrastate pipeline operator must report the summed energy (MMBtu) of natural gas delivered to each person receiving gas from the intrastate pipeline for purposes of estimating the CO_2i parameter as specified in paragraph (b)(6) of this section. Additionally, intrastate pipeline operators are required to estimate a value for CO_2j as specified in paragraph (b)(3) of this section for natural gas delivered to local distribution companies, interstate pipelines, energy service companies, and other intrastate pipelines. The CO_2l parameter (for storage and direct deliveries from producers) as specified in paragraph (b)(4) of this section must have a value of 0 (zero) for calculating emissions using equation 2.17-2 as provided in paragraph (b)(6) of this section.

(5) All importers of compressed or liquefied natural gas into New York and liquefied natural gas production facilities as described in paragraph (a)(4) of this section must report the annual quantities imported, and delivered or sold, respectively, in MMBtu, and report CO_2, CH_4, N_2O, and CO_2e annual mass emissions in metric tons separately for compressed natural gas and liquefied natural gas using the calculation methods in

subdivision (b) of this section.

(6) In addition to the information required in 40 CFR § 98.3(c) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), all local distribution companies and energy services companies that report biomass emissions from biomethane fuel that was contractually purchased by the LDC or energy service company on behalf of and delivered to end users, and all liquefied natural gas production facilities reporting biomass emission from biomethane, must report, for each contracted delivery, the information specified in section 1.4(f)(3) of this Part.

(7) All operators of facilities that make liquefied natural gas products as described in paragraph (a)(4) of this section must report end-user information for deliveries of liquefied natural gas to industrial facilities and natural gas utility customers, including customer name, address, and the annual quantity of liquefied natural gas delivered to each customer in MMBtu.

(8) All natural gas liquid fractionators identified in this section must report the total quantity in barrels of liquefied petroleum gas that is excluded from emissions reporting due to demonstration of a final destination outside New York.

(9) Local distribution companies and energy service companies must report annually a summary of monthly gas sales, transfers, or deliveries to end users in New York. The content of this report shall include for each county in the service area:

(i) the number of residential, commercial, or industrial meters receiving natural gas;

(ii) the total quantity of natural gas received through meters; and

(iii) the number of meters receiving quantities of natural gas that fall into discretized five-therm increments.

(e) Procedures for estimating missing data. Suppliers must follow the missing data procedures specified in 40 CFR § 98.405 (Amended November 18. 2024) (see Table 1, section 200.9 of this Title). The operator must document and retain records of the procedure used for all missing data estimates pursuant to the recordkeeping requirements of section 1.7 of this Part.

(f) A natural gas, natural gas liquids, compressed natural gas, and liquid natural gas supplier shall provide:

(1) the data used to calculate emissions from the utilization of the fuel delivered, transferred, or sold to large emission sources, pursuant to section 1.2(f) of this Part, and other Reporting Entities of this Part that are the customers or end users of this fuel; and

(2) the name(s) of the facility, the customer account number(s), and annual MMbtus delivered, transferred, or sold to large emission sources, pursuant to section 1.2(f) of this Part, and other Reporting Entities of this Part that are customers or end users of the fuel supplier to the department.

253-2.18 Upstream Out-of-State Emissions from Fossil Fuels or Products

Owners or operators of facilities, suppliers of fossil fuels or products into New York and electric power entities that are required to report under section 1.2 of this Part must comply with all applicable requirements below.

(a) Any fuel supplier, electric power entity, or facility shall report upstream out-of-state

emissions for each MMBtu of fuel or products sold or brought into New York for sale to an end user, or consumed or used at a facility, or used to produce electricity imported into New York.

(1) These emissions shall be reported by multiplying the emission factor provided in Table 2-6 of this section by the MMBtus reported as fossil fuel or products, sold to an end user, provided for sale to end users, or reported as used by a facility. Emission factors from Table 2-6 shall be utilized for fossil fuels or products as indicated in Table 2-6.1 of this section, unless otherwise specified in this Part.

Table 2-6: Upstream Out-of-State Emission Factors	
Fuel or Product Category	Emission factor (kg CO_2e per mmbtu)
Natural Gas	40.877
Coal	41.939
Diesel/Distillate Fuel	23.540
Gasoline/Blendstocks	28.866
Kerosene/Jet Fuel	18.193
LPG	26.474
Petroleum Coke	20.114
Residual Fuel	19.411
Asphalt and Road Oil	16.438
Lubricants	27.026
Waxes	26.386
Miscellaneous Petroleum Products	18.977
Special Naphthas	22.591

Table 2-6.1: Fuel or Product and Corresponding Fuel Category for Upstream Out-of-State Emission Factors	
Fossil Fuel or Product:	Fuel or Product Category (from Table 2-6):
Asphalt and Road Oil	Asphalt and Road Oil
Coal (all types)	Coal
Distillate (all types)	Diesel/Distillate Fuel

Blendstocks (all types)	Gasoline/Blendstocks
Kerosene	Kerosene/Jet Fuel
Kerosene-type Jet Fuel	Kerosene/Jet Fuel
Butylene	LPG
Ethylene	LPG
Isobutylene	LPG
Liquid Petroleum Gas (LPG)	LPG
Propane	LPG
Propylene	LPG
Lubricants	Lubricants
Miscellaneous Petroleum Products	Miscellaneous Petroleum Products
Butane	Natural Gas
Ethane	Natural Gas
Isobutane	Natural Gas
Natural Gas	Natural Gas
Pentanes Plus	Natural Gas
Petroleum Coke	Petroleum Coke
Residual Fuel (all types)	Residual Fuel
Special Naphtha	Special Naphtha
Waxes	Waxes

(2) A fuel supplier, electric power entity, or facility may use basin specific emission factors for natural gas provided in Table 2-7 of this section if it can demonstrate to the department through invoices, bills of lading, or other fuel analytical data that the origin of that natural gas can be shown to come from a specific production basin.

Table 2-7: Basin Specific Emission Factors	
Basin	Emission factor (kg CO_2e per mmbtu)
Gulf Conventional	44.740
East Texas Conventional	28.055
Anadarko Conventional	46.798
Arkoma Conventional	66.184
Appalachia Conventional	258.553
Gulf Shale	62.196
East Texas Shale	30.965
Anadarko Shale	28.843

Arkoma Shale	34.369
Appalachia Shale	29.798
Gulf Tight	27.325
East Texas Tight	35.158
Anadarko Tight	38.512

(b) Any fuel supplier shall report the following data or source information for fuel sold or brought into New York for sale to end user for each calendar year.

(1) The quantity of fuel by type as listed in Table 2-6 of this section in units of MMBtu for all fuels including solid, liquid, and gaseous fuels. Additionally, fuel suppliers must report the quantity of fuel by type imported into New York in units of metric tons for solid fuels, barrels for liquid fuels, or Mscf (a thousand standard cubic feet) for gaseous fuels.

(2) The corporation’s name and physical address of the fuel production facility or upstream entity that sold the fuel product to the fuel supplier. The physical address must include the street address, city, state, and zip code. If the fuel production facility or upstream entity does not have a physical street address, then the fuel supplier must provide the latitude and longitude representing the geographic centroid or center point of fuel production facility operations in decimal degree format. This must be provided in a comma-delimited “latitude, longitude” coordinate pair reported in decimal degrees to at least four digits to the right of the decimal point.

(3) The transportation distance of the imported fuel from the fuel production facility specified in subdivision (c) of this section to the New York border in miles and the mode of transportation used to transmit the fuel to the New York border. Fuel suppliers must report the distance traveled by the fuel for each mode used to transmit the fuel to the New York border in miles.

(4) Liquid fuel suppliers and petroleum fuel suppliers must report the following data for petroleum fuels imported into New York.

(i) The API gravity.

(ii) Carbon ratio in units of percent by weight.

(iii) Sulfur ratio in units of parts per million by weight.

(iv) Low heating value and high heating value in units of MMBtu per barrel.

(v) The portion of biofuels blended into the petroleum fuel in percent.

(vi) The modes used to transport the petroleum fuel from the fuel production facility to the New York border including, but not limited to, transport by rail, ocean tanker, barge, truck, or pipeline and the following information for the specific modes of transport:

('a') For rail transport, the energy intensity in MMBtu per ton-mile and average speed in meters per second of the rail.

('b') For ocean tanker or barge transport, the average speed in meters per second, power in horsepower, and load factor of the ship.

('c') For trucks, the fuel economy in miles per gallon.

('d') For pipelines, the fuel type transported in the pipeline and the energy intensity of the pipeline in MMBtu per ton-mile.

(5) Coal suppliers must report the following data for coal imported into New York.

(i) The high heating value as required under section 2.15(b)(1) of this

Part.

(ii) The type of coal imported including anthracite, bituminous, sub-bituminous, or lignite.

(iii) The methods used to transport the coal to the New York border including, but not limited to, transport by conveyor belt, truck, barge, ocean vessel, or train.

(iv) The percentage of total imported coal that is cleaned or processed to remove impurities.

(6) Natural gas suppliers must report the following fuel specifications for natural gas imported into New York.

(i) The low heating value and high heating value of the imported natural gas in units of MMBtu per Mscf (one thousand standard cubic feet).

(ii) The mass fraction of methane of the imported natural gas.

(c) Any fuel production facility or other entity that sells a fuel product to a fuel supplier must report the following data or information for each calendar year.

(1) Fuel producers shall report the quantity of fuel by type used on site or combusted by stationary fuel combustion sources described in 40 CFR § 98.30 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) in units of MMBtu.

(2) Petroleum refiners must comply with the data reporting requirements described in 40 CFR § 98.396(a) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title) and report the following data.

(i) The type of crude oil processed at the refinery including conventional crude oil, shale oil, or oil sands.

(ii) The share of total crude oil processed at the facility that is sourced from the United States, Canada, Mexico, the Middle East, Latin America, Africa, or other locations in percent. For crude oil sourced from the United States, report the source basin of crude oil processed at the facility.

(iii) The quantity of petroleum products by type sold to New York fuel suppliers specified in section 1.2 of this Part in units of barrels.

(iv) The mode of transportation, as specified in subparagraph (b)(4)(vi) of this section, used to transmit the crude oil from the original source or extraction point to the refinery and the distances traveled by the crude oil on each mode of transportation in miles. If the refiner does not know the modes used to transport crude oil to the refinery, then the refiner shall report the distance between the geographic origin of the fuel and the refinery.

(v) The API gravity of crude oil processed at the facility.

(vi) The sulfur content of crude oil processed at the facility in units of percent by weight.

(vii) The refinery heavy product yield or the ratio of the yield of residual fuel oil, asphalt, coke, slurry oil, and reduced crude in MMBtu to the yield of total products in MMBtu made at the refinery.

(viii) The Refinery Complexity Index (RCI) of the facility using Equation 2.18-1 as provided in this subparagraph:

Equation 2.18-1: $RCI = 1 + \Sigma_i [(Q_i/Q_o) * CF_i]$

Where:

Q*i* is the capacity of refinery operation *i* in barrels per day;

Q*o* is the distillation capacity of the refinery in barrels per day;

CF*i* is the Nelson complexity factor of the refinery operation ***i*** as defined in Table 2-8 of this section.

Table 2-8: Complexity Factors for Refining Operations	
Refinery Operation	Complexity Factor (CF*i*)
Atmospheric Distillation	1
Vacuum Distillation	2
Thermal cracking	2.75
Delayed coking	6
Catalytic cracking	6
Catalytic reforming	5
Catalytic hydrocracking	6
Catalytic hydrorefining	3
Catalytic hydrotreating	2
Alkylation	10
Polymerization/dimerization	10
Aromatics	15
Isomerization	15
Lubes Production	10
Oxygenate Production	10
Hydrogen Production	1
Asphalt Production	1.5

(ix) For gasoline products, report the following data.

('a') The percentage of ethanol blended into the fuel.

('b') The O_2 content of the gasoline product in units of percent by

weight.

(‘c’) The percentage share of corn, willow, poplar, switchgrass, miscanthus, corn stover, forest residue, sorghum, integrated corn/stover, sugarcane, or solid waste used as ethanol feedstocks.

(x) The source of H_2 production for use in the refinery including natural gas, proton exchange membrane electrolysis, or nuclear high temperature electrolysis.

(3) Coal mines must report the following data for each calendar year.

(i) The type of coal mined as specified in subparagraph (b)(5)(ii) of this section.

(ii) The transmission distance of the coal from the mine to the fuel supplier in units of miles and the mode of transport including conveyor belt, truck, barge, ocean vessel, or train.

(iii) The extraction method of the coal including underground mining or surface mining.

(4) Natural gas processing facilities must report the following data for each calendar year.

(i) The quantity of natural gas throughput at the facility in units of Mscf.

(ii) The source basin of the raw natural gas as specified in Table 2-7 of this section and the type of natural gas processed at the facility including conventional onshore gas, conventional offshore gas, associated gas, tight gas, shale gas, and coal bed methane.

(iii) The quantity of methane emitted from acid gas removal in units of kg

methane per kg natural gas.

(iv) The quantity of methane emitted from dehydrator venting, centrifugal compressor venting, and reciprocating compressor venting in units of metric tons.

(d) Monitoring, Data, and Records. Any fuel supplier or fuel production facility who is required to report under section 1.2 of this Part must maintain records supporting the receipt and sale of petroleum fuels, natural gas, or coal to an individual or retail location in New York. The suppliers must retain the following records for five years substantiating each of the supplies that they report.

(1) Invoices, an electronic record of transfers, or any other records used to determine or that can verify the quantities reported under subdivision (b) and subdivision (c) of this section.

(2) An electronic record of entities from which supplies were received or that the reporting entity supplied during each reporting year.

253-2.19 Waste Haulers and Transporters

A transporter of solid waste who is required to report under section 1.2 of this Part and that exceeds an applicability threshold under subdivision (a) of this section must report annual emissions and other data as specified in this section.

(a) Applicability Threshold. Transporters of solid waste are required to report under this section if they transport an amount of solid waste that exceeds any of the following threshold levels. Short tons shall be converted to metric tons where indicated.

(1) The estimated emissions from solid wastes transported to landfills or

combustion facilities outside of New York exceed 10,000 MT CO_2e emissions per year, using Equation 2.19-1 as provided in this paragraph. Unspecified waste shall be assessed in the same manner as waste deposited in a municipal solid waste (MSW) landfill and included in emission calculations for landfills. This threshold would be equivalent to the emissions from solid waste transported out of state to landfill facilities and/or that is unspecified waste exceeding 1,750 metric tons in any year, or to combustion facilities exceeding 12,220 metric tons in any year.

Equation 2.19-1: $CWE = (W_X*LWF) + (CW_X*CWF)$

Where:

CWE = Combined waste emissions

W_X = Annual tonnage of waste transported for the purposes of disposal in landfills or unspecified wastes (metric tons)

LWF = Landfill waste factor or 5.71t CO_2e per metric ton

CW_X = Annual tonnage of waste transported for the purposes of combustion (metric tons)

CWF = Emission factors for CO_2 for municipal solid waste and for CH_4 and N_2O for other solid fuels included in subpart C of 40 CFR part 98 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title).

(2) The estimated emissions from solid wastes transported to landfills outside of New York exceed 10,000 MT CO_2e emissions per year, using Equation 2.19-2 as provided in

subdivision (b) of this section.

(b) CH_4 from landfilled or unspecified waste. Applicable Reporting Entities under subdivision (a) of this section are required to report the mass of CH_4 that would result from the disposal of solid waste into industrial or MSW landfills located outside of New York. Unspecified waste shall be assessed in the same manner as waste deposited in a MSW landfill and included in emission calculations for landfills.

Equation 2.19-2: $CO_2e_{LW} = [G_{CH4} * (1\text{-}OX)] * GWP20_{CH4}$

Where:

CO_2e_{LW} = Annual CH_4 generation from solid wastes transported to landfills outside of New York or for which the ultimate destination is unspecified, starting with the first reporting year.

G_{CH4} = Methane generation rate following 40 CFR § 98.343(a) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) for MSW or unspecified waste or 40 CFR § 98.463(a) (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), incorporated by reference herein, using appropriate default values and where the start year of calculation (S) is the first reporting year.

OX = Oxidation fraction based on a default value of 0.10

(c) Combusted solid waste. Entities are required to report the mass of CO_2, CH_4, and N_2O emissions that would result from the combustion of solid waste transported to stationary

combustion facilities outside of New York, using Equation 2.19-3 as provided in this subdivision.

Equation 2.19-3: $CO_2e_{CW} = (CW * CWF_{CO2}) + (CW * CWF_{CH4} * GWP20_{CH4}) + (CW * CWF_{N2O} * GWP20_{N2O})$

Where:

CO_2e_{CW} = Annual CH_4 emissions from solid wastes transported to landfills outside of New York, starting with the first reporting year

CW = Annual tonnage of waste transported for the purposes of combustion (metric tons / year)

CWF = Emission factors for CO_2 for municipal solid waste and for CH_4 and N_2O for other solid fuels included in subpart C of 40 CFR part 98 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title)

(d) Additional Methane Data Collection. Transporters subject to reporting requirements under this section may apply to use a revised DOC following the solid waste composition verification procedures under section 2.20(b) of this Part.

(e) Additional data reporting requirements. Each entity must submit an annual report that summarizes transportation of solid waste from New York as follows.

(1) Total mass in metric tons of solid waste transported from New York to locations outside of New York.

(2) The aggregated annual quantity of solid waste in metric tons that can be attributed to the following.

(i) Name and location of the facility from which the waste was received.

(ii) The type of facility from which the waste was received including municipal or commercial.

(iii) Name and location of the final destination to which the waste was transported.

(iv) The type of facility to which the waste was transported including landfills, combustion facilities, composting and other organics processing facilities or organics recycling facilities, recyclables handling and recovery facilities, or unspecified facilities.

(f) Records. In addition to the data required under subdivision (d) of this section, entities must retain the following records for five years.

(1) Invoices, an electronic record of transfers, or any other records used to determine or that can verify the quantities reported under subdivision (e) of this section.

(2) An electronic record of entities from which wastes were received or that the reporting entity transported wastes to during each reporting year.

253-2.20 Additional Methane Data Collection

(a) Emissions Monitoring and Measurement Plan. Operators of solid and liquid waste management facilities that are required to report under sections 2.13 and 2.2 of this Part and exceed the applicability threshold in paragraph (1) of this subdivision shall develop and implement an operation or facility-specific Emissions Monitoring and Measurement Plan

(EMMP) in addition to meeting reporting requirements in sections 2.13 and 2.2 of this Part.

(1) Applicability: Operators are required to develop and implement an EMMP for facilities that met the following criteria.

(i) the operator of the anaerobic digester or liquid storage were required to report under section 2.2(a)(1) of this Part and were not eligible for abbreviated reporting under section 2.2(a)(2) of this Part; or

(ii) the operator of the solid waste landfill reported annual emissions exceeding 300,000 MT CO_2e emissions calculated according to section 2.13 of this Part.

(2) Department Approval: The operator of an applicable facility or operation must submit an EMMP proposal to the department no later than March 1, 2026, and every three years thereafter in a format approved by the department. Approval of the proposal by the department is required. Proposals must include the following.

(i) a timeline for completing and reporting EMMP results to the department by March 1, 2029, and every three years thereafter;

(ii) the name and contact information of an authorized representative of the facility operator along with their signed certification confirming that the statements and information submitted are true, accurate, and complete;

(iii) the name and contact information for any third parties involved in proposal development or implementation;

(iv) a scaled operation or facility site plan that delineates the area over which emissions will be monitored and identifies the locations of landfills, gas capture systems, gas flares, anaerobic digesters or reactors, liquid, or slurry waste storages and

other waste-derived emission sources;

(v) the duration of monitoring;

(vi) methods for accepting, comparing, and reconciling activity and operational data with emissions measurements; and

(vii) measurement and monitoring procedures that may be based on recommended guidance from the department and which may include but are not limited to the following:

(‘a’) reporting leak detection and repair for operations that include biogas flaring or biogas capture systems such as landfills and anaerobic digesters or reactors;

(‘b’) emissions detection exercises that are able to capture higher volume emission events that happen at a low frequency or intermittently;

(‘c’) detection exercises that are undertaken at an appropriate frequency to capture potential temporal variation in emissions;

(‘d’) detection exercises that capture emissions from an area that includes a statistically significant population of relevant emission sources;

(‘e’) measurement exercises that are undertaken at an appropriate frequency to capture potential temporal variation in emissions;

(‘f’) measurement exercises that capture emissions from an area that includes a statistically significant population of relevant emission sources;

(‘g’) measurement of emissions from all sources determined to be above a threshold which may be activity-based;

(‘h’) a process for disaggregating equipment-level emissions or other individual emission sources that are within the monitoring or measurement footprint for site-level methods;

(‘i’) quantification of uncertainty associated with the proposed emissions measurements and methods for assessing the uncertainty associated with individual emission sources and site-level emissions; or

(‘j’) plans for record keeping and documentation that may include leak detection and repair survey results, results of regular equipment performance testing and maintenance, calibration curves, and standard operating procedures for each analytical method or instrument.

(3) Results Submission: The operator of a facility must submit to the department the completed EMMP results for the previous calendar year in a format approved by the department no later than March 1, 2029, and every three years thereafter. The operator of a facility must submit a completed report that follows an approved EMMP and will include the information required to obtain accurate and unbiased emissions data from individual sources, pursuant to ECL 75-0105(4).

(4) Third-party services and group submissions: EMMP proposals may be developed by an entity other than the operator of the facility with expertise in emissions quantification methodologies and may incorporate monitoring at multiple facilities, operations, or on behalf of multiple operators.

(5) Cessation of EMMP. After an operator of a facility has completed and submitted one round of EMMP data collection and documentation, the department may then

determine that the operator is exempt from subsequent rounds of EMMP. Exemption from completing a round of EMMP does not exempt a facility operator from annual reporting of the facility's activity data or annual emissions to the department under sections 2.13 or 2.2 of this Part. If activity data or emissions reported to the department indicate the likely exceedance of 10,000 MT CO_2e emissions in any year after cessation requirements have been met, the department may require the operator to resume EMMP data collection, documentation, and submission, and the operator must meet all applicable requirements under this section.

(b) Solid Waste Composition Verification. Operators of landfill facilities and waste transporters required to report under sections 2.13 or 2.19 of this Part may apply to the department to revise the method used to calculate reported emissions if they are able to provide sufficient documentation that the degradable organic carbon fraction of the waste accepted by the facility is different from the degradable organic carbon fraction used in sections 2.13 or 2.19 of this Part. Applications must be submitted to the department before March 1st of each year and in a format that is acceptable to the department. Approval by the department is required before a revised degradable organic carbon value can be used in subsequent reporting.

(1) Methods for documenting the degradable organic carbon fraction of the waste accepted at a facility should be developed in coordination with the department and may include waste composition audits, quantifying variability in the degradable organic carbon fraction of the facility's total accepted waste during the reporting year, quantifying other sources of uncertainty in measurements of the degradable organic carbon fraction, and documentation of the quantity of waste audited relative to the quantity of waste accepted for placement at the

facility.

(2) Records that document or substantiate an application to revise the composition of the waste accepted by a facility must be retained for five years after the application is submitted to the department and must be made available to the department upon request. Such documentation may include but is not limited to invoices from organics diversion programs, invoices, and other documentation of waste audits by third parties, or bills of lading.

253-2.21 Fluorinated Greenhouse Gases

Operators of facilities required to report under sections 1.1 and 1.2 of this Part must comply with all applicable requirements below. This includes producers of industrial GHGs and facilities that use equipment that contains refrigerant.

(a) Producers of fluorinated GHGs. Operators of facilities required to report under section 1.2 of this Part must comply with the requirements of subpart L of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title).

(b) Fugitive Refrigerant Sources. Operators of facilities required to report under sections 1.1 and 1.2 of this Part must provide an annual report on fugitive refrigerant sources. Fugitive refrigerant sources are devices that contain 50 pounds or greater of fluorinated GHGs as refrigerants used for heat transfer purposes. Fugitive refrigerant sources include, but are not limited to, commercial air-conditioning or heat pump equipment or systems, industrial process equipment or systems, or other commercial refrigeration equipment or systems. The annual report must include the following.

(1) Annual emissions of fluorinated GHGs in CO_2e based on leak rate as

estimated using the rolling average method under 40 CFR § 82.152 (November 18, 2016) (see Table 1, section 200.9 of this Title). Annual emissions shall be product of the leak rate, refrigerant charge size, and GWP20 of the refrigerant, summed for all applicable fugitive refrigerant sources at the facility.

(2) Annual reporting information as provided in section 494-2.6(b) of this Title.

(c) Monitoring, Data, and Records.

(1) Production facilities subject to reporting requirements in this section must maintain records and make available upon request by the department a copy of the following information, pursuant to section 1.7 of this Part, where applicable.

(i) Invoices of all fluorinated GHGs distributed or received in New York through sale or transfer, indicating business names, business addresses, the date of sale or transfer, the quantity of each type of fluorinated GHG sold or transferred, and the name and email address of an authorized representative for the supplier and recipient.

(ii) A list of all known suppliers, purchasers, or other recipients for the previous five years, including business names, business address, and the name and email address of an authorized representative for each business.

(iii) Facility information, including the mailing address and the name, title, and email address for an authorized representative for each manufacturing, distribution, wholesale, destruction, or reclaim facility under the operational control of the person or business.

(iv) Any other records used to determine or that can verify the quantities reported under this section.

(2) Facilities subject to report under this section must maintain records as provided in section 494-2.7 of this Title.

(3) Fugitive refrigerant emission sources. Operators of facilities subject to reporting under subdivision (b) of this section must maintain records and make available to the department the following information, pursuant to section 1.7 of this Part.

(i) Documentation of all leak inspections, dates and locations of identified leaks, dates on which any automatic leak detection systems triggered an alert, and annual audit and calibrations for leak inspection devices and automatic leak detection systems.

(ii) Records of service and leak repairs including the name of the person performing the service, dates of refrigerant additions or equipment repairs.

(iii) Invoices of all purchases of regulated substances.

(iv) Records of all shipments of regulated substances for reclamation or destruction. The records must include all of the following information:

('a') name and address of the person the regulated substance was shipped to;

('b') date of shipment;

('c') regulated substance shipped; and

('d') purpose of shipment (e.g., reclamation or destruction).

(v) Records of all refrigeration or air conditioning component data, measurements, calculations, and assumptions used to determine the full refrigerant charge capacity and leak rate.

253-2.22 Industrial Product Data Reporting Requirements

(a) A large emission source from an industrial sector listed in Table 2-9 of this section must also report total annual production data associated with all NAICS codes applicable to activity at the facility, including but not limited to specific product descriptions and units of production for each specific product based on each such NAICS code.

(1) Large emission sources reporting industrial product data must report product data using consistent units for each reporting year. If applicable to the product, the product data should be reported in mass units. The department may accept a change of the reporting unit if a large emission source submits a written request justifying the change.

Table 2-9: Industrial Product Data Reporting NAICS Codes	
NAICS Sector Description	NAICS Code
Food Manufacturing	311XXX
Beverage and Tobacco Product Manufacturing	312XXX
Textile Mills	313XXX
Textile Product Mills	314XXX
Apparel Manufacturing	315XXX
Leather and Allied Product Manufacturing	316XXX
Wood Product Manufacturing	321XXX
Paper Manufacturing	322XXX
Printing and Related Support Activities	323XXX
Petroleum and Coal Products Manufacturing	324XXX
Chemical Manufacturing	325XXX
Plastics and Rubber Products Manufacturing	326XXX
Nonmetallic Mineral Product Manufacturing	327XXX
Primary Metal Manufacturing	331XXX
Fabricated Metal Product Manufacturing	332XXX
Machinery Manufacturing	333XXX
Computer and Electronic Product Manufacturing	334XXX
Electrical Equipment, Appliance, and Component Manufacturing	335XXX
Transportation Equipment Manufacturing	336XXX
Furniture and Related Product Manufacturing	337XXX
Miscellaneous Manufacturing	339XXX

Subpart 253-3. Additional Requirements for Reported Data

253-3.1 Substitution for Missing Data Used to Calculate Emissions from Stationary Combustion and CEMS Sources.

In lieu of the requirements for estimating missing data in subpart C of 40 CFR part 98 (Amended May 14, 2024) and subpart D of 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title), the operator of a facility who is reporting emissions under sections 2.5 or 2.7 of this Part must follow the applicable procedures of this section for estimating missing or invalid data. The operator must include the substituted data in the GHG emissions data report and maintain all records, calculations, and data used to estimate substituted data according to the requirements of section 1.7 of this Part and 40 CFR part 98 (Amended November 18, 2024) (see Table 1, section 200.9 of this Title). Alternatively, under the limited circumstances specified in this section for equipment breakdown, the operator may request approval of an interim data collection procedure as specified in subdivisions (h) and (i) of this section. For units combusting biomass-derived fuels or for sources using limited alternative emissions provisions in section 1.4(e) of this Part, the operator who is reporting emissions must follow either the requirements below or the requirements of 40 CFR § 98.35 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title). In the event that this section becomes applicable to a source, compliance with the requirements of this section does not relieve the operator from complying with other sections of this Part.

(a) Missing Data Substitution Procedures for Units Reporting Under 40 CFR Part 75. The operator of a unit that is reporting CO_2 using 40 CFR part 75 (July 1, 2023) (see Table 1,

section 200.9 of this Title) must follow the applicable missing data substitution procedures in subpart D of 40 CFR part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title) and appendix C to 40 CFR part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title) for CO_2 concentration, stack gas flow rate, fuel flow rate, high heat value, and fuel carbon content, except as otherwise provided in this section. Subdivisions (b) through (g) of this section do not apply to these units for CO_2 emissions. The operator may use applicable missing data procedures under 40 CFR part 75 (July 1, 2023) (see Table 1, section 200.9 of this Title) or the procedures in subdivisions (b) through (g) of this section for CH_4 and N_2O emissions that are not designated as limited alternative emissions as provided in section 1.4(e) of this Part if data required for calculating CH_4 and N_2O emissions are missing or invalid.

(b) Missing Data Substitution Procedures for Other Units Equipped with CEMS. The operator of a stationary combustion unit who monitors and reports emissions and heat input data for that unit under section 2.7 of this Part using Tier 4 of 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) must follow the applicable missing data substitution procedures in 40 CFR § 75.31-.37 (July 1, 2023) (see Table 1, section 200.9 of this Title). For the purpose of missing data substitution, for CEMS certified under 40 CFR part 60 (July 1, 2024) (see Table 1, section 200.9 of this Title), quality-assured data is defined according to the quality assurance/quality control procedures in appendix F to 40 CFR part 60 (July 1, 2024) (see Table 1, section 200.9 of this Title). Subdivisions (c) through (h) of this section do not apply to units using Tier 4 of 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for CO_2 emissions but do apply for CH_4 and N_2O emissions that are not designated as limited alternative emissions as

provided in section 1.4(e) of this Part if data required for calculating CH_4 and N_2O emissions are missing or invalid.

(c) Missing Data Substitution Procedures for Fuel Characteristic Data. When the applicable emissions estimation methods of this Part require periodic collection of fuel characteristic data (including carbon content, high heat value, and molecular weight), the operator must demonstrate every reasonable effort to obtain a fuel characteristic data capture rate of 100 percent for each emission year. When fuel characteristic data of a required fuel sample are missing or invalid, the operator must first attempt to either reanalyze the original sample or perform the fuel analysis on a backup sample, or replacement sample from the same collection period as specified in 40 CFR § 98.34(a)(2) through (3) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), to obtain valid fuel characteristic data. If the sample collection period has elapsed and no valid fuel characteristic data can be obtained from a backup or replacement sample, the operator must substitute for the missing data the values obtained according to the procedures in paragraphs (1) through (3) of this subdivision. The data capture rate for the emission year must be calculated using Equation 3.1-1 as provided in this subdivision for each type of fuel and each fuel characteristic parameter:

Equation 3.1-1: Data capture rate = S / T x 100%

Where:

S = Number of fuel samples for which valid fuel characteristic data were

obtained according to the applicable sampling requirements (including sampling schedule)

T = Total number of fuel samples required by the applicable sampling requirements

(1) If the fuel characteristic data capture rate is at least 90 percent for the emission year, the operator must substitute the arithmetic average of the values of that parameter immediately preceding and immediately following the missing data incident that are representative of the fuel type. If the “after” value has not been obtained by the time that the GHG emissions data report is due, the operator must use the “before” value for missing data substitution.

(2) If the fuel characteristic data capture rate is at least 80 percent but not more than 90 percent for the emission year, the operator must substitute for each missed value with the highest valid value recorded for that type of fuel during the emission year, as well as the two previous emission years.

(3) If the operator is unable to obtain fuel characteristic data such that less than 80 percent of a fuel characteristic data element are directly accounted for, the operator must then substitute for each missed data point as follows:

(i) If historical fuel characteristics data are available and kept according to the requirements of section 1.7 of this Part, substitute with the greater of the following:

(‘a’) the highest valid value recorded for that type of fuel for all records kept under the requirements of section 1.7 of this Part; or

(‘b’) the default value in Table 3-1 of this section (for carbon content) or table C-1 of 40 CFR part 98 (for high heat value) (Amended May 14, 2024) (see

Table 1, section 200.9 of this Title). If a substitute value is not available in Table 3-1 of this section or table C-1 of 40 CFR part 98 (Amended May 14, 2024) (see Table 1, section 200.9 of this Title), the operator must substitute the highest value recorded for that type of fuel for all records kept pursuant to the requirements of section 1.7 of this Part.

(ii) For carbon content data, if historical fuel characteristics data are not available and a default value is not listed in Table 3-1 of this section, use 90 percent for other liquid and gaseous fuels and 100 percent for other solid fuels in substituting for missed carbon content data.

Table 3-1: Default Carbon Content	
Parameter	Missing Data Value
Anthracite Coal	90%
Bituminous	85%
Subbituminous/Lignite	75%
Oil	90%
Natural Gas	75%

(d) Missing Data Substitution Procedures for Fuel Consumption Data. An operator subject to the requirements of this Part must demonstrate every reasonable effort to obtain a total facility fuel consumption data capture rate of 100 percent for each year for each type of fuel. The total facility fuel consumption for the emission year can be determined using any combination of meters and/or other fuel measurement devices or methods that individually meet the accuracy requirements of this Part, provided that the total amount of fuel consumed at the facility level is completely accounted for during each time period that the facility is in operation. For each fuel type, when the total facility fuel consumption data that meet the accuracy requirements of this Part are available during each time period that the facility is in

operation, but such data are missing or invalid at the unit level, the operator must either estimate missing unit-level fuel consumption data using other available data parameters that are routinely measured at the facility (e.g., electrical load, steam production, operating hours, production output, or fuel consumption data at other measurement points), or use an applicable missing data substitution procedure from paragraphs (1) through (3) of this subdivision. If during any time periods that the facility is in operation, a portion of the total facility fuel consumption is missing or cannot be determined at the accuracy required by this Part, the operator must use the applicable missing data substitution procedure from paragraphs (1) through (3) of this subdivision, so that the total facility fuel consumption quantity for the missing data periods is reconstructed. If a source is eligible for more than one procedure in paragraphs (1) through (3) of this subdivision, the operator has the option to choose one of the applicable procedures in paragraphs (1) through (3) of this subdivision. The requirements in paragraphs (1) through (3) of this subdivision are optional for sources that are not required to meet the accuracy standard specified in section 1.4(g) of this Part and for sources that do not use fuel consumption data for emission calculation.

(1) Continuous Fuel Flow Rate Data Using Load Ranges. The sources that meet the following criteria are eligible for using the procedures in this paragraph: the sources combust gaseous or liquid fuels, produce electrical or thermal output, use a fuel flow meter system to continuously measure fuel flow rate; and are equipped with a data acquisition and handling system or DAHS that continuously records fuel flow rates and measured electrical or thermal output on an hourly basis, which enables segregation of the fuel flow rate data into bins. The operator of such sources that applies the requirements in this paragraph must

substitute missing fuel flow rate data according to this paragraph.

Whenever quality-assured fuel flow rate data are missing and there is no backup system available to record the fuel flow rate, the operator must use the following procedures to account for the flow rate of fuel combusted at the source for each hour during the missing data period. Before using these procedures, operators must establish load ranges for the affected sources using the procedures in subdivision (f) of this section.

When load ranges are used for estimating missing fuel flow rate data, the operator must create and maintain separate fuel-specific databases for the source. The database for each type of fuel combusted must include the hours in which the fuel is combusted alone at the source and the hours in which it is co-fired with any other fuel types. The database must record fuel flow rate and corresponding electrical output or thermal output and assign these values into the established load bins. To be eligible to use the missing data procedures in this paragraph, measured electrical output or thermal output must be available for the hour(s) in which fuel flow rate data are missing. If output data are missing, the operator must follow the requirements of paragraph (3) of this subdivision.

(i) Single Fuel Type. For missing data periods that occur when only one type of fuel is being combusted, the operator must provide substitute data for each hour of the missing data period as follows: Substitute the arithmetic average of the hourly quality-assured fuel flow rate(s) measured and recorded by a fuel flowmeter system at the corresponding operating source load range during the previous 720 operating hours in which the source combusted only that same fuel. If 720 hours of fuel flow rate data are not available at the corresponding load range, the operator may combine available data with data from

higher load ranges if available until 720 hours are reached. If 720 hours of quality-assured fuel flow rate data are not available when combined with higher load ranges, the operator must substitute the maximum potential fuel flow rate for each hour of the missing data period.

(ii) Multiple Fuel Types. For missing data periods that occur when two or more different types of fuel are being co-fired, the operator must provide substitute fuel flow rate data for each hour of the missing data period as follows:

(‘a’) Substitute the maximum hourly quality-assured fuel flow rate(s) measured and recorded by a fuel flowmeter system at the corresponding operating source load range during the previous 720 operating hours when the fuel for which the flow rate data are missing was co-fired with any other type of fuel. If 720 hours of fuel flow rate data are not available at the corresponding load range, data from higher load ranges if available may be combined until 720 hours are reached. If 720 hours of quality-assured fuel flow rate data are not available when combined with higher load ranges, the operator must substitute the maximum potential fuel flow rate for each hour of the missing data period.

(‘b’) If, during an hour in which different types of fuel are co-fired, quality-assured fuel flow rate data are missing for two or more of the fuels being combusted, apply the procedures in clause (‘a’) of this subparagraph. separately for each type of fuel.

(‘c’) If the missing data substitution required in clauses (‘a’) and (‘b’) of this subparagraph causes the reported hourly heat input rate based on the combined fuel usage to exceed the maximum rated hourly heat input of the unit, adjust the substitute fuel flow rate value(s) so that the reported heat input rate equals the unit’s maximum rated hourly heat input.

(iii) Lookback Period. In any case where the missing data provisions of this section require substitution of data measured and recorded more than three years (26,280 clock hours) prior to the date and time of the missing data period, the operator must substitute the maximum potential fuel flow rate for each hour of the missing data period. In addition, for sources in operation less than three years (26,280 clock hours), until 720 hours of quality-assured fuel flowmeter data are available for the lookback periods described in subparagraphs (i) and (ii) of this paragraph, the methodology in paragraph (3) of this subdivision must be used to determine the appropriate substitute data values.

(2) Fuel Consumption Data Without Load Ranges. The sources that meet the following criteria are eligible to use the procedures in this paragraph: the facility operator has established and implemented a fuel monitoring plan as a part of the GHG Monitoring Plan specified in section 1.7(e) of this Part, has monitored fuel measurement equipment and maintained records of its proper operation by recording fuel consumption quantities at least weekly, and has compiled records of fuel consumption that are sufficient for the application of the procedures in this paragraph. For operators that apply the requirements in this paragraph, whenever quality-assured fuel consumption data are missing and there is no backup system available to record the fuel consumption, the operator must use the procedures in this paragraph to account for the consumption of fuel combusted at the unit during the missing data period. For fuels that are combusted less than 180 days in a calendar year, the operator must record fuel consumption at least daily on each day the fuel is combusted. For all other sources or fuels, the operator must record fuel consumption at least weekly.

The data capture rate for the emission year must be calculated using Equation 3.1-2 as provided in this paragraph for each unit with missing fuel consumption data:

Equation 3.1-2: Data capture rate = S / T x 100%

Where:

S = Number of fuel monitoring periods (e.g., days or weeks) in the emission year for which valid measured fuel consumption data are available.

Do not include fuel monitoring periods when the fuel was not combusted at the unit.

T = Total number of fuel monitoring periods (e.g., days or weeks) in the emission year that the fuel is combusted at the unit.

(i) Single Fuel. For missing data periods that occur when only one type of fuel is being combusted, the operator must provide substitute data for each missing data period as follows:

(‘a’) If the fuel consumption data capture rate is equal to or greater than 95 percent during the emission year, the operator must develop an estimate based on available process data that are routinely measured and recorded at the unit (e.g., electrical load, steam production, operating hours) or fuel consumption data recorded at other upstream or downstream measurement points.

(‘b’) If the fuel consumption data capture rate is equal to or greater

than 90 percent but less than 95 percent during the emission year, the operator must calculate substitute data as the 90th percentile value of the fuel consumption data recorded for the emission year as well as the two previous emission years.

(‘c’) If the fuel consumption data capture rate is at least 80 percent but less than 90 percent during the emission year, the operator must calculate substitute data as the 95th percentile value of the fuel consumption data recorded for the emission year as well as the two previous emission years.

(‘d’) If the fuel consumption data capture rate is less than 80 percent during the emission year, the operator must apply as substitute data the maximum potential fuel consumption rate.

(ii) Multiple Fuels. For missing data periods that occur when two or more different types of fuel are being co-fired, the operator must provide substitute fuel flow rate data for each missing data period as follows:

(‘a’) If the fuel consumption data for a single fuel are missing, provide substitute fuel consumption data for the missing data period using the procedures in subparagraph (i) of this paragraph.

(‘b’) If fuel consumption data are missing for two or more of the fuels being combusted, apply the procedures in subparagraph (i) of this paragraph (as applicable) separately for each type of fuel.

(‘c’) If the missing data substitution required in subparagraph (i) of this paragraph causes the reported heat input rate based on the combined fuel usage to exceed the maximum rated heat input of the source, adjust the substitute fuel consumption

value(s) so that the reported heat input rate equals the source's maximum rated heat input.

(iii) Prorating Substitute Value. When applying the procedures in subparagraphs (i) and (ii) of this paragraph, if an individual missing data period is shorter than the fuel consumption data monitoring period, the operator must prorate the specified value for the fuel consumption data monitoring period by the missing data period. For example, for a unit with a missing data period length of one day but weekly fuel consumption monitoring schedule, the operator may divide the substitute value, estimated on a weekly basis, by the number of days the unit operates in a week to obtain the substitute value for the missing data day.

(3) Alternate Missing Data Procedure for Fuel Consumption Data. This paragraph applies to fuel combusting units that cannot use the missing data procedures in paragraphs (1) and (2) of this subdivision. If fuel consumption data are missing or invalid for a fuel combusting unit, and the total facility fuel consumption data cannot be determined at the accuracy required by this Part for the particular missing data period, the operator must substitute for each hour of missing data using the maximum potential fuel consumption rate for the unit. If fuel consumption data at the facility level or at a higher aggregated-units level are available and meet the accuracy requirements of this Part, the operator may estimate the missing unit-level fuel consumption data using available process data that are routinely measured at the facility (e.g., electrical load, steam production, operating hours) or fuel consumption data recorded at other upstream or downstream measurement points that meet the accuracy requirements of this Part.

(e) Missing Data Substitution Procedures for Steam Production. The operator of a

steam-producing unit who calculates and reports emissions using Equation C-2c in 40 CFR § 98.33(a)(2) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) must apply the procedures in this subdivision to substitute for missing steam production data, unless a backup system to record steam production is available. For sources for which steam production data are not used to calculate emissions, the operator may develop an estimate using available process data that are routinely measured and recorded at the unit (e.g., electrical load, steam production, product output, operating hours) to estimate missing steam production.

If hourly steam production data are not available at the facility, the operator must record steam production data at least weekly and use the weekly records for substituting the missing steam production data. The operator must prorate the steam data using the same procedure in subparagraph (d)(2)(iii) of this section.

The data capture rate for the emission year must be calculated using Equation 3.1-3 as provided in this subdivision for each unit with a missing data period:

Equation 3.1-3: Data capture rate = S / T x 100%

Where:

S = Number of monitoring intervals (e.g., hourly, daily, or weekly) with valid measured steam production data.

T = Total number of monitoring intervals that the unit is operated in the emission year.

(1) If the steam production data capture rate is at least 90 percent during the emission year, the operator must develop an estimate using available process data that are routinely measured and recorded at the unit (e.g., electrical load, steam production, product output, and operating hours).

(2) If the steam production data capture rate is at least 80 percent but less than 90 percent during the emission year, the operator must calculate substitute data as the 90th percentile value of the steam production data recorded for the emission year.

(3) If the steam production data capture rate is less than 80 percent during the emission year, the operator must substitute the highest valid steam production value recorded in all records kept according to section 1.7(a) of this Part.

(f) Procedure for Establishing Load Ranges. This subdivision is applicable to units that produce electrical output or thermal output. For a single unit, the operator must establish 10 operating load ranges, each defined in terms of percent of the maximum hourly average gross load of the unit, in gross megawatts (MW). (Do not use integrated hourly gross load in MWh.) For a cogenerating unit or other unit at which some portion of the heat input is not used to produce electricity, or for a unit for which hourly average gross load in MW is not recorded separately, the operator must use the hourly gross steam load of the unit, in pounds of steam per hour at the measured temperature (°F) and pressure (psia), instead of gross MW.

(1) Beginning with the first hour of unit operation after installation and certification of the fuel flowmeter, for each hour of unit operation the operator must record a

number, 1 through 10, that identifies the operating load range corresponding to the integrated hourly gross load of the unit(s) recorded for each unit operating hour. The operator must calculate maximum values and percentile values determined by this procedure using bias adjusted values in the load ranges. When a bias adjustment is necessary for the fuel flowmeter, the operator must apply the adjustment factor to all data values placed in the load ranges. The operator must use the calculated maximum values and percentile values to substitute for missing flow rate according to the procedures in paragraph (d)(1) of this section.

(g) Department Approved Load Range. An operator may petition the department for approval to use an alternate load-based methodology for substituting missing data to using the procedures in paragraph (d)(1) of this section. The operator must be able to prove to the satisfaction of the department that there is a direct correlation between fuel consumption and the proposed load metric. At a minimum, the operator will have a system in place that electronically measures and records fuel consumption and load at least hourly. The alternate load metric must be a metric that can be accurately measured, correlated to fuel consumption, and divided into ten operating load ranges. To verify the feasibility of the methodology the department will require at least three years of fuel consumption and load data and may request up to the maximum years of data required to be retained under section 1.7(a) of this Part.

(h) Procedure for Approval of Interim Fuel Analytical Data Collection Procedure During Equipment Breakdowns.

(1) In the event of an unforeseen breakdown of the fuel characteristic data

monitoring or fuel flow monitoring equipment used to estimate emissions under this Part, the department may authorize an operator to use an interim data collection procedure under the circumstances specified below. The operator must satisfactorily demonstrate to the department that:

(i) the breakdown may result in a loss of more than 10 percent of a fuel characteristic data element or a fuel usage data element for the emission year, and back-up sampling for affected fuel characteristics is unavailable;

(ii) the affected monitoring equipment cannot be promptly repaired or replaced without shutting down a process unit significantly affecting facility operations, or the monitoring equipment must be replaced, and replacement equipment is not immediately available; and,

(iii) the interim procedure will not remain in effect longer than is reasonably necessary for repair or replacement of the malfunctioning monitoring equipment.

(2) An operator seeking approval of an interim data collection procedure must, within 60 days of the monitoring equipment breakdown, submit a written request to the department that includes all of the following:

(i) the proposed start date and end date of the interim procedure;

(ii) a detailed description of what data are affected by the breakdown;

(iii) a discussion of the accuracy of data collected during the interim procedure compared with the data collected under the usual procedure used by the operator;

(iv) a demonstration that the criteria in paragraph (1) of this subdivision are satisfied, and operator certification that no feasible alternative procedure exists that

would provide more accurate emissions data.

(3) The department may limit the duration of the interim data collection procedure to ensure the criteria in paragraph (1) of this subdivision are met.

(4) When reviewing an interim data collection procedure, the department shall determine whether the accuracy of data collected under the procedure is reasonably equivalent to data collected from properly functioning monitoring equipment, and if it is not, the relative accuracy to assign for purposes of assessing possible material misstatement under section 4.2 of this Part. Data collected pursuant to an approved interim data collection procedure shall be considered captured data for purposes of compliance with the capture rate requirements in this section.

(5) The department shall provide written notification to the operator of approval or disapproval of the interim data collection procedure within 60 days of receipt of the request, or within 30 days of receipt of any additional information requested by the department, whichever is later.

(i) Procedure for Approval of Interim Data Collection Procedure During Breakdown for Units Equipped with CEMS.

(1) In the event of an unforeseen breakdown of CEMS equipment at a combustion unit where the operator uses the Tier 4 Calculation Methodology in 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) to monitor and report emissions under this Part, the operator may request approval from the department to temporarily use the Tier 1 Calculation Methodology in 40 CFR § 98.33(a)(1) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for pipeline quality natural gas, or the Tier

2 Calculation Methodology in 40 CFR § 98.33(a)(2) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for pipeline quality natural gas, biomass, or MSW, or the Tier 3 Calculation Methodology in 40 CFR § 98.33(a)(3) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) for other fuels, to calculate combustion emissions during the equipment breakdown period. For cement kiln units where the operator uses the Tier 4 Methodology in 40 CFR § 98.33(a)(4) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) to report both combustion and process emissions, the operator may request approval from the department to temporarily use the clinker-based process emissions calculation methodology provided in 40 CFR § 98.83(d) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title). The operator must satisfactorily demonstrate to the department that:

(i) the breakdown will result in a loss of more than 10 percent of the concentration, flow rate, or other information used to calculate and report annual emissions for the emission year, and that back-up monitoring is unavailable;

(ii) the affected monitoring equipment cannot be promptly repaired or replaced without shutting down a process unit significantly affecting facility operations, or the monitoring equipment must be replaced, and replacement equipment is not immediately available; and,

(iii) the interim procedure will not remain in effect longer than is reasonably necessary for repair or replacement of the malfunctioning monitoring equipment.

(2) The operator must collect fuel samples and comply with all applicable requirements of the Tier 2 or Tier 3 Calculation Methodology in 40 CFR § 98.33(a)(2) or (3)

(Amended May 14, 2024) (see Table 1, section 200.9 of this Title), as modified by section 2.7 of this Part, during the equipment breakdown period. Fuel characteristics data provided by the fuel suppliers can be used if available. The operator must, within 60 days of the monitoring equipment breakdown, submit a written request to the department that includes all the following information:

(i) the proposed start date and end date of the interim procedure, including a demonstration that the interim procedure will not remain in effect longer than is reasonably necessary for repair or replacement of the malfunctioning equipment;

(ii) a detailed description of what data are affected by the breakdown; and,

(iii) an interim monitoring plan that meets the requirements of the Tiers 2 and 3 Calculation Methodologies in 40 CFR § 98.33(a)(2) or (3) (Amended May 14, 2024) (see Table 1, section 200.9 of this Title) as applicable by fuel type in section 2.7 of this Part, and, if applicable, the clinker-based process emissions calculation procedure in 40 CFR § 98.83(d) (Amended April 25, 2024) (see Table 1, section 200.9 of this Title) used to report cement kiln process emissions.

(3) The department may limit the duration of the interim data collection procedure to ensure the criteria in paragraph (1) of this subdivision are met.

(4) The department shall provide written notification to the operator of approval or disapproval of the interim data collection procedure within 60 days of receipt of the request, or within 30 days of receipt of any additional information requested by the department, whichever is later.

Subpart 253-4 Requirements for Verification of Greenhouse Gas Emissions Data Reports and Requirements Applicable to Emissions Data Verifiers; Requirements for Accreditation of Emissions Data

253-4.1 Requirements for Verification of Emissions Data Reports

An emission source who is subject to verification must obtain the services of an accredited verification body for purposes of verifying each emissions data report submitted under this Part, as specified in section 1.4(c) of this Part, unless exempt from verification under section 1.2(l)(2) of this Part.

(a) Annual Verification.

(1) Emission Sources that are required to obtain verification services, pursuant to section 1.4(c) of this Part, must meet the full verification requirements, pursuant to section 4.2 of this Part, in the first year of each continuous three-year period in which verification services are required. Upon receiving a positive verification statement, or statements, if applicable, under full verification requirements, the reporting entity may choose to obtain less intensive verification services as defined pursuant to this Part, for the remaining years of the continuous three-year period. Emission sources subject to this section are also required to obtain full verification services if any of the following apply:

(i) there has been a change in the verification body;

(ii) an adverse verification statement or qualified positive verification statement was issued for the previous year for either emissions data or product data, or both;

(iii) a change of operational control of the emission source occurred in the previous year.

(iv) Nothing in this paragraph shall be construed as preventing a verification body from performing a full verification in instances where there are changes in sources or emissions or industrial products. The verification body must provide information on the causes of the emission changes and justification in the verification report if a full verification was not conducted in instances where the total reported GHG emissions differ by greater than 25 percent relative to the preceding year's emissions data report.

(2) Emission sources subject to annual verification under this section shall not use the same verification body or verifier(s) for a period of more than six consecutive years, which includes any verifications conducted under this Part and for other third-party verifications, validations, or audits conducted under impartiality provisions substantively equivalent to section 4.4 of this Part, which may include third-party certification of environmental management systems to the standard of ISO 14001:2015 Environmental management systems — Requirements with guidance for use Published (Edition 3, 2015) (see Table 1, section 200.9 of this Title) or of third-party certification of energy management systems to the standard of ISO 50001:2018 Energy management systems —Requirements with guidance for use Published (Edition 2, 2018) (see Table 1, section 200.9 of this Title). This limitation applies only to those third-party verifications, validations, or audits that include the scope of activities or operations under the department identification number for the emissions data report.

(i) The six-year period begins on the date the reporting entity or its agent

first contracts for any third-party verifications, validations, or audits under any protocols, including department verification services, for the scope of activities or operations under the department identification number for the emissions data report, and ends on the date the final verification statement is submitted. Verification bodies may not provide verification services if the six-year period ends prior to 60 days after the emissions data report is certified by the emission source, unless a verification plan is agreed to by the emission source, the verification body, and the department. If the six-year time limit is exceeded, the emission source must engage a different verification body and meet the verification deadline. Even if these services are provided before the verification body or verifiers have received department accreditation, the six-year period still begins when these services are contracted for if accreditation is later received.

(ii) The six-year limit also applies to verification bodies and verifiers providing the department or any other third-party verifications, validations, or audits that include the scope of activities or operations under the department identification number for the emissions data report and does not reset upon a change in emission source ownership or operational control.

(3) If an emission source is required or elects to contract with another verification body or verifier(s), the emission source may contract verification services from the previous verification body or verifier(s) only after not using the previous verification body or verifier(s) for at least three years.

(i) If an emission source is required to select a new verification body to verify an emissions data report(s) that has been set aside pursuant to section 4.2(e) of this

Part, the emission source may continue to contract for verification services with its current verification body, subject to the six-year time limit.

(4) If an owner or operator of an emission source meets the requirements for cessation of reporting pursuant to section 1.2(n) or 1.2(o) of this Part, the owner or operator must continue to obtain the services of an accredited verification body for purposes of verifying the emissions data report for the year in which the facility's GHG-emitting processes and operations ceased to operate. Verification is not required for the emissions data report of the first full year of non-operation that follows. If the emission source was not subject to verification before meeting the cessation of reporting requirements pursuant to section 1.2(n) or 1.2(o) of this Part, verification is not required under this section for the year in which the facility's GHG-emitting processes and operations ceased to operate.

253-4.2 Requirements for Verification Services

Verification services shall be subject to the following requirements:

(a) Notice of Verification Services. After the department has provided a determination that the potential for a conflict-of-interest is acceptable as specified in section 4.4(f) of this Part and that verification services may proceed, the verification body shall submit a notice of verification services to the department. The verification body may begin verification services for the reporting entity after the notice is received by the department but must allow 14 days advance notice of the site visit unless an earlier date is approved by the department in writing. If the conflict-of-interest statement and the notice of verification services are submitted together, verification services cannot begin until 10 days after the department has

deemed acceptable the potential for conflict-of-interest as specified in section 4.4(f) of this Part. Verification services may not begin until the emission source certifies the emissions data report. The notice shall include the following information:

(1) A list of the staff who will be designated to provide verification services as a verification team, including the names of each designated staff member, the lead verifier, and all subcontractors, and a description of the roles and responsibilities each member will have during verification.

(2) Documentation that the verification team has the skills required to provide verification services for the reporting facility. This shall include a demonstration that a verification team includes at least one member accredited as a sector-specific verifier that is not also the independent reviewer, when required by subparagraph (i) through (iii) of this paragraph:

(i) for providing verification services to a supplier of petroleum products or biofuels; a supplier of coal; a transporter of solid waste; a supplier of natural gas, natural gas liquids, or liquefied petroleum gas, at least one verification team member must be accredited by the department as a transactions specialist;

(ii) for providing verification services to the operator of a petroleum refinery, hydrogen production unit or facility, or petroleum and natural gas system listed in section 1.2(k) of this Part, at least one verification team member must be accredited by the department as an oil and gas systems specialist;

(iii) for providing verification services to the operator of a facility engaged in anaerobic digestion and liquid waste storage, cement production, glass production,

electronics manufacturing, lime manufacturing, iron and steel production, solid waste management, or lead production, at least one verification team member must be accredited by the department as a process emissions specialist.

(3) General information on the reporting entity, including:

(i) the name of the reporting entity and the facilities and other locations that will be subject to verification services, reporting entity contact, address, telephone number, and e-mail address;

(ii) the industry sector and the NAICS code for the reporting facility;

(iii) the date(s) of the on-site visit, if required in section 4.1(a)(1) of this Part, with facility address and contact information;

(iv) a brief description of expected verification services to be performed, including expected completion date.

(4) If any of the information under paragraphs (1) or (3) of this subdivision changes after the notice is submitted to the department, the verification body must notify the department by submitting an updated conflict-of-interest self-evaluation form and updated notice of verification services as soon as the change is made. The conflict-of-interest must be reevaluated pursuant to section 4.4 of this Part and the department must approve any changes in writing.

(b) Verification Service Components. Verification services shall include, but are not limited to, the following:

(1) Verification Plan. The verification team shall develop a verification plan based on the following:

(i) Information from the reporting entity. Such information shall include:

(‘a’) information to allow the verification team to develop a general understanding of facility or emission source boundaries, operations, emission sources, product data, and electricity or fuel transactions as applicable;

(‘b’) information regarding the training or qualifications of personnel involved in developing the emissions data report;

(‘c’) description of the specific methodologies used to quantify and report GHG emissions, product data, electricity and fuel transactions, and associated data as needed to develop the verification plan;

(‘d’) information about the data management system used to track GHG emissions, product data, electricity and fuel transactions, and associated data as needed to develop the verification plan;

(‘e’) previous verification reports.

(ii) Timing of verification services. Such information shall include:

(‘a’) dates of proposed meetings and interviews with reporting facility personnel;

(‘b’) dates of proposed site visits;

(‘c’) types of proposed document and data reviews;

(‘d’) expected date for completing verification services.

(2) Planning Meetings with the Emission Source. The verification team shall discuss with the emission source the scope of the verification services and request any information and documents needed for initial verification services. The verification team shall

create a draft sampling plan and verification plan prior to the site visit during full verification. The verification team shall also review the documents submitted and plan and conduct a review of original documents and supporting data for the emissions data report.

(3) Site Visits. At least one accredited verifier in the verification team, including the sector-specific verifier, if applicable, shall at a minimum make one site visit, during each year full verification is required, to each facility for which an emissions data report is submitted. The verification team member(s) shall visit the headquarters or other location of central data management when the reporting entity is a retail provider, marketer, or fuel supplier. During the site visit, the verification team member(s) shall conduct the following:

(i) The verification team member(s) shall check that all sources specified in sections 2.1 to 2.22 of this Part, as applicable to the emission source and subject to verification, are identified appropriately.

(ii) The verification team member(s) shall review and understand the data management systems used by the reporting entity to track, quantify, and report GHG emissions and, when applicable, product data, and electricity and fuel transactions. The verification team member(s) shall evaluate the uncertainty and effectiveness of these systems.

(iii) The verification team shall carry out tasks that, in the professional judgment of the team, are needed in the verification process, including the following:

('a') interviews with key personnel, such as process engineers and metering experts, as well as staff involved in compiling data and preparing the emissions data report;

('b') making direct observations of equipment for data sources and equipment supplying data for sources determined in the sampling plan to be high risk;

('c') assessing conformance with measurement accuracy, data capture, and missing data substitution requirements, as well as department approved alternate methods, temporary methods, and department approved meter calibration postponements;

('d') reviewing financial transactions to confirm fuel, feedstock, product data and electricity purchases and sales, and confirming the complete and accurate reporting of required data such as facility fuel suppliers, fuel quantities delivered, and if fuel was received directly from an interstate pipeline.

(4) Review of Emission Source's Operations, Product Data and Emissions. The verification team shall review facility operations to identify applicable GHG emission sources and product data. This shall include a review of the emissions inventory and each type of emission source to ensure that all sources listed in sections 2.1 to 2.22 of this Part are properly included in the emissions data report. This shall also include a review of the product data to ensure that all product data listed in sections 2.1 to 2.22 of this Part are included in the emissions data report as required by this Part. The verification team shall also ensure that the reported current primary and any secondary (if reported) NAICS codes reported pursuant to section 1.5(c) of this Part accurately represent the NAICS-associated Activities listed in Table 2-9 in section 2.22 of this Part. Review of these NAICS codes and associated activities must be documented in the verification team's sampling plan.

(5) Other Emission Source Information. Emission sources shall make available

to the verification team all information and documentation used to calculate and report emissions, product data, fuels and electricity transactions, and other information required under this Part, as applicable.

(6) Sampling Plan. As part of confirming emissions data, product data, electricity transactions, or fuel transactions, the verification team shall develop a sampling plan that meets the following requirements:

(i) The verification team shall develop a sampling plan based on a strategic analysis developed from document reviews and interviews to assess the likely nature, scale, and complexity of the verification services for an emission source. The analysis shall review the inputs for the development of the submitted emissions data report, the rigor and appropriateness of data management systems, and the coordination within the emission source's organization to manage the operation and maintenance of equipment and systems used to develop emissions data reports.

(ii) The verification team shall include in the sampling plan a ranking of emission sources by amount of contribution to total CO_2e emissions for the emission source, and a ranking of emission sources with the largest calculation uncertainty. The verification team shall also include in the sampling plan a ranking of the product data by units specified in the appropriate section of this Part and a ranking of the product data with the largest uncertainty. As applicable and deemed appropriate by the verification team, fuel and electricity transactions shall also be ranked or evaluated relative to the amount of fuel or power exchanged and uncertainties that may apply to data provided by the emission source including risk of incomplete reporting.

(iii) The verification team shall include in the sampling plan a qualitative narrative of uncertainty risk assessment in the following areas as applicable under sections 2.1 to 2.22 and 3.1 of this Part:

('a') data acquisition equipment;

('b') data sampling and frequency;

('c') data processing and tracking;

('d') emissions calculations;

('e') product data;

('f') data reporting; and

('g') management policies or practices in developing emissions data reports.

(iv) After completing the analyses required by subparagraphs (i) through (iii) of this paragraph, the verification team shall include in the sampling plan a list which includes the following:

('a') emission sources, product data, and/or transactions that will be targeted for document reviews, and data checks as specified in paragraph (8) of this subdivision, and an explanation of why they were chosen;

('b') methods used to conduct data checks for each source, product data, or transaction;

('c') a summary of the information analyzed in the data checks and document reviews conducted for each emission source, product data, or transaction targeted.

The sampling plan list must be updated and finalized prior to the completion of verification services. The final sampling plan must describe in detail how the identified risks were addressed during the verification.

(v) The verification team shall revise the sampling plan to describe tasks completed by the verification team as information becomes available and potential issues emerge with material misstatement or nonconformance with the requirements of this Part.

(vi) The verification body shall retain the sampling plan in paper, electronic, or other format for a period of not less than 10 years following the submission of each verification statement. The sampling plan shall be made available to the department upon request.

(vii) The verification body shall retain all material received, reviewed, or generated to render a verification statement for a reporting entity for no less than 10 years. The documentation must allow for a transparent review of how a verification body reached its conclusion in the verification statement.

(7) Data Checks. To determine the reliability of the submitted emissions data report, the verification team shall use data checks. Such data checks shall focus on the largest and most uncertain estimates of emissions, product data and fuel and electricity transactions, and shall include the following:

(i) the verification team shall use data checks to ensure that the appropriate methodologies and emission factors have been applied for the emission sources, fuel and electricity transactions covered under sections 2.1 to 2.22 and 3.1 of this Part;

(ii) the verification team shall use data checks to ensure the accuracy of

product data reported under sections 2.1 to 2.22 of this Part;

(iii) the verification team shall choose data checks for emission sources, product data, and fuel and electricity transactions data, as applicable, based on their relative contributions to emissions and the associated risks of contributing to material misstatement or nonconformance, as indicated in the sampling plan;

(iv) the verification team shall use professional judgment in the number of data checks required for the team to conclude with reasonable assurance whether the total reported emissions and industrial product data are free of material misstatement. At a minimum, data checks must include the following:

('a') tracing data in the emissions data report to its origin;

('b') looking at the process for data compilation and collection;

('c') recalculating emission estimates to check original calculations;

('d') reviewing calculation methodologies used by the emission source for conformance with this Part; and

('e') reviewing meter and fuel analytical instrumentation measurement accuracy and calibration for consistency with the requirements of section 1.4(g) of this Part.

(v) As applicable, the verification team shall review the following information when conducting data checks for product data:

('a') product inventory and stock records;

('b') product sales records and contracts;

(‘c’) onsite and offsite product delivery records;

(‘d’) purchase and delivery records for inputs to product(s);

(‘e’) product measurement records; and

(‘f’) other information or documentation that provides financial or direct measurement information about total product(s) reported.

(vi) The verification team is responsible for ensuring via data checks that there is reasonable assurance that the emissions data report conforms to the requirements of this Part. In addition, and as applicable, the verifier’s review of conformance must confirm the following information is correctly reported:

(‘a’) for facilities that combust natural gas, natural gas supplier customer account number, service account identification number, or other primary account identifier(s) reported pursuant to section 2.7(l) of this Part;

(‘b’) for suppliers of natural gas, end-user names, account identification numbers, and natural gas deliveries in MMBtu, reported pursuant to section 2.17(d)(4) of this Part;

(‘c’) energy generation and disposition information reported pursuant to sections 1.5(d), 2.5(a), 2.5(b) of this Part and electricity and thermal energy purchases and acquisitions reported pursuant to sections 1.5(d)(1) and (2) of this Part, if any of the following apply:

(‘1’) the facility belongs to an industry sector (e.g., reported a NAICS code) listed in Table 2-9 in section 2.22 of this Part;

(vii) The verification team shall compare its own calculated results with

the reported data in order to confirm the extent and impact of any omissions and errors. Any discrepancies must be investigated. The comparison of data checks must also include a narrative to indicate which sources, product data, and transactions were checked, the types and quantity of data that were evaluated for each source, product data, and transaction, the percentage of reported emissions covered by the data checks, the percentage of product data covered by the data checks, and any separate discrepancies that were identified in emissions data or product data.

(8) Emissions Data Report Modifications. As a result of data checks by the verification team and prior to completion of a verification statement(s), the emission source must fix all correctable errors that affect emissions or industrial product data in the submitted emissions data report and submit a revised emissions data report to the department. Failure to do so will result in an adverse verification statement. Failure to fix misreported data that do not affect emissions or industrial product data represents a nonconformance with this Part but does not, absent other errors, result in an adverse verification statement. The emission source shall maintain documentation to support any revisions made to the initial emissions data report. Documentation for all emissions data report submittals shall be retained by the emission source for ten years pursuant to section 1.7 of this Part.

The verification team shall use professional judgment in the determination of correctable errors as defined pursuant to this Part, including whether differences are not errors but result from truncation or rounding or averaging.

If the verification team determines that the reported NAICS code(s) reviewed pursuant to paragraph (4) of this subdivision is inaccurate, and the emission source does not

submit a revised emissions data report to correct the current NAICS code(s), the result will be an adverse verification statement.

The verification team must document the source of any difference identified, including whether the difference results in a correctable error or whether the difference does not require further investigation because it is the result of truncation, rounding, or averaging.

(9) Findings. To verify that the emissions data report is free of material misstatements, the verification team shall make its own determination of emissions for checked sources and product data for checked data and shall determine whether there is reasonable assurance that the emissions data report does not contain a material misstatement in GHG emissions reported for the emission source, on a CO_2 equivalent basis and/or a material misstatement in product data for the emission source, using the units required by the applicable parts of this Part. To assess conformance with this Part, the verification team shall review the methods and factors used to develop the emissions data report for adherence to the requirements of this Part and ensure that other requirements of this Part are met.

(10) Log of Issues. The verification team must keep a log of any issues identified in the course of verification activities that may affect determinations of material misstatement and nonconformance, whether identified by the verifier or by the reporter regarding the original or subsequent certified reports or identified by department staff. The issues log must identify the regulatory section related to the nonconformance or potential nonconformance, if applicable, and indicate if the issues were corrected by the emission source prior to completing the verification. Any other concerns that the verification team has

with the preparation of the emissions data report, including with any limited alternative emissions calculations, must be documented in the issues log and communicated to the emission source during the course of verification activities. The log of issues must indicate whether each issue has a potential bearing on material misstatement, nonconformance, or both and whether an adverse verification statement may result if not addressed.

(11) Material Misstatement Assessment. Assessments of material misstatement are conducted independently on total reported emissions and total reported industrial product data (units from the applicable sections of this Part).

(i) In assessing whether an emissions data report contains a material misstatement, the verification team must separately determine whether the total reported emissions and total reported industrial product data contain a material misstatement using Equation 4.2-1 or 4.2-2 as provided in this subparagraph:

Equation 4.2-1:

$$Percent\ error\ (emissions) = \sum \frac{[Discrepancies + Omissions + Misreporting] * 100\%}{Total\ reported\ covered\ emissions}$$

Or

Equation 4.2-2:

$$Percent\ error\ (product\ data) = \sum \frac{[Discrepancies + Omissions + Misreporting] * 100\%}{Total\ industrial\ product\ data}$$

Where:

Discrepancies means any differences between the reported emissions or industrial product data and the verifier's review of emissions or industrial product data for a data source or product data subject to data checks in paragraph (8) of this subdivision.

Omissions means any emissions or industrial product data the verifier concludes must be part of the emissions data report but were not included by the reporting entity in the emissions data report.

Misreporting means duplicate, incomplete or other emissions the verifier concludes should, or should not, be part of the emissions data report or duplicate or other product data the verifier concludes should not be part of the emissions data report.

Total reported emissions or industrial product data means the total annual reporting entity emissions or total reported industrial product data for which the verifier is conducting a material misstatement assessment.

For instances in which a reporting entity reports industrial product data subject to data checks under paragraph (8) of this subdivision in different units of measurement or reports industrial product data under section 2.12 of this Part, the verifier must conduct a material misstatement evaluation according to the requirements of subparagraphs (iv) and (v) of this paragraph, respectively.

(ii) When evaluating a material misstatement or misstatements, verifiers must deem correctly substituted missing data to be accurate, regardless of the amount of missing data.

(iii) The omissions variable described in subparagraph (i) of this paragraph does not apply to excluded industrial product data as described in section 1.4(h) of this Part, such that excluded industrial product data is not considered in the material misstatement assessment.

(iv) Beginning with 2026 data reported in 2027, if multiple types of industrial product data are reported with different units of measurement, the verifier shall conduct a separate material misstatement evaluation for each product, except as provided in subparagraph (v) of this paragraph.

(v) Beginning with 2026 data reported in 2027, the verifier shall conduct a separate material misstatement evaluation for industrial product data reported pursuant to section 2.12 of this Part. If a facility reports industrial product data under section 2.12 of this Part, and another section(s) that requires reporting industrial product data, three (or more) separate industrial product data material misstatement assessments must be completed, and three (or more) separate product data verification statements must be issued.

(12) Review of Missing Data Substitution. If a source selected for a data check was affected by a loss of data used to calculate GHG emissions for the emission year:

(i) The verification team shall confirm that the reported emissions for that source were calculated using the applicable missing data procedures, or that an approved interim data collection procedure was used for the source.

(ii) If 20 percent or less of any single data elements used to calculate emissions are missing, and emissions are correctly calculated using the missing data requirements in sections 2.1 to 2.22 and 3.1 of this Part, these emissions will be considered

accurate and as meeting the reporting requirements for that source.

(iii) If greater than 20 percent of any single data element used to calculate emissions are missing or any combination of data elements are missing that would result in more than five percent of a facility's emissions being calculated using missing data requirements in sections 2.1 to 2.22 and 3.1 of this Part, the verifier must include a finding of nonconformance with the required emissions calculation methodology as part of the verification statement.

(iv) The verifier must note the date, time and source of any missing data substitutions discovered during the course of verification in the verification report.

(13) Review of Product Data. The verifier's review of product data must include the following, where applicable.

(i) Verifiers must confirm that data substitutions were not used for industrial product data.

(ii) Verifiers must confirm that all industrial product data specified in sections 2.1 to 2.22 of this Part conforms to the reporting requirements of this Part, including, but not limited to, meeting the applicable product data definitions, and meter accuracy and calibrations requirements. Industrial product data subject to this confirmation include underlying product data that are measured and reported to support the calculation of other industrial product data. Verifiers shall describe in their sampling plan how they determined that reported industrial product data conforms to the requirements of this Part.

(c) Verification Services Requirements. Completion of verification services must include:

(1) Verification Statement. Upon completion of the verification services specified in subdivision (b) of this section, the verification body shall complete an emissions data verification statement and product data verification statement(s) and provide those statements to the reporting entity and the department by the applicable verification deadline specified in section 1.4(c) of this Part. Before the emissions data verification statement and product data verification statement(s) are completed, the verification body shall have the verification services and findings of the verification team independently reviewed within the verification body by an independent reviewer who is a lead verifier not involved in services for that reporting entity during that year.

(2) Independent Review. The independent reviewer shall serve as a final check on the verification team's work to identify any significant concerns, including:

(i) errors in planning,

(ii) errors in data sampling, and

(iii) errors in judgment by the verification team that are related to the draft verification statement.

The independent reviewer must maintain independence from the verification services by not making specific recommendations about how the verification services should be conducted. The independent reviewer will review documents applicable to the verification services provided and identify any failure to comply with requirements of this Part or with the verification body's internal policies and procedures for providing verification services. The independent reviewer must concur with the verification findings before the verification statement(s) can be issued.

(3) Completion of Findings and Verification Report. The verification body is required to provide each reporting entity with the following:

(i) A detailed verification report, which shall at a minimum include:

(‘a’) a detailed description of the facility or emission source, including all emissions and product data sources and boundaries;

(‘b’) a detailed description of data acquisition, tracking and emission calculation/product data systems;

(‘c’) the verification plan;

(‘d’) the detailed comparison of the data checks conducted during verification services for emissions and product data sources;

(‘e’) the log of issues identified in the course of verification activities and their resolution;

(‘f’) any qualifying comments on findings during verification services; and

(‘g’) the calculation performed in subparagraph (b)(12)(i) of this section for emissions and product data.

The verification report shall be submitted to the emission source at the same time as or before the final emissions data verification statement and product data verification statement(s) are submitted to the department. The detailed verification report shall be made available to the department upon request.

(ii) The verification team shall have a final discussion with the emission source explaining its findings and notify the emission source of any unresolved issues noted

in the issues log before the verification statement(s) are finalized.

(iii) The verification body shall provide the verification statement(s) to the emission source and the department, attesting whether the verification body has found the submitted emissions data report to be free of material misstatements, and whether the emissions data report is in conformance with the requirements of this Part. For every qualified positive verification statement, the verification body shall explain the nonconformances contained within the emissions data report and shall cite the section(s) in this Part that corresponds to the nonconformance and why the nonconformances do not result in a material misstatement. For every adverse verification statement, the verification body must explain all nonconformances and material misstatements leading to the adverse verification statement and shall cite the section(s) in this Part that corresponds to the nonconformance(s) and material misstatements.

(iv) The lead verifier in the verification team shall attest that the verification team has carried out all verification services as required by this Part, and the lead verifier who has conducted the independent review of verification services and findings shall attest to their independent review on behalf of the verification body and their concurrence with the verification findings.

(‘a’) The lead verifier must attest in the verification statement, in writing, to the department as follows:

“I certify under penalty of the laws of the State of New York that the verification team has carried out all verification services as required by Part 253 of Title 6 of the New York Codes, Rules and Regulations.”

(‘b’) The lead verifier independent reviewer who has conducted the independent review of verification services and findings must attest in the verification statement, in writing, to the department as follows:

“I certify under penalty of the laws of the State of New York that I have conducted an independent review of the verification services and findings on behalf of the verification body as required by Part 253 of Title 6 of the New York Codes, Rules and Regulations and that the findings are true, accurate, and complete.”

(4) Adverse Verification Statement and Petition Process. Prior to the verification body providing an adverse verification statement for emissions or product data, or both, to the department, the verification body shall notify the emission source and the emission source shall be provided at least 14 days to modify the emissions data report to correct any material misstatements or nonconformance found by the verification team. The verification body must provide notice to the department of the potential for an adverse verification statement(s) at the same time it notifies the reporting entity and include a preliminary issues log. The modified report and verification statement(s) must be submitted to the department before the verification deadline, even if the reporting entity makes a request to the department as provided in subparagraph (i) of this paragraph.

(i) If the emission source and the verification body cannot reach agreement on modifications to the emissions data report that result in a positive verification statement or qualified positive verification statement for the emissions or product data because of a disagreement on the requirements of this Part, the emission source may petition the department before the verification deadline and before the verification statement

is submitted to make a final decision as to the verifiability of the submitted emissions data report. The emission source may petition either emissions or product data verification statements, or both. At the same time that the emission source petitions the department, the emission source must submit all information it believes is necessary for the department to make a final decision.

(ii) The department shall make a final decision no later than October 10 following the submission of a petition pursuant to subparagraph (i) of this paragraph. If at any point the department requests information from the verification body or the emission source, the information must be submitted to the department within 10 days. The department will notify both the emission source and the verification body of its determination, which may also include an assigned emissions level calculated pursuant to paragraph (5) of this subdivision, if applicable.

(5) Assigned Emissions Level. When an emission source fails to receive a verification statement for an emission year by the applicable deadline or receives an adverse emissions data verification statement, the department shall develop an assigned emissions level for the emission year for the emission source. Within 10 days of a written request by the department, the verification body (if applicable) shall provide any available verification services information or correspondence related to the emissions data. Within 10 days of a request by the department, the emission source shall provide the data that is required to calculate GHG emissions for the emission source according to the requirements of this Part, the preliminary or final detailed verification report prepared by the verification body (if applicable), and other information requested by the department, including the operating days

and hours of the emission source during the emission year. The emission source shall also make available personnel who can assist the department's determination of an assigned emissions level for the emission year.

(i) In preparing the assigned emissions level for the emission source, the department shall consider at a minimum the following information:

('a') the number, types and days and hours of operation of the sources operated by the emission source for the emissions emission year;

('b') any previous emissions data reports submitted by the emission source and verification statements rendered for those reports;

('c') the potential maximum fuel and process material input and output capacities for the emission source's emission sources during operating hours;

('d') for electric power entities, wholesale and retail transactions that would affect an assigned emissions level, for the applicable emission year and for previous years;

('e') emissions, electricity transactions, fuel use, or product output information reported to the department or other State, Federal, or local agencies.

(ii) In preparing the assigned emissions level for the reporting entity, the department may use the following methods, as applicable:

('a') the sector-specific calculation methodologies in this Part;

('b') in the event of missing data, the department will rely on the missing data provisions of this Part; and

('c') any information reported under this Part for this emission year

and past years.

(iii) The department shall assign the emissions level for the emission source using the best information available, including the information in subparagraph (i) of this paragraph and methods in subparagraph (ii) of this paragraph, as applicable. The department shall include an assigned emissions level in the decision made pursuant to subparagraph (4)(ii) of this subdivision, if applicable.

(d) Revision of Verification Statement Submission. Upon provision of the verification statement, or statements, if applicable, to the department, the emissions data report shall be considered final. No changes shall be made to the report as submitted to the department, and all verification requirements of this Part shall be considered complete except in the circumstance specified in subdivision (e) of this section.

(e) Re-Verification Upon Department Findings. If the department finds a high level of conflict-of-interest existed between a verification body and an emission source, an error is identified, or an emissions data report that received a positive or qualified positive verification statement fails a department audit, the department may set aside the positive or qualified positive verification statement issued by the verification body and require the emission source to have the emissions data report re-verified by a different verification body within 90 days. This subdivision applies to verification statements for emissions and product data. In instances where an error to an emissions data report is identified and determined by the department to not affect the emissions or industrial product data, the change may be made without a set aside of the positive or qualified positive verification statement.

(f) Provision of Emissions Report Data. Upon request by the department, the emission

source shall provide the data used to generate an emissions data report, including all data available to a verifier in the conduct of verification services, within 14 days.

(g) Provision of Full Verification Report and Supporting Material. Upon request of the department, the verification body shall provide the department the full verification report given to the emission source, as well as the sampling plan, contracts for verification services, and any other supporting documents and calculations, within 14 days.

(h) Department Audits. Upon written notification by the department, the verification body shall make itself and its personnel available for a department audit.

(i) Verifying Biomass-derived Fuels. In the absence of certification of the biomass-derived fuel by an accredited certifier of biomass-derived fuels, the verification body is subject to the requirements of this Subpart as modified in this subdivision when verifying biomass-derived fuel:

(1) General biomass-derived fuel verification requirements. The following requirements apply to the biomass-derived fuel verification:

(i) Annual Verification. Biomass-derived fuel is subject to annual verification as specified in section 1.4(c) of this Part.

(ii) Verification Services for Biomass-derived Fuels. When an emission source reports that biomass-derived fuels are used, the biomass-derived fuels must be considered when providing all verification services required under subdivision (b) of this section. The verification team must:

(‘a’) Review the emission source’s reported biomass-derived fuel emissions to ensure the biomass-derived fuels are properly listed in the emissions data

report as required in section 1.4(f) of this Part.

(‘b) Conduct separate data checks that are consistent with the requirements in subparagraph (2)(iv) of this paragraph for the fuel type being verified using the following documentation, as appropriate: the invoice, nomination, scheduling, storage, in-kind fuel purchase, allocation, transportation and balancing reports, or other documents used as evidence of the fuel delivery.

(‘1’) The emission source may arrange for the documentation to be supplied directly to the verifier if there are confidentiality issues that would prevent these documents from being made available to the emission source.

(iii) Completion of Verification Services for Biomass-derived Fuels.

(‘a’) All information used for the verification of biomass-derived fuels must be included in the independent review as required in paragraph (c)(2) of this section.

(‘b’) Conformance for biomass-derived fuels is evaluated against the requirements of this Part.

(2) Specific biomass-derived fuel verification requirements.

(i) For wood residuals recovered from construction and demolition debris, agricultural waste, and forest-derived wood and wood waste, the verifier must determine the emission source met the requirements of section 1.4(f) of this Part.

(ii) For biodiesel and fuel ethanol, the verifier must determine that the emission source met the requirements of section 1.4(f) of this Part and the following requirements:

(‘a’) At combustion sources that purchase biomass-derived fuels, verify records to demonstrate that volume purchased equals or exceeds volume reported.

(‘b’) At combustion sources that produce their own fuel, verify:

(‘1’) that raw material is sufficient to produce the quantity of fuel reported;

(‘2’) that the facility has the ability to produce the biomass-derived fuel reported;

(‘3’) that the emissions from the fuel are accurately reported and do not lead to the underreporting of fossil fuel emissions.

(iii) For municipal solid waste and tires, the verifier must determine the emission source met the requirements of section 1.4(f) of this Part.

(iv) For biomethane and biogas, the verifier must:

(‘a’) examine all nomination, invoice, scheduling, allocation, transportation, storage, in-kind fuel purchase and balancing reports from the producer to the emission source and have reasonable assurance that the emission source is receiving the identified fuel;

(‘b’) determine that no fossil-derived fuel is used to supplement the biomass-derived fuel deliveries except for documented fuel purchases to avoid loss of metered volumes in connection with the transportation of the biomethane to the emission source;

(‘c’) ensure any discrepancies in the fuel volumes, heat values and/or energies will be carried over into the evaluation of material misstatement for the

emission source.

253-4.3 Accreditation Requirements for Verification Bodies, Lead Verifiers, and Verifiers of Emissions Data Reports.

(a) Accreditation Requirements. The accreditation requirements specified in this section shall apply to all verification bodies, lead verifiers, and verifiers that wish to provide verification services under this Part.

(b) Accreditation from Outside New York. Upon receiving an application, the department may issue accreditation to verification bodies, lead verifiers, and verifiers that have active accreditation or recognition as a third-party verifier under the CARB's Mandatory Reporting of Greenhouse Gas Emissions program pursuant to the procedures referred to in section 95352 of title 17 of the California Code of Regulations (January 1, 2022) (see Table 1, section 200.9 of this Title), or the ANSI National Accreditation Board Accreditation Program for Greenhouse Gas Validation/Verification Bodies pursuant to the standard ISO 14065:2020 General principles and requirements for bodies validating and verifying environmental information Published (Edition 3, 2020) (see Table 1, section 200.9 of this Title). Provided that the verification body, lead verifier or verifier demonstrate to the department’s satisfaction, knowledge of the relevant methods and protocols in this Part. Accreditation may be limited to certain types or sources of emissions. The department may impose additional training and requirements on verifiers, and verification bodies originally accredited outside of New York.

(c) Requirements for Accreditation. The department may issue accreditation to

verification bodies, lead verifiers, and verifiers that meet the requirements specified in this section.

(1) Verification Body Accreditation Application. To apply for accreditation as a verification body, the applicant shall submit the following information to the department:

(i) A list of all verification staff and a description of their duties and qualifications, including department-accredited verifiers on staff. The applicant shall demonstrate staff qualifications by listing each person's education, experience, professional licenses, and other pertinent information.

('a') A verification body shall employ and retain at least two verifiers that have been accredited as lead verifiers, as specified in paragraph (2) of this subdivision. American National Standards Institute (ANSI) accredited verification bodies are exempt from this requirement.

('b') A verification body shall employ and retain at least five total full-time staff.

(ii) The applicant shall provide a list of any judicial proceedings, enforcement actions, or administrative actions filed against the body within the previous five years, with an explanation as to the nature of the proceedings.

(iii) The applicant shall provide documentation that the proposed verification body maintains a minimum of four million U.S. dollars of professional liability insurance and must maintain this insurance for three years after completing verification services. Neither general nor umbrella liability policies can be used for the professional liability insurance minimum for the purposes of this provision.

(iv) The applicant shall provide a demonstration that the verification body has policies and mechanisms in place to prevent conflicts of interest and to identify and resolve potential conflict-of-interest situations if they arise. The applicant shall provide the following information:

('a') identification of services provided by the verification body, the industries that the body serves, and the locations where those services are provided;

('b') a detailed organizational chart that includes the verification body, its management structure, and any related entities;

('c') the verification body's internal conflict-of-interest policy that identifies activities and limits to monetary or non-monetary gifts that apply to all employees and procedures to monitor, assess, and notify the department of potential conflicts of interest.

(v) The applicant shall provide a demonstration that the verification body has procedures or policies to support staff technical training as it relates to verification. This training shall include participating in all department-approved verifier training on an ongoing basis as it becomes available.

(vi) The verification body shall notify the department within 30 days of when it no longer meets the requirements for accreditation as a verification body in paragraph (1) of this subdivision. The verification body may request that the department provide additional time to hire additional staff to meet the requirements of this section.

(2) Lead Verifier Accreditation Application. To apply for accreditation as a lead verifier, the applicant shall submit documentation to the department that provides the evidence specified in subparagraphs (i), and (ii), or (iii) of this paragraph:

(i) evidence that the applicant meets the criteria in paragraph (3) of this subdivision; and,

(ii) evidence that the applicant has been a department-accredited verifier for two continuous years and has worked as a verifier in at least three completed verifications under the supervision of a department accredited lead verifier, with evidence of favorable assessment by the department for services performed; or,

(iii) evidence that the applicant has worked as a project manager or lead person for not less than four years, of which two may be graduate level work:

('a') in the development of GHG or other air emissions inventories; or,

('b') as a lead environmental data or financial auditor.

(3) Verifier Accreditation Application. To apply for accreditation as a verifier, the applicant shall submit the following documentation to the department:

(i) Evidence demonstrating the minimum education background required to act as a verifier for the department. Minimum education background means that the applicant has either:

('a') a bachelors level college degree or equivalent in science, technology, business, statistics, mathematics, environmental policy, economics, or financial auditing; or

('b') evidence demonstrating the completion of significant and relevant work experience or other personal development activities that have provided the applicant with the communication, technical, and analytical skills necessary to conduct

verification.

(ii) Evidence demonstrating sufficient workplace experience to act as a verifier, including evidence that the applicant has a minimum of two years of full-time work experience in a professional role involved in emissions data management, emissions technology, emissions inventories, environmental auditing, or other technical skills necessary to conduct verification.

(4) The applicant must take a department-approved and administered general verification training consistent with the requirements of this Part and receive a passing score of greater than an unweighted 70 percent on an exit examination. If the applicant does not pass the exam after the training, they may retake the exam a second time. Only one retake of the examination is allowed before the applicant is required to retake the department-approved general verification training course.

(5) Sector-Specific Verifiers.

(i) Sector-Specific Verifier. The applicant seeking to be accredited as a sector-specific verifier as specified in section 4.2(a)(2) of this Part must, in addition to meeting the requirements for accredited lead verifier or verifier qualification, have at least two years of professional experience related to the sector in which they are seeking accreditation, take department sector-specific verification training and receive a passing score of greater than an unweighted 70 percent on an exit examination. If the applicant does not pass the exam after the training, they may take the exam a second time. Only one retake of the examination is allowed before the applicant is required to retake the department -approved sector-specific verification training. Applicants seeking sector-specific verifier accreditation as

a process emissions specialist are exempt from the experience requirement.

(6) Nothing in this section shall be construed as preventing the department from requesting additional information or documentation from an applicant after receipt of the application for accreditation as a verification body, lead verifier, or verifier, or from seeking additional information from other persons or entities regarding the applicant's fitness for qualification.

(d) Department Accreditation

(1) Within 90 days of receiving an application for accreditation as a verification body, lead verifier, verifier, or sector-specific verifier, the department shall inform the applicant in writing either that the application is complete or that additional specific information is required to make the application complete.

(2) Upon a finding by the department that an application for accreditation as a verification body, verifier, lead verifier, or sector-specific verifier is complete, meets all applicable regulatory requirements, and passes a performance review as defined pursuant to this Part, the prescreening requirement is met and the applicant will be eligible to attend the verification training required by this section.

(3) Within 45 days following completion of the application process and all applicable training and examination requirements, the department shall act to withhold or grant accreditation for the verification body, lead verifier, sector-specific verifier, or verifier.

(4) The decision for accreditation is valid for a period of three years, whereupon the applicant may re-apply for accreditation as a verifier, lead verifier, sector-specific verifier, or verification body if the applicant has not been subject to department enforcement action

under this Part. All department-approved general or sector-specific verification training and examination requirements applicable at the time of re-application must be met for accreditation to be renewed by the department. In addition, the performance review requirement set forth in paragraph (2) of this subdivision must be met for accreditation to be renewed by the department.

(5) All verification body requirements in paragraph (b)(1) of this section must be met for the department to renew the verification body accreditation.

(6) Within 20 days of being notified of any nonconformance in another voluntary or mandatory GHG program, a department-accredited verification body, lead verifier, sector-specific verifier, or verifier shall provide written notice to the department of the corrective action. That notification shall include reasons for the corrective action and the type of corrective action. The verification body or verifier must provide additional information to the department upon request.

(e) Modification, Suspension, or Revocation of a Decision Approving a Verification Body, Lead Verifier, or Verifier, and Voluntary Withdrawal from the Accreditation Program. The department may review and, for good cause, including any violation of Subpart 4 of this Part or any similar action in an analogous GHG system, modify, suspend, or revoke a decision providing accreditation to a verification body, lead verifier, or verifier.

(1) During suspension or revocation proceedings, the verification body, lead verifier, or verifier may not continue to provide verification services.

(2) Within 10 days of suspension or revocation of accreditation, a verification body must notify all emission sources or authorized project designees for whom it is providing

verification services or has provided verification services within the past six months of its suspension or revocation of accreditation.

(3) An emission source or authorized project designee who has been notified by a verification body of a suspended or revoked accreditation must contract with a different verification body for verification services.

(4) An accredited verification body or natural person verifier may request to voluntarily withdraw its or their accreditation by providing a written notice to the department requesting such withdrawal.

(f) Subcontracting. The following requirements shall apply to any verification body that elects to subcontract a portion of verification services.

(1) All subcontractors must be accredited by the department to perform the verification services for which the subcontractor has been engaged by the verification body.

(2) The verification body must assume full responsibility for verification services performed by subcontractor verifiers.

(3) A verification body shall not use subcontractors to meet the minimum staff total or lead verifier requirements as specified in clauses (b)(1)(i)(‘a’) and (b)(1)(i)(‘b’) of this section.

(4) A verifier acting as a subcontractor to another verification body shall not further subcontract or outsource verification services for a reporting entity.

(5) A verification body that engages a subcontractor shall be responsible for demonstrating an acceptable level of conflict-of-interest, as provided in section 4.4 of this Part, between its subcontractor and the emission source for which it will provide verification

services.

(6) A verification body may not use a subcontractor as the independent reviewer.

253-4.4 Conflict-of-Interest Requirements for Verification Bodies

(a) Conflict-of-Interest Requirements. The conflict-of-interest provisions of this section shall apply to verification bodies, lead verifiers, and verifiers accredited by the department to perform verification services for emission sources. Any natural person or company that is hired by an emission source to contract with a verification body on behalf of the emission source is subject to the conflict-of-interest assessment in this Part. In such instances, the verification body must assess the potential conflict-of-interest between itself and the contracting person as well as between itself and the emission source and must also address the potential conflict-of-interest between the contracting person and the emission source, including a written assessment provided and signed by the contracting person.

(b) High Potential for Conflict-of-Interest. The potential for a conflict-of-interest must be deemed to be high where:

(1) the verification body and emission source share any management staff or board of directors membership, or any of the senior management staff of the emission source have been employed by the verification body, or vice versa, within the previous five years; or

(2) any employee of the verification body, or any employee of a related person, or a subcontractor who is a member of the verification team has provided to the emission source any of the following services within the previous five years:

(i) designing, developing, implementing, reviewing, or maintaining an inventory or information or data management system for facility air emissions, or, where applicable, electricity or fuel transactions, unless the review was part of providing GHG verification services;

(ii) developing GHG emission factors or other GHG-related engineering analysis, including developing or reviewing New York State Environmental Quality Review or SEQR, City of New York Environmental Quality Review or CEQR, National Environmental Policy Act or NEPA, or New York State Climate Act section 7(2) GHG analyses that include facility specific information;

(iii) designing energy efficiency, renewable power, or other projects that explicitly identify GHG reductions as a benefit;

(iv) designing, developing, implementing, conducting an internal audit, consulting, or maintaining a GHG emission reduction;

(v) owning, buying, selling, trading, or retiring shares, or stocks that was developed by or resulting reduction credits are owned by the emission source;

(vi) dealing in or being a promoter of credits on behalf of an authorized project designee where the credits are owned by the emission source;

(vii) preparing or producing GHG related manuals, handbooks, or procedures specifically for the emission source;

(viii) appraisal services of carbon or GHG liabilities or assets;

(ix) brokering in, advising on, or assisting in any way in carbon or GHG-related markets;

(x) directly managing any health, environment or safety functions for the emission source;

(xi) bookkeeping or other services related to accounting records or financial statements;

(xii) any service related to development of information systems, including consulting on the development of environmental management systems, such as those conforming to ISO 14001:2015 Environmental management systems — Requirements with guidance for use Published (Edition 3, 2015) (see Table 1, section 200.9 of this Title) or energy management systems such as those conforming to ISO 50001:2018 Energy management systems —Requirements with guidance for use Published (Edition 2, 2018) (see Table 1, section 200.9 of this Title), unless those systems will not be part of the verification process;

(xiii) appraisal and valuation services, both tangible and intangible;

(xiv) fairness opinions and contribution-in-kind reports in which the verification body has provided its opinion on the adequacy of consideration in a transaction, unless the resulting services will not be part of the verification process;

(xv) any actuarially oriented advisory service involving the determination of amounts recorded in financial statements and related accounts;

(xvi) any internal audit service that has been outsourced by the emission source that relates to the emission source’s internal accounting controls, financial systems or financial statements, unless the result of those services will not be part of the verification process;

(xvii) acting as a broker-dealer (registered or unregistered), promoter or underwriter on behalf of the emission source;

(xviii) any legal services;

(xix) expert services to the reporting entity, a trade or membership group to which the reporting entity belongs, or a legal representative for the purpose of advocating the emission source's interests in litigation or in a regulatory or administrative proceeding or investigation.

(xx) verification services that are not conducted in accordance with, or equivalent to, section 4.4 of this Part requirements, unless the systems and data reviewed during those services, as well as the result of those services, will not be part of the verification process.

(xxi) Member for the purposes of this section means any employee or subcontractor of the verification body or related entities of the verification body. Member also includes any natural person with majority equity share in the verification body or its related entities. Related entity for the purposes of this section means any direct parent company, direct subsidiary, or sister company.

(3) The potential for conflict-of-interest shall be deemed to be high when any staff member of the verification body provides any type of non-monetary incentive to an emission source to secure a verification services contract.

(4) The potential for a conflict-of-interest shall also be deemed to be high where any staff member of the verification body has provided verification services for the emission source except within the time periods in which the reporting entity is allowed to use the same

verification body as specified in section 4.1(a) of this Part.

(c) Low Potential for Conflict-of-Interest. The potential for a conflict-of-interest shall be deemed to be low where the following conditions are met:

(1) no potential for a high conflict-of-interest is found pursuant to subdivision (b) of this section; and

(2) any services provided by any member of the verification body or verification team to the emission source, within the last five years, are valued at less than 20 percent of the fee for the proposed verification services. Any verification conducted in accordance with, or equivalent to, section 4.4 of this Part provided by the verification body or verification team outside the jurisdiction of the department is excluded from this financial assessment but must be disclosed to the department in accordance with subdivision (e) of this section.

(3) Non-department verification services are deemed to be low risk if those services are conducted in accordance with, or equivalent to, section 4.4 of this Part, including, but not limited to, third-party certification of environmental management system under ISO 14001:2015 Environmental management systems — Requirements with guidance for use Published (Edition 3, 2015) (see Table 1, section 200.9 of this Title) or energy management system under ISO 50001:2018 Energy management systems — Requirements with guidance for use Published (Edition 2, 2018) (see Table 1, section 200.9 of this Title).

(d) Medium Potential for Conflict-of-Interest. The potential for a conflict-of-interest shall be deemed to be medium where the potential for a conflict-of-interest is not deemed to be either high or low as specified in subdivisions (b) and (c) of this section. The potential for conflict-of-interest will also be deemed to be medium where there are any instances of

personal or familial relationships between the members of the verification body and management or staff of the emission source and when a conflict-of-interest self-evaluation is submitted pursuant to subdivision (h) of this section.

(1) If a verification body identifies a medium potential for conflict-of-interest and intends to provide verification services for the reporting entity, the verification body shall submit, in addition to the submittal requirements specified in subdivision (e) of this section, a plan to avoid, neutralize, or mitigate the potential conflict-of-interest situation. At a minimum, the conflict-of-interest mitigation plan shall include:

(i) A demonstration that any natural persons with potential conflicts have been removed and insulated from the project.

(ii) An explanation of any changes to the organizational structure or verification body to remove the potential conflict-of-interest. A demonstration that any unit with potential conflicts has been divested or moved into an independent person or any subcontractor with potential conflicts has been removed.

(iii) Any other circumstance that specifically addresses other sources for potential conflict-of-interest.

(2) As provided in paragraph (f)(4) of this section, the department shall evaluate the conflict-of-interest mitigation plan and determine whether verification services may proceed.

(e) Conflict-of-Interest Submittal Requirements for Accredited Verification Bodies.

(1) Before the start of any work related to providing verification services to an emission source, a verification body must first be authorized in writing by the department to

provide verification services. To obtain authorization the verification body shall submit to the department a self-evaluation of the potential for any conflict-of-interest that the verification body, related entities, or any subcontractors performing verification services may have with the emission source for which it will perform verification services. The submittal shall include the following:

(i) identification of whether the potential for conflict-of-interest is high, low, or medium based on factors specified in subdivisions (b), (c), and (d) of this section;

(ii) identification of whether the verification body, related person, or any member of the verification team has previously provided verification services for the emission source or related entities and, if so, provide a description of such services and the years in which such services were provided;

(iii) identification of whether any member of the verification team, verification body, or related person has engaged in services of any nature, other than department verification services, with the emission source or related entities either within or outside New York during the previous five years. If services other than the department verification services have previously been provided, the following information shall also be submitted:

('a') identification of the nature and location of the work performed for the emission source or related person and whether the work is similar to the type of work to be performed during verification, such as emissions inventory, auditing, energy efficiency, renewable energy, or other work with implications for the emission source's GHG emissions pursuant to this Part;

(‘b’) the nature of past, present or future relationships of any member of the verification team, verification body, or related entities with the emission source or related entities including:

(‘1’) instances when any member of the verification team, verification body, or related entities has performed or intends to perform work for the emission source or related entities;

(‘2’) identification of whether work is currently being performed for the emission source or related entities, and if so, the nature of the work;

(‘3’) how much work was performed for the emission source or related entities in the last five years, in dollars;

(‘4’) whether any member of the verification team, verification body, or related entities has contracts or other arrangements to perform work for the emission source or a related person;

(‘5’) how much work related to greenhouse gases the verification team has performed for the emission source or related entities in the last five years, in dollars;

(‘c’) explanation of how the amount and nature of work previously performed is such that any member of the verification team’s credibility and lack of bias should not be under question;

(iv) a list of names of the staff that would perform verification services for the emission source, and a description of any instances of personal or family relationships with management or employees of the emission source that potentially represent a conflict-

of-interest; and,

(v) identification of any other circumstances known to the verification body, or emission source that could result in a conflict-of-interest; and

(vi) attest, in writing, to the department as follows:

“I certify under penalty of the laws of the State of New York the information provided in the Conflict-of-Interest submittal is true, accurate, and complete.”

(f) Conflict-of-Interest Determinations. The department must review the self-evaluation submitted by the verification body and determine whether the verification body is authorized to perform verification services for the reporting entity.

(1) The department shall notify the verification body in writing when the conflict-of-interest evaluation information submitted under subdivision (e) of this section is deemed complete. Within 20 days of deeming the information complete, the department shall determine whether the verification body is authorized to proceed with verification and must so notify the verification body.

(2) If the department determines the verification body or any member of the verification team meets the criteria specified in subdivision (b) of this section, the department shall find a high potential conflict-of-interest and verification services may not proceed.

(3) If the department determines that there is a low potential conflict-of-interest, verification services may proceed.

(4) If the department determines that the verification body and verification team have a medium potential for a conflict-of-interest, the department shall evaluate the conflict-of-interest mitigation plan submitted pursuant to subdivision (d) of this section and may

request additional information from the applicant to complete the determination. In determining whether verification services may proceed, the department may consider factors including, but not limited to, the nature of previous work performed, the current and past relationships between the verification body, related persons, and its subcontractors with the emission source and related persons, and the cost of the verification services to be performed. If the department determines that these factors when considered in combination demonstrate an acceptable level of potential conflict-of-interest, the department will authorize the verification body to provide verification services.

(g) Monitoring Conflict-of-Interest Situations.

(1) After commencement of verification services, the verification body shall monitor and immediately make full disclosure in writing to the department regarding any potential for a conflict-of-interest situation that arises. This disclosure shall include a description of actions that the verification body has taken or proposes to take to avoid, neutralize, or mitigate the potential for a conflict-of-interest.

(2) The verification body shall continue to monitor arrangements or relationships that may be present for a period of one year after the completion of verification services. During that period, within 30 days of the verification body or any verification team member entering into any contract with the emission source or related person for which the body has provided verification services, the verification body shall notify the department of the contract and the nature of the work to be performed, and revenue received. The department, within 30 days, will determine the level of conflict using the criteria in subdivisions (a) through (d) of this section, if the emission source must reverify its emissions

data report, and if accreditation revocation is warranted.

(3) The verification body shall notify the department within 30 days of any emerging conflicts of interest during the time verification services are being provided.

(i) If the department determines that a disclosed emerging potential conflict is medium risk and this risk can be mitigated, the verification body is deemed to have met the conflict-of-interest requirements to continue to provide verification services to the emission source and will not be subject to suspension or revocation of accreditation as specified in section 4.3(e) of this Part.

(ii) If the department determines that a disclosed emerging potential conflict is medium or high risk and this risk cannot be mitigated, the verification body will not be able to continue to provide verification services to the emission source and may be subject to suspension or revocation of accreditation under section 4.3(e) of this Part.

(4) The verification body shall report to the department any changes in its organizational structure, including mergers, acquisitions, or divestitures, for one year after completion of verification services.

(5) The department may invalidate a verification finding if a potential conflict-of-interest has arisen for any member of the verification team. In such a case, the emission source shall be provided 90 days to complete reverification.

(6) If the verification body or its subcontractor(s) are found to have violated the conflict-of-interest requirements of this Part, the department may rescind accreditation of the body, its verifier staff, or its subcontractor(s) as provided in section 4.2(d) of this Part.

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Here's how you know

NEW YORK STATE <https://ny.gov>

Department of Environmental Conservation

Things To Do | Places to Go | Nature | Environmental Protection | Regulatory | News | Get Involved | About

</>

System maintenance may impact the availability of several DEC applications between 7 and 9 p.m. on Monday, July 21. We apologize for any inconvenience this may cause.

Posted July 21, 2025, 9:51 am

Air Pollution Regulatory Revisions

On this page

Recently Proposed and Adopted Regulations and Policies

Proposed Rulemakings

6 NYCRR Part 253 – Mandatory Greenhouse Gas Reporting

As part of the State's ongoing efforts to gather information regarding sources of air pollutant emissions and to support the reduction of emissions to meet the statutory mandates of the Climate Leadership and Community Protection Act, Chapter 106 of the Laws of 2019, the New York State Department of Environmental Conservation (Department) is establishing a mandatory greenhouse gas (GHG) reporting program that would require certain GHG emission sources to report emissions to the Department. The reporting program would be implemented through Part 253, Mandatory Greenhouse Gas Reporting. The Department proposal also includes attendant revisions to 6 NYCRR Part 200 to capture all incorporation by reference documents from Part 253.

Rulemaking Documents

- Text of Proposed Part 253 (PDF) </sites/default/files/2025-03/part253expressterms.pdf>
- Text of Proposed Part 253 Summary (PDF) </sites/default/files/2025-03/part253expresstermssummary.pdf>

- Text of Proposed Part 200 (PDF) </sites/default/files/2025-03/200expterms.pdf>
- Regulatory Impact Statement (PDF) </sites/default/files/2025-03/ris_part253.pdf>
- Rural Area Flexibility Analysis (PDF) </sites/default/files/2025-03/ruralflexibilityanalysis_part253.pdf>
- Regulatory Flexibility Analysis for Small Businesses and Local Governments (PDF) </sites/default/files/2025-03/regflexanalysis_part253.pdf>
- Job Impact Statement (PDF) </sites/default/files/2025-03/jobimpactstatement_part253.pdf>

Additional documents, including a Fact Sheet and FAQ can be found on the Mandatory Greenhouse Gas Reporting webpage </environmental-protection/air-quality/mandatory-greenhouse-gas-reporting>.

Informational Webinars for Stakeholders

Webinar Recording

Webinar PPT (PDF) <https://dec.ny.gov/sites/default/files/2025-05/ghgreportingwebinar.pdf>

On May 15, 2025, the Department presented two identical informational webinars on the proposed Mandatory Greenhouse Gas Reporting (Part 253) regulation. These webinars were held to better inform stakeholders' public comments on the proposal by answering clarifying questions. While the Department accepted clarifying questions in anticipation of the webinars, these webinars were solely for informational purposes and did not constitute a public hearing pursuant to the State Administrative Procedures Act. For those who were unable to attend, please see a video of the webinar recording at the link above.

Public Comments on the Proposed Rulemaking

The public comment period ran from April 2, 2025, to July 1, 2025, and is now closed. The Department is currently working on addressing all comments received.

Public Comment Hearings

DEC hosted 2 virtual public comment hearings, and 3 in-person public comment hearings from June 3, 2025, to June 18, 2025. To view the full Notice of Public Comment visit Proposed Rulemakings <https://dec.ny.gov/regulatory/regulations/proposed-emergency-recently-adopted-regulations/air-pollution-regulatory-revisions>.

Environmental and Regulatory Impact Review

Pursuant to SEQR, DEC has determined that the proposed rulemaking will not have a significant adverse environmental impact. In accordance with the State Administrative Procedures Act, DEC has also prepared a Regulatory Impact Statement, a Regulatory Flexibility Analysis for small businesses and local governments, a Rural Area Flexibility Analysis, and a Job Impact Statement.

Recent Adoptions

Adopted Subpart 220-3- Asphalt Pavement Manufacturing Plants Express Terms- Effective September 5, 2024 (PDF) </sites/default/files/2025-01/adopted220rev.pdf>

This is the full text of the updated Express Terms for Subpart 220-3 as of the effective date of September 5, 2024.

Adopted Part 220 Full Rulemaking Package- Effective September 5, 2024 (PDF)

</sites/default/files/2025-01/adopted220.pdf>

The Department is proposing to repeal Subpart 212-4 and create a new Asphalt Pavement Manufacturing Plant regulation under Subpart 220-3. Subpart 220-3 will require new facilities to install control equipment that represents the best achieved industry standards. Existing facilities will be required to install similar controls on a scheduled reduction plan. These changes will reduce air emissions and streamline compliance. Existing Subpart 220-1, which regulates Portland cement plants, will be updated to reflect current particulate emission and nitrogen oxide (NOx) monitoring and reporting requirements. Subpart 220-2, Glass Plants, will remain unchanged.

DAR-23: Article 19 Violation Penalty Policy for Short Form Orders on Consent – Effective December 6, 2023 (PDF) </sites/default/files/2024-01/dar23.pdf>

This Program Policy provides a consistent approach to address New York State Environmental Conservation Law Article 19 air violations where the potential for harm and any actual harm to public health, the environment, or the regulatory system is minor. The penalty ranges and guidance contained in this policy will assist Department staff in efficiently and fairly deterring future violations and assessing appropriate penalties for the purpose of administrative settlement. Additionally, this policy will provide the regulated community with greater certainty regarding penalties for minor violations.

This Program Policy supersedes Program Policies DEE-23, dated March 14, 2005, and DEE-5, dated December 20, 1985, as well as DEE-5 Appendices I-VIII. The Department intends to formally rescind DEE-23 and DEE-5 (including Appendices I-VIII).

DAR-24: Calculation of Penalties for Article 19 Violations at Stationary Sources – Effective December 6, 2023 (PDF) </sites/default/files/2024-01/dar24.pdf>

This Program Policy provides guidance for calculation of recommended civil penalties for violations of New York State Environmental Conservation Law Article 19 air violations at stationary sources for the purpose of administrative settlement. The penalty ranges and guidance contained in this policy will assist Department staff in efficiently and fairly deterring future violations and assessing appropriate penalties. Additionally, this policy will provide the regulated community with greater certainty regarding Article 19 (air) violations at stationary sources.

Adopted Part 203 Oil and Natural Gas Sector, and Part 200 General Provisions - Effective March 3, 2022 (PDF) </docs/air_pdf/adopted203.pdf>

The Department has adopted 6 NYCRR Part 203 and Part 200. Part 203 will regulate volatile organic compounds (VOCs) and methane (CH_4) emissions from the oil and gas sector. This regulation will fulfil three New York State obligations: (1) reduce greenhouse gases (GHGs) in support of the requirements of the Climate Leadership and Community Protection Act (CLCPA), (2) reduce associated VOCs, and (3) fulfill the requirements of the Environmental Protection Agency's (EPA) 2016 Control Techniques Guidelines (CTG) for the oil and gas industry.

Adopted Repeal Parts 206, 250, 256, and Subchapter C, Air Quality Area Classifications Parts 260-317 - Effective January 26, 2024 (PDF)

<https://dec.ny.gov/sites/default/files/2024-01/206.pdf>

The Department has adopted the repeal of 6 NYCRR Part 206, "State Aid for General Air Pollution Work, New York City;" 6 NYCRR Part 250, "Miscellaneous Orders;" 6 NYCRR Part 256, "Air Quality Classification System;" and Subchapter C, Air Quality Area Classifications, 6 NYCRR Parts 260-317; because they are obsolete. The Department has also adopted the revisions to Part 257, "Air Quality Standards" to remove references to 6 NYCRR Part 256. In addition, the Department has adopted the revisions to Part 200, "General Provisions" to update and remove attendant references.

Adopted Subpart 217-5 Heavy Duty Inspection and Maintenance Program - Effective October 20, 2023 (PDF) </docs/air_pdf/adopted2175.pdf>

The Department is adopting a revision to 6 NYCRR Subpart 217-5, "Heavy Duty Inspection and Maintenance Program." The adopted rule revision will revise HDDV I/M requirements to be implemented through the next statewide New York Vehicle Inspection Program (NYVIP3). The adopted revisions to Subpart 217-5 are necessary to reflect NYVIP3 program requirements; improve the enforcement of HDDV I/M; revise smoke opacity cutpoints; allow the Department to more effectively audit ODEIS; and complement the implementation of the statewide NYVIP3 program. Attendant revisions are also being made to 6 NYCRR Part 200, "General Provisions."

Adopted Part 218 Advanced Clean Cars II (ACC II) - Effective September 4, 2023 (PDF) </docs/air_pdf/218acc2.pdf>

The amendments to 6 NYCRR Part 218 incorporate California's latest advanced clean cars (ACC II) zero emission vehicle (ZEV) and low emission vehicle (LEV IV) standards into New York's existing LEV program. The adopted ZEV amendments include an annual ZEV sales requirement for original equipment manufacturers, ZEV assurance measures, regulatory flexibilities, and simplified credit accounting. The LEV IV amendments remove ZEVs from the fleet average NMOG+NOx standard and increase the stringency of emission certification standards. The adopted ZEV amendments will apply

to 2026 and subsequent model year light-duty passenger cars (PC), light-duty trucks (LDT), and medium-duty passenger vehicles (MDPV). The adopted LEV IV amendments will apply to 2026 and subsequent model year PC, LDT, MDPV, and medium-duty vehicles.

Adopted Part 218 HD Omnibus/Phase 2 Greenhouse Gas (P2 GHG) - Effective September 4, 2023 (PDF) </docs/air_pdf/218hdomnibus.pdf>

The rulemaking incorporates the State of California's Heavy-Duty Omnibus Low NOx (oxides of nitrogen) regulation ("HD Omnibus") and Phase 2 Greenhouse Gas ("Phase 2 GHG") Standards for Medium- and Heavy-Duty vehicles. The Department's adoption of California's regulations applies to model year 2026 and subsequent heavy-duty engines intended for use in vehicle service classes in New York State. The amendments establish NOx and particulate matter (PM) exhaust emission standards and associated test procedures for heavy-duty engines and vehicles; amend on board diagnostic (OBD) system requirements; amend the heavy-duty in-use testing program; amend the emissions warranty period and useful life requirements; amend the emissions warranty information and reporting requirements and corrective action procedures; establish in-use emissions data reporting requirements; amend averaging, banking and trading program; amend portions of California's Phase 2 Heavy-Duty Greenhouse Gas (GHG) regulations; and establish powertrain test procedures for heavy-duty hybrid vehicles.

Adopted Part 218 Advanced Clean Trucks (ACT) - Effective January 29, 2022 (PDF)

</sites/default/files/2024-01/218act.pdf>

The Department has adopted amendments to 6 NYCRR Part 218 and 6 NYCRR Section 200 to incorporate California’s medium- and heavy-duty zero emission vehicle (ZEV) sales requirement and large entity reporting requirement, also referred to as the “Advanced Clean Trucks” (ACT) regulation.

Adopted Subpart 482-2 Operating Program Fee - Effective July 2, 2025 (PDF)

</sites/default/files/2025-07/482-2expressterms.pdf>

This regulation establishes the fee to be paid </environmental-protection/air-quality/controlling-pollution-from-facilities/permits-registrations-fees> by all facilities that are subject to the requirements of Title V of the Federal Clean Air Act.

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Governor Walz Announces $10 Million Drought Relief Package for Farmers, Producers

mn.gov/governor/newsroom/press-releases

September 24, 2021

[ST. PAUL, MN] – Today, Governor Tim Walz announced a $10 million drought relief package to support Minnesota farmers and livestock producers impacted by severe drought conditions during the 2021 growing season.

“Historic drought conditions have created extreme stress and financial hardship for our farmers and livestock producers during an already difficult time for the agricultural industry,” said Governor Walz. **“As governor, and as someone who grew up on a family farm, I stand with our farmers. This funding will provide much-needed relief to Minnesota’s agricultural community and help ensure our farmers can keep feeding Minnesota and the world.”**

“Minnesota’s farmers are essential to our economy and to our communities,” said Lieutenant Governor Peggy Flanagan. **“As we’ve traveled the state and heard directly from farmers, small and large, we know how critical relief is for families across Minnesota. This proposal provides meaningful support for our farmers and producers who have been hit hard by this year’s severe drought.”**

“Thanks to the Governor’s drought relief package, Minnesota’s livestock and specialty crop farmers will have an opportunity to recoup some of their losses,” said Minnesota Department of Agriculture Commissioner Thom Petersen. **“I encourage farmers and producers to apply for these grants and loans while they’re available.”**

"We're grateful to see the Governor take action toward providing swift, targeted relief to farmers who've been devastated by this historic drought,” said Gary Wertish, President of the Minnesota Farmers Union. **“Many livestock and specialty crop producers are struggling to plan for winter and upcoming season. Any relief we can get out now will help keep families on the farm."**

The Governor’s proposal includes $5 million in rapid response grants to provide drought relief for livestock producers and specialty crop producers. Examples of eligible costs include water handling equipment such as water tanks, pipeline, and water wagons, water hauling, wells, and irrigation equipment.

The funding proposal also includes $5 million for the Rural Finance Authority’s Disaster Recovery Loan Program. The Rural Finance Authority’s Disaster Recovery Loan Program makes zero-interest loans available immediately for Minnesota farmers whose operations are

suffering from lack of rain. The Disaster Recovery Loan Program can be used to help cover lost revenue or expenses not covered by insurance.

More details on the drought relief package will be announced soon.

This summer, Governor Walz met with agricultural leaders across the state to hear how the drought has impacted them. Governor Walz also met with President Joe Biden and USDA Secretary Tom Vilsack to ask that all levels of government work together to address the impacts of this drought on Minnesota's farmers.

Permalink: https://mn.gov/governor/newsroom/press-releases/index.jsp?id=1055-500585

Farmers face new challenges for crops, livestock

climate.state.mn.us/farmers-face-new-challenges-crops-livestock



Farmers are seeing the effects of warmer weather with pests, plant diseases, and heat-stressed livestock. Erratic weather conditions can devastate a crop season, according to the Minnesota Department of Agriculture.

Agriculture is highly dependent on specific climate conditions, and Minnesota's crop yields are affected by changes in temperature, humidity, cloud cover, and precipitation. Climate change is lengthening the growing season in the Midwest, in large part due to an earlier last spring freeze. While a longer growing season may cause some increases in crop production, other climate changes could outweigh this benefit.



Intense rain events can increase soil erosion, which harms the productivity of topsoil on farm fields. Warming temperatures encourage invasive species, plant diseases and pests that are new to Minnesota farmers. Wetter springs and increases in heavy rain events have delayed or even prevented spring planting for many Minnesota farmers in recent years. And extreme weather events like large hail, pounding rains, high winds, and prolonged droughts can devastate a crop season.

“There is no doubt that extreme weather has greatly impacted Minnesota’s agricultural producers over the last several years, and 2019 is no exception,” said Joe Martin, Executive Director for the USDA's Farm Service Agency in Minnesota. As summer came to a close in 2019, payments for crop insurance totaled more than $2.56 billion, with nearly $250 million going to farms in Minnesota.

Animal health, growth, and reproduction are also highly sensitive to temperature changes. Higher summer temperatures may lead to increased deaths due to heat stress, lower production of milk from dairy cattle and eggs from poultry, slower weight gain and corresponding longer time to market, and decreased reproduction that can result in smaller herds. Heat-stressed hogs eat less, and heat may interfere with breeding, gestation, and lactation. According to USDA, high summer heat costs the American swine industry more than $300 million annually.

These agricultural and economic challenges can seriously affect farmers' health and well-being and contribute to depression and other mental health concerns. The Minnesota Department of Agriculture has a number of resources to help struggling farmers and their families.

More information: Agriculture & food security in Minnesota (MDH)

Mega-rains overwhelm rivers, roads, and budgets

climate.state.mn.us/mega-rains-overwhelm-rivers-roads-and-budgets



Throughout the Midwest, heavy precipitation events have increased in frequency and intensity since 1901, and are projected to increase through this century, according to the latest National Climate Assessment.

The Department of Natural Resources identifies 19 “mega-rain” events in Minnesota, in which six inches of rain covered more than 1,000 square miles, and the core of the event topped eight inches. Rainfalls of this magnitude and geographic extent can be catastrophic.

Of the 19 events listed from 1866 to present, 10 have happened in just the last 20 years. Mega-rains are four times more common after the year 2000, compared to the previous 30 years.

In one instance, Duluth got 7.24 inches of rain over two days in June 2012—the most damaging flood in Duluth’s history. The St. Louis River at Scanlon set a new record crest at 16.62 feet, breaking the previous record from 1950. The river rose 10 feet in 24 hours, and some evacuation of homes was necessary.

Mega-rain events and flash flooding can be devastating for individuals and communities—destroying homes and businesses, damaging our infrastructure, contaminating drinking water, and causing physical injuries or even death. Flooded buildings can experience mold growth that can trigger asthma attacks and allergies during cleanup efforts, and mental stress following flooding can affect our health. These hazards create physical, mental, and emotional challenges for Minnesotans, and put an enormous financial burden on our communities.

Three years after the 2012 flood in Duluth, St. Louis County told the *Pioneer Press* it had spent $50 million on repairs in the wake of the flood, particularly on road work. The City of Duluth spent close to $50 million on repairing damage to city property. The flood also caused an estimated $100 million in personal property damage in Duluth.

The Minnesota Department of Transportation (MnDOT) had to repair and rebuild from significant damage, including Minnesota highway 210 in Jay Cooke State Park, which was closed for more than three years. MnDOT notes that our roads and bridges will be increasingly stressed by intense weather events caused by climate change.

More information: Historic Mega-Rain Events in Minnesota (DNR)

Photo: John Goodge

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Global Change Biology (2015) **21**, 550–565, doi: 10.1111/gcb.12687

RESEARCH REVIEW

Greenhouse gas emissions from dairy manure management: a review of field-based studies

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Abstract

Livestock manure management accounts for almost 10% of greenhouse gas emissions from agriculture globally, and contributes an equal proportion to the US methane emission inventory. Current emissions inventories use emissions factors determined from small-scale laboratory experiments that have not been compared to field-scale measurements. We compiled published data on field-scale measurements of greenhouse gas emissions from working and research dairies and compared these to rates predicted by the IPCC Tier 2 modeling approach. Anaerobic lagoons were the largest source of methane (368 ± 193 kg CH_4 hd^{-1} yr^{-1}), more than three times that from enteric fermentation (~120 kg CH_4 hd^{-1} yr^{-1}). Corrals and solid manure piles were large sources of nitrous oxide (1.5 ± 0.8 and 1.1 ± 0.7 kg N_2O hd^{-1} yr^{-1}, respectively). Nitrous oxide emissions from anaerobic lagoons (0.9 ± 0.5 kg N_2O hd^{-1} yr^{-1}) and barns (10 ± 6 kg N_2O hd^{-1} yr^{-1}) were unexpectedly large. Modeled methane emissions underestimated field measurement means for most manure management practices. Modeled nitrous oxide emissions underestimated field measurement means for anaerobic lagoons and manure piles, but overestimated emissions from slurry storage. Revised emissions factors nearly doubled slurry CH_4 emissions for Europe and increased N_2O emissions from solid piles and lagoons in the United States by an order of magnitude. Our results suggest that current greenhouse gas emission factors generally underestimate emissions from dairy manure and highlight liquid manure systems as promising target areas for greenhouse gas mitigation.

Keywords: dairy, emissions, emissions modeling, greenhouse gas, IPCC, livestock, manure

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Introduction

Animal agricultural currently accounts for 20% of non-CO_2 greenhouse gas (GHG) emissions globally (EPA, 2012). The majority of these emissions are derived from enteric fermentation by ruminants, especially beef and dairy cattle; however, as livestock agriculture is industrialized, manure management contributes an increasingly large proportion of GHG emissions. This is particularly the case for dairy production which, unlike beef production, occurs predominantly on feedlots in most industrialized countries. In the United States, approximately 43% of CH_4 emissions from dairies were from manure management (USDA, 2011), whereas in California, the state with the greatest dairy production, 54% of dairy CH_4 was estimated to come from manure management (CARB, 2011a). Manure management can also be an important source of nitrous oxide (N_2O) emissions, accounting for an estimated 5% of global (EPA, 2012) and US (EPA, 2013a) N_2O emissions. Modeling estimates suggested that N_2O emissions from manure management globally played a dominant role in the atmospheric increase in N_2O over the last 140 years (Davidson, 2009).

Emissions from dairy manure management are challenging to measure and model due to the variability in management systems. Greenhouse gas sources associated with manure management include solid and liquid manure storage systems and dairy surfaces in corrals and barns (Fig. 1). To facilitate estimates of GHG emissions from dairies, the Intergovernmental Panel on Climate Change (IPCC) developed a Tier 2 model using emission factors based on manure composition, manure production rates, biogeochemical reaction rates, temperature, pH, and moisture content (IPCC, 2006). Emission factors developed by the IPCC for dairies were largely based on a few lab or pilot-scale studies (IPCC, 2006; Sedorovich *et al.*, 2007; Chadwick *et al.*, 2011). However, the relationship between small-scale studies and actual field emissions is poorly constrained, with only one study making a qualitative comparison (Jungbluth *et al.*, 2001). Comparing emission rates calculated using the Tier 2

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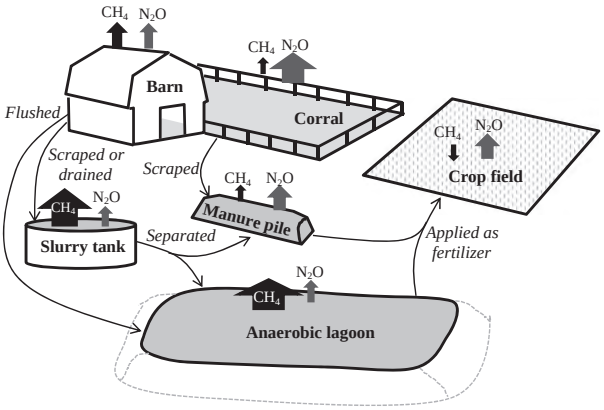

Fig. 1 Sources of N_2O and CH_4 on dairies. Thin arrows indicate movement of manure between locations. Thick arrows indicate relative emission rate. Hardstandings are not shown but have negligible emissions.

model with field measurements provides a valuable test of current emission factors.

Previous reviews of animal agriculture emissions have pooled a variety of livestock systems and scales of studies, i.e. laboratory, pilot, and field scales (Jungbluth *et al.*, 2001; Monteny *et al.*, 2001; Sedorovich *et al.*, 2007; Chadwick *et al.*, 2011; Borhan *et al.*, 2012). However, GHG emissions from dairies likely differ from other livestock industries due to differences in animal and manure management. For example, California dairy feedlots had 1.84 million milk cows and 0.78 million dairy heifers in 2009 which produced 16.4 million kg of volatile solids d^{-1} and 0.92 million kg N d^{-1}, over 55% of which was managed in anaerobic lagoons (CARB, 2011b). In contrast, California beef feedlots had 0.46 million heifers and steers which produced just 0.85 million kg volatile solids d^{-1} and 0.07 million kg N d^{-1}, 1% of which was managed as liquid slurry (CARB, 2011b). Accurately estimating the GHG production from this large stock of dairy manure is critical for designing successful climate change mitigation programs.

The goals of this study were to synthesize a global dataset on GHG emissions from manure management on dairies, compare the data with modeled values, and identify the greatest mitigation opportunities. Published field measurements of CH_4 and N_2O emissions from on dairy manure management on working and research dairies globally were reviewed. Carbon dioxide emission rates were also compiled but because they are not considered to contribute to climate change (IPCC, 2006; with some contention, e.g. Goodland, 2014) they are not discussed further. We compared mean emission rates from the field data with values calculated using the IPCC Tier 2 model to identify discrepancies between measured and modeled values. We used the field data to derive revised emission factors and used these to calculate new emissions estimates for dairy GHG emissions for the United States and Europe.

Sources of GHG on dairies

Many areas on dairies are potential sources of GHGs, in addition to the direct emissions from cows (Fig. 1). Manure is stored in solid or liquid form. Solid manure piles are composed of the solids scraped from dairy surfaces (manure and bedding) and/or the solids separated from slurry. They are heterogeneous in composition and can have both aerobic and anaerobic zones within the piles, depending on moisture content and management practices. Liquid manure systems were split into two groups: (i) anaerobic lagoons and (ii) slurry tanks and settling ponds, following the approach of the IPCC (2006). Lagoons are earthen and hold the liquid fraction after mechanical or gravity-driven separation of the manure plus wash water. They are not stirred and anaerobic conditions develop rapidly. Slurry tanks and settling ponds are filled with unseparated, minimally diluted manure. Slurry manure has more solids than anaerobic lagoon contents, some of which typically floats on the surface and forms a surface crust. The crust is important because it provides a substrate that spans anaerobic and aerobic environments, where N_2O production and CH_4 oxidation can both occur (Petersen *et al.*, 2005; Petersen & Sommer, 2011). Anaerobic digesters are another liquid manure management system, but no studies have attempted to measure greenhouse gas emissions from functioning anaerobic digesters. Biogas production from anaerobic digesters has been widely studied, but the literature has focused on the potential reduction compared to other manure storage, rather than quantifying greenhouse gas emissions from the anaerobic digester systems themselves. Emissions from digesters are likely to be dependent upon the type of system and operation practices (e.g. retention times, effectiveness of seals in preventing gas escape, and composition of material entering the digester) (Massé *et al.*, 2011; Tauseef *et al.*, 2013).

Corrals included dry lots, loafing pens, and hardstandings. Dry lot corrals are dirt-floored pens in which manure is deposited and occasionally scraped into piles and/or removed. Loafing pens are commonly dirt-floored and spread with some sort of bedding material, often dried manure solids. Milk cows are in loafing pens only when they are not in the milking parlor, dry lots, or freestalls, thus, loafing pens do not accumulate much manure. Some pasture-based dairies use standoff pads to hold cows during wet periods when the cows cannot be on the pastures. These are small corrals in

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which a thick (60–100 cm) layer of sawdust and bark chips is laid over plastic sheeting (Luo & Saggar, 2008). The sheeting allows the leachate from the pad to be collected and treated in liquid storage systems. Hardstandings are areas with solid surfaces, such as concrete, which may be used as corrals or as temporary holding pens, depending on their size and location on the dairy.

Barns were measured as entire barns or only barn floors, depending on measurement approach. Measurements of whole barns include pens and/or freestalls, manure removal and feeding alleys, and often the cows themselves. Barn floors are heterogeneous and typically have paved or slatted-floor areas for livestock movement, farmer access, and manure management, as well as stalls or pens with some sort of soft bedding where the cows can rest. Emissions for entire dairies were reported by two studies and were also included.

Field measurement data compilation

Thirty-eight studies met our criteria (Table 1), most of which were located in North America and Europe (Fig. 2; Table S1). Emission rates were measured using flux chambers or micrometeorological techniques. Measurement techniques varied by dairy source area, which was expected given the different spatial scales (piles vs. whole barns) or materials (liquid vs. solid) involved. Measurements were typically carried out every 1–2 months over 1–5 days for up to a year. Data compiled from the studies included farm characteristics such as the surface area of the pens and lagoons, and number of cows, as available; measurement and gas analysis technique; sampling duration and frequency; and climate data as mean annual temperature (MAT), mean annual precipitation (MAP), and temperature during sampling (Tables S2–S8). A difficulty in comparing literature data was the difference in, or lack of, information reported. When possible we remedied this by contacting the authors or providing reasonable estimates of missing information. Missing MAP and MAT data were estimated using data from the nearest city on www.worldclimate.com. Air temperature during sampling periods ('sampling temperature') was estimated using either the monthly averages from www.worldclimate.com or the almanac feature on www.wunderground.com. Methane fluxes that included enteric fermentation-derived emissions from barns, corrals, or whole dairies were corrected for enteric emissions by subtracting the IPCC regional estimate for enteric fermentation (IPCC, 2006). Specifically, we used 128 kg hd^{-1} d^{-1} for North American studies and 117 kg hd^{-1} d^{-1} for European and modern, high-producing Chinese dairies (rather than the default of 68 kg hd^{-1} d^{-1} for Asia, which assumes low-producing cows on small farms).

Most studies included measurements of the same area at different times (e.g. seasonally) and/or measurements from areas in which some management component was different (e.g. mixed vs. static manure piles, barns with different flooring and scraping mechanisms). Each permutation was included in the compilation. The mean emission rate for a given dairy area was calculated by first averaging the emission rates compiled from each article, then averaging those values, such that n is the number of studies rather than the number of measurements. This method avoided weighting the mean toward studies, management practices, and measurement techniques with more measurements. Some studies used climate data to extrapolate between measurements to calculate an annual emission rate. We included these annual estimates in the appendices, but they were excluded from the calculation of mean emission rates and the statistical analyses. Statistical analyses were performed using JMP 10.0.2 (SAS Institute, 2012). Correlations between GHG emission rates, climate variables, cow populations, manure volume, and other variables in Tables S2–S8 were explored using multiple linear regressions, with statistical significance determined as $P < 0.10$.

Measurement technique may have affected emissions measured from all manure management systems; large footprint techniques generally measured higher CH_4 and N_2O emissions than studies using dynamic or static chambers, with the exceptions of CH_4 from anaerobic lagoons and corrals. The varied composition and oxygen availability of manure stores creates CH_4 and N_2O emission hotspots in space and time, which can be missed by smaller footprint techniques (Parkin & Kaspar, 2004; Sommer *et al.*, 2004). Concurrent measurements using different techniques have not been made (with one exception: Sommer *et al.*, 2004), but are needed to resolve their impact on reported emissions. Because of the uncertainty in the extent of the impact of measurement technique, in the analysis below we calculated mean emissions from each area using all available data. In most cases, this likely produced a conservative estimate.

Emission rates are presented as the mass of trace gas emitted per head per time (kg trace gas hd^{-1} yr^{-1}) and per unit area per time (kg trace gas m^{-2} yr^{-1}). The discussion focuses on per head numbers for several reasons. The goal of this study was to evaluate our ability to estimate dairy emissions from manure management at regional to global scales; therefore, emissions factors needed to use units that were widely known. Most countries have fairly good estimates of the number of animals present, but estimates of the area of the various

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Table 1 Studies included in this review and the sources of greenhouse gases measured by each

Study	Lagoon	Slurry tank	Manure pile	Compost area	Corrals	Concrete pens	Barn	Whole dairy
Borhan *et al.* (2011a)	×			×	×		×	
Borhan *et al.* (2011b)	×				×		×	
Bjorneberg *et al.* (2009)	×				×			
Leytem *et al.* (2011)	×			×	×			
Leytem *et al.* (2013)	×						×	
Craggs *et al.* (2008)	×							
Safley and Westerman (1988)	×							
Safley and Westerman (1992)	×							
Todd *et al.* (2011)	×							
Husted (1994)		×	×					
Sneath *et al.* (2006)*		×	×					
Hensen *et al.* (2006)		×						×
Kaharabata *et al.* (1998)		×						
Khan *et al.* (1997)		×						
VanderZaag *et al.* (2011)		×						
Ahn *et al.* (2011)			×					
Amon *et al.* (2006)			×					
Brown *et al.* (2002)			×					
Gupta *et al.* (2007)			×					
Osada *et al.* (2001)			×					
Sommer *et al.* (2004)			×					
Kaharabata *et al.* (2000)					×			
Luo and Saggar (2008)					×			
Ellis *et al.* (2001)						×		
Gao *et al.* (2011)						×		
Misselbrook *et al.* (2001)						×		
Adviento-Borbe *et al.* (2010)							×	
Kinsman *et al.* (1995)							×	
Marik and Levin (1996)							×	
Ngwabie *et al.* (2009)							×	
Ngwabie *et al.* (2011)							×	
Samer *et al.* (2012)							×	
Snell *et al.* (2003)							×	
van Vliet *et al.* (2004)							×	
Wu *et al.* (2012)							×	
Zhang *et al.* (2005)							×	
Zhu *et al.* (2012)							×	
McGinn and Beauchemin (2012)								×

*Excludes slurry tank work which was pilot-scale.

manure handling systems have not been attempted with few exceptions (Chung *et al.*, 2013). Others (Place & Mitloehner, 2010; O'Brien *et al.*, 2012) have argued that reporting emissions in terms of the mass of milk produced gives a better sense of the GHG-efficiency of production. This is a useful approach for comparing different production systems. However, milk production varies significantly by breed, feed, cow age, and stage in lactation cycle (e.g. McCandlish, 1920; Zimmerman *et al.*, 1991); furthermore, it is not relevant to the emissions from different manure management approaches in which we are interested here. Few studies (only 11 of the 38 studies included here, with six of the studies measuring whole barns) reported milk production.

To compare the global warming potential (GWP) of the measured areas, N_2O and CH_4 emission rates were converted to 100-year CO_2e emission rates by multiplying by 298 and 34, respectively (Myhre *et al.*, 2013), and summing the two. When other inventories used the older GWPs for N_2O and CH_4 of 310 and 21 (IPCC, 1996), respectively, those emission rates were

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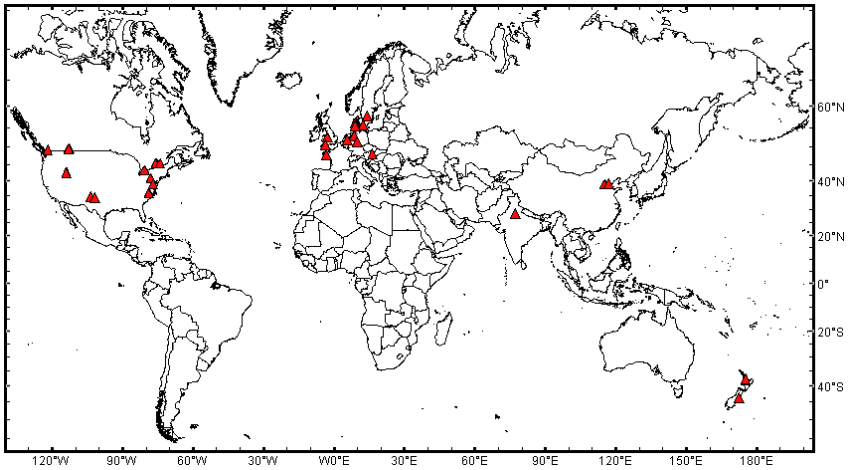

Fig. 2 Geographic distribution of sampling sites, marked as triangles (created in GeoMapApp v. 3.3.8, http://www.geomapapp.org/).

recalculated using the revised values to be comparable to ours.

Summary of field measurements

Anaerobic lagoons and slurry systems had the highest per head GWP on dairies, averaging 12.8 ± 7 Mg CO_2e hd^{-1} yr^{-1} and 3.5 ± 1.7 Mg CO_2e hd^{-1} yr^{-1}, respectively (Table 2a). Mean lagoon GWP was about 20 times higher than mean solid manure storage GWP. When expressed on an area basis, lagoons and slurry systems were similar, averaging 703 ± 195 kg CO_2e m^{-2} yr^{-1} and 827 ± 320 kg CO_2e m^{-2} yr^{-1}, respectively (Table 2b). These rates were high; for comparison, the highest landfill CH_4 emissions rates reported in Bogner *et al.* (1995) were 248 kg CO_2e m^{-2} yr^{-1}, less than half those from liquid manure systems. Barn floors had the lowest GWP (38 ± 7 kg CO_2e hd^{-1} yr^{-1}) of all the dairy environments studied. Methane emissions were the largest component of total GWP for all sources except for barns and corrals.

Liquid manure storage systems were the greatest source of CH_4, with anaerobic lagoons and slurry stores emitting 368 ± 193 kg CH_4 hd^{-1} yr^{-1} and 101 ± 47 kg CH_4 hd^{-1} yr^{-1}, respectively (Table 2a). Barns were the next largest source with 33 ± 19 kg CH_4 hd^{-1} yr^{-1}. This was unexpected given that only one study reported subfloor (deep pit) storage and that most others reported relatively frequent scraping and/or flushing that removed substrate for GHG production.

Barns had the greatest N_2O emissions by nearly an order of magnitude, with 10.3 ± 6.2 kg N_2O hd^{-1} yr^{-1} (Table 2a), although field data were highly variable (Table S6). Corrals and solid manure piles were the next largest N_2O source with 1.5 ± 0.8 kg N_2O hd^{-1} yr^{-1} and 1.1 ± 0.7 kg N_2O hd^{-1} yr^{-1}, respectively (Table 2a). Nitrous oxide emissions from anaerobic lagoons and slurry stores were also substantial, with 0.9 ± 0.5 kg N_2O hd^{-1} yr^{-1} and 0.3 ± 0.3 kg N_2O hd^{-1} yr^{-1}, respectively. The relatively large net N_2O flux from liquid manure storage was surprising given the predominantly anaerobic conditions typical of unaerated systems. Nitrogen in liquid manure is mostly in the form of ammonium (NH_4^+) and organic N (Harter *et al.*, 2002), and though anaerobic lagoons are generally anaerobic, aerobic conditions which could promote denitrification exist at inlets. Other N_2O formation reactions are also feasible, such as denitrification of nitrate (NO_3^-) produced through annamox [anaerobic NH_4^+ oxidation, (Mulder *et al.*, 1995; Maeda *et al.*, 2010)], Feammox [anaerobic NH_4^+ oxidation coupled to Fe reduction, (Yang *et al.*, 2012)], or Mnammox [anaerobic NH_4^+ oxidation coupled to Mn reduction, (Engström *et al.*, 2005)]. Hardstandings and barn floors, surfaces which were scraped or flushed frequently, had CH_4 and N_2O emissions generally one to three orders of magnitude lower than the other sources. These trends were consistent between the per head and per area data (Table 2b) and showed that the type of storage or surface measured was the greatest factor controlling emission rates.

Methane emissions from soils are known to be temperature dependent (Conrad, 2007) and models often assume that manure CH_4 emissions are positively correlated with MAT (Mangino *et al.*, 2002; IPCC, 2006). Individual field studies observed greater CH_4 emissions in summer and/or with warmer sampling temperatures for manure piles, barns, and whole dairies; however, there was no significant correlation between CH_4 emissions and temperature when all the studies for a given source area were considered. The lack of correlation for liquid systems may be due to the

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Table 2 Summary of the means and ranges of N_2O and CH_4 emission rates measured by the studies listed in Table 1, in (a) kg hd^{-1} yr^{-1} and (b) kg m^{-2} yr^{-1}

	Emission rate (kg hd^{-1} yr^{-1})			Emission global warming potential† (kg CO_2e hd^{-1} yr^{-1})		
	Mean* ± SE (*n*) Range			Mean* ± SE (*n*)		
	CH_4	N_2O	CO_2	From CH_4	From N_2O	Total (CH_4+N_2O)
(a)						
Anaerobic lagoons	368 ± 193 (9) 4–2814	0.9 ± 0.5 (4) 0.004–3.9	687 ± 266 (6) 4.8–2400	12 510 ± 7334	264 ± 131	12 775 ± 6699
Slurry stores	101 ± 47 (6) 0–328	0.3 ± 0.3 (3) 0–4.5	nm	3422 ± 1601	81 ± 76	3504 ± 1680
Solid‡	13 ± 11 (4) 0–99	1.1 ± 0.7 (4) 0.02–7	754 ± 695 (2) 59–3546	431 ± 372	315 ± 196	632 ± 470
Corrals§	−17 ± 24 (6) −128 to 210	1.5 ± 0.8 (4) 0.0–12	4242 ± 3040 (3) 134–20 292	−577 ± 844	454 ± 272	−124 ± 1073
Hardstandings§	1.2 ± 0.8 (3) −3.8 to 7.1	0.0004 ± 0.0001 (2) 0.0001–0.001	nm	40 ± 26	0.13 ± 0.02	40 ± 27
Barn floor	0.9 ± 0.7 (4) 0–4.4	0.03 ± 0.01 (4) 0.001–0.1	94 ± 39 (4) 25–250	30 ± 22	7.5 ± 4.4	38 ± 27
Whole barn§	33 ± 19 (10) −61 to 289	10 ± 6 (3) 0–22	7204 ± 5507 (3) 273–35058	1120 ± 931	3076 ± 3154	4197 ± 2496
Whole dairy§	96 ± 35 (18) −91 to 350	nm	nm	3252 ± 1191	nm	3252 ± 1194

	Emission rate (kg m^{-2} yr^{-1})			Emission global warming potential† (kg CO_2e m^{-2} yr^{-1})
	Mean* ± SE (*n*) Range			Mean* ± SE (*n*)
	CH_4	N_2O	CO_2	Total (CH_4+N_2O)
(b)				
Anaerobic lagoons	20 ± 5 (9) 0.3–84	0.09 ± 0.05 (4) 0.001–0.4	64 ± 34 (6) 2–312	703 ± 195
Slurry stores	24 ± 9 (7) 0–74	0.05 ± 0.04 (3) 0–0.7	nm	827 ± 320
Solid‡	2.8 ± 0.9 (6) 0–13	0.3 ± 0.1 (7) 0.005–1.0	268 ± 103 (4) 13–461	147 ± 49
Corrals§	−0.8 ± 0.9 (6) −5.2 to 3.8	0.03 ± 0.01 (4) 0.001–0.22	83 ± 52 (3) 12–365	−16 ± 35
Hardstandings§	0.5 ± 0.6 (3) −0.11 to 2.2	0.0003 ± 0.0001 (2) 0.000–0.001	nm	18 ± 21
Barn floor	0.2 ± 0.2 (4) 0–1.0	0.01 ± 0.01 (4) 0–0.4	21 ± 10 (4) 5–58	9.4 ± 7.0
Whole barn§	3.4 ± 2.0 (10) −2.8 to 31	0.9 ± 0.7 (3) 0–2.3	774 ± 578 (3) 39–3713	381 ± 277
Whole dairy§	nm	nm	nm	nm

*Mean emissions were calculated by first averaging measurements within studies then averaging across studies (*n* = number of studies). The exception was the whole dairy measurements which were treated individually and not grouped by study (i.e. *n* = number of dairies measured).

†Where 1 g CH_4 = 34 g CO_2e and 1 g N_2O = 298 g CO_2e. CO_2 is not included.

‡Excludes data from Gupta *et al.* (2007).

§Where necessary, methane emission rates have been corrected for enteric emissions as described in the text. Carbon dioxide emissions were not corrected for respiration.

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limited range of MAT represented by the field studies; all studies but one (Todd *et al.*, 2008) sampled liquid systems that were in regions where MAT was 6–15 °C. Air temperature during sampling had a larger range (−10.6 to 34.4 °C, Tables S2–S3), but overall liquid systems in warm climates were under-represented. Differences in volatile solid content, the other key factor determining CH_4 production (Mangino *et al.*, 2002), may have also confounded any temperature effect. Insufficient data were available to test the effect of volatile solid content on CH_4 emissions within or across studies.

Methane and N_2O emissions were strongly correlated with each other for solid manure piles ($r^2 = 0.73$, $P < 0.001$) and weakly correlated for corrals ($r^2 = 0.26$, $P < 0.08$). This suggests that in solid manure management systems, at least a portion of the N_2O fluxes were derived from denitrification, which requires the same general environmental conditions as methanogenesis (warm temperatures, abundant labile C, anaerobic conditions). Corral CH_4 emissions were negative, indicating soil uptake, in five of 18 cases (Table S4); negative fluxes occurred in late summer when the soils were dry, or in winter when the soils were cold or frozen. The highest corral N_2O emissions were measured in late spring when a combination of warmer temperatures and moist soils likely promoted nitrification and denitrification (Table S4). The lowest values were <50% of the highest emissions and occurred in late fall and winter (Table S4). Despite these seasonal patterns, neither CH_4 nor N_2O emissions from corrals were correlated with temperature and/or precipitation. Leytem *et al.* (2011) measured higher N_2O emission rates from manure piles in warmer months (May and June) than colder ones (September and March, Table S5), but no correlations were found when all manure pile data were pooled.

Specific management practices could have made it difficult to detect a temperature effect if one existed. Mixing solid manure piles resulted in increased CH_4 and N_2O emissions (Yamulki, 2006; Maeda *et al.*, 2010; Ahn *et al.*, 2011; Leytem *et al.*, 2011), contrary to expectations that mixing would aerate the pile and decrease CH_4 production. The addition or accumulation of fresh manure was another source of emissions. Addition of fresh material increased pile emissions (Leytem *et al.*, 2011) and the accumulation of fresh material in corrals was likely one of the most important factors driving positive CH_4 fluxes. Borhan *et al.* (2011) measured greater CH_4 and N_2O emissions from a dry lot corral than from loafing pens (Table S4), probably due to the corrals having a greater influx of fresh manure and localized, high-moisture urine patches. Methane emissions from the brick hardstanding were relatively high in the summer (Table S7) (Gao *et al.*, 2011), likely because scraping was less frequent compared to other dairies (every 1–4 weeks vs. daily for most other hardstandings, Table S7). Accordingly, Adviento-Borbe *et al.* (2010) observed a significant, positive correlation between CH_4 emissions and manure depth on the barn floor. However, Gao *et al.* (2011) was the only study of hardstandings to use an open path laser rather than flux chambers.

Emission rate modeling

The field measurements provide a test of emission rate models. The IPCC Tier 2 approach models CH_4 emissions (EF_{CH4}, g CH_4 hd^{-1} yr^{-1}) based on the volatile solid production by the cows (VS, kg VS hd^{-1} yr^{-1}), a CH_4 conversion factor (MCF, %) for the manure management practice, and the maximum possible CH_4 production rate from the volatile solids in the manure (B_o, m^3 CH_4 kg VS^{-1}):

$$EF_{CH4} = VS \times MCF/100 \times B_0 \times 662 \text{ g } CH_4 \text{ m}^{-3}CH_4 \quad (1)$$

Volatile solid production by cows can be determined from manure analysis (where volatile solids are the combustible components of solid manure) or estimated based on feed intake rate, digestibility, and dry matter content. No studies reviewed here included all the information necessary to calculate dairy specific VS so we used the IPCC regional values for international data (IPCC, 2006) and averages of state values for the United States (EPA, 2013b).

The IPCC Tier 2 approach models direct N_2O emissions based on annual N excretion rates, which themselves are a function of energy intake by the cows, crude protein content of feed, milk production rate, milk protein content, cow growth, typical animal mass, and an emission factor (EF_{N2O}, kg N_2O-N kg N $excreted^{-1}$) (equations 10.31, 10.32, and 10.33 in IPCC, 2006). EF_{N2O} can be converted into N_2O emission rates equivalent to those measured here (N_2O_D, g N_2O hd^{-1} d^{-1}, where the subscript *D* refers to direct emissions) using the typical animal mass (TAM, kg) and country- or region-specific N excretion rates (N_{ex}, kg N 1000 kg TAM^{-1} d^{-1}):

$$N_2O_D = EF_{N2O} \times 44/28 \times TAM \times N_{ex} \quad (2)$$

In our calculations, we used a TAM of 600 kg, the default for Western Europe (but similar to the North American default value of 604 kg) (IPCC, 2006). Indirect N_2O emissions, derived from the oxidation of gaseous emissions such as ammonia (NH_3) and nitrous oxides (NO_x), are important for calculating the amount

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of N remaining in manure for its use as an organic fertilizer (IPCC, 2006). We did not include indirect N_2O emissions in our calculations, and thus what is reported here should be considered minimum estimates.

We used the field measurement means and Eqns (1) and (2) to derive revised MCFs and EF_{N2O}s for the source areas. This is the first time broadly applicable, field measurement-derived MCFs and EF_{N2O}s have been calculated. Some revised MCFs and EF_{N2O}s were very different from current values.

Comparisons with modeled emissions

Measured vs. modeled CH_4 emissions

The means of the field-measured CH_4 emissions from slurry tanks and barns (deep pit storage) were three times larger than modeled emissions, while the measured CH_4 emissions from solid manure piles and corrals were lower than modeled values, although there was considerable variability in measured values (Table 3; Fig. 3). The modeled CH_4 emissions from the remaining sources (anaerobic lagoons and hardstandings) were within the standard error of the field means or were negligible. Modeled whole dairy CH_4 emissions (calculated using parameters for Western Europe) were slightly lower than the field measurement mean. The default MCFs were within the standard error of the field measurement-derived means except for slurry tanks and whole barns which had larger revised MCFs (Table 3).

The impact of the revised barn/deep pit and slurry store MCFs was evaluated using data on slurry storage in Europe because six of 13 barn studies were conducted in Europe, while slurry studies were distributed in temperate regions globally. We used 1990 and 2011 emissions inventory data for 12 European countries compiled by the United Nations Framework Convention on Climate Change (UNFCCC, 2014). Three of the 15 countries in the dataset were excluded due to lack of data or falling outside the cool MAT temperature zone. The European data did not distinguish between slurry stored in deep pits and tanks or ponds (i.e. one MCF was used for all slurry, that in deep pits and in ponds), whereas we calculated revised MCFs for each system. Thus, revised European slurry CH_4 emissions were calculated using each revised MCF to provide a range. However, deep pit storage is often a temporary holding for slurry that is eventually transferred to slurry tanks or ponds, so the MCF for slurry stores is likely more applicable.

Calculations using the revised deep pit MCF gave total CH_4 emissions from European slurry storage that were less than those using the country-specific slurry

Table 3 Methane emissions modeling inputs and results. VS = volatile solids, MCF = methane conversion factor, B_o = the maximum possible CH_4 production rate from the volatile solids in the manure

	VS (kg VS hd^{-1} yr^{-1})	VS data source	MCF (%)	MCF data source	B_o (m^3 CH_4 kg VS^{-1})	B_o data source	CH_4 emission rate		Field-derived MCF (%)
							Modeled (kg hd^{-1} yr^{-1})	Field (kg hd^{-1} yr^{-1})	
Anaerobic lagoon	2770	Average ID, NM, TX, NC*	74	Average ID, NM, TX, NC*	0.24	Default*†	326	368 ± 193 (9)	84 ± 44
Slurry stores	1861.5	Western Europe†	11	MAT=11, with crust†	0.24	Western Europe†	33	101 ± 47 (6)	34 ± 16
Manure pile	2750	Average TX and ID*	5	Static pile*	0.24	Default*	22	13 ± 11 (4)	2.9 ± 2.5
Corrals	2800	Average TX and ID*	1	Cool MAT*†	0.24	Default*†	4.4	−17 ± 24 (6)	−3.8 ± 5.5
Paved surfaces and barn floors	1861.5	Western Europe†	1	Cool MAT†	0.24	Western Europe†	3.0	0.9 ± 0.5 (6)	0.31 ± 0.16
Brick hardstanding	1022	Asia†	1	Cool MAT†	0.13	Asia†	0.9	1.6 ± 7.7 (1)	1.8 ± 8.8
Whole barn	1861.5	Western Europe†	3	Deep pit, cool MAT†	0.24	Western Europe†	8.9	33 ± 19 (10)	11 ± 6.4
Whole dairy (=corral + manure pile + slurry tank + whole barn)							56	96 ± 35 (18)	

*from (EPA, 2013b).
†from (IPCC, 2006).

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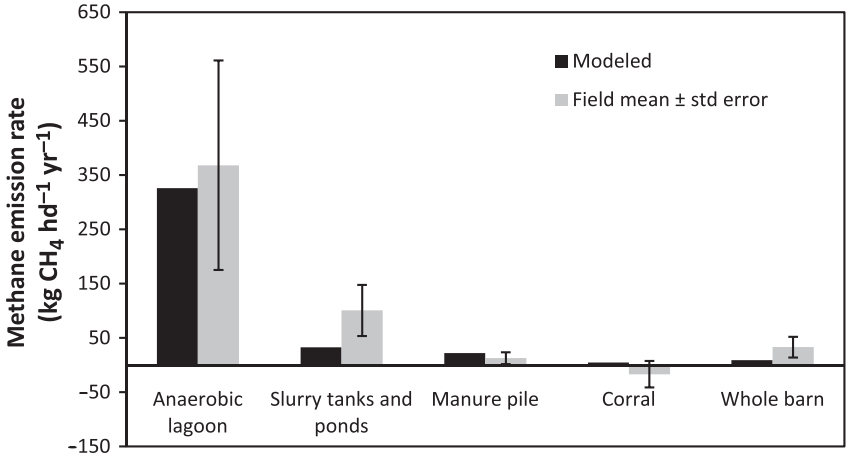

Fig. 3 Comparison of modeled CH_4 emissions and field measurement means and standard errors for the largest CH_4 sources.

MCFs (8.4 ± 4.6 Tg CO_2e yr^{-1} vs. 15.2 Tg CO_2e yr^{-1}, respectively, Table 4, Fig. 4). However, the revised slurry pond MCF increased CH_4 emissions from slurry for most countries, with total emissions of 25.9 ± 12.2 Tg CO_2e yr^{-1}, a gain of 10.7 Tg CO_2e yr^{-1} (Table 4, Fig. 4). Increases were greatest for the countries with the most manure in liquid systems (Denmark, Germany, the Netherlands, Switzerland, and Sweden). We found a similar trend using detailed data for the Netherlands (RIVM *et al*., 2013), with modeled slurry CH_4 emissions two times larger than those estimated in the current inventory (data and calculations not shown).

Table 4 Comparison of modeled slurry emissions in 13 cool MAT European countries using the 2011 liquid slurry MCFs (and other inputs) for each country (UNFCCC, 2014), the revised deep pit and slurry MCFs from Table 3. The top 5 countries for liquid manure management are Denmark, Germany, the Netherlands, Switzerland and Sweden

								Liquid manure emissions (Gg CH_4 yr^{-1})		
	Dairy cows (1000 hd)	VS (kg DM hd^{-1} d^{-1})	Bo (m3 CH4 kg^{-1} VS)	Liquid fraction (%)	Liquid MCF (%)	Revised MCF (deep pit) (%)	Revised MCF (slurry) (%)	Using current MCF	Using revised deep pit MCF	Using revised slurry MCF
Austria	527.39	4.27	0.24	31.61	8.7	11 ± 6	34 ± 16	3.6	4.5 ± 2.5	14.0 ± 6.6
Belgium	459.78	4.10	0.24	11.54	19	11 ± 6	34 ± 16	2.4	1.4 ± 0.8	4.3 ± 2.0
Denmark	565.11	6.09	0.24	88.41	10	11 ± 6	34 ± 16	17.7	19.4 ± 10.6	60.0 ± 28.2
Finland	285.53	4.94	0.24	46.41	10	11 ± 6	34 ± 16	3.8	4.2 ± 2.3	12.9 ± 6.1
France	3660.68	4.12	0.24	40.87	39	11 ± 6	34 ± 16	139.3	39.3 ± 21.4	121.4 ± 57.1
Germany	4190.10	4.01	0.23	73.52	14.4	11 ± 6	34 ± 16	98.6	75.6 ± 41.2	233.6 ± 109.9
Ireland	1086.11	2.98	0.24	28.60	39	11 ± 6	34 ± 16	20.9	5.9 ± 3.2	18.3 ± 8.6
Italy	1754.98	6.37	0.14	35.03	13.9	11 ± 6	34 ± 16	19.0	15.0 ± 8.2	46.4 ± 21.9
Luxembourg	40.45	4.56	0.24	34.20	39	11 ± 6	34 ± 16	1.4	0.4 ± 0.2	1.2 ± 0.6
Sweden	346.50	5.33	0.24	62.23	3.5	11 ± 6	34 ± 16	2.3	16.0 ± 8.7	22.7 ± 10.7
Switzerland	589.24	6.24	0.24	68.22	10	11 ± 6	34 ± 16	14.5	40.2 ± 21.9	49.4 ± 23.3
The Netherlands	1469.72	4.56	0.25	90.38	17	11 ± 6	34 ± 16	62.2	17.1 ± 9.3	124.4 ± 58.5
United Kingdom	1814.00	3.61	0.24	41.00	39	11 ± 6	34 ± 16	60.8	4.5 ± 2.5	53.0 ± 24.9
							All	446.5	246.4 ± 134.4	761.7 ± 358.4
							Top 5 liquid	195.3	158.6 ± 86.5	490.1 ± 230.6
							All (Tg CO2e)	15.2	8.4 ± 4.6	25.9 ± 12.2
							Top 5 liquid (Tg CO2e)	6.6	5.4 ± 2.9	16.7 ± 7.8

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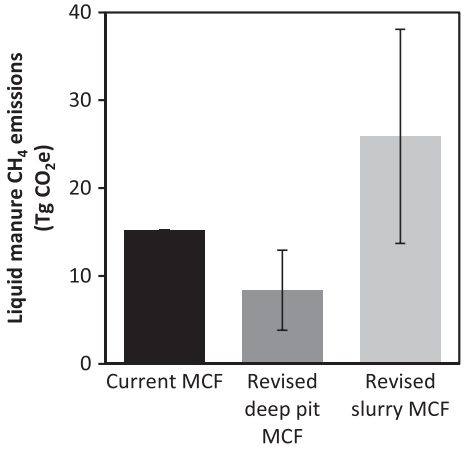

Fig. 4 Comparison of modeled CH_4 emissions for slurry using the current slurry MCF used by the European Union and the revised MCFs for deep pit storage and slurry storage calculated in this study (Table 4).

The uncertainty in slurry MCF has consequences for the evaluation of the European dairy industry's progress in mitigating its GHG emissions. Between 1990 and 2011, the 13 countries considered here decreased the total number of cows by nearly 8 million hd leading to a corresponding decrease in emissions from enteric fermentation by 515 Gg CH_4 (Table 5). The reduction in cows also decreased VS production by 7.8 Tg so there was less manure to manage and produce GHG. However, an increase in the proportion of manure in liquid management in most countries offset some of this decrease in CH_4 production; the current estimates suggest a total net decrease (combined change in enteric and manure management emissions) of 480 Gg CH_4 (Table 5). Using the revised slurry MCF for the 2011 estimates gives a smaller total net decrease of 166 Gg CH_4, with some countries (Denmark, Switzerland, and the Netherlands) having net increases of 30–50 Gg CH_4 rather than decreases (Table 5).

Measured vs. modeled N_2O emissions

Modeled N_2O emissions were less than half of the field measurement means for anaerobic lagoons, solid manure piles, and barns (Table 6). In contrast, the modeled value for slurry stores was greater than the field measurement mean. The other sources had modeled emissions that were within the standard error of the field means or were negligible. The revised EF_{N2O} values for anaerobic lagoons, manure piles, and barns were larger than the default values, and the slurry EF_{N2O} was the same as the default (Table 6).

The impact of revised EF_{N2O} values was evaluated using state-specific data from 2011 for the United States (Table 7) because eight of the nine anaerobic lagoon studies and five of the ten manure pile studies occurred in the United States or North America; therefore, the revised EF_{N2O} values should be applicable to this region. The EPA assumed zero N_2O emissions from anaerobic lagoons, whereas the revised EF_{N2O} gave 1.79 ± 0.90 Tg CO_2e yr^{-1} (Fig. 5). Nitrous oxide emissions from solid manure piles also increased from 0.51 Tg CO_2e yr^{-1} to 3.36 ± 2.04 Tg CO_2e yr^{-1} using the revised EF_{N2O} (Fig. 5). Combined, the revised values increased manure management N_2O emissions in the United States by more than 4.5 Tg CO_2e yr^{-1}, 25% of the 2011 estimate of 17.3 Tg CO_2e (EPA, 2013a).

Whole barn N_2O emissions varied widely between studies, and the measurements of Leytem *et al.* (2013) and Samer *et al.* (2012) suggested an order of magnitude increase in EF_{N2O}. They also indicated that barns may be significant, largely unaccounted sources of N_2O from dairies (2–3 times more kg N_2O hd^{-1} yr^{-1} than corrals or solid piles). No standard model has been established for calculating N_2O emissions from barns that do not have deep pit manure storage. If we assume that two-thirds of the cows in the 13 European countries in Table 4 were kept in barns (11 million hd) for half of the year, and emitted 1 kg N_2O hd^{-1} yr^{-1} (the approximate mean of the measurements by Zhang *et al.* (2005), which was the lowest of the three studies that measured N_2O), then barns emitted 1.64 Tg CO_2e, on the same scale as the revised N_2O emissions from anaerobic lagoons in the United States (Table 7). Using the field measurement mean of 10 kg N_2O hd^{-1} yr^{-1} for the calculation increased barn emissions by an order of magnitude (to 16.4 Tg CO_2e), equivalent to the warming potential of slurry system-derived CH_4 in Europe (Table 4). More data are needed to assess if barns are actually such large sources of N_2O.

Discussion and conclusions

Our results highlight potential issues with the application of IPCC Tier 2 models to estimate GHG emissions from livestock manure. Emission factors were typically based on few studies, many of which were not designed for GHG inventory estimation or were small-scale pilot or laboratory experiments, and spanned various livestock systems (Jungbluth *et al.*, 2001; Chung *et al.*, 2013). These approaches are unlikely to accurately approximate field-scale fluxes from manure management in a specific livestock system. Our review of field-based research on dairies suggests that current Tier 2 model parameters are generally underestimating dairy emissions.

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Table 5 Comparisons between 1990 and 2011 data for the 13 countries in Table 4 (UNFCCC, 2014). Negative values indicate a decrease from 1990 to 2011. The revised slurry MCF was used to recalculate 2011 emissions, not the revised deep pit MCF, and the 1990 value were not adjusted

	Cows (1000 hd)	VS production (Gg)	Liquid fraction (%)	Enteric fermentation emissions (Gg CH_4)	Manure management emissions (default MCF) (Gg CH_4)	Net emissions (default MCF) (Gg CH_4)	Manure management emissions (revised MCF) (Gg CH_4)	Net emissions (revised MCF) (Gg CH_4)
Austria	−377.22	−507.65	−1.04	−26.05	−2.44	−28.49	8.00	−18.05
Belgium	−378.92	−298.63	1.54	−25.54	−0.58	−26.12	1.31	−24.22
Denmark	−188.01	−266.24	18.37	−12.72	0.71	−12.01	43.07	30.35
Finland	−204.37	−162.88	23.87	−11.74	1.37	−10.37	10.47	−1.27
France	−1649.13	−1205.50	14.47	−83.06	29.58	−53.48	11.72	−71.34
Germany	−2164.45	−1937.47	18.61	−205.97	5.90	−200.06	140.89	−65.07
Ireland	−254.84	−168.89	−3.75	−13.47	−6.13	−19.61	−8.82	−22.29
Italy	−886.77	−2063.00	1.39	−40.39	−8.09	−48.48	19.35	−21.04
Luxembourg	−18.39	−12.17	11.20	−0.88	0.29	−0.58	0.11	−0.77
Sweden	−229.51	−400.16	39.63	−23.15	0.98	−22.16	21.33	−1.82
Switzerland	−193.86	−129.64	4.19	−7.01	−0.43	−7.43	34.46	27.45
The Netherlands	−407.96	−145.59	20.82	−18.72	11.48	−7.25	73.67	54.94
United Kingdom	−1034.26	−545.56	8.40	−46.30	1.43	−44.88	−6.37	−52.67
Total	−7987.70	−7843.38	–	−514.99	34.06	−480.93	349.20	−165.79
			Total Tg CO_2e	−17.51	1.16	−16.35	11.87	−5.64

Table 6 Nitrous oxide emissions modeling inputs and results. EF_{N2O} = emissions factor, TAM = typical animal mass, N_{ex} = country- or region-specific N excretion rates. EF_{N2O} uncertainty range is a factor of 2 for all but anaerobic lagoons and whole barns

	EF_{N2O} (kg N2O-N kg N excreted^{-1})	TAM (kg hd^{-1})	N_{ex} (kg N 1000 kg TAM^{-1} d^{-1})	EF_{N2O} and N_{ex} sources	N_2O emission rate		Field-derived EF_{N2O} (kg N_2O-N kg N excreted^{-1})
					Modeled (kg hd^{-1} yr^{-1})	Field (kg hd^{-1} yr^{-1})	
Anaerobic lagoon	0	600	0.25	Average of ID and TX*	0	0.9 ± 0.5 (4)	0.010 ± 0.005
Slurry tanks and ponds	0.005	600	0.44	North America, with crust†	0.8	0.3 ± 0.3 (3)	0.005 ± 0.005
Manure pile	0.005	600	0.26	ID*	0.4	1.1 ± 0.7 (4)	0.033 ± 0.020
Corrals	0.02	600	0.25	Average of ID and TX*	1.7	1.5 ± 0.8 (4)	0.048 ± 0.026
Barn floors and paved surfaces	0.02	600	0.44	North America†	3.0	0.02 ± 0.01 (6)	0.0001 ± 0.0001
Whole barn (deep pit)	0.002	600	0.48	Western Europe†	0.3	10 ± 6 (3)	0.062 ± 0.038

*from (EPA, 2013b).
†from (IPCC, 2006).

Data were conspicuously lacking from India and China, which have the fastest growing dairy industries in the world (growing by 10.7 and 7.6 million hd, respectively, between 2000 and 2010; FAO, 2014). Though data were not available on manure management practices in the two countries, estimated CH_4 emissions for each suggest that China is treating more manure in liquid form; for every million dairy milk

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Table 7 Comparison of N_2O emissions from anaerobic lagoons and solid manure piles modeled for the United States using the current EF_{N2O} (0 and 0.005 kg N_2O-N kg N excreted^{-1}, respectively) (EPA, 2013a) and the revised EF_{N2O} (0.01 ± 0.005 and 0.033 ± 0.02 kg N_2O-N kg N excreted^{-1}, respectively) from Table 6. For all states, dairy cow TAM = 680 kg, heifer TAM = 407, and heifer N_{ex} = 69 kg N 1000 kg TAM^{-1} d^{-1}

State	Milk cows (hd)	Heifers (hd)	Manure in solid pile (%)	Manure in anaerobic lagoons (%)	N_{ex} dairy cows (kg N hd^{-1} yr^{-1})	EPA solid pile N_2O emissions (kg N_2O yr^{-1})	Revised solid pile N_2O emissions (kg N_2O yr^{-1})	EPA lagoons N_2O emissions (kg N_2O yr^{-1})	Revised lagoons N_2O emissions (kg N_2O yr^{-1})
Alabama	11 000	6000	7	16	130	627	4141 ± 2510	0	2869 ± 1434
Alaska	500	200	34	24	128	131	866 ± 525	0	185 ± 93
Arizona	185 000	60 000	9	61	159	15 336	101 217 ± 61 344	0	207 887 ± 103 944
Arkansas	12 000	4000	10	9	122	870	5745 ± 3482	0	1567 ± 783
California	1 750 000	760 000	9	59	158	148 050	977 127 ± 592 198	0	1 941 095 ± 970 547
Colorado	123 000	75 000	11	64	159	13 314	87 874 ± 53 257	0	154 930 ± 77 465
Connecticut	19 000	9500	16	13	145	2691	17 757 ± 10 762	0	4372 ± 2186
Delaware	5000	3000	19	10	143	852	5621 ± 3406	0	896 ± 448
Florida	114 000	30 000	7	43	149	6816	44 986 ± 27 265	0	83 741 ± 41 871
Georgia	78 000	23 000	9	23	147	5970	39 404 ± 23 881	0	30 515 ± 15 257
Hawaii	2000	1000	9	57	130	145	956 ± 580	0	1835 ± 918
Idaho	574 000	320 000	11	65	157	60 731	400 822 ± 242 922	0	717 725 ± 358 863
Illinois	98 000	46 000	39	16	146	33 772	222 897 ± 135 089	0	27 711 ± 13 855
Indiana	172 000	62 000	29	24	150	43 943	290 021 ± 175 770	0	72 733 ± 36 366
Iowa	210 000	130 000	34	20	152	67 738	447 069 ± 270 951	0	79 692 ± 39 846
Kansas	122 000	85 000	21	36	151	24 608	162 414 ± 98 432	0	84 371 ± 42 185
Kentucky	77 000	50 000	14	3	134	9262	61 132 ± 37 050	0	3970 ± 1985
Louisiana	19 000	5000	10	9	125	1379	9103 ± 5517	0	2483 ± 1241
Maine	32 000	17 000	20	10	144	5674	37 450 ± 22 697	0	5674 ± 2837
Maryland	53 000	28 000	22	8	144	10 330	68 179 ± 41 320	0	7513 ± 3756
Massachusetts	13 500	7500	22	8	138	2554	16 856 ± 10 216	0	1857 ± 929
Michigan	361 000	148 000	24	29	158	80 977	534 445 ± 323 906	0	195 693 ± 97 847
Minnesota	470 000	290 000	39	17	145	166 961	1 101 942 ± 667 844	0	145 556 ± 72 778
Mississippi	15 000	7000	10	12	135	1236	8160 ± 4946	0	2967 ± 1484
Missouri	95 000	50 000	42	11	131	32 560	214 898 ± 130 241	0	17 055 ± 8528
Montana	14 000	7000	19	42	150	2425	16 007 ± 9701	0	10 722 ± 5361
Nebraska	58 000	20 000	26	29	150	13 233	87 337 ± 52 932	0	29 520 ± 14 760
Nevada	28 000	10 000	10	65	157	2569	16 958 ± 10 277	0	33 402 ± 16 701
New Hampshire	15 000	7500	19	10	149	2583	17 050 ± 10 333	0	2719 ± 1360
New Jersey	7500	4000	25	6	138	1603	10 581 ± 6412	0	769 ± 385
New Mexico	322 000	140 000	9	61	164	28 173	185 944 ± 112 693	0	381 905 ± 190 953
New York	610 000	330 000	17	13	151	96 041	633 869 ± 384 163	0	146 886 ± 73 443

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Table 7 (continued)

State	Milk cows (hd)	Heifers (hd)	Manure in solid pile (%)	Manure in anaerobic lagoons (%)	N_{ex} dairy cows (kg N hd^{-1} yr^{-1})	EPA solid pile N_2O emissions (kg N_2O yr^{-1})	Revised solid pile N_2O emissions (kg N_2O yr^{-1})	EPA lagoons N_2O emissions (kg N_2O yr^{-1})	Revised lagoons N_2O emissions (kg N_2O yr^{-1})
North Carolina	44 000	21 000	11	10	152	4440	29 306 ± 17 761	0	8073 ± 4037
North Dakota	20 000	10 000	38	15	142	6604	43 590 ± 26 418	0	5214 ± 2607
Ohio	270 000	125 000	38	15	145	89 967	593 780 ± 359 867	0	71 026 ± 35 513
Oklahoma	54 000	20 000	21	45	140	9409	62 100 ± 37 636	0	40 325 ± 20 162
Oregon	121 000	65 000	11	50	150	12 245	80 815 ± 48 979	0	111 315 ± 55 658
Pennsylvania	543 000	310 000	24	6	147	118 770	783 881 ± 475 079	0	59 385 ± 29 692
Rhode Island	1100	500	25	5	141	235	1549 ± 939	0	94 ± 47
South Carolina	16 000	7000	8	18	144	1108	7315 ± 4433	0	4988 ± 2494
South Dakota	90 000	25 000	24	31	150	18 635	122 989 ± 74 539	0	48 140 ± 24 070
Tennessee	50 000	35 000	12	4	140	5415	35 737 ± 21 659	0	3610 ± 1805
Texas	425 000	230 000	11	58	155	44 298	292 368 ± 177 193	0	467 144 ± 233 572
Utah	87 000	42 000	15	56	151	11 918	78 662 ± 47 674	0	88 991 ± 44 496
Vermont	135 000	61 000	17	13	145	20 068	132 448 ± 80 271	0	30 692 ± 15 346
Virginia	95 000	49 000	11	5	145	9285	61 282 ± 37 140	0	8441 ± 4220
Washington	252 000	122 000	11	56	160	26 658	175 941 ± 106 631	0	271 425 ± 135 712
West Virginia	10 000	5000	23	7	134	1900	12 543 ± 7602	0	1157 ± 578
Wisconsin	1 265 000	700 000	38	17	150	443 940	2 930 005 ± 1 775 761	0	397 210 ± 198 605
Wyoming	6000	5000	19	43	150	1123	7413 ± 4493	0	5084 ± 2542
					Total kg N2O yr^{-1}	1 709 175	11 280 554 ± 6 836 699	0	6 023 128 ± 3 011 564
					Total Tg CO_2e yr^{-1}	0.51	3.36 ± 2.04	0	1.79 ± 0.90

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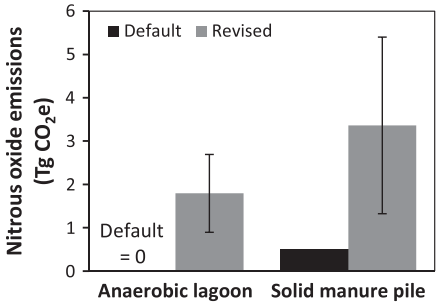

Fig. 5 Comparison of modeled N_2O emissions of solid manure piles and anaerobic lagoons calculated using current and revised EF_{N2O} values.

cows gained between 2000 and 2010, India's CH_4 emissions from manure management increased by 5 Gg CH_4, whereas China's increased by 9 Gg CH_4 per million hd (FAO, 2014). Accurately modeling these emissions is critical for policy decisions toward GHG emission reduction.

The disagreement between field measurements and modeled values provides mechanistic support for discrepancies reported by airborne measurements and modeling. In a top-down approach combining aircraft and tower measurements with an atmospheric transport model, Miller *et al.* (2013) calculated total CH_4 emissions for the United States that were 1.5 times greater than the EPA bottom-up approach. Underestimation of emissions from fossil fuel extraction was responsible for a significant part of this discrepancy, but emissions from livestock enteric fermentation and manure management were calculated to be twice that of the EPA estimate (Miller *et al.*, 2013). A smaller scale analysis for the Los Angeles Basin found similar dairy CH_4 fluxes between top-down and bottom-up approaches (Peischl *et al.*, 2013).

Despite the uncertainties in emissions inventories described above, targets for GHG reduction can be identified. As shown by the European example, decreasing the number of cows can reduce GHG emissions by decreasing both enteric fermentation and manure production (Ripple *et al.*, 2013). While this is the trend in developed countries, developing nations have growing livestock populations which must be managed appropriately to be sustainable (Eisler *et al.*, 2014). The most effective GHG mitigation approach for manure management depends on how manure is handled and stored. Where liquid manure management systems are common, particularly anaerobic lagoons which were the highest total and per cow CH_4 source, they represent the greatest opportunity for GHG emissions reduction. Some estimates suggest that the total CH_4 and N_2O emissions per head from anaerobic digesters are about 10% of the emissions from anaerobic lagoons (CARB, 2011a). The EPA (2011) estimated that adoption of anaerobic digesters by all US dairies for which this technology is feasible (those with liquid manure management systems and >500 hd, or approximately 2650 farms with 3 million hd) could reduce US CH_4 emissions by 41.25 Tg $CO_2e\ yr^{-1}$, or more than 85% of the total CH_4 emissions from dairy manure management. In addition, these anaerobic digesters would be capable of producing more than 6.8 million MWh yr^{-1} (EPA, 2011). According to the GHG equivalency calculator at www.epa.gov, this would offset an additional 17.6 Tg CO_2e of CO_2 emissions from energy production.

Our results show significant disagreement between measured and modeled GHG emissions from dairies globally. Revised emission factors based on the field data led to greater estimated GHG emissions from the United States and Europe. More field data are needed to refine these models. To maximize the usefulness of field measurements, better reporting of herd characteristics (number of milk cows and heifers, average mass, milk production, dry matter, and N intake), dairy characteristics (manure handling practices and storage dimensions, climate parameters, available land for manure spreading, typical management schedule), and manure characteristics (amount handled by each storage method, volume, volatile solid content, C and N content, manure temperature) are needed. Emission rates must be reported with the data necessary to convert between units of per head, per area, and per kg milk production in addition to units specific to certain types of sources, such as per HPU for barns or per volume for liquid storage. Future research should focus on GHG emissions from several major dairy industries, particularly China (the fastest growing), India (the largest), and California (the largest in the United States) (FAO, 2006). Each region has unique issues related to climate, development, and legislation that complicate estimating GHG emissions without direct measurements. Furthermore, longer monitoring periods are needed to disentangle the effects of management and climate on emissions and enable more accurate estimates of annual averages.

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References

Adviento-Borbe MA, Wheeler EF, Brown NE, Topper PA, Graves RE, Ishler VA, Varga GA (2010) Ammonia and greenhouse gas flux from manure in freestall barn with dairy cows on precision fed rations. *Transactions of the ASABE*, **53**, 1251–1266.

Ahn HK, Mulbry W, White JW, Kondrad SL (2011) Pile mixing increases greenhouse gas emissions during composting of dairy manure. *Bioresource Technology*, **102**, 2904–2909.

Amon B, Kryvoruchko V, Amon T, Zechmeister-Boltenstern S (2006) Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture, Ecosystems & Environment*, **112**, 153–162.

Bjorneberg DL, Leytem AB, Westermann DT, Griffiths PR, Shao L, Pollard MJ (2009) Measurement of atmospheric ammonia, methane, and nitrous oxide at a concentrated dairy production facility in southern Idaho using open-path FTIR spectrometry. *Transactions of the ASABE*, **52**, 1749–1756.

Bogner J, Spokas K, Burton E, Sweeney R, Corona V (1995) Landfills as atmospheric methane sources and sinks. *Chemosphere*, **31**, 4119–4130.

Borhan MS, Capareda S, Mukhtar S, Faulkner WB, McGee R, Parnell CB (2011a) Determining seasonal greenhouse gas emissions from ground-level area sources in a dairy operation in central Texas. *Journal of the Air & Waste Management Association*, **61**, 786–795.

Borhan MS, Capareda SC, Mukhtar S, Faulkner WB, McGee R, Parnell CB (2011b) Greenhouse gas emissions from ground level area sources in dairy and cattle feedyard operations. *Atmosphere*, **2**, 303–329.

Borhan S, Mukhtar S, Capareda S, Rahman S (2012) Greenhouse gas emissions from housing and manure management systems at confined livestock operations. In: *Waste Management - An Integrated Vision* (ed Rebellon LFM). InTech, Available at: http://www.intechopen.com/books/waste-management-an-integrated-vision/greenhouse-gas-emissions-from-housing-and-manure-management-systems-at-confined-livestock-operations (accessed 12 June 2013). ISBN: 978-953-51-0795-8.

Brown HA, Wagner-Riddle C, Thurtell GW (2002) Nitrous oxide flux from a solid dairy manure pile measured using a micrometeorological mass balance method. *Nutrient Cycling in Agroecosystems*, **62**, 53–60.

CARB (2011a) *California Greenhouse Gas Emissions Inventory: 2000-2009*. California Air Resources Board, Sacramento, CA.

CARB (2011b) *Annex 3B. Manure Management (IPCC 3A2) to the Technical Support Document for the 2000-2009 California's Greenhouse Gas Emissions Inventory*. California Air Resources Board, Sacramento, CA.

Chadwick D, Sommer S, Thorman R, Fangueiro D, Cardenas L, Amon B, Misselbrook T (2011) Manure management: implications for greenhouse gas emissions. *Animal Feed Science and Technology*, **166–167**, 514–531.

Chung ML, Shilton AN, Guieysse B, Pratt C (2013) Questioning the accuracy of greenhouse gas accounting from agricultural waste: a case study. *Journal of Environment Quality*, **42**, 654–659.

Conrad R (2007) Microbial ecology of methanogens and methanotrophs. *Advances in Agronomy*, **96**, 1–63.

Craggs R, Park J, Heubeck S (2008) Methane emissions from anaerobic ponds on a piggery and a dairy farm in New Zealand. *Australian Journal of Experimental Agriculture*, **48**, 142–146.

Davidson EA (2009) The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience*, **2**, 659–662.

Eisler MC, Lee MRF, Tarlton JF *et al.* (2014) Steps to sustainable livestock. *Nature*, **507**, 32–34.

Ellis S, Webb J, Misselbrook T, Chadwick D (2001) Emission of ammonia (NH3), nitrous oxide (N2O) and methane (CH4) from a dairy hardstanding in the UK. *Nutrient Cycling in Agroecosystems*, **60**, 115–122.

Engström P, Dalsgaard T, Hulth S, Aller RC (2005) Anaerobic ammonium oxidation by nitrite (anammox): implications for N2 production in coastal marine sediments. *Geochimica et Cosmochimica Acta*, **69**, 2057–2065.

EPA (2011) *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities*. U.S. Envronmental Protection Agency, Washington, DC.

EPA (2012) *Summary Report: Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990–2030*. Office of Atmospheric Programs, Climate Change Division, US Environmental Protection Agency, Washington, DC.

EPA (2013a) *Inventory of US Greenhouse gas Emissions and Sinks: 1990–2009*. US Environmental Protection Agency, Washington, DC.

EPA (2013b) *Inventory of US Greenhouse gas Emissions and Sinks: 1990–2009, Annexes*. US Environmental Protection Agency, Washington, DC.

FAO, Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, De Haan C (2006) *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agriculture Organization of the United Nations, Rome.

FAO (2014) *FAOSTAT, Food and Agriculture Organization of the United Nations*. FAO Statistics Division, Rome, Italy. faostat3.fao.org.

Gao Z, Yuan H, Ma W, Liu X, Desjardins RL (2011) Methane emissions from a dairy feedlot during the fall and winter seasons in Northern China. *Environmental Pollution*, **159**, 1183–1189.

Goodland R (2014) A fresh look at livestock greenhouse gas emissions and mitigation potential in Europe. *Global Change Biology*, **20**, 2042–2044.

Gupta PK, Jha AK, Koul S *et al.* (2007) Methane and nitrous oxide emission from bovine manure management practices in India. *Environmental pollution (Barking, Essex: 1987)*, **146**, 219–224.

Harter T, Davis H, Mathews MC, Meyer RD (2002) Shallow groundwater quality on dairy farms with irrigated forage crops. *Journal of Contaminant Hydrology*, **55**, 287–315.

Hensen A, Groot TT, van den Bulk WCM, Vermeulen AT, Olesen JE, Schelde K (2006) Dairy farm CH4 and N2O emissions, from one square metre to the full farm scale. *Agriculture, Ecosystems & Environment*, **112**, 146–152.

Husted S (1994) Seasonal Variation in Methane Emission from Stored Slurry and Solid Manures. *Journal of Environmental Quality*, **23**, 585–592.

IPCC (1996) Chapter 2: Radiative forcing of climate change. In: *Climate Change 1995: The Science of Climate Change* (eds Joughton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K), pp. 65–132. Cambridge University Press, Cambridge, UK.

IPCC (2006) Chapter 10: Emissions from livestock and manure management. In: *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme* (eds Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K), pp. 10.1–10.87. Cambridge University Press, Cambridge, United Kingdom.

Jungbluth T, Hartung E, Brose G (2001) Greenhouse gas emissions from animal houses and manure stores. *Nutrient Cycling in Agroecosystems*, **60**, 133–145.

Kaharabata SK, Schuepp PH, Desjardins RL (1998) Methane emissions from aboveground open manure slurry tanks. *Global Biogeochemical Cycles*, **12**, 545–554.

Kaharabata SK, Schuepp PH, Desjardins RL (2000) Estimating Methane Emissions from Dairy Cattle Housed in a Barn and Feedlot Using an Atmospheric Tracer. *Environmental Science & Technology*, **34**, 3296–3302.

Khan RZ, Muller C, Sommer SG (1997) Micrometeorological mass balance technique for measuring CH4 emission from stored cattle slurry. *Biology and Fertility of Solis*, **24**, 442–444.

Kinsman R, Sauer FD, Jackson HA, Wolynetz MS (1995) Methane and carbon dioxide emissions from dairy cows in full lactation monitored over a six-month period. *Journal of Dairy Science*, **78**, 2760–2766.

Leytem AB, Dungan RS, Bjorneberg DL, Koehn AC (2011) Emissions of ammonia, methane, carbon dioxide, and nitrous oxide from dairy cattle housing and manure management systems. *Journal of Environmental Quality*, **40**, 1383–1394.

Leytem AB, Dungan RS, Bjorneberg DL, Koehn AC (2013) Greenhouse gas and ammonia emissions from an open-freestall dairy in southern idaho. *Journal of Environmental Quality*, **42**, 10–20.

Luo J, Saggar S (2008) Nitrous oxide and methane emissions from a dairy farm standoff pad. *Australian Journal of Experimental Agriculture*, **48**, 179.

Maeda K, Toyoda S, Shimojima R, Osada T, Hanajima D, Morioka R, Yoshida N (2010) Source of nitrous oxide emissions during the cow manure composting process as revealed by isotopomer analysis of and amoA abundance in betaproteobacterial ammonia-oxidizing bacteria. *Applied and Environmental Microbiology*, **76**, 1555–1562.

Mangino J, Bartram D, Brazy A (2002) Development of a methane conversion factor to estimate emissions from animal waste lagoons. In: *11th International Emission Inventory Conference*. U.S. Environmental Protection Agency, Washington, DC. Available at: http://www.epa.gov/ttnchie1/conference/ei11/ammonia/mangino.pdf (accessed 15 October 2012).

Marik T, Levin I (1996) A new tracer experiment to estimate the methane emissions form a dairy cow shed using sulfur hexafluoride (SF6). *Global Biogeochemical Cycles*, **10**, 413–418.

Massé DI, Talbot G, Gilbert Y (2011) On farm biogas production: a method to reduce GHG emissions and develop more sustainable livestock operations. *Animal Feed Science and Technology*, **166–167**, 436–445.

McCandlish AC (1920) Environment and breeding as factors influencing milk production. *The Journal of Heredity*, **11**, 204–214.

McGinn SM, Beauchemin KA (2012) Dairy farm methane emissions using a dispersion model. *Journal of Environmental Quality*, **41**, 73–79.

Miller SM, Wofsy SC, Michalak AM *et al.* (2013) Anthropogenic emissions of methane in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **110**, 20018–20022.

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Misselbrook T, Webb J, Chadwick D, Ellis S, Pain B (2001) Gaseous emissions from outdoor concrete yards used by livestock. *Atmospheric Environment*, **35**, 5331–5338.

Monteny GJ, Groenestein CM, Hilhorst MA (2001) Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. *Nutrient Cycling in Agroecosystems*, **60**, 123–132.

Mulder A, Graaf AA, Robertson LA, Kuenen JG (1995) Anaerobic ammonium oxidation discovered in a denitrifying fluidized bed reactor. *FEMS Microbiology Ecology*, **16**, 177–184.

Myhre G, Shindell D, Breon F-M *et al*. (2013) Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ngwabie NM, Jeppsson K-H, Nimmermark S, Swensson C, Gustafsson G (2009) Multi-location measurements of greenhouse gases and emission rates of methane and ammonia from a naturally-ventilated barn for dairy cows. *Biosystems Engineering*, **103**, 68–77.

Ngwabie NM, Jeppsson K-H, Gustafsson G, Nimmermark S (2011) Effects of animal activity and air temperature on methane and ammonia emissions from a naturally ventilated building for dairy cows. *Atmospheric Environment*, **45**, 6760–6768.

O'Brien D, Shalloo L, Patton J, Buckley F, Grainger C, Wallace M (2012) Evaluation of the effect of accounting method, IPCC v. LCA, on grass-based and confinement dairy systems' greenhouse gas emissions. *Animal*, **6**, 1512–1527.

Osada T, Sommer SG, Dahl P, Rom HB (2001) Gaseous emission and changes in nutrient composition during deep litter composting. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science*, **51**, 137–142.

Parkin TB, Kaspar TC (2004) Temporal variability of soil carbon dioxide flux : effect of sampling frequency on cumulative carbon loss estimation. *Soil Science Society of America Journal*, **68**, 1234–1241.

Peischl J, Ryerson TB, Brioude J *et al*. (2013) Quantifying sources of methane using light alkanes in the Los Angeles basin, California. *Journal of Geophysical Research: Atmospheres*, **118**, 4974–4990.

Petersen SO, Sommer SG (2011) Ammonia and nitrous oxide interactions: roles of manure organic matter management. *Animal Feed Science and Technology*, **166–167**, 503–513.

Petersen SO, Amon B, Gattinger A (2005) Methane oxidation in slurry storage surface crusts. *Journal of Environmental Quality*, **34**, 455–461.

Place SE, Mitloehner FM (2010) Invited review: contemporary environmental issues: a review of the dairy industry's role in climate change and air quality and the potential of mitigation through improved production efficiency. *Journal of Dairy Science*, **93**, 3407–3416.

Ripple WJ, Smith P, Haberl H, Montzka SA, McAlpine C, Boucher DH (2013) Ruminants, climate change and climate policy. *Nature Climate Change*, **4**, 2–5.

RIVM, Coenen PWHG, van der Maas CWM *et al*. (2013) *Greenhouse gas Emission in The Netherlands*. National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands.

Safley LM, Westerman PW (1988) Biogas production from anaerobic lagoons. *Biological Wastes*, **23**, 181–193.

Safley LM, Westerman PW (1992) Performance of a dairy manure anaerobic lagoon. *Bioresource Technology*, **42**, 43–52.

Samer M, Ammon C, Loebsin C, Fiedler M, Berg W, Sanftleben P, Brunsch R (2012) Moisture balance and tracer gas technique for ventilation rates measurement and greenhouse gases and ammonia emissions quantification in naturally ventilated buildings. *Building and Environment*, **50**, 10–20.

Sedorovich DM, Rotz CA, Richard TL (2007) Greenhouse gas emissions from dairy farms. In: 2007 ASABE Annual International Meeting, Vol. 0300, p. Paper No. 074096. American Society of Agricultural and Biological Engineers.

Sneath RW, Beline F, Hilhorst MA, Peu P (2006) Monitoring GHG from manure stores on organic and conventional dairy farms. *Agriculture, Ecosystems & Environment*, **112**, 122–128.

Snell HGJ, Seipelt F, Van den Weghe HFA (2003) Ventilation rates and gaseous emissions from naturally ventilated dairy houses. *Biosystems Engineering*, **86**, 67–73.

Sommer SG, McGinn SM, Hao X, Larney FJ (2004) Techniques for measuring gas emissions from a composting stockpile of cattle manure. *Atmospheric Environment*, **38**, 4643–4652.

Tauseef SM, Premalatha M, Abbasi T, Abbasi SA (2013) Methane capture from livestock manure. *Journal of Environmental Management*, **117**, 187–207.

Todd RW, Cole NA, Rhoades MB, Parker DB, Casey KD (2008) Daily, monthly, seasonal, and annual ammonia emissions from Southern High Plains cattle feedyards. *Journal of Environmental Quality*, **40**, 1090–1095.

Todd RW, Cole NA, Casey KD, Hagevoort R, Auvermann BW (2011) Methane emissions from southern High Plains dairy wastewater lagoons in the summer. *Animal Feed Science and Technology*, **166–167**, 575–580.

UNFCCC (2014) 2013 annex 1 party GHG national inventory submissions. 2013 Annex 1 Party GHG National Inventory Submissions.

USDA (2011) *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2008. Technical Bulletin No. 1930*. Climate Change Program Office, Office of the Chief Economist, U.S. Department of Agriculture, Washington, DC.

VanderZaag AC, Wagner-Riddle C, Park K-H, Gordon RJ (2011) Methane emissions from stored liquid dairy manure in a cold climate. *Animal Feed Science and Technology*, **166–167**, 581–589.

van Vliet LJP, Patni NK, Matin MA (2004) GHG emissions from manure in a naturally ventilated, freestall dairy barn, comparing sand and sawdust bedding. In:*ASAE/ CSAE Meeting Paper No. 044161*, Vol. **0300**. ASAE, St. Joseph, MI.

Wu W, Zhang G, Kai P (2012) Ammonia and methane emissions from two naturally ventilated dairy cattle buildings and the influence of climatic factors on ammonia emissions. *Atmospheric Environment*, **61**, 232–243.

Yamulki S (2006) Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. *Agriculture, Ecosystems & Environment*, **112**, 140–145.

Yang WH, Weber KA, Silver WL (2012) Nitrogen loss from soil through anaerobic ammonium oxidation coupled to iron reduction. *Nature Geoscience*, **5**, 538–541.

Zhang G, Strøm JS, Li B, Rom HB, Morsing S, Dahl P, Wang C (2005) Emission of ammonia and other contaminant gases from naturally ventilated dairy cattle buildings. *Biosystems Engineering*, **92**, 355–364.

Zhu Z, Dong H, Zhou Z (2012) Ammonia and greenhouse gas emissions from a dairy cattle barn with a daily manure collection system. *Transactions of the ASABE*, **55**, 1959–1964.

Zimmerman CA, Rakes AH, Jaquette RD, Hopkins BA, Croom WJ (1991) Effects of protein level and forage source on milk production and composition in early lactation dairy cows. *Journal of Dairy Science*, **74**, 980–990.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Summary of the measurement techniques, locations, and climate data for each study.
Table S2. Anaerobic lagoon study characteristics and GHG emissions.
Table S3. Slurry tank and pond study characteristics and GHG emissions.
Table S4. Corral study characteristics and GHG emissions.
Table S5. Solid manure pile study characteristics and GHG emissions.
Table S6. Whole barn and barn floor study characteristics and GHG emissions.
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Table S8. Whole dairy study characteristics and GHG emissions.

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Symposium review: Greenhouse gas emissions from liquid dairy manure: Prediction and mitigation[1]

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ABSTRACT

The handling and use of manure on livestock farms contributes to emissions of the greenhouse gases (GHG) CH_4 and N_2O, especially with liquid manure management. Dairy farms are diverse with respect to manure management, with practices ranging from daily spreading to long-term storage for more efficient recycling of manure nutrients for crop production. Opportunities for GHG mitigation will depend on the baseline situation with respect to handling and storage, and therefore prediction and mitigation at the farm level requires a dynamic description of housing systems and storage conditions, and use of treatment technologies. Also, effects of treatment and handling on the properties of field-applied manure must be taken into account. Storage conditions and manure composition importantly define carbon and nitrogen transformations, and the resulting emissions of CH_4 and N_2O, as well as CO_2 and NH_3, which are all important for the GHG balance. Currently, inventories for CH_4 and N_2O emissions from manure are based on emission factors for a limited number of production systems, together with average annual temperature, but the inherent uncertainty of this approach is a barrier toward prediction and mitigation. Although more representative emission factors may be determined at country level, this is both challenging and costly, and effects of management changes for GHG mitigation are not easily quantified. An empirical model of CH_4 emissions during storage is discussed that is based on daily time steps, and a parameterization based on measurements. A distinction between emissions from manure in barns and outside storage facilities is important for assessing effects of treatment technologies, such as anaerobic digestion, where only posttreatment emissions are affected. Upon field application, manure and soil together define the equilibrium distribution of labile carbon and nitrogen between bulk soil and manure hotspots. This introduces heterogeneity with respect to potential for N_2O emissions, which is not represented in existing prediction models. Manure treatment and management options for GHG mitigation are discussed with emphasis on effects on manure volatile solids and N availability. Anaerobic digestion and acidification represent treatment technologies that are relevant for GHG mitigation on dairy farms.

Key words: manure management, methane, nitrous oxide, volatile solids

INTRODUCTION

According to a recent life cycle analysis (Thoma et al., 2013a), the United States dairy sector is responsible for 1.9% of total national greenhouse gas (**GHG**) emissions, whereas globally this contribution is 3 to 5% (FAO, 2010). Main sources are CH_4 emissions associated with enteric fermentation and manure management, and N_2O emissions from feed and food production, which are therefore also key targets of efforts to quantify emissions and mitigation potentials (Henriksson et al., 2011; Thoma et al., 2013a).

Dairy production systems are extremely diverse with respect to manure management practices and environmental conditions (Sommer et al., 2009; Thoma et al., 2013b), and this will influence the effectiveness of GHG mitigation measures. For example, Sommer et al. (2009) showed that CH_4 emissions from manure in 5 European countries were affected differently by several treatment technologies due to differences in management and storage temperature. Similarly, the 2 states in the United States with the largest dairy herds, California (**CA**) and Wisconsin (**WI**), are different with respect to both climate and manure management practices; a survey found that 50 to 67% of WI dairy farms spread manure year-round without storage, representing on average 45% of the manure volume (Turnquist et al., 2006), whereas this was the case on only 26 to 27% of CA dairy farms in a survey of 2 counties (Meyer et

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al., 2011). As a consequence, the potential for mitigating CH_4 emissions during storage would be greater for CA dairy farms, whereas the potential for improved N use efficiency and, in turn, N_2O mitigation would be greater for WI dairy farms. Effective mitigation strategies thus depend on an accurate description of on-farm conditions.

Contributions from CH_4 and N_2O

Greenhouse gas emissions on dairy farms are dominated by CH_4 and N_2O (Chianese et al., 2009; Kristensen et al., 2011). Even in regions where the number of cows have declined, such as North America and Western Europe, a change toward liquid manure management and extended storage have increased emissions of both gases (Wightman and Woodbury, 2016). The global warming potential (**GWP**) of CH_4 and N_2O are normally considered for a time horizon of 100 yr, and current estimates of GWP_{100} for CH_4 and N_2O are, respectively, 34 and 298 times the GWP_{100} of CO_2 (Myhre et al., 2013). However, CH_4 has a half-life in the atmosphere of only 12 to 13 yr, and thus for a 20-yr time horizon, GWP_{20}, the contribution of CH_4 is 2.5-fold higher at 86, which increases the relevance of CH_4 mitigation efforts to curb global warming in the short term.

Emissions of N_2O are associated with N transformations via nitrification and denitrification under oxygen-limited conditions (Maharjan and Venterea, 2013). Sustained emissions require that aerobic and anaerobic environments exist in close proximity, which may be the case in organic crusts formed during liquid manure storage (Wood et al., 2012), and in solid manure (Webb et al., 2011). Upon field application, factors such as manure composition, application method and soil conditions together determine the potential for N_2O emissions, but given the unpredictable effects of climate, effects of treatment and management can vary dramatically. A recent meta-analysis (Charles et al., 2017) found that liquid and solid organic residues (including manure) are characterized by N_2O emissions that are, respectively, above and below the emission factor currently used by most countries. However, the analysis also found strong positive interactions with soil N status, clay content, and precipitation, indicating that defining local conditions, as for CH_4, is critical for more accurate estimation of emissions.

Gaseous N losses through NH_3, nitrogen oxides (NO_x), and N_2, and leaching losses mainly as NO_3^-, are quantitatively much more important than direct emissions of N_2O (Venterea et al., 2012). Because both NH_3 volatilization and NO_3^- leaching are indirect sources of N_2O, the prevention of these losses through better N use efficiency is an effective strategy for N_2O mitigation.

Objectives

Predicting CH_4 and N_2O emissions from livestock farms is a significant challenge, and currently the uncertainty associated with emission estimates effectively prevents accountability, regulation, and mitigation. Several recent papers and meta analyses have reviewed GHG emissions from manure management and mitigation options (e.g., Hristov et al., 2011; Petersen et al., 2013a; Hou et al., 2015; Jayasundara et al., 2016). In this review, I will instead highlight selected aspects of manure treatment and management that research, from laboratory to practical scale, has shown to be of particular importance for gaseous emissions of carbon (CH_4, CO_2) and nitrogen (N_2O, NH_3). The main emphasis will be on dairy production systems. In view of the many potential interactions between different management stages, the discussion will address both manure management on the farm and subsequent field application.

DRIVERS OF GHG EMISSIONS FROM MANURE

Gerber et al. (2011) reported that the shares of solid and liquid manure management on dairy farms in North America were, respectively, 31 and 36%, whereas the corresponding numbers for Western Europe were 36 and 38%. In many parts of the world, the share of liquid manure management is increasing due to intensification of livestock production (Bouwman et al., 2013) and due to recommendations to store manure to recycle manure nutrients for crop production (Oenema et al., 2011). Because the potential for CH_4 production is estimated to be 4- to 20-fold higher with liquid compared with solid manure management depending on storage temperature (IPCC, 2006), it can be estimated that, for example, in Western Europe liquid manure accounts for >90% of total CH_4 emissions from solid and liquid storage. As stated above, the potential for N_2O emissions after field application is also higher from liquid manure (Charles et al., 2017), and the focus of this review is therefore on liquid manure management. It should be noted, however, that recently introduced deep litter systems also may have a high potential for CH_4 as well as N_2O emissions (Barberg et al., 2007; Galama, 2011).

Storage Environment

An overview of livestock manure handling systems was presented by Sørensen et al. (2013). Collection

inside barns may occur in deep or shallow pits, and excreta may be scraped or flushed, or exported by gravity flow, for outside storage. Outside storage can take place in a concrete tank or pond, or lagoon(s). Dairy farms rely on an in-house pit or outside storage, or both. In pits beneath slatted floors, a significant volume of manure may be maintained to enable mobilization of settling solids during export; a recent survey found that in Denmark the resulting hydraulic retention time (**HRT**) for cattle slurry was 30 to 40 d (Kai et al., 2015). Anaerobic lagoons are widely used in North America as a cost-effective method to stabilize effluents through biodegradation of organic matter and settling of solids, but due to the prolonged retention time and large surface area, the potential for CH_4 and NH_3 emissions is high compared with storage tanks (IPCC, 2006; McGinn et al., 2008). Depending on in-barn and outside storage temperatures, the retention time in barns and outside storage, and any treatment in between, can significantly influence the fate of manure organic matter and nutrients before land application.

A storage design parameter of potential importance for the GHG balance of manure management is surface-to-volume ratio. It is well established that the loss of N via NH_3 emission is high in the absence of a cover such as a natural crust, floating membrane, or roof structure on storages to restrict gas exchange (Sommer et al., 1993). However, C metabolism is also influenced by gas exchange across the manure-air interface because manure represents a sink for atmospheric O_2. The flux of O_2 is proportional to the concentration gradient across the diffusive boundary layer (Jørgensen and Revsbech, 1985; Hafner et al., 2017). Thus, with uncovered liquid manure the mass transfer of dissolved organic C to the surface through the effect of wind or convective heat transfer (Hafner et al., 2017) will result in steep dissolved organic C concentration gradients that enhance O_2 consumption compared with storages with a synthetic membrane or natural crust cover, because here the diffusive boundary layer is much greater and mixing less. Because the end product of aerobic heterotrophic activity is CO_2, processes at manure surfaces will influence the proportions of volatile solids (**VS**) lost as CH_4 and CO_2 (Møller et al., 2004). Furthermore, both $CO_2/HCO_3^-/CO_3^{2-}$ and NH_3/NH_4^+ are important components of the buffer system of manure (Sommer and Husted, 1995), and CO_2 emissions from manure can enhance NH_3 emissions by raising pH at the manure-air interface (Hafner et al., 2017). The relative importance of processes at this interface will also depend on the degree of filling; the surface-to-volume ratio thus increases after manure removal for field application.

The presence of active methanogens is a precondition for CH_4 emissions during storage, but methanogens in fresh excreta may not thrive in harsh liquid manure environments (Chen et al., 2008a), and this can delay the appearance of CH_4 emissions for weeks or even months (Sommer et al., 2007). Adaptation is therefore required, or inoculation with methanogens from residual manure in the pit, which is already adapted to this environment. Flushing and emptying of manure pits or storage tanks have been shown to delay the onset of methanogenesis (e.g., Haeussermann et al., 2006), but under practical storage conditions this can be difficult to achieve. Recently, Baldé et al. (2016) reported that removal of sludge from concrete tanks on a dairy farm in autumn had no detectable effect on CH_4 emissions during storage the following summer.

Manure Volatile Solids

Volatile solids in liquid cattle manure typically constitute 75 to 85% of TS, the rest being sand and minerals (Møller et al., 2002; Petersen et al., 2003). According to Møller et al. (2004), labile fractions (VFA, protein, lipids, degradable carbohydrate) constitute around 69% of VS in cattle manure, and 79% in finishing pig manure. Any bedding will add to the concentration of DM, whereas effects on VS concentration will depend on the material used, such as straw, sawdust, sand, or recycled manure solids, which differ with respect to CH_4 production potential, but also animal welfare, cost, and labor (Møller et al., 2004; Zdanowicz et al., 2004). Møller et al. (2002) found that 50% of TS in cattle manure were degraded during 7 mo of storage at 20°C. Assuming that labile pools of manure OM were lost to a greater extent than more recalcitrant components, the potential is significant for loss of labile VS, and thus CH_4 emissions, even within a few weeks of storage, which has implications for manure treatment and management.

During storage, organic particles may remain suspended, settle, or float to the surface to form a natural crust. Up-drift may be created by gas bubbles (consisting mainly of CH_4 and CO_2) derived from methanogenic activity, and crust formation on dairy cattle manure has been observed to coincide with the onset of CH_4 emissions (Misselbrook et al., 2005c; Wood et al., 2012). Also, Misselbrook et al. (2005c) reported that a glucose-starch additive promoted crust formation. Buoyancy of a crust is further supported by pockets of gas beneath the crust, which are intermittently deflated through cracks, as observed by Duan et al. (2017) using an oxygen microsensor. Thus, crust formation is a product of both recalcitrant and labile manure OM.

Depending on weather conditions (rainfall, temperature), a variety of microbial populations may develop in surface crusts. The microbial community will include populations of CH_4 oxidizing bacteria, or methano-

trophs (e.g., Petersen et al., 2005; Duan et al., 2017). Their activity depends on both availability of substrates (CH_4, O_2) and inhibitory effects of mineral N, but recent evidence suggests that mainly the activity of so-called type 1 methanotrophs responds to elevated CH_4 availability in aerated parts of the crust (Duan et al., 2017). However, at this time limited information is available about the importance of methanotrophic activity in surface crusts for CH_4 emissions. Natural crusts on manure storages are also a potential source of N_2O; this will be discussed later.

Manure Nitrogen

Manure recycling for crop production can significantly reduce the need for imported fertilizers, although ensuring a balanced nutrient supply with respect to N, P, K, and S can be difficult with manure alone. For dairy cattle manure a direct relationship exists between N intake and excretion (Kebreab et al., 2001). The N excreted is partly unavoidable losses associated with, for example, microbial cell walls and residual protein, and partly a variable fraction of excess N excreted mainly as urea in the urine (Petersen et al., 1998). Urea is rapidly hydrolyzed to form NH_4^+ and NH_3 (total ammoniacal N, **TAN**), whereas mineralization of organic N is slower and temperature dependent. Sommer et al. (2007) found that mineralization of organic N in liquid pig and cattle manure varied between 5 and 85% when stored at 10, 15, or 20°C for up to 200 d. Mineralization of organic N will increase manure N availability and pH (Eriksen et al., 2012), and therefore also the potential for environmental loss of TAN through NH_3 emission. Depending on length of storage and ambient temperature, effective recycling of N for crop production will require NH_3 mitigation measures.

Upon field application, both particle size distribution and soil properties influence redistribution of manure constituents. Vadas (2006) found that around 80% of the DM in liquid dairy and swine manure applied on top of a fine-loamy soil was retained at the surface, whereas the 20% of manure solids entering the soil was predominantly recovered within 10 mm distance from the surface. This is in accordance with the distribution of dissolved organic C and NH_4^+ observed in soil around cattle manure layers, that is, 2-dimensional manure hotspots, in laboratory setups (e.g., Petersen et al., 1996), suggesting that C and N transformations and N_2O emissions are concentrated within a limited soil volume in close contact with manure after field application. The VS in manure has a high water retention capacity compared with mineral soil; exponential relationships between manure VS concentration and water retention were described by Petersen et al. (2003).

PREDICTING GHG EMISSIONS FROM MANURE

The need to use a transparent and consistent methodology for national GHG inventories is widely accepted, and the United Nations' Framework Convention on Climate Change has recommended the use of guidelines developed by the Intergovernmental Panel on Climate Change (**IPCC**). This methodology is based on annual emission factors defined for a limited number of production systems, but several studies have pointed out that quantifying farm-level emissions is problematic with a methodology that is insensitive to local management (Weiske et al., 2006; Schils et al., 2007; Crosson et al., 2011; VanderZaag et al., 2013). Hence, more dynamic, yet transparent and consistent, methods to estimate GHG sources and sinks are needed, as well as mitigation potentials of treatment and management. This section discusses challenges and opportunities in relation to prediction of CH_4 and N_2O emissions from manure.

Controls of CH_4 Emissions

The IPCC methodology for estimating CH_4 emissions from manure management recommends use of a so-called methane conversion factor (**MCF**) to represent local manure storage conditions (IPCC, 2006). Default MCF values are proposed for a range of production systems based on average annual temperature, although countries are recommended to develop national or regional MCF through measurements, if possible. An MCF value must account for timing and length of storage, manure composition, presence of inoculum with adapted methanogens from older manure, daily and seasonal temperature variations, and retention time in the barn (IPCC, 2006). With such a wide range of storage conditions to be represented by a single value, the uncertainty associated with MCF is necessarily high, and it is relevant to consider the scope for a more dynamic description of key drivers.

Time is a key variable because management decisions influence storage conditions on a daily basis, and storage time before/after manure treatment if applicable. Manure volume and retention time in barns and outside storage facilities are readily calculated by day knowing the number of animals and grazing periods, excretion rate, and timing of transfer from barn to outside storage. This information can then be used to define storage temperature with daily time steps, which is critical to account for regional and seasonal differences in temperature that may be significant. For example, the average annual temperature in Milwaukee, WI, varied moderately between 4.4 and 13.1°C in the period from 1981 to 2010, but average monthly temperature

varied between −9.1 and 26.7°C (Prism Climate Group, 2017). Detailed information about local temperature is generally accessible and hence may support a better spatio-temporal resolution of CH_4 emission estimates.

The greatest challenge in predicting CH_4 emissions may be the documentation of CH_4 production rates. Four contrasting manure materials (pig manure, cattle manure, fresh digestate, and aged digestate) were found to have very similar activation energies, E_a (i.e., temperature sensitivity), of methanogenesis in the range of 5 to 37°C (Elsgaard et al., 2016), whereas actual CH_4 production rates were very different (Figure 1). The latter was partly explained by the differences in origin and treatment, but in practice CH_4 production potential also varies with feeding (Jayasundara et al., 2016), as well as age and storage temperature (Sommer et al., 2007), and storage environment (Barret et al., 2013). Across 90 individual manure samples from 4 storage tanks with either pig or dairy cattle manure, Barret et al. (2013) observed a negative effect of VFA (and positive effect of pH), presumably because methanogens were inhibited by the acidification associated with VFA accumulation (Chen et al., 2008a). There was also inter-storage and temporal variability in methangenic community composition, and a lower potential for CH_4 production near the surface in pig manure, but not dairy manure. Although a multiple linear regression equation was able to describe the observed CH_4 emissions based on 16 microbiological and chemical manure characteristics, it was acknowledged that additional complexity is introduced under practical storage conditions (Barret et al., 2013). Notably, the average age of the manure in a storage, and hence the extent of VS degradation at the time of observation, is typically unknown. In accordance with this, a sensitivity analysis found that estimates of CH_4 production rate in individual manure materials were much more sensitive to CH_4 production potential, as represented by lnA (see next section), than to temperature or VS composition (Petersen et al., 2016).

Aerobic degradation near the manure-air interface (Patni and Jui, 1987; Møller et al., 2004; Barret et al., 2013) further complicates the prediction of CH_4 emissions, since the removal of labile VS in the manure via aerobic degradation to CO_2 will change the balance between CH_4 and CO_2 associated with loss of VS during storage. Implications of aerobic degradation for CH_4 emissions will be greater for a pond with a surface area of up to several hectares (Leytem et al., 2011) compared with slurry tanks of 20 m diameter (Baldé et al., 2016). Observations from practical and pilot-scale storage confirm that proportions of CH_4 and CO_2 emitted are highly variable. In a study of emissions from a slurry tank, Laguë et al. (2005) observed CH_4-C/(CH_4-C + CO_2-C) ratios in 3 seasons that ranged from 0.36 to 0.45, whereas these ratios for 2 earthen basins averaged 0.24 (no cover) and 0.06 (straw cover). Viguria et al. (2015) found proportions of CH_4 in emissions from 2 lagoons during spring corresponding to 0.15 to 0.2 (range: 0.1 to 0.4). Sommer et al. (2007) compared CH_4-C/(CH_4-C + CO_2-C) ratios of slurry during simulated pit storage at 10, 15, and 20°C; whereas at 10°C the ratios were 0.1 to 0.3, at 20°C the ratios for cattle slurry shifted during storage from 0.2 to 0.5, and to 0.65 in pig slurry. For the data presented by Leytem et al. (2011), CH_4-C/(CH_4-C + CO_2-C) ratios of emissions from a dairy wastewater pond in early May, late May, August, and October were, respectively, 0.08, 0.25, 0.38, and 0.45 at temperatures of 5.0, 15.4, 20.8, and 15.3. The importance of methanogenesis may increase over time as a result of microbial adaptation or changes in the storage environment (Sommer et al., 2007; Barret et al., 2013), but will then, as mentioned above, be constrained by the remaining substrate.

Estimating On-Farm CH_4 Emissions from Manure

A dynamic method is needed to accurately estimate CH_4 emissions from manure management; some main drivers (retention time, storage temperature, and methanogenic potential) were discussed above. Production systems may be classified on the basis of housing and

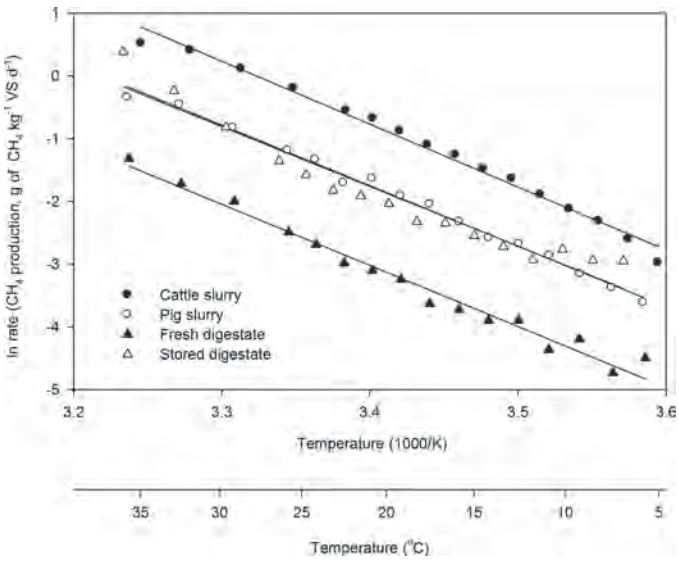

Figure 1. Arrhenius plots (ln rate versus inverse temperature, K) of the temperature response of CH_4 production in 4 contrasting liquid manure materials for the temperature range of 5 to 37°C. The manure materials were cattle slurry, pig slurry, fresh digestate from a thermophilic digester, and digestate from the same digester after several weeks of storage. The slopes of regression lines were not significantly different and averaged 81 kJ/mol. VS = volatile solids. Reproduced with permission from Elsgaard et al. (2016).

storage design, whereas treatment and management practices define manure retention times and storage temperatures in barn and outside storage. Estimation of daily emissions is needed to analyze effects of storage conditions and management in detail. Models using daily time steps for manure management include the Integrated Farm Systems Model (Chianese et al., 2009) and Manure-DNDC (Li et al., 2012). Both models depend on external parameters; that is, the temperature relationship of Integrated Farm Systems Model was adopted from Sommer et al. (2004) who in turn based values on a compilation of data from storage experiments, whereas Manure-DNDC relies on a submodel developed for soil environments, and a constant redox potential of −300 mV is used (Li et al., 2012). As an alternative approach, Petersen et al. (2016) proposed a method where estimation of CH_4 emissions is based on an in vitro anaerobic assay of CH_4 production rates in freshly collected samples when incubated at near-ambient temperature. Assuming this represents CH_4 emissions from the bulk liquid phase, rate measurements were used to parameterize a simple algorithm relating CH_4 emissions to temperature:

$$F_t = \left(\mathrm{VS_d} + 0.01\mathrm{VS_{nd}}\right) e^{\left(\mathrm{lnA} - \frac{E_a}{RT}\right)}. \quad [1]$$

In this equation, originally proposed by Sommer et al. (2004), F_t is CH_4 production rate (mg of CH_4/kg of VS/h); VS_d and VS_{nd} (kg/kg of VS) are degradable and recalcitrant ("nondegradable") manure organic matter; E_a is activation energy [81,000 J/mol (Elsgaard et al., 2016)] and lnA represents the pre-exponential factor (g of CH_4/kg of VS per hour) of an Arrhenius equation describing temperature sensitivity. Finally, R is the universal gas constant R (8.314 J/K/mol), and T is the ambient temperature at sampling (K). Sommer et al. (2004) calculated the VS_d from the biochemical composition of fresh excreta, but this approach is not feasible with partly degraded manure collected from a storage facility or pit, and Petersen et al. (2016) instead used an aerobic incubation assay to estimate VS degradability. This parameter, as well as the scaling factor of 0.01 between VS_d and VS_{nd} degradability, require further documentation, but a sensitivity analysis showed that model results mainly depended on the term lnA which represents the CH_4 production potential. The value of lnA can be estimated for the individual manure samples by rearrangement of Equation [1] once F_t has been determined. Although the individual estimate of lnA has little predictive power, a database of measurements for a given production system can provide an estimate and uncertainty range, the representativeness of which would improve as the database of system-specific CH_4 production rates expands.

Prediction of CH_4 emissions, however, also requires information about VS degradation during manure storage (Petersen et al., 2016). Existing models assume a constant ratio between CH_4 and CO_2 for estimation of VS loss (IPCC, 2006; Mangino et al., 2001; Sommer et al., 2004; Li et al., 2012), but as shown above this ratio is highly variable and may change with manure treatment and storage time. A separate assay would be needed to estimate C loss as CH_4 and CO_2 at the manure-air interface, and such an incubation system has yet to be developed. The method described thus requires further development, but has a potential for dynamic modeling of CH_4 emissions and VS loss during manure storage with direct reference to experimental data, where information about total C loss can help constrain estimates of VS_d.

Daily emission estimates can be recalculated to an MCF value for reporting, or separate MCF values can be calculated for in-barn and outside storage (Mikkelsen et al., 2016). This is important if manure treatment takes place following export from the barn because then only posttreatment emissions are affected. By reducing uncertainties for individual sources, it would allow for more effective GHG mitigation.

Controls of N_2O Emissions

Ammonia losses during manure management are a significant indirect source of N_2O (Hristov et al., 2011). McGinn et al. (2008) found that 13% of TAN was lost from a lagoon with cattle manure during summer storage in Western Canada. They further reported that wind speed and surface temperature together explained 59% of the variability in NH_3 emissions, and in accordance with this up to 35% of TAN may be lost in warmer climates (McGinn et al., 2008). Ammonia losses during manure storage can be reduced by around 80% with a cover in the form of a natural crust or synthetic membrane (Sommer et al., 1993; Miner et al., 2003). With a natural crust, however, the reduction of NH_3 emissions may be accompanied by direct emissions of N_2O produced around aerobic-anaerobic interfaces (Duan et al., 2017).

For liquid manure developing a natural crust, the IPCC (2006) guidelines recommend an N_2O emission factor of 0.005 kg of N_2O-N/kg of N stored, with an uncertainty range of 0.0025 to 0.01 kg of N_2O-N/kg of N. Available results from pilot-scale data are mostly within this range (Jayasundara et al., 2016), but there is a need for documenting emissions at a practical scale, and to better understand what constrains this source.

Typically crust formation is followed by a lag phase of several weeks before N_2O is observed (Sommer et al., 2000; Wood et al., 2012; Petersen et al., 2013b), which indicates that conditions in the crust do not support nitrification and denitrification activity during this period. Sommer et al. (2000) found that temporal dynamics were related to the water balance of the crust (precipitation minus evapotranspiration), suggesting that initially crust wetness is the limiting factor, but interactions between microbial activities and the physical and chemical environment of the crust are not well characterized at present.

For field-applied manure, as for mineral N fertilizers, an emission factor of 0.01 kg of N_2O-N/kg of N is recommended (IPCC, 2006). An increasing number of both experimental and model studies report that the relationship between N input and N_2O emissions is exponential rather than linear (e.g., McSwiney and Robertson, 2005; Philibert et al., 2012), and it has been proposed that high emissions are mainly associated with conditions where N input exceeds crop demand (i.e., where mineral N accumulates in the soil). However, meta-analyses also indicate that the uncertainty of N_2O emission estimates can be reduced by including aspects of management or soil characteristics (Shcherbak et al., 2014; Charles et al., 2017).

One source of variability, which has so far not been addressed in prediction models, is the spatial heterogeneity of manure in soil. The liquid phase of manure will partly infiltrate the soil in response to water potential gradients (Petersen et al., 2003), a process that is largely complete within 24 h (Misselbrook et al., 2005b). Temporally stable gradients in volumetric water content are established (Petersen et al., 2003), which therefore represent also the distribution of dissolved (and mostly labile) C and N shortly after manure application. The potential for partial reallocation of both C and N constituents is important for N_2O emissions because turnover of components infiltrating the bulk soil takes place in an environment with a higher O_2 availability than manure "hotspots" where both water content and O_2 demand is much higher than in the surrounding soil (Petersen et al., 1996; Baral et al., 2016). It is probably important to acknowledge that N_2O emissions associated with organic hotspots that are dominated by manure (or crop residues) follow different dynamics compared with N_2O emissions from bulk soil where the potential for emissions depends mainly on bulk soil properties such as gas diffusivity (Balaine et al., 2013).

Manure application method will evidently influence the size distribution of manure hotspots, with direct injection, band-spreading, and broadcasting representing methods with increasing contact between manure and soil. Manure distribution in soil following application has, however, mainly been described for injection methods (Petersen et al., 2003; Rahman et al., 2004) and surface application (Misselbrook et al., 2005b).

Estimating N_2O Emissions After Field Application

The IPCC methodology for estimating N_2O emissions from field-applied manure is based on annual emission factors, where the default (Tier 1) emission factor is 0.01 kg of N_2O-N/kg of N. The associated uncertainty range of 0.003 to 0.3 kg of N_2O-N/kg of N of the Tier 1 emission factor probably reflects inherent diversity of soil conditions that the emission factor is expected to represent because little improvement in precision was achieved by expanding the database (Stehfest and Bouwman, 2006). There is thus a pressing need for more informed estimates of N_2O emissions from N applied to soil. Experimental determination of N_2O emissions can provide Tier 2 emission factors at country level, although this requires a significant effort (e.g., Bell et al., 2015) and is not realistically done for all relevant combinations of N input and soil conditions. Dynamic models, referred to as Tier 3 in the IPCC terminology, have also been investigated for prediction of N_2O emissions from soil, but data requirement for parameterization is high, and deviations in the reproduction of temporal dynamics (e.g., Li et al., 2012) suggest that underlying processes are not fully understood.

Chen et al. (2008b) reviewed several process-based models for estimating N_2O emissions from soil, including NGAS-DAYCENT, DNDC, *ecosys*, NLOSS, Expert-N, WNMM, FASSET, and CERES-NOE. A common feature of these models is that they define soil layers assumed to be uniform with respect to physical, chemical, and microbiological characteristics. The application of liquid manure and other residues presents a challenge for such models insofar as individual constituents (water, C pools, N pools), and therefore labile C and N are in fact not evenly distributed within a given layer, but will be partly concentrated in manure-affected volumes that may be viewed as hotspots of intense C and N cycling. Size and distribution of manure hotspots will depend on application method and any subsequent tillage. Many studies have demonstrated how interactions between aerobic heterotrophic activity, nitrification, and denitrification in the gradient environment around such hotspots interact with soil conditions in determining the extent of denitrification and N_2O emissions (Nielsen and Revsbech, 1994; Petersen et al., 1996; Markfoged et al., 2011; Baral et al., 2016). Presumably the surface-to-volume ratio of manure hotspots is critical for predicting N_2O emissions, by determining the balance between aerobic and anaerobic degradation of labile C and N (Baral et al., 2016), and this could be

the reason why models that distribute manure constituents uniformly throughout a 2-dimensional soil layer fail to reproduce the dynamics of observed emissions (Chen et al., 2008b).

The distribution of manure C and N will approach a new equilibrium distribution within 24 h after field application of liquid manure (Misselbrook et al., 2005b). One way to account for this heterogeneity could be to use this new distribution as boundary conditions for transformations of labile manure C and N (including mineral N) after field application. Bulk soil conditions in the relevant soil layer could then be assumed for manure C and N transformations of the fraction infiltrating the soil. In contrast, separate conditions would need to be defined for an environment representing manure hotspots, to account for the co-occurrence of elevated water content and O_2 demand, and the coupling of nitrification and denitrification around aerobic-anaerobic interfaces (see Nielsen and Revsbech, 1994, and references therein). One requirement for this hypothetical model for manure distribution in soil is an estimate of the allocation of labile C and N between bulk soil and manure hotspots. An approach was proposed by Sommer et al. (2004) based on previously observed exponential relationships between water potential and VS in 22 manure materials including cattle manure, pig manure, and digestates:

$$f_R = 1 - 1/(1 + aVS), \quad [2]$$

and

$$a = 0.063 + 1.33e^{77.8\psi}, \quad [3]$$

where f_R is the proportion of manure water retained by VS, ψ (MPa) is soil water potential at the time of application, and a is a parameter defined by Ψ. Assuming that water retention in manure hotspots is a function of particulate VS (VS_{nd}, g/100 g) and a variable fraction (f_R) of labile VS (VS_d, g/100 g), that is, $VS_{hotspots} = VS_{nd} + f_R VS_d$, then f_R also defines the fraction of VS_d (and labile N) retained in hotspots, which can be determined by iteration. This empirical approach requires further validation, but could be a starting point for attempts to integrate heterogeneity in simulations of manure C and N turnover in soil.

MITIGATING GHG EMISSIONS FROM MANURE

The previous sections have indicated that both particulate (recalcitrant) and dissolved (labile) VS are important determinants of both CH_4 and N_2O emissions from manure management and after field application. During storage, labile C and N are sources of CH_4 and N_2O (in part via NH_3 emissions), whereas particulate VS may restrict atmospheric emissions if a natural crust forms. Surface crusts are themselves a potential site of CH_4 and N_2O metabolism. Upon field application, the amount and composition of VS in manure are important controls of the redistribution of labile C and N which, together with soil properties, determine the potential for N_2O emissions. In view of these and other mechanisms, by which manure VS can affect emissions, it may be useful to also discuss potential mitigation strategies in terms of their effect on manure VS composition or turnover.

Feeding

Jayasundara et al. (2016) presented a thorough review of relationships between cattle dietary changes and additives, and CH_4 emissions. The most consistent effects have been seen for lipid supplements, where a regression analysis indicated that a 9 to 12% reduction is achievable, but it was stressed that such effects may be reciprocated by higher CH_4 emissions from the manure, as exemplified by Hellwing et al. (2014). This negative interaction is compounded in warmer climates and stresses the need to consider GHG mitigation at farm level. Among additives, the most promising results have been with nitrate and 3-nitrooxypropanol, in some cases with CH_4 mitigation effects of 30 to 60% (Jayasundara et al., 2016). For these additives, however, more research is needed to fully document implications for environment and animal health. Reducing the protein in DMI of dairy cows will also influence the N content and composition of excretal returns, by selectively reducing the amount of N excreted as urea in the urine. A reduction of urinary N can reduce NH_3 losses (Petersen et al., 1998; Misselbrook et al., 2005a) and hence indirect N_2O emissions.

In-House Acidification

Ammonia emissions from liquid manure can be reduced by commercially available technologies for acidification. The manure in pits below slatted floors is acidified by pumping manure to an external treatment tank for daily adjustment to pH 5.5 with sulfuric acid (H_2SO_4) in a strictly contained and automated process, or acidification can take place directly in storage tanks or during field application (Fangueiro et al., 2015). Acidification effectively reduces NH_3 emissions from the liquid manure, but not from slats and soiled surfaces, and thus for cattle barns a reduction of 50% is acknowledged for regulatory purposes (http://www.vera-verification.eu/).

Table 1. Reduction in CH_4 emissions by anaerobic digestion (AD), and interaction with shorter hydraulic retention time (HRT) in the pit before digestion (Mikkelsen et al., 2016); model parameters are from Petersen et al. (2016)

Item	kg of CO_2 eq[1]/Mg of slurry, cattle	kg of CO_2 eq/Mg of slurry, pig	Gg of CO_2 eq/PJ of energy
Untreated	19.25	62.25	NA[2]
AD,[3] HRT of 20 d	−7.88	−15.32	−8.72
AD,[3] HRT of 7 d[4]	−13.75	−42.33	−20.75

[1]eq = equivalent.

[2]NA = not applicable.

[3]Digestate assumed to contain 58% cattle slurry and 42% pig slurry by volume, in accordance with national statistics for Denmark.

[4]Where possible.

Interestingly, storage experiments have also shown that H_2SO_4 addition inhibits CH_4 emissions from manure during storage. For example, reductions of 67 to 87% (Petersen et al., 2012) and 61 to 75% (Misselbrook et al., 2016) were observed in experiments with cattle manure stored for up to 3 mo, indicating that a 60% reduction of CH_4 emissions from manure management is realistic by in-house acidification. Petersen et al. (2012) also found significant CH_4 mitigation by SO_4^{2-} or methionine addition without pH change, and by acidification with an alternative acid, and it was speculated that different mechanisms contribute to inhibition of methanogenesis. Environmental issues to be considered with this technology are changes in the odor profile, and field application of S in excess of crop needs, because 5 to 6 kg/t of H_2SO_4 is needed for acidification of cattle slurry (Danish Centre for Verification of Climate and Environmental Technologies, 2012).

Anaerobic Digestion

Anaerobic digestion of livestock manure has several environmental benefits, including CH_4 and odor mitigation, and improved plant N availability (Massé et al., 2011). Anaerobic digestion (**AD**) technologies range from on-farm covers of pits or lagoons, with or without heating, to centralized reactors with heating and active mixing, and often organic co-digestates are included to boost gas production. According to Key and Sneeringer (2011), 60% of US dairy production takes place on farms where manure management systems allow AD treatment. Due to the moderate methanogenic potential of manure, profitability of AD is low, but it has been argued that environmental and societal benefits should also be taken into account (Yiridoe et al., 2009).

Manure can only be treated by AD following export from the barn, and therefore only posttreatment emissions are affected. Because VS degradation takes place also during the collection period, the in-barn HRT becomes critical for GHG mitigation (i.e., a shorter retention time in the pit before treatment can reduce CH_4 emissions and VS loss during collection while also boosting biogas yields). Annual MCF are evidently not useful for evaluating scenarios with different retention times. Instead the method represented by Equation [1] could be applied, as exemplified in Table 1 (Mikkelsen et al., 2016). Here, CH_4 mitigation by AD treatment of pig and cattle manure in Denmark was estimated for HRT in the barn of either 20 or 7 d before digestion. Increasing the frequency of export was in this example projected to increase the CH_4 mitigation potential of AD 2- to 3-fold. The most recent Danish national inventory for agricultural GHG emissions estimated a 41% reduction of CH_4 emissions by AD treatment of cattle manure using this approach (Nielsen et al., 2016).

Cover on Storage Facilities

It is well established that methanotrophs inhabit surface crusts on manure, and the 2006 IPCC guidelines assumed a 40% reduction of CH_4 emissions due to this activity (IPCC, 2006). However, no strong support has been found for an effect of this magnitude, and if in fact CH_4 escapes mainly via cracks, as discussed above, then CH_4 availability in the crust could be limiting. It has been proposed that an additional cover on manure storages combined with a crust, and with passive or active ventilation to maintain elevated CH_4 concentrations in the headspace, could enhance methanotrophic activity by increasing CH_4 availability in the air above the crust (Petersen and Miller, 2006). The most recent evidence regarding methanotrophs in surface crusts, their requirements for CH_4 and O_2, and sensitivity toward mineral N, indicates that there is indeed a potential for stimulating CH_4 oxidation in well-established natural crusts through controlled ventilation which should be explored (Duan et al., 2017). Covers for slurry tanks of concrete or tarpaulin are already available for protec-

tion against NH_3 losses, and could be adopted together with surveillance or even active control of O_2 and CH_4 availability.

Reducing Nitrogen Surplus

Several opportunities for management and treatment have already been discussed that can increase the manure N use efficiency (dietary changes, shorter HRT, cover on storages, acidification, and AD), although in some cases mitigation measures must be combined to avoid negative interactions between stages of management with respect to NH_3 emissions (Hutchings et al., 1996). Powell and Rotz (2015) discussed several strategies for mitigating N surplus in dairy production systems and concluded that in many cases both dietary CP intake and mineral fertilizer N can be reduced with little effect on productivity. Schils et al. (2006) reported a reduction of N surplus on Dutch dairy farms of 20%, from 300 to 240 kg of N/ha, between 1990 and 1999 as a result of less mineral fertilizer N applied and fewer grazing days, but because more manure was collected and stored on the farm, emissions of CH_4 increased. An overall reduction of GHG emissions of 6% was calculated, though with a potential for improvement by adopting mitigation measures against CH_4 emissions during manure storage.

Nitrification inhibitors have a potential to reduce N_2O emissions, as well as N leaching from manure and fertilizers, and the reduction may be as high as 40 to 50% according to some meta-analyses (e.g., Qiao et al., 2015). This is accompanied by positive trends in crop N uptake and N recovery, although for individual experiments these effects are often not statistically significant. This mitigation strategy certainly deserves attention, but to achieve GHG mitigation the N surplus should also be reduced to prevent that direct N_2O emissions are replaced by indirect emissions. In documenting effects of nitrification inhibitors, it is important to acknowledge the great diversity of active compounds in terms of water solubility, volatility, and persistence in the soil environment (Subbarao et al., 2007), and to investigate potential side effects (Kong et al., 2016).

Enteric Emissions vs. Manure Management

The relative importance of enteric fermentation and manure as sources of CH_4 emissions on dairy farms will depend on housing system, management, and storage conditions, including climate. In temperate regions the proportion of CH_4 emissions from liquid manure management on dairy farms is typically 15 to 20% (Chianese et al., 2009; Kristensen et al., 2011). However, in warmer climates the relative importance of CH_4 emissions from manure may be much greater. Thus, Owen and Silver (2015) reported that for US dairy farms the average proportion of CH_4 from manure management in 2011 was 43%, and in California as high as 54%.

Referring to the numbers given in previous subsections for effects of mitigation strategies, the CH_4 mitigation potential of dietary changes on dairy farms in temperate climates would be in the range of 7 to 10% (i.e., a 9–12% reduction of enteric emissions constituting 80 to 85% of total CH_4 emissions on dairy farms), and this assumes any increase in CH_4 emissions from manure is avoided. By comparison, the potential for mitigation of CH_4 emissions from manure through in-barn acidification may be 9 to 12% in temperate climates, and by AD treatment the potential may be 6 to 8%. Here, indirect effects on NH_3 emissions and N use efficiency should also be estimated. In warmer climates the CH_4 mitigation potential and relative importance of manure treatment technologies would be greater. Although uncertainties are present and further documentation is required for both dietary changes and manure treatment technologies, these estimated mitigation potentials do highlight the relevance of considering GHG mitigation for manure management.

CONCLUSIONS

The diversity of manure management practices on dairy farms is high, with intensification favoring liquid manure management. This trend increases the potential for both CH_4 and N_2O emissions, and the need for mitigation. The existing IPCC methodology for estimating emissions from manure is not well suited to describe management at the farm level, and effects of management changes or manure treatment are not easily quantified, which is also a barrier toward future regulation of emissions. Both recalcitrant and labile fractions of VS in liquid manure were shown to be important for CH_4 and N_2O emissions during storage and after field application. For accurate estimation of CH_4 emissions from manure, and CH_4 mitigation potentials, it is important to estimate VS loss during storage in barns and outside storages separately. Accounting for manure N availability in fertilizer plans is a precondition for effective N_2O mitigation. Adoption of GHG estimation methods with a better representation of temporal and spatial variability may offer the flexibility needed to quantify effects of manure treatment and management, and mitigation potentials.

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REFERENCES

Balaine, N., T. J. Clough, M. H. Beare, S. M. Thomas, E. D. Meenken, and J. G. Ross. 2013. Changes in relative gas diffusivity explain soil nitrous oxide flux dynamics. Soil Sci. Soc. Am. J. 77:1496–1505.

Baldé, H., A. C. VanderZaag, S. D. Burtt, R. J. Gordon, and R. L. Desjardins. 2016. Does fall removal of the dairy manure sludge in a storage tank reduce subsequent methane emissions? J. Environ. Qual. 45:2038–2043.

Baral, K. R., E. Arthur, J. E. Olesen, and S. O. Petersen. 2016. Predicting N_2O emissions from manure properties and soil moisture: An incubation experiment. Soil Biol. Biochem. 97:112–120.

Barberg, A. E., M. I. Endres, J. A. Salfer, and J. K. Reneau. 2007. Performance and welfare of dairy cows in an alternative housing system in Minnesota. J. Dairy Sci. 90:1575–1583.

Barret, M., N. Gagnon, E. Topp, L. Masse, D. I. Massé, and G. Talbot. 2013. Physico-chemical characteristics and methanogen communities in swine and dairy manure storage tanks: Spatio-temporal variations and impact on methanogenic activity. Water Res. 47:737–746.

Bell, M. J., N. Winning, R. M. Rees, J. M. Cloy, K. Topp, L. Cardenas, N. Donovan, T. Scott, C. Webster, A. Whitmore, J. Williams, H. Balshaw, F. Paine, and D. Chadwick. 2015. Nitrous oxide emissions from fertilised UK arable soils: Quantification and mitigation. Agric. Ecosyst. Environ. 212:134–147.

Bouwman, L., K. K. Goldewijk, K. W. Van Der Hoek, A. H. W. Beusen, D. P. Van Vuuren, J. Willems, M. C. Rufino, and E. Stehfest. 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proc. Natl. Acad. Sci. USA 110:20882–20887.

Charles, A., P. Rochette, J. K. Whalen, D. A. Angers, M. H. Chantigny, and N. Bertrand. 2017. Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. Agric. Ecosyst. Environ. 236:88–98.

Chen, D., Y. Li, P. Grace, and A. Mosier. 2008b. N_2O emissions from agricultural lands: A synthesis of simulation approaches. Plant Soil 309:169–189.

Chen, Y., J. J. Cheng, and K. S. Creamer. 2008a. Inhibition of anaerobic digestion process: A review. Bioresour. Technol. 99:4044–4064.

Chianese, D. S., C. A. Rotz, and T. L. Richard. 2009. Whole-farm greenhouse gas emissions: A review with application to a Pennsylvania dairy farm. Appl. Eng. Agric. 25:431–442.

Crosson, P., L. Shalloo, D. O'Brien, G. J. Lanigan, P. A. Foley, T. M. Boland, and D. A. Kenny. 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Anim. Feed Sci. Technol. 166–167:29–45.

Danish Centre for Verification of Climate and Environmental Technologies. 2012. Statement of Verification. Acidification of cattle slurry for reduced ammonia emission. Accessed Sep. 2, 2017. http://www.etv-denmark.com/files/agriculture/JH-Forsuring_Verification_Statement_Ver%201-6.pdf.

Duan, Y. F., S. Reinsch, P. Ambus, L. Elsgaard, and S. O. Petersen. 2017. Methanotrophic activity in slurry surface crusts as influenced by CH_4, O_2, and inorganic N. J. Environ. Qual. In press.

Elsgaard, L., A. B. Olsen, and S. O. Petersen. 2016. Temperature response of methane production in liquid manure and co-digestates. Sci. Total Environ. 539:78–84.

Eriksen, J., A. J. Andersen, H. V. Poulsen, A. P. S. Adamsen, and S. O. Petersen. 2012. Sulfur turnover and emissions during storage of cattle slurry: Effects of acidification and sulfur addition. J. Environ. Qual. 41:1633–1641.

Fangueiro, D., M. Hjorth, and F. Gioelli. 2015. Acidification of animal slurry–A review. J. Environ. Manage. 149:46–56.

FAO (Food and Agriculture Organization of the United Nations). 2010. Greenhouse gas emissions from the dairy sector. A life cycle assessment. Rome, Italy, 94 pp. Accessed Sep. 4, 2017. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf.

Galama, P. 2011. Prospects for bedded pack barns for dairy cattle. Wageningen UR Livestock Research, Publ. No. 16, 74 pp. Accessed Sep. 4, 2017. http://www.vrijloopstallen.nl/documenten/Prospects_for_bedded_pack_barns_for_dairy_cattle.pdf.

Gerber, P., T. Vellinga, C. Opio, and H. Steinfeld. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139:100–108.

Haeussermann, A., E. Hartung, E. Gallmann, and T. Jungbluth. 2006. Influence of season, ventilation strategy, and slurry removal on methane emissions from pig houses. Agric. Ecosyst. Environ. 112:115–121.

Hafner, S. D., S. G. Sommer, V. Petersen, and R. Markfoged. 2017. Effects of carbon dioxide hydration kinetics and evaporative convection on pH profile development during interfacial mass transfer of ammonia and carbon dioxide. Heat Mass Transf. 53:1335–1342.

Hellwing, A. L. F., M. R. Weisbjerg, and H. B. Møller. 2014. Enteric and manure-derived methane emissions and biogas yield of slurry from dairy cows fed grass silage or maize silage with and without supplementation of rapeseed. Livest. Sci. 165:189–199.

Henriksson, M., A. Flysjö, C. Cederberg, and C. Swensson. 2011. Variation in carbon footprint of milk due to management differences between Swedish dairy farms. Animal 5:1474–1484.

Hou, Y., G. L. Velthof, and O. Oenema. 2015. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: A meta-analysis and integrated assessment. Glob. Change Biol. 21:1293–1312.

Hristov, A. N., M. Hanigan, A. Cole, R. Todd, T. A. McAllister, P. M. Ndegwa, and A. Rotz. 2011. Ammonia emissions from dairy farms and beef feedlots. Can. J. Anim. Sci. 91:1–35.

Hutchings, N. J., S. G. Sommer, and S. C. Jarvis. 1996. A model of ammonia volatilization from a grazing livestock farm. Atmos. Environ. 30:589–599.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, ed. Published: IGES, Japan. Accessed Sep. 4, 2017. http://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Jayasundara, S., J. A. D. Ranga Niroshan Appuhamy, E. Kebreab, and C. Wagner-Riddle. 2016. Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: An updated review. Can. J. Anim. Sci. 96:306–331.

Jørgensen, B. B., and N. P. Revsbech. 1985. Diffusive boundary layers and the oxygen uptake of sediments and detritus. Limnol. Oceanogr. 30:111–122.

Kai, P., T. Birkmose, and S. Petersen. 2015. Slurry volumes and estimated storage time of slurry in Danish livestock buildings. AgroTech Report Dec 2015, 32 pp. (in Danish). Accessed Sep. 4, 2017. https://ens.dk/ansvarsomraader/bioenergi/biogas-taskforce.

Kebreab, E., J. France, D. E. Beever, and A. R. Castillo. 2001. Nitrogen pollution by dairy cows and its mitigation by dietary manipulation. Nutr. Cycl. Agroecosyst. 60:275–285.

Key, N., and S. Sneeringer. 2011. Climate Change Policy and the Adoption of Methane Digesters on Livestock Operations. USDA Economic Research Report No. 111, 47 pp.

Kong, X., Y.-F. Duan, A. Schramm, J. Eriksen, and S. O. Petersen. 2016. 3,4-Dimethylpyrazole phosphate (DMPP) reduces activity of ammonia oxidizers without adverse effects on non-target soil microorganisms and functions. Appl. Soil Ecol. 105:67–75.

Kristensen, T., L. Mogensen, M. T. Knudsen, and J. E. Hermansen. 2011. Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach. Livest. Sci. 140:136–148.

Laguë, C., É. Gaudet, J. Agnew, and T. A. Fonstad. 2005. Greenhouse gas emissions from liquid swine manure storage facilities in Saskatchewan. Trans. ASAE 48:2289–2296.

Leytem, A. B., R. S. Dungan, D. L. Bjorneberg, and A. C. Koehn. 2011. Emissions of ammonia, methane, carbon dioxide, and nitrous oxide from dairy cattle housing and manure management systems. J. Environ. Qual. 40:1383–1394.

Li, C., W. Salas, R. Zhang, C. Krauter, A. Rotz, and F. Mitloehner. 2012. Manure-DNDC: A biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutr. Cycl. Agroecosyst. 93:163–200.

Maharjan, B., and R. T. Venterea. 2013. Nitrite intensity explains N management effects on N_2O emissions in maize. Soil Biol. Biochem. 66:229–238.

Mangino, J., D. Bartram, and A. Brazy. 2001. Development of a methane conversion factor to estimate emissions from animal waste lagoons. US EPA 17th Annual Emission Inventory Conference, USEPA, Research Triangle Park, NC. 16–18 April 2002, Atlanta, GA. Accessed Sep. 4, 2017. https://www3.epa.gov/ttnchie1/conference/ei11/ammonia/mangino.pdf.

Markfoged, R., L. P. Nielsen, T. Nyord, L. D. M. Ottosen, and N. P. Revsbech. 2011. Transient N_2O accumulation and emission caused by O_2 depletion in soil after liquid manure injection. Eur. J. Soil Sci. 62:541–550.

Massé, D. I., G. Talbot, and Y. Gilbert. 2011. On farm biogas production: A method to reduce GHG emissions and develop more sustainable livestock operations. Anim. Feed Sci. Technol. 166–167:436–445.

McGinn, S. M., T. Coates, T. K. Flesch, and B. Crenna. 2008. Ammonia emission from dairy cow manure stored in a lagoon over summer. Can. J. Soil Sci. 88:611–615.

McSwiney, C. P., and G. P. Robertson. 2005. Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. Glob. Change Biol. 11:1712–1719.

Meyer, D., P. L. Price, H. A. Rossow, N. Silva-del-Rio, B. L. Karle, P. H. Robinson, E. J. DePeters, and J. G. Fadel. 2011. Survey of dairy housing and manure management practices in California. J. Dairy Sci. 94:4744–4750.

Mikkelsen, M. H., R. Albrektsen, and S. Gyldenkærne. 2016. Consequences of biogas production for greehouse gas emissions within agriculture (Biogasproduktions konsekvenser for drivhusgasudledning i landbruget). Aarhus University, DCE–National Centre for Environment and Energy, 41 pp. Report No. 197 (in Danish). http://dce2.au.dk/pub/SR197.pdf

Miner, J. R., F. J. Humenik, J. M. Rice, D. M. C. Rashash, C. Williams, and W. Robarge. 2003. Evaluation of a permeable, 5 cm thick, polyethylene foam lagoon cover. Trans. ASAE 46:1421–1426.

Misselbrook, T., J. Hunt, F. Perazzolo, and G. Provolo. 2016. Greenhouse gas and ammonia emissions from slurry storage: Impacts of temperature and potential mitigation through covering (pig slurry) or acidification (cattle slurry). J. Environ. Qual. 45:1520–1530.

Misselbrook, T. H., S. K. E. Brookman, K. A. Smith, T. Cumby, A. G. Williams, and D. F. McCrory. 2005c. Crusting of stored dairy slurry to abate ammonia emissions: Pilot-scale studies. J. Environ. Qual. 34:411–419.

Misselbrook, T. H., J. M. Powell, G. A. Broderick, and J. H. Grabber. 2005a. Dietary manipulation in dairy cattle: Laboratory experiments to assess the influence on ammonia emissions. J. Dairy Sci. 88:1765–1777.

Misselbrook, T. H., D. Scholefield, and R. Parkinson. 2005b. Using time domain reflectometry to characterize cattle and pig slurry infiltration into soil. Soil Use Manage. 21:167–172.

Møller, H. B., S. G. Sommer, and B. K. Ahring. 2002. Separation efficiency and particle size distribution in relation to manure type and storage conditions. Bioresour. Technol. 85:189–196.

Møller, H. B., S. G. Sommer, and B. K. Ahring. 2004. Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure. J. Environ. Qual. 33:27–36.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang. 2013. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, ed. Cambridge University Press, Cambridge, UK.

Nielsen, O.-K., M. S. Plejdrup, M. Winther, M. Nielsen, S. Gyldenkærne, M. H. Mikkelsen, R. Albrektsen, M. Thomsen, K. Hjelgaard, P. Fauser, H. G. Bruun, V. K. Johannsen, T. Nord-Larsen, L. Vesterdal, I. Callesen, E. Schou, K. Suadicani, E. Rasmussen, S. B. Petersen, L. Baunbæk, and M. G. Hansen. 2016. Denmark's National Inventory Report 2015 and 2016. Emission Inventories 1990–2014. Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE –Danish Centre for Environment and Energy. Scientific Report from DCE–Danish Centre for Environment and Energy. http://dce2.au.dk/pub/SR189.pdf.

Nielsen, T. H., and N. P. Revsbech. 1994. Diffusion chamber for nitrogen-15 determination of coupled nitrification-denitrification around soil-manure interfaces. Soil Sci. Soc. Am. J. 58:795–800.

Oenema, O., J. Salomez, C. Branquinho, M. Budnakova, P. Cermak, P. Geupel, P. Johnes, C. Tomkins, T. Spranger, J. W. Erisman, C. Pallière, L. Maene, R. Alonso, R. Maas, J. Magid, M. A. Sutton, and H. van Grinsven. 2011. Developing integrated approaches to nitrogen management. Pages 541–550 in European Nitrogen Assessment. M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven, and B. Grizzetti, ed. Cambridge University Press, UK. http://centaur.reading.ac.uk/20872/.

Owen, J. J., and W. L. Silver. 2015. Greenhouse gas emissions from dairy manure management: A review of field-based studies. Glob. Change Biol. 21:550–565.

Patni, N. K., and P. Y. Jui. 1987. Changes in solids and carbon content of dairy-cattle slurry in farm tanks. Biol. Wastes 20:11–34.

Petersen, S. O., B. Amon, and A. Gattinger. 2005. Methane oxidation in slurry storage surface crusts. J. Environ. Qual. 34:455–461.

Petersen, S. O., A. J. Andersen, and J. Eriksen. 2012. Effects of slurry acidification on ammonia and methane emission during storage. J. Environ. Qual. 41:88–94.

Petersen, S. O., M. Blanchard, D. Chadwick, A. del Prado, N. Edouard, J. Mosquera, and S. G. Sommer. 2013a. Manure management for greenhouse gas mitigation. Animal 7:266–282.

Petersen, S. O., N. Dorno, S. Lindholst, A. Feilberg, and J. Eriksen. 2013b. Emissions of CH_4, N_2O, NH_3 and odorants from pig slurry during winter and summer storage. Nutr. Cycl. Agroecosyst. 95:103–113.

Petersen, S. O., and D. N. Miller. 2006. Greenhouse gas mitigation by livestock waste storage and lagoon covers. J. Sci. Food Agric. 86:1407–1411.

Petersen, S. O., T. H. Nielsen, Å. Frostegård, and T. Olesen. 1996. Oxygen uptake, carbon metabolism, and denitrification associated with manure hot-spots. Soil Biol. Biochem. 28:341–349.

Petersen, S. O., H. H. Nissen, I. Lund, and P. Ambus. 2003. Redistribution of slurry in soil as influenced by organic matter content and injection method. J. Environ. Qual. 32:2399–2409.

Petersen, S. O., A. B. Olsen, L. Elsgaard, J. M. Triolo, and S. G. Sommer. 2016. Estimation of methane emissions from slurry pits under pig and cattle confinements. PLoS One 11:e0160968.

Petersen, S. O., S. G. Sommer, O. Aaes, and K. Søegaard. 1998. Ammonia losses from urine and dung of grazing cattle: Effect of N intake. Atmos. Environ. 32:295–300.

Philibert, A., C. Loyce, and D. Makowski. 2012. Quantifying uncertainties in N_2O emission due to N fertilizer application in cultivated areas. PLoS One 7:e50950. https://doi.org/10.1371/journal.pone.0050950.

Powell, J. M., and C. A. Rotz. 2015. Measures of nitrogen use efficiency and nitrogen loss from dairy production systems. J. Environ. Qual. 44:336–344.

Prism Climate Group. 2017. Prism Climate Data. Accessed Oct. 31, 2017. http://www.prism.oregonstate.edu/normals/.

Qiao, C., L. Liu, S. Hu, J. E. Compton, T. L. Greaver, and Q. Li. 2015. How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. Glob. Change Biol. 21:1249–1257.

Rahman, S., Y. Chen, K. Buckley, and W. Akinremi. 2004. Slurry distribution in soil as influenced by slurry application micro-rate and injection tool type. Biosyst. Eng. 89:495–504.

Schils, R., J. E. Olesen, A. del Prado, and J. F. Soussana. 2007. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livest. Sci. 112:240–251.

Schils, R. L. M., A. Verhagen, H. F. M. Aarts, P. J. Kuikman, and B. J. Sebek. 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Glob. Change Biol. 12:382–391.

Shcherbak, I., N. Millar, and G. P. Robertson. 2014. Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. Proc. Natl. Acad. Sci. USA 111:9199–9204.

Sommer, S. G., B. T. Christensen, N. E. Nielsen, and J. K. Schjorring. 1993. Ammonia volatilization during storage of cattle and pig slurry–Effect of surface cover. J. Agric. Sci. 121:63–71.

Sommer, S. G., and S. Husted. 1995. The chemical buffer system in raw and digested animal slurry. J. Agric. Sci. Camb. 124:45–53.

Sommer, S. G., J. E. Olesen, S. O. Petersen, M. R. Weisbjerg, L. Valli, L. Rodhe, and F. Béline. 2009. Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones. Glob. Change Biol. 15:2825–2837.

Sommer, S. G., S. O. Petersen, and H. B. Møller. 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutr. Cycl. Agroecosyst. 69:143–154.

Sommer, S. G., S. O. Petersen, and H. T. Søegaard. 2000. Greenhouse gas emission from stored livestock slurry. J. Environ. Qual. 29:744–750.

Sommer, S. G., S. O. Petersen, P. Sørensen, H. D. Poulsen, and H. B. Møller. 2007. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. Nutr. Cycl. Agroecosyst. 78:27–36.

Sørensen, C. A. G., S. G. Sommer, D. Bochtis, and A. Rotz. 2013. Technologies and logistics for handling, transport and distribution of animal manures. Pages 211–234 in Animal Manure Recycling. S. G. Sommer, M. L. Christensen, T. Schmidt, and L. S. Jensen, ed. 1st ed. J. Wiley & Sons Ltd., Chichester, UK.

Stehfest, E., and L. Bouwman. 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. Nutr. Cycl. Agroecosyst. 74:207–228.

Subbarao, G. V., O. Ito, K. L. Sahrawat, W. L. Berry, K. Nakahara, T. Ishikawa, T. Watanabe, K. Suenaga, M. Rondon, and I. M. Rao. 2007. Scope and strategies for regulation of nitrification in agricultural systems–Challenges and opportunities. Crit. Rev. Plant Sci. 25:303–335.

Thoma, G., J. Popp, D. Nutter, D. Shonnard, R. Ulrich, M. Matlock, D. S. Kim, Z. Neiderman, N. Kemper, C. East, and F. Adom. 2013a. Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. Int. Dairy J. 31:S3–S14.

Thoma, G., J. Popp, D. Shonnard, D. Nutter, M. Matlock, R. Ulrich, W. Kellogg, D. S. Kim, Z. Neiderman, N. Kemper, F. Adom, and C. East. 2013b. Regional analysis of greenhouse gas emissions from USA dairy farms: A cradle to farm-gate assessment of the American dairy industry circa 2008. Int. Dairy J. 31:S29–S40.

Turnquist, A., J. Foltz, and C. Roth. 2006. Manure Management on Wisconsin Farms. PATS Res. Rep. No. 15.

Vadas, P. A. 2006. Distribution of phosphorus in manure slurry and its infiltration after application to soils. J. Environ. Qual. 35:542–547.

VanderZaag, A. C., J. D. MacDonald, L. Evans, X. P. C. Vergé, and R. L. Desjardins. 2013. Towards an inventory of methane emissions from manure management that is responsive to changes on Canadian farms. Environ. Res. Lett. 8:035008–035013.

Venterea, R. T., A. D. Halvorson, N. Kitchen, M. A. Liebig, M. A. Cavigelli, S. J. Del Grosso, P. P. Motavalli, K. A. Nelson, K. A. Spokas, B. P. Singh, C. E. Stewart, A. Ranaivoson, J. Strock, and H. Collins. 2012. Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. Front. Ecol. Environ. 10:562–570.

Viguria, M., D. M. López, H. Arriaga, and P. Merino. 2015. Ammonia and greenhouse gases emissions from on-farm stored pig slurry. Water Air Soil Pollut. 226:285–292.

Webb, J., S. G. Sommer, T. Kupper, K. Groenestein, N. J. Huthings, B. Eurich-Menden, L. Rodhe, T. M. Misselbrook, and B. Amon. 2011. Emissions of ammonia, nitrous oxide and methane during the management of solid manures—A review. Sust. Agric. Rev. 8:67–107.

Weiske, A., A. Vabitsch, J. E. Olesen, K. Schelde, J. Michel, R. Friedrich, and M. Kaltschmitt. 2006. Mitigation of greenhouse gas emissions in European conventional and organic dairy farming. Agric. Ecosyst. Environ. 112:221–232.

Wightman, J. L., and P. B. Woodbury. 2016. New York dairy manure management greenhouse gas emissions and mitigation costs (1992–2022). J. Environ. Qual. 45:266–275.

Wood, J. D., R. J. Gordon, C. Wagner-Riddle, K. E. Dunfield, and A. Madani. 2012. Relationships between dairy slurry total solids, gas emissions, and surface crusts. J. Environ. Qual. 41:694–704.

Yiridoe, E. K., R. Gordon, and B. B. Brown. 2009. Nonmarket cobenefits and economic feasibility of on-farm biogas energy production. Energy Policy 37:1170–1179.

Zdanowicz, M., J. A. Shelford, C. B. Tucker, D. M. Weary, and M. A. G. von Keyserlingk. 2004. Bacterial populations on teat ends of dairy cows housed in free stalls and bedded with either sand or sawdust. J. Dairy Sci. 87:1694–1701.

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Review

Review on greenhouse gas emissions from pig houses: Production of carbon dioxide, methane and nitrous oxide by animals and manure

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ABSTRACT

The environmental impacts of livestock production are attracting increasing attention, especially the emission of greenhouse gases (GHGs). Currently, pork is the most widely consumed meat product in the world, and its production is expected to grow in the next few decades. This paper deals with the production of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by animals and by manure from pig buildings, with a focus on the influence of rearing techniques and nutrition. GHG emissions in piggeries originate from animals through CO_2 exhalation and CH_4 enteric fermentation, and from manure through the release of CO_2, CH_4 and N_2O. The level of the CO_2 exhalation (E-$CO_{2,\ pig}$) depends on the physiological stage, the body weight (BW), the production level and the feed intake of the animals concerned. Enteric CH_4 (E-$CH_{4,\ pig}$) is principally related to dietary fibre intake and the fermentative capacity of the pig's hindgut. Based on a review of the literature, the following equations are proposed in order to estimate E-$CO_{2,\ pig}$ (in kg day^{-1}) and E-$CH_{4,pig}$ (in g day^{-1}) for fattening pigs: E-$CO_{2,\ pig} = 0.136 \times BW^{0.573}$; E-$CH_{4,pig} = 0.012 \times$ dRes; with BW (in kg) and dRes for digestible residues (in g day^{-1}). Numerous pathways are responsible for GHG production in manure. In addition, the microbial, physical and chemical properties of manure interact and modulate the level of emissions. Influencing factors for removal systems for both liquid and solid fractions of manure have been investigated. A large range of parameters showing an impact on the level of GHG production from pig houses has been reported. However, few of these can be considered unquestionably as GHG mitigation techniques because some strategies have shown contradictory effects depending on the gas, the circumstances and the study. Nevertheless, frequent manure removal seems to be an efficient means to reduce concurrently CO_2-, CH_4- and N_2O-emissions from pig buildings for both slatted and bedded floor systems. Manure removal operations may be associated with specific storage conditions and efficient treatment in order to further reduce emissions. Several feeding strategies have been tested to decrease GHG emissions but they seem to be ineffective in reducing emissions both significantly and durably. In general, good management practices that enhance zootechnical performance will have beneficial consequences on GHG emission intensity. Taking into account the results described in the literature regarding CO_2-, CH_4- and N_2O-production from animals and manure in pig houses, we estimate total GHG emissions to 448.3 kg CO_2equiv. per slaughter pig produced or 4.87 kg CO_2equiv. per kg carcass. The fattening period accounts for more than 70% of total emissions, while the gestation, lactation and weaning periods each contribute to about 10% of total emissions. Emissions of CO_2, CH_4 and N_2O contribute to 81, 17 and 2% of total emissions from pig buildings, representing 3.87, 0.83 and 0.11 kg CO_2equiv. per kg carcass, respectively.
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1. Introduction

Globally, livestock production accounts for 18% of anthropogenic emissions of greenhouse gases (GHGs) (Steinfeld et al., 2006). Pork is the most widely consumed meat product in the world, and pig production is the second contributor of GHG emissions from livestock sector, with about 13% of total emissions being related to livestock (Tables 1 and 2; FAO, 2011). By 2050, worldwide pork consumption is expected to increase by almost 40% (FAO, 2011). Most of that increase in consumption will occur in developing countries, owing to demographic growth, changes in food preferences and better access to food due to the intensification of livestock systems close to growing urban populations (FAO, 2011). Presently, industrial farm animal production systems account for over half of pork production, and developing countries contribute to about half of this industrial production (Steinfield et al., 2006). In the future, these shares are expected to grow dramatically. Therefore, the environmental impact of industrial pig production represents a crucial issue for consideration in ensuring sustainability in meat production. Moreover, reducing GHG emissions would mitigate the adverse effects of GHGs on global climate change (increased temperature, higher sea level, drought, soil erosion and loss of global crop productivity) (IPCC, 2007).

Within this context, this paper aims to study the factors that influence the production levels of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by animals and manure at pig house level. Emissions associated with feed production, land use and land use change, energy consumption, manure spreading, transportation and food processing are not included in this discussion. Emissions associated with outside manure storage and manure treatments are also outside the scope of this review. These issues will, nevertheless, be briefly touched upon due to the link with emissions released from pig buildings. Direct CO_2 emissions from animals and from manure are usually excluded from GHG assessment because it is assumed that they are compensated by CO_2 consumption through the photosynthesis of plants used as feed. Consequently, CO_2 production by animals and by manure is rarely addressed in the literature. However, these CO_2 emissions at house level are not negligible and may differ from one rearing system to another (Philippe et al., 2007a,b). Moreover, since the synthesis pathways of carbon compounds are interlinked, it seems relevant to consider CO_2 and CH_4 emissions comprehensively. Indeed, a significant reduction in one gas could be compensated by an increase in another. Thus, the choice has been made to include CO_2 emissions in this paper in order to avoid any errors of judgement in assessing the environmental effect of a particular type of GHG mitigation technique.

The paper is organized as follows. Firstly, it describes the processes that are responsible for the production of CO_2, CH_4 and N_2O by animals and by manure at pig house level. Secondly, emission factors reported in the literature are reviewed according to the physiological stages of pig development, and an overall emission factor is proposed for the complete pig production process. Finally, the effects of pig rearing conditions (including dietary factors) on emissions are studied and some mitigation techniques are described.

2. Sources of emissions

2.1. Carbon dioxide

The emissions of CO_2 from pig houses come from two sources: exhalation by pigs and release from manure.

2.1.1. Exhalation by pigs

CO_2 production during respiration is related to the respiratory quotient, defined as the ratio between the volume of CO_2 production and the volume of oxygen consumption. In practice,

Table 1
Projected human population (in billion people) and global meat consumption (in million tons) from 2010 to 2050.
Source: adapted from FAO, 2011.

	2010	2020	2030	2050	Growth 2010–2050
Human population	6.91	7.67	8.31	9.15	+32%
Meat consumption					
Pig meat	102.3 (38%)	115.3 (36%)	129.9 (34%)	140.7 (30%)	+38%
Poultry meat	85.9 (32%)	111.0 (35%)	143.5 (38%)	193.3 (42%)	+125%
Bovine meat	67.3 (25%)	77.3 (24%)	88.9 (23%)	106.3 (23%)	+58%
Sheep/goat meat	13.2 (5%)	15.7 (5%)	18.5 (5%)	23.5 (5%)	+78%
All meat	268.7 (100%)	319.3 (100%)	380.8 (100%)	463.8 (100%)	+73%

Table 2
Contribution of livestock species to global greenhouse gas emissions.
Source: adapted from Steinfeld et al., 2006; FAO, 2013a,b.

Species	Greenhouse gas emissions (million tons CO_2equiv. $year^{-1}$)			
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total emissions
Cattle	1166.2 (61%)	2072.8 (81%)	661.6 (60%)	3900.6 (70%)
Small ruminants	69.9 (4%)	244.5 (10%)	202.6 (18%)	517.0 (9%)
Pigs	338.9 (18%)	237.3 (9%)	131.1 (12%)	707.3 (13%)
Poultry	332.2 (17%)	–	107.3 (10%)	439.5 (8%)
Total	1907.2 (100%)	2554.5 (100%)	1102.6 (100%)	5564.3 (100%)

CO_2equiv.: emissions of CO_2-equivalents, including CO_2, CH_4 and N_2O, taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.

the respiratory quotients reported in the literature are around 1.10 for growing pigs, around 1.00 for piglets and around 0.90 for reproductive sows (Moehn et al., 2004; Pedersen et al., 2008; Atakora et al., 2011b). CO_2 exhalation can also be derived from animal heat production (HP), which corresponds to the energy used for maintenance, production (growth or milk production) and thermoregulation (Noblet et al., 1989). The International Commission of Agricultural Engineering (CIGR, 2002) stated that HP should be estimated by taking into account the pig's body weight (BW), the production level and the feed energy intake. The production of respiratory CO_2- can be derived from these models, and corresponds to 2.23, 3.68, 0.88 and 1.70 kg CO_2 $head^{-1}$ day^{-1} for gestating sows, lactating sows, weaned piglets and fattening pigs, respectively (CIGR, 2002). Other experiments have been carried out to measure or estimate CO_2 exhalation from practical parameters. Models developed for fattening pigs are presented in Table 3 and illustrated in Fig. 1. In cases of a lack of data, models were simplified to express the CO_2 exhalation function of BW, according to data obtained by Aubry et al. (2004). An aggregation of the models reported in Table 3 gives the following equation proposed to predict CO_2 exhalation (E-$CO_{2,\,pig}$, in kg CO_2 day^{-1}) for pigs of 20–120 kg BW (Fig. 1; $R^2 = 0.91$):

$$E - CO_{2,\,pig} = 0.136\,BW^{0.573} \quad (1)$$

Thus, respiratory CO_2 production can be estimated to about 1.55 kg day^{-1} for a pig of 70 kg BW.

2.1.2. Release from manure

For many years, levels of CO_2 emissions from manure were believed to be negligible (Anderson et al., 1987; van 't Klooster and Heitlager, 1994). According to some recent research, the levels of CO_2 released from manure have been estimated to be 4–5% of the CO_2 exhaled by animals (CIGR, 2002; de Sousa and Pedersen, 2004; Dong et al., 2007). However, some authors have reported CO_2 release accounting for 10–30% of respiratory production (Jeppsson, 2000, 2002; Philippe et al., 2007a,b; Pedersen et al., 2008; Philippe et al., 2012a). During an experiment carried out in a commercial fattening unit, emissions from manure were evaluated to be at around 40% of the tranquil CO_2 exhalation rate (Ni et al., 1999b). The production of CO_2 from manure certainly needs to be taken into account, even though it is not the main source of CO_2 in pig houses.

In manure, CO_2 originates from three sources: (1) the rapid hydrolysis of urea into NH_3 and CO_2 catalysed by the enzyme urease; (2) the anaerobic fermentation of organic matter into intermediate volatile fatty acids (VFAs), CH_4 and CO_2; (3) the aerobic degradation of organic matter (Jeppsson, 2000; Moller et al., 2004; Wolter et al., 2004). For liquid manure, anaerobic processes have been frequently considered as the main source of CO_2 (Ni et al., 1999b). However, this conclusion is contradictory to the results of Moller et al. (2004), who observed under laboratory conditions that aerobic and anaerobic processes are of almost equal importance at a temperature of 20 °C, while a lower temperature (15 °C) favoured the aerobic processes. Moreover, crust formation at the surface of the slurry can also lead to CH_4 oxidation into CO_2 during the passage through the porous areas of the crust.

For solid manure, the principal origin of CO_2 is aerobic production, the so-called composting process, performed by a mesophilic/thermophilic microbial community that converts degradable organic matter (Hellmann et al., 1997; Wolter et al., 2004). The composting process is influenced by several factors, such as temperature, moisture content, carbon/nitrogen ratio, degradability of carbon compounds, pH level and the physical structure of the organic material (Andersson, 1996; Jeppsson, 2000; Paillat et al., 2005).

2.2. Methane

Methane originates from the anaerobic degradation of organic matter performed by bacteria in the digestive tract of the pigs and in the manure.

2.2.1. Enteric fermentation

The level of enteric CH_4 production is mainly determined by the fibre content of the diet and the fermentative capacity of the pig's hindgut. Thus, increased levels of dietary fibre are associated with increased CH_4 production, while fermentative capacity depends on the physiological stage of the pigs, with typically higher CH_4 production for adult pigs (Le Goff et al., 2002a).

Table 3
Equations proposed to estimate CO_2 exhalation by fattening pigs (E-$CO_{2,\,pig}$, in kg day^{-1}) according to body weight (BW, in kg).

References	Equations	Methodology
Müller and Schneider (1985)	$E - CO_{2,\,pig} = 0.114\,BW^{0.588}$	Pigs in metabolic crates (from 20 to 110 kg)
Feddes and DeShazer (1988)	$E - CO_{2,\,pig} = 0.136\,BW^{0.549}$	Data derived from feed intakes
van 't Klooster and Heitlager (1994)	$E - CO_{2,\,pig} = 2.88 \times 10^{-2} \times BW^{0.75} + 8.29 \times 10^{-2} \times BW^{0.549}$	Data derived from feed intakes
Ni et al. (1999a)	$E - CO_{2,\,pig} = 0.224\,BW^{0.46}$	Field measurements in a commercial fattening pig house
Brown-Brandl et al. (2004)	$E - CO_{2,\,pig} = 0.123\,BW^{0.62}$	Literature review
Pedersen et al. (2008)	$E - CO_{2,\,pig} = 0.0998\,BW^{0.646}$	Literature review
This review	$E - CO_{2,\,pig} = 0.136\,BW^{0.573}$	Literature review

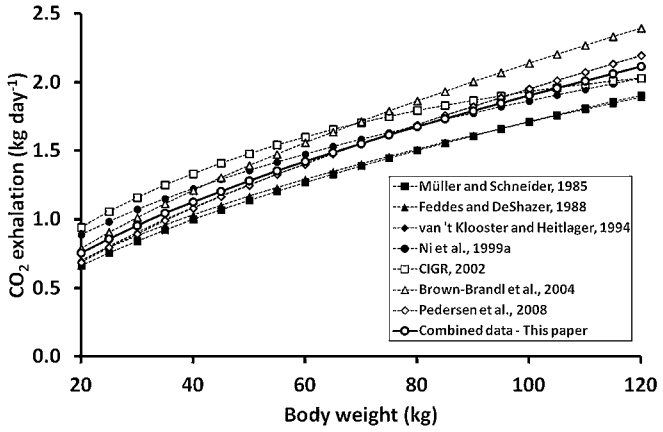

Fig. 1. Carbon dioxide (CO_2) exhalation by pigs estimated according to body weight.

Greater enteric production by sows can be explained by several factors, including increased feeding capacity, better intrinsic ability of bacterial flora to digest fibre, a greater number of bacteria, a reduction in the relative feeding level, and increased transit time (Le Goff et al., 2002a). Fig. 2 illustrates the production of enteric CH_4 for fattening pigs and adult sows reported in the literature according to the level of fibre intake, the so-called digestible residues (dRes), as proposed in INRA-AFZ (2004) and defined as the difference between digested organic matter and digested protein, fat, starch and sugar. By compiling these data, the following equations have been developed to predict the CH_4 enteric production (E-$CH_{4,pig/sow}$, in g CH_4 day^{-1}) from dRes intakes (g day^{-1}) for fattening pigs (Eq. (2)) and for adult sows (Eq. (3)):

$$E - CH_{4,pig} = 0.012 \times dRes (R^2 = 0.77) \quad (2)$$

$$E - CH_{4,sow} = 0.021 \times dRes (R^2 = 0.90) \quad (3)$$

For example, the ingestion of 300 g of dRes is associated with the enteric production of 3.6 g CH_4 by fattening pigs and 6.3 g CH_4 by adult sows. Enteric emissions represent energy losses of 56.65 kJ per g of CH_4 produced, which represents about 0.4–0.5% of digestible energy (DE) for fattening pigs and 1.0–1.5% DE for adult sows. According to the tier 1 methodology from the IPCC guidelines for national inventories (IPCC, 2006), enteric CH_4 is estimated at 1.5 kg per head per year, corresponding to 4.1 g CH_4 day^{-1}, whatever the diet composition and physiological stage. Taking into account conventional diet composition, level of ingestion and/or growth performance Vermorel et al. (2008) estimated for French production daily enteric CH_4 emissions to 0.8, 2.4 and 8.2 g CH_4 $head^{-1}$ for weaned piglets (up to 20 kg), fattening pigs (from 20 kg) and reproductive sows, respectively. Corresponding values for German production were proposed by Dämmgen et al. (2012a) at 0.9, 2.5 and 6.1 g CH_4, respectively.

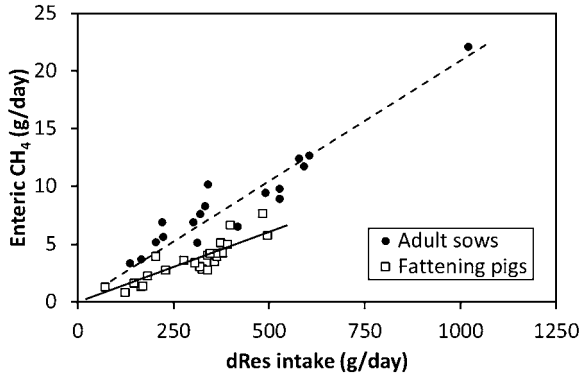

Fig. 2. Estimations of enteric methane (CH_4) production by adult sows and fattening pigs according to the intake of digestive residues (dRes defined as the difference between digested organic matter and digested protein, fat, starch and sugar).Source: adapted from Noblet et al., 1994; Jorgensen et al., 1996; Olesen and Jorgensen, 2001; Le Goff et al., 2002a,b; Ramonet et al., 2000; Galassi et al., 2004, 2005; Jorgensen, 2007; Jorgensen et al., 2007; Serena et al., 2008.

2.2.2. Release from manure

The release of CH_4 from manure originates from the temporal succession of microbial processes (Hellmann et al., 1997; Monteny et al., 2006). Initially, unspecified bacteria convert easily degradable substrates into VFAs, CO_2 and H_2. This extensive microbial activity increases the temperature of the manure and provides suitable conditions for methanogenic bacteria to convert acetate, CO_2 and H_2 into methane under a thermophilic environment. Factors that favour CH_4 production are lack of oxygen, high temperature, a high level of degradable organic matter, high moisture content, a low redox potential, a neutral pH, and a C/N ratio of between 15 and 30 (Moller et al., 2004; Amon et al., 2006; Kebreab et al., 2006).

According to the guidelines for National Greenhouse Gas Inventories (IPCC, 2006), CH_4 emissions from manure (E-$CH_{4,manure}$, in m^3) can be estimated based on the amount of excreted volatile solid (VS) or organic matter (OM), in kg; the ultimate CH_4 potential (B_0), in m^3 CH_4 per kg VS or OM; and the methane conversion factor (MCF), in percentage:

$$E - CH_{4,manure} = VS \times B_0 \times MCF$$

The IPCC (2006) recommends values for VS, B_0 and MCF, depending on the region of the world, the climate, the livestock categories and the type of manure. In Western Europe, the recommended value for VS is 0.30 kg pig^{-1} day^{-1} (IPCC, 2006). In the literature, B_0 values vary from 0.29 to 0.53 m^3 per kg VS or OM (Moller et al., 2004; Chae et al., 2008; Vedrenne et al., 2008; Jarret et al., 2011; Dämmgen et al., 2012b). The B_0 value proposed by the IPCC (2006) is 0.45 m^3 per kg VS. In the literature, extreme MCF values range from 2% to 80% according to manure type, manure management, storage duration, diet composition and temperature (Moller et al., 2004; Jarret et al., 2011; Dämmgen et al., 2012b; Rodhe et al., 2012). In their study, Moller et al. (2004) showed that during long-term storage (90 days), the slurry MCF value increased from 5.3 to 31.3% at temperatures ranging from 15 to 20 °C, respectively. On the other hand, at high temperatures, reducing the storage duration from 90 to 30 days decreased the MCF to 10.9%. Taking into account the proportion of manure management system usage, the emission factor for gas releases from swine manure in temperate Western Europe is estimated to 12 kg CH_4 $head^{-1}$ $year^{-1}$, or 32.9 g CH_4 day^{-1}, including inside and outside storage (IPCC, 2006).

2.3. Nitrous oxide

In pig houses, N_2O originates only from manure. Its formation mainly occurs during incomplete nitrification/denitrification processes performed by micro-organisms that normally convert NH_3 into non-polluting molecular nitrogen (N_2). The main microbial pathways involved in N_2O synthesis are presented in Fig. 3. An abiotic conversion of ammonium under acidic conditions, so-called chemo-denitrification, can also be at the origin of N_2O (Oenema et al., 2005; Petersen and Miller, 2006).

Nitrification, the process that converts ammonia into nitrate (NO_3^-), is usually carried out by autotrophic bacteria that require aerobic conditions with a pH value of above 5 (Kebreab et al., 2006). During nitrification, N_2O is synthesized as a by-product when there is a lack of oxygen and/or a nitrite accumulation. Denitrification is the reduction of NO_3^- into N_2, with many

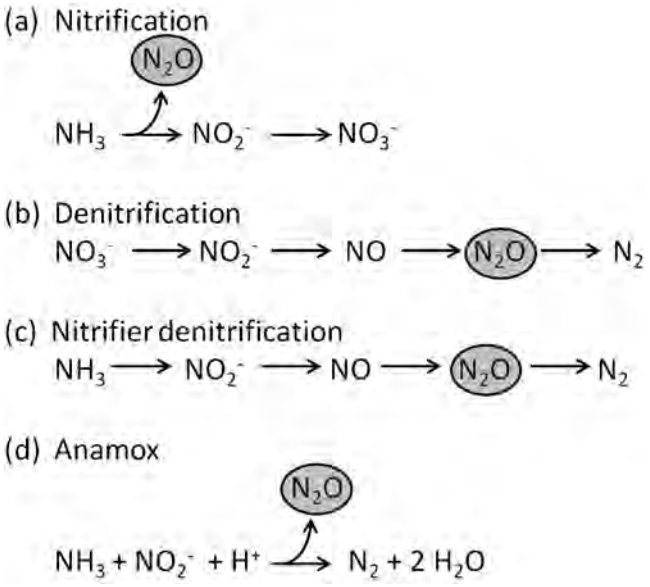

Fig. 3. Microbial pathways involved in N_2O synthesis in manure.

intermediate compounds being produced during the process (NO_2^-, nitric oxide (NO), and N_2O). In manure, denitrification is principally performed by heterotrophic facultative aerobic bacteria. The accumulation of N_2O in manure is favoured in the presence of oxygen and/or low availability of degradable carbohydrates (Poth and Focht, 1985; Driemer and Van den Weghe, 1997). The production of N_2O can also occur during other microbial pathways: the oxidation of ammonium under aerobic or anaerobic conditions, the so-called nitrifier denitrification and anamox processes, respectively. Most nitrifying and denitrifying microorganisms are mesophilic, and thus, the formation of N_2O is generally inhibited by temperatures above 40–50 °C (Hellmann et al., 1997; Kebreab et al., 2006). However, some authors have detected N_2O synthesis under thermophilic conditions (Wolter et al., 2004; Szanto et al., 2007). The relative contribution of these numerous pathways has still to be determined. Nevertheless, N_2O synthesis is known to require a close combination of aerobic and anaerobic areas. These heterogeneous conditions are largely encountered within litter but are rarer in slurry. However, N_2O emissions can occur from slurry when a dry crust is formed on the surface containing a combination of anaerobic and aerobic micro-sites. In any case, N_2O production from manure has a highly stochastic nature, especially due to its numerous sources of emission and environmental controls.

The guidelines for National Greenhouse Gas Inventories (IPCC, 2006) recommend estimating direct N_2O emissions by multiplying N excreted by animals (N_{ex}) by a specific conversion factor for each type of manure management system. For example, this conversion factor is 0.2% N_{ex} for pit storage under animals and 1% N_{ex} for deep bedding. Assuming 40 g N_{ex} pig^{-1} day^{-1}, this represents 0.13 and 0.63 g N_2O pig^{-1} day^{-1}, respectively.

3. Contribution by physiological stage

Several authors have measured GHG emissions from pig houses under practical conditions. Table 4 summarizes results from

Table 4
Emission factors at house level for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) related to the physiological stage of the pigs (kept on a slatted floor).

Physiological stage	Country	Greenhouse gas emissions (kg CO_2equiv. LU^{-1} day^{-1})			
		CO_2	CH_4	N_2O	Total
Gestating sows					
Lägue et al., 2004	Canada	11.98	2.13	0.00	14.10
Dong et al., 2007	China	5.92	0.24	0.22	6.38
Zhang et al., 2007	USA	8.16	2.39	0.00	10.55
Costa and Guarino, 2009	Italy	8.85	3.30	0.81	12.96
Philippe et al., 2011a	Belgium	5.70	0.60	0.33	6.63
Stinn et al., 2011	USA	8.95	7.07	0.03	16.04
Mean		8.26	2.62	0.23	11.11
Farrowing sows					
Lägue et al., 2004	Canada	21.50	4.56	0.00	26.06
Dong et al., 2007	China	7.49	0.24	0.16	7.89
Zhang et al., 2007	USA	14.08	6.69	0.00	20.77
Stinn et al., 2011	USA	27.86	3.59	0.07	31.53
Mean		17.73	3.77	0.06	21.56
Weaned piglets					
Lägue et al., 2004	Canada	29.85	14.69	0.00	44.54
Dong et al., 2007	China	29.67	1.46	0.38	31.51
Cabaraux et al., 2009	Belgium	10.70	0.74	0.05	11.48
Costa and Guarino, 2009	Italy	6.00	0.61	1.08	7.69
Mean		19.05	4.37	0.38	23.81
Fattening pigs					
Nicks et al., 2005	Belgium	13.86	3.24	0.75	17.85
Dong et al., 2007	China	16.73	0.80	0.26	17.79
Philippe et al., 2007a	Belgium	12.84	3.01	1.19	17.04
Costa and Guarino, 2009	Italy	13.64	4.75	0.97	19.35
Palkovicova et al., 2009	Slovak Republic	14.36	5.76	0.91	21.02
Guingand et al., 2010	France	17.82	1.95	0.47	20.24
Li et al., 2011	USA	16.20	0.53	1.71	18.44
Ngwabie et al., 2011	Sweden	16.38	3.78	0.37	20.53
Mean		15.23	2.98	0.83	19.03

CO_2equiv.: emissions of CO_2-equivalents, including CO_2, CH_4 and N_2O, taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.
LU: livestock unit, equal to 500 kg BW. In cases of a lack of data, default values for body weight (BW) were estimated to 200, 220, 18 and 70 kg for gestating sows, farrowing sows (including piglets), weaned piglets and fattening pigs, respectively.

research involving the study of CO_2, CH_4 and N_2O together for pigs kept on slatted floors at their different physiological stages. In order to facilitate a comparison between physiological stages and between gases, emissions are expressed in the table as CO_2-equivalents per livestock unit. The CO_2-equivalents (CO_2equiv.) take into account the global warming potential of each gas, which is evaluated to 25 and 298 times that of CO_2 over a 100-year period for CH_4 and N_2O, respectively (IPCC, 2007). The livestock unit (LU) is equal to 500 kg body weight.

The CO_2 emissions related to fattening pigs are quite similar between the studies, while the corresponding values for the other physiological stages shows greater variation, especially for weaned piglets. Similar findings have also been observed by Philippe et al. (2011b) regarding NH_3 emissions. The discrepancy between the results of the studies, as shown in Table 4, may be attributed to differences in housing conditions, ventilation systems, management practices, diet formulation and gas measurement method. Nevertheless, the average emission factors proposed by physiological stage seem consistent between the studies. Indeed, gestating sows present the lowest value (8.26 kg CO_2 LU^{-1} day^{-1}, or 3.3 kg CO_2 sow^{-1} day^{-1}), as influenced by their low feed intake (restricted feeding, low energy density of the diet) and metabolism. Farrowing sows (including piglets) and weaned piglets are associated with the highest emissions (17.73 kg CO_2 LU^{-1} day^{-1}, or 8.87 kg CO_2 sow^{-1} day^{-1}, and 19.05 kg CO_2 LU^{-1} day^{-1}, or 0.69 kg CO_2 pig^{-1} day^{-1}, respectively), as a consequence of ad libitum feeding and intensive productive status (milk production and growth). Emissions related to fattening pigs (15.3 kg CO_2 LU^{-1} day^{-1}, or 2.1 kg CO_2 pig^{-1} day^{-1}) are slightly lower than the latter.

The CH_4 emissions reported in the literature present a large range of variation within each physiological stage. In addition to the variation factors described above for CO_2, the manure removal strategy and the storage duration inside the building seem to play an important role regarding the level of emissions (see below). For the other physiological stages, higher emissions were also observed with a longer duration of indoor manure storage. Table 4 shows that, on average, the mean emission factors expressed per LU do not differ significantly between physiological stages, ranging from 2.62 kg CO_2equiv. LU^{-1} day^{-1} for gestating sows, to 4.37 kg CO_2equiv. LU^{-1} day^{-1} for weaned piglets, with intermediate values for fattening pigs (2.98 kg CO_2equiv. LU^{-1} day^{-1}) and farrowing sows (3.77 kg CO_2equiv. LU^{-1} day^{-1}). Corresponding values expressed per animal are 41.9, 6.3, 16.7 and 78.5 g CH_4 day^{-1}, respectively. The CH_4 emissions associated with gestating sows could be deemed quite low, considering the high fibre content of their diet and their large fermentative capacity. In fact, these effects are counterbalanced by the restricted feeding usually applied at this stage.

As can be seen in Table 4, the N_2O emissions measured from pig houses fitted with a slatted floor were relatively low whatever the pigs' physiological stage. In some experiments (Lägue et al., 2004; Zhang et al., 2007), the production of N_2O emissions was even lower than the detection limit of the measurement equipment, giving small mean values as a result. In this context, important relative differences between studies or physiological stages do not have significant meaning. Thus, it seems more appropriate to consider a generic emission factor for all the stages. Based on the values reported in Table 4, an average emission of 0.40 kg CO_2equiv. LU^{-1} day^{-1} could be proposed.

Also based on these values, total GHG emissions from pig buildings are estimated to 11.11 kg CO_2equiv. $LU^{-1}day^{-1}$ for gestating sows and around 20 kg CO_2equiv. $LU^{-1}day^{-1}$ for lactating sows, weaned piglets and fattening pigs, reflecting the relative metabolism rate of each physiological stage.

The contribution of each physiological stage to GHG emission intensity expressed per unit of product is estimated using the data from Table 4 and is presented in Table 5. Overall, GHG emissions from pig houses are estimated to 448.4 kg CO_2equiv. per slaughter pig produced or 4.87 kg CO_2equiv. per kg carcass. The fattening period accounts for more than 70% of total emissions, while the gestation, lactation and weaning periods each contribute to about 10% of total emissions. Thus, it can be concluded that efforts to reduce emissions should primarily target fattening pigs. Emissions of CO_2, CH_4 and N_2O contribute to 81, 17 and 2% of total emissions from buildings, representing 3.87, 0.83 and 0.17 kg CO_2equiv. per kg carcass, respectively. These figures show the important share of CO_2 in global emissions contributed by pigs and their manure. However, these sources of emission are usually neglected in GHG evaluation. Indeed, several authors have developed life cycle assessment (LCA) studies to estimate the intensity of emissions given off in pig production. These models exclude CO_2 emissions from respiration and manure but include GHG emissions for feed production, manure storage and spreading, and energy consumption. Reported values range from 3.07 to 5.79 kg CO_2equiv. per kg carcass (Vergé et al., 2009; Pelletier et al., 2010; Lesschen et al., 2011; Weiss and Leip, 2012). The discrepancy between these studies comes from the differences in methodology, type of pig production, boundaries of the system, emission categories and allocation.

4. Influencing factors

The GHG emissions from pig houses are principally influenced by floor type, manure management and nutrition of the pigs. The climatic conditions inside the building also impact emission levels.

Table 5
Contribution of the physiological stage of pigs on greenhouse gas emissions per unit of product (assuming no allocation to slaughter by-products).

Physiological stage	Days	Greenhouse gas emissions (kg CO_2equiv.[a])		
		Day^{-1} $animal^{-1}$[b]	Slaughter pig^{-1}[c]	kg $carcass^{-1}$[d]
Dry and gestating sows	125	4.44	55.6	0.60 (12%)
Lactating sows[e]	28	10.78	30.2	0.33 (7%)
Weaned piglets[f]	50	0.86	42.8	0.47 (10%)
Fattening pigs[g]	120	2.67	319.9	3.48 (71%)
Total	323	–	448.4	4.87 (100%)

[a] CO_2equiv.: CO_2-equivalent, including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.
[b] Derived from data presented in Table 4.
[c] Based on 10 slaughtered pigs per litter.
[d] Based on carcass weight of 92 kg (liveweight of 118 kg and dressing percentage of 78%).
[e] Including piglets of up to 8 kg BW.
[f] From 8 to 28 kg BW with 400 g of average daily gain.
[g] From 28 to 118 kg BW with 750 g of average daily gain.

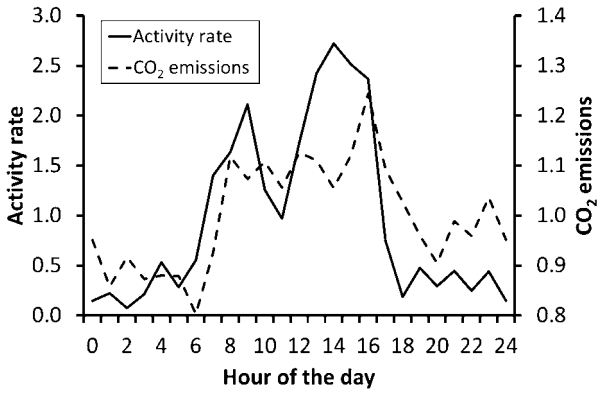

Fig. 4. Nycthemeral evolution around the daily mean (value = 1) of the activity rate of pigs and the carbon dioxide emissions associated with fattening pigs kept on a slatted floor.Source: adapted from Philippe et al., 2013.

4.1. Climatic conditions

Gaseous emissions are positively related to temperature and ventilation rate. An experiment carried out in a commercial pig house emptied of pigs showed that CO_2 emissions from slurry doubled when the manure temperature increased from 15 to 20 °C, and increased from 0.8 to 25.8 g CO_2 h^{-1} per m^2 of slurry when the ventilation rate ranged from 160 to 3350 m^3 h^{-1} (Ni et al., 1999b). Ngwabie et al. (2011) reported that CH_4 emissions doubled when the indoor temperature in a fattening pig unit increased from 16.8 to 22.8 °C. Blanes-Vidal et al. (2008) estimated the correlation between averaged ventilation flow and CH_4 emission to be 0.79 on an hourly basis.

Typically, gaseous emissions from pig houses present a diurnal pattern as a consequence of the comprehensive effects of temperature, ventilation rate and animal activity. The highest emission rates are usually observed during feeding time (Van Milgen et al., 1997; Moehn et al., 2004). For fattening pigs fed ad libitum, a first peak of emission occurs in the morning and a second peak in the afternoon, as illustrated for CO_2 emissions in Fig. 4 (adapted from Philippe et al., 2013). Modification of the feeding schedule can have an impact on the level of daily emissions, as demonstrated by Groenestein et al. (2003) with gestating sows.

The location of the fans in the building also contributes to a modulation of the emission levels. Air inlets or outlets located near the manure surface increase the level of emissions due to greater air flow at the interface (Hayes et al., 2006). In any case, using climate conditions to modulate the release of GHGs seems rather impractical since the ambient parameters must primarily respect the physiological needs of the animals. Nevertheless, optimization of the heating and ventilation in the housing system can have a beneficial effect on emission levels. Good practice includes insulation of the building, adaptation to internal (e.g. density of the pigs and their physiological stage) and external factors (e.g. season and weather), management of air circulation and regular monitoring of the ventilation devices. Regulation of climatic parameters also has an influence on the health, performance, welfare and behaviour of the pigs, thereby causing indirect effects on the level of emissions. In addition, energy saving related to optimal management of climatic factors can be considered environmentally and economically beneficial.

4.2. Floor type and manure management

In pig production, the most frequent housing conditions are based on a slatted floor with a deep pit underneath for the storage of slurry. Alongside this traditional system, bedded systems have met with renewed interest during recent decades, as these systems are related to improved welfare, reduced odour nuisance and a better brand image for livestock production. For both housing systems, a large range of parameters may influence the levels of GHG emissions.

4.2.1. Slatted floor systems

4.2.1.1. Proportion of the slatted area. It is usually assumed that the emission of pollutant gases can be reduced by lowering the slurry emitting surface. With the implementation of a partly slatted floor, some authors have observed a reduction in CO_2 production by 7–13% compared with a fully slatted floor, confirming that slurry is not the main source of emission (Table 6; Sun et al., 2008; Guingand et al., 2010). For CH_4 production, contradictory results have been reported in the literature, with decreased emissions (Lägue et al., 2004; Philippe et al., 2014a) or increased emissions being associated with partly slatted floors (Guingand et al., 2010). The effect of a slatted floor area on N_2O emissions has also shown conflicting results (Fitamant et al., 1999; Lägue et al., 2004; Guingand et al., 2010; Philippe et al., 2014a). In any case, absolute N_2O emissions from slurry have been shown to remain quite low, whatever the type of slatted floor. Cumulative emissions of GHGs (expressed in CO_2-equiv.) have been shown to be reduced by 4–13% by the application of a partly slatted floor compared with a fully slatted floor (Table 6).

Costs associated with partly slatted floors are quite similar to those of fully slatted floors despite a slightly higher labour cost due to pen fouling and the need for additional cleaning (Krieter, 2002). Application of partly slatted floors in existing fully slatted buildings is rather limited. Solid plates can be easily placed on the floor to create a partly slatted floor, but the total surface of the pit will remain unchanged, with no potential effects on emissions.

4.2.1.2. Slurry removal strategy. The increase in the slurry level could favour emissions, since it has been suggested that a smaller space between the slats and the surface of manure increases air turbulence and the release of gases (Ye et al., 2009). However, several authors have reported that a higher slurry depth does not

Table 6
Effect of the proportion of slatted floor (fully or partly slatted floor) on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively) associated with fattening pigs.

References	Fully slatted floor				Partly slatted floor			
	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Fitamant et al., 1999	–	–	1.10	–	–	–	1.59	–
Lägue et al., 2004	6.00	28.0	0.07	6.72	5.88	15.6	0.00	6.27
Sun et al., 2008	3.38	–	–	–	2.95	–	–	–
Guingand et al., 2010	2.48	9.7	0.19	2.78	2.31	11.2	0.24	2.66
Philippe et al., 2014a	1.45	5.4	0.23	1.64	1.46	4.8	0.21	1.65

promote the release of gases (Lägue et al., 2004; Haeussermann et al., 2006).

Nevertheless, frequent removal of manure has been proposed as a means to diminish the release of emissions from pig buildings. Total emissions within outside storage will also be reduced provided the temperature is lower outside than inside or where specific manure treatments are applied. In their study of CH_4 and N_2O emissions from pig units, Osada et al. (1998) showed that weekly removal of manure reduced the level of these emissions by about 10% compared with the traditional deep-pit system. With the same removal strategy, Guarino et al. (2003) observed a reduction of 19% in CH_4 emissions, but a doubling of N_2O emissions. Yet cumulative emissions (expressed in CO_2-equiv.) were shown to be lowered by 16%. Lavoie et al. (2006) found that when manure was removed three times a week instead of only once, CH_4 emissions were reduced by 16% and N_2O emissions remained insignificant. Results from these three studies regarding CO_2 emissions would suggest that the level of these emissions is not impacted by the removal frequency of manure (Osada et al., 1998; Guarino et al., 2003; Lavoie et al., 2006).

Pit flushing is also an efficient means to mitigate emissions. Sommer et al. (2004) estimated to 35% the reduction potential of cumulative GHGs (CH_4 and N_2O) with daily flushing compared with having a static pit. By combining frequent flushing (six times a day) with a reduced slurry surface, Lagadec et al. (2012) measured a 35% reduction in cumulative emissions (CH_4 and N_2O) with the use of manure gutters and by 55% with the use of a flushing tube, compared with having a static pit. Kroodsma et al. (1993) showed that the frequency, duration and pressure of the flushing water also impacted the efficiency of mitigation. Their results demonstrated that frequent flushing (every 1–2 h) for short periods (2 s) was more effective than prolonged (3–6 s) but less frequent flushing (every 3.5 h). The use of fresh water, as opposed to recycled water, has also been found to further reduce emissions (Kroodsma et al., 1993). This is especially the case for CH_4 because methanogenesis is rapidly initiated in the channel if a small proportion of the slurry remains in the pit after emptying. Without inoculums in the pit, CH_4 formation is low and is initiated after a few days (Sommer et al., 2007).

Accumulated manure can also be removed by scraping. The standard flat scraper system consists of a shallow slurry pit with a horizontal steel scraper under the slatted floor, allowing the manure to be removed from the building every day or several times a week (Groenestein, 1994). With this system, reductions of 15% for CO_2 emissions and of around 50% for CH_4 and N_2O emissions have been obtained under experimental conditions (Godbout et al., 2006; Lagadec et al., 2012). However under practical conditions, this technique has failed to significantly reduce CH_4 emissions (Lagadec et al., 2012).

Other systems have been developed to associate manure removal with under-slat separation of liquid/solid fractions. The V-shaped scraper system involves a channel with two inclined surfaces on each side of a central gutter. The liquid fraction runs off continuously under the force of gravity towards the gutter, and the solid fraction remaining on the inclined surfaces is frequently scraped (Godbout et al., 2006). These authors observed that, when manure was scraped every 2–3 days, although CO_2 emissions remained unchanged, CH_4 emissions reduced by 20%, in comparison with a deep-pit emptied once a week. Furthermore, Lagadec et al. (2012) demonstrated a 50% reduction in N_2O emissions in the case of a scraping frequency of between 3 and 12 times a day, compared with having a static pit. With the V-shaped conveyor belt system, urine constantly flows down in the middle of the belt under the force of gravity, and faeces are removed by the rotation of the belt (de Vries et al., 2013). Results obtained by de Vries et al. (2013) showed that this technique reduced CO_2 emissions by 47% and CH_4 emissions by 90%, but increased N_2O emissions by 250%. Overall, cumulative emissions (CO_2, CH_4 and N_2O) were lowered by 80% (de Vries et al., 2013).

Implementation of elementary frequent manure removal techniques does not seem to be associated with extra cost and could be easily applied in existing buildings. By contrast, flushing strategies (using manure gutters or flushing tubes) require major modifications to be made to existing houses. For new buildings, these systems are economically advantageous due to the reduced requirement to dig a shallow pit and the low operational costs (Guarino et al., 2003). For scraping systems, buildings costs are estimated to be higher than for traditional deep pit systems, i.e. +25 to +35% per animal place (Hamel et al., 2004; Lagadec et al., 2012). Aarnink et al. (2007) estimate the cost for new buildings to be fitted with V-shaped conveyor belts to be 10–15% lower than for traditional systems. However, applicability of these latest techniques in existing houses would appear difficult owing to the required modification of the existing manure outlets.

4.2.1.3. Other techniques. Some other original techniques have been developed to reduce GHG emissions from pig houses. Incorporation of humic acids into slurry has been shown to reduce CH_4 emissions by 34% by improving methanotrophic bacteria, but not to modify CO_2 or N_2O emissions (Shah and Kolar, 2012). The addition of quebracho tannins into slurry has also been shown to reduce CH_4 emissions by up to 95% due to the noxious effects of these compounds on methanogens. Soybean oil sprinkling and misting with essential oils have been shown to decrease CO_2 and CH_4 emissions by about 20% (Ni et al., 2008). By contrast, the addition of clay or zeolite to slurry has been shown to result in increased CH_4 emissions, as a consequence of the neutralization of the toxic effect of ammonia on methanogenic bacteria (Hansen et al., 1999; Kotsopoulos et al., 2008). The use of TiO_2-based paints and coatings has been shown to reduce CH_4 emissions by up to 27% due to the oxidative photocatalytic properties of the chemical (Costa et al., 2012). These findings would need to be confirmed in further studies and, in some cases, the underlying mechanisms require clarification.

4.2.1.4. Outside storage and slurry treatment. The release of gases during the outside storage of slurries is influenced by numerous factors. Seasonal and weather conditions, such as air temperature, relative humidity, wind speed and rainfall, modulate the production of GHGs from slurry (Lägue et al., 2004). Natural or synthetic coverings have been proposed as a means of mitigating emissions by reducing the emitting area, heating and turbulence at the slurry surface. However, some authors have reported increased emissions despite slurry cover (Loyon et al., 2006; Guarino et al., 2006; Van der Zaag et al., 2008). Several slurry treatments have been developed to facilitate the management of emissions and to mitigate their environmental impact. These slurry treatments include, among others, solid–liquid separation, biofiltration, vermifiltration and aerobic or anaerobic treatments (Godbout et al., 2003; Lägue et al., 2004; Loyon et al., 2007; Dinuccio et al., 2008; Lessard et al., 2009; Luth et al., 2011). Generally, strategies that reduce GHG emissions from slurry, preserve its energetic and agronomic values, and favour nutrient uptake for next steps are environmentally efficient. Among the numerous techniques available, anaerobic digestion of slurry with the production of a biogas rich in CO_2 and CH_4 offers an interesting opportunity to significantly reduce GHG emissions due to a lowered release of gases from manure, the production of renewable energy (electricity and heat) and the replacement of fossil fuel consumption. Adoption of an anaerobic digester in a pig farm for 100 fattening places has been estimated to offset a total of 125 t CO_2equiv. per year (Kaparaju and Rintala, 2011). The different

techniques used to treat manure can be combined, and numerous modifications/adaptations have been developed. The level of GHG emissions related to these techniques depends on various parameters such as the type and the duration of treatment, the stage of the process, and the volume and the composition of the manure fraction. Thus, knowledge of the specific conditions for the treatment is essential for precise environmental assessment.

4.2.2. Bedded floor systems

Compared with slatted floor systems, bedded floor systems are usually associated with reduced CH_4 emissions, increased CO_2 emissions, hugely elevated N_2O emissions, and an overall increase in CO_2equiv. emissions (Table 7). The specific environment encountered within the litter, especially the combination of aerobic and anaerobic areas, as opposed to strictly anaerobic slurry, explains these emission factors. Nevertheless, bedded systems combine a wide range of rearing techniques that impact the level of emissions. Indeed, the litter may differ by the bedding material, the amount and frequency of application, the space allowance, the litter management and the removal strategy. These parameters influence the physico-chemical characteristics of the manure, such as density, humidity, temperature, pH and C/N ratio, all of which interact to modulate gas emission levels (Dewes, 1996; Groenestein and Van Faassen, 1996; Misselbrook and Powell, 2005).

Implementation of a bedded system is associated with low building costs due to reduced digging requirements. This technique may also be easily applicable in existing buildings with a concrete solid floor. However, the price of bedding material and the labour involved in litter management induce an increased cost, estimated to be between +5 and 10% compared with slatted floor systems (Krieter, 2002; Philippe et al., 2006b). The availability of substrates may constitute important opportunities or limitations of application, resulting in a different economic balance from area to area.

4.2.2.1. Type of substrate. Several bedding materials have been tested regarding their GHG emissions. The most frequent substrate used is straw, but sawdust, wood shavings or peat may also be used (Jeppsson, 1998; Robin et al., 1999; Nicks, 2004). Results of studies comparing straw litters and sawdust litters show that sawdust litters produce fewer CH_4 emissions but hugely greater N_2O emissions (Table 8). Table 8 shows that, overall, the CO_2equiv. emissions from these studies are higher with the use of sawdust; this is mainly due to the greater contribution of N_2O emissions. Interactions within the litter may explain these results. Indeed, the higher manure density observed with sawdust impairs the composting process, which normally increases the temperature of the manure and amount of air exchange through it (Jeppsson, 2000). Comparing different bedding types under barn conditions, Jeppsson (2000) found manure temperatures of 23.9 and 35.5 °C, respectively, with wood shavings and chopped straw. Lower temperatures favour the activity of nitrifying and denitrifying bacteria, with a higher level of N_2O production as a by-product (Sommer, 2001; Hansen et al., 2006). By contrast, CH_4 production is very heat-dependent, and lower temperatures will significantly diminish these emissions (Hansen et al., 2006). Husted (1994) found that emissions of CH_4 from dung heaps could be divided by a factor ranging from 2.7 to 10.3 when heap temperatures were decreased by 10 °C. Moreover, CH_4 production is also controlled by the rate of its transport throughout the manure and by oxidation (Conrad, 1989). If CH_4 production is reduced and the path of its spread is slow in the presence of oxygen, oxidation is likely to occur and consequently lower CH_4 emissions will be released (Hao and Larney, 2011). Thus, the oxidation of CH_4 into CO_2 could counterbalance the reduction in CO_2 production via the composting process.

4.2.2.2. Amount of substrate and frequency of application. Studies of the effect of the amount of substrate on GHG emissions have shown conflicting results, except for N_2O, for which reductions have been systematically observed with increased amounts of bedding material (Yamulki, 2006; Sommer and Moller, 2000; Guingand and Rugani, 2013; Philippe et al., 2014b). Indeed, Guingand and Rugani (2013) reported that N_2O emissions were lowered by 57% when straw supplies increased from 60 to 90 kg per fattening period. Higher aeration of the litter and/or increased temperatures may explain this finding. For CO_2 and CH_4 production, the underlying mechanisms seem unclear, since contradictions appear in the literature between authors (Jeppsson, 2000; Sommer and Moller, 2000; Yamulki, 2006; Rigolot et al., 2010; Guingand and Rugani, 2013; Philippe et al., 2014b). For instance, Jeppsson (2000) showed that an increase of 25% in straw supply was associated with increased (+72%) CO_2 emissions, while Philippe et al. (2014b) observed unchanged emissions with a straw rate ranging from 50 kg to 100 kg per fattening pig. In practice, interactions between the microbial pathways and the physico-chemical properties of the litter modulate the level of emissions with variable effects according to specific conditions. The main characteristics of manure involved in these processes are dry matter content, C/N ratio, availability of carbohydrates, aeration and temperature. Regarding CH_4, on the one hand, extra substrate may inhibit gas production because of greater aeration (Rigolot et al., 2010; Yamulki, 2006; Sommer and

Table 7
Effect of floor type (bedded or slatted floor) on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

	Bedded floor					Slatted floor			
	Litter type	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Weaned piglets									
Cabaraux et al., 2009	Straw	0.33	0.75	0.03	0.36	0.30	0.91	0.00	0.32
Cabaraux et al., 2009	Sawdust	0.43	0.52	0.32	0.54	0.34	0.86	0.01	0.36
Fattening pigs									
Robin et al., 1999	Sawdust	–	–	4.72	–	–	–	0.79	–
Ahlgrimm and Breford, 1998	Straw	–	2.74	–	–	–	6.16	–	–
Kermarrec and Robin, 2002	Sawdust	–	–	5.53	–	–	–	–	–
Philippe et al., 2007a	Straw	1.97	16.03	1.11	2.70	1.74	16.32	0.54	2.31
Philippe et al., 2007b	Straw	1.77	8.88	0.68	2.19	1.61	15.20	0.67	2.19
Gestating sows									
Philippe et al., 2011a	Straw	2.83	9.20	2.27	3.74	2.41	10.12	0.47	2.80

Table 8
Effect of the type of substrate on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively) associated with a bedded system.

	Straw-based deep litter				Sawdust-based deep litter			
	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Weaned piglets								
Nicks et al., 2003	0.46	1.58	0.36	0.61	0.48	0.77	1.39	0.91
Cabaraux et al., 2009	0.33	0.75	0.03	0.36	0.43	0.52	0.32	0.54
Fattening pigs								
Nicks et al., 2004	1.30	7.39	0.03	1.49	1.32	4.96	2.09	2.07

Moller, 2000). On the other hand, extra substrate may promote emissions by providing degradable carbohydrates for methanogenic bacteria (Guingand and Rugani, 2013; Philippe et al., 2014b).

The effect of the frequency of straw application has been addressed by Guingand and Rugani (2013). The authors observed increased emissions of CH_4 (+40%) and N_2O (+167%) when straw was supplied every week compared with every 2 weeks, although the total amount of straw was similar for both frequencies.

4.2.2.3. Surface area of the bedded area. Some studies have examined the impact on emissions of the surface area of the bedded area. Based on experimental data, Hassouna et al. (2005) proposed two emission factors for N_2O emissions related to animal density: 4–12% N_{ex} with less than 2 m^2 fattening pig^{-1} and 2–8% N_{ex} with more than 2 m^2 fattening pig^{-1}. With gestating sows, Philippe et al. (2010) measured a reduction in CO_2-, CH_4- and N_2O-emissions by 12, 33 and 28%, respectively, when the available bedded area was increased from 2.5 to 3.0 m^2 per animal.

4.2.2.4. Litter removal strategy. As in the case of slurry systems, manure removal strategies have been proposed to reduce pollutant emissions from bedded systems.

The height of a manure pile influences the level of GHG emissions. Under laboratory conditions, Dong et al. (2011) increased manure height from 10 to 40 cm by increasing the amount of manure from 6.6 to 22.8 kg. The authors obtained a lowering of CO_2- and N_2O-emissions by 53 and 11%, respectively, but a doubling of CH_4 emissions, resulting from an increase in anaerobic conditions. With straw-based deep litters, GHG emissions increase regularly over the course of time throughout the same fattening period, principally due to the accumulation of dejection (Philippe et al., 2007a; Philippe et al., 2010; Philippe et al., 2012a). In their study, Nicks et al. (2004) found that the rearing of three successive batches of pigs on the same litter did not increase the CO_2 and N_2O emissions from one fattening period to another, but that it did significantly increase CH_4 emissions from 3.3 to 12.7 g CH_4 pig^{-1} day^{-1} between the first and the third batch. Thus, frequent manure removal has been suggested as a means to mitigate emissions, and straw flow systems have been developed in response (Bruce, 1990). In this system, straw is supplied at the top of a sloped lying area. It travels down the slope with the aid of pig motion, is mixed with dung and then goes out of the pen into a passage from which manure is regularly scraped and removed. This kind of manure management is efficient in diminishing GHG emissions, as observed by Philippe et al. (2012a), who measured a reduction by 10, 46 and 55% for CO_2-, CH_4- and N_2O-emissions, respectively, compared with deep-litter. Overall, these authors found that CO_2equiv. emissions (including CO_2, CH_4 and N_2O) were reduced by 50%.

During the outside storage of solid manure, air temperature seems not to significantly influence the level of emissions, in contrast with wind speed or rainfall episodes (Wolter et al., 2004). Manure operations such as turning, stacking or covering impact on GHG emissions, but there have been some contradictory findings between studies (Hellmann et al., 1997; Paillat et al., 2005; Szanto et al., 2007; Jiang et al., 2013). Interlinked relationships between biological, physical and chemical factors inside the manure heap may explain these discrepancies. Whatever the storage conditions and treatment of manure, it is imperative that these conserve the energetic and agronomic value of the manure.

4.3. Nutrition

The main dietary strategy proposed for the abatement of pollutant gas emissions is the manipulation of the levels of crude protein and fibre content in the diet. Some dietary additives have also been studied for their impact on GHG emissions.

Evaluation of the cost-effectiveness of dietary manipulation is made difficult principally due to the large fluctuation in raw material prices depending on market conditions. For instance, the economic impact of the level of crude protein in the diet is greatly affected by the cost of soybean meal, on the one hand, and synthetic amino acids on the other hand. For the 2004–2008 period, Pineiro et al. (2009) found that the cost difference between reduced crude protein diet supplemented with amino acids and the standard diet fluctuated from +5 to 6€ per pig produced. Feedstuffs rich in dietary fibre are quite inexpensive since they are usually by-products of the feed, food or biofuel industries (e.g.: sugar beet pulp, wheat bran and distiller's grain). However, the price of high fibre diets greatly depends on local opportunities and the availability of such ingredients. Dietary manipulations are mitigation methods that are easy for farmers to apply and that can be adapted according to the circumstances.

4.3.1. Crude protein content

Diets reduced in crude protein content (CPC) but supplemented with amino acids have been given to pigs to match the protein supply with their growth potential and so to improve the efficiency of protein utilization, with similar zootechnical performance but with resulting reduced N excretion and NH_3 production (Philippe et al., 2011b). Thus, it has been suggested that a lower CPC could also reduce N_2O emissions, since NH_3 is the precursor of the formation of N_2O (Misselbrook et al., 1998). However, experiments have failed to corroborate this hypothesis (Table 9). Indeed, laboratory-scale experiments based on slurry samples have resulted in similar levels of N_2O emissions despite CPC being reduced by 15–20% (Clark et al., 2005; Le et al., 2009; Osada et al., 2011). Under barn conditions with fattening pigs on litter, Philippe et al. (2006a) reported a doubling of N_2O emissions (1.02 vs. 0.52 g N_2O pig^{-1} day^{-1}) with CPC reduced by 18%. It has also been assumed that a lower CPC would reduce CO_2- and CH_4-emissions due to improved nutrient utilization, but contradictory findings have also been observed for these gases (Table 9). In studies

Table 9
Effects of a reduction in dietary crude protein content (CPC) on emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalents (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

References	CO_2	CH_4	N_2O	CO_2equiv.	Context
Quiniou et al., 1995	+7%	–	–	–	Respiratory chambers, fattening pigs, 17.7 vs. 24.3% CPC
Atakora et al., 2002	−5%	–	–	–	Respiratory chambers, gestating sows, 14.8 vs. 19.3% CPC
Atakora et al., 2002	−7%	–	–	–	Respiratory chambers, lactating sows, 12.0 vs. 16.3% CPC
Atakora et al., 2003	NS	−60%	–	–	Respiratory chambers, non-pregnant sows, 11.% vs. 14.6% CPC
Atakora et al., 2005	NS	NS	–	–	Respiratory chambers, fattening pigs, 11.2 vs. 16.8% CPC
Atakora et al., 2011a	NS	−27%	–	–	Respiratory chambers, fattening pigs, 12.0 vs. 19.5% CPC
Atakora et al., 2011b	NS	−19%	–	–	Respiratory chambers, fattening pigs, 16.2 vs. 19.0% CPC
Clark et al., 2005	+10%	+10%	NS	+10%	Slurry samples, fattening pigs, 13.9 vs. 16.8% CPC
Velthof et al., 2005	–	−21%	–	–	Slurry samples, fattening pigs, 14.2 vs. 18.0% CPC
Le et al., 2009	NS	NS	NS	NS	Slurry samples, fattening pigs, 12.0 vs. 15.0% CPC
Osada et al., 2011	–	NS	NS	–	Slurry samples, fattening pigs, 14.5 vs. 17.0% CPC
Philippe et al., 2006a	NS	−13%	+96%	+7%	Pens with fattening pigs on straw litter, 14.4 vs. 17.6% CPC

involving respiratory chambers, most results have shown a non-significant difference in CO_2-exhalation despite a CPC reduction of up to 45% (Atakora et al., 2003, 2005, 2011a,b). Quiniou et al. (1995) measured an increase of 7% in respiratory CO_2 production with fattening pigs, while Atakora et al. (2002) noted a decreased production of 5–7% with reproductive sows. Regarding CH_4 emissions, some authors have reported reductions ranging from 13% under field conditions (Philippe et al., 2006a) to 60% in respiratory chambers (Atakora et al., 2002). Reduced VFA production with a low CPC diet could explain these results, since VFAs are precursors of CH_4 (Velthof et al., 2005). However, non-significant differences or increases in CH_4 production have also been obtained by some authors in cases of reduced CPC (Atakora et al., 2005; Clark et al., 2005; Le et al., 2009; Osada et al., 2011). Philippe et al. (2006a) reported a 7% increase in cumulative GHG emissions (including CO_2, CH_4 and N_2O) with pigs on litter consuming a reduced CPC diet. This was due to a higher contribution of N_2O despite lower CH_4 emissions.

4.3.2. Dietary fibre

Several studies have dealt with the impact of dietary fibre on GHG emissions (Table 10). It has been established that diets rich in fibre increase CH_4 production from both sources – animal and manure. Linear relationships were given in Section 2.2.1 for predicting enteric CH_4 production from ingested dietary fibre. But digestive production can also be modulated by parameters such as the botanical origin, the solubility and the fermentability of the fibre (Philippe et al., 2008). An experiment on sows fed different diets with a similar dietary fibre content but different sources of fibre showed a higher CH_4 production in cases where maize bran was incorporated compared with wheat bran (7.6 vs. 5.1 g CH_4 sow^{-1} day^{-1}; Le Goff et al., 2002b). Indeed, soluble fibres, as found in maize bran, sugar beet pulp or potato pulp, have a higher digestibility and fermentability than insoluble fibres, as found in wheat bran, pea hulls or seed residues (Jorgensen et al., 2007).

Higher CH_4 releases from slurry in cases of a fibrous diet have been reported under laboratory conditions by some authors (Clark et al., 2005; Velthof et al., 2005; Jarret et al., 2012). Jarret et al. (2012) compared CH_4 production from the slurries of fattening pigs fed a conventional diet (11% NDF) or a fibrous diet with 20% dried distiller's grain with solubles (DDGS; 14% NDF) and they obtained higher emissions (+76%) with the fibrous diet. The authors explained this result in terms of the lower digestibility of high fibre diets and thus the higher quantity of excreted OM (0.32 vs. 0.19 kg pig^{-1} day^{-1}). The B_0 of excreta, on the other hand, did not differ significantly between treatments (around 0.38 m^3 per kg OM). By contrast to these results, Clark et al. (2005) did not observe a significant difference in CH_4 emissions under in vitro conditions, whatever the fibre content. At house level, CH_4 emissions have been shown to increase by 13–52% with fibrous diets as much with a slatted floor as with a bedded floor (Philippe et al., 2009, 2012a,b, 2013; Pepple et al., 2011).

Regarding CO_2 production, conflicting results have been reported depending on the study and the source of emissions (Table 10). Schrama et al. (1998) measured a 25% lowering of CO_2 exhalation as a consequence of a reduction in pig activity. At house level, Philippe et al. (2009) observed an increase of 24% in emissions with a diet based on sugar beet pulp (48% NSP) compared with a conventional diet based on cereals (26% NSP). The reduced feed efficiency observed with a fibrous diet could explain this result.

N_2O emissions from slurry-based systems are unaffected by dietary fibre content (Clark et al., 2005; Pepple et al., 2011; Philippe et al., 2012b), in contrast to bedded systems, for which emissions have been shown to reduce with a high-fibre diet (Philippe et al., 2009, 2012b). In fact, with a fibrous diet, the pig's motivation to

Table 10
Effects of dietary fibre content on emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalents (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

References	CO_2	CH_4	N_2O	CO_2equiv.	Context
Schrama et al., 1998	−25%	+96%	–	–	Respiratory chambers, fattening pigs, 12 vs. 18% NSP (0 vs. 17% SBP)
Wang et al., 2004	+6%	+153%	–	–	Respiratory chambers, fattening pigs, 4 vs. 11.6% NSP (0 vs. 12% SBP)
Li et al. 2011	−7%	+93%	–	–	Environmentally controlled pens, fattening pigs, 32 vs. 40% NDF (0 vs. 20% DDGS)
Clark et al., 2005	−17%	NS	NS	−5%	Slurry samples from fattening pigs, 0 vs. 20% SBP
Velthof et al., 2005	–	+74%	–		Slurry samples from fattening pigs, 13 vs. 25% NSP
Jarret et al., 2012	–	+76%	–		Slurry samples from fattening pigs, 11 vs. 14% NDF (0 vs. 13% DDGS)
Philippe et al., 2009	+24%	+13%	−61%	+5%	Pens with gestating sows on straw litter, 26 vs. 48% NSP (7 vs. 42% SBP)
Pepple et al., 2011	−13%	+45%	NS	+28%	Buildings with fattening pigs on a slatted floor, 0 vs. 20% DDGS
Philippe et al., 2013	−9%	+33%	NS	−6%	Pen with fattening pigs on a slatted floor, 18 vs. 30% NSP (0 vs. 23% SBP)
Philippe et al., 2012b	NS	+44%	NS	+6%	Pen with gestating sows on a slatted floor, 25 vs. 44% NSP (0 vs. 37% SBP)
Philippe et al., 2012b	+14%	+52%	−40%	+9%	Pen with gestating sows on straw litter, 25 vs. 44% NSP (0 vs. 37% SBP)

NSP: non-starch polysaccharides; SBP: sugar beet pulp; NDF: neutral detergent fibre, DDGS: dried distiller's grain with solubles.

manipulate and to chew the straw is reduced, as a sign of greater satiety (Philippe et al., 2008). Thus, the litter is more aerated with longer wisps of straw, which limits N_2O production.

Overall, cumulative GHG emissions (combining CO_2, CH_4 and N_2O) seem to be little influenced by the presence of dietary fibre. This can be seen in reports by authors regarding emissions within a context of pigs receiving increased dietary fibre. Emission levels at house level ranged from −6 to +9% compared with emissions produced by pigs consuming a conventional diet (Philippe et al., 2009, 2012a,b). An exception to this finding can be seen in the study of Pepple et al. (2011), who observed that CO_2equiv. emissions increased by 28% where pigs received a high fibre diet. The authors explained this result in terms of the large contribution of CH_4 in their experimental conditions due to a long storage duration of slurries inside the building.

4.3.3. Feed additives

Several feed additives have been studied for their influence on environmental factors, especially on ammonia emissions, but few experiments have dealt with greenhouse gas emissions resulting from these additives.

Most studies have argued that feed supplementations that improve nutrient digestibility and growth performance in pigs potentially reduce pollutant gas emissions on an absolute scale and per product unit (Moehn et al., 2007). However, this statement has rarely been experimentally tested and validated.

Cellulases and hemicellulases have been added to animal diets in order to counterbalance the anti-nutritional effects of fermentable fibres and to improve animal performance (O'Shea et al., 2010). A further beneficial effect of these enzymes may be a reduction in CH_4 production by enteric bacteria, which are linearly related to fibre ingestion. However, Moehn et al. (2007) observed a tendency for increased CH_4 emissions despite xylanase supplementation.

Dietary inclusion of acidifying salts has also been suggested as a means to modify GHG production. Yet Aarnink et al. (2008) did not observe a significant difference in CH_4 and N_2O emissions despite the addition of 1% benzoic acid in the diet of fattening pigs. Eriksen et al. (2010) showed that a diet supplemented with 2% benzoic acid resulted in a transient reduction in CH_4-emissions from slurries stored under laboratory conditions (from day 20 to 34 of storage). The authors explained this result in terms of the inhibition of methanogenic bacteria, possibly due to a reduction in manure pH, the toxic effect of sulphides or the direct impact of benzoic acid. The temporality of the reduction could reflect the adaptation of the bacteria to slurry acidification.

Yucca extract inclusion has been proposed as a means to inhibit urease activity and to chemically convert or bind NH_3 (Duffy and Brooks, 1998), leading to an improvement in the performance and health status of pigs (Colina et al., 2001). However, Amon et al. (1995) measured an increase in CO_2 production with the dietary addition of *Yucca shidigera* extract. The effects on CH_4 and N_2O emissions of the inclusion of *Yucca* extract in the diet of pigs are still unknown.

The addition of phytase, primarily used to reduce phosphorus excretion, has been shown to increase feed efficiency and protein deposition, and this could possibly lead to a decrease in emissions (Ball and Möhn, 2003). However, to the best of our knowledge, the addition of phytase has not been studied for its effect on GHG emissions.

Probiotic agents are believed to improve the microbial environment in the gut, leading to better digestibility, performance and health status as a result (Fuller, 1989; Tsukahara et al., 2001). Under laboratory conditions, Tsukahara et al. (2001) measured emissions from the intestinal content of piglets fed a diet supplemented with a mixture of live lactic acid bacteria (*Lactobacillus acidophilus*,*Bifidobacterium bifidum* and *Enterococcus faecalis*). The authors obtained reductions of approximately 50 and 35% for CO_2- and CH_4-emissions, respectively, explained by the fact that lactic acid bacteria are stoichiometrically less favourable to gas production (Stanier et al., 1986). Barn experiments would need to be carried out to confirm these findings on a larger scale.

5. Conclusion

This review has reported and analysed the results of studies in the literature regarding GHG emissions produced by animals and manure in pig houses. Taking into account the results regarding CO_2-, CH_4- and N_2O-production, cumulative emissions of GHGs produced by pigs and manure at pig house level are estimated to approximately 4.87 kg CO_2equiv. per kg of carcass. Although CO_2 is the main contributor of these emissions (accounting for about 81%), this gas is usually not included in the calculation of overall GHG production because it is assumed that CO_2 emitted by livestock is compensated during photosynthesis by plants used as feed. In addition in the past, CO_2 emissions from manure were often erroneously considered negligible, while they can represent up to 40% of respiratory production.

The production levels of CO_2, as for CH_4 and N_2O, can be altered by several factors, such as housing conditions, manure management and diet composition. For instance, comparisons between slatted and bedded floor systems show higher CO_2equiv. emissions from bedded floor systems due to greater CO_2 emissions but mainly due to high N_2O emissions that are not counterbalanced by the eventual reduction in CH_4 emissions. While litter systems are usually associated with a better brand image and are commonly required for environmental labelling, the data reported in this review show that the environmental benefits are not always so obvious for all aspects of the production process. Moreover, GHG emissions from bedded systems greatly depend on the type, the amount and the frequency of substrate supply. These parameters may interact, with variable impacts, on emission levels. Further studies need to be carried out in order to understand more precisely the underlying phenomena and interactions that modulate GHG production from litter.

Whatever the floor type, frequent manure removal is an efficient means used to diminish GHG emissions from pig buildings on the condition that emissions from outside storage operations are prevented. This is particularly true for CH_4 production, which increases greatly over the course of time and in ambient temperatures. Frequent manure removal seems particularly advantageous since manure treatments can be associated with the removal. In this sense, separation of the solid and liquid fractions of the slurry provides interesting opportunities. Indeed, this separation reduces storage requirements and transportation costs, and offers more homogenous materials for land spreading, recycling or other specific treatments in order to enhance the agronomic, energetic and environmental profitability of the processes.

Regarding dietary strategies, inclusion of fibre impacts on GHG production by increasing CH_4 emissions from the digestive tract and from the manure. For gestating sows fed with a high fibre diet and kept on a straw based deep litter, concurrent reductions in N_2O emissions have been observed, resulting in a limited effect on CO_2equiv. emissions. A reduction in dietary CPC, which is well-known to reduce N excretion, has been shown to fail to limit the release of N_2O from manure. Other feeding strategies have also been used to investigate the assumption that improved nutrient utilization can lower GHG emissions. However, this statement has not been systematically proven in experiments, since diets supplemented with feed additives such as acidifying salts, *Yucca*

extracts or probiotics seem ineffective in significantly reducing the intensity of GHG emissions. Nevertheless, innovative nutritional options could be examined in the future, as they appear to be efficient in reducing emissions. Recycling of the co-products from the feed-, food- or biofuel-processing industry into animal feed requires further investigation, as this could provide economical and ecological advantages due to the allocation of the cost and the impacts. Overall, feeding strategies offer the advantage of being easy to implement and quick to adapt according to the availability and cost of raw materials, which fluctuate temporally.

Good management practices that respect the physiological requirements of the animals and that promote their zootechnical potential will have beneficial consequences on performance and indirectly on the intensity of GHG emissions. In light of this, factors such as the design of the building, the regulation of bioclimatic parameters, the sanitary status of the herd and genetic selection may modulate the level of GHG production.

The choice of rearing technique is also guided by other elements, such as animal welfare, the agronomical value of manure, investment and operating costs. Specific field conditions lead to decisions in favour of mitigation techniques. Options presented in this review may contribute to a reduction in the intensity of emissions generated by pig production. However, in order to be universally efficient, these strategies would need to be integrated on a larger scale taking into account supplementary emissions associated with pre-, on- and post-farm processing, such as feed production, energy consumption, manure spreading and the transportation of animal and products.

References

Aarnink, A.J.A., Huis in 't Veld, J., Hol, J.M.G., Vermeij, I., 2007. Kempfarm Housing System for Growing-finishing Pigs: Environmental Emissions and Investment Costs. In Animal Sciences Group, Report 67. Wageningen University and Research Centre, Lelystad, The Netherlands.

Aarnink, A.J.A., Hol, A., Nijeboer, G.M., 2008. Ammonia Emission Factor for Using Benzoic Acid (1% Vevovitall®) in the Diet of Growing-Finishing Pigs. In Animal Sciences Group, Report 133. Wageningen University and Research Centre, Wageningen, The Netherlands p. 21.

Ahlgrimm, H., Breford, J., 1998. Methanemissionen aus der schweinemast. Landbauforschung Volkenrode 1, 26–34.

Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane: nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric. Ecosyst. Environ. 112, 153–162.

Amon, M., Dobeic, M., Misselbrook, T.H., Pain, B.F., Phillips, V.R., Sneath, R.W., 1995. A farm scale study on the use of de-odorase(R) for reducing odor and ammonia emissions from intensive fattening piggeries. Bioresour. Technol. 51, 163–169.

Anderson, G.A., Smith, R.J., Bundy, D.S., Hammond, E.G., 1987. Model to predict gaseous contaminants in swine confinement buildings. J. Agric. Eng. Res. 37, 235–253.

Andersson, M., 1996. Performance of bedding materials in affecting ammonia emissions from pig manure. J. Agric. Eng. Res. 65, 213–222.

Atakora, J.K., Moehn, S., Sands, J.S., Ball, R.O., 2011a. Effects of dietary crude protein and phytase–xylanase supplementation of wheat grain based diets on energy metabolism and enteric methane in growing finishing pigs. Anim. Feed Sci. Technol. 166, 422–429.

Atakora, J.K.A., McMillan, D.J., Moehn, S., Ball, R.O., 2002. Low protein diet for sows: effects on production of carbon dioxide and heat. Adv. Pork Prod. 13, Abstract #14.

Atakora, J.K.A., Moehn, S., Ball, R.O., 2003. Low protein diets for sows reduce greenhouse gas production. Adv. Pork Prod. 14, Abstract #16.

Atakora, J.K.A., Moehn, S., Ball, R.O., 2005. Performance and greenhouse gas emission in finisher pigs fed very low protein diet. Adv. Pork Prod. 16, Abstract #14.

Atakora, J.K.A., Moehn, S., Ball, R.O., 2011b. Enteric methane produced by finisher pigs is affected by dietary crude protein content of barley grain based, but not by corn based, diets. Anim. Feed Sci. Technol. 166–167, 412–421.

Aubry, A., Quiniou, N., Cozler, Y.L., Querne, M., 2004. New standardized criteria for GTE performances. Techni-Porc. 27, 37–41.

Ball, R.O., Möhn, S., 2003. Feeding strategies to reduce greenhouse gas emissions from pigs. Adv. Pork Prod. 14, 301–311.

Blanes-Vidal, V., Hansen, M.N., Pedersen, S., Rom, H.B., 2008. Emissions of ammonia, methane and nitrous oxide from pig houses and slurry: effects of rooting material, animal activity and ventilation flow. Agric. Ecosyst. Environ. 124, 237–244.

Brown-Brandl, T.M., Nienaber, J.A., Xin, H., Gates, R.S., 2004. A literature review of swine heat production. Trans. ASAE 47, 259.

Bruce, J.M., 1990. Straw-flow – a high welfare system for pigs. Farm Build. Prog. 102, 9–13.

Cabaraux, J.F., Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M., Nicks, B., 2009. Gaseous emissions from weaned pigs raised on different floor systems. Agric. Ecosyst. Environ. 130, 86–92.

Chae, K., Jang, A., Yim, S., Kim, I.S., 2008. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresour. Technol. 99, 1–6.

CIGR, 2002. Fourth Report of Working Group on Climatization of Animal Houses. Heat and Moisture Production at Animal and House Levels. Danish Institute of Agricultural Sciences, Horsens, Denmark, pp. 45.

Clark, O.G., Moehn, S., Edeogu, I., Price, J., Leonard, J., 2005. Manipulation of dietary protein and nonstarch polysaccharide to control swine manure emissions. J. Environ. Qual. 34, 1461–1466.

Colina, J.J., Lewis, A.J., Miller, P.S., Fischer, R.L., 2001. Dietary manipulation to reduce aerial ammonia concentrations in nursery pig facilities. J. Anim. Sci. 79, 3096–3103.

Conrad, R., 1989. Control of methane production in terrestrial ecosystems. In: Andreae, M., Schimel, D. (Eds.), Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere. John Wiley & Sons Ltd., Chichester, England, pp. 39–58.

Costa, A., Chiarello, G.L., Selli, E., Guarino, M., 2012. Effects of TiO_2 based photocatalytic paint on concentrations and emissions of pollutants and on animal performance in a swine weaning unit. J. Environ. Manage. 96, 86–90.

Costa, A., Guarino, M., 2009. Definition of yearly emission factor of dust and greenhouse gases through continuous measurements in swine husbandry. Atmos. Environ. 43, 1548–1556.

Dämmgen, U., Amon, B., Hutchings, N.J., Haenel, H.D., Rösemann, C., 2012a. Data sets to assess methane emissions from untreated cattle and pig slurry and solid manure storage systems in the German and Austrian emission inventories. Landbauforschung Volkenrode 62, 1–19.

Dämmgen, U., Schulz, J., Klausing, H.K., Hutchings, N.J., Haenel, H.D., Rösemann, C., 2012b. Enteric methane emissions from German pigs. Landbauforschung Volkenrode 62, 83–96.

de Sousa, P., Pedersen, S., 2004. Ammonia emission from fattening pig houses in relation to animal activity and carbon dioxide production. Agricultural Engineering International: CIGR Ejournal VI, Manuscript BC04 003.

de Vries, J.W., Aarnink, A.J.A., Groot Koerkamp, P.W.G., De Boer, I.J.M., 2013. Life cycle assessment of segregating fattening pig urine and feces compared to conventional liquid manure management. Environ. Sci. Technol. 47, 1589–1597.

Dewes, T., 1996. Effect of pH, temperature, amount of litter and storage density on ammonia emissions from stable manure. J. Agric. Sci. 127, 501–509.

Dinuccio, E., Berg, W., Balsari, P., 2008. Gaseous emissions from the storage of untreated slurries and the fractions obtained after mechanical separation. Atmos. Environ. 42, 2448–2459.

Dong, H., Zhu, Z., Shang, B., Kang, G., Zhu, H., Xin, H., 2007. Greenhouse gas emissions from swine barns of various production stages in suburban Beijing, China. Atmos. Environ. 41, 2391–2399.

Dong, H., Zhu, Z., Zhou, Z., Xin, H., Chen, Y., 2011. Greenhouse gas emissions from swine manure stored at different stack heights. Anim. Feed Sci. Technol. 166, 557–561.

Driemer, J., Van den Weghe, H., 1997. Nitrous oxide emissions during nitrification and denitrification of pig manure. In: Voermans, J.A.M., Monteny, G.J. (Eds.), Proceedings of the International Symposium on Ammonia and Odour Control from Animal Production Facilities, Dutch Society of Agricultural Engineering, Wageningen, The Netherlands, Vinkeloord, The Netherlands, pp. 389–396.

Duffy, C., Brooks, P., 1998. Using *Yucca* schidigera in pig diets: effects on nitrogen metabolism. In: Lyons, T.P., Jacques, K.A. (Eds.), Biotechnology in the Feed Industry. Alltach, Nicholasville, Kentucky, USA, pp. 61.

Eriksen, J., Adamsen, A.P.S., Norgaard, J.V., Poulsen, H.D., Jensen, B.B., Petersen, S.O., 2010. Emissions of sulfur-containing odorants, ammonia, and methane from pig slurry: effects of dietary methionine and benzoic acid. J. Environ. Qual. 39, 1097–1107.

FAO, 2011. World Livestock 2011– Livestock in Food Security. FAO, Rome, Italy.

FAO, 2013a. Greenhouse Gas Emissions From Pig and Chicken Supply Chains – A Global Life Cycle Assessment. FAO, Roma, Italy.

FAO, 2013b. Greenhouse Gas Emissions From Ruminant Supply Chains – A Global Life Cycle Assessment. FAO, Roma, Italy.

Feddes, J.J.R., DeShazer, J.A., 1988. Feed consumption as a parameter for establishing minimum ventilation rates. Trans. ASAE 31, 571–575.

Fitamant, D., Quillien, J.P., Callarec, J., Morvan, J., Lemasle, M., Laplanche, A., 1999. Nitrogen distribution and net flow in the form of gas and liquid from a piggery. Journées Rech. Porcine 31, 99–104.

Fuller, R., 1989. Probiotics in man and animals. J. Appl. Microbiol. 66, 365–378.

Galassi, G., Crovetto, G.M., Rapetti, L., Tamburini, A., 2004. Energy and nitrogen balance in heavy pigs fed different fibre sources. Livest. Prod. Sci. 85, 253–262.

Galassi, G., Crovetto, G.M., Rapetti, L., 2005. Trend of energy and nitrogen utilization of high fibre diets in pigs from 100 to 160 kg bodyweight. Ital. J. Anim. Sci. 4, 149–157.

Godbout, S., Lague, C., Lemay, S.P., Marquis, A., Fonstad, T.A., 2003. Greenhouse gas and odour emissions from swine operations under liquid manure management in Canada. In: Commission Internationale de Génie Rural (Ed.), Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal

Production Facilities, Danish Institute for Agricultural Sciences, Foulum, Denmark, pp. 426–443.
Godbout, S., Lemay, S.P., Marquis, A., Pouliot, F., Larouche, J.P., Hamel, D., Lachance, I., Belzile, M., Dufour, V., Turgeon, N., 2006. Évaluation Technico-économique D'un Système De Séparation Liquide/solide Des Déjections À La Source Dans Un Bâtiment Porcin Et Les Impacts Sur L'environnement. Institut de Recherche et de Développement en Agro-environnement, Quebec, Canada.
Groenestein, C.M., 1994. Ammonia emission from pig houses after frequent removal of slurry with scrapers. Proceedings of the XII World Congress on Agricultural Engineering. CIGR, Merelbeke, Belgium, pp. 543–550.
Groenestein, C.M., Hendriks, M., den Hartog, L.A., 2003. Effect of feeding schedule on ammonia emission from individual and group-housing systems for sows. Biosyst. Eng. 85, 79–85.
Groenestein, C.M., Van Faassen, H.G., 1996. Volatilization of ammonia, nitrous oxide and nitric oxide in deep-litter systems for fattening pigs. J. Agric. Eng. Res. 65, 269–274.
Guarino, A., Fabbri, C., Brambilla, M., Valli, L., Navarotto, P., 2006. Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. T. ASABE 49, 737–747.
Guarino, M., Fabbri, C., Navarotto, P., Valli, L., Mascatelli, G., Rossetti, M., Mazzotta, V., 2003. Ammonia, methane and nitrous oxide emissions and particulate matter concentrations in two different buildings for fattening pig. In: Commission Internationale de Génie Rural (Ed.), Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities, Danish Institute for Agricultural Sciences Foulum, Denmark, pp. 140–149.
Guingand, N., Quiniou, N., Courboulay, V., 2010. Comparison of ammonia and greenhouse gas emissions from fattening pigs kept either on partially slatted floor in cold conditions or on fully slatted floor in thermoneutral conditions. Journées Rech. Porcine 42, 277–284.
Guingand, N., Rugani, A., 2013. Incidence de la réduction de la quantité de paille et de la fréquence des apports sur les émissions d'ammoniac: de GES et d'odeurs chez les porcs en engraissement. Journées Rech. Porcine 45, 141–142.
Haeussermann, A., Hartung, E., Gallmann, E., Jungbluth, T., 2006. Influence of season ventilation strategy, and slurry removal on methane emissions from pig houses. Agric. Ecosyst. Environ. 112, 115–121.
Hamel, D., Pouliot, F., Leblanc, R., Godbout, S., Von Bermuth, R.D., Hill, J., 2004. Évaluation Technico-économique D'un Système De Séparation Liquide-solide Des Déjections À La Source Dans Un Bâtiment Porcin Et Les Impacts Sur L'environnement. Centre de développement du porc du Québec, Ste Foy Québec, Canada.
Hansen, K.H., Angelidaki, I., Ahring, B.K., 1999. Improving thermophilic anaerobic digestion of swine manure. Water Res. 33, 1805–1810.
Hansen, M.N., Henriksen, K., Sommer, S.G., 2006. Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: effects of covering. Atmos. Environ. 40, 4172–4181.
Hao, X., Larney, F.J., 2011. Reducing greenhouse gas emissions from animal manure. Manure Manage. Update 37–45.
Hassouna, M., Robin, P., Texier, C., Ramonet, Y., 2005. NH_3, N_2O, CH_4 emissions from pig-on-litter systems. Proceedings of the International Workshop on Green Pork Production, Paris, France pp. 121–122.
Hayes, E.T., Curran, T.P., Dodd, V.A., 2006. Odour and ammonia emissions from intensive pig units in Ireland. Bioresour. Technol. 97, 940–948.
Hellmann, B., Zelles, L., Palojarvi, A., Bai, Q.Y., 1997. Emission of climate-relevant trace gases and succession of microbial communities during open-window composting. Appl. Environ. Microbiol. 63, 1011–1018.
Husted, S., 1994. Seasonal variation in methane emission from stored slurry and solid manures. J. Environ. Qual. 23, 585–592.
INRA-AFZ, 2004. Tables De Composition Et De Valeur Nutritive Des Matières Premières Destinées Aux Animaux D'élevage. INRA Editions, Paris France.
IPCC, 2006. IPPC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Hayama, Japan.
IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Jarret, G., Cerisuelo, A., Peu, P., Martinez, J., Dourmad, J.-Y., 2012. Impact of pig diets with different fibre contents on the composition of excreta and their gaseous emissions and anaerobic digestion. Agric. Ecosyst. Environ. 160, 51–58.
Jarret, G., Martinez, J., Dourmad, J.-Y., 2011. Pig feeding strategy coupled with effluent management – fresh or stored slurry: solid phase separation – on methane potential and methane conversion factors during storage. Atmos. Environ. 45, 6204–6209.
Jeppsson, K.H., 1998. Ammonia emission from different deep-litter materials for growing-finishing pigs. Swed. J. Agric. Res. 28, 197–206.
Jeppsson, K.H., 2000. Carbon dioxide emission and water evaporation from deep litter systems. J. Agric. Eng. Res. 77, 429–440.
Jeppsson, K.H., 2002. Diurnal variation in ammonia, carbon dioxide and water vapour emission from an uninsulated: deep litter building for growing/finishing pigs. Biosyst. Eng. 81, 213–223.
Jiang, T., Schuchardt, F., Li, G.X., Guo, R., Luo, Y.M., 2013. Gaseous emission during the composting of pig feces from Chinese Ganqinfen system. Chemosphere 90, 1545–1551.
Jorgensen, H., Zhao, X.Q., Eggum, B.O., 1996. The influence of dietary fibre and environmental temperature on the development of the gastrointestinal tract digestibility, degree of fermentation in the hind-gut and energy metabolism in pigs. Br. J. Nutr. 75, 365–378.
Jorgensen, H., 2007. Methane emission by growing pigs and adult sows as influenced by fermentation. Livestock Sci. 109, 216–219.
Jorgensen, H., Serena, A., Hedemann, M.S., Knudsen, K.E.B., 2007. The fermentative capacity of growing pigs and adult sows fed diets with contrasting type and level of dietary fibre. Livestock Sci. 109, 111–114.
Kaparaju, P., Rintala, J., 2011. Mitigation of greenhouse gas emissions by adopting anaerobic digestion technology on dairy: sow and pig farms in Finland. Renewable Energy 36, 31–41.
Kebreab, E., Clark, K., Wagner-Riddle, C., France, J., 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: a review. Can. J. Anim. Sci. 86, 135–158.
Kermarrec, C., Robin, P., 2002. Nitrogenous gas emissions during the rearing of pigs on sawdust litter. Journées Rech. Porcine 34, 155–160.
Kotsopoulos, T.A., Karamanlis, X., Dotas, D., Martzopoulos, G.G., 2008. The impact of different natural zeolite concentrations on the methane production in thermophilic anaerobic digestion of pig waste. Biosyst. Eng. 99, 105–111.
Krieter, J., 2002. Evaluation of different pig production systems including economic, welfare and environmental aspects. Archiv fur Tierzucht 45, 223–236.
Kroodsma, W., Tveld, J., Scholtens, R., 1993. Ammonia emission and its reduction from cubicle houses by flushing. Livestock Prod. Sci. 35, 293–302.
Lagadec, S., Landrain, B., Landrain, P., Hassouna, M., Robin, P., 2012. Systèmes d'évacuations fréquentes des déjections Rapport d'étude, Chambres d'agriculture de Bretagne, p. 10.
Lägue, C., Marquis, A., Godbout, S., Legace, R., Fonstad, T.A., Lemay, S.P., Joncas, R., Jaulin, L., 2004. Greenhouse Gas Emissions from Swine Operations in Québec and Saskatchewan: Benchmark Assessments. University of Saskatchewan, Saskatchewan, Canada.
Lavoie, J., Beaudet, Y., Létourneau, C., Godbout, S., Lemay, S., Belzile, M., Lachance, I., Pouliot, F., 2006. Evaluation de la qualité de l'air dans les porcheries équipées d'un système de séparation liquide-solide des déjections, Report R-460; IRSST, Montréal, QC, Canada.
Le Goff, G., Dubois, S., Van Milgen, J., Noblet, J., 2002a. Influence of dietary fibre level on digestive and metabolic utilisation of energy in growing and finishing pigs. Anim. Res. 51, 245–260.
Le Goff, G., Le Groumellec, L., van Milgen, J., Dubois, S., Noblet, J., 2002b. Digestibility and metabolic utilisation of dietary energy in adult sows: influence of addition and origin of dietary fibre. Br. J. Nutr. 87, 325–335.
Le, P.D., Aarnink, A.J.A., Jongbloed, A.W., 2009. Odour and ammonia emission from pig manure as affected by dietary crude protein level. Livestock Sci. 121, 267–274.
Lessard, P., Bourgault, C., LeBihan, Y., Turgeon, N., Aubry, G., Buelna, G., 2009. Treatment of pig slurry by a process of biofiltration: study of formation of methane. Can. J. Civil Eng. 36, 1958–1962.
Lesschen, J.P., van den Berg, M., Westhoek, H.J., Witzke, H.P., Oenema, O., 2011. Greenhouse gas emission profiles of European livestock sectors. Anim. Feed Sci. Technol. 166–167, 16–28.
Li, W., Powers, W., Hill, G.M., 2011. Feeding distillers dried grains with solubles and organic trace mineral sources to swine and the resulting effect on gaseous emissions. J. Anim. Sci. 89, 3286–3299.
Loyon, L., Guiziou, F., Beline, E., Peu, P., 2007. Gaseous emissions (NH_3 N_2O, CH_4 and CO_2) from the aerobic treatment of piggery slurry – comparison with a conventional storage system. Biosyst. Eng. 97, 472–480.
Loyon, L., Guiziou, F., Picard, S., Saint-Cast, P., 2006. Impact of peat and polystyrene ball covers on the ammonia emissions from the storage and spreading of pig slurry: a farm-scale study. DIAS Report, Plant Production, 129–131.
Luth, R.P., Germain, P., Lecomte, M., Landrain, B., Li, Y., Cluzeau, D., 2011. Earthworm effects on gaseous emissions during vermifiltration of pig fresh slurry. Bioresour. Technol. 102, 3679–3686.
Misselbrook, T.H., Chadwick, D.R., Pain, B.F., Headon, D.M., 1998. Dietary manipulation as a means of decreasing N losses and methane emissions and improving herbage N uptake following application of pig slurry to grassland. J. Agric. Sci. 130, 183–191.
Misselbrook, T.H., Powell, J.M., 2005. Influence of bedding material on ammonia emissions from cattle excreta. J. Dairy Sci. 88, 4304–4312.
Moehn, S., Atakora, J., Sands, J., Ball, R., 2007. Effect of phytase–xylanase supplementation to wheat-based diets on energy metabolism in growing–finishing pigs fed ad libitum. Livestock Sci. 109, 271–274.
Moehn, S., Bertolo, R., Pencharz, P., Ball, R., 2004. Pattern of carbon dioxide production and retention is similar in adult pigs when fed hourly, but not when fed a single meal. BMC Physiol. 4, 11.
Moller, H.B., Sommer, S.G., Ahring, B.K., 2004. Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure. J. Environ. Qual. 33, 27–36.
Monteny, G.J., Bannink, A., Chadwick, D., 2006. Greenhouse gas abatement strategies for animal husbandry. Agric. Ecosyst. Environ. 112, 163–170.
Müller, W., Schneider, B., 1985. Heat: water vapour and CO_2 production in dairy cattle and pig housing. Part 1. Provisional planning data for the use of heat exchangers and heat pumps in livestock housing. Tierärztliche Umschau 40, 274–280.
Ngwabie, N.M., Jeppsson, K.H., Nimmermark, S., Gustafsson, G., 2011. Effects of animal and climate parameters on gas emissions from a barn for fattening pigs. Appl. Eng. Agric. 27, 1027–1037.
Ni, J.Q., Hendriks, J., Coenegrachts, J., Vinckier, C., 1999a. Production of carbon dioxide in a fattening pig house under field conditions I. Exhalation by pigs. Atmos. Environ. 33, 3691–3696.

Ni, J.Q., Vinckier, C., Coenegrachts, J., Hendriks, J., 1999b. Effect of manure on ammonia emission from a fattening pig house with partly slatted floor. Livestock Prod. Sci. 59, 25–31.
Ni, J.-Q., Heber, A.J., Lim, T.T., Tao, P.C., Schmidt, A.M., 2008. Methane and carbon dioxide emission from two pig finishing barns. J. Environ. Qual. 37, 2001–2011.
Nicks, B., 2004. Technical characteristics and environmental aspects of breeding fattening pigs and weaned piglets on accumulated litters. Ann. Méd. Vét. 148, 31–38.
Nicks, B., Laitat, M., Farnir, F., Vandenheede, M., Desiron, A., Verhaeghe, C., Canart, B., 2004. Gaseous emissions from deep-litter pens with straw or sawdust for fattening pigs. Anim. Sci. 78, 99–107.
Nicks, B., Laitat, M., Vandenheede, M., Desiron, A., Verhaeghe, C., Canart, B., 2003. Emissions of ammonia, nitrous oxide, methane, carbon dioxide and water vapor in the raising of weaned pigs on straw-based and sawdust-based deep litters. Anim. Res. 52, 299–308.
Nicks, B., Philippe, F.X., Laitat, M., Farnir, F., Canart, B., Vandenheede, M., 2005. Gaseous emissions in the raising of fattening pigs on fully slatted-floor or on straw-based deep litter. In: Krynski, A., Wrzesien, R. (Eds.), Animal and Environment. ISAH, Warsaw, Poland, pp. 373–377.
Noblet, J., Fortune, H., Shi, X., Dubois, S., 1994. Prediction of net energy value of feeds for growing pigs. J. Anim. Sci. 72, 344–354.
Noblet, J., Dourmad, J.Y., Le Dividich, J., Dubois, S., 1989. Effect of ambient temperature and addition of straw or alfalfa in the diet on energy metabolism in pregnant sows. Livestock Prod. Sci. 21, 309–324.
O'Shea, C.J., Sweeney, T., Lynch, M.B., Gahan, D.A., Callan, J.J., O'Doherty, J.V., 2010. Effect of beta-glucans contained in barley- and oat-based diets and exogenous enzyme supplementation on gastrointestinal fermentation of finisher pigs and subsequent manureodor and ammonia emissions. J. Anim. Sci. 88, 1411–1420.
Oenema, O., Wrage, N., Velthof, G., Groenigen, J.W., Dolfing, J., Kuikman, P., 2005. Trends in global nitrous oxide emissions from animal production systems. Nutr. Cycling Agroecosyst. 72, 51–65.
Olesen, C.S., Jorgensen, H., 2001. Effect of dietary fibre on digestibility and energy metabolism in pregnant sows. Acta Agric. Scand. Sect. A: Anim. Sci. 51, 200–207.
Osada, T., Rom, H.B., Dahl, P., 1998. Continuous measurement of nitrous oxide and methane emission in pig units by infrared photoacoustic detection. Trans. ASAE 41, 1109–1114.
Osada, T., Takada, R., Shinzato, I., 2011. Potential reduction of greenhouse gas emission from swine manure by using a low-protein diet supplemented with synthetic amino acids. Anim. Feed Sci. Technol. 166, 562–574.
Paillat, J.-M., Robin, P., Hassouna, M., Leterme, P., 2005. Predicting ammonia and carbon dioxide emissions from carbon and nitrogen biodegradability during animal waste composting. Atmos. Environ. 39, 6833–6842.
Palkovicova, Z., Knizatova, M., Mihina, S., Broucek, J., Hanus, A., 2009. Emissions of greenhouse gases and ammonia from intensive pig breeding. Folia Vet. 53, 168–170.
Pedersen, S., Blanes-Vidal, V., Jørgensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M., Aarnink, A., 2008. Carbon dioxide production in animal houses: a literature review. Manuscript BC 08 008.
Pelletier, N., Lammers, P., Stender, D., Pirog, R., 2010. Life cycle assessment of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. Agric. Syst. 103, 599–608.
Pepple, L., Burns, R., Xin H., Li, H., Patience, J., 2011. Ammonia, hydrogen sulfide, and greenhouse gas emissions from wean-to-finish swine barns fed diets with or without DDGS. Agric. Biosyst. Eng. Conference Papers, Posters and Presentations. Paper 138.
Petersen, S.O., Miller, D.N., 2006. Greenhouse gas mitigation by covers on livestock slurry tanks and lagoons. J. Sci. Food Agric. 86, 1407–1411.
Philippe, F.X., Cabaraux, J.F., Laitat, M., Stilmant, D., Wavreille, J., Nicks, B., 2013. Les Impacts Environnementaux Du Choix Des Modalités D'hébergement Des Porcs Charcutiers. University of Liège, Liège, Belgium, and Walloon Agricultural Research Centre, Gembloux, Belgium.
Philippe, F.X., Cabaraux, J.F., Nicks, B., 2011a. Ammonia emissions from pig houses: influencing factors and mitigation techniques. Agric. Ecosyst. Environ. 141, 245–260.
Philippe, F.X., Canart, B., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2010. Effects of available surface on gaseous emissions from group-housed gestating sows kept on deep litter. Animal 4, 1716–1724.
Philippe, F.X., Canart, B., Laitat, M., Wavreille, J., Vandenheede, M., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2009. Gaseous emissions from group-housed gestating sows kept on deep litter and offered an ad libitum high-fibre diet. Agric. Ecosyst. Environ. 132, 66–73.
Philippe, F.X., Laitat, M., Canart, B., Farnir, F., Massart, L., Vandenheede, M., Nicks, B., 2006a. Effects of a reduction of diet crude protein content on gaseous emissions from deep-litter pens for fattening pigs. Anim. Res. 55, 397–407.
Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M., Nicks, B., 2007a. Comparison of ammonia and greenhouse gas emissions during the fattening of pigs: kept either on fully slatted floor or on deep litter. Livestock Sci. 111, 144–152.
Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M., Nicks, B., 2007b. Gaseous emissions during the fattening of pigs kept either on fully slatted floors or on straw flow. Animal 1, 1515–1523.
Philippe, F.X., Laitat, M., Nicks, B., Cabaraux, J.F., 2012a. Ammonia and greenhouse gas emissions during the fattening of pigs kept on two types of straw floor. Agric. Ecosyst. Environ. 150, 45–53.
Philippe, F.X., Laitat, M., Vandenheede, M., Canart, B., Nicks, B., 2006b. Comparison of zootechnical performances and nitrogen contents of effluent for fattening pigs kept either on slatted floor or on straw-based deep litter. Ann. Méd. Vét. 150, 137–144.
Philippe, F.X., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2011b. Ammonia and greenhouse gas emission from group-housed gestating sows depends on floor type. Agric. Ecosyst. Environ. 140, 498–505.
Philippe, F.X., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2012b. Effets des fibres et du type de sol sur les émissions de gaz à effet de serre et d'ammoniac associées à l'élevage de truies. Journées Rech. Porcine 44, 133–134.
Philippe, F.X., Laitat, M., Wavreille, J., Nicks, B., Cabaraux, J.F., 2014a. Ammonia and greenhouse gases emissions associated to fattening pigs kept either on fully or partly slatted floor. Journées Rech. Porcine 46, 211–212.
Philippe, F.X., Laitat, M., Wavreille, J., Nicks, B., Cabaraux, J.F., 2014b. Effects of the amount of straw on ammonia and greenhouse gases emissions associated to fattening pigs kept on deep litter. Journées Rech. Porcine 46, 213–214.
Philippe, F.X., Remience, V., Dourmad, J.Y., Cabaraux, J.F., Vandenheede, M., Nicks, B., 2008. Food fibers in gestating sows: effects on nutrition behaviour, performances and waste in the environment. INRA Prod. Anim. 21, 277–290.
Pineiro, C., Montalvo, G., Garcia, M.A., Bigeriego, M., 2009. Influence of Soya Bean Meal and Synthetics Amino Acids Prices in the Cost of Nutritional Best Available Techniques in Spain. In: Book of Abstracts of the 60th Annual Meeting of the European Association for Animal Production. Wageningen Academic Publishers, Wageningen, The Netherlands p. 327.
Poth, M., Focht, D.D., 1985. N-15 kinetic-analysis of N_2O production by nitrosomonas-europaea – an examination of nitrifier denitrification. Appl. Environ. Microbiol. 49, 1134–1141.
Quiniou, N., Dubois, S., Noblet, J., 1995. Effect of dietary crude protein level on protein and energy balances in growing pigs: comparison of two measurement methods. Livestock Prod. Sci. 41, 51–61.
Ramonet, Y., van Milgen, J., Dourmad, J.Y., Dubois, S., Meunier-Salaun, M.C., Noblet, J., 2000. The effect of dietary fibre on energy utilisation and partitioning of heat production over pregnancy in sows. Brit. J. Nutr. 84, 85–94.
Rigolot, C., Espagnol, S., Robin, P., Hassouna, M., Beline, F., Paillat, J.M., Dourmad, J.Y., 2010. Modelling of manure production by pigs and NH_3 N_2O and CH_4 emissions. Part II: effect of animal housing, manure storage and treatment practices. Animal 4, 1413–1424.
Robin, P., de Oliveira, P.A., Kermarrec, C., 1999. Ammonia: nitrous oxide and water emissions from pigs housed on several types of litter during the growing period. Journées Rech. Porcine 31, 111–115.
Rodhe, L.K.K., Abubaker, J., Ascue, J., Pell, M., Nordberg, T., 2012. Greenhouse gas emissions from pig slurry during storage and after field application in northern European conditions. Biosyst. Eng. 113, 379–394.
Schrama, J.W., Bosch, M.W., Verstegen, M.W.A., Vorselaars, A., Haaksma, J., Heetkamp, M.J.W., 1998. The energetic value of nonstarch polysaccharides in relation to physical activity in group-housed, growing pigs. J. Anim. Sci. 76, 3016–3023.
Serena, A., Jorgensen, H., Bach Knudsen, K.E., 2008. Digestion of carbohydrates and utilization of energy in sows fed diets with contrasting levels and physico-chemical properties of dietary fiber. J. Anim. Sci. 86, 2208–2216.
Shah, S.B., Kolar, P., 2012. Evaluation of additive for reducing gaseous emissions from swine waste. Agric. Eng. Int.: CIGR J. 14, 10–20.
Sommer, S.G., 2001. Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. Eur. J. Agron. 14, 123–133.
Sommer, S.G., Moller, H.B., 2000. Emission of greenhouse gases during composting of deep litter from pig production – effect of straw content. J. Agric. Sci. 134, 327–335.
Sommer, S.G., Petersen, S.O., Moller, H.B., 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutr. Cycling Agroecosyst. 69, 143–154.
Sommer, S.G., Petersen, S.O., Sorensen, P., Poulsen, H.D., Moller, H.B., 2007. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. Nutr. Cycling Agroecosyst. 78, 27–36.
Stanier, R.Y., Ingraham, J.L., Wheelis, M.L., Painter, P.R., 1986. The Microbial World, fifth ed. Prentice-Hall, New Jersey.
Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, C., de Haan, C., 2006. Livestock's Long Shadow: Environmental Issues and Options. Food and Agriculture Organization of the United Nations, Rome, Italy.
Stinn, J.P., Xin H., Li, H., Shepherd, T., Burns, R., 2011. Quantification of greenhouse gas and ammonia emissions from a Midwestern swine breeding/gestation/farrowing facility. Agric. Biosyst. Eng. Conference Papers, Posters and Presentations. Paper 203.
Sun, G., Guo, H.Q., Peterson, J., Predicala, B., Lague, C., 2008. Diurnal odor, ammonia, hydrogen sulfide, and carbon dioxide emission profiles of confined swine grower/finisher rooms. J. Air Waste Manage. Assoc. 58, 1434–1448.
Szanto, G.L., Hamelers, H.M., Rulkens, W.H., Veeken, A.H.M., 2007. NH_3: N_2O and CH_4 emissions during passively aerated composting of straw-rich pig manure. Bioresour. Technol. 98, 2659–2670.
Tsukahara, T., Azuma, Y., Ushida, K., 2001. The effect of a mixture of live lactic acid bacteria on intestinal gas production in pigs. Microb. Ecol. Health D 13, 105–110.
Van Milgen, J., Noblet, J., Dubois, S., Bernier, J.F., 1997. Dynamic aspects of oxygen consumption and carbon dioxide production in swine. Br. J. Nutr. 78, 397–410.
Van der Zaag, A.C., Gordon, R.J., Glass, V.M., Jamieson, R.C., 2008. Floating cover to reduce gas emissions from liquid manure storage: a review. Appl. Eng. Agric. 24, 657–671.
van 't Klooster, C., Heitlager, B., 1994. Determination of minimum ventilation rate in pig houses with natural ventilation based on carbon dioxide balance. J. Agric. Eng. Res. 57, 279–287.

Vedrenne, F., Béline, F., Dabert, P., Bernet, N., 2008. The effect of incubation conditions on the laboratory measurement of the methane producing capacity of livestock wastes. Bioresour. Technol. 99, 146–155.
Velthof, G.L., Nelemans, J.A., Oenema, O., Kuikman, P.I., 2005. Gaseous nitrogen and carbon losses from pig manure derived from different diets. J. Environ. Qual. 34, 698–706.
Vergé, X.P.C., Dyer, J.A., Desjardins, R.L., Worth, D., 2009. Greenhouse gas emissions from the Canadian pork industry. Livestock Sci. 121, 92–101.
Vermorel, M., Jouany, J.P., Eugène, M., Sauvant, D., Noblet, J., Dourmad, J.Y., 2008. Evaluation quantitative des émissions de méthane entérique par les animaux d'élevage en 2007 en France. INRA Prod. Anim. 21, 403–418.
Wang, J., Zhu, Y., Li, D., Jørgensen, H., Jensen, B., 2004. The influence of different fiber and starch types on nutrient balance and energy metabolism in growing pigs. Asian-Aust. J. Anim. Sci. 17, 263–270.
Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149, 124–134.
Wolter, M., Prayitno, S., Schuchardt, F., 2004. Greenhouse gas emission during storage of pig manure on a pilot scale. Bioresour. Technol. 95, 235–244.
Yamulki, S., 2006. Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. Agric. Ecosyst. Environ. 112, 140–145.
Ye, Z., Zhang, G., Seo, I.H., Kai, P., Saha, C.K., Wang, C., Li, B., 2009. Airflow characteristics at the surface of manure in a storage pit affected by ventilation rate floor slat opening, and headspace height. Biosyst. Eng. 104, 97–105.
Zhang, Q., Zhou, X.J., Cicek, N., Tenuta, M., 2007. Measurement of odour and greenhouse gas emissions in two swine farrowing operations. Can. Biosyst. Eng. 49, 6.13–6.20.

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Research

Stratospheric ozone depletion due to nitrous oxide: influences of other gases

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The effects of anthropogenic emissions of nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4) and the halocarbons on stratospheric ozone (O_3) over the twentieth and twenty-first centuries are isolated using a chemical model of the stratosphere. The future evolution of ozone will depend on each of these gases, with N_2O and CO_2 probably playing the dominant roles as halocarbons return towards pre-industrial levels. There are nonlinear interactions between these gases that preclude unambiguously separating their effect on ozone. For example, the CH_4 increase during the twentieth century reduced the ozone losses owing to halocarbon increases, and the N_2O chemical destruction of O_3 is buffered by CO_2 thermal effects in the middle stratosphere (by approx. 20% for the IPCC A1B/WMO A1 scenario over the time period 1900–2100). Nonetheless, N_2O is expected to continue to be the largest anthropogenic emission of an O_3-destroying compound in the foreseeable future. Reductions in anthropogenic N_2O emissions provide a larger opportunity for reduction in future O_3 depletion than any of the remaining uncontrolled halocarbon emissions. It is also shown that 1980 levels of O_3 were affected by halocarbons, N_2O, CO_2 and CH_4, and thus may not be a good choice of a benchmark of O_3 recovery.

Keywords: nitrous oxide; stratospheric ozone; carbon dioxide; methane; halocarbon; ozone depletion potential

1. INTRODUCTION

There has been concern about anthropogenic chemical perturbations to the ozone layer for the past four decades. The early literature in the 1970s first focused on perturbations by nitrogen oxide radicals from supersonic aircraft flying in the stratosphere [1,2] and later chlorine radicals from rocket exhaust and chlorofluorocarbons (CFCs) [3,4]. As concern about supersonic aircraft and rocket exhaust impacts on stratospheric ozone died down owing to economic and air transportation issues, and the production of chlorinated compounds was rapidly increasing during the 1970s and 1980s, chlorine-induced ozone depletion received the majority of attention in the literature. The discovery of the ozone hole [5] further focused attention on effects of chlorine (and bromine) on stratospheric ozone. It became clear that ozone layer depletion was not a future but a current occurrence given the high impact of chlorine in the ozone hole observed in 1984 (approx. 40% column ozone loss, increasing to 70% column ozone loss in the 1990s). Thus, this focus was appropriate. Recent calculations show that continuous increased production of halocarbons at a high rate since the 1980s would have eventually caused the complete collapse of the ozone layer [6] and substantial climate warming [7]. Halocarbon production has been greatly reduced owing to the success of the Montreal Protocol (and subsequent amendments), and atmospheric chlorine levels have been measured to be slowly decreasing (first shown in the study of Montzka *et al*. [8]; see [9] for updates). Signs of the slowdown in the decline of ozone have been reported in the upper stratosphere [10] and extensive research is being carried out to find more evidence of recovery [9].

The effects of other source gases that can affect ozone (e.g. nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2)) received less attention during the 1980s and 1990s, in part because their effects over short (e.g. decadal) time periods are relatively small. Interest in the long-term recovery of the ozone layer has re-focused attention on the effects of these gases [11–13]. Much of this research built on the knowledge gained during the previous decades and added long scenario calculations into the future, and found that the effects on stratospheric ozone could be large. This paper will further explore this theme and, in particular, explore the interactions between these gases and stratospheric ozone. The paper is partially a review of basic chemical effects on stratospheric ozone and highlights recent research on the effects of the elimination of N_2O and controlled halocarbons. In addition, new material on the interaction between the various greenhouse gases (GHGs) is presented, emphasizing the role of N_2O. The effects of dynamic changes on ozone owing to GHG increases [9] and the potential effect of water vapour changes on ozone [14] will not be discussed. We focus on global mean total ozone as a metric for the effect of chemical

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perturbations on ozone. This is owing to the fact that global ozone depletion is what is generally used in determining ozone depletion potentials (ODPs) and that global mean changes approximately characterize ozone changes at mid-latitudes.

2. PHOTOCHEMISTRY OF NITROUS OXIDE

N_2O is produced at the surface and is relatively inert in the troposphere. Microbial activity in the soil is thought to be the largest source, but there are many smaller contributions (see [15] and the other papers in this issue for discussion). It is transported to the stratosphere and broken down in the middle stratosphere and above via photolysis

$$N_2O + h\nu \rightarrow N_2 + O(^1D) \tag{2.1}$$

and reaction with $O(^1D)$

$$N_2O + O(^1D) \rightarrow N_2 + O_2 \tag{2.2}$$

and

$$N_2O + O(^1D) \rightarrow 2NO. \tag{2.3}$$

The global lifetime of N_2O is approximately 114 years [15], which is determined by the above loss processes in conjunction with the strength of the stratospheric overturning circulation (a 20% uncertainty in the sink is reported in the study of IPCC [15]). The NO produced in reaction (2.3) is the primary source of reactive nitrogen (i.e. NO_x, defined below) in the lower and middle stratosphere (transport of mesospheric NO_x can be significant in the upper stratosphere). Approximately 10 per cent of the N_2O is converted to NO_x in the stratosphere. Figure 1*a* shows the distribution of N_2O produced in the National Oceanic and Atmospheric Administration/National Center for Atmospheric Research (NOCAR) two-dimensional model ([16] and references within). The shape of the contours is a reflection of the stratospheric circulation, upward in the tropics and downward in the extra-tropics. Figure 1*b* shows the production rate of NO_x owing to reaction (2.3) (the blue contours). This occurs at a somewhat lower altitude than the bulk of the N_2O destruction owing to reaction (2.1) (which does not produce NO_x). Reactive nitrogen can be destroyed chemically via

$$N + NO \rightarrow N_2 + O, \tag{2.4}$$

which is shown via the red contours on figure 1*b*. This is the major chemical loss process for total oxidized nitrogen (NO_y, defined below) and accounts for approximately 30 per cent loss of NO_y. The remainder of the NO_y is lost via transport the troposphere (approx. 70%).

3. BASIC OZONE PHOTOCHEMISTRY

The photochemistry of ozone was first described by Chapman [17]. Ozone is produced by the photolysis of O_2

$$O_2 + h\nu \rightarrow O + O \tag{3.1}$$

followed by the reaction of O and O_2

$$O + O_2 + M \rightarrow O_3 + M. \tag{3.2}$$

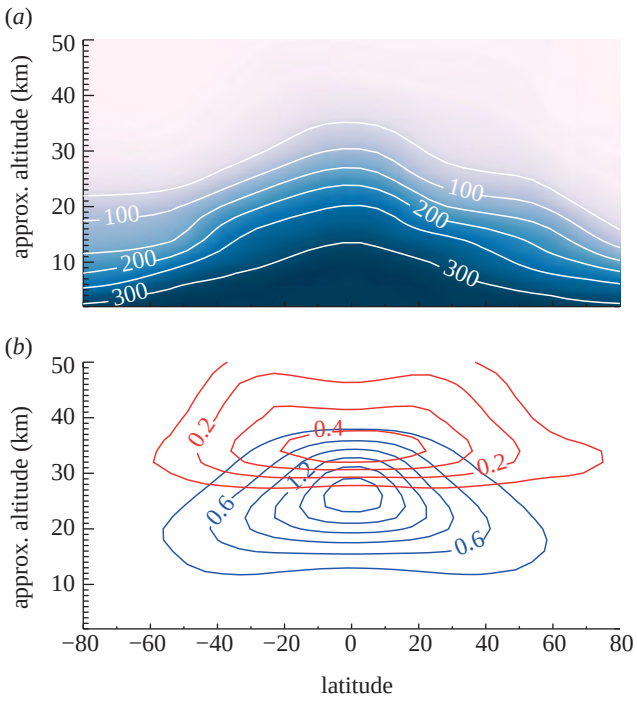

Figure 1. (*a*) The N_2O field (in ppbv) produced by the NOCAR two-dimensional model in year 2000. (*b*) Production of NO_x from N_2O (reaction (2.3), blue contours) and chemical loss rates of NO_x (reaction (2.4), red contours) in year 2000 (in ppbv d^{-1}).

O and O_3 are quickly cycled between each other via

$$O_3 + h\nu \rightarrow O_2 + O \tag{3.3}$$

followed by reaction (3.2). Thus, it is useful to define the $O_x = O + O_3$ family. The loss of O_x (and thus ozone) in the Chapman chemistry occurs via

$$O + O_3 \rightarrow O_2 + O_2 \tag{3.4}$$

with minor contribution by

$$O + O + M \rightarrow O_2 + M. \tag{3.5}$$

Since reactions (3.4) and (3.5) are much slower than reactions (3.2) and (3.3), O_x is much longer lived than either O or O_3 in the stratosphere making the use of the O_x family a conceptual simplification. The photolysis of ozone ($\lambda < 320$ nm) is also the primary source of $O(^1D)$ in the atmosphere, which plays an important role in N_2O chemistry (reactions (2.2) and (2.3)) and many other species.

Between 1930 and the 1970s, it became evident that other loss processes were necessary to explain the abundance of ozone in the ozone layer. It was realized that nitrogen oxide [1,2], hydrogen oxide [18] and chlorine radicals [3,4] also destroyed O_x (i.e. ozone) via catalytic cycles of the form

$$X + O_3 \rightarrow XO + O_2 \tag{3.6}$$

$$XO + O \rightarrow X + O_2 \tag{3.7}$$

and

$$\text{net}: O_3 + O \rightarrow 2O_2, \tag{3.8}$$

with $X = \{NO, HO, Cl\}$. The recycling of the X molecule allows one X to destroy many (typically

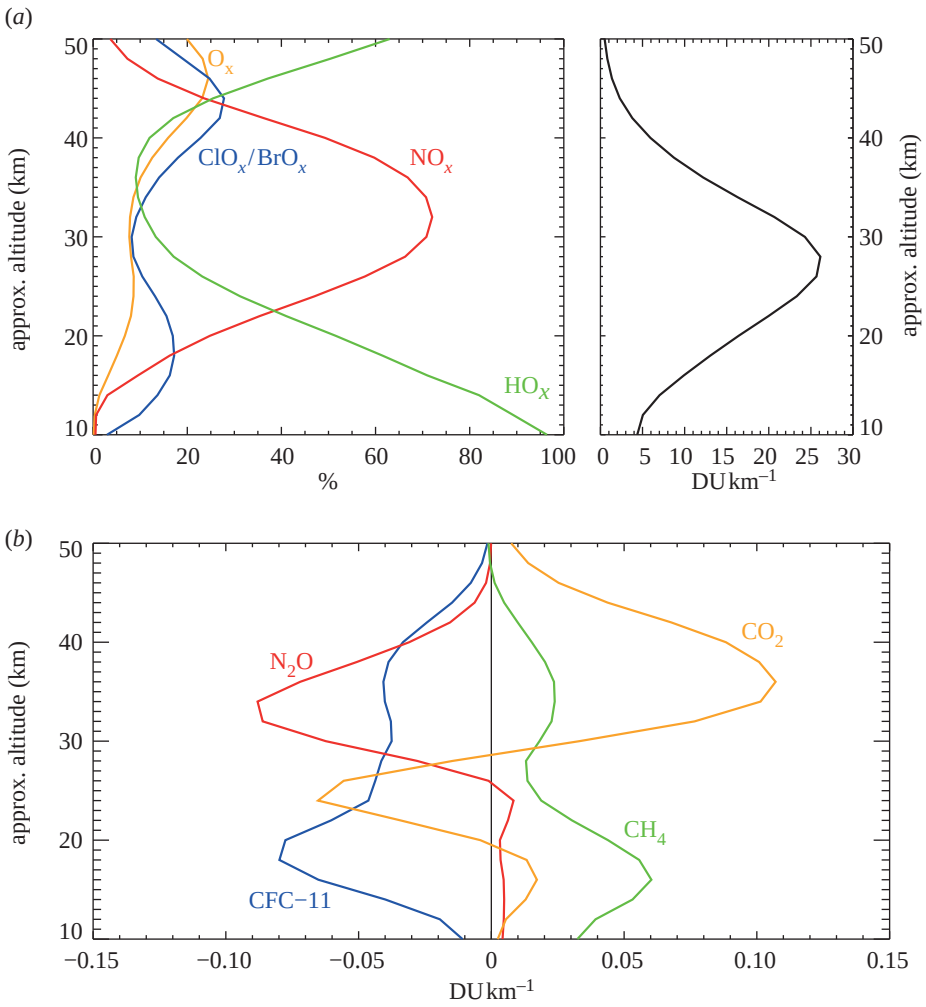

Figure 2. (*a*) The left panel shows the relative global mean ozone loss rates by chemical family computed for 2000 levels of source gases by the NOCAR two-dimensional model. The right panel shows the global mean ozone profile, which highlights the ozone layer maximum in the middle stratosphere. (*b*) The ozone changes by surface boundary condition perturbation for the following perturbation levels: 20 ppbv N_2O, 100 pptv CFC-11, 250 ppbv CH_4 and 50 ppmv CO_2. The background atmosphere is defined to be at 2000 levels for the non-perturbed gases according to the combined IPCC A1B/WMO A1 scenario. Note that Dobson Units (DU) are a measure of ozone column amount (1 DU $= 2.69 \times 10^{16}$ mol cm^{-2}) and DU km^{-1} is a density unit (1 DU km^{-1} $= 2.69 \times 10^{11}$ mol cm^{-3}).

10^3–10^5 [19]) ozone molecules before it is converted to a less-reactive molecule. This cycle is representative of the many forms of catalytic cycles that have been found to be important [20]. Bromine is interesting as its most important catalytic cycle is a combined ClO/BrO cycle, and thus increases in chlorine make bromine more potent as an ozone-destroying agent.

The individual radicals are short-lived and are also usefully modelled as part of long-lived families (e.g. $NO_x = N + NO + NO_2 + NO_3 + N_2O_5$; $NO_y = NO_x + HNO_3 + HNO_4 + ClONO_2 + BrONO_2$), where NO_x represents the sum of the short-lived nitrogen species and NO_y the sum of the short- and long-lived nitrogen species. In this framework, reaction (2.3) is the source of NO_y (and thus NO_x) and reaction (2.4) its chemical loss. Analogous definitions are obtained for ClO_x, Cl_y, BrO_x, Br_y and HO_x. The global annual mean ozone loss rates by the chemical families are shown in figure 2*a* as computed in the NOCAR two-dimensional model for the year 2000. It is evident that the NO_x cycle is dominant in the middle stratosphere, HO_x in the upper and lower stratosphere, and ClO_x/BrO_x in the upper and lower stratosphere. The global mean ozone profile is also shown in the figure, which shows the ozone maximum in the middle stratosphere. The NO_x-induced ozone loss is largest near the ozone maximum, which is one reason for its importance.

The relative abundance of the short-lived species (e.g. NO_x) compared with the long-lived species (e.g. HNO_3) plays an important role in determining the amount of ozone loss by a family. The long-lived species sequester reactive atoms in non-reactive (to ozone) forms and are called reservoirs. These reservoir species are slowly converted back to more reactive forms, typically by photolysis or reaction with OH. For example, the NO_x family's effect on ozone decreases from the middle to lower stratosphere largely because the HNO_3 reservoir becomes substantially more stable in the lower stratosphere. Similarly, in the ClO_x family, HCl and $ClONO_2$ are important reservoirs that control the effectiveness of ClO_x-induced ozone losses.

Anthropogenic influence on ozone occurs via changes in the emission of source gases. These source gas changes can affect all of the chemical

families both chemically (e.g. N_2O produces NO_x but also has a large effect on ClO_x via $ClONO_2$) and radiatively. Radiative changes can affect stratospheric temperatures and so dynamically alter the stratosphere. Changes in stratospheric temperature can also affect the chemistry via reaction rates and dynamic changes can affect the distribution of long-lived species (and thus the chemistry) and the ozone field itself. Figure 2*b* shows the effect of perturbations owing to the source gases N_2O, CH_4, CO_2 and CFC-11 for year 2000 levels of source gases on ozone. The primary effect of these source gas changes is as follows: N_2O causes more NO_x and NO_x-induced ozone loss; CFC-11 causes more ClO_x and ClO_x-induced ozone loss; CH_4 causes ozone increases via photochemical production chemistry that occurs not only in the troposphere but also in the lower stratosphere (the CH_4 effect in the upper stratosphere is described below); CO_2 has a radiative effect that cools the stratosphere and thus causes a reduction in the ozone loss via the strongly temperature-dependent reaction (3.4) (CO_2 increase also induces the strengthening of the Brewer–Dobson circulation in climate models which decreases/increases ozone in the tropical/extratropical lower stratosphere). These effects are discussed in more detail below.

4. TIME SERIES

Figure 2*b* shows the effect of particular steady-state perturbations of the source gases for non-varying year 2000 conditions. However, these long-lived source gases have been altered continuously by mankind during the twentieth century and are expected to continue to be in the future. In this paper, we use the Intergovernmental Panel on Climate Change (IPCC) A1B scenario for the GHGs and the World Meteorological Organization (WMO) A1 scenario for the halocarbons (this will be labelled A1B/A1). The A1B scenario has rapid increases in GHGs until the mid-twenty-first century and slower growth after that, with CO_2 and N_2O rising to 703 ppmv and 372 ppbv, respectively, by 2100 [21]. The WMO A1 scenario includes time series of 16 chlorine- and bromine-containing source gases (CFCs, hydrochlorofluorocarbons (HCFCs), methyl bromine, carbon tetrachloride, and so on) based on their measured (and estimated) rise and projected fall during the mid-twentieth century to 2100 [9]. It is widely recognized that the large halocarbon increases during the 1970s to the mid-1990s caused a large drop in the ozone during this time frame and that CO_2 and N_2O change in the twenty-first century will probably strongly perturb ozone into the future [9]. Figure 3 shows the modelled time series of ozone in the twentieth and twenty-first centuries using the A1B/A1 scenario along with ozone observations from satellites [22]. The halocarbon-induced ozone depletion in the period 1970–2000 is clearly evident. The year when the Montreal Protocol, which reduced emissions of halocarbons, entered into force is labelled on the figure. The recovery of ozone is evident in the model output during the twenty-first century. Using this scenario, ozone returns to values larger than were present in 1900. This is often called 'super-recovery' and is primarily caused by increase of CO_2 [12,23].

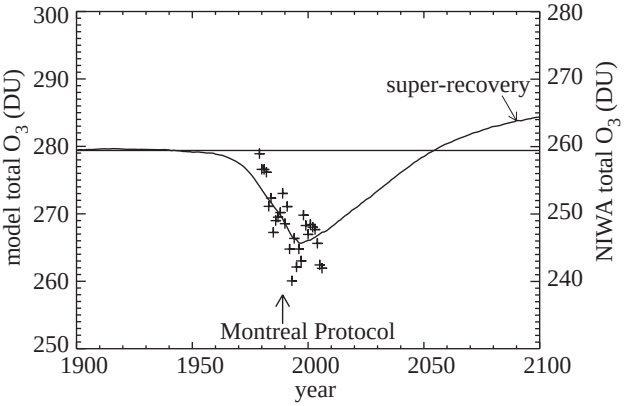

Figure 3. The global mean ozone time series computed with the NOCAR two-dimensional model using the IPCC A1B/WMO A1 scenario. The global mean ozone levels from satellite observations from the NIWA analysis [22] are shown by the crosses. The year when the Montreal Protocol limited halocarbon emissions is indicated. Global mean ozone shows a super-recovery (an evolution to larger values than in the past) in this scenario caused primarily by CO_2-induced changes on stratospheric temperatures. Solid line, model; plus symbols, satellite observations.

We use the global mean total ozone to compare the effects of the different gases, which is a common choice when the overall effect on ozone is desired as the effects of ozone changes at low and mid-latitudes are accounted for. It is also the metric used in comparing the ozone-depletion potentials (ODPs; see §6) of anthropogenic emissions of ozone-depleting substances (ODSs). Global mean ozone does not weight changes in the ozone hole very heavily because of the relatively small area involved and thus is not very sensitive to the effects of source gas changes on the ozone hole. The buildup of halocarbons caused the ozone hole and it is expected to recover when halocarbons return to natural levels. The ozone hole is caused by heterogeneous reactions on aerosol particles that convert chlorine reservoirs to active forms in the cold environment of polar winter in the lower stratosphere [24]. The NO_x and HO_x families do not cause an ozone hole as their reservoirs do not react on aerosol in that environment. In fact, HNO_3, the dominant nitrogen reservoir, is produced in many of the heterogeneous reactions. However, N_2O and CH_4 do somewhat alter the effect of ClO_x/BrO_x in the ozone hole while halocarbon levels remain high (and CO_2 can affect it through temperature and dynamic changes). Thus, the relative magnitudes of effects of the source gases discussed in this paper would be different if, for example, ozone at high latitudes were compared instead of global mean ozone.

5. NONLINEAR INTERACTIONS

The emission of a gas can induce a straightforward change in the chemistry of its chemical family (e.g. N_2O emission causing more NO_x production and more NO_x-induced ozone loss). However, the emission of a gas can also induce changes in other chemical families, which can arise owing to either chemical interactions or radiative effects on

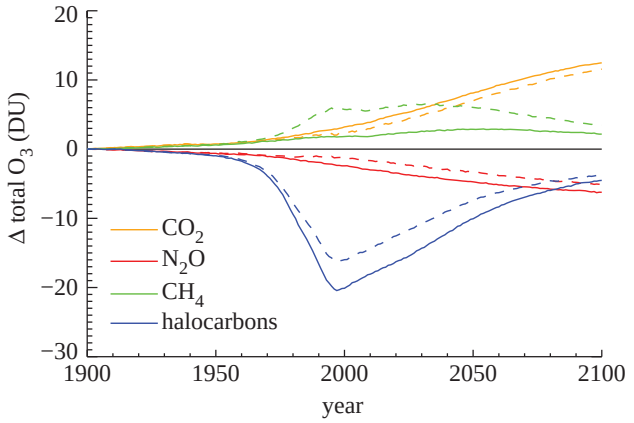

Figure 4. The individual source gas changes are isolated using different atmospheric base states (constant 1900 source gas levels and the combined IPCC A1B/WMO A1 scenario). In all cases, the size of the perturbation is obtained from the A1B/A1 scenario (dashed lines) minus constant 1900 source gas levels (solid lines). The degree to which the solid and dashed lines are different (for each gas) indicates the level of nonlinear interactions between the gases. These limit our ability to unambiguously separate the effect of these gases on ozone.

the temperature and dynamics. The magnitude of these effects is dependent on the levels of the other source gases that control the chemical families. These interactions make the impact on ozone levels of one gas to not be unambiguously separable from another. Thus, the impact of a perturbation of a source gas is nonlinear (i.e. it depends on the state of the system). One way to probe the magnitude of the nonlinearities is to compute the effect of individual perturbations of the gases but with different background concentrations of the other gases. In order to quantify the size of the nonlinear interactions, we compute the effect of the perturbations with two background conditions: constant 1900 source gas levels and the full A1B/A1 scenario. Figure 4 shows the result of this calculation on global mean ozone. The graph shows the effect of individual perturbations of each gas from 1900 source gas levels to the A1B/A1 scenario levels on ozone. The solid and dashed lines signify the different atmospheres to which the perturbations are added. The solid lines all use constant 1900 source gas levels for the non-perturbed gases while the dashed lines use the A1B/A1 scenario. The degree to which the dashed and solid lines (for each gas) differ gives an estimate of the size of the nonlinear interaction. The ozone changes (relative to 1900 levels) obtained in this calculation are also shown in table 1 for 1980, 2000 and 2100. The total of the individual perturbations is compared with their combined effect (i.e. the ozone changes for the actual scenario) in this table as well, quantifying the nonlinear contributions.

The largest nonlinear effects are evident between the halogens and methane. To first order they are caused by the reaction

$$\mathrm{Cl} + \mathrm{CH_4} \rightarrow \mathrm{HCl} + \mathrm{CH_3}, \tag{5.1}$$

which couples methane with chlorine by converting active chlorine (Cl) to a chlorine reservoir (HCl), a reservoir species that does not directly destroy ozone. The increase in methane converts active chlorine to the benign HCl reservoir, such that the fraction of active chlorine is smaller for larger methane levels given a fixed amount of chlorine. This shows that the global ozone loss from halocarbons would have been considerably more severe if the buildup of methane had not occurred. In this model, the difference is approximately 4 DU, which can be compared with a total loss of approximately 16 DU for the A1B/A1 scenario and approximately 20 DU for the constant 1900 base state. In other words, the concomitant increase in CH_4 with that of the halocarbons suppressed the extent of ozone depletion by roughly 20 per cent. Of course, without a choice of which gas change we consider primary and which is secondary, there is no way to unambiguously separate the effects of gases with nonlinear interactions. In the upper stratosphere, CH_4 increases cause HO_x increases and thus more ozone losses from HO_x catalytic cycles. This is relatively more important at low halocarbon levels as the coupling with HCl is decreased.

The effect of N_2O changes is also dependent on the background state, and by 2100 there is an approximately 1 DU difference from the N_2O perturbation because of the background state, out of a total depletion of approximately 5 DU for the A1B/A1 scenario base state. This is primarily caused by the CO_2 increases [25]. In contrast to the chemical influence of CH_4 on halocarbon-induced ozone depletion, the influence of CO_2 occurs via thermal changes to the stratosphere, which then alter the chemistry. The loss of NO_x from the stratosphere is partly controlled by reaction (2.4) (N+NO), but the concentration of N atoms is controlled by

$$\mathrm{N} + \mathrm{O_2} \rightarrow \mathrm{NO} + \mathrm{O}. \tag{5.2}$$

While the N+NO reaction is nearly insensitive to temperature, the $N+O_2$ reaction has a large activation energy (29.8 kJ mol^{-1}). Therefore, a temperature decrease caused primarily by the radiative effect of CO_2 (but also by O_3 changes and thus anything that affects ozone) will cause an increase in N atoms (relative to NO) and thus an increase in the loss rate of NO_y via reaction (2.4). In 2100, the effect of the CO_2 increase causes the ozone destruction owing to N_2O (relative to 1900 ozone levels) to be approximately 17 per cent less than it would be without the CO_2 increase.

There are also nonlinear effects between the halocarbons and N_2O (or more precisely the Cl_y and NO_y families). This comes about primarily because of the coupling between NO_x and ClO_x via chlorine nitrate ($ClONO_2$), which acts as a reservoir species for both families. The dominant effect is that $ClONO_2$ increases as NO_y increases (owing to N_2O) or as ClO_x increases (owing to halocarbons), and this tends to reduce the ozone loss owing to both families. This effect is dominant in the lower stratosphere and largely disappears as halocarbons return to pre-industrial levels, increasing the potency of N_2O [26].

In addition to the effect of thermal changes on the NO_y loss rate discussed above, thermal changes in the stratosphere have many other effects that can influence ozone [9]. These changes are particularly important while halocarbons are elevated and occur owing to temperature dependencies in both gas phase

Table 1. Global mean ozone changes between 1900 and the year listed for each of the perturbations using scenario IPCC A1B/WMO A1. The base state defines the levels of the non-perturbed gases and the ozone level about which the changes are computed. The base states are either defined at constant 1900 source gas levels or levels varying with the A1B/A1 scenario. The total row is the sum of the individual computations, whereas the combined row is the ozone changes with all gases following the A1B/A1 scenario (relative to 1900 ozone levels). The difference between these values for different base states gives one indication of how the nonlinear effects between the gases affect the ozone changes. All values are in Dobson Units (DU).

	1980		2000		2100	
perturbation	base state 1900	base state A1B/A1	base state 1900	base state A1B/A1	base state 1900	base state A1B/A1
halocarbons	−9.42	−7.81	−20.11	−15.97	−4.51	−3.75
CO_2	1.92	1.65	3.21	2.40	12.48	11.57
N_2O	−1.43	−1.17	−2.41	−1.18	−6.24	−5.15
CH_4	1.42	3.03	1.82	5.74	2.17	3.45
total	−7.51	−4.30	−17.50	−9.01	3.91	6.12
combined	−5.82		−13.35		4.97	

and heterogeneous processes. Many of these effects are particularly severe at high latitudes. For example, the stability of the polar vortex could be either enhanced (or weakened) by increases in GHGs, which could increase (or decrease) halocarbon-induced ozone loss in the vortex. There is presently no consensus on the magnitude (or even the sign) of this particular effect on ozone [9].

It is interesting to note that the ozone changes obtained in the model calculation for 1980 (relative to 1900 ozone levels) are not negligible. These values are listed in table 1, separated by source gas and including the combined effect. The modelled global mean ozone depletion owing to halocarbons is found to be between −7.81 and −9.42 DU, which is significant. However, the combined ozone change from all the gases is −5.82 DU, which illustrates the relatively large degree of opposing effects on ozone (the ozone losses from halocarbons and N_2O versus ozone increases owing to CH_4 and CO_2). The importance of CH_4 on the halocarbon effects, as noted above, is evident in 1980. The fact that 1980 ozone levels are already perturbed relative to 1900 is important to consider as many studies have used 1980 levels as a benchmark of ozone recovery. In reality, 1980 ozone levels are already affected by not just the halocarbons but by N_2O, CO_2 and CH_4 as well.

6. OZONE-DEPLETION POTENTIALS

It is useful to have a metric to compare the impact of various source gas emissions on ozone. The most commonly used metric is the ODP, defined as the time-integrated global ozone depletion induced by a perturbation of an equal mass emission of gas X relative to a reference gas (always taken to be CFC-11, labelled F11 below)

$$\mathrm{ODP_X} = \frac{\int_0^\infty [\Delta \mathrm{O_3}]^P_\mathrm{X} \mathrm{d}t}{\int_0^\infty [\Delta \mathrm{O_3}]^P_\mathrm{F11} \mathrm{d}t}, \tag{6.1}$$

where $[\Delta O_3]$ is the global mean total ozone change induced by the perturbation (the P superscript refers to the pulse emission and the subscript is the perturbation compound). It must be kept in mind that the ODP depends on the base state of the atmosphere and makes the assumption that the other sources gases do not change during the time integration. The potential magnitudes of these assumptions on the ODP are estimated by the effect of changes in the background atmosphere on ozone as shown in figure 4. For N_2O, these assumptions can cause the ODP to change by up to approximately 20 per cent for reasonable changes in other gases in the atmosphere. Since these changes are relatively small, ODPs remain a very useful metric for comparing emissions of ozone-destroying compounds.

The ODP is rarely calculated using the formula above. Instead, it can be re-written in steady-state form

$$\mathrm{ODP_X} = \frac{m_\mathrm{F11}}{m_\mathrm{X}} \frac{\Delta\mu_\mathrm{F11}}{\Delta\mu_\mathrm{X}} \frac{\tau_\mathrm{X}}{\tau_\mathrm{F11}} \frac{[\Delta \mathrm{O_3}]_\mathrm{X}}{[\Delta \mathrm{O_3}]_\mathrm{F11}}, \tag{6.2}$$

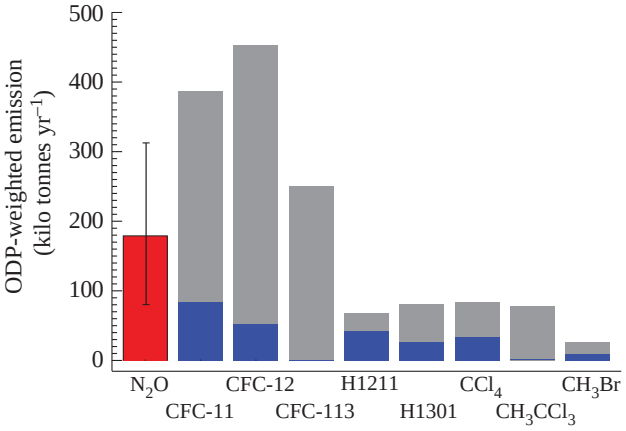

Figure 5. The ODP-weighted emission of anthropogenic N_2O (red) and the listed halocarbons for 1987 (grey) and 2008 (blue) emission levels. The ODP-weighted emission (i.e. the ODP multiplied by the emission level) is proportional to the total future global mean ozone loss from the emission (assuming no intervening changes). The ODP-weighted emission of N_2O was large even in 1987 when anthropogenic halocarbon emissions were near their peak and is larger than the individual halocarbons by 2008. Adapted from fig. 1 of Ravishankara *et al.* [26].

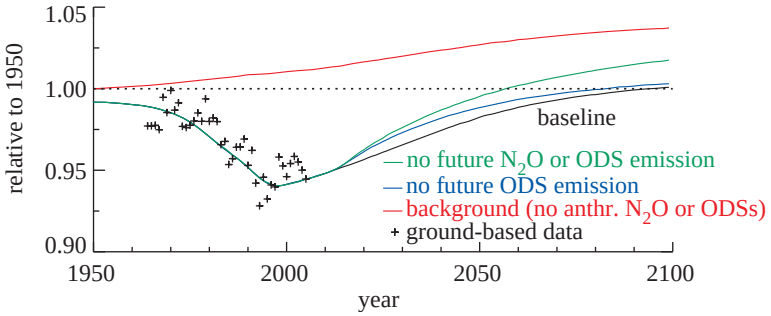

Figure 6. The changes in global mean ozone relative to 1950 computed with the NOCAR two-dimensional model. The full A1B/A1 scenario (labelled baseline) is shown along with scenarios that include removing the remaining unregulated halocarbon (i.e. ODS) emissions after 2010 and eliminating all anthropogenic N_2O emissions after 2010. The effect of eliminating future unregulated halocarbon emissions would increase ozone levels until approximately 2070, while the elimination of anthropogenic N_2O emissions has a larger effect by the end of the twenty-first century. The evolution of ozone without either anthropogenic halocarbon or N_2O emissions is shown by the red line, to which the green curve will slowly converge. Adapted from fig. 2 of Daniel *et al.* [28].

where m is the mass, $\Delta\mu$ the mixing ratio perturbation, τ the lifetime and $[\Delta O_3]$ is the steady-state annual and global mean total ozone change induced by the perturbation. This steady-state formulation is valid for source gases characterized by a first-order decay process. It also assumes that the ozone change is linear over the range of changes of gas X and CFC-11, which is valid for the sizes of perturbations considered here. The ODP of N_2O computed with the NOCAR model for year 2000 conditions is 0.017 [26].

The ODP provides the global mean ozone loss for a gas per unit mass emission relative to CFC-11. In order to estimate the effect of an actual emission amount on ozone, it is useful to compute the ODP-weighted emission (i.e. the ODP multiplied by the emission) as the emissions can vary by large factors (this is particularly true in the case of N_2O compared with the halocarbons). The total future ozone losses induced by emissions are approximately proportional to the ODP-weighted emissions (neglecting the nonlinear effects caused by other constituent changes). The ODP-weighted emissions of anthropogenic N_2O are compared with many of the important halocarbons for 2008 and 1987 as shown in figure 5 [26]. Note that the ODP-weighted emission of anthropogenic N_2O was significant when compared with the halocarbons even in 1987, when emissions of halocarbons were large immediately before the enactment of the Montreal Protocol. By 2008, anthropogenic N_2O was the most significant ozone-destroying compound being emitted. Owing to the phase-out of anthropogenic halocarbon emissions, it is likely to become even more dominant in the near future. This would only be expected to change if there were a large reduction in anthropogenic N_2O emissions in the future (this can probably only occur with changes in agricultural practices; see McElroy *et al.* [27] and the papers in this special issue).

Given the nonlinear effects discussed in the previous section, one would expect the ODP of N_2O to change by up to -20 per cent by the end of the twenty-first century because of changes in the other gases. This is primarily owing to the effect of increasing CO_2, which increases the loss of NO_y because of stratospheric cooling (as discussed above). While not negligible, these changes in the N_2O ODP do not alter the conclusions of the study of Ravishankara *et al.* [26] that N_2O will probably remain the dominant ozone-destroying compound emitted by human activities in the twenty-first century.

Despite the high level of success of the Montreal Protocol in avoiding deeper ozone depletion [7], additional policy options remain to increase future ozone levels. Future O_3 depletion can be reduced by further tightening halocarbon controls or reducing N_2O emissions. Increasing CO_2 (or to a lesser degree CH_4) could also counter global ozone loss but would induce other large global consequences (e.g. global warming, ocean acidification, sea level rise, and so on). Figure 6 shows the evolution of global ozone changes relative to 1950 owing to the full A1B/A1 scenario and the effect of eliminating halocarbon ODS and anthropogenic N_2O emissions after 2010 [28]. While eliminating halocarbon ODS emissions causes ozone increases in the 2010–2060 time period, their influences are small by 2100 as the halocarbons decay to near natural levels by that time even with only the current controls. In contrast, eliminating the anthropogenic N_2O emission would have a much larger effect by 2100. It should be noted that in all cases considered here, the global ozone levels by 2100 are expected to be above 1900 levels if CO_2 increases are as large as in the A1B/A1 scenario.

A comparison of the effect of eliminating the individual halocarbons (and anthropogenic methyl bromide and carbon tetrachloride) is shown in figure 7 [28]. This highlights the much larger potential for reducing future ozone depletion by anthropogenic N_2O reductions compared with the elimination of emissions of any of the individual halocarbons, including the banks (i.e. produced gases that already reside in devices, e.g. refrigerators, and could be recaptured), HCFC production, and emission of methyl bromide and carbon tetrachloride.

7. CONCLUSION

The changes in ozone over the 1900–2100 time period driven by changes in halocarbon, N_2O, CH_4

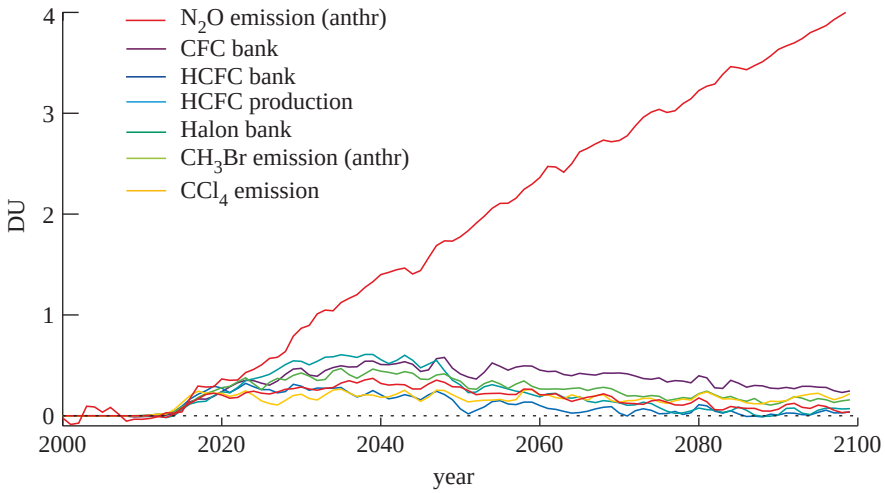

Figure 7. The changes in global mean ozone owing to elimination of anthropogenic N_2O emissions after 2010 when compared with the effect of eliminating the emissions of the CFC banks, HCFC production and banks, the halon banks, anthropogenic methyl bromide and carbon tetrachloride. The elimination of anthropogenic N_2O emission has the largest potential for reducing ozone depletion in the future. Adapted from fig. 4 of Daniel *et al.* [28].

and CO_2 concentrations have been explored with a model of the middle atmosphere. The future evolution of ozone will depend on all of these gases. The large negative effect of the halocarbons evident in ozone between 1950 and the present will decrease in the coming decades of the twenty-first century and non-halocarbon chemicals and climate change will largely control future ozone changes. N_2O is now the largest ozone-destroying gas emitted by human activities based on ODP-weighted emissions [26]. Whether ozone evolves to lower or higher values compared with pre-industrial values depends primarily on the levels of CO_2 relative to the level of N_2O. High emission of CO_2 could cause a so-called 'super-recovery' of ozone but would have a large influence on the global climate and oceans.

There is a limit to the extent to which the effect of the source gas emissions can be unambiguously separated owing to nonlinear interactions between the chemical families. The largest of these effects is between CH_4 and the halocarbons. The increase of CH_4 during the twentieth century reduced the effect of halocarbons on global mean ozone by approximately 20 per cent. There are also non-negligible interactions between CO_2 and N_2O on ozone. These effects are of the order of 20 per cent and do not alter the above conclusion of N_2O's dominant effect on ozone destruction in the future.

By 1980, the decrease in global mean ozone levels was already relatively large when compared with 1900 levels. The changes in ozone were not only due to the halocarbons but also significant changes had already taken place due to N_2O, CO_2 and CH_4. However, there are opposing effects from these gases that make the combined effect smaller than the depletion owing to halocarbons alone. This should be kept in mind by those who use 1980 levels of ozone as a benchmark of recovery.

The elimination of anthropogenic N_2O emissions would have a much larger effect than any of the unregulated halocarbon emissions, singularly or combined [28]. This underscores the opportunity that controlling N_2O emissions provides for reducing future ozone destruction, especially in the twenty-second century and beyond.

REFERENCES

1 Crutzen, P. J. 1970 The influence of nitrogen oxide on the atmospheric ozone content. *Q. J. R. Meteorol. Soc.* **96**, 320–327. (doi:10.1002/qj.49709640815)
2 Johnston, H. S. 1971 Reduction of stratospheric ozone by nitrogen oxide catalysts from supersonic transport exhaust. *Science* **173**, 517–522. (doi:10.1126/science.173.3996.517)
3 Molina, M. J. & Rowland, F. S. 1974 Stratospheric sink for chlorofluoromethanes: chlorine atomic-catalysed destruction of ozone. *Nature* **249**, 810–812. (doi:10.1038/249810a0)
4 Stolarski, R. S. & Cicerone, R. J. 1974 Stratospheric chlorine: possible sink for ozone. *Can. J. Chem.* **52**, 1610–1615. (doi:10.1139/v74-233)
5 Farman, J., Gardiner, B. & Shanklin, J. 1985 Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. *Nature* **315**, 207–210. (doi:10.1038/315207a0)
6 Newman, P. A. *et al.* 2009 What would have happened to the ozone layer if chlorofluorocarbons (CFCs) had not been regulated? *Atmos. Chem. Phys.* **9**, 2113–2128. (doi:10.5194/acp-9-2113-2009)
7 Velders, G. J. M., Andersen, S. O., Daniel, J. S., Fahey, D. W. & McFarland, M. 2007 The importance of the Montreal Protocol in protecting climate. *Proc. Natl Acad. Sci. USA* **104**, 4814–4819. (doi:10.1073/pnas.0610328104)
8 Montzka, S., Butler, J., Myers, R., Thompson, T., Swanson, T., Clarke, A., Lock, L. & Elkins, J. 1996 Decline in the tropospheric abundance of halogen from halocarbons: implications for stratospheric ozone depletion. *Science* **272**, 1318–1322. (doi:10.1126/science.272.5266.1318)
9 WMO (World Meteorological Organization) 2011 Scientific assessment of ozone depletion: 2010. Global Ozone Research Monitoring Project Report 52. Geneva, Switzerland, 516 pp.
10 Newchurch, M., Yang, E., Cunnold, D., Reinsel, G., Zawodny, J. & Russell, J. 2003 Evidence for slowdown in stratospheric ozone loss: first stage of ozone recovery. *J. Geophys. Res.* **108**, 4507. (doi:10.1029/2003JD003471)

11 Randeniya, L. K., Vohralik, P. F. & Plumb, I. C. 2002 Stratospheric ozone depletion at northern midlatitudes in the 21st century: the importance of future concentrations of greenhouse gases nitrous oxide and methane. *Geophys. Res. Lett.* **29**, 1051. (doi:10.1029/2001GL014295)
12 Rosenfield, J. E., Douglass, A. R. & Considine, D. B. 2002 The impact of increasing carbon dioxide on ozone recovery. *J. Geophys. Res.* **107**, 4049. (doi:10.1029/2001JD000824)
13 Chipperfield, M. P. & Feng, W. 2003 Comment on: stratospheric ozone depletion at northern midlatitudes in the 21st century: the importance of future concentrations of greenhouse gases nitrous oxide and methane. *Geophys. Res. Lett.* **30**, 1389. (doi:10.1029/2002GL016353)
14 Dvortsov, V. L. & Solomon, S. 2001 Response of the stratospheric temperature and ozone to past and future increases in stratospheric humidity. *J. Geophys. Res.* **106**, 7505–7514. (doi:10.1029/2000JD900637)
15 IPCC 2007 *Climate Change 2007: The Physical Science Basis. Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, H. L. Miller), 996 pp. Cambridge/New York, NY, UK/USA: Cambridge University Press.
16 Portmann, R. W. & Solomon, S. 2007 Indirect radiative forcing of the ozone layer during the 21st century. *Geophys. Res. Lett.* **34**, L02813. (doi:10.1029/2006GL028252)
17 Chapman, S. 1930 On ozone and atomic oxygen in the upper atmosphere. *Philos. Mag.* **10**, 369–383.
18 Bates, D. R. & Nicolet, M. 1950 Atmospheric hydrogen. *Publ. Astron. Soc. Pac.* **62**, 106–110. (doi:10.1086/126244)
19 Lary, D. 1997 Catalytic destruction of stratospheric ozone. *J. Geophys. Res.* **102**, 21 515–21 526.
20 Brasseur, G. P. & Solomon, S. 2005 *Aeronomy of the middle atmosphere*, 3rd edn. Dordrecht, The Netherlands: Springer.
21 Nakicenovic, N. *et al.* 2000 *Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change*, 599 pp. Cambridge, UK: Cambridge University Press.
22 Fioletov, V. E., Bodeker, G. E., Miller, A., McPeters, R. & Stolarski, R. S. 2002 Global and zonal total ozone variations estimated from ground-based and satellite measurements: 1964–2000. *J. Geophys. Res.* **107**, 4647. (doi:10.1029/2001JD001350)
23 Brasseur, G. & Hitchman, M. 1988 Stratospheric response to trace gas perturbations: changes in ozone and temperature distributions. *Science* **240**, 634–637. (doi:10.1126/science.240.4852.634)
24 Solomon, S. 1999 Stratospheric ozone depletion: a review of concepts and history. *Rev. Geophys.* **37**, 275–316. (doi:10.1029/1999RG900008)
25 Rosenfield, J. & Douglass, A. R. 1998 Doubled CO_2 effects on NO_y in a coupled 2D model. *Geophys. Res. Lett.* **25**, 4381–4384. (doi:10.1029/1998GL900147)
26 Ravishankara, A. R., Daniel, J. S. & Portmann, R. W. 2009 Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century. *Science* **326**, 123–125. (doi:10.1126/science.1176985)
27 McElroy, M. B., Wofsy, S. C. & Yung, Y. L. 1977 Nitrogen cycle: perturbations due to man and their impact on atmospheric N_2O and O_3. *Phil. Trans. R. Soc. Lond. B* **277**, 159–181. (doi:10.1098/rstb.1977.0009)
28 Daniel, J. S., Fleming, E. L., Portmann, R. W., Velders, G. J. M., Jackman, C.H. & Ravishankara, A.R. 2010 Options to accelerate ozone recovery: ozone and climate benefits. *Atmos Chem Phys.* **10**, 7697–7707. (doi:10.5194/acp-10-7697-2010)

[1]Includes all people who indicate they are American Indian or Alaska Native residents. Race/ethnic groups are not mutually exclusive; one person may be present in multiple categories; thus, the racial and ethnic categories do not sum to the total.
[2]Includes all people who indicate they are Native Hawaiian or other Pacific Islander.
[3]People of color (POC) was calculated as the total population minus the White non-Hispanic population.
[4]Ratio of the percent of people of other racial and ethnic groups to the percent of non-Hispanic Whites who live within 3 miles of a CAFO.

*Supplementary Table 2. Percent of population living within 3 miles of **any** CAFO by percent of households below the 200% poverty level by Census tract. In CA and NC, areas with a high poverty level (i.e., ≥35% of households below the 200% poverty level) have a larger percent of their population living within 3 miles of a Large CAFO than areas with a low poverty level (<20% of households below the 200% poverty level). In contrast, in IA, areas with higher poverty levels (≥35%) have a lower percent of their population <3 miles of a Large CAFO than areas with lower poverty levels (<35%).*

Percent of Households Below 200% Poverty Level	Population in Category <3 Miles of any CAFO	Total Population in Category	Percent of Population <3 Miles from Large CAFO	Ratio
CALIFORNIA				
Below 20%	362,826	1,673,184	21.68	1.00
20-34%	580,035	1,990,880	29.13	1.34
35-49%	576,616	1,511,127	38.16	1.76
≥50%	550,360	1747,992	31.49	1.45
IOWA				
Below 20%	278,996	780,581	35.74	1.00
20-34%	759,383	1,251,271	60.69	1.70
35-49%	101,825	399,609	25.48	0.71
≥50%	2108	113,480	1.86	0.05
NORTH CAROLINA				
Below 20%	42,595	1,254,755	3.39	1.00
20-34%	365,619	2,198,604	16.63	4.90
35-49%	635,957	2,022,555	31.44	9.26
≥50%	287,190	1,013,171	28.35	8.35

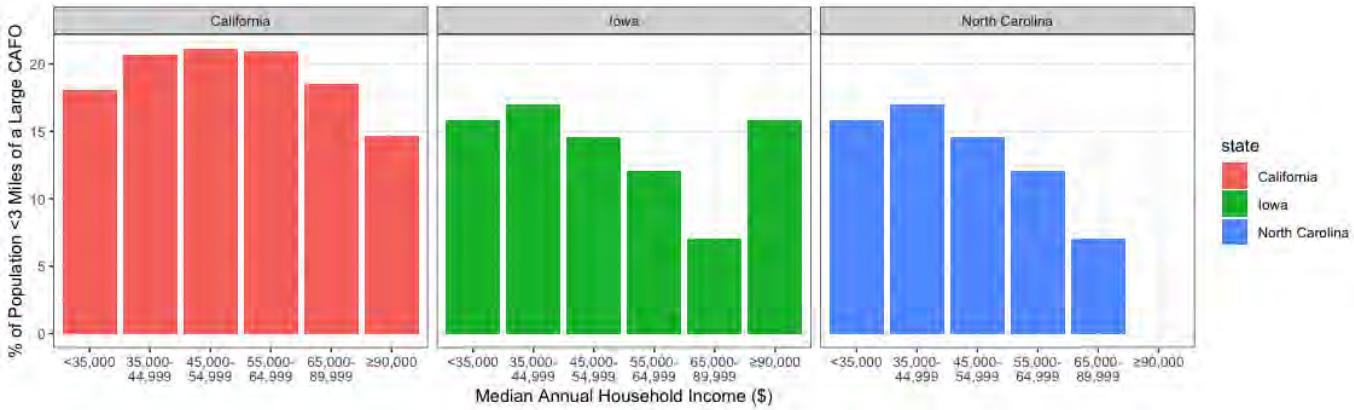

Supplementary Figure 1. Percent of population living within 3 miles of a CAFO by median household income in each block group (a visual of Table 6). In CA and IA, fewer rich households (≥$90,000) live near Large CAFOs than poorer households.

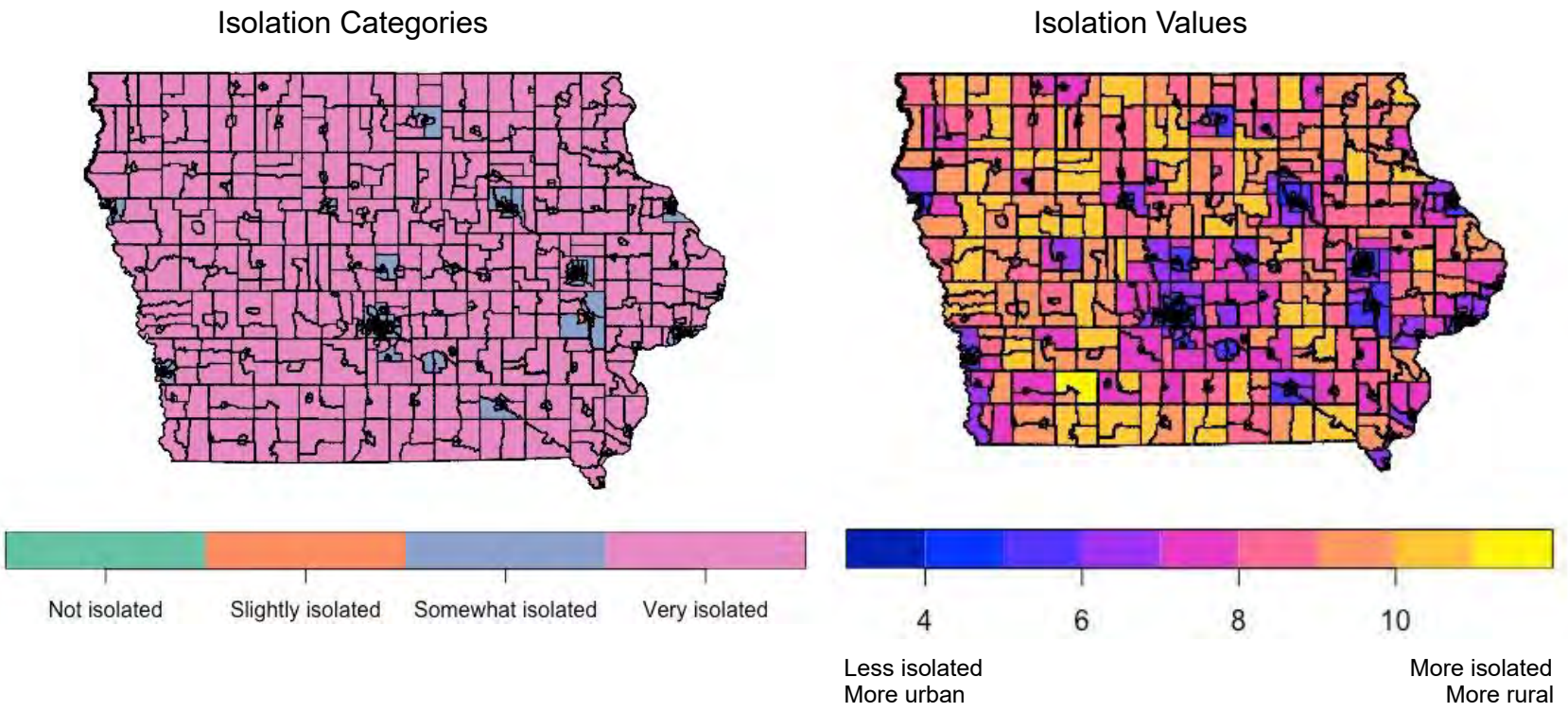

Supplementary Figure 2. Isolation categories and isolation values highlighting how widespread very isolated, rural areas are in Iowa.

Exhibit 6

DECLARATION OF LARRY BALDWIN

I, LARRY BALDWIN, declare and state as follows:

1. I am 66 years old, and I live in New Bern, North Carolina. I have devoted much of my life to combatting water pollution, especially water pollution from concentrated animal feeding operations ("CAFOs"). I currently work for Waterkeeper Alliance ("Waterkeeper") as the Campaign Coordinator for the Pure Farms, Pure Waters North Carolina campaign, and I've held this position since June 2021.

2. Waterkeeper is the largest and fastest-growing nonprofit focused solely on clean water. We fight for every community's right to drinkable, fishable, and swimmable water, and we work to hold polluters accountable. Consistent with our mission, Waterkeeper connects more than 300 member and affiliate organizations worldwide, including multiple Riverkeeper organizations headed by individual Riverkeepers.

3. Prior to my current position, I spent nearly 20 years working with Riverkeeper and Waterkeeper affiliate organizations. From 2002 to 2011, I was the Lower Neuse Riverkeeper, overseeing a river in a watershed with a high concentration of CAFOs. In 2011, I joined Waterkeeper as the North Carolina CAFO Coordinator. In that role, I worked with eight Riverkeeper programs throughout North Carolina to end the stranglehold that the CAFO industry has on communities and the environment. From 2016 to 2021, I was the Crystal Coast Waterkeeper, overseeing a group of rivers, creeks, and coastal waters.

4. As the Campaign Coordinator for the Pure Farms, Pure Waters North Carolina campaign, I help to lead the campaign, which focuses on calling attention to polluting practices at CAFOs, ensuring that CAFOs comply with federal law, and supporting independent and responsible family farmers. In addition, I help to train, manage, and coordinate Riverkeepers

working on CAFO pollution across North Carolina. And I partner with clean water and community advocates combatting CAFO pollution across the United States and internationally.

5. CAFOs generate a staggering amount of waste. Each pig produces about 10 times as much waste as a human being. So, a CAFO with 2500 swine produces roughly as much waste as a city with 25,000 people. Most cities have some sort of system for the treatment of human waste, but swine CAFOs generally do not. Instead, swine CAFOs typically store liquid waste in large pits, which the industry calls "lagoons." I think "cesspool" is a more accurate term. After enough waste builds up in a storage pit, CAFO workers spray it across nearby fields. But most CAFOs don't have enough land to absorb the volume of waste they generate, and it's expensive to move liquid waste very far. So, in my experience, CAFO operators typically overapply waste to the land they have, and they allow the excess to leach into groundwater or wash off fields into surface waters.

6. At Waterkeeper and our partner organizations, monitoring water quality and collecting water samples are important components of our work. All our samples are collected from public locations; we do not trespass. When we find evidence of CAFO pollution, we work to identify the facility responsible. Our work is challenging, in part, because discharges from land application sites to surface water are often intermittent. Unlike some other industrial facilities, a CAFO might discharge a substantial amount of water pollution from a land application site on one day and very little on another day. The amount of discharge depends on a variety of factors, including the CAFO's schedule for applying waste, its application methods, and the amount of precipitation. In addition, CAFO operators are aware of our work, and I believe that some operators change their behavior to avoid detection. For example, when we're

monitoring water quality from the air, we sometimes see people at CAFOs spot our plane, jump into pickup trucks, and rush to shut off the equipment that is spraying waste onto fields.

7. Although some water pollution from CAFOs can be intermittent, I do not believe that it is possible for CAFOs to avoid pollution altogether. This is especially true for Large CAFOs using wet manure management systems. Over the years, my colleagues and I have collected evidence of ubiquitous water pollution from CAFOs both through our water sampling and through our direct observations of discharges. The source of the problem, in my opinion, is apparent from the first word of the acronym: CAFOs are *concentrated*. The defining characteristic of a CAFO—that is, confining hundreds or thousands of animals in an enclosed space while they generate tremendous quantities of urine and feces—is a recipe for disaster. Not too long ago, there were more than 20,000 farms raising swine in North Carolina. Now, there are about 2,300 swine CAFOs, and they confine a larger number of swine overall. The CAFO industry and its allies like to characterize CAFOs as "farms," but that term conjures up images of idyllic green pastures and happy animals, like a real-life "Charlotte's Web." The truth is that CAFOs are industrial facilities, and they pollute on an industrial scale.

8. Based on my experience and observations, most CAFO operators do not spray animal waste on fields solely to fertilize those fields. Some CAFOs grow only Bermuda grass and other crops of very little value, so they don't have much of an incentive to fertilize. And CAFOs that grow more valuable crops, such as hay and alfalfa, sometimes leave baled crops on the fields. Eventually, the nutrients in those crops seep back into the soil, making it more likely that future waste applications will cause water pollution discharges. I've even seen baled crops dumped in wetlands.

9. In my opinion, the primary object of spraying waste is waste disposal. The CAFO industry has done a great job of hiding this reality, and they've worked to drive a wedge between environmentalists and community advocates, on one side, and CAFO operators, on the other. But I don't want to put CAFO operators out of business, and neither do my colleagues or partners. We want to put them out of the business of *pollution*. And, right now, pollution is a key part of the CAFO industry's business model. I believe it's possible to raise animals while respecting your fellow man and the environment. The first step is acknowledging your impact and obtaining necessary permits, just as family businesses in other industries do every day, all across the country. In my opinion, many CAFO operators want to do the right thing, but the structure of the industry makes it difficult.

10. The problem isn't only that animals are concentrated in CAFOs, but also that CAFOs are concentrated in certain parts of North Carolina, where they inflict disproportionate harm on Black, Latinx, Native American, and low-income communities. I do not believe that this concentration is accidental. Instead, I believe that the CAFO industry deliberately targets the communities with the least political and financial power. In my opinion, North Carolinians can do better than disrespecting our neighbors for the false promise of cheap meat. Under-regulated CAFOs don't really produce cheap meat anyway. They just shift the costs onto the people living next-door, who bear the brunt of CAFO pollution.

11. Over the years, I have seen the harm that CAFO pollution causes to people living in environmental justice communities in North Carolina, and I have spoken to many community members about their experiences. It is heart-wrenching. CAFO pollution is an ever-present, pervasive problem that community members can see, smell, and taste every day. Adding insult to injury, I have heard people suggest that anyone living near a CAFO should move away if they

don't like the pollution. But the communities were there first, and some families have deep roots in areas where CAFOs now are densely concentrated. Even if people wanted to leave, it's difficult to do so because CAFOs have damaged their health and driven down the value of their property.

12. I do not believe that CAFO operators set out to harm their neighbors or pollute the water. Instead, I think the CAFO industry and our current regulatory system incentivize unsustainable practices. A few major corporations control most animal production in this country, and it's not surprising that those corporations seek to maximize profits, while shifting the burdens of pollution elsewhere. That's why we need government agencies to provide oversight. Right now, I believe our agencies are failing.

13. It's my understanding that the North Carolina Department of Environmental Quality ("NC DEQ") inspects CAFOs only once each year. Those inspections are scheduled two weeks in advance, which means that CAFO operators have an opportunity to prepare for inspections by temporarily obscuring any obvious problems at their facilities. In addition, the inspections last only about 45 minutes, and inspectors often rely on a CAFO's self-created records instead of reaching their own conclusions by walking around the facility. As long as a CAFO operator claims that they comply with all relevant rules, inspectors seem to take their word for it.

14. Even when Waterkeeper and its partners present clear evidence of water pollution, NC DEQ usually ignores the evidence and fails to address the problem. One Riverkeeper, who focuses on the Catawba River, has filed over 600 complaints about water pollution from CAFOs. Even though he includes evidence to support his complaints, absolutely nothing has changed. I've had similar experiences myself, going back years. NC DEQ isn't even required to keep

complainants informed about the status of their complaints unless the agency issues a violation. It's very frustrating for Riverkeepers and others to spend time gathering evidence and making complaints, only to be ignored by the agency. I suspect that, instead of issuing violations, NC DEQ calls CAFO operators to warn them about our monitoring.

15. The time has come for the U.S. Environmental Protection Agency to ensure that all discharging CAFOs obtain National Pollutant Discharge Elimination System ("NPDES") permits, as required under the Clean Water Act. Unfortunately, NC DEQ is not doing its job, and we can't count on state lawmakers, because too many of them have close ties to the CAFO industry. Based on my experience, I believe NPDES permits help to increase transparency and reduce pollution. Many other industrial facilities obtain NPDES permits, comply with the CWA, respect their neighbors, and remain profitable. There's no reason why CAFOs should be treated differently.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 24TH day of October 2022.

Larry Baldwin

Exhibit 7

DECLARATION OF KATHRYN BARTHOLOMEW

I, KATHRYN BARTHOLOMEW, declare and state as follows:

1. I am 58 years old, and I live at [redacted] Schuyler County, New York. Schuyler County is a rural, agricultural area with a population of less than 18,000 people, located in New York's Finger Lakes region. My family's roots in this area go back six generations, and I have lived here my entire life. I care deeply about the natural resources and beauty of Schuyler County and the entire Finger Lakes region. I love to spend time walking through the woods, past gorges and waterfalls, and along the beach at nearby Seneca Lake. Since 2004, I have been the Chair of the Schuyler County Environmental Management Council.

2. I am dismayed by the increasing presence of concentrated animal feeding operations ("CAFOs") in Schuyler County and throughout the Finger Lakes region. Most of the farms in this area are small. However, large CAFOs started operating here in the early 1990s, and every year, CAFO owners build more confinement barns; purchase more fields to grow corn, soybeans, and alfalfa for their cows; and construct more slurry lagoons to hold their cows' urine and feces. CAFOs have also begun to partner with energy companies to construct biodigesters, which capture methane from slurry lagoons to make biogas.[1] I'm concerned that CAFOs will use the biogas projects as a means to further justify their existence. It seems that CAFOs are always expanding, and I am

[1] *See Bergen Farms, Glenview Dairy Sign on for Renewable Natural Gas Project in Schuyler*, The Odessa File (Sept. 12, 2022), http://www.odessafile.com/government.html.

worried that this expansion—without proper regulation—will endanger our community and environment.

3. CAFOs threaten every ecosystem in our watershed, particularly our water. Seneca Lake holds half of the water in all the Finger Lakes, and along with other members of my community, I am concerned about threats to its water quality. Several brooks and creeks in Schuyler County already are officially designated as "impaired" because of problems associated with CAFO manure.[2] Seneca Lake itself has been affected by harmful algal blooms, which experts link to manure runoff.[3] As CAFOs in this area expand in number and size, I am concerned that they might pose a serious threat to our water supply. There's only so much potable water, and serious contamination could take years to repair. Even though my drinking water comes from a deep well, I get it checked regularly to make sure that it is safe.

4. In addition to threatening our water, CAFO manure also produces an awful smell. I grew up across the street from a dairy farm, so I am used to the smell of cow patties; the smell of CAFO manure is something of another order altogether. I live three miles from

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[2] *See* N.Y. Dep't of Env't Conservation, 2018 Section 303(d) List of Impaired Waters Requiring a TMDL/Other Strategy, at 5, 23 (June 2020), https://www.dec.ny.gov/docs/water_pdf/section303d2018.pdf (listing Reeder Creek and Pond Brook as impaired for phosphorous and dissolved oxygen).

[3] *See* Kelly Coughlin & David Youst, *Seneca Lake Water Quality Overview* (Oct.2017), https://senecalake.org/resources/Documents/Water%20Quality/Publications/Seneca%20Lake%20Water%20Quality%20Overview%20Oct%202017.pdf (reporting high phosphorus levels and increasing numbers of harmful algal blooms in Seneca Lake and its tributaries); *see also* Patricia Glibert, *From Hogs to HABs: Impacts of Industrial Farming in the US on Nitrogen and Phosphorous and Greenhouse Gas Pollution*, 150 Biogeochemistry 139 (2020) (explaining that water pollution from CAFOs can lead to harmful algal blooms).

the closest CAFO, and I feel fortunate that I cannot smell the slurry lagoons at this distance. However, the CAFO applies slurry to corn and alfalfa fields adjacent to my property, and I find the smell of that slurry to be extremely unpleasant. After the CAFO workers spray the slurry, I won't hang my laundry outside because of the odor. In other areas of Schuyler County, where there are larger CAFOs closer together, the smell is truly terrible; when I drive by, I have to roll up my windows and hold my breath.

5. I am lucky that the CAFO closest to my home is operated reasonably well. To my knowledge, it complies with state and federal laws. Apart from two instances that I have witnessed, the CAFO workers generally do not apply slurry to the land when rain or snow is in the forecast. The CAFO operators try to be good neighbors. However, other residents in the region are not so fortunate. I have heard of manure spills in neighboring counties,[4] and as head of the Schuyler County Environmental Management Council, I have seen that the CAFO industry can be a Goliath, and community members aren't always able to address concerns about odors, noise, and water pollution; it is disturbing.

6. I think it is ridiculous that New York State does not require CAFOs to obtain National Pollutant Discharge Elimination System permits under the Clean Water Act. Based on my experience, there is no question that Large CAFOs pollute the water, and

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[4] *See* Carrie Chantler, *Owasco Lake Advocates Decry Runoff of Manure into Water*, Auburn Citizen (Apr. 6, 2014), https://auburnpub.com/news/local/owasco-lake-advocates-decry-runoff-of-manureintowater/article_498bd2fe-a7ec-5994-b4ed-005111da2e89.html (reporting that discharge from a Large CAFO caused a 25-by-75 foot plume of liquid manure to enter Lake Owasco in 2014); *see also* Matt Weinstein, *DEC: Manure Runoff Affecting Cayuga Lake*, Ithaca J. (Feb. 20, 2017), https://www.ithacajournal.com/story/news/local/2017/02/20/dec-manure-runoff-impacting-cayuga-lake/98152244/ (explaining that "emergency applications of manure," made in advance of "rapidly warming temperatures" in February 2017, had reached Cayuga Lake).

there is no reason why the CAFO industry should be treated differently than any other polluting industry. I believe that it is possible for CAFOs to be good neighbors, but we should not have to rely on a CAFO operator's good will when the health of our community and our environment is at stake. That's why we have environmental laws.

7. To protect our health and environment, I believe that U.S. Environmental Protection Agency should adopt a rebuttable presumption that Large CAFOs using wet manure management systems actually discharge water pollution.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 25 day of October, 2022.

Kathryn Bartholomew

Kathryn Bartholomew

Exhibit 8

DECLARATION OF EDITH HAENEL

I, EDITH HAENEL, declare and state as follows:

1. I am 71 years old. For the past 40 years, I have lived with my husband on 25 acres of land at [redacted], Worth County, Iowa. Our area is very rural. In fact, Worth County is among the most sparsely populated counties in Iowa. Northwood is the county seat, and it has a population of about 2,000 people.

2. I met my husband when I came to Iowa to pursue my master's degree in social work. At the time, he was working on a small farm growing crops and raising livestock. I fell in love with him and with the land. To this day, my husband and I value our rural lifestyle. We love our community. We love that our land is quiet.

3. When we first moved to the property where we live now, there were small farms all around us. However, about 20 years ago, we started to notice that the small farms were being replaced by concentrated animal feeding operations ("CAFOs"). According to the Iowa Department of Natural Resources ("IA DNR"), there are now 14 CAFOs in Worth County, including five Large swine CAFOs.[1] The nearest CAFO to us is about a mile from our home. According to IA DNR, it confines 2,486 swine, and it stores their waste in concrete pits beneath where the pigs stand and live. CAFO owners spread the stored waste onto fields, including the field that directly abuts our property.

4. The CAFO nearest to us sits right above a stream called Elk Creek. We are concerned that, over time, the CAFO will significantly impair the water in Elk Creek.

[1] *See* Iowa Dep't of Nat. Res., *Animal Feeding Operations Databases*, https://programs.iowadnr.gov/animalfeedingoperations/ (click "Search," input Worth in "County" dropdown).

5. In addition, I worry that the CAFO nearest to us will contaminate the groundwater. Like many CAFOs in Worth County,[2] this CAFO is built on top of a karst formation. Karst is made up of soft, porous limestone.[3] Building CAFOs on top of karst formations is risky, because it's easy for animal waste to pass through the karst and contaminate the groundwater underneath.[4] I am especially worried about the CAFO nearest to us because that CAFO is located above an aquifer, and the karst bedrock is only 13 feet below ground.

6. In addition, I am concerned that CAFOs could contaminate groundwater by applying more manure to fields than the land can hold. According to my husband, there is sandy soil in this area, and sandy soils might not be able to absorb as much manure as clay soil. I have heard that some CAFO operators in our area sometimes spread waste on the same fields, and I worry that this practice increases the risk of groundwater contamination.

7. The potential contamination of groundwater is especially worrisome to me because, like nearly everyone in our community, my husband and I get our drinking water from a well. As a result, we cannot rely on a rural water system to filter or clean our water before it reaches our home. Although the county offers free water testing, that testing does not cover contaminants associated with CAFO manure. I am afraid that we might learn of groundwater contamination only after people in our community start to get sick. I understand that, elsewhere

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[2] *See* Iowa Dep't of Nat. Res., *AFO Siting Atlas*, https://programs.iowadnr.gov/maps/afo/ (select "Sinkhole or Potential Karst" and "Animal Feeding Operations" map layers) (showing that the majority of CAFOs in Worth County are located on or within 500 feet of sinkholes and karst formations).

[3] *See* Iowa Dep't of Nat. Res., *AFO Construction Permits*, https://www.iowadnr.gov/Environmental-Protection/Animal-Feeding-Operations/AFO-Construction-Permits.

[4] *Id.*

in Iowa, people have gotten sick after drinking groundwater contaminated with pollutants that are associated with CAFOs.

8. I am also concerned about air pollution from CAFOs. I have epilepsy, and I worry that I could be especially vulnerable to CAFO pollution. I also worry about the effects of long-term exposure to CAFO pollution among children. My great-nieces and nephews live about three-quarters of a mile downwind from a CAFO, and I understand that children living near CAFOs may have a greater risk of developing asthma and other health conditions.

9. In addition to raising health concerns, air pollution from CAFOs smells terrible. My husband has lived in this area for his entire life, and he has worked on farms, so he is used to the smells of animals and agriculture. But even he thinks that CAFO odors are unbearable; he says that the smell from smaller farms cannot even compare. I know from conversations with friends and family that CAFO odors affect many areas.

10. I believe that CAFOs have attracted insects to our area, and I am especially concerned about biting flies. I see more biting flies near my home now than I did before the CAFOs moved in. I am very sensitive to chemicals on my skin, so I cannot use bug spray. The biting flies can be exceedingly annoying.

11. It's not only the pollution and insects that bother me. I am concerned that CAFOs are fundamentally changing our community. Over time, CAFOs have put many small farms in our area out of business, and they affect non-farm businesses too. It's my understanding that most CAFO operators do not buy supplies locally, and CAFOs tend to bring only low-paying jobs. Ultimately, I worry that CAFOs might cause many of my friends and neighbors to leave Iowa. I have spoken with people from across the state whose communities already have been significantly impacted by CAFOs. In addition, I have heard of people who left Iowa because

they were overwhelmed by water pollution, air pollution, odors, and pests from CAFOs; it just became impossible for them to remain in their homes any longer.

12. I think the CAFO industry has an outsize influence on our state and local government, and I worry that our community is losing its independence. Back when the CAFO nearest to us first moved in, I became more involved in local government, because I wanted to ensure that CAFO pollution would not destroy our home. I started going to Worth County Board of Supervisors meetings, and after every meeting, I would publish notes on Facebook so everybody had access to them. People who read my notes and shared my concerns about CAFOs started to attend meetings themselves. These people and I often have differing views from the Board of Supervisors, as some of the board members support the CAFO industry. Some of the board members did not welcome our opposing views. The Board began to cut down the amount of time in which members of the public were allowed to ask questions, until no questions were allowed unless we asked to be put on the agenda. It has become more difficult to have open discussions at the meetings where crucial decisions are made.

13. IA DNR is the watchdog agency that is supposed to protect Iowans from CAFO pollution and other environmental harms. However, I do not believe that IA DNR is doing its job. I have been disappointed by IA DNR's failure to engage with citizens concerned about CAFOs. I do not think IA DNR fairly reports the extent of damage to Iowa's waterbodies, and I believe its decision to approve biodigesters indicates that it does not take seriously the threats that CAFOs pose to people and the environment. At one point, IA DNR didn't even know how many CAFOs there are in the state.

14. I feel like my neighbors and I are being run over, and the agencies that are supposed to protect our health and our resources are not doing anything to stop it.

15. To empower Iowans and other people across the country, I hope the U.S. Environmental Protection Agency will ensure that CAFOs provide transparency about their operations, including information about their location, the number of animals they confine, and when and where they apply manure to fields. Without access to that information, people cannot protect their health, their families' health, or the environment.

I declare that under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 25th day of October, 2022.

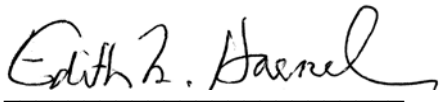

Edith Haenel

Exhibit 9

DECLARATION OF JEAN LAPPE

I, JEAN LAPPE, declare and state as follows:

1. I am 69 years old, and my husband and I have lived at [redacted] Louisa County, Iowa for 40 years. I grew up in this area and have lived within a 10-mile radius for most of my adult life. The reason we live in this rural area is because we love having open space and spending time outdoors, and our home is secluded, as our closest neighbor is a half-mile away. Our home is very important to us, and over the years, we have put a lot of blood, sweat, and tears into it. We hope to one day pass it along to our son.

2. For the first 30 or so years of our time living in our home, we routinely opened the windows on nice days and spent hours outside gardening, picking apples, walking near the local creeks, hanging clothes out to dry, and entertaining family and friends. I love feeling the breeze, and in the warmer months, we'd leave our windows open and let the wind flow through the house.

3. That all changed when concentrated animal feeding operations ("CAFOs") started popping up in our community. The first CAFO near our home started operating in the mid-2000s. Since 2014, more CAFOs have begun operating, confining tens of thousands of pigs essentially in our backyard. As shown on the following map, there are now 12 CAFOs within three miles of our house, and the closest one is just under a mile away from us. The operations around us generally have two confinement buildings, and each building houses just under 2,500 pigs.

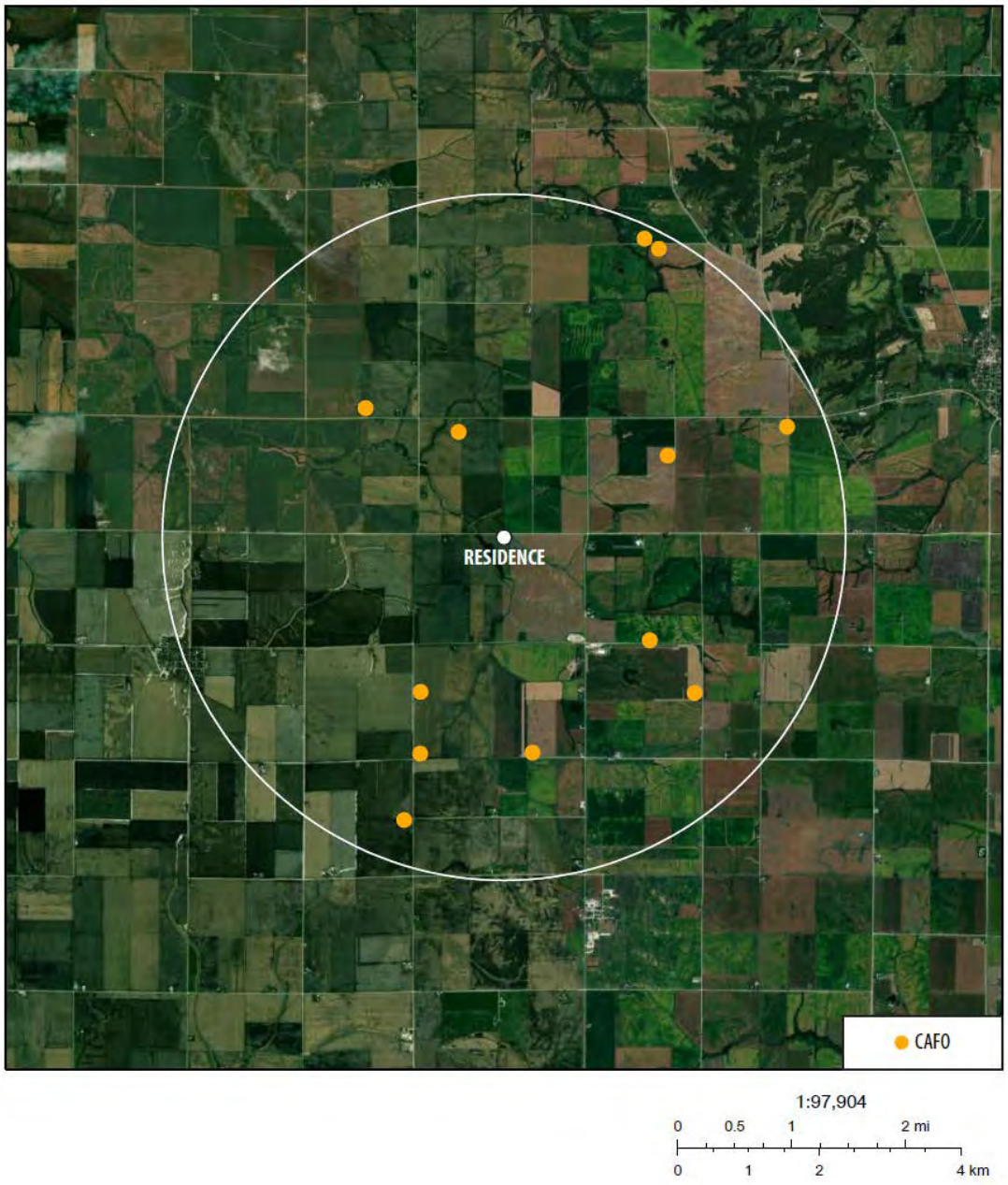

Source: Iowa Dep't of Nat. Resources, AFO Siting, https://programs.iowadnr.gov/maps/afo/?utm_medium=email&utm_source=govdelivery; Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

4. The CAFOs near my home generate millions of gallons of manure and, to my knowledge, they are all wet-manure management facilities, meaning that they store manure in liquid form—typically, in huge pits under the buildings where they confine the pigs. Sometimes,

the CAFOs contract with local farmers to haul the manure away. Other times, the CAFOs move the manure by pumping it through tubes and apply it to fields right near our home.

5. Being so close to CAFOs and land application fields has completely changed our lives. The stench can be simply unbearable. The pollution irritates my throat and sinuses and exacerbates health problems I experience due to an autoimmune disease. We've purchased two air purifiers, which help us breathe indoors, but the odor makes it difficult to go outside for even short periods of time. I miss my peaceful morning coffee in front of an open window or out on the deck. Now, if I spend too much time outside, I cough and get congested from the polluted air. When the stench is really bad, my husband and I waste no time getting into the house. I usually choose to stay inside to avoid the odor altogether, and consequently, I feel like I'm a prisoner in my own house.

6. The odor is especially bad during the months when local farmers spread manure on nearby fields. Recently, when they were spreading manure, the air was so unbreathable that I took my daughter's RV and left the area for three weeks. A couple of years ago, I went to visit my daughter in Colorado to escape the smell. I'm not the only one; I know many people in the community who leave the area to avoid odors and air pollution from manure application.

7. In addition to polluting the air, the animal waste generated by the CAFOs threatens drinking water. I would like to have our well tested by the state, but it is too expensive. Instead, I have done my own monitoring, and I have found that ammonia levels have increased since the CAFOs came to the area. One of my neighbors stopped drinking their well water altogether because it was contaminated with pollutants that probably came from the CAFOs. They are not alone: One recent study showed that, throughout Iowa, 40 percent of private wells

are contaminated with bacteria, which likely come from animal agriculture facilities.[1] A doctor once told me that no one in Iowa should be drinking their well water because contamination is so widespread.

8. I'm concerned that CAFOs also are polluting our local creeks. Several of the CAFOs near our house border East Fork Crooked Creek, which has been designated by the State of Iowa as an impaired waterway.[2] I used to participate in volunteer water quality monitoring, and we found that samples from the creek had high nitrate levels. We would test the nitrate levels before and after farmers applied manure near the creek, and the levels were higher after the manure applications. At times, the nitrate levels were 30 parts per million, which is well above the safe drinking water standard of 10 parts per million. But before we could report the results of our testing, we learned that the monitoring program had been shut down.

9. The pollution in East Fork Crooked Creek prevents us from enjoying it. We can't let our grandchildren wade in the water because contact with CAFO pollution could make them sick. And, when our children come home with their dogs in tow, we must make sure the dogs don't go in the creek, either. My daughter once had to take her golden retriever to the vet because he got a bad rash after going in the creek.

10. I have personally witnessed local farmers, whose fields run into East Fork Crooked Creek, engaging in dangerous manure management practices. For example, I have seen farmers applying manure right up to the banks of creek, without any buffers between the manure and the water. Applying the manure so close to the creek makes it easy for the waste to run off

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[1] *See* Env't Working Grp., *Iowa's Private Wells Contaminated by Nitrate and Bacteria* (Apr. 2019), https://www.ewg.org/interactive-maps/2019_iowa_wells/ (showing that, of 55,000 private wells in Iowa that were tested, 22,000 were contaminated with bacteria).

[2] *See* Iowa Dep't of Nat. Res., *Water Quality Assessments Impaired Water List: East Fork Crooked Creek*, https://programs.iowadnr.gov/adbnet/Segments/6268/Assessment/2022.

into the water. And one year during early December, just a quarter mile from my house, I saw a farmer applying manure to frozen fields, as you can see in the picture below. When farmers spread manure on frozen fields, it just sits on the ground, which means there's a significant chance that it will eventually wash off fields into nearby waterways. And manure applied to frozen fields continues to smell. We were smelling that manure for weeks—even many days later on Christmas morning!



Source: Jean Lappe

11. Over the past several years, I have repeatedly opposed new CAFOs opening in our area, because I am concerned about the threats CAFOs pose to our air and water. Along with other members of the grassroots non-profit organization Iowa Citizens for Community Improvement, I gave comments to the Iowa Environmental Protection Commission, explaining that the concentration of CAFOs in our community has caused dangerously high levels of

nitrates in local creeks. I drove three hours to speak to the Commissioners for only two minutes—but, in the end, the Commission didn't do anything to stop more CAFOs from polluting our community.

12. I have also submitted comments to IA DNR opposing new CAFOs and objecting to individual CAFOs' manure management plans. In those comments, I told IA DNR that adding more CAFOs to our community would only exacerbate already unlivable conditions. I also explained that IA DNR should prevent local farmers from engaging in unsafe manure management practices, like applying manure to fields that don't have buffering systems. Despite the outcry from our community, IA DNR has done nothing to protect us from the threats CAFOs pose to our water quality.

13. As a last resort, in 2014, I joined a coalition of community members and the nearby City of Mount Union to bring a lawsuit against local CAFO operators for producing odors, emissions, particulate matter, and flies, which make it impossible for us to enjoy our property. Unfortunately, that lawsuit failed, in part because the Iowa legislature and courts have erected numerous barriers to prevent community members from holding CAFOs accountable for their pollution.

14. Perhaps most distressing is the way that the CAFO industry has torn our community apart. We used to be a peaceful community, but now we're pitted against each other. Anybody who dares to stand up against the CAFO industry is subject to intimidation and harassment. One woman who joined the lawsuit was subjected to incessant bullying. She eventually committed suicide, and that tragedy caused an irreparable rift in the community. Our lives and the fabric of our community have become collateral damage to corporate agriculture.

15. We need the U.S. Environmental Protection Agency ("EPA") to protect us from the corporate greed that is destroying our way of life. To combat CAFO water pollution, CAFOs should be required to get permits under the Clean Water Act. We need to make sure that CAFOs are held to stricter standards. We also need more effective ways for community members to have their objections taken seriously—and to hold CAFOs accountable when they pollute. Right now, the system is simply broken.

16. EPA is supposed to protect us from corporate bullies who see nothing but dollar signs. Our water quality has been stolen, and our property values and quality of life have been destroyed. Please help us start the clean-up in Southeast Iowa before it's too late.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 24th day of October, 2022.

Jean Lappe

Jean Lappe

Exhibit 10

STATE LINE Observer

Frank Gibbs: Liquid manure is too wet

Written by David Green. Aug. 20, 2006

By DAVID GREEN

Don’t blame tile lines for discharges of liquid manure into drains, says soil scientist and farmer Frank Gibbs, and don’t blame the rich soil with its worm holes leading to the tile.

Put the blame on the watered down manure. That’s where the problem lies.

Gibbs, from the National Resources Conservation Service office in Findlay, Ohio, spoke to farmers last Wednesday at the annual Center for Excellence Field Day at Bakerlads Farm north of Clayton.

Gibbs told how he came to this conclusion several years ago, after he got a call from a producer in Ohio who had a problem. He was applying manure from his swine operation at only about half the recommended rate, but it was still finding its way into tile and drains.

A DNR officer told the farmer that he wouldn’t cite him for discharges this time, but it had to be stopped.

“I went down there thinking I’d see big cracks in the ground,” Gibbs said, “but the soil moisture was ideal. Impeccable shape. I saw lots and lots of night crawler holes and I thought, ‘My God, could this be what’s going on here?’”

Gibbs got ahold of some dye—similar to the kind used to check for leaks in a toilet tank—dumped it into the manure lagoon and agitated the mixture. After he dug down to a six-inch tile, manure was injected into the soil with a drag line. The tile was dry when the experiment began.

“We wondered how long it might take to percolate down to the tile lines. Twenty minutes? Should we go to lunch?”

There was no time for lunch, Gibbs said. The dye was there within seconds, and every time a pass was made over a lateral tile line, another pulse of colored liquid came through.

Gibbs wondered if the pressure from the applicator pump was the cause, so they next tried a gravity-feed system. Same problem. One more idea came to mind. This time they avoided the watery manure from the lagoon and loaded some of the thicker slurry from the pit under the hog barn.

“It didn’t go anywhere,” Gibbs said. “It behaved like manure. We dug up some areas with a back hoe and it was laying right where it was shot.”

He knew then not to fault the tile nor the healthy soil.

“The problem is simple. We’re watering manure down to where it behaves like water. Let me repeat that. We’re watering manure down to where it behaves like water. You don’t need to be a rocket scientist to understand that.”

Gibbs has heard the suggestion that no-till soil is at fault. Get rid of the worm holes and there’s no conduit for the manure.

Not true.

“Preferential flow will occur in conventional tillage through cracks and around the soil structure,” he said. “We need to stop confusing the issue with tillage. The issue is that we’re adding too much water.”

This is a situation that needs to be addressed, Gibbs said.

“We need to keep on top of this. We really do. I think some basic research could solve the problem.”

Maybe the percentage of solids needs to be up to four or five percent, he said. Or, from what he learned in Europe, even higher.

The Dutch method

With so many Dutch farmers investing in this area, Gibbs decided to take a trip to the Netherlands to see how they farmed in that country. He was in for a surprise.

He didn't see any of the watered down manure that the large dairies are using here. The solid content was at about eight percent.

He noticed a plastic membrane spread over a storage lagoon with rain water waiting to be pumped from an overnight storm. Gibbs figured it was to keep the water out of the lagoon, but he was wrong. It was to control odor.

Gibbs watched as a farmer loaded his applicator with manure and inserted a paper form into equipment that recorded his position by GPS. Once in the field, additional data was stamped onto the form. A sample bag of manure was collected to send for analysis by a government agency.

If manure exceeds the allowable nitrate rates, Gibbs was told, the farmer receives a bill from the government.

The Dutch farmer joked about having one government official for every farmer, but it isn't the heavy regulation that's hurting agriculture in Holland, he said, it's simply a lack of space.

Gibbs returned home knowing that the practice of watering down manure didn't come from Europe.

"That's our technology," he said. "We're going to all the work of writing up Comprehensive Nutrient Management Plans and then where does it go? Into the tile. We just need a little bit of research to figure this thing out so we don't have to scrap the whole thing."

Gibbs said he's made attempts to urge agricultural agencies to study the issue, but it's never gone far.

"Everybody's going off in other directions," he said. "We need to work together. We don't have to destroy our soils. We don't need to rip our tile out.

"What we should do is look at solids. Eight percent isn't that much. I don't know why we can't tweak that."

- Aug. 30, 2006

Stop it in the root zone

A visit to Wisconsin gave soil scientist Frank Gibbs additional hope for the future.

“They have some really good things going on there,” he said.

For example, the custom manure applicators have formed an association. They have standards and training, for those who choose to join the group. They work closely with the EPA. They practice cleanup of spills for when something goes wrong.

Gibbs was impressed with the beautiful crops growing on rolling hills. The key was the soil.

“They’ve got hay and they’ve got alfalfa and they put manure on it,” he said.

In this area, it’s almost always corn and soybeans, year after year. It’s the root system of a plant such as alfalfa that breaks up the soil to prevent compaction.

Custom applicators have to work with what they’re given, Gibbs said, and sometimes control structures are in order. Gibbs has built shut-off valves at the property line to stop the flow of liquid manure. A catch basin is added to collect the flow—a septic tank will do the job—and the manure can be pumped out and applied in a safe area between tile lines.

It’s just a Band-Aid approach, Gibbs said, not a solution, but it’s better than using rubber tile plugs in which case a farmer has no idea if the manure has left the tile. Besides, he asks, do we know where all the tile is? And if we miss one, who’s fault is it?

That’s when the arguing and finger-pointing begins. When manure flows into a drain, who is at fault—the farmer who owns the animals, the owner of the land where it’s being applied, or the person in charge of the application?

“If we do it the wrong way,” Gibbs said, “it’s going to be a mess.”

Any time manure enters a tile line, it’s wasted. At that point, Gibbs said, the nutrient is too deep to be absorbed by plants.

“We have to stop it in the root zone,” Gibbs said.

Smoke test highlights no-till

As a long-time proponent of no-till farming, Frank Gibbs often tries to convince other farmers to give it a try.

One of his early attempts was to dig out a cubic foot of his no-till soil and place it next to a sample from his neighbor’s sugar beet field that suffered from a lot of compaction due to trucks. Then he would pour a bottle of water onto each and watch it soak into his soil and run off his neighbor’s.

“It was kind of hokey,” Gibbs said. “Farmers would say, ‘You’re from the government. You probably poked holes in it.’ I needed a different way to show the value of no-till.”

He remembered a blower contraption a friend created for planting beans—it never worked right—and as a fan of Red Green, Gibbs got out the duct tape to rig up a device for blowing smoke into a tile line.

“I could make smoke come out of millions of worm holes,” he thought.

The smoke test shows good soil conditions and at the same time, it shows the avenue that liquid manure takes to reach tile lines. It takes the easiest route, Gibbs said, the path of least resistance. Through worm holes and cracks in the glacial till, manure can quickly makes its way to tile.

To set up the Center of Excellence Field Day at Bakerlads Farm, Gibbs dug a hole to reach a tile line. He found two hand-laid tile lines, then a plastic line, then another older line. Tile is everywhere.

He set up his blower, dropped in a smoke bomb and watched for smoke to start rising out of a soybean field. Smoke started to run toward the bean field, but the line made a turn and headed back into the cornfield. That’s the trouble with tile lines, he said, you never know how many there are or where they end up.

Watching smoke rise out of the soil is a great demonstration, Gibbs said, and a real attention-getter.

“It’s hard for folks to deny this stuff happens when there’s smoke coming up under their feet.”

Exhibit 11

DECLARATION OF DEVON HALL

I, DEVON HALL, declare and state as follows:

1. My name is Devon Hall. I am African-American, and I am 66 years old. I live at [redacted] in Warsaw, Duplin County, North Carolina. Duplin County is a rural area with a significant proportion of low-income African-American residents. I was born and raised in Duplin County, and I have lived here my whole life. My three brothers and three sisters live in Duplin County too, and our children grew up together here. Our roots are here.

2. In 2002, I co-founded the Rural Empowerment Association for Community Help ("REACH"). Currently, I am REACH's Executive Director. REACH works to address social, economic, and environmental inequities in and around Duplin County. We work to help people understand that everybody is somebody and has a right to be heard. I co-founded REACH because I saw that there was a lack of resources in Duplin County to help people like me and my family, and I worried that my grandchildren's generation might not have any future here.

3. For years, much of REACH's work has focused on pollution from concentrated animal feeding operations ("CAFOs"). According to the North Carolina Department of Environmental Quality ("NC DEQ"), there are more than 520 swine CAFOs in Duplin County. Together, these facilities confine almost two-and-a-half million pigs. Because there are so many swine CAFOs, some people call Duplin County the "hog capital of the world."

4. As the map below shows, there are at least 30 swine CAFOs within three miles of my home. Together, these CAFOs confine up to 150,388 pigs. All 30 CAFOs operate under North Carolina's Swine Waste Management System General Permit, rather than permits issued under the Clean Water Act's National Pollutant Discharge Elimination System. According to NC DEQ data on the number of animals confined in each CAFO, I understand that at least 12 of

these 30 CAFOs are allowed to meet or exceed the threshold for a "Large CAFO" set by the U.S. Environmental Protection Agency ("EPA"). The closest CAFOs of any size are only about a half-mile from my home. I drive by those CAFOs almost every day, and I can see the confinement barns when I drive by. The closest Large CAFOs are about a mile-and-a-half from my home.



Source: *See* N.C. Dep't of Env't Quality, List of Permitted Animal Facilities – 4-1-2020, https://deq.nc.gov/cafo-map; *see also* Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

5. By a conservative estimate, the pigs in the 30 CAFOs near my home together generate more than 250,000 tons of manure each year,[1] which is more than the amount of fecal matter annually produced by the combined population of North Carolina's five largest cities.[2] Almost all the CAFOs near my home store the pigs' urine and feces in giant uncovered pits, which the industry calls "lagoons." There are at least 48 lagoons within three miles of my home.

6. Hurricanes, storms, and even relatively light rainfall can cause lagoons to breach or overflow, flooding surrounding areas with urine and feces. After Hurricane Florence hit North Carolina in 2018, NC DEQ reported that 49 CAFO lagoons had breached or overflowed, releasing waste into surrounding areas. The flooding disrupted people's access to safe drinking water. Samples of private well water taken after the hurricane showed an increase in the presence of *E. coli*.[3] I worry that, because climate change is causing strong storms to hit the area more and more frequently, we will continue to experience flooding and flooding-related water pollution from CAFOs. But even light rainfall can cause lagoons to overflow. In June 2020, it

[1] According to NC DEQ, the CAFOs are permitted to confine a combined 150,388 pigs, which is approximately 21,860 1,000-pound animal units. According to the Natural Resources Conservation Service, hogs and pigs produce 63.1 pounds of manure per day per 1,000-pound animal unit, which amounts to 11.5 tons of manure per year per 1,000-pound animal unit. *See* Nat. Res. Conservation Serv., *RCA Issue Brief #7* (Dec. 1995), https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/rca/?cid=nrcs143_014211#table1.

[2] According to EPA, a person produces 0.5 pounds of fecal matter per day, which amounts to 0.091 tons of fecal matter per year. *See* EPA, *Risk Assessment Evaluation for Concentrated Animal Feeding Operations* 9, Tbl. 3.3 (2004). The combined population of Charlotte, Raleigh, Greensboro, Durham, and Winston-Salem is 2,183,425. *See* U.S. Census Bureau, *Quick Facts*, https://www.census.gov/quickfacts/fact/table/US/PST045219 (enter "Charlotte," "Raleigh," "Greensboro," "Durham," and "Winston-Salem" in the search bar).

[3] *See* John Murawski, *The Amount of E. coli and Fecal Matter in NC Wells Has Spiked Since Hurricane Florence*, The News & Observer (Oct. 25, 2018), https://amp.newsobserver.com/news/business/article220561095.html.

was reported that just two inches of rainfall flooded a lagoon in Sampson County, which is directly west of Duplin County, killing over 1,000 fish in surrounding waterways.[4]

7. To get rid of the waste stored in the lagoons, the CAFOs apply it to fields using mechanized sprinkler systems that spray it high into the air. There are sprayfields within three-quarters of a mile in either direction of my home. I know from my work at REACH that once waste is applied to fields, it can seep into groundwater and run off into nearby rivers and streams.

8. I have seen CAFO workers apply waste in ways that increase the risk that the waste will run off the field. For example, I have seen workers spray waste on fields during rainy weather, when the soil is more likely to become oversaturated and unable to absorb all the waste. I have also seen waste being sprayed when no one was monitoring the equipment to make sure it wasn't broken or overapplying the waste. In addition, I've seen workers spraying waste day and night when rain is forecasted, in order to reduce the amount of waste in the lagoons. Because the workers' main concern is reducing the waste in the lagoons, I think it's likely that they overapply it on the fields.

9. In addition to witnessing CAFOs apply waste in ways that are likely to cause water pollution, I have seen CAFO waste in ditches that lead to waterways. The waste is red and smells like manure. Once the waste is in the ditches, it's almost certain that it runs downstream into waterways.

10. I am concerned about the negative health and environmental consequences of water pollution from so many CAFOs being released in one relatively small area, in and around Duplin County. Because of my concerns, I have changed my behavior and given up activities I

[4] *See* Lisa Sorg, *1,000+ Dead Fish: NC DEQ Releases More Troubling Details on Hog Lagoon Spill*, NC Policy Watch (July 17, 2020), https://pulse.ncpolicywatch.org/2020/07/17/1000-dead-fish-deq-releases-more-troubling-details-on-hog-lagoon-spill/#sthash.wHd88Yfu.dpbs.

enjoy. For instance, I was once an avid fisherman, but I have not been fishing near my home in over a decade. I stopped fishing after I began to catch fish with open sores. I believe these sores are caused by bacteria and other pollution from CAFOs, and I do not think that fish with open sores are safe to eat. I have spoken with multiple REACH members who have also given up fishing after catching deformed fish, seeing dead fish floating in the water, and noticing that the water had turned an unusual color or begun to give off an unpleasant odor. Duplin County is a rural community; hunting and fishing are a way of life, and most people do not have extra income to spare. By forcing people to buy fish at the store, instead of fishing in the creeks and streams near their homes, CAFOs are harming our recreational interests and our economic interests, too.

11. In addition to giving up fishing, I have given up drinking tap water. The same is true for many REACH members. Most people in Duplin County used to drink well water, but many now receive county water instead. Even though my water comes from the county, I am not confident that it is safe to drink. I do not think that county water is any safer than well water; I am concerned that both water sources are contaminated with pollution from CAFOs. Some REACH members have complained that county water tastes like chlorine or that it looks milky. Most people buy bottled water instead. We always buy bottled water to serve at REACH meetings, and we distribute bottled water to community-members during and after hurricanes and other emergencies.

12. Not only do CAFOs pollute our water, but they also produce terrible odors. At first, I didn't know what chemicals were in the air, causing it to smell so terrible. I began to work as a citizen scientist in 2004, because I wanted to understand exactly what I was breathing and how it was likely to affect my body, so that I could better protect myself and help my

neighbors protect themselves. I learned that CAFOs smell terrible because they release toxic gases, like ammonia and hydrogen sulfide.

13. The odors that CAFOs produce cause serious health problems. I have personally experienced watery eyes, headaches, and nausea on days when the smell is bad. I have also spoken to hundreds of people whose health has suffered as a result of exposure to these gases. People have shared that they have experienced nausea, shortness of breath, watery eyes, and runny noses. I am also familiar with studies showing that CAFO odors cause people's stress levels to increase.

14. To avoid the nearly constant stench of animal waste, most people in Duplin County close their windows and stay indoors, relying on expensive air conditioning to keep cool. People here have given up some of the most cherished aspects of rural life, like gardening, drying clothes on a line, hosting cookouts, and spending time outdoors. Many of us worry about declining home values. One REACH member has said that he looks for excuses to leave home and stays away longer than necessary, "because the smell that is there depresses [him]."

15. My own published research confirms that under-regulated CAFOs pose serious risks to people living nearby. For instance, I contributed to a study showing that kids who attend school downwind of swine CAFOs are exposed to relatively high levels of hydrogen sulfide, putting them at greater risk of symptoms like difficulty breathing and impaired lung function.[5] I also worked on a study finding that the children of people who work in swine CAFOs are more

[5] *See* Virginia T. Guidry et al., *Hydrogen Sulfide Concentrations at Three Middle Schools Near Industrial Livestock Facilities*, 27 J. Exposure Sci. & Env't Epidemiology 167 (2017).

likely to carry dangerous antibiotic-resistant bacteria on their bodies—even though those children never set foot in industrial hog-growing operations themselves.[6]

16. The CAFO problem in Duplin County is only getting worse. Now, energy companies are collaborating with CAFOs to trap and sell the methane and carbon dioxide that CAFO lagoons generate. These "biogas" projects involve capping the lagoons to trap the methane and carbon dioxide, transporting it through pipelines, constructing facilities to process it, and injecting it into existing natural gas pipelines. These projects rely on and further the outdated and unsafe system of storing animal urine and feces in lagoons and spraying it on fields, which causes water and air pollution. Biogas projects may in fact worsen this pollution. I understand that capping CAFO lagoons causes an increase in ammonia and other harmful pollutants in the liquid waste that remains in the lagoons and is then sprayed on fields.[7]

17. In addition to the growing biogas industry, I have witnessed the poultry industry expand dramatically in Duplin County. It seems like I can't travel two miles from my house or from REACH's office without seeing a new poultry facility being built. I am aware of one report from 2016 that estimates that industrial poultry operations confine more than 16 million chickens and turkeys in Duplin County alone.[8] That report is old now, and, based on my personal experience, I believe the number of poultry operations has continued to increase. Like pig

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[6] *See* Sarah M. Hatcher et al., *The Prevalence of Antibiotic-Resistant* Staphylococcus aureus *Nasal Carriage Among Industrial Hog Operation Workers, Community Residents, and Children Living in their Households: North Carolina, USA*, 125 Env't Health Persps. 560 (2017).
[7] *See* Cameron Oglesby, '*This Plan Is a Lie': Biogas on Hog Farms Could Do More Harm than Good*, Southerly (Mar. 24, 2022), https://southerlymag.org/2022/03/24/biogas-could-do-more-harm-than-good-hog-industry/?utm_source=ActiveCampaign&utm_medium=email&utm_content=Weekend+Reader%3A&utm_campaign=Weekend+Reader+Email.
[8] Env't Working Grp. & Waterkeeper All., *Exposing Fields of Filth: Locations of Concentrated Animal Feeding Operations in North Carolina by County: Duplin County* (last visited July 18, 2020), https://www.ewg.org/interactive-maps/2016_north_carolina_animal_feeding_operations_bycounty.php.

operations, poultry facilities usually dispose of waste by applying it to fields without appropriate prior treatment. Poultry waste, too, can seep into groundwater or wash into nearby waterways. In light of the growing poultry and biogas industries in Duplin County, both of which contribute to water pollution, it is all the more important to ensure that CAFOs and the water pollution they cause are properly regulated.

18. In my experience, many of the CAFOs in Duplin County are essentially self-regulated. NC DEQ does not have enough people to inspect all the CAFOs appropriately, to ensure that they are properly permitted and complying with their permits. In light of NC DEQ's difficulties, EPA should act to require CAFOs to apply for the correct permits.

19. EPA action is also important because it difficult for community members to hold the CAFOs accountable for the pollution they cause. For example, I once made an anonymous complaint to NC DEQ after I saw a CAFO spraying waste when it was raining, which is a violation of the Swine Waste Management System General Permit. Later in the day, the CAFO operator called me and said that he knew that someone with my phone number had made a complaint about the CAFO. I invited the CAFO operator to come to the REACH office to talk about the issue, but he didn't take me up on the offer. After I got off the phone with the CAFO operator, I called NC DEQ and told them that they had dropped the ball by giving out my information. If complaints aren't kept anonymous, it deters people from reporting permit violations. The state legislature has also made it more difficult for community members to hold the CAFOs accountable. In 2018, the legislature passed a bill that makes it more difficult for neighbors to bring nuisance suits against CAFOs. Because it can be difficult for community members to hold CAFOs accountable at the state level, I think it would be beneficial to have more federal involvement in CAFO permitting in North Carolina.

20. REACH has no interest in putting anybody out of business. But we believe it is possible for CAFOs to be more environmentally friendly and more community friendly. It is very upsetting to me that some of the corporations providing jobs in our community are also polluting the environment, destroying quality of life, and making people sick. We only have one Earth, and everyone should want to help take care of it.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 28 day of September, 2022.

Devon J. Hall

Devon Hall

Exhibit 12

DECLARATION OF DANIELLE WIRTH

I, DANIELLE WIRTH, declare and state as follows:

1. I am 69 years old, and I live with my husband and our two English Labradors at [redacted], Boone County, Iowa. Boone County is a rural area with a population of about 26,700 people. My husband and I have lived here for 43 years, and during that time, we have done our best to restore and care for our land. Among other things, we pay close attention to the plants, the animals, and the weather cycles.

2. I am a naturalist, ecologist, and environmental educator. I hold a Ph.D. from the College of Agriculture and Life Sciences at Iowa State University, where I served as a lecturer in environmental ethics, with an emphasis on empirical science. For 10 years, I served as an assistant professor in Drake University's Environmental Science and Policy Program, where I taught courses on environmental science, ecological restoration, and nature writers throughout history. I also have worked at the Iowa Department of Natural Resources ("IA DNR"), both as a regulator in the Environmental Protection Bureau and as an education specialist, helping to run an environmental education facility. Before that, I served as a federal park ranger. Although I am retired now, I still try to make myself available as a resource and helper to young people who are working to protect our land and water.

3. As an engaged citizen of Iowa and a naturalist, ecologist, and environmental educator, I know that industrial animal agriculture—including concentrated animal feeding operations ("CAFOs")—heavily pollute rivers and streams in my state, degrading important and fragile ecosystems. CAFOs generate, store, and spread large amounts of manure, which contains high levels of nitrogen. When this manure is released in excessive quantities, as the result of spills or improper application, the nitrogen in the manure contaminates water in the form of

nitrate and nitrite, both of which promote algae growth. Algae, in turn, depletes dissolved oxygen levels and endangers aquatic species. Blue-green algae is particularly dangerous because it produces microcystins, a class of toxins that can cause serious health problems for humans, including dangerous skin infections. Microcystins can also cause liver damage in canines, potentially killing them within three hours of contact with contaminated water. In addition to nitrogen, CAFO manure also can carry dangerous pathogens that threaten human health, such as E. coli and Methicillin-resistant Staphylococcus aureus, a bacterium that is nearly impossible to kill with traditional antibiotics. It does not take a science degree to realize that we should do our best to keep these pollutants out of our water.

4. Many people assume that the rural Midwest is a bucolic place, full of red barns and animals grazing on green pastures, but that image has not been the reality for many decades. Now, many smaller, independent farms have been replaced by industrial agriculture facilities. According to the IA DNR, there are 42 concentrated animal feeding operations ("CAFOs") in Boone County, confining over 111,000 swine, along with 120,000 chickens and more than 4,000 cattle.[1] The swine CAFOs in Boone County *alone* produce about 285 million pounds of manure every year,[2] nearly eight times as much as the sanitary waste produced annually by the entire

[1] S*ee* Iowa Dep't of Nat. Res., *Animal Feeding Operations Databases*, https://programs.iowadnr.gov/animalfeedingoperations/ (click "Search," input Boone in "County" dropdown).

[2] This estimate is calculated using data available in the IA DNR Animal Feeding Operations Database, including animal type, number, and average weight, as well as daily manure production estimates. *See* Jeff Lorimor et al., *Manure Characteristics: Manure Management Systems Series* 13 (2004), https://www.canr.msu.edu/uploads/files/ManureCharacter isticsMWPS-18_1.pdf.

human population of Boone County.[3] Based on the information made available by IA DNR, I do not believe that any CAFOs in Boone County have federal permits authorizing them to discharge water pollution.

5. As industrial agriculture has taken over in Iowa, water quality has deteriorated, and I believe that CAFOs bear significant responsibility for the problem. I have seen CAFOs engaging in practices that pose serious risks of water pollution, such as applying manure to frozen ground. And I have collected data suggesting that these risky practices, in fact, are polluting our water. Starting in the 1990s, I helped to develop a statewide water quality testing program implemented by volunteers, including students, teachers, and other engaged citizens. At first, our testing revealed higher nitrate levels in the spring, when farmers typically apply synthetic fertilizers to crop fields. Around 2010, however, we began to observe very high nitrate levels in the fall, correlating with the land application of CAFO manure. When our findings started to get attention, Iowa DNR stopped allowing us to input our data. Soon after, the testing program was shut down. I believe that the decision to shut down the program was motivated by a desire to hide evidence that CAFOs degrade surface water quality.

6. Not only do I believe that CAFOs have degraded surface water, but I also am concerned that CAFOs threaten drinking water. To learn more about these threats, several friends and I requested and studied manure management plans submitted to IA DNR by CAFO owners and operators. With help from my husband, who is an archaeologist familiar with

[3] Based upon the 2020 U.S. Census, 26,715 people live in Des Moines, Iowa. The U.S. Government Accountability Office estimates that humans produce 3.72 pounds of sanitary waste per person per day. *See* U.S. Gov't Accountability Off., *Concentrated Animal Feeding Operations: EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern* 58 (2008), https://www.gao.gov/assets/gao-08-944.pdf. Thus, the human population in Boone County produces 36.2 million pounds of sanitary waste per year.

superficial and subsurface geology, I identified a CAFO from which discharge would flow directly into the Des Moines River, near the headwaters of Saylorville Lake. It's my understanding that Saylorville Lake is a source of drinking water for the city of Des Moines, but water from the lake is often too polluted for the city to use.[4] Based on my research, I believe the CAFO that I identified could be partly responsible for this problem.

7. My husband and I used to drink water from our well, until agricultural pollution made our well water unsafe. Now, we get our drinking water from Xenia Rural Water District, which is quite expensive compared to well water. Xenia Rural Water District purchases water from the city of Des Moines, which is about 35 miles southeast of our home. As a former employee of IA DNR, I know that Des Moines has had to develop one of the most sophisticated water treatment plants in the country, because it treats water that is heavily polluted by CAFOs and other industrial agriculture facilities. Not every city can afford such a sophisticated plant, and we cannot rely on industry to clean up on its own.

8. Because of my concerns about water pollution from CAFOs and other industrial agriculture facilities, I am no longer able to enjoy Iowa's waterbodies as I once did. For example, my husband and I love to canoe and kayak, but we no longer paddle in the Raccoon River near our home. I understand that there are 727 CAFOs, including 355 Large CAFOs, in the North and South Raccoon watersheds,[5] and we are concerned about coming into contact with pollution from these CAFOs that could threaten our health. In addition, we've stopped eating

[4] *See* Perry Beeman, *Water Works pays for Saylorville water too polluted to use, eyes $50M plant expansion*, July 6, 2021, https://iowacapitaldispatch.com/2021/07/06/water-works-pays-for-saylorville-water-too-polluted-to-use-eyes-50m-plant-expansion/.

[5] *See* Iowa Dep't of Nat. Res., *Animal Feeding Operations Databases*, https://programs.iowadnr.gov/animalfeedingoperations/; *see also* Snoflo, *North Raccoon Watershed*, https://snoflo.org/hydrology/watershed-h07100006-north-raccoon; Snoflo, *South Raccoon Watershed*, https://snoflo.org/hydrology/watershed-h07100007-south-raccoon.

fish from the river. And, much to their dismay, I will not allow my two English Labradors to swim there, because I do not want them to be exposed to pollution. I have reason to be concerned. While I was teaching, I heard from a colleague who took a class canoeing on the river that one student had developed a skin infection, and another had suffered an E. coli infection. After hearing this, I made sure that all my students wore protective gear when touching the water. But one should not have to wear nitrile gloves while paddling.

9. I enjoy viewing and identifying aquatic species—including clams, mussels, fish, frogs, otters, and great blue herons—and I am concerned that water pollution from CAFOs and other industrial agriculture facilities could be putting these species at risk. Our home is less than a quarter mile from the Des Moines River. Turtles used to climb up from the creek that runs through our land to try nesting in our yard, but I have not seen some of my favorite turtle species for many years. I believe that pollution from CAFOs and other industrial agriculture facilities has damaged these species' habitat and reduced their numbers. Piping plovers, wonderful little shorebirds that nest and feed along waterways, already are listed as endangered in Iowa—in part, because of our degraded water. And, recently, otters have been reintroduced to Iowa. I am thrilled to have otters back in waterbodies near my home, but I worry that pollution from CAFOs and other industrial agriculture facilities might prevent otters from thriving here.

10. CAFOs damage more than the environment. All across Iowa, small businesses are disappearing, and small towns are dying. Our young people are leaving the state, and I think it's because rural Iowa is being hollowed out by industrial agriculture. I see notices of small farms up for sale in the paper every day. Often, these small farms are bought by industrial operations. These days, there are very few independent farmers raising animals near me.

11. I think Iowans have been let down by officials who are too closely associated with industrial agriculture. I am especially disappointed with IA DNR; they are not transparent, and they are not thorough. For instance, it was extremely difficult for my friends and me to obtain the manure management plans mentioned above. In the end, we had to pay $600 for copies of those plans, because IA DNR did not have electronic versions available. And, based on conversations I have had with IA DNR staff, I believe the agency's CAFO permitting program is far too lax. It's my understanding that IA DNR staff do not always visit CAFOs to investigate whether they discharge. Instead, staff sometimes rely on maps and snapshots that don't show the full picture.

12. If the U.S. Environmental Protection Agency ("EPA") were to grant this petition and significantly increase the number of discharging CAFOs with NPDES permits, I would feel relieved and encouraged. In particular, I would welcome the opportunity to submit comments and attend public hearings about CAFO permits. The current system simply does not work, but increased oversight of CAFOs under federal law could be a first step toward protecting surface and drinking water, restoring recreation opportunities, helping aquatic species to recover, and rebuilding rural communities. Without action from EPA, Iowa's rural communities don't stand a chance against pollution from CAFOs and other industrial agriculture facilities.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 25th day of October, 2022.



Danielle Wirth

Exhibit 13

DECLARATION OF SANDY BIHN

I, SANDY BIHN, declare and state as follows:

1. I live in Lucas County, Ohio with my husband, Frank Bihn. I am the Executive Director of Lake Erie Waterkeeper. I founded Lake Erie Waterkeeper in 2004, and we became a licensed member of Waterkeeper Alliance in 2005.

2. Lake Erie Waterkeeper serves the entire Lake Erie watershed, which includes parts of Michigan, New York, Ohio, Indiana, and Ontario. We seek to ensure fishable, swimmable, and drinkable water throughout the watershed, and we advance this goal using advocacy, education, litigation, and innovation.

3. Lake Erie is an extremely important resource for the region. The lake provides drinking water for over 11 million people across the United States and Canada, and it is home to more fish than all the other Great Lakes combined. The lake is also an economic engine, attracting visitors who use the lake for sailing, swimming, kayaking, and other recreational activities.

4. I have always loved Lake Erie, ever since I first visited during family vacations as a kid. In 1987, my family built our home on the shores of Maumee Bay/Lake Erie, which is located in the western part of Lake Erie. My love for the lake is one reason why I was inspired to found Lake Erie Waterkeeper. The other reason is that, after seeing parts of the lake turn green with algae in the late 1990s, I realized that Lake Erie needed a spokesperson. So, I began advocating for the lake, which eventually led me to found Lake Erie Waterkeeper.

5. Concentrated animal feeding operations ("CAFOs") started coming to the Lake Erie watershed in the late 1990s, around the same time that the lake's water started to turn green. While farmers in the watershed used to raise animals in pastures, CAFO operators keep their

animals confined in buildings on small pieces of land. The animals in these CAFOs generate an enormous amount of urine, feces, and other waste. The swine and dairy cow CAFOs in the region store this waste in liquid form in concrete pits under the confinement buildings or in large open pits, and they get rid of it by spreading it on fields. There is a stark contrast between how CAFOs manage animal waste and how we manage human sewage. We make individuals repair their septic tanks to make sure their waste is treated, but CAFOs with millions of animals do not have to treat their waste at all before spreading it on the ground.

6. Most CAFOs in the Lake Erie watershed are located in the western portion of the watershed, in Indiana, Michigan, and Ohio. There are now approximately 2,500 confined animal feeding operations in the Western Lake Erie watershed, which together confine about 400,000 cows, 1.8 million pigs, and nearly 24 million chickens and turkeys.[1] The Ohio Department of Agriculture estimates that between 2002 and 2017, the number of animals in the Maumee watershed, which makes up just part of the Western Lake Erie watershed, increased by 88 percent.[2]

7. The massive amount of manure that is generated by animals in the Maumee/Western Lake Erie watershed and applied to fields by CAFOs and smaller operations overwhelms the soil and ends up in waterways. The Maumee/Western Lake Erie watershed has over 14,000 miles of ditches (which drained the Black Swamp) and the most tile-drained fields in the U.S. Tile drains are underground pipes with holes in them that take excess water out of the

[1] *See* Ethan Bahe et al., *EWG Analysis: In the Western Lake Erie Basin, Newly Identified Animal Feeding Operation Hot Spots Produce Excess Manure, Threatening Waterways and Human Health* (2022), https://www.ewg.org/research/ewg-analysis-western-lake-erie-basin-newly-identified-animal-feeding-operation-hot-spots.

[2] *See* Ohio Lake Erie Comm'n, Ohio Lake Erie Commission Meeting (June 9, 2021), https://lakeerie.ohio.gov/static/Meetings/Ohio+Lake+Erie+Commission_meeting+minutes_June_2021.pdf.

soil. When CAFO operators apply manure to these fields, it enters the drain tiles and flows directly into ditches, streams, and other waterways. Manure also washes off the fields when CAFO operators apply it before or during rainy weather.

8. I strongly suspect that CAFO operators commonly overapply manure on fields close to their confinement buildings, because it is too expensive for them to transport the manure to fields that are farther away and might have more need for the nutrients in the manure. My suspicions are based in part on an Ohio program called H2Ohio, which launched in 2019 and is meant to help CAFO operators reduce phosphorus runoff from manure application. Under the program, the state pays operators $35 per acre to apply poultry manure and $60 per acre to apply all other manure to fields that have phosphorus levels of 50 parts per million or less.[3] I think the state has decided to pay operators to apply manure on fields with lower phosphorus levels because, without the financial incentive, the operators will continue to apply it on fields that don't need additional phosphorus, which causes runoff.

9. CAFO manure causes serious water pollution throughout the Lake Erie watershed. Both Michigan and Ohio have declared that Western Lake Erie is an impaired waterbody under the Clean Water Act because of the massive toxic algal blooms that occur in the lake each year. The harmful algal blooms are caused by excess nutrients in the water. The state agencies acknowledge that agriculture is a primary source of the excess nutrients, but they don't distinguish between nutrients from commercial fertilizer and CAFO manure. However, it's clear that manure is a significant source of the excess nutrients. For example, in 2019, the region had a very rainy spring that prevented many farmers from planting crops, which meant that they

[3] *See* H2Ohio, Manure Incorporation (2020), https://hancockswcd.com/wp-content/uploads/Grants/H2Ohio/H2Ohio-Program-Manure-Incorpation-Guideline-Sheets.pdf.

applied less commercial fertilizer. But the algal bloom in 2019 was one of the worst that we've had. I think the algal bloom was so bad because the CAFO operators still had to get rid of their manure by spreading it on the fields, even though the fields weren't planted with crops. A lot of that manure then made its way to the lake and contributed to the algal bloom. In addition, scientific studies connect manure from CAFOs to nutrients in waterways. A recent study found that adding a CAFO to a region leads to an increase in phosphorus in the region's drainage basin.[4]

10. The annual toxic algal blooms in Lake Erie have serious consequences each year, but the one in 2014 was especially harmful. That year, an algae-induced toxin from the lake was found in a water treatment plant that supplied drinking water for Toledo. The governor declared a state of emergency and banned people from drinking and showering in the water. The ban affected nearly half-a-million people for almost three days.

11. To address the harmful algal blooms in Lake Erie, the United States and Canada entered into the Great Lakes Water Quality Agreement. As part of the Agreement, the countries set a goal of reducing the amount of nutrients entering Lake Erie by 40 percent by 2025.[5] The United States' domestic action plan requires reductions in nutrient runoff from Indiana, Michigan, and Ohio—where CAFOs in the Western Lake Erie watershed are concentrated—and the Canadian plan requires reductions from Ontario.[6]

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[4] *See* Zach Raff & Andrew Meyer, *CAFOs and Surface Water Quality: Evidence from Wisconsin*, 104 Am J. Agric. Econ. 161 (2022).

[5] *See* Kevin Bunch, International Joint Commission, *Binational Plans Call for 40 Percent Reduction to Algal-Fueling Nutrients* (Apr. 5, 2018), https://www.ijc.org/en/binational-plans-call-40-percent-reduction-algal-fueling-nutrients.

[6] *See id.*

12. In addition to causing toxic algal blooms, manure that enters waterways can kill fish. In 2017, three CAFO operators in Ohio applied manure to fields shortly before a heavy rainstorm, and the manure washed off into nearby creeks. Ammonia in the manure depleted oxygen levels in the creeks, which killed nearly 67,000 fish.[7]

13. CAFO pollution has disrupted my ability to enjoy the water near my home. After we built our home on Maumee Bay, we swam and drove WaveRunners in the water. But when the water started turning green with algae, it clogged the intakes of our WaveRunners and prevented us from using them. We installed a pool because we no longer wanted to swim in the bay, and we got rid of the WaveRunners. Then, during the 2019 algal bloom, the algae-laden water from the bay flowed into a ditch on our property and along a bike path in the area, and the smell was so bad that people didn't use the bike path all summer. The water had a putrid, septic smell that made people sick. The city spent about $40,000 to prevent it from happening again.

14. Exposure to harmful algal blooms can cause illness in humans and animals. I once got a call from people who had gone in the water when it was green, and they had gotten diarrhea. In another incident, water from the bay was on a slide in Maumee Bay State Park, and children who used the slide got severe diarrhea, which led to the slide being removed from the park. I also know of people who have gone into the water with open cuts and gotten infections. And I know of dogs that have died after coming into contact with the algae in the water.

15. The algal blooms also cause serious economic harm in the region. Reports show that the algal blooms reduce tourism, which costs the region both income and jobs. They also

[7] *See* Associated Press, *Fines Handed Out after Manure Spills Kills 67,000 Fish in Ohio*, Outdoor News (Oct. 13, 2017), https://www.outdoornews.com/2017/10/13/fines-handed-manure-spills-kill-67000-fish-ohio/.

lower property values and drive up people's water bills, which is the result of the increased cost of treating the polluted water.

16. In addition to causing destructive pollution, the CAFOs in the region have driven out small, independent farmers, which creates a rural environmental justice issue. Since the CAFOs came to the area, they have put about 80 percent of small farmers out of business. When I've visited the rural communities where those farmers once were, the people have told me that the number of churches and stores in the community has declined, which has reduced their quality of life.

17. CAFO pollution is also an urban environmental justice issue. Urban areas that get their drinking water from Lake Erie have to spend millions of dollars to treat the water, and this cost gets passed on to residents, who are often people of color. For example, one report found that in Toledo, where the percentage of residents of color is higher than the state average, a family of five's water bill includes almost $100 each year just to cover the cost of treating their drinking water.[8]

18. Although the Western Lake Erie watershed is full of CAFOs that are causing extensive water pollution, most CAFOs in the watershed do not have National Pollutant Discharge Elimination System ("NPDES") permits under the Clean Water Act. CAFOs avoid getting NPDES permits by claiming that they do not discharge any water pollution, but it's clear from the algal blooms in the watershed that this isn't true. CAFOs that avoid getting NPDES permits instead operate without water pollution permits at all or under state-law permits. This means that in the Western Lake Erie watershed—where CAFOs are located across three states—

[8] *See* All. for the Great Lakes, *Western Lake Erie Basin Drinking Water Systems: Harmful Algal Bloom Cost of Intervention* (May 2022), https://greatlakes.org/wp-content/uploads/2022/05/FINAL-COI-Report-051622.pdf.

CAFOs are subject to a patchwork of different rules. These disjointed rules fall short of the collective efforts that are necessary to protect the watershed.

19. I track when CAFO operators apply for construction permits, and I know that Ohio is reviewing permits for approximately 6,400 more dairy cows; 16,950 more pigs; and 120,000 more chickens and turkeys. Given the ongoing growth in the CAFO industry, at a minimum, the U.S. Environmental Protection Agency and states need to ensure that CAFOs have NPDES permits to better regulate the water pollution they cause.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 25th day of October, 2022.

Sandy Bihn

Sandy Bihn

Exhibit 14

DECLARATION OF KEMP BURDETTE

I, KEMP BURDETTE, declare and state as follows:

1. I am 48 years old. I live in Pender County, North Carolina with my partner and two daughters, aged 13 and 15. I am the Cape Fear Riverkeeper at Cape Fear River Watch ("CFRW"), and I have held this position for 12 years. Before that, I served as CFRW's Executive Director from 2009 to 2014. I have been a member of CFRW for 17 years.

2. The Cape Fear River Basin is the largest river basin in North Carolina, encompassing about 9,164 square miles, or approximately 16.5 percent of North Carolina's total land area. Nearly one-third of the State's population lives in the Cape Fear River Basin, and about 20 percent of North Carolinians get their drinking water from the Cape Fear River Basin, including people living in Greensboro, Fayetteville, and Wilmington. The Cape Fear River Basin also boasts some of North Carolina's most impressive remaining natural biodiversity, providing habitat for a variety of native, threatened, and endangered species and supporting a thriving tourism economy for recreational boaters, birders, and other nature-lovers.

3. As the Cape Fear Riverkeeper, I work to protect and improve the water quality of the Lower Cape Fear River, its estuary, tributaries, wetlands, and groundwater. I respond to citizen complaints of water pollution; carry out patrols in the air, on the ground, and on the water to identify threats to water quality; and collaborate with members, local partners, regulators, and legislators at the local, state, and federal levels to eliminate identified threats. I also conduct water-quality sampling in the Black, Northeast Cape Fear, and Cape Fear Rivers and associated waters, and I share this data with the public, so they know if and when it is safe to recreate in the water.

4. Concentrated animal feeding operations ("CAFOs") that confine swine and poultry are more densely concentrated in the Cape Fear River Basin than they are anywhere else on Earth. Each year, CAFOs in this region raise about 316 million birds and more than 10 million pigs.[1] Collectively, these animals generate a staggering quantity of waste, much of which finds its way into the Cape Fear River and associated waters.

5. Swine CAFOs typically store animal urine and feces in huge, uncovered pits, and they get rid of the waste by spraying it on fields. These practices cause a tremendous amount of water pollution. To illustrate the scale of this problem, I think it is helpful to compare the management of swine waste with the management of human waste. There are about 10 million people and 10 million pigs in North Carolina. Unlike the human population, however, swine are not distributed throughout the State; instead, almost all the pigs are concentrated in Eastern North Carolina. Each pig produces six to 10 times more waste than a person, which means that, in Eastern North Carolina alone, pigs are producing roughly as much waste as 100 million people. Although human waste is treated before disposal, swine waste typically is not. So, when CAFOs spray swine waste on fields in Eastern North Carolina, it's not too different from spraying untreated waste from a city with a population of 100 million out in the open, right near people's homes, which no one would ever dream of doing.

6. I have firsthand experience of water pollution from CAFOs in the Cape Fear River and associated waters. At CFRW, we patrol the river and surrounding areas by air at least once a month. From the air, it's easy to see that the basin is full of CAFOs, and many are very close to waterways. I don't think we have ever done an aerial patrol that didn't reveal either a

[1] *See CAFOs*, Cape Fear River Watch, https://capefearriverwatch.org/cafos/ (last visited Sept. 28, 2022).

swine or poultry CAFO violating state waste management rules in a manner that poses serious risks to our waterways. For example, we have seen swine CAFOs continuing to spray waste even as the waste runs off into waterways or pools on the field, which increases the risk of runoff. We have also seen swine CAFOs spraying waste into ditches that lead to waterways. During one recent flight, we saw a swine CAFO spraying waste on a field using a leaking pump. The waste leaking out of the pump was flowing right into a nearby stream. Figures One through Six at the end of this declaration show just some of the evidence that we have collected during our aerial patrols of runoff from land application by swine CAFOs.

7. Not only have I witnessed swine CAFOs discharging water pollution during the land application of waste, but I also am aware of CAFOs discharging from waste storage pits. As shown in Figure Seven, one of our aerial patrols revealed a swine CAFO using a hose to pump waste over the side of a waste pit and onto a neighboring field. Waste pit breaches and overflows can also cause discharges. For example, in June 2020, a waste pit at a swine CAFO breached, spilling three million gallons of urine and feces into the waters of the Cape Fear River Basin and killing at least 1,000 fish.[2]

8. Over the past decade, hurricanes and tropical storms have repeatedly caused CAFO waste pits to breach and overflow, releasing massive amounts of waste into waterways. During Hurricane Matthew in 2016, a number of waste pits in the Cape Fear River Basin overflowed. Just two years later, during Hurricane Florence, at least two waste pits breached and other pits overflowed. I toured parts of the basin affected by Hurricane Florence, and I saw that

[2] *See* Lisa Sorg, *1,000+ Dead Fish: DEQ Releases More Troubling Details on Hog Lagoon Spill*, The Pulse, N.C. Policy Watch (July 17, 2020), https://pulse.ncpolicywatch.org/2020/07/17/1000-dead-fish-deq-releases-more-troubling-details-on-hog-lagoon-spill/.

the two breached waste pits had released their entire contents, which totaled an estimated seven million gallons, into the flood waters.

9. Flood waters contaminated with CAFO waste have devastating effects. The contaminated waters flow into communities downstream and sometimes remain there for weeks, while animal waste seeps into homes, churches, schools, and anything else in the waters' path. The pollutants in the waste, including dangerous bacteria, can cause illness in people who return to clean up their communities, and they can also contaminate private drinking wells and public drinking water supplies. After Hurricane Florence, several public drinking water systems in North Carolina stopped supplying drinking water because of potential contamination from CAFO waste.[3]

10. During Hurricane Florence, my family and I experienced firsthand the damage that flooding at CAFOs causes. Our home was flooded, and the water reeked of swine waste. We weren't able to drive back to our home for three weeks, and we had to move out for three years while the damage was repaired. It takes a long time to recover from flooding, and some people aren't ever able to return to their homes. My next-door neighbor's house has been sitting empty since Hurricane Florence, with the door wide open. Other houses near mine have been torn down entirely.

11. In addition to seeing and experiencing water pollution from CAFOs, I have documented the effects of CAFO pollution on water quality. CFRW conducts water-quality sampling upstream and downstream of CAFOs, and we have found unbelievably high levels of bacteria in waterbodies near CAFOs. For example, in Stocking Head Creek, which has over 40

[3] *See* Wynne Davis, *Overflowing Hog Lagoons Raise Environmental Concerns in North Carolina*, NPR (Sept. 22, 2018), https://www.npr.org/2018/09/22/650698240/hurricane-s-aftermath-floods-hog-lagoons-in-north-carolina.

CAFOs in its watershed, we have gotten samples with fecal coliform bacteria levels of over 120,000 colony-forming units/100 milliliter ("mL")—that is, over 600 times the state standard of 200 colony-forming units/100 mL. Exposure to fecal coliform bacteria can cause nausea, vomiting, and diarrhea.

12. CFRW's water-quality sampling has also found high levels of nitrogen and phosphorus in waterbodies near CAFOs. Because animal waste contains these nutrients, I think CAFOs are responsible for the nutrients in the water. Recent research supports this conclusion. Researchers at the University of North Carolina Wilmington who have been monitoring water quality in the Lower Cape Fear River Basin for more than 25 years recently presented data that show steady and significant increases in nutrients and other indicators of CAFO pollution throughout the Lower Cape Fear River Basin.[4] The researchers concluded that the increases are likely the result of CAFOs and their waste management practices.[5]

13. During CFRW's aerial patrols, we have seen numerous algal blooms in the Cape Fear River and associated waters, which are a clear sign that there are too many nutrients in the water. Algal blooms cause serious harm to aquatic plants and animals. Algal blooms form on the top of the water, depriving aquatic vegetation of the sunlight necessary to grow. And when algae decays, it pulls dissolved oxygen out of the water, which kills fish and other aquatic wildlife.

14. Because of the CAFO water pollution that I have seen, my family and I don't fully enjoy the waterways near our home. I am an avid outdoorsman, fisherman, and bird enthusiast. I grew up in Wilmington, exploring the waterways, wetlands, and swamps of the

[4] *See* Michael A. Mallin et al., *Environmental Assessment of the Lower Cape Fear River System, 2020*, at 17 (2021), https://uncw.edu/cms/aelab/lcfrp/wq%20reports/2020-lcfrp-env-report.pdf.

[5] *Id.*

Cape Fear River Basin, and it's important to me that my daughters have the same opportunity to experience our region's incredible waterways. The opportunity to spend time near the water is one reason why we chose to live on the Black River, which is a tributary of the Cape Fear River. However, our home is downstream from many CAFOs; the headwaters of the Black River are in Sampson County, which has over 450 swine CAFOs that confine more than two million pigs, as well as an enormous number of poultry CAFOs. I used to fish in the river regularly, but I no longer fish as often as I would like to. I don't feel comfortable eating fish from the Black River knowing that they may have come into contact with bacteria or other CAFO pollutants. In addition, I don't let my daughters swim in the river very often, because I'm concerned that the CAFO pollutants will make them sick. I wish my family could enjoy the water near our home without having to question whether it is unsafe because of CAFO pollution.

15. In North Carolina, CAFO pollution is an environmental justice issue. Most CAFOs in North Carolina are in Sampson County and Duplin County, where there are high poverty rates, and a large proportion of the population is Black, Latinx, and Native American. The disparity in exposure to CAFO pollution is clear just from driving around the area—you don't see CAFOs next to country clubs or expensive houses; instead, you usually see them next to small homes in low-income communities.

16. To better protect waterways and communities from CAFO pollution, the U.S. Environmental Protection Agency ("EPA") should ensure that discharging CAFOs obtain National Pollutant Discharge Elimination System ("NPDES") permits consistent with the Clean Water Act ("CWA"), as federal law requires. Less than two percent of CAFOs in North Carolina

have NPDES permits,[6] so I think it is likely that much of the water pollution from CAFOs in the Cape Fear River Basin comes from CAFOs *without* NPDES permits.

17. Increasing NPDES permit coverage would help community members protect themselves and their local waterways from CAFO pollution by increasing transparency and giving people the opportunity to comment on CAFO nutrient management plans. If community members had access to nutrient management plans, they would know whether certain risky practices are allowed, which would help them identify and report permit violations. And if nutrient management plans were available for public comment, community members could help to improve them. For example, if I had the opportunity to comment on nutrient management plans, I would encourage the North Carolina Department of Environmental Quality ("NC DEQ") to include numeric limitations on the amount of nutrients that CAFOs can discharge, which could help reduce algal blooms in waterways.

18. In addition, EPA and NC DEQ should take more enforcement actions against CAFOs that discharge water pollution without CWA permits or otherwise violate state waste management rules. When my colleagues at CFRW and I witness these violations during our aerial patrols, we report them to NC DEQ, but it doesn't seem like there are any consequences because the violations keep happening.

19. The Cape Fear River Basin is my home, and I have committed my life to protecting the Cape Fear River and the communities that depend on it. I feel privileged to serve as the voice of the river and to represent the interests of CFRW members against polluting

[6] *See* EPA, *NPDES CAFO Permitting Status Report: National Summary, Endyear 2021, completed 07/20/22*, https://www.epa.gov/system/files/documents/2022-07/CAFO%20Status%20Report%202021.pdf.

industries. But my work has made clear to me that EPA and NC DEQ need to do more to address the serious harm that CAFOs are inflicting in the Cape Fear River Basin.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 26 day of October, 2022.

Kemp Burdette



Figure One. Runoff from land application by a swine CAFO.
Source: Kemp Burdette



Figure Two. Runoff from land application by a swine CAFO.
Source: Kemp Burdette



Figure Three. Runoff from land application by a swine CAFO.
Source: Kemp Burdette



Figure Four. Runoff from land application by a swine CAFO.
Source: Kemp Burdette



Figure Five. Runoff from land application by a swine CAFO.
Source: Kemp Burdette

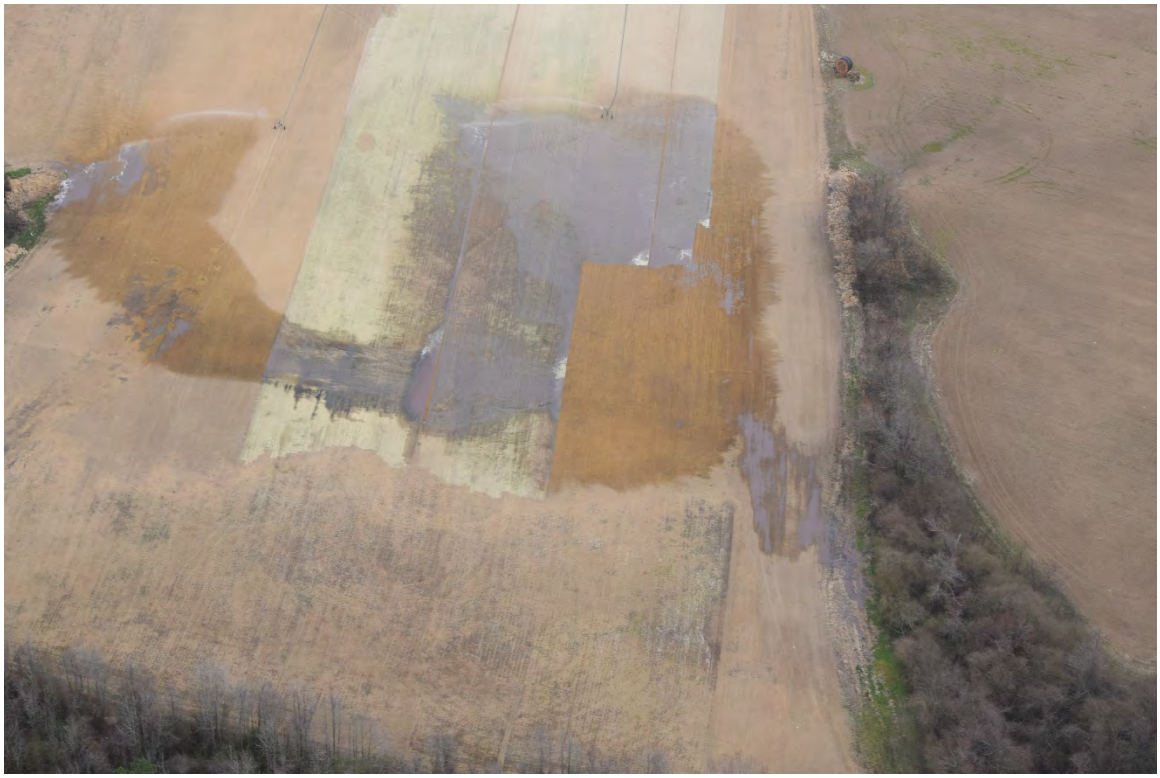

Figure Six. Runoff from land application by a swine CAFO.
Source: Kemp Burdette



Figure Seven. Swine CAFO pumping waste out of a waste pit and onto a neighboring field. Source: Kemp Burdette

Exhibit 15

DECLARATION OF DIANE ROSENBERG

I, DIANE ROSENBERG, declare and state as follows:

1. My name is Diane Rosenberg. I am 68 years old, and I live in Fairfield, Jefferson County, Iowa. Fairfield is a lively town of about 10,000 people. The town has a university, which has attracted people from all over the country.

2. I love the community and quality of life in Fairfield. For the first 40 years of my life, I lived in very congested suburban areas. I grew up in New York, and I have also lived in Boston and Washington, D.C. I moved to Fairfield in 1995 with my husband at the time. I quickly fell in love with the quiet and the fresh air in this area. The people here are very friendly, and we look out for each other.

3. The character of agriculture in Jefferson County has changed in the time that I have lived here. When I first moved to the area, I would see hogs out grazing, and I found it very charming. However, in the early 2000s, I noticed that I saw fewer hogs grazing. Around 2004, when I was an editor for a local newspaper, the paper published a series of articles on concentrated animal feeding operations ("CAFOs"). The articles alerted me to the prevalence of CAFOs in Jefferson County.

4. There are now approximately 80 CAFOs in Jefferson County. Together, the CAFOs confine nearly 200,000 pigs, which together generate at least 55 million gallons of manure per year. The CAFOs generally store this manure in liquid form in huge pits under the confinement buildings, or in the case of some of the older CAFOs, out in the open in uncovered lagoons, and they get rid of the manure by spreading it on fields.

5. I'm aware of CAFOs spreading manure on fields in ways that pose serious risks of water pollution. For example, I've seen workers spreading manure on fields with snow on

them, which is a sure way to cause water pollution. The snow prevents the manure from absorbing into the soil, leaving the manure to sit on the surface of the snow and ground. Then, when the temperature warms, the snowmelt mixes with the manure and carries it into nearby waterways. In addition, I'm aware of stories about CAFOs applying manure shortly before rainfall, which also can carry the manure into waterways. Once, a community member reported that rain had washed manure off a field and into a nearby stream. The manure formed a froth on top of the water. She reported the incident to the Iowa Department of Natural Resources ("IA DNR"), and the agency's water quality testing showed E. coli in the stream. I've even heard of one instance in which a company that had contracted with a CAFO to haul manure just dumped the manure in a field and left it there.

6. Not only do CAFOs apply manure in risky ways, but they also overuse application fields. I've reviewed many manure management plans for CAFOs in Jefferson County, and I worked with a college student to create a map of the fields designated for manure application in each plan. The map shows that some fields are included in more than one CAFO's manure management plan. In fact, some fields are included in four or five CAFOs' plans, and many of the fields that are receiving more than one CAFO's waste are directly adjacent to or near each other. When so many CAFOs are using one field, it's very likely that they are applying more manure than the soil and crops can take up, leaving the excess manure to run off into waterways. And when these fields are close to each other, they put nearby waterways at even greater risk of pollution from runoff. I am also aware that IA DNR can't adequately monitor how much of the manure is going where, when, and at what rates because they use an outdated paper system to file manure management plans, which makes it nearly impossible to keep on top of all the CAFOs' manure application practices.

7. CAFOs have created a water quality crisis in Iowa. Our waterways are full of pollutants that are associated with CAFOs, including nutrients like nitrogen and phosphorus and bacteria like E. coli and Campylobacter. One example that's close to home is Lake Darling in Washington County, just north of Jefferson County. When we first moved here, I would take my children to swim in the lake. Over the years, more and more CAFOs came to Washington County. As the number of CAFOs grew, nutrient and sediment pollution in the lake increased and eventually rendered it unusable. The state took six years and spent $16 million dollars to restore the lake. Right after it reopened, four CAFOs that together hold approximately 10,000 pigs were added to the watershed, and others have continued to come. Washington County is now home to over one million pigs. The CAFOs have made the expensive restoration of Lake Darling totally useless. Some of the fields that are in four or five CAFOs' manure management plans are in the Lake Darling watershed. Just about every week this year, there have been advisories that it isn't safe to swim in the lake because of high levels of E. coli and microcystin, which is a harmful toxin produced by certain bacteria. Last year, there were also many advisories for E. coli and microcystin. I've read articles warning dog owners to prevent their dogs from going into lakes polluted with microcystin because exposure can make their pets very ill or even kill them. This is just one lake, but it's an example of what CAFOs are doing to waterways all over Iowa.

8. In addition to polluting surface water, the CAFOs also contaminate drinking water. I know a woman in Howard County who had to stop using her drinking well after the water became unsafe to drink. She had to pay for bottled water and then "shock" the well by adding a large amount of chlorine to the water in order to use it again. I also know of other people who have had to stop using their drinking wells altogether and switch to the rural water

system at their own expense. Parts of Iowa—including Howard County—have karst terrain, which puts the aquifer at a particularly high risk of contamination. As we see in the case of the Howard County woman who lives in an area with karst terrain and sinkholes, pollutants from CAFOs are sometimes reaching the aquifer and contaminating drinking wells.

9. CAFOs also pollute the air and create noxious odors. I first smelled a CAFO when I drove by one with my daughter. I had heard how horrible the smell was, and I was curious to experience it myself. I rolled down the windows, and the odor that we smelled was indescribable. It made me sick to my stomach for about 20 minutes. The second time I experienced the smell, I was driving by a field where a CAFO was spreading manure. It was winter and all the car windows were up, but the smell still came inside. I was nauseous for about 20 minutes again. It's a kind of nausea that doesn't go away very quickly. I understand this nausea is caused by inhaling the hydrogen sulfide gas that CAFOs generate and emit, which then affects the central nervous system.

10. CAFO air pollution can harm community members' health. I once went on a bus tour of CAFOs in Davis County, which has even more operations than Jefferson County. After the tour, I developed the most miserable migraine, which I think was from breathing in all the hydrogen sulfide and ammonia that CAFOs emit. I also know of people who developed environmental asthma and irritable bowel syndrome, and who experienced nausea, vomiting, confusion, depression, and migraines from living near a CAFO. And I know of a woman who had to close her home-based elder care business after a CAFO was built nearby, because one of her residents developed respiratory problems, and she didn't want to risk the health of other

residents. Her daughter also stopped bringing her children to see their grandmother because of concerns for their respiratory health.[1]

11. I've spent a lot of time collecting information on the CAFOs in Jefferson County, because I think it's important for people to be informed about CAFOs in their community. Knowing where CAFOs and manure application fields are located is essential for protecting public health. For example, I know of studies showing that people who live near CAFOs can be exposed to Methicillin-Resistant *Staphylococcus aureus*, which can cause serious health problems.[2] People should know if they're close enough to a CAFO to be at risk of exposure. Knowing where manure application fields are located also is important for protecting water quality, and I believe that people deserve to know if their drinking water could be contaminated by CAFO pollutants. And regulators should know where the application fields are so they can ensure that each field receives only an appropriate amount of manure and monitor nearby groundwater and surface water for signs of contamination.

12. IA DNR is not doing enough to oversee CAFOs in the state. I've heard from people who work at IA DNR that they don't have enough staff to thoroughly review CAFO manure management plans. I've reviewed some of the plans myself, and I've found mistakes that impact how much manure the CAFOs can apply. IA DNR mostly leaves it up to the CAFO operators to complete and follow the manure management plans correctly. This self-policing

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[1] *See* Maria C. Mirabelli et al., *Asthma Symptoms Among Adolescents Who Attend Public Schools that are Located Near Confined Swine Feeding Operations*, 118 Pediatrics e66, e70 (2006) (finding that children attending schools up to three miles from CAFOs, who were thus estimated to be exposed to CAFO air pollutants, experienced asthma symptoms, including wheezing).

[2] *See* Shawn G. Gibbs et al., *Isolation of Antibiotic-Resistant Bacteria from the Air Plume Downwind of a Swine Confined or Concentrated Animal Feeding Operation*, 114 Env't Health Persps. 1032 (2006).

policy is like allowing the fox to guard the hen house, with serious consequences for our waterways.

13. IA DNR also fails to take adequate enforcement actions against CAFOs when they pollute waterways. When community members make complaints about runoff, the agency sometimes investigates, but not always. IA DNR doesn't have enough staff to investigate every incident. Over the years, they shifted from issuing more violations and fines to "coaching for compliance," which basically means they advise a CAFO owner on how to avoid the problem again. I don't feel this is a strong enough deterrent to encourage CAFOs to carefully follow regulations and best management practices. Even when IA DNR issues fines, the amounts are pathetic. The fines range from $3,000 to $10,000, which is low enough that the CAFOs just treat them as the cost of doing business. The fines provide little incentive for CAFOs to be more careful. The IA DNR has the option to refer more egregious violations to the State Attorney's Office to recommend larger fines, but they rarely do.

14. Right now, there aren't enough safeguards to protect people and the environment from CAFO pollution. While lots of people try to do the right thing, the bad actors take advantage of the system and harm Iowa's public health and environment. Almost every year, the number of polluted waterways in Iowa is the same or greater than the year before. The state's efforts haven't been enough to stop this trend. We need significant federal policy changes to ensure that CAFO pollution doesn't continue to harm people's lives and the environment.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 25 day of October, 2022.

Diane Rosenberg

Diane Rosenberg

Exhibit 16

DECLARATION OF JEAN MENDOZA

I, JEAN MENDOZA, declare and state as follows:

1. I am 77 years old, and I live in White Swan, Washington—an unincorporated community on the Yakama Indian Reservation in Yakima County. I am the Executive Director of Friends of Toppenish Creek ("FOTC"), and I have held this position for over 12 years.

2. Together with surrounding areas, Yakima County is a major agricultural hub. Portions of Yakima County and the Yakama Indian Reservation make up the Lower Yakima Valley, an approximately 1000-square-mile area where about half the land is irrigated and comprises the most productive agricultural region in Washington State. Among other things, Yakima County has over fifty dairy cow-confining concentrated animal feeding operations ("CAFOs"). Most dairy CAFOs in Yakima County are clustered in the Lower Yakima Valley, including about five located on the Yakama Indian Reservation.

3. The Lower Yakima Valley is an environmental justice community. About 80 percent of people living in the Lower Yakima Valley identify as Latino, and 10 percent identify as Native American.[1] By contrast, Latinos make up less than 14 percent of people living in Washington State as a whole, and Native Americans make up only two percent.[2] In addition, people in the Lower Yakima Valley tend to have relatively low incomes, as compared with the rest of the state. The median annual household incomes in Yakima County and the Lower

[1] *See* Jean Mendoza, Friends of Toppenish Creek, *Life is Cheap in Yakima County*, Front & Centered (Dec. 2, 2015), https://frontandcentered.org/life-cheap-yakima/.

[2] *See QuickFacts: Washington*, U.S. Census Bureau, https://www.census.gov/quickfacts/fact/table/WA/PST045221 (last visited Oct, 19, 2022).

Yakima Valley are $55,000 and $33,000, respectively, both of which fall far below the statewide median annual household income of around $77,000.[3]

4. A group of neighbors formed FOTC in 2008 when a dairy CAFO with 7,000 cows threatened to relocate to the banks of Toppenish Creek, an important tributary of the Yakima River, which in turn, is a tributary of the Columbia River. Even though it might seem to be a minor waterbody, Toppenish Creek is vital for our region, which receives relatively little rainfall. Based on our experiences with other dairy CAFOs in the area, my neighbors and I knew that the relocating CAFO would pose a major threat to our water and destroy our quality of life. We succeeded in opposing that CAFO, and we incorporated as a non-profit in 2009. We have since become a leader in the fight for clean water and clean air in Yakima County.

5. These days, FOTC continues to work for the protection and restoration of the Toppenish Creek, Yakima River, and Columbia River watersheds as natural and community resources. Because CAFOs cause significant harm to these watersheds, a major portion of our work focuses on CAFOs. Among other activities, we support community-led initiatives to raise awareness about the threats that CAFOs pose to our water, health, and environment. We gather and disseminate information about the problems we seek to address, including by testing drinking water for CAFO pollutants such as nitrates and phosphates. We regularly engage with the Yakima Regional Clean Air Agency and other government decision-makers. From 2012 to 2019, we were part of the Lower Yakima Valley Groundwater Management Area Advisory Committee, which focused on monitoring and reducing nitrate concentrations in groundwater through the development and implementation of educational campaigns and protective measures.

[3] *See* Don Meseck, Wash. State Emp't Sec. Dep't, *Yakima County Profile* (updated Apr. 2022), https://esd.wa.gov/labormarketinfo/county-profiles/yakima (last visited Oct. 19, 2022).

We also collaborate with other groups in advocating for the enforcement of our nation's Safe Drinking Water Act, Clean Water Act, and Clean Air Act. And we hold state agencies accountable for the implementation and enforcement of the state's laws and regulations protecting our air, land, and water. FOTC operates under the simple principle that all people deserve clean air, clean water, and protection from abuse that results when profit is favored over people.

6. Dairies have a long history in Yakima County, but the industry has changed significantly over time. In the 1980s, Yakima County had approximately 140 dairy operations, with a total population of roughly 20,000 milk cows. Since then, the number of small dairies has decreased, but the remaining operations have grown dramatically. Now, there are about 50 CAFOs in the area, confining approximately 100,000 milk cows. Each cow produces about as much waste as 23 adult humans. Together, CAFOs in Yakima County generate as much waste as a city of more than two million people,[4] but unlike cities, these CAFOs don't have sewage treatment systems to disinfect their waste.

7. CAFOs in the Lower Yakima Valley deplete our precious water supplies. It's my understanding that a 1945 law has been interpreted to allow CAFOs to withdraw virtually unlimited amounts of groundwater to maintain the animals they confine.[5] Years ago, that law

[4] The U.S. Government Accountability Office estimates that each person produces 3.72 pounds of sanitary waste per person per day. *See* U.S. Gov't Accountability Off., *Concentrated Animal Feeding Operations: EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern* 58 (2008), https://www.gao.gov/assets/gao-08-944.pdf. Lactating cows can produce up to 155 pounds of manure each day. *See* Jeff Lorimor et al., *Manure Characteristics: Manure Management Systems Series* 13 (2004), https://www.canr.msu.edu/uploads/files/ManureCharacteristicsMWPS-18_1.pdf.

[5] *See Five Corners Family Farmers v. State*, 268 P.3d 892, 900–01 (Wash. 2011) (finding that RCW 90.44.050 allows for the construction of wells and withdrawal of groundwater for stock-watering purposes without a permit and that such withdrawals are not limited to 5,000 gallons per day).

might not have raised alarm, but now, CAFOs withdraw millions of gallons of pure water from deep aquifers every day.[6] Unless CAFOs are monitored more closely, I worry that there might not be much water left for future generations of people in this area.

8. In addition, I believe that CAFOs in the Lower Yakima Valley routinely discharge water pollution. Based on my research and experience, I know that the vast majority of CAFOs in this area rely on wet manure management systems, which involve storing liquid manure in often-unlined pits before spraying it onto fields. However, storage pits do not prevent pollutants in manure, such as ammonia and nitrate, from leaching into soil and groundwater. In fact, recent samples of soil from the sidewall of a waste pit in Yakima County revealed nitrate concentrations of 113.1 parts per million ("ppm"), which is significantly higher than the target level of 45 ppm.[7]

9. Evidence of CAFO pollutants in wells in the Lower Yakima Valley indicates that CAFOs are discharging water pollution. In 2017, the U.S. Geological Survey determined that about 20 percent of wells tested in the Lower Yakima Valley consistently exceeded safe drinking water standards for nitrates.[8] The Washington State Department of Ecology also gathers quarterly water samples from 30 monitoring wells in the Lower Yakima Valley Groundwater Monitoring Area, and it found that 45 percent of the initial samples exceeded safe drinking water

[6] *See* Mendoza, *supra* note 1.

[7] *See* Anchor QEA, *H&S Bosma Dairy Lagoon No. 3 Abandonment Plan* 4–5 (2022), attached to petition as Exhibit 24.

[8] *See* Raegan L. Huffman, U.S. Geological Survey, *Concentrations of Nitrate in Drinking Water in the Lower Yakima River Basin, Groundwater Management Area, Yakima County, Washington, 2017* (2018), https://pubs.usgs.gov/ds/1084/ds1084.pdf.

standards for nitrates.[9] This is concerning because nitrates in drinking water are associated with a range of health problems, including birth defects, insulin-dependent diabetes, and cancer.

10. In 2015, a federal district judge concluded that several dairy CAFOs in the Lower Yakima Valley were responsible for contaminating neighboring drinking-water wells with nitrate pollution.[10] As part of a settlement agreement, the CAFOs agreed to line their waste pits. Lining the waste pits was supposed to reduce pollution, but unfortunately, nitrate levels have not decreased significantly over time.[11] In my opinion, wet manure management—and particularly, the storage of liquid manure—inevitably leads to groundwater contamination; merely lining storage pits is not enough to protect public health.

11. In addition to contaminating groundwater, I believe that CAFOs regularly pollute surface water in this area. There is a strong connection between groundwater and surface water here, so contaminated groundwater also affects creeks, rivers, and streams. In addition, sprayed waste sometimes drifts across fields into nearby waterbodies, and manure spills can reach waterbodies too.

12. I am concerned about surface water pollution from CAFOs because, for me and many other people living in the Lower Yakima Valley, life is intimately connected to fish and the Yakima River. In fact, some Native people believe that human life will cease if salmon do

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[9] *See* Lower Yakima Valley Groundwater Advisory Committee, *Ambient Monitoring Initial Report Part of GWMA Implementation Plan* (June 20, 2019), https://www.yakimacounty.us/DocumentCenter/View/21633/GWAC-Presentation---Monitoring-Well-Report-Overview---2019620-v20-1.

[10] *See Cmty. Ass'n for Restoration of the Env't, Inc. v. Cow Palace, LLC*, 80 F. Supp. 3d 1180 (E.D. Wash. 2015).

[11] *See* Letter from Vincent McGowan, Water Quality Program Manager, State of Wash. Dep't of Ecology, to Edward Kowalski, EPA Region 10 (July 11, 2022), https://ecology.wa.gov/DOE/files/dc/dc1cc49b-d818-419b-8664-349807c76073.pdf.

not return to this area to spawn. I moved to the White Swan area in 1995, and in the first few years after my move, I regularly saw people selling fish along the roadsides during fishing season. Fishermen sold locally caught salmon. Eating this beautiful food was one of the joys of my life. However, I no longer see people selling fish by the sides of the road, and locally caught fish is harder to find. Many salmon species in the region are now endangered. I know that there are many threats to waterbodies in this part of the country. Because declining fish populations have coincided with the increasing concentration of CAFOs in this area, I think that water pollution from CAFOs could be at least partly at fault for the population declines. And not only has water pollution from CAFOs contributed to declining fish populations, but it also adds to the mix of pollutants that makes fish caught in this area unsafe to eat.

13. I'm worried that the dairy industry's efforts to expand the use of biodigesters, which capture methane emitted by manure in CAFO waste pits to produce biogas, will exacerbate the contamination impacting our communities. Biodigesters fail to address the water pollution that CAFOs cause, and they ultimately produce little output compared to the effort required.[12]

14. Even though evidence suggests that they discharge water pollution, most CAFOs in this area lack National Pollutant Discharge Elimination System ("NPDES") permits under the Clean Water Act ("CWA"). According to the Washington State Department of Ecology ("WA Ecology"), there are over 100 Large CAFOs in Washington State, but only 24 have active

[12] *See* Friends of Toppenish Creek, *Air Pollution from CAFOs in Yakima County – Potential Impact of Digesters that Produce Natural Gas from Cow Manure*, http://www.friendsoftoppenishcreek.org/cabinet/data/Air%20Pollution%20from%20CAFOs%20in%20Yakima%20County%20III.pdf.

NPDES permits.[13] Based on my research and experience, I believe that the majority of CAFOs without NPDES permits are discharging water pollution in violation federal law, but I do not think that Washington officials will hold those CAFOs to account.

15. Under-regulated CAFOs in the Lower Yakima Valley threaten the health of people living in our community. For example, Campylobacter infection is very common here. Campylobacter species are widespread in dairy cows and other mammals, and campylobacter infection is a leading cause of diarrhea in humans. Rates of Campylobacter infection are about four times higher in the Lower Yakima Valley than they are elsewhere in the state.[14] And bacteria aren't the only problem. Agriculture-related ammonia pollution is almost twice as high in Yakima County as it is in any other county in Washington,[15] and Yakima County has high rates of health conditions associated with exposure to this pollution, including pre-term birth, myocardial infarction, and lung disease.[16]

16. I do not believe that Washington officials take adequate enforcement actions against CAFOs that discharge. Last spring, while I was visiting friends who live near a dairy CAFO, I noticed that a truck transporting liquid manure had spilled manure on the road. I reported the incident to the Washington State Department of Agriculture and WA Ecology. In

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[13] *See* Dep't of Ecology State of Wash., *Clean Water Permit for Large Livestock Operations, Manure Lagoons Available for Review* (updated July 7, 2022), https://ecology.wa.gov/About-us/Who-we-are/News/2022/June-22-Clean-water-permit-for-large-livestock-ope.

[14] *See* Margaret A. Davis et al., *Risk Factors for Campylobacteriosis in Two Washington State Counties with High Numbers of Dairy Farms*, 51 J. Clinical Microbiology 3921 (2013).

[15] *See* EPA, Envirofacts about Ammonia on Washington State in Agriculture Sectors (2020), https://enviro.epa.gov/envirofacts/embed/nei?pType=SECTOR&pReport=county&pState=&pState=53&pPollutant=&pPollutant=NH3&pSector=&pSector=38&pSector=18&pSector=31&pYear=2017&pCounty=&pTier=&pWho=NEI (last visited Oct. 19, 2022).

[16] *See* Wash. State Dep't of Health, *Washington Tracking Network*, https://fortress.wa.gov/doh/wtn/WTNPortal/#!q0=370.

addition, I took photos of the spill and submitted those photos to the agencies. Although the agencies were required to notify me of the outcome of their investigation, I never received an update. Instead, when I reached out for news, WA Ecology staff told me to submit a public records request. When I eventually received the investigative report, I saw that WA Ecology had waited several days to investigate my complaint. By that time, there was no manure on the road. WA Ecology staff ignored my photographs and concluded that the CAFO was following best management practices. They recommended that I ask the county to repave the road, but I do not believe that repaving is the best way to avoid future spills.

17. Along with others at FOTC, I have invested significant time and effort in working to strengthen Washington's NPDES program for CAFOs, including through successful litigation. But our time and efforts won't pay off unless discharging CAFO actually obtain NPDES permits. Accordingly, I urge the U.S. Environmental Protection Agency to protect public health and the environment by granting this petition and, thus, ensuring that the owners and operators of discharging CAFOs come into compliance with federal law.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 25 day of October, 2022.

Jean Mendoza

Jean Mendoza

Exhibit 17

DECLARATION OF RONALD J. WYSE

I, RONALD J. WYSE, declare and state as follows:

1. I am 83 years old, and I live with my wife in Mt. Pleasant, Henry County, Iowa. My wife and I moved to our current home in town about two years ago, but before that, we lived outside of town at [redacted], Henry County, Iowa. We lived there for about 40 years, and during some of that time, my son and his wife lived about a half mile down the road from us. After we moved into town, my son and his wife moved into our old home [redacted]. We have a herd of six grass-fed beef cows there, and I like to visit the farm just about every day.

2. In 2012, when my wife and I were living at our old home, a swine concentrated animal feeding operation ("CAFO") was built about 2,200 feet away from us. The CAFO confines just under 2,500 hogs in a single large confinement building. The CAFO stores the hogs' urine and feces in a pit below the confinement building, and it gets rid of the waste by spreading it on fields that are very close to our old home.

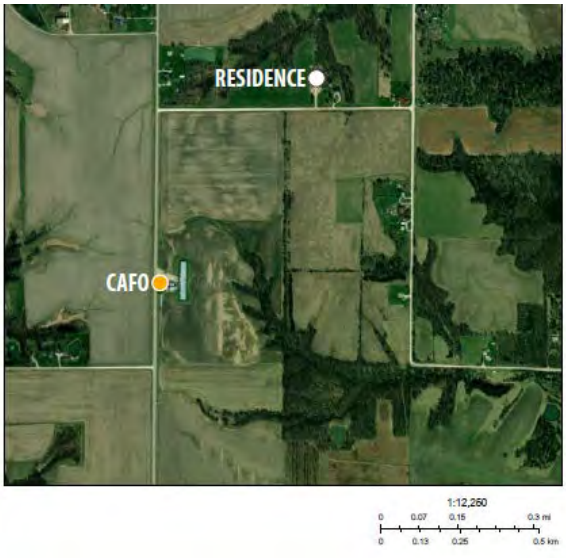

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

3. One Sunday morning about two years after the CAFO was built, the CAFO operator applied waste on their field before heavy rains, which caused the waste to run off their field and into a creek that is on our property. As we were leaving for church, we noticed that the CAFO operator was applying waste on a field just 1,800 feet from my son's home and 2,200 feet from our home. The field the CAFO operator was using has tile drains, which are underground pipes that take excess water and manure runoff out of the soil. The tile drains empty into a creek on our property that our cattle drink from. The field also has terraces that are meant to prevent waste from running off the field. Later that day, we got about three inches of rain, which caused the waste to run through the tile drains and into our creek. The rain also caused the waste to spill over the top of the terraces and into our creek. The liquid spilling onto our property was green and foamy, and it smelled terrible.

4. Two days after the waste spilled into our creek, I took a water sample and sent it to the University of Iowa to be tested. The tests showed that the levels of E. coli and nitrate in the water were just under the state's maximum acceptable level. Because two days had passed between the runoff and the sampling, the E. coli and nitrate levels likely would have been above the acceptable level right after the runoff. I reported the runoff and the test results to the Iowa Department of Natural Resources ("IA DNR"), but they said they couldn't do anything because they hadn't done the testing themselves. However, they did make a note of the incident. Since the incident, the CAFO operator has made the terraces taller, and waste hasn't spilled over them again.

5. Even when we don't have a heavy rain, CAFO waste still enters our creek because the tile drains empty into it. Around the time when my wife and I moved into town, we learned that if a pregnant cow drinks water contaminated with CAFO waste, it can kill the calf.

Our cattle could drink out of our creek, and we didn't want to risk losing a calf, so my son put up fences to prevent the cattle from accessing the creek. The fencing was expensive, and it felt unfair that we had to pay to protect our business from the CAFO's pollution.

6. In addition to polluting our creek, the CAFO also pollutes the air. The pollutants smell terrible, and they have made me sick. The CAFO smells nothing like the farms that I am used to being around. One of my neighbors has a herd of 50 beef cows, and when the wind blows from that direction, it is a pleasant smell that I don't mind. That is not the case for the CAFO.

7. I remember two incidents when the smell from the CAFO was particularly bad. The first incident happened one morning when I was mowing the lawn at our old home. When I went outside to start mowing, I immediately noticed a strong smell from the CAFO that was hardly bearable. As I was mowing, I started feeling sicker and sicker. After about two hours of mowing, I went inside and told my wife that I had a terrible headache and felt sick. She told me that my clothes smelled like I had been right next to the CAFO. I changed my clothes, took some asprin, and continued mowing. When I was back outside, I started feeling sick again, but I was able to finish mowing. The second incident happened at about 3:00 in the morning when I got up to stoke the fire in our fireplace. I walked outside to get some wood, and it smelled so terrible that I almost went right back inside. The smell hit me like a brick wall. I quickly grabbed the wood and retreated inside.

8. Although these two incidents are particularly clear in my mind, the smell from the CAFO is a constant problem. When we lived at our old home, we couldn't ever use the screened-in porch in the evenings, because when the wind blew from the direction of the CAFO and/or the air settled down around the house, the smell of the CAFO was terrible. The porch is

on the first floor of our old home, which is about eight feet lower than the land where the CAFO sits. The air pollution and odor from the CAFO settles down in the low-lying land. I felt angry and disappointed that the smell prevented us from fully enjoying the home that we had lived in for so long. Now, I drive by the CAFO every time I visit my son at my old home, and I smell the odor most of the times I drive by.

9. I wonder whether some of the illnesses I've had over the last nine years are because I've been exposed to the CAFO's air pollution. I've had respiratory problems, and I have to monitor my lungs very closely. I know that exposure to CAFO air pollution can cause respiratory problems, so I think the illnesses I've experienced could be from living next to a CAFO for so long.

10. It is increasingly difficult for community members to hold CAFOs accountable for the pollution they cause. I'm disappointed that IA DNR did not investigate or penalize the CAFO after I told them about the discharge into our creek and provided them the test results showing high levels of E. coli and nitrate in the creek. I was also disappointed to learn of the Iowa Supreme Court's recent decision making it more difficult for people to sue CAFOs for causing a nuisance.[1] Given the difficulties community members face holding CAFOs accountable, IA DNR, state legislators, and the U.S. Environmental Protection Agency need to do more to prevent CAFO pollution from occurring in the first place.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 22 day of October, 2022.

Ronald J. Wyse

[1] *See Garrison v. New Fashion Pork LLP*, 977 N.W. 2d 67 (2022).

Exhibit 18

15. U.S. EPA Region 5

Comments on Ohio's Preliminary Modeling Results for the Maumee Watershed Nutrient TMDL
EPA comments dated 08/17/2022

1. ***General Comment:*** EPA requests Ohio EPA (OEPA) to clarify the endpoint/location of the Maumee Watershed Nutrient (MWN) TMDL and describe how it will attain and maintain applicable WQS for Lake Erie. Is the compliance point the Waterville gage, the mouth of the Maumee River, or both?
    - Wherever OEPA decides that endpoint(s) to be, please review the draft PMR document and address any language which may be inconsistent with the choice of an end point (e.g., p. 95, *"…the TMDL target that will primarily be measured at the Waterville gage."* Updating this sentence would be necessary if the mouth of the Maumee River location was chosen to be the endpoint)

2. ***General Comment:*** OEPA does a sound job of explaining that the TMDL allocations described in the draft PMR are applicable to the "spring" season of March 1 through July 31. EPA is curious to understand OEPA's thoughts about the applicability of the TMDL, which is calculated to meet targets during 3/1 to 7/31, for remainder of the calendar year (August 1 through February 28).
    - Can one assume that allocations calculated to meet the spring season (i.e., 3/1 to 7/31) apply all year round? If yes, OEPA should state that someplace in the PMR.
    - Are there are any assumptions built in for the 8/1 to 2/28 time period for wasteload allocations (WLAs) and/or permits?
    - Section 2.2.4 (pp. 44-47) of the PMR document discusses numerous impacts on the delivery of phosphorus and time lags regarding phosphorus. Given this information, further discussion is needed on why it is appropriate to have WLAs that apply to the spring season only.

3. ***General Comment:*** How is the TMDL applicable to the period outside of the spring season? How will climate change be factored into the TMDL/TMDL analysis, including outside of the spring season?
    - Section 3.8.1, Pg. 90 - *"Phosphorus pollutant reduction targets are correlated with the HABs to serve as actionable acceptable levels related to Ohio's impairment metrics. These targets were developed by the binational Annex 4 subcommittee of the GLWQA (Annex 4, 2015). The phosphorus that directly contributes to the growth of the HABs was determined by the subcommittee to be primarily delivered with springtime snowmelt and rain. This resulted in targets limited to phosphorus delivered to Lake Erie from the Maumee River in the "spring" March 1 through July 31 period each year. The TMDL allocations are therefore only applicable during this spring season."*

4. ***General Comment:*** EPA appreciates that OEPA assigned individual WLAs to individual facilities/permittees within the Tables of Appendix 3. EPA notes that an EPA TMDL approval typically applies to WLAs assigned to individual facilities; the use of Group WLAs will need to be discussed with EPA, and that the use of watershed permits, compliance schedules, etc., will need to be addressed through the NPDES permit process. Please be aware that 40 C.F.R. §122.44(d)(1)(vii) provides that water quality-based effluent limits in NPDES permits must be consistent with the assumptions and requirements of a WLA in any approved TMDL.

5. ***General Comment:*** In several locations in the document, it is stated that dissolved reactive phosphorus (DRP) is the focus or the goal of the MWN TMDL (i.e., bottom of p. 2). However, this seems to imply that the MWN TMDL will address DRP, when the MWN TMDL is for total phosphorus (TP) only. Suggest replacing "focuses" with "includes discussion" or some other similar phrase. The current wording, especially so early in the document, implies that the TMDL is

addressing DRP, when the TMDL is developing loads for TP only. The language as noted below (Comment #34 below) is a better example.

6. ***General Comment:*** EPA requests additional information on how other sources of TP to the Western Lake Erie Basin (WLEB) are being addressed/considered in the MNW TMDL.

- Phosphorus contributions from other watersheds (e.g., Cedar-Toussaint Watershed, Portage Watershed) and how those contributions will be accounted for in the consideration of water quality, and the attainment of water quality targets for Western Lake Erie assessment units.
- Air deposition of phosphorus directly to waterbodies.
- Other contributions stated to be "negligible", such as direct discharges of manure (Section 2.2.1.1) and natural sources (Section 2.2.1.5). (Comment #10 below)

7. ***General Comment*:** EPA requests OEPA provide additional detail on the impaired uses and how designated uses and criteria will be attained. This detail can be provided in the revised PMR or the draft TMDL report.

- **p. 4, Section 2.1, 3rd paragraph below Section 2.1 heading:** The paragraph discussing the Lake Erie HAB recreation assessment methodology needs to be expanded. Annex 4 developed loads of TP and DRP to address algal blooms in Lake Erie. A notation that OEPA will "adhere" to the Annex 4 targets and "therefore" is directly applicable to the impairment will likely need further linkage. Suggest adding a paragraph or more on information from the 2022 IR regarding time periods (10 days), areal coverage (30%), and frequency (2 out of 6 years), and concentration (20,000 cells). Since there are no specific numeric criteria, there needs to be a clear link between the Annex 4 load and how the WQS will be attained.
- **p. 4, Section 2.1, 4th paragraph below Section 2.1 heading:** Similar to the comment above, further discussion is requested regarding the drinking water use. The discussion in the LAP (pp. 15 and 16) and 2022 IR (pp. H-4 and H-5) both contain important details on how HABs impact the use. We note that the LAP does not state that "…these impairments can be removed…" when the Annex 4 targets are achieved; microcystin sample results indicate use attainment, not algal bloom size.
- **p. 4, Section 2.1, 5th paragraph below Section 2.1 heading:** Regarding the aquatic life use (ALU) discussion in this paragraph. Similar to above, additional details are requested on the linkage between TP loads and aquatic life use. It is clear in this document and in others that OEPA is in the process of developing ALU assessment targets for the impaired segments. Since no numeric criteria (or assessment targets) currently exist, it will be important to note explicitly that OEPA is utilizing the goals of the Lake Erie Commission (LEC) to address ALU in the interim and explain why this is appropriate. Please provide reference to where the mesotrophic status goal or the 10-15 µg/L (assuming TP) is from.

8. **p. 8, paragraphs beneath Figure 6:** EPA requests that, overall, the PMR (and the TMDL) clarify the purpose of the SWAT model.

- EPA requests that the modeling section of the revised PMR or TMDL contains a discussion on the overall modeling approach (Mass Balance used for TMDL loads, SWAT for implementation details) to clarify which models are used for what purpose.
- EPA requests that the revised PMR or TMDL includes a summary paragraph of the Mass Balance model: how it was developed, how it was used, and potentially cite/direct the reader to any other resources (e.g., a more detailed report on the model, assuming there are other resources out there).
- EPA requests that the revised PMR or TMDL includes a summary paragraph on SWAT: what it is, and what it will be used for during this project.

9. **p. 16, 1st paragraph beneath *Fertilizer contribution to phosphorus pollution* heading**: This paragraph discusses phosphorus entering stream networks – is this both chemical and manure, or just chemical?

- **2nd paragraph beneath *Fertilizer contribution to phosphorus pollution* heading**: EPA recommends that OPEA clarify what "direct discharge(s)" of fertilizer means. Not all readers will understand that runoff from fields might not be considered as a "direct discharge". Given the high visibility regarding CAFOs and animal operations, suggest being very clear on terms and definitions. How is it known that direct discharges are a negligible proportion of the overall loading?
- **4th paragraph beneath *Fertilizer contribution to phosphorus pollution* heading**: Manure overapplication from CAFOs/CAFFs is noted as not being widespread in fields controlled by CAFO/CAFFs. It would be important to note the areas which are typically controlled by a CAFO – do most CAFOs control the land their manure is spread upon? What about the smaller non-CAFO designated facilities, do those facilities control the lands where manure is spread? It is also unclear where in Section 2.3 there is further discussion on the critical source areas regarding CAFOs and manure spreading.

10. ***General comment*:** Factors that are "negligible" or "minor" seem to be discounted, and EPA requests additional discussion/rationale of how these are handled.

- **p. 16, Section 2.2.1:** EPA requests additional rationale for how these direct discharges are addressed. *"While detrimental to the aquatic life of receiving streams during an episode (i.e., the near-field), direct discharges that have occurred represent a negligible proportion of the Maumee's overall seasonal far-field phosphorus load."*

- **p. 42, Section 2.2.2.2:** Stormwater discharges are 20% of WLA, but are considered minor here. *"Combined with information presented above, and the overall small proportion of developed land, stormwater from developed land is expected to be minor source of phosphorus to the Maumee."*

11. **p. 19:** There are a number of percentages noted on this page; some seem to imply differing messages. For example, the first paragraph notes that SWAT modeling noted that commercial fertilizer contributes an average of 58% TP and 42% DRP to Maumee Bay, and manure contributes 12% and 8% respectively. However, the last paragraph notes that the delivery ratio of phosphorus for commercial and manure fertilizer is 3% and 1%, which may imply that despite the predominance of fertilizer use, little is getting to Maumee Bay. While these are two different statistics (load vs ratio), it could be misinterpreted that these sources do not contribute to the problems in Maumee Bay.

12. **p. 21, 3rd paragraph below Fertilizer's role in increased DRP to Lake Erie heading:** The discussion on the IJC report suggests the impact conservation tillage has on DRP loads. This will need to be considered as the Reasonable Assurance Section is developed; relying on conservation tillage will be much more nuanced when this information is considered.

- Is there any way to quantify the impacts of conservation tillage, such as through modeling of scenarios under which conservation tillage is adopted by various percentages of acreage?
- Is the reduction in TP (particulate) phosphrous greater than the increase in DRP? This is somewhat discussed on Page 22, but a more explicit determination is needed.

13. ***General comment*:** EPA requests additional discussion regarding the nature of "legacy" phosphorus, how it is defined, and how it can and will be addressed.

- **p. 22-23, Soil and Legacy Sources Section:** "Legacy" phosphorus may be interpreted to be phosphorus that cannot be controlled, or is "just there". It will be important to emphasize that controlling legacy phosphorus will rely not only on controlling soil runoff, but also "turning off the tap" by reducing fertilizer use/reducing activities which add more phosphorus to the soil. EPA notes that subdividing phosphorus inputs to current fertilizer use vs legacy phosphorus could lessen the importance of many of the nonpoint source controls needed to reduce phosphorus.

14. **p. 26, top paragraph**: This paragraph regarding the Muenich et al (2016) scenarios should be carefully reviewed in regards to reasonable assurance.

15. **p. 32, Title of Subsection 2.2.2:** EPA recommends revising the heading of this subsection to "NPDES permitted point sources (including permitted stormwater) of phosphorus" to reference NPDES permitted point sources and to reflect the types of permitted facilities addressed in the subsection.

16. **p. 32, Table 3:** As discussed in the comment immediately below, NPDES Permits for CAFOs must be included in the summary of types of NPDES permitted entities in Table 3. EPA's NPDES program has identified 6 CAFOs within the Ohio portion of the Maumee Basin with NPDES permits, and 70 CAFOs without such permits. If confirmed by OEPA, please revise Table 3 to reflect this information.

17. **p. 34, 5th paragraph:** The first sentence reads, "*There are no NPDES permitted CAFO facilities within the Maumee Watershed*." Concentrated animal feeding operations are point sources under the CWA. EPA's NPDES program has identified 76 CAFOs in the Ohio portion of the Maumee watershed, 6 CAFOs with a NPDES permit and 70 CAFOs without a NPDES permit. EPA requests that OEPA characterize existing phosphorus loads from this point source sector, and establish allowable loads for all 76 identified CAFOs, including related production and land application areas, in the wasteload allocation portion of the forthcoming TMDL.

Such loads should account for (1) all releases from production areas and (2) all releases from land application areas that do not qualify for the agricultural storm water exclusion under the Act. *See* 40 C.F.R. § 122.23(e). Releases that qualify for the agricultural storm water exclusion may be placed in the load allocation portion of the TMDL. Releases that should be placed in the WLA include, but are not limited to, releases to a jurisdictional water (1) through artificial subsurface drainage (i.e., tile drainage), as well as (2) through ground water "if the addition of pollutants … is the functional equivalent of a direct discharge from the point source to navigable waters." *See* 140 S. Ct. 1462 (2020).

EPA offers the above as a point of emphasis in light of the statements on p. 34 and in Table 3 (p. 32) that no CAFOs in the watershed possess NPDES permits and the lack of CAFO discussions in the existing point source loading or waste load allocation sections of the draft PRM, as well as the following quote from p. 52, "*… 85 percent of Ohio's contribution of total phosphorus load was sourced from agricultural lands.*", as CAFOs operate within the broader agricultural sector.

18. **p. 36, paragraph beneath Figure 19**: The last sentence reads, "*…point sources contribute a similar proportion of phosphorus as manure fertilizer sources.*" and potentially highlights why the splitting of fertilizer into direct and legacy phosphorus sources may be misinterpreted. This could imply that point sources and manure are not really significant sources, and thus, make implementation of phosphorus source controls more difficult. It seems that manure inputs contribute not only to the

direct sources of phosphorus to the system, but also slow phosphorus loss/reduction from the legacy phosphorus "pool" within soils of the basin.

- It seems that in this last sentence of the paragraph beneath Figure 19, OEPA is summarizing an argument from the Kast et al. (2021) study and not making a definitive statement regarding the proportion of phosphorus from point sources vs. phosphorus contributions from manure?

19. **pp. 38-40, Existing facility-based (discharging) point source reduction efforts Section**: There appears to be no discussion of DRP reduction efforts in the existing facility discussion; is there a reason why DRP was left out of this section? DRP is acknowledged and discussed as part of the source discussion for numerous other sources in the draft PMR document.

20. ***General comment*:** EPA requests additional supporting language and rationale behind several conclusions including:

- **p. 74, Section 3.3.3:** Please provide more clarification for excluding these SSOs. Please provide more rationale behind the 15 percent removal and greater than 6 percent removal: *"Therefore, SSOs are excluded from the analysis unless flow volumes are reported. This report uses a wet weather loading nutrient concentration of 0.75 mg/L for total phosphorus, the median concentration of 131 samples reported from September 2014 to August 2017 by two Ohio sewer districts that are required to monitor total phosphorus at select CSO outfalls in their NPDES permit. When bypasses go through primary treatment, 15 percent removal is assumed by Ohio EPA to account for settling and sludge removal. This value is set to be greater than the 6 percent removal from septic tanks but not as high a removal rates observed when fine solids are removed via extended settling and/or anaerobic digestion."*

- **p. 75, Section 3.3.4:** Please provide additional discussion/rationale: *"For this study, 80 percent efficiency will be used because the studies reviewed by Beal used fresh soil columns and did not consider a reduction in efficiency with system age."*

- **p. 75, Section 3.3.4:** Please provide additional discussion/rationale: *"The value used for this study is 40 percent total phosphorus removal for failing soil adsorption systems, or half that is assumed for properly working systems."*

- **p. 76, Section 3.3.4, Table 14:** Please provide additional discussion/rationale to explain how this was adapted: *"Proportions of total HSTS systems grouped into categories for Ohio's Nutrient Mass Balance Study. Adapted from the 2012 ODH statewide inventory (ODH, 2013)."*

- **p. 78, Section 3.3.5.3:** Please provide additional discussion/rationale: *"Without adequate monitoring data to compare with other land uses, a small positive bias of 0.1 lbs./acre/year is assumed for natural lands."*

- **p. 83, Section 3.4.1.2:** What is the rationale behind the using the "second greatest?" *"With only a few exceptions, the individual wasteload allocation for each of these facilities is set based the second greatest spring season load each facility has discharged in the last five spring seasons (2017-2021). Many of these facilities do not monitor total phosphorus in their effluent. Similar assumption to those used to calculate the 2008, "existing", loads were used to determine these facilities total phosphorus concentrations."*

21. **p. 81 and Appendix 3:** It is important for EPA to understand how the individual WLAs in Tables A2.1 and A2.2 were calculated. Are the WLAs in the Appendix 3 tables calculated using the concentrations described in Table 17 (i.e., for GP1 facilities – flow * 0.5 mg/L * conversion factor…GP2 facilities – flow * 0.47 mg/L * conversion factor…etc)? Or are the WLA's in the Appendix 3 tables calculated using 1.0 mg/L?

- Are there any additional assumptions at play related to the calculation of WLAs in the Tables in Appendix 3? If yes, please explain.
- Please add additional columns to the Tables in Appendix 3 which include the flows and concentration values used to calculate the WLAs.

22. **p. 81, Footnote #1:** EPA R5 TMDL and OEPA TMDL staff had previous discussion (i.e., May-June 2022) regarding a scenario where a permittee has two assigned WLAs, one WLA from an earlier near-field TMDL (i.e., those projects described in Appendix 4) and a second WLA calculated in the development of WLAs for the MWN TMDL. EPA and OEPA came to the understanding that under these circumstances when there are two WLAs assigned to the same facility, ultimately the permit issued to the permittee must be consistent with the more stringent WLA.

- Please include language which explains this scenario and expectation that the more stringent WLA will be incorporated into the permit. This language can be included within the revised PMR or TMDL document.
- Unsure if the language in Footnote #1 is fully accurate given this understanding. Namely that all prior WLAs calculated for previous near-field TMDLs are not impacted by the WLAs from the MWN TMDL. The language of Footnote #1 could be interpreted to suggest that all WLAs from earlier near-field TMDLs would be more stringent than the WLAs calculated in the MWN TMDL.
- It would be very helpful for OEPA to designate (e.g., asterisk) those permittees that have a pre-existing WLA from an earlier near-field TMDL within the Tables of Appendix 3. Another option would be to include the previously approved WLA in Appendix 3 with a notation, so the PMR/TMDL would serve as the overall source of information regarding approved WLAs.
- Appendix 4 identifies many of the WLAs as annual loads. Please update any WLAs represented with annual loads to include a daily expression of the WLA in Appendix 4.
- EPA reminds OEPA that permits for discharges to impaired waters in the WLEB upstream from the mouth of the Maumee, which do not yet have a TMDL calculated to address that upstream impairment, must have a pre-TMDL Water Quality Based Effluent Limit (WQBEL) when the discharge is at a level that will cause, have the reasonable potential to cause, or contribute to an excursion above the applicable numeric or narrative water quality criterion.

23. **p. 82, Table 17:** Table 17 indicates that major publicly-owned treatment works that have a design flow equal to or greater than 10 million gallons a day (mgd) will receive a WLA equal to design flow times 0.37 milligrams per liter (mg/L) for a 153-day spring season, and that a monthly average effluent limit of 0.5 mg/L in a permit will drive performance to the 0.37 mg/L level. EPA appreciates the reference to an effluent limit of 0.5 mg/L for such POTWs because the *Great Lakes Water Quality Agreement* (*GLWQA*) provides that the United States and Canada are to, "assess and, where necessary, develop and implement programs such that municipal wastewater treatment facilities that discharge one million liquid gallons or more per day major municipal wastewater treatment plants discharging to the Lake Erie basin achieve a maximum of one-half of a milligram per liter of phosphorus in effluent." This quote from the international *Agreement* is not confined to the spring (i.e., March 1 to July 31). Furthermore, algae blooms can occur or continue after July 31, and phosphorus loadings outside of the spring timeframe contribute to legacy loads that the TMDL seeks to address. For these reasons, should the WLAs in the forthcoming TMDL (including those addressed

in the comment immediately below) apply during the growing season, an annual period that may end between September 30 and October 15?

24. **p. 82, Table 17:** Table 17 indicates (with language that is confusing) that POTWs that have a design flow equal to or greater than one but less than 10 mgd will receive a WLA equal to design flow times 0.47 mg/L for a 153-day spring season, and that a monthly average effluent limit of 0.66 mg/L in a permit will drive performance to the 0.47 mg/L level[1]. An effluent limit of 0.66 mg/L will not achieve the outcome to which the United States agreed in *GLWQA* (see quote in comment immediately above). EPA requests that OEPA explain how the WLAs are consistent with the objectives under the GLWQA. EPA notes that Ontario and Michigan are or will be applying an effluent limit of 0.5 mg/L to all of their major POTWs, including those with design flows equal to or greater than one but less than 10 mgd. Application of such limits to all major POTWs in the Ohio part of the Maumee basin will address equity across the three jurisdictions from the head of the Detroit River to the mouth of the Maumee.

25. **p. 83, Section 3.4.1.2, 2nd paragraph:** The text mentions that, *"…the individual wasteload allocation for each of these facilities is set based on the second greatest spring season load each facility has discharged in the last five spring seasons (2017-2021)."* The EPA requests further explanation of these assumptions and why they are appropriate. Would it be possible to provide an actual example WLA calculation using this method looks like? E.g., Flow * TP concentration (X mg/L) * conversion factor.

- Assume this calculative approach was used to set WLAs assigned in Table A2.2 in Appendix 3?

26. **p. 84, Section 3.4.1.3:** Is it appropriate to use 5/12 of the year for determining the CSO season?

- Are the CSOs effectively year-round, or are they more common in the spring?
- To clarify, no WLA (WLA=0) is assigned to SSOs? An explicit statement of this would be good.
- Note that this section would be a good place to identify presence and status of a Long Term Control Plan (LTCP).

27. **p. 85, Section 3.4.2, 1st sentence:** The text mentions *"natural infrastructure projects"*; can OEPA provide some examples of what these types of projects are? Are they green infrastructure (e.g., bioswales, rain gardens, impermeable pavement, curb cut etc.) related projects?

28. **p. 87, Section 3.4.5:** Is there any connection (i.e., story to tell) between the breakout of Landscape Allocations (i.e., Agricultural Land, Developed Land and Natural Land) from the Ohio 2020 DAP (e.g., Tables A5, A6, etc.) and this project effort?

- If, one were able to subdivide the LA value of Table 21 and Table 25 of the draft PMR into the landscape components (Agricultural, Developed and Natural) on the HUC-12 scale, would those values roughly agree with the summation of landscape estimates from the Ohio 2020 DAP (e.g., Tables A5, A6, etc.)?
- Would there be differences between these two sets (i.e., the Ohio 2020 DAP Landscape Allocation numbers (e.g., Tables A5, A6, etc.) and a hypothetical split of the Load Allocation (LA) on the HUC-12 scale for this TMDL effort) of values? If yes, what would those differences be and why?
- The draft-PMR document shares the message that the NPS contributions are the source which really needs to be improved upon (i.e., reduction of 92 MT to enhance NPS sinks and reduction of 366 MT to improve NPS management in Figure 44) to ultimately meet the WLEB total

[1] The GP2 text in Table 17 appears not agree with the final sentence in the GP2 narrative on page 83.

phosphorus (TP) targets. How will local stakeholders know what their goals/targets are for reducing nonpoint source contributions without greater specificity at the HUC-12 scale?

- It would be worthwhile for OEPA to provide more detail on LA and/or explain why it has chosen to have minimal detail on the LA.
    - Suggest a citation to 40 CFR 130.2(g) regarding the definition of "load allocation". *The portion of a receiving water's loading capacity that is attributed either to one of its existing or future nonpoint sources of pollution or to natural background sources. Load allocations are best estimates of the loading, which may range from reasonably accurate estimates to gross allotments, depending on the availability of data and appropriate techniques for predicting the loading. Wherever possible, natural and nonpoint source loads should be distinguished.*
- Is there an opportunity to highlight the LA portion of the TMDL for implementation purposes? To connect it to other documents (e.g., the DAP or existing Nine Key Element planning documents) which provide greater specificity to aid implementation planning?

29. **pp. 87-88, Section 3.4.7:** Can OEPA add some additional discussion regarding how it calculated the "*out of state boundary condition"* at 228.7 MT? How is the boundary condition divided between IN and MI (e.g., IN has 128.7 MT and MI has 100 MT)?

- Also, has OEPA consulted with TMDL staff at IDEM and MEGLE regarding this boundary condition calculation? Are their staff aware of this boundary condition set at the state border of IN-OH and MI-OH?

30. **pp. 88-89, Section 3.6, Margin of Safety:** The text mentions that, *"…conservative assumptions are made through TMDL development and implementation."* What are the specific conservative assumptions used in the report? These assumptions mustto be explicitly identified, and a detailed discussion of why they are conservative (i.e., what effect did the assumption have on the loading calculation, or what effect did the assumption have on reduction efforts, etc.?).

- Are there any conservative assumptions used in the Annex 4 target development, or the modeling effort?
- Explicit MOS: Why is 3% considered appropriate for the MWN TMDL? A detailed discussion, perhaps highlighting the significant data source at Watertown as well as other monitoring efforts, the SWAT modeling in progress that will provide more detailed analysis of loading and impacts, and any other work that will further refine the data should be considered and discussed when developing the MOS.
- In Section 4.2, 11.1 MT are noted as "unassigned" in the allocations. Can those 11.1 MT be used as MOS? That would raise the MOS to 4.8%.

31. **p. 89, Section 3.7, Allowance for Future Growth:** To confirm, Allowance for Future Growth (AFG) was considered, but there is no explicit, line item of AFG as part of the final TMDL, but OEPA did consider AFG as part of its implementation approach for certain NPDES facilities. Also, AFG was incorporated as part of OEPA's assumptions used to quantify the single WLA for the minor facilities covered under the Small Sanitary General Permit (OHS000005), and referenced in Section 3.4.1.2 on pp. 83-84. This approach is almost like an implicit AFG approach.

- Are there any other instances for AFG was considered or incorporated as part of the draft PMR effort?
- EPA recommends that OEPA revise Section 3.7 to expressly address
    - Proposed future increases in the number of animals at existing CAFO;
    - Proposed future increases in the number of animals at small- or medium-sized animal feeding operations such that a given operation would become a Large CAFO;
    - Proposed construction of new CAFOs;

- Proposed increases in the design flow of POTWs;
- Proposed construction of new (non-domestic) sources or increases in discharge from existing non-domestic sources;
- Proposed construction of new POTWs;
- Proposed expansion of the service area for municipal separate storm sewer systems; and
- Construction sites at which one or more acres of land will be disturbed. OEPA should consult with the Ohio Department of Agriculture regarding (1), (2), and (3) in the above list.

32. **p. 90, Section 3.8.2, Critical Conditions, 1st paragraph, 4th sentence:** EPA requests that the sentence that starts with "Because of this, the …" be reworded or potentially even deleted. "*Phosphorus delivered by the stream network that makes up the Maumee Watershed is causing the impairments in western Lake Erie. Because of this, the "near-field" concerns that phosphorus may bring out within the stream network near the point or non-point source areas are not applicable to this particular project.*"

- Is this sentence in reference to the idea that the MWN TMDL will not address impairments for "near-field" areas at this time? E.g., waters in the basin which still require TMDLs (e.g., the Lower Auglaize subwatershed) will not be addressed via the MWN TMDL and a future TMDL to address these impairments will still need to be developed in the future?

33. **p. 90, Section 3.8.2, Critical Conditions:** The discussion of critical condition seems to contradict some of the basis for the MWN TMDL, e.g., "*…the specific timing of phosphorus delivery, within the "targeted" spring period, is not relevant*." Using the Annex 4 targets for the spring season (March 1 to July 31) would seem to imply that March 1 to July 31 is the critical period, especially for phosphorus loading in order to attain the MNW TMDL calculations. While blooms may occur or continue later in the year, runoff from the spring season seems to have been identified in Annex 4 as the critical time to control phosphorus loading. The language of Section 3.8.2 will need additional clarifying language to present this point. The goal of the TMDL is to attain and maintain WQS throughout the year.

34. **p. 90, Section 4.1**: The last sentence on the page appears appropriate for discussion of DRP (*"Reducing the DRP portion of total phosphorus as much as possible is an explicit goal of the implementation plan for this TMDL*"). It appears to be more accurate to note this as a goal of the implementation plan and not the TMDL.

35. **p. 92, Section 4.2, Allocations for the Waterville monitoring point:** Confused by the different loading capacity values, 620.2 MT of TP (presented in Table 25) and 631.3 MT of TP (shared on p. 88 in the 2nd paragraph). We gather the difference between both values is 11.1 MT but what is happening to this 11.1 MT and why was it subtracted from the 631.1 MT value?

- The text mentions further explanation of the 11.1 MT difference is found in Section 3.4.8 of the draft PMR document, but there doesn't seem to be a Section 3.4.8 of the draft PMR document.

36. **p. 93, Section 4.3**: This information should be considered when determining the adequacy of the MOS and much of this information should also be summarized within the MOS discussion of Section 3.6. Demonstrating that the model and calculations are conservative can be used to determine/support how much MOS is needed in a TMDL. This is likely something we will need to discuss further.

37. **p. 95, Section 5:** The document describes adaptive management as a process to monitor the implementation of a TMDL over time. Section 5, describes how OEPA will adjust and assess the implementation of the TMDL. EPA recommends that Section 5 of the document be revised to reflect

that any adaptive management plans included in the implementation section of the TMDL will include specific milestones and timeframes that would trigger consideration and implementation of alternative strategies if certain metrics are not met within specific timeframes.

38. **p. 107, Section 5.3.1.1, above Ditch and Streamside Sources paragraph:** Should there be a paragraph here to discuss Non-Agricultural Stormwater?

39. **p. 115, Section 6, Reasonable Assurance:** EPA was interested to see the draft Reasonable Assurance discussions as part of the draft PMR document. Let's (EPA and OEPA) continue to brainstorm on content for this Section as part of the draft TMDL document, to be shared in December 2022. EPA is happy to look at early iterations of the draft Reasonable Assurance Section prior to December 2022.

40. ***General Comments for upcoming Reasonable Assurance (RA) discussion:***

An analysis of RA is required for TMDLs with mixed point and nonpoint sources. In order to appropriately evaluate RA in the context of this TMDL, EPA requests that OEPA provide additional information on Reasonable Assurance, including discussion on the following details:

- What actions and activities have the various State, counties, SWCDs, and Federal Programs implemented in in the basin over the last decade or so.
    - This should include information on funding, timelines, milestones, monitoring results (if any), and any estimates of pollutant reductions.
- What actions and activities are currently being developed in the basin by the various State, counties, SWCDs, and Federal Programs?
    - This should include information on funding, timelines, milestones, critical areas, monitoring results (if any), and any estimates of expected pollutant reductions.
- What actions and activities are planned in the basin by the various State, counties, SWCDs, and Federal Programs?
    - This should include information on funding, timelines, milestones, critical areas, monitoring plans, and any estimates of expected pollutant reductions.
    - This should also include the roles and responsibilities of the various organizations/governments.
- EPA requests that discussion be provided to better understand how the RA and implementation efforts will be adjusted over time. As noted in Section 2.2 of the PMR, SWAT modeling is ongoing in the basin. A process for incorporating the results of the SWAT model and BMP follow-up monitoring will be important in utilizing the adaptive management process envisions in the PMR.
- EPA requests that the upcoming discussion will also address the impacts of climate change on existing and proposed BMPs and projects.
- It will also be important to explain the process for overseeing all the various projects planned or underway in the basin, to ensure the overall goals of the TMDL are addressed. Many NPS projects are developed at the HUC-14 level, and understanding how all these various projects will "fit together" in an overall plan will be important. To date, ODNR and ODA have been active participants in the stakeholder meetings, and it will be important to identify how all these efforts will be overseen to ensure the goals of the TMDL are attained.

41. **General Comment:** Please describe how climate change impacts/influence were considered during the development of the draft PMR and the use of the empirical mass balance model.

42. **Appendix 3, Tables A2.1, A2.2, A2.3 and A2.4:** Please delineate/identify the facilities that are above Waterville and those below Waterville in these tables? Perhaps add an asterisk to their facility name within the Facility Name column?

43. **Appendix 3, Expression of WLAs:** Appendix 3 expresses WLAs in terms of mass (kilograms), so it is unclear if the proposed WLAs would result in reduced allowable pollution loads compared to existing effluent limits set in current NPDES permits. Please expand Appendix 3 or some other portion of the PMR to compare existing loadings and proposed WLAs, which would highlight any expected reductions from current discharges.

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Minor Edits:

+ **p. 21, 2nd to last paragraph above Section 2.2.1.2, last sentence:** Text reads, "*It shows that ~~high~~ improving fertilization rate, timing and placement of phosphorus could quickly reduce DRP loads*." It appears "high" may be a typo.

+ **p. 81, Section 3.4.1, 1st paragraph, last sentence:** Text mentions, "*…between currently authorized and actual loads shown above in Figure 21*." Should this be Figure 22 instead of Figure 21?

+ pp. 82-83, Table 17 and language beneath GP2 paragraph: In Table 17, the WLA calculation method for GP2 describes a concentration of 0.47 mg/L (which approximates to a 0.66 mg/L monthly limit over the 153 day spring season). Later in the language of the GP2 paragraph on p. 83, the numbers described are slightly different, 0.48 mg/L (long-term average) and a monthly concentration limit of about 0.59 mg/L.

- Should there be consistency between these two sets of numbers (i.e., Table 17 and GP2 paragraph)?

+ **Appendix 3:** Should the table names in this Appendix should read A3.1, A3.2 etc. Please double check.

Exhibit 19

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	CURRENT SPDES	FACILITY NAME													
2	NYA00E158	DUEPPENGIESSER DAIRY													
3	NYA00E164	AQUEDUCT RACETRACK													
4	NYA00E165	COON BROTHERS FARM, LLC.													
5	NYA00E166	ACE FARM, INC.													
6	NYA00E167	HAROLD BREY & SONS INC													
7	NYA00E168	HVFG, LLC													
8	NYA00E171	LABELLE FARM INC													
9	NYA00E173	BELLA POULTRY INC.													
10	NYA00E170	HITS-ON-THE-HUDSON													
11	NYA00E102	STANTON FARMS													
12	NYA00E180	BERKSHIRE VALLEY DAIRY, LLC.													
13	NYA00E176	WIL-ROC FARMS													
14	NYA00E253	HAGER FARMS													
15	NYA00E384	R & R Rarms LLC/DYKEMAN & SONS, INC.													
16	NYA00E331	GLENVUE FARM, LLC													
17	NYA00E385	MILK TRAIN, INC													
18	NYA00E373	SOUTHTOWN DAIRY													
19	NYA00E250	COOPERSTOWN HOLSTEIN CORPORATION													
20	NYA00E372	HEMLOCK VALLEY FARM, LLC													
21	NYA00E252	STITZEL'S WATERPOINT FARMS													
22	NYA00E275	CDS TILLAPAUGH													
23	NYA00E091	THREE L FARM													
24	NYA00E088	ADIRONDACK FARMS													
25	NYA00E097	CARTER FARMS, INC.													
26	NYA00E098	BUBBINS FARM													
27	NYA00E109	RUSTY CREEK FARM													

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
28	NYA00E450	GIROUX'S POULTRY FARM													
29	NYA00E407	CHA-LIZ FARMS													
30	NYA00E106	DIMOCK FARMS													
31	NYA00E093	REMILLARD FARMS													
32	NYA00E094	ASHLINE DAIRY													
33	NYA00E092	TRAINER FARM													
34	NYA00E110	OOMSVIEW HOLSTEINS													
35	NYA00E096	PAPAS DAIRY													
36	NYA00E099	BILOW FARMS													
37	NYA00E090	CARSADA DAIRY													
38	NYA00E125	SARATOGA HARNESS RACING													
39	NYA00E451	EILDON TWEED FARM													
40	NYA00E089	WELCOME STOCK FARM													
41	NYA00E107	KINGS-RANSOM FARM													
42	NYA00E108	BARBER BROTHERS DAIRY													
43	NYA00E105	TIASHOKE FARM													
44	NYA00E041	BROTHERHOOD FARM LLC													
45	NYA00E022	ALLENWAITE FARMS, INC.													
46	NYA00E305	KA SUNSET VIEW FARM, LLC.													
47	NYA00E120	WOLFF FARMS													
48	NYA00E304	CHAMBERS VALLEY FARMS, INC.													
49	NYA00E118	WOODY HILL FARMS, INC.													
50	NYA00E119	LANDVIEW FARM, LLC.													
51	NYA00E023	INSIGHT DAIRY													
52	NYA00E334	DANUBE DAIRIES													
53	NYA00E391	ENTWISTLE Bros, Farm, LLC													
54	NYA00E040	MURCREST FARMS													

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
55	NYA00E390	WOOD FARMS, LLC.													
56	NYA00E429	CTS DAIRY													
57	NYA00E431	BIRCH CREEK FARM													
58	NYA00E290	ONE MORE FARM													
59	NYA00E284	HILLCREST FARMS													
60	NYA00E039	SHELAND FARMS													
61	NYA00E430	BUTTERVILLE FARMS													
62	NYA00E424	MURROCK FARMS													
63	NYA00E291	HANCOR HOLSTEIN'S II													
64	NYA00E428	PORTERDALE FARMS													
65	NYA00E037	MILK STREET DAIRY													
66	NYA00E286	HANCOR HOLSTEINS													
67	NYA00E025	MOSERDALE DAIRY													
68	NYA00E034	KENNELL FARMS													
69	NYA00E289	DOUBLE E DAIRY													
70	NYA00E027	DEMKO DAIRY													
71	NYA00E425	BUTLER CREEK DAIRY FARM													
72	NYA00E426	HANNO FARMS													
73	NYA00E285	MARKS FARMS													
74	NYA00E388	HILLTOP FARMS													
75	NYA00E026	WOODS HILL FARMS													
76	NYA00E117	TRUANDVIN DAIRY													
77	NYA00E435	CURTIN DAIRY													
78	NYA00E438	CHAMPION FARMS													
79	NYA00E447	GALLAGHER FARMS													
80	NYA00E437	FINNDALE FARMS													
81	NYA00E003	VAILL BROTHERS DAIRY													

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
82	NYA00E436	BRABANT FARM													
83	NYA00E452	WOODCREST DAIRY LLC													
84	NYA00E454	BRANDY VIEW FARMS													
85	NYA00E115	ROYAL-J-ACRES													
86	NYA00E455	FOBARE FARM													
87	NYA00E374	Winsor Acres													
88	NYA00E410	GLEZEN FARMS, LLC.													
89	NYA00E007	OAKWOOD DAIRY LLC													
90	NYA00E310	CONQUEST CATTLE FEEDERS													
91	NYA00E008	SPRUCE HAVEN FARM LLC													
92	NYA00E419	LINCOLN DAIRY, LLC.													
93	NYA00E038	WILLET DAIRY LLC													
94	NYA00E009	AURORA RIDGE DAIRY, LLC													
95	NYA00E124	GREEN HILL DAIRY, INC.													
96	NYA00E460	ALLEN FARMS													
97	NYA00E042	VANS RIDGE FARM													
98	NYA00E422	PETER'S DAIRY, Inc													
99	NYA00E123	PATTERSON FARMS, INC.													
100	NYA00E417	ROACH FARM													
101	NYA00E031	SUNNYSIDE FARMS, INC.													
102	NYA00E418	PINE HOLLOW DAIRY, LLC													
103	NYA00E420	RIDGECREST DAIRY, LLC													
104	NYA00E421	HANEHAN FAMILY DAIRY LLC													
105	NYA00E340	RIVERSIDE DAIRY, LLC													
106	NYA00E462	WILLOW BREEZE FARM													
107	NYA00E461	CURRIE VALLEY DAIRY, LLC.													
108	NYA00E396	PREBLE HILL FARM, LLC													

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
109	NYA00E415	WHITE EAGLE FARMS, LLC													
110	NYA00E279	SPRINGWATER FARMS													
111	NYA00E306	HUDSON EGG FARMS													
112	NYA00E395	HOURIGAN DAIRY FARM, LLC													
113	NYA00E336	VENTURE FARMS LLC													
114	NYA00E122	BARBLAND FARMS, INC.													
115	NYA00E338	FABIUS GREENWOOD FARM LLC													
116	NYA00E409	ALLEN FAMILY FARMS LLC													
117	NYA00E309	ELMER RICHARDS & SONS													
118	NYA00E314	VOLLES DAIRY FARM													
119	NYA00E413	HOURIGAN FAMILY DAIRY, LLC													
120	NYA00E458	CO-VALE HOLSTIENS, LLC.													
121	NYA00E464	FESKO DAIRY, LLC.													
122	NYA00E308	TWIN BIRCH DAIRY													
123	NYA00E456	AA DAIRY													
124	NYA00E349	FARVIEW FARMS LLC													
125	NYA00E311	BECK FARMS, LLC.													
126	NYA00E416	MILLBROOK FARM													
127	NYA00E121	WALNUT RIDGE DAIRY, LLC.													
128	NYA00E473	LLOYDS USA DEVELOPMENT, INC.													
129	NYA00E017	MCCORMICK FAMILY DAIRY													
130	NYA00E353	OFFHAUS FARMS, INC.													
131	NYA00E401	LOR-ROB DAIRY FARM													
132	NYA00E016	BASKIN LIVESTOCK													
133	NYA00E184	ZUBER FARMS													
134	NYA00E186	MILLER'S SONSHINE ACRES													
135	NYA00E185	REYNCREST FARMS													

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136	NYA00E355	OAK ORCHARD DAIRY, LLC.													
137	NYA00E350	CY HEIFER FARMS, LLC													
138	NYA00E190	TORREY FARMS DAIRY, INC.													
139	NYA00E002	MAIN FACILITY													
140	NYA00E140	STEIN FARMS													
141	NYA00E029	LAMB FARMS													
142	NYA00E187	HILDENE FARMS													
143	NYA00E351	COYNE FARMS, INC.													
144	NYA00E352	MULLIGAN FARM, INC.													
145	NYA00E126	SPARTA FARMS, LP.													
146	NYA00E342	LA CASA DE LECHE, LLC.													
147	NYA00E444	DAIRY KNOLL FARMS, LLC.													
148	NYA00E130	THORNAPPLE DAIRY													
149	NYA00E439	MT. MORRIS DAIRY FARMS													
150	NYA00E142	ROLL-N-VIEW FARMS													
151	NYA00E145	T. JOSEPH SWYERS FARM													
152	NYA00E354	WALKER FARM													
153	NYA00E127	LAWNEL FARMS 2													
154	NYA00E341	DONNAN FARMS													
155	NYA00E400	ERNEST GATES & SONS, LLC													
156	NYA00E045	NOBLEHURST FARMS													
157	NYA00E147	FINGER LAKES RACING ASSOCIATION													
158	NYA00E132	WILLOW BEND FARM													
159	NYA00E135	WILL-O-CREST FARMS, LP													
160	NYA00E134	SCHUM-ACRES DAIRY OPS													
161	NYA00E466	DEBOOVER FAMILY FARMS LLC													
162	NYA00E441	HEMDALE FARMS													

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163	NYA00E317	HATHORN FARMS													
164	NYA00E318	LAWNHURST FARMS													
165	NYA00E136	HEIFER HAVEN FARMS													
166	NYA00E467	PHALEN FARMS													
167	NYA00E402	J. MINNS FARMS, LLC.													
168	NYA00E128	BONNA TERRA FARMS													
169	NYA00E192	JOHN, MARK, MAUREEN J. TORREY PA													
170	NYA00E440	BERGEN FARMS													
171	NYA00E469	CANOGA SPRING FARMS													
172	NYA00E470	HARTY HOG FARMS													
173	NYA00E056	MAYBURY-ROSENKRANS REAL ESTATE. LLC													
174	NYA00E474	GEORGE FAMILY FARMS, LLC													
175	NYA00E028	J.P. SWINE ENTERPRISES, LLC													
176	NYA00E150	WILKINS DAIRY FARM													
177	NYA00E137	DUNLEA DAIRY FARM													
178	NYA00E144	LENT HILL DAIRY FARM													
179	NYA00E141	LISMORE DAIRY													
180	NYA00E149	KARR DAIRY FARMS													
181	NYA00E033	DAMIN FARM													
182	NYA00E326	STONY BROOK FARM													
183	NYA00E151	WHITESVILLE POULTRY													
184	NYA00E316	RUTT FARMS													
185	NYA00E320	WAYNE COUNTY EGGS													
186	NYA00E035	MERRELL DAIRY, LLC													
187	NYA00E383	MAYLINE FARMS													
188	NYA00E382	BAINBRIDGE FARM													
189	NYA00E366	R & D ADAMS DAIRY FARMS, LLC.													

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190	NYA00E197	EDELWEISS FARMS													
191	NYA00E365	C & J DAIRY FARMS, INC.													
192	NYA00E218	MALLARDS DAIRY													
193	NYA00E362	BEAVERS DAIRY FARM, LLC.													
194	NYA00E364	SCHWAB DAIRY FARM, LLC.													
195	NYA00E361	COUNTRY AYRE FARMS, LLC.													
196	NYA00E367	RIDGELINE FARM, LLC.													
197	NYA00E036	SCHOFIELD FARMS, LLC													
198	NYA00E370	PHILLIPS FAMILY FARM, INC.													
199	NYA00E357	KREHER'S FARM FRESH EGGS, LLC.													
200	NYA00E363	EDEN VALLEY DAIRY, LLC.													
201	NYA00E358	PALMER DAIRY FARMS, LLC.													
202	NYA00E212	GASPORT VIEW DAIRY FARMS													
203	NYA00E201	MCCOLLUM FARMS													
204	NYA00E224	CHAFFEE FARMS, LLC.													
205	NYA00E228	ATWATER FARMS													
206	NYA00E210	LAKESHORE DAIRY, LLC													
207	NYA00E199	DZIEDZIC FARMS													
208	NYA00E015	BAKER BROOK DAIRY, LLC													
209	NYA00E378	PANKOW FARM													
210	NYA00E346	SOUTHVIEW FARMS, LP													
211	NYA00E376	TABLE ROCK FARM													
212	NYA00E406	SCHREIBERDALE HOLSTEINS, LLC													
213	NYA00E203	SYNERGY, LLC													
214	NYA00E359	MCCORMICK FARMS, INC. - DAIRY													
215	NYA00E229	BLISS CATTLE COMPANY													
216	NYA00E232	BROUGHTON FARM OPERATION													

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217	NYA00E476	ROBBIEHILL DAIRY FARM													
218	NYA00E206	HI-LAND FARMS													
219	NYA00E214	BOXLER DAIRY FARMS													
220	NYA00E156	OLD ACRE FARM													
221	NYA00E216	TRUE FARMS													
222	NYA00E381	SUNNY KNOLL FARMS													
223	NYA00E380	GARDEAU CREST FARM													
224	NYA00E196	EMERLING FARMS													
225	NYA00E377	HIGHBANKS DAIRY													
226	NYA00E211	VAN SLYKE'S DAIRY FARM													
227	NYA00E213	PERL FARMS													
228	NYA00E204	BREEZYHILL DAIRY													
229	NYA00E198	SWISS VALLEY FARMS, LLC.													
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Exhibit 20



December 27, 2019

Chery Sullivan
Director Dairy Nutrient Management Program
Washington State Department of Agriculture
Natural Resources Building, 2nd Floor
P.O. Box 42560
1111 Washington St. SE
Olympia, WA 98504-2560

Dear Ms. Sullivan,

Thank you for your e-mail of December 26, 2019 in response to Friends of Toppenish Creek's (FOTC) June 2019 request for information. We have several responsive observations.

1. When FOTC first approached officials with our concerns related to composting dead cows, we spoke with the WA State Dept. of Ecology (Ecology) and the Yakima Health District (YHD), the agencies responsible for environmental issues and public health. Both referred us to the WSDA Dairy Nutrient Management Program (DNMP). This has occurred in other situations. The Yakima Regional Clean Air Agency (YRCAA) and the WA State Board of Health (BOH) have asserted that problems related to dairies are all handled by the WSDA DNMP. As your citations of the law clearly demonstrate this is invalid. It appears to FOTC that some state and local agencies are avoiding their own responsibilities by attempting to shift them to your office.

Earlier this year a resident of the Lower Yakima Valley complained to the YHD about health issues related to manure storage. The health district actually told her to call the WSDA DNMP. Our neighbor shared your email stating that you had no authority but would contact the dairies and ask them to address her concerns. This was very nice but not very helpful overall.

2. Your email failed to include several Washington rules and laws that involve the DNMP.

- Agricultural composting operations are clearly cited under exemptions from solid waste permitting in RCW 70.95.205
- Dairy nutrient management plans are clearly cited under exemptions from solid waste permitting in WAC 173-350-220
- WAC 173-350-220 states, "Producers that fail to meet the conditions of RCW 70.95.306 (composting of bovine and equine carcasses) will be required to obtain a solid waste handling permit from the jurisdictional health department and must comply with all other conditions of this chapter."
- The only way to know that a dairy fails to meet the conditions of RCW 70.95.306 is through a dairy inspection by the DNMP.

3. Your email cited dairy inspections as the DNMP's method of detecting water quality violations. Quite frankly, this is insulting. There is one DNMP inspector for all of eastern Washington where 60% of the state's dairy cows are located. There are three or four inspectors for the Puget Sound area. Inspections occur approximately once every 22 months and last a few hours.

The questions for mortality composting operations that you listed are insufficient to evaluate whether there is leaching to groundwater. A subjective determination that composting takes place on "a hardened pad" is not the same as testing soil permeability. Evidence from the Lower Yakima Valley is clear. There is leakage from composting operations built on "hardened pads". (See Attachments 1 through 5).

The DNMP essentially ignores air emissions. Turning compost generates large dust clouds. In this case the dust comes from bovine carcasses and is inhaled by neighbors.

4. WSDA and Ecology know, or should know, that the Natural Resource Conservation Service (NRCS) Soil Web Survey considers the area where the mortality composting presumably occurs to be "very limited" for large animal mortality composting after a catastrophic event. Here is the NRCS explanation:

> *Rating class terms indicate the extent to which the soils are limited by all of the soil features that affect these uses. "Not limited" indicates that the soil has features that are very favorable for the specified use. Good performance and very low maintenance can be expected of a properly designed and installed system on these soils. "Somewhat limited" indicates that the soil has features that are moderately favorable for the specified use. The limitations can be overcome or minimized by special planning, design, or installation. Fair performance and moderate maintenance can be expected. "Very limited" indicates that the soil has one or more features that are unfavorable for the specified use. The limitations generally cannot be overcome without major soil*

reclamation, special design, or expensive installation procedures. Poor performance and high maintenance can be expected.

Since the 15th District Legislators are part of this conversation I have attached instructions on accessing NRCS Soil Survey data. (Attachment 6)

All this is complicated by the fact that monitoring wells drilled by the Lower Yakima Valley Groundwater Management Area (LYV GWMA) describe an aquifer that is already contaminated with nitrate. Here is a map from that program with 2019 nitrate levels next to the sites and a circle around the area where public records requests say the mortality composting occurs. Source https://www.yakimacounty.us/DocumentCenter/View/21633/GWAC-Presentation---Monitoring-Well-Report-Overview---2019620-v20-1

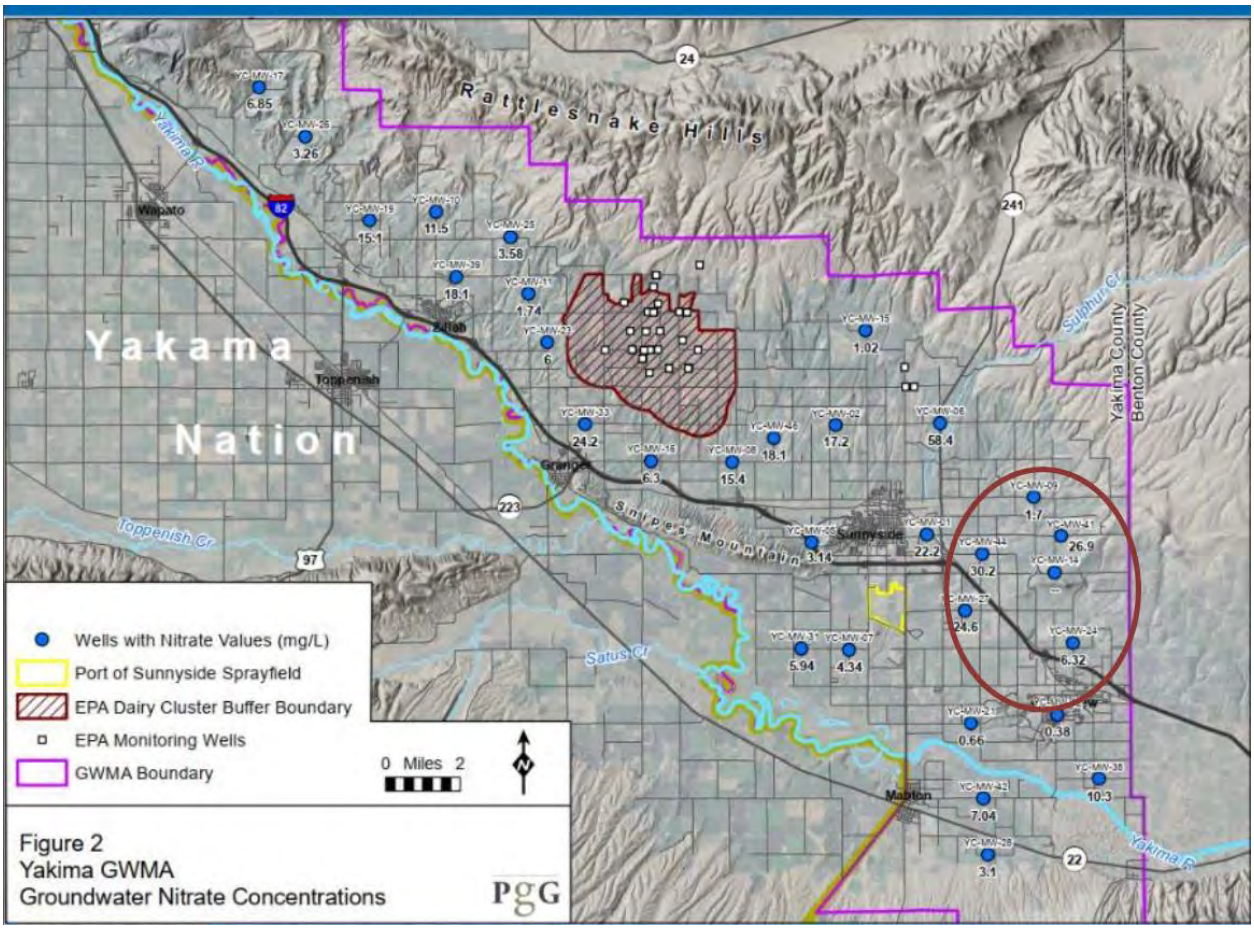

5. FOTC still has serious concerns about the impact of this mortality composting on public health. Our questions have not been answered, although it may not be within WSDA's authority to do so.

FOTC firmly believes that none of the officials who directed these operations from their climate controlled offices would allow composting of dead cows next to their own homes and families. The agencies have shown callous disregard for the health and welfare of the people who live in this area.

It now appears that there is no limit to the number of dead animals that can be composted in whatever sized area a CAFO chooses and there is essentially no regulatory oversight. Composting 1,000 animals at a time is the new normal, at least for Yakima County and this will likely change the definition of "agricultural activity" in Washington's Right to Farm Law, RCW 7.48.300 to 7.48.320. This is wrong and it contributes to mistrust of government to protect the citizens.

6. FOTC asks the WSDA DNMP to:

- Stop providing cover for other agencies that wish to avoid responsibility for environmental and health issues related to animal mortality composting
- Publicly acknowledge the need for groundwater testing around the mortality composting sites as the only way to evaluate leakage and/or spread of waterborne disease
- Publicly acknowledge the need for air monitoring to search for airborne pathogens and elevated levels of particulate matter

Thank you for reading and for addressing these serious observations. We look forward to hearing from you.

Sincerely,

Jean Mendoza

Jean Mendoza

Executive Director, Friends of Toppenish Creek

Exhibit 21

DECLARATION OF BUCK RYAN

I, BUCK RYAN, declare and state as follows:

1. I am 40 years old, and I live in Ada County, Idaho with my wife. I am the Founder, Executive Director, and first Waterkeeper of Snake River Waterkeeper. I founded Snake River Waterkeeper in 2014, and I have been the Executive Director since then. I am also an attorney, and I worked at a law firm in Eastern Idaho for three years before I founded Snake River Waterkeeper.

2. The Snake River is a vital resource for drinking water, recreation, wildlife, and tourism in Idaho. To protect the river and its tributaries, Snake River Waterkeeper monitors water quality, investigates citizen concerns, and demands enforcement of environmental laws. We also issue a SWIM Guide, which provides water quality conditions and safety warnings for sites across the Snake River and its tributaries. Snake River Waterkeeper's work spans the Snake River Basin, from the river's headwaters in Wyoming, across Idaho, to the river's confluence with the Columbia River in Washington. Our work also covers the river's tributaries, including the Clearwater and Salmon rivers. In total, our jurisdiction is approximately 100,000 square miles.

3. As the Executive Director of Snake River Waterkeeper, I have many duties. I do fundraising and accounting, maintain our social media pages and website, plan events, and interact with the group's members. I also speak with our attorneys about any lawsuits that we are involved in, which are aimed at holding polluters accountable and increasing protections for the Snake River and its tributaries.

4. Snake River Waterkeeper focuses much of its work on dams, fish hatcheries, and concentrated animal feeding operations ("CAFOs") in the Snake River Basin. These things are

significant sources of water pollution and harm to wildlife in the area, and the damage they cause is under-addressed.

5. As of 2021, there were at least 365 Large CAFOs in Idaho. Most of Idaho's CAFOs are dairies, and the Large dairy CAFOs confine at least 700 cows each, with some holding up to 150,000 cows in a single operation. The cows in Idaho's dairies produce an enormous amount of manure. Snake River Waterkeeper estimates that Idaho dairy operations generate approximately 4 billion pounds of manure each year. The dairy CAFOs typically store this waste in liquid form in large uncovered pits, and they get rid of it by spreading it on fields, either on their property or offsite. The fields often cannot retain all of the waste that CAFOs spread on them, so the waste runs off into nearby waterbodies, including the Snake River and its tributaries. For example, a prominent article on pollution in the Snake River explains that CAFOs along the river "have discharged manure by spreading it as a liquid three inches thick and miles wide on surrounding farm fields, which are crusted over with dried muck."[1]

6. Snake River Waterkeeper has repeatedly found pollutants associated with CAFOs in the river. For our SWIM Guide, we monitor sites along the river and its tributaries for nitrates and total dissolved solids, which can make the water unsafe for swimming. We used to monitor water quality at over 100 sites. For the last three years, we've monitored the 28 sites that are most popular for public use. We've found that, at least once during the summer, about a third of these sites will be too contaminated with nitrates or dissolved solids for children under the age of seven to swim in safely. Some sites are never clean enough to swim in. Nitrates and dissolved

[1] Richard Manning, *Idaho's Sewer System is the Snake River*, High Country News (Aug. 11, 2014), https://www.hcn.org/issues/46.13/idahos-sewer-system-is-the-snake-river?b_start:int=2#body.

solids are an indicator that the water is contaminated with manure, so I think the CAFOs along the river are responsible for the pollution.

7. In addition to polluting surface water, CAFOs in the area also pollute the groundwater. Our groundwater has high levels of nitrates, and I think this contamination is the result of manure percolating through the soil and bedrock after CAFOs apply it to fields, as well as manure seeping out of CAFO waste pits. Contaminated groundwater can enter people's drinking wells. I'm aware of research showing that, based on the bedrock in the area, the manure storage and disposal practices that CAFOs are employing on the surface now will threaten Idahoans' drinking water by 2050. About 95 percent of Idahoans get their drinking water from the Snake River Plain Aquifer, and nitrates and other CAFO pollutants in drinking water can cause serious health problems, so preventing CAFOs in the area from contaminating groundwater is very important.

8. Not only do CAFOs cause water pollution, but they also produce an overwhelming odor. If I'm driving in an area with a lot of CAFOs, I close my car windows and air vents and try to avoid stopping for gas. If you have your windows or air vents open, the odor can make you choke.

9. CAFOs in Idaho are located mostly in low-income communities and rural communities. As a result, these community members often experience the worst of the pollution the CAFOs cause, and they are at especially high risk of developing health problems from breathing the contaminated air and drinking the polluted water.

10. Although CAFOs in Idaho cause extensive water pollution, no CAFOs in the state have National Pollutant Discharge Elimination System ("NPDES") permits under the Clean Water Act. The CAFOs avoid operating under NPDES permits because the U.S. Environmental

Protection Agency ("EPA") relies on self-reporting by CAFO operators to determine which CAFOs discharge water pollution and, thus, require NPDES permits. But self-reporting is generally only effective when there is monitoring to document discharges, such as equipment at the end of a pipe that records the amount of pollutants that are discharged. CAFOs do not have that type of monitoring, so it is easy for them to claim that they do not discharge. In fact, every CAFO in Idaho claims that it does not discharge water pollution. In the article on pollution in the Snake River, the EPA director for Idaho recognized that Idaho CAFOs have "made the business decision" to not participate in NPDES permitting.[2]

11. CAFOs in Idaho are also able to avoid operating under NPDES permits because the Idaho Department of Environmental Quality ("ID DEQ") does very little to monitor them or take enforcement actions against them when they discharge. The lack of oversight from ID DEQ makes it easier for CAFOs to get away with claiming that they do not discharge. It also attracts more CAFOs to Idaho, because they know that they will not be held accountable for causing pollution.

12. From my experience, I think it's reasonable to assume that all CAFOs discharge water pollution. I have yet to see a CAFO that looks to have enough land to dispose of all the manure the animals generate without any of the manure running off the land and causing water pollution. I am also aware of specific instances of CAFOs discharging water pollution. For example, in 2017, a dairy CAFO with at least 1,000 cows and no NPDES permit discharged a significant amount of manure and other waste from a waste pit into a canal that flows into the

[2] *Id.*

Malad River and then into the Snake and Columbia rivers.[3] The CAFO operators cut the side of the waste pit open to allow the waste to flow into the canal. Because Idaho CAFOs discharge, they should have NPDES permits.

13. Increasing NPDES permit coverage for CAFOs in Idaho would benefit Snake River Waterkeeper and all Idahoans. The Clean Water Act requires that the public have access to CAFO nutrient management plans, which describe how a CAFO will store and dispose of the waste it generates and help CAFOs operators avoid discharging water pollution. Under Idaho law, however, manure disposal is considered a "trade secret," which is laughable. In Idaho, the public is barred from accessing a CAFO's nutrient management plan unless the CAFO is operating under a NPDES permit. Without access to information on where a CAFO is land applying its waste, the amount of waste it is applying, and the guidelines it should be following to prevent discharges, it is difficult for the public to monitor CAFOs and hold them accountable for causing discharges.

14. Increasing NPDES permit coverage would also complement Snake River Waterkeeper's efforts to strengthen Idaho's NPDES General Permit for CAFOs. ID DEQ is currently revising the NPDES General Permit, and Snake River Waterkeeper is participating closely in the revisions to ensure that the permit complies with the CWA. A permit that complies with the CWA will better protect the Snake River from CAFO pollution. However, our efforts to improve the NPDES General Permit will have less impact if CAFOs continue to operate without NPDES permits.

[3] *Shoshone Dairy, Owner Sentenced for Wastewater Violation Stemming from 2017 Flooding*, KMVT News (Mar. 17, 2021), https://www.kmvt.com/2021/03/17/shoshone-dairy-owner-sentenced-for-wastewater-violation-stemming-from-2017-flooding/.

15. Lastly, increasing NPDES permit coverage will allow Snake River Waterkeeper to use citizens suits to hold CAFOs accountable for causing water pollution. CAFOs operating under NPDES permits are subject to citizen suits for violating their permits, including by causing discharges. However, Idaho law does not provide for citizen suits. Snake River Waterkeeper identifies wastewater treatment plants and hatcheries that are violating their NPDES permits and brings citizen suits to bring them into compliance with the permits, and it would also do this for CAFOs operating under NPDES permits.

I declare under penalty of perjury that, to the best of my knowledge, the foregoing is true and correct. Executed this 20th day of October, 2022.



Buck Ryan

Exhibit 22

Industrial Hog Operations in North Carolina
Disproportionately Impact African-Americans, Hispanics and American Indians

Steve Wing and Jill Johnston
Department of Epidemiology
The University of North Carolina at Chapel Hill
August 29, 2014

Summary

Background: In 2014, the North Carolina Department of Environment and Natural Resources (NC-DENR) issued a swine waste management general permit (the General Permit), which is expected to cover more than 2,000 industrial hog operations (IHOs). These facilities house animals in confinement, store their feces and urine in open pits, and apply the waste to surrounding fields. Air pollutants from the routine operation of confinement houses, cesspools, and waste sprayers affect nearby neighborhoods where they cause disruption of activities of daily living, stress, anxiety, mucous membrane irritation, respiratory conditions, reduced lung function, and acute blood pressure elevation. Prior studies showed that this industry disproportionately impacts people of color in NC, mostly African Americans.

Methods: We obtained records on the sizes and locations of permitted IHOs from NC-DENR and calculated the steady state live weight (SSLW) of hogs as an indicator of the amount of feces and urine produced at each IHO. We obtained block-level information on race and ethnicity from the 2010 census of the United States. We compared the proportions of people of color (POC), Blacks, Hispanics, and American Indians living within 3 miles of an IHO to the proportion of non-Hispanic Whites. We quantified relationships between race/ethnicity, presence of one or more IHOs, and the SSLW of IHOs, using Poisson regression and linear regression to adjust for rurality.

Results: Analyses based on a study area that excludes the state's five major cities and western counties that have no presence of this industry show that the proportion of POC living within 3 miles of an industrial hog operation is 1.52 times higher than the proportion of non-Hispanic Whites. The proportions of Blacks, Hispanics and American Indians living within 3 miles of an industrial hog operation are 1.54, 1.39 and 2.18 times higher, respectively, than the proportion of non-Hispanic Whites ($p<0.0001$). In census blocks with 80 or more percent people of color, the proportion of the population living within 3 miles of an industrial hog operation is 2.14 times higher than in blocks with no people of color. This excess increases to 3.30 times higher with adjustment for rurality. Adjusted for rurality, the SSLW of hogs within 3 miles of a census block increases, on average, 100,000, 64,000, 243,000, and 93,000 pounds for every 10 percent increase in POC, Black, Hispanic, and American Indian population ($p<0.0001$).

Conclusions: IHOs in NC disproportionately affect Black, Hispanic and American Indian residents. Although we did not examine poverty or wealth in this study, the results are consistent with previous research showing that NC's IHOs are relatively absent from low-poverty White communities. This spatial pattern is generally recognized as environmental racism.

0207

Background

Swine production in North Carolina (NC) changed dramatically during the last decades of the 20th century. Between 1982 and 2006 the number of hog operations in the state declined precipitously while the hog population increased from approximately 2 to 10 million (Edwards and Driscoll 2009). Production became concentrated in eastern NC (Furuseth 1997).

Traditional NC producers raised small numbers of hogs, commonly fewer than 25, and hogs were one of several commercial crops on diversified farms (Edwards and Driscoll 2009). In contrast, industrial producers raise large numbers of hogs, often many thousands, in confinement houses that are designed to vent toxic gases and particles into the environment. Animal wastes are flushed into open cesspools and then sprayed on nearby fields. Pollutants emitted by IHOs include hydrogen sulfide, ammonia, a wide array of volatile organic compounds, and bioaerosols including endotoxins and other respiratory irritants (Cole et al. 2000) (Schiffman et al. 2001).

The negative impacts of particles and gases inside IHO confinements on worker health have been extensively described (Cole et al. 2000; Donham 1993; Donham et al. 1995; Donham et al. 2000; Donham 1990). Environmental pollutants from IHOs affect people who are more susceptible than workers due to young or old age, asthma or allergies, or other conditions. An extensive body of peer-reviewed scientific evidence shows that IHOs release contaminants into neighboring communities where they affect the health and quality of life of neighbors. Many of these studies have been conducted in NC. Hydrogen sulfide concentrations within 1.5 miles of IHOs in NC are associated with neighbors' ratings of hog odor and inability to engage in routine daily activities (Wing et al. 2008), increased stress and anxiety (Horton et al. 2009), irritation of the eyes, nose and throat, respiratory symptoms (Schinasi et al. 2011), and acute elevation of systolic blood pressure (Wing et al. 2013). A study of NC public middle school children who participated in an asthma survey, which was conducted by the NC Department of Health and Human Services, found that children attending schools within three miles of an IHO had more asthma-related symptoms, more doctor-diagnosed asthma, and more asthma-related medical visits than students who attended schools further away (Mirabelli et al. 2006). The same study reported a 23% higher prevalence of wheezing symptoms among children who attended schools where staff reported noticing livestock odor inside school buildings twice or more per month compared to children who attended schools where no livestock odor was reported (Mirabelli et al. 2006). Other studies in NC (Tajik et al. 2008) (Wing and Wolf 2000) (Bullers 2005) (Schiffman et al. 1995) and elsewhere (Donham et al. 2007) (Thu et al. 1997) (Radon et al. 2007) also document negative impacts of IHO air pollution on neighbors' health and quality of life.

Liquid contaminants from IHOs are released to the environment through leakage of animal waste storage pits, runoff from land application of liquid wastes, atmospheric deposition, and failure of the earthen walls of waste pits (Burkholder et al. 2007). Overflow of waste pits during heavy rain events results in massive spills of animal waste into neighboring communities and waterways. For example, in late September, 1999, 237 NC IHOs were located in flooded areas identified from satellite imagery provided by the NC Division of Emergency Management (Wing et al. 2002). Parasites, bacteria, viruses, nitrates, and other components of liquid IHO waste pose threats to human health (Burkholder et al. 2007; Cole et al. 2000).

Routine use of sub-therapeutic doses of antibiotics to promote weight gain of hogs promotes antibiotic resistance, making infections in humans more difficult to treat (Silbergeld et al. 2008). Airborne bacteria, including antibiotic resistant strains, have been isolated from IHO air emissions (Schulz et al. 2012) (Green et al. 2006) (Gibbs et al. 2006), and antibiotic resistant bacteria are associated with animal vectors near industrial animal operations, including flies (Graham et al. 2009), rodents (van de Giessen et al. 2009), and migratory geese that land on NC's IHO liquid waste pits (Cole et al. 2005). A recent medical records study from Pennsylvania shows that people living near IHO liquid waste application sites have elevated rates of infection with methicillin resistant *Staphylococcus aureus* (Casey et al. 2013). NC industrial livestock workers carry strains of *Staphylococcus aureus* that are associated with swine, including antibiotic resistant strains (Rinsky et al. 2013). These bacteria could be spread by liquid waste and airborne particles.

Using information from the United States Census of 1990 and locations of IHOs reported by the North Carolina Department of Environment and Natural Resources (NC-DENR) in 1998, we showed that the state's IHOs were disproportionately located in areas where more people of color (POC), primarily African Americans, live (Wing et al. 2000). We concluded that their disproportionate location in communities of color represented an environmental injustice. Since 1998 additional IHOs have obtained permission to operate and others are no longer in business. Additionally, between 1990 and 2010 the state's population size and spatial distribution changed due to births, deaths and migration. In this report we update our previous findings by evaluating whether IHOs operating under the general permit issued on March 7, 2014, will disproportionately impact POC, Blacks, Hispanics, and American Indians.

Materials and Methods

Lacking a list of the unique IHOs operating under the General Permit finalized in 2014, we used a list of all permitted industrial animal operations provided by NC-DENR on January 24, 2013 that we had prepared for prior research. First we excluded all non-swine operations from the list. Next we excluded swine operations with expired permits and permits with an allowable head count equal to zero. We also excluded permits that did not appear on a list of permitted animal operations published by DENR in January, 2014. We merged multiple permits issued for the same facilities to obtain a total head count for each operation. However the head count may be misleading as a measure of the pollution from each IHO because some facilities primarily house small pigs while others primarily house large hogs. We therefore calculated each facility's total steady state live weight (SSLW) using NC-DENR's formula based on the number and average weight of each growth stage of swine permitted at the facility. We interpret SSLW as a summary measure of the feces and urine produced by the swine of different growth stages at each facility.

Following the protocol provided in our previous study we excluded facilities operated by research institutions because they are subject to different location and management decisions than are commercial operations (Wing et al. 2000). Finally, we excluded facilities that do not hold a certificate of coverage to operate under the General Permit because they operate under individual permits or National Pollutant Discharge Elimination System general permits. The resulting facilities should closely approximate those expected to seek to continue operating under

the renewed General Permit. The renewed General Permit takes effect on October 1, 2014, at which time we plan to update the list created for this research.

The vulnerability of people of any race/ethnicity to having polluting facilities nearby can be affected by the race and ethnicity of other people in their community. For example, African-Americans who live in areas primarily populated by non-Hispanic Whites have, generally, a lower susceptibility to being near polluting facilities than African-Americans who live in areas primarily populated by Hispanics or American Indians. We therefore conducted our primary analyses of disproportionate impact using the POC category. We also conducted analyses for specific racial/ethnic categories. We defined the following racial/ethnic categories: non-Hispanic White (non-Hispanics who identified as White and no other race), POC (all people not categorized as non-Hispanic white), Black (people who identified themselves as African-American or Black with or without any other race), Hispanic of any race, and American Indian (people who identified themselves as American Indian with or without any other race). We used block-level race/ethnicity-specific population counts from the US Census of 2010.

As large-scale agricultural facilities, IHOs are not located in major cities. Following the protocol adopted in our prior research, we defined a study area for our primary analyses that excluded census blocks in the five major metropolitan areas of NC (Charlotte, Winston Salem, Greensboro, Durham and Raleigh) as well as 19 western counties that neither have an IHO nor border a county that has an IHO. We conducted additional analyses for the entire state.

We considered residents of blocks to be affected by IHOs within three miles of the block centroid. Blocks were categorized as either having, or not having, an IHO within three miles. Additionally, we calculated the total permitted SSLW of hogs within three miles of the centroid of each block as a measure of the total potential influence of pollutants from nearby IHOs on the residents of the block.

As in our prior study, we also calculated the population density of each block, defined as the number of people per square mile. Population density is a measure of rurality, which is strongly related to the availability of land for agriculture and the price of land. Racial/ethnic groups in NC differ in their urban vs. rural residence, making them differentially susceptible to types of polluting facilities that locate in rural vs. urban locations. For example, a larger proportion of non-Hispanic Whites in NC live in remote rural areas than do Blacks, the racial comparison is affected not only by the susceptibility of Whites vs. Blacks to IHOs, but also by differences in whether they live in rural vs. urban areas. By adjusting for population density (or rurality), we compare racial vulnerability to IHOs for racial groups within each level of rurality. This adjustment is analogous to other statistical adjustments in epidemiology, as when the death rates of two countries are compared: even though death rates at every age may be higher in a poor than a rich country, the poor country may have a lower overall death rate simply because it has a younger age distribution. In that case, age-adjustment is used to compare mortality in the two countries just as we use density-adjustment to compare the proximity to IHOs in areas with different racial/ethnic make-up.

We used weighted Poisson regression to quantify relationships between race/ethnicity and the presence of one or more IHOs within three miles of a block. We used weighted linear regression to quantify relationships between race/ethnicity and the SSLW of hogs permitted within three miles of a block. We used census block populations as weights. In density-adjusted models we included variables for the natural log of population density raised to the first, second and third power. As in our prior analysis, this cubic model fit the data well and additional power terms added little to the model fit (Wing et al. 2000). For the two largest racial/ethnic groups other than non-Hispanic Whites, POC and Blacks, we categorized race/ethnicity in groups of blocks 20% in width compared to blocks with no POC using indicator variables. Due to smaller numbers in these categories we did not fit models with indicator variables for Hispanics and American Indians. We also considered the percent of population of each race/ethnicity as a continuous variable, estimating the added burden of IHOs for a 10% increase in the population.

This study involves neither random sampling nor randomization of exposure to IHOs, therefore statistical significance testing is inappropriate and confidence intervals do not correspond to the probability that the true values of measures of association are within the interval. However, the US-EPA considers statistical significance in its assessment of environmental racism. We therefore report p-values for differences in proportions of each racial/ethnic group within 3 miles of an IHO using t-tests. We report 95% confidence intervals (CIs) as measures of precision of the associations estimated from regression models. 95% CIs that exclude the null value (1.0 for ratios and 0.0 for differences) are commonly considered to be statistically significant at $p<0.05$.

Results

We estimate that 2,055 IHOs were operating under the General Permit in January 2014, and that they were permitted to house approximately 1.2 billion pounds of swine (Table 1). The 160 (7.7%) IHOs permitted to house between 20 and 100 thousand pounds accounted for only 1% of the total permitted SSLW. The 342 (17.2%) IHOs permitted to house between 1 and 10.2 million pounds accounted for 46.5% of the total.

Table 2 shows that there are over 6.5 million residents of the study area. Approximately 986,000 (15.1%) of these live in census blocks whose centroid is within 3 miles of an IHO that operates under the General Permit. This includes 602,380 non-Hispanic Whites and 383,522 POC. 13.1% of non-Hispanic Whites and 19.9% of POC in the study area live in blocks within 3 miles of an IHO.

Based on the study area population in Table 2, Table 3 shows ratios of percentage of POC living within 3 miles of an IHO compared to the percentage of non-Hispanic Whites living within 3 miles of an IHO. The percentage of POC living within 3 miles of an IHO is 1.52 times higher than the percentage of non-Hispanic Whites. The percentages of Blacks, Hispanics and American Indians living within 3 miles of an IHO are 1.54, 1.39 and 2.18 times higher, respectively, than non-Hispanic Whites. If residents of the study area had been randomized to live within 3 miles of an IHO, the probabilities of observing differences of these magnitudes or greater are less than 0.0001; the observed differences are considered to be highly statistically significant.

We calculated these same ratios based on the entire state population of 9,535,483. The percentages of POC, Blacks, Hispanics and American Indians living within 3 miles of an IHO are 1.38, 1.40, 1.26 and 2.39 times higher than the percentage of non-Hispanic Whites, respectively. These ratios are considered to be highly statistically significant.

Figure 2 shows the percent of people living within 3 miles of an IHO in relation to the percent of people of color in blocks. In areas with less than 20% POC, just over 10% of the population lives within 3 miles of an IHO. In areas with 60-80% POC, over 20% of the population lives so close to an IHO. In areas with more than 80% POC, more than a quarter of the population lives within 3 miles of an IHO.

Table 4 presents ratios of the percent of people living within 3 miles of an IHO in blocks with >0 to <20%, 20 to <40%, 40 to <60%, 60 to <80% and 80 to 100% POC compared to blocks with no POC. The total population in these categories ranges from 526,305 in blocks with 60 to <80% POC to 2,577,015 in blocks with >0 to <20% POC. Ratios are statistically significantly elevated for all areas with more than 40% POC with or without adjustment for rurality. Ratios on the right side of Table 4 are adjusted for rurality. These ratios increase with the percentage POC. The highest ratios occur in areas with more than 80% POC, where over three times as many people live near IHOs, adjusted for rurality, compared to areas with no POC. These excesses are considered to be highly statistically significant.

Table 5 shows the results of analyses for Blacks parallel results to in Table 4 for all POC. Although ratios are somewhat lower for Blacks than POC, the percent of people living within 3 miles of an IHO is statistically significantly elevated in all groups of blocks that are more than 40% Black, with or without adjustment for rurality. In areas that are 80% or more Black, twice as many people live within 3 miles of an IHO compared to areas with no Blacks, a disparity that increases to three times more with adjustment for rurality. These excesses are considered to be highly statistically significant.

Table 6 presents the increased percent of the population living within 3 miles of an IHO for each additional 10 percent of the population of POC, Blacks, Hispanics, and American Indians. This analysis is similar to the results in Tables 4 and 5, but rather than using categories, the relationship between race/ethnicity and proximity to IHOs is modelled as a linear function. For every ten percent increase in POC, the proportion of people residing within 3 miles of an IHO increases, on average, by 10.7%. These values are 9.4, 8.5, and 16.2 for Blacks, Hispanics, and American Indians, respectively. Adjusting for rurality, 14.8% more people reside within 3 miles of an IHO for each additional ten percent POC. Adjusted values are 13.0, 16.3 and 11.8 for Blacks, Hispanics and American Indians, respectively. These linear relationships between race/ethnicity and living near IHOs are considered to be highly statistically significant.

Table 7 shows the difference in SSLW of hogs within 3 miles of residents of blocks with >0 to <20%, 20 to <40%, 40 to <60%, 60 to <80% and 80 to 100% POC compared to blocks with no POC. Blocks in categories with more than 20% POC have, on average, between 177 and 510 thousand pounds more hogs within 3 miles than blocks with no POC. Adjusting for population density, blocks with more than 60 percent POC have, on average, more than three-quarters of a

million pounds more hogs permitted within 3 miles than areas with no POC. These excesses are considered to be highly statistically significant.

Table 8 presents parallel results for percentage Black population. As for POC, areas with more than 20% Black residents have an excess SSLW of hogs compared to areas with no Black residents, and differences are greater with adjustment for rurality. Adjusted for population density, blocks with more than 40% Black residents have between 493,000 and 620,000 more pounds of hogs within 3 miles than areas with no Black residents. These excesses are considered to be highly statistically significant.

Table 9 provides the average additional SSLW of hogs permitted in areas with POC for each percent increase in specific racial/ethnic categories. Adjusted for population density, the permitted SSLW of hogs within 3 miles of blocks increases 100, 64, 242, and 92 thousand pounds for each ten percent increase in POC, Black, Hispanic, and American Indian population, respectively. These linear relationships between race/ethnicity and SSLW are considered to be highly statistically significant.

Figure 3 depicts the data analyzed above. Each dot represents an IHO that was operating under the General Permit in 2014. IHOs are concentrated in NC's Coastal Plain Region, between the Piedmont and Tidewater. The red areas of Figure 3 indicate that this region has more people of color than other parts of the study area.

Conclusion

IHOs operating under the NC-DENR General Permit in 2014 are disproportionately located near communities of color. The disparities are considered to be highly statistically significant for Blacks, Hispanics, American Indians, and all POC. IHOs pollute local ground and surface water. They routinely emit air pollutants that negatively impact the quality of life and health of nearby residents. In addition to their well-documented effects on physical, mental and social well-being, residents of areas with a high density of IHOs, and especially residents of color, have been subjected to intimidation including threats of legal action, violence, and job loss (Wing 2002). The industry's close ties with local and state government officials help it to avoid regulation that could protect neighbors, and creates barriers to democracy in rural communities of color (Thu 2001, 2003). These discriminatory impacts could be reduced by decreasing the density of production and use of technologies that prevent releases of pollutants.

References

Bullers S. 2005. Environmental Stressors, Perceived Control, and Health: The Case of Residents Near Large-Scale Hog Farms in Eastern North Carolina. Human Ecology 33:1-16.

Burkholder J, Libra B, Weyer P, Heathcote S, Kolpin D, Thorne PS, et al. 2007. Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality. Environ. Health Perspect. 115:308-312.

Casey JA, Curriero FC, Cosgrove SE, Nachman KE, Schwartz BS. 2013. High-Density Livestock Operations, Crop Field Application of Manure, and Risk of Community-Associated Methicillin-Resistant Staphylococcus Aureus Infection in Pennsylvania. JAMA Internal Medicine 173:1980-1990.

Cole D, Todd L, Wing S. 2000. Concentrated Swine Feeding Operations and Public Health: A Review of Occupational and Community Health Effects. Environ. Health Perspect. 108:685-699.

Cole D, Drum DJ, Stalknecht DE, White DG, Lee MD, Ayers S, et al. 2005. Free-living Canada Geese and Antimicrobial Resistance. Emerging Infectious Diseases 11:935-938.

Donham K. 1993. Respiratory Disease Hazards to Workers in Livestock and Poultry Confinement Structures. Seminars in Respiratory Medicine 14:49-59.

Donham K, Reynolds S, Whitten P, Merchant J, Burmeister L, Popendorf W. 1995. Respiratory Dysfunction in Swine Production Facility Workers: Dose-response Relationships of Environmental Exposures and Pulmonary Function. American Journal of Industrial Medicine 27:405-418.

Donham K, Cumro D, Reynolds S, Merchant J. 2000. Dose-Response Relationships Between Occupational Aerosol Exposures and Cross-Shift Declines of Lung Function in Poultry Workers: Recommendations for Exposure Limits. Journal of Occupational and Environmental Medicine 42:260-269.

Donham KJ. 1990. Health Effects from Work in Swine Confinement Buildings. American Journal of Industrial Medicine 17:17-25.

Donham KJ, Wing S, Osterberg D, Flora JL, Hodne C, Thu KM, et al. 2007. Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations. Environ. Health Perspect. 115:317-320.

Edwards B, Driscoll A. 2009. From Farms to Factories: The Environmental Consequences of Swine Industrialization in North Carolina. In: Twenty Lessons in Environmental Sociology, (Gould K, Lewis T, eds). New York: Oxford University Press, 153-175.

Furuseth O. 1997. Restructuring of Hog Farming in North Carolina: Explosion and Implosion. Professional Geographer 49:391-403.

Gibbs SG, Green CF, Tarwater PM, Mota LC, Mena KD, Scarpino PV. 2006. Isolation of Antibiotic-Resistant Bacteria from the Air Plume Downwind of a Swine Confined or Concentrated Animal Feeding Operation. Environ. Health Perspect. 114:1032-1037.

Graham JP, Price LB, Evans SL, Graczyk TK, Silbergeld EK. 2009. Antibiotic Resistant Enterococci and Staphylococci Isolated from Flies Collected near Confined Poultry Feeding Operations. Sci Total Environ 407:2701-10.

Green CF, Gibbs SG, Tarwater PM, Mota LC, Scarpino PV. 2006. Bacterial Plume Emanating from the Air Surrounding Swine Confinement Operations. Journal of Occupational and Environmental Hygiene 3:9-15.

Horton RA, Wing S, Marshall SW, Brownley KA. 2009. Malodor as a Trigger of Stress and Negative Mood in Neighbors of Industrial Hog Operations. American Journal of Public Health 99 Suppl 3:S610-615.

Mirabelli MC, Wing S, Marshall SW, Wilcosky TC. 2006. Asthma Symptoms Among Adolescents Who Attend Public Schools that are Located Near Confined Swine Feeding Operations. Pediatrics 118:e66-75.

Radon K, Schulze A, Ehrenstein V, van Strien RT, Praml G, Nowak D. 2007. Environmental Exposure to Confined Animal Feeding Operations and Respiratory Health of Neighboring Residents. Epidemiology 18:300-308.

Rinsky JL, Nadimpalli M, Wing S, Hall D, Baron D, Price LB, et al. 2013. Livestock-Associated Methicillin and Multidrug Resistant Staphylococcus Aureus Is Present Among Industrial, Not Antibiotic-Free Livestock Operation Workers in North Carolina. PloS One 8:e67641.

Schiffman S, Bennett J, Raymer J. 2001. Quantification of Odors and Odorants from Swine Operations in North Carolina. Agricultural and Forest Meteorology 108:213-240.

Schiffman SS, Sattely Miller EA, Suggs MS, Graham BG. 1995. The Effect of Environmental Odors Emanating from Commercial Swine Operations on the Mood of Nearby Residents. Brain Research Bulletin 17:369-375.

Schinasi L, Horton RA, Guidry VT, Wing S, Marshall SW, Morland KB. 2011. Air Pollution, Lung Function, and Physical Symptoms in Communities Near Concentrated Swine Feeding Operations. Epidemiology 22:208-215.

Schulz J, Friese A, Klees S, Tenhagen BA, Fetsch A, Rosler U, et al. 2012. Longitudinal Study of the Contamination of Air and of Soil Surfaces in the Vicinity of Pig Barns by Livestock-Associated Methicillin-Resistant Staphylococcus Aureus. Applied and Environmental Microbiology 78:5666-5671.

Silbergeld EK, Graham J, Price LB. 2008. Industrial Ffood Animal Production, Antimicrobial Resistance, and Human Health. Annual Review of Public Health 29:151-169.

Tajik M, Muhammad N, Lowman A, Thu K, Wing S, Grant G. 2008. Impact of Odor from Industrial Hog Operations on Daily Living Activities. New Solututions 18:193-205.

Thu K, Donham K, Ziegenhorn R, Reynolds S, Thorne P, Subramanian P, et al. 1997. A Control Study of the Physical and Mental Health of Residents Living near a Large-Scale Swine Operation. Journal of Agricultural Safety and Health 3:13-26.

Thu K. 2001. Agriculture, the Environment, and Sources of State Ideology and Power. Culture and Agriculture 23:1-7.

Thu K. 2003. Industrial Agriculture, Democracy, and the Future. In: Beyond Factory Farming: Corporate Hog Barns and the Threat to Public Health, the Evironment, and Rural Communities, (Ervin A, Holtslander C, Qualman D, Sawa R, eds). Saskatoon, Saskatchewan:Canadian Centre for Policy Alternatives.

van de Giessen AW, van Santen-Verheuvel MG, Hengeveld PD, Bosch T, Broens EM, Reusken CB. 2009. Occurrence of Methicillin-Resistant Staphylococcus Aureus in Rats Living on Pig Farms. Preventive Veterinary Medicine 91:270-273.

Wing S, Cole D, Grant G. 2000. Environmental Injustice in North Carolina's Hog Industry. Environ. Health Perspect. 108:225-231.

Wing S, Wolf S. 2000. Intensive Livestock Operations, Health, and Quality of Life among Eastern North Carolina Residents. Environ. Health Perspect. 108:233-238.

Wing S. 2002. Social Responsibility and Research Ethics in Community-Driven Studies of Industrialized Hog Production. Environ. Health Perspect. 110:437–444.

Wing S, Freedman S, Band L. 2002. The Potential Impact of Flooding on Confined Animal Feeding Operations in Eastern North Carolina. Environ. Health Perspect. 110:387-391.

Wing S, Horton RA, Marshall SW, Thu K, Tajik M, Schinasi L, et al. 2008. Air Pollution and Odor in Communities Near Industrial Swine Operations. Environ. Health Perspect. 116:1362-1368.

Wing S, Horton RA, Rose KM. 2013. Air Pollution from Industrial Swine Operations and Blood Pressure of Neighboring Residents. Environ. Health Perspect. 121:92-96.

Figure 1
North Carolina study area, 2014

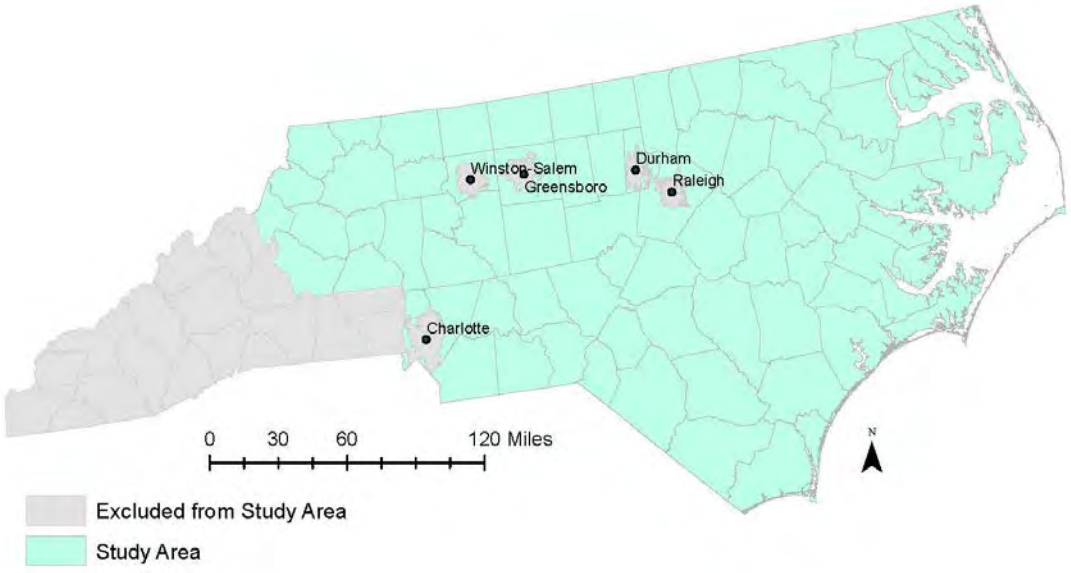

Figure 2
Percent of population living within 3 miles of an IHO
in relation to percent people of color, NC, 2014

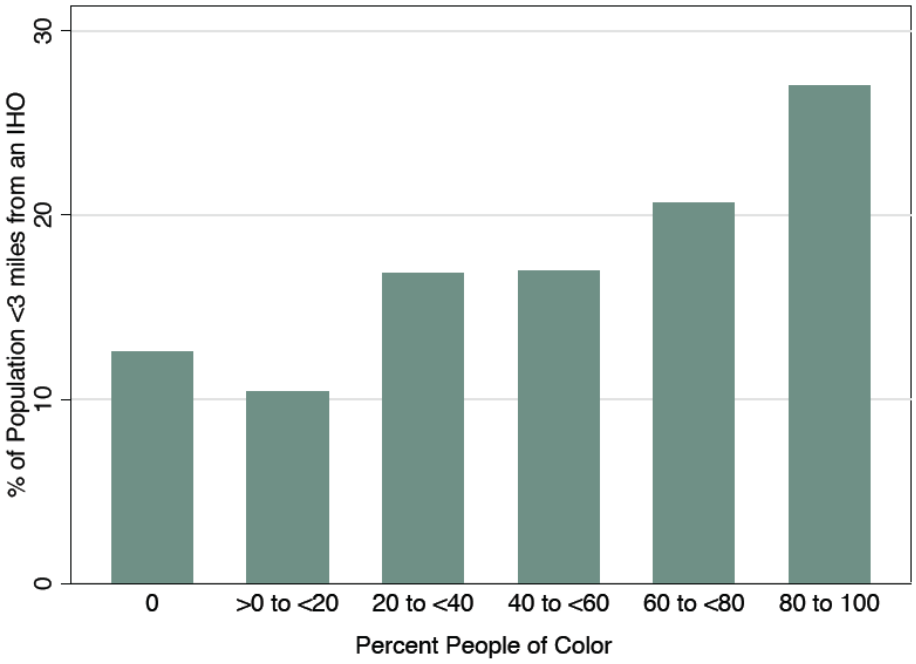

Figure 3
Racial and ethnic composition of census blocks and the locations
of NC IHOs operating under the General Permit, 2014

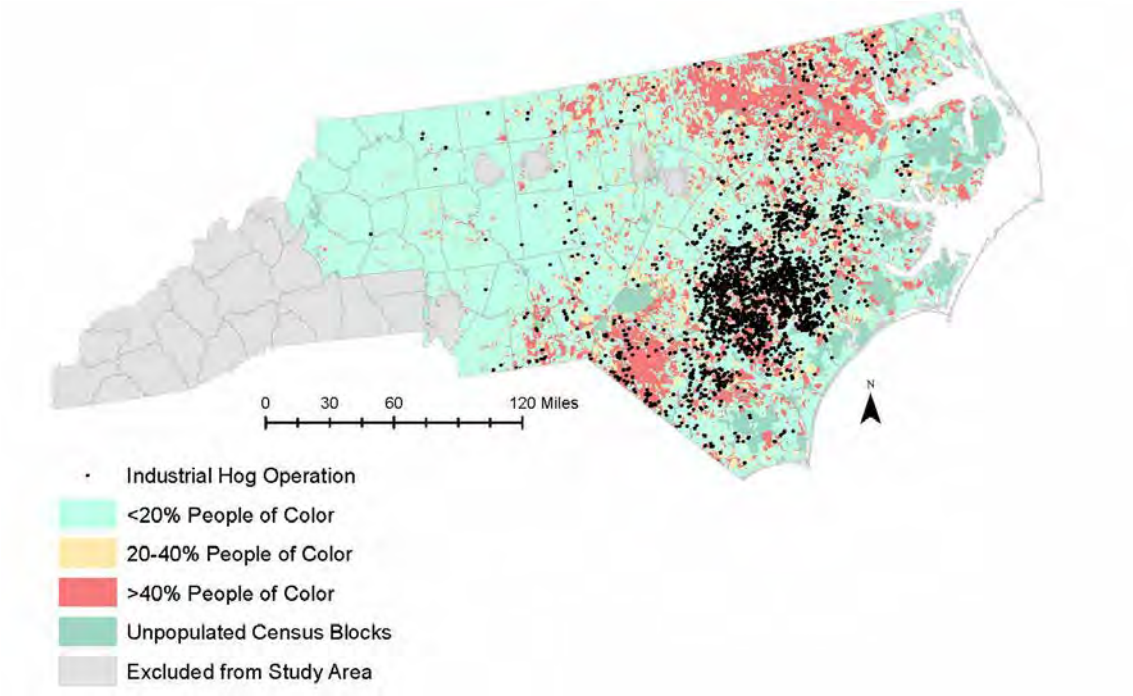

Table 1
Steady state live weight of IHOs
operating under the General Permit, NC, 2014

Permitted SSLW[1]	Number of IHOs	Percent of IHOs	Total SSLW[1]	Percent of total SSLW
20-	160	7.7	12,574	1.0
100-	447	21.6	76,626	5.9
250-	577	28.1	222,003	17.1
500-	529	25.4	383,918	29.6
1,000-10,200	342	17.2	603,354	46.5
Total	2055	100.0	1,298,474	100.0

[1]Thousands of pounds

Table 2
Racial and ethnic composition of NC census blocks within 3 miles
of an IHO and more than 3 Miles of an IHO, 2014

	≤3 miles from an IHO		≥3 miles from an IHO		
Racial Category	Number	Percent	Number	Percent	Total[1]
Non-Hispanic white	602,380	13.1	4,003,455	86.9	4,605,835
POC[1]	383,522	19.9	1,548,276	80.1	1,931,798
Black	277,199	20.2	1,096,795	79.8	1,373,994
Hispanic	92,679	18.1	418,292	81.9	510,971
American Indian	40,621	28.5	101,872	71.5	142,493
Total[1]	985,902	15.1	5,551,731	84.9	6,537,633

[1]POC can be counted in more than one racial/ethnic category. The total population is equal to the number of non-Hispanic Whites plus the number of POC.

Table 3
Ratios of POC compared to non-Hispanic Whites living within 3 Miles of an IHO operating under the General Permit, 2014

Racial/ethnic Category	Population	≤3 miles from an IHO Number	Percent	Ratio[2]	p-value[3]
Non-Hispanic white	4,605,835	602,380	13.1	1.00	--
POC[1]	1,931,798	383,522	19.9	1.52	<0.0001
Black	1,373,994	277,199	20.2	1.54	<0.0001
Hispanic	510,971	92,679	18.1	1.38	<0.0001
American Indian	142,493	40,621	28.5	2.18	<0.0001
Total[1]	6,537,633	985,902	15.1		

[1]People of color can be counted in more than one racial/ethnic category. The total population is equal to the number of non-Hispanic Whites plus the number of POC.
[2]Ratio of the percent of people of other racial/ethnic groups to percent of non-Hispanic Whites living within 3 miles of an IHO
[3]A difference in proportions of this magnitude or greater would be expected to occur less than one time in ten thousand if people of different racial/ethnic groups had been randomized to live within 3 miles of an IHO.

Table 4
Ratios comparing the percent of people residing within 3 miles of an IHO in blocks with POC compared to blocks with no POC

Percent POC	Population	Unadjusted Prevalence Ratio	95% CI	Adjusted[1] Prevalence Ratio	95% CI
0	694,747	1.0	referent	1.00	referent
>0 to <20	2,577,015	0.83	0.82, 0.83	1.01	1.00,1.02
20 to <40	1,364,923	1.34	1.33, 1.45	1.95	1.93, 1.97
40 to <60	799,124	1.35	1.34, 1.36	2.15	2.13, 2.16
60 to <80	526,305	1.64	1.62, 1.65	2.53	2.50, 2.55
80 to 100	575,519	2.14	2.12, 2.16	3.30	3.27, 3.32

[1]Adjusted for rurality using a cubic polynomial of the natural log of population density

Table 5
Ratios comparing the percent of people residing within 3 miles of an IHO in blocks with Black residents compared to blocks with no Black residents

Percent Black	Population	Unadjusted Prevalence Ratio	95% CI	Adjusted[1] Prevalence Ratio	95% CI
0	1,308,061	1.00	referent	1.00	referent
>0 to <20	2,941,746	0.93	0.92, 0.94	1.20	1.19,1.21
20 to <40	1,043,277	1.44	1.43, 1.45	2.07	2.05, 2.08
40 to <60	536,198	1.52	1.51, 1.53	2.18	2.17, 2.20
60 to <80	336,232	1.57	1.56, 1.59	2.19	2.17, 2.21
80 to 100	372,119	2.01	1.99, 2.02	3.06	3.04, 3.09

[1]Adjusted for rurality using a cubic polynomial of the natural log of population density

Table 6
Percent difference in the percent of people residing within 3 miles of an IHO for a ten percent increase in the population of each racial/ethnic group

Racial/ethnic group	Unadjusted Percent	95% CI	Adjusted[1] Percent	95% CI
POC	10.7	10.6, 10.8	14.8	14.7, 14.9
Black	9.4	9.3, 9.4	13.0	12.9, 13.1
Hispanic	8.5	8.4, 8.6	16.3	16.1, 16.4
American Indian	16.2	16.0, 16.4	11.8	11.6, 12.0

[1]Adjusted for rurality using a cubic polynomial of the natural log of population density

Table 7
Difference in SSLW of hogs within 3 miles of residents of blocks with POC compared to blocks with no POC

Percent POC	Unadjusted SSLW[2]	95% CI	Adjusted[1] SSLW	95% CI
0	Referent	-	Referent	-
>0 to <20	-35	-73, 3	190	154, 227
20 to <40	177	136, 219	535	495, 575
40 to <60	308	262, 353	717	672, 762
60 to <80	510	459, 561	896	846, 946
80 to 100	453	403, 503	837	788, 885

[1]Adjusted for rurality using a cubic polynomial of the natural log of population density
[2]1,000s of pounds

Table 8
Difference in SSLW of hogs within 3 miles of residents of blocks with Black residents compared to blocks with no Black residents

Percent Black	Unadjusted SSLW[2]	95% CI	Adjusted[1] SSLW	95% CI
0	Referent	-	Referent	-
>0 to <20	-4	-33, 25	237	207, 265
20 to <40	190	153, 227	493	457, 530
40 to <60	327	281, 372	620	576, 665
60 to <80	275	221, 330	547	494, 599
80 to 100	165	113, 218	494	444, 545

[1]Adjusted for rurality using a cubic polynomial of the natural log of population density
[2]1,000s of pounds

Table 9
Difference in SSLW of hogs within 3 miles of residents of blocks for a ten percent increase in population of each racial group

Racial/ethnic group	Unadjusted SSLW[2]	95% CI	Adjusted[1] SSLW	95% CI
POC	67	63, 71	100	96, 104
Black	38	34, 42	64	60, 68
Hispanic	183	174, 192	242	234, 251
American Indian	124	111, 137	92	80, 105

[1]Adjusted for rurality using a cubic polynomial of the natural log of population density
[2]1,000s of pound

Exhibit 23

May 6, 2022

Via First Class and Electronic Mail

Laura Watson, Director
Washington State Department of Ecology
P.O. Box 47600
Olympia, WA 98504-7600

Re: Environmental Justice and Washington Concentrated Animal Feeding Operations Permitting

Dear Director Watson,

Puget Soundkeeper Alliance, Friends of Toppenish Creek, Sierra Club, Waterkeeper Alliance, Center for Food Safety, and Western Environmental Law Center, and their tens of thousands of members, supporters, and volunteers throughout the State of Washington, are writing to express our concern with the Department of Ecology's (Ecology) failure to engage with communities impacted by discharge from Concentrated Animal Feeding Operations (CAFO) while drafting its general NPDES permit.[1]

Introduction

As we have made clear in our advocacy during the CAFO permitting process, Ecology must engage with the communities impacted by its regulatory decisions, particularly those already overburdened by past and ongoing environmental discrimination. Because Ecology is the state agency charged with protecting our air and water, this engagement is not only a moral imperative but also a legal requirement.

Ecology acknowledges this moral and legal requirement. Yet, in its efforts to develop a general NPDES permit for CAFOs, Ecology is failing to engage with the people directly harmed by pollution from these operations. Because of this, the agency is uninformed of the true impacts and interests of the people working and living in and around CAFOs, and is at risk of producing yet another inadequate and unprotective general permit.

CAFOs have profoundly negative impacts on the health of workers and the people who live in surrounding communities, including through pollutant discharge into water.[2] As a result,

[1] We use the terms "impacted" and "affected" to refer to regions and people subject to harms from CAFO discharges ranging from lack of access to healthy drinking water to impacts on fish that are an important source of food. Because there is the tendency for CAFOs to be located in regions where people experience cumulative environmental burdens, these terms overlap with the "vulnerable populations" and "overburdened communities" identified in the HEAL Act. *See* RCW 70A.02.010.

[2] *See, e.g.*, Grout et al., A Review of Potential Public Health Impacts Associated With the Global Dairy Sector, 4 GeoHealth 1 (January 30, 2020); Carrie Hribar, Understanding concentrated animal feeding operations and their impact on communities, National Association of Local Boards of Health at 7, 9 (2020) available at https://www.cdc.gov/nceh/ehs/docs/understanding_cafos_nalboh.pdf.

Ecology must actively engage members of communities affected by CAFO discharge in a dialogue regarding the impact of industrial dairy farms on their water, the legal requirements mandating NPDES permitting of these operations, the scope of the general permit, and the needs and wishes of the members of the local community regarding the regulation of these entities under federal and state clean water law. To do less is unacceptable in any case, but is particularly egregious here given the agency's professed commitment to environmental justice.

I. Ecology's mission and duties mandate attention, consultation, and engagement with people affected by CAFO discharge

Ecology's mission is to "[p]rotect, preserve and enhance Washington's land, air and water for current and future generations."[3] This mandate to protect our natural resources is broad, and is based on the "fundamental and inalienable right of the people of the state of Washington to live in a healthful and pleasant environment and to benefit from the proper development and use of its natural resources."[4] To carry out this mission effectively, Ecology, "in consultation with affected constituent groups, [must] continue appropriate public involvement and outreach mechanisms designed to provide cost-effective public input on their programs and policies."[5]

While the duty to consult with communities affected by pollution is not new, it is now informed by the specific duties of the HEAL Act, passed in 2021, requiring the agency to act towards realizing environmental justice for overburdened communities and vulnerable populations.[6] Ecology reaffirms this duty by stating that it is "committed to making decisions that do not place disproportionate environmental burdens" on communities in Washington State.[7] Further, the agency recognizes that full participation by impacted communities in decision-making is an essential step toward environmental justice.[8] This is consistent with the HEAL Act's requirement that Ecology adopts and implements a plan to engage overburdened communities and vulnerable populations by July 1, 2022.[9]

Because Ecology failed to draft a general permit that met the mandates under state and federal law, CAFOs in Washington State now operate under a permit that expired in March 2022.[10] Ecology's current timeline indicates it plans to release a draft general permit by late

[3] Ecology, About Us https://ecology.wa.gov/About-us (last visited April 8, 2022).

[4] RCW 43.21A.010.

[5] RCW 43.20A.005.

[6] Engrossed Second Substitute Senate Bill 5141 67th Leg. 2021 Reg. Session (HEAL Act).

[7] Ecology, Environmental Justice https://ecology.wa.gov/About-us/Who-we-are/Environmental-Justice (last visited May 2, 2022).

[8] *Id.*

[9] RCW 70A.02.050(1).

[10] Ecology, Concentrated Animal Feeding Operation https://ecology.wa.gov/Regulations-Permits/Permits-certifications/Concentrated-animal-feeding-operation (last visited May 4, 2022); *Washington State Dairy Fed'n v. State*, 18 Wash. App. 2d 259, 304, 490 P.3d 290 (2021).

spring 2022 for public comment.[11] This means the first stage of drafting will be complete before the July 1 date by which the HEAL Act requires Ecology to adopt its engagement plan. However, any attempt by Ecology to suggest it has some grace period not to engage because its plan is not required at the time the draft permit is released is contrary to stated policy and statutory mandates.

First, as discussed above, Ecology itself states that it is "committed to providing environmental justice to our most vulnerable communities."[12] It claims that environmental justice "is a priority in our efforts to restore and protect land, air, and water."[13] The agency does not tie this commitment to a timeline but indicates it is working towards environmental justice now. Second, under RCW 43.20A.005, the agency has a statutory duty predating the HEAL Act to make at least some effort toward facilitating public engagement.[14] Third, the Clean Water Act requires "[p]ublic participation in the development, revision, and enforcement of any regulation, standard, effluent limitation, plan, or program established by the Administrator or any State."[15] This was one of the legal mandates that Ecology violated in its last iteration of the permit according to the Washington State Court of Appeals.[16]

Finally, apart from policy declarations and statutory duties, any suggestion by Ecology that it is not prepared to effectively engage in outreach is belied by the fact that it already has started outreach efforts under the Climate Commitment Act.[17] Through this program, it is seeking input **from some of the very same communities most impacted by CAFOs**. Despite this overlap, Ecology is not coordinating these efforts.[18] Additionally, Ecology can look to the Environmental Justice Task Force Final Report, produced nearly two years ago, for detailed information about approaches for effectively facilitating community engagement.[19]

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[11] Ecology, Concentrated Animal Feeding Operation https://ecology.wa.gov/Regulations-Permits/Permits-certifications/Concentrated-animal-feeding-operation (last visited May 4, 2022).

[12] Ecology, Prioritizing EJ https://ecology.wa.gov/About-us/Who-we-are/Environmental-Justice/Prioritizing-EJ (last visited April 12, 2022).

[13] *Id.*

[14] RCW 43.20A.005.

[15] 33 U.S.C. § 1251(e).

[16] *Washington State Dairy Fed'n v. State*, 18 Wash. App. 2d 259, 304, 490 P.3d 290 (2021).

[17] *See* Ecology, Improving Air Quality in Overburdened Communities https://storymaps.arcgis.com/stories/1409205ca61847faa4194072330709cd (last visited May 4, 2022); *See also Ecology*, Overburdened communities https://ecology.wa.gov/Air-Climate/Climate-change/Reducing-greenhouse-gases/Climate-Commitment-Act/Overburdened-communities (last visited April 12, 2022).

[18] *Id.*

[19] Washington State Environmental Justice Task Force Final Report (Fall 2020).

II. To comply with its own policy goals and its legal duty to realize environmental justice, Ecology must engage those members of overburdened communities and vulnerable populations affected by CAFO discharge[20]

Environmental justice is an effort to redress the impacts of historical and ongoing racism and poverty on the distribution of environmental benefits and harms and resulting health outcomes. Currently, the pattern seen across the United States and within Washington State is the inequitable distribution of environmental burdens and benefits, where the cumulative harms of pollutants and other environmental risk factors fall hardest on people of color, Indigenous and Tribal people, and low-income residents, among others.[21] These disparate environmental impacts result in clear patterns of higher mortality rates and worse general health outcomes for people with historically marginalized identities.[22] The discrimination driving the decision-making by governmental entities that lead to these patterns is directly related to failures to ensure that people with historically marginalized identities have a voice and power in decisions directly affecting them. Thus, a governmental entity, such as Ecology, in working towards repairing its and other entities' legacies of discrimination must ensure the right of individuals most impacted by environmental decisions to "participate as equal partners at every level of decision-making, including during needs assessment, planning, implementation, enforcement, and evaluation."[23] Waiting until decision-making processes have already reached draft form is too late because, at this point, members of these communities have already been stripped of the power to drive the shape and parameters of the governmental action.

In Washington State, many CAFOs regulated under Ecology's general permit occur in regions, such as Yakima County, with a higher proportion of low-income and Indigenous people,

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[20] The HEAL Act defines an "overburdened community" as "a geographic area where vulnerable populations face combined, multiple environmental harms and health impacts, and includes, but is not limited to, highly impacted communities as defined in RCW 19.405.020." RCW 70A.02.010(11). It defines "vulnerable populations" as

> population groups that are more likely to be at higher risk for poor health outcomes in response to environmental harms, due to: (i) Adverse socioeconomic factors, such as unemployment, high housing and transportation costs relative to income, limited access to nutritious food and adequate health care, linguistic isolation, and other factors that negatively affect health outcomes and increase vulnerability to the effects of environmental harms; and (ii) sensitivity factors, such as low birth weight and higher rates of hospitalization.

RCW 70A.02.010(14)(a).

The Heal Act states that the term "vulnerable populations" "includes, but is not limited to: (i) Racial or ethnic minorities; (ii) Low-income populations; (iii) Populations disproportionately impacted by environmental harms; and (iv) Populations of workers experiencing environmental harms." *Id.*

[21] *See, e.g.*, Julie Sze, Environmental Justice in a Moment of Danger (2020); Clifford Villa et al., Environmental Justice: Law, Policy & Regulation, Third Edition (2020).

[22] *See, e.g.*, Rachel Morello-Frosch et al., Understanding the Cumulative Impacts of Inequalities in Environmental Health: Implications for Policy, 30 Health Affairs 879 (May 2011).

[23] *See* First National People of Color Environmental Leadership Summit, Principles of Environmental Justice (1991), available at https://www.ejnet.org/ej/principles.html.

people of color, and Tribal members living and working in the area.[24] People with these historically marginalized identities who live and work in the regions where CAFOs tend to be clustered experience elevated environmental burdens where community members suffer worse health outcomes as a result of air and water pollution, including higher rates of asthma, lower birth rates, and shorter life-spans.[25]

Ecology's current regulatory approach for addressing the environmental damage of CAFOs is through its NPDES general permitting program. Under federal law, as reiterated and reaffirmed by the Washington State Court of Appeals in June 2021, Ecology must provide a means for the public to comment on the draft NPDES permit for regulating CAFO discharge. Under state law, Ecology must work to engage and consult with impacted communities. Finally, Ecology's commitment to equity and environmental justice makes it imperative that it ensure the full participation of local communities in the process.

III. Ecology's public outreach to date has been inadequate

So far, unfortunately, Ecology has failed to engage impacted communities sufficiently.[26] In contrast, the agency has reached out to and visited the *regulated* community.[27] Fortunately, there is still time for Ecology to take the necessary steps to engage the public before finalizing the draft permit.

As Ecology is well aware, the permitting process is complex. Fundamental, therefore, to enfranchising people who are not experts in the technical or legal field, but are experts in their own lived experience, is effectively communicating to the public the impacts of CAFOs on water, the function of NPDES permitting to address these impacts, the process by which Ecology goes about developing these permits, and how affected individuals can be involved in the process. Ecology's website is one obvious place where the agency should host this information.

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[24] U. S. Census, Quickfacts Washington State https://www.census.gov/quickfacts/fact/map/WA,US/PST045221 (last visited April 28, 2022).

[25] *See, e.g.*, E. Min, Quantifying the Distribution of Environmental Health Threats and Hazards in Washington State Using a Cumulative Environmental Inequality Index, 14 Environmental Justice 298 (2021) (determining that pollution burdens in general, are significantly higher for people of color and those living in poverty in Washington State); Esmy Jimenez, New Map Shows Hotspots Of Environmental Health Hazards For Washington Neighborhoods, Northwest Public Broadcasting (January 10, 2019) (describing Yakima County's reduced health outcomes as appearing like "a big, red blemish" on the Washington State Health Disparities Map) available at https://www.nwpb.org/2019/01/10/new-map-shows-hotspots-of-environmental-health-hazards-for-washington-neighborhoods/; Jacques Colon, The Disproportionate Burden of Fossil Fuel Air Pollution on Communities of Color in Washington State, Front and Centered Report (June 15, 2016) (describing shorter life-spans on average resulting from community exposure to cumulative environmental harms).

[26] Chelsea Morris mentioned that she was sending information to one community group at our meeting with her on January 7, 2022.

[27] Statements by Chelsea Morris during the September 21, 2021 meeting between Ecology's Chelsea Morris, Jeff Killelea, Nathan Lubliner, and members of Center for Food Safety, Friends of Toppenish Creek, and Puget Soundkeeper Alliance.

Currently, Ecology's website does not provide this information. In particular, it does not explain the permitting process, discuss why permitting is needed for CAFOs, or describe exactly how the agency develops the CAFO permit.[28] Instead, the website briefly mentions the current development of the general permit as a direct response to the June 2021 court opinion, with little further information, and no indication of how public input functions as part of what it is considering.

Further, the website's information about opportunities to comment is stale, as it is limited to links for the two "listening sessions" held in October 2021 and a link to an "online comment form" that closed on Sunday, October 24, 2021.[29] Information such as the "Detailed Explanation of the Permits" discusses the previous iteration of the permit and is long and dense rather than user-friendly.[30]

Ecology has provided a Spanish-language focus sheet discussing the NPDES permit regulation of CAFOs, including a description of the potential for the operations to pollute drinking water, and instructions for reporting contamination.[31] This sheet provides one possible starting point for developing more information on the website itself. However, it does not provide a discussion of the current permitting process, nor does it invite input.[32] So it does not solve the website's fundamental lack of information regarding the permitting process.

Another approach to outreach is public forums, including listening sessions. Ecology had two virtual listening sessions in October 2021. Unfortunately, these listening sessions did not represent effective forums for communication. They did not provide clear information but rather meandered through the dense technical weeds of the court opinion and Ecology's concerns.

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[28] The site links to a fact sheet in Spanish that at least provides some basic explanation of the problem. Translating some of this fact sheet back to English, particularly in the discussion of the impact of CAFO discharge on drinking water could be one, of many, ways Ecology could update the landing site to make it more relevant and useful to people affected by CAFO discharge in their region. *See,* Ecology, Hoja de Enfoque: Permiso de Operación de Alimentación de Animales Confinados (April 2022) available at https://apps.ecology.wa.gov/publications/parts/1710002part1.pdf .

[29] As we communicated to Ecology during the January 7, 2022 meeting, those "listening sessions" were deeply flawed.

[30] Ecology, Fact Sheet for the Concentrated Animal Feeding Operation National Pollutant Discharge Elimination System and State Waste Discharge General Permit and Concentrated Animal Feeding Operation State Waste Discharge General Permit (June 15, 2016) available at https://ecology.wa.gov/DOE/files/a3/a36ceb3d-7767-4a21-a354-d4b7c1965c95.pdf.

[31] Ecology, Hoja de Enfoque: Permiso de Operación de Alimentación de Animales Confinados (April 2022) available at https://apps.ecology.wa.gov/publications/parts/1710002part1.pdf . The opportunity to report violations is not currently an effective way for people in the community to protect their waters given apparent failures in agency response to these reports. This is, in part, the result of the 2011 Memorandum of Understanding between Ecology and the Washington State Department of Agriculture, which has led to holes between permitting under state and federal clean water law and enforcement in situations where dairies are violating the law.

[32] It is a positive step that Ecology provides the possibility of translated materials via contacting Chelsea Morris or Ecology's Language Access Team. But this service still requires a member of the community know what information it is he/she/they seek, take the step of asking for that information to be translated, and be prepared to wait however long it takes the agency to return the translated materials.

Further, the information provided was not always accurate. The webinars were hosted on a platform that disenfranchised participants because people could not see each other, and the webinars were not moderated in any way to facilitate comments by those not part of the regulated community. Finally, when people, for example from the regulated community, spoke the agency did not provide information about these speakers and their involvement and interests in the process or correct the misinformation that was provided.

Providing clarity of process and a sense that input is valued and can impact agency decision-making is essential to effective engagement. Unfortunately, as described above, Ecology does not explain how it will use public input in its permit development process. And by stating on its website that it "will not create a formal response to verbal or written comments during [its] listening session comment period"[33] it gives the appearance of relieving itself of any duty to consider the comments.

This opacity of process, apparent lack of interest in community dialogue, and failure to even do the minimum on its website or in forums to reduce barriers to access for members of the impacted community is unacceptable. We know Ecology can do better.

V. Ecology must engage in far more effective outreach as it develops the draft and final CAFO general permit

As mentioned above, Ecology has the internal knowledge, connections, and resources to far more effectively engage and empower members of impacted communities in the process of CAFO permit development than it has done so far. Given the legal and policy landscape under which it is undertaking this process, the agency does not have a choice. It must do a better job. Although ultimately, it is the agency's role to develop an engagement plan, we provide some basic expectations below for how the agency might improve its outreach and engagement with impacted communities moving forward.

These expectations arise out of our recognition of the barriers to engagement experienced by members of impacted communities resulting from the systems of oppression, including White supremacy, settler colonialism, capitalist hegemony, patriarchy, and Christian hegemony threaded through agency culture and structure.[34] These barriers include lack of access and information, failure of effective communication, apathy and a sense of burden, lack of clear and transparent process, lack of resources, lack of a sense of potential for influence, lack of trust, and a failure to recognize different types of knowledge.[35] Many of these barriers result from Ecology's fundamental failure to recognize its role as the steward of the state's clean water, and the expertise people in communities impacted by CAFOs have regarding their own life experiences. Realizing environmental justice requires Ecology to approach these communities with humility, an interest

[33] Ecology, Concentrated animal feeding operations, https://ecology.wa.gov/Regulations-Permits/Permits-certifications/Concentrated-animal-feeding-operation (last visited May 4, 2022).

[34] Washington State Environmental Justice Task Force Final Report at Appendix C (Fall 2020).

[35] *Id.* at 64, Appendix C.

in what people can tell them about their experience, and a willingness to allow that information to impact its decision-making.

We recognize that the agency will continue to work through the more fundamental structural and cultural barriers to achieving environmental justice. Related to this, however, Ecology must do a much better job of reaching out to the communities most impacted by pollution from CAFOs. Below are some of the first steps we expect to see from Ecology as it develops the CAFO general permits.

A. Provide better information.

As described above, Ecology has not provided easy access to or effective communication of information about the CAFO permitting process, including how Ecology will consider comments from community members. **Ecology should improve the website, as described above, and host community events, whether virtual or in-person, to provide basic, jargon-free information about the problem, process, and potential for engagement.** Optimally, this information would be provided in English and languages other than English, and delivered through a variety of media, recognizing that providing information only through the written word often presents a barrier in and of itself.

B. Use a variety of platforms and media to communicate information.

Currently, Ecology's failure to widely distribute information across different platforms disenfranchises members of the impacted community. **Ecology must distribute information about CAFOs, their impact, the permits, the permitting process, and opportunities to engage, both online and via meetings, across platforms, to those individuals in regions affected by the permits through electronic and other means (such through churches, colleges, community centers, groceries, food banks, feed stores, hardware stores, the Yakima Herald Republic, Cascadia Weekly, and Radio KDNA).**

C. Coordinate internally to identify groups and individuals in the communities impacted by CAFOs to invite them into the conversations about the CAFO permitting process.

As discussed above, Ecology is already conducting outreach and listening sessions consistent with the Climate Commitment Act in regions also affected by entities covered by the CAFO general NPDES permit. By failing to coordinate internally, the agency disenfranchises members of the communities by failing to make a reasonable effort to reach out to them about CAFO impacts and additionally burdening the local communities with trying to understand the agency's role in the region. **Ecology should therefore coordinate with those agency employees developing the Air Quality in Overburdened Communities Initiative to identify common regions of concern and reach out to people already engaged with the agency in these areas.**[36]

[36] For example, the agency now has a list with addresses and phone numbers of individuals who had expressed concerns about Yakima air quality over the years as a result of efforts on the part of Friends of Toppenish Creek. This is exactly the sort of resource that should be shared within the agency. It is an obvious first step to mail information about the CAFO permitting process, in multiple languages, to these people.

D. Convene organizations and individuals to gather input on how best to reach out to and communicate with those directly impacted by CAFOs

People and organizations in Whatcom County and Yakima are experts in their experience of the impact of CAFOs. They are also knowledgeable about each other and how to communicate with people living and working in these regions. Yet, Ecology has not made an effort to gather input on outreach from these groups and individuals. Instead, it expects the communities and individuals to do the outreach that it should be doing. This further burdens groups and individuals already stretched thin by multiple overlapping crises[37] and ensures that barriers to access are strengthened rather than dismantled. **Given the wealth of expertise available and recognizing the burdens already faced by organizations and individuals, Ecology should convene these groups and individuals and collect information from them regarding how best to conduct outreach. These meetings should follow best practices in recognizing barriers to participation in meetings and Ecology should communicate how it intends to use the information. It should also provide follow-up demonstrating that it relied on the information as a way to establish the value of the input of these organizations and individuals.**

E. Host more frequent and more accessible meetings that empower members of the community.

Ecology's approach to meetings creates barriers to access. **Ecology should provide more opportunities for the impacted community to discuss their lived experience of CAFOs with the agency.** Optimally, these opportunities would be in person, although we recognize that the pandemic continues to make this difficult. Regardless, these events must be organized to ensure that people feel empowered rather than excluded. **At a minimum, Ecology must provide the information participants need to feel comfortable speaking up in such a space. Further, participants must be able to see one another, the discussion must be sensitive to different abilities and languages, and Ecology should make sure that, when members of the regulated community provide inaccurate information, that information is challenged.**

VI. Conclusion

Ecology has a moral and a legal duty to engage people impacted by the entities they regulate, particularly members of those communities harmed by a history of discriminatory environmental decision-making. Yet, in the process of developing its general CAFO NPDES permit, the agency has, time and again, failed to make even the most basic attempt to include impacted community members. We urge Ecology to comply with law and policy as it moves forward in the process.

[37] Isabel Carrera Zamanill, Covid-19 Gap Analysis, Front & Centered Report (February 2021) available at https://frontandcentered.org/wp-content/uploads/2021/02/FC-COVID-19-Gap-Analysis.pdf; Alison Saldanha and Elise Takahama, Graphics tell story of COVID's unequal toll across WA, Seattle Times (April 12, 2022) available at https://www.seattletimes.com/seattle-news/health/tracking-covids-unequal-unpredictable-toll-across-washington/; Brandi Fullwood and Libby Denkmann, Whatcom County in Recovery Braces for More Floods, KUOW (February 3, 2022) available at https://www.kuow.org/stories/whatcom-county-in-recovery-braces-for-more-floods.

People most impacted by CAFOs in the state are themselves currently dealing with ongoing emergent situations ranging from the COVID-19 pandemic to flooding.[38] Indeed, COVID-19 has had a particularly harmful impact on the lives of people in Yakima Valley.[39] These multiplying crises mean that, rather than using COVID-19 as an excuse for its failure to engage the people impacted by CAFOS, the agency must redouble its efforts to protect these communities and empower their members in the process of permit development.

We look forward to supporting Ecology in these efforts. If you have questions or would like to talk with us further please feel free to reach out to Jennifer Calkins, at calkins@westernlaw.org or (206) 607-9867.

Sincerely,

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[38] Isabel Carrera Zamanill, Covid-19 Gap Analysis, Front & Centered Report (February 2021) available at https://frontandcentered.org/wp-content/uploads/2021/02/FC-COVID-19-Gap-Analysis.pdf; Alison Saldanha and Elise Takahama, Graphics tell story of COVID's unequal toll across WA, Seattle Times (April 12, 2022) available at https://www.seattletimes.com/seattle-news/health/tracking-covids-unequal-unpredictable-toll-across-washington/; Brandi Fullwood and Libby Denkmann, Whatcom County in Recovery Braces for More Floods, KUOW (February 3, 2022) available at https://www.kuow.org/stories/whatcom-county-in-recovery-braces-for-more-floods.

[39] Isabel Carrera Zamanill, Covid-19 Gap Analysis, Front & Centered Report (February 2021) available at https://frontandcentered.org/wp-content/uploads/2021/02/FC-COVID-19-Gap-Analysis.pdf; Alison Saldanha and Elise Takahama, Graphics tell story of COVID's unequal toll across WA, Seattle Times (April 12, 2022) available at https://www.seattletimes.com/seattle-news/health/tracking-covids-unequal-unpredictable-toll-across-washington/ .

Exhibit 24

DRAFT

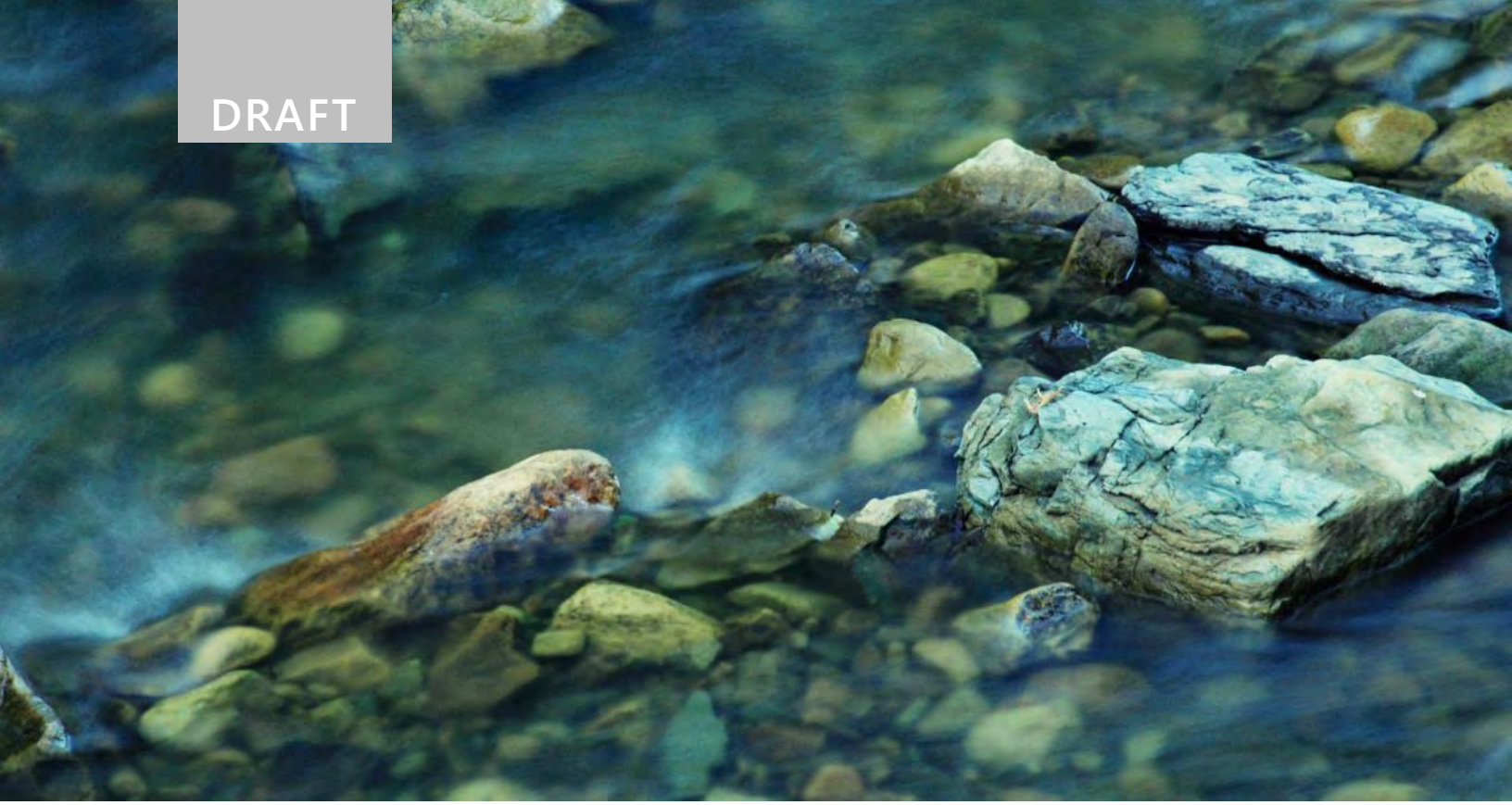

January 18, 2022
H&S Bosma Dairy Lagoon No. 3
Administrative Order on Consent Docket No. SDWA-10-2013-0080

ANCHOR QEA

H&S Bosma Dairy
Lagoon No. 3 Abandonment Plan

Prepared for H&S Bosma Dairy

January 18, 2022
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Administrative Order on Consent Docket No. SDWA-10-2013-0080

H&S Bosma Dairy
Lagoon No. 3 Abandonment Plan

Prepared for
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ABBREVIATIONS

Consent Order	Administrative Order on Consent SDWA-10-2013-0080
Dairy	H&S Bosma Dairy
EPA	U.S. Environmental Protection Agency
H:V	horizontal to vertical (ratio)
mg N/kg	milligrams nitrogen per kilogram
Plan	Lagoon Abandonment Plan
SVID	Sunnyside Valley Irrigation District
WA NRCS	Washington State Natural Resources Conservation Service

1 Introduction

This Lagoon Abandonment Plan (Plan) was prepared by Anchor QEA, LLC, on behalf of H&S Bosma Dairy (the Dairy) as required by the U.S. Environmental Protection Agency (EPA) Region 10 Administrative Order on Consent SDWA-10-2013-0080 (Consent Order). The abandonment work described in this plan has been initiated in 2021 and will be completed according to the schedule described in this Plan.

The Dairy is completing the abandonment of Lagoon No. 3 as part of a larger group of lagoon lining and abandonment projects outlined in the *Final Modified Lagoon Work Plan* (Anchor QEA 2016). Lagoon No. 3 was previously used to collect and store stormwater and manure generated from the Dairy's operations. However, the use of the lagoon has been terminated and it has been emptied of manure and associated liquids. The lagoon will no longer be required due to implemented storage and waste management improvements.

As part of lagoon abandonment, the lagoon will be regraded to support crop production. Two active lagoons (Lagoon Nos. 1 and 2) remain to the south of Lagoon No. 3. The abandonment and regrading of Lagoon Nos. 1 and 2 will be addressed in a separate abandonment plan to be prepared during 2022.

This Plan implements the requirements of the *Final Modified Lagoon Work Plan* (Anchor QEA 2016) as approved by EPA. It also exceeds the requirements of Washington State Natural Resources Conservation Service (WA NRCS) *Conservation Practice Standard 360 – Waste Facility Closure* (WA NRCS 2013a) and demonstrates compliance with nutrient management requirements of WA NRCS *Conservation Practice Standard No. 590 – Nutrient Management* (WA NRCS 2013b).

1.1 Report Organization

The remaining sections of this Plan are organized as follows:

- **Section 2 – Existing Conditions.** This section reviews the current conditions of the Dairy and presents the approximate pre-abandonment dimensions of Lagoon No. 3.
- **Section 3 – Abandonment Procedures.** This section discusses the removal of liquids and organic solids and initial soil testing procedures, both of which have been completed. The section also discusses the proposed treatment of elevated soil nutrient levels, confirmation soil testing, and submission of the final completion report.
- **Section 4 –Schedule.** This section outlines the abandonment timeline.
- **Section 5 – References.** This section provides references for the materials cited in this Plan.

2 Existing Conditions

The Dairy is located at 5860 East Zillah Drive Road in Granger, Washington. Figure 1 shows the location of Lagoon No. 3. The estimated dimension and capacity of the lagoon prior to abandonment are provided in Table 1.

The lagoon was originally created within a natural depression in the topography, bounded by Kirks Road and the Sunnyside Canal (owned by the Sunnyside Valley Irrigation District [SVID]), with the addition of earthen berms at the southern ends of what would become Lagoon No. 3. The lagoon is constrained by SVID drainage easement to the west, cropland to the east, Kirks Road to the north, and Lagoon No. 2 to the south.

Lagoon No. 3 has historically been used to store stormwater runoff and manure waste generated from Dairy operations. Liquid collected within the lagoons is stored and then pumped to application fields or to the existing lagoon system.

Table 1
Lagoon No. 3 Approximate Dimensions and Capacity

Lagoon	Length (feet)	Width (feet)	Depth (feet)	Capacity (million gallons)	Capacity (acre-feet)	Approximate Interior Side Slope
3	580	120	10	2.3	7.2	3H:1V

3 Abandonment Procedures

This section describes the lagoon abandonment procedures, including the following:

- Liquids and organic solids removal (completed 2021)
- Initial soil testing (completed 2021)
- In situ soil treatment and testing
- Interim reporting
- Completion report submittal

Most of the lagoon abandonment activities will be performed by Dairy personnel and equipment. Soil confirmation testing, irrigation sensor maintenance, interim reporting, and completion report submittal will be performed by Anchor QEA and Agrimanagement, Inc. The abandonment efforts will be completed consistent with the schedule presented in Section 4.

3.1 Liquids and Organic Solids Removal

Prior to sampling, the liquids and organic solids were removed from the lagoon. Liquids contained within the lagoon were transferred to an in-service, lined lagoon. After liquid removal, organic solids were removed and placed in the composting area. Solids were removed down to the current lagoon soil foundation material. The condition of the lagoon after manure removal is shown in Photograph 1.

Photograph 1
Condition of Lagoon No. 3 in December 2021 Following Manure and Liquids Removal



3.2 Initial Soil Testing

Following removal of the manure, soil testing was conducted within the lagoon to document the ammonia and nitrate concentrations in the subsurface soil. Confirmation testing was conducted at six locations within Lagoon No. 3, including one sample from the lower portion of each sidewall and two samples from the lagoon bottom. Figure 2 shows the actual sampling locations.

Soil sampling from the lagoon interior was performed using the following methods:

1. A backhoe was used to excavate test pits to a depth of 10 feet deep at each testing location. Soil samples were removed with the backhoe bucket at each sampling interval for sampling.
2. Initial soil samples were collected from a depth interval of 0 to 12 inches below ground surface.
3. Subsequent samples were collected at each of nine 1-foot intervals to a depth of 10 feet below ground surface.
4. Sampling personnel recorded the location and depth of each soil sample.
5. After samples were collected, the samples were placed in appropriate containers, and a custody seal bearing the sampler's name or initials and date were placed on the container.

Laboratory analysis of the soil samples was performed by SoilTest Farm Consultants, Inc., a State of Washington-certified analytical laboratory and a North American Proficiency Testing-accredited laboratory located at 2925 Driggs Drive, Moses Lake, Washington. Sample management, packing, shipment, analytical testing, and quality assurance/quality control were consistent with those defined in the *Dairy Facility Application Field Management Plan* (Anchor QEA 2018) as follows:

- Ammonium (as nitrogen) by Western Coordinating Committee S-3.50
- Nitrate (as nitrogen) by Western Coordinating Committee S-3.10

Soil samples were analyzed in a single phase. Results of testing are summarized in Table 2. Results of soil testing demonstrated that ammonia and/or nitrate concentrations in excess of the target level (45 milligrams nitrogen per kilogram [mg N/kg]) were present at depths between 3 and at least 10 feet below ground surface, with an average depth of just over 6 feet. Depths exceeding the target level were greatest for the east and west sidewalls, both of which exceeded the target level at the deepest depths (10 feet below ground surface) sampled.

Table 2
Results of Initial Soil Testing

Station ID	Depth Range (inches)	Nitrate-N (mg N/kg)	Ammonia-N (mg N/kg)	Available N (mg N/kg)	Exceeds 45 mg N/kg?
S-01 (North Sidewall)	**0–12**	147.7	1.7	**149.4**	**Yes**
	12–24	89.5	ND (u)	**89.5**	**Yes**
	24–36	47.7	2.6	**50.3**	**Yes**
	36–48	93.8	3.1	**96.9**	**Yes**
	48–60	18.3	3.6	21.9	No
	60–72	17.3	2.9	20.2	No
	72–84	14.2	3.1	17.3	No
	84–96	28.8	2.6	31.4	No
	96–108	20.3	3.5	23.8	No
	108–120	30.4	3.6	34	No
S-02 (West Sidewall)	**0–12**	26.8	97.5	**124.3**	**Yes**
	12–24	1.0	30.8	31.8	No
	24–36	1.0	23.1	24.1	No
	36–48	1.8	25.0	26.8	No
	48–60	28.5	25.2	**53.7**	**Yes**
	60–72	39.9	1.9	41.8	No
	72–84	51.6	3.3	**54.9**	**Yes**
	84–96	67.0	8.5	**75.5**	**Yes**
	96–108	41.7	ND (u)	41.7	No
	108–120	45.6	7.2	**52.8**	**Yes**
S-03 (East Sidewall)	**0–12**	83.3	ND (u)	**83.3**	**Yes**
	12–24	188.2	ND (u)	**188.2**	**Yes**
	24–36	103.1	ND (u)	**103.1**	**Yes**
	36–48	85.5	ND (u)	**85.5**	**Yes**
	48–60	131.3	4.2	**135.5**	**Yes**
	60–72	56.6	ND (u)	**56.6**	**Yes**
	72–84	44.6	2.3	**46.9**	**Yes**
	84–96	69.5	ND (u)	**69.5**	**Yes**
	96–108	76.7	1.8	**78.5**	**Yes**
	108–120	113.1	2.7	**115.8**	**Yes**

Station ID	Depth Range (inches)	Nitrate-N (mg N/kg)	Ammonia-N (mg N/kg)	Available N (mg N/kg)	Exceeds 45 mg N/kg?
S-04 (South Sidewall)	**0–12**	5.9	67.9	**73.8**	**Yes**
	12–24	ND (u)	81.7	**81.7**	**Yes**
	24–36	ND (u)	61.6	**61.6**	**Yes**
	36–48	2.9	10.7	13.6	No
	48–60	21	21.6	42.6	No
	60–72	1.8	6.0	7.8	No
	72–84	6.6	5.0	11.6	No
	84–96	6.8	6.1	12.9	No
	96–108	3.4	4.5	7.9	No
	108–120	6.9	2.4	9.3	No
B-N (North Bottom Sample)	**0–12**	23.7	251.3	**275**	**Yes**
	12–24	1.9	139.7	**141.6**	**Yes**
	24–36	15.4	128.6	**144**	**Yes**
	36–48	0.8	208	**208.8**	**Yes**
	48–60	ND (u)	20.5	20.5	No
	60–72	4.8	18.5	23.3	No
	72–84	1.1	32.6	33.7	No
	84–96	ND (u)	14.3	14.3	No
	96–108	1.4	10.1	11.5	No
	108–120	0.7	8.2	8.9	No
B-S (South Bottom Sample)	**0–12**	176.8	109.5	**286.3**	**Yes**
	12–24	6.0	92.8	**98.8**	**Yes**
	24–36	24.4	6.6	**31.0**	**Yes**
	36–48	11.2	65.2	**76.4**	**Yes**
	48–60	11.8	118.7	**130.5**	**Yes**
	60–72	45.6	10.3	**55.9**	**Yes**
	72–84	19.8	5.7	25.5	No
	84–96	9.8	5.6	15.4	No
	96–108	21.0	7.8	28.8	No
	108–120	15.4	10.1	25.5	No

Notes:

ND: Not detected

Bolded available nitrogen values exceed the target value of 45 mg N/kg.

3.3 In Situ Soil Treatment

This section describes how nutrients will be extracted from the soils beneath the lagoon using in situ treatment. Soil treatment will be performed agronomically using a combined forage crop including alfalfa and chicory. Alfalfa and chicory were selected to maximize nitrogen extraction rates, particularly from deep soil horizons, and details are provided as follows:

- **Alfalfa:** Alfalfa is a perennial forage crop that is well suited to deep rooting and high dry matter production (resulting in high nitrogen extraction rates). Research has shown that alfalfa can extract nutrients up to a depth of 120 centimeters (approximately 4 feet) within the first year after establishment. Roots can continue to push deeper through Years 2–4 until extraction has been observed up to a depth of 270 centimeters (over 8 feet) (Entz et al. 2001). In addition to crop age, soil and irrigation conditions can affect the depth of rooting. Even though alfalfa can obtain nitrogen for growth via symbiotic nitrogen fixation, it is also very effective in removing inorganic nitrogen from the soil (Russelle 1991). Research shows that alfalfa is an excellent crop for extraction of inorganic nitrogen from soil (Russelle et al. 2001). At a mono-crop yield of 9 tons/acre per year, alfalfa can typically extract nitrogen at a rate of up to 585 pounds nitrogen/acre per year.
- **Chicory:** Chicory is a deep-rooted, broad-leafed perennial that is very drought tolerant and hardy and responds well to higher levels of nitrogen within the soil. It can send roots over 3 meters (over 9 feet) deep within the first 3 months of growth and extend to 4 meters deep (over 13 feet) by Year 2 (Rasmussen 2020). At a mono-crop yield of 5.5 tons/acre per year, chicory can typically extract nitrogen at a rate of up to 185 pounds nitrogen/acre per year (Ditsch and Sears 2007).

As a mixed crop, the nitrogen extraction rate will likely be between 525 and 585 pounds per year. The mixed crop can be managed and harvested together efficiently. The mixing of the two crops is intended not to drive up overall nitrogen extraction, but rather to optimize the following: 1) the rate of extraction throughout the lagoon area; and 2) the removal of nitrogen from deeper soil horizons. The mixed crop can be expected to recover available nitrogen from depths at and below 10 feet. Removal rates can be expected to be highest in the upper soil horizon. Deeper soil extraction will likely increase over time as shallow soil reservoirs are exhausted.

Advantages of the soil treatment approach in comparison to other methods (e.g., soil excavation, export and backfill with clean soil) include the following:

- **Ability to treat all lagoon areas:** The western portion of Lagoon No. 3 is located adjacent to SVID irrigation infrastructure located within an SVID easement. Excavation of nutrient-rich soils would be precluded within this area, whereas in situ treatment is not.

- **Soil conservation:** The in situ treatment approach will not damage the food production value of the existing soils in comparison to an excavation approach and will not require import of clean soil.
- **Lower fuel consumption:** Overall fuel consumption (and associated production of greenhouse gas emissions) will be much lower for the in situ treatment approach in comparison to an excavation and backfill approach.
- **Incidental treatment of soils below the treatment target:** Though not required to complete lagoon abandonment, the in situ treatment approach will be applied throughout the Lagoon No. 3 footprint with the same deep-penetrating crop mix. This means that nutrient extraction will occur in all lagoon areas, even those that currently are below treatment objectives.

The treatment crop will be planted throughout the former lagoon footprint. Agrimanagement will install an irrigation sensor within the former lagoon bottom to help optimize both yields and deep root penetration while minimizing potential downward flux of nitrogen through soil leaching. Deep root penetration is achieved best by establishing a healthy crop and then restricting its moisture to drive roots deeper in a search for water. This restriction must not, however, be excessive or nutrient extraction rates will fall off.

The irrigation sensor will be consistent with those used to monitor shallow soil moisture levels in the existing nutrient application fields at the Dairy. However, the soil sensors will be installed at the following adjusted depths: 1 foot, 3 feet, and 5 feet below ground surface.

Irrigation will be provided as necessary to support optimal crop growth and root penetration. The irrigation will be provided using solid sets or equivalent. Irrigation will follow irrigation needs estimates provided by Agrimanagement. Irrigation records will be maintained to document the dates and duration of irrigation, and these will be summarized in interim annual reports and in the completion report.

Treatment is expected to require between 3 and 4 years to complete. A single planting with multiple harvests each year is expected to be sufficient for soil treatment. The forage mix will be harvested periodically consistent with standard agronomic practices to remove the extracted nutrients from the treatment area.

At the end of an initial 2-year treatment period, soil confirmation testing will be completed using the same locations, depths, and procedures as described in Section 3.2. Sampling shall be repeated adjacent to each of the six initial testing locations. Testing will document soil ammonia-nitrogen and nitrate-nitrogen to depths of 10 feet at each location and will be used to update the expected treatment duration.

If testing confirms that the target nitrogen concentrations have been reached after 2 years, then treatment will be considered complete. If nitrogen concentrations remain in excess of the treatment target, then treatment will be conducted for an additional 1- or 2-year period. The duration will be estimated based on observed nitrogen extraction rates and soil testing data.

Final confirmation testing will be implemented at the end of the 3- or 4-year treatment period. Final confirmation testing will be completed using the same locations, depths, and procedures as described in Section 3.2. Sampling shall be repeated adjacent to each of the six initial testing locations. Testing will document soil ammonia-nitrogen and nitrate-nitrogen to depths of 10 feet at each location and will be used to update the expected treatment duration.

3.4 Interim Reporting

During the treatment period, an interim treatment report will be submitted to EPA following each calendar year. The report will summarize the following:

- Results of soil moisture monitoring
- Crop yield achieved during the calendar year harvests
- Estimated nitrogen extraction rates
- Results of soil confirmation testing (Year 2 only)
- Recommended final treatment duration (Year 2 only)

3.5 Completion Report

Following completion of soil treatment and final confirmation testing, Anchor QEA will prepare and submit a completion report. That report will include the following information:

- A short narrative describing the lagoon abandonment work completed, including a discussion of crop yields and nutrient extraction accomplished during the treatment period
- Copies of construction photographs showing the lagoon after emptying and during soil treatment
- Results of all soil testing
- Results of soil moisture monitoring
- Statement that the closure followed WA NRCS *Conservation Practice Standard 360 – Waste Facility Closure* (WA NRCS 2013a) practices
- Documentation of site conditions following soil treatment

4 Schedule

The abandonment activities described in this plan are partially complete (manure removal and initial soil testing). Crop planting and soil moisture sensor installation will be completed following EPA approval of this plan. Planting will be conducted during spring or fall months. Planting during the summer months is not recommended for crop health and nutrient extraction performance.

Interim reports will be submitted at the end of each calendar year until treatment is complete. The reports will be submitted to EPA by February 15 following the treatment year.

The completion report will be submitted to EPA by February 15 of the year when treatment targets have been achieved as documented through final confirmation testing. The current expected treatment duration is between 3 and 4 years.

5 References

Anchor QEA (Anchor QEA, LLC), 2016. *Final Modified Lagoon Work Plan*. Prepared for Liberty Dairy, LLC/H&S Bosma Dairy. December 2016.

Anchor QEA, 2018. *Dairy Facility Application Field Management Plan*. Prepared for Cow Palace, LLC, George DeRuyter & Son Dairy, LLC/D&A Dairy, LLC/George & Margaret, LLC, and Liberty Dairy, LLC/H&S Bosma Dairy. February 2018.

Chicory Factsheet. https://keys.lucidcentral.org/keys/v3/pastures/Html/Chicory.htm.

Ditsch, D.C., and B. Sears, 2007. *Chicory: Alternative Livestock Forage*. University of Kentucky Extension Service. AGR-190. 2007.

Entz, M.H., W.J. Bullied, D.A. Foster, R. Gulden, and J.K. Vessey, 2001. "Extraction of Subsoil Nitrogen by Alfalfa, Alfalfa-Wheat, and Perennial Grass Systems." *Agronomy Journal* 93(3): 495–503. DOI: 10.2134/agronj2001.933495x

Rasmussen, C.R., 2020. "Uptake of Subsoil Water Below 2 m Fails to Alleviate Drought Response in Deep-Rooted Chicory (*Cichorium intybus* L.)." *Plant Soil* 2020(446): 275–290. DOI: 10.1007/s11104-019-04349-7.

Russelle, M.P., 1991. "The Environmental Impacts of N2 Fixation by Alfalfa. USDA-ARS-Plant Science Research Unit and US Dairy Forage Research Center (Minnesota Cluster)." *Proceedings, National Alfalfa Symposium, 13–15 December 2004, San Diego, CA, UC-Davis Cooperative Extension*.

Russelle, M.P., J.F.S. Lamb, D.W. Elsenheimer, B.S. Miller, and C.P. Vance, 2001. "Alfalfa Rapidly Remediates Excess Inorganic Nitrogen at a Fertilizer Spill Site." *Journal of Environmental Quality* 30 (January-February 2001): 30–36.

Pennington, 2019. Forage Chicory-Cichorium intybus. Pennington Seed Inc. 2019. https://www.pennington.com/all-products/wildlife/resources/forage-chicory-cichorium-intybus

WA NRCS (Washington State Natural Resources Conservation Service), 2013a. *Conservation Practice Standard No. 360 – Waste Facility Closure*. January 2013.

WA NRCS, 2013b. *Conservation Practice Standard No. 590 – Nutrient Management*. December 2013.

Figures



SOURCE: Aerial from Microsoft (Bing) 4/11/2018
HORIZONTAL DATUM: Washington State Plane South, NAD83, U.S. ft

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ANCHOR QEA

Figure 1
H&S Bosma Dairy Lagoon Map

Lagoon No. 3 Abandonment Plan
H&S Bosma Dairy

DRAFT

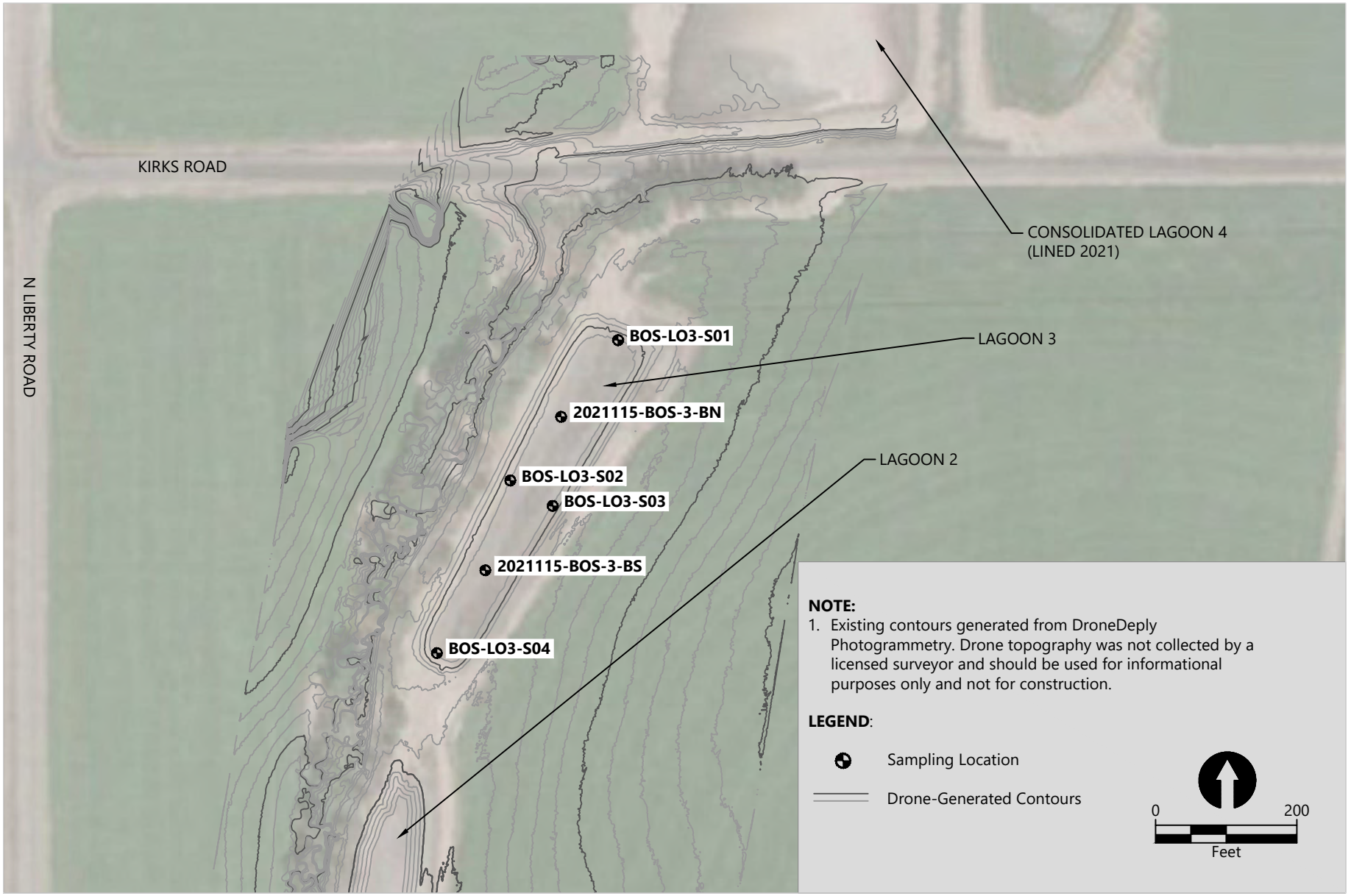

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Filepath: K:\Projects\0996-Perkins Coie\Yakima Dairies Project\Lagoons - 2021\Figures\0996-RP03-2021 (Bosma 1_2_3_Abandonment)_recover.dwg Figure X

ANCHOR QEA

Figure 2
Sampling Locations

Lagoon No. 3 Abandonment Plan
H&S Bosma Dairy

Exhibit 25

DEC Region	County	Town / City	Farm Name	SPDES ID	Incident Description	CAFO	Non--CAFO	Farm Size	Date of Incident
4	Albany	New Scotland	Hill Top	NYA000576	Complaint of manure stockpile in a field possibly contaminated a private well	X		Medium	29--Mar--14
	Montgomery	Florida	STONY BROOK, INC.	NYA000144	Reported that manure spread on a snow covered field ran off into a neighbor's pond during snow melt	X		Medium	Mar--14
	Montgomery	Root			Reported that manure spread on a snow covered field ran off into a neighbor's pond during snow melt		X		Mar--14
	Montgomery	Palentine			Complaint of possible manure contamination of private well.		X		Mar--14
5	Clinton				Report of manure runoff from a field to a roadside ditch. No discharge to surface water or groundwater has been reported.		X		Mar--14
	Clinton	Beekmantown	Fessette Farm	NYA000313	Pt Au Roche Road, 1 well positive for bacterial contamination, other wells in the area were not impacted. Further investigation showed that the well had a surface connection with water infiltrating around the perimeter of casing	X		Medium	3/27/14
	Clinton	Champlain	Leduc's Green Acres	NYA000086	Reported manure spreading incident near Eden Lane. 6 wells were positive for bacterial contamination.	X		Medium	3/31/14
	Clinton	Champlain	Giroux's Poultry Farm	NYA000460	Same as above	X		Large	3/31/14
6	Oneida	Chadwicks	Collins Knoll Farm	NYA000063	Self reported manure runoff event. No water quality violation	X		Large	3/11/14
	Lewis	Harrisville	"Larry Atkin's Farm"		Complaint of manure runoff to surface water		X		12/27/13
	St. Lawrence	Hermon	Gebarten Acres	NYA001325	Complaint of manure runoff to surface water	X		Large	1/13/14
	Jefferson	Adams Center	Porterdale	NYA000038	Self reported manure runoff event. No water quality violation	X		Large	4/3/14
	Jefferson	Adams	Hy--Light	NYA001459	Complaint of manure runoff to surface water	X		Medium	4/1/14
	Jefferson	Clayton	Woods Farm	NYA000351	Complaint of manure runoff to surface water	X		Large	3/4/14
7	Onondaga	Marietta	Ralph Volles	NYA000548	Report of manure runoff into a neighbor's basement through a window.	X		Large	3/11/14
	Onondaga	Marietta	Ralph Volles	NYA000548	Report of an additional runoff event at this farm	X		Large	3/11/14
	Cayuga	Scipio	Allen Farms	NYA000323	Report of manure runoff and well contamination event including runoff to a tributary of Owasco Lake (drinking water source for the City of Auburn)	X		Large	3/11/14

	Cayuga	Locke	Pine Hollow Dairy	NYA00621	Cayuga County Health Department staff reported ponded manure-contaminated water approximately 100 ft from a private well.	X		Large	3/11/14
	Cayuga	Genoa			ECO observed foam and manure odor in Salmon Creek.		X		
	Cayuga	Venice	Willet Dairy	NYA000002	Reported manure spill from charging drag hose, most contained, some discharged to L. Salmon Ck.	X		Large	5/3/14
	Cortland	Homer	New Hope View Dairy	NYA000636	Reported manure spill during drag line start up due to frozen line. Most contained and cleaned up. Some material entered drainage ditch.	X		Large	3/17/14
	Cortland	Truxton	Whey Street Dairy	NYA000094	Report of manure runoff from frozen field onto neighboring property. Contained, diverted and cleaned up.	X		Medium	3/25/14
	Madison	Canastota	Springwater Farms	NYA000545	Madison County Soil and Water Conservation District responded to a manure runoff event. Runoff was contained. No discharge to surface water	X		Medium	03/20/14
8	Livingston	Caledonia	Stein Family Farms	NYA000241	Manure and septic contamination confirmed for 2 private wells.	X		Medium	2/24/14
	Livingston	Caledonia	D&D Dairy (Stein Family)	NYA000578	Complaint of possible contamination of shallow (26') well with no casing above the ground surface.	X		Medium	3/17/14
	Livingston	Leicester	Thornapple Farms	NYA000242	Reported manure runoff event. No discharge, berms in place to contain runoff.	X		Medium	3/12/14
	Ontario	Seneca Castle	Hemdale Farms	NYA000490	Reported manure runoff event. DER responded and contained	X		Large	3/7/14
	Genesee	Oakfield	Lamb Farms	NYA000123	Reported manure contamination of private wells on Batavia-Oakfield Townline Rd.	X		Large	3/14/14
	Genesee	Oakfield	Lamb Farms	NYA000123	Reported manure runoff incident with impact to a tributary of Oak Orchard Creek.	X		Large	3/7/14
	Monroe				Complaint of manure contamination of private well.				2/28/14
	Steuben	Bath	Leo Dickson and Sons	NYA000178	Discharge of manure from land application. ECO ticket issued to farm for contravention of water quality standards.	X		Medium	3/13/14
	Steuben	Bath	Wilkins Dairy	NYA001520	Complaint of over application of manure, stockpiling of solids and runoff.	X		Medium	12/13; 2/14
	Steuben	Prattsburg	Damin Farms	NYA000121	Complaint of well contamination	X		Large	3/11/14
	Steuben	Prattsburg	Damin Farms	NYA000121	Complaints of manure runoff into Keuka Lake.	X		Large	3/11/14

	Wayne	Wolcott	Merrell Farms	NYA000120	Complaint of manure runoff, manure flowed onto the property of a church, and may have impacted the basement. .	X		Large	3/31/14
9	Wyoming	Perry	Dueppengies ser Dairy Co	NYA000130	Report of manure discharge to Little Beards Creek.	X		Large	Mar--14
	Allegany	Scio			Non-CAFO farm that is not operating under a CNMP made a manure application on a frozen snow covered field, resulting in alleged manure runoff onto a neighboring yard and into their basement and possibly a nearby creek.		X		3/11/14
	Chautauqua	Ellington	Breeze Acres	NYA000248	Failure in manure transfer pipe resulted in discharge of approx. 6,000 gal. to road ditch. Manure was absorbed into snowpack with minimal impact to Clear Creek. Contaminated snow was collected and field applied.	X		Medium	3/12/14
	Cattaraugus	Freedom			Complaint of milkhouse waste runoff into creek		X		unknown
	Chautuauqa	French Creek			Alleged manure lagoon failure and discharge into trib. of French Creek		X		Apr--14

Exhibit 26

STATE OF MICHIGAN
DEPARTMENT OF ENVIRONMENTAL QUALITY
LANSING

JENNIFER M. GRANHOLM
GOVERNOR

STEVEN E. CHESTER
DIRECTOR

April 4, 2008

U.S. Environmental Protection Agency Docket Center
EPA West, Room B102
1301 Constitution Avenue, NW
Washington, DC

ATTENTION: Docket ID No. EPA-HQ-OW-2005-0037

SUBJECT: Revised National Pollutant Discharge Elimination System Permit Regulations for Concentrated Animal Feeding Operations; Supplemental Notice of Proposed Rulemaking

The Michigan Department of Environmental Quality (MDEQ) has reviewed the proposed rule published in the March 7, 2008, Federal Register and has several comments. We appreciate the fact that the U.S. Environmental Protection Agency (USEPA) has attempted to respond to the Waterkeeper Decision, and that the USEPA is contemplating various permitting options to deal with both the decision and the practicalities of permitting concentrated animal feeding operations (CAFO) and protecting the nation's waters.

Self-Certification Process

We strongly recommend that the USEPA withdraw the proposal for the voluntary option for CAFOs to certify that the CAFO does not discharge or propose to discharge. We believe that this option as proposed is seriously flawed. This provision appears to have been advanced by the lobbyists for the factory farms as a self-serving means of exempting factory farms from regulation, contrary to any other sector regulated under the Clean Water Act. Instead, we recommend that the USEPA refocus its efforts on clearly identifying the attributes that will constitute a discharge or proposal to discharge, and how these would be determined. We have this recommendation based on the following:

(1) The proposed rule is contrary to the plain language of the Clean Water Act; not responsive to the Waterkeeper Decision in that it does not define what constitutes a proposal to discharge; sets a minimum design, operation, and management scheme that will not prevent discharge; does not provide a clear defined process for determining when a nonpermitted CAFO must apply for a permit; and has the sole purpose to provide liability protection for those who chose not to enter the permitting process.

The self-certification provision is not needed and serves no purpose other than to provide a safe haven for CAFOs that will likely discharge but do not want to apply for a permit. CAFOs should have to decide either to obtain a permit and thus obtain the liability protection for duty to apply that goes along with being permitted; or not obtain a permit and take their chances with the compliance/enforcement actions that may follow a discharge. It is unfair to those CAFOs that do obtain permits to give the same liability protection to those that simply decide to self-certify.

The self-certification process, through the liability protection from the duty to apply, would make it much more difficult to compel CAFOs that have had a discharge or discharges to take the appropriate steps to correct the problems that lead to the discharges. This would be further complicated by the lack of any requirement for self-certified CAFOs to report discharges and a three day period to simply report that they no longer met the certification requirements, which would result in most discharges being dissipated before the agency even knew about them. Also, as written, the certification and recertification process after a discharge would encourage a discharging CAFO to maximize its illegal discharge to acquire more operating capacity to provide time to "correct" a noted problem and then recertify in lieu if obtaining permit coverage.

The immunity from the duty to apply provision is most likely not legal, except to the extent that the USEPA desires to exert enforcement discretion, because it is in conflict with the Clean Water Act. Notably, the immunity from the duty to apply provision is only mentioned in the preamble and is not a part of the regulation *per se.* In fact, we find no authority in the Clean Water Act that allows the USEPA to establish a self-certification process in lieu of a permit for dischargers, let alone to arbitrarily establish such a process for a select group of dischargers contrary to how all other dischargers are regulated. This proposal, if enacted, would undoubtedly result in additional litigation and the resulting confusion that it would bring. This provision also attempts to negate the citizen rights to sue provisions of the Clean Water Act by eliminating a statutory provision by administrative regulations.

The proposed USEPA criteria to be used to determine if a CAFO qualifies for the self-certification are not detailed enough to be useful in specific situations. The criteria need to be much more specific and established by appropriate state or similar regions. Michigan has established criteria in national pollutant discharge elimination system permits for CAFOs with discharges, but the criteria are much more specific than the proposed criteria, and are more specific to the particular conditions in Michigan. It is unlikely that the proposed USEPA criteria will serve any meaningful test to certify that there is no discharge; instead, these criteria will only show that the discharges are less frequent.

The USEPA frequently uses the phrase "in an unlikely event of a discharge from a certified CAFO." We do not agree that such a discharge would be "unlikely." Michigan's experience is that virtually all CAFOs with lagoons and/or land application have discharges. In fact, in administering the CAFO program in Michigan for about 200 CAFOs, we have found that only about five percent of the CAFOs can be determined to have No Potential to Discharge. Michigan has received 17 requests for a no potential to discharge determination. Of these, nine have been determined to meet this determination; however, four other CAFOs who thought they had no discharge were found to be discharging at the time of inspection. To date, the CAFOs in Michigan determined to not discharge are those that are not proximate to surface waters, have their CAFO waste sheltered from the elements (either under barn or in dry storage), and have particularly well managed facilities. Even these situations must be carefully assessed on a facility specific basis, as we have found some operations that met these criteria, did in fact have a discharge. For one such poultry CAFO with dry manure stored inside and no land application, we documented a discharge twice in one month as a

result of exhaust of dust and subsequent storm water run off, with high pollutant concentrations in the discharge (especially biochemical oxygen demand, *E. coli* and ammonia). This serves to point out the difficulty of CAFOs self-certifying that they will not discharge, particularly without very specific criteria to use in making the evaluation.

The proposed certification process essentially gives CAFOs a license to discharge with no consequences, and ties the hands of enforcing agencies. The self-certification process also creates a significant work load for the states without any commensurate additional environmental protection. The burden of handling all of the additional paperwork associated with the certification would be substantial. In addition, considerable additional resources would be required to determine if each facility was actually in compliance with their certification and whether there were discharges or not. The only apparent result of finding a facility not in compliance with their certification or having a discharge would be for the facility to "fix" the problem causing the discharge and then to reapply for a new certification.

In addition, the certification process eliminates the ability of the public to comment on the appropriateness of certifying a facility. Often public comment can be valuable in identifying CAFOs that have had discharges.

This proposal will severely undermine the efforts of those states that have implemented programs to adequately regulate CAFOs. The USEPA has encouraged states to do this in the interim time period between the Waterkeeper Decision and the final promulgation of regulations consistent with that decision by the USEPA. Despite the argument that the USEPA will make that the states are free to implement requirements more restrictive than the federal requirements, the reality is that the states will be under increasing pressure to change their requirements to be "consistent with" the federal requirements. This would result in not only significantly reduced effectiveness of controlling pollution from CAFOs, but also a waste of scarce state resources in the effort to redo their regulations.

If the USEPA persists in this wrong headed effort to have CAFOs self-certify, we recommend the following modifications to at least mitigate some of the worst features of the proposal. However, we must note that even with these changes we find the provision inadequate, contrary to law, and not protective of the environment and public health:

A. All documents related to the certification should be signed by a registered engineer (for structural issues) or a National Resource Conservation Service (NRCS) certified technical service provider (for other Comprehensive Nutrient Management Plan [CNMP] issues).
B. Any Nutrient Management Plan (NMP) developed for certification must not only meet NRCS standards but also any standards or conditions established by states that permitted CAFO's must comply. The CAFO must also specifically certify to this fact.
C. The rule needs to define what constitutes lands "under the control" of the CAFO.
D. The rule needs to clearly state that before a CAFO could be certified, it must have in place and operating all required elements of the design, operation

and maintenance plan, and the NMP. A certification cannot be "conditional" based on a schedule.

E. The rule needs to provide that the certification is null and void if the permitting authority finds that a certified CAFO has or has had a discharge, does not have required records onsite or available, or in any way is not in conformance with the certification conditions.
F. The proposed rule states that if the conditions at a certified CAFO change, the CAFO "should" make the necessary adjustments to accommodate the changes. This duty should be a mandate. The word "should" needs to be changed to "shall."
G. The certification statement has 5 conditions. Condition 5 should be changed to include, "an official signature that.....make the CAFO legally responsible for its representations to the Director regarding the design, construction, operation and maintenance of the CAFO ***and the NMP."***
H. Add a requirement for the certified CAFO to notify the permitting authority whenever a change is made to certifying documents, procedures, or designs.
I. All documents related to the certification should be submitted to the Director and available to the public.
J. A CAFO that has had, or has a discharge should not be eligible for certification or re-certification.
K. A certified CAFO that has had a discharge should be required to report that discharge to the Director immediately, but no later then 24 hours. The report must detail the date, time, volume, duration of the discharge, what actions were taken to minimize the discharge, and the cause of the discharge.
L. The immunity from the duty to apply should be eliminated from the proposed regulations.

(2) The use of CNMPs alone to control discharges is not acceptable. In Michigan, we have found that CNMPs similar to the NRCS CNMPs are not sufficient to prevent discharges to surface waters. Also, CAFOs with such CNMPs tend to ignore their CNMPs unless there are specific permit requirements associated with these documents. As such, using CNMPs without associated permit requirements will likely result in improper waste, management, and subsequent discharges.

Instead of self-certification by CAFOs, the USEPA should establish criteria as to what constitutes a discharge. This would include using information that clearly shows discharges occur with lagoons and land application of CAFO waste if there are surface waters nearby. The proximity of surface waters would be a clear criterion for this determination.

(3) The self-certification program should be withdrawn. CAFOs are like other discharges associated with wet weather, such as combined sewer overflows, municipal separate storm sewer system overflows, and industrial storm water discharges. These discharges are inherently different than continuous point sources, like publicly owned treatment works. Wet weather discharges only occur during certain precipitation or snowmelt events, which are uncontrollable. This country has a relatively long history of dealing with continuous point sources, but a relatively short history with wet weather discharges. As such, we do not have a strong technical development of necessary controls and/or numerical effluent limits for wet weather discharges.

Nor do we have a strong understanding on how and when discharges occur. As such, when dealing with wet weather facilities, a strong understanding of when and how discharges occur is needed before deciding to allow a "self-certification" program that discharges do not occur. We sincerely doubt that the USEPA has such an understanding in regards to CAFOs, and in particular doubt that this has been developed with any rigor for the entire United States. Therefore, we have no confidence in the proposed "self-certification" program, and strongly recommend that it be withdrawn at this time.

Terms of the Nutrient Management Plan

We believe that the three prong approach described in the Preamble has merit. However, it is impossible to thoroughly comment on this issue without having actual draft regulations. We request that the USEPA not act on these rules until such time that the actual draft regulations covering this topic have been public noticed and an opportunity for public comment provided.

We appreciate the opportunity to comment. If you have any questions on these comments, please contact Mr. William Creal, Chief, Permits Section, Water Bureau, at 517-335-4114, or you may contact me.

Sincerely,

Richard A. Powers, Chief
Water Bureau
517-335-4176

cc: Mr. Jim Sygo, Deputy Director, MDEQ
Mr. James K. Cleland, MDEQ
Mr. Frank Baldwin, MDEQ
Mr. William Creal, MDEQ
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Article

Proximity to Industrial Food Animal Production and Asthma Exacerbations in Pennsylvania, 2005–2012

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Abstract: The research on industrial food animal production (IFAP) and asthma exacerbations in the United States has relied on small sample sizes and/or self-reported outcomes. We assessed associations of proximity to large-scale and densely stocked swine and dairy/veal IFAP with three types of asthma exacerbations: hospitalizations, emergency encounters, and oral corticosteroid (OCS) medication orders from Geisinger Clinic in Pennsylvania. We used a diagnosis code (*International Classification of Diseases, 9th Revision, Clinical Modification* code 493.x) and medication orders from electronic health records to identify these exacerbations among asthma patients (n = 35,269) from 2005–2012. We compared residential proximity to swine or dairy/veal IFAP (dichotomized as <3 miles (4.8 km) or ≥3 miles) among asthma patients with and without exacerbations and estimated odds ratios using multilevel logistic regression. In adjusted models, proximity to IFAP was associated (odds ratio (95% confidence interval)) with OCS orders (1.11 (1.04–1.19)) and hospitalizations (1.29 (1.15–1.46)), but not emergency encounters (1.12 (0.91–1.37)). This study contributes to growing evidence that IFAP may impact health, in this case clinically-documented asthma exacerbations. No prior study has evaluated the association of IFAP and clinically-documented asthma exacerbations in the United States.

Keywords: asthma; asthma exacerbation; concentrated animal feeding operation (CAFO)

1. Introduction

Living or attending school near industrial food animal production (IFAP)—large-scale, densely stocked, and highly specialized farms—has been linked to adverse health outcomes [1]. Of particular concern are asthma exacerbations. Asthma is a chronic condition characterized by recurring symptoms (including cough, wheezing, shortness of breath, and chest tightness) that affects over 25 million people in the United States [2,3]. IFAP facilities are a source of odors and several air pollutants, including particulate matter, hydrogen sulfide, and ammonia [4], and these air pollutants and odors have been associated with asthma exacerbations [2,5,6]. Most, but not all, studies on IFAP and asthma exacerbations have found IFAP to be a risk factor for decreased lung function and asthma symptoms [1,5,7–15]. However, the research on IFAP and asthma exacerbations in the United States has relied on small sample sizes and/or self-reported outcomes [5,7–10], and studies that have used

clinically-documented events, from the Netherlands, reported no association or a protective association of IFAP and asthma exacerbations [14–16]. In this study, we used electronic health record (EHR) data from the Geisinger Clinic, located in central and northeastern Pennsylvania, to conduct a case-control study of the association between proximity to swine or dairy/veal IFAP and clinically-documents asthma exacerbations in a population of patients with asthma.

2. Materials and Methods

2.1. IFAP Data and Study Population

Swine and dairy/veal IFAP were identified in nutrient management plans from the Pennsylvania Department of Environmental Protection and County Conservation Districts in the Geisinger Clinic's service area and adjacent counties, as described in a prior study [4]. In Pennsylvania, the Department of Environmental Protection and County Conservation Districts regulate IFAP, both concentrated animal feeding operations (CAFOs, defined as operations with >1000 animal equivalent units (AEUs; 1 AEU = 1000 lbs or 454 kg)) and concentrated animal operations (CAOs, defined as >2 AEUs/acre) under Act 38. Act 38 requires operators to produce nutrient management plans every two years. We located swine and dairy/veal IFAP in the Geisinger Clinic's service area and adjacent counties using these plans and assigned each a latitude and longitude based on the location of operation's center [4].

The study population consisted of primary patients with asthma, and we identified the study population from the Geisinger Clinic population, which is representative of the general population in the region, using methods described in a prior study [17]. Briefly, we considered patients with at least two encounters with asthma diagnoses on different days (using *International Classification of Diseases, 9th Revision, Clinical Modification* code 493.x), or at least one encounter with an asthma diagnosis and at least one medication order with an asthma diagnosis on different days, to be patients with asthma [18]. Patients were geocoded to their home addresses using ArcGIS Advanced for Desktop, v10.1 (Esri, Redlands, CA, USA) and restricted the study population to the Geisinger Clinic's service area and adjacent counties (Figure 1). We identified the following asthma exacerbations among the study population in the EHR: hospitalizations (2005–2012), emergency encounters (2005–2012), and new oral corticosteroid (OCS) orders (2008–2012; OCS orders were only consistently captured in the EHR from 2008 and on). We used both primary and secondary diagnosis codes for asthma for hospitalizations and emergency encounters because we were unable to differentiate between asthma exacerbations that led to hospitalizations and asthma exacerbations that occurred while patients were hospitalized. We identified new OCS medication orders for asthma exacerbations by excluding standing orders and requiring that the outpatient visit reason or medication order diagnosis was asthma-related [17]. The study was approved by the Geisinger Institutional Review Board (approval number 2013-0114, with an Institutional Review Board authorization agreement with Johns Hopkins Bloomberg School of Public Health).

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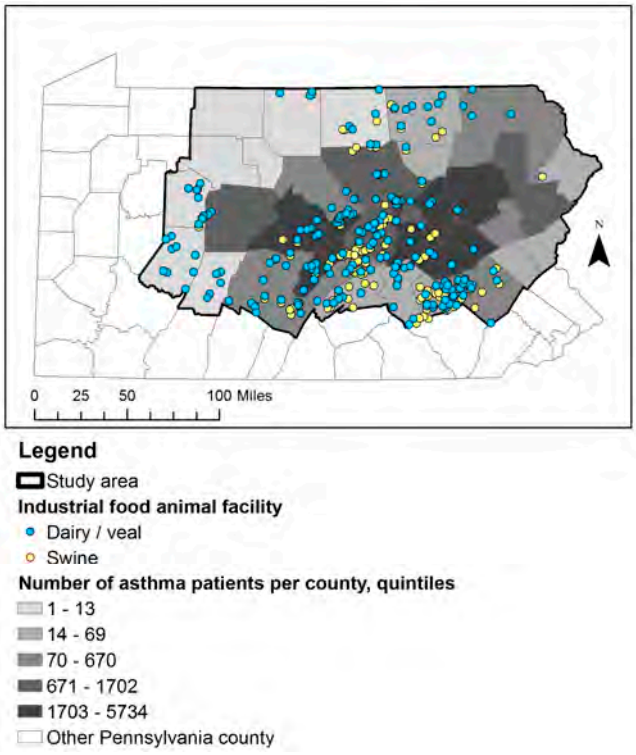

Figure 1. The location of swine and dairy/veal industrial food animal production facilities and the residential location of Geisinger Clinic asthma patients.

2.2. Comparison Subjects and Matching

For each type of asthma exacerbation, we compared patients with at least one exacerbation of that type during the study period to comparison subjects who were asthma patients with no or less severe exacerbations (OCS order < OCS order < emergency department < hospitalization) during the study period. We frequency-matched comparison subjects to cases on age category (5–12, 13–18, 19–44, 45–61, 62–74, 75+ years), sex (male, female), and year of event. For cases, the date of their first event was used as the year for frequency matching and as the date to assign time-varying covariates. For comparison subjects, we needed a date for frequency matching by year and to assign time-varying covariates, so we used randomly selected a date on which the patient had contact with the health system. Hospitalization cases were matched to comparison subjects at 1:3, emergency department cases were matched at 1:5, and OCS cases were matched at 1:1.

2.3. Statistical Analysis

For each outcome, we evaluated unadjusted and adjusted multilevel logistic regression models with a random intercept for community to account for patient clustering within communities (in cities, census tracts; in townships and boroughs, minor civil divisions). Proximity to IFAP was defined as a swine or dairy/veal operation within a three mile (4.8 km) buffer of the patient's residence; this distance was chosen based on a prior study [9]. Covariates in the adjusted model included those created using the EHR: age category, year, sex, self-reported race/ethnicity (white, black, Hispanic, other/missing; race/ethnicity is a well-documented confounder in asthma studies [2]), season, smoking status, family history of asthma, overweight/obesity (using body mass index (BMI) percentile for children and BMI (kg/m^2) for adults [19]), Medical Assistance (a means tested program that is an indicator of low family socioeconomic status), and type 2 diabetes; and those created using patients' geocoded coordinates: distance to nearest major and minor road and community socioeconomic deprivation (CSD) [4,17,20,21]. Because distance from patient address to the closer of the two major Geisinger hospitals, where 96% of asthma hospitalizations and 85% of asthma emergency encounters took place, was a potential confounding variable, it was included in the

hospitals, where 96% of asthma hospitalizations and 85% of asthma emergency encounters took place, was a potential confounding variable, it was included in the hospitalization and emergency encounter models. Distance to hospital was not included in the OCS model, as OCS orders were handled at outpatient locations and over the phone. Continuous covariates were included with linear and quadratic terms to allow for non-linearity.

2.4. Sensitivity Analyses

We conducted several sensitivity analyses. Because we were interested in effect modification by age, we evaluated whether associations between IFAP and asthma exacerbations were different among children and adults by adding a cross-product of proximity to IFAP and an indicator for childhood age (5–18 years) to the final model for each outcome. To evaluate the impact of including patients in urban areas, we completed a sensitivity analysis that excluded patients in cities. We evaluated associations among patients who had more than one exacerbation of a given type by repeating the primary analysis only including cases with more than one of a given type of exacerbation. Because of concern about confounding by distance to hospital, in a sensitivity analysis for the hospitalization and emergency department outcomes, we individually matched (1:1) cases to comparison subjects on age, sex, and distance to hospital in five mile increments. Because of the individual matching, for this analysis we evaluated unadjusted and adjusted conditional logistic regressions, which included the same covariates as in the primary analysis. To evaluate the impact of using patients with asthma exacerbations less severe than the cases as comparison subjects on our associations, or each outcome, we completed a sensitivity analysis in which asthma patients with that type of exacerbation were compared to patients with no asthma exacerbations of any type during the study period, and we then evaluated associations using crude and adjusted logistic regressions.

3. Results

3.1. Description of Study Population

We identified 35,269 patients with asthma in the study area. The study population was 92% white, 58% female, had a median age of 31 years in 2012, and 59, 30, and 11% of the population lived in townships, boroughs, and cities, respectively. The hospitalization analysis included 3552 cases and 10,640 comparison subjects, the emergency encounter analysis included 1445 cases and 7225 comparison subjects, and the OCS analysis included 13,137 cases and 13,044 comparison subjects. Cases for each of the three outcomes were more likely than comparison subjects to have a family history of asthma, be current smokers, have Medical Assistance, be obese, and live in communities in the highest quartile of CSD (Tables 1 and 2). Cases in the hospitalization and emergency analyses, but not the OCS analysis, were less likely to be white non-Hispanic and more likely to live closer to major and minor roads. We identified 123 swine and 203 dairy/veal operations, and 8399 (24%) patients lived within 3 miles of one of these (Figure 1).

Table 1. Descriptive statistics of cases and comparison subject characteristics by exacerbation type.

Variable, *n* (% [a]), Unless Specified	Hospitalization		Emergency Visit		OCS [b]	
	Case *n* = 3552	Comparison Subject *n* = 10,640	Case *n* = 1445	Comparison Subject *n* = 7225	Case *n* = 13,137	Comparison Subject *n* = 13,044
Race/ethnicity						
White non-Hispanic	3297 (92.8)	10,065 (94.6)	1218 (84.3)	6720 (93)	12,126 (92.3)	11,998 (92)
Black non-Hispanic	107 (3)	257 (2.4)	124 (8.6)	221 (3.1)	428 (3.3)	468 (3.6)
Hispanic/other/missing	148 (4.1)	318 (3.0)	103 (7.1)	284 (3.9)	583 (4.5)	578 (4.5)
	p [c] < 0.01		p < 0.01		p = 0.43	
Family history of asthma	404 (11.4)	999 (9.4)	265 (18.3)	871 (12.1)	1668 (12.7)	1354 (10.4)
	p < 0.01		p < 0.01		p < 0.01	

Table 1. *Cont.*

Variable, *n* (% [a]), Unless Specified	Hospitalization		Emergency Visit		OCS [b]	
	Case ***n* = 3552**	**Comparison Subject** ***n* = 10,640**	**Case** ***n* = 1445**	**Comparison Subject** ***n* = 7225**	**Case** ***n* = 13,137**	**Comparison Subject** ***n* = 13,044**
Smoking status						
Never	1529 (43)	5567 (52.3)	656 (45.4)	4148 (57.4)	7424 (56.5)	7975 (61.1)
Current	895 (25.2)	1913 (18)	276 (19.1)	1100 (15.2)	2219 (16.9)	1777 (13.6)
Former/missing	1128 (31.8)	3160 (29.7)	513 (35.5)	1977 (27.4)	3494 (26.6)	3292 (25.2)
		$p < 0.01$		$p < 0.01$		$p < 0.01$
Medical Assistance	1094 (30.8)	2024 (19)	542 (37.5)	1991 (27.6)	3683 (28.0)	3369 (25.8)
		$p < 0.01$		$p < 0.01$		$p < 0.01$
Body mass index						
Normal/underweight	794 (22.4)	2873 (27)	445 (30.8)	2574 (35.6)	3887 (29.6)	4693 (36)
Overweight	786 (22.1)	2758 (25.9)	304 (21)	1708 (23.6)	3103 (23.6)	3164 (24.3)
Obese	1972 (55.5)	5009 (47.1)	696 (48.2)	2943 (40.7)	6147 (46.8)	5187 (39.8)
		$p < 0.01$		$p < 0.01$		$p < 0.01$
Type 2 diabetes	558 (15.7)	1033 (9.7)	114 (7.9)	405 (5.6)	1051 (8.0)	1010 (7.7)
		$p < 0.01$		$p < 0.01$		$p = 0.44$
Age [d] (years)						
5–12	301 (8.5)	903 (8.5)	376 (26)	1880 (26)	2975 (22.6)	2975 (22.8)
13–18	222 (6.3)	666 (6.3)	156 (10.8)	780 (10.8)	1325 (10.1)	1298 (10)
19–44	1347 (37.9)	4041 (38)	576 (39.9)	2880 (39.9)	4065 (30.9)	4065 (31.2)
45–61	946 (26.6)	2838 (26.7)	234 (16.2)	1170 (16.2)	3177 (24.2)	3110 (23.8)
62–74	470 (13.2)	1410 (13.3)	70 (4.8)	350 (4.8)	1146 (8.7)	1146 (8.8)
75+	266 (7.5)	782 (7.3)	33 (2.3)	165 (2.3)	449 (3.4)	450 (3.4)
Female	2502 (70.4)	7506 (70.5)	868 (60.1)	4340 (60.1)	8133 (61.9)	8040 (61.6)
Year						
2005	527 (14.8)	1581 (14.9)	166 (11.5)	830 (11.5)		
2006	504 (14.2)	1512 (14.2)	147 (10.2)	735 (10.2)		
2007	436 (12.3)	1308 (12.3)	195 (13.5)	975 (13.5)		
2008	378 (10.6)	1134 (10.7)	179 (12.4)	895 (12.4)	3356 (25.5)	3356 (25.7)
2009	431 (12.1)	1293 (12.2)	206 (14.3)	1030 (14.3)	2986 (22.7)	2986 (22.9)
2010	398 (11.2)	1194 (11.2)	182 (12.6)	910 (12.6)	2405 (18.3)	2378 (18.2)
2011	422 (11.9)	1266 (11.9)	174 (12.0)	870 (12.0)	2342 (17.8)	2342 (18.0)
2012	456 (12.8)	1352 (12.7)	196 (13.6)	980 (13.6)	2048 (15.6)	1982 (15.2)

[a] Percentages may not add to 100 due to rounding; [b] Oral corticosteroid (OCS) medication orders; [c] For categorical variables, the *p*-value reported is from a chi-squared test; [d] Cases were frequency-matched to comparison subjects on age, sex, and year.

Table 2. Place-level descriptive statistics of cases and comparison subjects by exacerbation type.

Variable, *n* (% [a]), Unless Specified	Hospitalization		Emergency Visit		OCS [b]	
	Case ***n* = 3552**	**Comparison Subject** ***n* = 10,640**	**Case** ***n* = 1445**	**Comparison Subject** ***n* = 7225**	**Case** ***n* = 13,137**	**Comparison Subject** ***n* = 13,044**
IFAP [c] within 3 miles of home address	832 (23.4)	2706 (25.4)	214 (14.8)	1849 (25.6)	3350 (25.5)	3042 (23.3)
		p [d] = 0.02		$p < 0.01$		$p < 0.01$
Community socioeconomic deprivation, quartiles						
1	870 (24.5)	2839 (26.7)	289 (20)	1935 (26.8)	3424 (26.1)	3536 (27.1)
2	815 (22.9)	2573 (24.2)	298 (20.6)	1728 (23.9)	3093 (23.5)	3129 (24.0)
3	855 (24.1)	2694 (25.3)	345 (23.9)	1811 (25.1)	3389 (25.8)	3203 (24.6)
4	1012 (28.5)	2534 (23.8)	513 (35.5)	1751 (24.2)	3231 (24.6)	3176 (24.3)
		$p < 0.01$		$p < 0.01$		$p = 0.06$
Distance to nearest major road, miles (mean)	1.59	1.66	1.35	1.73	1.69	1.69
		$p = 0.16$		$p < 0.01$		$p = 0.91$
Distance to nearest minor road, miles (mean)	0.92	1.09	0.62	1.12	1.09	1.09
		$p < 0.01$		$p < 0.01$		$p = 0.87$
Distance to hospital, miles (mean)	19.4	32.4	10.3	32.9	32.5	30.8
		$p < 0.01$		$p < 0.01$		$p < 0.01$

[a] Percentages may not add to 100 due to rounding; [b] Oral corticosteroid (OCS) medication orders; [c] Industrial food animal production; [d] For continuous variables, the *p*-value reported is from a *t*-test. For categorical variables, the *p*-value reported is from a chi-squared test.

3.2. Association of IFAP and Asthma Exacerbations

In unadjusted models, proximity to IFAP was not associated with hospitalizations (odds ratio OR = 1.11, 95% CI: 0.97–1.27) or emergency encounters (OR = 0.90, 95% CI: 0.70–1.16), but was associated with increased odds of OCS orders (OR = 1.11, 95% CI: 1.03–1.19). After distance to hospital was added to the model, proximity to IFAP was associated with increased odds in the hospitalization

model and was not associated in the emergency encounters model. Adding the remaining covariates did not substantially change the associations (Table 3).

Table 3. Associations of proximity to industrial food animal production (defined as a facility within 3 miles of home address) and asthma exacerbation outcomes.

Variable (95% CI [a])	Outcome		
	Asthma Hospitalizations [b]	Asthma Emergency Department Visits [b]	New Asthma OCS [c] Orders [d]
Proximity to industrial food animal production [e]	1.29 (1.15–1.46)	1.12 (0.91–1.37)	1.11 (1.04–1.19)
Race/ethnicity (ref: white non-Hispanic)			
Black non-Hispanic	1.05 (0.81–1.36)	1.86 (1.4–2.46)	0.84 (0.73–0.97)
Hispanic	1.23 (0.99–1.54)	1.47 (1.11–1.93)	0.95 (0.84–1.08)
Family history of asthma (ref: no)	1.27 (1.11–1.45)	1.68 (1.4–2.01)	1.27 (1.17–1.37)
Smoking status (ref: never)			
Current	1.45 (1.3–1.62)	1.35 (1.12–1.63)	1.39 (1.29–1.5)
Former	1.18 (1.08–1.3)	1.45 (1.25–1.68)	1.15 (1.08–1.22)
Medical Assistance (ref: no)	1.87 (1.69–2.07)	1.32 (1.13–1.54)	1.06 (0.998–1.13)
Body mass index (ref: normal/underweight)			
Overweight	1.07 (0.95–1.21)	1.07 (0.89–1.28)	1.24 (1.16–1.33)
Obese	1.36 (1.22–1.51)	1.3 (1.11–1.52)	1.53 (1.43–1.62)
Type 2 diabetes (ref: no)	1.63 (1.43–1.85)	1.29 (0.99–1.69)	0.93 (0.84–1.03)
Community socioeconomic deprivation (ref: quartile 1)			
Quartile 2	0.97 (0.83–1.13)	1.28 (1.01–1.63)	0.99 (0.91–1.08)
Quartile 3	0.97 (0.83–1.14)	1.41 (1.10–1.82)	1.01 (0.93–1.11)
Quartile 4	0.94 (0.79–1.12)	1.41 (1.10–1.82)	0.98 (0.89–1.08)
Distance to nearest major arterial road, z-transformed			
z-transformed	0.94 (0.84–1.04)	1.10 (0.93–1.31)	0.97 (0.91–1.03)
squared	1.07 (1.02–1.12)	1.04 (0.97–1.12)	1.02 (0.99–1.05)
Distance to nearest minor arterial road			
z-transformed	1.08 (0.97–1.19)	1.03 (0.87–1.22)	0.98 (0.92–1.04)
squared	0.998 (0.95–1.05)	0.89 (0.79–1.003)	1.003 (0.98–1.03)
Distance to nearest Geisinger hospital			
z-transformed	0.46 (0.42–0.51)	0.10 (0.08–0.13)	
squared	1.14 (1.07–1.21)	1.35 (1.09–1.66)	f

[a] Confidence interval; [b] Multilevel models with a random intercept for community, adjusted for race/ethnicity (white, black, Hispanic, other), family history of asthma (yes, no), smoking status (never, former, current, missing), Medical Assistance (yes vs. no), overweight/obesity (normal, body mass index (BMI) < 85th percentile or BMI < 25 kg/m^2; overweight, BMI = 85th < 95th percentile or BMI = 25 < 30 kg/m^2; obese, BMI $\geq$ 95th percentile or BMI $\geq$ 30 kg/m^2, for children and adults, respectively; BMI missing), type 2 diabetes (yes vs. no), community socioeconomic deprivation (quartiles), distance to nearest major and minor arterial road (truncated at the 98th percentile, meters, z-transformed), squared distance to nearest major and minor arterial road (truncated at the 98th percentile, meters, z-transformed), distance to nearest Geisinger hospital (truncated at the 98th percentile, kilometers, z-transformed), squared distance to nearest Geisinger hospital (truncated at the 98th percentile, kilometers, z-transformed), age category (5–12, 13–18, 19–44, 45–61, 62–74, 75+ years), sex (male, female), and year of event (2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012); [c] Oral corticosteroid; [d] Multilevel model with a random intercept for community, adjusted for race/ethnicity (white, black, Hispanic, other), family history of asthma (yes, no), smoking status (never, former, current, missing), Medical Assistance (yes vs. no), overweight/obesity (normal, body mass index (BMI) < 85th percentile or BMI < 25 kg/m^2; overweight, BMI = 85th < 95th percentile or BMI = 25 < 30 kg/m^2; obese, BMI $\geq$ 95th percentile or BMI $\geq$ 30 kg/m^2, for children and adults, respectively; BMI missing), type 2 diabetes (yes vs. no), community socioeconomic deprivation (quartiles), distance to nearest major and minor arterial road (truncated at the 98th percentile, meters, z-transformed), squared distance to nearest major and minor arterial road (truncated at the 98th percentile, meters, z-transformed), age category (5–12, 13–18, 19–44, 45–61, 62–74, 75+ years), sex (male, female), and year of event (2008, 2009, 2010, 2011, 2012); [e] Within 3 miles of home address; f, Distance to hospital was not included in this model.

3.3. Results of Sensitivity Analyses

The *p*-value of the cross-product of proximity to IFAP and an indicator for childhood age were 0.53, 0.73, and 0.82 for the hospitalization, emergency department, and OCS analyses, respectively, indicating that associations in children and in adults were similar. The odds ratios from the sensitivity analysis that excluded patients in cities (for hospitalizations, OR = 1.29, 95% CI: 1.14–1.46; for emergency

encounters, OR = 1.09, 95% CI: 0.89–1.34; and for OCS orders, OR = 1.12, 95% CI: 1.04–1.20) were similar to those in the primary analysis. In the sensitivity analysis that included cases with more than one of a given type of event, we found similar results as in the primary analysis (for hospitalizations, OR = 1.39, 95% CI: 1.09–1.76; for emergency encounters, OR = 1.12, 95% CI: 0.91–1.37; and for OCS orders, OR = 1.14, 95% CI: 1.02–1.27). In the sensitivity analysis that individually matched cases to comparison subjects on age, sex, and distance to hospital, in adjusted models, associations were similar to those from the primary analysis for hospitalizations (OR = 1.24, 95% CI: 1.09–1.40) and for emergency encounters (OR = 1.07, 95% CI: 0.86–1.33). In the sensitivity analysis that used patients with no asthma exacerbations during the study period as comparison subjects, associations were similar to the primary analysis for hospitalizations (OR = 1.29, 95% CI: 1.13–1.46) and stronger though still not statistically significant for emergency encounters (OR = 1.19, 95% CI: 0.97–1.46).

4. Discussion

We evaluated associations of IFAP with three kinds of clinically-documented asthma exacerbations, and conducted a number of sensitivity analyses, in a large population of asthma patients in a region with many IFAP facilities. We found 11% and 29% increased odds of OCS orders and asthma hospitalizations, respectively, among asthma patients living within 3 miles of IFAP, compared to living farther away. We did not observe effect modification by childhood age. We found similar results using individual matching on distance to hospital, and using patients with no asthma exacerbations during the study period as the comparison group.

Our study found that distance to hospital was an important confounder in the hospitalization analysis. A study from the Netherlands found that proximity to livestock farms (<500 m from home address) was negatively associated with the number of patient contacts with general practitioners (including encounters, home visits, and telephone consultations), but in contrast to our study, their association was unchanged when distance to general practice was added to the model [16].

We report different results than two prior studies from the Netherlands that used clinically-documented asthma (as opposed to self-reported) to assess the association of IFAP and asthma. The first study evaluated asthma prevalence, not exacerbations, so it is not relevant to our findings [14]. The other study concluded that proximity to IFAP was not associated with asthma exacerbations [15]. They found no association of distance to nearest swine or poultry farm with asthma exacerbations, as measured by an increase in the dose or a new medication order for asthma medications. In contrast to that study, we found an increased risk of new OCS orders for asthma and for asthma hospitalizations among asthma patients living close to swine or dairy/veal IFAP compared to farther away.

Our study had limitations. The buffer proximity approach treated swine and dairy/veal facilities as the same, though emissions may differ between the two, and did not incorporate animal count, IFAP building characteristics, or wind direction. Furthermore, we did not have information on poultry IFAP and we did not take air samples. Proximity was based on distance from residential address (ascertained in 2013) to closest IFAP operation, so it might misclassify exposures at school or work, or if the patient had recently moved, though an analysis in a prior study of this population indication low residential mobility [8]. We did not have information on study participants' housing conditions, which could contribute to asthma exacerbations. We did not ascertain events that occurred outside the Geisinger system. The EHR only captures events for which patients seek care, so we do not have data on asthma symptoms that patients could treat on their own without medical care. We only collected information on IFAP in 2010 and 2011, and we assumed facilities were in the same location for the entire study period. However, we verified the locations of a random sample of 20 IFAP in Google Earth's historical aerial imagery, and all were present in the images since at least 2005, so we believe this was a reasonable assumption. Strengths of this study included a large sample size consisting of both children and adults. We incorporated both swine and dairy/veal IFAP, unlike previous studies in the

United States that only incorporated swine IFAP [1,8,9]. We used asthma exacerbations documented in an EHR instead of relying on self-reported outcomes [1,5,8], which can result in recall bias [22].

5. Conclusions

Our study observed an association of clinically-documented asthma exacerbations, a serious public health concern, in relation to IFAP in Pennsylvania. The finding is biologically plausible and was robust in a number of relevant sensitivity analyses.

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Author Contributions: Sara G. Rasmussen co-designed the study, conducted statistical analyses, created the figure, and prepared the first draft of the manuscript. Joan A. Casey co-designed the study, created exposure metrics, and provided critical revision of the manuscript. Karen Bandeen-Roche helped with study design, helped interpret results, and provided critical revision of the manuscript. Brian S. Schwartz co-designed the study, acquired the health data, helped interpret results, and provided critical revision of the manuscript.

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References

1. Casey, J.A.; Kim, B.F.; Larsen, J.; Price, L.B.; Nachman, K.E. Industrial food animal production and community health. *Curr. Environ. Health Rep.* **2015**, *2*, 259–271. [CrossRef] [PubMed]
2. National Heart, Lung, and Blood Institute; National Asthma Education Program; Expert Panel on the Management of Asthma. *Expert Panel Report 3: Guidelines for the Diagnosis and Management of Asthma: Full Report*; U.S. Department of Health and Human Services, National Institutes of Health, National Heart, Lung, and Blood Institute: Bethesda, MD, USA, 2007.
3. Moorman, J.E.; Akinbami, L.J.; Bailey, C.M.; Johnson, C.A.; King, M.E.; Liu, X.; Zahran, H.S. National surveillance of asthma: United States, 2001–2010. *Vital Health Stat. Ser. Anal. Epidemiol. Stud.* **2012**, *35*, 1–58.
4. Casey, J.A.; Curriero, F.C.; Cosgrove, S.E.; Nachman, K.E.; Schwartz, B.S. High-Density livestock operations, crop field application of manure, and risk of Community-Associated Methicillin-Resistant Staphylococcus Aureus infection in Pennsylvania. *JAMA Intern. Med.* **2013**, *173*, 1980–1990. [CrossRef] [PubMed]
5. Loftus, C.; Yost, M.; Sampson, P.; Torres, E.; Arias, G.; Breckwich Vasquez, V.; Hartin, K.; Armstrong, J.; Tchong-French, M.; Vedal, S.; et al. Ambient ammonia exposures in an agricultural community and pediatric asthma morbidity. *Epidemiology* **2015**, *26*, 794–801. [CrossRef] [PubMed]
6. Johnston, N.W.; Sears, M.R. Asthma Exacerbations. 1: Epidemiology. *Thorax* **2006**, *61*, 722–728. [CrossRef] [PubMed]
7. Sigurdarson, S.T.; Kline, J.N. School proximity to concentrated animal feeding operations and prevalence of asthma in students. *Chest* **2006**, *129*, 1486–1491. [CrossRef] [PubMed]
8. Mirabelli, M.C.; Wing, S.; Marshall, S.W.; Wilcosky, T.C. Asthma symptoms among adolescents who attend public schools that are located near confined swine feeding operations. *Pediatrics* **2006**, *118*, e66–e75. [CrossRef] [PubMed]
9. Pavilonis, B.T.; Sanderson, W.T.; Merchant, J.A. Relative exposure to swine animal feeding operations and childhood asthma prevalence in an agricultural cohort. *Environ. Res.* **2013**, *122*, 74–80. [CrossRef] [PubMed]
10. Schinasi, L.; Horton, R.A.; Guidry, V.T.; Wing, S.; Marshall, S.W.; Morland, K.B. Air pollution, lung function, and physical symptoms in communities near concentrated swine feeding operations. *Epidemiology* **2011**, *22*, 208–215. [CrossRef] [PubMed]
11. Borlee, F.; Yzermans, C.J.; van Dijk, C.E.; Heederik, D.; Smit, L.A. Increased respiratory symptoms in COPD patients living in the vicinity of livestock farms. *Eur. Respir. J.* **2015**, *46*, 1605–1614. [CrossRef] [PubMed]
12. Radon, K.; Schulze, A.; Ehrenstein, V.; van Strien, R.T.; Praml, G.; Nowak, D. Environmental exposure to confined animal feeding operations and respiratory health of neighboring residents. *Epidemiology* **2007**, *18*, 300–308. [CrossRef] [PubMed]

13. Schulze, A.; Rommelt, H.; Ehrenstein, V.; van Strien, R.; Praml, G.; Kuchenhoff, H.; Nowak, D.; Radon, K. Effects on pulmonary health of neighboring residents of concentrated animal feeding operations: Exposure assessed using optimized estimation technique. *Arch. Environ. Occup. Health* **2011**, *66*, 146–154. [CrossRef] [PubMed]
14. Smit, L.A.; Hooiveld, M.; van der Sman-de Beer, F.; Opstal-van Winden, A.W.; Beekhuizen, J.; Wouters, I.M.; Yzermans, C.J.; Heederik, D. Air pollution from livestock farms, and asthma, allergic rhinitis and COPD among neighbouring residents. *Occup. Environ. Med.* **2014**, *71*, 134–140. [CrossRef] [PubMed]
15. Van Dijk, C.E.; Garcia-Aymerich, J.; Carsin, A.E.; Smit, L.A.; Borlee, F.; Heederik, D.J.; Donker, G.A.; Yzermans, C.J.; Zock, J.P. Risk of exacerbations in copd and asthma patients living in the neighbourhood of livestock farms: Observational study using longitudinal data. *Int. J. Hyg. Environ. Health* **2016**, *219*, 278–287. [CrossRef] [PubMed]
16. Van Dijk, C.E.; Smit, L.A.; Hooiveld, M.; Zock, J.; Wouters, I.M.; Heederik, D.J.; Yzermans, C.J. Associations between proximity to livestock farms, primary health care visits and self-reported symptoms. *BMC Fam. Pract.* **2016**, *17*, 22. [CrossRef] [PubMed]
17. Rasmussen, S.G.; Ogburn, E.L.; McCormack, M.; Casey, J.A.; Bandeen-Roche, K.; Mercer, D.G.; Schwartz, B.S. Association between unconventional natural gas development in the marcellus shale and asthma exacerbations. *JAMA Intern. Med.* **2016**, *176*, 1334–1343. [CrossRef] [PubMed]
18. Pacheco, J.A.; Avila, P.C.; Thompson, J.A.; Law, M.; Quraishi, J.A.; Greiman, A.K.; Just, E.M.; Kho, A. A highly specific algorithm for identifying asthma cases and controls for Genome-Wide Association Studies. *AMIA Annu. Symp. Proc.* **2009**, *2009*, 497–501. [PubMed]
19. Ogden, C.L.; Carroll, M.D.; Kit, B.K.; Flegal, K.M. Prevalence of childhood and adult obesity in the United States, 2011–2012. *JAMA* **2014**, *311*, 806. [CrossRef] [PubMed]
20. Nau, C.; Schwartz, B.S.; Bandeen-Roche, K.; Liu, A.; Pollak, J.; Hirsch, A.; Bailey-Davis, L.; Glass, T.A. Community socioeconomic deprivation and obesity trajectories in children using electronic health records. *Obesity* **2015**, *23*, 207–212. [CrossRef] [PubMed]
21. Liu, A.Y.; Curriero, F.C.; Glass, T.A.; Stewart, W.F.; Schwartz, B.S. Associations of the burden of coal abandoned mine lands with three dimensions of community context in Pennsylvania. *ISRN Public Health* **2012**. [CrossRef]
22. Casey, J.A.; Schwartz, B.S.; Stewart, W.F.; Adler, N.E. Using electronic health records for population health research: A review of methods and applications. *Annu. Rev. Public Health* **2015**, *37*, 61–81. [CrossRef] [PubMed]



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Manure and Groundwater Quality

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Manure and Groundwater Quality

Literature Review

by

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Washington State Department of Ecology
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Abstract

Agriculture is important to the vitality of Washington State. There are concerns about impacts to groundwater quality from manure generated at animal production facilities (concentrated animal feeding operations; CAFOs).

The purpose of this report is to (1) review current scientific information on manure management and present strategies for measuring the effectiveness of these management practices and (2) identify practices and treatment technologies that assure that groundwater quality will be maintained and protected.

Land application of manure is a waste management tool that uses land treatment to beneficially reuse the nutrients to grow a crop. If manure is not properly managed, it can adversely affect groundwater quality. Research indicates that this typically occurs when (1) manure is applied in amounts greater than crops can use, (2) manure is applied when crops are not growing, (3) manured fields are over-irrigated, or (4) manure is stored in lagoons not constructed to a recognized standard.

This report summarizes information presented in the literature in the following areas:

- Documented impacts to groundwater quality.
- Effectiveness of manure management practices including application rates, crop uptake, timing of application, soil mechanics, irrigation water management, and storage lagoon design.
- Sampling protocols for crops, manure, soil, groundwater, and mass balance calculations.
- Manure management practices that adversely impact groundwater.
- Tools to assess manure management practices, quantify available nitrogen, and determine application rates and times.
- Evaluating impacts to groundwater quality using site-specific soil nitrate threshold limits and groundwater monitoring.

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Executive Summary

This literature review compiles existing studies and describes what is known about impacts to groundwater quality resulting from manure management at concentrated animal feeding operations (CAFOs). The intent is provide the scientific basis to support and guide our continued conversations with the agricultural community to work together to better protect groundwater quality in Washington State as well as foster sustainable agricultural practices. Based on the outcomes of these conversations, changes to Washington's CAFO general water quality discharge permit will be proposed.

Manure management is a key component to assuring that groundwater is protected and that farmers are in compliance with groundwater quality standards. CAFOs land-apply manure as a fertilizer to grow crops. By beneficially re-using their manure, CAFOs treat and manage their wastes and grow crops. When manure is appropriately land-applied in the right amounts and at the right times, the nutrients will be taken up by plants and will not seep into groundwater. Constructed ponds, called lagoons, are a common way manure is stored, allowing producers to contain manure until it can be applied to crops during the growing season.

Washington State groundwater quality standards are in place to protect all of the benefits groundwater provides, including the most common use of drinking water. Yet, there are documented adverse impacts to groundwater quality from some Washington CAFO manure management practices. Research indicates that this typically occurs when too much manure is applied, manure is applied during the wrong time, or manure is stored in a lagoon that is not constructed to a recognized standard.

The purpose of this report is to review current scientific information on manure management and present strategies for measuring the effectiveness of these management practices. The report summarizes the most current findings from more than 170 published research documents. These research documents are from local, state, national, and international sources including government agencies, scientific research groups, and academic institutions.

Primary Questions This Literature Review Attempts to Answer

- Is manure management impacting water quality?
- Which management practices are important to protect water quality?
- What kind of monitoring is most effective for evaluating management practices?
- Do storage lagoons leak? Are they causing problems? How should they be constructed?
- How do we know when a facility is operating in a way that protects water quality?
- What are the common conclusions and recommendations made by researchers?

Key Findings

- CAFOs and other animal operations can impact groundwater quality.
- There are documented impacts to groundwater quality in Washington State from CAFO manure management practices. Impacts to groundwater quality from other areas are also summarized.
- Manure management strategies that are critical to protecting groundwater quality are summarized. These management practices include:
    - Application rates – applying the right amount of nutrients to maintain a viable crop while minimizing impacts to water quality.
    - Timing – applying manure only during the growing season when the crop can use the nutrients. Three tools are cited to provide producers methods for determining the growing season based on their location and the crop grown.
    - Storing manure in a lagoon (constructed to recognized standards) during the non-growing season.
    - Managing irrigation water to prevent leaching of nitrate to groundwater.
- Monitoring is important to assess how well a facility is operating.
    - Spring and fall soil monitoring is recommended. Soil monitoring should be conducted in the spring to determine how much soil nitrate is present and how much additional nutrients are needed to maintain a viable crop. Fall soil monitoring should be conducted to assess the effectiveness of the previous year's manure management.
    - Literature offers recommendations on appropriate soil nitrate. Researchers recommend that spring soil nitrate should range from 16 to 30 ppm, and fall soil nitrate should range from 5 to 24 ppm. Researchers also provide recommended actions depending on different soil nitrate concentrations.
    - A tool was developed to assist in quantifying the potential nitrate leaching to groundwater based on the soil nitrate concentration and other site-specific factors.
    - Problems are noted with soil storage of nutrients during the non-growing season and year-round application of manure.
    - Groundwater monitoring is identified as the only way to measure impacts to groundwater quality.
- Typical nitrogen loss estimates are summarized for nitrogen volatilization, mineralization, nitrification, and denitrification.
- Success stories show benefits to CAFOs and groundwater quality.

Introduction

Agriculture has a strong historical presence in Washington State and provides many commodities and economic benefits. One segment of the agricultural industry is the production of animals and animal products. This industry segment is composed of animal feeding operations (AFOs), concentrated animal feeding operations (CAFOs), and other pasture and rangeland operations. The waste generated from animal operations is required to be managed to assure that water quality is protected. This literature review consolidates and summarizes information from relevant literature to provide a scientific basis for assessing manure management practices.

AFOs and CAFOs use collection systems to consolidate manure and other wastes from the facility production areas where animals are housed and products are produced. This collected waste is typically land-applied to provide nutrients for crops, or it is stored in a lagoon until crops can utilize the nutrients. Manure is a waste or by-product from animal production and is rich in nutrients that crops need, especially nitrogen. Manure can be beneficially used as a resource to grow crops. However, if manure is not managed properly it can adversely impact groundwater quality.

When nitrogen inputs to the soil system exceed crop needs, excess nitrate could enter groundwater. Adverse impacts to water quality can be minimized through management practices. Understanding the processes that affect nitrogen transformation and mobilization in the environment can help in efficiently managing nitrogen in land treatment systems.

Report Goals

The purpose of this report is to review current scientific information on manure management and present strategies for measuring the effectiveness of these management practices. The goal is to identify practices and treatment technologies that assure that groundwater quality will be maintained and protected. This report primarily focuses on the potential adverse impacts of animal wastes on groundwater quality and how these impacts can be monitored, assessed, and mitigated. This report summarizes the current scientific information presented in the literature in the following areas:

- Documented manure impacts to groundwater quality.
- Manure management related to groundwater impacts.
- Effectiveness of manure management practices including application rates, crop uptake, timing of application, soil mechanics, storage lagoon design and management, vegetative buffers and setbacks to surface waters.
- Use of mass balance calculations.
- Sampling protocols for crops, manure, soil, and groundwater.
- Tools to assess manure management effectiveness, quantify available nitrogen, and determine application rates and times.
- Strategies for evaluating impacts to groundwater quality using site-specific soil nitrate thresholds and groundwater monitoring.

Methods

The intent of this review is to include only peer-reviewed published work found in journals, technical reports generated by government agencies, scientific research groups, academic institutions, and other similar reputable scientific sources. Standard widely accepted practices are also included in some instances, when it is the basis for treatment practices or monitoring protocols.

Preliminary findings, raw data, work that is in progress, or work that has not been peer reviewed were not considered adequate to meet the goals of this report. Additionally, personal opinion and biased work were not included.

There is a tremendous amount of literature on agricultural practices. An effort was made to find the most current and relevant literature that addressed the report goals and met the above criteria. However, this review is not exhaustive.

Background

Nitrate is one of the most prevalent groundwater contaminants in the world (Nolan and Stoner, 2000; Rosenstock et al., 2014), and concentrations are increasing (Spalding and Exner, 1993). The National Academy of Engineering (2008) identified nitrogen management as one of the grand challenges facing the United States.

Numerous studies document that agricultural activities are a source of elevated nitrate in groundwater: Almasri, and Kaluarachchi, 2004; Hudak, 2002; Harter et al., 2002; Lindsey et al., 1998; Dzurella et al., 2012, Sánchez-Pérez et al., 2003; Yin et al., 2007; Erickson and Norton, 1990; Zebarth et al., 1998; Carey and Harrison, 2014; EPA, 2013a and 2013b; Burkholder et al., 2007; Sajil Kumar et al., 2013; Ju et al., 2006; Nolan and Stoner, 2000; Rosenstock et al., 2014; and Olson et al., 2009.

Nolan and Stoner (2000) concluded that in agricultural areas within the United States that 19% of the shallow groundwater wells do not meet the groundwater standard of 10 mg N/L. They also concluded that groundwater nitrate concentrations are higher in agricultural areas than in urban areas.

Previous Literature Reviews

Washington State University (Hermanson et al., 2000) conducted a literature search titled *Nitrogen Use by Crops and the Fate of Nitrogen in the Soil and Vadose Zone*. The primary goal of this review was to provide to the Washington State Department of Ecology (Ecology) information for management of process wastewater for land application, including sources from municipal, food processing, and livestock manure. This report focuses on nitrogen use by crops and the interactions between soil, water, and nitrogen.

Hermanson et al. (2000) provided the following general principles and recommendations drawn from their comprehensive review:

- The estimation of agronomic rate for a crop must factor in all sources of nitrogen available during the growing season. This includes mineralization, residual inorganic nitrogen, and contribution from irrigation water. Agronomic rate is defined as the recommended rate of nitrogen addition to the soil that is needed to produce an expected yield, while minimizing adverse environmental effects.
- In waste management scenarios, agronomic rate and the application rate may be different. When the application rate is in excess of the agronomic rate, close attention must be given to the environmental consequences of this practice.
- All nitrogen applied to the soil, that is not volatilized, will eventually convert to nitrate. The total transformation to nitrate may take a few weeks to a few years, depending on the nature of the organic waste.
- Nitrate moves readily with water in the soil profile and can reach groundwater if not taken up by the crops, denitrified, or volatilized. Other forms of nitrogen are less mobile.
- Soil nitrogen that moves below the root zone will eventually leach to groundwater as nitrate. Steps should be taken to minimize movement of nitrogen below the root zone during the growing and non-growing seasons.
- Denitrification may reduce nitrate loading to groundwater under some conditions, though it is of little importance in well-drained soils.
- Nitrogen applied at the time and in the amounts needed by the crop will minimize the buildup of soil nitrogen.
- Wastes applied substantially before or after maximum crop demand may result in the buildup of inorganic soil nitrogen that will subsequently be susceptible to nitrate leaching.
- Use of winter cover crops can minimize movement of nitrogen deeper into the soil profile by utilizing the nitrogen in the root zone, storing it in the plant tissue, and ultimately returning it to the soil surface after the cover crop dies. Cover crops temporarily store nitrogen removed from the root zone.
- Winter cover crops are not a reason to over-apply nitrogen. If excess nitrogen is applied in one growing season, it must be offset by decreased nitrogen application the following season to avoid residual nitrogen buildup and subsequent nitrogen leaching.
- Poor irrigation management will prevent efficient nitrogen management and recovery.
- The nitrogen composition of the manure should be determined before application because it will affect the timing of nitrogen availability and the susceptibility to nitrate leaching.
- Maximizing nitrogen removal by crops (by attempting to maximize crop production and increase nitrogen uptake) will generally increase the risk of nitrate accumulation in the soil.
- Organic wastes applied during the non-growing season will partially or totally convert to nitrate before the next growing season. The fraction mineralized will depend on the manure composition, the soil temperature and moisture conditions. The depth that nitrates will travel in the soil before the next growing season will depend on the soil hydraulic properties and the volume of recharge (precipitation and irrigation).

- Nitrate leached beyond the root depth of the crops to be grown during the following season will be susceptible for transport to groundwater.
- Steps should be taken to minimize movement of nitrogen below the root zone during the growing and non-growing season.
- Applying organic wastes during the non-growing season has an inherent risk in terms of leaching nitrogen to groundwater.
- The use of storage facilities to minimize waste applications during the non-growing season is a safe alternative.

This literature review builds on the work completed by Hermanson et al. (2000) and focuses on current environmental issues related to manure management with a specific focus on groundwater.

AFOs, CAFOs, and Dairies

Understanding the regulatory authority and history is helpful to the development of manure management practices within Washington State. Authority to regulate manure and provide technical assistance is divided between several agencies. Ecology has authority to issue general permits[1] as well as protect groundwater and surface water quality. Ecology has developed technical guidance documents for other similar types of land application discharges. A brief overview of the regulatory authority and related guidance is contained in Appendix B.

CAFOs generally have not been required to demonstrate compliance with groundwater quality standards. This is the case for both permitted and unpermitted facilities. Within Ecology's CAFO general permit; there is no requirement to monitor groundwater. Therefore, documenting a discharge and the associated impacts to groundwater (a water of the State) has been problematic. If a CAFO is not managing its manure properly (e.g., applying too much, applying at the wrong time, over-irrigating, or storing manure in a lagoon not constructed to a recognized standard), groundwater impacts are the likely result.

Within the framework of a water quality permit, disposal is not the goal; waste treatment and water quality protection are the goal. Manure management requires beneficially reusing nutrients in a manner that will not promote leaching. Maximizing crop yield is not equivalent to maximizing crop uptake since maximizing crop yield often entails applying excessive nutrients. Maximizing crop yield is not the goal of a land treatment system; the goal is to maintain a viable crop which utilizes the nutrients applied (Ecology, 2004a).

Dairies

In 1993 the Washington State legislature passed the Dairy Nutrient Management Act (Chapter 90.64 RCW). Dairies are one type of AFO. AFOs include CAFOs and the entire animal agricultural industry as a whole (e.g., beef, poultry, dairy, swine, horses), not just dairy farms.

[1] General permits are a type of permit that covers a category of discharger where there is a group of facilities that have similar discharge characteristics and utilize similar treatment mechanisms.

As a result of the Dairy Nutrient Management Program, the number of dairies and their locations are documented, while the same level of information has not been compiled for other types of AFOs. Because information on dairies is readily available, dairies have generally become the focal point of AFO-related discussions.

Dairies produce milk, cheese, butter, yogurt and other dairy products. Milk is Washington State's second most valuable agricultural commodity, second only to apples. Washington State ranked 10th nationally, producing 690 million gallons of milk in 2010. (WSDA, 2011)

In 2010, Washington had 443 commercial dairy farms with approximately 250,000 mature cows. WSDA (2011) notes that while the number of dairy farms has dropped over the years, the number of dairy cows has remained relatively constant.

Dairy farms are located in 28 of the 39 Washington counties. Table 1 describes the dairy size classifications (small, medium, and large) based on the U.S. Environmental Protection Agency (EPA) AFO definition. Figure 1 illustrates the distribution of classes within the state. Whatcom County is home to the most dairies with 125 farms, which collectively house a total 46,588 mature cows. Yakima County has the highest number of mature cows with 93,606 animals housed on 67 farms. (WSDA, 2011)

Table 1. Dairy size and distribution (WSDA, 2011).

Dairy Size	Number of Cows	Percent
Small	1 – 199	40%
Medium	200 – 699	37%
Large	700 +	23%
	>2,500	4% (16 of the large dairies)

Seventy percent of Washington's large dairies are located in Yakima County and the Columbia Basin. The majority of small and medium sized dairies are located in western Washington (WSDA, 2011). Figure 1 illustrates the locations of dairies.



Figure 1. Dairy distribution in Washington State by size (WSDA, 2011).

Nitrate Impacts to Groundwater in Washington State

In Washington State, nitrate has contaminated public and private drinking water supplies. Groundwater is considered contaminated when it does not meet (exceeds) a drinking water standard. The drinking water standard set by EPA for nitrate is 10 mg N/L. Figure 2 highlights locations where elevated nitrate levels in groundwater have been documented. Nitrate groundwater contamination is a persistent widespread issue in the Lower Yakima Valley, the Lower Columbia Basin, and the Sumas-Blaine area in Whatcom County.

It is difficult to assess the direct impacts of AFOs on groundwater quality in Washington State, since few AFOs are required to monitor groundwater. In addition, there are only a few groundwater studies that assess impacts of AFOs in Washington State. EPA (2012 and 2013) recently conducted a groundwater investigation in the Lower Yakima Valley which linked CAFO discharges to groundwater contamination.

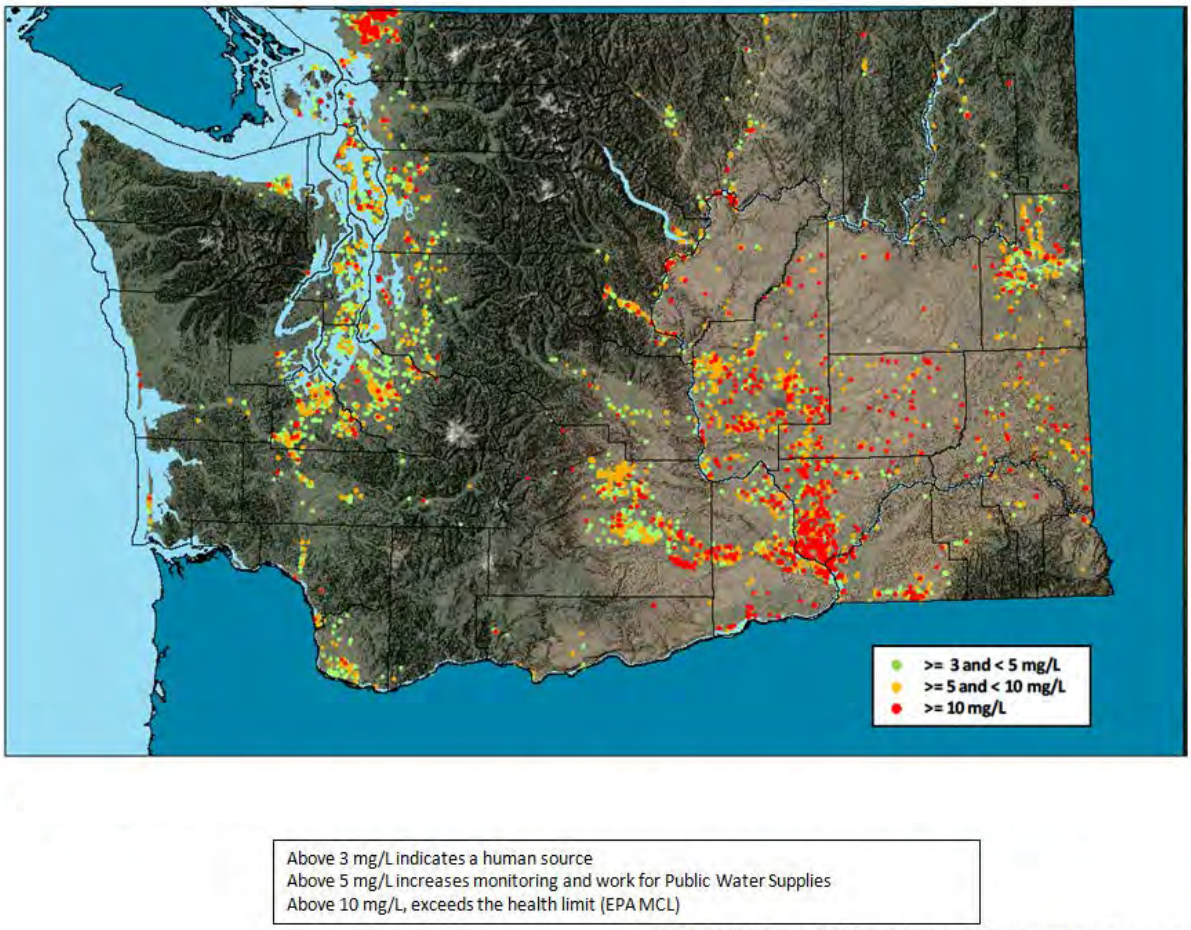

Figure 2. Groundwater nitrate occurrences in Washington State (Morgan, 2012).

Based on data from Washington State Department of Health Public Water Supply (2000-2011), Washington State Department of Ecology EIM (1982-2012), and U.S. Geological Survey (USGS) National Water Information System (1970-2011).

Nitrogen Loading by Sources

Nitrogen is a natural element that is concentrated through many sources and activities. It is present in human and animal wastes, plants, fertilizers, and precipitation. Nitrogen exists in different forms and behaves differently depending upon its form. Nitrate is the most prevalent form in groundwater and is the most mobile form. The primary forms of nitrogen in manure are organic nitrogen and ammonium. Plant-available nitrogen includes ammonium and nitrate. Appendix A describes the nitrogen cycle in more detail.

EPA (1999) summarized national data from animal operations. They calculated that the amount of manure produced by AFOs was 13 times greater than the sewage waste generated by humans in 1992 (on a dry weight basis). These AFOs produced 2.07 trillion pounds of manure in the U.S. and contained 11.6 billion pounds of nitrogen and 3.5 billion pounds of phosphorous.

Recent studies in the Lower Yakima Valley (EPA, 2013a) and the Sumas-Blaine aquifer in Whatcom County (Almasri and Kaluarachchi, 2004) assessed nitrogen contributions from various nitrogen sources. These two areas in Washington State have high groundwater nitrate concentrations. These studies assessed nitrogen sources in slightly different ways; however, the results described below, in percentages, are very similar.

The Lower Yakima Valley nitrogen sources are illustrated in Figure 3 and Table 2 (EPA, 2012). These percentages are based on the amount of nitrogen generated by the activity and the potential loading to the ground; they do not represent loadings to groundwater.

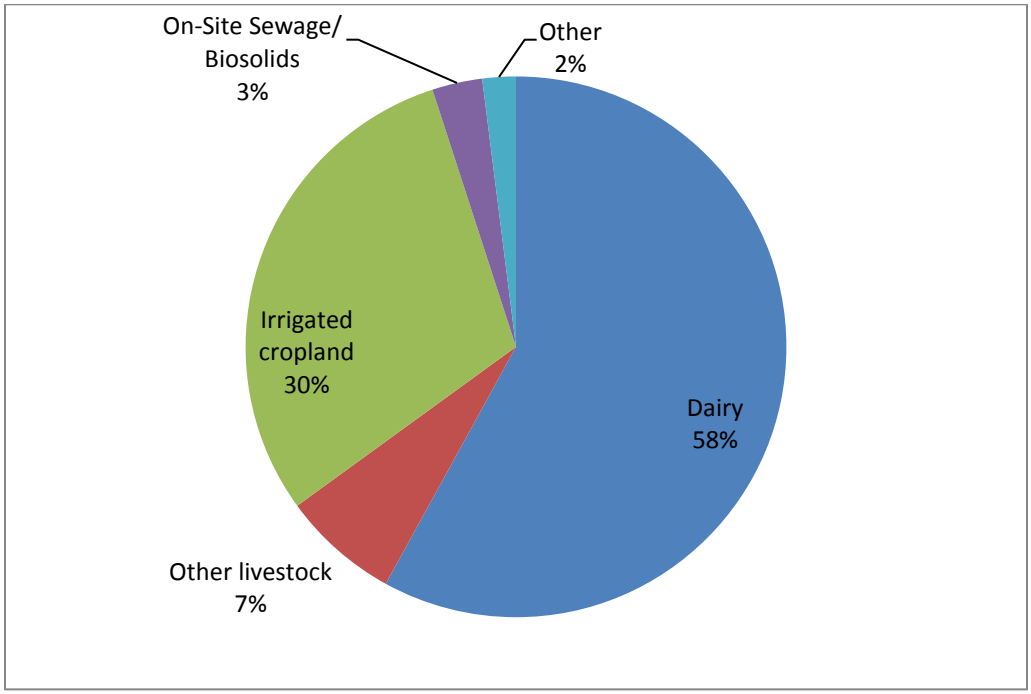

Figure 3. Estimates of nitrogen generated by sources in the Lower Yakima Valley (modified from EPA, 2013a).

Table 2. Estimates of nitrogen generated by sources in the Lower Yakima Valley.

Nitrogen Sources	%	lbs/year
Dairy	58	32,132,000
Other livestock	7	3,878,000
Irrigated cropland	30	16,620,000
On-site sewage/biosolids	3	1,662,000
Other	2	1,108,000

(Modified from EPA, 2013a.)

EPA (2012) estimated nitrogen generated based on area-specific assumptions for the identified sources in the Lower Yakima Valley. The on-site sewage estimates for the Lower Yakima Valley assume 6 lbs of nitrogen are generated per person per year, based on the total population in the area. Since the entire population is included in this calculation and many area residences do not use on-site sewage systems, this number overestimates the actual load from on-site sewage systems. This number more accurately reflects total nitrogen load from human wastewater, since it also includes loading from biosolids. The *other* category is composed of nitrogen loading from precipitation and from fertilizer used on lawns, parks, and golf courses.

The Sumas-Blaine aquifer (Whatcom County) nitrogen sources are illustrated in Figure 4 and Table 3 (Almasri and Kaluarachchi, 2004; Cox and Kahle, 1999). These percentages are based on the amount of nitrogen generated by the activity and the potential loading to the ground; they do not represent loadings to groundwater.

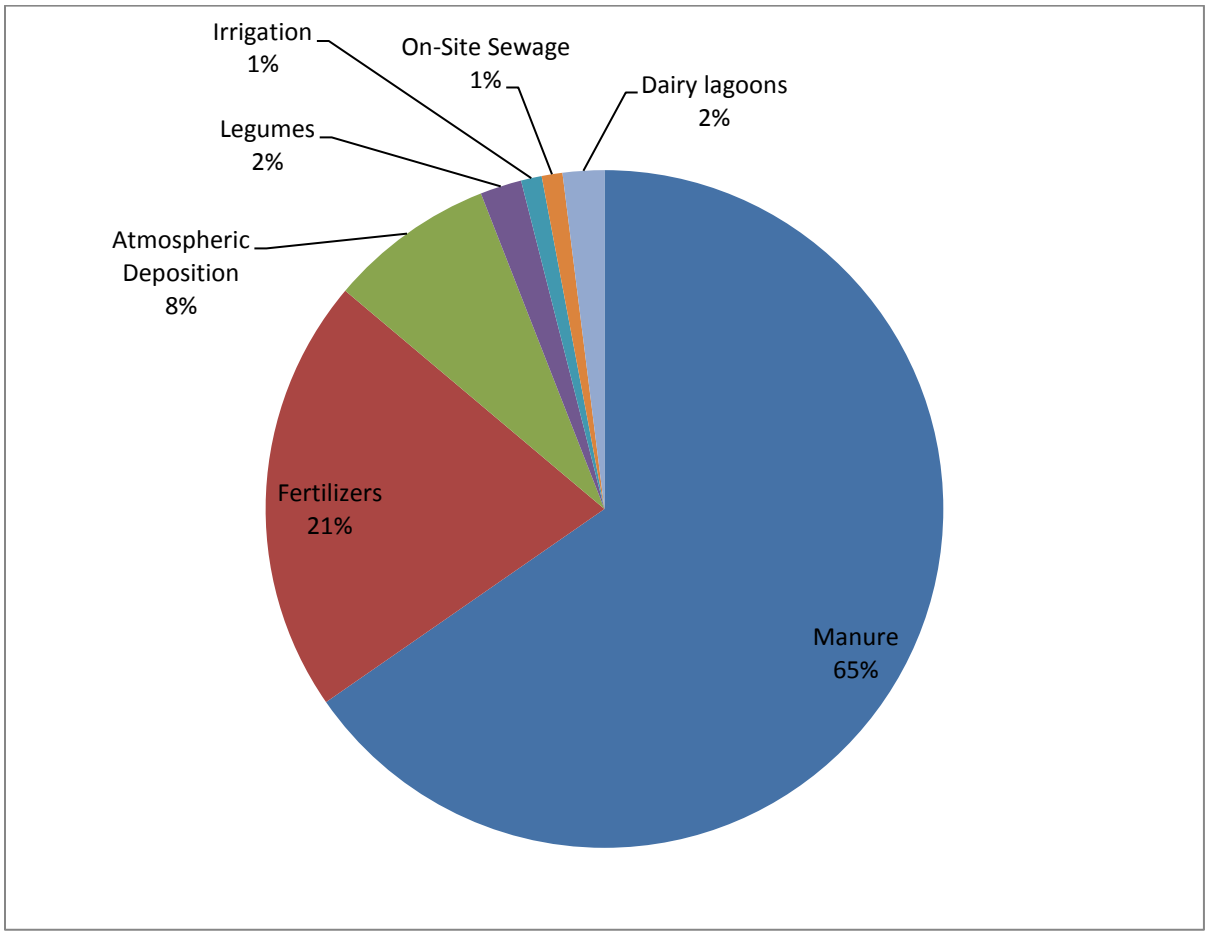

Figure 4. Nitrogen loading to the ground over the Sumas-Blaine aquifer (modified from Almasri and Kaluarachchi, 2004).

Table 3. Nitrogen loading to the ground over the Sumas-Blaine aquifer.

Nitrogen Sources	Percentage (%)	N Loading (lbs/acre/year)	Area (acre)	Total Nitrogen Load (lbs/year)
Manure	66	356	41,252	14,689,837
Fertilizers	21	73	63,196	4,625,947
Atmospheric deposition	8	7	236,196	1,724,231
Legumes	2	5	85,604	428,020
Irrigation	1	2	106,298	170,077
		(lbs/unit)	(units)	
On-site sewage	1	23	11,619	264,913
Dairy lagoons	2	1900	190	361,000

(Modified from Almasri and Kaluarachchi, 2004.)

Almasri and Kaluarachchi (2004) estimated nitrogen loading to the land, based on area assumptions for the Sumas-Blaine aquifer. Manure nitrogen contribution is calculated based on the number and the average nitrogen contribution for each type of cow category (Table 4). The contribution from dairy lagoons was calculated based on the following assumptions: (1) lagoons are filled from October through April, and (2) there is a leakage rate of 0.1 to 5 mm/day, (3) with an average ammonium concentration of 840 mg N/L, and (4) an average surface area of 30,000 square feet. (Almasri and Kaluarachchi, 2004; Cox and Kahle, 1999).

Atmospheric deposition includes dissolved nitrogen in precipitation (wet) and dry deposition. Dry deposition is the nitrogen that has volatilized into the atmosphere from manure and has been redeposited. Dry redeposition is calculated to contribute approximately 15 lbs/acre/year. (Almasri and Kaluarachchi, 2004; Cox and Kahle, 1999). These loading calculations consider the concentration of nitrate, the volume of precipitation, and the corresponding areas of land. The regional annual deposition rate for western Washington is estimated at 1 lb/acre/year, based on the assumption that precipitation contains an average of 0.26 mg N/L. (Cox and Kahle, 1999). This value is consistent with the average nitrate concentration of 0.24 mg N/L which Hem (1985), presents as the average of four studies where nitrogen was measured from rainfall.

Almasri and Kaluarachchi (2004) estimated the nitrogen loading from on-site sewage systems at 10 lbs per capita per year, and assumed 26,400 people were using on-site sewage systems. Legumes were assumed to contribute 5 lbs N/acre over the hay and pasture land class (clover is a common hay/pasture crop in the area). (Almasri and Kaluarachchi, 2004; Cox and Kahle, 1999).

Almasri and Kaluarachchi (2004) note that while the percentage contributions from on-site sewage systems (1%) and dairy lagoons (2%) may be small, these sources could cause localized impacts to groundwater.

Table 4. Nitrogen contribution based on cow type.

Dairy Cow Type	Number	Average N/head (lbs)
Milking	53,000	165 – 250
Dry	7,500	120 - 180
Heifer	12,800	60 – 90
Calves	7,600	74 - 112

(Almasri and Kaluarachchi, 2004)

Documented Manure Impacts on Groundwater

The long-term elevated nitrate groundwater concentrations in the Lower Yakima Valley (Ecology, 2010b) and the Sumas-Blaine aquifer (Redding, 2008) highlight a concern about nitrogen management and groundwater quality. Findings on impacts to groundwater quality from manure management practices are consistent within Washington State, in other areas of the United States, and the world.

Lower Yakima Valley

In the Lower Yakima Valley surface water is impacted by nutrient loading to the land surface, and groundwater is contaminated with elevated concentrations of nitrate. Numerous studies over the last 20 years indicate that elevated nitrate concentrations in groundwater are impacting public and private drinking water wells.

The EPA (2013a) recently conducted a groundwater investigation in the Lower Yakima Valley, which linked CAFO discharges to groundwater contamination. Over 20% of the private wells sampled during the study did not meet the nitrate drinking water standard of 10 mg N/L. The EPA determined that local CAFOs are a source of nitrate in the Lower Yakima Valley and have impacted groundwater quality. They estimated that dairies and other livestock operations contribute 65% of the nitrogen load to the land surface (Figure 3). Groundwater nitrate concentrations from monitoring wells directly downgradient of one CAFO were 190 mg N/L. The mean nitrate concentration in eight downgradient wells near the site was 45.1 mg N/L. This report also concluded that land application or fertilizer applications on irrigated crop fields are a likely contributing source of nitrate and that septic systems could also be a source of nitrate in groundwater, but that there was insufficient information to confirm this. (EPA, 2013a and 2013b)

Sumas-Blaine Aquifer

The Sumas-Blaine aquifer is the primary drinking water source for the majority of residents in rural northwestern Whatcom County. The aquifer has been impacted with elevated concentrations of nitrate. Numerous studies conducted over the last 30 years document that nitrate did not meet the drinking water standard of 10 mg N/L in 29% of sampled wells (Carey and Cummings, 2012). An increasing nitrate trend in groundwater was noted from March 2003 to March 2005 based on samples collected every other month from 35 wells. The mean nitrate

concentration for these wells was 11.5 mg N/L, with 26% of the wells consistently not meeting the standard for every sampling (Redding, 2008).

Elevated nitrate concentrations in groundwater are well documented in the Sumas-Blaine aquifer: Obert, 1973; Erickson and Norton, 1990; Erickson, 1991; Erickson, 1992; Garland and Erickson, 1994; Zebarth et al., 1998; Cox and Kahle, 1999; Hughes-Games and Zebarth, 1999; Carey, 2002; Mitchell et al., 2005; Chesnaux et al., 2007; Redding, 2008; Redding, 2011; Carey and Harrison, 2014.

The assessment conducted by Almasri and Kaluarachchi (2003) indicated that agriculture is the predominant source of nitrogen in the area (Figure 4), with manure contributing the largest portion of nitrogen to the land surface.

Studies Documenting Impacts to Groundwater Quality in Other Areas

The following sections summarize research studies which identify impacts to groundwater quality from manure management practices, including land application, lagoon storage, pens and corrals, and impacts to surface water.

Land Application

Spalding and Exner (1993) evaluated over 200,000 nitrate data points across the United States to determine the extent and spatial distribution of groundwater contamination. These researchers correlated elevated levels of groundwater nitrate with areas over well drained soils and irrigated cropland where there are excessive manure and fertilizer applications.

The USGS installed 30 monitor wells near irrigated agricultural fields in the Central High Plains States to evaluate the effects of irrigated agriculture on groundwater quality. These researchers sampled nutrients, pesticides, inorganic constituents, tritium, and nitrogen isotopes. The monitoring wells were designed to capture recently recharged water. They found 70% of sampled wells were affected by agricultural land use activities. Forty-three percent of the wells were impacted by commercial fertilizer, and 13% were determined to be impacted by an animal manure source. (Bruce et al., 2003)

Elrashidi et al. (2005) determined that loss of nutrients from agricultural lands through runoff to surface water and leaching to groundwater have contaminated waters in the United States.

Kirchmann et al. (2002) concluded that traditional farming practices and increased density of animals per unit of land base contributes to elevated nitrate to groundwater and surface water in Sweden.

In 1998 the USGS estimated that over 9% of the private domestic wells in Oregon's Willamette Valley were contaminated with nitrate from agricultural sources.

Sánchez-Pérez et al. (2003) noted that nitrate pollution of groundwater in northern Spain occurs in agricultural areas where there are excessive nitrogen applications.

Manure is a significant source of the nitrate in groundwater in the Lower Susquehanna River Basin in Pennsylvania and Maryland (Lindsey et al., 1998).

Fox et al. (2001) summarized water quality studies in Southeastern Pennsylvania, Chesapeake Bay, and the Gulf of Mexico, which document nitrate contamination of groundwater and surface water from agricultural areas.

Feaga and Selker (2004) correlated elevated soil nitrate concentrations with poultry manure applied at greater than agronomic rates.

Burkholder et al. (2007) conclude from a review of data in the literature that waste management practices from livestock operations are not effective to adequately protect water quality from nutrients, pathogens, and pharmaceuticals. These researchers state that this occurs when manure is over-applied to the crops but also note that impacts to groundwater quality can also occur when application is at recommended rates. These researchers note that in addition to application rates, the timing of application, residual nitrogen, crop, and climatic conditions also affect nitrate leaching to groundwater.

Sajil Kumar et al. (2013) documented impacts to groundwater quality in India as a result from manure and fertilizer applications.

Ju et al. (2006) studied manure application impacts to groundwater quality in North China. They documented nitrate leaching from all three cropping systems studied and exceedances of the drinking water standard in shallow groundwater where nitrogen application was in excess of the crop requirements. They also noted the presence of high residual soil nitrate.

Nolan and Stoner (2000) studied shallow groundwater quality across the United States from 20 study areas and 2,130 wells from 1992 to 1995 (including the central Columbia Plateau in Washington State). These researchers statistically evaluated data from different land uses. They found the highest median nitrate concentration of 3.4 mg N/L beneath agricultural areas, which include animal manure, inorganic fertilizer and atmospheric deposition. Additionally they detected nitrate in 71% of the samples, with 15% of the wells not meeting the drinking water standard.

Olson et al. (2009) found elevated nitrate concentrations in shallow groundwater in areas with irrigated manure, with maximum concentrations of 100 mg N/L in Alberta, Canada.

Rosenstock et al. (2014) concluded that agriculture has significantly impacted groundwater quality in California's Salinas Valley and Tulare Lake Basin. They estimate that the nitrate concentration in recharge water has doubled over the last 30 years, due to increased manure and fertilizer applications.

Dzurella et al. (2012) acknowledge that while on-site sewage systems are locally a significant source of nitrate in groundwater, in the agriculturally dominated region of California's Central Valley, animal manure practices are the predominant source of nitrate contamination in groundwater.

The Council of Canadian Academies (2013) expert panel noted that in Canada where residual soil nitrate is elevated, shallow groundwater nitrate concentrations are also elevated. These experts stated that groundwater systems tend to respond more slowly to changes in land management between nitrogen application and impacts to groundwater. Timing is important to evaluate success with groundwater quality. The legacy effects from over-application of nitrogen may take years to fully impact groundwater. Therefore, these experts state that it is important to make positive changes in areas where groundwater has been impacted.

The European Union introduced a *Nitrate Directives* in 1991. This directive identifies nitrate from manure and fertilizer applications as the main cause of pollution from diffuse sources affecting European communities. This cooperative directive concluded that high numbers of concentrated livestock results in manure production that is out of balance with available land and crop requirements, which in turn creates a surplus of nutrients ultimately lost to water and air. The European Union has imposed a number of management directives that are improving both groundwater and surface water quality. For example, nitrate-vulnerable zones were designated where nitrogen applications were restricted in the amount and the times of application. The results from this directive have been difficult to quantify; however, the European Union (2010) found that from 2004 to 2007 there were stable or decreasing nitrate trends in 70% of surface water samples and stable or decreasing trends in 66% of the groundwater samples. Sutton et al. (2011) released "The European Nitrogen Assessment" as a scientific approach to address the nitrogen issues raised by the European Directive.

Lagoons

Erickson (1994) investigated the effects of dairy lagoons on groundwater quality in Washington State. This researcher found leakage at three of the four lagoons investigated, and two had sufficient leakage to impact local groundwater quality. He also noted that the proximity of the water table to the lagoon liner was an important factor that affected the ammonium load to the subsurface. This study also found elevated levels of chloride, total dissolved solids (TDS), bacteria, total organic carbon, chemical oxygen demanding substances, and ammonium in groundwater near leaking lagoons. The predominance of ammonium over nitrate was attributed to the close proximity of the lagoons to the water table and the saturated soils beneath the lagoon, which created anaerobic conditions. The maximum concentration of ammonium was 180 mg N/L, with a typical range of 30 to 60 mg N/L. Some level of nitrification occurred with nitrate concentrations in groundwater noted at over 90 mg N/L at one site, over 80 mg N/L at another, and concentrations that exceeded the 10 mg N/L groundwater standard at the third site.

Garland and Erickson (1994) conducted a groundwater quality evaluation in the area in and around a dairy lagoon in Whatcom County, Washington. Sampling began before the lagoon was used and continued for three years after. These researchers concluded that leakage from the lagoon adversely impacted groundwater quality (causing exceedances of the drinking water standard) in the immediate vicinity of the lagoon.

Ham (2002) noted that discharge from manure lagoons occurs and these losses can affect groundwater quality.

McNab et al. (2006) sampled monitor wells at a manure lagoon in the San Joaquin Valley, California to evaluate nitrogen loading and nitrogen transformations in groundwater. These researchers measured dissolved gases in manure lagoon contents and in groundwater along with gases released to the atmosphere. This profile identified the unique geochemical composition that was used as a tracer to track manure leakage. They concluded that at this site, leakage from the lagoon definitively migrated to groundwater.

The Minnesota Pollution Control Agency (MPCA) compiled a summary report (2001) for four studies, evaluating the effects of liquid manure storage systems on groundwater quality. These researchers concluded that manure storage systems impact groundwater quality. Specifically, they determined that unlined manure storage units have a greater impact on groundwater quality than open feedlots or earthen (cohesive, soil-lined) or concrete-lined storage systems. They found evidence of impacts to shallow groundwater downgradient of manure storage areas at each site studied although these impacts varied widely. These researchers documented the plume length and concentrations of nutrients and other inorganic parameters.

Rudolf (2015) evaluated agricultural best management practices (BMPs) in Woodstock, Ontario, Canada, where public drinking water supply wells had been contaminated with elevated nitrate concentrations. This community decided to purchase an additional 275 acres of land with the goal to keep the agricultural land in production but to change BMPs to reduce water quality to below (meet) drinking water standards. The application rate was reduced from 100 lbs/acre to 54 lbs/acre. The result was a 60% reduction in soil nitrate concentrations, from 20 ppm to 8 ppm. Agricultural production increased slightly from 135 bu/acre to 140 bu/acre of corn grown at this site. This researcher concluded that incentives to producers are influential for improvements in water quality. (Rudolf, 2015; Rudolf et al., 2015)

Stephen et al. (1999) evaluated groundwater monitoring data from dairies in New Mexico. These researchers found the mean nitrate concentrations in wells located directly downgradient of clay-lined lagoons were significantly higher than wells located near synthetic-lined lagoons.

Miller et al. (1976) monitored soil beneath manure lagoons at four hog farms. Elevated concentrations of ammonium were present below all lagoons. Elevated ammonium concentrations were found at depths up to 20 – 30 cm (8 – 12 in) in fine-grained soils, but in medium- and coarse-grained soils, elevated ammonium concentrations were found down to the water table. These researchers concluded that earthen manure lagoons are not appropriate over medium- and coarse-grained soils.

Baram et al. (2012) investigated the fate of ammonium and nitrate below earthen waste lagoons at a dairy in Israel. Lysimeters were used to collect leachate over four years. These researchers concluded that there are two distinct infiltration processes that occur. The first is the slow constant infiltration from the base of the lagoon. And the second is the fast infiltration of wastewater and precipitation through desiccation cracks that form on the inside of the lagoon banks. This is an area with high clay content soils, which facilitated nitrification coupled with denitrification within the top 0.5 m. This coupled nitrification-denitrification phenomenon (CND) resulted in 90 to 100% reduction in total nitrogen in the vadose zone. Average wastewater ammonium concentrations were 2,012 mg/L (+/-482 mg/L) with average groundwater nitrate concentrations under the lagoon of 71 mg N/L (+/- 19). These nitrate

concentrations were 3.5 times higher than the mean concentration in regional groundwater. These researchers concluded that the presence of this nitrate indicates leachate from the waste lagoon have reached groundwater.

Baram et al. (2014) conducted a subsequent investigation in the Beer-Tuvia region, Israel which is a historical dairy farming area (1960 to 2010). These researchers developed a methodology to assess the past and future impacts of lagoons on regional groundwater quality using spatial analysis of chloride and total nitrogen. They found that while irrigated agriculture is the predominant contributor of nitrate and chlorides to the aquifer, that lagoon leakage is also a contributor. They determined that lagoons contributed 6% of the total mass of chloride and 12.6 % of the total mass of nitrate even though lagoons comprised less than 1% of the land use in the area. These researchers also noted that allowing the lagoons to go through a drying period resulted in a reduction of 11% of chloride and a 25% reduction in the nitrate contribution to the subsurface.

DeSutter et al. (2005) investigated the movement of manure leachate below four animal waste lagoons. Ammonium in the top 0.5 m (1.6 ft) ranged between 94 to 1139 mg/kg (ppm) with elevated concentrations as deep as 4 m (13 ft) below the base of the lagoon.

Ham and DeSutter (2000) determined that leachate from manure lagoons can affect groundwater quality, and they recommend synthetic liners in areas with vulnerable groundwater.

Koike et al. (2007) detected tetracycline in groundwater from manure seepage from unlined lagoons.

Ham (2002) conducted a study in Kansas investigating 20 anaerobic manure lagoons using a water balance method. These lagoons included 1 dairy, 5 cattle, and 14 swine facilities. Ham concluded that the swine manure had 3 to 5 times the nitrogen content as cattle or dairy manure. For dairy and cattle, the mean ammonium load discharged through the lagoon is 385 kg/ha/yr. This researcher also collected soil profiles beneath old lagoons. He found the highest concentrations of ammonium, organic nitrogen, and phosphorous and other cations, directly below the lagoon liner to a maximum depth of 3 m (10 ft), where concentrations declined to background conditions. Anions, such as chloride and nitrate, were not retained in the soils and migrated deeper. Ham determined that the ammonium retention was dependent upon the cation exchange capacity of the soils, the chemical composition of the manure (particularly other cations), and depth to groundwater.

Reddi et al. (2005) advocate using chloride as a conservative tracer of lagoon leakage rather than ammonium or nitrate. These researchers explained that most of the nitrogen is in the organic or ammonium form. In these forms, it is readily attenuated in the subsurface and can be dependent on the cation exchange capacity of the soils. Chloride is highly mobile, moves with water, and is not attenuated due to its negative charge. Chloride concentrations are elevated, typically greater than 1,000 mg/L.

The MPCA (2001) monitored the bottoms, perimeters, tiles, and sidewalls from different lagoon types. Chloride concentrations were used to illustrate the predominant location of leakage from

these lagoons. The highest concentrations were detected in the sidewalls, and bottom of the lagoon, with perimeter and center tiles showing elevated concentrations in some lagoons.

Nicholson et al. (2002) conducted a risk assessment of a variety of storage methods looking at water pollution, odor, ammonia emissions, and pathogen inactivation. These researchers determined that earthen liners pose the greatest risk to groundwater and that above-ground, lined structures with a cover were best, since they provided a high level of protection to groundwater and prevented atmospheric emissions and odors.

Pens and Corrals

Animal holding areas include pens and corrals. They typically have unlined compacted soil floors, but some have concrete floors. There is little research available on impacts or seepage from these areas. (Harter et al., 2014)

Contributions from CAFO pens and corrals have not been extensively investigated. Miller et al. (2008) investigated the seepage difference between coarse- and fine-textured soils. These researchers found that there was no difference between the different soil types. They determined that leaching below the earthen floor of the feedlots was restricted by three distinct layers: manure, a black interface layer, and underlying soil. These layers are created from a unique process which occurs from compaction by cattle, physical clogging of pores by manure, and the dispersion of clay from sodium and potassium. The result is a restrictive zone that does not promote infiltration or leaching. Because this self-sealing process occurs readily with coarse-textured soils, the researchers found that soil texture is not a factor. These researchers also noted that this restrictive black interface layer should be maintained and not disturbed when cleaning pens. (Miller et al., 2008)

Miller et al. (2008) investigated three feedlots using chloride as a conservative tracer of leakage. They found elevated chloride concentrations down 2.3 feet below land surface before they returned to background concentrations. These researchers also determined that the surface permeability was 4 to 93 x 10^{-7} cm/sec.

Vaillant et al. (2009) found elevated levels of ammonium, nitrate, and chloride at the land surface in the animal holding areas and noted that these concentrations decreased to background levels below 3 to 7 feet below land surface.

van der Schans et al. (2009) calculated that urine and manure from the animal holding areas contribute approximately 20 in/yr of liquid to the corral area. However, these researchers determined that this is mostly lost to evaporation.

Surface Water Impacts from Winter Manure Application

While the primary focus of this literature review is on groundwater, the documented continuity between surficial groundwater and surface water in Washington State lends itself to considering the potential risks to surface water (Ecology, 2010a; Winter et al., 1998).

The risk of fecal coliform bacteria runoff to surface waters increases when manure application occurs during high precipitation periods. Nunez-Delgado et al. (2002) noted that fecal coliform levels increase in soils after land application of manure. Fecal coliform bacteria survival is highly variable and is dependent upon a number of factors including salinity, temperature, moisture, sunlight, predation, organic content, and nutrient content.

In a 2003-2004 study, Nennich et al. (2005) observed that after dairy manure had been land-applied during the winter at a field in western Washington, fecal coliform counts in soils increased 100 to 10,000 times the original concentration approximately three weeks after application (Figure 5 early December application and Figure 6 late January application). Fecal coliform die-off to original levels took approximately 60 days during both application periods.

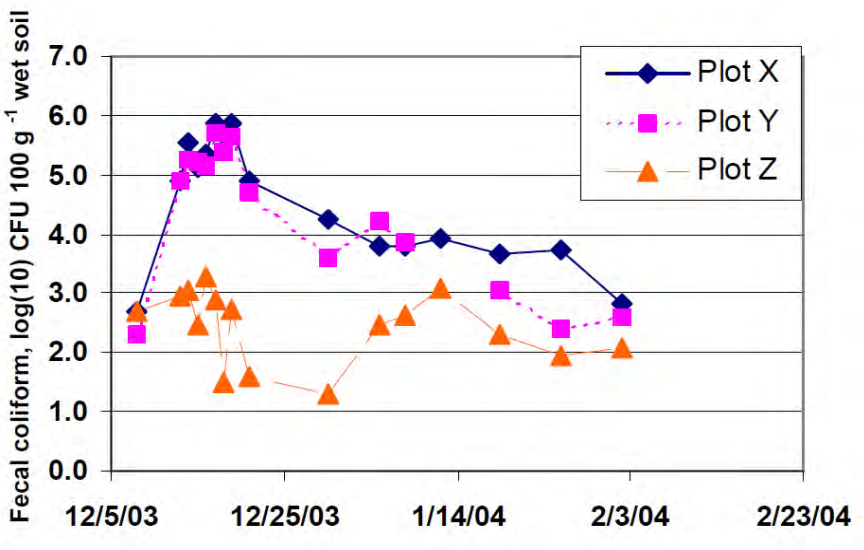

Figure 5. Fecal coliform bacteria survival in soil, 2003-2004 (Nennich et al., 2005).

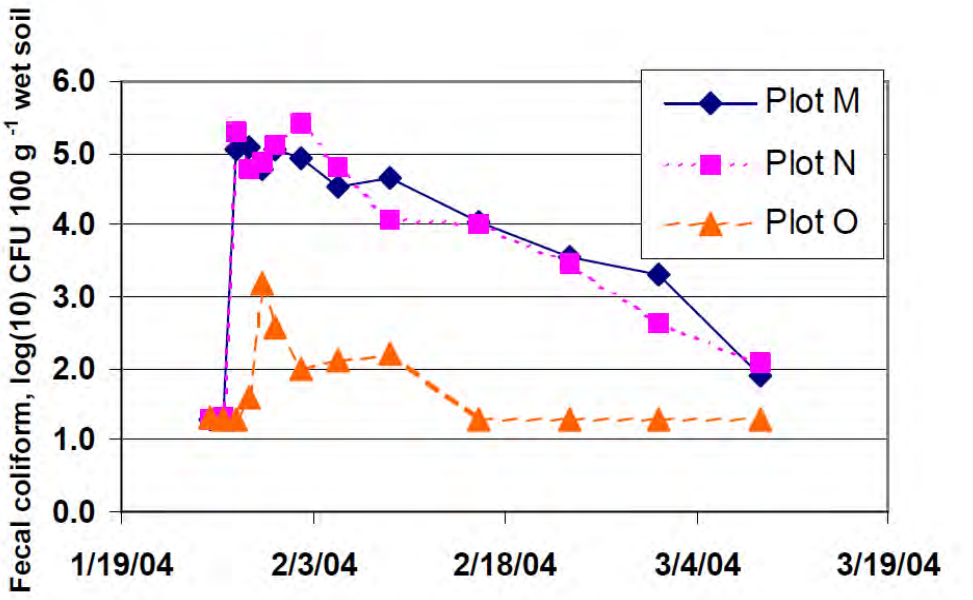

Figure 6. Fecal coliform bacteria survival in soil, 2004 (Nennich et al., 2005).
Plot O is located in the vegetative buffer.

For two monitored soil plots within the manure application area, Nennich et al. (2005) noted that it took 52 and 42 days for the fecal coliform levels in soils to return to background levels following a manure application. Other researchers have noted longer recovery times; Stoddard et al. (1998) observed 60 days for fecal coliform bacteria, and Avery et al. (2004) observed 162 days for E. coli to return to background levels.

Researchers noted that bacteria present in manure can survive in soils for long periods of time. (Hubbs, 2002; Nunez-Delgado et al., 2002). During winter, the increased frequency, intensity, and duration of precipitation events and increased volume of rainfall can combine with bacteria in soils, increasing susceptibility of impacts to ground and surface water. Both Nennich et al. (2005) and Nunez-Delgado et al. (2002) documented fecal coliform transport into vegetative buffer zones during precipitation events.

Nennich et al. (2005) studied the fate and transport of manure to surface water. These researchers found that fecal coliform bacteria can impact surface water through runoff from pasture land three or more days after manure application in the winter. They also noted that a 2.2-inch (5.6 cm) rainfall event three days after a light manure application (25% to 30% of normal applications) in January caused direct runoff of bacteria from the application area into the setback area (Figure 6). It took 17 days for bacteria levels in the setback area to return to background levels.

Panhorst (2002) noted that in soils where dairy manure was applied to cropland, complete fecal coliform destruction took 130 to 165 days from the date of application (Figure 7). This researcher also noted that in soils where dairy manure was applied to pastureland, complete destruction of fecal coliform bacteria took between 125 to 145 days from the date of application (Figure 8). Figures 7 and 8 illustrate the elevated bacteria levels that were present in manure, and the gradual, slow die-off that occurred in the environment.

Hubbs (2002) studied fecal coliform concentrations in runoff from manure applied to grass plots following multiple rainfall events. Fecal coliform concentrations remained high (1,000 – 10,000 CFU/100 mL) 30 days after the manure application (Figure 9).

Additionally, authors note that increased wintertime precipitation can result in a seasonally high water table. Under saturated soil conditions, the infiltration rates may be lower, resulting in higher potential runoff to surface water.

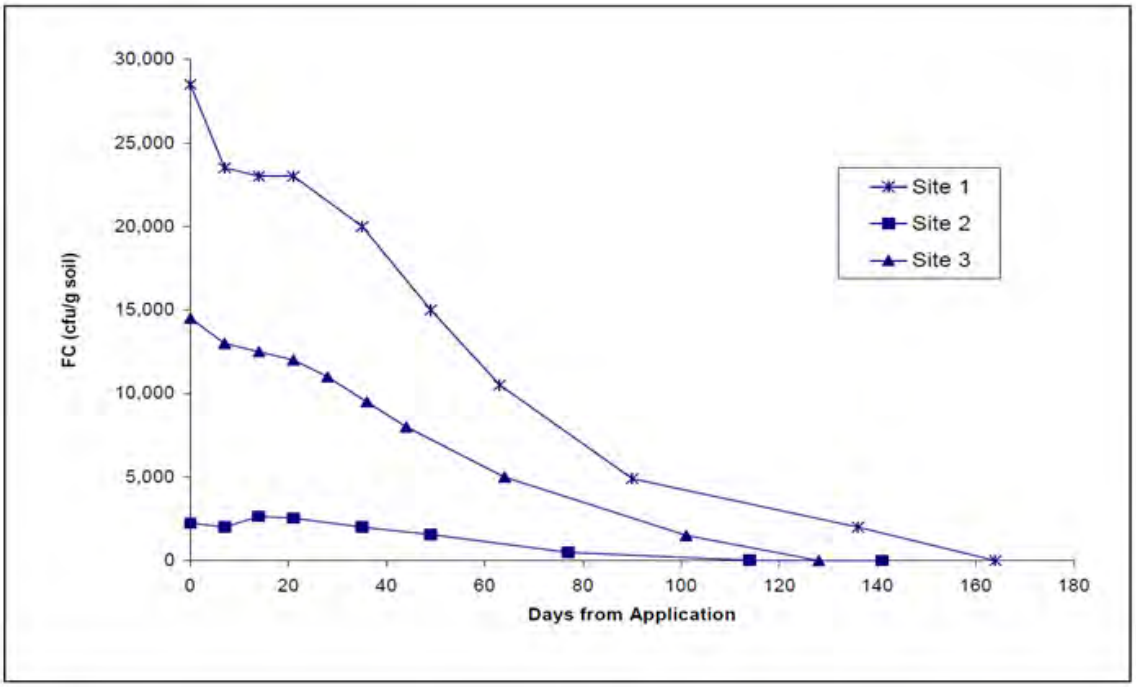

Figure 7. Fecal coliform concentrations in soil for dairy manure applied to cropland (Panhorst, 2002).

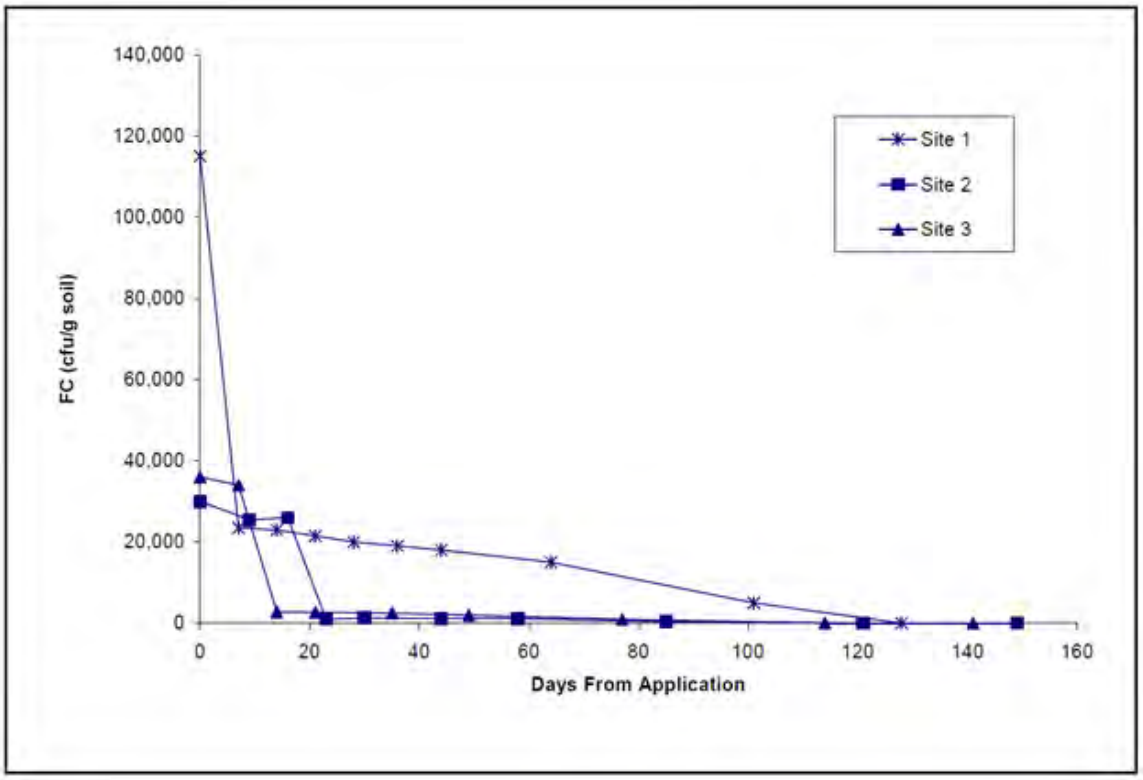

Figure 8. Fecal coliform concentrations in soil for dairy manure applied to pastureland (Panhorst, 2002).

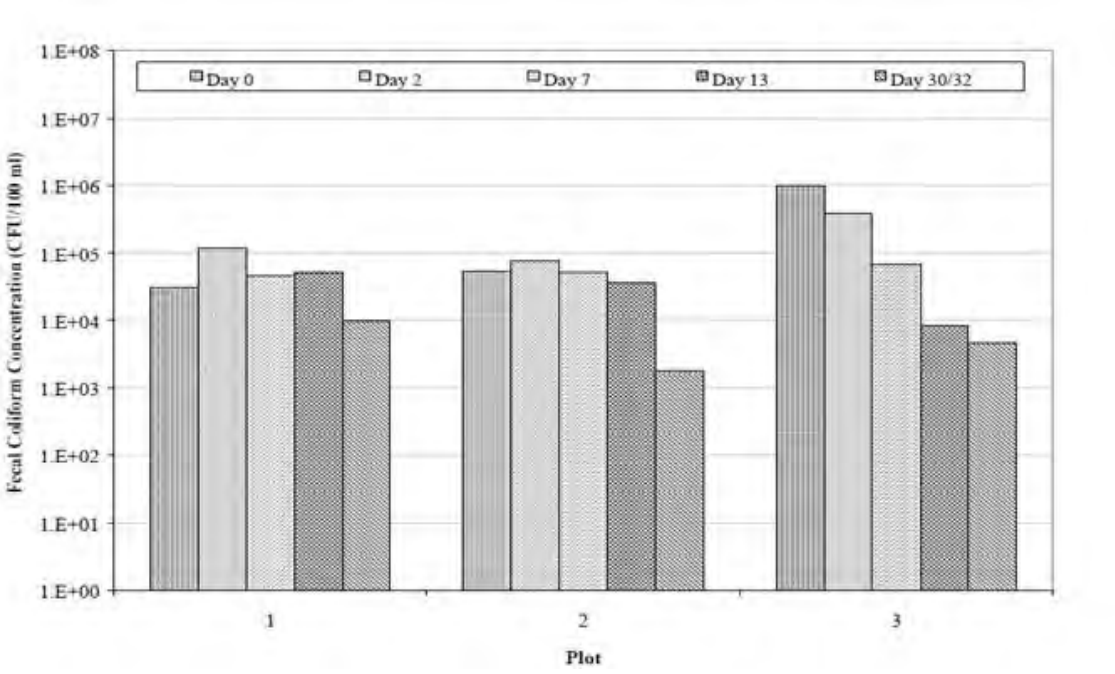

Figure 9. Die-off of fecal coliform bacteria from 0 to 32 days (Hubbs, 2002).

Manure Management and Treatment

Manure is generated during AFO operations as a waste by-product that must be properly managed to prevent water quality problems. Manure can be managed in several ways: collection, storage, treatment, utilization, and transfer (NRCS, 2009b). This section on manure management and treatment focuses on the effectiveness of commonly used manure management practices that utilize the nutrients (application rates, crop uptake, and timing), treatment of manure through attenuation (soil mechanics, vegetative buffers, and setbacks) and storage in constructed lagoons.

Manure is typically managed in three forms: solid, liquid, and slurry. In western Washington waste is generally managed as slurry and is land-applied to crops. In eastern Washington the solids are generally dry-stacked and then land-applied. Liquids are stored in lagoons and then later land-applied.

The most common manure treatment method is land application and crop uptake. Land application of manure is used to grow crops and enhance soil health (NRCS, 2005) and can be part of the treatment system for the waste produced by an AFO. If manure is managed properly, the nutrients contained within this by-product can be a beneficial resource when used as a fertilizer for crop production and can protect water quality (Hermanson et al., 2000).

Dzurella et al. (2012) recommend a suite of manure management practices that can help to protect and improve the quality of groundwater. These include: optimizing application rates, more precisely timing the application of irrigation water and manure to better match crop needs, evaluating crop rotation strategies, improving storage and handling of manure, and reducing fertilizer applications. These researchers state that effective manure storage and management are essential to protecting groundwater quality.

Application Rates

Summary

*A review of literature on manure management illuminated the inconsistent use of the term "**agronomic rate**." Consistent definition and use of terms is important to implementing consistent manure management practices. This section describes various definitions of "agronomic rate," discusses factors affecting manure application rates, then proposes the use of "**application rates**" to avoid confusion tied to historic definitions.*

Several factors identified in the literature affect application rates. These include accounting for all sources of nitrogen, the type of nutrients applied, when they are applied, the type of crop grown, the type of soils, and climate. Researchers agree that all sources of nitrogen be considered in the total load. Residual soil nitrate and continued mineralization of organic nitrogen are often overlooked sources.

Studies verify that there is a positive correlation between nitrogen application rates and crop uptake and that there is also a positive correlation between nitrogen application rates and residual soil nitrate. Soil nitrate accumulation is related to nitrate leaching. Researchers have observed that improvements to manure management practices can reduce the soil nitrate concentrations, as well as significantly improve groundwater quality.

Researchers note that at a higher than optimum nitrogen application point, the crop yield and economic return declines. Other researchers have observed that even under optimal conditions and appropriate application rates, nitrate leaching can occur.

Definitions

The term *agronomic rate* has many definitions depending upon the objective of the activity. Agricultural activities have different goals for irrigation and fertilizer use than a land treatment system where the goal is waste treatment. The primary goal of agricultural production is to maximize crop yields. The primary goal for a land treatment system, such as an AFO that generates manure, is waste management; it is not to maximize crop yields. (Ecology, 2004a)

The Implementation Guidance for the Groundwater Quality Standards defines *agronomic rate* for land treatment systems, as *the rate at which a viable crop can be maintained and there is minimal leaching of chemicals downwards below the root zone.* (Kimsey, 2005). This definition is appropriate for manure treatment.

The Natural Resources Conservation Service (NRCS, 2005) utilizes "*realistic yield goals*" as their criteria for nitrogen application. The NRCS (2009c) defines "*agronomic rate*" as the amount of crop nutrients required to achieve the expected yield after considering the contribution of the soil, plant, water, and atmospheric nutrient sources.

In a literature review on nitrogen use by crops (Hermanson et al., 2000) the term *agronomic rate* is defined as the recommended rate of nitrogen addition to the soil that is needed to produce an expected yield, while minimizing adverse environmental effects.

The EPA defines *agronomic rates* for two similar types of nutrient land application: (1) for biosolids, agronomic rate is defined as the rate at which plants require nitrogen during a defined growth period, and (2) for sewage sludge, agronomic rate is defined as the amount of nitrogen needed by a crop or vegetation grown on the land, while minimizing the amount of nitrogen that passes below the root zone of the crop or vegetation and enters groundwater (EPA, 1994).

Maximizing crop yield is not equivalent to maximizing crop uptake. Maximizing crop yield is not the goal of a land treatment system. (Ecology, 2004a)

Factors Affecting Application Rates

Several factors identified in the literature could affect application rates. These include accounting for all sources of nitrogen, the type of nutrients applied, the time they are applied, the type of crop grown, the type of soils, and climate. The following paragraphs summarize information that addresses cropping and leaching as affected by the factors listed above.

NRCS (2014) practice standard 590 identifies essential criteria to be considered when choosing application rates. The NRCS requires that a nutrient management plan be developed which includes a nutrient budget for nitrogen, phosphorus, and potassium from all potential sources, with the goal to manage the rate, source, placement, and timing of nutrients.

Fertilizer guides offered from the land grant universities provide extensive information on application rates based on climate and crop type. http://www.extension.uidaho.edu/crops.aspx

Hermanson et al. (2000) state that the estimation of agronomic rate for a crop must factor in all sources of nitrogen available to the crop during the growing season, including: mineralization, residual inorganic nitrogen in the root zone, and nitrogen in the irrigation water. These researchers also note that if the agronomic rate is properly calculated and utilized, this will help minimize the buildup of soil organic nitrogen.

Cogger (2000) concluded that in Washington State there is a history of manure applications that have resulted in increased rates of mineralized soil nitrogen. This buildup of soil nitrate reduces the need to supplement soils with manure or fertilizer.

Chesnaux et al. (2007) concluded that soil nitrate concentrations are higher in manured fields than fields using synthetic fertilizer when the same amount of nitrogen is applied. These researchers attribute this to the high organic nitrogen content in manure, and the total organic carbon contribution to the soils which acts to retain nitrogen for a longer period of time. Once this nitrogen mineralizes, it becomes available to the plant or is susceptible to leaching to groundwater. These researchers conclude that it is essential to consider the mineralized soil nitrogen as a source when calculating application rates.

Lindsey et al. (1998) investigated manure management in karst topography. They concluded that the application rate of manure is one of the most important factors in managing nitrate concentrations in streams.

Harter and Menke (2004) found that changes to nutrient management can result in significant improvements to water quality. These researchers specifically showed that there was a 70% improvement in groundwater quality beneath fields where manure is land-applied when the following changes were made: (1) eliminating the use of commercial fertilizer, (2) reducing manure applications, and (3) applying manure only during the crop growth stages. These researchers noted that these measures did not result in a considerable reduction in crop yield.

Carey and Harrison (2014) found that groundwater nitrate concentrations near the top of the water table were close to the groundwater standard of 10 mg N/L when manure application rates were similar to the crop removal rates and when manure was applied during the growing season.

Feaga and Selker (2004) found that once manure application rates were reduced, the soil nitrate concentrations also declined.

Carey (2002) found that estimated nitrogen application rates from manure on a grass field in western Washington that exceeded the typical grass crop uptake resulted in median groundwater nitrate concentrations at the top of the water table of 27 to 31 mg N/L with a maximum concentration of 74 mg N/L. This was in contrast to a grass field in the same area where estimated manure nitrogen application rates were similar to crop uptake rates. In this case the resulting groundwater nitrate concentrations were close to 10 mg N/L.

Accurate crop yield estimates are necessary for planning nitrogen application rates. Sawyer et al. (2006) noted the amount of nitrate leached to groundwater increases as the rate of applied nitrogen increases. These researchers demonstrated that increasing the applied nitrogen above the optimum crop uptake actually yielded a smaller crop and a smaller economic return. They also noted that the amount of nitrogen in underlying soil pore water and groundwater dramatically increased, as illustrated in Table 5 and Figure 10.

Buss et al. (2005) describes the relationship between crop yield and nitrogen application. This is dependent upon site-specific soil conditions, such as soil texture, pH, organic content, crop type, the method of planting, irrigation, and fertilizer application. These researchers developed a typical crop nitrogen response curve and noted that for each crop and set of conditions, there is a nitrogen application rate at which crop yield is maximized and leaching is minimized. These researchers also noted that even with optimal conditions and appropriate application rates, significant nitrate leaching tends to occur.

Cornell University (2012) developed nitrogen guidelines for corn, based on the soil nitrate concentration (Table 6). The pre-sidedress soil nitrate test (PSNT) is a springtime test to determine the amount of nitrogen present in the soils prior to the start of the growing season. This test provides an estimate of the amount of nitrogen which needs to be applied to support crop growth. These researchers also noted that above 25 ppm soil nitrate concentration, that there is no increased economic benefit anticipated by adding additional nitrogen. These findings are similar to those from Sawyer et al. (2006) presented in Figure 10.

Table 5. Diminishing economic returns and yields with increasing nitrogen application.

Annual N Rate (lbs/acre)	Grain Yield (bushels /acre)	Economic Return (dollars/acre)	Nitrate as N in Soil Pore Water at 7.5 ft (mg N/L)
0	82	--	2
75	141	95	4
150	168	130	17
225	164	103	32

(Sawyer et al., 2006.)

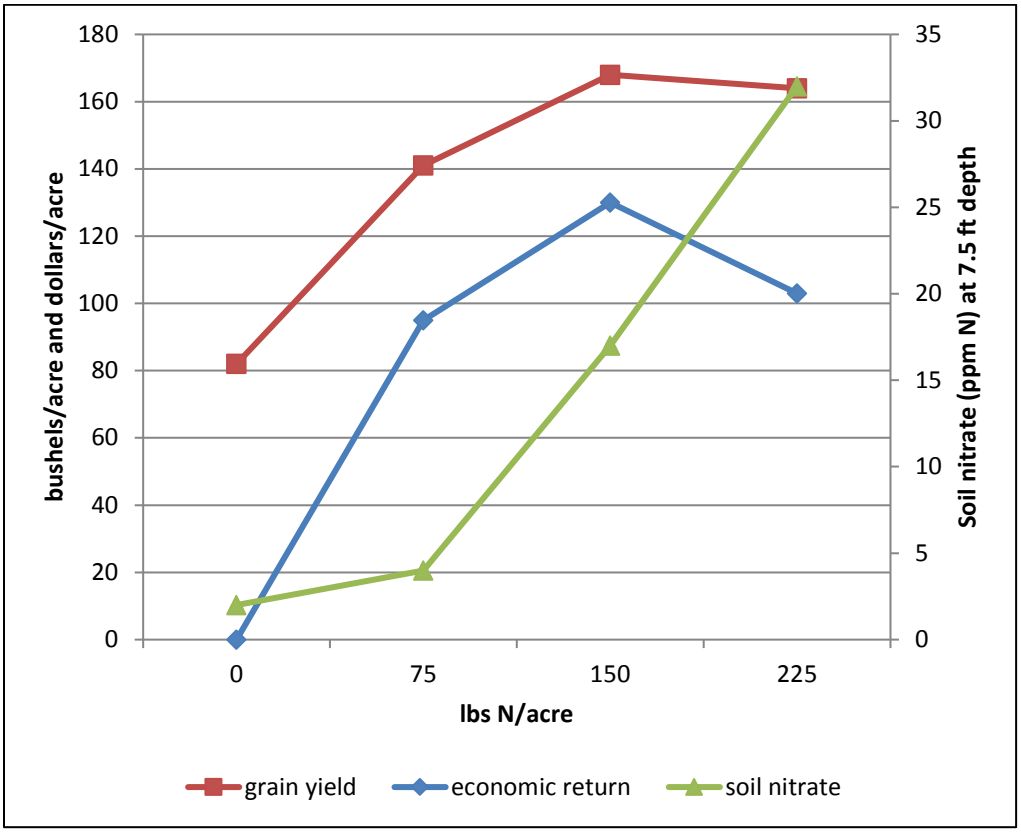

Figure 10. Application rates effect on crop yield, economic return and soil nitrate concentrations (modified from Sawyer et al., 2006).

Yin et al. (2007) concluded that soil nitrate accumulation in China is closely related to nitrate leaching, which can result in elevated nitrate concentrations in groundwater. These researchers concluded that there is a positive correlation between nitrogen application rates and the nitrogen uptake of corn. However, they also found a positive correlation between nitrogen application rates and residual soil nitrogen. Elevated soil nitrate creates a risk of increased nitrogen losses.

Table 6. Cornell University (2012) interpretation of the pre-sidedress nitrate test for corn.

PSNT ppm nitrate (as N)	Likelihood of an economic benefit to extra N	N guideline
>= 25	Low	No additional N needed
21 - 24	About 10%	If you expect a yield response, consider sidedressing 25 to 50 lbs N/acre
< 21	High	Apply sidedress N according to the Cornell N guidelines for corn

Crop Uptake

Summary

Crop uptake is the primary nitrogen treatment mechanism and removal component for manure land treatment systems. The type of crop grown and the site-specific climatic conditions are the main factors influencing the treatment capacity of the system. Winter cover crops are useful for removing residual soil nitrate still present after the growing season.

Crop uptake is one of the components in a mass balance equation that determines the appropriate application rate (Harter et al., 2012). Land treatment systems rely upon several factors to treat nutrients and minimize potential leaching of excess nitrate to groundwater. Usually, no pre-treatment is provided to the manure before it is land applied, so the crop and the soils are the predominant treatment mechanisms. A land treatment system relies on crop uptake, nutrient removal during harvest, attenuation and degradation in the soils. Once nitrate migrates below the root zone, it will move with water and eventually reach groundwater (Hermanson et al., 2000). Crop uptake and removal is the most significant mechanism for nitrate removal within a land treatment system. (Hermanson et al., 2000)

The timing and amount of nitrogen applied is dependent upon the crop grown and climatic conditions. Winter cover crops planted in fields with annual crops also utilize residual nitrogen and can reduce nitrate leaching to groundwater. The crop type influences the amount of nitrogen that can be utilized from a field. Perennial crops, like grasses with root systems that function for several years between re-plantings, remove more nitrogen than row crops. (Kirchmann et al., 2002; Hermanson et al., 2000)

Literature-Recommended Soil Nitrate Concentrations

Summary

Soil nitrate values are a proven tool for helping to determine nitrogen crop requirements and the effectiveness of manure management.

The research summarized from the literature in this section indicates there are two time periods when soil nitrate samples are typically collected: in the spring before manure application begins and in the fall after the crop has been harvested. These two sampling times have different purposes and provide different information. The fall soil nitrate test provides information on the effectiveness of manure management practices from the previous season. The spring soil nitrate test provides information about the amount of plant-available nitrogen present in the soil at the start of the growing season. This test also provides information for assessing appropriate nitrogen application rates at the beginning of the growing season.

A summary of the recommended soil nitrate threshold limits cited in the reviewed literature is compiled in Table 7. Recommended targets for fall soil nitrate values range from 5 to 24 ppm,

depending upon the site-specific conditions. The recommended targets for spring soil nitrate values range from 16 to 30 ppm.

Soil nitrate only represents the amount of nitrate present in the soils. It does not account for nitrate that has already leached to groundwater, nor does it account for nitrogen mineralization over time.

Researchers agree that soil nitrate tests are not a surrogate for groundwater monitoring. However, the majority of researchers also agree that residual soil nitrate can indicate when excess nitrogen has been land-applied and when there is a risk that groundwater may have been (or could be) impacted from nitrate leaching.

Table 7. Summary of soil nitrate threshold limits determined from the literature.

Soil Threshold	Notes	Reference
Fall (post-harvest) Soil Nitrate Test (at the one-foot depth) -- Acceptable nitrogen		
15 to 20 ppm	Western WA and OR, based on crop type	Sullivan and Cogger (2003)
5 to 15 ppm	Based on a 1 ft and 2 ft sampling depth	Sullivan and Cogger (2002)
15 to 20 ppm	30 ppm is excessive	Bary et al. (2000)
5 to 15 ppm	Biosolids risk management	Ecology (2000)
< 8 or <11 ppm	Maryland, based on crop type	Kratochvil and Steinhilber (2013)
24 ppm	BC Ministry of Agriculture and Lands	Kowalenko et al. (2007)
7.5 ppm	Canadian National Agri-Environmental	Drury et al. (2005)
Spring (Pre-sidedress) Soil Nitrate Test (at the one-foot depth) -- No additional nitrogen application		
25 ppm	Western WA and OR	Staben et al. (2003).
25 ppm or 16	Iowa (use 16 ppm if heavy precipitation in the spring)	Iowa State University (1997)
21 ppm	Wisconsin	Laboski (2008).
25 ppm	New York	Cornell University (2012)
25 ppm	Indiana -- corn	Camberato et al. (2013)
25 - 30 ppm	vegetables	Heckman (2003)
25 ppm	Oregon -- corn	Hart et al. (2009)

Fall Soil Nitrate Test (Post-Harvest Soil Nitrate)

The fall soil nitrate test is intended to evaluate the effectiveness of manure management practices by estimating the residual nitrate that remains in the soil after crop uptake and harvest are complete. It provides the grower with a measure of how effective their manure management practices were at the end of the growing season. The fall soil nitrate test provides a snapshot of the residual nitrate that remains in the soil at the time and the location the sample was collected. This test specifically focuses on nitrate, the nitrogen species that is mobile and moves with

water. This test measures the soil nitrate concentration and does not account for the organic nitrogen present. After the growing season, any nitrate still present in the soils (including the root zone) is susceptible to leaching to groundwater. This measured residual soil nitrate after the last harvest indicates the amount of nitrate that could leach to groundwater. The risk of leaching is also a function of winter recharge and is therefore greater in areas of higher precipitation.

Sullivan and Cogger (2003) recommend the post-harvest (fall) soil nitrate testing as a tool for assessing nitrogen management where manure is land-applied to crops. The post-harvest soil nitrate test was not intended to project impacts to groundwater. This test only indicates the nitrate concentration in the sampled soil profile after harvest; it does not address nitrate concentrations in the lower soil depths or the mass of nitrate that has already leached to groundwater. The interpretations presented in Table 8 are crop-specific and are recommended for producers in western Washington and Oregon. It is designed to evaluate past manure management practices, taking into account the amount of nitrogen applied and the amount removed in the crop.

Table 8. Manure management based on soil nitrate for western Washington.

Post-Harvest Soil Nitrate (0 to 1 foot depth)	Corn	Grass for Hay or Silage
<20 ppm	Continue present N management.	
<15 ppm		Continue present N management.
20-45 ppm	Reduce manure application after August 1. Reduce manure N application by 10 – 25%.	
15-30 ppm		Reduce manure N application by 10 – 25% and apply earlier in the season.
>45 ppm	Eliminate manure application after August 1. Reduce manure N application by 25 – 40%.	
>30 ppm		Reduce manure application after August 1. Reduce manure N application by 25 – 40% and apply earlier in the season.

(Refer to Sullivan and Cogger, 2003, for additional recommendations.)

Sullivan and Cogger (2002) developed a generalized matrix that provides interpretation for soil nitrate values at the two-foot depth (Table 9).

The Columbia Basin Groundwater Management Area (GWMA) in eastern Washington utilizes deep soil sampling to assess nitrate in the soil profile from the land surface down to ten feet (GWMA, 2009). This nitrate profile is used to assess the effectiveness of nitrogen application management practices and determine the extent of accumulation in the subsurface. The Columbia Basin GWMA is a local non-regulatory consortium whose goal is to identify management practices that protect groundwater.

Bary et al. (2000) recommend the use of fall soil nitrate values to determine the effectiveness of manure application. If the fall soil nitrate in the top foot of soil is greater than 15-20 mg/kg (ppm), these researchers suggest that too much nitrogen was applied and they recommend that the amount be reduced in subsequent years. They further state that soil nitrate values greater than 30 mg/kg (ppm) are excessive.

Table 9. Manure management based on soil nitrate at the one and two foot depths.

Risk	Measured Soil Nitrate (ppm)	Estimated Mass of Soil Nitrate for 1-ft sample (lbs/N /acre)	Estimated Mass of Soil Nitrate for 2-ft sample (lbs/N /acre)	Interpretation
Low	< 5	0 - 15	0 - 25	Evaluate crop performance. If yield is low, insufficient N may have been applied. If yields are adequate and irrigation is not excessive, the low nitrate levels reflect excellent management.
Medium	5 - 15	15 - 55	25 - 75	Nitrogen application rate was adequate for the yield with little to moderate nitrate accumulation. Continue current nitrogen application.
High	15 - 30	55 - 105	75 - 150	Considerable N was not utilized by the crop at the end of the growing season. Evaluate N inputs and application. Decrease N application rates or improve management to increase N removal.
Very High	> 30	> 105	> 150	Major management changes may be needed. Check agronomic rate assumptions and calculations.

(Sullivan and Cogger, 2002.)

Biosolids are the treated solids component of human waste. While biosolids receive a higher level of treatment than manure, the established nitrogen classifications can provide a useful comparison to manure. Ecology (2000) establishes risk guidelines for application of biosolids based on soil nitrate levels in Table 10. Soil nitrate is a measure of the fraction of nitrogen that poses a risk to leaching to groundwater if the nitrate is not taken up by plants. This document provides risk classification for biosolids management. When soil nitrate exceeds 30 ppm, the guidelines state that the risk of groundwater contamination is very high and direct the following actions: (1) make major management changes (2) discontinue biosolids application, and (3) re-assess the agronomic rate assumptions and calculations. (Ecology, 2000)

Table 10. Biosolids groundwater contamination risk classification.

Soil Nitrate Level (mg/kg = ppm) in the top 1 foot	Risk Classification
< 5	Low
5 – 15	Medium
15 – 30	High
>30	Very high

(Ecology, 2000.)

Risk to groundwater is a function of soil nitrate concentration, precipitation and irrigation, manure application rates, timing of application and soil properties.

Gehl et al. (2006) determined that elevated post-harvest soil nitrate concentrations indicate that excessive fertilizer was applied. This residual represents the nitrate available to leach. These researchers also noted that there is considerable evidence that verifies nitrate leaching in the presence of elevated soil nitrate concentrations in the lower part of the soil profile. This occurs when residual nitrate that is not utilized by plants migrates downward with excess precipitation or irrigation. Once the residual nitrate is below the root zone it will eventually migrate to groundwater.

Hart et al. (2009) state that in Oregon post-harvest soil nitrate values below 20 ppm indicate that the silage corn utilized the majority of plant-available soil nitrogen. These researchers note that a low fall soil nitrate test does not indicate that too little nitrogen was applied, since continued mineralization of nitrogen is likely to occur and will increase the amount of plant-available nitrate in the soils.

A positive correlation between the spring soil nitrate (PSNT) results and the fall soil nitrate results was found by Hart et al. (2009) based on data collected in Whatcom County, Washington and western Oregon (Figure 11). This correlation indicates that the PSNT can be used as an indicator of whether nitrogen application is necessary; additionally, it can be used as an indicator of post-harvest fall soil nitrate.

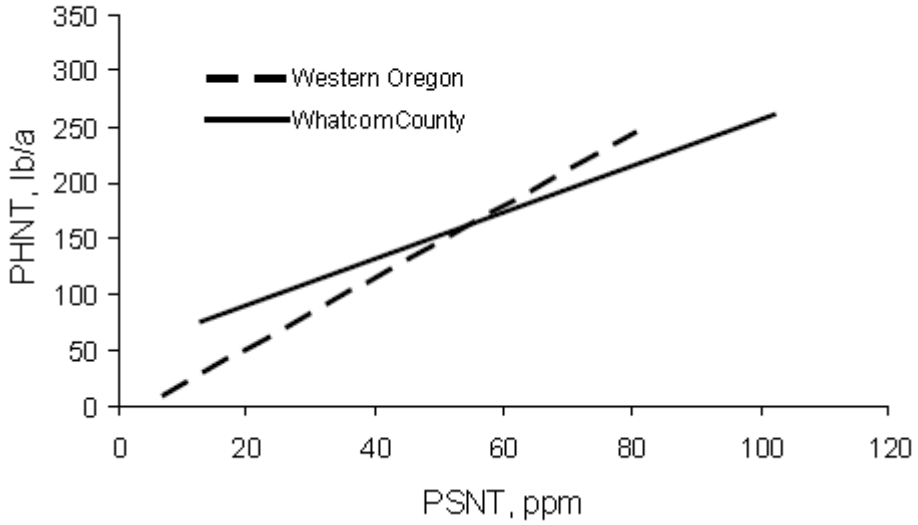

Figure 11. Positive correlation of spring and fall soil nitrate testing (Hart et al., 2009).
PHNT = post-harvest nitrate test; PSNT = pre-sidedress nitrate test

Hart et al. (2009) recommends that plant development should be used to time manure applications rather than the calendar.

The British Columbia (Canada) Ministry of Agriculture and Lands proposed soil nitrate concentrations based on risk of groundwater contamination (Table 11) in the Lower Frazier River Valley, which is an area of high winter precipitation. These researchers establish 89 lbs N/acre (24 ppm) in the top two feet as a high risk for groundwater contamination (Kowalenko et al., 2007).

Table 11. British Columbia Ministry of Agriculture and Lands proposed environmental risk classes for soil nutrient interpretation.

Risk Classes	Residual Soil Nitrate + Ammonium in top 2 feet (60 cm)		
	Kg N/ha	Lbs N/acre	ppm
Low	0 to 49	0 to 44	0 - 12
Medium	50 to 99	45 to 88	12 - 24
High	100 to 200	89 to 178	24 - 50
Very High	> 200	> 178	> 50

(Modified from Kowalenko et al., 2007)

Drury et al. (2005) propose an environmental risk matrix based on soil nitrate concentrations (Table 12). These researchers suggest 27 lb N/acre (7.5 ppm) as a high risk for groundwater contamination.

Table 12. Environmental risk matrix based on soil nitrate concentrations.

Risk Classes	National Agri-Environmental Indicator for Residual Soil Nitrate		
	Kg N/ha	Lbs N/acre	ppm
Low	0 to 20	0 to 18	0 - 5
Medium	20 to 30	18 to 27	5 – 7.5
High	30 to 40	27 to 37	7.5 - 10
Very High	> 40	> 37	> 10

(Modified Drury et al., 2005)

Spring Soil Nitrate Test (Pre-sidedress Soil Nitrate Test)

Spring soil sampling is used to assess conditions before the growing season and to calculate the application rates based on the crop needs. Northwest researchers advocate using the Pre-sidedress Soil Nitrate Test (PSNT) for corn in western Oregon and western Washington. They recommend that no additional nutrients be added if the soil nitrate value is greater than 25 ppm (Staben et al., 2003). This test measures nitrate concentrations only and does not account for organic nitrogen that is present in the soil.

Iowa State University (1997) researchers recommend that the nitrogen application rate be based on the springtime soil nitrate test in conjunction with springtime precipitation. Their work concludes that no manure be applied if the soil nitrate value is greater than 25 ppm, or greater than 16 ppm if there is excessive springtime precipitation (Table 13).

The University of Wisconsin recommends the use of the PSNT to assess the nitrogen in soils prior to application of additional nutrients. It was concluded that if the concentration of nitrogen in the one foot-depth soil sample is greater than 21 ppm, then no additional fertilizer is needed for the crop (Laboski, 2008).

Table 13. Manure nitrogen recommendations for soils based on the springtime soil nitrate test.

Soil Nitrate Test	Recommended Nitrogen Rate	
	Excessive rainfall (>5” in May)	Normal rainfall
(ppm N)	(lbs N/acre)	
0 – 10	90	90
11 – 15	60	60
16 – 25	0	30
>25	0	0

(Iowa State University, 1997)

Hart et al. (2009) note that in western Oregon early season nitrogen uptake by corn is minimal, and that rapid nitrogen uptake occurs between the 10-leaf stage and silk emergence, which is approximately mid-June through the end of July (Figure 12). During this time of rapid uptake, corn uses close to 3 lbs/acre/day. These researchers recommend that the PSNT should be conducted when the corn has 5 or 6 leaves, in order to measure soil nitrate during the growing season before the crop's greatest nitrogen demand.

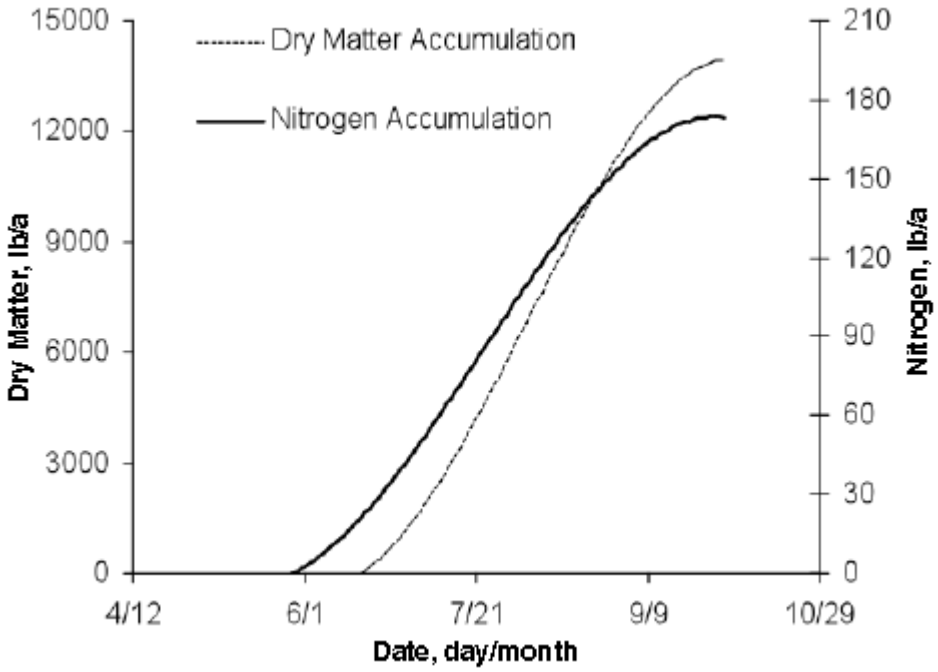

Figure 12. Nitrogen and dry matter accumulation and timing of uptake silage corn.
Based on data from California, Oregon and New Jersey, 1984-2009 (Hart et al., 2009).

Table 14 provides nitrogen application recommendations based on soil nitrate values. These researchers recommend that if the PSNT value is greater than 25 ppm, then the addition of nitrogen is not needed. Hart et al. (2009) also developed guidelines that interpret the soil nitrate results. These are presented in Table 15.

Table 14. Nitrogen application rate recommendations for western Oregon using the pre-sidedress nitrate test in the spring.

PSNT soil Nitrate value (mg N/L)	Application Rate (lbs/acre)
0 – 10	100 – 175
11 – 20	50 – 100
21 – 25	0 – 50
> 25	0

Hart et al. (2009).

Table 15. Soil nitrate test results interpretation.

Soil Nitrate (mg N/L)	Interpretation
0 – 20	Acceptable
21 – 45	High
> 45	Excessive

Hart et al. (2009).

Hart et al. (2009) also note that soil nitrate values can be as low as 5-10 ppm without compromising yields.

Cornell University (2012) recommends to their producers that if the PSNT results are greater than or equal to 25 ppm, then no additional nitrogen is needed for a corn crop.

Soil nitrate concentrations can be used to assist in planning nitrogen management on a field with optimum concentrations of 25 ppm for corn in Indiana (Camberato et al., 2013).

Heckman (2003) found that when the soil nitrate concentration was 25 to 30 ppm that there was sufficient available nitrogen to grow a wide variety of vegetables (sweet corn, celery, lettuce, cabbage, peppers, pumpkin, winter squash, and sugar beets). Heckman also provides a soil nitrate test interpretation in Table 16.

Table 16. Interpretation of soil nitrate tests for annual crops (Heckman, 2003).

Soil Nitrate (as N) Test (ppm)	Interpretation
< 20	Very likely N deficient, sidedress N is recommended.
20 to 24	May be sufficient for some crops. A low rate of sidedress N may be applied to ensure that N is sufficient.
25 to 30	Sufficient N is available for most crops. Sidedress N is usually not recommended.
> 30	Sidedress N is not recommended.
> 50	Excessive. Indicates excessive application of manure, compost, or other sources of N.

Timing of Nutrient Application

Summary

Most studies indicate that there are two primary manure management mechanisms that affect leaching of nitrate to groundwater: (1) application rates and (2) the timing of manure application. Timing is important since it is recommended to coincide with the crop growth, but it is also related to nitrogen transformations in the subsurface that create the opportunity for mineralization and the opportunity to leach.

Researchers agree that applying nutrients during the non-growing season (when plant uptake of nitrogen has ceased or has significantly slowed) poses an increased risk to surface water from runoff and an increased risk to groundwater from leaching of nitrate and other contaminants. Additionally, there is general consensus that there is a higher risk of leaching and runoff when precipitation and irrigation exceeds evapotranspiration and when crop growth is slow.

Researchers advise that nutrients only be available when crops can utilize them, and they generally characterize this timeframe as the growing season.

References are provided that use site-specific climate data to assist in determining the appropriate timeframes for land application to specific crops.

Hermanson et al. (2000) note that nitrogen application at the time of maximum crop demand will result in the maximum removal of nitrogen from the soils. Nitrogen applied without regard to the seasonally variable nitrogen demand will result in a buildup in the soils of inorganic nitrogen that is susceptible to leaching. Late season applications in areas of Washington with high winter precipitation are particularly risky from a leaching standpoint.

Figure 13 illustrates the typical nitrogen uptake during the growth cycle of an annual crop. During phase 1 (typically spring), early plant growth, nitrogen uptake is relatively slow. Phase 2 (typically late spring to early summer) is the period of rapid plant growth and rapid nitrogen uptake. During phase 3 (typically summer through early fall), vegetative growth has slowed or stopped. Nitrogen uptake during phase 3 is slow and the addition of nutrients during this time is not effective in increasing crop yields (Heckman, 2003).

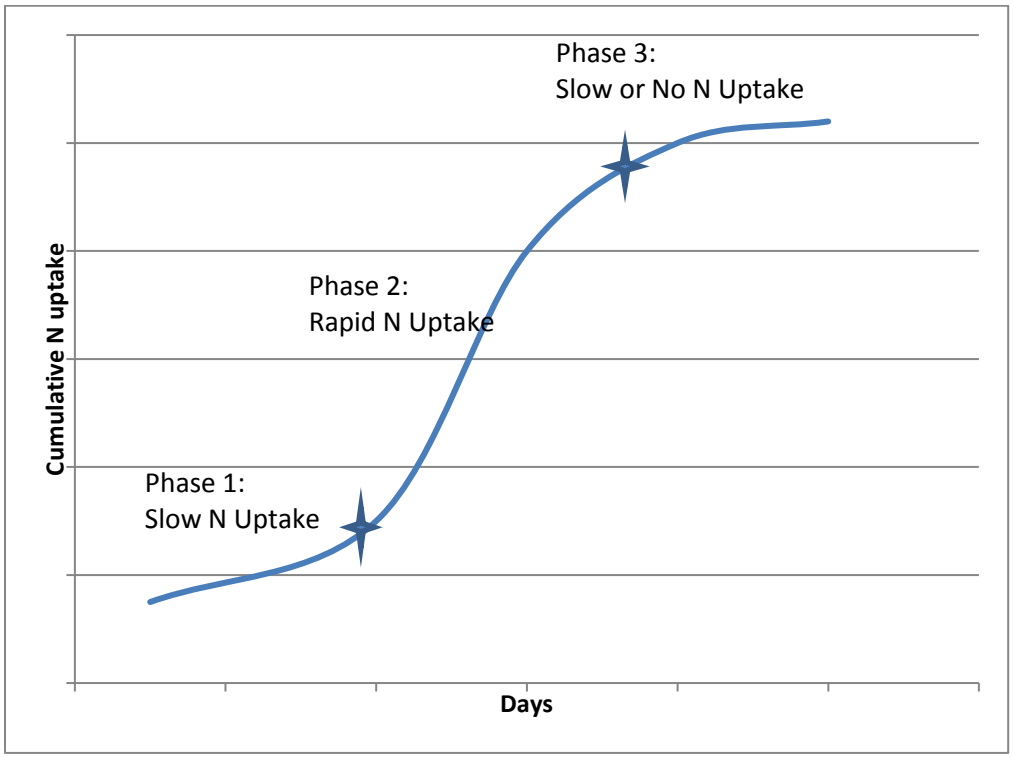

Figure 13. Nitrogen accumulation curve (modified from Heckman, 2003).

Chesnaux et al. (2007) determined that controlling the timing of application is important to minimizing leaching to groundwater.

Cogger (2000) found that there is no yield response to sidedress nitrogen applied in the spring to corn fields receiving manure in the Abbotsford-Sumas aquifer. The additional applied 135 kg N/ha resulted in an average increase of post-harvest soil nitrate of 130 kg N/ha in 1995 and 100 kg N/ha in 1996. This indicates that most of the nitrogen (96% in 1995 and 74% in 1996) applied in the spring was not used by the crop and was vulnerable to leaching in the fall.

Sawyer et al. (2006) determined that nitrogen is used more efficiently if applied during the growing season just prior to the time of maximum uptake. Most crops have the greatest capacity to take up soil nitrogen when it is applied in the spring or summer.

In Arkansas, Slaton et al. (2004) found that applying additional nitrogen in the fall is not necessary, even when a winter cover crop is grown. They concluded there was sufficient nitrogen in the soils to fully support crop growth. This conclusion was based on comparing crop yields to measured values of soil nitrate and ammonium concentrations. These combined soil nitrogen values ranged from 9.2 ppm to 42.8 ppm.

Sullivan (2008) concluded that in western Washington and Oregon, residual fall soil nitrate is usually sufficient to support winter cover crops. Sullivan also concluded that applying manure in the fall is generally not an efficient use of nitrogen. Jégo et al. (2008) recommended that in areas where groundwater was vulnerable to contamination and where agricultural practices are present, that nitrogen-based fertilizers not be applied in the fall.

Hermanson et al. (2000) state that winter cover crops temporarily store nitrogen from the root zone and return it to the surface, making it available for crop uptake the next season. Furthermore, these researchers conclude that the use of winter cover crops does not imply that nitrogen can be applied above agronomic rates without increasing the amount of nitrate leaching. If excess nitrogen is applied in one growing season, it must be offset by decreased nitrogen application in the following season to avoid residual nitrogen buildup and subsequent nitrate leaching (Hermanson et al., 2000).

Carey and Cummings (2012) characterize the vulnerable times for groundwater when nutrient application causes an increased risk. The timeframe from mid-September to mid-March were identified as the most vulnerable in Whatcom County, WA. The average precipitation is highest when the percent grass growth is lowest. Applying manure or fertilizer during this vulnerable period presents a high risk for leaching and runoff.

Vulnerable time periods also exist in eastern Washington, depending upon the crop growth, manure applications, irrigation, and precipitation events.

Carey and Harrison (2014) note that groundwater nitrate concentrations are sensitive to departures from agronomic nutrient application on the land surface. A manure application in early October 2006, just outside the normal growing season, resulted in an almost immediate increase in soil nitrate at the one-foot level, followed by an increase of up to 16 mg N/L in shallow monitoring wells beneath the field in Whatcom County.

The NRCS (2005) characterizes the winter period from October 1 to March 1. Application during this timeframe needs to meet specific risk criteria to minimize nutrients and associated contaminants from moving to surface water and groundwater. Some of these criteria include characterizing the fall soil nitrate content, assessing the potential for ponding, flooding, heavy rains, and frozen or saturated ground.

Nitrogen applied to land in the form of ammonium or organic nitrogen will convert to nitrate during the non-growing season and will leach out of the soils and migrate to the groundwater. Applying wastewater to the land during the non-growing season does not reliably protect the groundwater (Ecology, 2004a).

Hermanson et al. (2000) noted that organic nitrogen applied during the non-growing season will partially or totally convert to nitrate before the next growing season and that the amount converted will depend on the type of nitrogen applied, soil temperature, and moisture conditions. These researchers concluded that applying organic nitrogen during the non-growing season has an inherent risk of leaching nitrogen to groundwater. Additionally they advocate that steps be taken to minimize movement of nitrogen below the root zone during the growing and non-growing season. These researchers emphasize that there are enough uncertainties and uncontrollable variables associated with nitrogen dynamics in the subsurface to conclude that applying nitrogen to crops and soil systems during the non-growing season is not reliably protective of groundwater.

Application Risk Management

The Whatcom County Conservation District developed the Application Risk Management approach (ARM) to determine under what conditions, if any, manure could be safely land-applied during the non-growing season without an adverse impact to groundwater or surface water. This publication has recently been released, but the data from the multi-year ARM investigation were not included in this review for several reasons. It is not a peer-reviewed study and therefore does not fulfill the criteria of acceptable literature in this review. Also, the groundwater section of the study is being developed by USGS and is not yet complete. Finally, the raw data are not accessible beyond the District and EPA. Any conclusions about the degree of protection provided from this study cannot be included in this review until these issues are addressed. It is suggested that EPA, who funded the study and has access to the data, provide comment on the degree of protectiveness when the study, including the USGS groundwater portion, is complete.

Timing Considerations for Surface Water Quality

Fleming and Fraser (2000) conducted a literature review of the impacts of manure application on surface water quality. These researchers found that there were many similarities and a few conflicts in the literature, but they identified common themes:

- Nitrogen runoff to surface water from winter manure applications varies from negligible to over 20% of the applied nitrogen.
- The manure lost to surface water runoff is generally greatest during the winter months.

- Frozen soils are generally impervious, and snowmelt and rainfall are likely to cause manure runoff to surface waters.
- If the ground is not frozen, the water will infiltrate and leach to groundwater.
- The risk to surface waters is the same, whether the manure is applied to frozen bare ground or snow-covered ground.
- Manure application to a winter cover crop does not necessarily reduce the risk of runoff to surface waters.
- Some researchers concluded that applying solid manure can reduce the amount of runoff and associated soil erosion by acting as a mulch to slow the flow of runoff.
- Spreading solid manure, as a form of mulch, can impede runoff.
- One of the studies reviewed evaluated runoff rates for two sites with slopes of 10% and 20%. They found they had similar runoff rates. (Lower slopes were not evaluated in this one study).
- Pathogen die-off cannot be guaranteed during the winter months. Pathogens can remain viable in cold weather for extended periods of time.
- Volatilization rates are diminished during the winter, especially if the manure is covered by snow.

Fleming and Fraser (2000) concluded that weather is the biggest factor controlling surface water runoff.

Tools to Determine Timing of Manure Applications

Climate plays an important role in determining when manure should be applied. The following references provide site-specific information based on climate and crops to assist in determining the appropriate land application timeframes.

Washington Irrigation Guide

The Washington Irrigation Guide (NRCS, 1997) is a resource that reports the growing season for different crops based on the climate in different areas of the state. This guide provides both crop irrigation requirements as well as crop consumptive use estimates. It includes mean temperature and total precipitation by month.
http://www.nrcs.usda.gov/wps/portal/nrcs/detail/wa/technical/engineering/?cid=nrcs144p2_036314

Figure 14 is an example of the information contained in the Washington Irrigation Guide for Aberdeen, Washington. The crop consumptive use (CU) is the amount of water the specific crop needs. The crop irrigation requirement (CIR) is consumptive use minus the effective precipitation. The CIR is the amount of water that is needed to sustain the crop by meeting the consumptive use requirements in the different months. While this guide does not necessarily address nutrient requirements, the CU term provides information on the crop growing season, which is indicative of when crops would utilize nutrients.

APPENDIX B

WASHINGTON STATE - WEST OF CASCADES

CIR - CROP IRRIGATION REQUIREMENT and CU - CROP CONSUMPTIVE USE

ABERDEEN 46.97 LATITUDE

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
MEAN TEMPERATURE (F)	40.0	42.5	44.5	48.4	53.0	57.2	60.2	60.8	58.9	52.7	45.4	41.5	
TOTAL PRECIPITATION (IN)	12.38	9.96	9.17	5.68	3.57	2.60	1.45	1.78	3.73	7.57	11.37	13.75	83.01
REFERENCE CROP ET (IN)	0.11	0.56	1.37	2.19	3.22	3.51	3.91	3.10	2.47	1.46	0.36	0.04	22.30
EFFECTIVE PRECIP (IN)	0.11	0.56	1.35	2.16	2.31	1.80	1.04	1.22	2.15	1.43	0.36	0.04	14.53

PASTURE/TURF

	BEG	END	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SEASON
CIR	1/ 2	12/31	0.00	0.00	0.00	0.00	0.75	1.54	2.67	1.72	0.19	0.00	0.00	0.00	6.88
CU			0.10	0.53	1.30	2.08	3.06	3.33	3.71	2.95	2.35	1.39	0.34	0.04	21.19

FIELD CORN

	BEG	END	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SEASON
CIR	6/11	10/29	0.00	0.00	0.00	0.00	0.00	0.00	1.52	2.02	0.56	0.00	0.00	0.00	4.10
CU			0.00	0.00	0.00	0.00	0.00	1.11	2.54	3.26	2.72	1.20	0.00	0.00	10.82

Figure 14. Washington Irrigation Guide information example (NRCS, 1997).

Wetlands Climate Guide

The WETS tables are geographic area-based tables incorporating historic temperature and precipitation information for establishing the normal growing season range (NRCS, 1995).
http://www.wcc.nrcs.usda.gov/climate/wets_doc.html

WETS Station : DE SMET, SD2302
Latitude: 4423 Longitude: 09733 Elevation: 01750
State FIPS/County(FIPS): 46077 County Name: Kingsbury
Start yr. - 1971 End yr. - 2000
Temperature: 30 years available out of 30 requested in this analysis
Precipitation: 30 years available out of 30 requested in this analysis

	Temperature (Degrees F.)			Precipitation (Inches)				
					30% chance will have		avg # of days w/.1 or more	avg total snow fall
Month	avg daily max	avg daily min	avg	avg	less than	more than		
COL #1	COL #2	COL #3	COL #4	COL #5	COL #6	COL #7	#8	#9
January	23.0	2.4	12.7	0.60	0.31	0.78	2	6.6
February	29.3	9.0	19.2	0.68	0.41	0.89	2	7.0
March	41.3	21.1	31.2	1.60	0.87	1.95	3	8.9
April	58.7	34.2	46.5	2.26	1.28	2.75	4	1.6
May	71.1	45.8	58.5	3.05	1.82	3.69	5	0.0
June	80.3	55.8	68.0	4.02	2.59	4.84	6	0.0
July	86.2	61.1	73.7	3.25	1.96	3.93	4	0.0
August	83.9	58.6	71.3	2.44	1.51	2.95	4	0.0
September	73.7	48.7	61.2	2.14	1.03	2.61	4	0.0
October	61.0	36.8	48.9	1.78	0.83	2.25	3	0.8
November	41.7	22.5	32.1	0.92	0.34	1.11	2	5.4
December	26.7	8.1	17.4	0.58	0.32	0.73	1	6.0
Annual					19.83	26.03		
Average	56.4	33.7	45.1	------	------	------	--	----
Total	-----	-----	-----	23.30	------	------	40	36.3

GROWING SEASON DATES
Requested years of data: 30 Available years of data: 30
Years with missing data 24 deg = 0, 28 deg = 0, 32 deg = 0
Years with no occurrence 24 deg = 0, 28 deg = 0, 32 deg = 0
Data years used 24 deg = 30, 28 deg = 30, 32 deg = 30

	Temperature		
Probability	24 F or higher	28 F or higher	32 F or higher
COL #10	COL #11	COL #12	COL #13
	Beginning and Ending Dates Growing Season Length		
50 percent *	4/16 to 10/22 189 days	4/27 to 10/ 9 165 days	5/ 4 to 9/29 148 days
70 percent *	4/12 to 10/27 198 days	4/22 to 10/13 174 days	5/ 1 to 10/ 3 155 days

* Percent chance of the growing season occurring between the Beginning and Ending dates.

Figure 15. Wetlands Climate Guide information example (NRCS, 1995).

T-Sum 200

This is a method that was developed for western Oregon to calculate when to begin pasture fertilization. It is tied to the commencement of spring grass growth and involves summing daily heat units. A heat unit is defined as the average of each day's high and low temperatures. Starting on January 1, the average of the daily maximum and minimum air temperatures in °C (centigrade) is added for each day until the cumulative total reaches 200°C. At this point, the method assumes that at this time plants will begin growing and will require nutrients. Alternatively, this method can also use 360° Fahrenheit as the heat unit threshold. To calculate daily heat units in degrees Fahrenheit the following formula is used:

$$Daily\ Heat\ Units = [(daily\ maximum\ temperature\ °\mathrm{F} + daily\ minimum\ temperature\ °\mathrm{F}) \div 2] - 32$$

(Oregon State University Extension Service, 1996)

Soil Mechanics

Summary

The soil horizon and vadose zone are the locations where nitrogen treatment and transformations occur. These processes include crop uptake and removal, volatilization, mineralization, denitrification, and leaching. These processes are influenced by a variety of site-specific factors, and they also affect the fate and transport of chemicals in the environment.

***Volatilization** of nitrogen compounds after manure has been incorporated into the soils is minimal with documented rates of approximately 5%.*

***Mineralization** is the transformation of organic nitrogen to ammonium and it occurs year-round, even during the winter months, although the rate varies seasonally. Studies have shown that mineralization and nitrification can occur at significant rates in frozen soils especially in the presence of organic matter. In Canada, investigations have demonstrated that soil organic nitrogen and immobilized nitrogen contributed one-third to one-half of the nitrogen lost during the non-growing season.*

Several researchers noted that tilling or disturbance to the fields can stimulate mineralization.

Generally, the reviewed studies concluded that mineralization is a significant source of nitrogen in fields where manure has been applied. Additionally it was concluded that due to the continued mineralization during cold and freezing temperatures that fall-applied nitrogen poses a risk of leaching to groundwater, particularly in fine-textured soils.

***Denitrification**: Researchers conclude that denitrification may reduce nitrate loading to groundwater by 5% to 16% under some conditions, though they determined that it is of little importance in well-drained soils. It was observed that some degree of denitrification occurs at*

all sites, but high denitrification rates reported in some literature are not representative of shallow sandy aquifers.

Nitrogen Storage in the Subsurface: *Researchers have cautioned that the practice of storing nutrients in the soils during the winter for use by crops in the spring poses a risk to groundwater. Mineralization continues during the winter months. Climatic conditions such as temperature and precipitation, and subsequently nitrogen transformations, are not elements that can be precisely controlled. These uncontrolled elements can promote nitrate leaching. Soil storage of nutrients is a practice that has not been proven to protect groundwater.*

The vadose zone includes the soil horizon and the unsaturated zone between the ground surface and the water table where applied nitrogen can be transformed, utilized, and mobilized (Figure 16). The primary forms of nitrogen in manure are organic nitrogen and ammonium. Organic nitrogen must be transformed into plant-available nitrogen (ammonium or nitrate) before it can be taken up by plant roots. These transformations are part of the nitrogen cycle and are explained in more detail in Appendix A.

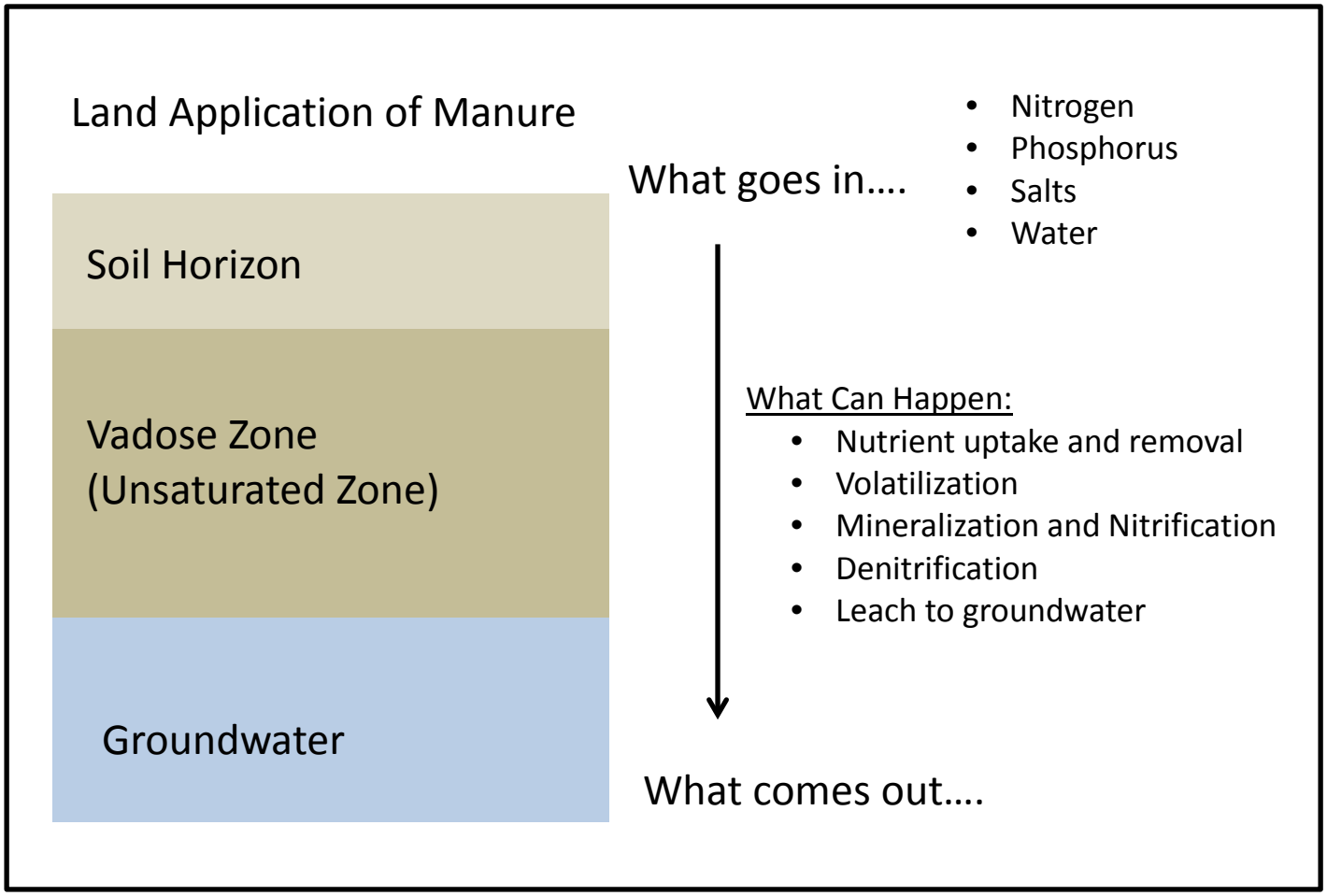

Figure 16. Soil treatment and transformation processes.

A University of California (2005) committee of experts recommends that a total nitrogen mass balance can be used to predict atmospheric losses prior to land application, but that it requires extensive data management and record keeping but it is also associated with significant estimation errors. These researchers advocate measuring or estimating losses based on site-specific conditions, and they caution against using one percentage for all situations.

Land treatment systems use the soil horizon and the vadose zone for attenuation, uptake, and degradation of nutrients and other constituents. Mineralization is the process that converts organic nitrogen into ammonium, while nitrification is the process that converts ammonium into nitrate. Volatilization and denitrification losses are minimal and occur under specific conditions (van der Schans et al., 2009; Sullivan et al. 2000; Dzurella et al., 2012; Hermanson et al., 2000). Nitrate and ammonium are the plant-available forms of nitrogen that are available for crop uptake in the root zone during the growing season. Once nitrate migrates below the root zone, it is no longer available to the crop and will eventually migrate to groundwater (Hermanson et al., 2000).

Green et al. (2008a) investigated the nitrogen transport processes that occur in the vadose zone at several sites across the United States including Washington State. Their goal was to verify previous findings that suggest a positive correlation exists between higher nitrate concentrations in groundwater and thicker unsaturated zones. These findings are inconsistent with vulnerability assessment methodology which assumes longer transport times in the vadose zone result in lower nitrate concentrations in groundwater due to denitrification. These researchers concluded that advective transport is the predominant process that influences nitrogen below the root zone. They found nitrogen fluxes to the water table ranged from 7 to 99 kg/ha/year. Values at the high end of the nitrogen range were measured at coarse-grained sites with high nitrogen application rates. They concluded that nitrogen application rates, water application, and evapotranspiration were the dominant factors that accounted for the differences between nitrogen concentrations at sites, not denitrification.

Volatilization

The percent of nitrogen in land-applied manure that is lost to volatilization in the soil was estimated by van der Schans et al. (2009) to be 5% or less.

Nitrogen losses were measured from different units within a farm, including animal exercise yards and feeding areas, liquid manure holding ponds, and land application areas. These researchers found that there was an average volatilization loss of 35% from the liquid manure ponds. Additionally these researchers concluded that volatilization and denitrification losses in the vadose zone are not significant. (van der Schans et al., 2009)

The University of California (2005) committee of experts estimates atmospheric losses from liquid manure range between 20 and 40% and that this figure does not include losses occurring during land application.

Mineralization

Nitrogen mineralization generally increases during warmer weather and slows during cooler weather, but the fraction of nitrogen that mineralizes and becomes available for crop uptake or leaching to groundwater is difficult to accurately estimate. Watts et al. (2007) state that nitrogen mineralization is most influenced by temperature and note that the greatest mineralization occurs at 77°F (25°C). However, recent studies show that significant mineralization occurs during the winter months, creating an additional soil nitrate load that is susceptible to leaching.

Lamb (2012) observed that the conversion of organic nitrogen to nitrate nitrogen typically occurs when the soil temperatures are greater than 50°F (10°C), but that this transformation continues at a decreased rate at lower temperatures until soil temperatures reach 43°F (6°C). Kowalenko et al. (2007) concluded that mineralization of soil nitrogen does not cease in the fall after the crop has been harvested but continues during the winter months in British Columbia.

Clark et al. (2009) investigated the fate of fall nitrogen application of manure (pig slurry) to loamy and clay soils. These researchers observed that nitrification and mineralization continued during the wintertime in frozen soils, but mineralization and nitrification were higher in clay soils and immobilization was higher in loamy soils. They also noted that at temperatures between -2°C and 2°C a significant portion of the ammonium in the slurry was nitrified, but little immobilization occurred even with soil amendments of organic matter. They found that nitrogen immobilization ceases at a higher temperature than nitrification, potentially resulting in an excess of nitrate. These researchers concluded that microbial activity occurs in frozen soils, with mineralization and nitrification occurring at significant rates, especially in the presence of organic matter. These researchers concluded that fall-applied nitrogen could pose a risk of leaching to groundwater, particularly in fine-textured soils.

Cookson et al. (2002) noted significant mineralization in temperate soils (2-15°C) amended with clover residues at temperatures as low as 2°C. These researchers concluded that nitrogen amendments applied in the winter pose a risk to groundwater leaching and recommend that nitrogen applications be limited until the spring.

Winter groundwater nitrate levels at the downgradient edge of a raspberry field at the top of the Abbotsford-Sumas aquifer in southern British Columbia indicated a continued source of newly mineralized nitrate throughout the winter (Kuipers et al., 2014).

Moberg et al. (2013) evaluated mineralization rates in manured agricultural soils during different seasons. Based on samples collected from October to February, the mean soil nitrate concentration was 24.4 mg/kg (ppm). These researchers reported an annual precipitation rate of 118 cm/yr (3.9 feet/yr). If this mineralized soil nitrogen were mixed with recharge, it would result in approximately 8 mg N/L of nitrate available to leach to groundwater.

Chantigny et al. (2014) state that the residual soil nitrate measured at harvest represents the risk of nitrate loss to groundwater during the non-growing season. These researchers utilized ^{15}N isotopes as a tracer of nitrogen from applications of pig slurry. Their data indicate that 30% to 60% of nitrogen applied in the spring was still present in the soils at the fall harvest. Further,

these researchers found that in clay soils, 16% of the nitrate was lost to groundwater and 45% was lost to groundwater in sandy soils. This work provides evidence that soil organic nitrogen and immobilized nitrogen contributed one-third to one-half of the nitrogen lost during the non-growing season in Canada. Similar research by Jayasundara et al. (2010) discovered nitrogen losses of 16% to 29% from the fall application of pig slurry during the non-growing season. These researchers caution that measuring the fall soil nitrate concentration is inadequate to completely assess the risk of nitrate leaching to groundwater.

Uncertainty in the timing and rate of mineralization and nitrification makes it challenging to accurately estimate the amount of plant-available nitrate in the soil. These rates are dependent upon the amount of organic matter, climate, temperature, and biological activity. Dessureault-Rompré et al. (2010) assessed the variables that predict nitrogen mineralization rates in agricultural soils. These researchers found that soil bacteria in colder climates (mean annual temperature less than 2°C) adapt more readily to declining temperatures compared to bacteria in warmer climates (mean annual temperature greater than 6°C). This research verifies that mineralization occurs in the winter and that rates can be higher in colder climates. These researchers also noted a greater mineralization response to temperature in agricultural soils than in forested soils.

Denitrification

Sullivan et al. (2000) determined that denitrification rates in manured soils typically range from 5% to 15% with the highest rate of 16% noted in October and November after the soil was saturated following a dry summer. These researchers also noted that the remaining soil nitrate (85% to 95%) is lost to groundwater through leaching.

Denitrification requires low oxygen environments and the presence of electron donors, such as organic matter or reduced minerals. Green et al. (2008b) investigated natural attenuation of agricultural nitrate contamination in four areas within the United States, including the Yakima watershed in Washington State. This research utilized methods to analyze all nitrogen species simultaneously to determine nitrogen transformations. In Yakima they found that the zones of denitrification were not uniform across the watershed and were not consistent. They determined that this variability resulted from differences in land use and the intensive application of manure in some areas.

Green et al. (2008b) state that some degree of denitrification occurs at all sites but that the high denitrification rates reported in the literature are not representative of shallow sandy aquifers. These researchers concluded that many of the denitrification values reported in the literature were far higher than what they observed. They caution that assuming high denitrification rates based on reported literature values may be skewed due to method limitations and biased site selection, since in some denitrification studies the sites are often chosen for promoting higher denitrification rates. These researchers concluded that the electron donor concentrations from recharge were insufficient to promote high denitrification rates. They estimate that it would require decades or longer to denitrify the existing groundwater contamination to background conditions.

Singleton et al. (2007) investigated denitrification in shallow groundwater under dairy operations. These researchers anticipated that high rates of denitrification would occur under lagoons due to the saturated conditions created by the continuous seepage. However, they concluded that the prevalence of this phenomenon is unknown, due to the uncertainties in assessing the spatial extent of anaerobic conditions, the transport of organic carbon in different environments, and differing nutrient management practices.

Dzurella et al. (2012) estimate that 10% of the nitrogen in the applied manure in the California Central Valley is lost to denitrification.

Hermanson et al. (2000) noted that denitrification may reduce nitrate loading to groundwater under some conditions, though it is of little importance in well-drained soils.

Storage of Nitrogen in the Subsurface

Nitrogen storage in the subsurface during the winter months poses a high risk to groundwater, particularly where winter recharge is high. Manure contains primarily organic nitrogen and ammonium, which do not readily move with downward flowing water and are adsorbed to the soil matrix. Mineralization increases as temperatures increase, converting the organic nitrogen to ammonium and then to nitrate (Moberg et al., 2013). Mineralization has been documented to continue through the winter and in freezing conditions. The end of winter and early spring when temperatures rise are also typically times of high precipitation and low crop uptake. If nitrogen is converted to nitrate and is not utilized by a crop, recharge can cause nitrate to migrate below the root zone and leach into groundwater. Since temperature, microbial activity, precipitation, and recharge cannot be controlled at a field scale, and the amount of nitrogen cannot be precisely gauged to the crop's limited needs at this time, researchers have stated that the application of nitrogen outside of the growing season is a risk to groundwater (Hermanson et al., 2000; Qui et al., 2005).

Erickson and Matthews (2002) conducted an extensive five-year groundwater monitoring study to evaluate the effectiveness of storing manure over the winter in a newly constructed lagoon in Thurston County. Monitoring was conducted before and after lagoon construction. This allowed a comparison of impacts to groundwater when manure is applied year-round vs. manure applied only during the growing season. These researchers noted improvements in groundwater nitrate concentrations, although the mean concentrations remained elevated above the drinking water standard at the end of the study. They concluded that the improvements to groundwater quality were attributed to the lagoon which facilitated the following: (1) increased volatilization of ammonium during storage, (2) dilution of nutrients with the addition of precipitation to the lagoon, and (3) uniform application of manure to fields during the growing season (April through October).

Hermanson et al. (2000) conclude that it is not protective of groundwater quality to store nitrogen in the soils during the winter months when crops are dormant and to assume the nitrogen will remain available in the root zone when crops will utilize it.

Vegetative Buffers and Setbacks to Surface Water

Summary

Vegetative buffers and setbacks to surface waters are management tools that can protect surface water quality. A setback is defined as the distance from an area where an activity is occurring, such as manure application to fields and to waters of the state. A vegetative buffer zone is an undeveloped area composed of different types of vegetation directly adjacent to the body of water (Mathieu, 2012). Vegetative buffers and setbacks to surface water are transition areas between land uses that provide protection to surface water from manure runoff.

The primary purpose of a vegetative buffer zone is to reduce runoff to surface water by increasing infiltration into soil where nutrients, pathogens, and other contaminants can be utilized by vegetation or attenuated in the subsurface. Buffer zones also help to stabilize soils, reduce erosion, enhance wildlife habitat, and improve water quality (Mathieu, 2012). The NRCS recommends the use of vegetative buffers and setbacks if no other BMPs that reduce discharges to surface water are installed. They also note that when vegetative buffers and setbacks are used in combination they are more effective.

Researchers evaluate pathogen viability and transport distances based on different climatic conditions, vegetation type, and soils. Pathogens, such as enteric bacteria have the ability to survive in manure for as long as 3 to 4 months, depending upon the temperature and water content. (Wang et al., 2004; Sinton et al., 2007). Sinton et al. (2007) noted that in the first 1 to 3 weeks after manure application, populations of most bacteria increased in most conditions, with temperature being the primary influence on growth. They noted that bacteria levels remain elevated if moisture content was above 80%. Reductions of 90% of original bacteria populations took as long as 56 days, with the primary influence being desiccation caused by water content below 70% to 75%. Wang et al. (2004) concluded that manure management practices that store manure at temperatures greater than 41°C will decrease populations of E. coli and fecal coliform bacteria but not fecal streptococci.

Fecal coliform bacteria can survive in soil at high concentrations for a period of weeks to months after land application (Nennich et al., 2005). This poses a risk to water quality, since manure can still impact surface water at a later date. Bacteria can be remobilized with successive precipitation events, eventually migrating to surface waters. This means that the first rainfall after a manure application might not result in impacts to adjacent surface waters, but later events may (Hubbs, 2002; Nunez-Delgado et al., 2002; Sinton et al., 2007).

Increased buffer zone width allows a greater distance for contaminants to be removed and greater vegetation growth, which enhances the removal of nitrate. The Minnesota Pollution Control Agency (2000) states that vegetative buffer strips are an effective means of protecting surface water quality. They advocate that vegetative buffers be at least 60 feet wide and contain a variety of trees, shrubs, plants, and grasses.

Infiltration is greater in permanently vegetated areas rather than in agricultural areas, and the additional infiltration also acts to dilute chemical concentrations. Entry et al. (2000) determined that the effectiveness of vegetative buffer strips can be greatly reduced in the winter months when vegetation is dormant.

Storage Lagoons

Summary

Storage lagoons are an important part of manure management. Researchers advocate the use of storage facilities during the non-growing season.

Numerous studies have documented leakage from manure lagoons and some have documented impacts to groundwater from nitrate, ammonium, veterinarian pharmaceuticals, chloride, TDS, and bacteria.

Adequate storage lagoon design includes consideration of the following elements: soils, location, liner permeability, liner material, environmental conditions such as minimum vertical separation and seasonal high water table.

Storage lagoons are an important management component for liquid and slurry wastes generated by CAFOs. Lagoons provide storage during the non-growing season and during times when land-applying wastes is not protective of water quality. During times when a crop is not actively growing, or when the growth rate is very slow due to low air and soil temperatures, continued application will most likely exceed crop needs. Since manure is typically generated year-round, a storage lagoon is often used to temporarily store manure during those times when crops do not require supplemental nutrients. Manure contains elevated concentrations of total dissolved solids, BOD, total nitrogen, phosphorus, chloride, and microbiological pathogens.

Hermanson et al. (2000) state that the use of storage facilities to minimize nitrogen applications during the non-growing season is a safe alternative to protect groundwater instead of year-round application.

The literature indicates that the important considerations during AFO lagoon design and site selection for manure storage and reducing the potential groundwater impacts include:

- *Lagoon design and construction*
- *Suitable soils*
- *Liner permeability*
- *Seasonal high water table*
- *Minimum vertical separation*

These elements are described in greater detail below.

Lagoon Design

There is general agreement in the literature that lagoon design and construction is an important component to minimize the potential for adverse impacts to groundwater from lagoon seepage. The NRCS Agricultural Waste Management Field Handbook (NRCS, 2009b) is the industry standard and describes the protocols and specifications for storage lagoons. Table 17 classifies the soils based on their composition and permeability. Table 18 describes the soils that are suitable for constructing lagoons.

Table 17. Soil classification based on composition and permeability ranges.

USDA Group Definitions	Percent fines	Plasticity Index (PI)	Estimated Range of Permeability (cm/sec)	
			low	high
I	<20	< 5	3×10^{-3}	2
II	>= 20	<= 15	5×10^{-6}	5×10^{-4}
	<20	>= 5		
III	>= 20	16 to 30	5×10^{-8}	1×10^{-6}
IV	>= 20	> 30	1×10^{-9}	1×10^{-7}

(NRCS, 2009b; USDA, 1993)

Table 18. Soil permeability, classification, and groups suitable for lagoon construction.

Unified Soil Classification System				Permeability (K) (cm/sec) [2]	USDA Group [1]
Coarse-Grained Soils	Clean Gravels	GW	Well graded gravels, gravel-sand mixtures, or sand-gravel-cobble mixtures	$> 10^{-2}$	I
		GP	Poorly graded gravels, gravel-sand mixtures, or sand-gravel-cobble mixtures	$> 10^{-2}$	I
	Gravels with Fines	GM	Silty gravels, gravel-sand-silt mixtures	10^{-3} to 10^{-4}	II
		GC	Clayey gravels, gravel-sand-clay mixtures	10^{-6} to 10^{-8}	III
	Clean Sands	SW	Well graded sands, gravelly sands	$> 10^{-3}$	I
		SP	Poorly graded sands, gravelly sands	$> 10^{-3}$	I
	Sands with Fines	SM	Silty sands, sand-silt mixtures	10^{-3} to 10^{-6}	II
		SC	Clayey sands, sand-clay mixtures	10^{-6} to 10^{-8}	III
Fine-Grained Soils	Silts	ML	Inorganic silts, clayey silts of low to medium plasticity	10^{-3} to 10^{-6}	II
		MH	Inorganic silts, micaceous or diatomaceous silty soils, elastic silts	10^{-4} to 10^{-6}	III
	Clays	CL	Inorganic clays of low to medium plasticity, gravelly, sandy, and silty clays	10^{-6} to 10^{-8}	III
		CH	Inorganic clays of high plasticity, fat clays, sandy clays of high plasticity	10^{-6} to 10^{-8}	IV
	Organic Silts and Clays	OL	Organic silts and clays of low to medium plasticity, sandy organic silts and clays	10^{-4} to 10^{-6}	N/A
		OH	Organic silts and clays of high plasticity, sandy organic silts and clays	10^{-6} to 10^{-8}	N/A
Organic Soils		PT	Peat	N/A	N/A

Shading – acceptable to reduce lagoon seepage.

N/A – not appropriate for use as foundation or base material.

[1] NRCS, 2009b; NRCS, 2009a; USDA, 1993.

[2] Freeze and Cherry, 1979.

The NRCS Handbook (2009b) describes conditions where an additional measure of safety from lagoon seepage is necessary and when a constructed liner is warranted. (Constructed liners include compacted clay, concrete, and synthetic materials.) These circumstances include:

- Locations near a well, spring, or other vulnerable water source.
- Areas where there are less than two feet of soil between the land surface and the seasonal high groundwater or bedrock.
- Group I soils.
- Some Group II soils. These include Group III flocculated clays, and Group IV highly plastic clays with blocky structure.
- Other soil properties that affect permeability include: dry density, structure, chemical composition, high calcium and magnesium content, alluvial soils, and other deposition forces that create anisotropic conditions.

Other measures advocated by the NRCS (2009b) to minimize lagoon liner seepage, include:

- Clay liner of a maximum permeability of 1×10^{-7} cm/sec.
- Flexible membrane liner.
- Geosynthetic clay liner (GCL).

Nicholson et al. (2002) examined environmental effects and developed a rating system for different storage methods for slurry and solid manure. Based on the rating system these researchers developed, they determined that for slurry storage, the most protective to least protective systems are: (1) cylindrical above-ground tanks, (2) weeping wall storage, (3) below-ground concrete tanks, (4) lined lagoons, and (5) unlined lagoons. For solid manure storage, the most protective to the least protective are: (1) roofed storage with a concrete base, (2) a concrete pad with a tank, (3) a concrete pad without a tank, (4) field heap with a different site each year, and (5) field heap with the same site each year.

Suitable Soils for Lagoons

Natural soils in permeability groups III and IV (Tables 17 and 18) are usually acceptable to reduce lagoon seepage. These soils need at least 15% clay content. Clean sands and gravels always require a liner. (NRCS, 2009b; USDA, 1993)

Organic soils (OL, OH, PT) have a high organic content, which makes them unsuitable for use as a base foundation. The organic matter decays over time, which alters the soil structure; this ultimately can cause instability. As decay occurs, the pore space increases, making the soil susceptible to subsidence associated with hydrocompaction. (NRCS, 2009b; USDA, 1993)

Liner Permeability

The NRCS (2009b) recommends an allowable seepage quantity of $1 \text{ X } 10^{-7}$ cm/sec (based on the historical permeability for clay liners). Ecology (Kimsey, 2002 [appendix C]) specify that agricultural wastewater lagoons have a final maximum liner permeability of $1 \text{ X } 10^{-7}$ cm/sec or less. This permeability can be achieved through the use of adequate soils, liner design, and

sealing from manure. Soils with a permeability of 1 x 10^{-5} cm/sec are suitable for lagoon construction since this provides a base for constructing a lagoon, which will ultimately achieve the maximum recommended liner permeability through compaction or amendments. The optimal lagoon design has a maximum ratio of 8:1 lagoon depth to liner thickness, with a minimum liner thickness of one foot. This flexibility allows for utilizing site-specific conditions to achieve the best design. (NRCS, 2009b) This approach provides an optimal combination of liner thickness and permeability to achieve an effective and economical liner design.

Sealing of the soils is the result of physical, chemical, and biological processes. Suspended fines settle and clog soil pores, anaerobic bacteria produce byproducts that accumulate at the soil/water interface and reinforce the seal. Salts can cause dispersion of some of the aggregates that act to clog the soil voids and enhance the sealing mechanism. Additionally, the soil structure can be enhanced by the metabolism of organic material. (NRCS, 2009b)

The degree of sealing depends upon many site-specific variables. NRCS (2009b) cautions that even though manure sealing is well documented, it may not be adequate in all instances. Conservatively, the addition of manure to a lagoon can reliably contribute one order of magnitude reduction in seepage. (NRCS, 2009b)

Ham (2002a) noted that there are similarities between all the animal manure lagoons. The physical, chemical, and biological processes of the manure act similarly to create an additional restrictive layer that decreases the hydraulic conductivity of the lagoon to a mean of 1.8 X 10^{-7} cm/sec. The variations in discharge (seepage) rates were found to be relatively small, despite the large differences in soil types, manure composition, and depth to water found at the 20 sites studied.

Ecology modeled the impacts of various lagoon designs, estimated the impacts to groundwater quality, and determined the appropriate design, based on an acceptable level of degradation. The recommended maximum liner permeability was determined to be $1x10^{-6}$cm/sec, with the assumption that manure sealing will provide approximately an order of magnitude of additional protection resulting ultimately in a permeability of $1x10^{-7}$ cm/sec. (Kimsey, 2002). This paper is found in Appendix C.

MPCA (2001) monitored an earthen manure storage unit that was upgraded with a geosynthetic liner with a bentonite clay liner. The liner was then covered with a foot of native soil. Additionally, a filter strip was installed downgradient of the pens and corrals. The results indicate that within three years of these improvements, total nitrogen concentrations in groundwater decreased by 55%; phosphorus and organic carbon decreased as well.

Leakage of contaminants below the lagoon liner is a function of many factors including the seepage rate, constituent concentrations, and the soil mineralogy underlying the lagoon. Researchers advocate using caution when interpreting soil results to compare one site to another. A thorough understanding of individual lagoon design, construction, concentrations, and management strategies are important when evaluating monitoring results.

Seepage Rates

Glanville et al. (2001) used a whole basin water balance approach to calculate leakage rates from 28 earthen manure storage structures and lagoons in Iowa. They determined that 53% of the storage structures had leakage rates close to the 1.6 mm/d regulatory rate in Iowa, 4% had significantly greater leakage, and 43% had significantly less leakage.

Ham and DeSutter (1999) investigated seepage losses from three animal waste lagoons in Kansas using a water balance method. These researchers found that seepage can be decreased to less than 1.6 mm/day by increasing the thickness of the soil liners from 0.3 to 0.46 m (assuming adequate soils and construction methods are used).

Reddi et al. (2005) noted that there is a relationship between seepage rates and liner permeability. They recommend that permeability should be between 1 X 10^{-6} and 1X 10^{-7} cm/sec in order to achieve the Kansas seepage rate goal of 0.25 in/day (0.64 cm/day). These researchers also noted that liner thickness is an important consideration in retaining liquids in the lagoon, and they recommended a minimum liner thickness of 0.5 m (1.6 ft). They found liner thickness was more important than liquid depth. Based on modeling, they found that when liner thickness was increased from 0.15 m to 0.9 m, chloride breakthrough from the lagoon reaching groundwater occurred up to 60 years later.

Studies investigating lagoon design and the seepage of contaminants are summarized in Table 19.

Table 19. Summary of lagoon design and discharge characteristics.

Lagoon Seepage (Leakage) (mm/d)			Hydraulic Conductivity (cm/s)			Nitrogen Loading	Mean Liquid Depth in Lagoon	Liner Thickness	Reference
min	max	mean	min	max	mean	lbs N/ac/yr			
0.2	2.4	1.1			1.8 X 10^{-7}	385 kg/ha/yr		0.3 m (assumed)	Ham, 2002b
0.3	1.6	Range of 75% lagoons studied							Ham, 2002b
		1.3					3.5 m		DeSutter and Pierzynski, 2000
		1.2					1.8 m		Glanville et al., 2001
		2.7 ft/yr				270 lbs/ac/yr			Van der Shans et al., 2009
0.8	1.1	1.0	1.5 X 10^{-7}	7.8 X 10^{-8}		2187 - 2726 kg/ha/yr	5.6 m	0.3 - 0.46 m	Ham and DeSutter, 1999
0.6	1.0						1.66 m		Ham, 2002a
						Recommended		0.5 m	Reddi et al., 2005

Glanville et al. (2001) investigated 15 slurry pits and 12 lagoons. These researchers determined that there was no statistically significant difference in leakage rates between these two types of storage facilities.

Ham (2002a) tested and validated his theory that a precise water balance can be used to estimate seepage rates (+/- 0.25 mm/day) from animal waste lagoons and earthen structures. This method can be completed with five consecutive days of good weather by collecting detailed measurements of depth changes, and cumulative evaporation. This researcher advocates this method to quantify whole lagoon seepage since it has been determined that design permeability data do not adequately predict actual seepage rates.

Sidewall Seepage

Ham (2002) studied the differences in discharge rates from the floor of the lagoon and the side-wall embankments. He found that the permeability of the lagoon floor decreased from the effects of manure sealing. He also noted that the side-walls were susceptible to impacts from climatic effects such as freezing and thawing, wetting and drying, erosion, and from the formation of macropores (from earthworms and weeds).

MPCA (2001) investigated seepage losses from the bottom of the lagoon, the sidewall, and the center and perimeter tile. Chloride was used as a conservative tracer of manure migration. These researchers concluded that there is greater seepage through the sidewalls than the bottoms of the basins.

Glanville et al. (2001) studied 27 lagoons and slurry pits in Iowa. They determined that significantly greater leakage occurs through the sidewalls than the floor of the lagoon. They attributed this to manure sealing of the floor and greater compaction during construction.

Seasonal High Water Table Considerations in Lagoon Design

Groundwater levels naturally fluctuate seasonally. Saturated conditions can affect the treatment capacity of the soils and this can create reducing conditions. The fate and transport of contaminants is dependent upon the ability of the soils to treat and attenuate contaminants, which is affected by the soil conditions. (EPA, 2002) Saturated soils can be present in both western and eastern Washington, depending on the local hydrologic conditions.

The seasonal high water table is traditionally determined through visual inspection by digging a hole during the wet season to observe the level of standing water. (NRCS, 2009b) Seasonal groundwater can also be determined from static water levels taken from wells.

Fletcher and Veneman (2012) advocate that during the drier months, the highest groundwater levels can also be estimated from examining the soil morphology, mottling, and discoloration. Soils without excess water during the year usually are aerated and exhibit a yellow-brown color. Soils with high water tables will exhibit gray coloration during some part of the year at the depth of the high water mark and below. Gray colors are typically associated with saturated and chemically reducing soil environments, while yellow-brown colors are typically related to aerobic and chemically oxidizing conditions. The more distinct the wet period is, the grayer the soil. Many soils exhibit both gray and yellowish-brown colors, reflecting the presence of an elevated water table in spring and a drier, more aerated condition during late spring and summer when the water table subsides. The Munsell color identification system is a standard tool for delineating soil colors. (Fletcher and Veneman, 2012)

Soil saturation occurs when all the soil pores are filled with water. During this process of saturation, there is a chemical reduction of iron in soils. Soils are primarily made up of gray silicate minerals with small amounts of iron oxides that are brown or red. When anaerobic conditions are created (as with the inundation of groundwater), the iron is reduced and becomes dissolved. This allows the underlying gray silicate materials to become more pronounced. A mixture of the gray and red coloration is called mottling and is indicative of alternating oxidizing and reducing conditions. This is an indicator of a seasonal high water table. (NRCS, 2009b)

Soil saturation and reducing conditions are often correlated; however, it is not a universal occurrence. It was determined that it takes approximately 29 days of saturation to create reducing conditions, or 8% of the year (Franzmeier and Jenkinson, 2004).

Thurston County, WA requires a winter water study to determine the seasonal high water level. This is defined as the highest water level for seven consecutive days, or the highest mottling in soil profile (Thurston County, 1999).

Minimum Vertical Separation

Vertical separation is defined as the distance between the bottom of the lagoon liner and the top of the water table, at its highest level during the season. Maintaining an aerobic unsaturated environment beneath the lagoon is important to the attenuation and destruction (inactivation) of bacteria and viruses. (EPA, 2002). The minimum vertical separation provides this treatment space. Soils generally function as attenuation zones by filtering the larger bacteria and adsorbing the smaller viruses onto the negatively charged particles in the soil where they are inactivated by soil microbes. (EPA, 2002) The literature indicates that manure lagoons have a potential to impact groundwater quality if the microbiological pathogens are not destroyed in the vadose zone. (EPA, 2002)

Vertical separation is also important in maintaining the integrity of the liner. Lagoon liners which are inundated by water from below are more prone to failure. (NRCS, 2009b)

The minimal acceptable vertical separation is dependent upon site-specific characteristics, including soil texture. In fine-grained soils, a minimum of 2 feet may be adequate; but in coarser-grained soils, 10 to 12 feet may be necessary to remove all pathogens. Groundwater mounding from excessive infiltration can become a concern when the mound reduces the vertical separation by artificially raising the water table, such that pathogen attenuation is no longer effective (EPA, 2002; Hall, 1990). Researchers agree that if there is insufficient vertical separation, the lagoon should be constructed above ground.

Hall (1990) conducted a literature review on vertical separation as a treatment component for on-site sewage systems. This summary recommended that 2 to 4 feet of vertical separation is needed between the bottom of the pipes and the top of the water table to adequately attenuate bacteria and other pathogens. The literature also advised that additional separation may be necessary to account for groundwater mounding.

Monitoring

Monitoring a land treatment system provides an understanding of how the system is operating and if management practices need to be adjusted to meet performance goals.

This section describes the monitoring elements found in the literature that may be used to determine nitrogen availability for crops, and fate and transport of nitrate in the environment. Published researchers agree that a well-planned and comprehensive monitoring program provides information on the effectiveness of operations and impacts to the environment. This information can be incorporated into a site-specific plan that can be a vehicle for a producer to make informed decisions about manure and farm management. An accurate assessment allows producers to optimize nutrient application while protecting groundwater quality.

Harter et al. (2014) present various monitoring approaches to assess impacts of animal feeding operations (AFOs) on the environment. The Netherlands have established an extensive monitoring program focusing on soils, shallow groundwater, and deep groundwater. The Dutch have a national monitoring network in a randomized fashion by soil type, aquifer type, and farm type. In New Mexico all dairy farms must establish groundwater monitoring networks. California originally required groundwater monitoring networks but is now putting more emphasis on source management. The California Water Resources Control Board has adopted a combination of source management monitoring in conjunction with regional groundwater monitoring for dairies in the Central Valley.

Researchers recommend that a comprehensive monitoring plan include:

- Mass balance calculations
- Crop monitoring
- Manure monitoring
- Soil monitoring
- Irrigation water monitoring
- Groundwater monitoring

A more detailed description of standard sampling methodology is included in Appendix D for manure, soil, and groundwater.

Mass Balance

Mass balance accounting is an application of conservation of mass by accounting for all the nitrogen entering and leaving a treatment system. The nitrogen transformations or unmeasurable components can be accounted for with this technique.

A mass balance is an accounting of inputs and outputs (Equation 1). The difference between inputs and outputs is an indicator of the relative environmental risk. Nutrient and hydraulic mass balances calculated for each field where manure is land-applied provides a characterization of nutrient loadings and an assessment of environmental impacts. This exercise assists in determining accurate application rates that supply the correct amount of nutrients to the crop at

the time when the crop needs them and in a way that manages the waste in an environmentally responsible way

Equation 1. Mass Balance Equation

$$Net\ Nitrogen\ (Gains\ or\ Losses)\ =\ Nitrogen\ Inputs\ -\ Nitrogen\ Outputs$$

Summary

Researchers advocate the use of mass balance calculations to plan and refine manure management practices depending upon changing conditions. An accurate mass balance takes all nitrogen inputs into account, including; irrigation water, commercial fertilizer, manure, wastewater, crop residue, precipitation, and any other nitrogen additions. Some researchers have noted problems if the mass balance is not calculated for the entire farm, with monthly balances calculated for each field.

Several researchers advise caution against using the mass balance to determine if there are impacts to groundwater quality. Impacts to groundwater have been documented in circumstances where the mass balance calculations indicate a balanced treatment system. One study observed a correlation with changes in the mass balance corresponding with shallow groundwater nitrate concentrations increasing and decreasing.

Researchers in California observed that nutrient imbalances were typically the result of increasing herd size without the proportional increase in land base. They concur with other studies that if the amount of nutrients generated on the farm exceeds the ability of the crops to utilize the nutrients, the nutrients will accumulate in the soil and result in an increased risk of nitrate loss to groundwater.

A mass balance may be used to characterize nutrient loading, hydraulic loading, and salt loading. Harter and Menke (2004) recommend that a whole farm nutrient mass balance be computed for each field with monthly inputs and outputs. An annual summary indicates excess nutrient availability and the risk of adverse impacts to groundwater quality. Averaging applications over the year is not recommended, since timing is a critical component to achieving appropriate application rates.

Jégo et al. (2008) recommend that all nitrogen inputs be taken into account, including irrigation water, commercial fertilizer, manure, wastewater, crop residue, precipitation, and any other nitrogen additions. Harter et al. (2012) advocate that the elements in Table 20 be considered in calculating the nitrogen additions and losses as part of a mass balance.

Table 20. Nitrogen inputs and outputs.

Nitrogen Inputs	Nitrogen Outputs
Manure Application	Crop Removal
Inorganic Fertilizer	Volatilization
Mineralization of Soil Organic Matter	Denitrification
Previous Season Legume Crops	Leaching to Groundwater
Irrigation Water	
Precipitation	

Researchers found that mass balance estimates for nitrogen based on data from dairy farms in California were consistent with nitrogen leaching rates from a field-calibrated groundwater flow transport model. This suggests that nutrient mass balances can be a good tool to indicate potential impacts to groundwater (Harter, 2002; van der Schans et al., 2009).

Carey and Harrison (2014) found that mass balance increases or decreases corresponded with increases and decreases in shallow groundwater nitrate concentrations at an intensively monitored field in Whatcom County. However, actual concentrations of nitrate in groundwater were significantly higher than indicated by the mass balance estimates. These researchers speculate that this problem may be affected by the nitrogen that accumulates in the soils over time and then gradually mineralizes.

Calculating mass balances considers inputs and outputs and is most accurate when computed on a monthly basis for each field and compiled annually. Calculating mass balances by averaging the loading rates over the entire site or over the entire year can result in localized impacts to groundwater quality. Good recordkeeping is essential to developing an accurate assessment of manure management (Cogger, 2000).

Harter and Menke (2004) state that mass balance calculations are the primary management tool for determining how effectively the land treatment system is utilizing nutrients and when excess nitrogen is being applied. Cogger (2000) concluded that there is no single, simple, economical way to correct nutrient imbalances. Nutrient imbalances are typically the result of an increasing herd size without a proportional increase in land base for manure application. If the amount of nutrients generated on the farm exceeds the ability of the crops to utilize the nutrients, the nutrients will accumulate in the soil or leach to groundwater.

Two large scale indicators were developed for Canadian agricultural lands to assess risk to the environment. Drury et al. (2007) created the concept of residual soil nitrogen (RSN), which is the amount of inorganic nitrogen that remains in the soil at the end of the growing season after the crops have been harvested. This residual is calculated as the difference between nitrogen inputs and outputs. The RSN was calculated on a provincial and national scale for five years to assess trends. DeJong et al. (2007) created the second large-scale assessment called the "indicator risk of water contamination by nitrate" (IROWC-N). This indicator links the RSN to climate and soil conditions to determine the risk of nitrate losses. These results were mapped to calculate spatial and temporal changes in nitrate losses.

Cogger (2000) recommends the following practices as part of the nutrient management plan (NMP), which will assist in developing an accurate mass balance:

- Testing nutrients in manure and soil.
- Determining crop nutrient yields.
- Measuring nutrient application rates for each field and crop.
- Determining appropriate timing of applications.
- Calibrating application equipment.
- Measuring applications to determine if nutrient goals were met.
- Using manure storage during periods when manure cannot be safely applied.
- Isolating stormwater runoff from manure.
- Using buffers to protect surface water.
- Keeping accurate records.

Harter and Menke (2004) caution against presuming that there is a "negligible threat to groundwater" even when the mass balance calculations indicate a balanced treatment system.

Hermanson et al. (2000) recommend that if the mass balance indicates an excess of nutrients have been applied to the field, or if the soil nitrate, or groundwater concentrations are elevated, the nutrient management plan needs to be revised to address how excess manure will be managed and how surface water and groundwater quality will be protected.

Crop Monitoring

Crops are an important part of the land treatment process. Removing crops during harvest is part of the manure treatment process and is an important component in the mass balance calculation. Field measurements of crop nitrogen removal provide a verification of the amount of nitrogen removed from each field as part of the mass balance calculation. Equation 2 calculates the nitrogen use efficiency (NUE) which is based on measurements of crop removal and the amount of nitrogen applied in manure (EPA, 2011). Equation 2 is an estimate since the accuracy depends on the validity of the measurements for all inputs and outputs.

$$Nitrogen\ Use\ Efficiency\ (NUE) = \frac{Amount\ of\ nitrogen\ applied}{Amount\ of\ nitrogen\ removed\ in\ crop}$$

Equation 3 calculates the amount of nitrogen potentially available for leaching to groundwater, which is the difference between the amount of nitrogen applied to a field and the amount removed in the crop (EPA, 2011). Equation 3 is also an estimate since it does not account for all inputs and outputs.

Equation 3. Nitrogen at Risk to Leach to Groundwater Equation

$$Amount\ of\ nitrogen\ potentially\ available\ for\ leaching\ =\ (Amount\ of\ nitrogen\ applied)\ -\ (Amount\ of\ nitrogen\ removed\ in\ crop)$$

The higher the NUE, the less residual nitrogen that is left in the soils and the lower the risk for leaching to groundwater. Dzurella et al. (2012) estimate that it is unrealistic to achieve a NUE of greater than 80% due to uncontrolled and unpredictable nature of precipitation events, recharge, mineralization rates of soil organic nitrogen, the spatial variability of soils, and the need to leach salts from the root zone.

Actual field measurements verify how much of the applied nitrogen was removed from fields with the harvested crop. Yield estimates need to be current and accurate to enable producers to be successful in maximizing their NUE.

Table 21 contains the nutrient uptake values for common forage crops in Washington State where manure is commonly applied (NRCS, 2009c). These values are based on the percent of dry matter for crops and realistic yield goals for planning purposes when developing NMPs (Equation 4). The "general" category applies when the growth stage at harvest is unknown. Additional crops are contained in the USDA-NRCS PLANTS database (http://plants.usda.gov/java/). Actual removal from fields varies, making field measurements important to determine how much of the applied nitrogen is removed with the crop.

Equation 4. Nutrient Uptake Values (NRCS, 2009c)

$$Dry\ Matter\ Yield\ (lbs/acre) = Harvest\ Yield\ (lbs/acre)\ *\ \%\ Dry\ Matter$$

$$Nutrient\ Uptake\ \left(\frac{lbs}{acre}\right) =\ Dry\ Matter\ Yield\ \left(\frac{lbs}{acre}\right) *\ Nutrient\ \%\ of\ Dry\ Matter$$

Default dry matter % when estimates are unknown: silage = 25%; hay = 88% (NRCS, 2009c).

Table 21. Nutrient uptake values for common Washington forage crops (NRCS, 2009c).

Grass Forage	Nutrient % of Dry matter		
(mixed species)	N	P	K
General	1.93	0.28	2.61
vegetative	2.68	0.39	2.84
early bloom	2.12	0.32	2.34
late bloom	1.54	0.3	2.19

Alfalfa Forage	Nutrient % of Dry matter		
	N	P	K
General	2.61	0.27	2.26
vegetative	3.21	0.33	2.93
early bloom	3.11	0.3	2.74
late bloom	2.6	0.3	2.4

Grass / Clover Forage	Nutrient % of Dry matter		
(mixed species)	N	P	K
General	2.17	0.27	2.3
vegetative	2.84	0.34	2.78
early bloom	2.56	0.31	2.52
late bloom	2.22	0.3	2.29

Clover Forage	Nutrient % of Dry matter		
(mixed species)	N	P	K
General	2.41	0.26	1.99
vegetative	3	0.3	2.71
early bloom	3	0.3	2.71
late bloom	2.9	0.3	2.4

Grass / Alfalfa Forage	Nutrient % of Dry matter		
	N	P	K
General	2.27	0.28	2.44
vegetative	2.95	0.36	2.88
early bloom	2.61	0.31	2.54
late bloom	2.07	0.3	2.29

Timothy, Forage	Nutrient % of Dry matter		
	N	P	K
General	1.63	0.28	1.86
vegetative	2.1	0.36	2.17
early bloom	1.59	0.27	1.77
late bloom	1.29	0.26	1.72

Grain Crops Forage	Nutrient % of Dry matter		
	N	P	K
Corn silage	1.23	0.26	1.16
Cereal grains	2.13	0.43	1.84

N = nitrogen
P = phosphorous
K = potassium

Manure Monitoring

The nutrient content of manure is highly variable and is dependent on many factors including: type of bedding used, storage conditions, manure age, manure handling, and animal diet (Bary et al., 2000). An accurate assessment of the manure nutrient content is critical to calculate an accurate mass balance.

Sullivan (2008) determined that manure nutrients are highly variable. Manure analysis prior to land application assists in establishing appropriate application rates.

Appropriate application rates are based on crop needs. This requires an accurate assessment of the existing plant-available nitrogen present in the soils. Manure nutrient samples provide the

nitrogen content which allows accurate application rates to be calculated. Since the nitrogen content in manure is variable, these researchers recommend sampling manure during application to each field, to quantify the actual total nitrogen application. (Bary et al., 2000)

If a facility processes other waste streams on site, such as offsite feedstock for an anaerobic digester, more frequent pre-application sampling of the digester effluent may be necessary to adequately characterize nutrients that are available prior to land application.

A more detailed description of recommended manure monitoring protocols is contained in Appendix D.

Soil Monitoring

Summary

The literature recommends that soil samples be collected two times a year: (1) after the fall harvest to assess the effectiveness of previous manure management practices and (2) in the spring before the first nutrient application to determine how much nitrogen is needed. Sampling the top foot of soil is the standard practice for assessing manure management practices.

Numerous studies have documented the variability of soil nitrate with depth and time, indicating that soil nitrate values are only indicative of the conditions at the time and location of sampling. Researchers clarify the limitations with soil nitrate data, stating that it cannot be used to extrapolate soil nitrate conditions at other locations or depths, or to estimate nitrate concentrations in groundwater.

It is generally accepted in the literature that excess nitrate in soils poses a risk of leaching to groundwater. Due to the mobility of nitrate and the uncontrolled nature of precipitation, soil nitrate can be mobilized and migrate to groundwater. Soil nitrate sampling provides a snapshot of what is present in the soils at the time the soil sample was collected. It cannot provide information on what has already moved through the soils to groundwater, what has moved below the sampling depth, or how much organic nitrogen will be converted to nitrate throughout the year and will leach to groundwater. Soil nitrate can indicate when excessive nitrate is present in soil and therefore poses a risk to leach to groundwater, but it cannot provide assurance that groundwater has been protected.

Variability in Soil Nitrate Concentrations with Time

Nitrogen availability from soil can change rapidly. Lamb (2012) notes that soil nitrate concentrations taken from the same locations between early August and late October varied dramatically (by as much as 75 lbs/acre) with no observed consistent trends over time. This researcher concluded that the results from soil sampling are indicative only of the nitrate available at the time and location the sample was collected.

Sullivan and Cogger (2003) suggest that soil sampling and analysis be conducted twice annually: in the spring before nutrient application and in the fall soon after the last harvest but before winter precipitation. These researchers advocate monitoring at the top 1 foot of soil to assess manure management. Kowalenko et al. (2007) recommend that fall soil nitrate be measured concurrently with the crop harvest in the fall.

Intensive soil nitrate sampling at a manured grass field over 5 years in Whatcom County, WA, illustrates the substantial fluctuations in soil nitrate concentrations that can occur at the 1-foot depth. The difference between the minimum and maximum weekly soil nitrate samples collected between September and October each year fluctuated by 14 to 24 ppm (43 to 74 lbs/acre). These researchers also observed nitrate concentrations in the top 1 foot of soil varied 45 mg/kg (ppm) within 1 week in November following a heavy rainfall. (Carey and Harrison, 2014)

Environmental factors that influence the conversion of organic nitrogen and ammonium to nitrate are soil pH, precipitation, and temperature (Heckman, 2003). In general, soil nitrate accumulates in the spring as temperatures increase and organic nitrogen mineralizes. In the summer the soil nitrate decreases as crops utilize nutrients. Any residual soil nitrate remaining after the crop has been harvested is susceptible to leaching with rainfall and irrigation.

Staben et al., (2003) noted a high temporal and spatial variability with soil nitrate samples as nitrogen transforms and migrates downward in the soil profile. In order to characterize this variability, they recommend sampling for nitrogen (nitrate and ammonium) at least two times during both fall and spring, with roughly one week between sampling. These researchers also recommend that all plant nutrients can be sampled, including nitrogen, phosphorus, and potassium.

Variability in Soil Nitrate Concentrations with Depth

Soil nitrate concentrations also vary with depth. Gehl et al. (2006) estimate that in sandy soils a large amount of nitrogen accumulated at depths between 60 and 210 cm (2 to 7 ft), with the greatest accumulation between 120 and 150 cm (4 to 5 ft). These researchers state that elevated post-harvest soil nitrate concentrations are an indicator that excessive nitrogen was applied. These researchers conclude that nitrate leaching to groundwater occurs when recharge mobilizes soil nitrate present in the lower part of the soil profile, below the root zone.

Camberato et al. (2013) indicate that normal background soil concentrations in sandy mineral soils in Indiana within the upper 1 foot of soil range from 5 to 10 ppm nitrate and 4 to 8 ppm ammonium. These researchers also noted that nitrogen concentrations were slightly lower in the 1 to 2 foot depth of soil. When the goal is to assess nitrate leaching losses, these researchers recommend sampling at the 1 foot depth and the 2 foot depth for both nitrate and ammonium. Sampling soil nitrate deeper within the soil profile is recommended in areas of high precipitation where the depth to water is greater than 2 feet. These researchers state that the residual soil nitrogen will eventually become nitrate, regardless of the form of nitrogen that was applied to the soils. Due to the complex biological transformations of nitrogen in the soils and the variable influences, it is difficult to accurately estimate the amount of nitrate loss that may have occurred at any point in time. Soil sampling is a way to determine soil nitrate concentrations at a particular point in time at the depth and location where sampling occurred.

Sullivan and Cogger (2002) indicate that sampling the upper 1 foot of the soil zone to characterize nitrate is appropriate in areas where wintertime precipitation is low, such as eastern Washington (east of the Cascade Mountains). However, they recommend deeper soil sampling, to 2 feet, in western Washington where heavier precipitation or recharge moves nitrate deeper into the soil profile.

Sánchez-Pérez et al. (2003) measured soil nitrate concentrations for 1 year at a cultivated field at 5 depths. Figure 17 graphs the soil nitrate concentrations over the year and at various depths. This illustrates the temporal and spatial fluctuations with the vertical movement in the soil column during the growing season and the non-growing season. These researchers also measured cumulative soil nitrate at 5 depths (Figure 18). It is interesting to note the downward migration of the nitrate peak during the year. Based on these findings it is clear that nitrate is not preferentially located in the top foot of soil. Together, Figures 16 and 17 illustrate the variability of soil nitrate concentrations over time and with depth.

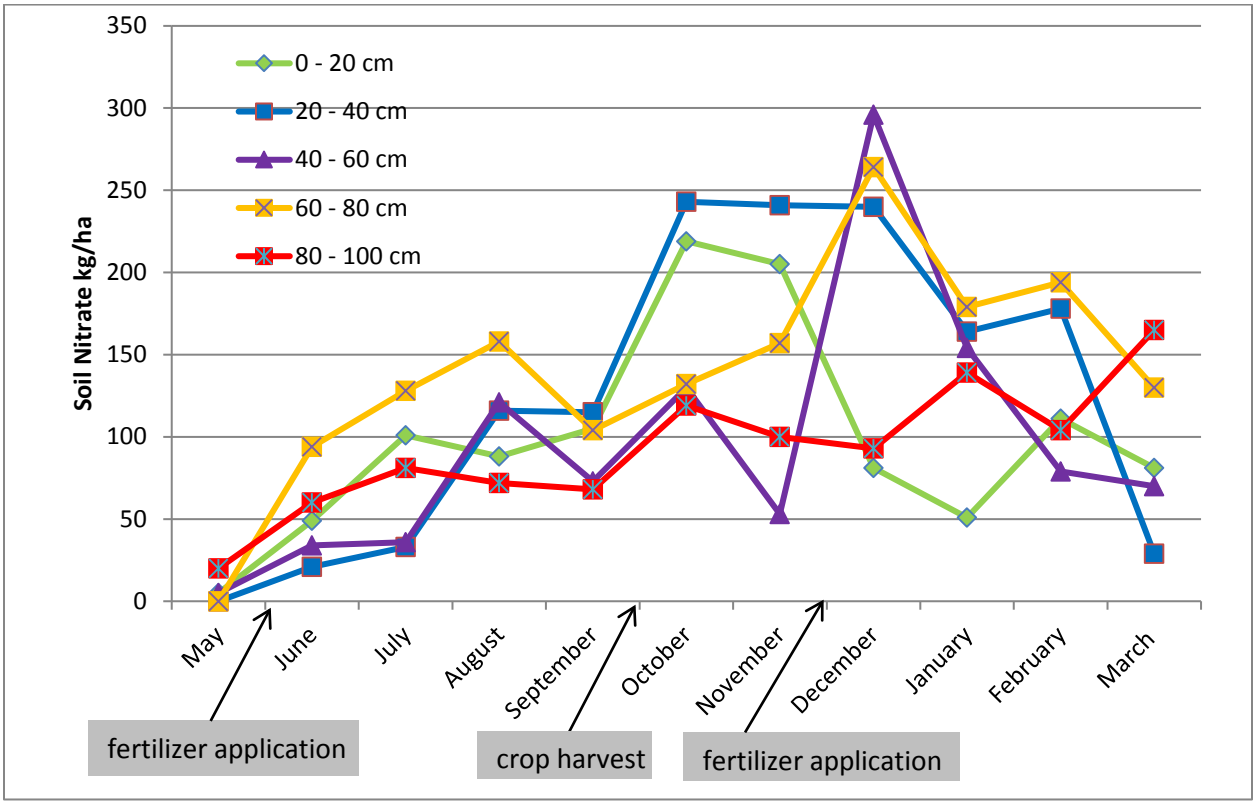

Figure 17. Soil nitrate concentration versus depth measured on a cultivated field over one year (modified from Sánchez-Pérez et al., 2003).

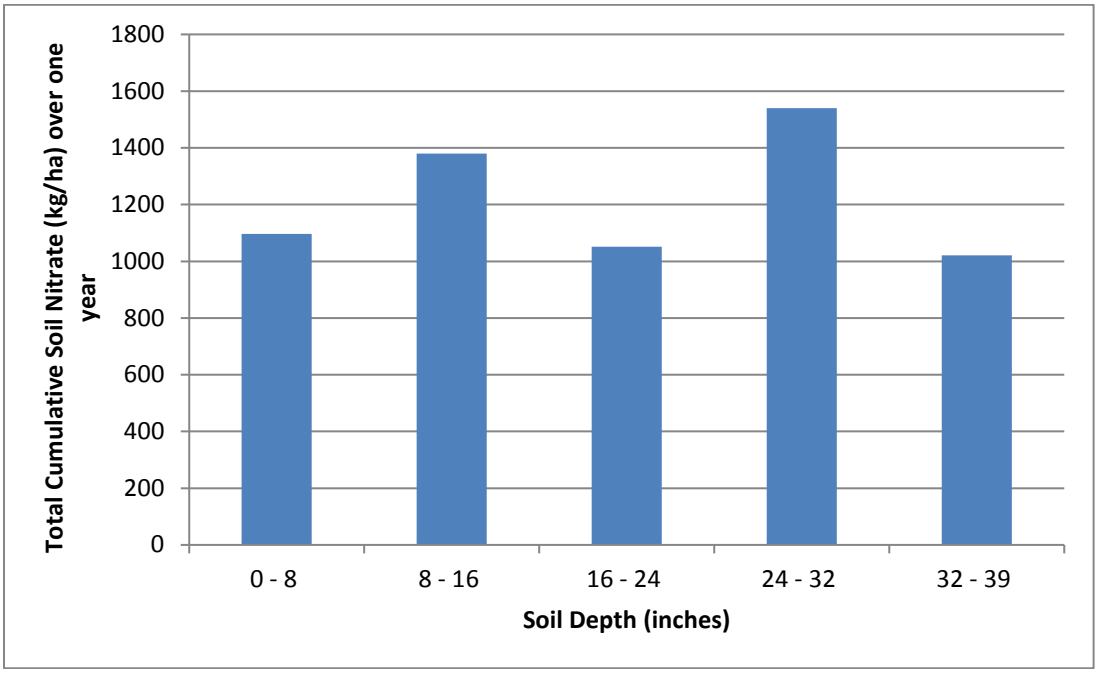

Figure 18. Total cumulative soil nitrate over one year by depth (modified from Sánchez-Pérez et al., 2003).

Recommended Soil Sampling Strategies

Soil nitrate samples provide a snapshot of the nitrate concentrations at the particular time and at the particular depth that the sample was collected. Soil nitrate concentrations vary as organic nitrogen is mineralized, as crops uptake ammonium and nitrate, and as excess recharge (precipitation and irrigation) mobilizes nitrate downward out of the sampling horizon.

Authors recommend that soil nitrate samples be collected during two times of the year: (1) in the spring before manure application begins and (2) in the fall after the crop has been harvested. These two sampling events have different goals and provide different information. The spring sampling is an indication of the current nitrate available to crops and is often used to generate nutrient budgets and application rates. Producers can use this information to adjust the amount of applied manure to more accurately meet the crop needs during the growing season. The fall soil nitrate sampling indicates the residual nitrate that the crop did not utilize and that is available for leaching during the winter non-growing months. The residual soil nitrate measured within the upper 1 foot is only part of the total nitrate pool that is subject to leaching over the year, because it does not take into account the residual nitrate in the lower soil profile or the fraction of nitrate which has already leached to groundwater. Accurate estimates of residual nitrate load is also a way for producers to adjust the future applications so that leaching to groundwater is minimized. (Kowalenko and Bittman, 2002).

Sampling the soil profile at 1 foot depth increments down to the water table provides the best estimate of the total residual soil nitrate, as well as the estimated nitrate load that poses a risk of leaching to groundwater.

Hart et al. (2009) further specify the optimal time for sampling fall soil nitrate based on soil texture and rainfall. To sample after the harvest and before the heavy rainfall begins, these researchers recommend that in medium- to fine-textured soils, the samples should be taken before 5 inches of cumulative rainfall occurs after September 1. In coarse-textured soils, samples should be taken before 3 inches of cumulative rainfall occurs after September 1.

Sullivan and Cogger (2003) found that it can take 3 to 5 years following improvements in field management for elevated soil nitrate concentrations to equilibrate with the new management practices. This highlights the importance of long-term management strategies for improving site conditions.

Soil monitoring protocols found in the literature are described in more detail in Appendix D.

Soil Monitoring Limitations

Soil samples can be useful in evaluating nitrogen crop use efficiency, residual soil nitrate in the fall, and the available nitrate for plant uptake in the spring. Standard soil tests are not accurate tools for quantifying the risk of nitrate leaching, especially when only the top one foot of soil is sampled. Few studies have tested the link between soil nitrate concentrations, leachate, and groundwater nitrate concentrations. Harter et al. (2012) found that the loading estimates calculated from soil nitrate concentrations underestimate the potential loading to groundwater estimated from an evaluation of nitrate leachate samples.

Soil nitrate values are useful in determining the amount of nitrate available to the crop at the time of sampling within the root zone. But because of the heterogeneity and complex biochemical reactions in the vadose zone and within individual fields, soil nitrate samples at the 1 foot depth were not found to be an accurate indicator of groundwater nitrate concentrations. (Carey and Harrison, 2014)

Low soil nitrate values may not identify all of the available nitrogen, especially if large amounts of organic nitrogen are present and mineralization occurs after sampling. The soil nitrate test provides only a limited prediction of the soil's nitrate-leaching potential (Flaten, 2001).

Gehl et al. (2006) investigated the post-harvest soil nitrate distribution in sandy soils under an irrigated corn field in Kansas. These researchers concluded that relatively low nitrate concentrations in the post-harvest soil samples do not necessarily indicate the lack of leaching to groundwater. Rather, the low soil nitrate concentrations could indicate that soil nitrate has already leached to groundwater before the growing season ended. In other words, a low soil nitrate concentration may or may not indicate impacts to groundwater quality. However, a high fall soil nitrate concentration indicates that leaching to groundwater is more likely to occur and there is an increased risk to groundwater.

Groundwater Monitoring

Summary

The majority of researchers agree that groundwater monitoring is the only way to definitively determine impacts to groundwater quality from residual soil nitrate. Monitoring other media, such as soils, can indicate whether manure management practices need to be adjusted, but it cannot conclusively determine the extent of the impacts to groundwater quality.

Researchers agree that soil nitrate will leach to groundwater during the winter with recharge (irrigation and precipitation). The extent of leaching is dependent upon the climate, soil type, mass of nitrogen present, and the hydraulic loading. Studies document nitrate leaching to groundwater under varying conditions.

Researchers have also been successful using other contaminants as indicators of impacts from manure applications. These include veterinarian pharmaceuticals, antibiotics, steroid hormones, calcium, chloride, magnesium, sodium, boron, bromide, and argon.

Groundwater monitoring provides a direct assessment of impacts to groundwater quality from land uses and is an important tool for determining how effective manure management practices are being implemented and thus minimizing impacts to groundwater. Groundwater monitoring is also an effective verification tool used to help evaluate the fate and transport of nitrate in the subsurface.

Leaching of Nitrate to Groundwater

Irrigation, manure application, and salt leaching practices can mobilize soil nitrate. Jégo et al. (2008) demonstrated that excessive irrigation could dramatically increase nitrate leaching to groundwater. Sawyer et al. (2006) noted the amount of nitrate leached to groundwater increases as the rate of applied nitrogen increases. Yin et al. (2007) concluded that groundwater in agricultural areas is especially vulnerable where salt leaching is practiced to maintain soil health.

Hermanson et al. (2000) conducted a literature review on nitrogen dynamics in the soil. The purpose of this review was to determine the fate and transport of nitrogen in subsurface soils for land treatment systems. The following is a list of the relevant general principles identified in this review:

- All nitrogen applied to the soil, and not utilized by crops, volatilized, or denitrified, will eventually convert to nitrate.
- Soil nitrate that moves below the root zone will eventually leach to groundwater.
- Nitrogen applied substantially before or after maximum crop demand may result in nitrate leaching.
- Organic nitrogen applied during the non-growing season will partially or totally convert to nitrate before the next growing season.

Research by Kowalenko and Bittman (2002) indicates that essentially complete nitrate loss occurs during the fall and winter, due to the distribution of heavy rainfall and fluctuating temperatures. They recommend minimizing residual soil nitrate at the end of the growing season to minimize losses to groundwater.

Studies conducted in British Columbia, Canada found that most (80%) of the nitrate and ammonium in the soils were leached to groundwater during the winter months (Zebarth et al., 1995; Kowolenko, 1987).

Chesnaux et al. (2007) applied a simulation model for the northern portion of the Abbotsford-Sumas aquifer with nitrate fertilizer applied at a rate of 80 lbs/acre. This model showed that nitrate from commercial fertilizer migrates through the vadose zone at a faster rate than manure. It also projected that nitrate applied at the surface of the model in mid-April would reach groundwater in August and be completely leached to groundwater by mid-November, with a travel time of seven months. These researchers also noted that depth to water table had little effect on the groundwater nitrate concentration, and the additional time to reach groundwater was not linear. Shallow groundwater concentrations were similar to the estimated concentrations modeled using simulations based on soil nitrate. They concluded that with the amount of recharge at this location, a loading rate of 41 lbs/acre of fertilizer would result in an exceedance of the groundwater standard of 10 mg N/L, assuming maximum crop uptake.

Carey and Harrison (2014) did not find a correlation between post-harvest soil nitrate concentrations and groundwater concentrations. However, they did note a correlation between fall manure applications and increases in shallow groundwater nitrate concentrations.

Groundwater monitoring protocols described in the literature are described in Appendix D.

Indicators as Evidence of Manure Impacts

EPA (2012 and 2013) recently conducted an investigation in the Lower Yakima Valley, to assess the source of nitrate contamination in groundwater. Multiple indicator parameters were used to assist in identifying sources. Analyzed parameters included nitrate, bacteria, nutrients, metals, ions, pesticides, trace organics, pharmaceuticals and personal care products (PPCPs), veterinary pharmaceuticals, hormones, and isotopes. This study found veterinarian pharmaceuticals and several inorganic constituents (calcium, chloride, magnesium, sodium, and boron) to be good indicators of manure sources.

Hudak (2002) recommends using chloride/bromide ratios to determine sources of nitrate in groundwater. This researcher compiled typical ratios for different contaminant sources. He concluded that there was no statistically significant difference between animal sources when using chloride/bromide ratios, but there was a statistically significant difference between animal waste, human waste, and synthetic fertilizer.

Batt et al. (2006) concluded that in Washington County, Idaho, CAFOs are the source of antibiotics in groundwater. This study found elevated concentrations of nitrate and ammonium, and detected two veterinarian pharmaceuticals, sulfamethazine and sulfadimethoxine, in six

groundwater wells. Since these pharmaceuticals were only approved for veterinarian uses, these researchers concluded the impacts originated from animal wastes.

Watanabe et al. (2008) investigated various waste streams from two dairy farms in California. These researchers found monensin in the flush lane water, in the lagoon and in groundwater wells adjacent to (and downgradient from) the lagoon. Groundwater concentrations were an order of magnitude lower than the lagoon concentrations. Monensin was not detected in groundwater at the land application area, but was in the flush lanes and lagoon, indicating that biodegradation and sorption are likely occurring in the soils. Since monensin is a veterinarian antibiotic, the researchers concluded that monensin transport into the shallow alluvial aquifer was linked to leakage from the dairy lagoon.

Reddi et al. (2005) advocate using chloride as a conservative tracer of lagoon leakage rather than ammonium or nitrate. These researchers explained that most of the nitrogen is in the organic or ammonium form. In these forms, it is readily attenuated in the subsurface and can be dependent on the cation exchange capacity of the soils. Chloride is highly mobile, moves with water, and is not attenuated, due to its negative charge. Chloride concentrations are elevated, typically greater than 1,000 mg/L.

McNab et al. (2007) found that argon can serve as a unique tracer for lagoon seepage distinguishing this discharge from fertilizer application. Other isotope tracers they evaluated were not effective as indicators for animal waste.

Kolodziej et al. (2004) investigated the presence of androgens, estrogens, and progestins at a dairy farm in California. These steroid hormones were present in the dairy waste lagoon, and were detected in surface water samples. There were no detections in groundwater. The absence of steroid hormones in groundwater suggests that biodegradation and sorption may be effective treatment mechanisms.

Tools Presented in the Literature to Evaluate Nutrient Impacts

Summary

This section presents examples found in the literature of tools that can be used to evaluate the fate and transport of nitrogen in the subsurface. The combination of calculating the mass load of nitrate in soil with using the groundwater Nitrate Loading Mass Balance Model can indicate potential impacts to groundwater. This can be used as a screening tool to indicate when groundwater monitoring is important. These tools are limited in that they cannot assure that groundwater is protected; they can only indicate when groundwater is at risk of contamination. These tools provide an estimate of impacts to groundwater quality.

The literature summarized in previous sections of this report indicates that it is difficult to accurately predict impacts to groundwater quality based solely on soil nitrate samples. There is a general consensus among groundwater scientists that the most reliable way to determine impacts to groundwater quality is through groundwater monitoring.

In the absence of acceptable groundwater monitoring data, soil nitrate values can be used as a tool to estimate potential impacts and to determine if groundwater monitoring is necessary. This section provides examples of broad scale tools for assessing nutrient impacts, such as estimating the potential nitrate leaching concentration from soil nitrate samples and using a nitrate loading mass balance model.

Soil nitrate is routinely monitored at manure land treatment sites. These data, combined with recharge and soil bulk density, can provide an estimate of the nitrate leaching potential. Tables 22 and 23 contain ranges of soil nitrate values under various conditions and project the concentration of nitrate in the soil water. These values were calculated using Equations 5, 6, and 7 (Kimsey, 1997). These are predictive nitrate concentrations. They are intended to be used as a screening tool for farm management but are not intended to be a precise predictor of groundwater impacts.

These equations require measured soil nitrate concentrations, soil bulk density, and local recharge rates. Soil nitrate values are converted into a mass loading rate by factoring in the weight of the soil based on the bulk density. The following equations estimate the mass in million pounds (Equation 5), the mass of soil nitrate (Equation 6), and the concentration of nitrate leaching to groundwater based on the soil nitrate concentration and recharge (Equation 7). This method yields a general estimate that only accounts for nitrate in the zone where the sample was collected. This limitation results in an underestimate of the total nitrate in the soil profile since nitrate in the lower depths is not included. These equations assume the entire soil nitrate mass migrates to groundwater. Additionally, these equations do not account for the nitrate fraction that may have leached to groundwater prior to sample collection. A more accurate estimate of residual nitrate would involve soil nitrate sampling at multiple depths to the water table and calculating the cumulative mass using Equation 5 for each depth.

Similar approaches to calculating impacts are used by many researchers: Harter and Menke, 2005; Meisinger et al., 2008; Barik, 2012; Feaga and Selker, 2004; Camberato et al., 2011; Elrashidi et al., 2005; Zebarth et al., 1995; van der Shans et al., 2009.

Equation 5. Soil Mass.

$$Soil\ Mass\ (million\ lbs/acreft) = [\frac{\left[\left(Bulk\ Density\ \frac{gm}{cm3}\right) * \left(0.00220462\ \frac{lbs}{gm}\right)\right]}{\left(8.107\ X\ E - 10\ \frac{acreft}{cm3}\right)}] * (1\ E + 6)$$

Equation 6. Mass of Soil Nitrate.

$$Mass\ of\ Soil\ Nitrate\ \left(\frac{lbs}{acre}\right) = (soil\ nitrate\ (ppm)) * (soil\ mass\ (million\ lbs))$$

Equation 7. Nitrate Available to Leach to Groundwater.

$$Nitrate\ Concentration\ (mg\ N/L) available\ to\ leach\ to\ groundwater = Mass\ of\ nitrate\left(\frac{\frac{lbs}{acre}}{year}\right) \div Recharge\ \left(\frac{acreft}{year}\right) x\ (0.3677) a\ x\ [0.9\ b\ ]$$

a) 0.3677 is a conversion factor that adjusts measurements of lbs/acre/year and acre/feet/year into mg N/L.
b) 0.9 is a standard assumption that 10% of the nitrate is lost to denitrification. This factor can be altered if site-specific data indicates a different percentage is appropriate.

Equations 5, 6, and 7 are the basis for the values in Tables 22 and 23. These tables are designed to be a general guide to project impacts to groundwater and to establish protective targets for soil nitrate values.

The following conditions and assumptions are used in Equations 5, 6, and 7:

- This method is intended to be used as a screening tool and is not intended to be a precise predictor of impacts to groundwater quality.
- Soil nitrate samples are typically taken from the 1 foot depth. A more accurate estimate would account for the nitrate present lower in the soil profile.
- Sampling at additional depths provides more information on the extent of nitrate distribution throughout the soil horizon.
- The average weight of one acre-foot of soil in eastern Washington based on bulk density, is assumed to be 4.0 million pounds. The average weight of one acre-foot of soil in western Washington is assumed to be 3.2 million pounds. The average statewide value is 3.6 million pounds. (Sullivan and Cogger, 2002)
- Typically the percent of nitrogen lost to volatilization is 5% or less, and this occurs under specific conditions (van der Schans et al., 2009). Therefore, volatilization of ammonia is not considered in the calculation.
- Equation 7 assumes that there is negligible nitrate in the recharge water. If the nitrate concentration of the recharge water is significant, this can be factored into the total nitrate available to leach to groundwater.
- Recharge water includes the fraction of irrigation water plus precipitation which infiltrates into the ground.
- These equations assume that the soil nitrate mass is completely mixed with the volume of recharge water for the period of interest. Tables 22 and 23 provide nitrate leachate estimates based on assumed recharge rates of 0.5, 1, 2, and 3 feet. A more precise measurement of recharge could be substituted in Equation 6 to more accurately assess the potential leachate concentration.
- The conversion rate of 0.3677 in Equation 7 adjusts the measurements of lbs/acre/year, and acre/feet/year into mg N/L.
- Equation 7 assumes 10% loss of nitrogen from denitrification.
- These equations assume annual applications of nitrogen and water.

Table 22. Soil nitrate concentrations and projected concentrations available to leach to groundwater in eastern Washington.

Eastern Washington (with 10% denitrification)					
Soil Nitrate (ppm)	Soil Nitrate (lbs/acre)	Nitrate Leachate (mg N/L)			
		0.5 ft annual recharge	1 ft annual recharge	2 ft annual recharge	3 ft annual recharge
4	16	11	5	3	2
8	32	21	11	5	4
11	44	29	15	7	5
15	60	40	20	10	7
23	92	61	30	15	10
30	120	79	40	20	13
38	152	101	50	25	17
45	180	119	60	30	20
60	240	159	79	40	26

(Harter and Menke, 2005; Meisinger et al., 2008; Barik, 2012; Feaga and Selker, 2004; Camberato et al., 2011; Elrashidi et al., 2005).

Table 23. Soil nitrate concentrations and projected concentrations available to leach to groundwater in western Washington.

Western Washington (with 10% denitrification)					
Soil Nitrate (ppm)	Soil Nitrate (lbs/acre)	Nitrate Leachate (mg N/L)			
		0.5 ft annual recharge	1 ft annual recharge	2 ft annual recharge	3 ft annual recharge
4	13	8	4	2	1
8	26	17	8	4	3
11	35	23	12	6	4
15	48	32	16	8	5
23	74	49	24	12	8
30	96	64	32	16	11
38	122	80	40	20	13
45	144	95	48	24	16
60	192	127	64	32	21

(Harter and Menke, 2005; Meisinger et al., 2008; Barik, 2012; Feaga and Selker, 2004; Camberato et al., 2011; Elrashidi et al., 2005).

These tabled values (Tables 22 and 23) provide possible screening values to identify combinations of soil nitrate values and recharge rates that may migrate to groundwater. The concept is that the mass of soil nitrate is mixed with the amount of recharge to provide the resulting concentration. These tables also include a 10% loss to account for denitrification. For example, if a soil nitrate value collected in eastern Washington (Table 22) is 4 ppm in an area

with one foot of annual recharge from a combination of precipitation and irrigation, then the estimated nitrate concentration in the leachate migrating to groundwater would be 5 mg N/L.

The Washington State groundwater standard for nitrate is 10 mg N/L (Chapter 173-200 WAC). This is the same standard for the groundwater quality standards, the Washington State drinking water standards, and the federal maximum contaminant levels (MCLs). The groundwater quality standards apply to all activities that can impact groundwater quality and protect all waters in the saturated zone.

Recharge

Recharge water includes the annual fraction of irrigation water plus precipitation that is not used by crops and infiltrates into the ground. The method of using recharge and soil nitrate concentrations as a screening tool for possible impacts to groundwater quality is supported by researchers (Harter and Menke, 2004; Chesnaux et al., 2007). De Jong et al. (2005) advocate using recharge to estimate the nitrate concentration that will leach to groundwater as a result of the soil nitrate concentration. Zebarth et al. (1995) suggest that 1000 mm (39.37 in) of recharge water will dilute 100 kg N/ha (89.21 lbs N/acre) residual soil nitrate to 10 mg N/L in the leachate that migrates to groundwater. This is consistent with the values in tables 19 and 20.

Sánchez-Pérez et al. (2003) found a correlation between elevated soil nitrate concentrations and elevated groundwater concentrations. These researchers noted that this correlation was dependent upon the amount of recharge. The scale of nitrate leaching depends on the amount of recharge, nitrogen applied to the soils, and the residual nitrogen that exists in the soils. They state that in temperate and humid zones, precipitation mobilizes the soil nitrate and is the vehicle which carries the nitrate to groundwater.

Nitrate Loading Mass Balance Model

Groundwater nitrate concentrations can be predicted using a *Nitrate Loading Mass Balance Model*. (Kimsey, 1997; Frimpter et al., 1990). This model is currently used by Ecology's Water Quality Program (Ecology, 2008; Ecology, 2011). This model includes: (1) an assessment component that describes the potential impact to groundwater quality and (2) a mitigation component that establishes a soil nitrate concentration threshold limit, which helps in minimizing impacts to groundwater quality and with achieving compliance with established groundwater goals. Model variables are described in Table 24.

The combination of calculating the mass load of nitrate in soil (Equations 5 and 6) with the use of the groundwater Nitrate Loading Mass Balance Model, described below, can estimate potential impacts to groundwater. This can be used as a screening tool to indicate when groundwater monitoring is important. These tools are limited in that they cannot assure that groundwater is protected; they can only indicate when groundwater is at risk of contamination.

The *Nitrate Loading Mass Balance Model* (Kimsey, 1997) focuses on the following four factors: (1) the residual soil nitrate, (2) the amount of recharge, (3) the aquifer's ability to assimilate the contaminants, and (4) target soil nitrate values to help achieve compliance with water quality standards.

1. Equations 5, 6, and 7 (Tables 22 and 23) are used to estimate the mass of nitrate and the nitrate concentration that could migrate to groundwater through the soils, based on soil nitrate measurements and recharge rates. This value is $N_{Leachate.}$

2. The *Assessment Component* of the model calculates the impacts from the residual soil nitrate on groundwater quality at the downgradient property boundary. The assessment component is composed of three calculations: (1) the volume of recharge that is contributed over the property, (2) the groundwater discharge, and (3) the resulting estimated groundwater nitrate concentration (Equations 8, 9, and 10). Equation variables are defined in Table 23.

Equation 8. Volumetric rate of recharge (gpd) which falls over the manured land application area.

$$\mathbf{V_R = A_{LA}R\ (0.0017)}$$

Equation 9. Volumetric rate of groundwater flowing into the upgradient end of the property (gpd).

$$\mathbf{Q = KibW_A\ (7.48)}$$

Equation 10. Nitrate concentration in mg N/L in groundwater at the downgradient property boundary after the recharge mobilizes the soil nitrate and disperses with upgradient groundwater.

$$\mathbf{N_{GW} = [QN_B + V_RN_{Leachate}]/\ Q + V_R}$$

The $N_{Leachate}$ value is the groundwater leachate value calculated from Equations 5 and 6 (which can also be found in Tables 22 and 23).

3. The *Mitigation Component* of the model calculates the target soil nitrate concentration which would suggest that the AFO is in compliance with the Groundwater Quality Standards (Chapter 173-200 WAC). Since this is only a screening tool, this method cannot be used to assure compliance with the groundwater quality standards; it can only indicate a potential, estimated risk. The nitrate concentration (mg N/L) derived from the mitigation component is determined using Equations 11 and 12.

The information from these tools can assist in determining where groundwater monitoring is likely to be important.

Equation 11 projects the nitrate leachate concentration from soils that would theoretically be protective of groundwater quality under the assumptions described here. $\mathbf{N_{GW}}$ is established based on the groundwater quality enforcement limit or target goal.

$$\mathbf{N_{Leachate} = [N_{GW}(Q + V_R) - N_B Q]/ V_R}$$

This calculation determines the concentration of leachate from the residual soil nitrate. The value $\mathbf{N_{Leachate}}$ equals the nitrate concentration (mg N/L) available to leach to groundwater. This value can be converted into soil nitrate by using Equation 12. This soil nitrate value is an approximate value that would be expected to be protective of groundwater given the site-specific conditions.

Equation 12. Soil nitrate concentration which is protective of groundwater quality.

$$\frac{Nitrate\ Leachate(\frac{mg}{L})}{Recharge\ (acre-ft)(0.9\ denitrification\ rate)(1.342)} = Soil\ Nitrate\ ppm\ (\frac{mg}{kg})$$

The soil nitrate concentration calculated in Equation 12 is the soil nitrate threshold value that is estimated to be protective of groundwater quality under the described assumptions.

The tools described in this section are offered as a way to estimate the relative impacts to groundwater quality and the risk when soil nitrate monitoring is the only assessment tool. These models can be used as a preliminary tool to assess whether it is important to conduct groundwater monitoring at a specific site. These tools are estimates and cannot provide the same level of assurance that groundwater monitoring can.

Table 24. Variables used in calculating nitrate impacts to groundwater.

Variable Description	Variable	Units
Volumetric rate of recharge over land treatment area (V_R)	$\mathbf{V_R}$	gpd
Area where manure is land-applied (A_{LA})	$\mathbf{A_{LA}}$	ft^2
Recharge rate (R) (sum of infiltrated precipitation and irrigation)	**R**	in/yr
Nitrate concentration in the leachate from land treatment area. This value can be found in Tables 19 and 20 ($N_{Leachate}$)	$\mathbf{N_{Leachate}}$	mg N/L
Aquifer discharge (Q)	**Q**	gpd
Horizontal hydraulic conductivity of aquifer (K)	**K**	ft/day
Horizontal hydraulic gradient (i)	**i**	ft/ft
Thickness of vertical dispersion in aquifer (b)	**b**	ft
Width of property boundary (W_A) perpendicular to flow direction	$\mathbf{W_A}$	ft
Downgradient groundwater nitrate concentration (N_{GW})	$\mathbf{N_{GW}}$	mg N/L
Nitrate concentration of upgradient gw (N_B)	$\mathbf{N_B}$	mg N/L

gpd = gallons per day
mg N/L = milligrams nitrate nitrogen per liter
ft = feet
in/yr = inches per year

Other Groundwater Models

Many groundwater models are available to assist in projecting impacts to groundwater quality. Some require intensive site-specific data, which typically generate more accurate results. NLEAP is a model developed by Shaffer et al. (1991) that stands for Nitrate Leaching and Economic Analysis Package. It is designed for use by farmers and the NRCS (formerly SCS) and other agricultural assistance agencies to estimate nitrate leaching potential under areas with agricultural crops. This model has a three-phased approach. An annual screening provides an initial estimate of nitrate leachings and more detailed monthly and event-based assessments.

GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) is a model that was developed to evaluate the movement of agricultural chemicals, specifically pesticides, through the root zone (Leonard et al., 1987). This model augments CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) which was the field scale model developed by Knisel (1980).

The U.S. Geological Survey (USGS) developed MODFLOW in 1984 as a standard three-dimensional, finite difference groundwater model which is suited to larger watershed assessments. It was originally developed in 1984, but since then has been modified from being solely a groundwater flow model to now include contaminant transport, unsaturated zone transport, and water use by vegetation, as well as other capabilities. MODFLOW is a data-intensive model that requires an accurate knowledge of environmental conditions.

Success Stories

This section contains a compilation of success stories that were discovered during this literature review. These are investigations that, in some cases, employed innovative solutions resulting in improvements to water quality. In several instances, there were also reports of improved crop yield.

Harter and Menke (2004) found that changes to nutrient management can result in significant improvements to water quality. These researchers specifically showed that there was a 70% improvement in groundwater quality beneath fields where manure is land-applied when the following changes were made: (1) eliminating the use of commercial fertilizer, (2) reducing manure applications, and (3) applying manure only during the crop growth stages. These researchers noted that these measures did not result in a considerable reduction in crop yield.

Rudolf (2015) evaluated agricultural best management practices (BMPs) in Woodstock, Ontario, Canada, where public drinking water supply wells had been contaminated with elevated nitrate concentrations. This community decided to purchase an additional 275 acres of land with the goal to keep the agricultural land in production but to change BMPs to reduce water quality to below (meet) drinking water standards. The application rate was reduced from 100 to 54 lbs/acre. The result was a 60% reduction in soil nitrate concentrations, from 20 to 8 ppm. Agricultural production increased slightly from 135 to 140 bu/acre of corn grown at this site. This researcher concluded that incentives to producers are influential for improvements in water quality. (Rudolf, 2015; Rudolf et al., 2015)

The European Union introduced a *Nitrate Directives* in 1991. This directive identifies nitrate from manure and fertilizer applications as the main cause of pollution from diffuse sources affecting European communities. This cooperative directive concluded that high numbers of concentrated livestock result in manure production that is out of balance with available land and crop requirements, which in turn creates a surplus of nutrients ultimately lost to water and air. The European Union imposed a number of management directives that are improving both groundwater and surface water quality. For example, nitrate vulnerable zones were designated where nitrogen applications were restricted in the amount and the times of application. The results from this directive have been difficult to quantify; however, the European Union (2010) found that from 2004 to 2007 there were stable or decreasing nitrate trends in 70% of surface water samples and stable or decreasing trends in 66% of the groundwater samples. Sutton et al. (2011) released "The European Nitrogen Assessment" as a scientific approach to address the nitrogen issues raised by the European Directive.

MPCA (2001) monitored an earthen manure storage unit that was upgraded with a geosynthetic liner with a bentonite clay liner. The liner was then covered with a foot of native soil. Additionally, a filter strip was installed downgradient of the pens and corrals. The results indicate that within three years of these improvements, total nitrogen concentrations in groundwater decreased by 55%; phosphorus and organic carbon decreased as well.

Carey and Harrison (2014) found that groundwater nitrate concentrations near the top of the water table were close to the groundwater standard of 10 mg N/L when manure application rates were similar to the crop removal rates and when manure was applied during the growing season. Feaga and Selker (2004) found that once manure application rates were reduced, soil nitrate concentrations also declined.

Sullivan and Cogger (2003) found that it can take 3 to 5 years following improvements in field management for elevated soil nitrate concentrations to equilibrate with the new management practices. This highlights the importance of long-term management strategies for improving site conditions.

The Council of Canadian Academies (2013) expert panel noted that in Canada where residual soil nitrate is elevated, shallow groundwater nitrate concentrations are also elevated. These experts stated that groundwater systems tend to respond more slowly to changes in land management between nitrogen application and impacts to groundwater. Timing is important to evaluate success with groundwater quality. The legacy effects from over-application of nitrogen may take years to fully impact groundwater. Therefore, these experts state that it is important to make positive changes in areas where groundwater has been impacted.

Summary of Conclusions Drawn from the Literature

This report summarizes the relevant literature on manure management practices and the potential impacts on water quality. There are some predominant themes and innovative approaches to treating, managing, monitoring, and assessing land application of manure.

Potential Impacts to Groundwater

There are documented examples of manure impacts on groundwater quality in Washington State. In the Lower Yakima Valley, an EPA (2012 and 2013) investigation concluded that dairy manure contributed to groundwater contamination of the local unconfined aquifer. The Sumas-Blaine aquifer in Whatcom County, Washington has documented long-term groundwater contamination. While there continues to be on-going research into the source of this contamination, a groundwater study at a dairy farm correlated manure applications with increases in groundwater nitrate concentrations. Research in both the Lower Yakima Valley and the Sumas-Blaine aquifer identify manure as the predominant source of nitrogen loading in these areas.

Additionally, numerous studies from other areas in the United States and elsewhere document manure impacts to groundwater quality.

Hermanson et al. (2000) emphasizes the uncertainties associated with nitrogen dynamics in the subsurface and concludes that applying wastewater to crops and soil systems during the non-growing season is not reliably protective of groundwater. These researchers conclude that applying organic wastes during the non-growing season has an inherent risk and requires close soil monitoring to avoid nitrate leaching. The use of winter cover crops helps to mitigate the problem but does not guarantee a solution. These researchers advocate, as a safe alternative, the use of storage facilities to minimize waste applications during the non-growing season.

Hermanson et al. (2000) provides general principles and recommendations based on their comprehensive review of literature on nitrogen land treatment systems. This review is summarized in the "Background" section of this report.

It is apparent from this literature review that land application of manure has a potential to adversely impact groundwater quality. These studies concluded that land application of manure creates a risk to groundwater when:

- Manure is applied at application rates greater than what is necessary to maintain a viable crop.
- Crops are not present to use the nitrogen present in the soils.
- Manure is applied outside of the growing season.
- Manure is stored in a lagoon not constructed to a recognized standard.
- Manure is applied on irrigated cropland where irrigation water is applied in excess of what crops can use.

Treatment

Land treatment of manure involves applying manure in the right amounts at the right time.

Application Rates

Several factors that affect application rates are identified in the literature. These include accounting for all sources of nitrogen, the type (form) of nutrients applied, time they are applied, the type of crop grown, the type of soils, and climate. Researchers agree that all sources of nitrogen need to be considered in the total load. Residual soil nitrate and continued mineralization are often overlooked sources.

Studies verify that there is a positive correlation between nitrogen application rates and crop uptake, and that there is also a positive correlation between nitrogen application rates and residual soil nitrate. Maximizing crop yield is not equivalent to maximizing crop uptake. Maximizing crop yield is not the goal of a land treatment system. Hermanson et al. (2000) cautions that maximizing crop yield will generally increase the risk of nitrate accumulation in the soil.

Nitrogen applied at the time and in the amounts needed by the crop will minimize the buildup of soil nitrogen (Hermanson et al., 2000). Soil nitrate accumulation poses a risk to nitrate leaching. Researchers have observed that changes to manure management and application rates can result in a decline in the soil nitrate concentrations, as well as result in significant improvements to groundwater quality.

Winter cover crops generally do not require the addition of nutrients to the soils.

If excess nitrogen is applied in one growing season, it must be offset by decreased nitrogen application the following season to avoid residual nitrogen buildup and subsequent nitrogen leaching (Hermanson et al., 2000).

There is general agreement in the literature that applying manure at rates greater than what is consumed by the crop has been demonstrated to cause elevated nitrate levels in groundwater. These researchers recommend that nitrogen applications be governed by the crop nitrogen requirements with the goal to treat the wastewater, minimize leaching, and minimize the impact to groundwater quality.

Soil Nitrogen

Soil nitrate values are a proven tool to determine plant-available nitrogen present in the soils as well as providing the effectiveness of manure management. Research summarized from the literature note that there are two times when soil nitrate samples typically are collected: in the spring before manure application begins, and in the fall after the crop has been harvested. These two sampling events have different purposes and provide different information. The fall soil nitrate test provides information on the effectiveness of manure management practices from the previous season. The spring soil nitrate test provides information about the amount of plant-

available nitrogen at the start of the growing season and provides information on appropriate application rates.

Soil nitrate concentrations are subject to a high level of temporal and spatial variability. Soil samples estimate nitrate concentration at the location and the time the sample was collected. During the non-growing season, this nitrate concentration represents the amount available to leach to groundwater. However, soil samples do not measure nitrate that has previously migrated to groundwater. Nitrate that has travelled below the soil sample location has either reached groundwater, or is in the soil profile below the sample. Therefore, soil samples alone cannot provide assurance that groundwater is not, or will not, be impacted.

Researchers agree that soil nitrate tests are not a surrogate for groundwater monitoring. However, the majority also agree that residual soil nitrate can indicate when excessive nitrogen has been land-applied and when groundwater may have been impacted from leaching.

The soil nitrate threshold limits recommended in the literature are summarized in Table 7. These values are limits that researchers from 14 publications have advocated: that there is either enough nitrogen available to support a crop or that no additional nitrogen should be applied. Recommended targets for fall soil nitrate values range from 5 to 24 ppm depending on the site-specific conditions. Recommended targets for spring soil nitrate values range from 16 to 30 ppm depending on the site-specific conditions.

The soil nitrate values recommended in the literature correlate well with the site-specific assessment tool developed in *Tools Presented in the Literature to Evaluate Nutrient Impacts* section.

Timing of Manure Application

In addition to application rates, the literature states that protecting groundwater is also tied to the timing of manure application, the opportunity for mineralization, and the opportunity for leaching.

Researchers agree that a high-risk time to apply nutrients is during the non-growing season (when plant uptake of nitrogen has ceased or has significantly slowed) or during periods when precipitation and irrigation exceed evapotranspiration. This time period poses an increased risk to surface water from runoff and an increased risk to groundwater from leaching of nitrate and other contaminants. The growing season is dependent upon a number of factors including the crop grown, temperature, and precipitation.

Researchers noted a correlation between excessive fall manure applications and increases in groundwater nitrate concentrations. Researchers advocate that nutrients be available when crops can use them, and they generally characterize this timeframe as the growing season.

Manure applied substantially before or after maximum crop demand may result in the buildup of inorganic soil nitrogen that will subsequently be susceptible to nitrate leaching. Applying organic wastes during the non-growing season has an inherent risk in terms of leaching nitrate to groundwater. (Hermanson et al., 2000)

Winter manure application has not been demonstrated in the literature to be protective of groundwater quality. Scientific literature is not evident to support the theory that nutrients can be stored in the soils during the winter or that manure land application during the non-growing season is protective of groundwater quality.

This report identifies three sources that use site-specific climate data that can be used to identify the growing season for specific crops and the appropriate timeframe to land-apply manure:

- Washington Irrigation Guide
- Wetlands Climate Guide
- T-Sum 200

Soil Mechanics

The soil horizon and the vadose zone are the places where nitrogen treatment and transformations occur. These processes include crop uptake and removal, volatilization, mineralization, denitrification, and leaching to groundwater. These processes are influenced by a variety of site-specific factors, and they also affect the fate and transport of chemicals in the environment.

Volatilization of nitrogen compounds once the manure has been incorporated into the soils is minimal with documented rates of approximately 5%.

Organic nitrogen from applied manure accumulates in soil and gradually mineralizes to ammonium. Researchers have recently concluded that mineralization continues during the winter months, although at a slower rate. Studies have shown that mineralization and nitrification can occur at significant rates in frozen soils especially in the presence of organic matter. In Canada, investigations have demonstrated that soil organic nitrogen and immobilized nitrogen contributed one-third to one-half of the nitrogen lost to leaching during the non-growing season.

Several researchers noted that tilling or disturbance to fields stimulates mineralization.

Generally, the reviewed studies concluded that mineralization is a significant source of nitrogen in fields where manure has been applied. Additionally it was concluded that, due to the continued mineralization during cold and freezing temperatures, applying nitrogen in the fall poses a risk of over-loading the soils with nitrogen.

Denitrification losses may reduce nitrate loading to groundwater. Denitrification rates were found by researchers to be dependent upon site-specific conditions, but were generally found to be low. Furthermore, some studies stated that it is of little importance in well-drained soils. In the reviewed literature, denitrification rates ranged from 5% to 16%. Some researchers observed that some degree of denitrification occurs at all sites, but that the high denitrification rates reported in the literature are not representative of shallow sandy aquifers. In the absence of site-specific data, denitrification may be assumed to be approximately 10%.

Soil Storage of Nitrogen

Nitrogen storage in the subsurface is the practice of applying manure during the non-growing season with the assumption that the nitrogen will remain in the root zone until the crop needs it in the spring. This practice has not been proven to protect groundwater. Mineralization continues during the winter months. Climatic conditions such as temperature and precipitation, and subsequently nitrogen transformations, are not elements that can be precisely controlled. These uncontrolled elements can promote nitrate leaching. Researchers have cautioned that attempting to store nutrients in the soils during the winter for use by crops in the spring poses a risk to groundwater.

Storage Lagoons

Storage lagoons are an important part of manure management. Researchers advocate the use of storage facilities to minimize nitrogen applications during the non-growing season as a safe alternative to protect groundwater instead of year-round application.

Studies have documented leakage from manure lagoons and some have documented impacts to groundwater from nitrate, ammonium, veterinarian pharmaceuticals, chloride, TDS, and bacteria. Adequate storage lagoon design includes consideration of the following elements; soils, location, liner permeability, liner material, and environmental conditions such as minimum vertical separation and seasonal high water table.

Storage lagoons are part of the manure management system and provide a place for manure generated during the non-growing season to be stored until the spring when the manure can be land-applied for crop use. Literature indicates that winter storage lagoons constructed to a permeability of less than 1×10^{-7} cm/sec (1×10^{-6} cm/sec before manure sealing) are consistent with current guidance and will reduce the likelihood of groundwater impacts.

Researchers agree that lagoon liners are not an impermeable barrier to the downward movement of contaminants. In general, they note that contaminant concentrations are greatest near the floor of the lagoon and decrease with depth.

Chloride is commonly used as a tracer to evaluate leakage from storage lagoons. Chloride moves readily with water and is not attenuated in the subsurface, making it a useful indicator of migration of contaminants from lagoons.

The use of storage facilities is a safe alternative to minimize waste applications during the non-growing season (Hermanson et al., 2000).

Monitoring

Monitoring provides an assessment of manure management practices.

Mass Balance

Conducting a mass balance is critical to good manure management. This involves quantifying all inputs and outputs every month for the entire farm and for each field. All nitrogen inputs are taken into account, including irrigation water, commercial fertilizer, manure, wastewater, mineralized organic nitrogen, crop residue, precipitation, and any other nitrogen additions. Researchers advocate the use of mass balance calculations to determine if excess nutrients are being generated that cannot be utilized by crops.

Several researchers caution against using the mass balance to determine if there are impacts to groundwater quality. Impacts have been documented in circumstances where the mass balance calculations indicate a balanced treatment system. One study observed that patterns with the mass balance increases or decreases corresponded with shallow groundwater nitrate concentrations.

Researchers in California observed that nutrient imbalances were typically the result of increasing herd size without a proportional increase in land base. They concur with other studies that if the amount of nutrients generated on the farm exceeds the ability of the crops to utilize the nutrients, the nutrients will accumulate in the soil and result in an increased risk of nitrate loss to groundwater.

Soil Monitoring

Studies have documented the variability of soil nitrate with depth and with time, indicating that soil nitrate values are only indicative of the conditions at that time and location. Researchers clarify the limitations of soil nitrate data, stating that soil nitrate results cannot be used to extrapolate conditions in other locations, at other depths, or in groundwater. Soil nitrate can indicate when excessive nitrate is present in the soils and poses a risk to leach to groundwater, but it cannot provide assurance that groundwater has been protected.

It is generally accepted in the literature that excess nitrate in soils poses a risk of leaching to groundwater. Due to the mobility of nitrate and the uncontrolled addition of precipitation, soil nitrate can be mobilized and migrate to groundwater. Soil nitrate sampling only provides a snapshot of what is present in the soils at the time the soil sample was collected. It cannot provide information on what has already moved through the soils to groundwater, what has moved below the sampling depth, or how much organic nitrogen will be converted to nitrate throughout the year and leach to groundwater. Soil samples cannot provide assurance that groundwater quality has been protected.

Groundwater Monitoring

The majority of researchers agree that groundwater monitoring is the only way to conclusively assess impacts of nutrient management practices on groundwater quality. Monitoring other media, such as soils, can indicate whether manure management practices need to be adjusted, but it cannot conclusively determine the extent of impacts to groundwater quality.

Researchers agree that soil nitrate will leach to groundwater during the winter with recharge (irrigation and precipitation). The extent of leaching is dependent upon the climate, soil type, the amount of nitrogen present, and the hydraulic loading. Studies document nitrate leaching to groundwater under varying conditions.

Researchers have also been successful in analyzing other contaminants as indicators of impacts from manure applications. These include veterinarian pharmaceuticals, antibiotics, steroid hormones, calcium, chloride, magnesium, sodium, boron, bromide, and argon.

Assessment Tools

The literature summarized in this report indicates that it is difficult to accurately predict impacts to groundwater quality based on soil nitrate samples. There is a general consensus among groundwater scientists that the best way to determine impacts to groundwater quality is to collect and analyze groundwater samples.

In the absence of acceptable monitoring wells, soil nitrate values can be used as a rough tool to estimate the potential for groundwater impacts and determine if groundwater monitoring is necessary to determine actual impacts. This can be achieved by using a combination of tools presented in the literature. Soil nitrate concentrations combined with area recharge rates can be used to estimate the amount of nitrate potentially available to leach to groundwater. The soil nitrate values listed in Tables 22 and 23 provide a reference for estimating when excess nitrate may be present in the soils.

The Nitrate Loading Mass Balance Model is a useful tool that can be used to assess potential impacts to groundwater quality and to estimate soil nitrate threshold limits which would likely be protective of groundwater quality.

Recommendations

A review of the scientific literature highlighted several manure treatment components and assessment strategies that promote the goal of water quality protection:

- Application rates
- Timing of manure applications
- Mass balance calculations
- Soil nitrate concentrations
- Groundwater monitoring Manure management

Application Rate Definition

A review of literature on manure management illuminated the inconsistent use of the term *"agronomic rate"*. There are numerous definitions for agronomic rate established for different purposes. Consistent definition and use of terms is a critical component to implementing consistent manure management practices. A standardized definition of "*application rate*" is needed to reflect the wastewater treatment goal and the need to protect groundwater quality. The definition for *manure application rates* is recommended: *the rate at which a viable crop can be maintained with minimal leaching of contaminants downwards below the root zone.* Land application of manure at rates that do not meet this definition pose a risk to groundwater quality.

Timing of Manure Application

A standardized tool is needed to establish growing season dates based on the crop grown and site-specific climatic conditions. This report describes three references that can be used to develop such a tool: the Washington Irrigation Guide, the WETS climate data, and T-Sum 200.

Manure should not be applied to land during the non-growing season, due to the high risk of groundwater contamination.

Plant development should be the key factor used to time manure applications rather than the calendar.

Monitoring and Assessment

Mass Balance

A mass balance calculation accounts for all nitrogen inputs and outputs in a land treatment system. Soil samples provide a way to measure the accuracy of the mass balance approach. Researchers advocate calculating mass balances on a monthly basis for each individual field and for the entire farm. They caution that averaging values over the entire site or over the entire year is not recommended and will not accurately reflect impacts to groundwater quality.

Soil Nitrate Concentrations

Soil nitrate concentrations can be used as an initial assessment of the effectiveness of manure management. If soil nitrate values indicate that groundwater quality is at risk, then the nutrient management plan should be revised to reduce nutrient levels in subsequent years.

Assessment tools should be adopted to determine the mass load of soil nitrate that is potentially available to leach to ground (Equations 5 and 6, Tables 22 and 23). The use of the Groundwater Nitrate Loading Mass Balance Model can provide site-specific soil threshold limits based on potential impacts to groundwater quality. These values can be used as threshold limits to identify when excessive nitrate is likely to be present in the subsurface and when groundwater quality is at risk.

Groundwater Monitoring

Animal feeding operations (AFOs) that apply manure to crops as part of their treatment system can adversely impact groundwater. Groundwater monitoring is the most reliable and direct means of measuring impacts to groundwater from manure applications. Soil samples provide limited information to evaluate nutrient management practices. They can indicate over-application of manure, current available nitrate concentrations in the soil, and effectiveness of management practices. However, soil nitrate is not a direct or reliable indicator of impacts to groundwater quality.

Models are tools that can assist in projecting future conditions that cannot be measured. They can simulate possible impacts from different management strategies to help provide direction for planning.

Manure Management

Effective manure management beneficially utilizes the available nutrients in a manner that protects water quality. The research summarized in this report documents that manure management that is protective of water quality has the following characteristics:

- Manure application will not degrade groundwater quality.
- Migration of contaminants below the root zone will be minimized.
- A whole farm nutrient mass balance is conducted as a part of manure management.
- Manure application rates consider the following:
  - Manner of application
  - Timing of application
  - Irrigation management
  - Crop uptake
  - Residual soil nitrogen
  - Appropriate land base for application

- Vegetative buffers and setbacks to surface waters are used as protective measures to mitigate pathogen impacts to surface water quality.
- Lagoons are used to store manure during the non-growing season as another treatment component. Storage lagoons are properly engineered, sufficiently sized, constructed, and maintained to contain manure during the non-growing season, or until it is possible to apply manure to crops during the growing season.

References

Almasri, M. and Kaluarachchi, J., 2004. Implications of On-Ground Nitrogen Loading and Soil Transformations on Groundwater Quality Management. Journal of the American Water Resources Association, Volume 40, Issue 1, pp. 165-186.

Baram, S., Arnon, S., Ronen, Z., Kurtzman, D., and Dahan, O., 2012. Infiltration Mechanism Controls Nitrification and Denitrification Processes under Dairy Waste Lagoon. Journal of Environmental Quality, pp. 1623 -1632.

Baram, S., Kurtzman, D., Ronen, Z., Peeters, A., Dahan, O., 2014. Assessing the impact of dairy waste lagoons on groundwater quality using a spatial analysis of vadose zone and groundwater information in a coastal phreatic aquifer. Journal of Environmental Management, pgs 135-144.

Barik, S., 2012 (43). Personal communication, email 11/1/12 regarding CAFO General Permit. Water Quality Program, Central Regional Office, Washington State Department of Ecology.

Bary, A., Cogger, C., and Sullivan, D.M., 2000. Fertilizing with manure. Washington State University Extension, Publication PNW0533, 16 pp.

Batt, A., Snow, D., and Aga, D., 2006. Occurrence of sulfonamide antimicrobials in private water wells in Washington County, Idaho, USA. Chemosphere, Vol. 64, No. 11, pp. 1963-1971.

British Columbia Ministry of Agriculture, 1994. On-farm measurement of ammonia in manure with Agro Quick Tester. Order No. 652.000-1, 2 pp.

Bruce, B., Becker, M., Pope, L., and Gurdak, J., 2003. Ground-Water Quality beneath Irrigated Agriculture in the Central High Plains Aquifer, 1999-2000. USGS, Water-Resources Investigations Report 03-4219, 39 pp.

Burkholder, J., Libra, B., Weyer, P., Heathcote, S., Kolpin, D., Thorne, P., and Wichman, M., 2007. Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality. Environmental Health Perspectives, Volume 115, Number 2, pp. 308 – 312.

Buss, S.R., Rivett, M.O., Morgan, P., and Bemment, C.D., 2005. Attenuation of Nitrate in the Sub-Surface Environment, Environment Agency, Science Report SC030155/SR2, 100 pp. http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/scho0605bjcs-e-e.pdf

Camberato, J., Nielsen, R., and Joern, B., 2013. Assessing Available Nitrogen from Fall- and Spring-Applied Nitrogen Applications, Purdue University, Department of Agronomy, 5 p.

Carey, B., 2002. Effects of Land Application of Manure on Groundwater at Two Dairies over the Sumas-Blaine Surficial Aquifer: Implications for Agronomic Rate Estimates. Washington State Department of Ecology, Olympia, WA. Publication No. 02-03-007, 75 pp. https://fortress.wa.gov/ecy/publications/SummaryPages/0203007.html

Carey, B. and Cummings, R., 2012. Sumas-Blaine aquifer nitrate contamination summary. Washington State Department of Ecology, Olympia, WA. Publication No. 12-03-026. 55 pp. https://fortress.wa.gov/ecy/publications/publications/1203026.pdf

Carey, B. and Harrison, J., 2014. Nitrogen mass balance: manure, soil, crop removal, and groundwater at a grass field overlying the Sumas-Blaine aquifer in Whatcom County. Washington State Department of Ecology, Olympia, WA. Publication No. 14-03-001, 110 pp. + appendices. https://fortress.wa.gov/ecy/publications/SummaryPages/1403001.html

Chantigny, M., Angers, D., Rochette, P., Pomar, C., and Pelster, D., 2014. Evidencing Overwinter Loss of Residual Organic and Clay-fixed Nitrogen from Spring-applied, ^{15}N-labelled Pig Slurry. Canadian Journal of Soil Science, 94: pp. 1-8.

Chesnaux, R., Allen, D., and Graham, G., 2007. Assessment of the impact of Nutrient Management Practices on Nitrate Contamination in the Abbotsford-Sumas Aquifer. Environmental Science and Technology, Volume 41, pp. 7229-7234.

Cogger, C., 2000. Abbotsford/Sumas Aquifer Nitrate Management Project, Addendum to Final Report, Washington State University, Puyallup, WA, 19 pp.

Columbia Basin Groundwater Management Area, 2009. http://cbgwma.org/index.php?option=com_content&task=view&id=18&Itemid=40

Cookson, W., Cornforth, I., and Rowarth, J., 2002. Winter Soil Temperature (2-15°C) Effects on Nitrogen Transformations in Clover Green Manure Amended or Unamended Soils; a laboratory and Field Study. Soil Biology and Biochemistry, Volume 34, Issue 10, pp. 1401-1415.

Cornell University, 2012. Pre-sidedress Nitrate Test, Cooperative Extension, Nutrient Management Spear Program, Agronomy Fact Sheet Series #3, 2 pp.

Council of Canadian Academies, 2013. Water and Agriculture in Canada: Towards Sustainable Management of Water Resources. The Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada, Ottawa, Canada, 259 pp.

Cox, S. and Kahle, S., 1999. Hydrogeology, Ground-Water Quality, and Sources of Nitrate in Lowland Glacial Aquifers of Whatcom County, Washington, and British Columbia, Canada, U.S. Geological Survey, Water-Resources Investigations Report 98-4195, 251 pp.

De Jong, R., Yang, J., Drury, C., Huffman, E., Kirkwood, V., and Yang, X., 2005. Nitrogen, pp. 124-130. In Lefebvre, A., Eiler, W., and Chunn, B. (eds) Environmental Sustainability of Canadian Agriculture: Agri-Environmental Indicator Report Series – Report #2, Agriculture and Agri-Food Canada, Ottawa, Ontario.

De Jong, R., Yang, J., Drury, C., Huffman, E., Kirkwood, V., and Yang, X., 2007. The Indicator of Risk of Water Contamination by Nitrate-Nitrogen. Canadian Journal of Soil Science, 87: pp. 179-188.

Dessureault-Rompré, J., Zebarth, B., Georgallas, A., Burton, D., Grant, C., and Drury, C., 2010. Temperature Dependence of Soil Nitrogen Mineralization Rate: Comparison of Mathematical Models, Reference Temperatures and Origin of the Soils. Geoderma, 157: pp. 97-108.

DeSutter, T., Pierzynski, G., and Ham, J., 2005. Movement of Lagoon-Liquor Constituents below Four Animal-Waste Lagoons. Journal of Environmental Quality, Volume 34, pp. 1234-1242.

Drury, C., Yang, J., DeJong, R., Huffman, T., Kirkwood, V., Yang, X., and Reid, K., 2005. Nitrogen Use Efficiency, pp. 68-75. In Lefebvre, A., Eiler, W., and Chunn, B. (eds) Environmental Sustainability of Canadian Agriculture: Agri- Environmental Indicator Report Series – Report #2, Agriculture and Agri-Food Canada, Ottawa, Ontario.

Drury, C., Yang, J., De Jong, R., Yang, X., Huffman, E., Kirkwood, V., and Reid, K., 2007. Residual Soil Nitrogen Indicator for Agricultural Land in Canada. Canadian Journal of Soil Science, 87: pp. 167 -177.

Dzurella, K., Medellin-Azuara, J., Jensen, V. et al., 2012. Nitrogen Source Reduction to Protect Groundwater Quality. Technical Report 3 in: Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature. Center for Watershed Sciences, University of California Davis.

Ecology, 2000. Biosolids Management Guidelines for Washington State. Solid Waste and Financial Assistance Program, Washington State Department of Ecology. Publication No. 93-80. https://fortress.wa.gov/ecy/publications/SummaryPages/9380.html

Ecology, 2004a. Guidance on Land Treatment of Nutrients in Wastewater, with Emphasis on Nitrogen. Water Quality Program, Washington State Department of Ecology. Publication No. 04-10-081, 5 pp. https://fortress.wa.gov/ecy/publications/SummaryPages/0410081.html

Ecology, 2004b. Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies. Washington State Department of Ecology. Publication No. 04-03-030, 100 pp. https://fortress.wa.gov/ecy/publications/summarypages/0403030.html

Ecology, 2006. Concentrated Animal Feeding Operation (CAFO) National Pollutant Discharge Elimination System (NPDES) and State Waste Discharge General Permit. Water Quality Program, Washington State Department of Ecology, 34 pp.

Ecology, 2008. Criteria for Sewage Works Design. Chapter E3, Effluent Disposal to Groundwater, Water Quality Program, Washington State Department of Ecology, 98-37 WQ. https://fortress.wa.gov/ecy/publications/summarypages/9837.html

Ecology, 2010a. Groundwater and Surface Water, A Single Resource in Washington. Water Resources Program, Washington State Department of Ecology, 19 pp.

Ecology, 2010b. Lower Yakima Valley Groundwater Quality; Preliminary Assessment and Recommendations Document. Water Quality Program, Publication # 10-10-009, 87 pp.

Ecology, 2011. Water Quality Program Permit Writer's Manual. Washington State Department of Ecology, Publication 92-109.

Ecology, 2013. Concentrated Animal Feeding Operations General Permit website. Water Quality Program, Washington State Department of Ecology. http://www.ecy.wa.gov/programs/wq/permits/cafo/index.html

Elrashidi, M., Mays, M., Fares, A., Seybold, C., and Harder, J., 2005. Loss of Nitrate-Nitrogen by Runoff and Leaching for Agricultural Watersheds, University of Nebraska – Lincoln, Soil Science, Vol. 170, No. 12, pp. 969-984.

Entry, J., Hubbard, R., Thies, J., and Fuhrmann, J., 2000. The Influence of Vegetation in Riparian Filterstrips on Coliform Bacteria: I. Movement and Survival in Water. J. Environ. Qual. 29:1206-1214 (2000).

EPA, 1999. Preliminary Data Summary, Feedlots Point Source Category Study. Office of Water, Washington DC, EPA-821-R-99-002, 50 pp. + appendices.

EPA, 2002. Onsite Wastewater Treatment Systems Manual. U.S. Environmental Protection Agency, Office of Water, Office of Research and Development, EPA/625/R-00/008.

EPA, 2011. Reactive nitrogen in the United States: An analysis of inputs, flows, consequences, and management options. U.S. Environmental Protection Agency, Science Advisory Board. EPA-SAB-11-013, 140 pp.

EPA (revised), 2013a. Relation Between Nitrate in Water Wells and Potential Sources in the Lower Yakima Valley - Revised, Washington. U.S. Environmental Protection Agency, Region 10, EPA-910-R-13-004, 311 pp. http://www.epa.gov/region10/pdf/sites/yakimagw/nitrate_in_water_wells_study_march2013.pdf

EPA, 2013b. Monitoring Well and Installation and Data Summary Report, Lower Yakima Valley, Yakima County, Washington. U.S. Environmental Protection Agency, Region 10, Seattle, WA, 63 pp. http://www.epa.gov/region10/pdf/sites/yakimagw/monitoring_well_installation_and_data_summary_report_march2013.pdf

Erickson, D., and Matthews, W., 2002. Effects of Land Application of Dairy Manure and Wastewater on Groundwater Quality: Pre-and Post-Animal Waste Holding Pond Monitoring, Washington State Department of Ecology, Olympia, WA. Publication No. 02-03-002. https://fortress.wa.gov/ecy/publications/summarypages/0203002.html

Erickson, D. and Norton, D., 1990. Washington State Agricultural Chemicals Pilot Study, Washington State Department of Ecology, Olympia, WA. 76 pp. Publication No. 90-46. https://fortress.wa.gov/ecy/publications/SummaryPages/9046.html.

Erickson, D., 1991. Edaleen Dairy Lagoon Groundwater Quality Assessment, February 1990 to February 1991. Washington State Department of Ecology, Olympia, WA. Publication No. 91-e11. 32 pp. + appendices. https://fortress.wa.gov/ecy/publications/SummaryPages/91e11.html

Erickson, D., 1992. Groundwater Quality Assessment Whatcom County Dairy Lagoon #2-Lynden, Washington. Washington State Department of Ecology, Olympia, WA. Publication No. 92-e25. 26 pp. + appendices. https://fortress.wa.gov/ecy/publications/SummaryPages/92e25.html

Erickson, D., 1994. Effects of Leakage from Four Dairy Waste Storage Ponds on Groundwater Quality, Final Report. Washington State Department of Ecology, Olympia, WA 50 pp. Publication No. 94-109. https://fortress.wa.gov/ecy/publications/SummaryPages/94109.html

European Union, 1991. Concerning the Protection of Waters Against Pollution Caused by Nitrates from Agricultural Sources. Brussel, Belgium: EU, Council Directive 91, 91/676/EEC.

European Union, 2010. The European Union Nitrates Directive, Brussels, Belgium: EU.

Feaga, J. and Selker, J., 2004. Field Measurements of Nitrate Leaching below Willamette Valley Row and Mint Crops. Oregon State University, Extension Service, EM 8851, 8 pp.

Flaten, D., 2001. The Nitrate Soil Test: Is it Reliable? University of Manitoba, Agricultural and Food Sciences, Manitoba Agronomists Conference, Winnipeg, Canada, pp. 95-101.

Fleming, R., and Fraser, H., 2000. Impacts of Winter Spreading of Manure on Water Quality – Literature Review. University of Guelph, Ontario, Canada, 11 pp.

Fletcher, P. and Veneman, P., 2012. Soil Morphology as an Indicator of Seasonal High Water Tables. USDA, SCS, and University of Massachusetts, Department of Plant and Soil Sciences. http://nesoil.com/properties/eshwt.htm

Fox, R., Zhu, Y., Toth, J., Jemison, J., and Jabro, J., 2001. Nitrogen Fertilizer Rate and Crop Management Effects on Nitrate Leaching from an Agricultural Field in Central Pennsylvania. The Scientific World, Proceedings of the 2nd International Nitrogen Conference on Science and Policy.

Franzmeier, D. and Jenkinson, B., 2004. DSat8 and Seasonal High Water Tables in Indiana Soils, Department of Agronomy, Purdue University; 10 pp. http://www.isco.purdue.edu/irss/pdf/Manuscript.pdf

Freeze, R.A. and Cheery, J., 1979. Groundwater. Prentice-Hall, Inc., New Jersey, 604 pp.

Frimpter, M., Donohue, J., Rapacz, M., 1990. A Mass-Balance Nitrate Model for Predicting the Effects of Land Use on Ground-Water Quality. U.S. Geological Survey, Boston, Massachusetts, Open-File Report 88-493, 17 pp. + appendices.

Garland, D. and Erickson, D., 1994. Groundwater Quality Survey near Edaleen Dairy, Whatcom County, Washington. Washington State Department of Ecology, Olympia, WA. 20 pp. Publication No. 94-37. https://fortress.wa.gov/ecy/publications/SummaryPages/9437.html

Gehl, R., Schmidt, J., Godsey, C., Maddux, L., and Gordon, W., 2006. "Post-Harvest Soil Nitrate in Irrigated Corn: Variability among Eight Field Sites and Multiple Nitrogen Rates", Soil Science Society of America Journal, 70:1922-1931.

Glanville, T., Baker, J., Melvin, S., and Agua, M., 2001. Measurement of Leakage from Earthen Manure Structures in Iowa. American Society of Agricultural Engineers, Volume 44, Number 6, pp. 1609-1616.

Green, C., Fisher, L., and Bekins, B., 2008a. Nitrogen Fluxes through Unsaturated Zones in Five Agricultural Settings Across the United States. Journal of Environmental Quality, Volume 37, pp. 1073-1085.

Green, C., Puckett, L., Böhlke, J.K., Bekins, B., Phillips, S., Kauffman, L, Denver, J., and Johnson, H., 2008b. Limited Occurrence of Denitrification in Four Shallow Aquifers in Agricultural Areas of the United States. Journal of Environmental Quality, Volume 37, pp. 994-1009.

Hall, S., 1990. Vertical Separation: A review of available scientific literature and a listing from fifteen other states. Washington State Department of Health, Office of Environmental Health, 16 pp.

Ham, J., 2002a. Uncertainty Analysis of the Water Balance Technique for Measuring Seepage from Animal Waste Lagoons. Journal of Environmental Quality, Volume 31, Number 4, pp. 1370-1379.

Ham, J., 2002b. Seepage Losses from Animal Waste Lagoons: A Summary of a Four-Year Investigation in Kansas. American Society of Agricultural Engineers, Volume 45, Number 4, pp. 983-992.

Ham, J. and DeSutter, T., 1999. Seepage Losses and Nitrogen Export from Swine-Waste Lagoons: A Water Balance Study. Journal of Environmental Quality, Volume 28, Number 4, pp. 1090-1099.

Ham, J. and DeSutter, T., 2000. Toward Site-Specific Design Standards for Animal-Waste Lagoons: Protecting Groundwater Quality, Journal of Environmental Quality, Volume 29, No. 6, pp. 1721-1732.

Hart, J., Sullivan, D., Gamroth, M., Downing, T., and Peters, A., 2009. Silage Corn (Western Oregon). Oregon State University, Extension Service, Nutrient Management Guide, EM 8978-E, 13 pp.

Harter, T., Davis, H., Mathews, M.C. and Meyer, R.D., 2002. Shallow groundwater quality on dairy farms with irrigated forage crops. Journal of Contaminant Hydrology, 55(3–4), 287–315.

Harter, T. and Menke, J., 2004. Cow Numbers and Water Quality – Is there a Magic Limit? A Groundwater Perspective. Proceedings, National Alfalfa Symposium, 13-15 December 2004, San Diego, CA; UC Cooperative Extension, University of California, Davis, 12 pp.

Harter, T., Joshua H. Viers, Daniel Liptzin et al., 2012. Nitrogen Sources and Loading to Groundwater--Technical Report 2: Assessing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature. California Nitrate Project, Implementation of Senate Bill X2 1. 323 pp. + appendices. http://groundwaternitrate.ucdavis.edu/files/139110.pdf

Harter, T., Kourakos, G, and Lockhart, K., 2014. Assessing Potential Impacts of Livestock Management on Groundwater. NI R 14-03 Supplemental Paper 2. Durham, NC: Duke University, 20 pp.

Heckman, J., 2003. Soil Nitrate Testing as a Guide to Nitrogen Management for Vegetable Crops. Rutgers University, New Jersey Agricultural Cooperative Extension, E285, 6 pp.

Hem, J., 1985. Study and Interpretation of the Chemical Characteristics of Natural Water. U.S. Geological Survey, Water-Supply Paper 2254, Washington D.C., 263 pp.

Hermanson, R., Pan, W., Perillo, C., Stevens, R., Stockle, C., 2000. Nitrogen Use by Crops and the Fate of Nitrogen in the Soil and Vadose Zone – A Literature Search, Washington State University, for Washington State Department of Ecology. Publication No. 00-10-015. https://fortress.wa.gov/ecy/publications/SummaryPages/0010015.html

Hubbs, A.K.B., 2002. M.S. Thesis: Fecal Coliform Concentration in Surface Runoff from Pastures with Applied Dairy Manure. Louisiana State University, Agricultural and Mechanical College.

Hudak, P., 2002. Chloride/Bromide Ratios in Leachate Derived from Farm-Animal Waste, Environmental Pollution, 121, pp. 23-25.

Hughes-Games, G. and B. Zebarth, 1999. Nitrogen Recommendations for Raspberries. Ministry of Agriculture and Food, Soil Fact Sheet, British Columbia, Canada. 6 pp.

Iowa State University, 1997. Nitrogen Fertilizer Recommendations for Corn in Iowa, University Extension, Ames, Iowa, Pm-1714, 4 pp.

Jayasundara, S., Wagner-Riddle, C., Parkin, G., Lauzon, J., and Fan, M., 2010. Transformations and Losses of Swine Manure ^{15}N as Affected by Application Timing at two Contrasting Sites. Canadian Journal of Soil Science, 90: pp. 55-73.

Jégo, G., Martínex, M., Antigüedad, M., Launay, J.M., Sánchez-Pérez, E., and Justes, E., 2008. Evaluation of the Impact of Various Agricultural Practices on Nitrate Leaching under the Root Zone of Potato and Sugar Beet using the STICS Soil-Crop Model, Science of the Total Environment, 394, pp. 207-221.

Jennings, J., 2013. Personal communication. Washington State Department of Ecology, Water Quality Program.

Ju, X., Kou, C., Zhang, F., and Christie, P., 2006. Nitrogen Balance and Groundwater Nitrate Contamination: Comparison among Three Intensive Cropping Systems on the North China Plain. Environmental Pollution, Volume 143, Issue 1, pp. 117-125.

Killpack, S. and Buchholz, D., 1993. Nitrogen Cycle. University of Missouri Extension, Department of Agronomy, Pub WQ 252.

Kimsey, M., 1997. Estimating Potential Impacts to Groundwater Quality from Nitrogen Loading. In Proceedings of the 9th Northwest On-Site Wastewater Treatment Short Course and Equipment Exhibition, Seattle, WA, pp. 143-157.

Kimsey, M., 2002. Construction of Dairy Lagoons below the Seasonal High Groundwater Table. Washington State Department of Ecology, Water Quality Program, Issue paper, 2002.

Kimsey, M., 2005 (original 1996). Implementation Guidance for the Groundwater Quality Standards, Washington State Department of Ecology, Water Quality Program. Publication No. 96-02, 135 pp. https://fortress.wa.gov/ecy/publications/SummaryPages/9602.html

Kirchmann, H., Johnston, A.E.J., and Bergström, L., 2002. Possibilities for Reducing Nitrate Leaching from Agricultural Land. Royal Swedish Academy of Sciences, Ambio Vol. 31, No. 5, pp. 404-408.

Knisel, W., 1980. CREAMS: A field-scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. U.S. Department of Agriculture, Science and Education Administration, Conservation Research Report No. 26, 643 pp.

Koike, S., Krapac, I., Oliver, H., Yannarell, A., Chee-Sanford, J., Aminov, R., and Mackie, R., 2007. Monitoring and Source Tracking of Tetracycline Resistance Genes in Lagoons and Groundwater Adjacent to Swine Production Facilities over a 3-Year Period. Applied and Environmental Microbiology, Volume 73, No. 15, pp. 4813-4823.

Kolodziej, E., Harter, T., and Sedlak, D., 2004. Dairy Wastewater, Aquaculture, and Spawning Fish as Sources of Steroid Hormones in the Aquatic Environment. Environmental Science & Technology, Vol. 38, No. 23, pp. 6377-6384.

Kowalenko, C. and Bittman, S., 2002. Crop Management Factors that Affect Soil Nitrate, Presented at the Fall Soil Nitrate Workshop, Puyallup, WA, pp. 16-19.

Kowalenko, C.G., Schmidt, O., and Hughes-Games, G., 2007. Fraser Valley Soil Nutrient Study 2005, A Survey of the Nitrogen, Phosphorus and Potassium Contents of Lower Fraser Valley Agricultural Soils in Relation to Environmental and Agronomic Concerns. The Canada – British Columbia Environmental Farm Plan Program, British Columbia Agriculture Council, 47 pp.

Kratochvil R.L., and Stenhilber, P., 2013. Fall Soil Nitrate Test. University of Maryland, College of Agriculture and Natural Resources, Department of Plant Science and Landscape Architecture, Extension Brief, EBR 15.

Kuipers, P., Ryan, C., and Zebarth, B., 2014. Estimating Nitrate Loading from an Intensively Managed Agricultural Field to a Shallow unconfined Aquifer. Water Quality Research, Journal of Canada, Volume 49, No. 1. pp. 10-22.

Laboski, C., 2008. Potential for Nitrogen Loss from Heavy Rainfalls, University of Wisconsin – Madison Soil Science Extension, 4 pp.

Lamb, J., 2012. Fall Soil Sampling for Nitrate-N, University of Minnesota, Extension, 3 pp.

Leonard, R., Knisel, W., and Still, D., 1987. GLEAMS: Groundwater Loading Effects of Agricultural Management Systems. American Society of Agricultural Engineers, Vol 30, No. 5, pp. 1403-1418.

Lindsey, B., Breen, K., Bilger, M., and Brightbill, R., 1998. Water Quality in the Lower Susquehanna River Basin, Pennsylvania and Maryland, 1992-95: U.S. Geological Survey, Circular 1168.

Mahler, R. and T. Tindall, 1997. Soil sampling. University of Idaho Cooperative Extension, Bulletin 704, 8 pp.

Marti, P., 2011a. Standard Operating Procedure for Purging and Sampling Monitoring Wells, Version 1.0. Washington State Department of Ecology, Olympia, WA. SOP Number EAP078. http://www.ecy.wa.gov/programs/eap/qa/docs/ECY_EAP_SOP_PurgingSamplingMonitoringWell_V1.0EAP078.pdf

Marti, P., 2011b. Standard Operating Procedure for Purging and Sampling Water Supply Wells, Version 1.0. Washington State Department of Ecology, Olympia, WA. SOP Number EAP077. http://www.ecy.wa.gov/programs/eap/qa/docs/ECY_EAP_SOP_PurgingSamplingWaterSupplyWell_V1_0EAP077.pdf

Mathieu, N., 2012. Personal communication. Environmental Assessment Program, Washington State Department of Ecology, Olympia, WA.

McNab, E., Singleton, M., Moran, J., and Esser, B., 2006. Assessing the Impact of Animal Waste Lagoon Seepage on the Geochemistry of an Underlying Shallow Aquifer. Environmental Science and Technology, UCRL-JRNL-219615, 21 pp.

McNab, W., Singleton, M., Moran, J., and Esser, B., 2007. Assessing the Impact of Animal Waste Lagoon Seepage on the Geochemistry of an Underlying Shallow Aquifer, Environmental Science & Technology, Volume 41, No. 3, pp. 753-758.

Miller, M., Bobinson, J., and Gallagher, D., 1976. Accumulation of Nutrients in Soil Beneath Hog Manure Lagoons, Journal of Environmental Quality, Volume 5, No. 3, pp. 279-282.

Miller, J., Curtis, T., Larney, F., McAllister, T., and Olson, B., 2008. Physical and Chemical Properties of Feedlot Pen Surfaces Located on Moderately Coarse and Moderately Fine Textured Soils in Southern Alberta. Journal of Environmental Quality, Volume 37, Number 4, pp. 1589-1598.

Minnesota Pollution Control Agency, 2000. Vegetative buffers for protecting and improving groundwater quality. Environmental Outcomes Division, Groundwater Monitoring & Assessment Program, 2 pp.

Minnesota Pollution Control Agency, 2001. Effects of Liquid Manure Storage Systems on ground Water Quality – Summary Report. Ground Water Monitoring Assessment Program, 36 pp.

Mitchell, R., Babcock, S., Hirsch, H., McKee, L., Matthews, R., and Vandersypen, J., 2005. Water Quality: Abbotsford-Sumas Final Report. Western Washington University, Bellingham, WA, 144 pp.

Moberg, D., Johnson, R., and Sullivan, D., 2013. Comparison of Disturbed and Undisturbed Soil Core Methods to Estimate Nitrogen-Mineralization Rates in Manured Agricultural Soils, Communications in Soil Science and Plant Analysis, Vol 44, pp. 1722-1732.

Momohara, D., 2012. Washington State Department of Ecology, Manchester Environmental Laboratory, personal communication.

Morgan, L., 2012. GIS Map of Nitrate Occurrences in Washington State. Washington State Department of Ecology, Water Quality Program.

National Academy of Engineering, 2008. Grand Challenges. Accessed on 10/10/2014. http://www.engineeringchallenges.org/cms/8996/9132.aspx The Grand Challenges for Engineering were made public at a news conference during the AAAS meeting in Boston on Feb. 15, 2008.

Nennich, T. Harrison, J., and Davidson D., 2005. Evaluation of the survivability of fecal coliform in soil after winter application of dairy slurry on a transitional-organic, grazing based dairy. Proceedings Symposium: State of the Science Animal Manure and Waste Management, January 5-7, 2005, San Antonio, Texas. Sponsored by National Center for Manure and Animal Waste Management. http://www.cals.ncsu.edu/waste_mgt/natlcenter/sanantonio/Nennich.pdf

Nicholson, R., Webb, J., and Moore, A., 2002. Review Paper: A Review of the Environmental Effects of Different Livestock Manure Storage Systems, and a Suggested Procedure for Assigning Environmental Ratings. Biosystems Engineering, Volume 81, Number 4, pp. 363-377.

Nolan, B., and Stoner, J., 2000. Nutrients in Groundwaters of the Conterminous United States, 1992-1995. Environmental Science and Technology, Volume 34, No. 7, pp. 1156-1165.

NRCS, 1995. WETS Table Documentation. National Resources Conservation Service. http://www.wcc.nrcs.usda.gov/climate/wets_doc.html and http://www.wcc.nrcs.usda.gov/climate/navigate_wets.html

NRCS, 1997. Irrigation Guide. National Engineering Handbook, Part 652, National Resources Conservation Service, U.S. Department of Agriculture, Washington D.C., 820 pp.

NRCS, 2005. Winter Period Application of Manure in Washington State. National Resources Conservation Service, U.S. Department of Agriculture, Technical Note Agronomy 14, Spokane, WA, 7 pp.

NRCS, 2009a. Part 651 Agricultural Waste Management Field Handbook, Chapter 7 “Geologic and Groundwater Considerations” 2010, 210-VI-AWMFH, Amend. 38.

NRCS, 2009b. Part 651 Agricultural Waste Management Field Handbook, Appendix 10D Design and Construction Guidelines for Waste Impoundments Lined with Clay or Amendment-Treated Soil (27 29).

NRCS, 2009c. Part 651 Agricultural Waste Management Field Handbook, Chapter 6 “Role of Plants in Waste Management” 2010, 210-VI-AWMFH, Amend. 38.

NRCS, 2014. Conservation Practice Standard 590, Nutrient Management. Washington State, 9 pp. http://www.extension.org/sites/default/files/590_stnd_021814%202014.pdf

Nunez-Delgado, A., Lopez-Periago, E., and Diaz-Fierros Viqueira, F., 2002. Chloride, sodium, potassium and faecal bacteria levels in surface runoff and subsurface percolates from grassland plots amended with cattle slurry. Biores. Technol. 82:261–271.

Obert, W., 1973. Nitrate in Groundwater, Western Whatcom County, Washington. Western Washington University, Bellingham, Washington, MS thesis. Department of Geography. 167 pp.

O'Leary, M., Rehm, G., and Schmitt, M., 2002. Understanding Nitrogen in Soils, University of Minnesota, Extension, Pub WW-03770-GO. http://www.extension.umn.edu/distribution/cropsystems/dc3770.html

Olson, B., Bennett, D., McKenzie, R., Ormann, T., and Atkins, R., 2009. Nitrate Leaching in two Irrigated Soils with Different Rates of Cattle Manure. Journal of Environmental Quality, Volume 38, Number 6, pp. 2218-2228.

Oregon State University Extension Service, 1996. Timing of Nitrogen Fertilizer for Western Oregon Pastures. Polk County.

Panhorst, K.A. 2002. Estimating Bacterial Loadings to Surface Waters from Agricultural Watersheds. Virginia Polytechnic Institute and State University.

Peters, J., Combs, S.M., Hoskins, B., Jarman, J., Kovar, J., Watson, M.E., and Wolf, A.M., 2003. Recommended methods of manure analysis. University of Wisconsin Cooperative Extension, Report No. A3769, 57 pp.

Plotnikoff, R., Hallock, D., Pickett, P., and Sargeant, D., 2006. Preparing Elements of a Quality Assurance Monitoring Plan to Conduct Water Quality Monitoring Near Dairies and CAFOs. Washington State Department of Ecology. Publication No. 06-03-015, 38 pp. https://fortress.wa.gov/ecy/publications/SummaryPages/0603015.html

Qui, H., Zhao, B., Wu, J., and Chen, S., 2005. Report of Technical Review of Basic American Foods, Moses Lake Wastewater Land Treatment System. Washington State University, Pullman, WA. 60 pp.

Reddi, L., Davalos, H., and Vonala, V., 2005. Seepage and Transport through Anaerobic Lagoon Liners, in Animal Waste Containment in Lagoons. Manuals and Reports on Engineering Practice No. 105, Environmental Water Resources Institute of the American Society of Civil Engineers, Reston, Virginia, 204 pp.

Redding, M., 2008. Nitrate Trends in the Central Sumas-Blaine Surficial Aquifer, Washington State Department of Ecology, Olympia, WA. Publication No. 08-03-018, 117 pp. https://fortress.wa.gov/ecy/publications/SummaryPages/0803018.html

Redding, M., 2011. Sumas-Blaine aquifer Long-Term Groundwater Quality Monitoring Network; 2009 Annual Report, Washington State Department of Ecology, Olympia, WA. Publication No. 11-03-015, 38 pp.

Rosenstock, T., Liptzin, D., Dzurella, K., Fryjoff-Hung, A., Hollander, A., Jensen, V., King, A., Kourakos, G., McNally, A., Pettygrove, G. S., Quinn, J., Viers, J., Tomich, T., and Harter, T., 2014. Agriculture's Contribution to Nitrate Contamination of Californian Groundwater (1945 – 2005). Journal of Environmental Quality, pp. 895-907.

Rudolf, D., 2015. Influence of Vadose Zone Dynamics on the Fate of Agricultural Nutrients. Keynote address given on 4/14/2015 at the 10th Washington Hydrogeology Symposium, Tacoma, WA.

Rudolf, D., Devlin, J., and Bekeris, L., 2015. Challenges and a Strategy for Agricultural BMP Monitoring and Remediation of Nitrate Contamination in Unconsolidated Aquifers. Groundwater Monitoring and Remediation, Volume 35, Number 1, pp. 97-109.

Sajil Kumar, P.J., Babu, T., and Delson, D., 2013. Level and Distribution of Nitrate in Groundwater in Parts of Vellore District, Tamil Nadu, India. Elixir Pollution, Volume 55, pp. 12782-12784.

Sánchez-Pérez, José-Miguel and Antiguedad, I. and Arrate, I. and Linares, C. and Morell, Ignacio, 2003. The influence of nitrate leaching through unsaturated soil on groundwater pollution in an agricultural area of the Basque country: a case study. Science of the Total Environment, Vol. 317. pp. 173-187. ISSN 0048-9697.

Sawyer, J., Nafziger, E., Randall, G., Bundy, L., Rehm, G., and Joern, B., 2006. Concepts and Rationale for Regional Nitrogen Rate Guidelines for Corn, Iowa State University, University Extension, Agronomy A-2, 28 pp.

Shaffer, M., Halvorson, A., and Pierce, F., 1991. Nitrate Leaching and Economic Analysis Package (NLEAP): Model Description and Application. Soil Science Society of America, in Managing Nitrogen for Groundwater Quality and Farm Profitability, pp. 285 – 322.

Singleton, M., Esser, B., Moran, J., Hudson, G., McNab, W., and Harter, T., 2007. Saturated Zone Denitrification: Potential for Natural Attenuation of Nitrate Contamination in Shallow Groundwater Under Dairy Operations. American Chemical Society, Volume 41, Number 3, pp. 759-765.

Sinton, L., Braithwaite, R., Hall, C., and Mackenzie, M., 2007. Survival of Indicator and Pathogenic Bacteria in Bovine Feces on Pasture, Applied and Environmental Microbiology, Vol. 73, No. 24, pp. 7917-7925.

Slaton, N.A., Mozaffari, M., DeLong, R.E., Norman, R.J., and Ross, W.J., 2004. Influence of Nitrogen Fertilizer Application Rate and Time on Winter Wheat Yields, Wayne E. Sabbe Arkansas Soil Fertility Studies, AAES Research Series 525, pp. 95-99.

Spalding, R. and Exner, M., 1993. Occurrence of Nitrate in Groundwater – A Review. Journal of Environmental quality, Vol 22, pp. 392-402.

Staben, M.L., Ellsworth, J.W., Sullivan, D.M., Horneck, D., Brown, B.D., and Stevens, R.G., 2003. Monitoring Soil Nutrients Using a Management Unit Approach, Pacific Northwest Extension. Publication PNW 570-E, 13 pp.

Stephen, A., Meister, D., and Edward, A., 1999. Dairy Feedlot Contributions to Groundwater Contamination, A Preliminary Study in New Mexico, Journal of Environmental Health, Volume 62, Issue 2, pp. 16-20.

Stoddard, C., Coyne, M., and Grove, J., 1998. Fecal bacteria Survival and Infiltration Through a Shallow agricultural Soil: Timing and Tillage Effects. Journal of Environmental Quality. 27:1516-1523.

Sullivan, D.M., Bierlink, H., and Matthews, W., 1994. Tools for getting more value out of dairy manure. pp. 55-65. In: Proceedings of the 26th Annual Dairy Producers Short Course, Feb. 8-9, 1994, Clearbrook, BC, Canada. Ministry of Agriculture, Fisheries and Food, Chilliwack, BC (available from Dan Sullivan, Department of Crop and Soil Science, Oregon State University).

Sullivan, D., Cogger, C., and Bary, A., 1997. Which test is best? Customizing dairy manure nutrient testing. Oregon State University, PNW 505, 12 pp.

Sullivan, D., Cogger, C., Bary, A., and Fransen, S., 2000. Timing of Dairy Manure Applications to Perennial Grass on Well Drained and Poorly Drained Soils. Journal of Soil and Water Conservation, Volume 55, Number 2, pp. 147-152.

Sullivan D. and Cogger, C., 2002. Guidance for Sampling and Interpretation. Presented at the Fall Soil Nitrate Workshop, Puyallup, WA.

Sullivan, D.M. and Cogger, C.G., 2003. Post-harvest Soil Nitrate Testing for Manured Cropping Systems West of the Cascades. Oregon State University Extension Service, EM 8832-E, 17 pp.

Sullivan, D., 2008. Estimating Plant-available Nitrogen from Manure. Oregon State University, Extension Service, EM 8954-E, 21 pp.

Sutton, M., Howard, C., Erisman, J., Billen, G., Bleeker, A., Grennfelt, P., 2011. The European Nitrogen Assessment, New York, NY: Cambridge University Press.

Thurston County, 1999. Permitting Systems Policies and Procedures, Determination of Highest Seasonal High Water Table. 2 pp.
http://www.co.thurston.wa.us/health/ehoss/pdf/designer/DetermineHighestSeasonalWaterTable.pdf

U.S. Department of Agriculture, 1993. Design and Construction Guidelines for Considering Seepage from Agricultural Waste Storage Ponds and Treatment Lagoons. Soil Conservation Service, Engineering, Technical Note 716, 37 pp.

U.S. Geological Survey, variously dated. National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1-A9, http://water.usgs.gov/owq/FieldManual/

University of California, 2005 (revised). Managing Dairy Manure in the Central Valley of California. Division of Agriculture and Natural Resources, Committee of Experts on Dairy Manure Management, 10 pp.

University of Western Australia, 2013. Plant/Animal Production, The Role of Nitrogen in Agricultural Production Systems. http://hsc.csu.edu.au/agriculture/production/3363/nitrogen.htm

Vaillant, G., Pierzynski, G., Ham, J., and DeRouchey, J., 2009. Nutrient Accumulation Below Cattle Feedlot Pens in Kansas. Journal of Environmental Quality, Volume 38, Number 3, pp. 909-918.

van der Schans, M.L., Harter, T., Leijnse, A., Mathews, M.C., and Meyer, R.D., 2009. Characterizing sources of nitrate leaching from an irrigated dairy farm in Merced County, California. Journal of Contaminant Hydrology 11.

Wang, L., Mankin, K., and Marchin, G., 2004. Survival of Fecal Bacteria in Dairy Cow Manure, American Society of Agricultural Engineers, Vol. 47 (4) pp. 1239-1246.

Watanabe, N, Harter, T., and Beramaschi, B., 2008. Environmental Occurrence and Shallow Groundwater Detection of the Antibiotic Monensin from Dairy Farms, Journal of Environmental Quality, Volume 37, pp. 1-8.

Watts, D., Torbert, H., and Prior, S., 2007. Mineralization of Nitrogen in Soils Amended with Dairy Manure as Affected by Wetting/Drying Cycles. Communications in Soil Science and Plant Analysis, Vol 38, pp. 2103-2116.

Winter, T., Harvey, J., Franke, O.L., and Alley, W., 1998. Groundwater and Surface Water, A Single Resource. U.S. Geological Survey, Circular 1139, Denver, CO, 79 pp.

WSDA, 2011. Washington Dairies and Digesters. Washington State Department of Agriculture, Dairy Nutrient Management Program. AGR PUB 602-343 (N/10/11), 19 pp.

WSDA, 2013. NPDES CAFO Permit. Washington State Department of Agriculture. http://agr.wa.gov/FoodAnimal/Livestock-Nutrient/NPDESCAFOpermit.aspx

Yin, F., Fu, B., and Mao, R., 2007. Effects of Nitrogen Fertilizer Application Rates on Nitrate Nitrogen Distribution in Saline Soil in the Hai River Basin, China. J Soils Sediments 7(3), pp. 136-142.

Zebarth, B., Bowen, P. and Toivonen, P., 1995. Influence of Nitrogen Fertilization on Broccoli Yield, Nitrogen Accumulation and Apparent Fertilizer-Nitrogen Recovery. Canadian Journal of Plant Science, 75, pp. 717-725.

Zebarth, B., B. Hii, H. Liebscher, K. Chipperfield, J. Paul, G. Grove, and S. Szeto, 1998. Agricultural Land Use Practices and Nitrate Contamination in the Abbotsford Aquifer, British Columbia, Canada. Agriculture Ecosystem Environment, Volume 69, pp. 99-112.

Appendices

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Appendix A: The Nitrogen Cycle

Nitrogen is a dynamic element. It exists in many forms and undergoes many complex transformations in the environment. The aggregate of these transformations is known as the nitrogen cycle (Figure A-1). The nitrogen cycle is a series of biological processes which are influenced by climatic conditions, the physical and chemical properties of a soil, and management of the land.

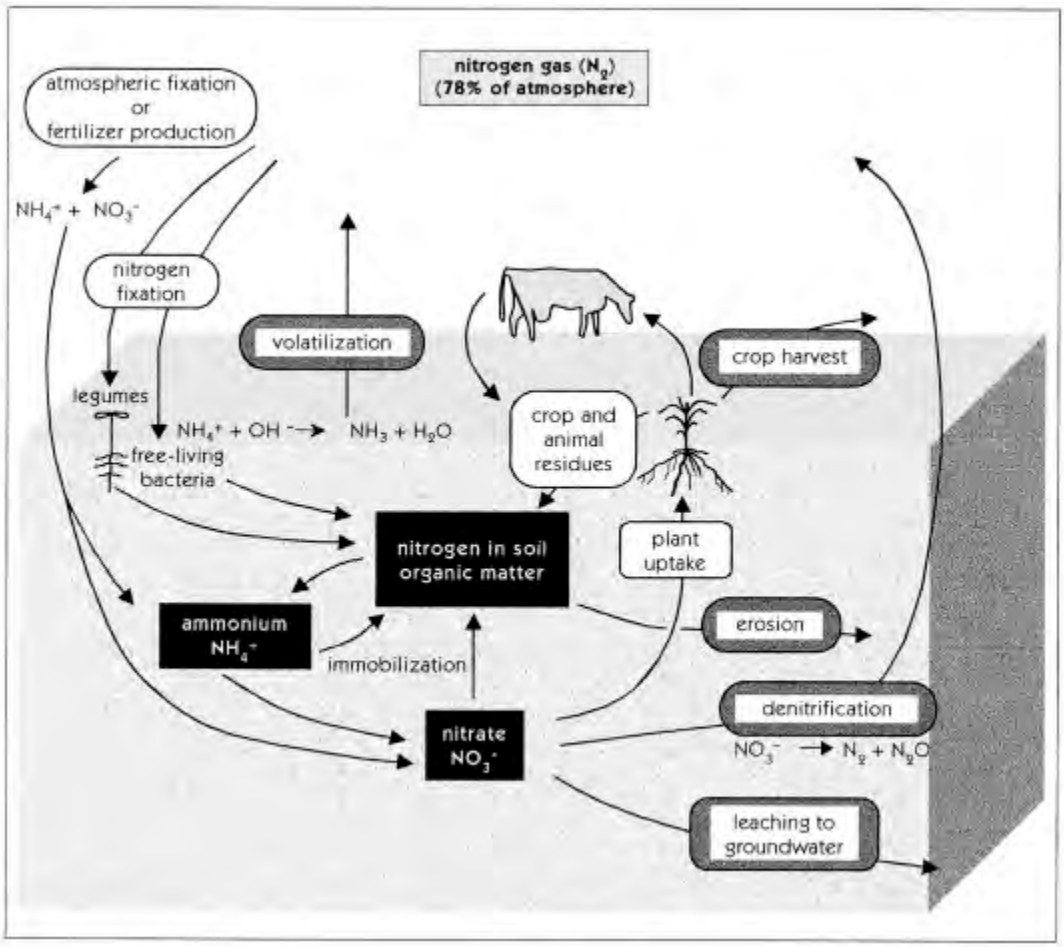

Figure A-1. Nitrogen Cycle (University of Western Australia, 2013).

Plants require nitrogen to grow. Animal manures and other organic wastes are sources of nitrogen for plant growth. The amount of nitrogen supplied by manure varies with the type of livestock, handling, rate applied, and method of application. The primary forms of nitrogen in manure are organic nitrogen and ammonium. Organic nitrogen must first be converted to an inorganic form (either ammonium or nitrate) before it can be taken up through roots and used by plants. When plants die, the organic matter becomes part of the soil. Then it is converted by bacteria, used by plants, and reverts back to organic matter. Table A-1 describes the different forms of nitrogen. Table A-2 describes the transformations that convert nitrogen into its different forms. (Killpack and Buchholz, 1993)

Table A-1. Nitrogen Forms.

Nitrogen Form	Chemical Formula	Description
Nitrogen gas Nitrous Oxide	N_2 N_2O	The atmosphere contains 78% nitrogen gas. Nitrogen gas must be transformed into usable forms before it is available for plant uptake.
Organic Nitrogen	Various forms	Organic nitrogen is the dominant form of nitrogen in manure. Organic nitrogen originates in living material; it is present in animal and human wastes and decomposing plant material. Organic nitrogen is not usable by plants directly; it must first be converted to an inorganic form (ammonium, nitrate).
Ammonia	NH_3	Ammonia can be present in either a liquid or gas state. Ammonia can escape from the surface of the soil under certain conditions. Anhydrous ammonia is the basic nitrogen form found in commercial fertilizers.
Ammonium	NH_4^+	Ammonium is an inorganic form of nitrogen and is available for plant uptake. Attenuation in soils occurs through cation exchange complexes.
Nitrite	NO_2^-	Nitrite is an intermediate product in the conversion of ammonium to nitrate (nitrification). It is usually present in low quantities but is toxic to plants.
Nitrate	NO_3^-	Nitrate is an inorganic form of nitrogen and is available for plant uptake. Nitrate is very soluble in water and highly mobile.

(Killpack and Buchholz, 1993)

Table A-2. Nitrogen Transformation Processes.

Nitrogen Process	Forms	Description
Nitrogen Fixation	N_2 => NH_4^+	Nitrogen fixation is the process that allows plants to convert nitrogen gas from the atmosphere into a form usable for growth. Industrial fixation is the manmade process of creating fertilizers.
Mineralization (Ammonification)	Organic nitrogen => NH_4^+	Mineralization is the conversion of organic nitrogen to ammonium. Bacteria are necessary in this process. Mineralization increases as microbial activity increases, which is directly related to soil temperature and water content.
Immobilization		Immobilization occurs when nitrate or ammonium present in the soil is used by bacteria to build proteins. These actively growing bacteria immobilize some soil N and break down soil organic matter to release N during the growing season. There is often a net gain of N during the growing season, because the additional N in the residue will be the net gain after immobilization-mineralization processes.
Nitrification	NH_4^+ => NO_2^- NO_2^- => NO_3^-	Nitrification is the conversion of ammonium to nitrite, and nitrite to nitrate. Nitrification is a biological process which increases rapidly in warm, wet aerobic conditions. Nitrification slows when soil temperatures decrease below 50°F.
Denitrification	NO_3^- => N gas	Denitrification is the conversion of nitrate to atmospheric forms of nitrogen. Denitrification is a bacterial process and occurs in anaerobic zones typically created by saturated soils and the presence of organic matter. Denitrifying bacteria use nitrate instead of oxygen in their metabolic process.
Volatilization	NH_3 => N gas.	Volatilization is the loss of gaseous ammonia to the atmosphere. Volatilization can occur from manure and fertilizer products containing urea. Ammonia is an intermediate form of nitrogen during the process in which urea is transformed to ammonium.

(O'Leary et al., 2002; University of Western Australia, 2013)

Processes that Affect Nitrogen Fate and Transport

Table A-3 summarizes the physical, chemical, and biological processes that result in gains and losses of nitrogen, which occur as part of the nitrogen cycle. These processes directly affect the fate and transport of nitrogen in the environment.

When nitrogen inputs to the soil system exceed crop needs, there is a possibility that excessive amounts of nitrate may leach to groundwater or runoff to surface water. Minimizing impacts to groundwater quality can be achieved through sound management practices. Understanding the characteristics of nitrogen in the environment can help in efficiently managing nitrogen in land treatment systems.

Table A-3. Processes and conditions that affect nitrogen fate and transport

Nitrogen Process	Result	Description
Attenuation		The effect of all processes that reduce contaminant concentrations. Ammonium is a positively charged ion which allows it to be immobilized by binding to negatively charged soil and soil organic matter. Ammonium does not move downward in soils unless all the cation exchange sites are saturated.
Leaching	Loss to groundwater	Leaching is a physical process in which nitrate moves with soil water. Nitrate is a negatively charged ion and is not attenuated by negatively charged soil particles. Nitrate is water soluble and, once it migrates below the root zone, may leach to groundwater.
Run-off	Loss to surface water	Runoff to surface water occurs when fields are frozen or saturated and nitrogen cannot infiltrate into the soil pores. Water ponds and moves downhill towards drains, ditches, or surface water.
Consumption	Loss	Consumption of nitrogen by plants and other organisms occurs while nitrogen is retained in the root zone.
Decomposition	Loss	Any portion of a plant that is left after harvest, including roots and nodules, supplies N to the soil system. When the plant material decomposes, N is released.
Precipitation	Gain	Small amounts of N are added to the soil from precipitation.
Addition of Fertilizers or Manure	Gain of N to soil	Direct additions of manure, wastewater, or commercial fertilizers to crops.
Crop Removal	Loss	Crop removal during harvest accounts for the majority of the N that leaves the soil system.
Soil Organic Matter	Gain of nitrate. Loss of organic nitrogen	Decomposition of organic matter proceeds at a slow rate and releases approximately 20 lb N/acre/year for each percent of organic matter.

(O'Leary et al., 2002; University of Western Australia, 2013)

Appendix B: Regulatory Authority

Animal Feeding Operations (AFOs)

Ecology combines the National Pollutant Discharge Elimination System (NPDES) and State Waste Discharge (SWD) requirements in permits it issues for CAFOs. A permit issued to a CAFO that has a discharge may be an individual or general permit. Individual permits are a type of permit that is written for one specific facility. The permit requirements are unique and tailored to the activities taking place at that facility. General permits are a type of permit that covers a category of discharger. A category of discharger is usually a group of facilities that have similar discharge characteristics and utilize similar treatment mechanisms. Once a general permit is issued, facilities in that category can apply for coverage under the general permit. All facilities covered under a general permit have the same requirements. (Ecology, 2006)

There are legal classifications for defining AFOs and CAFOs, which are defined in 40 CFR 122.23 and are based on the type of animals, the number of animals, and how the animals are managed.

Large and medium size CAFOs are required to apply for a permit if they have (or had) a discharge to surface or groundwater of the state. For small CAFOs, and CAFOs with an animal type not listed in the federal CAFO rule, part of the process of designating the facility may be requiring the facility to apply for a permit. (Ecology, 2006)

The federal CAFO rule (current revision 2012) is the authority upon which Ecology bases its permits. It requires that CAFO permits be no-discharge permits. Discharges from CAFOs under a permit are prohibited, except in a narrow range of circumstances. CAFO permit requirements are designed to protect water quality through requiring the use of facility and manure management practices and record keeping requirements.

There is no requirement to monitor groundwater in the expired general permit, even when there are indications of groundwater impacts. Therefore, determining a discharge to groundwater (which is a water of the state) has been problematic. If a CAFO is not managing its manure properly, if manure is over-applied, if manure is applied at the wrong time, or if manure is stored in a lagoon not constructed to a recognized standard, then groundwater quality is likely impacted. Up to this point, CAFOs generally have not had to demonstrate compliance with groundwater quality standards. (Ecology, 2006)

In 1993, the Dairy Nutrient Management Act (Chapter 90.64 RCW) was passed by the state legislature. This legislation created a state Livestock Nutrient Management Program at Ecology, focused on regulating discharges from dairy operations. Part of the program was issuing permits to dairies that discharge. In 2003, the legislature moved this program from Ecology to the Washington State Department of Agriculture (WSDA). However, Ecology retained the authority to issue permits for facilities with discharges. This essentially split the program between Ecology and WSDA. The two state agencies coordinate resources: Ecology is responsible for administering, developing, and processing CAFO permits; WSDA inspects unpermitted dairies and permitted CAFOs and provides technical support to the operators of CAFOs. (WSDA, 2013; Ecology, 2013)

As a result of the Dairy Nutrient Management Program, the number of dairies and their locations is known. Because dairies are a known quantity and easily identifiable, they generally become the focal point of AFO related discussions. AFOs include CAFOs and the entire animal agricultural industry as a whole (e.g., beef, poultry, dairy, swine, horses), not just dairy farms. For example, based on USDA agricultural Census for 2007, there were approximately 243,000 milking cows in Washington State. At the same time, there were approximately 274,000 beef cows, 571,000 other cattle, 5.7 million laying hens, and 4.6 million broilers.

Washington State currently has 12 permitted CAFOs. One of these facilities is under an individual permit as a very large beef finishing operation. The remaining 11 facilities are 4 beef operations, 1 laying hens, and 6 dairies. These 11 facilities meet the requirements to continue coverage under the expired general permit and will most likely be rolled over into the next CAFO general permit that Ecology issues. (Jennings, 2013)

All dairies are required under Chapter 90.64 RCW to have a nutrient management plan. However, there is no legal requirement to implement the NMP on site or to collect or report annual soil test results. There are also no requirements for any environmental monitoring other than soil monitoring. These data are reviewed when WSDA inspects the dairy, which occurs approximately once every 2 years. Although a facility may be adhering to a site-specific NMP, it does not guarantee that a facility will be in compliance with water quality standards. Since there are no monitoring requirements for groundwater or surface water quality, there are no definitive means to verify that a dairy is complying with water quality laws and regulations. (Jennings, 2013)

Water Quality Regulatory Authority

Groundwater quality in Washington State is protected by the Water Pollution Control Act (Chapter 90.48 RCW), and the Groundwater Quality Standards (Chapter 173-200 WAC). These regulatory mandates are intended to protect all waters in the saturated zone, and apply to any activity which has a potential to pollute groundwater quality, including discharges from AFOs, waste storage facilities, and other agricultural activities.

The goal of the Groundwater Quality Standards is to maintain high quality groundwater and to protect existing and future beneficial uses through the reduction or elimination of contaminants discharged to the subsurface. This goal is achieved through treatment standards (AKART), the antidegradation policy, and the numeric criteria. The relevant criteria are listed below in Table B-1.

Table B-1. Groundwater criteria.

Groundwater Parameter	Groundwater Criteria (Standard)
Total Coliform Bacteria	1 colony/100 ml
Nitrate + Nitrite (as N)	10 mg N/L
Total Dissolved Solids (TDS)	500 mg/L

Ecology Guidance on Land Treatment Systems

Ecology regulates other land treatment systems by issuing permits, setting permit requirements, and monitoring water quality. Ecology developed a guidance document (*Guidance on Land Treatment of Nutrients in Wastewater, with Emphasis on Nitrogen*) to assist in managing these facilities. A land treatment system is intended to maximize nutrient uptake by the crop and minimize contaminant leaching below the root zone to protect the beneficial uses of the groundwater. Maximizing crop yield is not equivalent to maximizing crop uptake. Maximizing crop yield is not the goal of a land treatment system. Land treatment systems that have been approved and permitted by Ecology require that water and nutrients must not be applied in excess of the agronomic rate of the site's cover crop. (Ecology, 2004a)

Dairies

Dairies are one type of AFO that in some cases may be defined as a CAFO. Dairies produce milk and other dairy-related products. Milk is Washington State's second most valuable agricultural commodity, second only to apples. Washington State was ranked 10th nationally, producing 690 million gallons of milk in 2010. (WSDA, 2011)

In 2010, Washington housed 443 commercial dairy farms with approximately 250,000 mature cows. WSDA (2011) notes that the number of dairy farms has dropped over the years, yet the number of dairy cows have remained relatively constant.

Dairy farms are located in 28 of the 39 Washington counties. Table B-2 describes the dairy size classifications and Figure 1 illustrates the distribution of classes within the state. Whatcom County is home to the most dairies, with 125 farms housing a total 46,588 mature cows. Yakima County has the highest number of cows with 93,606 mature cows housed on 67 farms. Seventy percent of the large dairies are located in Yakima County and the Columbia Basin. The majority of small and medium dairies are located in western Washington. (WSDA, 2011)

Table B-2. Dairy size and distribution.

Dairy Size	Number of Cows	Percent of Total Dairies in Washington State
Small	1 – 199	40%
Medium	200 – 699	37%
Large	700 +	23%
	>2,500	4% (16 of the large dairies)

(WSDA, 2011)

Appendix C: Construction of Dairy Lagoons Below the Seasonal High Groundwater Table

Issue Paper

Construction of Dairy Lagoons Below the Seasonal High Groundwater Table

Washington State Department of Ecology
Water Quality Program, Southwest Regional Office
Melanie Kimsey, Hydrogeologist
January 18, 2002

Issue

There are a number of dairies in Washington State that are located above a seasonally high (near surface) groundwater table, that have requested NRCS (Natural Resources Conservation Service) design assistance for their waste management system. To obtain the required certified nutrient management plan, all dairies must meet NRCS specifications for waste storage ponds. The NRCS Waste Storage Facility Pond Criteria (313-Practice Standard) requires that all ponds have a bottom elevation that is a minimum of 2 feet above the seasonal high groundwater table. NRCS has indicated that building a soil embankment waste storage pond 2 feet above the seasonal high groundwater table, using imported soil material, is cost prohibitive for these dairies.

The NRCS is requesting assistance from Ecology in developing alternatives for these dairies that are also consistent with water quality standards. The primary alternative that NRCS is asking Ecology to consider is a liquid manure storage pond and if it can be designed and built below the seasonal high groundwater table and still protect groundwater quality.

The technical justification provided by NRCS in support of this proposal only considers the hydraulic issues and does not address impacts to water quality. If the unsaturated zone is diminished or eliminated, the soil treatment capacity for pathogens is also eliminated. Lagoon leakage studies previously conducted by Ecology identify groundwater contamination in areas where there are direct discharges to groundwater.

Dairy lagoons are an important part of the operation and management of dairy wastes. The lagoons provide storage during the non-growing season and during times when it is not possible to land-apply wastewater at agronomic rates. Dairy manure contains elevated concentrations of total dissolved solids, BOD, total nitrogen, phosphorus, chloride, and microbiological pathogens. This is detailed in Table C-1.

Dairy Lagoon Wastewater Characterization

Table C-1. Typical Dairy Lagoon Wastewater Characterization.

Parameter	Average Concentration	Range
Total Dissolved Solids	4,232 mg/l	2,890 – 6,850 mg/l
BOD	5,980 mg/l	1,300 –14,600 mg/l
Total Nitrogen	456 mg N/L	275 – 600 mg N/L
Phosphorus	71 mg/l	26 – 133 mg/l
Chloride	221 mg/l	139 – 399 mg/l
Total Coliform	3,678,000 cfu/100 ml	230,000 – 7,400,000 cfu/100 ml
Fecal Coliform	1,755,000 cfu/100 ml	200,000 – 5,800,000 cfu/100 ml

Derived from Department of Ecology (Ecology, 1994a).

Total coliform bacteria has a groundwater quality criterion of 1 cfu/100 ml. Without any pretreatment, these contaminants will be directly discharged to groundwater and will cause a violation of the groundwater quality standards.

Nitrogen Assimilation

Conventional parameters such as nitrogen and total dissolved solids can be managed by reducing the specific discharge from the lagoon and calculating the amount of assimilation that will occur in the aquifer at the downgradient property boundary. This exercise was conducted in 1993 when Ecology modeled the impacts of various lagoon designs, estimated the impacts to groundwater quality, and determined the appropriate design based on an acceptable level of degradation. This exercise resulted in a recommended liner permeability of $1x10^{-6}$cm/sec, with the assumption that manure sealing would provide approximately an order of magnitude of additional protection resulting ultimately in a permeability of $1x10^{-7}$ cm/sec. These modeling results were used to establish lagoon design standards that are protective of groundwater quality.

Minimum Vertical Separation

Vertical separation between the point of discharge and the top of the water table is one of the most important variables in preventing the transmission of disease from animal and human wastewater. For dairy lagoons, the primary pathogen treatment mechanism is an adequate vadose zone. The vadose zone allows microorganisms to be attenuated. Dairy lagoons can impact groundwater quality if the microbiological pathogens are not treated in the unsaturated zone. The minimum vertical separation provides the space for treatment to occur. Soils generally function as attenuation zones by filtering the larger bacteria and adsorbing the smaller viruses onto the negatively charged particles in the soil. Survival is prolonged under saturated and cool conditions. Inactivation is related to the activity of the native soil microorganisms and their antagonistic effects. Maintaining an aerobic, unsaturated environment beneath the lagoon is essential to the attenuation and inactivation of bacteria and viruses.

Microbiological pathogens, such as bacteria and viruses, can remain viable for extended periods of time in the subsurface depending upon the environmental conditions. Survival rates for these organisms depend upon the soil moisture, rainfall, temperature, pH, and the organic content of the soil (Bitton and Gerba, 1984). Scientific studies have noted pathogens surviving for extended periods of time and travelling considerable distances in the subsurface. Enteric bacteria can survive up to 100 days in favorable conditions and viral movement has been documented 1312 feet in sandy soils. (Canter and Knox, 1985; Keswick and Gerba, 1980)

The degree of vertical separation is dependent upon site-specific characteristics, including soil texture. In fine-grained soils, a minimum of 2 feet may be adequate; but in coarser-grained soils, 10 to 12 feet may be necessary to remove all pathogens. Groundwater mounding can become a concern when the mound reduces the vertical separation by artificially raising the water table, such that pathogen attenuation is no longer effective (Cogger, 1989).

Therefore, if microbiological pathogens are not removed or treated in the unsaturated zone and they are allowed to migrate to groundwater, they can be transported great distances, potentially contaminating groundwater and affecting drinking water wells, surface water bodies, and shellfish habitat.

Dairy Lagoon Studies

Ecology's Environmental Assessment Program has conducted several studies that investigate the impacts of dairy lagoons on groundwater quality. Two of these studies consider lagoons that are located below the seasonal high groundwater table on an intermittent basis. Both of these dairies are located in Whatcom County (Ecology, 1991; 1994a; 1994b).

These reports conclude that the vertical separation distance between the bottom of the lagoon and the top of the water table may account for elevated groundwater concentrations for many constituents in downgradient wells. Bacterial concentrations were only detected intermittently in groundwater. However, there is a direct correlation between total coliform and fecal coliform concentrations when the water table elevation was higher than the bottom of the lagoon.

Consistency with Washington State's Regulatory Philosophy

A lagoon constructed below the seasonal high groundwater table is a direct discharge to groundwater. The liquid contained in a dairy lagoon is untreated manure. Ecology has not permitted the direct discharge of untreated wastewater or treated wastewater into groundwater for other activities. Ecology has not permitted the direct injection of wastewater into groundwater without treatment and monitoring constraints.

- The UIC (Underground Injection Control) program prohibits the direct injection of any wastewater, including stormwater, into groundwater.
- The reclaimed water standards have very stringent requirements for direct groundwater recharge, including a high level of treatment and rigorous reliability and redundancy requirements.

- The Department of Health on-site sewage system regulations require a minimum of three feet of vertical separation between the bottom of the septic system drainfield and the top of the water table.
- Ecology's stormwater manual recommends that all facilities be located at least three feet above the seasonal high water mark, bedrock (or hardpan), and/or impermeable layer.

Ecology and the State of Washington have established a regulatory precedent which prohibits a direct discharge of untreated waste into groundwater.

NRCS Proposal

In areas where a seasonal high groundwater table exists, the NRCS is advocating a single membrane-lined lagoon with a soil cover as a cost-effective dairy lagoon design.

This proposed design below the seasonal high water table is not a viable option because this constitutes a direct discharge of untreated manure into groundwater, since all liners leak. This option removes the vadose zone, which acts as the only treatment for pathogens. Based on the elevated concentrations of pathogens in dairy manure, and the fact that pathogens can remain viable in the subsurface for extended periods of time and travel considerable distances once in groundwater, a design of this nature would cause a violation of the groundwater quality standards. This option is also inconsistent with other regulatory approaches to treating wastewater that is discharged to the subsurface.

Options

Due to the persistent and mobile nature of pathogens, dilution is not an acceptable form of treatment. It is not possible to calculate an acceptable volume of wastewater discharge that will be protective of groundwater quality if the proposed direct discharge occurs. It is imperative that the wastewater either be contained or treated prior to being discharged to groundwater. Two main options exist for designing dairy lagoons in areas with seasonally high groundwater tables and providing required protection of groundwater quality from microbiological pathogens.

Option #1

The lagoon shall have a bottom elevation that is a minimum of 2 feet above the seasonal high groundwater table. In areas where the seasonal high groundwater table is less than 2 feet, additional soil should be used to create an above-ground lagoon.

This option provides a treatment zone for the attenuation and inactivation of pathogens, which is necessary to achieve compliance with the groundwater quality standards (Chapter 173-200 WAC). This option is similar to the NRCS Practice Standard 313 Waste Storage Structures. The main difference is that this proposed option does not allow the use of perimeter drains to artificially lower the water table.

Option #2

Construct a non-discharging lagoon by designing a double membrane lined lagoon with a leak detection system. This option achieves containment of the dairy wastewater and creates a non-discharging lagoon. A properly designed double membrane lagoon with a leak detection system should achieve compliance with the groundwater quality standards. This design could be situated below the seasonal high groundwater table.

The recommended design of the proposed double membrane lined lagoon with a leak detection system, the design considerations, and construction quality assurance are described below (Garin Schrieve, Department of Ecology, written communication, January 2002).

Recommended Design
The recommended default approach for double-liner systems where the bottom will be constructed below the seasonal high groundwater table is the following:

Two flexible membrane liners of minimum 30-mil thickness (60-mil if HDPE) separated by a suitable granular or geosynthetic leak detection layer. The leak detection layer must be capable of transmitting any leakage through the primary liner to a collection point or sump without becoming saturated to its full depth. Leakage accumulating in the collection point or sump should be periodically measured and removed such that potential for leakage through the secondary liner is minimized.

This recommendation is consistent with the draft Surface Impoundment Standards in *Minimum Functional Standards for Solid Waste Management* (formerly Chapter 173-304 WAC now proposed as Chapter 173-350 WAC). These standards call for liners consisting of either a single membrane liner with groundwater monitoring or a double membrane liner equipped with a leak detection and collection layer.

Other types of double-liner systems may be suitable for this application. However, due to concerns with cyclic hydration/desiccation of the secondary liner with the fluctuation of the groundwater table, soil liners and geosynthetic clay liners (GCL) may not be suitable for secondary liners in these types of systems. The design engineer should consult the literature in determining the applicability of these materials for a particular impoundment.

Further Design Considerations
It is beyond the scope of this report to discuss all the design elements that should be considered for each waste containment impoundment. However, some areas of particular concern for these types of systems include:

- *Membranes.* The type of membrane selected must perform well under the service loadings and be amenable to standard welding and seam testing techniques. The membrane must be protected from protruding objects in the subgrade, leak detection layer, and cover material (if used). Particular attention should be paid to the potential for damage of the membranes during placement of overlying layers.
- *Leak Detection Layer.* The layer must have the hydraulic capacity under the design loadings to transmit primary liner leakage without becoming saturated. The design must consider

reductions in transmissivity due to creep, blockage by soil particulates, or biological fouling. If soil or GCL is used as a liner, appropriate measures must be included to prevent migration of soil particles into the detection layer.

- *Foundation soils*. Foundation soils must be capable of supporting the pond without deformation that would jeopardize the liner system. Soils must provide suitable bedding for the membrane—consult ASTM standards on installation of geomembrane for specifics on acceptable subgrade conditions.
- *Uplift.* Special attention should be paid to the potential for damage to the liner system by groundwater uplift forces under various fill depths.
- *Static and seismic stability*. The stability of embankments and geosynthetics should be evaluated. Particular attention should be paid to material interfaces and uplift forces by groundwater which may reduce interface friction. Due to saturated soil conditions, special attention should also be paid to the susceptibility to liquefaction of the foundation soils. Design review by Ecology's Dam Safety Section is triggered for impoundments capable of containing 3,259,000 gallons.

Construction Quality Assurance

The importance of construction quality control and quality assurance for waste containment facilities cannot be overemphasized. The only way to ensure that the facility will perform as designed is to prepare and implement a Construction Quality Assurance Plan which lays out the program of inspection and testing that will be conducted during construction. The EPA guidance document, *Quality Assurance and Quality Control for Waste Containment Facilities* (EPA/600/R-93/182) represents the state of the practice for construction quality assurance at waste containment facilities and should be followed.

Additional Concerns

- Ecology acknowledges the agreement made with the NRCS in 1994 regarding the minimum vertical separation requirement and is not proposing to increase this requirement at this time. However, current scientific knowledge points to the use of maintaining a minimum vertical separation of 3 feet or greater, depending upon the soil type. Incorporating these elements into lagoon siting and construction designs would provide consistency with the regulatory requirements for minimum vertical separation established by the Department of Health for On-Site Sewage Systems and by Ecology for stormwater infiltration systems.

- There is a discrepancy between the construction standards for dairy lagoons and those standards required for all other waste impoundments. In order to obtain equal protection for groundwater and to comply with Chapter 173-240 WAC, manure lagoons should be designed, constructed, and installed consistent with the requirements for other waste impoundments.

References (for Appendix C)

Bitton, G. and C. Gerba, 1984. Groundwater Pollution Microbiology: The Emerging Issue. Groundwater Pollution Microbiology, 7 pp.

Canter, L. and R. Knox, 1985. Septic Tank System Effects on Groundwater Quality". Lewis Publishers Inc., 336 pp.

Cogger, C., 1989. Seasonal High Water Tables, Vertical Separation and System Performance. Proceedings from the 6th On-Site Wastewater Treatment Short Course, Seattle, WA, pp. 204-220.

Ecology, 1991. Edaleen Dairy Lagoon Groundwater Quality Assessment, February 1990 to February 1991. Washington State Department of Ecology. Publication No. 91-e11, 32 pp. https://fortress.wa.gov/ecy/publications/SummaryPages/91e11.html

Ecology, 1994a. Effects of Leakage from Four Dairy Waste Storage Ponds on Groundwater Quality, Final Report. Washington State Department of Ecology. Publication No. 94-109, 50 pp. https://fortress.wa.gov/ecy/publications/SummaryPages/94109.html

Ecology, 1994b. Groundwater Quality Survey near Edaleen Dairy, Whatcom County, Washington, January 1990 to April 1993. Washington State Department of Ecology. Publication No. 94-37, 20 pp. https://fortress.wa.gov/ecy/publications/SummaryPages/9437.html

Keswick, B. and C. Gerba, 1980. Viruses in Groundwater. Environmental Science Technology 14: pp. 1290-1297.

Appendix D: Sampling Guidelines

Manure Sample Collection

Understanding manure composition is an important part of the monitoring process. The results of the manure analyses will be used to determine the amount of manure to apply based on the Nutrient Management Plan. This section contains procedures for sampling both liquid and solid manure.

Quality Assurance information, guidance, and project plan templates can be found at Ecology's website: http://www.ecy.wa.gov/programs/eap/quality.html.

A Quality Assurance Project Plan (QAPP) should be developed which describes the sampling procedures and goals. Guidance on developing this plan can be found at: https://fortress.wa.gov/ecy/publications/SummaryPages/0403030.html

A laboratory should be used that routinely analyzes manure samples. Manure nitrogen analyses can be reported in two ways:

- Reported "as-received" is used to determine application rates. This is described as ammonium and total nitrogen in lbs/ton.
- Reported "dry-weight basis" is used to track manure nitrogen composition that can indicate consistency over time and is described as nitrogen in mg/kg.

(Sullivan et al., 1997; Bary et al., 2000)

All laboratories used must be accredited and must supply quality assurance results with the data. Details on the volumes of manure samples needed and sample containers can be arranged with the laboratory. Table D-1 describes the manure monitoring parameters and analytical methods. (Bary et al., 2000; Peters et al., 2003; Momohara, 2012).

Table D-1. Manure monitoring parameters and analytical methods.

Analyte	Analytical Method	Units
pH	SW-846-9045D	Standard Units
Dry matter/Solids	SM 2540G	Percent
Electrical conductivity	SW-846-9050	µmhos/cm
Ammonium-Nitrogen	SM-4500-NH_3 B+ C, D, E, or G	mg/kg
Total Kjeldahl Nitrogen	Combustion: Micro-Dumas Method [1] Analysis: SM-4500-N_{org} B or C	mg/kg
Phosphorus	SM 4500-P B+E or F; Digestion EPA 200.2+Analysis 200.7 or SW-846-6010	mg/kg
Potassium	Digestion SW-846-3050; Analysis SW-846-6010, 846-6020, EPA 200.7, or 200.8	mg/kg
Chloride	SW-846-9056	mg/kg
Total Carbon	SW-846-9060	mg/kg

[1] Hauck (1982) and Wolfgang (1983) http://sisbl.uga.edu/udumas.html
SM: Standard Methods for the Examination of Water and Wastewater, 20th Edition.
EPA: EPA Methods for Chemical Analysis of Water and Wastes, EPA 600/4-79-020.
SW 846 --U.S. Environmental Protection Agency (U.S. EPA). Test Methods for Evaluation of Solid Waste, Physical/Chemical Methods. EPA Publication SW-846.

Liquid Manure

The following are recommended procedures for sampling liquid manure.

- Before manure application:
  - Sample from the storage facility after agitating the storage facility for a minimum of 2 to 4 hours (Peters et al., 2003).
  - Collect at least 5 sub-samples, using a clean 5-gallon bucket.
  - Combine the subsamples in a clean container.
  - Mix thoroughly.
  - Pour samples into laboratory-supplied sample bottles.
  - Send samples to the laboratory.

- While manure is being applied: Use either collection method 1 or 2 as described below.

Method 1. Sample manure from application equipment

- Collect at least 3 composite grab samples from a sampling port in the manure application equipment during the application to the field (i.e., after ¼ of the field has received manure, ½ of the field, and ¾ of the field).
- Grab samples should be composited in a clean 5-gallon bucket.
- Mix thoroughly with a clean ladle or other mixing device.

- Send samples to the laboratory.

Method 2. Sample manure from field during application

- Collect subsamples in clean 5-gallon buckets located within the field to catch manure from the spreader.
- Combine the subsamples and mix thoroughly.
- Pour into laboratory-supplied sample bottles.
- Send samples to the laboratory. (Sullivan et al., 1997)

- Freeze samples if mailing to the laboratory or refrigerate if delivering directly.

- Ensure that samples reach the laboratory within 48 hours of collection and that the laboratory can analyze them within established holding times.

Solid Manure

The following are recommended procedures for sampling solid manure (Bary et al., 2000; Peters et al., 2003):

- Sampling during loading: This method is recommended for sampling from a stack or bedded pack.
  - Take at least 10 to 20 samples while loading several spreader loads.
  - Combine to form one composite sample.
  - Thoroughly mix the composite sample (about 5 gallons).
  - Take a 1-pound/1- quart subsample using a 1-gallon plastic bag or other container, as recommended by the laboratory.
  - Sampling directly from a stack or bedded pack is not recommended.

- Sampling during spreading
  - Spread a clean tarp in the field.
  - Catch the manure from one pass of the applicator.
  - Repeat this process at several locations.
  - Create a composite sample.
  - Thoroughly mix the composite sample.
  - Take a 1-pound/1-quart sample with a 1-gallon plastic bag or other container recommended by the laboratory.

- Freeze samples if mailing to the laboratory or refrigerate if delivering directly.

- Ensure that samples reach the laboratory within 48 hours of collection and that the laboratory can analyze them within established holding times.

Field Measurements

Field meters, such as an Agros Meter, can provide a quick and reliable field test for ammonium-N to compare with laboratory results (Sullivan et al., 1997; Sullivan et al., 1994; British Columbia Ministry of Agriculture, 1994). The Agros Meter can be used with both liquid manure and diluted solid manure.

Soil Sample Collection

Soil samples should be collected in a manner that is representative of the entire field and the sampling depth. Soil probes or augers should be used to collect samples. A shovel should not be used since it will not collect a uniform sample with depth.

Samples locations should be planned in advance using field maps. These locations should be recorded with a GPS and sampled consistently each sampling event to assess variability over time. At each location, samples should be collected using a grid or a random zig-zag pattern, making sure to sample where manure is routinely applied, and areas which represent average crop growth. (Sullivan and Cogger, 2003; Staben et al., 2003)

Soil samples should be collected by scraping away any crop residue or manure present at the soil surface. Only the soil should be collected for analysis. If the manure has been injected into the soils, then care should be taken to avoid the injection sites, and a larger number of soil cores should be collected to promote representativeness. (Sullivan and Cogger, 2003)

Composite samples should be collected in a bucket and then mixed thoroughly before a subsample is taken. Samples should be placed in containers provided by the laboratory and then kept refrigerated or frozen. Samples should be shipped to the laboratory within 48 hours of collection.

Number of Samples

Soil composition varies spatially. Soil samples should be composite samples consisting of 15 to 30 soil cores from each field. The number of subsamples needed to characterize conditions at each depth depends on the size of the field as shown in Table D-2.

Table D-2. Number of subsamples recommended for a representative composite sample, based on field size (Mahler and Tindall, 1997).

Field Size (acres)	Number of Subsamples
Fewer than 5	15
5 to 10	18
10 to 25	20
25 to 50	25
More than 50	30

Soil Sampling Depth

Samples should be taken at one-foot depth intervals from the land surface to one foot above the water table or to a confining layer (Ecology, 2000).

Sample Collection and Handling

Soil samples should be analyzed for the parameters listed in Table D-3.

Table D-3. Laboratory analytes and analytical methods for soil samples.

Analyte	Analytical Method
pH	SW-846-9045D
Organic Matter	Dry combustion method (USDA/NRCS, 2004)
Cation Exchange capacity	Effective cation-exchange capacity (USDA/NRCS, 2004)
Nitrate	SM 4500-NO_3 E, F, or H
Ammonium-Nitrogen	SM-4500-NH3 B+ C, D, E, or G
Total Kjeldahl Nitrogen	SM 4500-N_{org}B; SM 4500-N_{org}C
Phosphorus	SM 4500-P B+E or F; Digestion EPA 200.2+Analysis 200.7 or SW-846-6010

SM: Standard Methods for the Examination of Water and Wastewater, 20th Edition.
SW-846: U.S. Environmental Protection Agency (U.S. EPA). Test Methods for Evaluation of Solid Waste, Physical/ Chemical Methods. EPA Publication SW-846.
EPA: EPA Methods for Chemical Analysis of Water and Wastes, EPA 600/4-79-020.
Soil Survey Investigations Report No. 42, Soil Survey Laboratory Information Manual, Version 4.0, 2004, USDA/NRCS.

Groundwater Quality Monitoring

A groundwater monitoring plan, in the form of a Quality Assurance Project Plan, should be developed and approved consistent with the *Implementation Guidance for the Groundwater Quality Standards* (Kimsey, 2005) and the *Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies* (Ecology, 2004b). This plan should include the following elements:

- Install a sufficient number of upgradient and downgradient monitoring wells to determine groundwater flow direction and impacts from the CAFO on groundwater quality. These wells should be tagged with an Ecology-issued, unique well ID number, and they must be constructed according to Chapter 173-160 WAC, Minimum Standards for the Construction and Maintenance of Wells.
- Groundwater sampling should follow Ecology's standard operating procedures for sampling monitoring wells (Marti, 2011a) and water supply wells (Marti, 2011b).
- A sampling plan should be developed which includes:
  - Well location and construction information.
  - Hydrogeologic description of the site.

- Groundwater flow direction.
- Identification of a background well.
- Sample frequency -- Quarterly groundwater monitoring.
- Well purging criteria.
- Sample collection procedures.
- Sample analysis by an accredited laboratory.
- Field measurements of groundwater temperature, pH, conductivity, and dissolved oxygen.
- Static groundwater elevations measured to a NAVD88 datum and groundwater flow direction determined.
- Quality assurance samples (field blanks, equipment blanks, duplicates).
- Groundwater quality data and water level data should be entered into Ecology's Environmental Information Management System (EIM).

The U.S. Geological Survey (variously dated) developed and maintains the *National Field Manual for the Collection of Water Quality Data.* This manual contains sampling procedures for the accurate assessment and management of surface water and groundwater resources.

Surface Water Monitoring

The Department of Ecology developed a guidance document that describes the important elements for characterizing water quality conditions of streams and lakes near dairy and concentrated animal feeding operations (CAFOs) (Plotnikoff et al., 2006). This document describes elements for developing a monitoring program that produces reliable data. Examples are provided for establishing monitoring sites, selecting water quality parameters, and analyzing data. An extensive list of references is included for planning more complex projects.

Sample Identification, Handling and General Considerations

Each sample container should be labeled with information regarding the farm name, date, and time collected. Manure application method and location should be recorded for long-term records.

All manure samples should be kept frozen and shipped on ice to the laboratory within 24 to 48 hours of collection. Samples may be refrigerated if delivered immediately to the laboratory.

Quality Assurance

Each CAFO permit will need a Quality Assurance Project Plan (QAPP) that includes all sampling and analysis as described in https://fortress.wa.gov/ecy/publications/summarypages/0403030.html . This guidance should be used in developing the QAPP to ensure reliable, representative results.

Laboratory analyses must be conducted by a laboratory accredited in Washington State.

A minimum of 10% blind duplicate samples are necessary to provide adequate quality assurance. For instance, if composite samples are collected at 10 fields in one day, a duplicate composite sample is needed at one of the fields.

Samples collected from an agitated lagoon should include a minimum of one duplicate per round.

One method for collecting a blind duplicate composite sample is to use two buckets at the field where a duplicate is collected. Each time a grab sample is collected during the manure application (3 times for each field), manure can be added to both buckets. At the end of the manure application to the field, each bucket should be treated the same as a typical sample, to ensure that the samples have different sample identification numbers.

A standard reference material should be submitted to the laboratory annually to evaluate accuracy of results (Peters et al., 2003).

Laboratory quality assurance results for all samples should be evaluated to ensure that results are reliable.

Appendix E: Glossary, Acronyms, and Abbreviations

Glossary

Agronomic rate: The rate at which a viable crop can be maintained and there is minimal leaching of chemicals downwards below the root zone. Crops should be managed for maximum nutrient uptake when crops are used for wastewater treatment.

Anthropogenic: Human-caused.

Application efficiency (Ea): The ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied, expressed as a percentage. Also referred to as AE.

Average annual precipitation: The long-term or historic (generally 30 years or more) arithmetic mean of precipitation (rain, snow, dew) received by an area.

Bulk density: Mass of dry soil per unit volume, determined by drying to constant weight at 105°C, usually expressed as gm/cc or lb/ft^3. Rock fragments 2 mm or larger are usually excluded or corrected for after measurement.

Capillary water: Water held in the capillary, or small pores of the soil, usually with soil water pressure (tension) greater than 1/3 bar. Capillary water can move in any direction.

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Contamination: Water that has been degraded such that it does not meet the groundwater quality criteria listed in Chapter 173-200 WAC.

Crop rooting depth: Crop rooting depth is typically taken as the soil depth containing 80 percent of plant roots, measured in feet or inches.

Crop water use: Calculated or measured water used by plants, expressed in inches per day. Same as ETc except it is expressed as daily use only.

Effective precipitation (Pe): The portion of precipitation that is available to meet crop evapotranspiration. It does not include precipitation that is lost to runoff, deep percolation, or evaporation before the crop can use it.

Effective rooting depth: The depth from which roots extract water. The effective rooting depth is generally the depth from which the crop is currently capable of extracting soil water. However, it may also be expressed as the depth from which the crop can extract water when mature or the depth from which a future crop can extract soil water. Maximum effective root depth depends on the rooting capability of the plant, soil profile characteristics, and moisture levels in the soil profile.

Effluent: An outflowing of water from a natural body of water or from a man-made structure. For example, the treated outflow from a wastewater treatment plant.

Evaporation pan: (1) A standard U.S. Weather Bureau Class A pan (48-inch diameter by 10-inch deep) used to estimate the reference crop evapotranspiration rate. Water levels are measured daily in the pan to determine the amount of evaporation. (2) A pan or container placed at or about crop canopy height containing water. Water evaporated from the device is measured and adjusted by a coefficient to represent estimated crop water use during the period.

Evaporation: The physical process by which a liquid is transformed to the gaseous state, which in irrigation generally is restricted to the change of water from liquid to vapor. Occurs from plant leaf surface, ground surface, water surface, and sprinkler spray.

Evapotranspiration (ET): The combination of water transpired from vegetation and evaporated from soil and plant surfaces. Sometimes called consumptive use (CU).

Field capacity: The amount of water retained by a soil after it has been saturated and has drained freely by gravity. Can be expressed as inches, inches per inch, bars suction, or percent of total available water.

Gross irrigation requirement (Fg): The total irrigation requirement including net crop requirement plus any losses incurred in distributing and applying water and in operating the system. It is generally expressed as depth of water in acre inches per acre or inches.

Growing season: The period, often the frost-free period, during which the climate is such that crops can be produced.

Hydraulic conductivity: The ability of a soil to transmit water flow through it by a unit hydraulic gradient. It is the coefficient k in Darcy's Law. Darcy's Law is used to express flux density (volume of water flowing through a unit cross-sectional area per unit of time). It is usually expressed in length per time (velocity) units, i.e., cm/s, ft/d. In Darcy's Law, where $V = ki$, k is established for a gradient of one. Sometimes called permeability.

Infiltration, infiltration rate: The downward flow of water into the soil at the air-soil interface. Water enters the soil through pores, cracks, wormholes, decayed-root holes, and cavities introduced by tillage. The rate at which water enters soil is called intake rate or infiltration rate.

Irrigation efficiency (Ei): The ratio of the average depth of irrigation water beneficially used to the average depth applied, expressed as a percentage. Beneficial uses include satisfying the soil water deficit, leaching requirement for salinity control, and meeting other plant needs. Generally used to express overall field or farm efficiency, or seasonal irrigation efficiency.

Irrigation: Applying water to the land for growing crops, reclaiming soils, temperature modification, improving crop quality, or other such uses.

Leaching fraction: The ratio of the depth of subsurface drainage water (deep percolation) to the depth of infiltrated irrigation water. (See Leaching requirement.)

Leaching requirement: (1) The amount of irrigation water required to pass through the plant root zone to reduce the salt concentration in the soil for reclamation purposes. (2) The fraction of water from irrigation or rainfall required to pass through the soil to prevent salt accumulation in the plant root zone and sustain production. (See leaching fraction.)

Leaching: Removal of soluble material from soil or other permeable material by the passage of water through it.

Mass Balance: An application of conservation of mass to the analysis of physical systems. By accounting for material entering and leaving a system, mass flows can be identified which might have been unknown, or difficult to measure, without this technique.

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Net irrigation water requirement: The inches of water, exclusive of effective precipitation, stored soil moisture, or groundwater, that is required for meeting crop evapotranspiration for crop production and other related uses. Such uses may include water required for leaching, frost protection, cooling, and chemigation.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Nutrient management: Managing the application rate and timing of nutrients (contained in manure, wastewater, or fertilizers) to optimize crop use and reduce potential pollution of groundwater and surface water.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Pathogen: Disease-causing microorganisms such as bacteria, protozoa, viruses.

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land are cleared.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will,

or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Pre-sidedress soil nitrate test: The pre-sidedress soil nitrate test (PSNT) is a springtime test to determine the amount of nitrogen present in the soils prior to the commencement of the growing season. This test provides a measure of the amount of nitrogen that needs to be applied to support crop growth.

Root zone: Depth of soil that plant roots readily penetrate and in which the predominant root activity occurs. Preferred term is plant root zone.

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and water courses within the jurisdiction of Washington State.

Water table: The upper surface of a saturated zone below the soil surface where the water is at atmospheric pressure.

Acronyms and Abbreviations

AKART	All Known Available and Reasonable methods of prevention control and Treatment
ASTM	American Society of Testing and Materials
BMP	Best management practices
CAFO	Confined animal feeding operation
CFU	Colony forming unit
NMP	Nutrient management plan
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
GCL	Geosynthetic clay liner
HDPE	High-density polyethylene
N	Nitrogen
NPDES	National Pollutant Discharge Elimination System
NRCS	National Resources Conservation Service
NUE	Nitrogen use efficiency
POTW	Publically owned treatment works
PSNT	Pre-sidedress Soil Nitrate Test
RCW	Revised Code of Washington
SWDP	State Waste Discharge Permit
UIC	Underground Injection Control
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WRIA	Water Resource Inventory Area
WSU	Washington State University
WWTP	Wastewater treatment plant

Units of Measurement

ft	feet
g	gram, a unit of mass
mg	milligram
kg	kilograms, a unit of mass equal to 1,000 grams
mgd	million gallons per day
m	meter
mg/L	milligrams per liter (parts per million)
mg N/L	milligrams of nitrogen per liter (parts per million)

Unit Conversions

units	multiply by	to get
lbs N/acre	1.1198	kg N/ha
kg N/ha	0.893	lbs N/acre
mg/kg	equals	ppm
mg/L	equals	ppm
lbs/acre/yr	1.120849251	kg/ha/yr
kg/ha/yr	0.892179438	lbs/acre/yr
acre-ft	1,233,481	liter
acre-ft	43,560	cubic feet
acre-ft	325,851	gallons
gpd	3.78541	liters/day
1 acre	43560	square feet
1 acre	0.404686	hectare
1 cm	0.393701	in
°C	32	°F
1 gallon	3.78541	liters
1 inch	2.54	centimeter
1 foot	0.3048	meters
pounds	0.453592	kilogram
kilogram	2.20462	pound
hectare	2.47105	acre

Minnesota Center for Environmental Advocacy

Jay Eidsness <jeidsness@mncenter.org>

Feedlots information request

11 messages

Richards, Leonard (MPCA) <leonard.richards@state.mn.us> Thu, Jun 26, 2025 at 7:39 AM
To: "jeidsness@mncenter.org" <jeidsness@mncenter.org>

Hi Jay,

Aside from the Air Emissions & Odor Control Plans, are you asking for all applications for each site or just the most current application for each site?

Thanks,

Lenny Richards

Minnesota Pollution Control Agency (MPCA)

520 Lafayette Road | St Paul, MN | 55155

Voice (651) 757-2667

leonard.richards@state.mn.us

MINNESOTA POLLUTION CONTROL AGENCY

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Jay Eidsness <jeidsness@mncenter.org> Thu, Jun 26, 2025 at 9:35 AM
To: "Richards, Leonard (MPCA)" <leonard.richards@state.mn.us>

HI Leonard,

Thanks for your email and I appreciate you being so swift with helping gather the information I am looking for.

I am interested in the Air Emission Plans that the facilities included as part of its feedlot permit application under Minn. R. 7020.0505, subp. 4(B)(1). The most current application with an Air Emissions Plan would be perfect.

Does that clarify the request?

Thanks, Leonard.

-Jay
[Quoted text hidden]

Richards, Leonard (MPCA) <leonard.richards@state.mn.us> Thu, Jun 26, 2025 at 9:46 AM
To: Jay Eidsness <jeidsness@mncenter.org>

Hi Jay,

Yes, that clarifies. Will get back to you when I get responses from staff.

Thanks,

Lenny

From: Jay Eidsness <jeidsness@mncenter.org>
Sent: Thursday, June 26, 2025 9:35 AM
To: Richards, Leonard (MPCA) <leonard.richards@state.mn.us>
Subject: Re: Feedlots information request

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Jay Eidsness <jeidsness@mncenter.org> Thu, Jun 26, 2025 at 9:50 AM
To: "Richards, Leonard (MPCA)" <leonard.richards@state.mn.us>

I appreciate it.

-Jay
[Quoted text hidden]

Richards, Leonard (MPCA) <leonard.richards@state.mn.us> Mon, Jun 30, 2025 at 6:47 AM
To: Jay Eidsness <jeidsness@mncenter.org>

Hi Jay,

The applicant is basically checking a box when filling out their application to indicate that they agree with the standard plan and after they check the box it shows up in the Copy of Record that they “Affirmed” that they will employ the plan.

Sincerely,

Lenny

From: Jay Eidsness <jeidsness@mncenter.org>
Sent: Thursday, June 26, 2025 9:35 AM
To: Richards, Leonard (MPCA) <leonard.richards@state.mn.us>
Subject: Re: Feedlots information request

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HI Leonard,

[Quoted text hidden]
[Quoted text hidden]

4 attachments

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4446753 - 72561 - PUBLIC - - COPY OF RECORD.PDF - TEMPO_Copy of Record (2).pdf
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4451308 - 49139 - PUBLIC - - COPY OF RECORD.PDF - TEMPO_Copy of Record.pdf
166K

Jay Eidsness <jeidsness@mncenter.org> Mon, Jun 30, 2025 at 4:09 PM
To: "Richards, Leonard (MPCA)" <leonard.richards@state.mn.us>

Thanks for the records and information, Leonard. I have some questions about the "standard plan" you mentioned in your email. If I would like to make a records request about this plan, may I do that here or would you like me to submit another records request?

Thanks

-Jay
[Quoted text hidden]

Richards, Leonard (MPCA) <leonard.richards@state.mn.us> Tue, Jul 1, 2025 at 6:21 AM
To: Jay Eidsness <jeidsness@mncenter.org>

Hi Jay,

No need to make another request. Let me know your questions so I can relay to staff for answers.

Thanks,

[Quoted text hidden]

Jay Eidsness <jeidsness@mncenter.org> Tue, Jul 1, 2025 at 9:50 AM
To: "Richards, Leonard (MPCA)" <leonard.richards@state.mn.us>

Hi Lenny,

Thanks for being flexible. I appreciate it.

I am interested in knowing more about the standard air emission plan that you mentioned. Can you provide information about how and when MPCA created the standard plan? I am interested in documents or correspondence involving agency staff that worked to create the standard air emission plan.

I am also interested in how the standard plan option appears on the application portal. Can you provide screenshots or documents showing how that option appears on the application website or form explaining what the standard plan is and what it covers? I am also interested in the question that asks feedlot permit applicants about their air emission plan. How does MPCA ask the feedlot permit applicant about the expected air emissions from the proposed feedlot and ways those emissions will be controlled or mitigated?

Thanks, Lenny. Let me know if you have questions about this request.

-Jay
[Quoted text hidden]

Richards, Leonard (MPCA) <leonard.richards@state.mn.us> Tue, Jul 1, 2025 at 3:07 PM
To: Jay Eidsness <jeidsness@mncenter.org>

Hi Jay,

The first response I received is below and now waiting on a second response from another staff member. I'm off shortly and out tomorrow but will get back to you Thursday 7/3.

Sincerely,

Lenny

Staff response:

I'm not sure how or when the standard air emission plan was developed because there was a standard air emissions plan before I started working from the MPCA. Thus, I also don't have documents or correspondence involving agency staff that worked to create the standard air emission plan.

I did do a quick search in an old permit application from 2010 and there was a standard form at that time, but I'm also guessing there was a standard form that existed before 2010 too. I'm guessing that when the requirement was put into rule (I know it has been in rule since 2000) the initial air emissions plans that were submitted varied greatly so the agency probably developed a standardized form to assist feedlot owners and so that owners would have a list of potential mitigation measures that could be used and there would be more consistency in both what got submitted and mitigation methods that were likely to help reduce odor.

Below is a screenshot of what the online service looks like when an applicant is filling out an application.

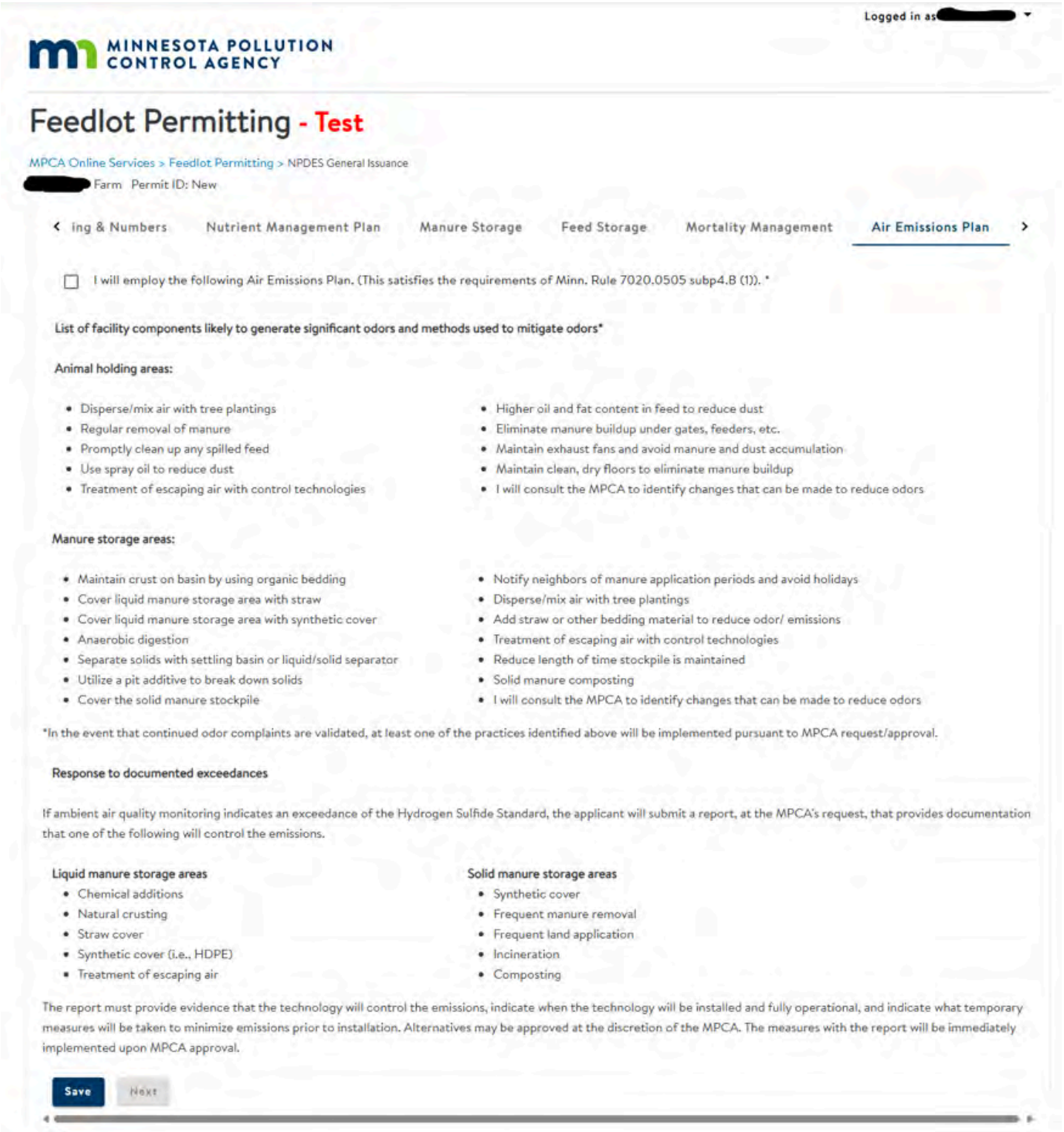

Logged in as [redacted]

MINNESOTA POLLUTION CONTROL AGENCY

Feedlot Permitting - Test

MPCA Online Services > Feedlot Permitting > NPDES General Issuance

[redacted] Farm Permit ID: New

ing & Numbers | Nutrient Management Plan | Manure Storage | Feed Storage | Mortality Management | Air Emissions Plan

☐ I will employ the following Air Emissions Plan. (This satisfies the requirements of Minn. Rule 7020.0505 subp4.B (1)). *

List of facility components likely to generate significant odors and methods used to mitigate odors*

Animal holding areas:

- Disperse/mix air with tree plantings
- Regular removal of manure
- Promptly clean up any spilled feed
- Use spray oil to reduce dust
- Treatment of escaping air with control technologies
- Higher oil and fat content in feed to reduce dust
- Eliminate manure buildup under gates, feeders, etc.
- Maintain exhaust fans and avoid manure and dust accumulation
- Maintain clean, dry floors to eliminate manure buildup
- I will consult the MPCA to identify changes that can be made to reduce odors

Manure storage areas:

- Maintain crust on basin by using organic bedding
- Cover liquid manure storage area with straw
- Cover liquid manure storage area with synthetic cover
- Anaerobic digestion
- Separate solids with settling basin or liquid/solid separator
- Utilize a pit additive to break down solids
- Cover the solid manure stockpile
- Notify neighbors of manure application periods and avoid holidays
- Disperse/mix air with tree plantings
- Add straw or other bedding material to reduce odor/ emissions
- Treatment of escaping air with control technologies
- Reduce length of time stockpile is maintained
- Solid manure composting
- I will consult the MPCA to identify changes that can be made to reduce odors

*In the event that continued odor complaints are validated, at least one of the practices identified above will be implemented pursuant to MPCA request/approval.

Response to documented exceedances

If ambient air quality monitoring indicates an exceedance of the Hydrogen Sulfide Standard, the applicant will submit a report, at the MPCA's request, that provides documentation that one of the following will control the emissions.

Liquid manure storage areas

- Chemical additions
- Natural crusting
- Straw cover
- Synthetic cover (i.e., HDPE)
- Treatment of escaping air

Solid manure storage areas

- Synthetic cover
- Frequent manure removal
- Frequent land application
- Incineration
- Composting

The report must provide evidence that the technology will control the emissions, indicate when the technology will be installed and fully operational, and indicate what temporary measures will be taken to minimize emissions prior to installation. Alternatives may be approved at the discretion of the MPCA. The measures with the report will be immediately implemented upon MPCA approval.

Save Next

[Quoted text hidden]

Jay Eidsness <jeidsness@mncenter.org> Tue, Jul 1, 2025 at 3:22 PM
To: "Richards, Leonard (MPCA)" <leonard.richards@state.mn.us>

Thanks, Lenny. This is very helpful.

-Jay
[Quoted text hidden]

Richards, Leonard (MPCA) <leonard.richards@state.mn.us> Thu, Jul 3, 2025 at 6:31 AM
To: Jay Eidsness <jeidsness@mncenter.org>

Hi Jay,

Final staff response:

There has been a standardized form for a long time. I would estimate we developed the first one around shortly after our first large scale re-issuance of general NPDES permits, 2006 maybe. Certain groups had their form they promoted (eg. Pork producers) and we developed a standardized one to streamline the application and review process – much like we did with the Emergency Response Plan and more recently the Manure Management Plan. Standardized forms ensure that necessary information is given in a clear, concise, and consistent manner which benefits the applicant, the MPCA staff, and those wanting to review the documents – far less back and forth and different versions of plans.

The current format evolved following the MPCAs experience with enforcing/implementing air emissions plans in response to an extreme hydrogen sulfide violation case in northern MN around 2009/2010. The agency desired to establish “minimum content” for the plans to provide more clear and concise content to efficiently implement the plans going forward and in particular the part about responding to exceedances of the hydrogen sulfide standard. This way it was clear for all, what the MPCA expected for the air emissions plan before it could be approved as part of the permit issuance process.

The current application process presents the minimum plan as more of an agreement that applicant must comply with as part of the permit application. Again, presenting a clear, concise, standardized document for all to easily understand and follow while still meeting the intent of the plan in the first place – how will the applicant respond to odor complaints and exceedances of the hydrogen sulfide standard.

[Quoted text hidden]

Big Farms and Flawless Fries Are Gulping Water in the Land of 10,000 Lakes

nytimes.com/interactive/2023/09/03/climate/minnesota-drought-potatoes.html

Dionne Searcey, Mira Rojanasakul September 3, 2023

UNCHARTED WATERS

When Minnesota farmers cranked up their wells in a drought, they blew through state limits. Thirsty crops included corn, soybeans and perfect, fry-friendly potatoes.





Dionne Searcey drove across Minnesota and Mira Rojanasakul analyzed decades of water data to report this article. Photographs by David Guttenfelder.

The second article in a series on the causes and consequences of disappearing water.

The drought that gripped Minnesota in the summer of 2021 was one of the worst on record. Day after day a blazing sun shriveled leaves, dried up waterfalls and turned ponds to puddles.

In a state known for its 10,000 lakes, many people could do little except hope for rain.

But big farmers had another option. They cranked up their powerful irrigation wells, drenching their fields with so much water that they collectively pumped at least 6.1 billion gallons more groundwater than allowed under state permits. Nearly a third of the overuse happened on land affiliated with one company, R.D. Offutt Farms.

The water helped R.D. Offutt to achieve its objective of creating long, smooth potatoes that effortlessly sail through the slicers at frozen food processors so Americans could have one of their favorite foods: McDonald's French fries.

It takes a lot of water to make a perfect fry.

By turning on the taps in the depths of drought, R.D. Offutt and other farmers in the state — where thousands of wells irrigate potatoes and other water-intensive crops like corn, soybeans and sugar beets — blew through limits designed to protect aquifers that supply drinking water to millions of people.

For some Minnesotans, it significantly worsened the drought's effects. And it exposed how dependent much of the state has become on aquifers that are fragile and often poorly understood.

A bar chart showing Minnesota's groundwater use for irrigation over time. The x-axis extends from 1988 to 2021. The bars show a general upward trend, peaking in the drought year of 2021 at above 150 billion gallons.

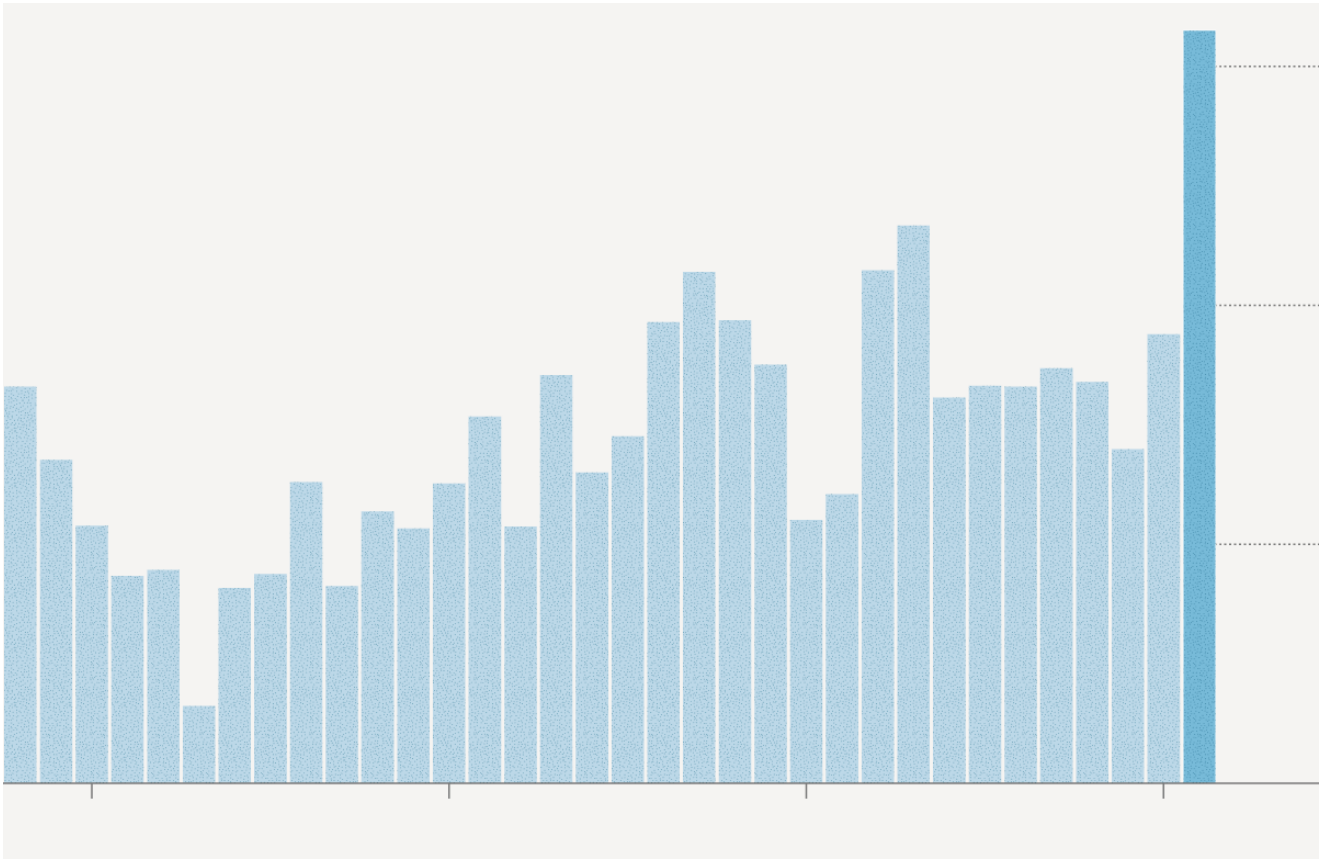

The increasing overuse of groundwater is a nationwide problem, a New York Times data investigation found, with big cities and industrial farms alike draining aquifers at alarming rates. The practice threatens not only drinking water supplies for millions of Americans but also the nation's status as a leading exporter of food.

In Minnesota, watersheds started to dry as the heavy irrigation in 2021 lowered aquifer levels. Trout streams warmed when huge wells siphoned away the cooler underground water that normally fed the streams, scientists said, threatening fish populations. And in parts of Minnesota, people reported backyard wells drying up, sometimes leaving kitchen faucets to cough and sputter as though they were gasping.

Officials in Warren, Minn., partly surrounded by sugar beet fields, had to physically lower the pump at the town's well by 63 feet in order to keep providing drinking water to more than 1,500 residents, including those in a hospital and nursing home. One older woman outside Warren said the only way she could get water after her own well went dry was to drive her riding mower to a neighbor's house to fill water bottles. State officials wound up suspending four irrigation permits in the area.

In Backus, Minn., Mike Tauber, whose forested land abuts potato fields affiliated with R.D. Offutt, was shocked to find dried-up, exposed banks along a pond so big he had nicknamed it "Super Pond." And in the northwestern part of the state, members of the White Earth Nation worried that farmers' irrigation wells were draining culturally significant bodies of water.



Trout fishermen worry that the Straight River is warming as irrigation wells pump out cooler groundwater that would normally feed the river.



Mike Tauber with his wife and their dog near the family home.



The Taubers' forest abuts an irrigated potato field.

"I understand farmers have got to make a living, too, but at the same time they've got to take other human beings into consideration," said Trevor Milbrett, of Eagle Bend, Minn., who sometimes drove his pregnant wife and toddler to his parents' house for showers and supper that summer because nearby irrigation had left him with no water.

Potato farming is not the only big agricultural user of groundwater in Minnesota. The state is one of the nation's top producers of corn, another heavily irrigated crop. But potato farming in particular shows how a host of seemingly unrelated factors — the demands of industrial French fry production, for example, or the fact that people will spend more money for fries with fewer unappetizing dark spots — can send water use soaring.

In a written statement, Warren Warmbold, vice president of R.D. Offutt Farms, said, “The story of 2021 was either going to be about water overages or food shortages.” Along with other farmers, he said, “we had to make difficult decisions around water use in order to save our crops and keep the food supply secure and affordable.”

Mr. Warmbold also said that, over the years, R.D. Offutt had used less water than its permits allocated 97 percent of the time. “We don’t take these decisions lightly,” he wrote.

The practice of irrigating mainly with groundwater, once concentrated in America’s arid West, is marchingeastward across the country even as it declines in many Western states, where aquifers are drying up.

A map of the continental United States, showing where irrigated acres of land saw net increases or decreases between 1997 and 2017. Net decreases are concentrated in the west, and net increases in the Midwest and elsewhere.

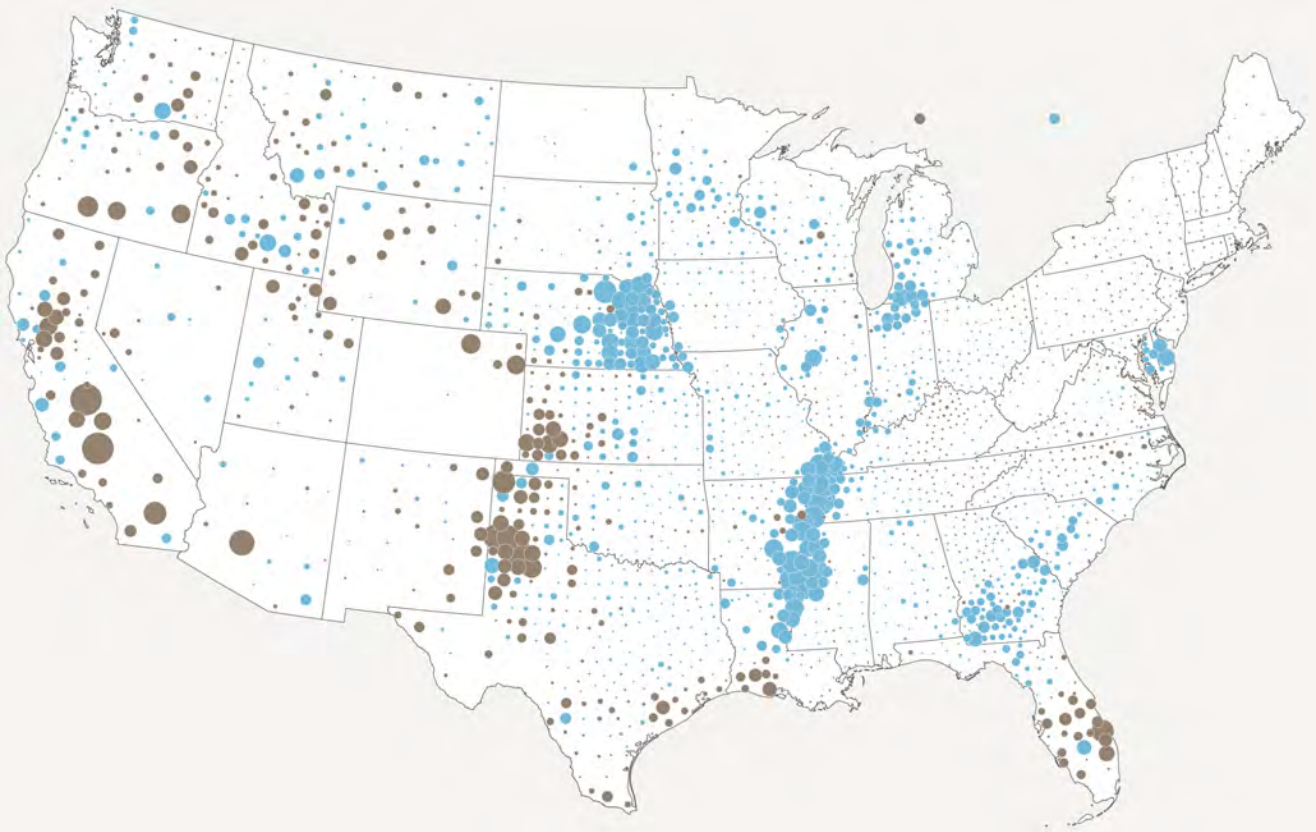

Irrigation Heads East

Source: U.S.D.A. | Irrigated acres from any water source

Minnesota in the early 1960s had fewer than 50 permits for irrigation wells. By 2022, there were over 7,000 of them.

And, like many other states, Minnesota uses an honor system for reporting water use from wells like these. Farmers self-report their usage annually.

This year, Minnesota lawmakers moved to rein in irrigators by increasing fines for pumping too much water, but it's unclear whether regulators will use the new tools. Officials said that in 2021, they were hesitant to fine farmers who were already struggling with crop loss.

What happened in Minnesota offers a warning to the rest of the country. Even in a state with a culture tied to watery abundance, groundwater overuse in some areas quickly had dire consequences. And it remains unclear whether the steps taken to prevent a repeat are strong enough.

"We have this really intensive groundwater use, expanding to aquifers we don't yet understand very well, in places where domestic wells have never had to compete for groundwater," said Ellen Considine, a hydrologist supervisor with the state's Department of Natural Resources. As a result, she said, "we may not be leaving enough groundwater for future generations."

Thirsty Farmland

To understand why big farms use so much water, consider potato aesthetics.

People don't want French fries that just taste good, they want them to look good, too. And since the late 1960s, the United States Department of Agriculture has set voluntary grading standards for potatoes and French fries, essentially defining what gives them value.

One important variable is French fry coloring: Those with dark markings have little chance at being called "Grade A" fries.

For farmers, that means making sure potatoes don't have lumps, which can cause uneven coloring. Growing potatoes in fluffy, sandy soil allows them to expand into smoother shapes.

Watering is important, too. A potato can end up shaped like a bowling pin if it doesn't get consistent water. That matters to growers because an oblong spud can produce more fries, and more profit.

Demand for potatoes is soaring with the spread of fast food restaurants around the world. More than a third of America's potatoes end up in the frozen market in grocery stores or restaurants, most of them as French fries, according to the Department of Agriculture. Or they end up on lunch trays at schools, another big buyer of fries.



The ideal: long, golden, uniform fries Carlos Gonzalez/Star Tribune, via Getty Images



R.D. Offutt employees in a potato field near Park Rapids, Minn.

In Minnesota, R.D. Offutt, which has its headquarters in North Dakota and is one of the largest potato growers in America, has planted crops on thousands of acres of land where a timber company once harvested wood from a lush pine forest. R.D. Offutt converted the land to farming to take advantage of the sandy, potato-friendly soil beneath the trees.

R.D. Offutt executives said they had put into place more efficient irrigation methods in recent years. And the company said it has partnered with scientists to develop new varieties of potatoes that aren't as water-intensive.

In the summer of 2021, faced with the worst drought in decades, fields linked to R.D. Offutt were doused with water from more than 500 wells. R.D. Offutt supplies potatoes to companies that make fries for fast-food restaurants, including McDonald's. It owns fields but also leases land to and from other farmers as part of its practice of rotating potatoes with other crops every few years.

In the drought year, about one-third of R.D. Offutt's fields were planted with potatoes, executives said. But growing any crops in the sandy, porous soil requires significantly more water.



A potato plant on an R.D. Offutt farm near Park Rapids.



Center-pivot irrigation equipment near the White Earth reservation.



A lake where White Earth members harvest wild rice.

It's not just industrial farms that gulp groundwater. Cities, power plants, factories and golf courses do, too. (In 2021 in Minnesota, a company digging an oil pipeline also breached an aquifer, sending groundwater gushing.) But irrigation is consistently one of the biggest users, and the agricultural industry's political might, along with farming's revered place in the American self-image, means that unsustainable irrigation practices have expanded despite the risk to agriculture itself.

The phenomenon can be seen from the window of any airplane flying over America's flatlands. Those circles of green on the land below are the work of immense "center pivot" irrigation sprinklers that often use groundwater, tapping wells that are sometimes hundreds

of feet deep.

Minnesota tries to put the brakes on excessive groundwater use with permits that consider how wells affect the area around them. But the system isn't perfect.

"Think of our water supply as a giant milkshake glass and each well is a straw in the glass," said Robert Glennon, author of the book "Water Follies," who has studied agriculture's effect on groundwater. "What most states permit is a limitless number of straws in the glass."

500 Gallons a Minute

Many of the wells linked to R.D. Offutt and those of other farmers tap the Pineland Sands Aquifer, which is huge but also delicate, partly because it is shallow in places. Extracting water from the shallow spots can sometimes affect surface water in the region, lowering the levels of rivers or other bodies of water.

"If you just take a little bit, it's very sensitive," said John Nieber, an agricultural engineering and hydrology professor at the University of Minnesota. Pumping out even relatively small amounts from aquifers can lower surface water if snowmelt and rain aren't replenishing them quickly enough.

Early indications suggest the Pineland Sands Aquifer may have recovered from the setbacks in 2021, and R.D. Offutt says its studies show "imperceptible" changes in water levels in past years. Still, state officials said that straining an aquifer year after year can have wide-reaching effects, drying out wetlands and streams.

The fact that so many Minnesotans statewide were forced to scramble for groundwater after just one summer of intense drought highlights the fragility of aquifers even in parts of the country not usually thought of as water-stressed. This year parts of Minnesota are again experiencing a drought, prompting new complaints that irrigation is drying out residents' wells.

Many of the state's irrigation wells are concentrated in areas of sandy soil.

A map of Minnesota uses blue dots to show the location of irrigation wells in relation to areas of sandy soil, which are depicted with a light brown color. The wells are clustered mostly around the middle of the state and south of the Twin Cities. The location of the White Earth Reservation is also shown, in the upper left portion of the map.

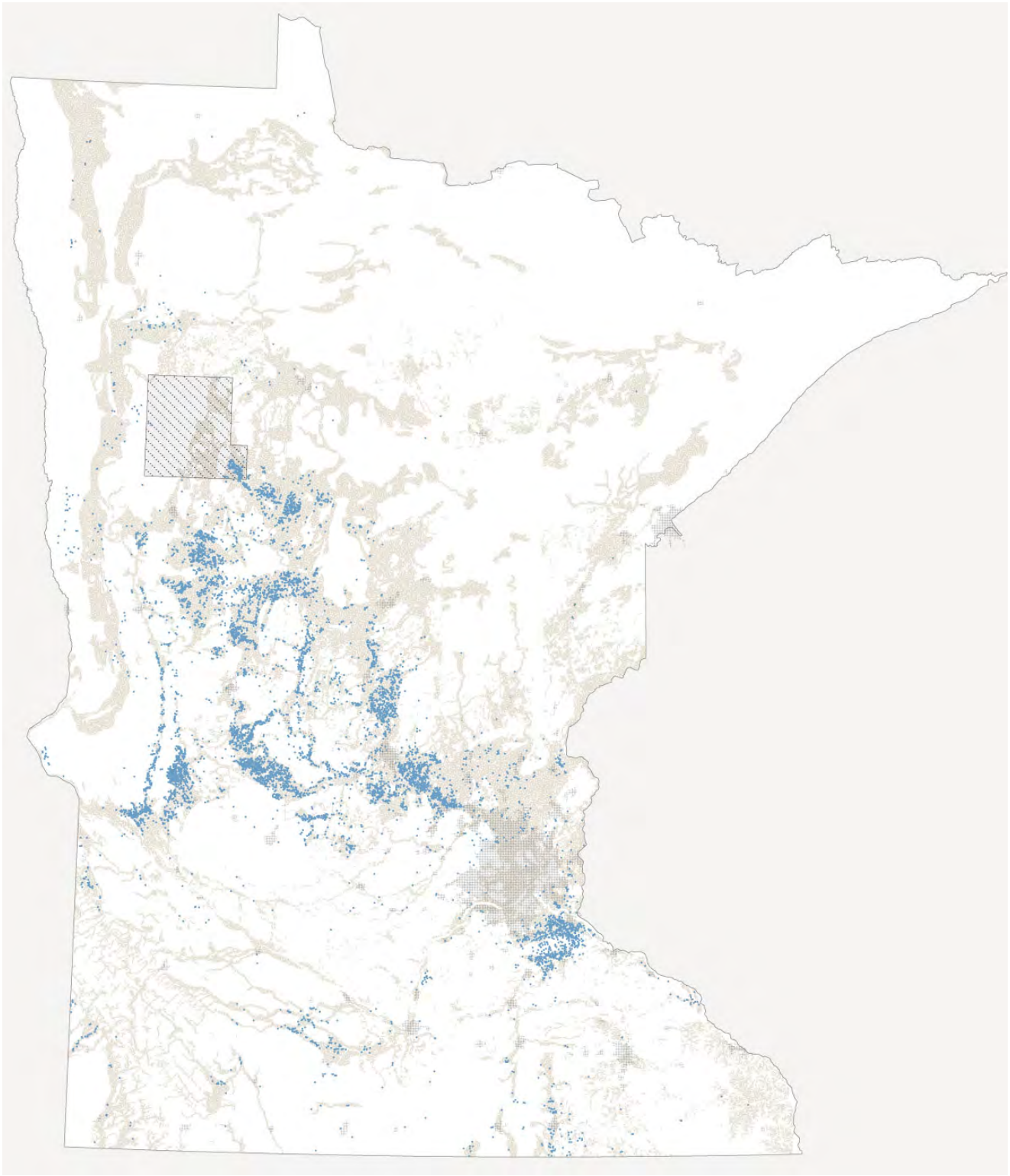

Sandy Soils

Source: Minnesota Geological Survey

Dr. Nieber is partnering with the White Earth Nation to study irrigation's effects on the Pineland Sands Aquifer. The southeast corner of the reservation sits atop the aquifer and is adjacent to dozens of wells operated by R.D. Offutt as well as other farmers, according to the

tribe.

For years, White Earth members have complained about fertilizers and pesticides used by farmers. Among their concerns is that both the chemicals and the pumping for irrigation threaten tribal lakes and streams where White Earth members fish and harvest wild rice, which is culturally significant and an important revenue source.

Frustrated by what members see as an inadequate response by the state to address the effects of irrigated farming, this year the White Earth passed a measure that requires tribal officials to sign off on any new irrigation wells that farmers want to install within five miles of the reservation, a swath of territory where the White Earth says it has hunting and fishing rights.

The measure may invite legal challenges, leaders acknowledged, but is intended to send a message that more irrigation is not welcome. “We are pushing back,” said Jamie Konopacky, a White Earth attorney.



White Earth community members prayed for bountiful fish and rice.



Austin Tersteeg’s corn and soybean irrigation dried out neighbors’ wells.

During the summer drought in 2021, complaints about irrigation were filed with the Department of Natural Resources faster than inspectors could keep up with them. Many came from poorer families or older people with limited income, according to a review of the complaints and interviews with residents who filed them.

In Red Lake County, Allan Armstrong said he went without water for a month at his home. But Mr. Armstrong also faced another crisis: Nearby, his parents had also lost water in their well at a time when his father was receiving hospice care at home.

“He was panicking and flipping out and running out of water,” Mr. Armstrong said of his father.

His complaint to the state expressed the urgency. “We need water now!” Mr. Armstrong wrote.

About three miles from Mr. Armstrong’s home, a neighboring farm owned by the Tersteeg family had installed a new 500-gallon-a-minute well.

The Tersteegs were trying to keep their corn and soybeans from withering. Their water use was well within their annual permitted limit, but still enough to dry out Mr. Armstrong’s smaller well and also contribute to problems for three other families’ wells.

The state required the Tersteegs to pay more than $10,000 to dig a new well for Mr. Armstrong.

Austin Tersteeg said farmers were sometimes forced to pay to replace old wells that, sooner or later, would need replacing anyway. Footing the bill for a brand new well, he said, “far exceeds the quantity and quality of water that they previously had there.”

He has asked the state to reimburse him for what he spent on his neighbors’ wells under a program to help farmers who needed more watering during the drought.

The Tersteeg farm’s headquarters is just outside Erskine, which, like many communities in Minnesota, has for decades held an annual water carnival. Mr. Tersteeg said he was confident that his farmland would be fine for generations, despite the warning signs.

“My grandkids will be irrigating from these wells,” he said. “There’s a lot of water in this area.”

His farm is awaiting approval for two new state permits for irrigation wells.



NEWS | AUGUST 4, 2022

We're challenging the NC permit for hog waste operations causing pollution and harm to communities

With about two million hogs, the highest number of hogs in the United States, Duplin County in North Carolina is inundated with industrial hog operations and pollution from their waste pits and spraying of hog feces and urine onto fields. (Cornell Watson)

On behalf of the Environmental Justice Community Action Network and Cape Fear River Watch, we challenged a one-size-fits all permit issued by the North Carolina Department of Environmental Quality that would allow hog operations to use giant pits of untreated hog feces and urine to produce methane gas <https://www.selc.org/wp-content/uploads/2022/07/2022-07-28-petition.pdf> while spraying the harmful waste on surrounding fields.

This outdated practice continues a long history of water and air pollution and harm to the families – disproportionately Black, Latino, and Native American people – living nearby.

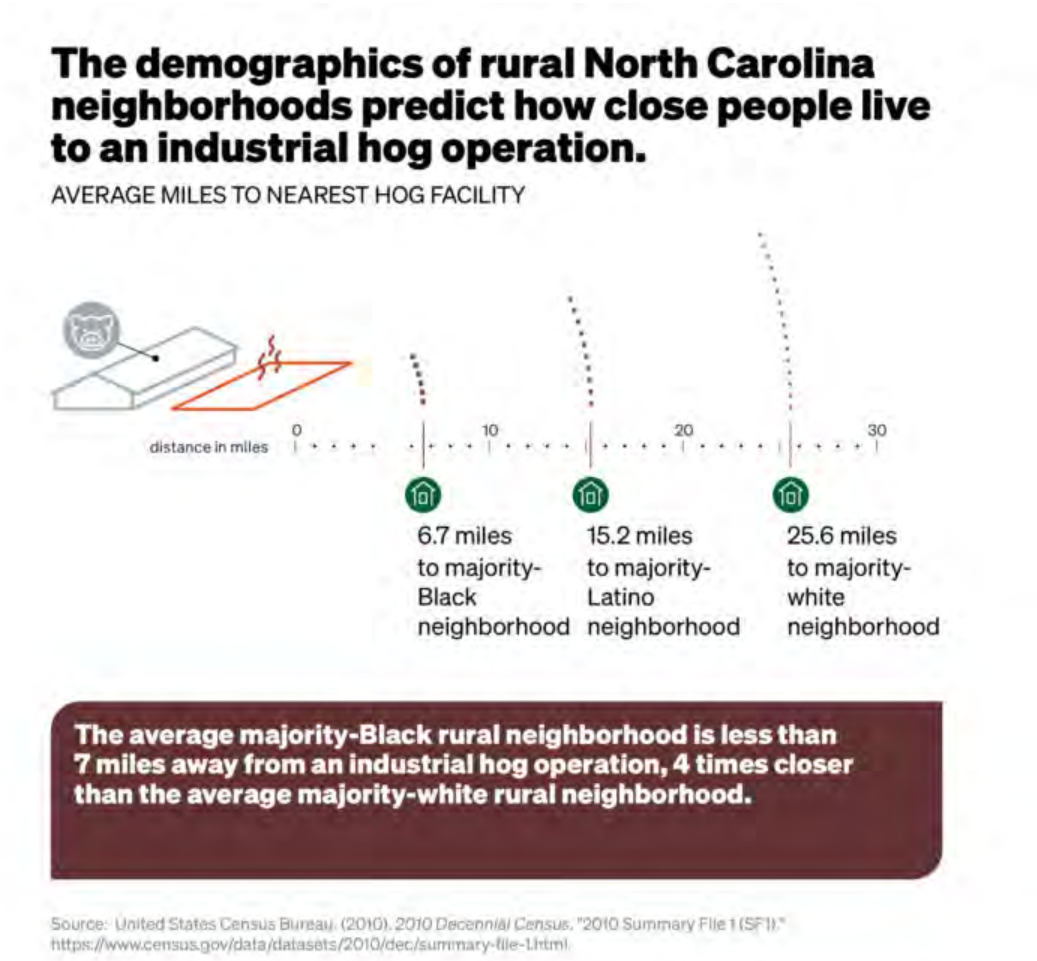

In the summer of 2021, despite strong opposition from impacted communit y groups, the North Carolina General Assembly passed, and Governor Cooper signed into law the 2021 Farm Act <https://www.selc.org/press-release/farm-act-bill-signed-into-law/>, which charged DEQ with developing a fast-tracked, one-size-fits

all permit – or general permit – for swine waste-to-energy projects. DEQ issued the final general permit <https://www.selc.org/press-release/north-carolina-allows-more-hog-waste-pollution-despite-disproportionate-harm-to-communities-of-color/> on June 30, 2022.

“This general permit continues a long legacy of injustice by a powerful industry, entrenching pollution and harms onto people with less political power despite the availability of cleaner, better solutions,” says Southern Environmental Law Center Senior Attorney Blakely Hildebrand. “The state has a responsibility under the law to protect people from pollution.”

The general permit fails to comply with a state law requirement for cleaner technology and does not include protections against pollution for nearby families, waterways, or air quality.



EJCAN members and staff, including Sherri White-Williamson (second from right) meet with SELC staff to discuss the harms of biogas on communities. (Cornell Watson)

“Frontline community members strongly opposed the Farm Act and demanded more from DEQ in issuing this permit, but these community concerns fell on deaf ears. Instead, this permit will add to the already heavy

burden that communities of color have borne for decades and continue a long-standing environmental injustice," says Sherri White-Williamson, co-founder of the Environmental Justice Community Action Network.

In issuing the general permit, the legislature and DEQ ignored long-standing and well documented environmental justice and pollution concerns. The general permit issued by DEQ allows the use of an outdated practice of using the waste lagoon and sprayfield system in which untreated hog waste from thousands of animals is collected in large pits and sprayed onto neighboring fields. It also increases harms and is unlikely to result in the benefits claimed by the hog industry.

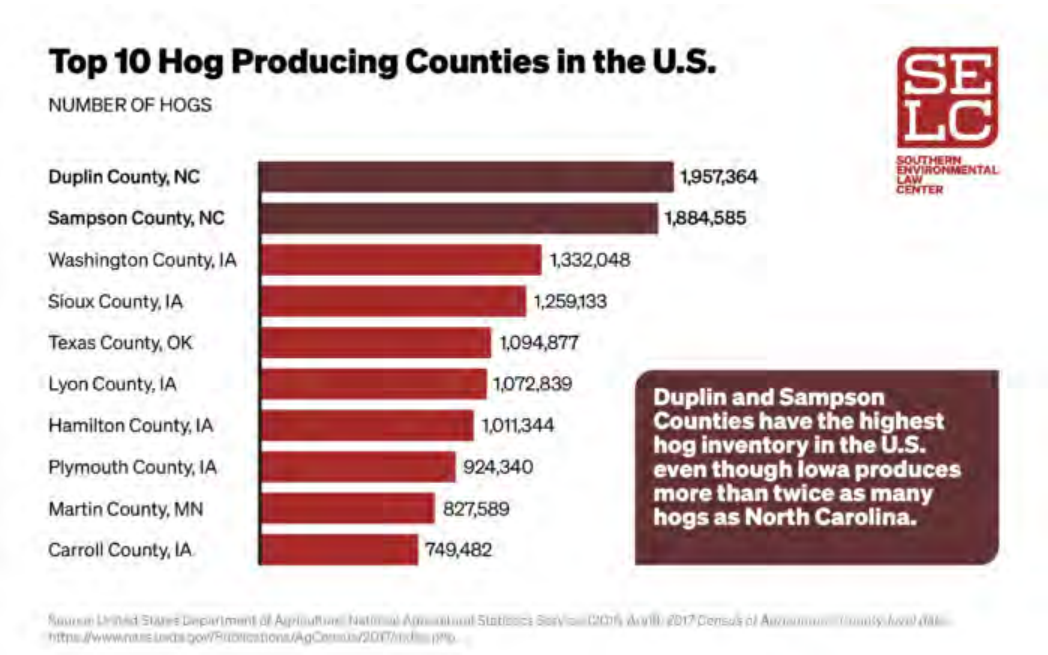

"The legislature's passage of the Farm Act and DEQ's issuance of this permit are just the latest in a long line of decisions that ignore the devastating effect that the hog industry has on our environment," says Kemp Burdette, Cape Fear Riverkeeper at Cape Fear River Watch. "Far from a solution to our climate crisis, this permit gives industry a rubber stamp to keep polluting our air and water rather than holding them accountable to the law."

Cleaner technologies for managing billions of gallons of hog waste were developed in North Carolina and address many of these concerns but have not been widely adopted by the hog industry. The groups are asking the court to require the Department of Environmental Quality to comply with a law mandating cleaner technology to manage hog waste.

Learn more about how SELC is confronting pollution from industrial animal operations.

LET'S GO <https://www.selc.org/topic/pollution-from-industrial-animal-operations/>

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Cow Poop is Now a Big Part of California Fuel Policy

Are the state's new low-carbon fuel regulations full of BS?



AARON SMITH
JAN 22, 2024

26 2 Sha



Every day, California farmers milk 1.7 million cows. Each cow generates about 7 gallons of milk and 100 gallons of waste. Most farmers process the waste (mostly manure) by washing it into lagoons where microbes break it down and, in the proce emit methane, a potent greenhouse gas.

These facts raise two questions. First, can we prevent the manure-eating microbes from sending methane into the atmosphere? Second, can we capture the methane a use it for energy?

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California has answered yes to both questions. On the first question, it aims to redu methane emissions from livestock manure by 40% below 2013 levels by 2030 (codifie in SB 1383). One way to achieve this goal would be to place the burden on farmers b charging them a methane emissions fee or requiring them to use practices or technologies that reduce methane emissions. This approach would raise the cost of producing milk and therefore increase the price consumers pay for dairy products. cost increase may cause some farmers to move out of state, taking their methane emissions with them. This response, known as leakage, arises in many environment policies, including in California's cap and trade program, as explained by Meredith in this blog.

California has chosen a different path. It has shoehorned dairy methane into a transportation program: the low carbon fuel standard (LCFS). This structure avoids leakage, but it makes consumers and producers of gasoline and diesel pay for reductions in dairy manure emissions.

Manure in the LCFS

To capture methane from manure lagoons, farmers install anaerobic digesters, whic are essentially giant covers that seal manure in the lagoon to keep oxygen out while microbes feed on the contents. The captured methane — known as biogas — is the cleaned and injected into a natural gas pipeline, from which it has multiple uses including fueling a natural-gas powered vehicle and generating electricity.

This dairy biogas earns LCFS credits because it is considered a low carbon fuel. Th LCFS sets a target for the average carbon intensity of transportation fuels consume in the state. Fuels that are more carbon intensive than the target accrue deficits tha must be balanced by credits earned by fuels that are less carbon intensive. The figu below shows that gasoline and diesel producers generate deficits, which they can

offset by buying credits from producers of biogas and other lower-GHG fuels like electricity and renewable diesel.

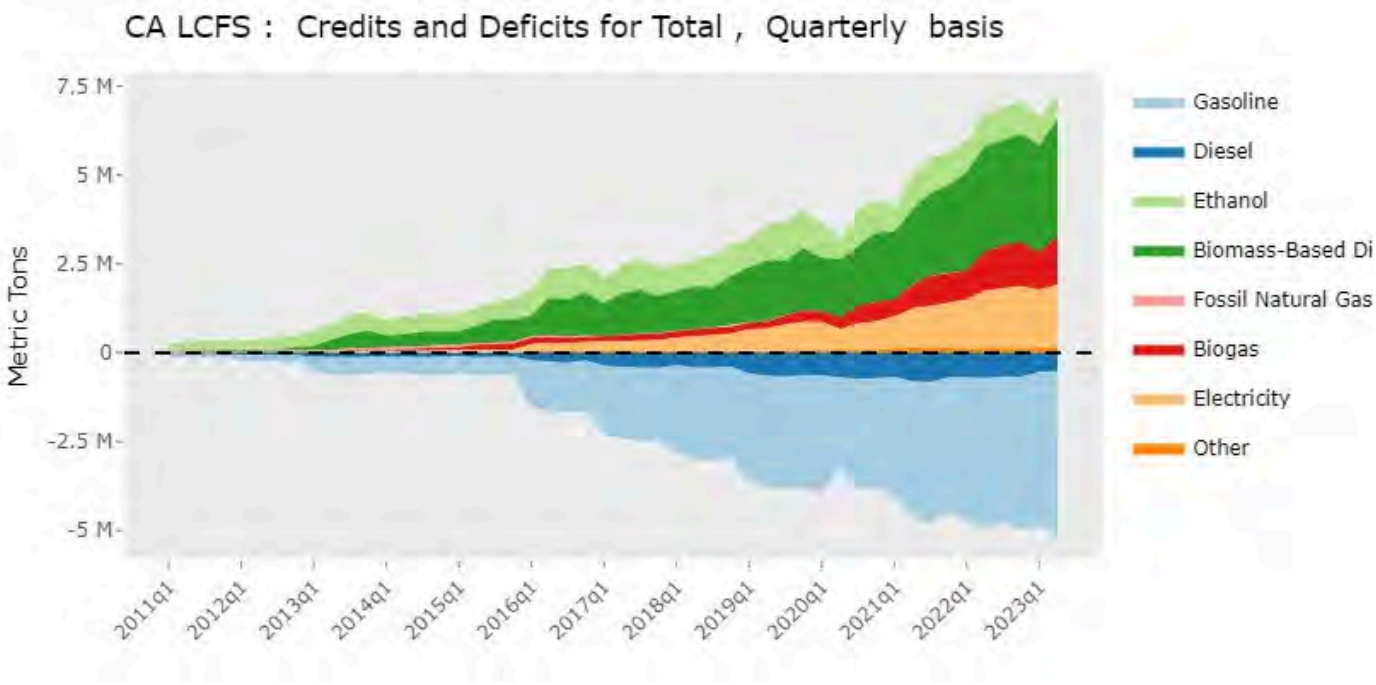

Source: Our LCFS Data App. Click to view and download data using your web browser.

In the most recent LCFS data, dairy biogas contributed almost 20% of the credits in the LCFS program, yet it provided less than 1% of energy used for transportation. Dairy biogas has an outsized impact in the LCFS because it is treated very different than most fuels. Last month's proposed LCFS amendments indicate that this differential treatment will continue.

The LCFS Assigns Dairy Biogas a Large Negative Carbon Intensity

Carbon intensity is the number of grams of carbon dioxide emissions produced per megajoule of energy. The California Air Resources Board (CARB) calculates this number for each fuel source using a life cycle analysis that accounts for tailpipe emissions as well as potential emissions throughout the fuel production process. Fc example, petroleum gasoline has a carbon intensity of 100.82 and an electric car powered by solar-generated electricity has a carbon intensity of zero. Most other fu have carbon intensities between zero and 100.

The carbon intensity of dairy biogas ranges between -102.79 and -790.41 depending characteristics of the digester. The current average carbon intensity for dairy bioga -269.

CARB assigns dairy biogas a negative carbon intensity because it gives credit for preventing methane emissions that would otherwise have occurred. Their argumen that, if a farmer had not installed a digester on a manure lagoon, then it would have sent methane into the atmosphere.

Microbes produce different amounts of gas inside a digester than they would in an open lagoon because of differing environmental factors such as oxygen exposure an temperature. The carbon intensity number is determined by the estimated emissior from the open lagoon (avoided methane) per unit of biogas produced. For example, highly productive digesters, the amount of prevented methane is low as a proportio of the biogas produced, so such a digester would get a relatively small negative carb intensity.

In the LCFS, fuels with a negative carbon intensity are very helpful in meeting the policy target because they can offset a lot of high-carbon fuel. For example, adding average biogas-powered vehicle to the fleet would produce enough LCFS credits to cover the deficits incurred by 26 similar gasoline-powered vehicles.

This accounting scheme is one reason why dairy biogas has increased from almost non-existent five years ago to half of all natural gas used for transportation in the state. The other half is contributed by biogas captured from landfills. However, lanc gas gets a carbon intensity of 53 because it does not get credit for avoided-methane emissions. So, even though its fuel volumes are similar to dairy, it generates only a fraction of the credits, as shown in the figure below. Biogas can also earn LCFS cre by generating hydrogen or electricity for use in transportation, but these pathways have been used very little so far.

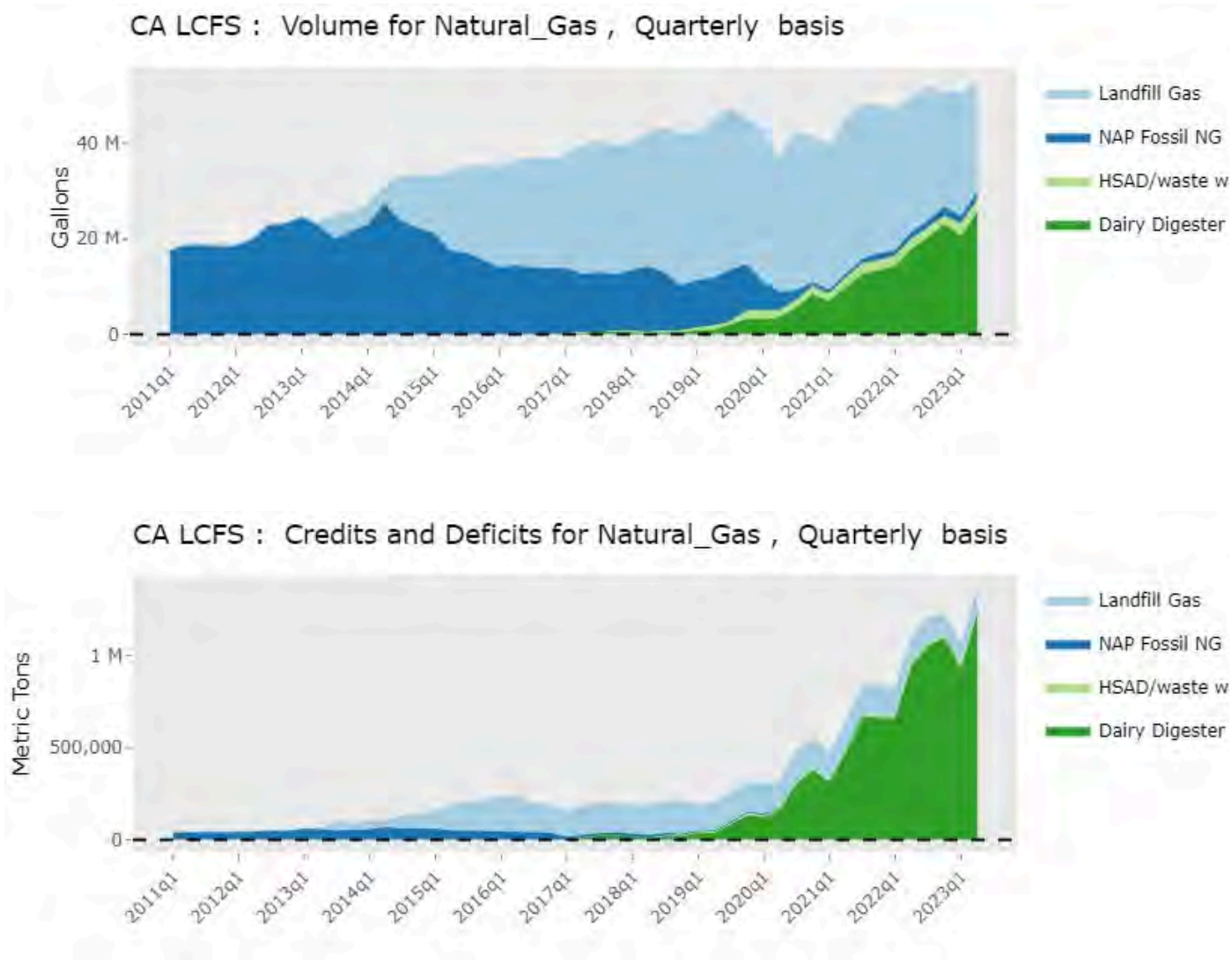

Source: Our LCFS Data App. Click to view and download data using your web browser.

Costs and Benefits of Anaerobic Digesters

In this 2023 Ag Data News article, I showed that the cost of an anaerobic digester is about 10 times the market value of the gas it produces. A representative new digest costs about about $1130 per milking cow per year, comprising $490 in capital costs $440 in operating costs, plus $200 in trucking costs if unable to connect directly to a gas pipeline. In 2023, revenue from selling gas was about $128, for a net cost of abou $1000 per milking cow per year. This representative digester has a carbon intensity -355, which corresponds to about 6 metric tons of CO2 equivalent emissions per milking cow per year.

So, for $1000 we reduce CO2 emissions by 6 metric tons, or $167 per ton.

Methane is a far more powerful greenhouse gas than CO2, but it doesn't last nearly long in the atmosphere. There is a vigorous scientific debate over how best to conv methane emissions into CO2 equivalent accounting for both how much it warms ar when. Using an alternative approach would reduce the estimated emissions reducti by a factor of three and therefore raise the cost per ton by a factor of three. Moreov all these numbers assume that CARB correctly estimates the amount of prevented emissions.

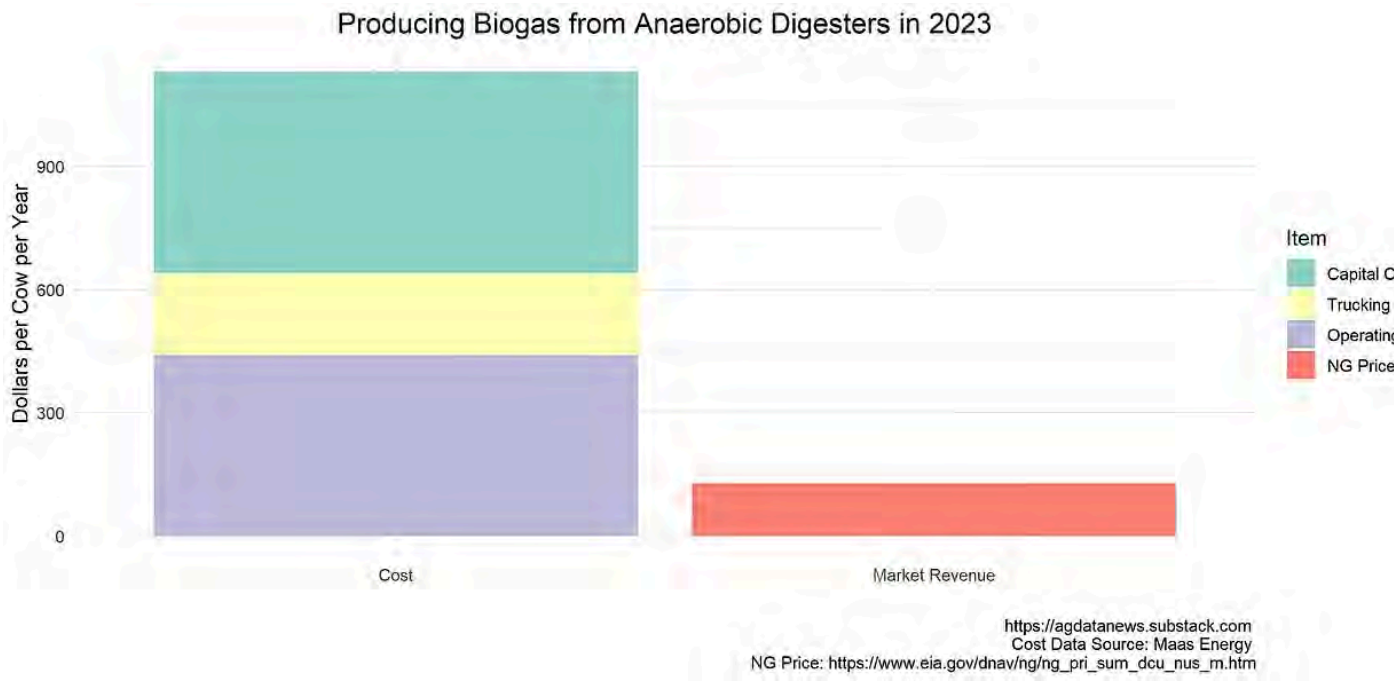

Incentives Facing Farmers

Anaerobic digesters receive government support through three programs. First, usi proceeds from the state's cap and trade program, the California Department of Foo and Agriculture offers grants to cover up to half the capital costs of building digest Second, sellers of dairy biogas generate credits in the federal renewable fuel standa (known as RINs). Third, they earn LCFS credits.

Between mid 2018 and the end of 2021, revenues from selling biogas and the associ RIN and LCFS credits were approximately double the cost of installing and running typical digester, as shown in the figure below. LCFS credit prices have declined in t last two years, making the typical digester closer to a break even proposition. If and when credit prices go back up, then the profits will return.

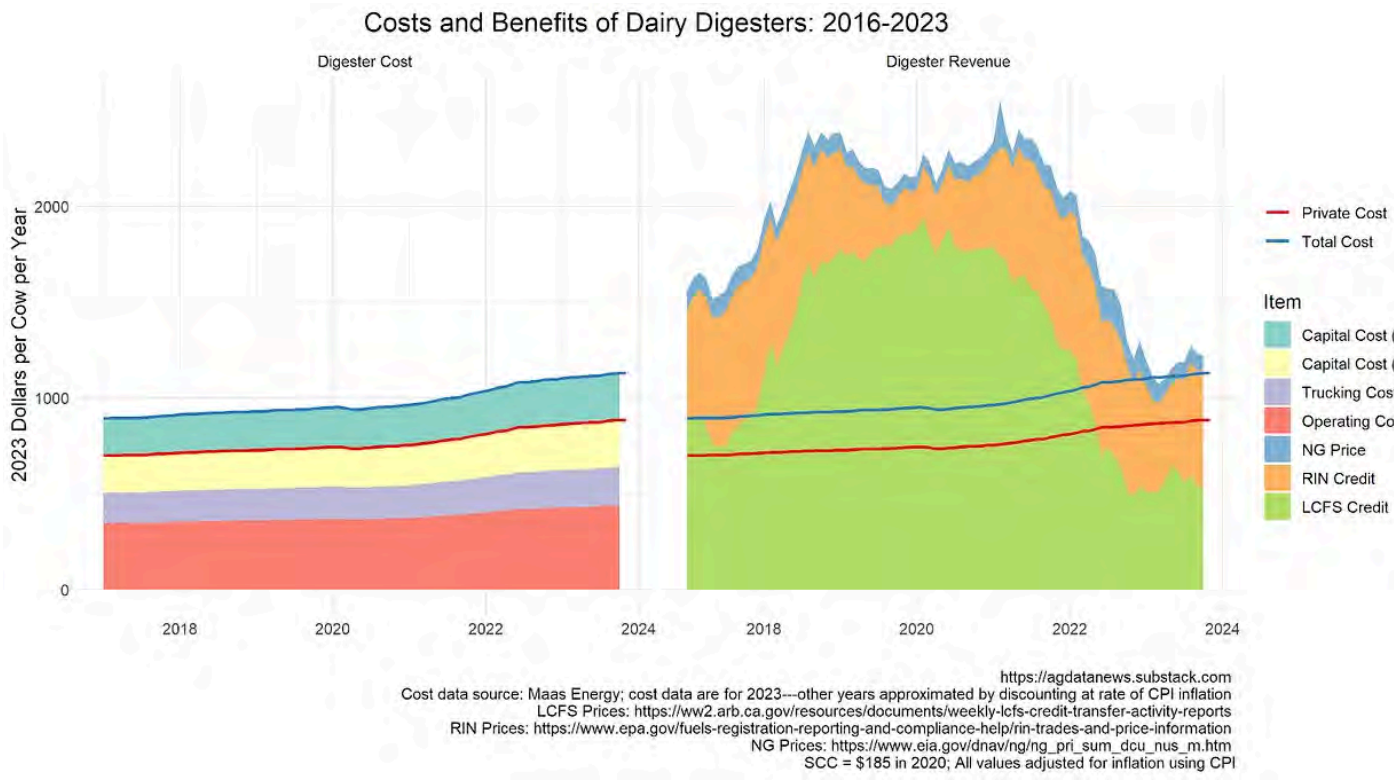

High profits from operating digesters create the incentive for farmers to expand da herds for the purpose of generating manure rather than for producing milk. Betwee 2014 and 2019, California dairy cow numbers declined by 50,000 while the number c cows in other western states increased by 100,000 (see figure below). Since 2019, cov numbers have been relatively flat throughout the west.

It is possible that the advent of digesters in California stemmed the flow of cows ou the state. Dairy farmers outside California can access only two of the three digester programs accessible to California farmers. They are eligible to earn LCFS and RIN credits for their biogas, but they cannot receive California Department of Food and Agriculture grants to cover capital costs. Whether this grant funding is the differen

between leaving and staying in California is an important topic for further research given the potential for emissions leakage if the state were to remove negative credit but still require farmers to reduce manure methane emissions as per SB 1383.

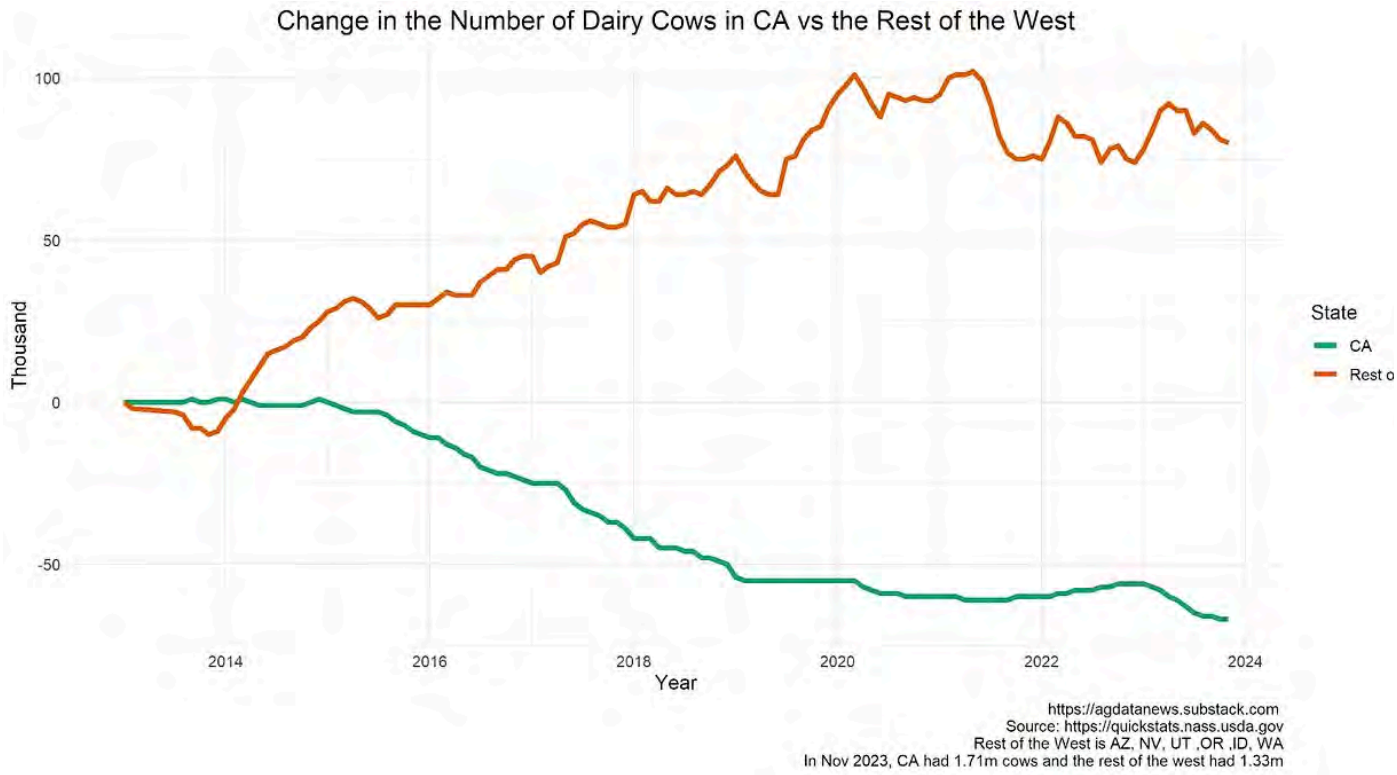

What Next?

CARB is proposing several amendments to the LCFS. It considered removing the negative crediting of dairy biogas projects, but its proposal (which is currently out f comment) opted to continue negative credits until 2040 for biogas used directly in transportation and until 2045 for biogas used to produce hydrogen for transportatic

There is a long tradition in agriculture of governments paying farmers for environmental improvement, rather than placing the burden on farmers to make th improvements. As a result, consumers do not see the full cost to society of the food they eat. Instead, those costs are shifted to taxpayers or, in the case of dairy biogas, gasoline and diesel consumers. Such mispricing can cause costly misallocations of resources, as articulated often on this blog.

Leakage is the main argument given for continuing negative crediting. There are several ways to mitigate leakage. Some, such as border adjustments (tax dairy produ coming into California) would be very difficult to operationalize. A good rule in pol is to directly target the problem you are trying to solve. In this case, the problem would be methane-mitigation costs imposed on farmers that cause them to move ou of state. Negative crediting in the LCFS is a convoluted solution with numerous drawbacks. A direct solution could involve the state sharing the costs of methane mitigation practices, which they already do to some extent through California Department of Food and Agriculture programs.

I made the last three figures using this R code. This article is cross posted at the Energy Institute blog.

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Melissa Moore Jan 22, 2024

I see that a lot of the movement out of state started in 2015. Could that be related to drought ra than methane mitigation regulation?

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What's Worth More: A Cow's Milk or its Poop?



AARON SMITH

FEB 03, 2021

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Sha



Dairy digester in California. Image courtesy of Dairy Cares.

Anaerobic digesters turn cow manure into biogas. Like natural gas, biogas is mostly methane, so it can substitute for natural gas in electricity generation and powering vehicles. Last week, the California Air Resources Board (CARB) released new data c the Low Carbon Fuel Standard (LCFS) program showing a big jump in the use of biogas from dairy farms to power vehicles.

Anaerobic digestion works by sealing manure in a giant pit to keep oxygen out whil microbes feed on the contents, producing biogas as a byproduct. One of the first

applications of this technology was in the late 1800s at a leper colony in Matunga, India. They captured gas from septic tanks to run a gas engine for pumping sewage and also for lighting and cooking. Professor Gilbert Fowler took this picture of the digester for his 1934 book on biochemistry.

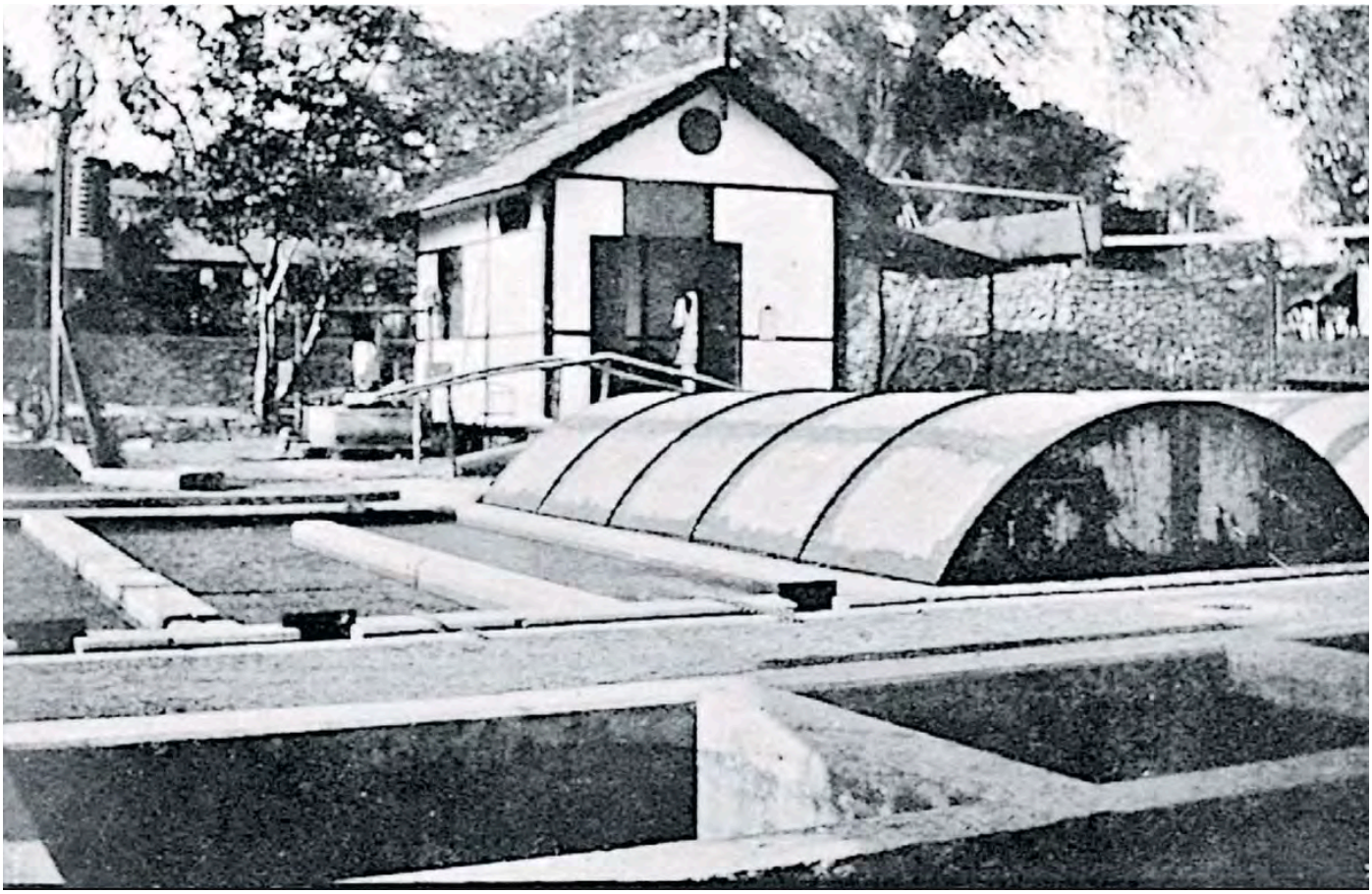

Sewage farm and pump station at Matunga in 1934, photo by Prof Gilbert Fowler, Indian Institute of Science from "An Introduction to the Biochemistry of Nitrogen Concentration" (photo circa 1934 from archive.org)

There are currently 207 anaerobic digesters operating on America's 40,000 dairy far Many were installed in 2006-13 in the Midwest and Northeast with Farm Bill fundi through USDA's Rural Energy for America Program. In the last five years, most ne dairy digesters have been in California.

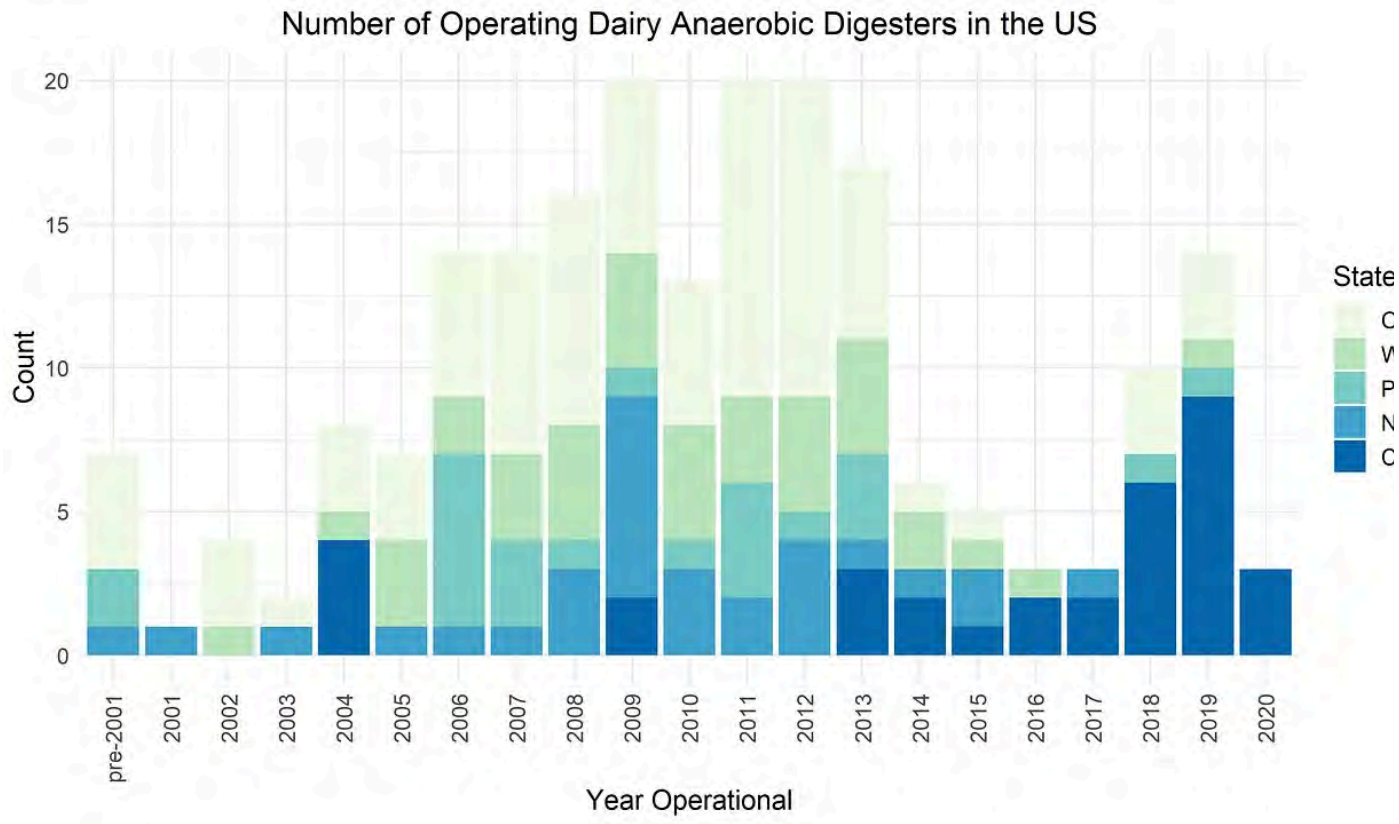

Source: EPA Agstar and R code linked at end of article

Equal numbers of California digesters are employed to produce CNG for transportation and to generate electricity. Most digesters outside California produc biogas that is used to generate electricity or in cogeneration plants, which produce electricity and heat.

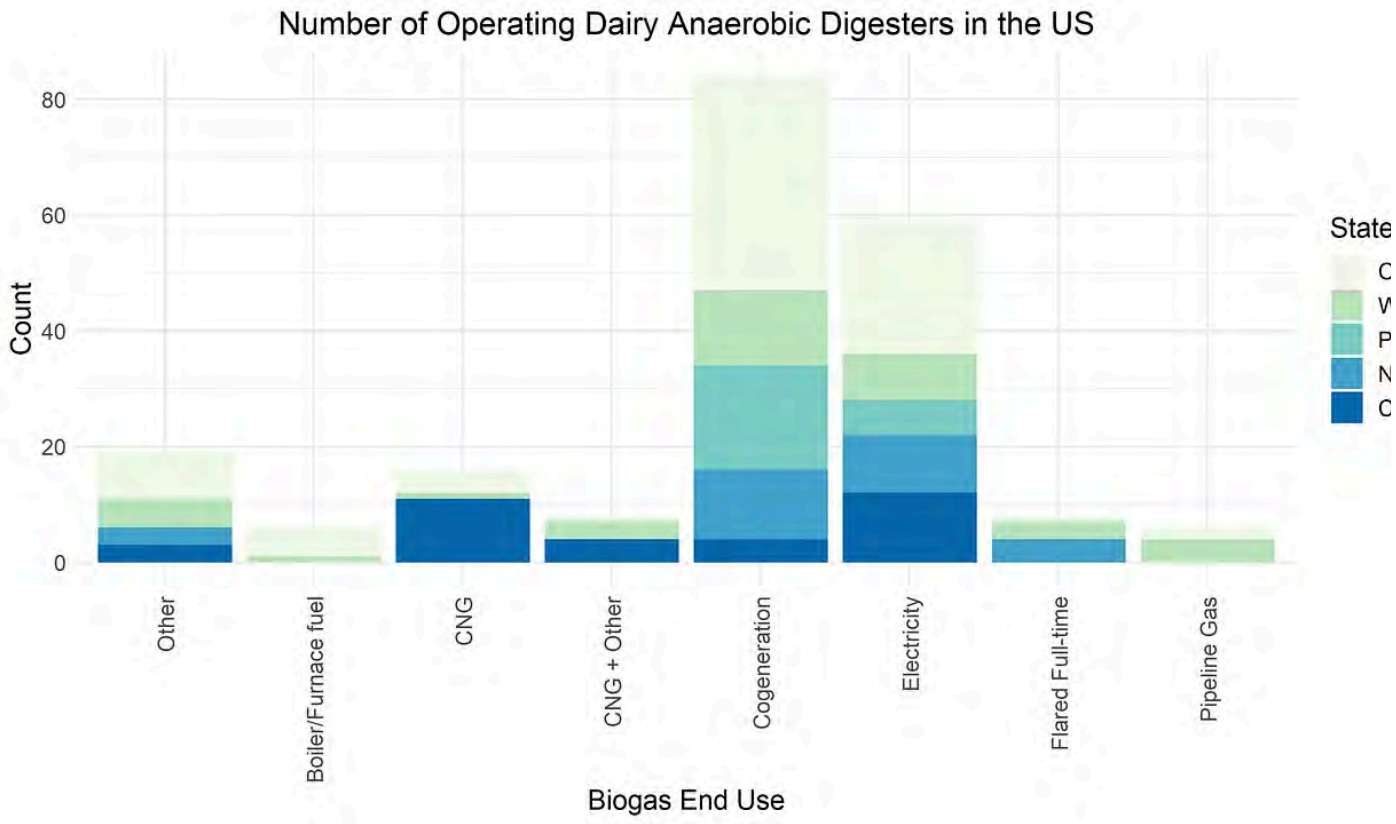

Source: EPA Agstar and R code linked at end of article

Anaerobic digesters are an expensive way to produce natural gas; they are about fou times more expensive than pulling it out of the ground. Specifically, the spot price natural gas is about $3 per MMBTU. Using CARB numbers, this article by my colleagues Hyunok Lee and Dan Sumner reports that a digester costs about $588,00 per year for a 2000-cow dairy, or $294 per cow. That cow generates approximately 2 MMBTU of gas per year, which is worth $68.

Update (2/4/21): These cost numbers exclude capital costs of installing the digester, which total $4.8m. Amortized over 10 years at 7% discount rate, capital costs equal $683,000 per year, or $342 per cow. The total annual cost of installing, running and maintaining the digester is therefore 342+294 = $636 per cow. I exclude capital costs because they are often paid by government grants rather than the farmer.

It costs $294 to get $68 worth of gas from a cow's manure.

Policy incentives make it profitable for dairy farmers to install digesters. The larges such incentive in California comes through the Low Carbon Fuel Standard (LCFS), which I wrote about here and here. In the most recent quarter for which data are available, the LCFS offered subsidies of $12 per diesel-gallon equivalent, which translates to $86 per MMBTU.

Our cow generates a subsidy of $1,935 from its 22.5 MMBTU of gas per year, more than enough to cover the $294 cost of running and maintaining the digester.

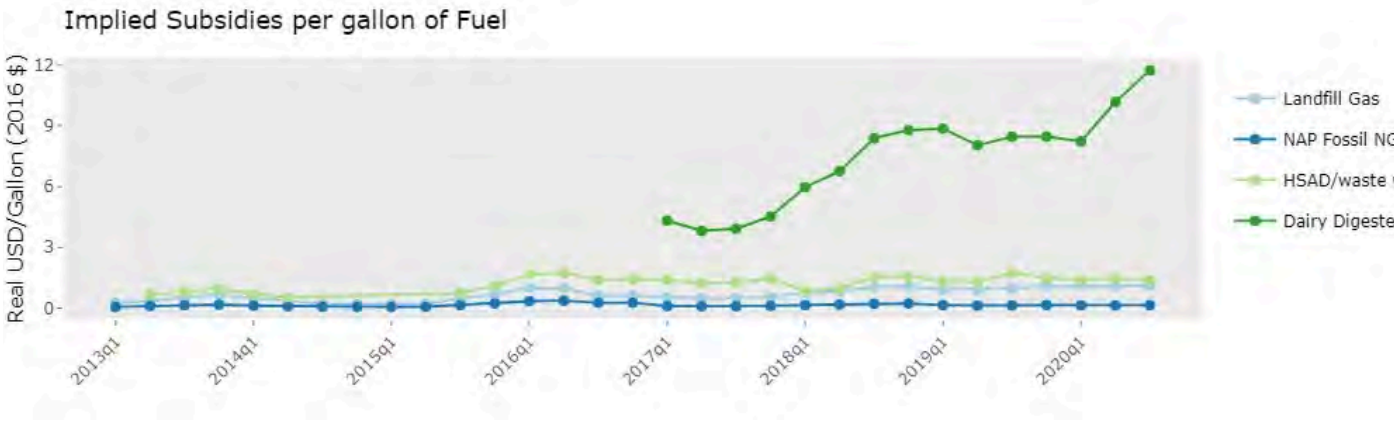

Source: Our LCFS app

Why the big subsidies? Methane is a powerful greenhouse gas, and if it were not captured, it would have been emitted into the atmosphere and caused warming. Th farmers are being paid to reduce their methane emissions, and they produce a little biogas for transportation as a by-product. The value is in prevented emissions.

There is still considerable scope for biogas from dairy digesters to grow in the LCF especially given the large subsidy. In 2012, essentially all natural gas used in transportation in the state was from fossil sources. In the ensuing years, biogas fro landfills drove fossil gas out of the market. Now, dairy biogas is poised to drive out landfill sources.

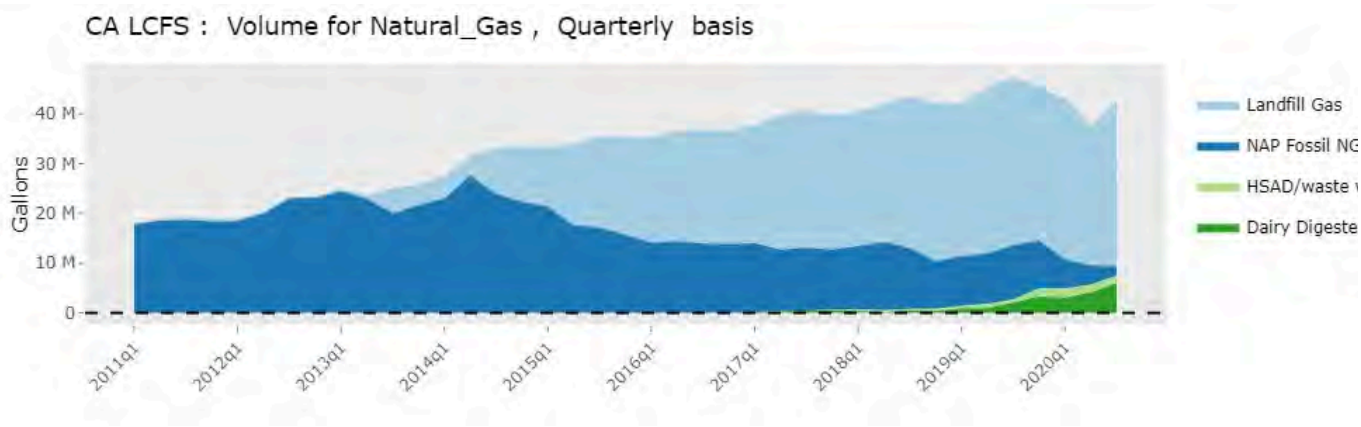

Source: Our LCFS app

To implement the LCFS, CARB determines the carbon intensity (CI) of each transportation fuel using a life cycle analysis of the fuel pathway, accounting for potential emissions throughout the fuel production process. Gasoline and diesel inc deficits because they have high CI's (i.e., high carbon emissions per unit energy). Fu such as ethanol, biodiesel, renewable diesel, electricity, biogas, and hydrogen earn credits because they have low CI's. The credits have to balance out the deficits.

Because it receives credit both for reducing methane emissions from manure and replacing a dirtier fuel, dairy biogas generates a subsidy 10 times higher than landfi gas. Thus, even though it accounts for only a seventh of natural gas fuel volume, da biogas generates more LCFS credits than landfill gas. Dairy biogas generated 330,(MT of credits in the most recent quarter; it would generate 2.3 million credits if it were to replace all natural gas fuel.

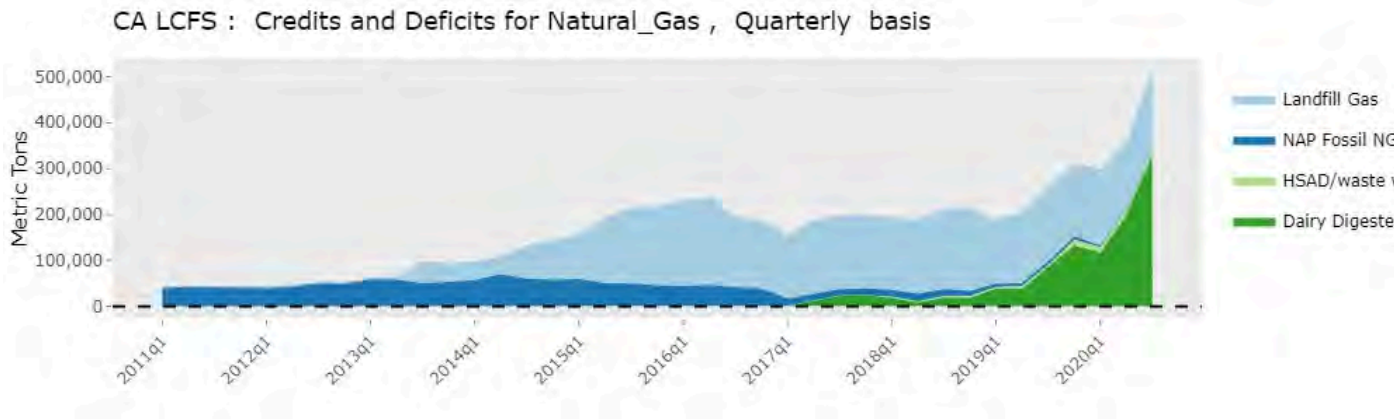

Source: Our LCFS app

In recent quarters, total LCFS deficits and credits have been about 4 million per quarter. If dairy digester credits were to reach 2.3 million per quarter, then it would relieve some pressure on the policy.

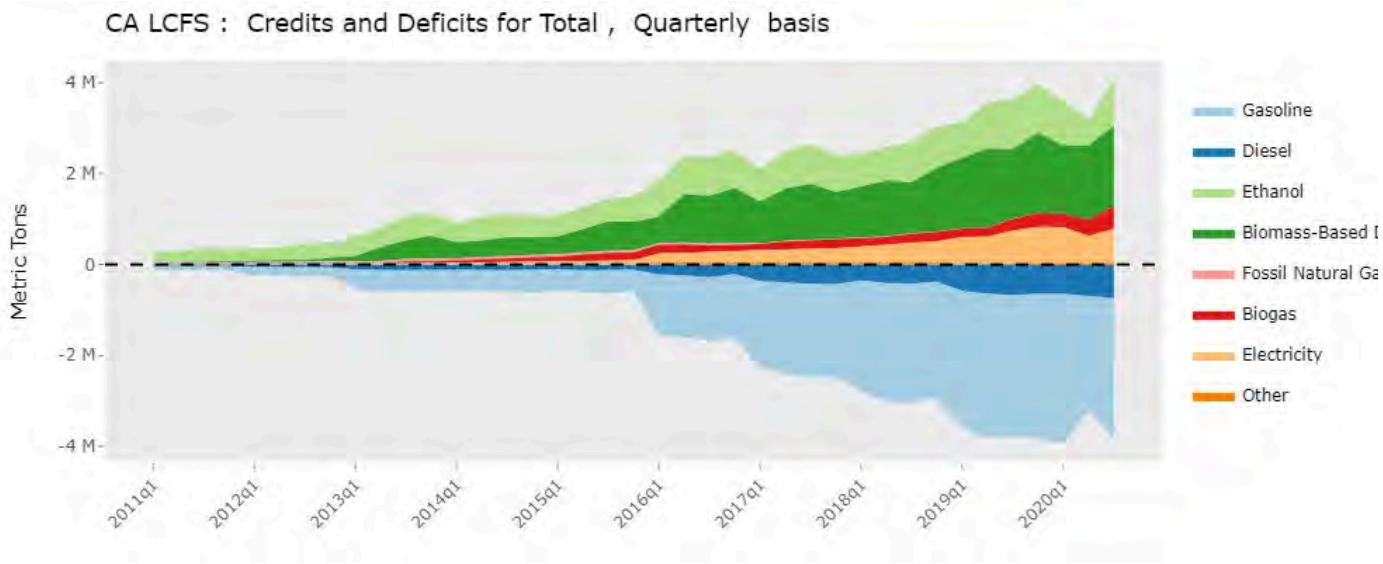

Source: Our LCFS app

A sign that the policy has been under pressure is that the LCFS credit bank has been declining for three years. However, in the most recent quarter, the bank increased by 130,000 credits, about the same as the increase in dairy digester credits that quarter.

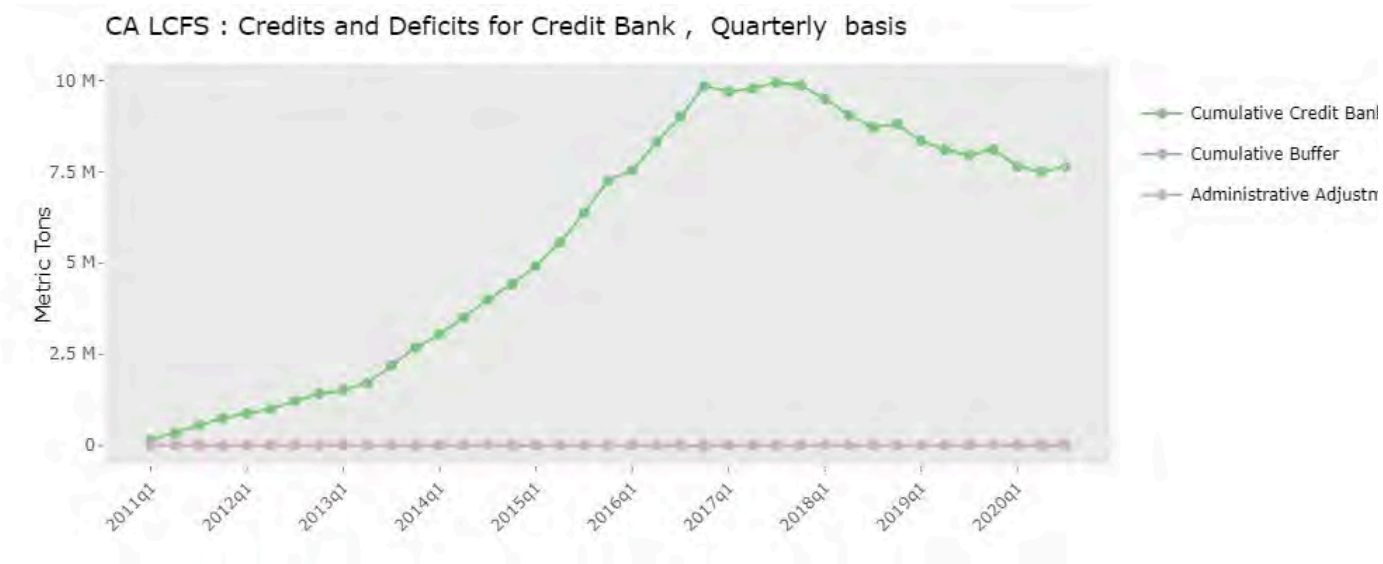

Source: Our LCFS app

A typical California dairy cow produces 230 cwt of milk each year. At a price of $16.50/cwt, the cow produces $3,800 of milk per year. This is twice as much as the subsidy the cow gets from the LCFS.

So, the cow's milk is worth more than its poop, but the poop is worth a lot.

This fact should make us pause. The large subsidy is deigned to prevent methane emissions that would have happened otherwise. But, what if the farmer adds cows *because of* the subsidy? Then we are no longer paying to reduce emissions.

I generated the first two figures using this R code. The remainder of the figures co from our LCFS data app. Huge kudos to UC Davis ARE PhD student Dan Mazzone for his great work putting this app together and keeping it up to date.

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POLITICS

Minnesota looks to tighten regulations on feedlots to deal with persistent pollution from manure

The state will consider changes to regulations on 17,000 feedlots for first time in 25 years.

By Greg Stanley
The Minnesota Star Tribune

JUNE 13, 2025 AT 11:30AM



Minnesota plans to update its regulations on livestock feedlots. (Glen Stubbe/The Minnesota Star Tribune)

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For the first time in 25 years, Minnesota pollution regulators will step up their oversight of thousands of feedlots across the state. The new rules could change how and when the manure amassed by increasingly large livestock operations is stored and spread on fields, as that manure continues to contaminate drinking water in rural Minnesota.

While no new regulations have been proposed, officials with the Minnesota Pollution Control Agency (MPCA) said they want to find ways to reduce the amount of nitrate from feedlot manure that has infiltrated private wells and groundwater and caused sporadic fish kills in rivers and streams.

They said they want to make sure the state's rules address new technology and the changing make-up of livestock, dairy and poultry operations across the state, which have consolidated to put more animals on fewer farms.

"With the move to larger facilities there's different techniques and practices in terms of how people store and manage the feed that the animals use," said Lisa Scheirer, the agency's feedlot program manager. "There's been an increase in manure that is sold or given away for a third party to apply. Generally, there's more liquid manure."

Minnesota has also been getting more extreme and unpredictable rain storms than it did when its rules were last updated, which have caused manure lagoons to overflow and increased runoff on farms, Scheirer said.

There are roughly 17,000 feedlots in the state. The review of the rules comes in response to a 2023 directive from the Environmental Protection Agency that the state take several steps to address nitrate contamination in southeast Minnesota. Minnesota promised then that it would act quickly to help residents with dangerous levels of nitrate in their wells.

Last spring, state officials worked to provide water to affected residents who were pregnant or had infants. Lawmakers directed $16 million in 2024 toward tests and inventories of wells in the region and clean-up of those polluted with farm runoff, among other issues. This year, the state also added new cover crop and manure monitoring requirements for some of Minnesota's largest feedlots – those with more than 1,000 animal units.

State officials will hold public meetings throughout Minnesota to hear about how people feel about the current rules and what they'd like to see changed. The state will accept comments from groups and individuals until July 22. Then pollution regulators will create a task force with farmers, environmentalists and other residents and spend about two years drafting new rules.

Under current rules, every feedlot is required to register with the state. All have to follow the state's standards for manure storage systems. Farmers must only apply as much manure as their crops need, according to rates set by the University of Minnesota. Every feedlot with more than 100 animal units is required to test manure for nutrient content and to keep records of all manure applications. Those with more than 300 animal units need to write up more detailed manure management plans.

An update is long overdue, said Joy Anderson, a lawyer for the Minnesota Center for Environmental Advocacy (MCEA), one of the groups that first asked the EPA to order the state to do more to address nitrate contamination.

"We didn't use to have 10,000 cows on a dairy farm in Minnesota, and now we do," Anderson said. "And the problem is that when you have all those animals consolidated in one area, the manure is really heavy and really expensive to transport, so it tends to get spread thickly near where it's produced."

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The MCEA is asking the state to add more manure spreading protections for vulnerable landscapes like southeast Minnesota, such as requiring farmers to plant cover crops if they spread manure in the fall. The group is also asking the state to require more feedlots to get federal pollution discharge permits, lowering the threshold to 600 animal units from 1,000.

“Right now, it’s really only the 1,200 biggest feedlots in the state that have to get those water pollution permits,” Anderson said.

The MPCA will try to balance environmental protection with practical and region-specific solutions, Scheirer said.

“We’re hearing that the agency should be flexible,” she said. “Minnesota is a big state, and what might be appropriate or work in the southeast might not be appropriate in the northwest.”

Any changes to the state’s feedlot rules would most likely be felt most by small to medium-size farms – those with more than 50 animal units, said Loren Dauer, the Minnesota Farm Bureau Federation’s director of public policy.

“Our state has a long history and vested interest in small-to-medium farms,” he said.

Farmers have shown they’re ready to work with the state to try to keep nutrients from washing off fields, he said.

“A lot more farmers today are investing, especially in the southeast, in having cover crop continuously growing,” he said. “Our folks live on the same ground where they utilize these nutrients. Fertilizer and manure are such valuable resources in today’s farming economy, it would be ridiculous for that to go to waste.”

Updating feedlot rules is going to be a long process, Dauer said.

“If we do hear about certain requirements coming through this change that would be too economically impactful, we will want our

members to voice their concerns," he said.

The state has been trying to reduce nitrate pollution from decades, with little success. About 90% of the nitrate in southeastern Minnesota's water comes from farming fertilizer spread on cropland, a state study found in 2013.

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ABOUT THE WRITER

Greg Stanley

REPORTER

Greg Stanley is an environmental reporter for the Minnesota Star Tribune. He has previously covered water issues, development and politics in Florida's Everglades and in northern Illinois.

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Jennifer Brooks



Crops have been slow to develop in the upper Midwest

smithfieldgrain.com/story-crops-been-slow-develop-upper-midwest-0-255565



The spring of 2025 has been a mixed scenario for crop producers in the upper Midwest, as they have tried to get this year's corn and soybean crop planted and off to a good start. Favorable weather conditions in mid-April and again in mid-May allowed for corn and soybean planting to be completed in many areas of the Midwest; however, heavy rainfall events during much of May have slowed planting progress in some portions on the eastern and southern Corn Belt. A cooler than normal weather pattern during the last half of May slowed corn and soybean development in the upper Midwest. The western Corn Belt and northern Plains states were also negatively impacted by very strong winds and dust storm on May 15 and 16 that caused some significant crop damage in some areas.

Total rainfall amounts across the primary crop production regions of the U.S. during the month of May were quite variable. Most areas received some precipitation during May, with portions of the south central U.S. getting excess rainfall that delayed planting and caused some crop loss. On the other hand, some portions of the western Corn Belt received less than normal rainfall in May and continue to have some drought concern as we advance through the 2025 growing season. Some long range weather forecasts are still indicating a higher than normal chance of a major drought in portions of the region later this year.



As of May 28, the University of Minnesota Research and Outreach Center at Waseca had recorded 3.51 inches of rainfall during May, with a high percentage of the precipitation occurring from May 20-22. The May rainfall in Waseca is about an inch below the long-term average monthly precipitation for May. The Waseca location received 3.78 inches of precipitation in April, which was slightly above normal. As of May 28, the U of M Southwest Research and Outreach Center at Lamberton had received only 2.31 inches of rainfall during May, which is about 1.3 inches below normal. This followed an April precipitation total of 2.01 inches, which was also below normal. Total stored soil measurements at the Lamberton site on May 15 were below the long-term average and were at the lowest level in the past five years,

A large portion of Minnesota, Iowa, Nebraska, North Dakota and South Dakota dealt with strong winds and a severe dust storm on May 15 and 16. In many areas, this the worst dust storm in over a decade. The dust storm resulted in light to moderate damage to thousands of acres of crop land in the affected states. A majority of the corn and soybeans in the affected region were small enough that they should recover; however, there were some isolated reports of replanting being necessary on earlier planted corn and soybeans. There was also some reported damage to small sugar beet plants in portions of western Minnesota.

The U.S. Drought Monitor that was released on May 29 showed that large portions of the central and northern Plains states were experiencing some level of drought. Moderate to severe drought conditions covered much of Nebraska, with some moderate drought conditions in Kansas and South Dakota. Abnormally dry to moderate drought conditions also existed in western and northern Minnesota, western Iowa, northern Illinois, and portions of North Dakota. Thanks to some timely rainfall during May, the corn and soybean crop in many of these areas is off to a good start; however, timely rains will be needed to properly sustain the corn and soybean crop in the coming weeks.

Cooler than normal temperature during the second half of May slowed corn and soybean development; however, fairly warm temperatures have improved conditions during the final few days of May. Due to some extremely warm temperatures during the first half of May, the monthly average temperature for the month of May ended up being above normal in most portions of Minnesota and the adjoining areas of neighboring States. Crops in areas that have adequate soil moisture should benefit greatly from the warmer temperatures in late May and early June.

The level of growing degree units, which measure growing conditions for corn and soybeans, was near normal for the month of May at many locations in the Midwest; however, most areas dealt with very extreme GDU accumulation, from very high in early May to almost zero

later in the month. As of May 28, a total of 314 GDUs had accumulated at the U of M Research Center at Waseca since May 1, which is slightly ahead of normal but is lower than the 337 GDUs accumulated by May 28, 2024. As of May 26, the GDU accumulation during the month of May at the U of M Research Center at Lamberton was slightly ahead of normal. The very warm temperatures at the end of May and the first few days of June should help push crop development ahead of normal, except in areas with limited moisture, as well as in locations with replant acres or late planted row crops.

Based on the May 27 USDA Crop Progress Report, 87% of the corn in the U.S. was planted, which compares to a five-year average of 85% planted by that date. As of May 27, corn planting was over 90% completed and corn emergence was ahead of normal in Minnesota, Iowa, Nebraska, and Missouri; however, corn planting completion was at only 54% in Ohio, 76% in Indiana, and 82% in Illinois. The May 27 USDA Report showed that 76% of the soybeans nationwide were planted, which is well-above the planting pace in 2024 and compares to a five-year average soybean planting rate of 68% by that date. Similar to corn, soybean planting well ahead of normal in the major soybean-producing states in the upper Midwest but trailed the normal planting pace in the eastern Corn Belt and some southern soybean producing states.

The first 2025 national crop rating for corn was also released on May 27 and indicated that 68% of the U.S. corn crop was rated “good to excellent,” which is very close five-year average for corn in the higher rating categories. Iowa topped the initial late May statewide corn condition ratings with 83% of the corn rated “good to excellent.” Other fairly strong crop ratings for corn included Illinois at 77%, Missouri at 76%, Nebraska and Indiana at 70%, and Minnesota at 69%. On the other hand, Ohio was at 41% and North Dakota at 48% of the corn rated “good-to-excellent.” The lower ratings in those states were primarily due to either excessive rainfall in Ohio or developing drought conditions in some portions of North Dakota.

Based on research from the University of Illinois, there is very little correlation between the initial U.S. corn condition ratings in late May and the final U.S. corn yield. By late July, there is about a 90% correlation between the national corn condition rating and the final U.S. corn yield. Given the better than average start to the 2025 growing season in many key corn producing states, there is certainly potential that the 2025 U.S. corn yield could meet or exceed the U.S. “trendline” corn yield near 181 bushels per acre. However, the growing drought area in the Plains states and large area of abnormally dry conditions in many locations across the Midwest has raised some concerns regarding the final 2025 corn yield levels in some areas.

The other factor besides the national average crop yields that will affect final 2025 U.S. corn and soybean production will be the final 2025 planted crop acreage. The March 30 USDA Planting Intentions Report estimated that 95.3 million acres of corn and 83.5 million acres of soybeans would be planted in 2025. The big questions are how many prevented planted or abandoned crop acres will there be this year and were crop acres switched from corn to soybeans due to the later planting dates in the eastern and southern Corn Belt? We should get a much clearer indication of the final corn and soybean planting numbers in the June 30 USDA Crop Acreage Report and the 2025 prevented planted acreage data in July.

Kent Thiesse is a Farm Management Analyst and writes the weekly "Focus on Ag" column. Contact him by phone at (507) 381-7960 or by email at kentthiesse@gmail.com.

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Global nitrous oxide budget (1980–2020)

Hanqin Tian[1,2], Naiqing Pan[1], Rona L. Thompson[3], Josep G. Canadell[4], Parvadha Suntharalingam[5], Pierre Regnier[6], Eric A. Davidson[7], Michael Prather[8], Philippe Ciais[9], Marilena Muntean[10], Shufen Pan[11,1], Wilfried Winiwarter[12,13], Sönke Zaehle[14], Feng Zhou[15], Robert B. Jackson[16,17], Hermann W. Bange[18], Sarah Berthet[19], Zihao Bian[20], Daniele Bianchi[21], Alexander F. Bouwman[22], Erik T. Buitenhuis[5], Geoffrey Dutton[23,33], Minpeng Hu[24], Akihiko Ito[25,26], Atul K. Jain[27], Aurich Jeltsch-Thömmes[28,29], Fortunat Joos[28,29], Sian Kou-Giesbrecht[30,31], Paul B. Krummel[32], Xin Lan[23,33], Angela Landolfi[34,18], Ronny Lauerwald[35], Ya Li[36], Chaoqun Lu[37], Taylor Maavara[38], Manfredi Manizza[39], Dylan B. Millet[40], Jens Mühle[39], Prabir K. Patra[41,42,43], Glen P. Peters[44], Xiaoyu Qin[36], Peter Raymond[45], Laure Resplandy[46], Judith A. Rosentreter[47,48], Hao Shi[36], Qing Sun[28,29], Daniele Tonina[49], Francesco N. Tubiello[50], Guido R. van der Werf[51], Nicolas Vuichard[9], Junjie Wang[22], Kelley C. Wells[40], Luke M. Western[23,52], Chris Wilson[53,54], Jia Yang[55], Yuanzhi Yao[56], Yongfa You[1], and Qing Zhu[57]

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Abstract. Nitrous oxide (N_2O) is a long-lived potent greenhouse gas and stratospheric ozone-depleting substance that has been accumulating in the atmosphere since the preindustrial period. The mole fraction of atmospheric N_2O has increased by nearly 25 % from 270 ppb (parts per billion) in 1750 to 336 ppb in 2022, with the fastest annual growth rate since 1980 of more than 1.3 ppb yr^{-1} in both 2020 and 2021. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6), the relative contribution of N_2O to the total enhanced effective radiative forcing of greenhouse gases was 6.4 % for 1750–2022. As a

core component of our global greenhouse gas assessments coordinated by the Global Carbon Project (GCP), our global N_2O budget incorporates both natural and anthropogenic sources and sinks and accounts for the interactions between nitrogen additions and the biogeochemical processes that control N_2O emissions. We use bottom-up (BU: inventory, statistical extrapolation of flux measurements, and process-based land and ocean modeling) and top-down (TD: atmospheric measurement-based inversion) approaches. We provide a comprehensive quantification of global N_2O sources and sinks in 21 natural and anthropogenic categories in 18 regions between 1980 and 2020. We estimate that total annual anthropogenic N_2O emissions have increased 40 % (or 1.9 Tg N yr^{-1}) in the past 4 decades (1980–2020). Direct agricultural emissions in 2020 (3.9 Tg N yr^{-1}, best estimate) represent the large majority of anthropogenic emissions, followed by other direct anthropogenic sources, including fossil fuel and industry, waste and wastewater, and biomass burning (2.1 Tg N yr^{-1}), and indirect anthropogenic sources (1.3 Tg N yr^{-1}) . For the year 2020, our best estimate of total BU emissions for natural and anthropogenic sources was 18.5 (lower–upper bounds: 10.6–27.0) Tg N yr^{-1}, close to our TD estimate of 17.0 (16.6–17.4) Tg N yr^{-1}. For the 2010–2019 period, the annual BU decadal-average emissions for both natural and anthropogenic sources were 18.2 (10.6–25.9) Tg N yr^{-1} and TD emissions were 17.4 (15.8–19.20) Tg N yr^{-1}. The once top emitter Europe has reduced its emissions by 31 % since the 1980s, while those of emerging economies have grown, making China the top emitter since the 2010s. The observed atmospheric N_2O concentrations in recent years have exceeded projected levels under all scenarios in the Coupled Model Intercomparison Project Phase 6 (CMIP6), underscoring the importance of reducing anthropogenic N_2O emissions. To evaluate mitigation efforts and contribute to the Global Stocktake of the United Nations Framework Convention on Climate Change, we propose the establishment of a global network for monitoring and modeling N_2O from the surface through to the stratosphere. The data presented in this work can be downloaded from https://doi.org/10.18160/RQ8P-2Z4R (Tian et al., 2023).

1 Executive summary

The global N_2O budget has been perturbed through direct and indirect anthropogenic emissions as well as through perturbations to the natural N_2O sources and sinks via climate change, increasing atmospheric CO_2, and land-cover change. Ice core data show a relatively constant tropospheric N_2O mixing ratio over the past 2 millennia (Canadell et al., 2021; MacFarling Meure et al., 2006; Fischer et al., 2019), followed by an increase from about 270 ppb (parts per billion) in 1750 to well above 300 ppb in the 2010s. The tropospheric N_2O mole fractions, precisely measured at a global network of stations, increased from 301 ppb in 1980 to 333 ppb in 2020 and 336 ppb in 2022. The tropospheric N_2O mole fraction in 2022 is higher than at any time in the last 800 000 years. The current growth rate of atmospheric N_2O is unprecedented with respect to the ice core record covering the last deglacial transition (with decadal to centennial resolution) and likely unprecedented relative to the ice core records of the past 800 000 years. The mean annual tropospheric growth rate increased from 0.76 (lower–upper bounds: 0.55–0.95) ppb yr^{-1} in the decade from 2000 to 2009 to 0.96 (0.79–1.15) ppb yr^{-1} in the decade from 2010 to 2019. In 2020, the N_2O tropospheric growth rate was 1.33 ppb yr^{-1} (1.38 ppb yr^{-1} in 2021), the highest observed rate since 1980 and over 30 % higher than the average in the 2010s.

Global N_2O emissions have significantly increased in the last 4 decades. The magnitudes of global N_2O emissions estimated by the bottom-up (BU) and top-down (TD) approaches were comparable during the overlapping period from 1997 to 2020, but TD estimates found a larger interannual variability and a faster rate of increase. BU approaches estimated that global N_2O emissions increased from 17.4 Tg N yr^{-1} (10.3–24.0 Tg N yr^{-1}) in 1997 to 18.5 Tg N yr^{-1} (10.6–27.0 Tg N yr^{-1}) in 2020, with an average increase rate of 0.043 Tg N yr^{-2} ($p < 0.05$). In contrast, according to TD estimates, global emissions increased from 15.4 Tg N yr^{-1} (13.9–16.7 Tg N yr^{-1}) in 1997 to 17.0 Tg N yr^{-1} (16.6–17.4 Tg N yr^{-1}) in 2020, implying a higher increase rate of 0.085 Tg N yr^{-2} ($p < 0.05$).

According to BU estimates, the increase in global N_2O emissions was primarily due to a 40 % increase in anthropogenic emissions from 4.8 (3.1–7.3) Tg yr^{-1} in 1980 to 6.7 (3.3–10.9) Tg yr^{-1} in 2020. Among all anthropogenic sources, direct agricultural emissions made the largest contribution, increasing from 2.2 (1.6–2.8) Tg N yr^{-1} in 1980 to 3.9 (2.9–5.1) Tg N yr^{-1} in 2020. The concurrent indirect agricultural N_2O emissions also steadily increased from 0.9 (0.7–1.1) to 1.3 (0.9–1.6) Tg N yr^{-1}. In contrast, other direct anthropogenic emissions (including emissions from fossil fuel and industry, biomass burning, and waste and wastewater) did not show a significant trend, while fluxes induced by perturbations to climate, atmospheric CO_2, and land cover were negative and caused a reduction in N_2O emissions that grew from −0.4 (−0.9 to 1.0) Tg yr^{-1} in 1980 to −0.6 (−2.2 to 1.8) Tg yr^{-1} in 2020. Unlike anthropogenic emissions, global natural land and ocean N_2O emissions

were relatively stable. According to the BU approaches, the total amount of global natural N_2O emissions fluctuated between 11.7 and 12.1 Tg yr^{-1} during 1980–2020. Among all sources, natural emissions from shelves, inland waters, and lightning and atmospheric production were assumed to be constant during 1980–2020. According to BU approaches, the total natural emissions from these sources were 1.8 (1.0–3.0) Tg N yr^{-1}.

During 2010–2019, similar estimates of global total N_2O emissions were obtained using both the BU and TD approaches, with decadal mean values of 18.2 (10.6–25.9) Tg N yr^{-1} and 17.4 (15.8–19.2) Tg N yr^{-1}, respectively (Fig. 1). According to the BU estimates, natural sources contributed 65 % to the total emissions (11.8, 7.3–15.9 Tg N yr^{-1}). Specifically, natural soils contributed the most, with a decadal average of 6.4 (3.9–8.6) Tg N yr^{-1}, followed by open oceans (3.5, 2.5–4.7 Tg N yr^{-1}), the natural source from shelves (1.2, 0.6–1.6 Tg N yr^{-1}), lightning and atmospheric production (0.6, 0.3–1.2 Tg N yr^{-1}), and inland waters, estuaries, and coastal vegetation (0.1, 0.0–0.1 Tg N yr^{-1}). Anthropogenic sources contributed 35 % to the total N_2O emissions (6.5, 3.2–10.0 Tg N yr^{-1}). Direct agricultural emissions accounted for 56 % of the total anthropogenic emissions (3.6, 2.7–4.8 Tg N yr^{-1}), followed by emissions from other direct anthropogenic sources (2.1, 1.8–2.4 Tg N yr^{-1}), including fossil fuel and industry (1.1, 1.0–1.2 Tg N yr^{-1}), waste and wastewater (0.3, 0.3–0.3 Tg N yr^{-1}), and biomass burning (0.8, 0.5–1.0 Tg N yr^{-1}), and indirect anthropogenic emissions (1.2, 0.9–1.6 Tg N yr^{-1}). Perturbed fluxes from climate, CO_2, and land-cover changes had a net negative effect (i.e., reduced) on N_2O emissions (−0.6, −2.1 to 1.2 Tg N yr^{-1}). Increased CO_2 and land conversion from mature forest reduced N_2O emissions, but climate change resulted in N_2O emission of 0.7 (0.2–1.2) Tg N yr^{-1}.

Among the 18 regions considered in this study, only Europe, Russia, Australasia, and Japan and Korea had decreasing N_2O emissions. Europe had the largest rate of decrease, with an average of -13.2×10^{-3} Tg N yr^{-2} during 1980–2020 (31 % reduction), largely resulting from reduced fossil fuel and industry emissions, which changed from 0.49 Tg N yr^{-1} in 1980 to 0.14 Tg N yr^{-1} in 2020. In addition to the large reduction in fossil fuel and industry emissions in Europe, direct and indirect agricultural emissions also declined during 1980–2020; however, the decreasing trend in direct agricultural emissions had leveled off by the 2000s.

China and South Asia had the largest increases in N_2O emissions from 1980 to 2020. The rates of increase in anthropogenic emissions from China and South Asia were 18.9×10^{-3} Tg N yr^{-2} (82 % increase) and 14.3×10^{-3} Tg N yr^{-2} (92 % increase), respectively. In these two regions, direct nitrogen additions in agriculture made the largest contribution, while other direct and indirect emissions also steadily increased.

The atmospheric chemistry transport models used in this study show an increase in the atmospheric N_2O burden, from 1527 (1504–1545) Tg N in 2000–2009 to 1606 (1592–1621) Tg N in 2020, and, proportional to this, a small increase in the atmospheric loss, from 12.1 (12.0–12.6) to 12.9 (12.5–13.2) Tg N yr^{-1}. The estimated increase in the atmospheric N_2O burden is comparable to estimates by satellite and photolysis models, showing an increase from 1528 Tg N in the 2000s to 1570 Tg N in the 2010s and 1592 Tg N in 2020. The atmospheric chemistry transport models, however, did not show any significant trend in the lifetime, which is in contrast to results based on satellite observations in the stratosphere; these observations indicate that the atmospheric lifetime of N_2O decreased from 119 years in the 2000s to 117 years in the 2010s. The reason for the discrepancy is not yet known and needs to be further investigated.

The following major uncertainties have been identified:

1. Inversion estimates are the most uncertain in the areas of South America, Africa, central and southern Asia, and Australasia, where the inversions are poorly constrained by observations.

2. Large uncertainties exist in the estimates of soil N_2O emissions from tropical ecosystems in the Amazon Basin, the Congo Basin, and Southeast Asia as well as in regions with high fertilizer application rates and emissions, including eastern China, northern India, and the US Corn Belt.

3. The largest uncertainties in the estimates of ocean emissions are found in the equatorial Pacific, the Benguela upwelling region of the Atlantic, and the eastern equatorial Indian Ocean. The highest uncertainty in the equatorial upwelling and low-oxygen waters is associated with high subsurface N_2O production.

4. The N_2O fluxes from atmospheric CO_2, mature forest conversion, and biomass burning are poorly understood and quantified. The relatively sparse distribution of current N_2O observation sites underscores the necessity to establish more sites and regular aircraft profiles, especially in tropical and subtropical regions, to better constrain emission estimates from inversion models.

Based on this analysis and associated uncertainties, we propose the urgent development of a comprehensive terrestrial and ocean N_2O flux monitoring and analysis network to better resolve spatiotemporal patterns and reduce uncertainties in N_2O emissions. Such a development is a requirement to better constrain the future contribution of N_2O to climate change and guide policy choices to reduce N_2O emissions.

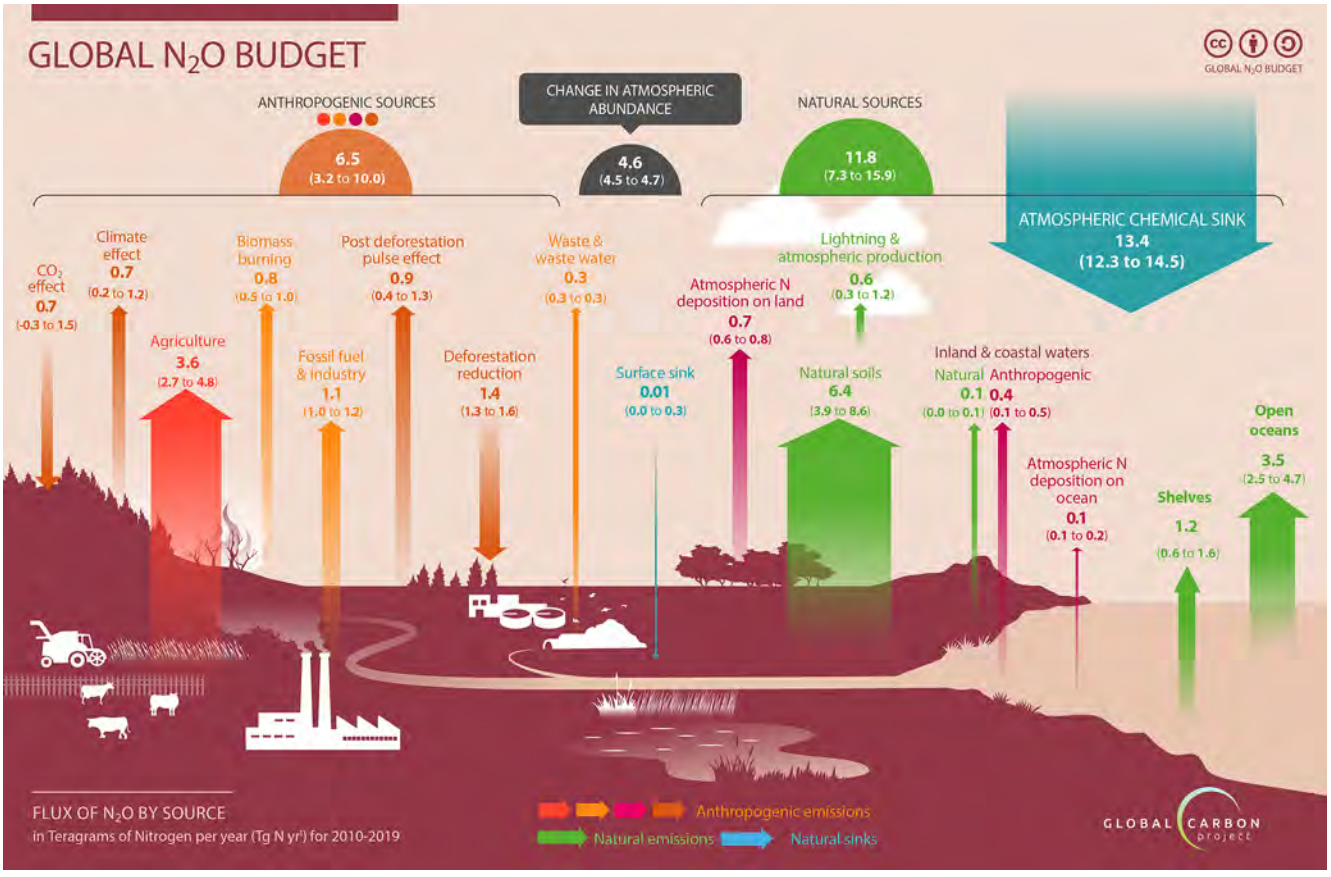

Figure 1. Global N_2O budget during 2010–2019. The colored arrows represent N_2O fluxes (in Tg N yr^{-1} for 2010–2019) as follows: red – direct emissions from nitrogen additions in the agricultural sector (agriculture); orange – emissions from other direct anthropogenic sources; maroon – indirect emissions from anthropogenic nitrogen additions; brown – perturbed fluxes from changes in climate, CO_2, or land cover; and green – emissions from natural sources. The anthropogenic and natural N_2O sources are derived from BU estimates. The blue arrows represent the surface sink and the observed atmospheric chemical sink, about 1 % of which occurs in the troposphere. The total budget (sources + sinks) does not exactly match the observed atmospheric accumulation, as each of the terms has been derived independently and we do not force TD agreement by rescaling the terms. This imbalance falls within the overall uncertainty in closing the N_2O budget, as reflected in each of the terms. The N_2O sources and sinks are given in teragrams of nitrogen per year (Tg N yr^{-1}). © The Global Carbon Project.

2 Introduction

Nitrogen (N) is an essential element for the survival of all living organisms and is required by numerous biological molecules such as nucleic acids, proteins, and chlorophyll (Galloway et al., 2021; Scheer et al., 2020). The addition of excess reactive N compounds to terrestrial and oceanic ecosystems stimulates emissions of nitrous oxide (N_2O), which is the most important depleting substance of stratospheric ozone (World Meteorological Organization, 2022) and a long-lived potent greenhouse gas with an atmospheric lifetime of more than 100 years (Myhre et al., 2013; Prather et al., 2015). Atmospheric N_2O mole fractions have increased by nearly 25 % since the preindustrial era, from 270 ppb (parts per billion) in 1750 (MacFarling Meure et al., 2006) to 336 ppb in 2022, and have shown an increase of 35 ppb (10 %) since 1980 (Fig. 2). The current mole fraction is higher than at any time in the last 800 000 years (Schilt et al., 2010). The increase rate of atmospheric N_2O in the 20th century is unprecedented over the past 20 000 years, covering the last glacial–interglacial transition, and likely unprecedented compared to the lower-resolution ice core records of the past 800 000 years (Joos and Spahni, 2008; Schilt et al., 2010; Canadell et al., 2021 AR6, WGI, Chap. 5). The observation networks of the Advanced Global Atmospheric Gases Experiment (AGAGE; Prinn et al., 2018), the National Ocean and Atmospheric Administration (NOAA; Hall et al., 2007), and the Commonwealth Scientific and Industrial Research Organization (CSIRO; Francey et al., 2003) all show an overall increasing trend in the growth rate of atmospheric N_2O: the mean annual growth rate increased from 0.76 (0.55–0.95) ppb yr^{-1} in the 2000s to 0.96 (0.79–

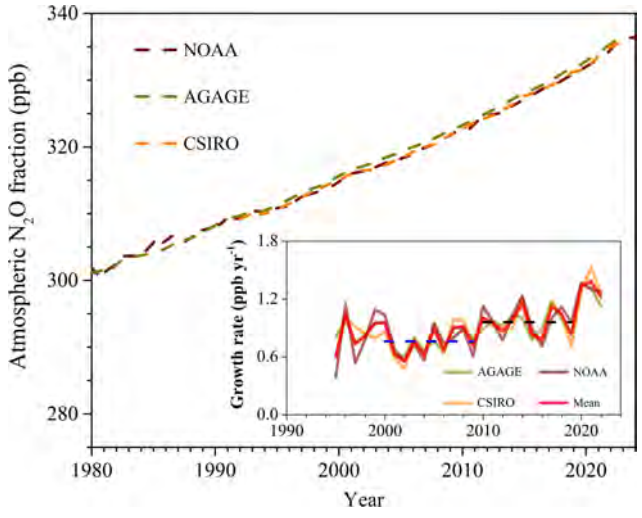

Figure 2. Global mean atmospheric N_2O dry mole fraction (atmospheric concentration) (1980–2022) and its annual growth rate (1995–2022) estimated by the AGAGE, NOAA, and CSIRO observing networks. The blue and black dashed lines represent the mean annual growth rate in the 2000s and 2010s, respectively.

1.15) ppb yr^{-1} in the 2010s, with significant seasonal and interannual variation. In 2020, the N_2O atmospheric growth rate was 1.33 ppb yr^{-1} (1.38 ppb yr^{-1} in 2021), higher than any previous observed year, and more than 30 % higher than the average value in the 2010s.

Due to the rapid increase in global N_2O emissions, observed atmospheric N_2O mole fractions in recent years have begun to exceed the predicted levels under all scenarios in the Coupled Model Intercomparison Project Phase 6 (CMIP6) for the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021; Gidden et al., 2019; Tian et al., 2020). N_2O emissions are expected to continue increasing in the coming decades due to the growing demand for food, feed, fiber, and energy as well as a rising source from waste generation and industrial processes (Davidson and Kanter, 2014; Reay et al., 2012). Reducing N_2O emissions will contribute to the mitigation of global warming and the recovery of stratospheric ozone (Jackson et al., 2019). It is noted that, although increased stratospheric NO_x due to rising levels of N_2O can lead to incremental stratospheric O_3 loss, it is unlikely to cause catastrophic ozone loss the way that anthropogenic halogens did, as stratospheric NO_x from N_2O has offset halogen-catalyzed stratospheric ozone loss through various buffering reactions, e.g., the formation of halogen reservoir species like $ClONO_2$ (Wennberg et al., 1994; Nevison et al., 1999; Ravishankara et al., 2009). Significant reductions in N_2O emissions are required along with net CO_2 emissions to stabilize the global climate system. For pathways consistent with the remaining carbon budget of 1.5, 1.7, and 2 °C stabilization, and assuming that all greenhouse gases (GHGs) should be cut in equal proportion to their contribution to anthropogenic radiative forcing, global N_2O emissions need to be reduced by 22 %, 18 %, and 11 %, respectively, by 2050 (Rogelj and Lamboll, 2024). In addition, N_2O mitigation could reduce ozone loss comparable to the depletion potential of the global chlorofluorocarbons (CFCs) stock in old air conditioners, refrigerators, insulation foams, and other units (UNEP, 2013). All in all, implementing N_2O mitigation will contribute to achieving a set of United Nations Sustainable Development Goals (United Nations, 2016).

Nitrification and denitrification are the two key microbial processes controlling N_2O production (Butterbach-Bahl et al., 2013; Gruber and Galloway, 2008; Kuypers et al., 2018; Firestone and Davidson, 1989), making the largest contribution to global N_2O emissions (Syakila and Kroeze, 2011; Tian et al., 2020); abiotic processes also play a role in the production of N_2O. We categorize the processes governing N_2O sources and sinks in 23 different categories (Fig. 3): (1) $F_{\text{fossil fuel}}$ – N_2O emissions from fossil fuel combustion; (2) F_{industry} – N_2O emissions from the chemical industry; (3) $F_{\text{waste water}}$ – N_2O emissions from wastewater treatment and discharge; (4) $F_{\text{natural inland waters}}$ – natural N_2O emissions from inland waters (rivers, lakes, and reservoirs); (5) $F_{\text{human inland waters}}$ – anthropogenic N_2O from inland waters (rivers, lakes, and reservoirs); (6) $F_{\text{direct soil emission}}$ – direct N_2O emissions from agricultural soils; (7) $F_{\text{manure left on pasture}}$ – N_2O emissions from manure left on pasture; (8) $F_{\text{manure management}}$ – N_2O emission from manure management; (9) $F_{\text{aquaculture}}$ – N_2O emissions from coastal and freshwater aquaculture; (10) $F_{\text{land use/land cover changes}}$ – N_2O emission/reduction due to land-cover change/deforestation; (11) $F_{\text{natural soil emissions}}$ – natural soil N_2O emission; (12) $F_{\text{biomass burning}}$ – N_2O emissions from biomass burning; (13) $F_{\text{surface uptake}}$ – surface N_2O uptake; (14) $F_{\text{N deposition land}}$ – indirect N_2O emissions from anthropogenic nitrogen additions on land; (15) $F_{\text{Climate effect}}$ – perturbed N_2O fluxes from climate change; (16) $F_{CO_2\text{ effect}}$ – perturbed N_2O fluxes from CO_2 change; (17) F_{shelves} – N_2O emission from continental shelves; (18) F_{oceans} – N_2O emission from open ocean; (19) $F_{\text{N deposition ocean}}$ – N_2O emissions from anthropogenic N deposition on oceans; (20) $F_{\text{lightning and atmospheric production}}$ – lightning and atmospheric production of N_2O; (21) $F_{\text{stratospheric sink}}$ – stratospheric N_2O sink; (22) $F_{\text{natural coastal water}}$ – natural N_2O emissions from estuaries and coastal vegetation; and (23) $F_{\text{N dep and leaching}}$ – N_2O emissions from nitrogen deposition and leaching to estuaries and coastal vegetation. There is also a small amount of N_2O emission from termite mounds, but such an N_2O flux is not quantified in the current budget analysis due to limited data.

Biogenic N_2O emissions from land are regulated by multiple environmental factors, including soil moisture, temperature, oxygen status, pH, vegetation type, topography, atmospheric CO_2 concentration, and soil N and C availabil-

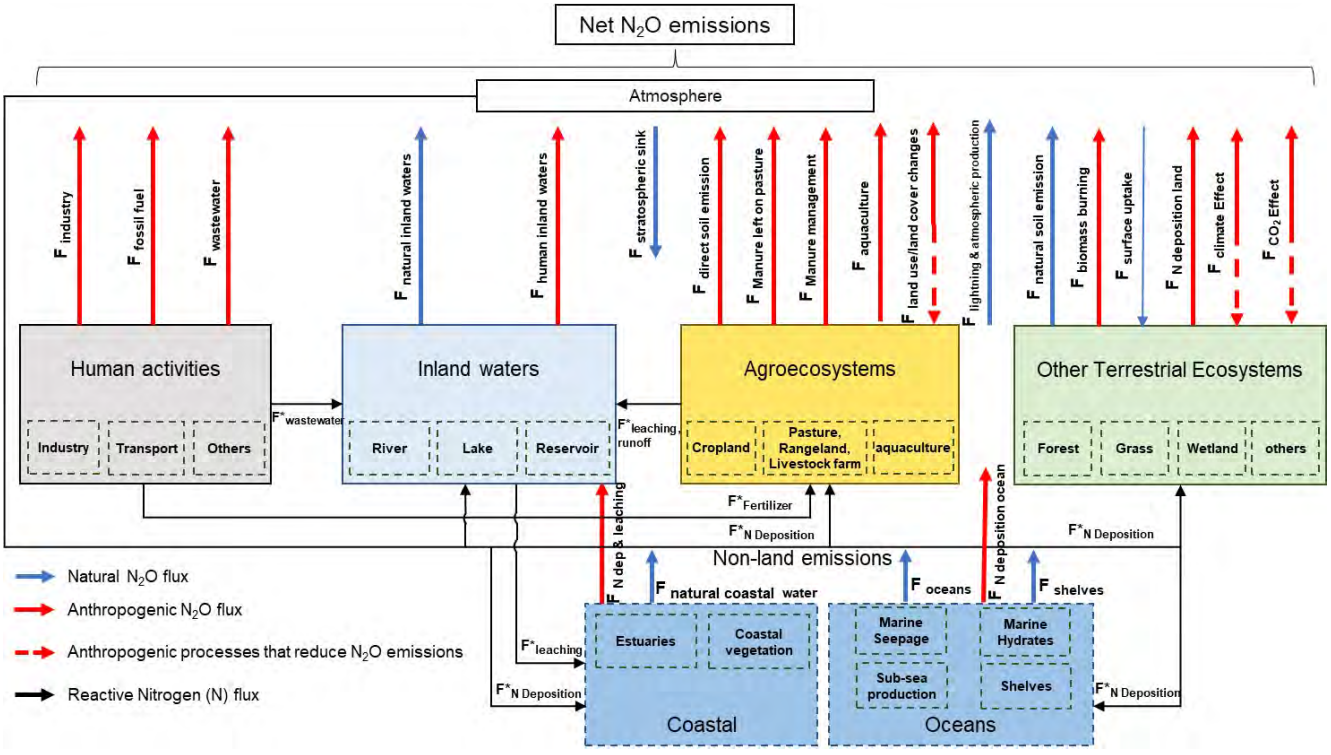

Figure 3. N_2O sources and sinks and flux partitions contributing to the global N_2O budget. Upward-pointing arrows indicate a source to the atmosphere, whereas downward-pointing arrows represent a sink.

ity (Butterbach-Bahl et al., 2013; Dijkstra et al., 2012; Li et al., 2020; Tian et al., 2016, 2019; Yin et al., 2022; H. Yu et al., 2022). The effects of these environmental factors on N_2O emissions have strong spatial and temporal heterogeneity, making upscaling field N_2O measurements to regional and global scales difficult. Studies using atmospheric N_2O inverse modeling suggest a greater source of N_2O from land and ocean under the colder and wetter La Nina conditions and vice versa in the warmer and drier El Niño conditions (Patra et al., 2022; Thompson et al., 2014). Ongoing environmental changes, such as ocean warming (and associated changes in stratification and ice coverage), decreasing pH (i.e., increasing acidification), loss of dissolved oxygen (i.e., deoxygenation), and eutrophication due to increasing anthropogenic inputs of nutrients via rivers and atmospheric deposition of nitrogen aerosols, might significantly alter the production and consumption of N_2O in the upper ocean, its distribution pattern, and, ultimately, its release to the atmosphere (Bange et al., 2019; Bange, 2022; Wilson et al., 2020), exerting a small but uncertain feedback on global warming in the long term (Battaglia and Joos, 2018; Forster et al., 2021).

In this study, we construct a comprehensive global and regional N_2O budget based on the processes and framework shown in Fig. 3 and following the framework of Tian et al. (2020). The figure summarizes the pathways of N_2O formation, consumption, emission, and absorption, and it helps to guide consistent estimations and comparisons of N_2O budgets among regions and upscaling of regional budgets to the globe. N_2O fluxes are grouped into two major categories based on the sources.

The first category is natural N_2O fluxes (blue arrows in Fig. 3), which are N_2O fluxes in the absence of climate change and anthropogenic disturbances, including natural soil emissions, soil uptake, N_2O emission from natural disturbances causing wetland loss and degradation, lightning, and atmospheric production. This category also includes natural emissions from inland waters, coastal ecosystems, and the ocean.

The second category is anthropogenic N_2O fluxes (red arrows in Fig. 3). The direct emissions from nitrogen additions in the agricultural sector ("Agroecosystems" box in Fig. 3) include emissions from the direct application of synthetic nitrogen fertilizers and manure (henceforth "Direct soil emissions"), manure left on pasture, manure management, and aquaculture, while other direct anthropogenic sources include fossil fuel combustion and industry, waste and wastewater, and biomass burning. Indirect N_2O emissions derive from anthropogenic nitrogen additions, such as atmospheric nitrogen deposition (NDEP) on land and ocean, and the effects of anthropogenic loads of reactive nitrogen in inland waters, estuaries, and coastal vegetation.

In the anthropogenic N_2O fluxes category, we also consider N_2O fluxes from the anthropogenic perturbations to climate, CO_2, and land use/land cover (hereafter perturbation fluxes). In terrestrial ecosystems, perturbation fluxes can be caused by increasing CO_2 concentration, climate change (e.g., warming-induced thawing of permafrost), and land-use change (e.g., converting natural lands to lands for human uses, such as croplands, mining, logging, and the post-deforestation pulse effect – the long-term effect of reduced mature forest area). N_2O emissions can either increase or decrease during land conversion, depending on the type and phase of the land-use change. For example, when tropical forests are first converted to agriculture, there is often a pulse of N_2O emissions for the first year or for as long as 5 years, depending upon the circumstances; following deforestation, emissions decline below those of the original forest if pastures degrade and if croplands are not fertilized, such as in slash-and-burn agriculture (Davidson and Artaxo, 2004; Meurer et al., 2016). When agriculture is abandoned and a secondary forest is allowed to regrow, N_2O emissions gradually increase but usually remain lower than those of the original mature forest or from fertilized croplands (Davidson et al., 2007; Sullivan et al., 2019).

Numerous efforts have estimated individual sources and sinks of N_2O across global ecosystems. Prominently, anthropogenic N_2O emissions have been annually reported for the past 2 decades by Annex I Parties (developed countries) to the United Nations Framework Convention on Climate Change (UNFCCC) (https://unfccc.int/reports, last access: 1 November 2020). As a result of the Paris Agreement, over 190 signatory countries are now required to report their national GHG inventory biannually, if not already reported annually, with sufficient detail and transparency to track progress towards their nationally determined contributions. However, national GHG inventories only provide a partial picture of the observed changes in atmospheric N_2O. They do not cover natural sources and have large uncertainties in the emission factors and activity data. Additionally, data are limited in many regions of the world, e.g., South America and Africa (Tian et al., 2020).

Tian et al. (2020) built the first comprehensive global N_2O budget using multiple BU and TD methods as part of a partnership between the Global Carbon Project (GCP) and the International Nitrogen Initiative (INI). Based on Tian et al. (2020) and the budget framework established in Fig. 3, our study presents an improved and updated global N_2O budget and its regional attribution to 18 land regions and the global ocean. The budgets cover the decades of 1980–1989, 1990–1999, 2000–2009, and 2010–2019 and includes a complete budget extension to 2020 and atmospheric N_2O changes in 2021 and 2022. The work allows us to explore the relative temporal and spatial importance of multiple sources and sinks that drive the atmospheric burden of N_2O, their uncertainties, and interactions between anthropogenic and natural forcings. This study also consolidates the international scientific capacity and networks that contribute to this assessment with the aim of providing improved and updated N_2O budgets at regular intervals.

This global effort builds from and contributes to the set of global GHG assessments that the GCP has established, including regular updates of the carbon (CO_2-C), methane (CH_4), and (now) N_2O budgets as well as other biogeochemical budgets of global significance. The budgets have been designed to (a) support global and national scientific assessments (e.g., IPCC and WCRP annual reports), (b) align scientific research and data products to support climate mitigation and sustainability policy needs, and (c) contribute to the Global Stocktake of the Paris Agreement to track progress towards nationally determined contributions and the ultimate goal of achieving net-zero GHG emissions. Integration of all GHGs in robust and shared methodological approaches and data delivery platforms are central goals of the GCP.

3 Methodology and data

3.1 Definitions, terminology, and the unit of N_2O sources and sinks

This study provides an estimation of the global N_2O budget considering all quantifiable sources, sinks, and perturbations, resulting in a total of 21 N_2O fluxes. To simplify our analysis, we further grouped these fluxes into six major categories: (1) "Natural baseline fluxes", which is the source in the absence of climate change and anthropogenic disturbances and includes emissions from soils, surface uptake, shelf and ocean emissions, lightning and atmospheric production, and emissions from inland waters, estuaries, and coastal vegetation; (2) direct emissions from nitrogen additions in the agricultural sector ("Agriculture"), which includes emissions from the direct application of nitrogen fertilizers and manure (henceforth direct soil emissions), manure left on pasture, manure management, and aquaculture; (3) "Perturbed fluxes from climate, CO_2, and land-cover change", which includes the effects of CO_2, climate, the post-deforestation pulse, and the long-term effect of reduced mature forest area; (4) indirect emissions from anthropogenic nitrogen additions, which includes atmospheric nitrogen deposition (NDEP) on the land, atmospheric NDEP on the ocean, and the effects of anthropogenic loads of reactive nitrogen in inland waters, estuaries, and coastal vegetation; (5) other direct anthropogenic sources, which includes fossil fuel and industry, waste and wastewater, and biomass burning; and (6) the atmospheric sink in the stratosphere (via photolysis and oxidation by O^1D). Our anthropogenic N_2O emission categories are aligned with those compiled by the national GHG inventories using IPCC (2006) methodologies and reported to the UNFCCC (Table A1).

In this study, N_2O fluxes are expressed in teragrams of N_2O-N per year, where 1 Tg N_2O-

$N\,yr^{-1}$ ($1\,Tg\,N\,yr^{-1} = 10^{12}\,g\,N_2O\text{-}N\,yr^{-1} = 1.57 \times 10^{12}\,g\,N_2O\,yr^{-1}$, with change rates in N_2O fluxes expressed in teragrams of nitrous oxide-nitrogen per year squared ($Tg\,N\,yr^{-2}$), representing the first derivative of annual N_2O fluxes calculated by the linear regression method. Atmospheric N_2O is expressed as dry air mole fractions, in parts per billion (ppb), with atmospheric N_2O annual increases expressed in parts per billion per year ($ppb\,yr^{-1}$). The conversion factor from the unit "$ppb\,yr^{-1}$" to the unit "$Tg\,N\,yr^{-1}$" is $4.79\,Tg\,N\,ppb^{-1}$ (Prather et al., 2012). Unless specified, uncertainties are reported in parentheses as minimum and maximum values of all estimates, following Tian et al. (2020).

We focus on N_2O fluxes and their change rates during three periods: 1997–2020, 1980–2020, and 2010–2019. For the time span from 1980 to 2020, which is the entire study period, we report temporal variations in BU estimates of N_2O emissions from different sources to depict the overall trends of these fluxes. For the time span from 1997 to 2020, which is the overlapping period of BU and TD approaches, we compare BU and TD estimates to exam their consistency. For the time span from 2010 to 2019, which is the most recent decade, we report the magnitudes of emissions from different sources to give best estimates of their latest status and relative importance.

3.2 Definition of regions

As anthropogenic emissions are often reported at the country level, we divide global land into 18 regions and define these regions based on a country list (Table A2). This approach is compatible with all TD and BU approaches considered here. The number of regions was close to the widely used TransCom intercomparison map (Gurney et al., 2004) but with subdivisions to separate the contribution of important countries or regions to the global N_2O budget (such as China, South Asia, and the USA). This regionalization is also compatible with the REgional Carbon Cycle Assessment and Processes (Poulter et al., 2022) after aggregation into 10 regions. The 18 regions are the United States (USA), Canada (CAN), Central America (CAM), northern South America (NSA), Brazil (BRA), southwestern South America (SSA), Europe (EU), northern Africa (NAF), equatorial Africa (EQAF), southern Africa (SAF), Russia (RUS), Central Asia (CAS), the Middle East (MIDE), China (CHN), Korea and Japan (KAJ), South Asia (SAS), Southeast Asia (SEAS), and Australasia (AUS). The region definition is the same as that used for the GCP methane and N_2O budgets (Saunois et al., 2020; Stavert et al., 2022; Tian et al., 2019).

3.3 Overview of methods used for global N_2O budget synthesis

Four major methods are available to estimate large-scale N_2O emissions: atmospheric inversion models (method 1), activity- and emission-factor-based inventories (method 2), empirically based algorithms and machine learning algorithms (method 3), and process-based ecosystem models (method 4). Atmospheric inversion models (method 1), a TD approach, utilize measurements of atmospheric N_2O mixing ratios combined with atmospheric transport models, driven by meteorological fields, to estimate the emissions of N_2O (Thompson et al., 2014). Atmospheric inversion models usually use Bayesian statistics, which, starting from a prior emission estimate, find the optimal N_2O emissions (i.e., those that best agree with observed atmospheric N_2O mixing ratios) while also being guided by the prior emission and observation uncertainties (Nevison et al., 2018; Thompson et al., 2019).

TD approaches generally only estimate the total N_2O emission, which is spatially and temporally resolved, but do not constrain the contributions from different sources. The other three methods belong to BU approaches, which are capable of quantifying N_2O emissions from different sources. Emission-activity- and emission-factor-based inventories (method 2) use a prescribed emission factor (EF) to calculate N_2O emissions. This approach has been widely used in national emission inventories and global studies (Davidson, 2009; Oreggioni et al., 2021; Crippa et al., 2021; Winiwarter et al., 2018). Nevertheless, the fixed EFs cannot capture the nonlinear response of agricultural soil N_2O emissions to N inputs (Gerber et al., 2016) and also cannot fully reflect the dependence of EFs on climate, management practices, and soil physical and biochemical conditions (e.g., Marzadri et al., 2022). Therefore, a spatially referenced nonlinear model (SRNM), which outperformed the default EF method, was developed to simulate N_2O emissions in response to fertilizer application under various environmental and management conditions (Zhou et al., 2015). In recent years, machine learning algorithms (method 3) have been applied to estimate soil N_2O emissions. A random forest model was used to estimate global terrestrial background N_2O emissions (Yin et al., 2022) and N_2O emissions from intensively managed cropping systems (Saha et al., 2021). Moreover, a machine-learning-based stochastic gradient boosting model was developed to predict global terrestrial nitrification and its fraction in N_2O emissions (Pan et al., 2021).

Compared with the three abovementioned methods, process-based ecosystem models (method 4) have two notable advantages (Xu et al., 2020; Tian et al., 2019): (1) they are capable of modeling the key processes affecting N_2O production and emission, such as autotrophic nitrification, denitrification, plant nitrogen uptake, ammonia volatilization, nitrate leaching, and soil thermal and hydrological processes, although their accuracy in representing these processes needs

further improvement; and (2) they integrate various driving factors controlling soil N_2O emissions, such as fertilizer use, atmospheric N deposition, land-use change, climate change, and atmospheric CO_2 concentration change and, thus, can disentangle the effects of different driving factors. Although multiple process-based models have estimated global soil N_2O emissions, large discrepancies exist in these estimates due to the diverse parameterizations of biogeochemical processes in different models, our limited understanding of the mechanisms responsible for N_2O emissions, and the uncertainties in input data. The Global N_2O Model Intercomparison Project (NMIP) was launched (Tian et al., 2018, 2019) to develop a multi-model ensemble estimation of global soil N_2O emissions during 1861–2016 and quantify the contributions of different driving factors.

We consider global N_2O emissions from land and ocean including natural fluxes and anthropogenic emissions based on BU and TD approaches (Fig. 4). The BU methods considered include eight process-based terrestrial biosphere models from NMIP2 (global Nitrogen/N_2O Model Intercomparison Project phase 2); six ocean models (Battaglia and Joos, 2018; Berthet et al., 2023; Buitenhuis et al., 2018; Carroll et al., 2020; Landolfi et al., 2017); one machine-learning-based observational shelf product (Yang et al., 2020); a mix of five approaches relying on meta-analysis and statistical and process-based models for inland waters and coastal ecosystems (Hu et al., 2016; Lauerwald et al., 2019; Maavara et al., 2019; Yao et al., 2020; Marzadri et al., 2021; Marzadri et al., 2022; Rosentreter et al., 2023); four GHG emission databases – Emissions Database for Global Atmospheric Research (EDGAR) v7.0 (Crippa et al., 2021, https://edgar.jrc.ec.europa.eu/dataset_ghg70, last access: 10 February 2022), FAOSTAT (Tubiello et al., 2015), UNFCCC (https://unfccc.int/reports, last access: 1 November 2020), and GFED4s (van der Werf et al., 2017) (only for biomass burning); and one statistical model (SRNM) only for cropland soils (Wang et al., 2020). The TD approach consisted of four independent atmospheric inversion frameworks, namely INVICAT (Wilson et al., 2014), PyVAR-CAMS (Thompson et al., 2014), MIROC4-ACTM (Patra et al., 2022), and GEOS-Chem (Wells et al., 2018).

3.4 Model and inventory data synthesis

3.4.1 Natural N_2O fluxes

"Natural soil baseline" emissions were obtained from the ensemble mean of the eight terrestrial biosphere models that participated in NMIP-2 that run with preindustrial land cover (Table 1): (1) the Canadian Land Surface Scheme including Biogeochemical Cycles (CLASSIC) (Asaadi and Arora, 2021; Melton et al., 2020; Kou-Giesbrecht and Arora, 2022); (2) the Dynamic Land Ecosystem Model (DLEM) (Tian et al., 2015; Xu et al., 2017; You et al., 2022); (3) the E3SM Land Model (ELM) (Zhu et al., 2019); (4) the Integrated Science Assessment Model (ISAM) (Shu et al., 2020; X. Xu et al., 2021); (5) the Land Processes and eXchanges model – Bern (LPX-Bern v1.4) (Lienert and Joos, 2018; Joos et al., 2020); (6) O-CN (Zaehle et al., 2011); (7) Organising Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) (Goll et al., 2017); and (8) the Vegetation Integrated SImulator for Trace gases (VISIT) (Ito et al., 2018).

Natural emission from "Inland water, estuaries, and coastal vegetation", including inland and coastal waters, were obtained from models by Yao et al. (2020), Maavara et al. (2019), Lauerwald et al. (2019), and Marzadri et al. (2021) as well as the meta-analyses by Hu et al. (2016) and Rosentreter et al. (2023). As the data (rivers, lakes, reservoirs, and estuaries) provided by Hu et al. (2016), Maavara et al. (2019), Lauerwald et al. (2019), and Marzadri et al. (2021) are for the year 2000, we assumed that these values are constant during 1980–2020. Yao et al. (2020) provided annual riverine N_2O emissions using DLEM during 1980–2019. Here, we averaged riverine estimates from Yao et al. (2020), Maavara et al. (2019), Hu et al. (2016), and Marzadri et al. (2021), assuming that the estimates of Maavara et al. (2019) and Hu et al. (2016) represent emissions from larger rivers only, while Yao et al. (2020) and Marzadri et al. (2021) also account for emissions from streams and small rivers. Note further that the estimate by Marzadri et al. (2021) is not fully global, as it excludes river systems north of 60° N. Therefore, we did not use this assessment for the regions of Canada, the USA, Russia, and Europe. DLEM also estimated annual N_2O emissions from global reservoirs, and we averaged these estimates with those from Maavara et al. (2019) to represent emissions from reservoirs during 1980–2020. The estimate for global and regional lakes was based on the long-term average values provided by Lauerwald et al. (2019) and an estimate by the DLEM-TAC model (Li et al., 2024). For estuaries, we combined the estimate of Maavara et al. (2019), which relies on a process-based modeling approach, with a new metadata analysis by Rosentreter et al. (2023). The analysis of Rosentreter et al. (2023) is observation-based and includes the contribution of coastal vegetated ecosystems, a contribution not accounted for in Maavara et al. (2019). Estuaries and coastal vegetation data are from studies published between 1975 and 2020, and we assume fluxes are constant during 1980–2020 (Rosentreter et al., 2023). To disentangle natural and anthropogenic fluxes, we considered the emissions in the year 1900 simulated by DLEM (Yao et al., 2020) as equivalent to the natural emission, assuming that the N load from land was negligible in that period (Kroeze et al., 1999). Using this approach, we estimated that N_2O emissions from natural sources of rivers, reservoirs, lakes, and estuaries accounted for 44 % (36 %–52 %) of the total emissions from inland waters, taking into account all N inputs (i.e., inorganic, organic, dissolved, and particulate forms).

N_2O emissions from continental shelves were calculated using one data-driven estimate and three high-resolution model estimates for various time periods (Resplandy et

Table 1. Methods, spatial and temporal resolution, and data sources for the synthesis of the global N_2O budget.

Model/data name	Spatial resolution	Time period	References
Inventories (anthropogenic)			
EDGAR v7.0	0.1° × 0.1°	1980–2020	Crippa et al. (2021)
GFED4s	0.25° × 0.25°	1997–2020	van der Werf et al. (2017)
FAOSTAT	Country level	1980–2020	Tubiello et al. (2022)
UNFCCC	Country level	1990–2020	https://di.unfccc.int/time_series (last access: 1 November 2020)
Terrestrial biosphere models that participated in NMIP2 (both anthropogenic and natural)			
CLASSIC	0.5° × 0.5°	1980–2020	Asaadi and Arora (2021), Kou-Giesbrecht and Arora (2022)
DLEM	0.5° × 0.5°	1980–2020	Tian et al. (2015), Xu et al. (2017)
ELM	0.5° × 0.5°	1980–2020	Zhu et al. (2019)
ISAM	0.5° × 0.5°	1980–2020	Shu et al. (2020), X. Xu et al. (2021)
LPX-Bern	0.5° × 0.5°	1980–2020	Lienert and Joos (2018), Joos et al. (2020)
O-CN	1° × 1°	1980–2020	Zaehle et al. (2011)
ORCHIDEE	0.5° × 0.5°	1980–2020	Vuichard et al. (2019)
VISIT	0.5° × 0.5°	1980–2020	Ito et al. (2018)
Ocean biogeochemical models (natural)			
Bern-3D	9° × 4.5° × 32 levels	1980–2019	Battaglia and Joos (2018)
NEMOv3.6-PISCESv2-gas	1° × 1° × 75 levels	1980–2020	Berthet et al. (2023), Séférian et al. (2019)
NEMO-PlankTOM10.2	2° × (0.5–2°) × 30 levels	1980–2016	Buitenhuis et al. (2018)
UVic2.9	3.6° × 1.8° × 19 levels	1980–2020	Landolfi et al. (2017)
Continental shelf products (natural)			
MEM-RF	0.25° × 0.25°	1988–2017 mean	Yang et al. (2020)
CNRM-0.25°	0.25° × 0.25°	1998–2018 mean	Berthet et al. (2019)
ECCO2-Darwin and ECCO-Darwin	1/3° (ECCO-Darwin), −1/6° (ECCO2-Darwin)	1998–2013 mean (ECCO-Darwin), 2006–2013 mean (ECCO2-Darwin)	Ganesan et al. (2020), Carroll et al. (2020)
Inland waters, estuaries, and coastal vegetation (both anthropogenic and natural)			
DLEM-TAC	0.5° × 0.5°	1980–2019	Yao et al. (2020), Tian et al. (2020)
Mechanistic stochastic model	0.5° × 0.5°	2000	Lauerwald et al. (2019), Maavara et al. (2019)
Meta-analysis-based upscaling	Watershed level, 18 regions	2000, 1975–2020	Hu et al. (2016), Rosentreter et al. (2023)
Integrated ML and physical model	0.5° × 0.5°	2000	Marzadri et al. (2021)
Atmospheric inversion models			
INVICAT	5.625° × 5.625°	1997–2020	Wilson et al. (2014)
PyVAR-CAMS	3.75° × 1.875°	1997–2020	Thompson et al. (2014)
MIROC4-ACTM	∼ 2.8° × 2.8°	1997–2019	Patra et al. (2018, 2022)
GEOS-Chem	5° × 4°	1997–2019	Wells et al. (2018)
Other models and datasets (anthropogenic)			
SRNM (direct soil emission)	1/12° × 1/12°	1980–2020	Wang et al. (2020)
Bookkeeping method (perturbed fluxes from land-cover change)	0.25° × 0.25°	1980–2020	Tian et al. (2020), Keller and Reiners (1994)
IMAGE-GNM	Country level	1980–2020	Bouwman et al. (2011, 2013a)

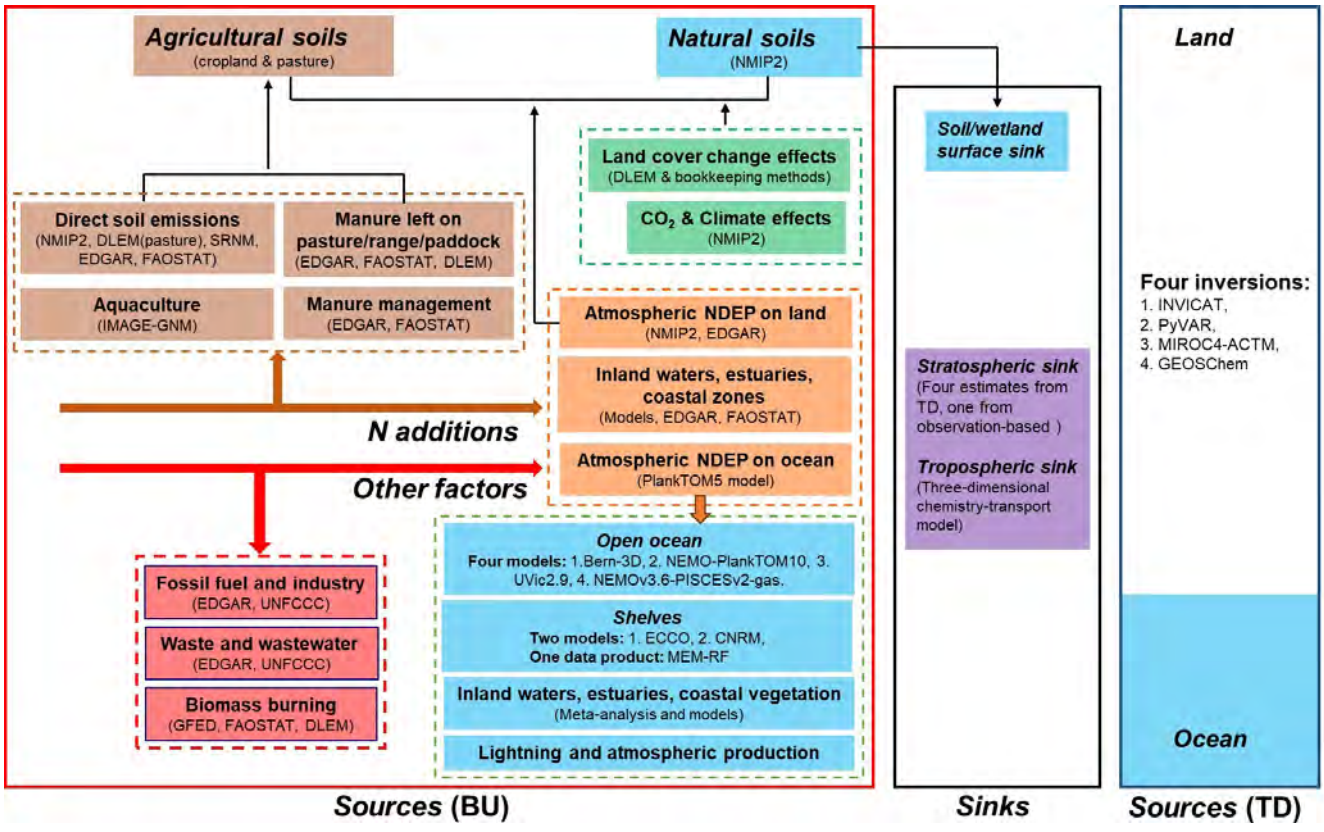

Figure 4. Methodologies used to estimate each of the main flux categories contributing to the global N_2O budget. We use both BU and TD approaches, including 20 BU and 4 TD estimates of N_2O fluxes from land and oceans. For sources estimated by the BU approach, we include eight process-based terrestrial biosphere modeling studies; six process-based ocean biogeochemical models and one shelf observational product; one nutrient budget model; five inland and coastal water modeling or meta-analysis studies; one statistical model SRNM based on spatial extrapolation of field measurements; and four greenhouse gas inventories – EDGAR v7.0, FAOSTAT, UNFCCC, and GFED. Previous estimates of the surface sink, lightning and atmospheric production, model-based tropospheric sink, and observed stratospheric sink are included in the current synthesis. The nutrient budget model provides nitrogen flows in global freshwater and marine aquaculture over the 1980–2020 period. Model-based estimates of N_2O emissions from inland and coastal waters include rivers and reservoirs, lakes, estuaries, coastal vegetation (i.e., seagrasses, mangroves, and salt marsh), and coastal upwelling.

al., 2024, also see Sect. S7), namely an observation-based estimate that relied on a random forest (RF) algorithm to interpolate N_2O data (Yang et al., 2020), based on a synthesis of over 158 000 observations of the N_2O mixing ratio, partial pressure, and concentration in the surface ocean from the MEMENTO database (MEM-RF) (Kock and Bange, 2015); an estimate relying on the high-resolution configuration (Berthet et al., 2019) of the global ocean–biogeochemical component of CNRM-ESM2-1 (CNRM-0.25°); and two estimates relying on the ECCO-Darwin model run at 1/3° (ECCO-Darwin1) and 1/6° (ECCO-Darwin2), respectively. Considering that ECCO-Darwin1 and ECCO-Darwin2 relied on the same model, their mean N_2O fluxes were used.

Estimates of natural N_2O emissions from open oceans are derived from four global ocean biogeochemistry models, including Bern-3D (Battaglia and Joos, 2018), NEMOv3.6-PISCESv2-gas (Berthet et al., 2023), NEMO-PlankTOM10 (Buitenhuis et al., 2018), and UVic2.9 (Landolfi et al., 2017). Towards the N_2O budget synthesis, modeling groups reported gridded monthly fluxes at a $1° \times 1°$ resolution for the 1980–2020 period. Specific details on ocean model configurations and N_2O parameterizations are reported in the individual model publications.

We combined the estimate from lightning with that from atmospheric production into an integrated category "Lightning and atmospheric production" (Kohlmann and Poppe, 1999; Dentener and Crutzen, 1994). We simplified the Lightning and atmospheric production category as purely natural, although atmospheric production is affected to some extent by anthropogenic activities, such as enhancement of the concentrations of the reactive species NH_3 and NO_2. This category is, in any case, very small, and the anthropogenic enhancement effect is uncertain. The estimate of "Surface sink" was obtained from Schlesinger (2013) and Syakila et al. (2010).

3.4.2 Direct emissions from nitrogen additions (agriculture)

Agriculture N_2O emissions consist of four components: "Direct soil emissions", "Manure left on pasture", "Manure management", and "Aquaculture". Data for direct soil emissions were obtained as the ensemble mean of N_2O emissions from the average of two inventories (EDGAR v7.0 and FAOSTAT), the SRNM and DLEM models, and the NMIP2 and DLEM models. The statistical model SRNM only covers cropland N_2O emissions. Thus, we added the DLEM-based estimate of pasture N_2O emissions into the two estimates of cropland to represent direct agricultural soil emissions (i.e., SRNM/DLEM or NMIP2/DLEM). Manure left on pasture is the ensemble mean of EDGAR v7.0, FAOSTAT, and DLEM. Manure management emissions are the mean of EDGAR v7.0 and FAOSTAT. FAOSTAT emission factors for N additions are based on the 2006 guidelines. Global N flows (i.e., fish feed intake, fish harvest, and waste) in freshwater and marine aquaculture were obtained from Bouwman et al. (2011, 2013a) and Beusen et al. (2016) and based on the IMAGE-GNM aquaculture nutrient budget model for the 1980–2020 period. We then calculated global aquaculture N_2O emissions as a 1.8 % loss of N waste in aquaculture, i.e., the same EF used in Hu et al. (2012) and MacLeod et al. (2019). The uncertainty range of the EF is from 0.5 % (Eggleston et al., 2006) to 5 % (Williams and Crutzen, 2010), the same range used in the UNEP report (Bouwman et al., 2013b).

3.4.3 Emissions from other direct anthropogenic sources

This category includes "Fossil fuel and industry", "Waste and wastewater", and "Biomass burning". Both emissions from fossil fuel and industry and waste and wastewater were calculated as the ensemble means of EDGAR v7.0 and UNFCCC databases. The biomass burning emission is the ensemble mean of FAOSTAT, DLEM, and GFED4s databases. In EDGAR v7.0, the Waste and wastewater category includes "Waste incineration" and "Wastewater handling". We merged "Transportation", "Energy", "Industry", and "Residential and other sectors" to represent the total emission from fossil fuel and industry. The FAOSTAT emissions database of the Food and Agriculture Organization of the United Nations (FAO) covers emissions of N_2O from agriculture and land use by country and globally, from 1961 to 2020 for agriculture and from 1990 for relevant land-use categories, i.e., cultivation of Histosols, biomass burning, etc., applying only Tier-1 coefficients (Tubiello et al., 2021, 2022; Conchedda and Tubiello, 2020; Prosperi et al., 2020). In addition to the IPCC agriculture burning categories "Burning crop residues" and "Burning savannah", we included FAOSTAT estimates for N_2O emissions from deforestation fires, forest fires, and peatland fires (Prosperi et al., 2020).

3.4.4 Indirect emissions from anthropogenic N additions

This category considers N deposition on land and the ocean ("N deposition on land" and "N deposition on ocean") as well as the N leaching and runoff from upstream ("Inland and coastal waters"). The emission from N deposition on ocean was provided by Suntharalingam et al. (2012) and includes emission from both open oceans and continental shelves, while emission from N deposition on land was the average of two estimates by NMIP2/EDGAR v7.0 and NMIP2. EDGAR v7.0 provided estimates of indirect emissions from both agricultural and non-agricultural sectors; however, here, we sum the ensemble mean of NMIP2 estimates of indirect emissions from agricultural sectors with indirect emissions from the non-agricultural sector of EDGAR v7.0 (i.e., NMIP2/EDGAR v7.0) to represent N-deposition-induced soil emissions from both agricultural and non-agricultural sectors. The N_2O emissions from inland and coastal waters consist of rivers, reservoirs, lakes, estuaries, and continental shelves, which is the ensemble mean of an average of two inventories (EDGAR v7.0 indirect N_2O emissions – leaching and runoff – and FAOSTAT), and the mean of meta-analysis and models. The anthropogenic emission from inland freshwaters estimated by Yao et al. (2020) considered annual N inputs and other environmental factors (i.e., climate, elevated CO_2, and land-cover change). The results in Yao et al. (2020) suggested that 56 % of the total N_2O emissions from rivers, reservoirs, estuaries, and lakes was attributed to anthropogenic N additions. Empirical methods (empirical models and meta-analysis) adopted this ratio to calculate long-term average anthropogenic N_2O emissions from inland waters, consistent with Tian et al. (2020). Seagrass, mangrove, and salt marsh N_2O emissions were updated from Rosentreter et al. (2023).

3.4.5 Perturbation of N_2O fluxes from climate, CO_2, and land-cover change

The estimate of climate and CO_2 effects on emissions was based on eight NMIP2 models, and we used SH1–SH7 and SH1–SH8 to model the effects of CO_2 and climate on global terrestrial soil N_2O emissions (Table 2), respectively. The effect of land-cover change on N_2O dynamics includes the reduction due to the "Long-term effect of reduced mature forest area" and the additional emissions due to the "Post-deforestation pulse effect". The two estimates were based on the bookkeeping approach and the DLEM model simulation. The bookkeeping method has been developed by Houghton et al. (1983) to account for carbon flows due to land use. In the original bookkeeping model developed by Houghton et al. (1983), land conversion and the affected carbon pools are tracked each year. The initial values of carbon pools are set for each type of land use. Annual changes in carbon pools in areas affected by land-use change or some land management practices (like wood harvest and fire man-

agement) are prescribed in the model using response curves, which are usually a function of the age of the newly converted land use. These response curves are specific for each type of land-cover type and land-use change and do not include the effects of environmental changes (Houghton and Castanho, 2023). For each age cohort, it either gains carbon (afforestation or reforestation) or loses carbon (deforestation) until its carbon pools reach a new stable state (the response curve converges). A similar bookkeeping method was developed to account for N_2O emission due to deforestation. Here, different from the original bookkeeping model calculating carbon fluxes through tracking changes in vegetation or soil pools, response curves directly tracking annual N_2O emissions after deforestation, which are also a function of the age of newly converted land use, were developed in our bookkeeping method (for details, please refer to Sect. S9).

3.4.6 Atmospheric production of reactive nitrogen

N_2O production in the atmosphere is a relatively small component of the global budget. N_2O is produced by the gaseous-phase oxidation of NH_3 in the troposphere; however, there are few published estimates of this source, and it remains poorly constrained. In this paper, we refer to the two known published estimates, which are 0.4 Tg N yr^{-1} (Kohlmann and Poppe, 1999) and 0.6 (0.3–1.1) Tg N yr^{-1} (Dentener and Crutzen, 1994), that are derived using global models of atmospheric chemistry and transport. As human activities have greatly affected the atmospheric abundance of NH_3, a significant portion of this source may be considered anthropogenic. Lightning production of NO_x indirectly leads to N_2O emission through its oxidation and subsequent deposition on land and the ocean. A recent study estimated the global lightning production of NO_x to be 9 Tg N yr^{-1} (Nault et al., 2017), which is larger than previous estimates of 5 (2–8) Tg N yr^{-1} (Schumann and Huntrieser, 2007). In this study, we assume an effective emission factor of 1 % (De Klein et al., 2006); using the median estimate of 5 Tg N yr^{-1} of NO_x, we then estimate a global source of N_2O of 0.05 (0.02–0.09) Tg N yr^{-1}. There is also N_2O production from $N_2 + O(^1D)$, which amounts to about 2 % of the atmospheric source in the stratosphere (Estupiñán et al., 2005).

3.5 Atmospheric observation data synthesis

3.5.1 Atmospheric burden and trends from tropospheric observations

The monthly tropospheric N_2O mole fraction and its growth rate are derived from three different atmospheric observational networks: the Advanced Global Atmospheric Gases Experiment (AGAGE; Prinn et al., 2018), the Commonwealth Scientific and Industrial Research Organization (CSIRO; Francey et al., 2003), and the National Ocean and Atmospheric Administration (NOAA; Dutton et al., 2023; Lan et al., 2022). Further information on the three networks' stations, instruments, calibration, and uncertainties as well as access to data are provided in Sect. S12 "Atmospheric N_2O Observation Networks".

The atmospheric burden and its rate of change during 1980–2020 were derived from mean maritime surface abundance (mole fraction) of N_2O (Prather et al., 2023) with a conversion factor of 4.79 Tg N ppb^{-1} (Prather et al., 2012). Combining uncertainties in measuring the annual mean surface mole fraction, which are < 1 ppb (Dlugokencky et al., 1994), with those of converting surface mole fractions to a global mean abundance, we estimate a ± 1.4 % uncertainty in the absolute burden (Prather et al., 2012). The uncertainty in the conversion from parts per billion to teragrams does not affect the trend uncertainty. This uncertainty is estimated to be ± 0.2 ppb or ± 1 Tg N between any 2 years over any recent period, based on the combined NOAA and AGAGE record of surface N_2O taken from Table 2.1 of the IPCC AR5 (Hartmann et al., 2013). Thus, the uncertainty in the burden change between 2 decades (e.g., 2000s to 2010s) is bounded by ± 1 Tg N (< 0.1 %).

3.5.2 Atmospheric loss rates and trends from stratospheric observations

The NASA Aura Microwave Limb Sounder (MLS) satellite instrument has provided consistent global measurements of stratospheric N_2O, O_3, and temperature (T) since August 2004. These have been used with simple stratospheric chemistry models to calculate the monthly mean stratospheric loss of N_2O due to photolysis and oxidation by $O(^1D)$ (Prather et al., 2015, 2023; Minschwaner et al., 1998). Tropospheric chemical loss also occurs, although at a very low rate (< 1 % of the total) and is, thus, not included in the calculations.

3.5.3 Atmospheric inversion estimates of N_2O emissions and losses

For the TD constraints on both land and ocean N_2O fluxes for the 1998–2020 period, we used estimates from four independent atmospheric inversion frameworks (INVICAT, PyVAR-CAMS, MIROC4-ACTM, and GEOS-Chem), all of which used a Bayesian inversion method (see the Supplement for details on the inversion frameworks).

The inversion frameworks INVICAT and PyVAR-CAMS used the transport models TOMCAT and LMDz5, respectively, which were both driven by ECMWF ERA5 meteorology, while MIROC4-ACTM used the transport model ACTM, which was driven by JRA-55 meteorology, and GEOS-Chem used the transport model of the same name, which was driven by MERRA-2 meteorology. All inversion frameworks assumed that the prior distribution of emissions followed a normal distribution, with the multivariate mean taken from different models and data products, with standard

Table 2. Simulation design of NMIP2.

Historical	Climate	CO_2	Land cover	Irrigation	NDEP	Nfer	Manure N
SH0	1901–1920	1850	1850	1850	1850	1850	1850
SH1	*	*	*	*	*	*	*
SH2	*	*	*	*	*	*	1850
SH3	*	*	*	*	*	1850	*
SH4	*	*	*	*	1850	*	*
SH5	*	*	*	1850	*	*	*
SH6	*	*	1850	*	*	*	*
SH7	*	1850	*	*	*	*	*
SH8	1901–1920	*	*	*	*	*	*
SH9	1901–1920	1850	1850	1850	1850	*	*
SH10	*	1850	1850	1850	1850	1850	1850
SH11	*	*	1850	1850	*	1850	1850
SH12	*	*	*	1850	*	1850	1850

Note: for historical simulations, "*" indicates that the forcing during 1850–2020 is included in the simulation, "1901–1920" indicates that the 20-year mean climate condition during 1901–1920 will be used over the entire simulation period, and "1850" indicates that the forcing will be fixed in 1850 over the entire period. Climate data are only available from 1901; we assume the 20-year average value between 1901 and 1920 for the years 1850–1900. N deposition (NDEP) is available only from 1850. N fertilizer (Nfer) before 1910 was zero. Manure N is available only from 1860; we assume manure N at the 1860 value for the years 1850–1860.

deviations detailed in the Supplement. Specifically, GEOS-Chem, INVICAT, and PyVAR-CAMS built prior flux distributions for natural soil emissions from the terrestrial biospheric model O-CN (Zaehle et al., 2011) and for biomass burning emissions from GFED-v4s (van der Werf et al., 2017). For anthropogenic emissions from agricultural and non-agricultural sectors (excluding biomass burning), estimates from EDGAR v5 were used to build the prior for the 2005–2020 period (as these estimates were only available up to 2015, the emissions for 2016–2020 were estimated based on those of the year 2015), and the estimates from EDGAR-v4.32 were used for the 1997–2004 period. On the other hand, MIROC4-ACTM used the estimate from the terrestrial biospheric model VISIT for natural soil emissions and EDGAR v4.2 estimates for all anthropogenic emissions.

The inversion frameworks used atmospheric observations from ground-based networks, specifically NOAA, AGAGE, and CSIRO (see the Supplement for details).

The atmospheric transport models also calculate the loss of N_2O in the stratosphere by photolysis and oxidation by $O(^1D)$ radicals (Minschwaner et al., 1998). The TD mean posterior estimates for the 18 land regions were calculated by integrating the gridded fluxes at $1° \times 1°$ over each region (the fluxes were interpolated from the original model resolution to $1° \times 1°$).

4 Results

4.1 Trends in atmospheric mole fractions and implied emissions

4.1.1 Trends in atmospheric N_2O mole fractions

The three observation networks AGAGE, NOAA, and CSIRO show consistent growth in atmospheric N_2O mole fractions from 315.8 (315.5–316.2) ppb in 2000 to 335.9 (335.6–336.1) ppb in 2022. The mean annual growth rate increased from 0.76 (0.55–0.95) ppb yr^{-1} in the 2000s to 0.96 (0.79–1.15) ppb yr^{-1} in 2010s with significant seasonal and interannual variation. In 2020 and 2021, the N_2O atmospheric growth rate was 1.33 and 1.38 ppb yr^{-1}, respectively, both higher than any previous observed year (since 1980), and it was more than 30 % higher than the average value in the decade of the 2010s (Fig. 2). As is shown in Fig. 5, the observed N_2O mole fraction in 2020 (333.2, 332.7–333.5 ppb) has exceeded predicted levels across the four illustrative Representative Concentration Pathways (RCPs) (329.2–331.5 ppb) used in CMIP5 (Meinshausen et al., 2011) and the seven illustrative Socioeconomic Pathways (SSPs) (330.5–331.9 ppb) used in CMIP6 (Meinshausen et al., 2020).

4.2 N_2O sources and sinks: BU estimates

4.2.1 Anthropogenic sources

Global anthropogenic emissions during 1980–2020

Global total anthropogenic emissions increased in the last 4 decades, from 4.8 (3.1–7.3) Tg N yr^{-1} in 1980 to 6.7 (3.3–

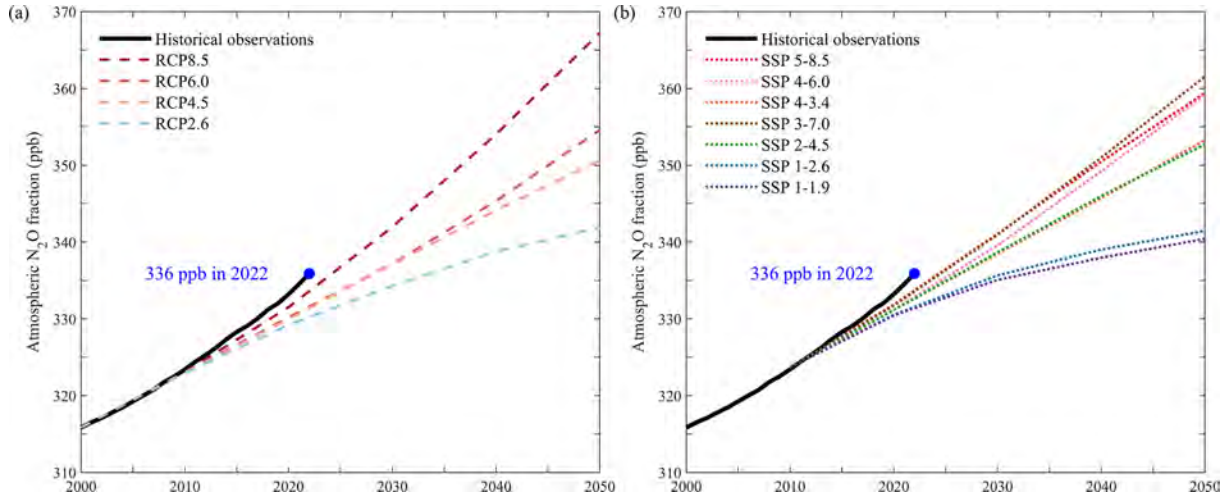

Figure 5. Comparison between the measured global N_2O mole fractions from the three GHG observing networks and the projected mole fractions from **(a)** the four illustrative Representative Concentration Pathways (RCPs) in the IPCC Fifth Assessment Report and **(b)** the seven illustrative Socioeconomic Pathways (SSPs) used in CMIP6.

10.9) Tg N yr^{-1} in 2020 (Fig. 6). Among all anthropogenic sources, direct emissions from nitrogen additions in the agricultural sector made the largest contribution to the increase, which grew from 2.2 (1.6–2.8) Tg N yr^{-1} in 1980 to 3.9 (2.9–5.1) Tg N yr^{-1} in 2020. Indirect N_2O emissions also steadily increased during the study period, from 0.9 (0.7–1.1) Tg N yr^{-1} in 1980 to 1.3 (0.9–1.6) Tg N yr^{-1} in 2020. In contrast, other direct anthropogenic emissions did not have a trend, and the total amount fluctuated around 2.1 Tg N yr^{-1}. Perturbed fluxes from climate, CO_2, and land-cover change led to a small increase in the N_2O sink, from −0.4 (−0.9 to 1.0) Tg N yr^{-1} in 1980 to −0.6 (−2.2 to 1.8) Tg N yr^{-1} in 2020.

Direct emissions from nitrogen additions in the agricultural sector (agriculture)

In the past 4 decades, N_2O emissions from all four sources within the agricultural sector significantly increased (Fig. 7), with the largest contribution from direct soil emissions (from 1.1 Tg N yr^{-1} in 1980 to 2.1 Tg N yr^{-1} in 2020), followed by manure left on pasture (from 0.9 Tg N yr^{-1} in 1980 to 1.4 Tg N yr^{-1} in 2020), aquaculture (from 0.01 Tg N yr^{-1} in 1980 to 0.12 Tg N yr^{-1} in 2020), and manure management (from 0.24 Tg N yr^{-1} in 1980 to 0.26 Tg N yr^{-1} in 2020).

Direct soil emissions accounted for the largest proportion of emissions from the agriculture sector. All four estimates show a steady increase in direct soil emissions since 1980 (Fig. 7a). Among them, NMIP2/DLEM exhibited the largest magnitude and the fastest increase rate, from 1.1 Tg N yr^{-1} in 1980 to 2.6 Tg N yr^{-1} in 2020. By contrast, SRNM/DLEM suggested the slowest increase rate, from 1.0 Tg N yr^{-1} in 1980 to 1.7 Tg N yr^{-1} in 2020. The estimates of the two inventories (FAOSTAT and EDGARv7.0) exhibited similar magnitudes and trends, especially after 1990. All three estimates suggested a significant increasing trend for N_2O emissions from manure left on pasture over the 1980–2020 period. Although all methods showed an increasing trend, they had significant differences in magnitude and increase rate (Fig. 7b). FAOSTAT showed the largest magnitude and increase rate, from 1.2 Tg N yr^{-1} in 1980 to 1.9 Tg N yr^{-1} in 2020. However, DLEM showed a smaller magnitude and a slower increase rate, from 0.5 Tg N yr^{-1} in 1980 to 0.9 Tg N yr^{-1} in 2020. Although the two inventory estimates for emissions from manure management showed similar temporal variations, FAOSTAT has a larger magnitude than EDGARv7.0 (Fig. 7c). According to the IMAGE-GNM aquaculture nutrient budget model, N_2O emissions from aquaculture increased more than 10-fold, from 0.01 Tg N yr^{-1} in 1980 to 0.12 Tg N yr^{-1} in 2020 (Fig. 7d).

Other direct anthropogenic sources

Fossil fuel and industry emissions accounted for the largest proportion of N_2O emissions from other direct anthropogenic sources. Estimates from two approaches showed different trends during their overlapping period: EGDARv7.0 had an increasing trend from 0.9 Tg N yr^{-1} in 1990 to 1.1 Tg N yr^{-1} in 2020, while EDGAR/UNFCCC did not show a trend with 1.0 Tg N yr^{-1} in 1990 and 1.0 Tg N yr^{-1} in 2020 (Fig. 8a). These inventories, however, do not capture a strong increase in emissions from adipic acid production since 2010 (Davidson and Winiwarter, 2023). Both EDGARv7.0 and EDGAR/UNFCCC show a steady and significant increase in N_2O emissions from waste and wastewater. Although EDGAR/UNFCCC shows a larger magnitude than EGDARv7.0, these two inventory estimates display sim-

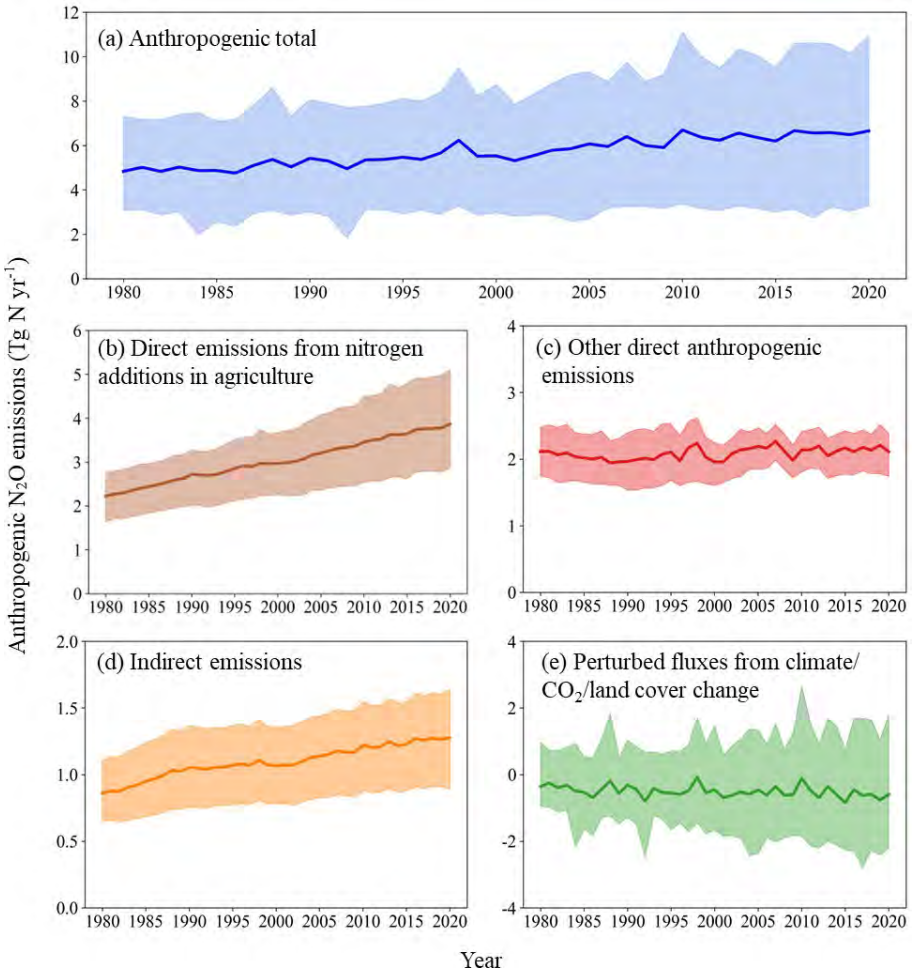

Figure 6. Changes in global anthropogenic N_2O emissions **(a)** and N_2O emissions from different sectors **(b–e)** during 1980–2020. In each panel, the line represents the mean N_2O emission of different estimates, and the shaded area shows minimum and maximum estimates.

ilar growth rates (Fig. 8b). There are large uncertainties in the magnitude and temporal trend in N_2O emissions from biomass burning (Fig. 8c). DLEM and GFED show a larger magnitude of emissions than FAOSTAT. Both DLEM and GFED have a decreasing trend over the overlapping period from 1997 to 2020, but FAOSTAT shows no significant trend during this period.

Indirect emissions from anthropogenic nitrogen additions

Global anthropogenic N_2O emissions from inland waters, estuaries, and coastal vegetation continuously increased during 1980–2020 (Fig. 9a). Although all methods revealed an overall increasing trend in emissions, process-based models show a much smaller magnitude and increase rate than the two inventories. According to meta-analysis and models, anthropogenic emissions from inland and coastal waters increased from 0.1 Tg N yr^{-1} in 1980 to 0.15 Tg N yr^{-1} in 2020. In contrast, EGDARv7.0 and FAOSTAT showed that emissions increased from 0.33 and 0.35 Tg N yr^{-1} in 1980 to 0.53 and 0.57 Tg N yr^{-1} in 2020, respectively. Emissions from N deposition on land also continued to increase during 1980–2020 (Fig. 9b). NMIP2 and NMIP2/EDGAR v7.0 show emissions increasing from 0.6 and 0.4 Tg N yr^{-1} in 1980 to 0.9 and 0.6 Tg N yr^{-1} in 2020, respectively.

Perturbation fluxes from climate, CO_2, and land-cover change

The spread between different estimates (DLEM and the bookkeeping method) of the post-deforestation pulse effect increased from the 1980s to the 2010s. The post-deforestation pulse effect was 0.8 (0.6–1.1) Tg N yr^{-1} in 1980 and 0.8 (0.4–1.3) Tg N yr^{-1} in 2020 (Fig. 10a). In contrast, DLEM and empirical approaches are comparable in terms of the magnitude and temporal changes in the long-term reduction effect of deforestation, with both approaches suggesting a strong long-term reduction effect, which grew from −1.2 (−1.0, −1.4) Tg N yr^{-1} in 1980 to −1.4 (−1.3, −1.6) Tg N yr^{-1} in 2020 (Fig. 10b). In general,

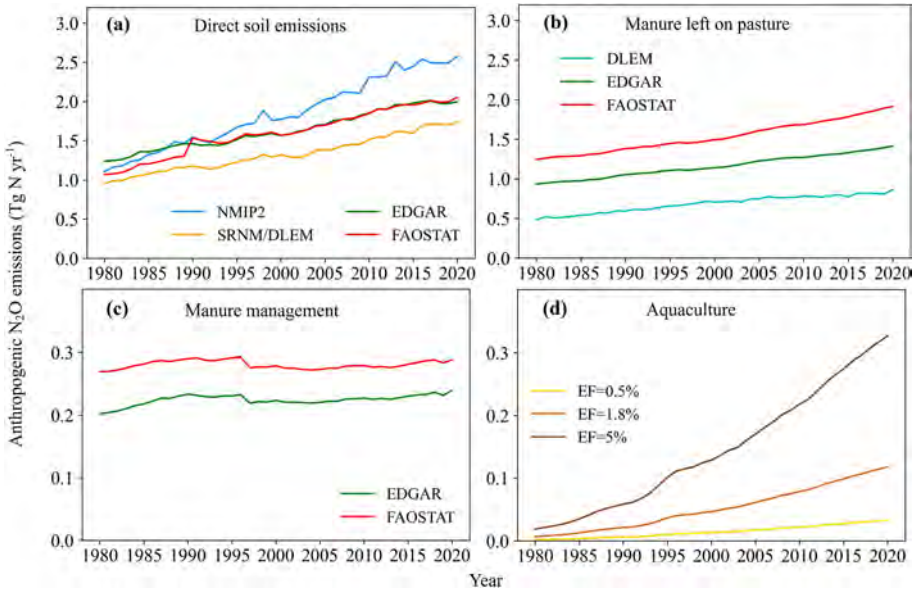

Figure 7. Changes in global direct N_2O emissions from fertilizer and manure applied on agricultural soils **(a)**, manure left on pasture **(b)**, manure management **(c)**, and aquaculture **(d)** during 1980–2020.

deforestation had a negative effect on global soil N_2O emissions. However, most NMIP2 models suggested a positive effect of climate change on soil N_2O emissions, although with large uncertainty and significant interannual variation; this positive climate feedback significantly increased during the past 4 decades (Fig. 10c). In contrast to climatic effects, most NMIP2 models suggested a negative effect of rising atmospheric CO_2 concentration on soil N_2O emissions through increasing nitrogen use efficiency and, hence, reducing soil N availability (Fig. 10d). However, NMIP2 models have large discrepancies in the CO_2 fertilization effect on N_2O emissions; ELM and ISAM suggested a positive effect, while all the other models suggest a negative effect.

4.2.2 Natural N_2O sources

Emissions from natural soils and open oceans remained relatively steady throughout the study period from 1980 to 2020, with mean estimates fluctuating between 9.9 and 10.3 Tg N yr^{-1} (minimum estimates: 6.2–7.1 Tg N yr^{-1}; maximum estimates: 12.8–13.6 Tg N yr^{-1}). Natural emissions from all other sources including shelves, inland waters, and lightning and atmospheric production were assumed to be constant during 1980–2020. According to BU approaches, the total natural emissions from these sources were 1.8 (1.0–3.0) Tg N yr^{-1}. The mean value of global N_2O emissions from all of the abovementioned sources fluctuated between 11.7 and 12.1 Tg N yr^{-1}, with an average of 11.9 Tg N yr^{-1}. Global natural N_2O emissions also have a large uncertainty, with the maximum estimates (15.8–16.6 Tg N yr^{-1}) roughly double the minimum estimates (7.1–8.1 Tg N yr^{-1}).

Natural soil N_2O emission baseline

The natural soil N_2O emission baseline represents the preindustrial soil N_2O emissions derived from NMIP2 simulations, driven by potential vegetation/land cover and other environmental factors in the preindustrial period (1850). Global natural soil N_2O emissions are estimated to be 6.4 Tg N yr^{-1}, and they account for 55 % of the total natural emissions. However, N_2O emissions from natural soils estimated by the NMIP2 showed large divergences among eight models. Among the NMIP2 models, ELM had the highest estimate with an average of 8.6 Tg N yr^{-1}, which was more than double the estimate from the CLASSIC model (3.9 Tg N yr^{-1}).

Natural N_2O emission baseline from the open ocean and continental shelves

We also estimated N_2O emissions from the open oceans and continental shelves. Open ocean is the second largest source of natural N_2O emissions, with a global mean value fluctuating between 3.4 and 3.8 Tg N yr^{-1} during 1980–2020. Open-ocean N_2O emissions were estimated by four ocean models. Among these models, NEMOv3.6-PISCESv2-gas had the highest estimate, with an average of 4.6 Tg N yr^{-1}, while NEMO-PlankTOM10 had the lowest estimate, with an average of 2.8 Tg N yr^{-1}. The four ocean models show different trends in open-ocean emissions. NEMOv3.6-PISCESv2-gas shows a slight increasing trend, whereas the other three models show consistent decreasing trends. In addition to open oceans, shelves are an important source of N_2O emissions that was not quantified in the previous global N_2O budget (Tian et al., 2020). Global shelf N_2O emis-

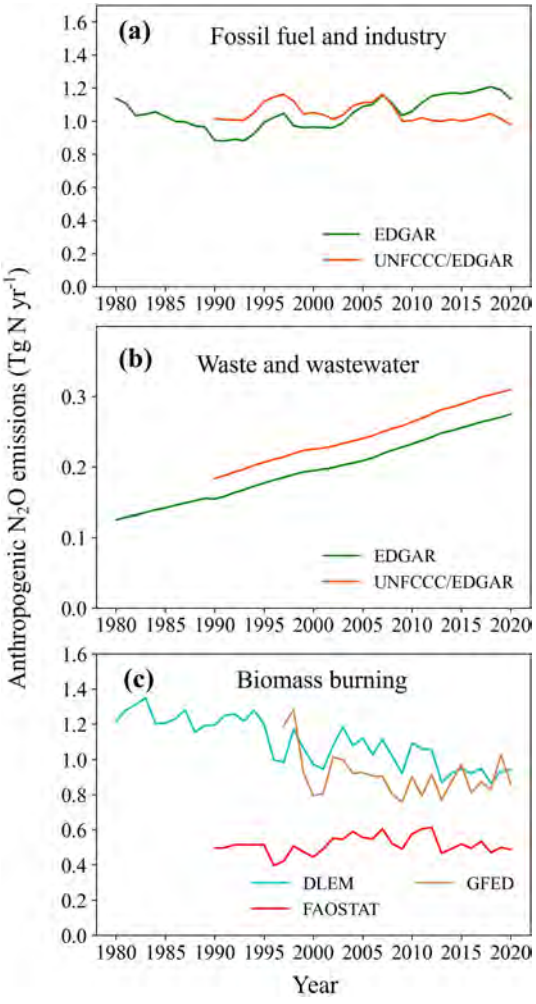

Figure 8. Changes in N_2O emissions from other direct anthropogenic sources between 1980 and 2020: fossil fuel **(a)**, waste and wastewater **(b)**, and biomass burning **(c)**.

sions were estimated by two high-resolution models (CNRM and ECCO) and one data product (MEM-RF). The average of the three estimates is 1.2 Tg N yr^{-1}, ranging from 0.6 Tg N yr^{-1} (ECCO) to 1.6 Tg N yr^{-1} (MEM-RF).

Natural N_2O emission from inland waters, estuaries, and coastal vegetation

Natural N_2O emissions from inland waters and estuaries were much smaller than emissions from the soils, oceans, and shelves. These emissions have an average value of 0.08 Tg N yr^{-1}, ranging from 0.05 to 0.14 Tg N yr^{-1}. Rivers are the largest source: they emit 0.04 (0.01–0.08) Tg N yr^{-1} of N_2O and account for 48 % of the natural emissions from inland waters and estuaries. The global natural N_2O emissions from lakes and estuaries were 0.02 (0.01–0.03) and 0.02 (0.02–0.03) Tg N yr^{-1}, respectively.

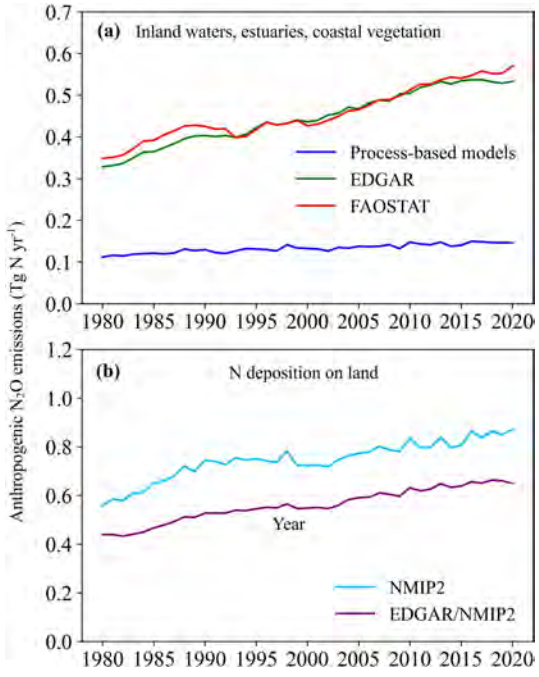

Figure 9. Changes in indirect N_2O emissions from anthropogenic nitrogen additions to inland waters (rivers, lakes, and reservoirs), estuaries, and coastal vegetation **(a)** as well as N deposition on land **(b)** during 1980–2020.

Lightning, atmospheric production, and natural sinks

The source of reactive N from lightning (and its contribution to N_2O) and the direct production of N_2O from NH_3 in the atmosphere are relatively small, and we have no new estimates in this work. However, synthesizing the available estimates in the scientific literature, we estimate lightning to contribute 0.05 (0.02–0.09) Tg N yr^{-1} (median and range) (Nault et al., 2017; Schumann and Huntrieser, 2007) and atmospheric production to contribute 0.5 (0.3–1.1) Tg N yr^{-1} (Kohlmann and Poppe, 1999; Dentener and Crutzen, 1994).

Similarly, the surface sink of N_2O is small. Again, we do not produce a new estimate in this budget and rather only synthesize available estimates from the literature. We estimate the global surface sink to be 0.01 (0.0–0.3) Tg N yr^{-1}.

4.3 N_2O sources and sinks: TD estimates

4.3.1 TD total source

Ensemble estimates across the four atmospheric inversions show that the long-term average global N_2O emissions during 1997–2020 were 16.6 Tg N yr^{-1} (minimum: 15.5 Tg N yr^{-1}; maximum: 18.2 Tg N yr^{-1}). All four inversions show a significant increasing trend in global N_2O emissions ($p < 0.05$) with a mean rate of increase of 0.10 Tg N yr^{-2} (0.08–0.12 Tg N yr^{-2}) (Fig. 11a).

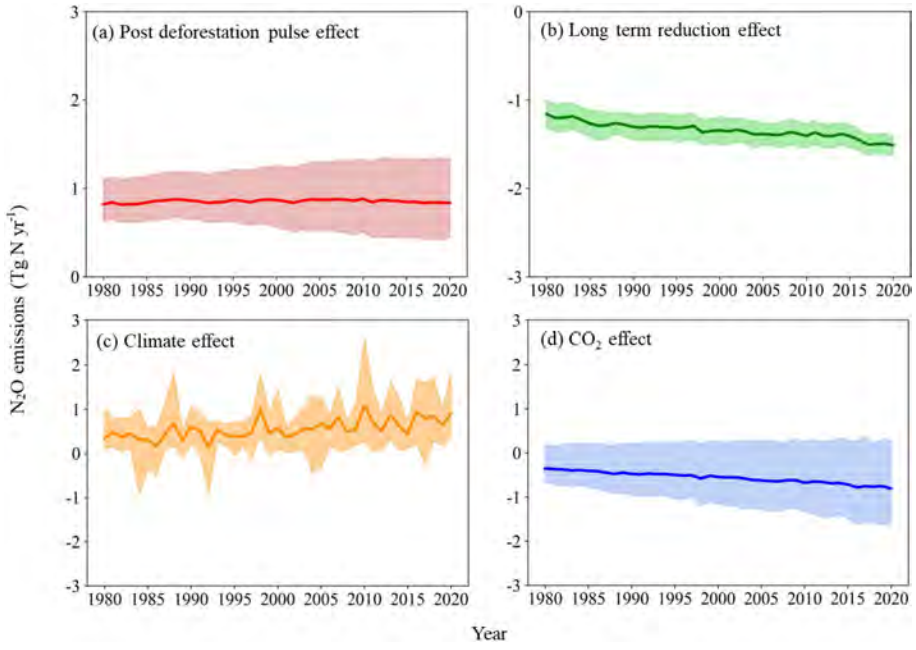

Figure 10. Changes in perturbed N_2O fluxes from changes in climate, CO_2, and land cover during 1980–2020. In each panel, the line represents the mean N_2O emission of different estimates, and the shaded area shows minimum and maximum estimates.

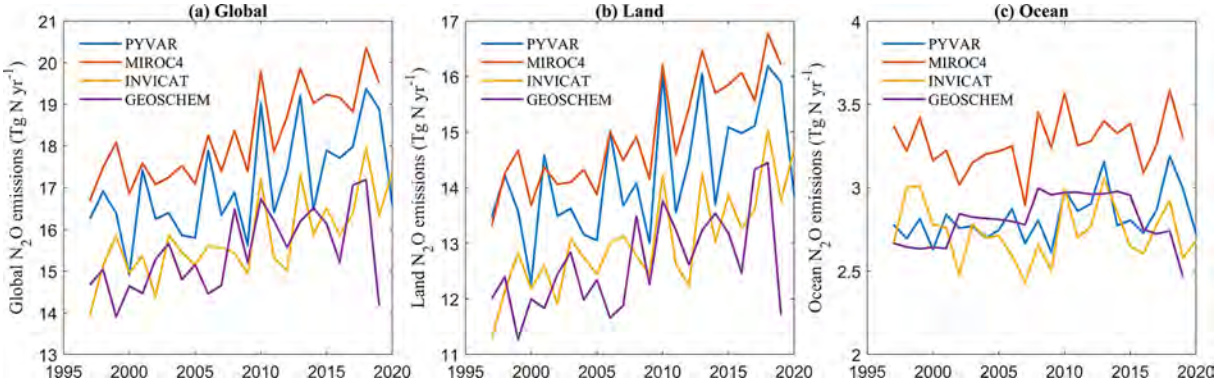

Figure 11. Annual global N_2O emissions during 1997–2020 estimated by four atmospheric inversions (TD models): **(a)** total global emission, **(b)** land emission, and **(c)** ocean emission.

TD land emission

The estimates derived from the four inversions show that the land-based emission is the dominant source of N_2O emissions, over ocean sources, and the long-term average land N_2O emission during 1997–2020 was 13.7 Tg N yr^{-1} (minimum: 12.6 Tg N yr^{-1}; maximum: 15.0 Tg N yr^{-1}), contributing 80 %–85 % of the global N_2O emissions. Land sources dominated the interannual variability in global N_2O emissions and the trend (Fig. 11b). All TD models suggested a significant increasing trend in land N_2O emissions during the study period from 1997 to 2020 ($p < 0.05$), with increase rates ranging from 0.09 to 0.13 Tg N yr^{-2}, which were higher than the increase rates of prior fluxes (mean: 0.04 Tg N yr^{-2}; range: 0.00–0.08 Tg N yr^{-2}).

TD ocean emission

The magnitude of N_2O emissions from oceans is much smaller than that from land (Fig. 11c). The mean ocean N_2O emission during 1997–2020 derived from four inversion models was 2.9 Tg N yr^{-1}, ranging from a minimum of 2.7 Tg N yr^{-1} to a maximum of 3.3 Tg N yr^{-1}. The estimates of MIROC4 were much higher than the estimates of other models. The four inversions show divergent interannual variability, and none suggested a significant trend. The TD estimates of ocean N_2O emission are much smaller than the values estimated by four ocean biogeochemical models, with a global mean value fluctuating between 3.4 and 3.8 Tg N yr^{-1} during 1980–2020.

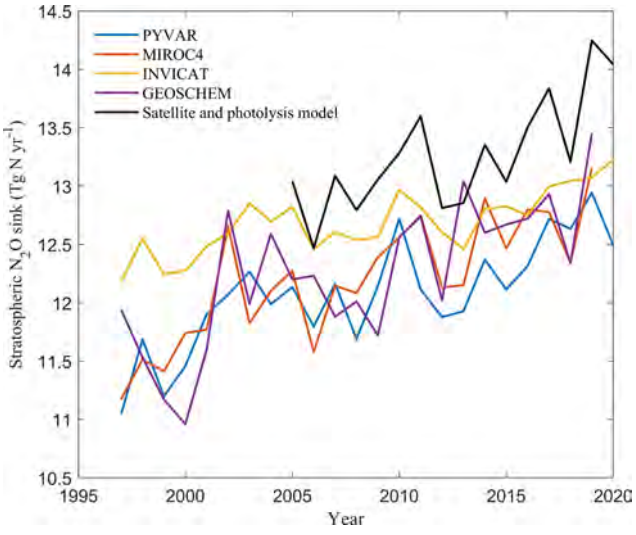

Figure 12. Global stratospheric N_2O sink estimated by atmospheric inversions and a satellite and photolysis model during 1997–2020.

4.3.2 TD stratospheric sink

The four inversions have comparable magnitudes of global stratospheric N_2O sink (via photolysis and oxidation by the electronically excited atomic oxygen, $O(^1D)$, in the stratosphere), with an average value of 12.4 Tg N yr^{-1} (minimum and maximum of 12.2 and 12.7 Tg N yr^{-1}, respectively) for 2000–2020 (Fig. 12). All four inversions found that the global stratospheric N_2O sink increased during 1997–2020 (Fig. 13) in proportion to the growing atmospheric N_2O abundance, with an average rate of increase of 0.05 Tg N yr^{-2} (0.03–0.07 Tg N yr^{-2}). Differences among the estimates decreased after 2000, likely due to improvements in observation coverage and accuracy but also possibly due to the decreasing influence of the initial mixing ratio fields, which differed among the inversion frameworks. Although the inversions show comparable trends in the sink, they differ with respect to their interannual variability.

We also provide an independent estimate of the stratospheric sink based on satellite observations and a photolysis model. This estimate likewise showed that the sink increased, from 12.8 Tg N yr^{-1} in the 1990s to 14.0 Tg N yr^{-1} in the 2010s (Table 3), with higher annual loss rates than estimated by the inversions and an average loss of 13.4 Tg N yr^{-1} for 2005–2021. This estimate also showed large quasi-biennial interannual variability with an amplitude of 7 %. More interestingly, over this time period, the abundance of N_2O in the middle stratosphere, where the greatest loss of N_2O occurs, was increasing at a rate of 5.0 ± 1.2 % per decade, which is faster than the increase in the tropospheric abundance of 2.9 ± 0.0 % per decade. This resulted in a greater loss of N_2O (i.e., more than proportionate to the mean atmospheric increase) and, thus, a decrease in the mean atmospheric lifetime (burden divided by loss) of 2.1 ± 0.7 % per decade, from 119.3 years in the 2000s to 117 years in the 2010s (Prather et al., 2023; also see Table 3). These changes are thought to be a result of an increase in the intensity of the Brewer–Dobson circulation (BDC), which would transport N_2O more rapidly from the troposphere into the midstratosphere. An increase in the intensity of BDC is predicted by climate models (Oberländer-Hayn et al., 2016). However, we note that none of the atmospheric inversions found a significant trend in the atmospheric lifetime (although the total loss increased; Fig. 12), and more research is needed to identify why there is this discrepancy.

4.4 Decadal patterns and trend in the global N_2O budget: comparisons between BU and TD approaches

BU approaches provide estimates of N_2O fluxes for the identified sources and sinks during 1980–2020, while TD approaches only provide the total net flux during 1997–2020. In the following analyses of the decadal global N_2O budget, the comparison between BU and TD approaches is only for total N_2O estimates. We rely on BU approaches to quantify all identified sources and sinks (Table 3, Fig. 1).

4.4.1 Global N_2O budget in recent decade (2010–2019)

The BU and TD approaches give remarkably consistent estimates of global total N_2O emissions in the 2010s, with values of 18.2 (10.6–25.9) Tg N yr^{-1} and 17.4 (15.8–19.2) Tg N yr^{-1} (Fig. 1, Table 3), respectively. However, the BU estimate shows a large uncertainty range, in part because of the spread of estimates from process-based models. TD approaches estimate that the stratospheric sink (i.e., N_2O losses via photolysis and reaction with $O(^1D)$ in the stratosphere) for the 2010s was 12.6 (12.3–12.9) Tg N yr^{-1}. However, the atmospheric sink estimate based on satellite observations and a photolysis model for the 2010s was 13.4 (12.3–14.5) Tg N yr^{-1}. The imbalance of sources and sinks of N_2O derived from the averaged BU and TD estimates is 4.7 Tg N yr^{-1}. This imbalance agrees well with the observed increase in atmospheric abundance of N_2O between 2010 and 2019 of 4.6 (4.5–4.7) Tg N yr^{-1}. Based on the BU-based estimates, natural sources contributed 65 % of total emissions (11.8, 7.3–15.9 Tg N yr^{-1}) during this period. Specifically, the natural soil flux contributed the most, with the decadal mean of 6.4 (3.9–8.6) Tg N yr^{-1}, followed by the open-ocean emissions (3.5, 2.5–4.7 Tg N yr^{-1}), shelf emissions (1.2, 0.6–1.6 Tg N yr^{-1}), lightning and atmospheric production (0.6, 0.3–1.2 Tg N yr^{-1}), and natural emissions from inland waters and estuaries (0.1, 0.0–0.1 Tg N yr^{-1}) (Fig. 1).

Anthropogenic sources contributed, on average, 35 % to the total N_2O emissions (6.5, 3.2–10.0 Tg N yr^{-1}) in the 2010s. Direct emissions from nitrogen additions in agriculture were 3.6 (2.7–4.8) Tg N yr^{-1}, contributing 56 % of

Table 3. The global N_2O budget (in Tg N yr^{-1}) for the 1980s, the 1990s, the 2000s, the 2010s, and the year 2020.

		1980–1989	1990–1999	2000–2009	2010–2019	2020
Anthropogenic sources (BU)		Mean (min, max)	Mean (min, max)	Mean (min, max)	Mean (min, max)	Mean (min, max)
Agricultural	Direct soil emissions	1.2 (1.1, 1.3)	1.5 (1.2, 1.6)	1.7 (1.4, 2.0)	2.0 (1.6, 2.4)	2.1 (1.7, 2.6)
	Manure left on pasture	0.9 (0.5, 1.3)	1.1 (0.6, 1.4)	1.2 (0.7, 1.6)	1.3 (0.8, 1.8)	1.4 (0.9, 1.9)
	Manure management	0.2 (0.2, 0.3)	0.3 (0.2, 0.3)	0.2 (0.2, 0.3)	0.3 (0.2, 0.3)	0.3 (0.2, 0.3)
	Aquaculture	0.0 (0.0, 0.0)	0.0 (0.0, 0.1)	0.1 (0.0, 0.2)	0.1 (0.0, 0.3)	0.1 (0.0, 0.3)
	Subtotal	2.4 (1.8, 3.0)	2.8 (2.1, 3.4)	3.2 (2.3, 4.0)	3.6 (2.7, 4.8)	3.9 (2.9, 5.1)
Other direct anthropogenic	Fossil fuels and industry	1.0 (1.0, 1.0)	1.0 (0.9, 1.1)	1.1 (1.0, 1.1)	1.1 (1.0, 1.2)	1.1 (1.0, 1.1)
sources	Waste and wastewater	0.1 (0.1, 0.1)	0.2 (0.2, 0.2)	0.2 (0.2, 0.2)	0.3 (0.3, 0.3)	0.3 (0.3, 0.3)
	Biomass burning	0.9 (0.5, 1.2)	0.9 (0.5, 1.2)	0.8 (0.5, 1.0)	0.8 (0.5, 1.0)	0.8 (0.5, 0.9)
	Subtotal	2.0 (1.7, 2.4)	2.1 (1.6, 2.4)	2.1 (1.8, 2.4)	2.1 (1.8, 2.4)	2.1 (1.7, 2.4)
Indirect emissions from anthropogenic	Inland waters, estuaries, and coastal vegetation	0.3 (0.1, 0.4)	0.3 (0.1, 0.4)	0.4 (0.1, 0.5)	0.4 (0.1, 0.5)	0.4 (0.1, 0.6)
nitrogen additions	Atmospheric nitrogen deposition on land	0.5 (0.5, 0.6)	0.6 (0.5, 0.7)	0.7 (0.6, 0.8)	0.7 (0.6, 0.8)	0.8 (0.6, 0.9)
	Atmospheric nitrogen deposition on ocean	0.1 (0.1, 0.2)	0.1 (0.1, 0.2)	0.1 (0.1, 0.2)	0.1 (0.1, 0.2)	0.1 (0.1, 0.2)
	Subtotal	0.9 (0.7, 1.2)	1.1 (0.8, 1.4)	1.1 (0.8, 1.4)	1.2 (0.9, 1.6)	1.3 (0.9, 1.6)
Perturbed	CO_2 effect	−0.4 (−0.8, 0.2)	−0.5 (−1.0, 0.2)	−0.6 (−1.3, 0.3)	−0.7 (−1.5, 0.3)	−0.8 (−1.6, 0.3)
fluxes from	Climate effect	0.4 (0.1, 0.8)	0.5 (0.2, 0.7)	0.6 (0.1, 0.8)	0.7 (0.2, 1.2)	0.9 (0.4, 1.8)
climate, CO_2, and land-cover change	Post-deforestation pulse effect	0.8 (0.6, 1.1)	0.9 (0.6, 1.2)	0.9 (0.5, 1.3)	0.9 (0.4, 1.3)	0.8 (0.4, 1.3)
	Long-term effect of reduced mature forest area	−1.2 (−1.1, −1.4)	−1.3 (−1.2, −1.5)	−1.4 (−1.2, −1.5)	−1.4 (−1.3, −1.6)	−1.5 (−1.4, −1.6)
	Subtotal	−0.4 (−1.1, 0.7)	−0.5 (−1.4, 0.6)	−0.6 (−1.9, 0.8)	−0.6 (−2.1, 1.2)	−0.6 (−2.2, 1.8)
Anthropogenic total		5.0 (3.0, 7.3)	5.5 (3.1, 7.9)	5.8 (3.1, 8.6)	6.5 (3.2, 10.0)	6.7 (3.3, 10.9)
Natural fluxes (BU)						
Natural soil baseline		6.4 (3.9, 8.5)	6.4 (3.8, 8.6)	6.4 (3.9, 8.5)	6.4 (3.9, 8.6)	6.4 (3.8, 8.7)
Open-ocean baseline		3.7 (3.0, 4.6)	3.6 (2.8, 4.5)	3.6 (2.7, 4.7)	3.5 (2.5, 4.7)	3.5 (2.5, 4.7)
Continental shelves		1.2 (0.6, 1.6)	1.2 (0.6, 1.6)	1.2 (0.6, 1.6)	1.2 (0.6, 1.6)	1.2 (0.6, 1.6)
Natural (inland waters, estuaries, coastal vegetation)		0.1 (0.0, 0.1)	0.1 (0.0, 0.1)	0.1 (0.0, 0.1)	0.1 (0.0, 0.1)	0.1 (0.0, 0.1)
Lightning and atmospheric production		0.6 (0.3, 1.2)	0.6 (0.3, 1.2)	0.6 (0.3, 1.2)	0.6 (0.3, 1.2)	0.6 (0.3, 1.2)
Surface sink (soils and wetlands)		0.0 (0.0, −0.3)	0.0 (0.0, −0.3)	0.0 (0.0, −0.3)	0.0 (0.0, −0.3)	0.0 (0.0, −0.3)
Natural total		12.0 (7.9, 15.8)	11.9 (7.7, 15.8)	11.9 (7.5, 15.9)	11.8 (7.3, 15.9)	11.8 (7.4, 16.1)
BU total net flux (source)		16.9 (10.9, 23.1)	17.4 (10.7, 23.6)	17.7 (10.6, 24.5)	18.2 (10.6, 25.9)	18.5 (10.6, 27.0)
TD ocean				2.8 (2.6, 3.2)	3.0 (2.7, 3.3)	2.7 (2.7, 2.7)
TD land				13.2 (12.1, 14.3)	14.5 (13.0, 15.9)	14.3 (13.9, 14.7)
TD total net flux (source)				16.0 (14.9, 17.5)	17.4 (15.8, 19.2)	17.0 (16.6, 17.4)
TD stratospheric sink				12.2 (11.7, 12.6)	12.6 (12.3, 12.9)	12.9 (12.5, 13.2)

Table 3. Continued.

	1980–1989	1990–1999	2000–2009	2010–2019	2020
Atmospheric chemical sink[a]			12.8 (11.7, 13.8)	13.4 (12.3, 14.5)	14.0 (12.8, 15.2)
Change in atmospheric abundance[b]			3.6 (3.6, 3.7)	4.6 (4.5, 4.7)	6.4 (6.2, 6.5)
Atmospheric burden			1528	1570	1592
Lifetime ("obs" from MLS)			119.3	117	

Notes: BU estimates include four categories of anthropogenic source and one category for natural sources and sinks. The sources and sinks of N_2O are given in teragrams of nitrogen per year (Tg N yr^{-1}). The atmospheric burden is given in teragrams of nitrogen (Tg N). Detailed information on calculating each subcategory is shown in tables in the Supplement. [a] Calculated from satellite observations with a photolysis model (about 1 % of this sink occurs in the troposphere). [b] Calculated from the combined NOAA and AGAGE record of surface N_2O and adopting the uncertainty of the IPCC Fifth Assessment Report (Chap. 6), with a conversion factor of 4.79 Tg N ppb^{-1}.

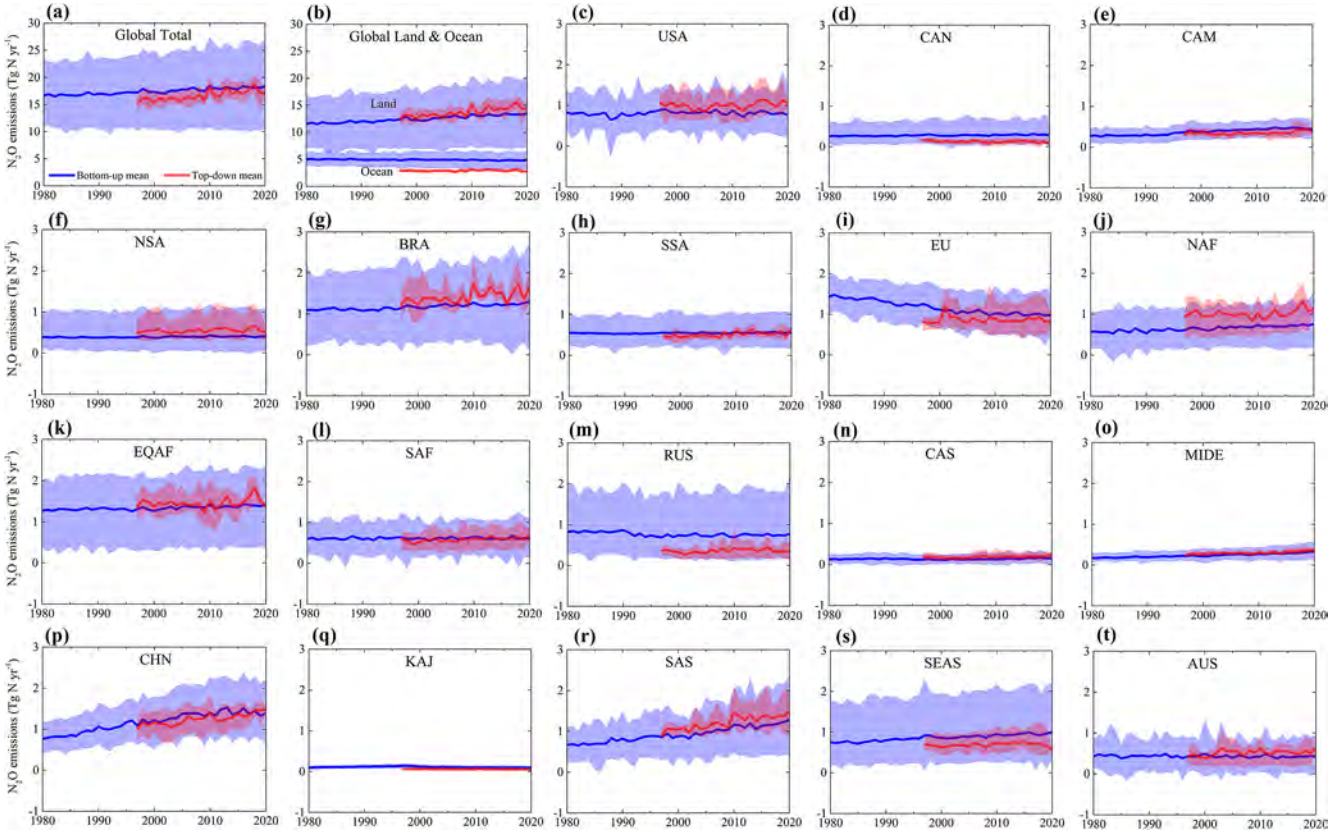

Figure 13. Comparison of global and regional N_2O emissions estimated using BU and TD approaches. The 18 regions include the United States (USA), Canada (CAN), Central America (CAM), northern South America (NSA), Brazil (BRA), southwestern South America (SSA), Europe (EU), northern Africa (NAF), equatorial Africa (EQAF), southern Africa (SAF), Russia (RUS), Central Asia (CAS), the Middle East (MIDE), China (CHN), Korea and Japan (KAJ), South Asia (SAS), Southeast Asia (SEAS), and Australasia (AUS). The blue lines represent the mean N_2O emission from BU methods, and the shaded areas show minimum and maximum estimates; the red lines represent the mean N_2O emission from TD methods, and the shaded areas show minimum and maximum estimates.

the total anthropogenic emissions (Table 3). Emissions from other direct anthropogenic sources made the second largest contribution, with a decadal mean of 2.1 (1.8–2.4) Tg N yr^{-1}. Indirect emissions from anthropogenic nitrogen additions contributed 19 % of the total anthropogenic emissions, with a decadal mean of 1.2 (0.9–1.6) Tg N yr^{-1}. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions (−0.6, −2.1 to 1.2 Tg N yr^{-1}), mainly because of the negative effects of reduced mature forest area (−1.4, −1.6 to −1.3 Tg N yr^{-1}) and increasing CO_2 concentration (−0.7, −1.5 to −0.3 Tg N yr^{-1}).

4.4.2 Decadal trend in the global N_2O budget

Global N_2O emissions estimated by the BU and TD approaches were comparable in magnitude during the over-

lapping period from 1997 to 2020, but TD estimates implied a larger interannual variability and a faster rate of increase (Fig. 13a). BU and TD approaches diverge when estimating the magnitude of land emissions compared with ocean emissions, although they are consistent with respect to trends (Fig. 13b). According to the BU approaches, global N_2O emissions increased from 17.4 Tg N yr^{-1} (10.3–24.0 Tg N yr^{-1}) in 1997 to 18.5 Tg N yr^{-1} (10.6–27.0 Tg N yr^{-1}) in 2020, with an average increase rate of 0.043 Tg N yr^{-2} ($p < 0.05$). In contrast, TD approaches suggested that global emissions increased from 15.4 Tg N yr^{-1} (13.9–16.7 Tg N yr^{-1}) in 1997 to 17.0 Tg N yr^{-1} (16.6–17.4 Tg N yr^{-1}) in 2020, implying a higher increase rate of 0.085 Tg N yr^{-2} ($p < 0.05$). The BU estimate during 1997–2010 was on average 1.6 Tg N yr^{-1} higher than the TD estimate. However, after 2010, the difference in the magnitude of emissions between the two approaches is smaller, due to the rapid increase in the TD estimates. From the year 1980, BU approaches suggested a significant increase in global N_2O emissions that was primarily driven by anthropogenic sources (Table 3). Satellite and photolysis models estimate that the atmospheric N_2O burden increased from 1528 Tg N in the 2000s to 1570 in the 2010s and 1592 Tg N in 2020, which is comparable to estimates by atmospheric chemistry transport models, showing an increase in the atmospheric N_2O burden from 1527 (1504–1545) Tg N in the 2000s to 1606 (1592–1621) Tg N in 2020.

4.5 Regional BU and TD estimates and their trends

To assess regional N_2O budgets, we divide the global land into 18 regions (as described in Sect. 3). Our regional analyses include the following: (1) trends and variations in regional total N_2O emissions from all sources derived from available TD (1997–2020) and BU (1980–2020) estimates (Fig. 13), (2) trends and variations in region anthropogenic N_2O emissions from all identified sources during 1980–2020 derived from a BU approach (Fig. 14), and (3) decadal regional N_2O budget (2010–2019) derived from both BU and TD approaches (Fig. 15). The following sections provide detailed estimates for each of the 18 regions.

4.5.1 United States of America (USA)

For the USA, the TD estimates show higher total N_2O emissions than the BU estimates over the 1997–2020 period (Fig. 13c), with 1.00 (0.69–1.39) and 0.82 (0.31–1.42) Tg N yr^{-1}, respectively. Both approaches suggest that the total N_2O emissions from the USA remained relatively stable during 1997–2020. Based on the BU estimates, changes in climate, CO_2, and land cover caused emission decline over 1980–2020. The flux fluctuated between −0.30 and −0.12 Tg N yr^{-1}, with an average of −0.20 Tg N yr^{-1}. Indirect emissions from anthropogenic nitrogen additions increased from 0.11 Tg N yr^{-1} in 1980 to 0.13 Tg N yr^{-1} in 1995 and then decreased to 0.10 Tg N yr^{-1} in 2020. Direct emissions from nitrogen additions in agriculture increased from 0.25 Tg N yr^{-1} in 1980 to 0.30 Tg N yr^{-1} in 2020. However, the increase in direct agricultural emissions was offset by the trend in emissions from other direct anthropogenic sources, which decreased from 0.26 Tg N yr^{-1} in 1980 to 0.19 Tg N yr^{-1} in 2020. The total anthropogenic N_2O emissions slightly increased during 1980–2020, at an average rate of 0.6×10^{-3} Tg N yr^{-2}. This increase primarily occurred during 1980–1997 (Fig. 14).

In the 2010s, the BU estimates (0.81, 0.29–1.43 Tg N yr^{-1}) were on average 0.22 Tg N yr^{-1} lower than the TD estimates (1.03, 0.71–1.45 Tg N yr^{-1}) (Fig. 15). According to the BU results, natural sources contributed 48 % of total emissions (0.39, 0.22–0.65 Tg N yr^{-1}) during this period. Direct emissions from nitrogen additions in agriculture were 0.30 (0.18–0.38) Tg N yr^{-1}, contributing 37 % of the total emissions. Emissions from other direct anthropogenic sources made the second largest contribution to anthropogenic emissions, with a decadal mean of 0.21 (0.18–0.23) Tg N yr^{-1}. Indirect emissions from anthropogenic nitrogen additions contributed 14 % of the total anthropogenic emissions, with a decadal mean of 0.11 (0.07–0.14) Tg N yr^{-1}. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of −0.19 Tg N yr^{-1} and range of −0.37 to 0.03 Tg N yr^{-1}. Recent study has indicated that N_2O emissions could be increased by freeze–thaw cycles (Del Grosso et al., 2022) and tillage practices (Lu et al., 2022). Our BU estimates did not consider freeze–thaw cycles or tillage practices and, thus, may have underestimated N_2O emissions.

4.5.2 Canada (CAN)

BU approaches suggested a larger magnitude of total N_2O emissions from Canada than TD approaches over the 1997–2020 period (Fig. 13d), with values of 0.29 (0.05–0.69) and 0.12 (0.06–0.19) Tg N yr^{-1}, respectively. BU and TD estimates also showed divergent trends: TD estimates decreased at a rate of -1.5×10^{-3} Tg N yr^{-2}, whereas BU estimates increased at a rate of 0.7×10^{-3} Tg N yr^{-2}. According to the BU results, the increase in total N_2O emissions from Canada was mainly driven by the direct emissions from nitrogen additions in agriculture, which increased from 0.02 Tg N yr^{-1} in 1980 to 0.05 Tg N yr^{-1} in 2020. Perturbed fluxes from changes in climate, CO_2, and land cover showed an overall increase from 0.00 Tg N yr^{-1} in 1980 to 0.02 Tg N yr^{-1} in 2020. Indirect N_2O emissions from Canada were relatively stable during the study period, while emissions from other direct anthropogenic sources had large interannual variability (Fig. 14).

In the 2010s, the BU estimates of Canada's total N_2O emissions (0.29, 0.07–0.69 Tg N yr^{-1}) were over 2 times higher than the TD estimates (0.12, 0.06–0.20 Tg N yr^{-1})

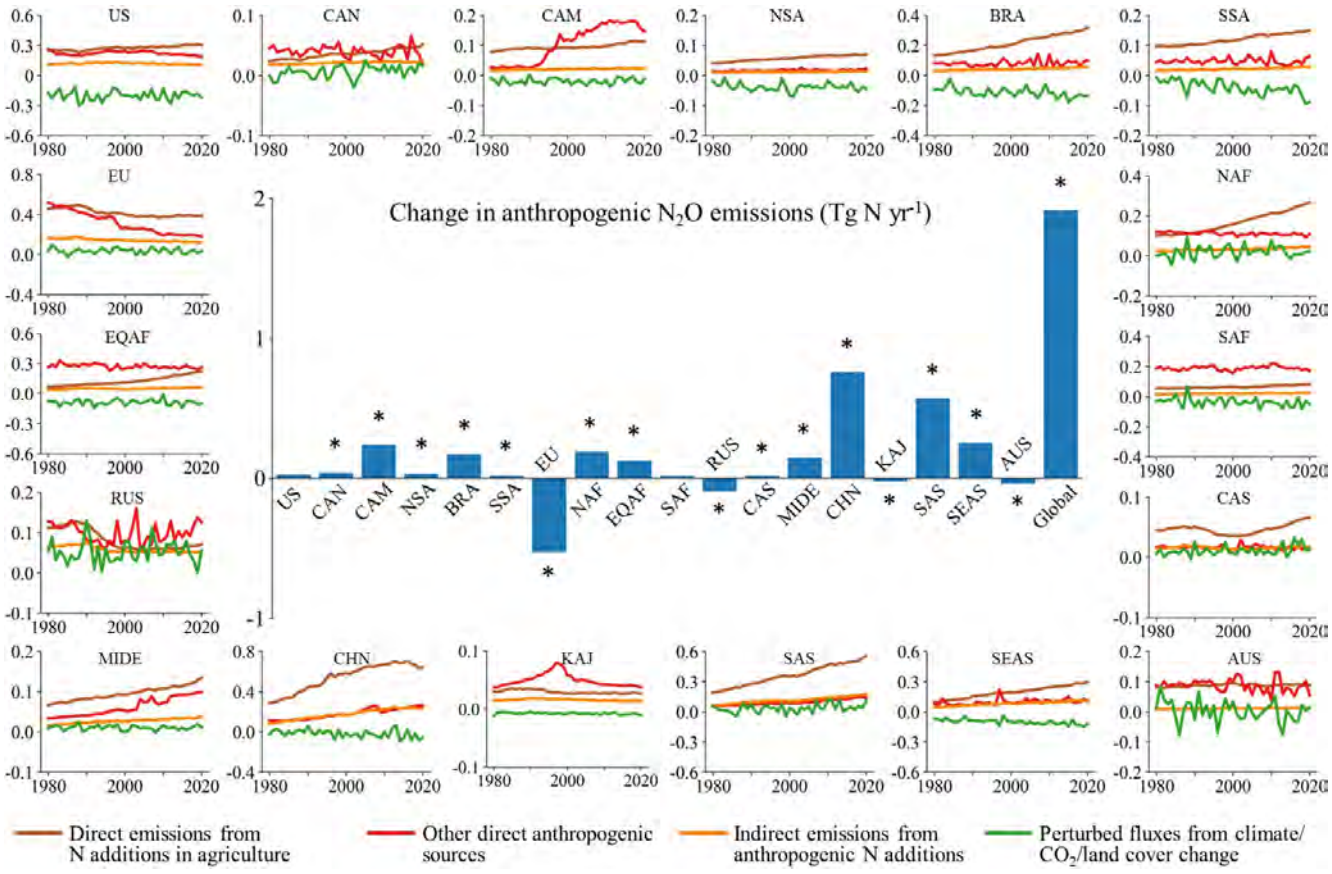

Figure 14. Ensembles of regional anthropogenic N_2O emissions over the 1980–2020 period. The bar chart in the center shows the total changes in regional and global N_2O emissions during the study period from 1980 to 2020. Error bars indicate the 95 % confidence interval for the average of the changes. A Mann–Kendall test was performed to establish any trends globally and for each region over the 1980–2020 period. The changes were calculated from the annual change rate (Tg N yr^{-2}), determined from a linear regression, multiplied by 40 years. All regions except Australasia and the USA show a significant increasing or decreasing trend in the estimated ensemble N_2O emissions during 1980–2020. An asterisk (∗) denotes significance at the $P < 0.05$ level.

(Fig. 15). According to the BU results, natural sources contributed 59 % of total emissions (0.17, 0.04–0.43 Tg N yr^{-1}) during this period. Direct emissions from nitrogen additions in agriculture were 0.05 (0.03–0.06) Tg N yr^{-1}, contributing 15 % of the total emissions. Emissions from other direct anthropogenic sources and indirect emissions from anthropogenic nitrogen additions were 0.04 (0.02–0.08) and 0.02 (0.02–0.03) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall positive effect on N_2O emissions, with a mean value of 0.01 Tg N yr^{-1} and a range of −0.04 to 0.09 Tg N yr^{-1}.

4.5.3 Central America (CAM)

TD and BU estimates are comparable with respect to the magnitudes and trends of N_2O emissions from Central America (Fig. 13e), with mean values of 0.42 (0.21–0.64) and 0.35 (0.25–0.47) Tg N yr^{-1} for the BU and TD approaches, respectively. During 1997–2020, the rate of increase of the BU estimates (4.7×10^{-3} Tg N yr^{-2}) was higher than that of TD estimates (2.5×10^{-3} Tg N yr^{-2}). Emissions from other direct anthropogenic sources increased from 0.03 Tg N yr^{-1} in 1980 to 0.15 Tg N yr^{-1} in 2020 and were the major driver of the increase in N_2O emissions from Central America. Direct agricultural emissions increased during the study period, from 0.08 Tg N yr^{-1} in 1980 to 0.11 Tg N yr^{-1} in 2020. Indirect emissions and perturbed fluxes from changes in climate, CO_2, and land cover were relatively stable during this period (Fig. 14).

The BU and TD approaches gave comparable estimates of total N_2O emissions from Central America in the 2010s, with values of 0.46 (0.24–0.68) and 0.36 (0.24–0.48) Tg N yr^{-1} for the BU and TD approaches (Fig. 15), respectively. Natural sources contributed 37 % of total emissions (0.17, 0.07–0.26 Tg N yr^{-1}) during this period. Emissions from other direct anthropogenic sources contributed 39 % of the total emissions (0.18, 0.17–0.18 Tg N yr^{-1}). Direct and indirect emissions were 0.11 (0.07–0.14) and 0.02 (0.02–

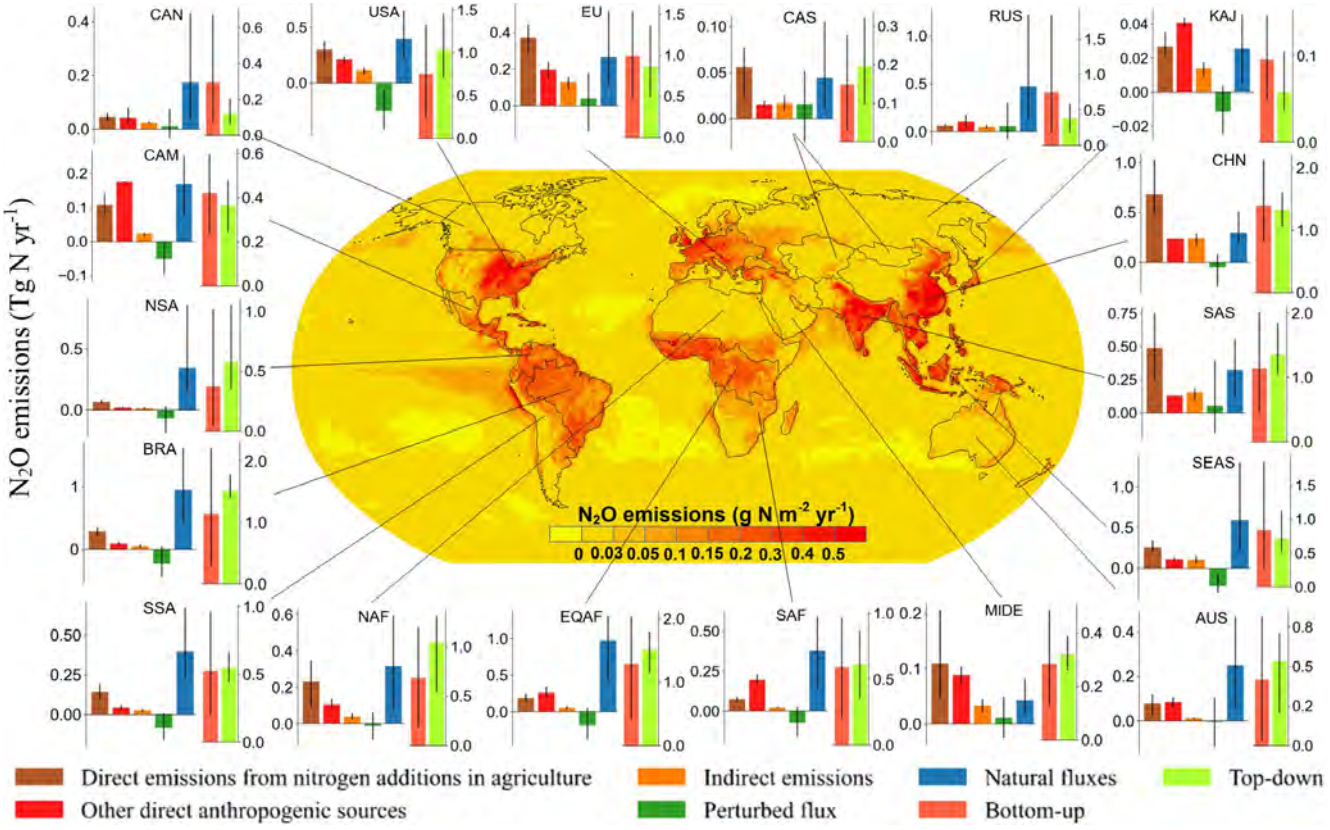

Figure 15. Regional N_2O emissions during 2010–2019. Each subplot shows the emissions from five subsectors using BU approaches, followed by the sum of these five categories using BU approaches (coral) and the estimates from TD approaches (lime). Error bars indicate the spread between the minimum and the maximum values. The center map shows the spatial distribution of 10-year average N_2O emissions from land and the ocean based on the land and ocean models.

0.03) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of −0.02 Tg N yr^{-1} and a range of −0.10 to 0.07 Tg N yr^{-1}.

4.5.4 Northern South America (NSA)

TD approaches suggested a larger magnitude of total N_2O emissions from northern South America than BU approaches over the 1997–2020 period (Fig. 13f), with respective values of 0.55 (0.34–0.98) and 0.40 (0.04–1.08) Tg N yr^{-1} for each approach. During 1997–2020, the increase rate of the TD estimates (2.2×10^{-3} Tg N yr^{-2}) was higher than that of BU estimates (0.8×10^{-3} Tg N yr^{-2}). Direct agricultural emissions made the largest contribution to the increase in N_2O emissions from northern South America, increasing from 0.04 Tg N yr^{-1} in 1980 to 0.07 Tg N yr^{-1} in 2020 (Fig. 14). N_2O emissions from the other three anthropogenic sectors did not have a significant trend during 1980–2020.

The BU estimates in the 2010s (0.41, 0.03–1.09 Tg N yr^{-1}) were on average 0.17 Tg N yr^{-1} lower than the TD estimates (0.58, 0.35–1.06 Tg N yr^{-1}) (Fig. 15). The average natural emission was 0.35 Tg N yr^{-1} in the 2010s, contributing 85 % of total emissions. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.07 (0.05–0.09), 0.02 (0.01–0.02), and 0.01 (0.01–0.02) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of −0.04 Tg N yr^{-1} and a range of −0.19 to 0.10 Tg N yr^{-1}.

4.5.5 Brazil (BRA)

The average total N_2O emission from Brazil estimated by the BU approaches was 1.21 Tg N yr^{-1}, ranging from 0.26 to 2.32 Tg N yr^{-1} (Fig. 13g), which was lower than the TD estimates (1.42, 1.18–1.75 Tg N yr^{-1}). Both approaches detected a notable increasing trend in total N_2O emissions during 1997–2020. TD approaches suggested a higher increase rate (11.6×10^{-3} Tg N yr^{-2}) than BU approaches (4.3×10^{-3} Tg N yr^{-2}). Direct agricultural emissions, which increased from 0.13 Tg N yr^{-1} in 1980 to 0.32 Tg N yr^{-1} in 2020, made the largest contribution to the increase in N_2O emissions from Brazil (Fig. 14). Indirect emissions also showed an increase from 0.03 Tg N yr^{-1} in 1980 to 0.06 Tg N yr^{-1} in 2020. Emissions from other anthropogenic

sources and perturbed fluxes from changes in climate, CO_2, and land cover did not have an obvious trend during the study period.

The TD estimates in the 2010s (1.51, 1.40–1.79 Tg N yr^{-1}) were on average 0.28 Tg N yr^{-1} higher than the BU estimates (1.23, 0.24–2.41 Tg N yr^{-1}) (Fig. 15). According to the BU results, the average natural emission was 0.95 Tg N yr^{-1} in the 2010s, contributing 77 % of total emissions. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.28 (0.22–0.35), 0.09 (0.06–0.11), and 0.05 (0.02–0.07) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of −0.14 Tg N yr^{-1} and a range of −0.48 to 0.25 Tg N yr^{-1}.

4.5.6 Southwest South America (SSA)

BU and TD estimates are consistent with respect to the magnitude of the total N_2O emissions from southwestern South America during 1997–2020, with values of 0.55 (0.18–1.03) and 0.51 (0.40–0.63) Tg N yr^{-1} (Fig. 13h), respectively. TD estimates increased at a rate of 5.3×10^{-3} Tg N yr^{-2} over 1997–2020, whereas BU estimates did not have an obvious trend during this period. Among the four anthropogenic sectors, direct agricultural emissions had the largest increase, from 0.10 Tg N yr^{-1} in 1980 to 0.15 Tg N yr^{-1} in 2020 (Fig. 14). Indirect emissions also increased from 0.02 Tg N yr^{-1} in 1980 to 0.03 Tg N yr^{-1} in 2020. Perturbed fluxes from changes in climate, CO_2, and land cover had a decreasing trend, while emissions from other sectors fluctuated over the study period.

The BU and TD approaches gave similar estimates of total N_2O emissions from southwestern South America in the 2010s, with values of 0.55 (0.19–1.04) and 0.55 (0.44–0.67) Tg N yr^{-1} (Fig. 15), respectively. The mean natural emission was 0.39 Tg N yr^{-1} in the 2010s, accounting for 71 % of total emissions. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.14 (0.09–0.19), 0.05 (0.03–0.06), and 0.03 (0.01–0.03) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of −0.05 Tg N yr^{-1} and a range of −0.16 to 0.08 Tg N yr^{-1}.

4.5.7 Europe (EU)

The BU estimates suggest that Europe had the largest decrease rate of regional N_2O emissions among the 18 regions, and the average decrease rate during 1980–2020 was -13.3×10^{-3} Tg N yr^{-2} (Fig. 13i). For the 1997–2020 period, this decreasing trend, as estimated by the BU approaches, slowed down (-7.7×10^{-3} Tg N yr^{-2}), whereas the TD approach suggests a small increase of 1.6×10^{-3} Tg N yr^{-2} (Fig. 13i). Emissions from other direct anthropogenic sources (including fossil fuel and industry, waste and wastewater, and biomass burning), which decreased from 0.51 Tg N yr^{-1} in 1980 to 0.18 Tg N yr^{-1} in 2020, made the largest contribution to the decreasing trend in N_2O emissions from Europe. Direct agricultural emissions and indirect emissions show overall decreasing trends from 0.46 and 0.16 Tg N yr^{-1} in 1980 to 0.38 and 0.12 Tg N yr^{-1} in 2020, respectively, mainly due to a reduction in fertilizer use after the collapse of the Soviet Union (Tian et al., 2022). However, the decreasing trend in direct agricultural emissions has leveled off since the 2000s. Perturbed fluxes from changes in climate, CO_2, and land cover decreased during 1980–1985 and then slowly increased (Fig. 14).

The BU and TD approaches gave comparable estimates of European N_2O emissions in the 2010s, with values of 1.00 (0.45–1.57) and 0.86 (0.49–1.36) Tg N yr^{-1} (Fig. 15), respectively. According to the BU results, natural sources only contributed 26 % of total emissions (0.26, 0.11–0.52 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.38 (0.32–0.44), 0.19 (0.15–0.24), and 0.13 (0.08–0.16) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall positive effect on N_2O emissions, with a mean value of 0.03 Tg N yr^{-1} and a range of −0.21 to 0.22 Tg N yr^{-1}.

4.5.8 Northern Africa (NAF)

For northern Africa, TD approaches suggested a larger magnitude of the total N_2O emissions than BU approaches over the 1997–2020 period (Fig. 13j), with values of 1.01 (0.52–1.32) and 0.69 (0.18–1.27) Tg N yr^{-1}, respectively. Both approaches suggest that N_2O emissions from northern Africa significantly increased during 1997–2020, and the increase rates estimated by the BU and TD approaches were 4.9×10^{-3} and 4.7×10^{-3} Tg N yr^{-2}, respectively. Direct emissions increased from 0.10 Tg N yr^{-1} in 1980 to 0.27 Tg N yr^{-1} in 2020, making the largest contribution to the increase in N_2O emissions from northern Africa (Fig. 14). Indirect emissions also significantly increased from 0.02 Tg N yr^{-1} in 1980 to 0.04 Tg N yr^{-1} in 2020. In contrast, other anthropogenic emissions decreased from 0.12 Tg N yr^{-1} in 1980 to 0.11 Tg N yr^{-1} in 2020. N_2O fluxes caused by changes in climate, CO_2, and land cover remained relatively stable during 1980–2020.

In the 2010s, the BU estimates (0.72, 0.17–1.30 Tg N yr^{-1}) were on average 0.32 Tg N yr^{-1} lower than the TD estimates (1.04, 0.54–1.31 Tg N yr^{-1}) (Fig. 15). Natural sources accounted for 44 % of total emissions (0.32, 0.07–0.60 Tg N yr^{-1}) during this period. Direct emissions from nitrogen additions in agriculture were 0.23 (0.09–0.34) Tg N yr^{-1}, contributing 32 % of the total emissions. Emissions from other direct anthropogenic sources made the second largest contribution to anthropogenic emissions, with a decadal mean of 0.11 (0.08–0.14) Tg N yr^{-1}. Indirect emissions and perturbed fluxes from changes in climate,

CO_2, and land cover were 0.04 (0.02–0.06) Tg N yr^{-1}, and 0.02 (−0.10 to 0.16), respectively.

4.5.9 Equatorial Africa (EQAF)

Similar to northern Africa, TD approaches suggested a larger magnitude of total N_2O emissions from equatorial Africa than BU approaches over the 1997–2020 period (Fig. 13k), with values of 1.45 (1.15–1.78) and 1.36 (0.36–2.22) Tg N yr^{-1}, respectively. Both approaches suggested that N_2O emissions from equatorial Africa significantly increased during 1997–2020, and the increase rates estimated by the BU and TD approaches were 4.4×10^{-3} and 2.1×10^{-3} Tg N yr^{-1}, respectively. Direct emissions more than tripled during the study period, from 0.07 Tg N yr^{-1} in 1980 to 0.22 Tg N yr^{-1} in 2020, dominating the increase in N_2O emissions from equatorial Africa (Fig. 14). Indirect emissions also steadily increased from 0.04 Tg N yr^{-1} in 1980 to 0.06 Tg N yr^{-1} in 2020. On the contrary, perturbed fluxes from changes in climate, CO_2, and land cover showed an overall decreasing trend with large interannual variability. Emissions from other anthropogenic sources showed relatively stable values.

The BU and TD approaches gave comparable estimates of N_2O emissions from equatorial Africa in the 2010s, with values of 1.38 (0.38–2.28) and 1.50 (1.15–1.80) Tg N yr^{-1} (Fig. 15), respectively. According to the BU results, natural emissions were the dominant component, accounting for 71 % of total emissions (0.98, 0.42–1.32 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.18 (0.13–0.25), 0.26 (0.19–0.34), and 0.05 (0.03–0.08) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of −0.09 Tg N yr^{-1} and a range of −0.40 to 0.29 Tg N yr^{-1}.

4.5.10 Southern Africa (SAF)

BU and TD estimates are consistent with respect to the magnitude of the total N_2O emissions from southern Africa during 1997–2020, at 0.61 (0.13–1.09) and 0.58 (0.33–0.86) Tg N yr^{-1} (Fig. 13l), respectively. TD estimates increased at a rate of 4.5×10^{-3} Tg N yr^{-2} over 1997–2020, whereas BU estimates did not show an obvious trend during this period. According to the BU results, direct agricultural emissions increased from 0.05 Tg N yr^{-1} in 1980 to 0.08 Tg N yr^{-1} in 2020, while emissions from other anthropogenic sources slightly decreased from 0.19 Tg N yr^{-1} in 1980 to 0.17 Tg N yr^{-1} in 2020. Both indirect emissions and perturbed fluxes from changes in climate, CO_2, and land cover had no significant trend (Fig. 14).

BU and TD approaches gave consistent estimates of total N_2O emissions from southern Africa in the 2010s, with values of 0.62 (0.13–1.10) and 0.61 (0.35–0.87) Tg N yr^{-1} for the BU and TD approaches (Fig. 15), respectively. Natural emissions were the dominant components, accounting for 61 % of total emissions (0.38, 0.13–0.61 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.07 (0.05–0.09), 0.19 (0.17–0.23), and 0.02 (0.01–0.03) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of −0.05 Tg N yr^{-1} and a range of −0.24 to 0.14 Tg N yr^{-1}.

4.5.11 Russia (RUS)

During 1997–2020, the average total N_2O emission from Russia estimated by the BU approaches was 0.74 Tg N yr^{-1}, ranging from 0.15 to 1.84 Tg N yr^{-1} (Fig. 13m), which was much higher than the estimates of TD approaches (0.36, 0.18–0.52 Tg N yr^{-1}). Both approaches suggested that Russia's total N_2O emissions increased during 1997–2020, and the increase rates estimated by the BU and TD approaches were 1.2×10^{-3} and 1.7×10^{-3} Tg N yr^{-2}, respectively. Direct agricultural emissions, other direct emissions, and indirect emissions had divergent trends before and after 1997. From 1980 to 1997, N_2O emissions from all three of these sectors decreased. After 1997, direct agricultural emissions and other direct emissions had an overall increasing trend, while indirect emissions remained relatively stable. Perturbed fluxes from changes in climate, CO_2, and land cover remained relatively stable with large interannual variability (Fig. 14).

In the 2010s, the BU estimates (0.74, 0.15–1.84 Tg N yr^{-1}) were on average 0.36 Tg N yr^{-1} higher than the TD estimates (0.38, 0.18–0.59 Tg N yr^{-1}) (Fig. 15). Natural sources accounted for 64 % of total emissions (0.47, 0.12–1.22 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.06 (0.05–0.07), 0.10 (0.04–0.18), and 0.05 (0.03–0.07) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall positive effect on N_2O emissions, with a mean value of 0.05 Tg N yr^{-1} and a range of −0.10 to 0.30 Tg N yr^{-1}.

4.5.12 Central Asia (CAS)

TD approaches suggested a larger magnitude of total N_2O emissions from Central Asia than BU approaches over the 1997–2020 period (Fig. 13n), with values of 0.19 (0.10–0.29) and 0.14 (0.01–0.27) Tg N yr^{-1}, respectively. BU and TD estimates were consistent with respect to the trend in total N_2O emissions during 1997–2020, with increase rates of 1.9×10^{-3} and 2.0×10^{-3} Tg N yr^{-2}, respectively. Direct emissions increased from 0.05 Tg N yr^{-1} in 1980 to 0.07 Tg N yr^{-1} in 2020, making the largest contribution to the increase in N_2O emissions from Central Asia. Other direct emissions and indirect emissions had no significant trend. Fluxes from changes in climate, CO_2, and land cover

showed an overall increasing trend with large interannual variability (Fig. 14).

In the 2010s, the TD estimates (0.20, 0.10–0.32 Tg N yr^{-1}) were on average 0.05 Tg N yr^{-1} higher than the BU estimates (0.15, 0.01–0.30 Tg N yr^{-1}) (Fig. 15). Natural sources accounted for 30 % of total emissions (0.04, 0.01–0.11 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.06 (0.02–0.08), 0.02 (0.01–0.02), and 0.02 (0.01–0.03) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall positive effect on N_2O emissions, with a mean value of 0.02 Tg N yr^{-1} and a range of −0.04 to 0.07 Tg N yr^{-1}.

4.5.13 The Middle East (MIDE)

BU and TD estimates are comparable with respect to the magnitude of the total N_2O emissions from the Middle East during 1997–2020, with values of 0.27 (0.11–0.45) and 0.30 (0.25–0.36) Tg N yr^{-1} (Fig. 13o), respectively. BU and TD estimates were consistent regarding the trend in total N_2O emissions during 1997–2020, with increase rates of 4.4×10^{-3} and 3.9×10^{-3} Tg N yr^{-2}, respectively. According to the BU results, direct agricultural emissions increased from 0.07 Tg N yr^{-1} in 1980 to 0.13 Tg N yr^{-1} in 2020. Emissions from other anthropogenic sources (fossil fuel and industry, particularly) had the largest increase, from 0.03 Tg N yr^{-1} in 1980 to 0.10 Tg N yr^{-1} in 2020. Indirect emissions also continuously increased from 0.02 Tg N yr^{-1} in 1980 to 0.04 Tg N yr^{-1} in 2020. Perturbed fluxes from changes in climate, CO_2, and land cover had no significant trend (Fig. 14).

BU and TD approaches gave consistent estimates of total N_2O emissions from the Middle East in the 2010s, with values of 0.29 (0.12–0.49) and 0.32 (0.26–0.39) Tg N yr^{-1} for the BU and TD approaches (Fig. 15), respectively. Natural emissions were 0.04 (0.02–0.08 Tg N yr^{-1}), accounting for 15 % of total emissions during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.12 (0.05–0.21), 0.09 (0.07–0.10), and 0.03 (0.02–0.04) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall positive effect on N_2O emissions, with a mean value of 0.01 Tg N yr^{-1} and a range of −0.04 to 0.05 Tg N yr^{-1}.

4.5.14 China (CHN)

BU and TD approaches agreed very well regarding the magnitudes and trends of N_2O emissions from China. Both approaches suggested that China's total N_2O emissions significantly increased during 1997–2020, and the increase rates estimated by the BU and TD approaches were 12.6×10^{-3} and 16.5×10^{-3} Tg N yr^{-1}, respectively (Fig. 13p). According to the BU results, China's total N_2O emissions increased from 0.76 Tg N yr^{-1} in 1980 to 1.38 Tg N yr^{-1} in 2020. Direct emissions from N additions in agriculture made the largest contribution to the increase in China's N_2O emissions, which increased from 0.29 Tg N yr^{-1} in 1980 to 0.71 Tg N yr^{-1} in 2016 and then decreased to 0.64 Tg N yr^{-1} in 2020 due to decreased N fertilizer application (Fig. 14). Both indirect emissions and other direct emissions continuously increased, from 0.09 and 0.11 Tg N yr^{-1} in 1980 to 0.24 and 0.27 Tg N yr^{-1} in 2020, respectively. The total anthropogenic N_2O emissions from China increased at an average rate of 18.9×10^{-3} Tg N yr^{-2} during 1980–2020, which was the largest among the 18 regions and contributed 40 % of the increase in global anthropogenic N_2O emissions.

The BU and TD approaches gave consistent estimates of China's total N_2O emissions in the 2010s, with values of 1.41 (0.82–2.23) and 1.33 (1.06–1.60) Tg N yr^{-1} for the BU and TD approaches (Fig. 15), respectively. According to the BU results, natural sources only contributed 21 % of total emissions (0.29, 0.20–0.51 Tg N yr^{-1}) during this period. Nitrogen additions in agriculture were the dominant source of N_2O emissions, contributing 48 % of the total emissions (0.68, 0.48–1.03 Tg N yr^{-1}). Emissions from other direct anthropogenic sources and indirect emissions from anthropogenic nitrogen additions were 0.23 (0.23–0.23) and 0.24 (0.17–0.28) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of −0.03 Tg N yr^{-1} and a range of −0.25 to 0.18 Tg N yr^{-1}.

4.5.15 Korea and Japan (KAJ)

TD approaches suggested a smaller magnitude of total N_2O emissions from Korea and Japan than BU approaches over the 1997–2020 period (Fig. 13q), with values of 0.06 (0.03–0.11) and 0.11 (0.06–0.16) Tg N yr^{-1}, respectively. Both approaches suggested that total N_2O emissions from Korea and Japan decreased during 1997–2020, and the decrease rates estimated by the BU and TD approaches were -1.4×10^{-3} and -0.5×10^{-3} Tg N yr^{-2}, respectively. Other direct emissions (fossil fuel and industry, particularly) dominated the temporal variations in N_2O emissions from Korea and Japan, which increased from 0.04 Tg N yr^{-1} in 1980 to 0.08 Tg N yr^{-1} in 1997 and then decreased to 0.04 Tg N yr^{-1} in 2020. Emissions from agriculture, indirect sources, and perturbed fluxes remained relatively stable during 1997–2020 (Fig. 14).

In the 2010s, BU estimates (0.10, 0.05–0.15 Tg N yr^{-1}) of total N_2O emissions were on average 0.04 Tg N yr^{-1} higher than the TD estimate (0.06, 0.04–0.11 Tg N yr^{-1}) (Fig. 15). Natural sources accounted for 26 % of total emissions (0.03, 0.00–0.05 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.03 (0.02–0.04), 0.04 (0.04–0.04), and 0.01 (0.01–0.02) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on

N_2O emissions, with a mean value of -0.01 Tg N yr^{-1} and a range of -0.02 to 0.01 Tg N yr^{-1}.

4.5.16 South Asia (SAS)

BU and TD estimates are comparable in terms of both the magnitude and trend of the total N_2O emissions from South Asia (Fig. 13r). During 1997–2020, the magnitudes of total N_2O emissions estimated by the BU and TD approaches were 1.04 (0.35–1.80) and 1.21 (0.96–1.56) Tg N yr^{-1}, respectively. Both approaches suggested that the total N_2O emissions from South Asia significantly increased during 1997–2020, and the increase rates estimated by the BU and TD approaches were 17.7×10^{-3} and 20.2×10^{-3} Tg N yr^{-2}, respectively. Direct emissions from nitrogen additions in agriculture made the largest contribution to the increase in N_2O emissions in South Asia, which increased from 0.19 Tg N yr^{-1} in 1980 to 0.55 Tg N yr^{-1} in 2020 due to increased N fertilizer application (Fig. 14). Other direct emissions and indirect emissions also significantly increased, from 0.06 and 0.06 Tg N yr^{-1} in 1980 to 0.14 and 0.17 Tg N yr^{-1} in 2020, respectively. Fluxes from changes in climate, CO_2, and land cover showed an overall increasing trend with large interannual variability.

BU estimates (1.15, 0.41–2.06 Tg N yr^{-1}) were on average 0.21 Tg N yr^{-1} lower than the TD estimate in the 2010s (1.36, 1.05–1.84 Tg N yr^{-1}) (Fig. 15). Natural sources accounted for 28 % of total emissions (0.32, 0.12–0.56 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.49 (0.25–0.75), 0.13 (0.13–0.13), and 0.15 (0.10–0.19) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall positive effect on N_2O emissions, with a mean value of 0.06 Tg N yr^{-1} and a range of -0.19 to 0.43 Tg N yr^{-1}.

4.5.17 Southeast Asia (SEAS)

TD approaches suggested a smaller magnitude of the total N_2O emissions from Southeast Asia than BU approaches over the 1997–2020 period (Fig. 13s), with values of 0.69 (0.50–1.02) and 0.92 (0.24–2.04) Tg N yr^{-1}, respectively. Both approaches suggested that total N_2O emissions from Southeast Asia increased during 1997–2020, and the rates of increase estimated by the BU and TD approaches were 5.1×10^{-3} and 2.3×10^{-3} Tg N yr^{-2}, respectively. Direct agricultural emissions, other direct emissions, and indirect emissions significantly increased during the study period, from 0.09, 0.08, and 0.04 Tg N yr^{-1} in 1980 to 0.30, 0.11, and 0.12 Tg N yr^{-1} in 2020, respectively. Meanwhile, perturbed fluxes from changes in climate, CO_2, and land cover significantly decreased from -0.07 Tg N yr^{-1} in 1980 to -0.12 Tg N yr^{-1} in 2020 (Fig. 14).

The BU and TD approaches gave comparable estimates of the total N_2O emissions from Southeast Asia in the 2010s, with values of 0.95 (0.24–2.09) and 0.72 (0.51–1.12) Tg N yr^{-1} for the BU and TD approaches (Fig. 15), respectively. Natural sources accounted for 62 % of total emissions (0.59, 0.24–1.30 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.26 (0.20–0.35), 0.11 (0.09–0.14), and 0.10 (0.06–0.14) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of -0.12 Tg N yr^{-1} and a range of -0.35 to 0.16 Tg N yr^{-1}.

4.5.18 Australasia (AUS)

BU and TD estimates are comparable in terms of the magnitude of the total N_2O emissions from Australasia during 1997–2020 (Fig. 13t). The magnitudes of the total N_2O emissions estimated by the BU and TD approaches were 0.43 (0.01–0.92) and 0.52 (0.21–0.72) Tg N yr^{-1}, respectively. TD estimates increased at a rate of 4.4×10^{-3} Tg N yr^{-2} over 1997–2020, whereas BU estimates did not show a notable trend during this period (Fig. 13t). According to the BU results, direct agricultural emissions increased from 0.08 Tg m yr^{-1} in 1980 to 0.09 Tg N yr^{-1} in 2020, while emissions from all the other three anthropogenic sectors remained stable (Fig. 14).

In the 2010s, the magnitudes of total N_2O emissions estimated by the BU and TD approaches were 0.42 (0.01–0.91) and 0.53 (0.20–0.71) Tg N yr^{-1}, respectively. Natural sources accounted for 59 % of total emissions (0.25, 0.05–0.50 Tg N yr^{-1}) during this period. Direct agricultural emissions, other direct emissions, and indirect emissions were 0.09 (0.06–0.11), 0.08 (0.06–0.11), and 0.01 (0.01–0.02) Tg N yr^{-1}, respectively. Changes in climate, CO_2, and land cover had an overall negative effect on N_2O emissions, with a mean value of -0.01 Tg N yr^{-1} and a range of -0.17 to -0.17 Tg N yr^{-1} (Fig. 15).

5 Data availability

The accompanying database includes two Excel files and 27 txt files. The two Excel files are organized into the following spreadsheets.

The global N_2O budget 1980–2020 – global emission data spreadsheet includes the following items:

1. a summary;
2. bottom-up estimates – global BU N_2O budget from 1980 to 2020, including 20 individual sources and sinks;
3. top-down estimates – N_2O emissions from land, ocean, and global during 1997–2020 estimated by the four atmospheric inversion models;

4. Atmospheric_chemical_sink – global atmospheric chemical sink estimated by the four atmospheric inversion models (1997–2020) and one satellite and photolysis model (2005–2020);

5. N_2O_dry_mole_fraction – monthly N_2O dry mole fraction and its growth rate during 2000–2020 estimated by the three observation networks;

6. Future_N_2O_dry_mole_fraction – the projected N_2O dry mole fractions from the four illustrative Representative Concentration Pathways (RCPs) in the IPCC Fifth Assessment Report (2000–2050) as well as the seven illustrative Socioeconomic Pathways (SSPs) used in CMIP6 (2005–2050).

The global N_2O budget 1980–2020 – regional emission data spreadsheet includes the following items:

1. a summary;

2. Anthropogenic_sectors_1980_2020 – N_2O emissions from the four anthropogenic sources for the 18 regions during 1980–2020;

3. Bottom-up_estimates – total N_2O emissions from the 18 regions during 1980–2020 estimated by the BU approaches;

4. Top-down_estimates – N_2O emissions from the 18 regions during 1997–2020 estimated by the four atmospheric inversion models;

5. Decadal_mean_2010s – regional N_2O emissions estimated by the TD and BU approaches in the 2010s.

The global N_2O budget 1980–2020 – modeled gridded emission data spreadsheet includes the spatial patterns of N_2O emissions from different sources (unit: $g\,N\,m^{-2}\,yr^{-1}$) estimated by different models as follows:

1. NMIP2 – a total of 16 maps showing the spatial distribution of soil N_2O emissions, including estimates of eight process-based models that participated in NMIP2 (CLASSIC, DLEM, ELM, ISAM, LPX-Bern, O-CN, ORCHIDEE, and VISIT) and two periods (the 1850s and 2010s);

2. open-ocean emissions – a total of four maps showing the spatial distribution of open-ocean N_2O emissions, including estimates of four ocean models, namely, Bern-3D, NEMO-PlankTOM10.2, NEMOv3.6-PISCESv2-gas, and UVic2.9;

3. shelf emissions – a total of three maps showing the spatial distribution of continental shelves' N_2O emissions, including estimates of three products, namely, CNRM, ECCO, and MEM-RF;

4. top-down estimates – a total of four maps showing the global distribution of N_2O emissions, including estimates of four atmospheric inversion models, namely, GEOS-Chem, INVICAT, MIROC4-ACTM, and PyVAR-CAMS.

The data presented in this work can be downloaded from https://doi.org/10.18160/RQ8P-2Z4R (Tian et al., 2023).

6 Discussion

6.1 Emission sources and comparison with previous estimates of the global N_2O budget

In comparing the global N_2O budget estimates with previous studies, the definitions and terminology used in this study for N_2O sources and sinks are consistent with those in Tian et al. (2020). In this new synthesis, we have also included a new emission source, namely "Continental shelves", corresponding to the shallow portion of the ocean overlying continental shelves (Laruelle et al., 2013), which was not explicitly reported in the previous global N_2O budget (Tian et al., 2020). Thus, a total of 18 sources and 3 sinks are quantified in the global N_2O budget reported here. We utilized a similar methodology to synthesize multiple TD and BU estimates. The TD estimates of global total emissions in this study are consistent with Tian et al. (2020). However, the TD estimates of emissions from the ocean are about $2.3\,Tg\,N\,yr^{-1}$ lower than the previous estimate in the 2000s, whereas the TD estimates of land emissions are about $2.4\,Tg\,N\,yr^{-1}$ higher than the previous estimate for the decade 2007–2016 (Tian et al., 2020). Global BU estimates in this study are about $1.2\,Tg\,N\,yr^{-1}$ higher than the previous estimate, primarily due to the inclusion of emissions from continental shelves ($1.2\,Tg\,N\,yr^{-1}$), and $0.8\,Tg\,N\,yr^{-1}$ higher than the previous estimate for the natural soil baseline.

According to our analysis, natural soils contributed more than half of terrestrial N_2O emissions (Table 3), consistent with previous studies (Denman et al., 2007; Tian et al., 2020). The global natural soil emissions derived from this study are estimated to be $6.4\,Tg\,N\,yr^{-1}$, with a large uncertainty ranging from 3.9 to $8.6\,Tg\,N\,yr^{-1}$. Using the emission factor from the 2006 IPCC guidelines, Syakila and Kroeze (2011) estimated that global preindustrial N_2O emission from natural soils was $7\,Tg\,N\,yr^{-1}$. Xu et al. (2017) suggested that global natural soil N_2O emissions were about $6.2\,Tg\,N\,yr^{-1}$, with an uncertainty range of 4.8 to $8.1\,Tg\,N\,yr^{-1}$. Tian et al. (2019) estimated global soil N_2O emissions derived from NMIP using seven process-based terrestrial biosphere models and suggested a global soil N_2O emission of $6.3 \pm 1.1\,Tg\,N\,yr^{-1}$ in the 1860s.

The total of direct agricultural emissions, other direct anthropogenic emissions, and indirect anthropogenic emissions in this study is the same as the previous estimates (Tian et al., 2020). However, the total anthropogenic emission in

this study is lower than our previous estimate (Tian et al., 2020), mainly because of the differences in perturbed fluxes from climate, CO_2, and land-cover change. According to our new estimate derived from NMIP2, the average perturbed flux from climate, CO_2, and land-cover change was -0.6 (-2.1 to 1.2) Tg N yr^{-1} during 2010–2019 (Table 3). By contrast, the average perturbed flux during 2007–2016 reported by Tian et al. (2020) was 0.2 (-0.6 to 1.1) Tg N yr^{-1}, which was based on the first phase of NMIP (Tian et al., 2018). This study suggests a larger negative effect of increased CO_2 concentration and reduced mature forest area on N_2O emissions than Tian et al. (2020). Much uncertainty exists in estimating the perturbed fluxes of atmospheric CO_2 and mature forest conversion, as discussed in the following section on uncertainties.

Our estimate indicates that agricultural emissions were the major drivers of the increase in anthropogenic emissions during the past 4 decades, increasing from 3.0 Tg N yr^{-1} in 1980 to 5.0 Tg N yr^{-1} in 2020 (Fig. 16). Direct agricultural emissions had a larger increase than indirect agricultural emissions (2.2 Tg N yr^{-1} in 1980 to 3.9 Tg N yr^{-1} in 2020 versus 0.8 Tg N yr^{-1} in 1980 to 1.2 Tg N yr^{-1} in 2020). Agricultural emissions contributed 74 % of total anthropogenic emissions in the 2010s, with 56 % from direct agricultural emissions and 18 % from indirect emissions. Non-agricultural anthropogenic emissions had a slight decreasing trend during 1980–2020 because of a higher estimate of changes in climate, CO_2, and land cover than previous estimate.

This study divides the global land into 18 regions and provides a more detailed regional budget than a previous study, which had only 10 regions (Tian et al., 2020), thereby enhancing our understanding of the N_2O budget in subregions of North America, South America, Africa, and East Asia. In the 1980s, Europe made the largest contribution to global anthropogenic N_2O emissions (23.6 %), followed by China (11.6 %), South Asia (8.0 %), the USA (7.8 %), and Russia (7.3 %). During the study period, Europe and Russia had the largest decline in the share of anthropogenic N_2O emissions, from 23.6 % and 7.3 % in the 1980s to 11.8 % and 4.3 % in the 2010s, respectively. In contrast, China and South Asia had the largest increase, from 11.6 % and 8.0 % in the 1980s to 17.8 % and 13.2 % in the 2010s, respectively. In the 2010s, China (17.8 %), South Asia (13.2 %), Europe (11.8 %), the USA (6.7 %), and equatorial Africa (6.5 %) were the top five contributors to global anthropogenic N_2O emissions (Fig. 17).

Among the 18 regions identified in this study, only Europe, Russia, Australasia, and Japan and Korea had decreasing N_2O emissions. Europe had the largest rate of decrease, with an average of -13.2×10^{-3} Tg N yr^{-2} during 1980–2020 (31 % reduction), largely resulting from reduced emissions from fossil fuel and industry, which changed from 0.49 Tg N yr^{-1} in 1980 to 0.14 Tg N yr^{-1} in 2020. In addition to the large reduction in fossil fuel and industry emissions in Europe, direct agricultural emissions and indirect emissions showed overall decreasing trends from 0.46 and 0.16 Tg N yr^{-1} in 1980 to 0.38 and 0.12 Tg N yr^{-1} in 2020, respectively. However, the decreasing trend in agricultural emissions has leveled off since the 2000s.

China and South Asia had the largest increase in N_2O emissions during the study period. The rates of increase in the anthropogenic emissions from China and South Asia were 18.9×10^{-3} and 14.3×10^{-3} Tg N yr^{-2}, respectively. The rates of increase in the anthropogenic emissions from China and South Asia contributed 40 % and 30 % to the global anthropogenic increase rate (0.05 Tg N yr^{-2}), respectively. In these two regions, direct nitrogen additions in agriculture made the largest contribution, while other direct emissions and indirect emissions also steadily increased. Our results show a significant increase in anthropogenic N_2O emissions from South America, which is consistent with the previous budget (Tian et al., 2020). Moreover, we reveal that Brazil had a higher increase rate in anthropogenic N_2O emissions (4.2×10^{-3} Tg N yr^{-2}) than northern South America (0.8×10^{-3} Tg N yr^{-2}) and southwestern South America (0.4×10^{-3} Tg N yr^{-2}) during 1980–2020, and direct emissions from agriculture made the largest contribution. Our results suggest that northern Africa made the largest contribution (58 %) to the increase in anthropogenic N_2O emissions from Africa, followed by equatorial Africa (38 %) and southern Africa (4 %). Anthropogenic N_2O emissions from the USA and Canada show similar weak increasing rates of 0.6×10^{-3} and 0.9×10^{-3} Tg N yr^{-2} during the 1980–2020 period, respectively. Central America shows a higher anthropogenic N_2O emission increase rate (5.9×10^{-3} Tg N yr^{-2}), which is attributed to an increase in emissions from fossil fuels and industry, from 0.01 Tg N yr^{-1} in the 1980s to 0.16 Tg N yr^{-1} in the 2010s. The data for Mexico from EDGAR have a known problem with their estimates of N_2O emissions from industry, and this issue requires further exploration. To support countries' N_2O mitigation, it is essential to accurately estimate sources and sinks of N_2O at the national level.

6.2 Sources of uncertainties and suggestions for improvements

6.2.1 Uncertainties in N_2O emission factors

Four inventories of N_2O emissions (EDGAR, FAOSTAT, GFED, and UNFCCC) are integrated into the current synthesis of anthropogenic N_2O emissions. These EF-based inventory datasets (where EF refers to emission factors) used the IPCC default EFs at regional and global scales. Uncertainty in FAOSTAT N_2O emissions is ~ 60 % across typologies. In fact, it is asymmetrical, following the 2006 guideline values and IPCC uncertainty formulae, with $u_{min} \sim -30$ % and $u_{max} \sim 90$ % (Tubiello et al., 2013); for N_2O in EDGAR, the global uncertainty ranges defining the 95 % confidence intervals of a lognormal distribution are ± 113 % for energy, be-

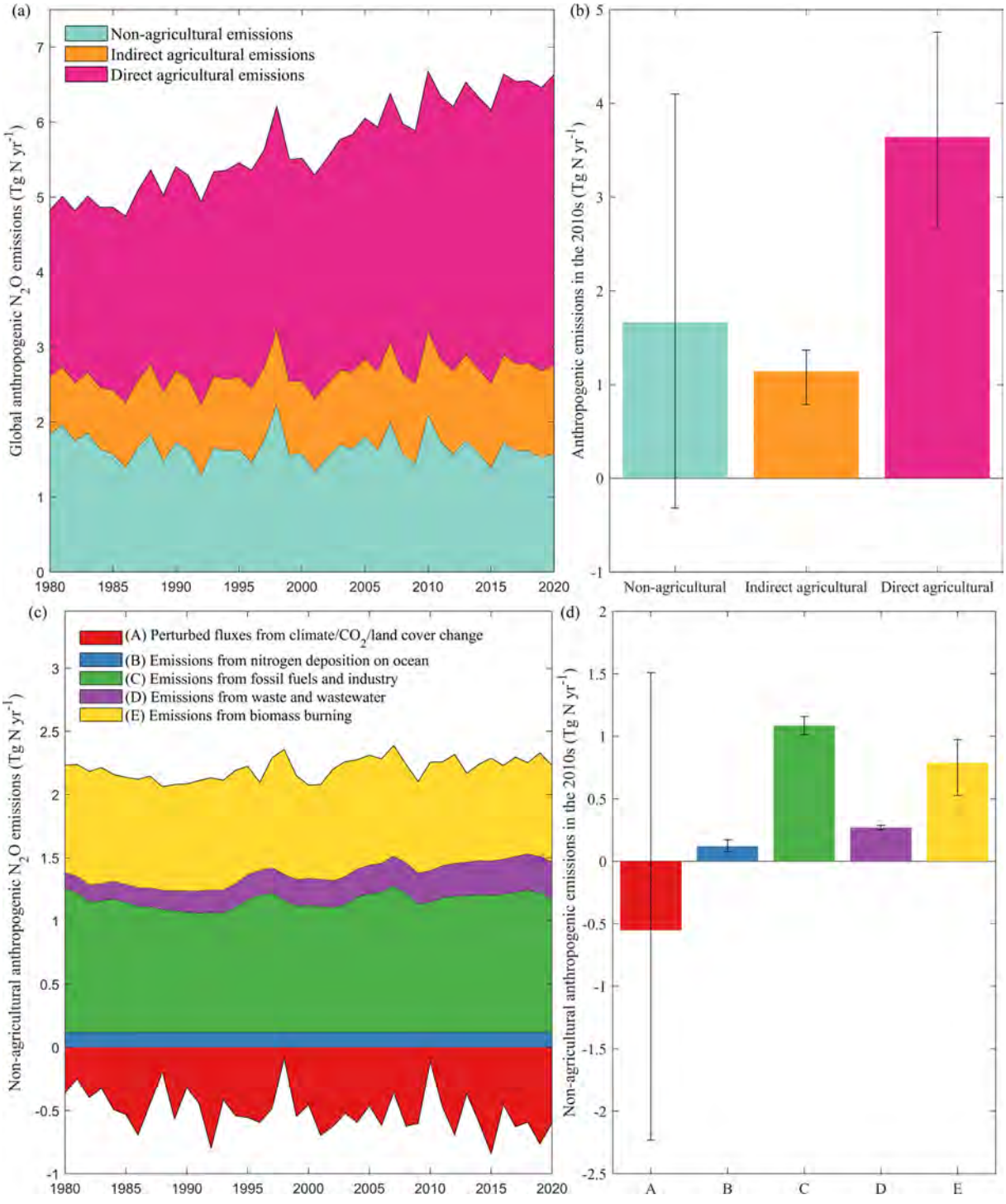

Figure 16. Changes in N_2O emissions from anthropogenic emissions from agricultural and non-agricultural sources during 1980–2020 **(a, c)**. Panels **(b)** and **(d)** show average anthropogenic emissions from different sources during 2010–2019; error bars indicate the spread between the minimum and the maximum values. Here, direct agricultural emissions include emissions from fertilizer and manure applied on agricultural soils, manure left on pasture, manure management, and aquaculture. Indirect agricultural emissions include emissions from anthropogenic nitrogen additions to inland waters, estuaries, and coastal vegetation as well as N deposition on land. Other anthropogenic emissions are classified as non-agricultural anthropogenic emissions. The letters A–E in panel **(d)** represent perturbed N_2O fluxes from climate, CO_2, and land-cover change; emissions from nitrogen deposition on the ocean; emissions from fossil fuels and industry; emissions from waste and wastewater; and emissions from biomass burning, respectively.

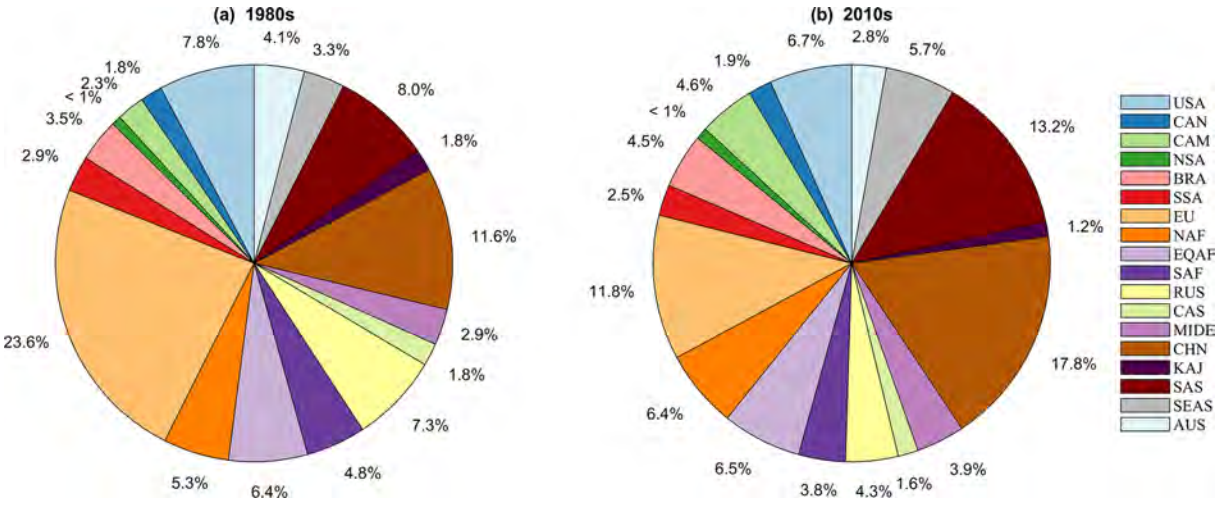

Figure 17. Contributions of the 18 regions to global anthropogenic N_2O emissions in the 1980s **(a)** and 2010s **(b)**.

tween −12 % and +16 % for industrial processes and product use, between −225 % and +302 % for agriculture, between −159 % and +203 % for waste, and ±112 % for other sectors (Solazzo et al., 2021). However, the poorly captured dependence of EFs on regional climate, management practices such as tillage, legume effect, and soil physical and biochemical conditions are key causes of the large uncertainty in the estimates of agricultural N_2O emissions (Shcherbak et al., 2014; Tian et al., 2019; Lu et al., 2022), particularly for croplands where EFs have high spatial heterogeneity (Shang et al., 2019; Wang et al., 2020). There is evidence of a greater-than-linear dependence of emissions on N input where there is an excess of N; however, this is not represented in inventories that assume a linear dependence on N input (Cui et al., 2021). Higher IPCC-tier GHG inventories using the alternative EFs that are disaggregated by environmental factors and management-related factors (Buendia et al., 2019) could provide more accurate estimates, especially for regions where N input surplus is high, such as eastern China, India, and the USA. For example, the US national inventory uses a Tier-3 modeling approach (Del Grosso et al., 2022). Establishing national and regional N_2O flux measurement networks could improve the accuracy of EF estimates for regions with different vegetation types and management measures. Furthermore, inventory datasets based on EF methods also suffer from large uncertainties induced by the underlying agriculture and rural data and statistics used as input, including statistics on fertilizer applications, livestock manure availability, storage and applications, and nutrient, crop, and soil management.

According to the ensemble of process-based land model emissions derived from NMIP2, we estimate that the EF of fertilizer and manure applied on global croplands was 1.9 % (1.2 %–3.3 %) in the 2010s, which is significantly larger than the IPCC Tier-1 default for direct emission of 1 %. This higher EF derived from process-based models suggests a strong interactive effect between N additions and other global environmental changes (Perturbed fluxes from climate, atmospheric CO_2, and land-cover change in Table 3). Figure 18 shows the spatial pattern of the cropland N_2O EF during the 2010s and highlights that the EF was high in eastern China, Southeast Asia, western Europe, and the central USA where anthropogenic N inputs were high (Fig. B3). Previous field experiments reported a better fit to local observations of soil N_2O emissions when assuming a nonlinear response to fertilizer N inputs under varied climate and soil conditions (Shcherbak et al., 2014; Wang et al., 2020). The nonlinear response is also likely associated with long-term N accumulation in agricultural soils from N fertilizer use and in aquatic systems from N loads (the legacy effect) (Van Meter et al., 2016), which provides more substrate for microbial processes (Firestone and Davidson, 1989). The increasing N_2O emissions estimated by process-based models (Tian et al., 2019) also suggest that recent climate change (particularly warming) may have boosted soil nitrification and denitrification processes, contributing to the growing trend in N_2O emissions with rising N additions to agricultural soils (Griffis et al., 2017; Pärn et al., 2018; Smith, 1997).

6.2.2 Uncertainties in estimates of soil N_2O emissions

Both process-based land biosphere modeling and measurement-based upscaling approaches have been used to estimate global soil N_2O emissions (Table 3), with large uncertainties in their estimates. As shown in Fig. 19, NMIP2 models exhibit the highest uncertainties in the estimates of soil N_2O emissions from tropical forests, such as the Amazon Basin, the Congo Basin, and Southeast Asia, as well as in regions with high fertilizer application rates, including eastern China, northern India, and the US Corn Belt. For NMIP2 estimates of direct agricultural

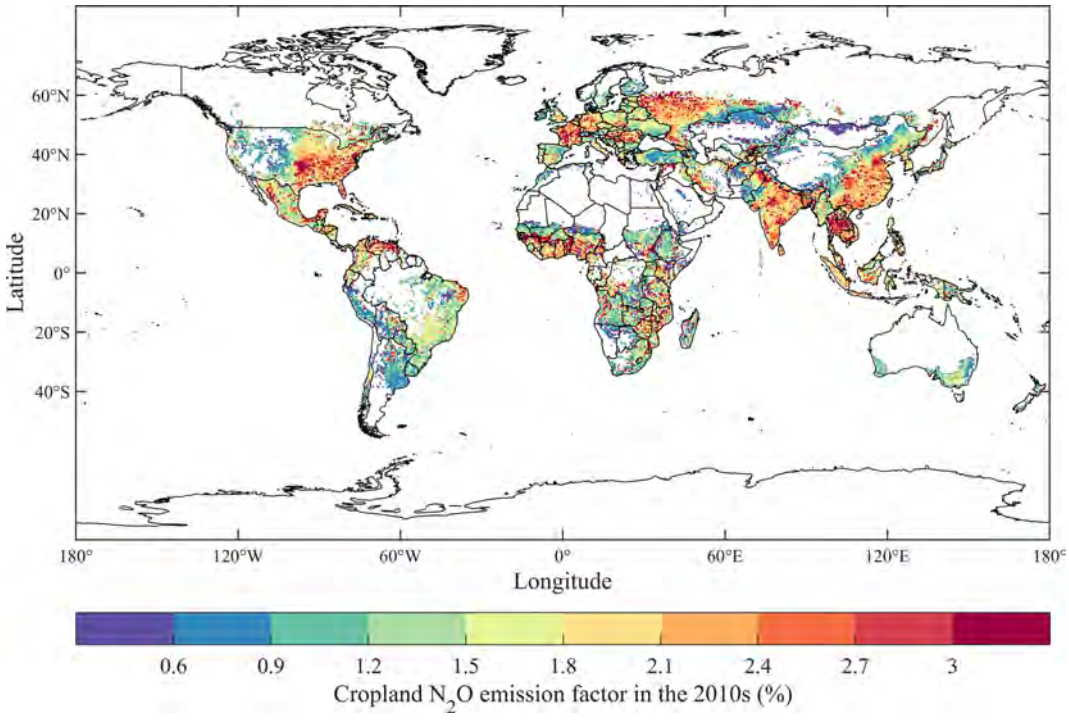

Figure 18. Spatial pattern of the emission factor (EF) of fertilizer and manure applied on global croplands in the 2010s derived from NMIP2.

emissions, the maximum estimate is about 60 % higher than the ensemble mean, and the minimum estimate is about 40 % lower than the ensemble mean. A large discrepancy in natural soil emissions among NMIP2 models exists, ranging from 3.9 to 8.6 Tg N yr^{-1}, which needs to be reconciled in future research.

Uncertainties associated with NMIP2 models

The uncertainties in process-based models primarily stem from differences in model configuration and process parameterization as well as from the missing processes and critical information (Tian et al., 2019).

First, the NMIP2 models use divergent schemes to represent the flows of reactive N through ecosystems (biological N fixation, N deposition, N leaching, N volatilization, nitrification, and denitrification), which could result in large discrepancies in soil mineral N that serves as substrates for N_2O production. Explicit representation of these processes is a critical need with respect to enhancing model simulation accuracy.

Second, several important processes are missing in most process-based land models. Human management measures like tillage and legume cultivation can alter the physical and chemical characteristics of soil in croplands (Raji and Dörsch, 2020; Z. Yu et al., 2020), but they are not adequately represented in most NMIP2 models. Parameterizing these processes in the models is necessary to reduce uncertainty. Additionally, N addition in pasture and rangeland (e.g., livestock excreta deposition, manure, and mineral fertilizer application) constitutes an important source of global soil N_2O emissions (Davidson, 2009), accounting for more than half of the global agricultural N_2O emissions (Dangal et al., 2019). However, only DLEM considered these processes. The consideration of N addition in managed grasslands is an essential task for process-based models to estimate grassland soil N_2O emissions accurately. Moreover, most process-based models did not explicitly consider seasonal freeze–thaw processes or the thawing of permafrost, which can emit substantial amounts of N_2O (Marushchak et al., 2011, 2021; Repo et al., 2009; Voigt et al., 2017; Del Grosso et al., 2022). It is recommended to include explicit representation of permafrost physics and seasonal freeze–thaw processes in process-based models, as this would help better catch the "hotspot" and "hot moment" of soil N_2O emissions in northern regions (Wagner-Riddle et al., 2017). Current process-based models also face challenges in adequately representing the fine-grained landscape structure of Arctic ecosystems (e.g., landscape elements that act as ultra-emitters of N_2O, like organic soil non-vegetated fractions); thus, integrating sub-grid information and processes into models may provide a solution for fine-grained physical–hydrological modeling.

Third, microbial nitrification and denitrification processes are regulated by multiple environmental factors, including substrate availability, precipitation, temperature, oxygen status, pH, vegetation type, and atmospheric CO_2 concentration (Butterbach-Bahl et al., 2013; Dijkstra et al., 2012; Li et al., 2020; Tian et al., 2019; Yin et al., 2022; Yu et

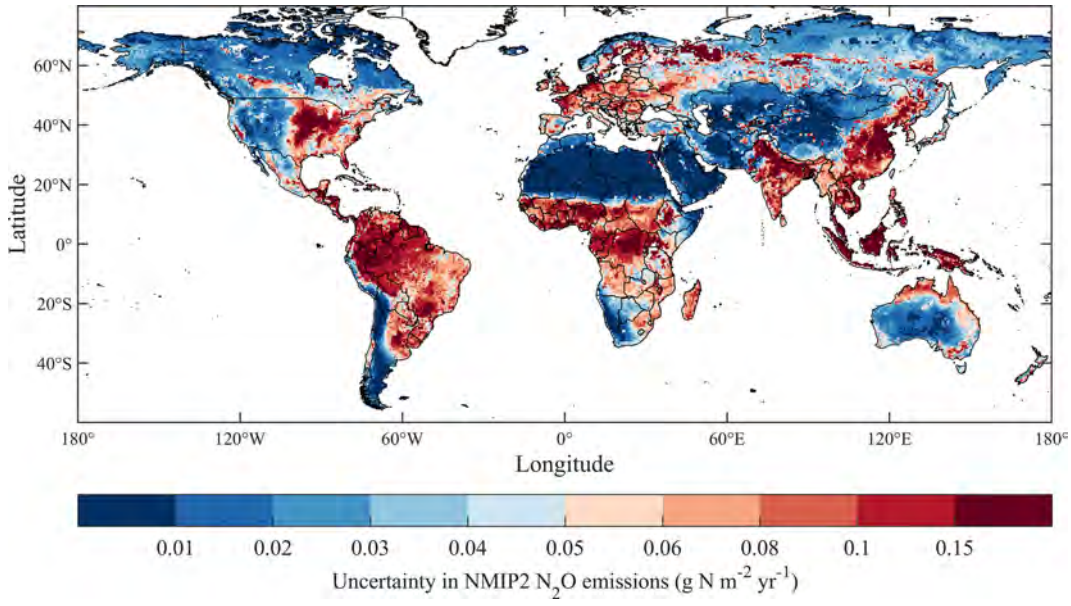

Figure 19. Spatial distribution of uncertainty (1 standard deviation) in NMIP2 estimations of soil N_2O emissions in the 2010s.

al., 2022). However, there is significant divergence among NMIP2 models in their response to these factors. For example, simulated soil N_2O emissions in response to N addition (i.e., fertilizer and manure N applications and N deposition) exhibit large divergence among the participating NMIP2 models, primarily due to differences in model representation of N processes and parameterization schemes. Moreover, in contrast to our findings indicating N fertilizer application and manure additions as dominant drivers, Harris et al. (2022) identified N deposition as the primary contributor to anthropogenic N_2O emissions, accounting for 41 ± 14 % of all anthropogenic emissions. These different findings highlight the complex nature of N_2O emissions and the need for further research to better understand the relative contributions of different N sources. For the climatic effects on soil N_2O emissions, our NMIP2 models indicate enhanced N_2O emissions due to warming, consistent with findings from experiment-based studies (Smith, 1997; Cui et al., 2018; Voigt et al., 2017; Wang et al., 2017), as the denitrifying bacteria community may adapt to higher temperature (Pärn et al., 2018). Additionally, considering that microbial nitrification and denitrification are also largely controlled by soil moisture (Butterbach-Bahl et al., 2013), it is important to address the discrepancies in NMIP2 models concerning soil moisture representation, such as soil depth, root distribution, root water uptake, and water movement processes (Ostle et al., 2009; Raats, 2007; Raoult et al., 2018).

At the global scale, although NMIP2 models show large discrepancies in the CO_2 effect on soil N_2O emissions, most NMIP2 models show a negative effect, suggesting that enhanced plant N uptake caused by a rising CO_2 concentration played a dominant role (Usyskin-Tonne et al., 2020; Tian et al., 2019). Nevertheless, observation-based results of the CO_2 effect diverge among different ecosystem types, with some studies reporting reduced N_2O emissions in forests under elevated CO_2 (Phillips et al., 2001), while others found increased emissions in grasslands (Moser et al., 2018; Regan et al., 2011). It should be noted that the interactions among environmental factors influencing soil N_2O emissions are still poorly represented in the NMIP2 models. Further targeted continuous measurements and manipulation experiments are needed to better represent the interactive effects of multiple environmental factors on N_2O emissions in the models to improve the simulation of complex N_2O dynamics. Finally, simulations targeted to explain the reconstructed increase in terrestrial N_2O emissions over the deglaciation and during past abrupt climate events will further help to constrain process-based models (Fischer et al., 2019; Joos et al., 2020).

Land-cover change/deforestation

The two methods for estimating deforestation-induced N_2O changes have their limitations. The accuracy of the empirical estimates of post-deforestation pulse N_2O emissions in tropical forests strongly depends on the availability of paired N_2O observations in deforested and nearby intact forest sites (Melillo et al., 2001; Verchot et al., 1999), which are extremely scarce. Moreover, a fixed value was adopted as the default reference N_2O emission rate for tropical forests to simplify computation, but it inevitably ignored the spatiotemporal heterogeneity in tropical forest N_2O emissions (Barthel et al., 2022). It is also noted that there were no empirical post-deforestation N_2O emission estimates in extra-

tropical areas, as no feasible empirical relationships between N_2O emissions and years after deforestation were available. The accuracy of process-based estimates (specifically by DLEM here) could be regulated by model-specific configurations for land-use change pathways. For example, in modeling tropical shift cultivation, DLEM assumed that agricultural lands newly converted from forests can only be reforested after at least 15 years to be consistent with the LUHv2 data (Hurtt et al., 2020). Meanwhile, treatments of different nitrogen pools (such as leaf, stem, root, and litter pools) during land conversion would directly influence the nitrogen substrate for nitrification and denitrification. The DLEM model follows the biomass allocation scheme proposed by previous studies (Houghton et al., 1983; McGuire et al., 2001), which may introduce uncertainty in varied land management practices. A bias in the LUHv2 land-use change data in regions experiencing drastic land conversions could also contribute to uncertainty in deforestation-induced GHG emissions, for example, in areas with large-scale plantations (Yu et al., 2022).

In addition, developing forcing datasets with high quality and high spatiotemporal resolution is also important for reducing uncertainties in simulated N_2O fluxes. Among various input variables, precise information regarding fertilizer and manure application (including crop-specific application rate, type, timing, and frequency) is pivotal for improving the accuracy of model simulations. However, this crucial information was not unified in NMIP2 simulations, leading to increased modeling uncertainty. To mitigate this issue, it is strongly recommended to use improved fertilizer and manure datasets that provide detailed information on crop-specific application rate, timing, and frequency to drive models in future intercomparison projects. Moreover, with the availability of additional high-precision datasets from manipulation field experiments (e.g., microbial data), we could use these datasets to constrain our models and delve deeper into the underlying mechanisms that regulate N_2O fluxes (e.g., the role of soil microbes) and further incorporate these mechanisms into models to reduce uncertainties.

Uncertainties associated with the measurement-based upscaling approach

Measurement-based upscaling estimates are subject to uncertainties due to various factors. One major reason is the limited recording of microscale variables and the incomplete quantification of local EFs related to microbial N_2O production. Sampling limitations also contribute to uncertainties, as the frequency and repeatability of measurements may not fully capture the high spatiotemporal variability in the N_2O flux. The lack of the history of control sites further complicates the exclusion of observation data with significant legacy fluxes, thereby biasing our estimates. Additionally, gaps in global agricultural management datasets, particularly regarding fertilization details, enlarge the prediction

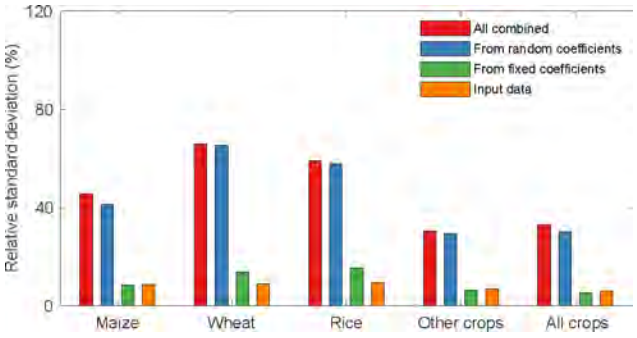

Figure 20. Relative standard deviation in the global cropland N_2O EF. The figure breaks down the uncertainty in the EF per source of uncertainty (i.e., random coefficients, fixed coefficients, input data, or all combined). The uncertainty due to each source can be quantified by holding the coefficients for the other sources fixed.

interval of EFs and introduce uncertainties. We then used a Monte Carlo simulation to estimate three sources of uncertainty for predicting EFs based on a flux upscaling approach: (i) the fixed coefficients, (ii) the random coefficients, and (iii) input data. The uncertainty from sampling frequency and replication is reflected in the first source, while the uncertainty from unquantified sources related to field measurements is reflected in the second source. Each of the crop-specific SRNM models was run by randomly generating the fixed and random coefficients from their fitted multivariate normal distribution as well as climate, soil, and other relevant factors following independent normal distributions with the mean of the value in our dataset and standard deviation of the absolute difference between the dataset used in this study and other global datasets. Fertilizer frequency was randomly selected using a Bernoulli distribution. Predicted values were calculated through 1000 iterations to construct a 95 % prediction interval. The breakdown of uncertainty revealed that the random coefficients contributed the most to the estimation uncertainty, with observations showing that they explained more variance in EFs compared with fixed effects (47 %–74 % versus 19 %–35 %) and contributed to most of estimation uncertainty (Fig. 20).

To address these limitations and reduce uncertainties, concerted efforts should be made to enhance the availability of N_2O observations representing diverse agroecological conditions. Meanwhile, improving the availability of high-precision datasets (e.g., microbial data) and integrating these datasets and the derived underlying mechanisms to our models could also reduce uncertainties. Currently, most available field N_2O observations (see the Supplement) are made in Europe, the USA, and China and are scarce in most developing countries (such as sub-Saharan Africa). Therefore, extending the global coverage of direct and indirect N_2O flux measurements to encompass all major agricultural land-use types and climates, land-use changes, and management practices as well as conducting long-term high-frequency monitoring

are particularly important to increase the reliability of EFs as well as upscale results from site to regional scales.

6.2.3 Uncertainties in estimates of ocean N_2O emissions

Global open-ocean N_2O emissions derived from the ocean biogeochemistry models (Table 1) for the 2010–2019 period are estimated to be 3.5 (2.5–4.7) Tg N yr^{-1}. All models show the highest emissions associated with equatorial and coastal upwelling zones as well as with the major oxygen minimum zones (OMZs; e.g., the eastern equatorial Pacific and the Arabian Sea region of the northern Indian Ocean; see Fig. 21). These are regions characterized by high levels of biological productivity and higher subsurface organic matter remineralization, resulting in higher N_2O yields in suboxic waters. The four participating models capture these characteristics but also show varying degrees of intensity in regional N_2O emissions. The models also show good agreement with respect to representing the ocean regions of relatively low N_2O ocean–atmosphere fluxes (i.e., open-ocean gyres where biological productivity is low).

The spatial distribution of uncertainty in ocean N_2O emissions among the models (Fig. 21) is similar to that of the net N_2O ocean–atmosphere flux, with the highest uncertainties observed in the equatorial upwelling and low-oxygen waters associated with high subsurface N_2O production (Babbin et al., 2020; Ganesan et al., 2020). The largest uncertainties are found in the equatorial Pacific, the Benguela upwelling region of the Atlantic, and the eastern equatorial Indian Ocean. Uncertainties in the ocean models' representation of N_2O fluxes result from a range of model characteristics (Zamora and Oschlies, 2014; Martinez-Rey et al., 2015; Buitenhuis et al., 2018; Battaglia and Joos, 2018; Landolfi et al., 2017; Berthet et al., 2023), including the following: (i) uncertainties in ocean circulation – particularly the representation of upwelling zones and the ocean circulation features (often sub-grid scale) that control the extent and intensity of OMZs; (ii) simulation of ocean organic matter productivity, export production, and mesopelagic remineralization (a driver of the subsurface source function for N_2O production in models); (iii) the model biogeochemical parameterizations representing N_2O production and consumption from marine nitrification and denitrification processes, including their dependence on local dissolved oxygen concentrations and thresholds; and (iv) parameterization of ocean–atmosphere gas-exchange fluxes.

Model simulations of oceanic N_2O are closely linked to the underlying modeled oxygen distributions, as the embedded biogeochemical parameterizations for N_2O include the sensitivity of N_2O cycling processes (e.g., nitrification and denitrification) to the local oxygen level (Ji et al., 2018). Significant uncertainties in modeled N_2O fluxes result from model biases in the representation of dissolved oxygen, especially in low-oxygen zones such as the eastern equatorial Pacific (Zamora and Oschlies, 2014; Martinez-Rey et al., 2015). Many ocean model simulations of dissolved oxygen display biases, especially in OMZs critical for N_2O cycling (Martinez-Rey et al., 2015). To reduce potential sources of error from model-simulated oxygen, one N_2O model in this analysis employs observation-based oxygen distributions when simulating ocean N_2O (Buitenhuis et al., 2018). However, this approach also restricts a model's response to climate-related feedback on ocean oxygen. In addition, the models in this analysis include optimization and calibration of N_2O cycle parameters by incorporating constraints from ocean observations (e.g., surface and interior N_2O and microbially mediated process rates) (Battaglia and Joos, 2018; Buitenhuis et al., 2018; Berthet et al., 2023). A more detailed error analysis of N_2O model parameters (including uncertainty in gas-exchange fluxes) in one of the component models (Buitenhuis et al., 2018) suggests estimated uncertainties in global fluxes from biogeochemical parameter specifications of $\sim 33\,\%$. Further, a 1000-member ensemble with 11 parameters varied with one of the models and constrained with both surface and subsurface N_2O observations yields an observation-constrained standard deviation of $\pm 36\,\%$ around the median of 4.3 Tg N yr^{-1} (Battaglia and Joos, 2018), consistent with a recent surface pN_2O-based estimate of 4.2 ± 1 Tg N yr^{-1} (Yang et al., 2020).

Landolfi et al. (2017) also note that uncertainties arise in current model predictions of marine N_2O fluxes due to the neglect of feedback from impacts of external nutrient sources and ocean acidification on marine productivity and the ocean nitrogen and oxygen cycles. Reducing uncertainties in model estimates of the evolution of ocean N_2O fluxes will require accounting for these impacts in the underlying biogeochemical parameterizations. In addition, due to the high sensitivity of modeled N_2O production and consumption rates to oxygen level in the key ocean OMZ zones, an important priority in reducing modeled ocean N_2O flux uncertainties is to achieve a more accurate simulation of the ocean circulation and oxygen distribution of these regions.

6.2.4 Uncertainties in emissions estimates from the continental shelves

Estimates of N_2O emissions vary by a factor of 2–3 in the continental shelf (one observation-based product and two models). The MEM-RF observational estimate (1.63 Tg N yr^{-1}; Yang et al., 2020) falls at the high end of the two high-resolution model estimates (1.39 and 0.61 Tg N yr^{-1} for CNRM-0.25° and ECCO-Darwin, respectively). Shelf N_2O flux emissions from MEM-RF, CNRM-0.25°, and ECO-Darwin broadly agree with respect to the main patterns and magnitude. Emission hotspots in productive, low-O_2 upwelling systems (e.g., eastern boundary upwellings and upwellings of the northwestern Indian Ocean) appear to be underestimated by models. Lower emissions in models likely reflect the inability of models to resolve com-

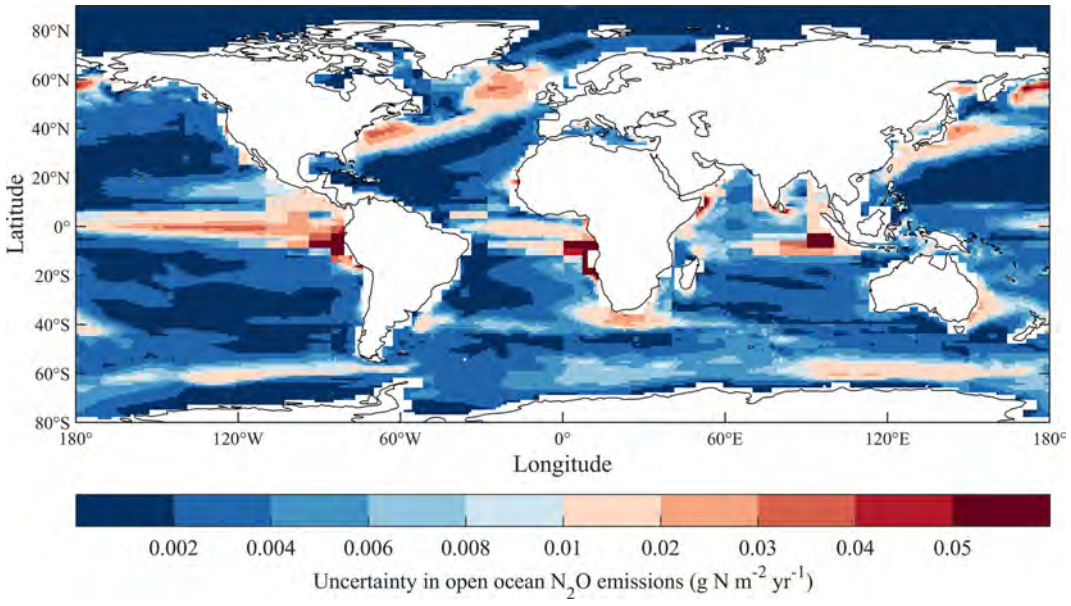

Figure 21. Spatial uncertainty distribution (1 standard deviation) in open-ocean N_2O emissions in the 2010s. Note that the color scale in this figure is different from that in Fig. 19.

plex near-shore dynamical circulation and biogeochemical processes key to the production, transport, and evasion of N_2O. This includes under-resolved dynamics in upwelling systems and shallow OMZs with high N_2O emissions (Resplandy et al., 2024), strong spatial gradients introduced by patterns of high production/high remineralization and enhanced land–sea inputs of N in shallow shelves (e.g., Baltic Sea as well as Southeast and East Asia), sedimentary processes, and production in estuarine and coastal vegetated ecosystems, which is subsequently transported offshore. Conversely, our ability to reconstruct spatial patterns in N_2O air–sea fluxes from observations (MEM-RF; Yang et al., 2020), in particular along continental margins, is severely limited by the number of N_2O observations, which is 2 orders of magnitude smaller than for CO_2. Observations tend to be localized in regions of strong air–sea disequilibrium and, thus, might be biased high (e.g., Babbin et al., 2020; Ganesan et al., 2020). In addition, many coastal regions remain undersampled, further limiting the performance of MEM-RF. For instance, models point to coastal N_2O flux hotspots along midlatitude western boundaries (e.g., the US East Coast, the North Pacific east of Japan, the southeast coast of Australia, and the southeastern tip of Africa) that are not diagnosed in the observational product (Resplandy et al., 2024). Furthermore, N_2O fluxes are highly spatially heterogeneous (scales of 1 to 100 km) due to land–ocean gradients and mesoscale and submesoscale features such as eddies (Arévalo-Martínez et al., 2017, 2019; Yang et al., 2020; Grundle et al., 2017). Eddies are instrumental in setting suboxic conditions favorable for N_2O production, and it has been suggested that N_2O production weakens within eddies during their transit across the shelf and further offshore (Arévalo-Martinez et al., 2016). These small-scale circulation features are important controls on N_2O dynamics but are poorly accounted for in data-based reconstructions and models.

This assessment provides the most up-to-date estimate of N_2O climatological emissions from the global shelves, but the variability in these emissions remains uncertain. Each product covers a different time period and only provides limited or missing information on seasonal fluctuations, interannual variability, and long-term trends. For instance, only a handful of observations per year are available in most regions, providing a limited picture of seasonality and even more limited information on interannual variability (e.g., El Niño–Southern Oscillation and Pacific Decadal Oscillation) and global longer-term trends. Disentangling such influences from limited observations alone remains a major challenge. The effects of extreme events, such as storms and marine heat waves, on N_2O fluxes are also currently not captured, and the intra-annual variability in hotspot regions, such as coastal upwelling systems, remains poorly constrained. Despite these limitations, data-based reconstructions and models suggest a vigorous seasonal cycle and, potentially, important variability on interannual timescales (Yang et al., 2020; Ganesan et al., 2020). The development of a global N_2O ocean observation network (N_2O-ON; Bange et al., 2019; Bange, 2022) is critically needed to better resolve spatiotemporal patterns and reduce uncertainties in N_2O emissions. Increasing the density of observations in regions of high N_2O disequilibrium and collecting long time series of N_2O measurements will allow for better characterization of interannual changes and their dynamics. Meanwhile, algo-

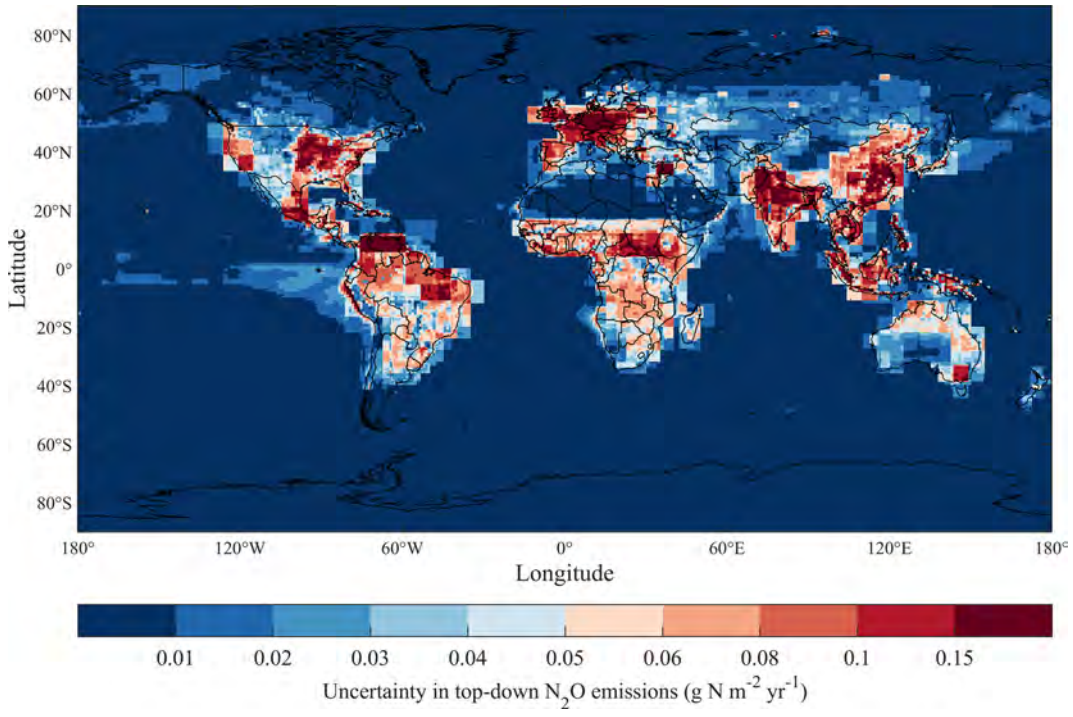

Figure 22. Spatial distribution of posterior uncertainty (1 standard deviation) in TD model estimates of N_2O emissions in the 2010s.

rithmic approaches that address the observational limitations should be developed and refined to extrapolate N_2O measurements to global and interannual timescales, leveraging advancements made for CO_2 disequilibrium and flux reconstructions.

Parallel efforts based on the development of mechanistic models are also needed to strengthen our understanding of the dynamics underlying interannual N_2O flux variability and to detect and attribute long-term anthropogenic effects. However, the representation of N_2O processes in biogeochemical models remains limited, and very few climate models include marine emissions of N_2O fluxes (only 4 out of 26 CMIP6 models considered in Séférian et al., 2020). Uncertainty persists regarding the various (micro-)biological processes that drive N_2O cycling in coastal waters and sediments (Bange, 2022). Current global ocean biogeochemical models typically adopt an indirect representation of N_2O production, which is diagnosed from environmental conditions (e.g., temperature) and O_2 consumption during remineralization of organic matter, without explicitly representing the bacterial pools and chemical reactions responsible for N_2O production in suboxic waters (e.g., Aumont et al., 2015; Battaglia and Joos, 2018). In addition, key aspects of air–sea N_2O exchange, such as the effects of surfactants in the sea surface microlayer (Kock et al., 2012), remain poorly understood. Finally, the interannual variability in N_2O fluxes and its attribution to climatic and anthropogenic drivers is largely unknown. Disentangling these influences will benefit from (1) interannually varying observational N_2O flux reconstructions at scales fine enough to capture high emissions along continental margins, (2) statistical methods that address the limited number of observations in space and time, and (3) N_2O cycle simulations with forward mechanistic models. A blueprint for this work already exists with the approaches developed by the oceanic CO_2 community (Gruber, 2022). Similar approaches would enable attribution of N_2O flux changes to specific drivers, leading to better predictability.

6.2.5 Uncertainties in emissions estimates from atmospheric inversions

The four atmospheric inversion frameworks show uncertainties in the estimates of N_2O emissions, especially in hotspot regions such as eastern China, India, Europe, the US Corn Belt, and northern South America (Fig. 22). The uncertainties in inversion estimates are mainly from errors in the modeled atmospheric transport, the dependence on the prior information, and the availability of atmospheric observations. Every inversion framework in this study used a different atmospheric transport model with different horizontal and vertical resolutions (Table 1). By including estimates from multiple inversion frameworks with different modeled atmospheric transport, the systematic error can be assessed to some extent. The inversion estimates are dependent on the spatial pattern and magnitude of the prior flux estimates to an extent that is determined by the density of the observations. Using the same prior information might reduce the range in

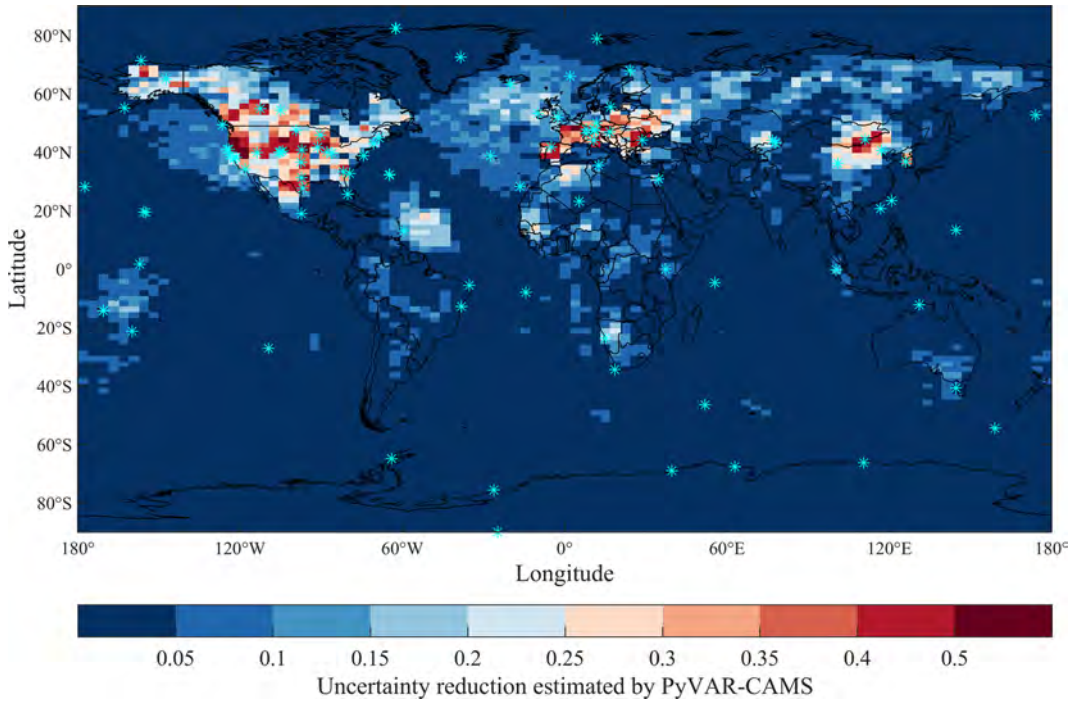

Figure 23. Uncertainty reduction (1 – sigma_posterior/sigma_prior) from the PyVAR-CAMS inversion framework. Asterisks (∗) represent atmospheric observational stations used in the inversion framework.

the atmospheric inversion estimates but not the uncertainty, as this depends on the spatiotemporal density of the atmospheric observations and the accuracy of the modeled transport. The uncertainty reduction (calculated as 1 minus the ratio of the posterior to prior uncertainty) indicates the degree of constraint on the inversion estimates (Fig. 23). It shows that the areas of South America, Africa, central and southern Asia, and Australasia are poorly constrained by observations. The relatively sparse distribution of current N_2O observation sites underscores the necessity of establishing more sites and regular aircraft profiles, especially in tropical and subtropical regions, to better constrain inversion models and to further reduce the posterior uncertainty.

6.2.6 Other missing fluxes

We recognize that N_2O emissions contributed by termites could be a significant natural source in tropical and subtropical ecosystems (Brümmer et al., 2009; Miambi et al., 2022). The metabolic activity of microbial symbionts in the termite gut can maintain steep oxygen gradients, which facilitates nitrification and denitrification processes and the production of N_2O (Brauman et al., 2015; Brune et al., 1995). Nevertheless, termites have a wide trophic diversity, and their N_2O emission rates vary significantly, with some species creating emission hotspots (Brümmer et al., 2009), while others function as net sinks (Majeed et al., 2012). Feeding habits and the abundance of nitrifiers and denitrifiers in the gut are reported to be the key factors determining net N_2O emission of termites (Brauman et al., 2015; Miambi et al., 2022). Termites that consume N-rich material, such as soil organic matter and fungi, exhibit high N_2O production rates and emit N_2O into the atmosphere, while those feeding on N-deficient wood can consume atmospheric N_2O (Brauman et al., 2015). It is difficult to scale up calculations of net N_2O emission by termites due to the lack of data on their abundance and biomass across global ecosystems; therefore, our understanding of the precise contribution of termites to the atmospheric N_2O budget on a global scale remains limited, and it is not considered in our analysis.

Appendix A: Additional tables

Table A1. Comparison of terminologies used in this study and previous reports.

GCP terminology (this study)		IPCC AR6 (IPCC, 2021)	National GHG inventories (used by UNFCCC according to IPCC, 2006, 2019)	UNFCCC/IPCC 2006 source sector
Anthropogenic sources				
Direct emissions of N additions in the agricultural sector (agriculture)	Direct soil emissions (mineral N and manure fertilization, cultivation of organic soils, and crop residue returns)	Agriculture	Direct N_2O emissions from managed soils (except due to grazing animals)	Part of 3C4
	Manure left on pasture		Urine and dung deposited by grazing animals	Part of 3C4
	Manure management		Manure management	2A2
	Aquaculture	–	–	–
Other direct anthropogenic sources	Fossil fuel and industry	Fossil fuel combustion and industrial processes	Energy and industrial processes	1, 2
	Waste and wastewater	Human excreta	Waste	4C1, 4C2 4D1, 4D2
	Biomass burning (from crop residue, grassland, shrubland and savannas, peat fires, tropical forests, boreal forests, and temperate forests)	Biomass and biofuel burning	Prescribed burning of savannas, field burning of agricultural residues	3E, 3F
Indirect emissions from anthropogenic N additions	Inland and coastal waters (rivers, lakes, reservoirs, estuaries, and coastal vegetation)	Rivers, estuaries, coastal vegetation	Indirect emissions due to leaching and runoff	Part of 3C5, 3C6
	Atmospheric N deposition on land	Atmospheric deposition on land	Indirect emissions due to atmospheric deposition (of agricultural as well as other anthropogenic compounds emitted)	Part of 3C5, 5A
	Atmospheric N deposition on ocean	Atmospheric deposition on ocean		Part of 3C5, 5A
Perturbed fluxes from climate, CO_2, and land cover change	CO_2 effect	–	–	–
	Climate effect	–	–	–
	Post-deforestation pulse effect	–	–	–
	Long-term effect of reduced mature forest area	–	–	–
Natural sources and sinks				
Natural soil baseline		Soils under natural vegetation	–	–
Coastal and open-ocean baseline		Oceans	–	–
Natural (rivers, lakes, reservoirs, estuaries, and coastal vegetation)		–	–	–
Lightning and atmospheric production		Lightning	–	–
		Atmospheric chemistry	–	–
Soil and wetland surface sink		Surface sink	–	–
Atmospheric sink		Atmospheric sink		

Table A2. List of the countries used to define the 18 regions.

Region no.	Region name	Countries or territories
1	USA	USA with Alaska and Bermuda Islands
2	Canada	Canada
3	Central America	Anguilla, Antigua and Barbuda, the Bahamas, Barbados, Belize, British Virgin Islands, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Nicaragua, Panama, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Turks and Caicos Islands, and the United States Virgin Islands
4	Brazil	Brazil
5	Northern South America	Aruba, Colombia, French Guiana, Grenada, Guyana, Suriname, Trinidad and Tobago, and Venezuela
6	Southwest South America	Argentina, Bolivia, Chile, Ecuador, Falkland Islands (Malvinas), Paraguay, Peru, and Uruguay
7	Europe	Albania, Andorra, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Channel Islands, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Hungary, Iceland, Ireland, Isle of Man, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Montenegro, the Netherlands, North Macedonia, Norway, Poland, Portugal, Republic of Moldova, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, and the United Kingdom
8	Northern Africa	Algeria, Cabo Verde, Chad, Cote d'Ivoire, Djibouti, Egypt, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Libya, Mali, Mauritania, Morocco, Niger, Saint Helena, Sao Tome and Principe, Senegal, Somalia, Republic of the Sudan, South Sudan, Tunisia, and Western Sahara
9	Equatorial Africa	Benin, Burkina Faso, Burundi, Cameroon, Central African Republic, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Ghana, Kenya, Liberia, Nigeria, Rwanda, Sierra Leone, Tanzania, Togo, and Uganda
10	Southern Africa	Angola, Botswana, Comoros, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Namibia, Reunión, Seychelles, South Africa, Zambia, and Zimbabwe
11	Russia	Russia
12	Central Asia	Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, and Uzbekistan
13	The Middle East	Armenia, Azerbaijan, Bahrain, Georgia, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Türkiye, United Arab Emirates, and Yemen
14	China	China mainland, Hong Kong SAR, Macao SAR, and Taiwan
15	Korea and Japan	Japan, North Korea, and South Korea
16	South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka
17	Southeast Asia	Brunei Darussalam, Cambodia, Cook Islands, Fiji, French Polynesia, Guam, Indonesia, Kiribati, Laos, Malaysia, Maldives, Marshall Islands, Myanmar, Nauru, New Caledonia, Niue, Norfolk Islands, Northern Mariana Islands, Pacific Islands Trust Territory, Palau, Papua New Guinea, Philippines, Pitcairn, Samoa, Singapore, Solomon Islands, Thailand, Timor-Leste, Tokelau, Tonga, Tuvalu, Vanuatu, Viet Nam, and Wallis and Futuna Islands
18	Australasia	Australia and New Zealand

Table A3. The sectors in the N_2O budget and its sources. (An asterisk denotes that a sector only includes the maximum, mean, and minimum.)

ID	N_2O budget sectors (global scale)	Sources
1	Aquaculture	EF0.5, EF5, and EF1.8
2	Manure left on pasture	DLEM, EDGAR, and FAO
3	Manure management	EDGAR
4	Direct soil emissions global	EDGAR, FAO, NMIP2/DLEM, and SRNM/DLEM
5	Inland water, estuaries, and coastal vegetation; anthropogenic	Meta-analysis and process-based models, EDGAR, and FAO
6	N deposition on land	NMIP2/EDGAR v7.0 and NMIP2
7	CO_2	CLASSIC, DLEM, ELM, ISAM, LPX-Bern, O-CN, ORCHIDEE, and VISIT
8	Climate	CLASSIC, DLEM, ELM, ISAM, LPX-Bern, O-CN, ORCHIDEE, and VISIT
9	Post-deforestation pulse effect	DLEM and bookkeeping model
10	Natural soil baseline	CLASSIC, DLEM, ELM, ISAM, LPX-Bern, O-CN, ORCHIDEE, and VISIT
11	Open ocean	BERN, CNRM, UViC, and UEA-NEMO-PlankTOM
12	N deposition on ocean*	Suntharalingam et al. (2012)
13	Biomass burning	FAO, DLEM, and GFED
14	Fossil fuel industry	EDGAR and EDGAR/UNFCCC
15	Waste and wastewater	EDGAR/UNFCCC
16	Inland water, estuaries, and coastal vegetation; natural*	DLEM, stochastic mechanistic model, RF model, and meta-analyses-based estimates
17	Lightning and atmospheric production*	Schlesinger (2013) and Syakila et al. (2010)
18	Long-term reduction effect	DLEM and bookkeeping model
19	Continental shelves*	ECCO, CNRM, and MEM-RF

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Table A4. Continued.

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Appendix B: Additional figures

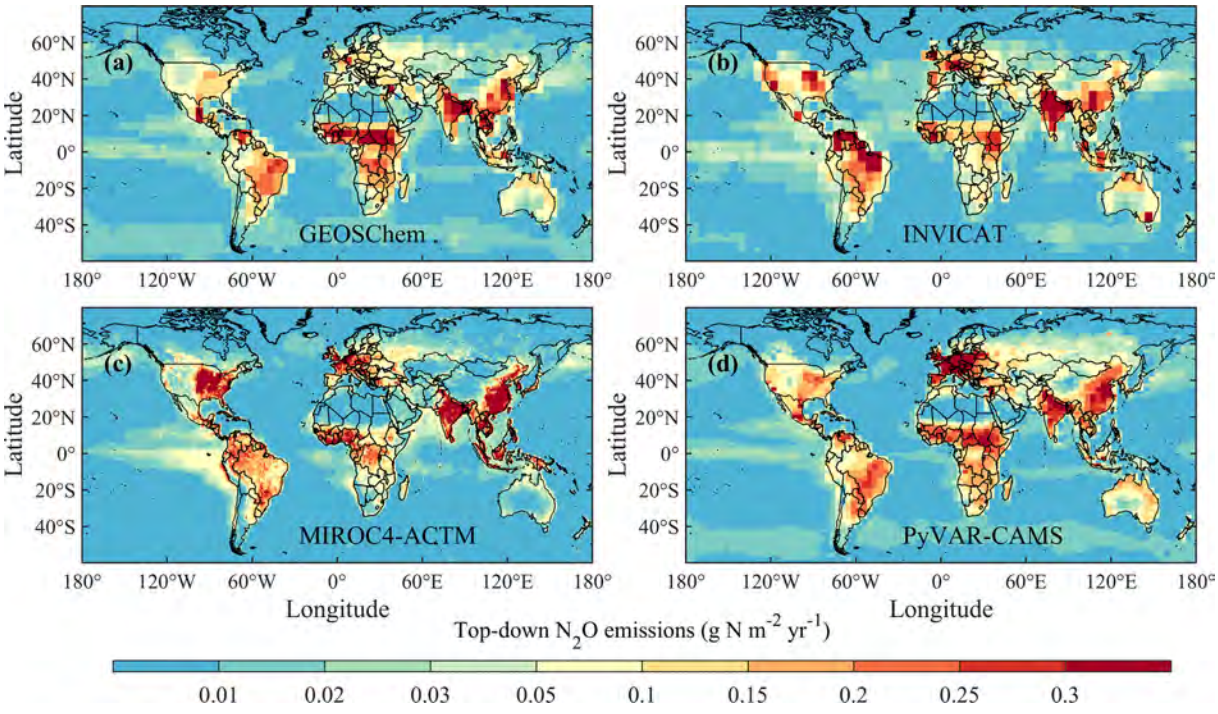

Figure B1. Spatial distribution of global N_2O emissions in the 2010s estimated by different atmospheric inversion frameworks (TD approach).

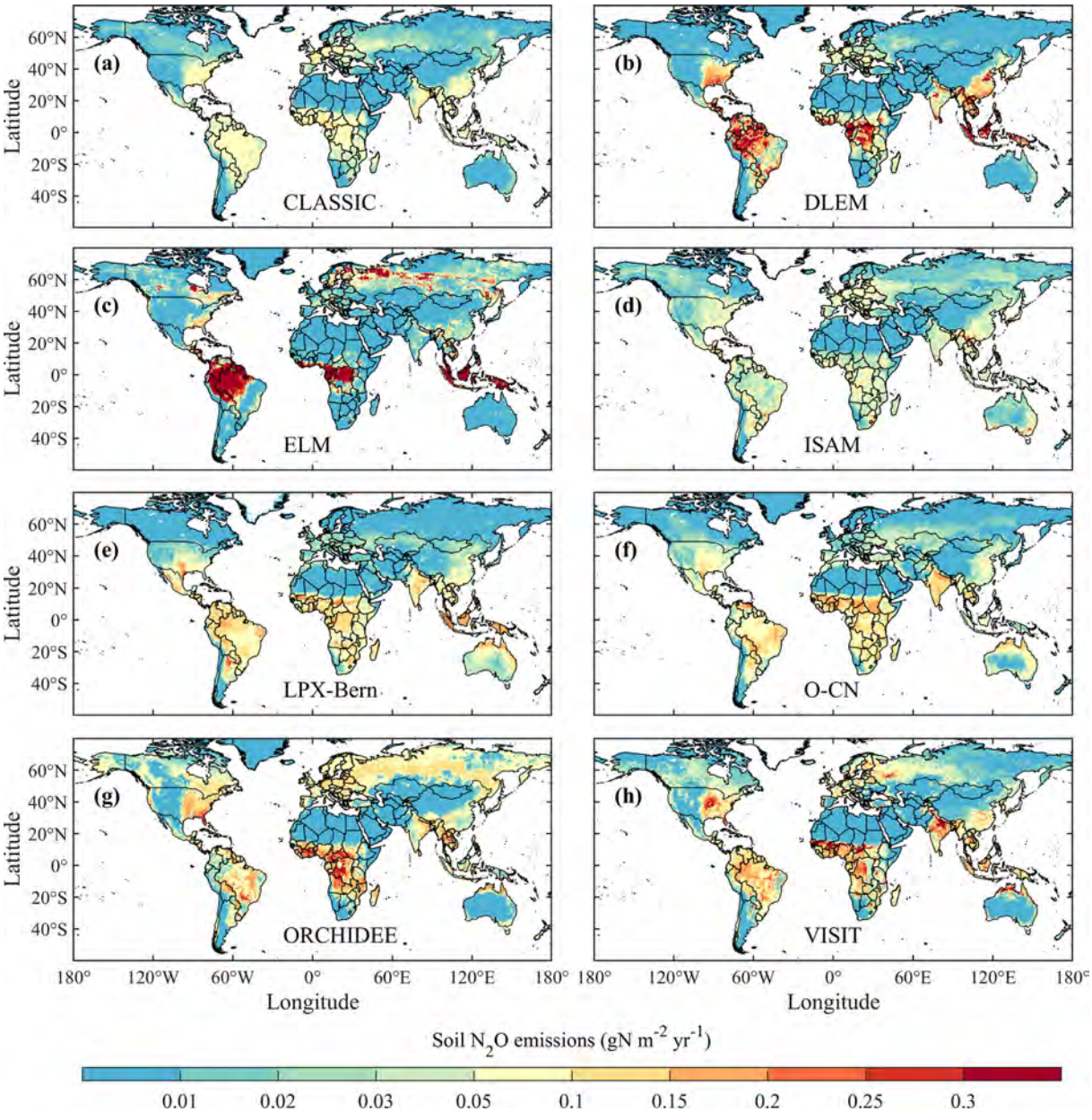

Figure B2. Spatial distribution of preindustrial (1850s) soil N_2O emissions estimated by different NMIP2 terrestrial biosphere models.

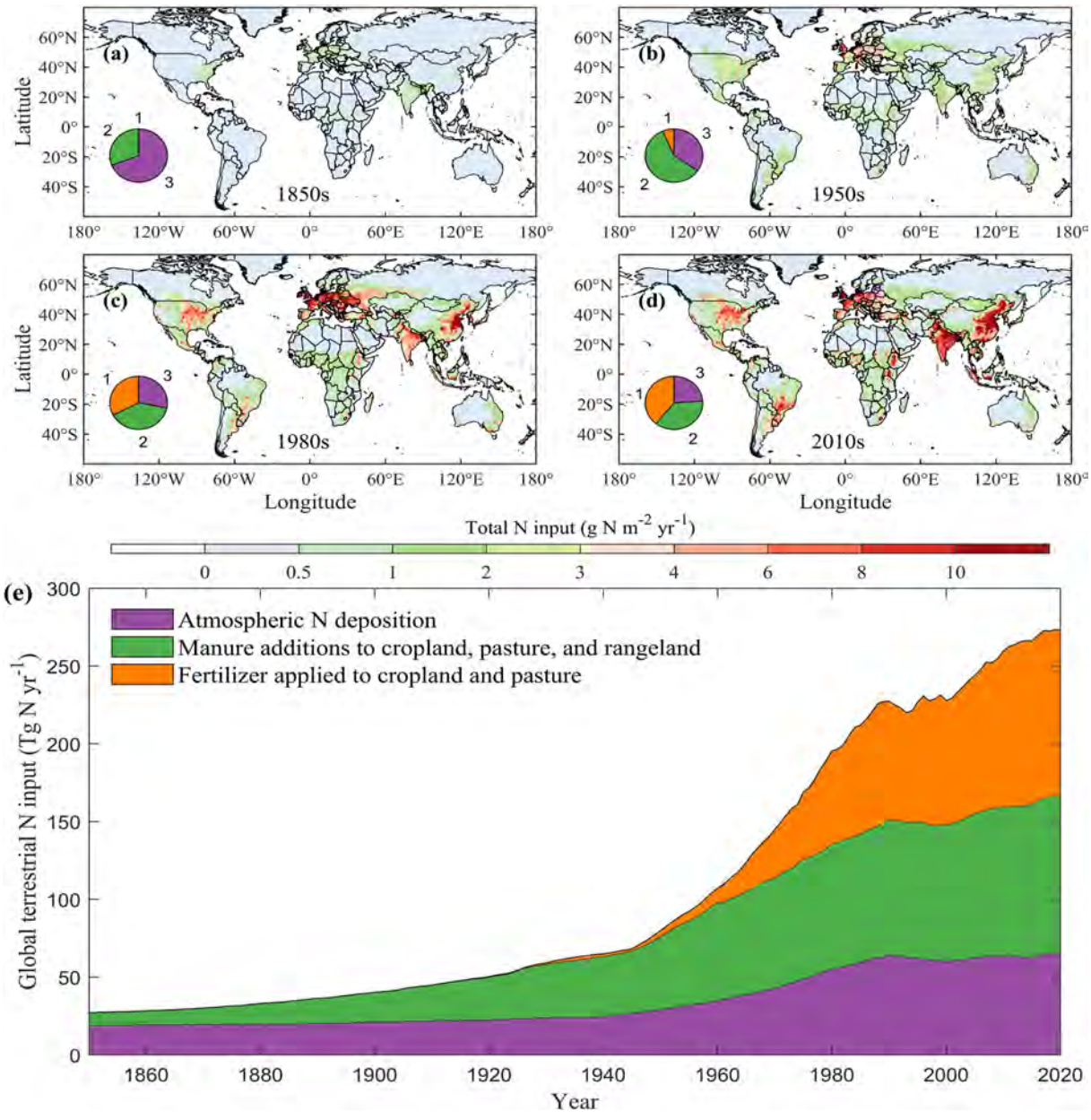

Figure B3. Spatial–temporal changes in fertilizer N and manure N applications as well as atmospheric N deposition to global terrestrial ecosystems derived from the HaNi dataset (Tian et al., 2022), which were used to drive NMIP2 terrestrial biosphere models.

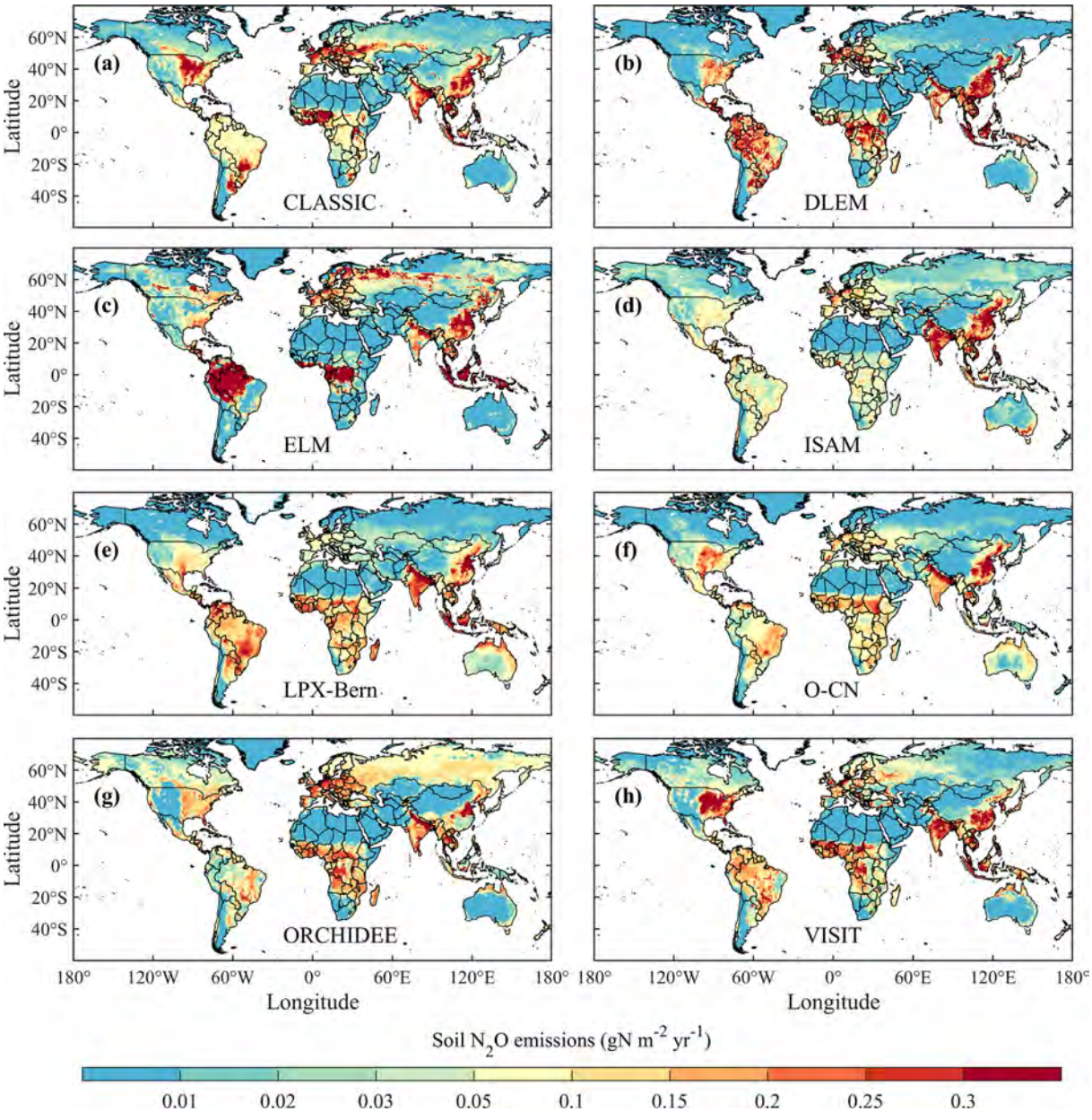

Figure B4. Spatial distribution of soil N_2O emissions during 2010–2019 estimated by NMIP2 terrestrial biosphere models.

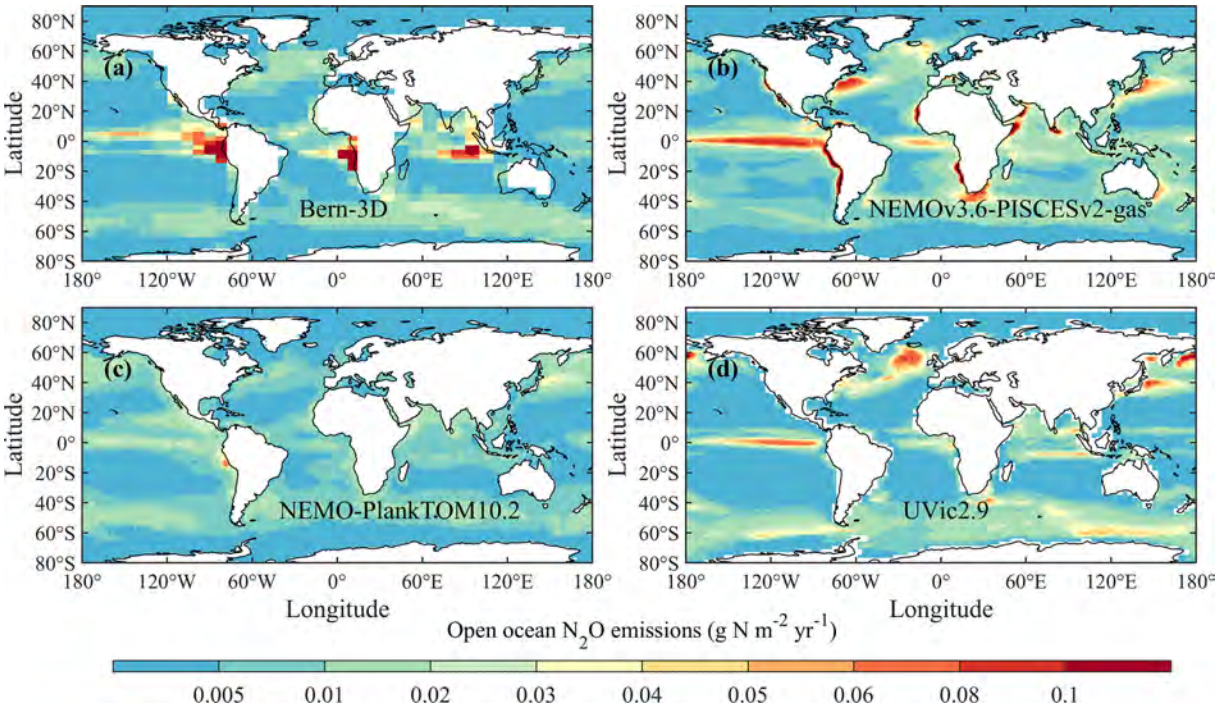

Figure B5. Spatial distribution of N_2O emissions from open oceans during 2010–2019 estimated by different ocean biogeochemistry models and Earth system models.

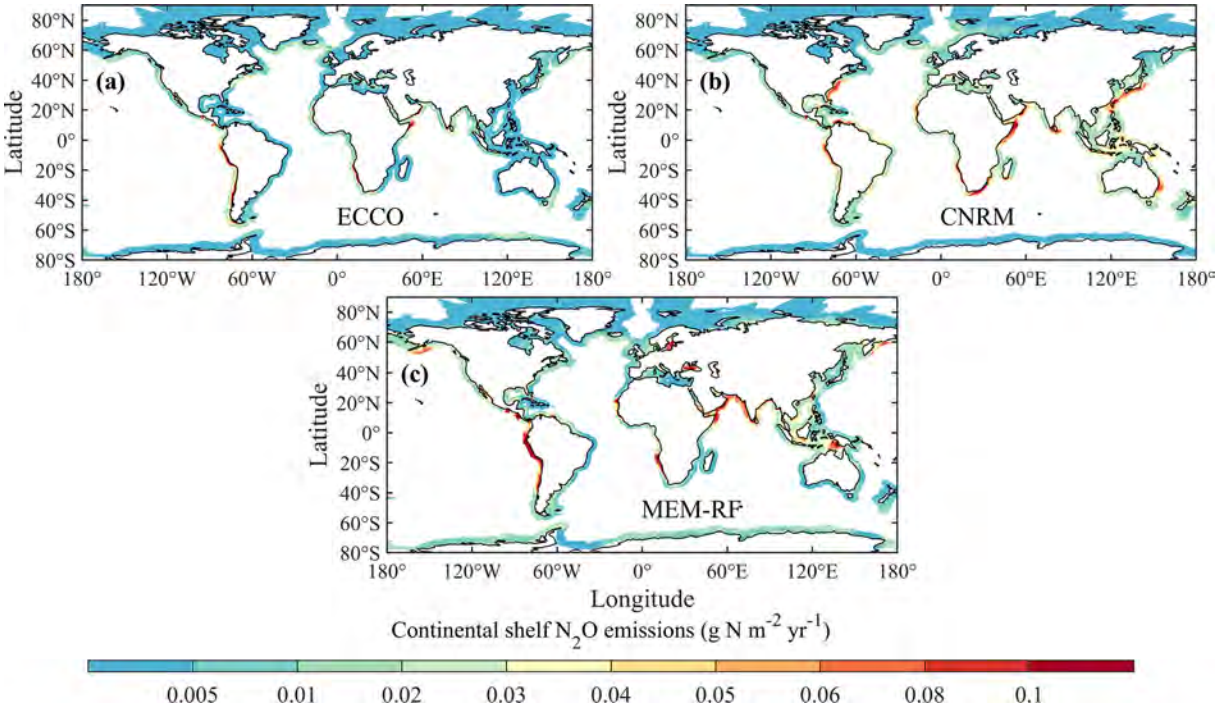

Figure B6. N_2O emission from continental shelves as estimated by three methods.

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Author contributions. HT, RLT, and JGC designed and coordinated the study. HT, NP, SP, YL, RLT, PS, and PR gathered the bottom-up and top-down datasets and performed the post-processing, analysis, and synthesis. HT, NP, RLT, JGC, PS, PR, EAD, MJP, PC, MM, SP, WW, SZ, FZ, and RBJ wrote the paper. RLT led atmospheric inversions, teaming with PKP, KCW, DBM, and CW; HT led land biosphere modeling, teaming with NP, SP, SZ, AI, AKJ, FJ, SKG, CL, HS, QS, and QZ; PS led ocean biogeochemical modeling, teaming with EB, AL, SB, AJT, and FJ; PR led the synthesis of LOAC (Land–Ocean Aquatic Continuum), teaming with RL, TM, YY, MH, PR, JR, LR, MM, SB, HB, DB, and HT; JW and LB provided the N_2O flux from aquaculture data. GRW and JY provided the N_2O emissions from biomass burning data. FZ provided cropland N_2O flux data from a statistical model and field observations. MM, FNT, and WW provided N_2O inventory data. MJP provided stratospheric and tropospheric sink data. GP provided RCP and SSP scenario data and analysis. XL and GD provided a global N_2O monitoring dataset of NOAA/ESRL GMD. JM and LMW provided a global N_2O monitoring dataset of AGAGE stations. PK provided a global N_2O monitoring dataset of CSIRO stations. All coauthors reviewed and commented on the manuscript.

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References

Arévalo-Martínez, D. L., Kock, A., Löscher, C. R., Schmitz, R. A., Stramma, L., and Bange, H. W.: Influence of mesoscale eddies on the distribution of nitrous oxide in the eastern tropical South Pacific, Biogeosciences, 13, 1105–1118, https://doi.org/10.5194/bg-13-1105-2016, 2016.

Arévalo-Martínez, D. L., Kock, A., Steinhoff, T., Brandt, P., Dengler, M., Fischer, T., Körtzinger, A., and Bange, H. W.: Nitrous oxide during the onset of the Atlantic cold tongue, J. Geophys. Res.-Oceans, 122, 171–184, https://doi.org/10.1002/2016JC012238, 2017.

Arévalo-Martínez, D. L., Steinhoff, T., Brandt, P., Körtzinger, A., Lamont, T., Rehder, G., and Bange, H. W.: N_2O Emissions From the Northern Benguela Upwelling System, Geophys. Res. Lett., 46, 3317–3326, https://doi.org/10.1029/2018GL081648, 2019.

Asaadi, A. and Arora, V. K.: Implementation of nitrogen cycle in the CLASSIC land model, Biogeosciences, 18, 669–706, https://doi.org/10.5194/bg-18-669-2021, 2021.

Aumont, O., Ethé, C., Tagliabue, A., Bopp, L., and Gehlen, M.: PISCES-v2: an ocean biogeochemical model for carbon and ecosystem studies, Geosci. Model Dev., 8, 2465–2513, https://doi.org/10.5194/gmd-8-2465-2015, 2015.

Babbin, A. R., Boles, E. L., Mühle, J., and Weiss, R. F.: On the natural spatio-temporal heterogeneity of South Pacific nitrous oxide, Nat. Commun., 11, 3672, https://doi.org/10.1038/s41467-020-17509-6, 2020.

Bange, H. W.: Non-CO_2 greenhouse gases (N_2O, CH_4, CO) and the ocean, One Earth, 5, 1316–1318, https://doi.org/10.1016/j.oneear.2022.11.011, 2022.

Bange, H. W., Arévalo-Martínez, D. L., de la Paz, M., Farías, L., Kaiser, J., Kock, A., Law, C. S., Rees, A. P., Rehder, G., Tortell, P. D., Upstill-Goddard, R. C., and Wilson, S. T.: A Harmonized Nitrous Oxide (N_2O) Ocean Observation Network for the 21st Century, Front. Mar. Sci., 6, 157, https://doi.org/10.3389/fmars.2019.00157, 2019.

Barthel, M., Bauters, M., Baumgartner, S., Drake, T. W., Bey, N. M., Bush, G., Boeckx, P., Botefa, C. I., Dériaz, N., Ekamba, G. L., Gallarotti, N., Mbayu, F. M., Mugula, J. K., Makelele, I. A., Mbongo, C. E., Mohn, J., Mandea, J. Z., Mpambi, D. M., Ntaboba, L. C., Rukeza, M. B., Spencer, R. G. M., Summerauer, L., Vanlauwe, B., Van Oost, K., Wolf, B., and Six, J.: Low N_2O and variable CH_4 fluxes from tropical forest soils of the Congo Basin, Nat. Commun., 13, 330, https://doi.org/10.1038/s41467-022-27978-6, 2022.

Battaglia, G. and Joos, F.: Marine N_2O Emissions From Nitrification and Denitrification Constrained by Modern Observations and Projected in Multimillennial Global Warming Simulations, Global Biogeochem. Cy., 32, 92–121, https://doi.org/10.1002/2017GB005671, 2018.

Berthet, S., Séférian, R., Bricaud, C., Chevallier, M., Voldoire, A., and Ethé, C.: Evaluation of an Online Grid-Coarsening Algorithm in a Global Eddy-Admitting Ocean Biogeochemical Model, J. Adv. Model. Earth Syst., 11, 1759–1783, https://doi.org/10.1029/2019MS001644, 2019.

Berthet, S., Jouanno, J., Séférian, R., Gehlen, M., and Llovel, W.: How does the phytoplankton–light feedback affect the marine N_2O inventory?, Earth Syst. Dynam., 14, 399–412, https://doi.org/10.5194/esd-14-399-2023, 2023.

Beusen, A. H. W., Bouwman, A. F., Van Beek, L. P. H., Mogollón, J. M., and Middelburg, J. J.: Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum, Biogeosciences, 13, 2441–2451, https://doi.org/10.5194/bg-13-2441-2016, 2016.

Bouwman, A. F., Pawłowski, M., Liu, C., Beusen, A. H. W., Shumway, S. E., Glibert, P. M., and Overbeek, C. C.: Global Hindcasts and Future Projections of Coastal Nitrogen and Phosphorus Loads Due to Shellfish and Seaweed Aquaculture, Rev. Fish. Sci., 19, 331–357, https://doi.org/10.1080/10641262.2011.603849, 2011.

Bouwman, A. F., Beusen, A. H. W., Overbeek, C. C., Bureau, D. P., Pawlowski, M., and Glibert, P. M.: Hindcasts and Future Projections of Global Inland and Coastal Nitrogen and Phosphorus Loads Due to Finfish Aquaculture, Rev. Fish. Sci., 21, 112–156, https://doi.org/10.1080/10641262.2013.790340, 2013a.

Bouwman, L., Daniel, J. S., Davidson, E. A., de Klein, C., Holland, E., Ju, X., Kanter, D., Oenema, O., Ravishankara, A. R., and Skiba, U. M.: Drawing down N_2O to protect climate and the ozone layer, A UNEP Synthesis Report, UNEP – United Nations Environment Programme, https://nora.nerc.ac.uk/id/eprint/505848 (last access: 5 April 2021), 2013b.

Brauman, A., Majeed, M. Z., Buatois, B., Robert, A., Pablo, A.-L., and Miambi, E.: Nitrous Oxide (N_2O) Emissions by Termites: Does the Feeding Guild Matter?, PLOS ONE, 10, e0144340, https://doi.org/10.1371/journal.pone.0144340, 2015.

Brümmer, C., Papen, H., Wassmann, R., and Brüggemann, N.: Termite mounds as hot spots of nitrous oxide emissions in South-Sudanian savanna of Burkina Faso (West Africa), Geophys. Res. Lett., 36, L09814 https://doi.org/10.1029/2009GL037351, 2009.

Brune, A., Emerson, D., and Breznak, J. A.: The termite gut microflora as an oxygen sink: microelectrode determination of oxygen and pH gradients in guts of lower and higher termites, Appl. Environ. Microbiol., 61, 2681–2687, 1995.

Buendia, E. C., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., and Federici, S.: Refinement To the 2006 Ipcc Guidelines for National Greenhouse Gas Inventories, IPCC, Geneva, Switzerland, https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/0_Overview/19R_V0_00_Cover_Foreword_Preface_Dedication.pdf (last access: 17 February 2020), 2019.

Buitenhuis, E. T., Suntharalingam, P., and Le Quéré, C.: Constraints on global oceanic emissions of N_2O from observations and models, Biogeosciences, 15, 2161–2175, https://doi.org/10.5194/bg-15-2161-2018, 2018.

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, Philos. T. Roy. Soc. B, 368, 20130122, https://doi.org/10.1098/rstb.2013.0122, 2013.

Canadell, J. G., Monteiro, P. M. S., Costa, M. H., Cunha, L. C. D., Cox, P. M., Eliseev, A. V., Henson, S., Ishii, M., Jaccard, S., Koven, C., Lohila, A., Patra, P. K., Piao, S., Syampungani, S., Zaehle, S., Zickfeld, K., Alexandrov, G. A., Bala, G., Bopp, L., Boysen, L., Cao, L., Chandra, N., Ciais, P., Denisov, S. N., Dentener, F. J., Douville, H., Fay, A., Forster, P., Fox-Kemper, B., Friedlingstein, P., Fu, W., Fuss, S., Garçon, V., Gier, B., Gillett, N. P., Gregor, L., Haustein, K., Haverd, V., He, J., Hewitt, H. T., Hoffman, F. M., Ilyina, T., Jackson, R., Jones, C., Keller, D. P., Kwiatkowski, L., Lamboll, R. D., Lan, X., Laufkötter, C., Quéré, C. L., Lenton, A., Lewis, J., Liddicoat, S., Lorenzoni, L., Lovenduski, N., Macdougall, A. H., Mathesius, S., Matthews, D. H., Meinshausen, M., Mokhov, I. I., Naik, V., Nicholls, Z. R. J., Nurhati, I. S., O'sullivan, M., Peters, G., Pongratz, J., Poulter, B., Sallée, J.-B., Saunois, M., Schuur, E. A. G., I. Seneviratne, S., Stavert, A., Suntharalingam, P., Tachiiri, K., Terhaar, J., Thompson, R., Tian, H., Turnbull, J., Vicente-Serrano, S. M., Wang, X., Wanninkhof, R. H., Williamson, P., Brovkin, V., Feely, R. A., and Lebehot, A. D.: Global Carbon and other Biogeochemical Cycles and Feedbacks, chap. 5, https://hal.science/hal-03336145 (last access: 25 June 2022), 2021.

Carroll, D., Menemenlis, D., Adkins, J. F., Bowman, K. W., Brix, H., Dutkiewicz, S., Fenty, I., Gierach, M. M., Hill, C., Jahn, O., Landschützer, P., Lauderdale, J. M., Liu, J., Manizza, M., Naviaux, J. D., Rödenbeck, C., Schimel, D. S., Van der Stocken, T., and Zhang, H.: The ECCO-Darwin Data-Assimilative Global Ocean Biogeochemistry Model: Estimates of Seasonal to Multidecadal Surface Ocean pCO_2 and Air-Sea CO_2 Flux, J. Adv. Model. Earth Syst., 12, e2019MS001888, https://doi.org/10.1029/2019MS001888, 2020.

Conchedda, G. and Tubiello, F. N.: Drainage of organic soils and GHG emissions: validation with country data, Earth Syst. Sci. Data, 12, 3113–3137, https://doi.org/10.5194/essd-12-3113-2020, 2020.

Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Banja, M., Olivier, J., Grassi, G., and Rossi, S.: GHG emissions of all world countries, Publications Office of the European Union, https://publications.jrc.ec.europa.eu/repository/handle/JRC126363 (last access: 12 October 2022), 2021.

Cui, X., Zhou, F., Ciais, P., Davidson, E. A., Tubiello, F. N., Niu, X., Ju, X., Canadell, J. G., Bouwman, A. F., and Jackson, R. B.: Global mapping of crop-specific emission factors highlights hotspots of nitrous oxide mitigation, Nat. Food, 2, 886–893, 2021.

Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., Zhang, W., Mi, G., Miao, Y., and Li, X.: Pursuing sustainable productivity with millions of smallholder farmers, Nature, 555, 363–366, 2018.

Dangal, S. R., Tian, H., Xu, R., Chang, J., Canadell, J. G., Ciais, P., Pan, S., Yang, J., and Zhang, B.: Global nitrous oxide emissions from pasturelands and rangelands: magnitude, spatiotemporal patterns, and attribution, Global Biogeochem. Cy., 33, 200–222, 2019.

Davidson, E. A.: The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860, Nat. Geosci., 2, 659–662, 2009.

Davidson, E. A. and Artaxo, P.: Globally significant changes in biological processes of the Amazon Basin: results of the Large-scale Biosphere–Atmosphere Experiment, Global Change Biol., 10, 519–529, 2004.

Davidson, E. A. and Kanter, D.: Inventories and scenarios of nitrous oxide emissions, Environ. Res. Lett., 9, 105012, https://doi.org/10.1088/1748-9326/9/10/105012, 2014.

Davidson, E. A. and Winiwarter, W.: Urgent abatement of industrial sources of nitrous oxide, Nat. Clim. Change, 13, 599–601, https://doi.org/10.1038/s41558-023-01723-3, 2023.

Davidson, E. A., de Carvalho, C. J. R., Figueira, A. M., Ishida, F. Y., Ometto, J. P. H. B., Nardoto, G. B., Sabá, R. T., Hayashi, S. N., Leal, E. C., Vieira, I. C. G., and Martinelli, L. A.: Recuperation of nitrogen cycling in Amazonian forests following agricultural abandonment, Nature, 447, 995–998, https://doi.org/10.1038/nature05900, 2007.

De Klein, C. A. M., Smith, L. C., and Monaghan, R. M.: Restricted autumn grazing to reduce nitrous oxide emissions from dairy pastures in Southland, New Zealand, Agr. Ecosyst. Environ., 112, 192–199, 2006.

Del Grosso, S. J., Ogle, S. M., Nevison, C., Gurung, R., Parton, W. J., Wagner-Riddle, C., Smith, W., Winiwarter, W., Grant, B., and Tenuta, M.: A gap in nitrous oxide emission reporting complicates long-term climate mitigation, P. Natl. Acad. Sci. USA, 119, e2200354119, https://doi.org/10.1073/pnas.220035411, 2022.

Denman, K. L., Brasseur, G. P., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D. A., Heinze, C., Holland, E. A., and Jacob, D. J.: Couplings Between Changes in the Climate System and Biogeochemistry, in: Climate Change 2007: The Physical Science Basis, Cambridge University Press, ISBN 978-0521-70596-7, 2007.

Dentener, F. J. and Crutzen, P. J.: A three-dimensional model of the global ammonia cycle, J. Atmos. Chem., 19, 331–369, https://doi.org/10.1007/BF00694492, 1994.

Dijkstra, F. A., Prior, S. A., Runion, G. B., Torbert, H. A., Tian, H., Lu, C., and Venterea, R. T.: Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: evidence from field experiments, Front. Ecol. Environ., 10, 520–527, 2012.

Dlugokencky, E. J., Steele, L. P., Lang, P. M., and Masarie, K. A.: The growth rate and distribution of atmospheric methane, J. Geophys. Res.-Atmos., 99, 17021–17043, 1994.

Dutton, G. S., Hall, B. D., Dlugokencky, E. J., Lan, X., Nance, J. D., and Madronich, M.: Combined Atmospheric Nitrous Oxide Dry Air Mole Fractions from the NOAA GML Halocarbons Sampling Network, 1977–2023, Version: 2023-04-13, NOAA, https://doi.org/10.15138/GMZ7-2Q16, 2023.

Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K.: 2006 IPCC guidelines for national greenhouse gas inventories, http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm (last access: 2 January 2023), 2006.

Estupiñán, E. G., Nicovich, J. M., Li, J., Cunnold, D. M., and Wine, P. H.: Investigation of N_2O Production from 266 and 532 nm Laser Flash Photolysis of $O_3/N_2/O_2$ Mixtures, J. Phys. Chem. A, 106, 5880–5890, https://doi.org/10.1021/jp014242c, 2002.

Firestone, M. K. and Davidson, E. A.: Microbiological basis of NO and N_2O production and consumption in soil, in: Exchange of trace gases between terrestrial ecosystems and the atmosphere, edited by: Andreae, M. O. and Schimel, D. S., John Wiley & Sons, New York, 7–21, ISBN 978-0-471-92551-4, 1989.

Fischer, H., Schmitt, J., Bock, M., Seth, B., Joos, F., Spahni, R., Lienert, S., Battaglia, G., Stocker, B. D., Schilt, A., and Brook, E. J.: N_2O changes from the Last Glacial Maximum to the preindustrial – Part 1: Quantitative reconstruction of terrestrial and marine emissions using N_2O stable isotopes in ice cores, Biogeosciences, 16, 3997–4021, https://doi.org/10.5194/bg-16-3997-2019, 2019.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D. J., Mauritsen, T., Palmer, M. D., Watanabe, M., Wild, M., and Zhang, H.: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity, in: Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Pèan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, UK and New York, NY, USA, 923–1054, https://doi.org/10.1017/9781009157896.009, 2021.

Francey, R. J., Steele, L. P., Spencer, D. A., Langenfelds, R. L., Law, R. M., Krummel, P. B., Fraser, P. J., Etheridge, D. M., Derek, N., and Coram, S. A.: The CSIRO (Australia) measurement of greenhouse gases in the global atmosphere, Baseline Atmospheric Program Australia, edited by: Tindale, N. W., Derek, N., and Fraser, P. J., Bureau of Meteorology and CSIRO Atmospheric Research, Melbourne, 42–53, 2003.

Galloway, J. N., Bleeker, A., and Erisman, J. W.: The human creation and use of reactive nitrogen: a global and regional perspective, Annu. Rev. Environ. Resour., 46, 255–288, 2021.

Ganesan, A. L., Manizza, M., Morgan, E. J., Harth, C. M., Kozlova, E., Lueker, T., Manning, A. J., Lunt, M. F., Mühle, J., Lavric, J. V., Heimann, M., Weiss, R. F., and Rigby, M.: Marine Nitrous Oxide Emissions From Three Eastern Boundary Upwelling Systems Inferred From Atmospheric Observations, Geophys. Res. Lett., 47, e2020GL087822, https://doi.org/10.1029/2020GL087822, 2020.

Gerber, J. S., Carlson, K. M., Makowski, D., Mueller, N. D., Garcia de Cortazar-Atauri, I., Havlík, P., Herrero, M., Launay, M., O'Connell, C. S., and Smith, P.: Spatially explicit estimates of N_2O emissions from croplands suggest climate mitigation opportunities from improved fertilizer management, Global Change Biol., 22, 3383–3394, 2016.

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L.,

Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., and Takahashi, K.: Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, Geosci. Model Dev., 12, 1443–1475, https://doi.org/10.5194/gmd-12-1443-2019, 2019.

Goll, D. S., Vuichard, N., Maignan, F., Jornet-Puig, A., Sardans, J., Violette, A., Peng, S., Sun, Y., Kvakic, M., Guimberteau, M., Guenet, B., Zaehle, S., Penuelas, J., Janssens, I., and Ciais, P.: A representation of the phosphorus cycle for ORCHIDEE (revision 4520), Geosci. Model Dev., 10, 3745–3770, https://doi.org/10.5194/gmd-10-3745-2017, 2017.

Griffis, T. J., Chen, Z., Baker, J. M., Wood, J. D., Millet, D. B., Lee, X., Venterea, R. T., and Turner, P. A.: Nitrous oxide emissions are enhanced in a warmer and wetter world, P. Natl. Acad. Sci. USA, 114, 12081–12085, https://doi.org/10.1073/pnas.1704552114, 2017.

Gruber, N.: The ocean carbon sink-recent highlights and challenges, in: IOC Carbon Meeting, Integrated Ocean Carbon Research workshop, http://hdl.handle.net/20.500.11850/595969 (last access: 8 December 2022), 2022.

Gruber, N. and Galloway, J. N.: An Earth-system perspective of the global nitrogen cycle, Nature, 451, 293–296, https://doi.org/10.1038/nature06592, 2008.

Grundle, D. S., Löscher, C. R., Krahmann, G., Altabet, M. A., Bange, H. W., Karstensen, J., Körtzinger, A., and Fiedler, B.: Low oxygen eddies in the eastern tropical North Atlantic: Implications for N_2O cycling, Sci. Rep., 7, 4806, https://doi.org/10.1038/s41598-017-04745-y, 2017.

Gurney, K. R., Law, R. M., Denning, A. S., Rayner, P. J., Pak, B. C., Baker, D., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fung, I. Y., Heimann, M., John, J., Maki, T., Maksyutov, S., Peylin, P., Prather, M., and Taguchi, S.: Transcom 3 inversion intercomparison: Model mean results for the estimation of seasonal carbon sources and sinks, Global Biogeochem. Cy., 18, GB1010, https://doi.org/10.1029/2003GB002111, 2004.

Hall, B. D., Dutton, G. S., and Elkins, J. W.: The NOAA nitrous oxide standard scale for atmospheric observations, J. Geophys. Res.-Atmos., 112, D09305, https://doi.org/10.1029/2006JD007954, 2007.

Harris, E., Yu, L., Wang, Y.-P., Mohn, J., Henne, S., Bai, E., Barthel, M., Bauters, M., Boeckx, P., Dorich, C., Farrell, M., Krummel, P. B., Loh, Z. M., Reichstein, M., Six, J., Steinbacher, M., Wells, N. S., Bahn, M., and Rayner, P.: Warming and redistribution of nitrogen inputs drive an increase in terrestrial nitrous oxide emission factor, Nat. Commun., 13, 4310, https://doi.org/10.1038/s41467-022-32001-z, 2022.

Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y. A. R., Dentener, F. J., Dlugokencky, E. J., Easterling, D. R., Kaplan, A., Soden, B. J., Thorne, P. W., Wild, M., and Zhai, P.: Observations: Atmosphere and surface, in: Climate Change 2013 the Physical Science Basis, vol. 9781107057999, Cambridge University Press, 159–254, https://doi.org/10.1017/CBO9781107415324.008, 2013.

Houghton, R. A. and Castanho, A.: Annual emissions of carbon from land use, land-use change, and forestry from 1850 to 2020, Earth Syst. Sci. Data, 15, 2025–2054, https://doi.org/10.5194/essd-15-2025-2023, 2023.

Houghton, R. A., Hobbie, J. E., Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R., and Woodwell, G. M.: Changes in the Carbon Content of Terrestrial Biota and Soils between 1860 and 1980: A Net Release of CO_2 to the Atmosphere, Ecol. Monogr., 53, 235–262, https://doi.org/10.2307/1942531, 1983.

Hu, M., Chen, D., and Dahlgren, R. A.: Modeling nitrous oxide emission from rivers: a global assessment, Global Change Biol., 22, 3566–3582, https://doi.org/10.1111/gcb.13351, 2016.

Hu, Z., Lee, J. W., Chandran, K., Kim, S., and Khanal, S. K.: Nitrous oxide (N_2O) emission from aquaculture: a review, Environ. Sci. Technol., 46, 6470–6480, 2012.

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krisztin, T., Lawrence, D., Lawrence, P., Ma, L., Mertz, O., Pongratz, J., Popp, A., Poulter, B., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., Tubiello, F. N., van Vuuren, D. P., and Zhang, X.: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, Geosci. Model Dev., 13, 5425–5464, https://doi.org/10.5194/gmd-13-5425-2020, 2020.

IPCC: Guidelines for national greenhouse gas inventories, Prepared by the National Greenhouse Gas Inventories Programme, edited by: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Japan, http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm (last access: 8 May 2020), 2006.

IPCC: Climate Change 2021: The Physical Science Basis, in: Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp., https://doi.org/10.1017/9781009157896, 2021.

Ito, A., Nishina, K., Ishijima, K., Hashimoto, S., and Inatomi, M.: Emissions of nitrous oxide (N_2O) from soil surfaces and their historical changes in East Asia: a model-based assessment, Prog. Earth Planet. Sci., 5, 55, https://doi.org/10.1186/s40645-018-0215-4, 2018.

Jackson, R. B., Solomon, E. I., Canadell, J. G., Cargnello, M., and Field, C. B.: Methane removal and atmospheric restoration, Nat. Sustainabil., 2, 436–438, 2019.

Ji, Q., Buitenhuis, E., Suntharalingam, P., Sarmiento, J. L., and Ward, B. B.: Global Nitrous Oxide Production Determined by Oxygen Sensitivity of Nitrification and Denitrification, Global Biogeochem. Cy., 32, 1790–1802, https://doi.org/10.1029/2018GB005887, 2018.

Joos, F. and Spahni, R.: Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years, P. Natl. Acad. Sci. USA, 105, 1425–1430, https://doi.org/10.1073/pnas.0707386105, 2008.

Joos, F., Spahni, R., Stocker, B. D., Lienert, S., Müller, J., Fischer, H., Schmitt, J., Prentice, I. C., Otto-Bliesner, B., and Liu, Z.: N_2O changes from the Last Glacial Maximum to the preindustrial – Part 2: terrestrial N_2O emissions and carbon–nitrogen cycle interactions, Biogeosciences, 17, 3511–3543, https://doi.org/10.5194/bg-17-3511-2020, 2020.

Keller, M. and Reiners, W. A.: Soil-atmosphere exchange of nitrous oxide, nitric oxide, and methane under secondary succession of pasture to forest in the Atlantic lowlands of Costa Rica, Global Biogeochem. Cy., 8, 399–409, https://doi.org/10.1029/94GB01660, 1994.

Kock, A. and Bange, H. W.: Counting the ocean's greenhouse gas emissions, Eos: Earth Space Sci. News, 96, 10–13, 2015.

Kock, A., Schafstall, J., Dengler, M., Brandt, P., and Bange, H. W.: Sea-to-air and diapycnal nitrous oxide fluxes in the eastern tropical North Atlantic Ocean, Biogeosciences, 9, 957–964, https://doi.org/10.5194/bg-9-957-2012, 2012.

Kohlmann, J.-P. and Poppe, D.: The Tropospheric Gas-Phase Degradation of NH_3 and Its Impact on the Formation of N_2O and NO_x, J. Atmos. Chem., 32, 397–415, https://doi.org/10.1023/A:1006162910279, 1999.

Kou-Giesbrecht, S. and Arora, V. K.: Representing the Dynamic Response of Vegetation to Nitrogen Limitation via Biological Nitrogen Fixation in the CLASSIC Land Model, Global Biogeochem. Cy., 36, e2022GB007341, https://doi.org/10.1029/2022GB007341, 2022.

Kroeze, C., Mosier, A., and Bouwman, L.: Closing the global N_2O budget: A retrospective analysis 1500–1994, Global Biogeochem. Cy., 13, 1–8, https://doi.org/10.1029/1998GB900020, 1999.

Kuypers, M. M. M., Marchant, H. K., and Kartal, B.: The microbial nitrogen-cycling network, Nat. Rev. Microbiol., 16, 263–276, https://doi.org/10.1038/nrmicro.2018.9, 2018.

Lan, X., Dlugokencky, E. J., Mund, J. W., Crotwell, A. M., Crotwell, M. J., Moglia, E., Madronich, M., Neff, D., and Thoning, K. W.: Atmospheric Nitrous Oxide Dry Air Mole Fractions from the NOAA GML Carbon Cycle Cooperative Global Air Sampling Network, 1997–2021, Version: 2022-11-21, NOAA, https://doi.org/10.15138/53g1-x417, 2022.

Landolfi, A., Somes, C. J., Koeve, W., Zamora, L. M., and Oschlies, A.: Oceanic nitrogen cycling and N_2O flux perturbations in the Anthropocene, Global Biogeochem. Cy., 31, 1236–1255, https://doi.org/10.1002/2017GB005633, 2017.

Laruelle, G. G., Dürr, H. H., Lauerwald, R., Hartmann, J., Slomp, C. P., Goossens, N., and Regnier, P. a. G.: Global multi-scale segmentation of continental and coastal waters from the watersheds to the continental margins, Hydrol. Earth Syst. Sci., 17, 2029–2051, https://doi.org/10.5194/hess-17-2029-2013, 2013.

Lauerwald, R., Regnier, P., Figueiredo, V., Enrich-Prast, A., Bastviken, D., Lehner, B., Maavara, T., and Raymond, P.: Natural Lakes Are a Minor Global Source of N_2O to the Atmosphere, Global Biogeochem. Cy., 33, 1564–1581, https://doi.org/10.1029/2019GB006261, 2019.

Li, L., Zheng, Z., Wang, W., Biederman, J. A., Xu, X., Ran, Q., Qian, R., Xu, C., Zhang, B., Wang, F., Zhou, S., Cui, L., Che, R., Hao, Y., Cui, X., Xu, Z., and Wang, Y.: Terrestrial N_2O emissions and related functional genes under climate change: A global meta-analysis, Global Change Biol., 26, 931–943, https://doi.org/10.1111/gcb.14847, 2020.

Li, Y., Tian, H., Yao, Y., Shi, H., Bian, Z., Shi, Y., Wang, S., Maavara, T., Lauerwald, R., and Pan, S.: Increased nitrous oxide emissions from global lakes and reservoirs since the pre-industrial era, Nat. Commun., 15, 942, https://doi.org/10.1038/s41467-024-45061-0, 2024.

Lienert, S. and Joos, F.: A Bayesian ensemble data assimilation to constrain model parameters and land-use carbon emissions, Biogeosciences, 2909–2930, https://doi.org/10.5194/bg-15-2909-2018, 2018.

Lu, C., Yu, Z., Zhang, J., Cao, P., Tian, H., and Nevison, C.: Century-long changes and drivers of soil nitrous oxide (N_2O) emissions across the contiguous United States, Global Change Biol., 28, 2505–2524, https://doi.org/10.1111/gcb.16061, 2022.

Maavara, T., Lauerwald, R., Laruelle, G. G., Akbarzadeh, Z., Bouskill, N. J., Van Cappellen, P., and Regnier, P.: Nitrous oxide emissions from inland waters: Are IPCC estimates too high?, Global Change Biol., 25, 473–488, https://doi.org/10.1111/gcb.14504, 2019.

MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A., and Elkins, J.: Law Dome CO_2, CH_4 and N_2O ice core records extended to 2000 years BP, Geophys. Res. Lett., 33, L14810, https://doi.org/10.1029/2006GL026152, 2006.

MacLeod, M., Hasan, M. R., Robb, D. H., and Mamun-Ur-Rashid, M.: Quantifying and mitigating greenhouse gas emissions from global aquaculture, Food and Agriculture Organization of the United Nations, http://www.fao.org/documents/card/en/c/ca7130en (last access: 15 November 2022), 2019.

Majeed, M. Z., Miambi, E., Robert, A., Bernoux, M., and Brauman, A.: Xylophagous termites: A potential sink for atmospheric nitrous oxide, Eur. J. Soil Biol., 53, 121–125, https://doi.org/10.1016/j.ejsobi.2012.10.002, 2012.

Martinez-Rey, J., Bopp, L., Gehlen, M., Tagliabue, A., and Gruber, N.: Projections of oceanic N_2O emissions in the 21st century using the IPSL Earth system model, Biogeosciences, 12, 4133–4148, https://doi.org/10.5194/bg-12-4133-2015, 2015.

Marushchak, M. E., Pitkämäki, A., Koponen, H., Biasi, C., Seppälä, M., and Martikainen, P. J.: Hot spots for nitrous oxide emissions found in different types of permafrost peatlands, Global Change Biol., 17, 2601–2614, https://doi.org/10.1111/j.1365-2486.2011.02442.x, 2011.

Marushchak, M. E., Kerttula, J., Diáková, K., Faguet, A., Gil, J., Grosse, G., Knoblauch, C., Lashchinskiy, N., Martikainen, P. J., Morgenstern, A., Nykamb, M., Ronkainen, J. G., Siljanen, H. M. P., van Delden, L., Voigt, C., Zimov, N., Zimov, S., and Biasi, C.: Thawing Yedoma permafrost is a neglected nitrous oxide source, Nat. Commun., 12, 7107, https://doi.org/10.1038/s41467-021-27386-2, 2021.

Marzadri, A., Amatulli, G., Tonina, D., Bellin, A., Shen, L. Q., Allen, G. H., and Raymond, P. A.: Global riverine nitrous oxide emissions: The role of small streams and large rivers, Sci. Total Environ., 776, 145148, https://doi.org/10.1016/j.scitotenv.2021.145148, 2021.

Marzadri, A., Bellin, A., Tank, J. L., and Tonina, D.: Predicting nitrous oxide emissions through riverine networks, Sci. Total Environ., 843, 156844, https://doi.org/10.1016/j.scitotenv.2022.156844, 2022.

McGuire, A. D., Sitch, S., Clein, J. S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D. W., Meier, R. A., Melillo, J. M., Moore III, B., Prentice, I. C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L. J., and Wittenberg, U.: Carbon balance of the terrestrial biosphere in the Twentieth Century: Analyses of CO_2, climate and land use effects with four process-based

ecosystem models, Global Biogeochem. Cy., 15, 183–206, https://doi.org/10.1029/2000GB001298, 2001.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A., Velders, G. J. M., and van Vuuren, D. P. P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Climatic Change, 109, 213, https://doi.org/10.1007/s10584-011-0156-z, 2011.

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., Smith, S. J., van den Berg, M., Velders, G. J. M., Vollmer, M. K., and Wang, R. H. J.: The shared socioeconomic pathway (SSP) greenhouse gas concentrations and their extensions to 2500, Geosci. Model Dev., 13, 3571–3605, https://doi.org/10.5194/gmd-13-3571-2020, 2020.

Melillo, J. M., Steudler, P. A., Feigl, B. J., Neill, C., Garcia, D., Piccolo, M. C., Cerri, C. C., and Tian, H.: Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon, J. Geophys. Res.-Atmos., 106, 34179–34188, https://doi.org/10.1029/2000JD000036, 2001.

Melton, J. R., Arora, V. K., Wisernig-Cojoc, E., Seiler, C., Fortier, M., Chan, E., and Teckentrup, L.: CLASSIC v1.0: the open-source community successor to the Canadian Land Surface Scheme (CLASS) and the Canadian Terrestrial Ecosystem Model (CTEM) – Part 1: Model framework and site-level performance, Geosci. Model Dev., 13, 2825–2850, https://doi.org/10.5194/gmd-13-2825-2020, 2020.

Meurer, K. H. E., Franko, U., Stange, C. F., Rosa, J. D., Madari, B. E., and Jungkunst, H. F.: Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil – a critical review, Environ. Res. Lett., 11, 023001, https://doi.org/10.1088/1748-9326/11/2/023001, 2016.

Miambi, E., Jusselme, T. M. D., des Châtelliers, C. C., Robert, A., Delort, A., and Le Roux, X.: Potential gross and net N_2O production by the gut of different termite species are related to the abundance of nitrifier and denitrifier groups, Front. Microbiom., 1, 1017006, https://doi.org/10.3389/frmbi.2022.1017006, 2022.

Minschwaner, K., Carver, R. W., Briegleb, B. P., and Roche, A. E.: Infrared radiative forcing and atmospheric lifetimes of trace species based on observations from UARS, J. Geophys. Res.-Atmos., 103, 23243–23253, https://doi.org/10.1029/98JD02116, 1998.

Moser, G., Gorenflo, A., Brenzinger, K., Keidel, L., Braker, G., Marhan, S., Clough, T. J., and Müller, C.: Explaining the doubling of N_2O emissions under elevated CO_2 in the Giessen FACE via in-field ^{15}N tracing, Global Change Biol., 24, 3897–3910, https://doi.org/10.1111/gcb.14136, 2018.

Myhre, G., Samset, B. H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T. K., Bian, H., Bellouin, N., Chin, M., Diehl, T., Easter, R. C., Feichter, J., Ghan, S. J., Hauglustaine, D., Iversen, T., Kinne, S., Kirkevåg, A., Lamarque, J.-F., Lin, G., Liu, X., Lund, M. T., Luo, G., Ma, X., van Noije, T., Penner, J. E., Rasch, P. J., Ruiz, A., Seland, Ø., Skeie, R. B., Stier, P., Takemura, T., Tsigaridis, K., Wang, P., Wang, Z., Xu, L., Yu, H., Yu, F., Yoon, J.-H., Zhang, K., Zhang, H., and Zhou, C.: Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations, Atmos. Chem. Phys., 13, 1853–1877, https://doi.org/10.5194/acp-13-1853-2013, 2013.

Nault, B. A., Laughner, J. L., Wooldridge, P. J., Crounse, J. D., Dibb, J., Diskin, G., Peischl, J., Podolske, J. R., Pollack, I. B., Ryerson, T. B., Scheuer, E., Wennberg, P. O., and Cohen, R. C.: Lightning NO_x Emissions: Reconciling Measured and Modeled Estimates With Updated NO_x Chemistry, Geophys. Res. Lett., 44, 9479–9488, https://doi.org/10.1002/2017GL074436, 2017.

Nevison, C., Andrews, A., Thoning, K., Dlugokencky, E., Sweeney, C., Miller, S., Saikawa, E., Benmergui, J., Fischer, M., Mountain, M., and Nehrkorn, T.: Nitrous Oxide Emissions Estimated With the CarbonTracker-Lagrange North American Regional Inversion Framework, Global Biogeochem. Cy., 32, 463–485, https://doi.org/10.1002/2017GB005759, 2018.

Nevison, C. D., Solomon, S., and Gao, R. S.: Buffering interactions in the modeled response of stratospheric O_3 to increased NO_x and HO_x, J. Geophys. Res.-Atmos., 104, 3741–3754, https://doi.org/10.1029/1998JD100018, 1999.

Oberländer-Hayn, S., Gerber, E. P., Abalichin, J., Akiyoshi, H., Kerschbaumer, A., Kubin, A., Kunze, M., Langematz, U., Meul, S., Michou, M., Morgenstern, O., and Oman, L. D.: Is the Brewer-Dobson circulation increasing or moving upward?, Geophys. Res. Lett., 43, 1772–1779, https://doi.org/10.1002/2015GL067545, 2016.

Oreggioni, G. D., Monforti Ferraio, F., Crippa, M., Muntean, M., Schaaf, E., Guizzardi, D., Solazzo, E., Duerr, M., Perry, M., and Vignati, E.: Climate change in a changing world: Socio-economic and technological transitions, regulatory frameworks and trends on global greenhouse gas emissions from EDGAR v.5.0, Global Environ. Change, 70, 102350, https://doi.org/10.1016/j.gloenvcha.2021.102350, 2021.

Ostle, N. J., Smith, P., Fisher, R., Ian Woodward, F., Fisher, J. B., Smith, J. U., Galbraith, D., Levy, P., Meir, P., McNamara, N. P., and Bardgett, R. D.: Integrating plant–soil interactions into global carbon cycle models, J. Ecol., 97, 851–863, https://doi.org/10.1111/j.1365-2745.2009.01547.x, 2009.

Pan, B., Lam, S. K., Wang, E., Mosier, A., and Chen, D.: New approach for predicting nitrification and its fraction of N_2O emissions in global terrestrial ecosystems, Environ. Res. Lett., 16, 034053, https://doi.org/10.1088/1748-9326/abe4f5, 2021.

Pärn, J., Verhoeven, J. T. A., Butterbach-Bahl, K., Dise, N. B., Ullah, S., Aasa, A., Egorov, S., Espenberg, M., Järveoja, J., Jauhiainen, J., Kasak, K., Klemedtsson, L., Kull, A., Laggoun-Défarge, F., Lapshina, E. D., Lohila, A., Lõhmus, K., Maddison, M., Mitsch, W. J., Müller, C., Niinemets, Ü., Osborne, B., Pae, T., Salm, J.-O., Sgouridis, F., Sohar, K., Soosaar, K., Storey, K., Teemusk, A., Tenywa, M. M., Tournebize, J., Truu, J., Veber, G., Villa, J. A., Zaw, S. S., and Mander, Ü.: Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots, Nat. Commun., 9, 1135, https://doi.org/10.1038/s41467-018-03540-1, 2018.

Patra, P. K., Takigawa, M., Watanabe, S., Chandra, N., Ishijima, K., and Yamashita, Y.: Improved chemical tracer simulation by MIROC4.0-based atmospheric chemistry-transport model (MIROC4-ACTM), Sola, 14, 91–96, 2018.

Patra, P. K., Dlugokencky, E. J., Elkins, J. W., Dutton, G. S., Tohjima, Y., Sasakawa, M., Ito, A., Weiss, R. F., Manizza, M., and Krummel, P. B.: Forward and inverse modelling of atmospheric

nitrous oxide using MIROC4-atmospheric chemistry-transport model, J. Meteorol. Soc. Jpn. Ser. II, 100, 361–386, 2022.

Phillips, R. L., Whalen, S. C., and Schlesinger, W. H.: Influence of atmospheric CO_2 enrichment on nitrous oxide flux in a temperate forest ecosystem, Global Biogeochem. Cy., 15, 741–752, https://doi.org/10.1029/2000GB001372, 2001.

Poulter, B., Bastos, A., Canadell, J., Ciais, P., Gruber, N., Hauck, J., Jackson, R., Ishii, M., Müller, J. D., and Patra, P.: Inventorying Earth's land and ocean greenhouse gases, Eos, 103, https://doi.org/10.1029/2022EO179084, 2022.

Prather, M. J., Holmes, C. D., and Hsu, J.: Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry, Geophys. Res. Lett., 39, L09803, https://doi.org/10.1029/2012GL051440, 2012.

Prather, M. J., Hsu, J., DeLuca, N. M., Jackman, C. H., Oman, L. D., Douglass, A. R., Fleming, E. L., Strahan, S. E., Steenrod, S. D., Søvde, O. A., Isaksen, I. S. A., Froidevaux, L., and Funke, B.: Measuring and modeling the lifetime of nitrous oxide including its variability, J. Geophys. Res.-Atmos., 120, 5693–5705, https://doi.org/10.1002/2015JD023267, 2015.

Prather, M. J., Froidevaux, L., and Livesey, N. J.: Observed changes in stratospheric circulation: decreasing lifetime of N_2O, 2005–2021, Atmos. Chem. Phys., 23, 843–849, https://doi.org/10.5194/acp-23-843-2023, 2023.

Prinn, R. G., Weiss, R. F., Arduini, J., Arnold, T., DeWitt, H. L., Fraser, P. J., Ganesan, A. L., Gasore, J., Harth, C. M., Hermansen, O., Kim, J., Krummel, P. B., Li, S., Loh, Z. M., Lunder, C. R., Maione, M., Manning, A. J., Miller, B. R., Mitrevski, B., Mühle, J., O'Doherty, S., Park, S., Reimann, S., Rigby, M., Saito, T., Salameh, P. K., Schmidt, R., Simmonds, P. G., Steele, L. P., Vollmer, M. K., Wang, R. H., Yao, B., Yokouchi, Y., Young, D., and Zhou, L.: History of chemically and radiatively important atmospheric gases from the Advanced Global Atmospheric Gases Experiment (AGAGE), Earth Syst. Sci. Data, 10, 985–1018, https://doi.org/10.5194/essd-10-985-2018, 2018.

Prosperi, P., Bloise, M., Tubiello, F. N., Conchedda, G., Rossi, S., Boschetti, L., Salvatore, M., and Bernoux, M.: New estimates of greenhouse gas emissions from biomass burning and peat fires using MODIS Collection 6 burned areas, Climatic Change, 161, 415–432, https://doi.org/10.1007/s10584-020-02654-0, 2020.

Raats, P. A. C.: Uptake of water from soils by plant roots, Transp. Porous Med., 68, 5–28, https://doi.org/10.1007/s11242-006-9055-6, 2007.

Raji, S. G. and Dörsch, P.: Effect of legume intercropping on N_2O emissions and CH_4 uptake during maize production in the Great Rift Valley, Ethiopia, Biogeosciences, 17, 345–359, https://doi.org/10.5194/bg-17-345-2020, 2020.

Raoult, N., Delorme, B., Ottlé, C., Peylin, P., Bastrikov, V., Maugis, P., and Polcher, J.: Confronting Soil Moisture Dynamics from the ORCHIDEE Land Surface Model With the ESA-CCI Product: Perspectives for Data Assimilation, Remote Sens., 10, 1786, https://doi.org/10.3390/rs10111786, 2018.

Ravishankara, A. R., Daniel, J. S., and Portmann, R. W.: Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century, Science, 326, 123–125, https://doi.org/10.1126/science.1176985, 2009.

Reay, D. S., Davidson, E. A., Smith, K. A., Smith, P., Melillo, J. M., Dentener, F., and Crutzen, P. J.: Global agriculture and nitrous oxide emissions, Nat. Clim. Change, 2, 410–416, https://doi.org/10.1038/nclimate1458, 2012.

Regan, K., Kammann, C., Hartung, K., Lenhart, K., Müller, C., Philippot, L., Kandeler, E., and Marhan, S.: Can differences in microbial abundances help explain enhanced N_2O emissions in a permanent grassland under elevated atmospheric CO_2?, Global Change Biol., 17, 3176–3186, https://doi.org/10.1111/j.1365-2486.2011.02470.x, 2011.

Repo, M. E., Susiluoto, S., Lind, S. E., Jokinen, S., Elsakov, V., Biasi, C., Virtanen, T., and Martikainen, P. J.: Large N_2O emissions from cryoturbated peat soil in tundra, Nat. Geosci., 2, 189–192, https://doi.org/10.1038/ngeo434, 2009.

Resplandy, L., Hogikyan, A., Müller, J. D., Najjar, R. G., Bange, H. W., Bianchi, D., Weber, T., Cai, W.-J., Doney, S. C., Fennel, K., Gehlen, M., Hauck, J., Lacroix, F., Landschützer, P., Le Quéré, C., Roobaert, A., Schwinger, J., Berthet, S., Bopp, L., Chau, T. T. T., Dai, M., Gruber, N., Ilyina, T., Kock, A., Manizza, M., Lachkar, Z., Laruelle, G. G., Liao, E., Lima, I. D., Nissen, C., Rödenbeck, C., Séférian, R., Toyama, K., Tsujino, H., and Regnier, P.: A Synthesis of Global Coastal Ocean Greenhouse Gas Fluxes, Global Biogeochem. Cy., 38, e2023GB007803, https://doi.org/10.1029/2023GB007803, 2024.

Rogelj, J. and Lamboll, R. D.: Substantial reductions in non-CO_2 greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget, Commun. Earth Environ., 5, 1–5, https://doi.org/10.1038/s43247-023-01168-8, 2024.

Rosentreter, J. A., Laruelle, G. G., Bange, H. W., Bianchi, T. S., Busecke, J. J. M., Cai, W.-J., Eyre, B. D., Forbrich, I., Kwon, E. Y., Maavara, T., Moosdorf, N., Najjar, R. G., Sarma, V. V. S. S., Van Dam, B., and Regnier, P.: Coastal vegetation and estuaries are collectively a greenhouse gas sink, Nat. Clim. Change, 13, 579–587, https://doi.org/10.1038/s41558-023-01682-9, 2023.

Saha, D., Basso, B., and Robertson, G. P.: Machine learning improves predictions of agricultural nitrous oxide (N_2O) emissions from intensively managed cropping systems, Environ. Res. Lett., 16, 024004, https://doi.org/10.1088/1748-9326/abd2f3, 2021.

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P. M., Covey, K., Curry, C. L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M. I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K. M., Joos, F., Kleinen, T., Krummel, P. B., Langenfelds, R. L., Laruelle, G. G., Liu, L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R. J., Peng, C., Peng, S., Peters, G. P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W. J., Rosentreter, J. A., Segers, A., Simpson, I. J., Shi, H., Smith, S. J., Steele, L. P., Thornton, B. F., Tian, H., Tohjima, Y., Tubiello, F. N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T. S., van Weele, M., van der Werf, G. R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., and Zhuang, Q.: The Global Methane Budget 2000–2017, Earth Syst. Sci. Data, 12, 1561–1623, https://doi.org/10.5194/essd-12-1561-2020, 2020.

Scheer, C., Pelster, D. E., and Butterbach-Bahl, K.: Editorial Overview: Climate change, reactive nitrogen, food security and sustainable agriculture –the case of N_2O, Curr. Opin. Environ. Sustain., 47, A1–A4, https://doi.org/10.1016/j.cosust.2020.11.001, 2020.

Schilt, A., Baumgartner, M., Schwander, J., Buiron, D., Capron, E., Chappellaz, J., Loulergue, L., Schüpbach, S., Spahni, R., Fischer, H., and Stocker, T. F.: Atmospheric nitrous oxide during the last 140,000 years, Earth Planet. Sc. Lett., 300, 33–43, https://doi.org/10.1016/j.epsl.2010.09.027, 2010.

Schlesinger, W. H.: An estimate of the global sink for nitrous oxide in soils, Global Change Biol., 19, 2929–2931, https://doi.org/10.1111/gcb.12239, 2013.

Schumann, U. and Huntrieser, H.: The global lightning-induced nitrogen oxides source, Atmos. Chem. Phys., 7, 3823–3907, https://doi.org/10.5194/acp-7-3823-2007, 2007.

Séférian, R., Nabat, P., Michou, M., Saint-Martin, D., Voldoire, A., Colin, J., Decharme, B., Delire, C., Berthet, S., Chevallier, M., Sénési, S., Franchisteguy, L., Vial, J., Mallet, M., Joetzjer, E., Geoffroy, O., Guérémy, J.-F., Moine, M.-P., Msadek, R., Ribes, A., Rocher, M., Roehrig, R., Salas-y-Mélia, D., Sanchez, E., Terray, L., Valcke, S., Waldman, R., Aumont, O., Bopp, L., Deshayes, J., Éthé, C., and Madec, G.: Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of Earth System Processes in Present-Day and Future Climate, J. Adv. Model. Earth Syst., 11, 4182–4227, https://doi.org/10.1029/2019MS001791, 2019.

Séférian, R., Berthet, S., Yool, A., Palmiéri, J., Bopp, L., Tagliabue, A., Kwiatkowski, L., Aumont, O., Christian, J., Dunne, J., Gehlen, M., Ilyina, T., John, J. G., Li, H., Long, M. C., Luo, J. Y., Nakano, H., Romanou, A., Schwinger, J., Stock, C., Santana-Falcón, Y., Takano, Y., Tjiputra, J., Tsujino, H., Watanabe, M., Wu, T., Wu, F., and Yamamoto, A.: Tracking Improvement in Simulated Marine Biogeochemistry Between CMIP5 and CMIP6, Curr. Clim. Change Rep., 6, 95–119, https://doi.org/10.1007/s40641-020-00160-0, 2020.

Shang, Z., Zhou, F., Smith, P., Saikawa, E., Ciais, P., Chang, J., Tian, H., Del Grosso, S. J., Ito, A., Chen, M., Wang, Q., Bo, Y., Cui, X., Castaldi, S., Juszczak, R., Kasimir, Å., Magliulo, V., Medinets, S., Medinets, V., Rees, R. M., Wohlfahrt, G., and Sabbatini, S.: Weakened growth of cropland-N_2O emissions in China associated with nationwide policy interventions, Global Change Biol., 25, 3706–3719, https://doi.org/10.1111/gcb.14741, 2019.

Shcherbak, I., Millar, N., and Robertson, G. P.: Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen, P. Natl. Acad. Sci. USA, 111, 9199–9204, https://doi.org/10.1073/pnas.1322434111, 2014.

Shu, S., Jain, A. K., Koven, C. D., and Mishra, U.: Estimation of Permafrost SOC Stock and Turnover Time Using a Land Surface Model With Vertical Heterogeneity of Permafrost Soils, Global Biogeochem. Cy., 34, e2020GB006585, https://doi.org/10.1029/2020GB006585, 2020.

Smith, K.: The potential for feedback effects induced by global warming on emissions of nitrous oxide by soils, Global Change Biol., 3, 327–338, https://doi.org/10.1046/j.1365-2486.1997.00100.x, 1997.

Solazzo, E., Crippa, M., Guizzardi, D., Muntean, M., Choulga, M., and Janssens-Maenhout, G.: Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory of greenhouse gases, Atmos. Chem. Phys., 21, 5655–5683, https://doi.org/10.5194/acp-21-5655-2021, 2021.

Stavert, A. R., Saunois, M., Canadell, J. G., Poulter, B., Jackson, R. B., Regnier, P., Lauerwald, R., Raymond, P. A., Allen, G. H., Patra, P. K., Bergamaschi, P., Bousquet, P., Chandra, N., Ciais, P., Gustafson, A., Ishizawa, M., Ito, A., Kleinen, T., Maksyutov, S., McNorton, J., Melton, J. R., Müller, J., Niwa, Y., Peng, S., Riley, W. J., Segers, A., Tian, H., Tsuruta, A., Yin, Y., Zhang, Z., Zheng, B., and Zhuang, Q.: Regional trends and drivers of the global methane budget, Global Change Biol., 28, 182–200, https://doi.org/10.1111/gcb.15901, 2022.

Sullivan, B. W., Nifong, R. L., Nasto, M. K., Alvarez-Clare, S., Dencker, C. M., Soper, F. M., Shoemaker, K. T., Ishida, F. Y., Zaragoza-Castells, J., Davidson, E. A., and Cleveland, C. C.: Biogeochemical recuperation of lowland tropical forest during succession, Ecology, 100, e02641, https://doi.org/10.1002/ecy.2641, 2019.

Suntharalingam, P., Buitenhuis, E., Le Quéré, C., Dentener, F., Nevison, C., Butler, J. H., Bange, H. W., and Forster, G.: Quantifying the impact of anthropogenic nitrogen deposition on oceanic nitrous oxide, Geophysical Research Letters, 39, L07605, https://doi.org/10.1029/2011GL050778, 2012.

Syakila, A. and Kroeze, C.: The global nitrous oxide budget revisited, Greenhouse Gas Meas. Manage., 1, 17–26, https://doi.org/10.3763/ghgmm.2010.0007, 2011.

Syakila, A., Kroeze, C., and Slomp, C. P.: Neglecting sinks for N_2O at the earth's surface: does it matter?, J. Integr. Environ. Sci., 7, 79–87, https://doi.org/10.1080/1943815X.2010.497492, 2010.

Thompson, R. L., Chevallier, F., Crotwell, A. M., Dutton, G., Langenfelds, R. L., Prinn, R. G., Weiss, R. F., Tohjima, Y., Nakazawa, T., Krummel, P. B., Steele, L. P., Fraser, P., O'Doherty, S., Ishijima, K., and Aoki, S.: Nitrous oxide emissions 1999 to 2009 from a global atmospheric inversion, Atmos. Chem. Phys., 14, 1801–1817, https://doi.org/10.5194/acp-14-1801-2014, 2014.

Thompson, R. L., Lassaletta, L., Patra, P. K., Wilson, C., Wells, K. C., Gressent, A., Koffi, E. N., Chipperfield, M. P., Winiwarter, W., Davidson, E. A., Tian, H., and Canadell, J. G.: Acceleration of global N_2O emissions seen from two decades of atmospheric inversion, Nat. Clim. Change, 9, 993–998, https://doi.org/10.1038/s41558-019-0613-7, 2019.

Tian, H., Yang, Q., Najjar, R. G., Ren, W., Friedrichs, M. A., Hopkinson, C. S., and Pan, S.: Anthropogenic and climatic influences on carbon fluxes from eastern North America to the Atlantic Ocean: A process-based modeling study, J. Geophys. Res.-Biogeo., 120, 757–772, 2015.

Tian, H., Lu, C., Ciais, P., Michalak, A. M., Canadell, J. G., Saikawa, E., Huntzinger, D. N., Gurney, K. R., Sitch, S., Zhang, B., Yang, J., Bousquet, P., Bruhwiler, L., Chen, G., Dlugokencky, E., Friedlingstein, P., Melillo, J., Pan, S., Poulter, B., Prinn, R., Saunois, M., Schwalm, C. R., and Wofsy, S. C.: The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. Nature, 531, 225–228, https://doi.org/10.1038/nature16946, 2016.

Tian, H., Yang, J., Lu, C., Xu, R., Canadell, J. G., Jackson, R. B., Arneth, A., Chang, J., Chen, G., Ciais, P., Gerber, S., Ito, A., Huang, Y., Joos, F., Lienert, S., Messina, P., Olin, S., Pan, S., Peng, C., Saikawa, E., Thompson, R. L., Vuichard, N., Winiwarter, W., Zaehle, S., Zhang, B., Zhang, K., and Zhu, Q.: The Global

N_2O Model Intercomparison Project, B. Am. Meteorol. Soc., 99, 1231–1251, https://doi.org/10.1175/BAMS-D-17-0212.1, 2018.

Tian, H., Yang, J., Xu, R., Lu, C., Canadell, J. G., Davidson, E. A., Jackson, R. B., Arneth, A., Chang, J., Ciais, P., Gerber, S., Ito, A., Joos, F., Lienert, S., Messina, P., Olin, S., Pan, S., Peng, C., Saikawa, E., Thompson, R. L., Vuichard, N., Winiwarter, W., Zaehle, S., and Zhang, B.: Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: Magnitude, attribution, and uncertainty, Global Change Biol., 25, 640–659, https://doi.org/10.1111/gcb.14514, 2019.

Tian, H., Xu, R., Canadell, J. G., Thompson, R. L., Winiwarter, W., Suntharalingam, P., Davidson, E. A., Ciais, P., Jackson, R. B., Janssens-Maenhout, G., Prather, M. J., Regnier, P., Pan, N., Pan, S., Peters, G. P., Shi, H., Tubiello, F. N., Zaehle, S., Zhou, F., Arneth, A., Battaglia, G., Berthet, S., Bopp, L., Bouwman, A. F., Buitenhuis, E. T., Chang, J., Chipperfield, M. P., Dangal, S. R. S., Dlugokencky, E., Elkins, J. W., Eyre, B. D., Fu, B., Hall, B., Ito, A., Joos, F., Krummel, P. B., Landolfi, A., Laruelle, G. G., Lauerwald, R., Li, W., Lienert, S., Maavara, T., MacLeod, M., Millet, D. B., Olin, S., Patra, P. K., Prinn, R. G., Raymond, P. A., Ruiz, D. J., van der Werf, G. R., Vuichard, N., Wang, J., Weiss, R. F., Wells, K. C., Wilson, C., Yang, J., and Yao, Y.: A comprehensive quantification of global nitrous oxide sources and sinks, Nature, 586, 248–256, https://doi.org/10.1038/s41586-020-2780-0, 2020.

Tian, H., Bian, Z., Shi, H., Qin, X., Pan, N., Lu, C., Pan, S., Tubiello, F. N., Chang, J., Conchedda, G., Liu, J., Mueller, N., Nishina, K., Xu, R., Yang, J., You, L., and Zhang, B.: History of anthropogenic Nitrogen inputs (HaNi) to the terrestrial biosphere: a 5 arcmin resolution annual dataset from 1860 to 2019, Earth Syst. Sci. Data, 14, 4551–4568, https://doi.org/10.5194/essd-14-4551-2022, 2022.

Tian, H., Pan, N., Thompson, R. L., Canadell, J. G., Suntharalingam, P., Regnier, P., Davidson, E. A., Prather, M., Ciais, P., Muntean, M., Pan, S., Winiwarter, W., Zaehle, S., Zhou, F., Jackson, R. B., Bange, H. W., Berthet, S., Bian, Z., Bianchi, D., Bouwman, A. F., Buitenhuis, E. T., Dutton, G., Hu, M., Ito, A., Jain, A. K., Jeltsch-Thömmes, A., Joos, F., Kou-Giesbrecht, S., Krummel, P. B., Lan, X., Landolfi, A., Lauerwald, R., Li, Y., Lu, C., Maavara, T., Manizza, M., Millet, D. B., Mühle, J., Patra, P. K., Peters, G. P., Qin, X., Raymond, P., Resplandy, L., Rosentreter, J. A., Shi, H., Sun, Q., Tonina, D., Tubiello, F. N., van der Werf, G. R., Vuichard, N., Wang, J., Wells, K. C., Western, L. M., Wilson, C., Yang, J., Yao, Y., You, Y., and Zhu, Q.: Data supplement to: Tian et al. (2023): Global Nitrous Oxide Budget 1980–2020, Earth Syst. Sci. Data, Global Carbon Project [data set], https://doi.org/10.18160/RQ8P-2Z4R, 2023.

Tubiello, F. N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., and Smith, P.: The FAOSTAT database of greenhouse gas emissions from agriculture, Environ. Res. Lett., 8, 015009, https://doi.org/10.1088/1748-9326/8/1/015009, 2013.

Tubiello, F. N., Salvatore, M., Ferrara, A. F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R. D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M. J., Srivastava, N., and Smith, P.: The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990–2012, Global Change Biol., 21, 2655–2660, https://doi.org/10.1111/gcb.12865, 2015.

Tubiello, F. N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., Obli-Laryea, G., Wanner, N., Qiu, S. Y., Barros, J. D., Flammini, A., Mencos-Contreras, E., Souza, L., Quadrelli, R., Heiðarsdóttir, H. H., Benoit, P., Hayek, M., and Sandalow, D.: Greenhouse gas emissions from food systems: building the evidence base, Environ. Res. Lett., 16, 065007, https://doi.org/10.1088/1748-9326/ac018e, 2021.

Tubiello, F. N., Karl, K., Flammini, A., Gütschow, J., Obli-Laryea, G., Conchedda, G., Pan, X., Qi, S. Y., Halldórudóttir Heiðarsdóttir, H., Wanner, N., Quadrelli, R., Rocha Souza, L., Benoit, P., Hayek, M., Sandalow, D., Mencos Contreras, E., Rosenzweig, C., Rosero Moncayo, J., Conforti, P., and Torero, M.: Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems, Earth Syst. Sci. Data, 14, 1795–1809, https://doi.org/10.5194/essd-14-1795-2022, 2022.

UNEP: Drawing Down N_2O to Protect Climate and the Ozone Layer, A UNEP Synthesis Report, UNEP – nited Nations Environment Programme, Nairobi, Kenya, http://www.unep.org/publications/ebooks/UNEPN2Oreport/ (last access: 22 October 2021), 2013.

United Nations: The Sustainable Development Goals 2016, eSocialSciences, https://EconPapers.repec.org/RePEc:ess:wpaper:id:11456 (last access: 3 April 2022), 2016.

Usyskin-Tonne, A., Hadar, Y., Yermiyahu, U., and Minz, D.: Elevated CO_2 has a significant impact on denitrifying bacterial community in wheat roots, Soil Biol. Biochem., 142, 107697, https://doi.org/10.1016/j.soilbio.2019.107697, 2020.

van der Werf, G. R., Randerson, J. T., Giglio, L., van Leeuwen, T. T., Chen, Y., Rogers, B. M., Mu, M., van Marle, M. J. E., Morton, D. C., Collatz, G. J., Yokelson, R. J., and Kasibhatla, P. S.: Global fire emissions estimates during 1997–2016, Earth Syst. Sci. Data, 9, 697–720, https://doi.org/10.5194/essd-9-697-2017, 2017.

Van Meter, K. J., Basu, N. B., Veenstra, J. J., and Burras, C. L: The nitrogen legacy: emerging evidence of nitrogen accumulation in anthropogenic landscapes, Environ. Res. Lett., 11, 035014, https://doi.org/10.1088/1748-9326/11/3/035014, 2016.

Verchot, L. V., Davidson, E. A., Cattânio, H., Ackerman, I. L., Erickson, H. E., and Keller, M.: Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia, Global Biogeochem. Cy., 13, 31–46, https://doi.org/10.1029/1998GB900019, 1999.

Voigt, C., Marushchak, M. E., Lamprecht, R. E., Jackowicz-Korczyński, M., Lindgren, A., Mastepanov, M., Granlund, L., Christensen, T. R., Tahvanainen, T., Martikainen, P. J., and Biasi, C.: Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw, P. Natl. Acad. Sci. USA, 114, 6238–6243, https://doi.org/10.1073/pnas.1702902114, 2017.

Vuichard, N., Messina, P., Luyssaert, S., Guenet, B., Zaehle, S., Ghattas, J., Bastrikov, V., and Peylin, P.: Accounting for carbon and nitrogen interactions in the global terrestrial ecosystem model ORCHIDEE (trunk version, rev 4999): multi-scale evaluation of gross primary production, Geosci. Model Dev., 12, 4751–4779, https://doi.org/10.5194/gmd-12-4751-2019, 2019.

Wagner-Riddle, C., Congreves, K. A., Abalos, D., Berg, A. A., Brown, S. E., Ambadan, J. T., Gao, X., and Tenuta, M.: Globally important nitrous oxide emissions from croplands induced by freeze–thaw cycles, Nat. Geosci., 10, 279–283, https://doi.org/10.1038/ngeo2907, 2017.

Wang, C., Lai, D. Y. F., Sardans, J., Wang, W., Zeng, C., and Peñuelas, J.: Factors Related with CH_4 and N_2O Emissions from a Paddy Field: Clues for Management implications, PLOS ONE, 12, e0169254, https://doi.org/10.1371/journal.pone.0169254, 2017.

Wang, Q., Zhou, F., Shang, Z., Ciais, P., Winiwarter, W., Jackson, R. B., Tubiello, F. N., Janssens-Maenhout, G., Tian, H., Cui, X., Canadell, J. G., Piao, S., and Tao, S.: Data-driven estimates of global nitrous oxide emissions from croplands, Natl. Sci. Rev., 7, 441–452, https://doi.org/10.1093/nsr/nwz087, 2020.

Wells, K. C., Millet, D. B., Bousserez, N., Henze, D. K., Griffis, T. J., Chaliyakunnel, S., Dlugokencky, E. J., Saikawa, E., Xiang, G., Prinn, R. G., O'Doherty, S., Young, D., Weiss, R. F., Dutton, G. S., Elkins, J. W., Krummel, P. B., Langenfelds, R., and Steele, L. P.: Top-down constraints on global N_2O emissions at optimal resolution: application of a new dimension reduction technique, Atmos. Chem. Phys., 18, 735–756, https://doi.org/10.5194/acp-18-735-2018, 2018.

Wennberg, P. O., Cohen, R. C., Stimpfle, R. M., Koplow, J. P., Anderson, J. G., Salawitch, R. J., Fahey, D. W., Woodbridge, E. L., Keim, E. R., Gao, R. S., Webster, C. R., May, R. D., Toohey, D. W., Avallone, L. M., Proffitt, M. H., Loewenstein, M., Podolske, J. R., Chan, K. R., and Wofsy, S. C.: Removal of Stratospheric O_3 by Radicals: In Situ Measurements of OH, HO_2, NO, NO_2, ClO, and BrO, Science, 266, 398–404, https://doi.org/10.1126/science.266.5184.398, 1994.

Williams, J. and Crutzen, P. J.: Nitrous oxide from aquaculture, Nat. Geosci., 3, 143–143, https://doi.org/10.1038/ngeo804, 2010.

Wilson, C., Chipperfield, M. P., Gloor, M., and Chevallier, F.: Development of a variational flux inversion system (INVICAT v1.0) using the TOMCAT chemical transport model, Geosci. Model Dev., 7, 2485–2500, https://doi.org/10.5194/gmd-7-2485-2014, 2014.

Wilson, S. T., Al-Haj, A. N., Bourbonnais, A., Frey, C., Fulweiler, R. W., Kessler, J. D., Marchant, H. K., Milucka, J., Ray, N. E., Suntharalingam, P., Thornton, B. F., Upstill-Goddard, R. C., Weber, T. S., Arévalo-Martínez, D. L., Bange, H. W., Benway, H. M., Bianchi, D., Borges, A. V., Chang, B. X., Crill, P. M., del Valle, D. A., Farías, L., Joye, S. B., Kock, A., Labidi, J., Manning, C. C., Pohlman, J. W., Rehder, G., Sparrow, K. J., Tortell, P. D., Treude, T., Valentine, D. L., Ward, B. B., Yang, S., and Yurganov, L. N.: Ideas and perspectives: A strategic assessment of methane and nitrous oxide measurements in the marine environment, Biogeosciences, 17, 5809–5828, https://doi.org/10.5194/bg-17-5809-2020, 2020.

Winiwarter, W., Höglund-Isaksson, L., Klimont, Z., Schöpp, W., and Amann, M.: Technical opportunities to reduce global anthropogenic emissions of nitrous oxide, Environ. Res. Lett., 13, 014011, https://doi.org/10.1088/1748-9326/aa9ec9, 2018.

World Meteorological Organization: Scientific Assessment of Ozone Depletion, 2022 GAW Report No. 278, https://www.csl.noaa.gov/assessments/ozone/2022 (last access: 26 February 2023), 2022.

Xu, R., Tian, H., Lu, C., Pan, S., Chen, J., Yang, J., and Zhang, B.: Preindustrial nitrous oxide emissions from the land biosphere estimated by using a global biogeochemistry model, Clim. Past, 13, 977–990, https://doi.org/10.5194/cp-13-977-2017, 2017.

Xu, R., Tian, H., Pan, S., Prior, S. A., Feng, Y., and Dangal, S. R. S.: Global N_2O Emissions from Cropland Driven by Nitrogen Addition and Environmental Factors: Comparison and Uncertainty Analysis, Global Biogeochem. Cy., 34, e2020GB006698, https://doi.org/10.1029/2020GB006698, 2020.

Xu, R., Tian, H., Pan, N., Thompson, R. L., Canadell, J. G., Davidson, E. A., Nevison, C., Winiwarter, W., Shi, H., Pan, S., Chang, J., Ciais, P., Dangal, S. R. S., Ito, A., Jackson, R. B., Joos, F., Lauerwald, R., Lienert, S., Maavara, T., Millet, D. B., Raymond, P. A., Regnier, P., Tubiello, F. N., Vuichard, N., Wells, K. C., Wilson, C., Yang, J., Yao, Y., Zaehle, S., and Zhou, F.: Magnitude and Uncertainty of Nitrous Oxide Emissions From North America Based on Bottom-Up and Top-Down Approaches: Informing Future Research and National Inventories, Geophys. Res. Let., 48, e2021GL095264, https://doi.org/10.1029/2021GL095264, 2021.

Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F. N., Smith, P., Campbell, N., and Jain, A. K.: Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods, Nat. Food, 2, 724–732, https://doi.org/10.1038/s43016-021-00358-x, 2021.

Yang, S., Chang, B. X., Warner, M. J., Weber, T. S., Bourbonnais, A. M., Santoro, A. E., Kock, A., Sonnerup, R. E., Bullister, J. L., Wilson, S. T., and Bianchi, D.: Global reconstruction reduces the uncertainty of oceanic nitrous oxide emissions and reveals a vigorous seasonal cycle, P. Natl. Acad. Sci. USA, 117, 11954–11960, https://doi.org/10.1073/pnas.1921914117, 2020.

Yao, Y., Tian, H., Shi, H., Pan, S., Xu, R., Pan, N., and Canadell, J. G.: Increased global nitrous oxide emissions from streams and rivers in the Anthropocene, Nat. Clim. Change, 10, 138–142, 2020.

Yin, Y., Wang, Z., Tian, X., Wang, Y., Cong, J., and Cui, Z.: Evaluation of variation in background nitrous oxide emissions: A new global synthesis integrating the impacts of climate, soil, and management conditions, Global Change Biol., 28, 480–492, https://doi.org/10.1111/gcb.15860, 2022.

You, Y., Tian, H., Pan, S., Shi, H., Bian, Z., Gurgel, A., Huang, Y., Kicklighter, D., Liang, X.-Z., Lu, C., Melillo, J., Miao, R., Pan, N., Reilly, J., Ren, W., Xu, R., Yang, J., Yu, Q., and Zhang, J.: Incorporating dynamic crop growth processes and management practices into a terrestrial biosphere model for simulating crop production in the United States: Toward a unified modeling framework, Agr. Forest Meteorol., 325, 109144, https://doi.org/10.1016/j.agrformet.2022.109144, 2022.

Yu, H., Wang, T., Huang, Q., Song, K., Zhang, G., Ma, J., and Xu, H.: Effects of elevated CO_2 concentration on CH_4 and N_2O emissions from paddy fields: A meta-analysis, Sci. China Earth Sci., 65, 96–106, https://doi.org/10.1007/s11430-021-9848-2, 2022.

Yu, Z., Lu, C., Hennessy, D. A., Feng, H., and Tian, H.: Impacts of tillage practices on soil carbon stocks in the US corn-soybean cropping system during 1998 to 2016, Environ. Res. Lett., 15, 014008, https://doi.org/10.1088/1748-9326/ab6393, 2020.

Zaehle, S., Ciais, P., Friend, A. D., and Prieur, V.: Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions, Nat. Geosci., 4, 601–605, https://doi.org/10.1038/ngeo1207, 2011.

Zamora, L. M. and Oschlies, A.: Surface nitrification: A major uncertainty in marine N_2O emissions, Geophys. Res. Lett., 41, 4247–4253, https://doi.org/10.1002/2014GL060556, 2014.

Zhou, F., Shang, Z., Zeng, Z., Piao, S., Ciais, P., Raymond, P. A., Wang, X., Wang, R., Chen, M., Yang, C., Tao, S., Zhao, Y., Meng, Q., Gao, S., and Mao, Q.: New model for capturing the variations of fertilizer-induced emission factors of N_2O, Global Biogeochem. Cy., 29, 885–897, https://doi.org/10.1002/2014GB005046, 2015.

Zhu, Q., Riley, W. J., Tang, J., Collier, N., Hoffman, F. M., Yang, X., and Bisht, G.: Representing Nitrogen, Phosphorus, and Carbon Interactions in the E3SM Land Model: Development and Global Benchmarking, J. Adv. Model. Earth Syst., 11, 2238–2258, https://doi.org/10.1029/2018MS001571, 2019.

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Review

Review: Environmental impact of livestock farming and Precision Livestock Farming as a mitigation strategy

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HIGHLIGHTS

- PLF allows to monitor, model and control continuously animal bio-responses.
- PLF, optimizing livestock performance, indirectly reduces environmental impact.
- More positive effects of PLF on air, water and soil should be further investigated.
- PLF could enter fully-fledged among BATs, if its potential will be confirmed.

GRAPHICAL ABSTRACT

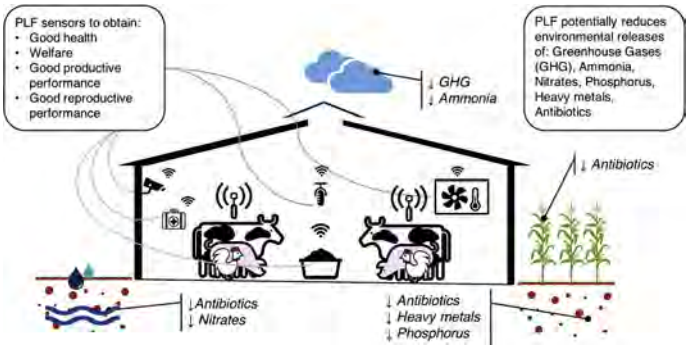

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ABSTRACT

This paper reviews the environmental impact of current livestock practices and discusses the advantages offered by Precision Livestock Farming (PLF), as a potential strategy to mitigate environmental risks.
PLF is defined as: "the application of process engineering principles and techniques to livestock farming to automatically monitor, model and manage animal production". The primary goal of PLF is to make livestock farming more economically, socially and environmentally sustainable and this can be obtained through the observation, interpretation of behaviours and, if possible, individual control of animals. Furthermore, adopting PLF to support management strategies, may lead to the reduction of the environmental impact of farms. Currently, few studies reported PLF efficacy in reducing the environmental impact, however further studies are necessary to better analyze the actual potential of PLF as a mitigation strategy.
Literature shows the potentiality of the application of PLF, as the introduction of PLF in farms can lead to a reduction of Greenhouse gases (GHG) and ammonia (NH3) emission in air, nitrates and antibiotics pollution in water bodies, phosphorus, antibiotics and heavy metals in the soil.

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1. Introduction

The actual size of global animal production is the result of human dietary evolution that, consume more animal products as their income increases. Worldwide, about 65 billion chickens, 1.5 billion pigs, 1 billion goat and sheep and around 330 million cattle and buffaloes are reared for meat production (FAOSTAT, 2016). In the same report, it is stated that cows used for milk production are almost 234 million, and that egg production sector counts 7.6 billion laying hens. The livestock sector contributes up to 50% of the global agricultural gross domestic product (Herrero et al., 2016), and supports the livelihoods and food security of almost a 1.3 billion people in developing countries (FAO, 2017).

In addition to the increase in animal number, significant intensification in livestock farming has also occurred, achieved by increasing animal densities and production units; using concentrated feed, pharmaceuticals, and vaccinations; improving infrastructure and feed efficiencies (Ramankutty et al., 2018). Industrial-scale livestock production is the most common and widespread means of livestock production and occurs within facilities known as concentrated, or confined, animal feeding operations (CAFOs) (Mallin et al., 2015). CAFOs can generate large quantities of manure (Ebner, 2017), far from areas of intensive crop farming where the excreta could be used as fertilizer (Li et al., 2016). Application of liquid manure in agricultural land from livestock is a general practice to enrich soil with nutrients and/or for sustainable nutrient recycling (Sukul et al., 2009), but this practice unintentionally encourages the contamination of different environmental compartments through the entry of hazardous materials contained in the liquid manure.

Unfortunately, the high density of animals reared in relatively small areas, results in the deposition of large amounts of excretory nitrogen, phosphorus, organic matter, and fecal microbes in the watershed where the CAFO is located (Mallin et al., 2015), resulting in the contamination of water systems globally, such as surface water eutrophication and groundwater nitrate enrichment (Li et al., 2016).

Thus, the livestock sector is an important user of natural resources and has significant influence on air quality, global climate, soil quality, biodiversity and water quality, by altering the biogeochemical cycles of nitrogen, phosphorus and carbon, giving rise to environmental concerns (Leip et al., 2015).

Therefore, livestock farming should be oriented towards more sustainable systems, applying management strategies and technologies to reach this goal. According to Berckmans (2014) the application of Precision Livestock Farming (PLF) could be a good approach to reach the environmental sustainability of livestock farming, since it allows to have the control on animal health and welfare and on the microclimate of the barn.

PLF is defined as: “the application of process engineering principles and techniques to livestock farming to automatically monitor, model and manage animal production” and converting bio response into relevant information that can be easily applied to different management aspects focusing both on the animal and on the environment (Tullo et al., 2017).

To develop a PLF system, it is necessary to identify and classify the animal bio-response (labelling), i.e., animal behaviours, vocalization and parameters deriving from animals-environment interaction. The following step is to develop the algorithm to model the target bio-responses and successively, the algorithm should be validated in order to verify if the predictions correspond to reality. In this way it is possible to model, monitor and control animal bio-response and provide accurate feedback to the farmer, thus his ability to keep contact with animals is enhanced.

With cameras, microphones, sensors (such as 3D accelerometers, temperature sensors, skin conductivity sensors and glucose sensors), wireless communication tools, internet connections and cloud storage it is possible to automated monitor and control environmental, physiological and behavioral variables, ensuring livestock performance and well-being in relation to their environment without any disturbance or handling (Berckmans, 2014).

The primary goal of PLF is to make livestock farming more economically, socially and environmentally sustainable (Vranken and Berckmans, 2017). PLF can be applied to monitor animal growth and behavior, product yield, endemic disease and the physical environment of livestock buildings including the microenvironment and the emission of gaseous pollutants (Fournel et al., 2017).

Until today PLF technologies have been developed and applied to improve health and consequently the welfare of animals (Neethirajan et al., 2017), to improve traceability (De Montis et al., 2017; Lima et al., 2018; Vranken and Berckmans, 2017), and to create added value to the farmer (Halachmi et al., 2015; Kamphuis et al., 2015; Lopes et al., 2016). With PLF, farmers can ensure good health and welfare of his animals, reaching good productive and reproductive performance, and lowering the environmental impact per unit of animal product.

Ensuring animal health and welfare is the necessary condition to obtain good productive and reproductive performance, lowering the environmental impact per unit of animal product.

To date, the environmental impact of livestock farming can be mitigated by the adoption of several practices, such as technical improvements (manure treatments, intensification, management strategies) and/or dietary changes. Although PLF is not designed to directly reduce the environmental impact of livestock farming, several authors claim that it is possible (Berckmans, 2017; Hristov et al., 2013; Llonch et al., 2017; Shields and Orme-Evans, 2015). The aim of this review is to assess, through the analysis of the published literature, the current effects of livestock farming practices adopted as mitigation strategies and the effectiveness of PLF in reducing the environmental impact of livestock farming.

2. Environmental effects of livestock farming

2.1. Environmental impact on soil and water

In the past few decades the so called “livestock revolution” has occurred, implying a growth in meat consumption worldwide, which led to an increase of waste by livestock systems that pose dangers to the environment (Delgado et al., 2016). Often, nutrients such as minerals and protein content in diets are in excess respect to the real necessity of animals, and only a small amount of them is absorbed by the animal (Knapp, 2015; Wilkinson and Garnsworthy, 2017). Frequently, field

application of livestock manure supplies an excessive amount of nutrients than real crop removal, so it should be treated to rebalance the ratio of nutrients.

Livestock effluents have, in general, a high content of organic matter, suspended solids, nutrients, metals and pharmaceutical compounds. As the consequence of unbalanced land application of livestock manure, nutrients and antibiotics may seep from soils into ground and surface waters, having a devastating effect on water quality, favoring the growth of algae, accelerating eutrophication and promoting the spread of antibiotic resistant bacteria (Almeida et al., 2017; Girard et al., 2014; Hooda et al., 2000; Martinez, 2009).

To tackle this issue the European Community first introduced the Nitrates Directive in 1991 (Directive 91/676/EEC) with the aim of reducing water pollution caused or induced by nitrates from agricultural sources setting strict limits both in surface and ground water for the concentration of nitrates (50 mg l^{-1}) (Martinez et al., 2009).

This Directive is the most important European Regulation for diminishing environmental impacts of fertilizer and manure, increasing at the same time the nitrogen use efficiency (Van Grinsven et al., 2012). The Nitrates Directive defines "Nitrate Vulnerable Zones" setting spatial and temporal limits to the application and imposing the threshold of 170 kg ha^{-1} per year as the maximum amount of organic N that can be supplied to fields.

According to EC report on the Implementation of Council Directive 91/676/EEC, the Directive has had some positive effects. In 2012–2015, 13.2% of groundwater monitoring stations exceeded 50 mg l^{-1} of nitrates. This is a slight improvement compared to the previous reporting period 2008–2011, in which 14.4% stations exceeded the same threshold. Regarding surface fresh water monitoring stations, only 1.8% exceeded 50 mg l^{-1}, an improvement compared to the previous reporting period 2008–2011, in which 2.5% stations exceeded the same threshold (EU Commission, 2013).

In addition to nitrogen, phosphorus is also regulated in order to limit its dispersion in the environment, both from agricultural sources and urban sources (wastewater treatment plants - WWTP). Phosphorus (P) losses from agricultural fields can cause eutrophication and ecological deterioration of surface waters. Although there is no general European Phosphorus Regulation or Directive, some European Member States address the agricultural phosphorus losses via national or regional legislation restricting the application of phosphorus. Most of this legislation concerns implementations of the Nitrates Directive (91/676/EEC) in terms of National Action Plans, the Water Framework Directive (2000/60/IEC) in terms of River Basin Management Plans that sets phosphorous concentration limit between 50 and 120 μg l^{-1} (Loyon et al., 2016) and the Industrial Emissions Directive (2010/75/EU) (Amery and Schoumans, 2014).

Livestock utilize phosphorus inefficiently, excreting 60 to 80% of that consumed (Knowlton et al., 2004) and after its land application tends to accumulate in the soil. Only 3–20% reaches the waters as a result of runoff or leaching processes. The combination of high soil content of fertilized phosphorous with manure is more than what crops need; therefore, this promotes losses in the environment (Carpenter et al., 1998).

Recovering phosphorus from livestock waste by using different treatment technologies (P-precipitation, solid-liquid separation) or waste management solutions (waste relocation) can mitigate the excessive phosphorus load in soils (Burton, 2007; Sampat et al., 2018; Szogi and Vanotti, 2009).

In addition to macronutrients, the possible impact of micronutrients, as copper and zinc, used as additives in animal feed must also be considered (Berenguer et al., 2008). As a further example, pigs expel about 72–80% of the ingested copper and 92–96% of the zinc. The field application of livestock manure brings to the soil these metals that tend to accumulate rather than being absorbed by plants (Mantovi et al., 2003). Consequently, they can reach the food chain, with negative effects on environments and human health (Ouyang et al., 2018).

Another impact of livestock farming on soil is the environmental pollution by antibiotics. Antibiotics, especially tetracyclines, sulfonamides, ionophores, pleuromutilins and fluoroquinolones are widely used all over the world, particularly in the farming industry, where they are often used as veterinary drugs and growth promoters for therapeutic purposes (Zhao et al., 2017). Antibiotics together with their metabolites are excreted and reach the environment via different routes depending on pharmacokinetic and pharmacodynamic parameters in the organisms (Sukul et al., 2009), once administered to animals they are absorbed and partially metabolized before being excreted in urine and feces. According to Li et al. (2018) between 30 and 90% of these antibiotics are excreted non-metabolized into the environment through manure. Furthermore, antibiotics administrated to animals allow the selection of antibiotic resistant bacteria (ARBs) to develop in animal intestines, which end up in the manures and eventually in the environment (Xie et al., 2018a). Consequently, when manure and slurry are used as fertilizers, the antibiotics with their metabolites are released to the land, interacting with different soil components and entering the food chain via uptake by plants, translocation into groundwater, or soil surface runoff into surface waters (Sukul et al., 2009).

According to Jechalke et al. (2014), antibiotics tend to accumulate in the soil, interacting with the soil solid phase and are prone to microbial transformation, resulting in a re-transformation in still active metabolites. Soil is a natural source of antibiotics and antibiotic resistance genes (ARGs) since they are important constituents of the environmental resistome. Soil bacteria can acquire resistance from exogenous sources, such as the ARG introduction from animal manures into agricultural soils, through the process of horizontal gene transfer (Xie et al., 2018a; Xie et al., 2018b).

Thus, contamination of antibiotics in the environment by anthropogenic activities increases the competitive advantage of antibiotic resistant bacteria by gradually reshaping the resistome in the environment (Xie et al., 2018a).

Forsberg et al. (2012) reported that some strains of soil bacteria and human pathogens have in common some ARGs, indicating the clinical importance of antibiotic resistance in soils.

The consequence of the selection of these resistant bacteria (Martinez, 2009), is the development of antibiotic-resistant infections that add considerable costs to health care systems.

These infections require the use of antibiotics that are more toxic for the patient and frequently more expensive. Hospital stays became longer and patient can experience a higher incidence of long-term disability (Ventola, 2015).

Consequenlty, in intensive livestock production areas, an appropriate management of manure is necessary, especially to comply with legislation, but also as a matter of social concern (Torrellas et al., 2018).

2.2. Environmental impact on air

Livestock farming impacts even on air through the emissions of ammonia (NH_3) and Green House Gases (GHG) represented by methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), arising simultaneously from animal housing, yards, manure storage and treatment, and land spreading (Baldini et al., 2018; Hou et al., 2016). NH_3 emissions have a severe impact on human health and environment, as they are the major responsible gas in eutrophication and acidification processes, and in particulate in matter formation (Erisman et al., 2008). High concentrations of NH_3 in livestock buildings are dangerous for animal health, since high concentrations of this gas indoor reduce food consumption and animal growth (Seedorf and Hartung, 1999).

IN the EU-28, the contribution of agriculture is more than the 94% of the total antropogenic NH_3 emission (European Environmental Agency, 2017), and it is worth noting that the 75% of NH_3 emissions are originated by management of livestock manure (Webb et al., 2005).

Among all livestock categories, considering the whole chain of manure management, housing, storage, application and grazing, cattle are

responsible for the 53% of NH_3 emissions, pig for 25%, poultry for 15% and others for 7% (Oenema et al., 2007).

Livestock farming is responsible for approximately 15% of the global GHG emission (Gerssen-Gondelach et al., 2017) and ruminants are the major responsible for their release. About 44% of the emissions generated by livestock are represented by CH_4, which is released during enteric fermentation (eructation in ruminants) and from manure decomposition; 27% are in the form of CO_2 emitted during the production and transport of animal products and feed, and 29% are N_2O attributable to manure and fertilizer (Shields and Orme-Evans, 2015).

Undeniably, low feed conversion rates, long reproduction intervals, and the features of their digestive system make ruminants significantly contributing to climate change (Steinfeld and Gerber, 2010).

Eggs, dairy, non-trawling seafood, traditional (non-recirculating) aquaculture, poultry and pork all have much lower emissions per gram of protein than ruminant meat (Tilman and Clark, 2014), that accounts for an estimated 65–77% of the total livestock-related GHG emissions (Gerssen-Gondelach et al., 2017).

Nonetheless, recent studies estimated that the contribution of poultry and pork production to the global livestock GHG emissions is not negligible, being around 9.7 and 9.5%, respectively (Gerber et al., 2013).

Nitrogen, in the form of ammonia (NH_3) and nitrogen oxides ($NO_x = NO + NO_2$) contribute to the formation of secondary particulate matter and tropospheric ozone, both with serious impacts on air quality (Tilman and Clark, 2014). Reactive nitrogen deposition (NH_3, NO_x and N_2O) reduces species richness through eutrophication, acidification, direct foliar impacts, and exacerbation of other stresses (Leip et al., 2015).

Today all those emissions are regulated by international protocols, European directives and national regulations. Control of NH_3 emissions is regulated by the EU National Emissions Ceilings Directive (EC, 2001) resulting from the Gothenburg Protocol (United Nations Convention on Long-range Transboundary Air Pollution – CLRTP,(UNECE, 1999)) while emissions of CH_4 and N_2O from livestock farming are regulated by the Kyoto Protocol under the United Nations Framework Convention on Climate Change – UNFCCC (UN, 1997).

Recently, the European Community adopted the Industrial Emissions Directive 2010/75/EU (EC, 2010), based on the previous Integrated Pollution Prevention and Control Directive IPPC 96/61/EC (EC, 1996), to address the problem of emissions reduction from intensive pig and poultry farming.

The Directive introduces the innovative concept of the integrated approach to prevent and reduce emissions in air, water, soil.

2.3. Impact on crops

Field application of livestock manure supply nutrients and microelements useful to crop growth, but also elements that can accumulate in their tissues and enter in the food chain. Heavy metals tend to be absorbed in very limited amounts, while antibiotic absorption still needs further study (Pan and Chu, 2017). Crop uptake of tetracyclines tends to be easier than sulfonamides and macrolides because they are relatively hydrophilic at pH range of soils (Kumar et al., 2005). The behavior and fate of antibiotics in soil and plants are still unclear (Pan and Chu, 2017).

3. Strategies to mitigate environmental risks

To address all the above mentioned issues, livestock production systems and the related farming activities should be oriented towards more sustainable processes.

The concept of sustainability applied to agricultural/livestock farming systems means that the production levels are maintained within the capacity of the ecosystem supporting it, or in other words: “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (Duru and Therond, 2015).

So, the livestock sector is in a difficult position since it should guarantee high production levels while improving at the same time its environmental performance.

Nowadays, sustainability is a main topic in world leader debates and summits. The most recent action relative to this theme was the endorsement of Seventeen Sustainable Development Goals (SDGs) in September 2015 during the General Assembly of the United Nations. This new Agenda emphasizes a holistic approach to achieving sustainable development for all, covering the period 2016–2030 (and beyond).

The SDGs provides a guiding framework for all countries to develop their own roadmaps towards sustainable development in all of its dimensions. The achievement of those goals is challenging, since the agenda is simultaneously addressing: i) Global food security and health, ii) Equity and growth and iii) Resources and climate.

In this Agenda agriculture was recognized as a key point to reach the expected results, with at least half of the SDGs directly or indirectly linked with the way people produce, process and consume food (Doberman, 2016). To review in detail the contribution of livestock to the SDGs of the UN Agenda 2030, more than 170 stakeholders of the livestock sector met in Panama in 2016 for the 6th multi-stakeholder partnership meeting of the Global Agenda for Sustainable Livestock. From that meeting it appeared evident that although all SDGs were seen as important and relevant to livestock (Fig. 1), 5 out of 17 seem to be the most urgent: SDG 1 (no poverty), SDG 2 (zero hunger), SDG 13 (climate action), SDG 15 (life on land) and SDG 17 (partnership for the goals).

Thus, in a context of resources scarcity and in the perspective of GHG emission reduction, the sector should reach the maximum efficiency in term of production, animal welfare and profitability for the farmer adopting practices and technologies to reduce the environmental impact.

According to Kaufmann (2015), to tackle climate change impact of livestock farming several mitigation strategies should be adopted, such as: i) improving production efficiency, breeding and animal health, ii) using manure management practices to recycle and recover nutrients and energy contained in it, iii) sourcing low emission inputs such as feed, iv) using of feed additives like amino acids, enzymes and gut modulating products such as pre- and probiotics, organic acids and phytobiotic and v) the adoption of new technologies. Summarizing, mitigation potentials can be grouped under three major categories: 1) intensification and the associated structural changes of livestock system; 2) technical and management interventions; and 3) moderation of demand for livestock products (Herrero et al., 2016). This last category, however, seems to be the more unrealistic, due to the global increasing hunger for protein and product of animal origin (Rojas-Downing et al., 2017).

3.1. Technical improvement

Intensification, despite deemed a nonsense, could be a reasonable mitigation strategy. The opportunity to mitigate environmental effects relies on the lower GHG emission potential obtainable per unit of animal product in high-producing animals Vs low-producing animals (Hristov et al., 2013), thus fewer animals are needed to achieve the same production level (Wall et al., 2010).

As reported by Gerber et al. (2013) a dairy cow producing 40 kg milk/day would produce about 50% lower CO_2-eq emissions per kg of edible protein than a cow milking 10 kg/day. Similarly, emissions would be 70% lower from beef cattle gaining 1.5 vs 1.0 kg/day, 40% lower from a growing or fattening pig gaining 900 vs 500 g/day, and 60% lower from a laying hen with 90 vs 50% laying performance.

Both intensification and technical management interventions can be achieved through enhancement of animal genetics, feeding strategies, health and by the adoption of technologies on farms (Herrero et al., 2016; Hristov et al., 2013; Shields and Orme-Evans, 2015).

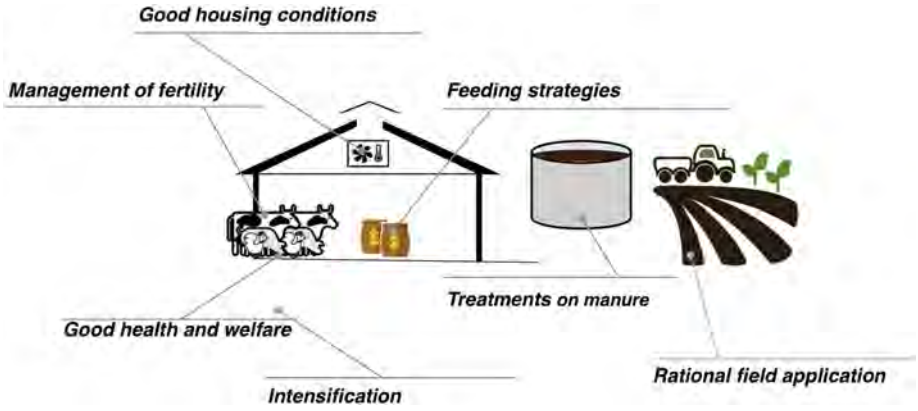

Fig. 1. Current mitigation strategies adopted in livestock farming.

Another technical intervention that can be considered a valid emission mitigation strategy is the accurate management of fertility. Poor fertility means that more animals are required to meet production and reproduction goals (Wilkinson and Garnsworthy, 2017).

In a wider perspective, maintaining health and welfare at optimal levels, could be an effective mitigation strategy, since metabolic changes deriving from impaired health and welfare may increase culling rates, reduced feed efficiency and reduced production (Llonch et al., 2017; Wall et al., 2010). To this end, significant improvements in welfare and productivity can be achieved introducing some simple husbandry changes and innovation (Herrero et al., 2016; Llonch et al., 2017).

Manure treatments are practices that can reduce the environmental impact. The more widespread treatments are represented by solid-liquid separation, anaerobic digestion, and aerobic biological processes (composting and nitrification-denitrification).

Unfortunately, most strategies focus just on a single aspect of the manure management system.

The separation effectively removes nutrients, particularly phosphorus, along with the organic solids, making it easier to delocalize the solid fraction(De Vries et al., 2015). The drawback of this technique is related to the increased emission of NH_3 and GHG (Dinuccio et al., 2008).

Anaerobic digestion reduces GHG emissions compared to the simple storage (Aguirre-Villegas and Larson, 2017), however the digestate could emit more NH_3 during the storage period (Clemens et al., 2006).

Aerobic biological processes, despite their high efficiency in the reduction of gaseous emissions, often are not very common, due to their high service and maintenance costs (Chadwick et al., 2011).

Possible benefits deriving from manure treatments could be threaten by wrong field application.

Land application techniques such as close or open-slot injection or band spreading are preferable to broadcast spreading because they reduce the exposed slurry surface, reducing NH_3 emissions (EC, 2017). A possible disadvantage of slurry injection in the soil could be the increase of NO_2 emission (Hou et al., 2015).

3.2. Dietary changes

For pigs and poultry farming, there are some mandatory indications for technical and management interventions, suitable to reduce the environmental impact. According to the IPPC directive, farmers have to gradually adopt solutions (plants, management and control) defined as "best available techniques (BATs)" and reported in the "Reference Document on Best Available Techniques for The Intensive Rearing of Poultry and Pigs" (BREF -(EC, 2017)).

In particular, this document covers on-farm processes and activities related to nutritional management of poultry and pigs, housing and manure processing and spreading.

Regarding the environmental impact deriving from farming activities (in particular, animals and housing) the BREF provides clear indications on feeding strategies (additives, calibrated diets), and how pig and poultry housing construction and management to reduce gaseous, dust and odor emissions (ventilation, heating/cooling and air treatment systems).

A key-point is on feeding strategies, as they possess a great potential for reducing excretions of nitrogen and phosphorus. For nitrogen the techniques defined in the BAT conclusions are: reducing crude protein content by using a N-balanced diet; multiphase feeding; addition of essential amino acids to a low crude protein diet.

Reported techniques regarding phosphorus are: multiphase feeding; use of feed additives which reduce the total excreted phosphorus (e.g. phytase); use of highly digestible inorganic phosphates for partial replacement of conventional sources of phosphorus in feed. Among the technical and management intervention to reduce emission in ruminants, the most viable option to modify the diet, such as feed additives, chemical inhibitors, and biological approaches in order to alter methanogen populations (Knapp et al., 2014). Other interventions include barn design and manure continuum management (Mendes et al., 2017).

To reduce rumen methanogenesis several approaches are adopted, including the supplementation with anti-metanogenic agents, ionophores (classified as antibiotics), dietary lipids, and electron receptors (usually nitrates). Despite their proven efficacy, these supplementations have detrimental side effects for animal health and welfare (Llonch et al., 2017; Shields and Orme-Evans, 2015).

Furthermore, ionophores and electron receptors have a well-known impact on the environment, being the former responsible for antibiotic resistance phenomena (Hao et al., 2014) and the latter responsible for nitrate pollution in water bodies (Llonch et al., 2017) and nitrous oxide emission in dairy cows (Petersen et al., 2015). Increasing diet digestibility can potentially reduce emissions by 27% to 41% of baseline emissions, amounting to 7.7 to 12 million tons of CO_2-eq (Shields and Orme-Evans, 2015). Unfortunately, increasing the diet digestibility to lower methane emission (McAllister and Newbold, 2008) with starch or with the reduction of particles size can result in an increased risk of acute or subacute ruminal acidosis (Humer et al., 2018b).

Although the integration of additives to diets would decrease CH_4 emissions from manure management by 13%, on the other hand N_2O emissions would be increased by 21% due to diet amendment (Caro et al., 2016).

3.3. Precision livestock farming

Several authors (Berckmans, 2017; Hristov et al., 2013; Llonch et al., 2017; Shields and Orme-Evans, 2015) identified in Precision Livestock

Farming (PLF) a valuable tool to reduce environmental impact of livestock farming.

Few studies focus on the relation between PLF and environmental impact, some focus on ventilation to improve indoor air quality in pig houses (Zhang et al., 2013), measuring procedures for ammonia emission (Vranken et al., 2013), monitoring dust in poultry houses (Demmers et al., 2015; Peña Fernández et al., 2017) and on the application of PLF to obtain environmental friendly poultry production (Bartzanas et al., 2015).

In literature there is no reference to PLF technology specifically developed to reduce the environmental load of livestock farming. Nevertheless, adopting PLF to support management strategies, can lead to the reduction of farms environmental impact. According to Zhang et al. (2013) emissions of NH_3 can be reduced by 60–65% through the application of a PLF system for the management of the ventilation.

The great potential of PLF relies on early warnings, that give the possibility to the farmer, to take actions as soon as first signals of impaired welfare or health appear (Dominiak and Kristensen, 2017). As an example, the use of real time technology (sensors, microphone and preventive diagnostic tools) has the potential to improve animal welfare, increase the technical results, and minimize the environmental footprint (Van Hertem et al., 2017). This potential was validated by several authors with a Life Cycle Assessment approach (Anestis et al., 2015; Chen et al., 2016; Poulopoulou and Chatzipapadopoulos, 2015; Todde et al., 2017).

Behind PLF there is an accurate development of prediction models, that are able to send alert messages to farmers based on animal and environmental input information (health, welfare, behaviours, microclimate), and may help in identifying any deviation from the normal pattern. Thanks to the precise information registered, regarding the status of their animals, farmers can take management corrective actions rapidly.

As discussed previously, the first strategy to reduce emission is to modify the diet. However, these modifications can have serious effects on animal welfare, being toxic or harmful for animals (Llonch et al., 2017; Shields and Orme-Evans, 2015). To overcome these issues, precision feeding (PF) can be used on farms.

PF is a recent concept in livestock production that uses information technology and management processes to optimize economic, social, and environmental farm performance, reducing losses, increasing the product quality, optimizing available resources, thus improving the overall efficiency, meeting each individual animal's or pens of animals' nutrient requirements more accurately (Lovato et al., 2017; White and Capper, 2014).

Several authors include it among PLF practices, being PF and PLF strictly connected in the basic principles and sharing goals and benefits for animals and the environment (Monteiro et al., 2017; van Empel et al., 2016).

Feed is the most important and costly parameter in livestock farming and should be carefully calibrated to fulfill animals' energetic requirements during their lifetime, avoiding over-feeding and the subsequent wasting of nutrients in the environment.

Several studies (Andretta et al., 2016b; Monteiro et al., 2017; Pomar et al., 2014) showed that feeding growing pigs individually with daily tailored diets may be a key tool to optimize the sustainability of pig farming, improving use of nutrients and reducing the excretion of mal-absorbed nutrients (up to 60% for excreted Nitrogen and up to 15% for excreted Phosphorus) without compromising the pig's performance.

Furthermore, since food is individually delivered, PF systems can eliminate competition for food improving animal welfare at the same time (Andretta et al., 2016a; Shields and Orme-Evans, 2015).

Similarly, in cows, feeding behavior is constantly monitored. Rumination is a clear indicator of welfare and in particular rumination time can be reduced by acute stress as well as anxiety, disease and greater stocking density (Soriani et al., 2012).

To this purpose, several PLF devices have been demonstrated to be effective in the control of dairy cows feeding behavior and rumination in intensive and extensive conditions (Chen et al., 2017; Molfino et al., 2017; Paudyal et al., 2017; Pereira et al., 2018; Reiter et al., 2018; Werner et al., 2018). Rumination and feeding behavior depend on the quality of forage and on the level of feed intake and are related to the emission of methane, depending on the quality of the silage, and it is possible to obtain a reduction of CH_4 emission up to 11% (Blaise et al., 2017; Warner et al., 2017). Therefore, managing and continuously controlling these parameters can be the correct strategy to reduce environmental impact.

As stated by Llonch et al. (2017), environmental impact can be reduced by limiting unwanted emissions that can occur when animals face health and stress problems, so, numerous PLF tools have been applied to detect lameness (Hansen et al., 2018; McConnel et al., 2018; Shrestha et al., 2018; Van Nuffel et al., 2015; Zhao et al., 2018), subacute rumen acidosis and impaired rumen functionality (Beauchemin, 2018; Bougouin et al., 2018; Humer et al., 2018a; Neubauer et al., 2018a; Neubauer et al., 2018b; Villot et al., 2018; Zhang et al., 2017a; Zhang et al., 2017b) and mastitis (King et al., 2018; Wang et al., 2017).

Regarding lameness, depending on the severity of the pathology, it may cause environmental impact increases of more than 7–9% for global warming, acidification, eutrophication and fossil fuel depletion. (Chen et al., 2016). According to their results, it is clear that the implementation of real time management systems has the potential to make a positive meaningful contribution on the environmental impact and economic aspect of dairy farming.

Considering mastitis, Hospido and Sonesson (2005) predicted a reduction of 2.5% (GWP) to 5.8% (depletion of abiotic resources) as a consequence of the decrease in clinical (from 25 to 18%) and sub-clinical mastitis rates (from 33 to 15%), making important and relevant the prevention of this pathology.

Among indirect mitigation strategies aiming to reduce the environmental impact of livestock farming there is also the correct management of fertility. It has been estimated that if fertility is maintained at the maximum rates, it is possible to reduce GHG emissions by more than 20% per herd. (Wilkinson and Garnsworthy, 2017). According to several studies, PLF tools can be fundamental in fertility herd management because the correct moment for insemination in cows and sheep can be detected through devices, algorithms, and sensors, increasing conception rates and therefore the success of mitigation strategies (Alhamada et al., 2017; Arcidiacono et al., 2018; Burnett et al., 2017; Crowe et al., 2018; Gu et al., 2017; Sanderink et al., 2017; Silper et al., 2017; Tian et al., 2017). Bell et al. (2014) showed that improved efficiencies of production associated with health and fertility, as well as feed efficiency in dairy farms could reduce GHG emissions of 0.9% per unit of product.

According to Gerber et al. (2013), improving animal health and reducing animal morbidity and mortality has the potential to reduce both CH_4 and N_2O from enteric fermentation and animal manure, providing also benefits to the livestock producer. Undeniably, reduced mortality and morbidity lead to greater saleable output, diluting non-CO_2 emissions per unit product.

Preserving animal health has another environmental benefit as maintaining animals healthy can reduce the use of antibiotics, representing an effective strategy to limit the antibiotic resistance phenomena (Thanner et al., 2016).

Diagnostic tools based on PLF principles (autonomous, continuous, real-time monitoring and control of all aspects of livestock management) can provide a valuable support to accurately manage and monitor animal health (Neethirajan et al., 2017). Behavioral changes that precede or accompany subclinical and clinical diseases may have diagnostic value (Matthews et al., 2016). Technological advances and validation of ideas and prototypes lead to the development of PLF diagnostic tools able to identify problems in the farm without handling or stressing animals and give the possibility to recognize a disease outbreak days before the farmer (King, 2017).

Several PLF diagnostic tool has been developed so far, to recognize respiratory diseases in pigs (Vranken and Berckmans, 2017) and calves (Vandermeulen et al., 2016) through sound analysis, to control of helminth ruminant with image analysis (Vercruysse et al., 2018), and to detect coccidiosis in poultry farms through the analysis of volatile organic compounds emitted by infected birds (Grilli et al., 2018).

All the above mentioned systems allow the early detection of pathologies as soon as the first symptoms appear; in this way it is possible to treat a restricted number of animals (no mass treatment) or to use principles other than antimicrobials (Grilli et al., 2018). This could be a real, environmental friendly, and effective solution to try to solve the problem of antibiotic pollution, that, at the moment, represents a serious problem involving human and animal health (Laxminarayan et al., 2016).

PLF technologies could be also applied to reduce carbon footprint. As reported by Todde et al. (2017) a real time milk analysis and separation system can allow a sensible reduction of energetic costs for cheese production. This system allows the re-organization of milk logistic according to its coagulation property, in order to deliver milk with high casein content directly to the cheese factory, saving about 44% of energy and reducing the emissions of CO_2 by 69%.

Fountas et al. (2015) pointed the attention on profitability of the system, since cost for investment often represents the main obstacle to adopt PLF systems (Hartung et al., 2017).

In this perspective, they highlighted the benefits for the farmers such as the improved decision making, the attraction of young farmers and the positive influence in resolving the analytical shortcomings of the end user (farmer) by transforming raw data into useful information, through the analysis and the expert interpretation (Table 1.)

4. Conclusions

PLF is designed to monitor continuously and in real time animal health and welfare, while environmental impact and climate change mitigation strategies are not its primary goals.

As reported by many authors, livestock environmental impact mitigation can be obtained enhancing productivity levels, reproduction traits, and maintaining a good health.

Regarding antibiotic pollution, the overall banning of antibiotic use in livestock farming is impractical. Therefore, there is the necessity to develop and apply methods and technologies to improve the efficacy of treatments and to decrease the incidence of infections by improving the conditions under which animals are raised.

Table 1
Available PLF tools and potential mitigation effects.

PLF tools	Species	Mitigation effect	Soil	Water	Air	Crops	References
Indoor air quality	▪ Pigs ▪ Poultry	Reduction of: ▪ NH_3			x		▪ Vranken et al. (2013) ▪ Zhang et al. (2013) ▪ Bartzanas et al. (2015) ▪ Demmers et al. (2015) ▪ Peña Fernández et al. (2017))
Ventilation	▪ Poultry	Reduction of: ▪ NH_3			x		▪ Zhang et al. (2013)
Precision feeding	▪ Pigs	Reduction of: ▪ N and P	x	x	x		▪ Pomar et al. (2014) ▪ Andretta et al. (2016a, 2016b) ▪ Monteiro et al. (2017)
Rumination and feeding behavior	▪ Dairy cattle	Reduction of: ▪ CH_4			x		▪ Chen et al. (2017) ▪ Molfino et al. (2017) ▪ Paudyal et al. (2017) ▪ Pereira et al. (2018) ▪ Reiter et al. (2018) ▪ Werner et al. (2018)
Rumen functionality	▪ Dairy cattle	Reduction of: ▪ CH4 ▪ N ad P ▪ Antibiotics	x	x	x	x	▪ Zhang et al. (2017a, 2017b) ▪ Beauchemin (2018) ▪ Bougouin et al. (2018) ▪ Humer et al. (2018a) ▪ Neubauer et al. (2018a, 2018b) ▪ Villot et al. (2018);
Lameness detection	▪ Dairy cattle	Reduction of: ▪ CH4 ▪ N ad P ▪ Antibiotics	x	x	x	x	▪ Hansen et al. (2018) ▪ McConnel et al. (2018) ▪ Shrestha et al. (2018) ▪ Van Nuffel et al. (2015) ▪ Zhao et al. (2018)
Mastitis detection	▪ Dairy cattle	Reduction of: ▪ CH4 ▪ N ad P ▪ Antibiotics	x	x	x	x	▪ Wang et al. (2017) ▪ King et al. (2018);
Fertility management	▪ Dairy cattle ▪ Sheep	Reduction of: ▪ CH4			x		▪ Bell et al., 2014 ▪ Alhamada et al. (2017) ▪ Arcidiacono et al. (2018) ▪ Burnett et al. (2017) ▪ Gu et al. (2017); ▪ Sanderink et al. (2017) ▪ Silper et al. (2017) ▪ Tian et al. (2017) ▪ Crowe et al. (2018)
PLF diagnostic tool for respiratory diseases	▪ Pigs ▪ Calves	Reduction of: ▪ Antibiotics	x	x		x	▪ Vandermeulen et al. (2016) ▪ Van Hertem et al. (2017)
Parasite control	▪ Cattle ▪ Poultry	Reduction of: ▪ Antibiotics	x	x		x	▪ Grilli et al. (2018) ▪ Vercruysse et al. (2018)
Real time milk analysis	▪ Dairy cattle	Reduction of: ▪ GHG			x		▪ Todde et al., 2017

PLF constant monitoring allows the farmer to intervene as soon as animals show the first signs of impaired welfare or pathologies. Rapid intervention, in case of disease, or modification in the management strategy, in case of stress, can actually and effectively improve the animal status. Thus, good productive performance that relies on animal health and welfare achieved through PLF, can mitigate the environmental impact of livestock, reducing also the emergence and dissemination of resistant bacteria in the environment.

Comparing PLF to already verified mitigation strategies, appears to be a valid tool to improve animal health and welfare, overall income and the environment.

Surely, the introduction of new technologies and management techniques poses several issues related to the ethics of food animal production, human workforce, animal-human relationship, and environmental burden relative to the production and operating PLF device on farms. There is a social consensus that agriculture should not be industrialized, but the introduction of simple technologies such as Bluetooth, GPS or RFID in farms offers the opportunity to modify the duration of work, the content and the nature of the tasks carried out by farmers, their mental workload, and the relationship between farmers and their animals.

Currently, few studies reported PLF efficacy in the reduction of the environmental impact, and indeed more studies are necessary to extend the actual potential of PLF as a mitigation strategy. Undeniably, if this potential is confirmed, PLF could enter among the BATs, according to BREF prescriptions.

References

Aguirre-Villegas, H.A., Larson, R.A., 2017. Evaluating greenhouse gas emissions from dairy manure management practices using survey data and lifecycle tools. J. Clean. Prod. 143, 169–179.

Alhamada, M., Debus, N., Lurette, A., Bocquier, F., 2017. Automatic oestrus detection system enables monitoring of sexual behaviour in sheep. Small Rumin. Res. 149, 105–111.

Almeida, C.M.R., Santos, F., Ferreira, A.C.F., Lourinha, I., Basto, M.C.P., Mucha, A.P., 2017. Can veterinary antibiotics affect constructed wetlands performance during treatment of livestock wastewater? Ecol. Eng. 102, 583–588.

Amery, F., Schoumans, O.F., 2014. Agricultural Phosphorus Legislation in Europe: Institute for Agricultural and Fisheries Research (ILVO).

Andretta, I., Pomar, C., Kipper, M., Hauschild, L., Rivest, J., 2016a. Feeding behavior of growing–finishing pigs reared under precision feeding strategies. J. Anim. Sci. 94, 3042–3050.

Andretta, I., Pomar, C., Rivest, J., Pomar, J., Radünz, J., 2016b. Precision feeding can significantly reduce lysine intake and nitrogen excretion without compromising the performance of growing pigs. Animal 10, 1137–1147.

Anestis, V., Bartzanas, T., Kittas, C., 2015. Life cycle inventory analysis for the milk produced in a Greek commercial dairy farm - the link to precision livestock farming. Precision Livestock Farming 2015 - Papers Presented at the 7th European Conference on Precision Livestock Farming, ECPLF 2015, pp. 670–680.

Arcidiacono, C., Porto, S.M.C., Mancino, M., Cascone, G., 2018. A software tool for the automatic and real-time analysis of cow velocity data in free-stall barns: the case study of oestrus detection from ultra-wide-band data. Biosyst. Eng. 173, 157–165.

Baldini, C., Bava, L., Zucali, M., Guarino, M., 2018. Milk production life cycle assessment: a comparison between estimated and measured emission inventory for manure handling. Sci. Total Environ. 625, 209–219.

Bartzanas, T., Papanastasiou, D.K., Skoufos, I., Tzora, A., Fidaros, D., Baxevanou, C., et al., 2015. Environmental friendly poultry production using novel precision livestock techniques. Precision Livestock Farming 2015 - Papers Presented at the 7th European Conference on Precision Livestock Farming, ECPLF 2015, pp. 811–819.

Beauchemin, K.A., 2018. Invited review: current perspectives on eating and rumination activity in dairy cows. J. Dairy Sci. 101, 4762–4784.

Bell, M.J., Garnsworthy, P.C., Stott, A.W., Pryce, J.E., 2014. Effects of changing cow production and fitness traits on profit and greenhouse gas emissions of UK dairy systems. J. Agric. Sci. 153, 138–151.

Berckmans, D., 2014. Precision livestock farming technologies for welfare management in intensive livestock systems. Rev. Sci. Tech. 33, 189–196.

Berckmans, D., 2017. General introduction to precision livestock farming. Anim. Front. 7, 6–11.

Berenguer, P., Cela, S., Santiveri, F., Boixadera, J., Lloveras, J., 2008. Copper and zinc soil accumulation and plant concentration in irrigated maize fertilized with liquid swine manure. Agron. J. 100, 1056–1061.

Blaise, Y., Andriamandroso, A., Heinesch, B., Beckers, Y., Castro Muñoz, E., Lebeau, F., et al., 2017. Influences of feeding behaviour and forage quality on diurnal methane emission dynamics of grazing cows. Precision Livestock Farming '17, pp. 759–769.

Bougouin, A., Ferlay, A., Doreau, M., Martin, C., 2018. Effects of carbohydrate type or bicarbonate addition to grass silage-based diets on enteric methane emissions and milk fatty acid composition in dairy cows. J. Dairy Sci. 101, 6085–6097.

Burnett, T.A., Madureira, A.M.L., Silper, B.F., Fernandes, A.C.C., Cerri, R.L.A., 2017. Integrating an automated activity monitor into an artificial insemination program and the associated risk factors affecting reproductive performance of dairy cows. J. Dairy Sci. 100, 5005–5018.

Burton, C., 2007. The potential contribution of separation technologies to the management of livestock manure. Livest. Sci. 112, 208–216.

Caro, D., Kebreab, E., Mitloehner, F.M., 2016. Mitigation of enteric methane emissions from global livestock systems through nutrition strategies. Clim. Chang. 137, 467–480.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 8, 559–568.

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., et al., 2011. Manure management: implications for greenhouse gas emissions. Anim. Feed Sci. Technol. 166-167, 514–531.

Chen, W., White, E., Holden, N.M., 2016. The effect of lameness on the environmental performance of milk production by rotational grazing. J. Environ. Manag. 172, 143–150.

Chen, Y.J., He, D.J., Fu, Y.X., Song, H.B., 2017. Intelligent monitoring method of cow ruminant behavior based on video analysis technology. Int. J. Agric. Biol. Eng. 10, 194–202.

Clemens, J., Trimborn, M., Weiland, P., Amon, B., 2006. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. Agric. Ecosyst. Environ. 112, 171–177.

Crowe, M.A., Hostens, M., Opsomer, G., 2018. Reproductive management in dairy cows - the future. Ir. Vet. J. 71.

De Montis, A., Modica, G., Arcidiacono, C., 2017. AgInformatics. In: Schintler, L.A., McNeely, C.L. (Eds.), Encyclopedia of Big Data. Springer International Publishing, Cham, pp. 1–4.

De Vries, J.W., Groenestein, C.M., Schröder, J.J., Hoogmoed, W.B., Sukkel, W., Groot Koerkamp, P.W.G., et al., 2015. Integrated manure management to reduce environmental impact: II. Environmental impact assessment of strategies. Agric. Syst. 138, 88–99.

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., Courbois, C., 2016. Livestock to 2020: the next food revolution. Outlook on Agriculture. 30, pp. 27–29.

Demmers, T.G.M., Tong, Q., Rooijakkers, L., Koenders, E., 2015. Monitoring dust concentration in broiler houses. Precision Livestock Farming 2015 - Papers Presented at the 7th European Conference on Precision Livestock Farming, ECPLF 2015, pp. 525–530.

Dinuccio, E., Berg, W., Balsari, P., 2008. Gaseous emissions from the storage of untreated slurries and the fractions obtained after mechanical separation. Atmos. Environ. 42, 2448–2459.

Doberman, A., 2016. Looking forward to 2030: Nitrogen and the sustainable develop. 2016 International Nitrogen Initiative Conference, "Solutions to Improve Nitrogen Use Efficiency for the World", Melbourne, Australia.

Dominiak, K.N., Kristensen, A.R., 2017. Prioritizing alarms from sensor-based detection models in livestock production - a review on model performance and alarm reducing methods. Comput. Electron. Agric. 133, 46–67.

Duru, M., Therond, O., 2015. Livestock system sustainability and resilience in intensive production zones: which form of ecological modernization? Reg. Environ. Chang. 15, 1651–1665.

Ebner, P., 2017. CAFOs and public health: pathogens and manure. Public Health 501, 356.

EC, 1996. Council directive 96/61/EC concerning integrated pollution prevention and control. Off. J. L 257, 26–40.

EC, 2001. Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on National Emission Ceilings for Certain Atmospheric Pollutans. http://eur-lex.europa.eu.

EC, 2010. Directive 2010/75/EU of the European parliament and the council of 24 November on industrial emissions. Off. J. Eur. Union 2010 (L 334/17-119.17.12.2010).

EC, 2017. Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs.

Erisman, J.W., Bleeker, A., Hensen, A., Vermeulen, A., 2008. Agricultural air quality in Europe and the future perspectives. Atmos. Environ. 42, 3209–3217.

EU Commission, 2013. Report from the Commission to the Council and the European Parliament on the Implementation of Council Directive 91/676/EEC Concerning the Protection of Waters Against pollution Caused by Nitrates from Agricultural Sources Based on Member State Reports for the Period 2008–2011. Brussels Google Scholar.

European Environmental Agency (EEA), 2017. Air quality in Europe. Report No 13/2017.

FAO, 2017. The state of food and agriculture. Leveraging Food Systems for Inclusive Rural Transition. Rome, Italy.

FAOSTAT, 2016. FAOSTAT Emissions Database, Agriculture, Agriculture Total.

Forsberg, K.J., Reyes, A., Wang, B., Selleck, E.M., Sommer, M.O.A., Dantas, G., 2012. The shared antibiotic resistome of soil bacteria and human pathogens. Science 337, 1107–1111.

Fournel, S., Rousseau, A.N., Laberge, B., 2017. Rethinking environment control strategy of confined animal housing systems through precision livestock farming. Biosyst. Eng. 155, 96–123.

Gerber, P.J., Henderson, B., Makkar, H.P., 2013. Mitigation of greenhouse gas emissions in livestock production. A Review of Technical Options for Non-CO2 Emissions. FAO.

Gerssen-Gondelach, S.J., Lauwerijssen, R.B.G., Havlík, P., Herrero, M., Valin, H., Faaij, A.P.C., et al., 2017. Intensification pathways for beef and dairy cattle production systems: impacts on GHG emissions, land occupation and land use change. Agric. Ecosyst. Environ. 240, 135–147.

Girard, M., Nikiema, J., Brzezinski, R., Buelna, G., Heitz, M., 2014. A review of the environmental pollution originating from the piggery industry and of the available mitigation technologies: towards the simultaneous biofiltration of swine slurry and methane. J. Environ. Eng. Sci. 9, 80–92.

Grilli, G., Borgonovo, F., Tullo, E., Fontana, I., Guarino, M., Ferrante, V., 2018. A pilot study to detect coccidiosis in poultry farms at early stage from air analysis. Biosystems Engineering.
Gu, J., Wang, Z., Gao, R., Wu, H., 2017. Recognition method of cow behavior based on combination of image and activities. Nongye Jixie Xuebao/Transactions of the Chinese Society for Agricultural Machinery. 48, pp. 145–151.
Halachmi, I., Tello, A.S., Fernández, A.P., van Hertem, T., Sibony, V., Weyl-Feinstein, S., et al., 2015. 5. Discussion: how PLF delivers added value to farmers. Precision Livestock Farming Applications: Making Sense of Sensors to Support Farm Management. Wageningen Academic Publishers, pp. 113–118.
Hansen, M.F., Smith, M.L., Smith, L.N., Abdul Jabbar, K., Forbes, D., 2018. Automated monitoring of dairy cow body condition, mobility and weight using a single 3D video capture device. Comput. Ind. 98, 14–22.
Hao, H., Cheng, G., Iqbal, Z., Ai, X., Hussain, H.I., Huang, L., et al., 2014. Benefits and risks of antimicrobial use in food-producing animals. Front. Microbiol. 5, 288.
Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., et al., 2016. Greenhouse gas mitigation potentials in the livestock sector. Nat. Clim. Chang. 6, 452.
Hooda, P.S., Edwards, A.C., Anderson, H.A., Miller, A., 2000. A review of water quality concerns in livestock farming areas. Sci. Total Environ. 250, 143–167.
Hospido, A., Sonesson, U., 2005. The environmental impact of mastitis: a case study of dairy herds. Sci. Total Environ. 343, 71–82.
Hou, Y., Velthof, G.L., Oenema, O., 2015. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. Glob. Chang. Biol. 21, 1293–1312.
Hou, Y., Bai, Z., Lesschen, J.P., Staritsky, I.G., Sikirica, N., Ma, L., et al., 2016. Feed use and nitrogen excretion of livestock in EU-27. Agric. Ecosyst. Environ. 218, 232–244.
Hristov, A., Ott, T., Tricarico, J., Rotz, A., Waghorn, G., Adesogan, A., et al., 2013. Special topics—mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options. J. Anim. Sci. 91, 5095–5113.
Humer, E., Aschenbach, J.R., Neubauer, V., Kroger, I., Khiaosa-Ard, R., Baumgartner, W., et al., 2018a. Signals for identifying cows at risk of subacute ruminal acidosis in dairy veterinary practice. J. Anim. Physiol. Anim. Nutr. (Berl) 102, 380–392.
Humer, E., Petri, R., Aschenbach, J., Bradford, B., Penner, G., Tafaj, M., et al., 2018b. Invited review: practical feeding management recommendations to mitigate the risk of subacute ruminal acidosis in dairy cattle. J. Dairy Sci. 101, 872–888.
Jechalke, S., Heuer, H., Siemens, J., Amelung, W., Smalla, K., 2014. Fate and effects of veterinary antibiotics in soil. Trends Microbiol. 22, 536–545.
Kamphuis, C., Steeneveld, W., Hogeveen, H., 2015. 2. Economic modelling to evaluate the benefits of precision livestock farming technologies. Precision Livestock Farming Applications: Making Sense of Sensors to Support Farm Management. Wageningen Academic Publishers, pp. 163–171.
Kaufmann, T., 2015. Sustainable livestock production: low emission farm–the innovative combination of nutrient, emission and waste management with special emphasis on Chinese pig production. Anim. Nutr. 1, 104–112.
King, A., 2017. Technology: the future of agriculture. Nature 544, S21–S23.
King, M.T.M., LeBlanc, S.J., Pajor, E.A., Wright, T.C., DeVries, T.J., 2018. Behavior and productivity of cows milked in automated systems before diagnosis of health disorders in early lactation. J. Dairy Sci. 101, 4343–4356.
Knapp, J., 2015. Impact of Trace Mineral Variation within Forages on the Ration Formulation Process.
Knapp, J.R., Laur, G.L., Vadas, P.A., Weiss, W.P., Tricarico, J.M., 2014. Invited review: Enteric methane in dairy cattle production: quantifying the opportunities and impact of reducing emissions. J. Dairy Sci. 97, 3231–3261.
Knowlton, K.F., Radcliffe, J.S., Novak, C.L., Emmerson, D.A., 2004. Animal management to reduce phosphorus losses to the environment1. J. Anim. Sci. 82, E173–E195.
Kumar, K., Gupta, S., Baidoo, S., Chander, Y., Rosen, C., 2005. Antibiotic uptake by plants from soil fertilized with animal manure. J. Environ. Qual. 34, 2082–2085.
Laxminarayan, R., Sridhar, D., Blaser, M., Wang, M., Woolhouse, M., 2016. Achieving global targets for antimicrobial resistance. Science 353, 874–875.
Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S., et al., 2015. Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environ. Res. Lett. 10, 115004.
Li, F., Cheng, S., Yu, H., Yang, D., 2016. Waste from livestock and poultry breeding and its potential assessment of biogas energy in rural China. J. Clean. Prod. 126, 451–460.
Li, X., Liu, C., Chen, Y., Huang, H., Ren, T., 2018. Antibiotic residues in liquid manure from swine feedlot and their effects on nearby groundwater in regions of North China. Environ. Sci. Pollut. Res. Int. 25, 11565–11575.
Lima, E., Hopkins, T., Gurney, E., Shortall, O., Lovatt, F., Davies, P., et al., 2018. Drivers for precision livestock technology adoption: a study of factors associated with adoption of electronic identification technology by commercial sheep farmers in England and Wales. PLoS One 13, e0190489.
Llonch, P., Haskell, M., Dewhurst, R., Turner, S., 2017. Current available strategies to mitigate greenhouse gas emissions in livestock systems: an animal welfare perspective. Animal 11, 274–284.
Lopes, S., Bexiga, R., Araújo, J., Cerqueira, J., Abreu, C., Paredes, C., et al., 2016. Precision livestock farming for reproductive performance optimization: a survey. Food futures: Ethics, Science and Culture. Wageningen Academic Publishers, pp. 3197–3211.
Lovato, G.D., do Vale, M.M., de Oliveira, V., Klein, D.R., Branco, T., 2017. Application of a precision nutrition tool for growing and finishing pigs. Rev. Bras. Zootec. 46, 755–759.
Loyon, L., Burton, C.H., Misselbrook, T., Webb, J., Philippe, F.X., Aguilar, M., et al., 2016. Best available technology for European livestock farms: availability, effectiveness and uptake. J. Environ. Manag. 166, 1–11.
Mallin, M.A., McIver, M.R., Robuck, A.R., Dickens, A.K., 2015. Industrial swine and poultry production causes chronic nutrient and fecal microbial stream pollution. Water, Air, & Soil Pollution. 226, p. 407.
Mantovi, P., Bonazzi, G., Maestri, E., Marmiroli, N., 2003. Accumulation of copper and zinc from liquid manure in agricultural soils and crop plants. Plant Soil 250, 249–257.
Martinez, J.L., 2009. Environmental pollution by antibiotics and by antibiotic resistance determinants. Environ. Pollut. 157, 2893–2902.
Martinez, J., Dabert, P., Barrington, S., Burton, C., 2009. Livestock waste treatment systems for environmental quality, food safety, and sustainability. Bioresour. Technol. 100, 5527–5536.
Matthews, S.G., Miller, A.L., Clapp, J., Plotz, T., Kyriazakis, I., 2016. Early detection of health and welfare compromises through automated detection of behavioural changes in pigs. Vet. J. 217, 43–51.
McAllister, T., Newbold, C., 2008. Redirecting rumen fermentation to reduce methanogenesis. Aust. J. Exp. Agric. 48, 7–13.
McConnel, C.S., McNeil, A.A., Hadrich, J.C., Lombard, J.E., Heller, J., Garry, F.B., 2018. A comparison of a novel time-based summary measure of dairy cow health against cumulative disease frequency. Ir. Vet. J. 71, 7.
Mendes, L.B., Pieters, J.G., Snoek, D., Ogink, N.W.M., Brusselman, E., Demeyer, P., 2017. Reduction of ammonia emissions from dairy cattle cubicle houses via improved management- or design-based strategies: a modeling approach. Sci. Total Environ. 574, 520–531.
Molfino, J., Clark, C.E.F., Kerrisk, K.L., Garciá, S.C., 2017. Evaluation of an activity and rumination monitor in dairy cattle grazing two types of forages. Anim. Prod. Sci. 57, 1557–1562.
Monteiro, A., Bertol, T., De Oliveira, P., Dourmad, J.-Y., Coldebella, A., Kessler, A., 2017. The impact of feeding growing-finishing pigs with reduced dietary protein levels on performance, carcass traits, meat quality and environmental impacts. Livest. Sci. 198, 162–169.
Neethirajan, S., Tuteja, S.K., Huang, S.T., Kelton, D., 2017. Recent advancement in biosensors technology for animal and livestock health management. Biosens. Bioelectron. 98, 398–407.
Neubauer, V., Humer, E., Kroger, I., Braid, T., Wagner, M., Zebeli, Q., 2018a. Differences between pH of indwelling sensors and the pH of fluid and solid phase in the rumen of dairy cows fed varying concentrate levels. J. Anim. Physiol. Anim. Nutr. (Berl) 102, 343–349.
Neubauer, V., Humer, E., Kroger, I., Meissl, A., Reisinger, N., Zebeli, Q., 2018b. Technical note: changes in rumen mucosa thickness measured by transabdominal ultrasound as a noninvasive method to diagnose subacute rumen acidosis in dairy cows. J. Dairy Sci. 101, 2650–2654.
Oenema, O., Oudendag, D., Velthof, G.L., 2007. Nutrient losses from manure management in the European Union. Livest. Sci. 112, 261–272.
Ouyang, W., Wang, Y., Lin, C., He, M., Hao, F., Liu, H., et al., 2018. Heavy metal loss from agricultural watershed to aquatic system: a scientometrics review. Sci. Total Environ. 637-638, 208–220.
Pan, M., Chu, L., 2017. Fate of antibiotics in soil and their uptake by edible crops. Sci. Total Environ. 599, 500–512.
Paudyal, S., Maunsell, F.P., Richeson, J.T., Risco, C.A., Donovan, D.A., Pinedo, P.J., 2017. Rumination time and monitoring of health disorders during early lactation. Animal 1–9.
Peña Fernández, A., Tong, Q., Youssef Ali Amer, A., Norton, T., Demmers, T., Berckmans, D., 2017. Monitoring Dust Concentration in Poultry Houses Using Broiler Activity and Ventilation Rate.
Pereira, G.M., Heins, B.J., Endres, M.I., 2018. Technical note: validation of an ear-tag accelerometer sensor to determine rumination, eating, and activity behaviors of grazing dairy cattle. J. Dairy Sci. 101, 2492–2495.
Petersen, S.O., Hellwing, A.L.F., Brask, M., Højberg, O., Poulsen, M., Zhu, Z., et al., 2015. Dietary nitrate for methane mitigation leads to nitrous oxide emissions from dairy cows. J. Environ. Qual. 44, 1063–1070.
Pomar, C., Pomar, J., Dubeau, F., Joannopoulos, E., Dussault, J.-P., 2014. The impact of daily multiphase feeding on animal performance, body composition, nitrogen and phosphorus excretions, and feed costs in growing–finishing pigs. Animal 8, 704–713.
Poulopoulou, I., Chatzipapadopoulos, F., 2015. Saving resources using a cloud livestock farm management tool. Precision Livestock Farming 2015 - Papers Presented at the 7th European Conference on Precision Livestock Farming, ECPLF 2015, pp. 276–282.
Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., et al., 2018. Trends in global agricultural land use: implications for environmental health and food security. Annu. Rev. Plant Biol. 69, 789–815.
Reiter, S., Sattlecker, G., Lidauer, L., Kickinger, F., Öhlschuster, M., Auer, W., et al., 2018. Evaluation of an ear-tag-based accelerometer for monitoring rumination in dairy cows. J. Dairy Sci. 101, 3398–3411.
Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T., Woznicki, S.A., 2017. Climate change and livestock: impacts, adaptation, and mitigation. Clim. Risk Manag. 16, 145–163.
Sampat, A.M., Martín-Hernández, E., Martín, M., Zavala, V.M., 2018. Technologies and logistics for phosphorus recovery from livestock waste. Clean Techn. Environ. Policy 1–17.
Sanderink, F.E.P., Gerritsen, J.W., Groot Koerkamp, P.W.G., van Mourik, S., 2017. Automatic detection of oestrus cows via breath sampling with an electronic nose: a pilot study. Biosyst. Eng. 156, 1–6.
Seedorf, J., Hartung, J., 1999. Survey of ammonia concentrations in livestock buildings. J. Agric. Sci. 133, 433–437.
Shields, S., Orme-Evans, G., 2015. The impacts of climate change mitigation strategies on animal welfare. Animals 5, 361–394.
Shrestha, A., Loukas, C., Le Kernec, J., Fioranelli, F., Busin, V., Jonsson, N., et al., 2018. Animal lameness detection with radar sensing. IEEE Geosci. Remote Sens. Lett. 1–5.
Silper, B.F., Madureira, A.M.L., Polsky, L.B., Soriano, S., Sica, A.F., Vasconcelos, J.L.M., et al., 2017. Daily lying behavior of lactating Holstein cows during an estrus synchronization protocol and its associations with fertility. J. Dairy Sci. 100, 8484–8495.

Soriani, N., Trevisi, E., Calamari, L., 2012. Relationships between rumination time, metabolic conditions, and health status in dairy cows during the transition period1. J. Anim. Sci. 90, 4544–4554.
Steinfeld, H., Gerber, P., 2010. Livestock production and the global environment: consume less or produce better? Proc. Natl. Acad. Sci. U. S. A. 107, 18237–18238.
Sukul, P., Lamshöft, M., Kusari, S., Zühlke, S., Spiteller, M., 2009. Metabolism and excretion kinetics of 14C-labeled and non-labeled difloxacin in pigs after oral administration, and antimicrobial activity of manure containing difloxacin and its metabolites. Environ. Res. 109, 225–231.
Szogi, A.A., Vanotti, M.B., 2009. Removal of phosphorus from livestock effluents. J. Environ. Qual. 38, 576–586.
Thanner, S., Drissner, D., Walsh, F., 2016. Antimicrobial resistance in agriculture. MBio 7, e02227-15.
Tian, F., Cao, D., Dong, X., Zhao, X., Li, F., Wang, Z., 2017. Behavioral features recognition and oestrus detection based on fast approximate clustering algorithm in dairy cows. IOP Conference Series: Earth and Environmental Science. 69.
Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522.
Todde, G., Caria, M., Gambella, F., Pazzona, A., 2017. Energy and carbon impact of precision livestock farming technologies implementation in the milk chain: from dairy farm to cheese factory. Agriculture 7.
Torrellas, M., Burgos, L., Tey, L., Noguerol, J., Riau, V., Palatsi, J., et al., 2018. Different approaches to assess the environmental performance of a cow manure biogas plant. Atmos. Environ. 177, 203–213.
Tullo, E., Fontana, I., Diana, A., Norton, T., Berckmans, D., Guarino, M., 2017. Application note: labelling, a methodology to develop reliable algorithm in PLF. Comput. Electron. Agric. 142, 424–428.
UN, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. NY, USA.
UNECE, 1999. Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg protocol).
van Empel, M., Makkar, H.P., Dijkstra, J., Lund, P., 2016. Nutritional, technological and managerial parameters for precision feeding to enhance feed nutrient utilization and productivity in different dairy cattle production systems. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, p. 11.
Van Grinsven, H., Ten Berge, H., Dalgaard, T., Fraters, B., Durand, P., Hart, A., et al., 2012. Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under the nitrates directive: a benchmark study. Biogeosciences 9, 5143–5160.
Van Hertem, T., Rooijakkers, L., Berckmans, D., Peña Fernández, A., Norton, T., Berckmans, D., et al., 2017. Appropriate data visualisation is key to precision livestock farming acceptance. Comput. Electron. Agric. 138, 1–10.
Van Nuffel, A., Zwertvaegher, I., Van Weyenberg, S., Pastell, M., Thorup, V.M., Bahr, C., et al., 2015. Lameness detection in dairy cows: part 2. Use of sensors to automatically register changes in locomotion or behavior. Animals 5, 861–885.
Vandermeulen, J., Bahr, C., Johnston, D., Earley, B., Tullo, E., Fontana, I., et al., 2016. Early recognition of bovine respiratory disease in calves using automated continuous monitoring of cough sounds. Comput. Electron. Agric. 129, 15–26.
Ventola, C.L., 2015. The Antibiotic Resistance Crisis: Part 1: Causes and Threats. P T. 40 pp. 277–283.
Vercruysse, J., Charlier, J., Van Dijk, J., Morgan, E.R., Geary, T., von Samson-Himmelstjerna, G., et al., 2018. Control of helminth ruminant infections by 2030. Parasitology 1–10.
Villot, C., Meunier, B., Bodin, J., Martin, C., Silberberg, M., 2018. Relative reticulo-rumen pH indicators for subacute ruminal acidosis detection in dairy cows. Animal 12, 481–490.
Vranken, E., Berckmans, D., 2017. Precision livestock farming for pigs. Anim. Front. 7, 32–37.
Vranken, E., Cabaraux, J.-F., Berckmans, D., 2013. Development of a simplified measuring procedure for ammonia emission from agricultural constructions. Precision Livestock Farming '13, p. 899.
Wall, E., Simm, G., Moran, D., 2010. Developing breeding schemes to assist mitigation of greenhouse gas emissions. Animal 4, 366–376.
Wang, W., Li, C., Wang, W., Jiang, H., 2017. Innovation, practical benefits and prospects for the future development of automatic milking systems. Front. Agric. Sci. Eng. 4, 37–47.
Warner, D., Bannink, A., Hatew, B., van Laar, H., Dijkstra, J., 2017. Effects of grass silage quality and level of feed intake on enteric methane production in lactating dairy cows1. J. Anim. Sci. 95, 3687–3699.
Webb, J., Menzi, H., Pain, B., Misselbrook, T., Dämmgen, U., Hendriks, H., et al., 2005. Managing ammonia emissions from livestock production in Europe. Environ. Pollut. 135, 399–406.
Werner, J., Leso, L., Umstatter, C., Niederhauser, J., Kennedy, E., Geoghegan, A., et al., 2018. Evaluation of the RumiWatchSystem for measuring grazing behaviour of cows. J. Neurosci. Methods 300, 138–146.
White, R.R., Capper, J.L., 2014. Precision diet formulation to improve performance and profitability across various climates: modeling the implications of increasing the formulation frequency of dairy cattle diets. J. Dairy Sci. 97, 1563–1577.
Wilkinson, J., Garnsworthy, P., 2017. Impact of diet and fertility on greenhouse gas emissions and nitrogen efficiency of milk production. Livestock 22, 140–144.
Xie, W.-Y., Shen, Q., Zhao, F.J., 2018a. Antibiotics and antibiotic resistance from animal manures to soil: a review. Eur. J. Soil Sci. 69, 181–195.
Xie, W.-Y., Yuan, S.-T., Xu, M.-G., Yang, X.-P., Shen, Q.-R., Zhang, W.-W., et al., 2018b. Long-term effects of manure and chemical fertilizers on soil antibiotic resistome. Soil Biol. Biochem. 122, 111–119.
Zhang, G., Kai, P., Zong, C., 2013. Precision ventilation to improve indoor air quality and reduce ammonia emission of pig production housing. Precision Livestock Farming 2013 - Papers Presented at the 6th European Conference on Precision Livestock Farming, ECPLF 2013, pp. 883–892.
Zhang, L., Lu, J., Nogami, H., Okada, H., Itoh, T., Arai, S., 2017a. Solid-state pH sensor prototype for real-time monitoring of the rumen pH value of Japanese cows. Microsyst. Technol. 24, 457–463.
Zhang, L., Lu, J., Okada, H., Nogami, H., Itoh, T., Arai, S., 2017b. Low-power highly sensitive pH sensor with μ dots protective structures for monitoring rumen in cows in real-time. IEEE Sensors J. 17, 7281–7289.
Zhao, X., Wang, J., Zhu, L., Ge, W., Wang, J., 2017. Environmental analysis of typical antibiotic-resistant bacteria and ARGs in farmland soil chronically fertilized with chicken manure. Sci. Total Environ. 593-594, 10–17.
Zhao, K., Bewley, J.M., He, D., Jin, X., 2018. Automatic lameness detection in dairy cattle based on leg swing analysis with an image processing technique. Comput. Electron. Agric. 148, 226–236.









MITIGATING EMISSIONS FROM CALIFORNIA'S DAIRIES

Considering the Role of Anaerobic Digesters in Mitigating Emissions from California's Dairies

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I. Introduction

This white paper addresses several contested and commonly-raised issues related to the promotion of dairy digesters as the primary policy mechanism to reduce greenhouse gas (GHG) emissions from dairy operations in California. The purpose of this paper is to provide context for ongoing conversations regarding the role of dairy digesters in California's Low Carbon Fuel Standard (LCFS), as well as potential dairy methane regulations pursuant to SB 1383 (2016). The report analyzes and offers key takeaways for each of the following issues:

- The variety of manure management systems used on dairies and their respective prevalence and emissions;
- The appropriateness and applicability of the life cycle analysis used by the Air Resources Board (CARB) to evaluate the carbon intensity of fuels derived from dairy biogas in the LCFS program;
- The relationship between LCFS incentives for dairy biogas and dairy consolidation;
- The risk of emissions leakage were CARB to regulate dairy methane;
- The role of LCFS credits for fuels derived from dairy biogas in meeting California's climate targets.

II. Manure Management Systems and GHG Emissions

California's Low Carbon Fuel Standard (LCFS) assumes that liquid manure management systems are the standard practice for dairies and, as a result, that they are the appropriate baseline against which to compare a given climate intervention. By setting liquid manure management systems as the reference scenario, emissions reductions from digesters appear to be relatively higher because this method of manure management generates more emissions that can then be captured. While liquid manure management systems are the predominant approach in California, they are one of the more polluting manure management systems available. They are also less common in other dairying states. Dairies in all states, however, are eligible for LCFS credits and shaped by that program's incentives. This section describes how common liquid manure management systems are and what alternatives are available.

The major sources of GHG emissions in the dairying process are feed production, enteric fermentation, and manure management. These are present in all dairy operations to varying degrees. The relative contributions of feed, enteric fermentation, and manure management vary based on the practices employed. Emissions from feed production, for example, can be especially high in "high-yielding milk production systems."[2] Manure management emissions can vary significantly based on the scale of the operations and the specific practices employed, while enteric emissions tend to scale proportionally to herd size. While estimates of relative contributions vary, methane from enteric fermentation and feed production are generally thought to be the largest sources, followed by manure management.

A. Common Manure Management Systems

Livestock produce waste. Historically, when dairy farms were pasture-based and much smaller than the contemporary American dairy, cows deposited their waste in the pasture where it would degrade and incorporate into the soil over time. As dairy industrialized over the course of the 20th century, and particularly as the industry consolidated over the past 30 years, the amount of waste produced at the largest operations has become too great for the available land to absorb safely. When manure is

2 M. Henriksson, C. Cederberg, and C. Swensson, *Carbon Footprint and Land Requirement for Dairy Herds Rations: Impacts of Feed Production Practices and Regional Climate Variations*, 8 Animal 8, 1329 (2014), https://doi.org/10.1017/S1751731114000627.

land-applied above agronomic rates, or above the rate at which the crops and soil can absorb nutrients, it results in contamination to local waterways. As a result, larger-scale dairy (and other livestock) operations have had to develop new methods that allow them to collect the waste and store it until land is available and weather conditions allow for it to be safely disposed of.[3]

Manure management systems can be divided into three components: "1) manure handling, the method of manure removal or management in animal housing or grazing areas; 2) manure storage, the infrastructure and method for holding manure until its application; and 3) manure application and manner in which manure is land applied, typically for crop fertilization."[4] Different practices are available to dairies at each step in this process.

Different approaches are more suitable to different operations based on scale and location. The scale of the operation impacts the choice of manure management system for several reasons. On large-scale operations, there is generally inadequate pastureland available for grazing and inadequate cropland for manure application. As a result, feed must be purchased[5] and manure must be stored until the conditions are right and the land is available for spreading. The manure lagoon is the dominant form of manure storage for these large-scale operations. Anaerobic lagoons are designed minimize the amount of land required for spreading.[6] Concentrating manure production creates risks to air and water[7] so manure transport, storage, and spreading must all be carefully managed.

At the smaller-scale, dairies typically graze their cows and supplement with little to no purchased feed. Manure is produced at quantities and concentrations less likely to cause nutrient pollution and is typically land-applied on a regular basis (though some small and mid-sized farms may also use short-term storage for manure).

A key point of differentiation between dairy manure management systems is manure consistency: Some farms maintain their manure in solid form and others liquify the manure. Larger farms with manure lagoons tend to transport manure in liquid form, often using flush systems. Smaller farms more often maintain solid manure that can be land-applied daily.[8]

The specific practices adopted throughout the different parts of the manure management system affect one another as well, with the initial choice of manure consistency imposing decisive constraints.[9] One study found "clear patterns of related strategies, largely determined by the handling of manure as a liquid, slurry, or solid."[10] The diagram below was developed out of a survey of Wisconsin dairies to study how certain practices tend to lead to others. For example, larger operations tend to use freestall barns. The survey found that 68% of operations using freestall barns select a skid steer over various alternatives to collect

3 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, J. of Cleaner Production 143 (2017) 169e179, http://dx.doi.org/10.1016/j.jclepro.2016.12.133. This Wisconsin survey found that farms had more land per "animal unit" than larger farms, likely because "neither large farms nor permitted facilities have the sufficient land to agronomically recycle excreted P (Table C.4), suggesting that land is not increasing proportionally to the number of cows as farms grow."

4 Meredith T. Niles et al., *Manure Management Strategies Are Interconnected with Complexity Across U.S. Dairy Farms*, 17 PLoS One 6 (2022), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9165779/.

5 Food and Water Watch, *The Economic Cost of Food Monopolies: The Dirty Dairy Racket* (January 2023), https://www.foodandwaterwatch.org/wp-content/uploads/2023/01/RPT2_2301_EconomicCostofDairy-WEB.pdf ("Larger farms are less likely to graze their cattle on pasture and instead rely on purchased feed, which is the single largest source of livestock industry greenhouse gas emissions"); *see also* U.N. Food and Agriculture Organization, *Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities* (2013), https://www.fao.org/3/i3437e/i3437e.pdf ("Feed production and processing, and enteric fermentation from ruminants are the two main sources of emissions, representing 45 and 39 percent of sector emissions, respectively. Manure storage and processing represent 10 percent. The remainder is attributable to the processing and transportation of animal products.")

6 Missouri State University Extension, Lagoons for Storage/Treatment of Dairy Waste, https://extension.missouri.edu/publications/wq304.

7 *See* A. Naranjo et al., *Greenhouse Gas, Water, and Land Footprint Per Unit of Production of the California Dairy Industry Over 50 Years*, 103 J. Dairy Sci. 4 (Feb. 6, 2020), https://www.journalofdairyscience.org/article/S0022-0302(20)30074-6/fulltext

8 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, *supra* note 3.

9 *See generally* Meredith T. Niles et al., *Manure Management Strategies Are Interconnected with Complexity Across U.S. Dairy Farms*, *supra* note 4.

10 *Id.*

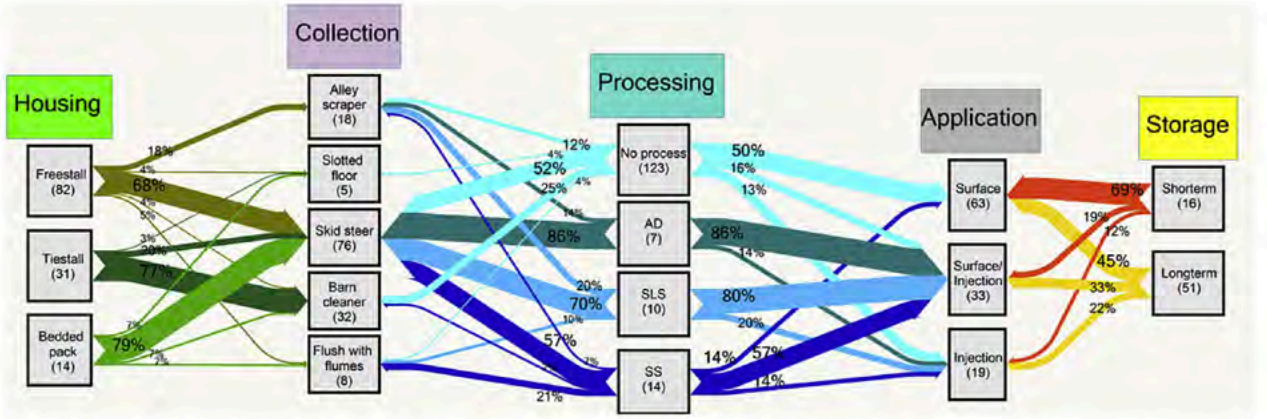

Fig. 3. Probabilities (%) of adopting a manure management practice (rectangular boxes) given the adoption of another practice. Values in parenthesis represent number of farms. Totals <100% indicate missing values.

FIGURE 1 Via H.A. Aguirre-Villegas and R.A. Larson, Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using SurveyData and Lifecycle Tools, Journal of Cleaner Production 143 (2017) 169e179, http://dx.doi.org/10.1016/j.jclepro.2016.12.133.

manure. Smaller operations tend to use tiestall barns and the survey found that 77% of tiestall barns select a barn cleaner over various alternatives to collect manure. The kinds of collection processes in turn impact the ways that manure can be efficiently stored, processed, and so on.

The fact that manure management processes are interrelated matters because it determines how flexible and open to change these systems are. The Wisconsin study came to the crucial conclusion that: "the inter-related nature of these systems demonstrates how MMS [Manure Management Systems] are often locked in across farm systems through structural and equipment investments... This suggests that changing MMS is complex and requires not only a shift in the potential handling method, but also potential shifts in storage and application equipment as well. Flush handling can't easily shift to scraper handling, without potentially shifting from liquid to a slurry and then investing in a surface application tank or truck system."[11]

The study also found that dairies using solid manure management systems were "highly heterogenous, where farmers may have a suite of alternative manure management strategies available to them, and substitution is viable."[12] The study found that dairies using liquid manure management systems, on the other hand, had "very few substitutes in their MMS, suggesting greater investment in certain infrastructures, which are not easily changed."[13]

This of particular concern in California, where liquid manure management systems dominate. It is not good news for advocates interested in relying on technological changes to reduce emissions from the dairy industry. It means that mitigation interventions can be constrained by decisions about manure consistency and ultimately by the scale of operation. This means that taking dairy decarbonization seriously requires reconsidering the federal and state policies that have consistently favored industrial-scale facilities.

1. Prevalence of Different Manure Management Systems

Confinement dairies with liquid manure management systems are more common in California than nationally. Manure lagoons are used on 58%

11 *Id.*
12 *Id.*
13 *Id.*

Manure Share (MS) and Methane Conversion Factor (MCF) of Manure Management Systems

Waste Management System	Pasture	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit
MS by system and location						
■ U.S. Average	7%	15%	23%	21%	32%	2%
■ California	1%	11%	9%	21%	58%	0%
■ Wisconsin	7%	12%	42%	24%	12%	4%
MCF by system and location						
■ U.S. Average	1.2%	0.2%	2.6%	28.6%	69.9%	28.6%
■ California	1.5%	0.5%	4.0%	35%	75%	35%
■ Wisconsin	1.0%	0.1%	2.0%	22%	66%	22%

FIGURE 2 Via Jeongwoo Han, Marianne Mintz, and Michael Wang, Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6, note 13.

percent of dairies in California and 32% percent of dairies nationally.[14] In Tulare and Glenn Counties specifically, one survey found that 96% of dairies use storage or treatment ponds.[15] A 2011 survey of California dairies found that most had freestalls for housing and collect manure thorough flushing and/or daily scraping.[16]

Wisconsin is the number two state for dairy nationally after California, but the practices of Wisconsin dairies look different than those in California. Manure lagoons and liquid manure management systems are less common than in California. A survey of Wisconsin dairies found that they are prevalent on larger operations[17] but uncommon on smaller farms. Because Wisconsin had more smaller farms at the time of the survey, liquid systems were less common overall. 70% of permitted (larger) facilities used liquid manure management systems while 80% of smaller farms used solid manure management systems. Smaller Wisconsin operations tend to land-apply manure immediately, while the largest permitted operations rely heavily on long-term storage (lagoons). The major processing techniques used in the Wisconsin survey were: sand separation (50%), anaerobic digestion and solid-liquid separation (20%), solid-liquid separation and sand separation (10%).

Note that a key difference between dairies in California and colder climates like Wisconsin is that land application is rarely possible during the winter, because the ground is frozen. Instead, permitted facilities typically land apply in batches in the spring and the fall. Additionally, concerns around runoff due to rains when manure is land applied several times a week may be reduced due to California's drier climate.

California's model of dairying generally and manure management specifically has proliferated

14 Jeongwoo Han, Marianne Mintz, and Michael Wang, *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6*, Argonne National Laboratory (September 2011), https://publications.anl.gov/anlpubs/2011/12/71742.pdf.

15 D. Meyer et al., *Survey of Dairy Housing and Manure Management Practices in California*, 94 J. Dairy Sci. 9, 4744 (Sept. 2011), https://www.journalofdairyscience.org/article/S0022-0302(11)00489-9/fulltext.

16 H.A. Aguirre-Villegas and R.A. Larson, citing Meyer et al. 2011.

17 *Id.* ("large and permitted facilities handle slurry and liquid manure and have freestalls.")

in other states in recent years.[18] Some analyses distinguish between "traditional" dairying states like New York and Wisconsin, which still tend to have smaller farms on average, and "modern" dairying states, which tend to be in the West where the California-model has become more common.

2. *GHG Impacts of Different Manure Management Systems*

The variability in the climate, geography, scale, and practices of American dairies makes it challenging to make general comparisons regarding their emissions. Due in part to the many possible permutations of these practices and scales, there are limited comparative studies of emissions from small, pasture-based operations and large-scale dairy CAFOs. However, one of the few such studies "indicated that for the metric of milk production per farmland area, the environmental impact (in relation to potential resource utilization and pollutants) was lower for the pasture-based system than the confinement system. Furthermore, the pasture-based system had a lower total environmental impact compared with the confinement system."[19]

The same study acknowledged, however, that "some studies suggested that economies of scale and efficient management could put large farms in a better environmental position (Saam et al., 2005)."[20] The California dairy industry regularly makes this claim, touting its increasing efficiency as decreasing emissions intensity per cow. However, this perspective "misses the holistic economic and environmental impact of concentrating production on larger farms."[21]

Scale, of course, affects emissions and other environmental impacts on dairies. The volume of manure produced has direct implications for GHG emissions. Not only does more manure mean more emissions, but it typically means longer storage periods during which manure can emit GHGs.[22]

The manure form/consistency also has direct implications for GHG emissions. For example, "solid manures have less available water and are usually stored in stock piles that promote aeration, which reduces CH4 emissions. Liquid manures are stored on pits that promote anaerobic conditions, increasing CH4 emissions. Larger dilutions of manure imply larger manure volumes to be handled, which affects GHG emissions due to increased energy consumption"[23] Liquifying manure using flush systems can reduce ammonia emissions in the barn, but increases methane emissions.[24]

18 Rick Barrett and Lee Bergquist, *Industrial Dairy Farming is Taking Over in Wisconsin, Crowding Out Family Operations and Raising Environmental Concerns*, Milwaukee Journal Sentinel (Dec. 6, 2019), https://www.jsonline.com/in-depth/news/special-reports/dairy-crisis/2019/12/06/industrial-dairy-impacts-wisconsin-environment-family-farms/43186671002/ ("...massive milking operations, popularized in California, shatter the traditional model of Wisconsin farms. With so many cattle, they run the risk of contaminating groundwater and overwhelming lakes, rivers and streams with runoff pollution while making it harder for smaller farms to compete."); Lilli LeGardeur, *Milk It*, Louisiana Life (Jan. 4, 2008), https://www.louisianalife.com/milk-it/ ("90 percent of Louisiana dairy farms are "pasture-based," ... In confinement dairying – a relatively new style popular out West – cows are fenced inside dirt-floor lots and have all their food delivered ... Confinement dairying, by the way, is also called California-style dairying, after the state where it originated. So, to a Louisiana dairy farmer, those TV commercials depicting California cows gallivanting in fields of clover are doubly irritating. They know that most of those California critters never set foot in a grassy pasture. As one local farmer so adroitly observed, "Happy Cows – my ass.""); David Barboza, *America's Cheese State Fights to Stay that Way, Wisconsin Struggles to Keep Pace with West*, New York Times (June 28, 2001), https://www.nytimes.com/2001/06/28/business/america-s-cheese-state-fights-stay-that-way-wisconsin-struggles-keep-pace-with.html ("With the California-style operations, as they are called, about 2,000 megafarms, with an average herd size of 650 cows, produce more milk than 18,000 mostly smaller farms in Wisconsin, where the average herd is 80.")

19 Alice Moscovici Joubran et al., *Invited Review: A 2020 Perspective on Pasture-Based Dairy Systems and Products*, 104 J. Dairy Sci. 7, 7364 (July 2021), citing O'Brien et al., 2012; O'Brien and Hennessy, 2017, https://www.sciencedirect.com/science/article/pii/S0022030221005166.

20 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, *supra* note 3.

21 Claire Kelloway, *Fewer Global Dairy Corporations Drive Overproduction and Pollution, Harming Small Farmers, Report Finds*, Food & Power (July 18, 2020), https://www.foodandpower.net/latest/2020/06/18/fewer-global-dairy-corporations-drive-overproduction-and-pollution-harming-small-farmers-report-finds?rq=dairy.

22 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*.

23 *Id*. at 172.

24 Cal. Air Res. Board, Short-Live Climate Pollutant Reduction Strategy (March 2017), https://ww2.arb.ca.gov/sites/default/files/2020-07/final_SLCP_strategy.pdf; Alice Rocha, *How Handling Manure Waste from Dairy Cattle Impacts Greenhouse Gas Emissions and Climate Impacts*, UC Davis CLEAR Center (May 14, 2021), https://clear.ucdavis.edu/explainers/how-handling-manure-waste-dairy-cattle-impacts-greenhouse-gas-emissions-and-climate ("Scraping and vacuuming, on the other hand, may leave thin layers of manure on the ground which can come in contact with cattle urine causing the emission of ammonia. The latter is generated by a reaction between urea in urine and the urease enzyme in manure.")

The Wisconsin survey modeled emissions from the dairy industry there, and found that:

- Long-term storage is common on larger farms handling liquid manure, which generally increases GHG emissions.
- A natural crust formation during storage creates aerobic conditions on the surface and reduces wind velocity, decreasing methane and ammonia emissions respectively, but increasing nitrous oxide emissions. Total GHG emissions are higher without this crust.
- Frequent manure application reduces both GHG and ammonia emissions from storage due to the shorter retention times and the reduced surface area. These emissions can increase, however, during application as more ammoniacal nitrogen and volatile solids are available to promote nitrous oxide, methane, and ammonia release. Daily or weekly application can also lead to runoff and leaching during precipitation events or snowmelt, resulting in potential eutrophication and loss of valuable nutrients.[25]

Regarding anaerobic digestion in particular, the Wisconsin survey found that:

- Out of the reported processing technologies, anaerobic digestion is the most effective to reduce GHG emissions from both energy and manure.
- Emission reductions from energy come from the displaced emissions that biogas-based electricity has when replacing grid electricity.
- Reductions from manure are mostly from the capture of methane during digestion which is then converted to carbon dioxide during combustion, as well as the reduction of carbon available to produce methane in storage.
- Solid-liquid separation further reduces GHG emissions as fewer volatile solids enter long term storage within the liquid fraction.
- After digestion, ammonia emissions are increased during digestate storage because: 1) mineralization in the digester increases ammoniacal nitrogen, and 2) the inexistence of a natural crust on the storage surface reduces the physical barrier that prevents aeration.[26]

B. Enteric and Other Non-Manure Management Emissions

Reducing emissions from manure management is critical. However, manure management contributes fewer emissions than enteric fermentation.[27] The reduction of enteric emissions has generally been sidelined as a more challenging technical problem because it is based on the natural feature of the ruminant digestive system. Considering the impact of various interventions on both enteric and manure management emissions, however, should be a component of any effort to meet climate targets for dairy.

While enteric fermentation and manure management primarily generate methane, the substantial emissions from feed production include nitrous oxide which is "emitted from cultivated soils and significantly influenced by cultivation practices, especially nitrogen (N) fertilization."[28] Emissions from feed vary based on the amount of feed imported and the composition of rations which themselves can vary based on geography and climate. Dairy feed can be homegrown—either on pasture or harvested corn or grass fermented as silage—or imported (including concentrates, silage, byproducts, and other grains).

Most dairy cows in California eat what's called

25 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, *supra* note 3.
26 *Id.*
27 *Id.*
28 M. Henriksson, C. Cederberg, and C. Swensson, *Carbon Footprint and Land Requirement for Dairy Herds Rations: Impacts of Feed Production Practices and Regional Climate Variations*, citing Bouwman et al., 2002, *supra* note 2.
29 Conor McCabe, *Dairy Cows – the Original Upcyclers: How Ruminant Digestion Turns Byproducts into High-Quality Nutrition*, UC Davis CLEAR Center (Jan. 07, 2022), https://clear.ucdavis.edu/explainers/dairy-cows-original-upcyclers.

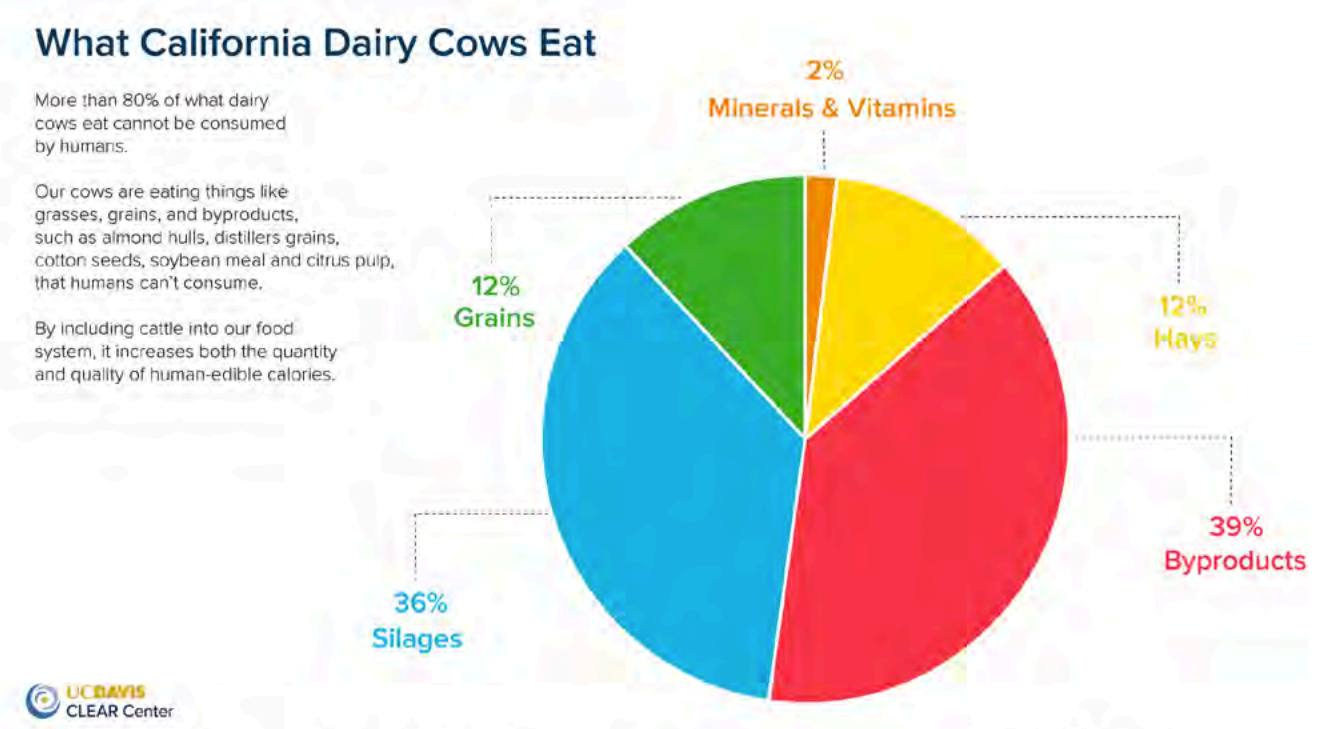

Figure 3: Composition of dairy cattle diets across 40 California dairies. Byproducts include cotton seeds, canola meal, dried distillers grains, almond hulls, soy hulls, whey, fat supplements, soybean meal, corn gluten, wheat byproducts, and rice bran.
Credit: CLEAR Center

FIGURE 3 Via Conor McCabe, Dairy Cows – the Original Upcyclers: How Ruminant Digestion Turns Byproducts into High-Quality Nutrition, supra note 29.

a "total mixed ration."[29] Total mixed ration "is essentially a nutritionally formulated feed mix, combining feeds formulated to a specific nutrient content. Such feeds may contain forage (grass silage, hay, or straw), grains (corn, oats, wheat, and barley), protein feeds (soybean, cottonseed, linseed, and groundnut), minerals, vitamins, feed additives, and by-products."[30]

The nutrition profile of grasses consumed through grazing, in contrast, is different, "with potential nutritional benefits, compared with conventional milk derived from total mixed ration."[31] The emissions intensity of each method is also different, depending on the particular composition of grazing forage and of a total mixed ration diet. For example, "Some studies have demonstrated benefits of inclusion of white clover in pasture, due to its ability to reduce nitrous oxide emissions, fix atmospheric nitrogen, and reduce carbon footprint (Ledgard et al., 2009; Yan et al., 2013)."[32] The UC Davis article also cites a Cornell study claiming that the emissions from using byproducts as dairy feed are 60% less than the alternative, which they define as sending the byproducts to a landfill for incineration.

30 Alice Moscovici Joubran et al., *Invited Review: A 2020 Perspective on Pasture-Based Dairy Systems and Products, supra* note 19.
31 *Id.*
32 *Id.*

C. California's Dairy Methane Reduction Strategy

According to California's Short-Lived Climate Pollutant Strategy, "California's dairy and livestock industries account for more than half of the State's total methane emissions and for about five percent of the State's GHG inventory."[33] On dairies, the strategy attributes 20% of emissions to enteric fermentation and 25% to manure management. California has more dairy cows and more dairy methane emissions than any other state.[34] Crucially, the strategy explains that California "also has higher per-milking cow methane emissions than most of the rest of the United States, due to the widespread use of flush water lagoon systems for collecting and storing manure."

The SLCP Strategy noted several potential mitigation measures, including switching away from flush water lagoon systems and switching to pasture-based dairy management.[35] CARB also convened a sub-working group in 2018, which put forth many recommendations on non-digester interventions. In practice, however, CARB has overwhelmingly focused mitigation efforts on the construction and operation of anaerobic digesters ("biogas control systems") on dairy operations and applies a high baseline emissions standard to California operations. Digesters capture the methane emitted from anaerobic lagoons, resulting in the perpetuation of flush water lagoon systems.

California's Alternative Manure Management Program (AMMP) has sought to support measures to mitigate manure emissions other than digesters. All measures other than digesters have been deemed "alternative manure management strategies," despite the fact that they remain commonplace practices is other parts of the country. From 2015-2021, the California Department of Food and Agriculture awarded $195 million to dairy digester projects through the DDRP program and $68.3 million to AMMP projects.

D. Key Takeaways: Manure Management Systems and GHG Emissions

Generalizing about GHG emissions from manure management can be challenging because emissions vary based on factors including soil type, climate, and the specific GHG, but the following are generally true:

- **The more cows an operation has, the more manure is produced, and the more methane is generated**, all else being equal. Decreasing per-cow emissions will not necessarily lead to overall methane reductions if the industry grows.

- **Anaerobic lagoons generate more methane emissions than shorter-term manure storage or more frequent land application.** This is because the manure is stored for a longer period of time and generates more emissions in liquid form.

- **Liquifying manure using flush systems can decrease ammonia emissions but will increase methane emissions**. Flushing also requires large quantities of water. See CARB's Short-Lived Climate Strategy for a discussion of emissions from California dairy practices.

- **Manure lagoons and liquid manure management systems are standard on industrialized dairies because they operate at a scale that makes regular land application of manure unsafe, requiring long-term manure storage.** The industrialized model of dairying generates too much manure to spread regularly on the land without causing nutrient pollution. As a result, industrial-scale dairies must store

33 Cal. Air Res. Board, Short-Live Climate Pollutant Reduction Strategy (March 2017), https://ww2.arb.ca.gov/sites/default/files/2020-07/final_SLCP_strategy.pdf.
34 *Id*. at 63.
35 *Id*. at 65.

manure for long periods of time, land applying only when cropland is available and the climactic conditions are appropriate. This requires operations to transport manure from barns to manure lagoons where it can be stored.

- **Manure lagoons and liquid manure management systems are far less common on small and mid-sized dairies, which can apply manure to land more frequently.** Smaller operations often have adequate land to spread manure safely at more regular intervals. As a result, they don't have to store manure for long periods of time—one of the major sources of methane emissions. This also gives smaller operations more flexibility and a greater range of options for how they manage manure. Not only do smaller operations generate fewer emissions, but their systems are less rigid than those of industrial operations. They can adapt to new mitigation measures more easily.

- **The industrialized model of dairying was pioneered in California and exported nationally. Industrialized dairies are more common in California than anywhere else in the country.[36] California's incentives for digesters are again promoting an industrialized model of dairying nationwide.** Dairy digesters, and the lucrative LCFS credits that manure biogas can generate, are only feasible on the largest dairies operations. While industrial-scale facilities are the norm in California, this isn't the case in many other dairying states where smaller operations are still more common. Smaller scale dairies aren't suited to digesters precisely because they do not have highly emitting lagoons; however, lucrative LCFS incentives for digesters are available nationwide. At the same time, additional revenue from LCFS credits further bolsters the competitive edge of the largest operations. Creating incentives for dairies to adopt liquid manure management practices with anaerobic lagoons could increase emissions in other states where these polluting systems are less common.

- **California is also promoting alternative manure management practices, but these have been funded at a fraction of the rate of digesters.** What CARB calls "alternative manure management strategies" are not radical departures from dairying practice. The Alternative Manure Management Program (AMMP) defines these practices as essentially anything that's not a digester (those practices "that don't include use of an anaerobic digester, and support management of manure in a dry form.")[37] The broad range of practices that fit within this definition—like solid separation, conversion from flush to scrape in conjunction with some form of drying or composting of collected manure, and pasture-based management—are common nationwide.[38]

- **Even with CARB's aggressive digester push, California is significantly behind on its methane targets** and, according to CARB's analysis, relying on digesters alone to reach the target would cost an additional $3.9 billion. See CARB's 2022 Dairy and Livestock Methane Progress Report here.

36 See, e.g., Dr. John W. Siebert, *A Word from the Bad Guys*, UC Davis (Oct. 1984), http://s3-us-west-2.amazonaws.com/ucldc-nuxeo-ref-media/c709e8dc-9761-4850-bd9d-735f0d1092d9; (UC Davis professor speaks directly to dairy farms outside of California to address the perception that California dairies are "heartless corporate farms"); Rick Barrett and Lee Bergquist, *Industrial Dairy Farming Is Taking Over in Wisconsin, Crowing out Family Operations and Raising Environmental Concerns*, Milwaukee Journal Sentinel (Feb. 11, 2020), https://www.jsonline.com/in-depth/news/special-reports/dairy-crisis/2019/12/06/industrial-dairy-impacts-wisconsin-environment-family-farms/4318671002/ ("...massive milking operations, popularized in California, shatter the traditional model of Wisconsin farms..."); Lili LeGardeur, *Milk It*, Louisiana Life (Jan. 4, 2008), https://www.louisianalife.com/milk-it/ ("90 percent of Louisiana dairy farms are "pasture-based," ... In confinement dairying – a relatively new style popular out West – cows are fenced inside dirt-floor lots and have all their food delivered ... Confinement dairying, by the way, is also called California-style dairying, after the state where it originated.").

37 Cal. Dep't of Food and Ag., Alternative Manure Management Program, https://www.cdfa.ca.gov/oefi/AMMP/.

38 *Id.*

Around the country, in California, and in the Central Valley itself, farmers and community members are reimagining our food systems. California policymakers have a crucial role to play leading the nation in this conversation. California policymakers should be thinking creatively and holistically about what a just transition would look like for California dairies and the policy mechanisms that would be required to support a more sustainable industry.

III. Life Cycle Analysis Assumptions and Applications

The Low Carbon Fuel Standard (LCFS) allows dairies to generate credits for the production of manure biogas-derived transportation fuels. These credits are intended to incentivize the construction and operation of anaerobic digesters on dairy operations.

The LCFS calculates the carbon intensity (CI) of different transportation fuels by analyzing the life-cycle greenhouse gas emissions associated with a given fuel. To conduct these life cycle analyses, the LCFS uses "fuel pathways," which delineate which processes are included in a given fuel's life cycle. The program employs a version of the "GREET" model, which stands for the "The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation" model.[39] The GREET model was developed by Argonne National Laboratory.

There are several different kinds of pathways in the LCFS program. Lookup table pathways are applied to conventional fuels where the basic values are well-established. Fuel producers can simply look up the CI values for these fuels because they are set by CARB. Tier 1 pathways allow producers of alternative fuels to input operational data into a simplified version of the CA-GREET model to calculate the CI of their fuel. Tier 2 pathways allow alternative fuel producers to use the full CA-GREET model to conduct a custom CI analysis.

Evaluating the completeness and accuracy of LCFS manure biogas life cycle analyses is challenging because almost all participating swine and dairy operations have opted to use the customizable Tier 2 pathway. This means there is not one single life cycle analysis for biogas; instead, most of the several hundred producers that generate credits for the capture of manure methane have conducted their own customized analysis using the CA-GREET model. However, there are several issues apparent in CARB's Tier 1 pathway and considerations regarding the GREET model overall.

Life cycle analyses generally could be critiqued on a number of bases, including the emissions they opt to include, the reference scenario they assume, how emissions are quantified, and whether the model's assumptions are borne out in on-the-ground monitoring. Based on forthcoming research, it is our understanding is that, *when all is working as intended*, CARB's life cycle analysis for manure-derived biofuels generally reflects the actual emissions and reductions from biogas control systems. That is, if we accept the assumptions built into the model, the emissions and reductions counted by the model are generally accurate in practice when biogas systems are functioning as intended. The primary issues with the life cycle analyses for manure-derived biofuels, therefore, are high-level disagreements about the appropriate reference scenario and the life cycle analysis' focus on transportation emissions at the expense of agricultural emissions, as well as more specific monitoring to groundtruth those assumptions and to monitor for fugitive emis-

39 Argonne National Laboratory, *GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model: The Gold Standard for Life Cycle Analysis of Technologies and Energy Systems* (May 2020), https://www.anl.gov/sites/www/files/2020-10/GREET_Impact_Sheet.pdf.

40 Our research on this topic was informed by a background interview with an environmental scientist who shared their evaluation of monitoring concerns as well information about forthcoming research.

sions, which are a "substantial" concern.[40]

A. Groundtruthing Life Cycle Analysis Estimates and Reported Reductions with Data

One article describes the downside to "bottom-up" emissions analyses like CARB's:

> *Bottom-up inventories, including those used by the US Environmental Protection Agency (US EPA, 2017) and the California Air Resources Board (Charrier, 2016), estimate dairy emission rates at the state level based on the total number of cows and herd demographics and on the average statewide manure management approach, CH_4 emissions factor, and climate. However, livestock emissions, especially from dairies, remain one of the largest uncertainties in these inventories (Maasakkers et al., 2016), as there is no comprehensive information source for the number of cows or manure management strategies*.[41]

California has a lot riding on the reported (on-paper) emissions reductions from dairy digesters. These estimates should be groundtruthed with actual monitoring. On its own terms—that is, if concerns about the assumptions made in CARB's life cycle analysis models are temporarily set aside—forthcoming research based on a single facility suggests that CARB's manure biogas life cycle analyses are accurate when biogas control systems are working as intended. However, biogas control systems may not always work as intended. One environmental scientist our team spoke with cited "substantial" concern about fugitive emissions from digester systems. Fugitive emissions are essentially leaks where the captured methane can escape and be vented to the atmosphere.

CARB itself came to this conclusion in the wake of a methane survey, acknowledging:

> "As expected with any new technology, during the initial operational deployment of [anaerobic digesters (AD)] situations may arise including leaks or higher-than-predicted venting that can impact the desired methane control efficiency. Characterizing potential AD fugitive emissions through the use of tools like the NASA JPL flyovers can help achieve and maintain the expected methane reductions by helping digester operators optimize their systems and reduce revenue loss."[42]

CARB requires an engineering review for biogas pathway applications, but no ongoing monitoring at the facility level, and does not conduct ongoing monitoring at the regional level itself. Monitoring for methane from dairies overall is challenging because the emissions are so dispersed, intermittent, and can depend on variables like soil type and weather. Unfortunately, unlike other air pollutants like ammonia, methane monitoring is not well-suited to community monitoring efforts. Fortunately, California is home to environmental scientists with this expertise. One environmental scientist suggested that a cost-effective approach to monitoring that prioritized measurable and preventable emissions would be third-party monitoring of fugitive emissions from biogas control systems. At a bare minimum, CARB should be collaborating with these scientists to ensure the methane emissions it reports as captured are not leaking out through biogas control system.

41 Alison R. Marklein et al., *Facility-Scale Inventory of Dairy Methane Emissions in California: Implications for Mitigation*, 13 Earth System Sci. Data 3 (March 22, 2021), https://essd.copernicus.org/articles/13/1151/2021/essd-13-1151-2021.html.

42 Cal. Air Res. Board, *Introduction to the Phase I Report of the California Methane Survey from the Staff of the California Air Resources Board* (October 2, 2017), https://ww2.arb.ca.gov/sites/default/files/2020-07/ca_ch4_survey_phase1_report_2017.pdf.

B. High-Level Life Cycle Analysis Concerns: Reference Scenario Assumptions

The purpose of the CA-GREET model is to estimate the CI of transportation fuels. In evaluating the emissions impact of the displacement of conventional fuels by new, alternative fuels, the structure of the analysis is to assume a static baseline or reference scenario. The analysis can then evaluate a specific alternative fuel intervention against that reference scenario, where the new fuel is the only change. In the manure biogas life cycle analyses, therefore, the model assumes a dairying reference scenario upon which the transportation fuel intervention operates. CARB's reference scenario is based on the dominant approach to dairying in California. That is, CARB's life cycle analysis assumes the ongoing presence of industrial-scale confinement dairies with liquid manure management systems. There are two important critiques of this assumption:

- Rather than seek to change the dairying model to one that generates fewer GHG emissions, CARB takes this system as a given and builds on top of it.
- Because LCFS credits are available nationally, but the reference scenario is based on the (more-polluting) California model of dairying, the program could incentivize a harmful shift in practices from out-of-state dairies at the same time it entrenches those practices at home.

The reference scenario is illustrated concretely by the life cycle analysis' assumption that, if not for the addition of an anaerobic digester, manure would be stored in anaerobic lagoons and, if not for the digester, manure methane would be vented directly to the atmosphere. This is not the case on many of the thousands of farms otherwise eligible for LCFS credits nationwide.[43] Rather than devise a mitigation intervention applicable to these farms, CARB simply excludes them from the program if their practices do not match those in the reference scenario. This is unfortunate, because it limits eligibility for the lucrative LCFS credits to operations with the most polluting practices (those that match the reference scenario).[44]

Manure lagoons are used on 58% percent of dairies in California but only 32% percent of dairies nationally.[45] One early GREET study acknowledged that not all dairies use anaerobic lagoons, explaining: "EPA also estimates MCFs of wet (e.g. anaerobic lagoon, liquid slurry and deep pit) and dry (e.g. daily spread and pasture) manure management systems for cool, temperate and warm climate zones... Note that in Wisconsin, solid storage is used for a larger share and anaerobic lagoons for a smaller share of manure than in the United States as a whole, while in California more than 50% of manure is treated by anaerobic lagoon."[46] But given the concentration of this model of dairying in California's Central Valley, CARB has settled on this reference scenario.

In addition to ensuring that LCFS credits are only available to the largest polluters, this reference scenario allows these operations to claim massive emissions reductions since reductions are equivalent to their "captured" or "avoided" emissions.[47]

43 LCFS credits are not limited to California dairies. Operators need only to inject the resulting natural gas into a common carrier pipeline in North America and link the energetic attributes of that biogas with a pipeline withdrawal for natural gas sold in California. The same principle is applied for electricity generated in the combustion of biogas on-site. (Note, however, that the 2023 SRIA for the new LCFS regulation did propose altering the book-and-claim accounting system.)

44 Traditional pasture-based dairies leave manure in pasture where it is deposited by cows. This is possible because manure is produced in quantities below agronomic rates—the available land can adequately and safely absorb the nutrients from the manure. Industrial scale operations collect and store manure for two reasons. First, they generally hold livestock in confinement, so the manure isn't deposited in pasture as a matter of course and needs to be cleaned out of barns. Second, too much manure is produced on industrial-scale facilities for the available land to absorb nutrients without creating serious environmental harms. As a result, manure is collected and stored in "lagoons." To transport manure into lagoons, manure is typically flushed out of barns, liquifying it and creating new emissions in the process. Manure from the lagoons can periodically be spread on land ("land-applied") at or below agronomic rates.

45 Jeongwoo Han, Marianne Mintz, and Michael Wang, *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6*.

46 *Id.*

This means that the more emissions they generate, the more they can capture, the more reductions they can claim publicly, and the more revenue they obtain through LCFS credits. Finally, by calculating credits that are issued nationally based on a California-specific reference scenario, the program risks shifting practices in other states towards California's more polluting model of dairying.

C. High-Level Life Cycle Analysis Concerns: Focus on Transportation, Not Agriculture

The goal of the GREET model used by CARB is to estimate life cycle emissions of transportation fuels, not to estimate emissions from agriculture. Transportation fuel life cycle analyses differ markedly from agriculture life cycle analyses.[48] Biofuels like manure biogas straddle agriculture and transportation fuel life cycle analyses, requiring value judgements about where to set system boundaries. Life cycle analyses for biofuels are well-characterized by the paper cited above as follows:

> *Particularly with biofuels, policy-related requirements, modeling assumptions, analysis limitations, and software can have a significant effect on results (Agostini, Giuntoli, Marelli, & Amaducci, 2020; Hoekman & Broch, 2018; Obnamia, Dias, MacLean, & Saville, 2019). As a result, users need to carefully consider the context, usefulness, and applicability of these complex analyses. Many biofuel life cycle accounting policies and studies try to evaluate the changes that biofuel production has on food production systems. To evaluate impacts to production systems, most analyses use some metric to first assess the status quo such as a reference system (Hoekman & Broch, 2018), business-as-usual (BAU) scenario, or baseline, and then quantify changes that biofuel production creates. As a result, most biofuel-related system boundaries (Figure 8) also include quantifications which involve product substitution or displacement (Vadenbo, Hellweg, & Astrup, 2017).*[49]

A paper by Argonne National Laboratory scientists reiterates that, in the case of biofuels, "GHG emissions for RNG pathways are highly dependent on the specifics of the reference case, as well as on the process energy emissions and methane conversion factors assumed for the RNG pathways."[50] The goal of the LCFS biogas life cycle analysis is to compare the status quo with an alternative where anaerobic digesters are used to capture methane and the resulting transportation fuel displaces conventional fuel use.

Concretely:[51] the GREET model's life cycle anal-

47 Cal. Air Res. Board, *Tier 1 Simplified CI Calculator Instruction Manual: Biomethane from Anaerobic Digestion of Dairy and Swine Manure*, https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/tier1-dsm-im.pdf?_ga=2.140068787.1623257348.1702923028-1380165209.1657241991.

48 Writing on fuel life cycle analyses, scientists from Argonne National Library explained: "A fuel cycle typically includes feedstock recovery and transportation, fuel production, transportation and distribution, and combustion as an end use." Jeongwoo Han, Marianne Mintz, and Michael Wang, *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6*. A different paper by Argonne National Laboratory scientists characterized the system boundaries for animal agriculture systems, on the other hand, as follows: "The process considered for animal systems in cradle-to-farm-gate system boundaries normally include feed production, animal husbandry, manure storage and farm management. Farm-gate-to-grave systems include processes such as transportation of product from farm to processing plants, manufacturing of packing materials such as bottles for milk and cartons for eggs, and distribution to retailers and consumers." Heidi Sieverding et al., *A Life Cycle Analysis (LCA) Primer for the Agricultural Community*, 112 Agronomy J. 5, 3788 (May 6, 2020), https://acsess.onlinelibrary.wiley.com/doi/pdfdirect/10.1002/agj2.20279.

49 *Id.*

50 *Id.*

51 The LCFS calculator for Tier 1 pathway for biogas from swine and dairy manure requires applicants to "add facility information and verifiable monthly feedstock, operational energy use, fuel production and co-product data, and transport distances used in calculating the CI of biomethane from dairy and swine manure digesters." Cal. Air Res. Board, *Tier 1 Simplified CI Calculator Instruction Manual Biomethane from Anaerobic Digestion of Dairy and Swine Manure* (June 20, 2023), https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/t1_biomethane_DSM_instruction_manual_v0620023.pdf. The Tier 1 calculator quantifies baseline emissions (of anaerobic lagoons and non-anaerobic storage) as well as emissions associated with the biogas control systems themselves (like emissions from venting events and emissions from effluent ponds), and other emissions not related to the biogas control system itself. The calculator then quantifies avoided methane by comparing baseline methane emissions to project methane emissions. Note that new models for the life cycle analysis are expected to be published for public comment on Tuesday, December 19, 2023. The Tier 2 pathway for manure biogas is simply a customized version of the full CA-GREET 3.0 model. As such, it requires far more input from the producer than the simplified Tier 1 pathway. Additionally, users can choose either a United States or IPCC reference scenario. If they choose a United States reference scenario, they can further specify a reference scenario by state.

ysis for manure biogas begins at manure storage in the lagoon. Beginning the life cycle analysis with manure storage leaves out all emissions that occur before storage: emissions from feed production, general dairy operations, enteric fermentation, and the collection and transportation of manure to lagoons. The justification for starting the life cycle analysis with manure storage in the lagoon is that the manure will be stored in lagoons regardless of the addition of an anaerobic digester incentivized by LCFS credits.[52] That is, CARB assumes a reference scenario based on liquid manure management systems with anaerobic lagoons, as discussed *supra*. Upstream emissions should be considered if CARB seeks to understand the impact of the LCFS on agricultural emissions. Excluding these emissions is justifiable to the extent that CARB limits use of the life cycle analysis to claims about transportation fuel reductions.

At the other end, the life cycle analysis model is bounded by the end-use of the energy generated, either the combustion of RNG as transportation fuel or as electricity. The life cycle analysis also excludes emissions from the storage and disposal of digestate,[53] the by-product of anaerobic digestion. The exclusion of digestate is justifiable if CARB also excludes emissions from manure land application in the reference scenario. An environmental scientist consulted for this research explained that forthcoming research at a single dairy found that emissions from land application and from digestate application are likely comparable. The scientist also stressed that a generalized comparative analysis of manure application versus digestate application would be extremely challenging to implement because emissions are dispersed and vary based on soil conditions, climate, and the specific pollutant studies.[54]

Focusing life cycle analyses on transportation fuels is an intentional and understandable choice by CARB given the intended function of the LCFS. CARB is required to "[c]onsider the significance of the contribution of each source or category of sources to statewide emissions of greenhouse gases."[55] Transportation is the largest source of greenhouse gas emissions in California at 38%.[56] Agriculture is responsible for 9% of emissions in California.[57] Because CARB focuses on transportation fuel life cycle emissions (and, by extension, assumes the existing system of dairying), the Board's decision not to include upstream emissions from dairy operations is justifiable. No life cycle analysis can include all processes and all systems. The exclusion of upstream emissions, however, remains justifiable *only so long as* CARB's focus remains fixed on transportation emissions. CARB should not claim reductions from dairying overall without having analyzed emissions upstream of manure storage.

However, CARB makes a great deal of the avoided methane from agriculture, in addition to the displacement of conventional transportation fuels. This is a key reason that LCFS credit values are so high. CARB also frequently touts emissions reductions from the dairy sector on the basis of

52 Jeongwoo Han, Marianne Mintz, and Michael Wang, *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6* (waste is collected in both the reference case (current manure management) and the "new" AD cases.").

53 Anaerobic digester residue is eventually land-applied and still generates emissions, as one GREET study acknowledged. *Id.* That study explained that "62% of the C in the residue is assumed to become CO 2 , and the rest (38%) is assumed to remain stored in the soil." *Id.* That study further asserted that the impacts of anaerobic digester residue land application, "that is, synthetic fertilizer displacement and N2 O and NOx emissions—should be included in LCAs of AD pathways." *Id.* The solid digestate "may be recycled for animal bedding or as a soil amendment, but this is not considered in our analysis." Heidi Sieverding et al., *A Life Cycle Analysis (LCA) Primer for the Agricultural Community*, *supra* note 48.

54 Indeed, existing literature shows variation in emissions based on a number of factors including different methods of digestate storage and processing. Holly et al., for example, found that storage of digestate with limited oxygen increased nitrous oxide emissions. Holly et al., *Greenhouse Gas and Ammonia Emissions from Digested and Separated Dairy Manure During Storage and After Land Application*, 239 Ag., Ecosystems, and Env't 410 (Feb. 15, 2017), https://www.sciencedirect.com/science/article/pii/S0167880917300701. That study also concluded that "[nitrous oxide] from digester separated solids was much higher than the separated solids without digestion." *Id.*

55 Cal. Health & Safety Code § 38562.

56 Cal. Air Res. Board, Current California GHG Emission Inventory Data, https://ww2.arb.ca.gov/ghg-inventory-data.

57 *Id.*

the LCFS analysis. While the LCFS can estimate a total quantity of emissions captured by anaerobic digesters, the narrow transportation focus of the LCFS has allowed the agency to ignore the fact that this invention locks in the most highly emitting form of dairying, precluding broader reductions.

The dairy sector is responsible for more than half of California's methane emissions.[58] Making claims about reductions from the dairy sector requires a full analysis of dairy emissions. Yet in CARB's *Analysis of Progress Towards Achieving the 2030 Dairy and Livestock Sector Methane Emissions Targets*, the agency begins with primacy of digesters, rather than with a holistic analysis of dairy emissions.[59] CARB's narrative of its process reflects this, stating: "To understand what level of resources are needed to achieve the target, CARB staff looked at existing dairy methane emissions reduction efforts, including both grant programs that fund the initial capital costs and market-based programs that incentivize GHG emissions reductions or low carbon fuel production."[60] But existing emissions reduction efforts have been defined through the transportation lens of the LCFS, which assumes the perpetuation of California's most highly-emitting dairying model. This assumption should not be the starting point for CARB's dairy mitigation strategy.

There is a second broader critique of the limitations of a baseline scenario based on the status quo at a time when we need to decarbonize all sectors simultaneously. The choice is less between the status quo and anaerobic digesters but between anaerobic digesters and a host of other policy choices. Because the dairy digester intervention only evaluates how transportation emissions will change as a result, it risks locking in or increasing dairying emissions at a time when they, too, need to decline.

While relying on a static reference scenario is necessary in any single analysis to draw a meaningful comparison between two alternatives, we are in a time of major transition: We need to decarbonize all sectors—including agriculture—simultaneously, using multiple different tactics. This presents conceptual difficulties for a binary life cycle analysis comparing a static baseline and one potential intervention. The LCFS relies on a static reference scenario of "Current Manure Management" to find that this intervention is better, but it's an intervention that increases the value of manure while other interventions could decrease the value of the manure. The manure biogas life cycle analysis' reliance on a static baseline freezes the reference scenario, both in theory and practice, first by assuming its existence into the future and second by investing in transportation fuel reductions that rely on that status quo.

D. Key Takeways: Life Cycle Analysis Assumptions and Applications

- **We need to decarbonize all sectors—including both agriculture and transportation—simultaneously**. California policymakers should work to ensure that interventions in one sector are not locking in or increasing emissions elsewhere.

- **Because the LCFS focuses on transportation sector emissions, the fact that the dairy digester intervention locks in emissions-intensive practices in the dairy sector has been given little attention.** CARB's life cycle analysis for biogas-derived fuels assumes the ongoing presence of industrial-scale confinement dairies with liquid manure management systems, locking these systems in both in theory and practice. Because the life cycle

58 Cal. Air Res. Board, Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target (March 2022), https://ww2.arb.ca.gov/sites/default/files/2022-03/final-dairy-livestock-SB1383-analysis.pdf.

59 *Id.*

60 *Id.*

analysis uses this dairying model as its baseline scenario, only dairies that use this model are eligible for lucrative LCFS credits.

- **The LCFS rewards captured (or "avoided") methane. This means that the more emissions dairy operations generate, the more they can capture, the more reductions they can claim publicly, and the more revenue they obtain through LCFS credits.**

- **The life cycle analysis used for transportation fuels is not an appropriate analysis to apply when analyzing overall dairy emissions, because it excludes the bulk of emissions from dairy operations.** The LCFS life cycle analysis was designed to measure the change in transportation sector emissions; it should not be used as the starting point for CARB's broader dairy mitigation strategy.

- **Dairy emissions and leaks from biogas systems are not actively monitored to groundtruth the LCFS' bottom-up estimates for captured methane despite concerns about fugitive emissions.**

IV. Consolidation and LCFS Credits

Dairy industry stakeholders argue[61] that the trend towards consolidation in dairy predates and is independent of the adoption of digester technology and Low Carbon Fuel Standard (LCFS) incentives. This is correct. Consolidation in the dairy industry is a consistent, long-term trend that far predates the LCFS and the embrace of dairy digesters. This fact does not preclude the possibility that LCFS incentives for digesters contribute to that trend in a meaningful way. This section describes the history, geography, and major drivers of consolidation in the American dairy industry. We cannot draw clear conclusions about the impact of the LCFS yet—the data needed to evaluate its effects will be released later in 2024 in the 2022 USDA Agriculture Census. Understanding the drivers of consolidation and pressures on dairy operations still provides essential context for understanding the stakes of incentivizing dairy digesters over other potential interventions.

Among other impacts, dairy consolidation has resulted in the loss of thousands of small and mid-sized farms, contributed to the decline of rural economies and communities, and increased environmental and environmental justice concerns by densely concentrating operations in a few parts of the country. Consolidation matters in the context of the LCFS and the dairy digester push for several reasons:

- First, consolidation of the dairy industry set the stage for the dairy digester push. The consolidation trend has resulted in the dominance of ever-larger, industrial-scale operations over the smaller-scale dairies that were dominant as recently as the 1980s. These factory farms rely on manure lagoons to store the manure they generate, which generates methane emissions for the duration of storage.

- Second, the credits provided by the LCFS may impact the consolidation trend, by encouraging the growth of already-large operations or encouraging operations to merge in order to take advantage of the lucrative credits available for operations that can manage a biogas control system.

- Third, even if the LCFS does not directly incentivize operations to grow or merge, it provides an additional revenue stream for the large-scale operations where digesters are an appropriate intervention. This impact would

61 Ermias Kebreab, Frank Mitloenher, and Daniel A. Sumner, *Meeting the Call: How California is Pioneering a Pathway to Significant Dairy Sector Methane Reduction*, UCDavis CLEAR Center (December 2022), https://clear.ucdavis.edu/sites/g/files/dgvnsk7876/files/inline-files/Meeting-the-Call-California-Pathway-to-Methane-Reduction_0.pdf.

not necessarily be limited to California, as LCFS credits are available to dairies nationwide.

A. Dairy consolidation is a long-term trend.

The trend towards consolidation in dairy is unmistakable and far predates the adoption of the LCFS (adopted in 2009).[62] The trend is clear both nationally and in California. A 2020 USDA report using data from the most recent USDA Agricultural Census (2017) found that since at least the late 1980s, the average dairy herd size has risen consistently, and the number of dairy operations has decreased consistently.[63] The decline in dairies and increase in herd sizes reflects the loss of small and mid-sized farms as production has shifted toward much larger farms.[64] Not only have larger dairies proliferated during this period, but frontier of what is considered "large" has progressively increased.[65]

1. Dairy consolidation coincided with a decline of small farms in the Midwest and the East and growth in industrial-scale operations in the West.

The dairy industry has trended towards consolidation nationally, but the geography of consolidation has varied. The Midwest and the Northeast have "long had many small commercial dairy farms, while production in the major Western Dairy States has revolved around large farms."[66] As the industry has consolidated, the decline of small commercial dairy farms has been "concentrated in the Midwest and the Northeast and in four states in particular: Minnesota, New York, Pennsylvania, and Wisconsin."[67] Alongside the decline in Midwestern and Northeastern small commercial dairies, "[p]roduction has shifted to Western States and is concentrated in a smaller number of counties."[68] That is to say: the decline of small farms in the Midwest and the Northeast (as well as California's dwindling pasture-based operations in Marin and Sonoma Counties)[69] have fueled the growth of the industrial-scale dairies that populate California's Central Valley and other western states.

62 Cal. Air Res. Bd., *Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways* (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-9-CARB.pdf.

63 Commercial dairies declined at an annual average rate of 4.2 percent from 1978 through 2017.The median herd size increased dramatically over this period as well. The report found that the midpoint herd size has risen consistently from 80 or more cows in 1987 to 1,300 cows in 2017. James M. MacDonald, Jonathan Law, and Roberto Mosheim, *Consolidation in U.S. Dairy Farming*, ERR-274 (July 2020), https://www.ers.usda.gov/webdocs/publications/98901/err-274.pdf (this number is for dairies with over 10 cows which closely correlates to dairies that sell milk.)

64 *Id.* at Report Summary. The small commercial farms of 10-99 cows that were typical in 1992 have seen "large and persistent declines." *Id.* at 10. These operations have decreased by "over 80 percent in 1992–2017 for farms with 10–49 cows and over 70 percent for those with 50–99 cows." *Id.* at 10. In 2017 they made up only 12.6 percent of U.S. dairies. *Id.* at 10. Large dairies, on the other hand, make up a larger share of the industry than ever before. The USDA report found that, "In 1992, the census counted 564 farms with at least 1,000 cows, and those farms accounted for less than 10 percent of all cows. Twenty-five years later, nearly 2,000 farms had herds of that size, and they accounted for 55 percent of U.S. inventory." *Id.* at 11.

65 However, the total number of farms with at least 2,000 cows doubled between the 1997 and 2002 censuses, and then nearly doubled again between the 2002 and 2012 censuses, with continuing increases since. The frontier—the size of a dairy farm that we would call "large"—keeps expanding." *Id.*

66 *Id.*

67 *Id.*

68 *Id.*

69 Greig Tor Guthey, Lauren Gwin, and Sally Fairfax, *Creative Preservation in California's Dairy Industry,* 93 Geo. R. 2 (April 2003), 171, https://www.jstor.org/stable/30033905.

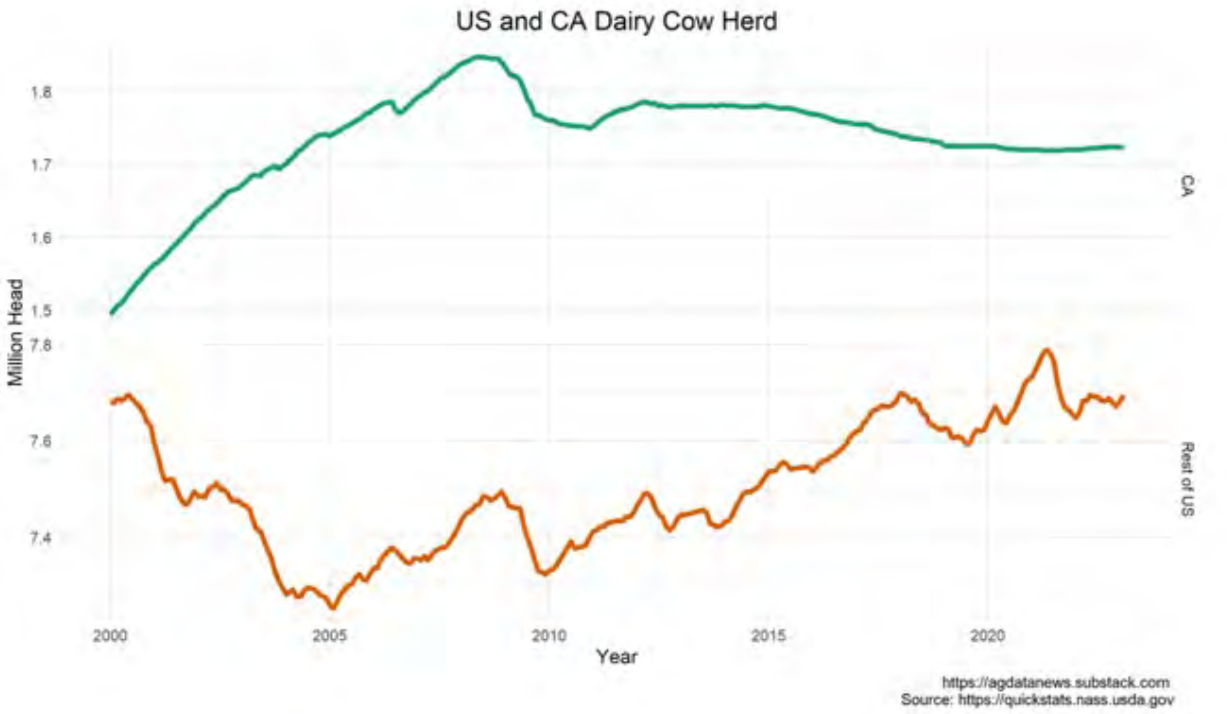

FIGURE 4 Via Aaron David Smith, Are Manure Subsidies Causing Farmers to Milk More Cows? (April 7, 2023), available at https://asmith.ucdavis.edu/news/are-digesters

The California dairy industry began consolidating before other major dairying states like Wisconsin and New York, generating pressure for other states to consolidate in order to compete with California's new mega-dairies. California surpassed Wisconsin as the top producer of milk nationally in 1993 and has held that position ever since.[70]

California led the way nationally in consolidating and industrializing the industry[71] for several reasons. The University of California provided essential research (as respective land grant universities did in other states); the intense urbanization pressures around Los Angeles County resulted in several cycles of "urban encroachment, farm relocation, and herd expansion" throughout the mid-century; and California's unique geography "created ideal conditions for growth, despite several setbacks related to land prices, water availability, and the relatively late start for the industry."[72]

The industrialization of California dairies was facilitated by University of California research into "breeding and genetic experimentation to increase the productivity of cows and milkfat content of the milk and the development of dairy-farm building plans that were structurally appropriate

70 Sophie Barrowman, *Transformations in California's Dairy Industry: Mapping Regional Variations in Milk Production and Operations,* Master of Arts Thesis, University of Cal. Davis Geo. Dep't, https://escholarship.org/uc/item/4tx1m87s (citing Sumner 2020).

71 In California, dairies are concentrated in the San Joaquin Valley, in particular in Tulare and Merced counties. The dairies in this region are "almost all confinement-style dairies." There are also some remaining dairies in western San Bernadino and Riverside Counties, but these areas have seen significant decline due to urbanization. North of San Francisco, in Marin, Sonoma, and Humboldt Counties, there is a small cohort of smaller-scale pasture-based and organic dairies. Daniel A. Sumner, California Agriculture: Dimensions and Issues, Chapter 6: California Dairy: Resilience in a Challenging Environment, 143, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

72 Sophie Barrowman, *Transformations in California's Dairy Industry: Mapping Regional Variations in Milk Production and Operations,* Master of Arts Thesis, University of Cal. Davis Geo. Dep't, (citing Butler andWolf 2000). *See also* James Sterngold, *Urban Sprawl Benefits Dairies in California*, New York Times (Oct. 22, 1999), https://www.nytimes.com/1999/10/22/us/urban-sprawl-benefits-dairies-in-california.html. Other contributing factors included: "the geographic isolation of the state requiring sufficient in-state processing facilities; the large and diverse population creating demand and labor for the industry; and the early adoption, or rather invention, of dairy science technology." *Id.*

for California's warmer climate."[73] The combination of advances in breeding, the pressures of urbanization, and the introduction of drylot feeding by Dutch immigrants pushed industrialization forward, beginning with Los Angeles County.[74] While urban encroachment in the broader Los Angeles area pushed farms out of the region, farmers were often able to sell land at high prices to developers giving them the capital needed to build out newer, larger facilities, often in the Central Valley.

Drylot feeding (also known as zero-grazing) is the "practice of concentrating cows into a small acreage and bringing their food to them." This practice was "revolutionary" for the dairy industry in California.[75] It was well-suited to California and particularly to the Central Valley, because "the abundance of local agricultural by-products like sugar beets and citrus and the availability of cheap hay made drylot feeding affordable, actually increasing milk production per cow compared to grazing."[76] The abundance of agricultural by-products remains a major benefit to California's dairy industry today.

California's climate also contributed to the unprecedented growth of the state's dairy industry. A UC Davis marketing memo from 1984 aimed at changing eastern and midwestern dairies' perception of California dairies as "heartless corporate farms," explained that the climate also facilitated regular expansion: "Due to the ideal climate, cows do not need the elaborate shelter that is required in other parts of the U.S. That means that when times are good, California dairy farmers add cows. In contrast, dairy farmers in other areas of the U.S. must add facilities before they can add cows."[77] Traditional dairying states like New York and Wisconsin experience weather variation throughout the year that requires modifying their practices, including but not limited to housing.

The California dairy industry only benefitted from the loss of small farms in the Midwest and East, however, until other states, particularly other western states, adopted the scale and industry structure that had given California dairies a competitive edge. In 2004, California dairies had the largest herd size in the country. Since then (through 2017, at least, the most recent year for which we have consistent USDA data) other major dairying states have increased herd sizes dramatically to compete, or as Sumner asserts simply: "dairy industries in other states have become more like those in California."[78]

73 *Id.* citing Hutchison 1946.
74 *Id.* citing Gilbert and Wehr 2003.
75 *Id.* citing Gilbert and Wehr 2003.
76 *Id.*
77 Dr. John W. Siebert, *A Word from the Bad Guys*, UC Davis (Oct. 1984), http://s3-us-west-2.amazonaws.com/ucldc-nuxeo-ref-media/c709e8dc-9761-4850-bd9d-735f0d1092d9.
78 Daniel A. Sumner, California Agriculture: Dimensions and Issues, Chapter 6: California Dairy: Resilience in a Challenging Environment, 143, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

Figure 6.4. Index of Number of Dairy Farms in California and Major Dairy States, 2004–2017

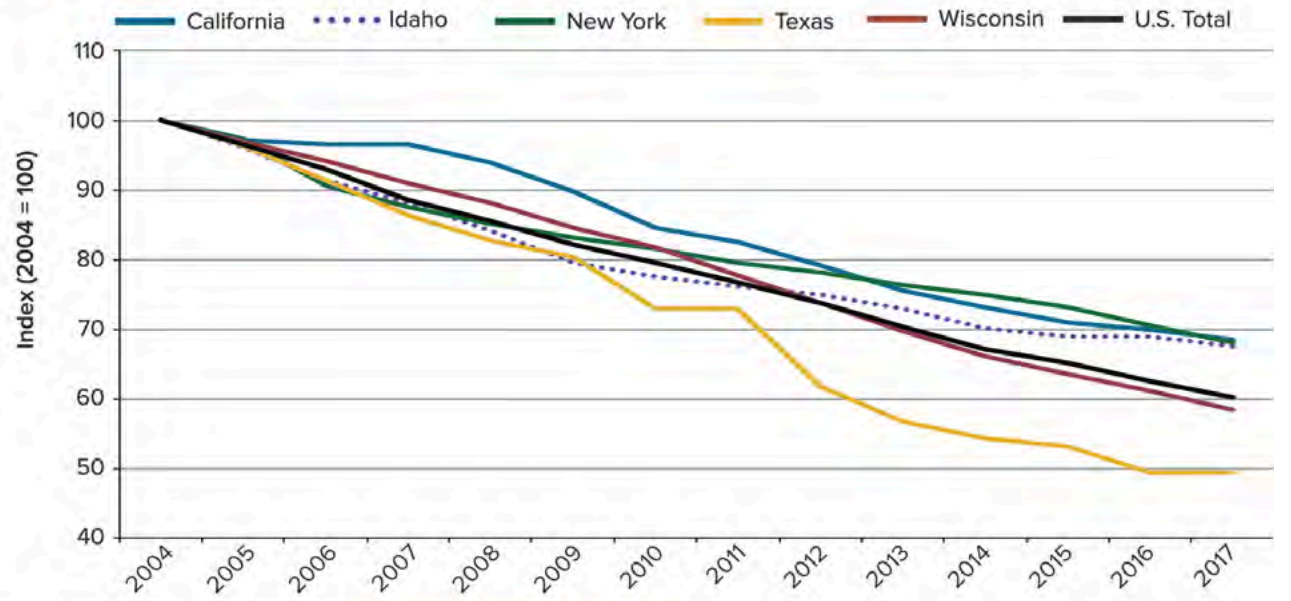

Source: USDA/NASS Quickstats. Available at: https://www.nass.usda.gov/Quick_Stats/

FIGURE 5 Via Daniel Sumner, California Agriculture: Dimensions and Issues (data sourced from USDA/NASS Quickstats), https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

2. *Drivers of consolidation include declining domestic demand, dismantling of supply management policies, trade policies that promote exports, and economies of scale.*

Major drivers of consolidation include declining domestic demand, changes to federal programs and subsidies, and economies of scale. Analyses of consolidation often point vaguely to "economic forces,"[79] but these economic forces have been constructed by policy choices. A Food and Power piece characterizes the problem like this:

> *Dairy farmers, particularly in the U.S. and Europe, are stuck in a cycle of consolidation and overproduction. Fewer, more powerful buyers, paired with declining domestic demand and dismantled supply management policies, have pushed the prices paid to farmers below their cost of production. In response, farmers seek to lower their costs per gallon and survive on high volumes. But as more farms seek a larger scale, milk production continues to increase, perpetuating oversupply, low milk prices, and a reliance on export markets.*[80]

The 2020 USDA report described "powerful cost incentives behind farm consolidation." Due to economies of scale, "larger farms are more likely to realize positive net financial returns to milk production..."[81] But economies of scale apply to most agricultural operations and the pace

79 See *e.g.* Ermias Kebreab, Frank Mitloenher, and Daniel A. Sumner, *Meeting the Call: How California is Pioneering a Pathway to Significant Dairy Sector Methane Reduction*, UCDavis CLEAR Center (December 2022), https://clear.ucdavis.edu/sites/g/files/dgvnsk7876/files/inline-files/Meeting-the-Call-California-Pathway-to-Methane-Reduction_0.pdf.

80 Claire Kelloway, *Fewer Global Dairy Corporations Drive Overproduction and Pollution, Harming Small Farmers, Report Finds* (June 18, 2020), Food & Power, https://www.foodandpower.net/latest/2020/06/18/fewer-global-dairy-corporations-drive-overproduction-and-pollution-harming-small-farmers-report-finds?rq=dairy.

81 For more on economies of scale, *see* James Macdonald, *Scale Economies Provide Advantages to Large Dairy Farms* (August 3, 2020), U.S.D.A. Econ. Res. Service, https://www.ers.usda.gov/amber-waves/2020/august/scale-economies-provide-advantages-to-large-dairy-farms/.

of dairy consolidation "far exceeds the pace of consolidation seen in most of U.S. agriculture."[82]

One of the major developments that exacerbated the trend towards consolidation was the embrace of export markets in the early 2000s. Historically,[83] the American dairy industry was focused on the domestic market.[84] Around the turn of the 21st century this began to change. A 2016 USDA report on the dairy export[85] market explains: "From 2004 to 2014, the value of U.S. dairy product exports more than quadrupled."[86] This was a "significant change for an industry previously focused primarily on domestic rather than international demand."[87]

According to the 2016 USDA report, exports increased due to increasing incomes in developing countries ("demand"), free trade agreements opening up new markets (the North American Free Trade Agreement in particular), market-based reforms in China, and finally, a reduction of "domestic support and export subsidies for dairy products in recent years, bringing about greater openness of world markets."[88]

At the domestic level, major changes came to longstanding price supports for dairy, which had long set floors on dairy prices. According to the 2016 USDA report: "The Milk Price Support Program (MPSP) was established by the Agricultural Act of 1949 and was amended several times over the years. Through the program, the Federal Government purchased dairy products in order to support milk prices at specified levels."[89] The purpose of the program (ultimately repealed in the 2014 Farm Act) was to correct for an oversupply of dairy that made it impossible for dairy farmers to adequately support themselves.

Removing the price supports that made smaller-scale dairying possible was necessary to embrace export markets but created incentives for consolidation. Today, American dairies "must compete aggressively for a share of consumer food budgets and for resources and investment capital," not just in the United States but globally.[90] The growth of the export market and broader globalization of the dairy industry has also "tended to emphasize the strength of multinational dairy firms."[91] At the level of the individual dairy operation, industrial-scale facilities are better able to operate in this landscape and contend with the greater and demand price volatility.

At the international level, the Uruguay Round of the General Agreement on Tariffs and Trade concluded in 1994 "with an agreement that fundamentally changed the treatment of national agricultural policies under the multilateral rules of global trade."[92] The Uruguay Round Agreement on Agriculture[93] brought national agricultural policies under the purview of the newly formed World Trade Organization, such that "trade-distorting policies" could be disciplined or constrained.[94]

82 *Id.*

83 Protectionism in agriculture has often been framed as a national security concern (or more recently as food sovereignty). These concerns remain very live today. See, e.g. Dr. Krista Versteeg, *It's Time to Talk about Food and Agricultural Security* (March 21, 2023), U.S. Dep't Homeland Sec. Science and Tech., https://www.dhs.gov/science-and-technology/news/2023/03/21/its-time-talk-about-food-and-agriculture-security.

84 Jess Cessna, Lindsay Kuberka, Christopher G. Davis, and Roger Hoskin, *Growth of U.S. Dairy Exports*, U.S.D.A. Econ. Res. Service (November 2016), https://www.govinfo.gov/content/pkg/GOVPUB-A93-PURL-gpo75564/pdf/GOVPUB-A93-PURL-gpo75564.pdf.

85 Note that dairy exports are typically dry milk or milk powder, which is "traded internationally at higher volumes than liquid milk products, since liquid products are bulky and often perishable, making them costly to ship and store." Powdered milks are often reconstituted in low-income countries, but are also common products in other dairy products and can be used as animal feed. Other dairy products traded internationally include cheese, infant formula, butter or butterfat products, whey products, casein products, and lactose. *Id.*

86 *Id.*

87 *Id.*

88 *Id.*

89 *Id.* at 21.

90 Donald Blayney and Mark Gehlhar, *U.S. Dairy at a New Crossroads in a Global Setting*, U.S.D.A. Econ. Res. Service, https://www.ers.usda.gov/amber-waves/2005/november/u-s-dairy-at-a-new-crossroads-in-a-global-setting/.

91 *Id.*

92 *Id.* quoting Burfisher, 2001. *See also* Don P. Balyney, Terry L. Crawford, and Christopher G. Davis, *Dairy Export Markets: Changing the Structure of US Dairy Demand*, 19 Int'l Food and Agribus. Mgmt Rev. B (2016), https://www.ifama.org/resources/Documents/v19ib/1220150087.pdf.

93 Agriculture became the most important issue in the failed Doha Round.

94 Donald Blayney and Mark Gehlhar, *U.S. Dairy at a New Crossroads in a Global Setting*.

Figure 11

U.S. imports and commercial exports of milk in all products on a skim-solids milk-equivalent basis

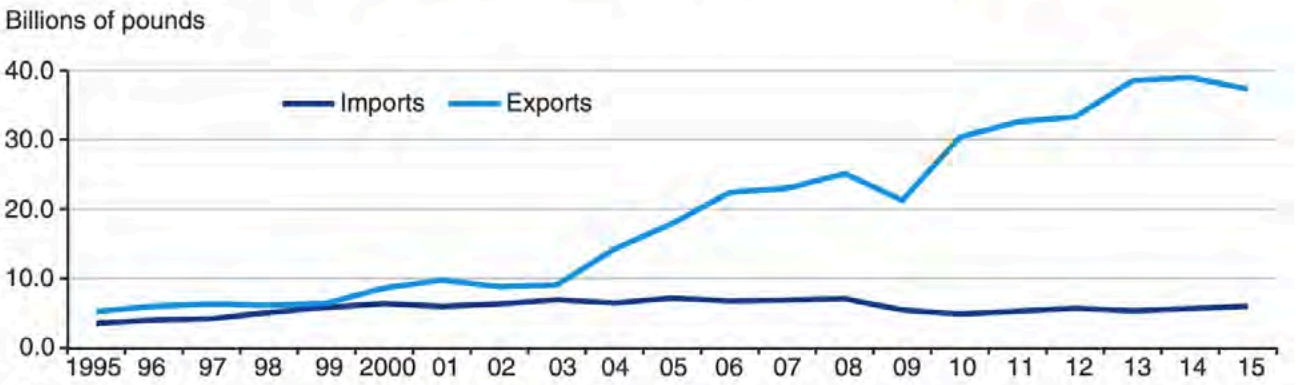

Sources: USDA/National Agricultural Statistics Service, USDA/Farm Service Agency, USDA/Foreign Agriculture Service, U.S. Department of Commerce Bureau of the Census, California Department of Food and Agriculture, USDA/Economic Research Service calculations. Numerous sources were used for conversion factors. See the workbook "Trade data conversion factors and sources" at http://www.ers.usda.gov/data-products/dairy-data.aspx.

FIGURE 6 Via Jess Cessna, Lindsay Kuberka, Christopher G. Davis, and Roger Hoskin, Growth of U.S. Dairy Exports, U.S.D.A. ECON. RES. SERVICE, supra note 84.

Implementation was phased in over a 6-year period that concluded in 2000 – 2001, just as U.S. dairy exports began dramatically increasing.

The growth of the U.S. dairy export market has not only accelerated consolidation but resulted in "greater variability in demand and prices."[95] California's dairy industry exports "about a third of all U.S. dairy exports, about twice its share of national production," making it particularly susceptible to the pressures of the global market, as will be discussed in more detail in the leakage section.[96]

B. Data that can be used to analyze the impact of the LCFS will become available in 2024.

The USDA consolidation report uses the most recent agriculture census data from 2017, but the LCFS adopted the inclusion of fuels from dairy and swine manure in 2017.[97] The use of fuels from dairy and swine manure in California appears to have taken off in earnest in 2018,[98] and therefore the impacts on the industry as a whole are not likely to be observable in the 2017 agriculture census data. (UC Davis agro-economist Aaron David Smith notes, "Data from the 2022 census will enable us to see whether the number of cattle on large farms has increased during the digester boom, but it will not be released until next year.")[99] USDA recently announced that the 2022 Agriculture Census will be released on February 13, 2024.[100]

95 *Id.*

96 Daniel A. Sumner, California Agriculture: Dimensions and Issues, Chapter 6: California Dairy: Resilience in a Challenging Environment, 143, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

97 Cal. Air Res. Bd., *Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways* (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-9-CARB.pdf but it says specifically a simplified calculator was adopted in 2019 and we know most applications are tier 2 anyway. The presentation says there were already 67 applied DSM pathways by Jan 1 2019. Table on slide 7 suggests credits first generated for dairy biomethane in 2017.

98 Cal. Air Res. Bd., *Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways*.

99 Aaron David Smith, *Are Manure Subsidies Causing Farmers to Milk More Cows?* Ag Data News (April 7, 2023), https://asmith.ucdavis.edu/news/are-digesters.

100 U.S. Dep't of Ag., Agriculture Census, https://www.nass.usda.gov/AgCensus/.

Figure 6.10. California Dairy Product Destinations, Share of 2018 Exports

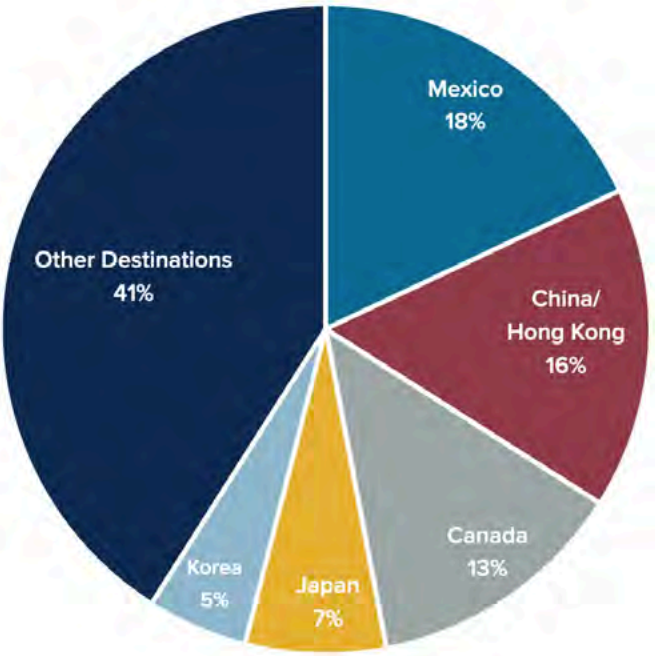

Source: University of California Agricultural Issues Center

FIGURE 7 Via Daniel A. Sumner, CALIFORNIA AGRICULTURE: DIMENSIONS AND ISSUES, Chapter 6: California Dairy: Resilience in a Challenging Environment, 143, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

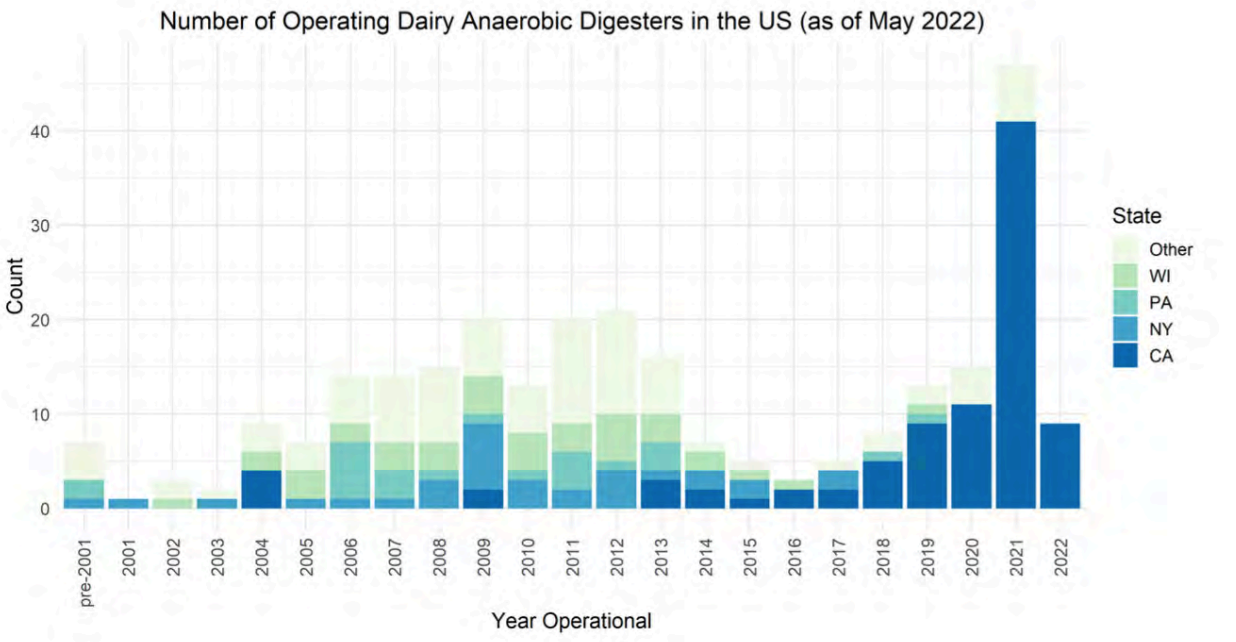

FIGURE 8 Via Aaron David Smith, Are Manure Subsidies Causing Farmers to Milk More Cows? (April 7, 2023), Ag Data News https://asmith.ucdavis.edu/news/are-digesters.

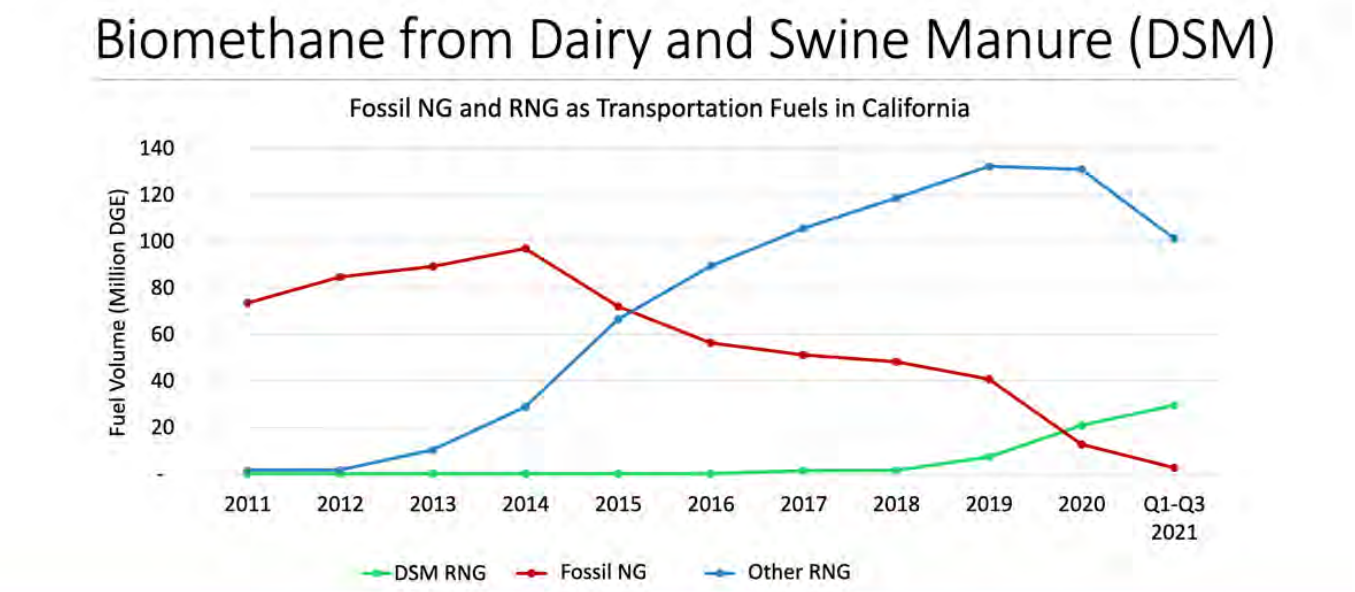

FIGURE 9 Via Cal. Air Res. Bd., Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-9-CARB.pdf.

C. Key Takeaways: Consolidation and LCFS Credits

- **The data required to analyze the impact of the LCFS on dairy consolidation will not be available until February 13, 2024.** The most recent Agriculture Census year is 2017, which is too early to show the effects of LCFS credits on California dairy. Any impact from the LCFS would likely be small, but dairy operations operate on slim margins so even a small shift in incentives could accelerate the pre-existing trend.

- **Dairy consolidation is a long-term trend driven by policy choices.** Small and mid-sized dairies in the Midwest and the East declined dramatically over past decades, as mega-dairies concentrated in the West, and particularly in California, have ballooned. There are many causes of consolidation including the dismantling of supply side management programs and the opening of export markets, which multiplied economies of scale.

- **There is a symbiotic relationship between industrialization, consolidation, and the push for dairy digesters.** Consolidation has resulted in fewer, ever-larger dairy operations. The larger operations become, the more manure they must manage and the more likely they are to rely on a manure lagoon. Dairy consolidation has set the stage for the digester push as the California dairy industry has become dominated by industrial-scale operations with manure lagoons.

- **Investing in industrial dairies further bolsters the competitive edge of these mega-operations at the expense of more sustainable dairying models and burdens environmental justice communities.** Smaller-scale dairies and pasture-based dairies have been fighting to preserve their competitive edge, but the LCFS provides credits that are generally only available to the largest dairies. Industrial dairying also contributes to and exacerbates ongoing environmental justice harms (the EPA states: "The San Joaquin Valley has some of the nation's worst air quality, fail-

ing to meet federal health standards for both ozone (smog) and particulate pollution").[101] And because industrial dairying has been historically prevalent in California, California environmental justice communities in the Central Valley have long experienced these harms.

V. Emissions Leakage Risk

Industry stakeholders assert that regulating methane from dairies[102] will push dairies out of business or out of state, exacerbating overall GHG emissions.[103] The movement of an industry and its emissions to another jurisdiction in order to avoid regulatory costs is called emissions leakage, and could present legal concerns.

AB 32 (2006) requires CARB to "minimize leakage to the extent feasible" in regulations promulgated under Parts IV and V of the Global Warming Solutions Act of 2006.[104] This includes the LCFS, promulgated under Part IV as an early action measure. The statute defines leakage as "a reduction in emissions of greenhouse gases within the state that is offset by an increase in emissions of greenhouse gases outside the state."[105] SB 1383 (2016) also requires CARB to "minimize and mitigate leakage to other states or countries as appropriate" in any potential regulation of dairy methane.[106]

The claim that regulating dairy methane will result in leakage has two parts that demand scrutiny. The first is the predictive assertion that if regulation is implemented, facilities will a) not be able to bear the costs of doing business and b) will be adequately mobile to move. The second is the premise that California leads the nation in "climate-smart dairy farming." If California dairies generate more emissions than dairies in other states,[107] outmigration of dairies won't necessarily result in equivalent or increased overall GHG emissions.

Additional political concerns are sometimes wrapped into the legal leakage claims. Generally, these arguments slip other value-laden claims about the loss of California dairy operations into the discussion, including the loss of jobs, the economic and cultural loss of the dairy industry, and sometimes implications that industry moving out-of-state will result in greater environmental degradation beyond GHG emissions. These important points bear discussion, but they are distinct from the legal emissions leakage argument.

The argument that methane regulation could lead to emissions leakage holds water if:

a) Other states are a more appealing place to operate than California;
b) The industry is adequately mobile to move;
c) The move would result in equivalent or a net increase in emissions.[108]

Legally, regulators are not required to prevent leakage altogether. They are required to "minimize" leakage in the context of the LCFS and to "minimize and mitigate" leakage in the context

101 U.S. Env't Prot. Agency, EPA Activities for Cleaner Air, https://www.epa.gov/sanjoaquinvalley/epa-activities-cleaner-air.
102 Excluding dairies from the LCFS should not result in inter-state leakage, because out-of-state dairies are currently eligible for LCFS credits. That is: there is no existing benefit to California dairies that CARB could remove at their expense relative to out-of-state operations. The claim the adoption of new regulations will result in leakage, however, deserves more attention.
103 A Dairy Cares comment letter, for example, argued: *"The analysis also shows that misguided efforts to change course by forced conversion to pasture-based operations, direct regulation of dairy farms, or limitations on dairy digester incentives will not only fail to achieve the desired greenhouse gas emission reductions but will exacerbate the problem by causing significant emissions "leakage". As demand for dairy products continues to increase across the U.S. and world, the dairy industry is likely to respond to costly direct regulation by leaving for states with less costly regulations and less commitment to climate protection."* The Dairy Cares website, for example, asserts: "California leads the nation in climate-smart dairy farming, and cows leaving results in a "leakage" of methane emissions."
104 Cal. Health & Safety Code § 38562 (b)(8).
105 Cal. Health & Safety Code § 38562 (b)(8).
106 Cal. Health & Safety Code § 39730.7.
107 I use climate-friendly, rather than climate-smart to convey an industry generating fewer GHG emissions. Climate smart is a term favored by industry that doesn't require overall emissions to decrease but simply for the industry to employ "smart" technologies. As such, it does the work of defining success on the industry's terms while conveying a more general sense of climate-friendly practices.
108 The leakage argument typically focuses exclusively on GHG emissions, but a consideration of other forms of pollution is appropriate as well.

of new dairy methane regulations pursuant to SB 1383. This discussion surveys research on leakage risk generally before evaluating each of the three criteria above and offering a final analysis of the risk of legal leakage if methane regulations are enacted or LCFS credits are diminished.

A. Leakage Risk Generally

Emissions leakage describes the movement of industry, and by extension that industry's emissions, out of one jurisdiction and into another in response to emissions regulation.[109] Leakage is a greater risk in industries that are "trade-exposed"[110] and in industries that are mobile. Trade-exposed industries are competing on the slim margins of global market and, if they are mobile, able to relocate with relative ease.

There is very little evidence that leakage in response to emissions regulation is common in practice.[111] Despite significant theoretical backing for leakage, research has consistently found virtually no evidence of emissions leakage.[112] A CARB-commissioned analysis from 2016 found that most early empirical studies on the trade effects of pollution control regulations established "no relationship, or a counter-intuitive positive relationship, between energy costs and net imports."[113] One "more sophisticated" study determined that "for most industries, environmental compliance costs have been too small to affect trade flows in an economically significant way."[114] One explanation for the low rates of leakage is the effective use of various policy tools to mitigate leakage risk.[115] These tools will be discussed further below in the legal analysis section.

The concept of leakage rests on an idealized notion of a frictionless global market. In practice, uprooting industries comes with its own costs and global markets have not operated as seamlessly as in economics textbooks. Research has found that risk of leakage is linked to the measure of industry's mobility. The Fowlie et al. study cited above found that while more mobile industries are indeed susceptible to leakage, "pollution intensity is positively correlated with [industry's] measures of immobility."[116] That is: more mobile industries are susceptible to leakage but the most polluting industries tend to be the most immobile.

Additionally, while regulation can result in a decline of in-state industry, typically only a portion of the decline in in-state production ends up migrating out-of-state.[117] A different CARB analysis on leakage risk from several food sectors, including cheese processing, found that a $20 million carbon compliance cost in California

109 Meredith L. Fowlie, Mar Reguant, and Stephen P. Ryan, *Measuring Leakage Risk* (May 2016), https://ww2.arb.ca.gov/sites/default/files/cap-and-trade/meetings/20160518/ucb-intl-leakage.pdf. A 2016 CARB-commissioned analysis on mitigating leakage characterizes the basic concern as follows: "An increase in relative operating costs can, in turn, adversely impact the ability of regulated firms to compete in a global market. If this shifts production outside the regulated jurisdiction, any associated increase in emissions can undermine the effectiveness of regional policies."

110 RFF uses the term "trade-exposed industry" and one RFF reports notes that highly emitting industries and industries highly exposed to international competition are particularly prone to leakage. Juha Siikamäki, Clayton Munnings, Jeffrey Ferris, and Daniel Morris, *Climate Policy, International Trade, and Emissions Leakage,* Resources for the Future, https://media.rff.org/documents/RFF-Bck-EmissionsLeakage.pdf. See also *Mitigating Emissions Leakage in Incomplete Carbon Markets,* 9 J. of the Ass'n of Env't and Res. Econ. 2, 307-343, 2022.

111 Meredith L. Fowlie, Mar Reguant, and Stephen P. Ryan, *Measuring Leakage Risk* (May 2016), *supra* note 109, at 8.

112 Michael Grubb *et al., Carbon Leakage, Consumption, and Trade*, 47 Ann. R. of Env't and Res. 753 (Sept. 2022), https://www.annualreviews.org/doi/pdf/10.1146/annurev-environ-120820-053625 (Studies find no evidence that climate policies lead to carbon leakage, but this is partly due to shielding of key industrial sectors, which is incompatible with deep decarbonization."); Florian Misch and Philippe Wingender, Revisitng Carbon Leakage, IMF Working Papers, 207 (Aug. 6, 2021), https://www.elibrary.imf.org/view/journals/001/2021/207/article-A001-en.xml ("The large body of the existing theoretical literature (which we review in the Appendix) has not reached consensus on the approximate magnitude or even the sign of carbon leakage... The empirical literature is smaller, and the results mostly imply that carbon leakage is limited.")

113 *Id.;* A 2015 report on the European Union's Emissions Trading System found "no evidence for production displacement," "no evidence for future 'carbon leakage' risk, and that "industry confirm[ed] lack of 'carbon leakage' risk." Carbon Market Watch, *Carbon Leakage Myth Busters* (Oct. 2015), https://carbonmarketwatch.org/wp-content/uploads/2015/10/CMW-Carbon-leakage-myth-buster-WEB-single-final.pdf.

114 *Id.*

115 *Commentary: What is Carbon Leakage? Clarifying Misconceptions for a Better Mitigation Effort*, London School of Econ. And Poli. Sci. (Dec. 8, 2021), https://www.lse.ac.uk/granthaminstitute/news/what-is-carbon-leakage-clarifying-misconceptions-for-a-better-mitigation-effort/.

116 *Id.*

117 Meredith L. Fowlie, Mar Reguant, and Stephen P. Ryan, *Measuring Leakage Risk* (May 2016), *supra* note 109 (about 1/6th of production decline moves out of state).

would lead to production decrease of .05% of the California cheese supply or 525.07 metric tons. That study further concluded that for cheese, 57% of that .05% California decrease would move out of state, resulting in a production leakage of 301.83 metric tons.[118] (Note that cheese processing is distinct from dairying, so these numbers, while instructive generally, are not directly on point for our purposes.)[119]

The food processing leakage study explained that emissions leakage can be determined from these production leakage numbers by "adjusting the market transfer effect for the relative emissions-intensity of the plants acquiring and losing market."[120] The authors refrained from making concrete predictions for cheese processing emissions leakage, instead citing variability in practices. They did, however, suggest that California food processing relies more on natural gas while other states rely more on coal, so some emissions leakage would likely occur in that sector.[121]

Overall, the research on emissions leakage suggests that the risk of major production leakage—of entire industries moving out of state—is low. Instead, depending on the costs of newly imposed regulation, the more likely outcome is a small decline in California production and some portion of that decline shifting out-of-state. Moving alone (production leakage), even because of emissions regulation, is not necessarily emissions leakage. Operations must move because of emissions regulation and must, in their new jurisdiction, emit as much or more methane as they had in California. In the context of dairy, the relevant comparison would be whether the practices of out-of-state dairies are more- or less-carbon intensive than in-state dairies.

It is impossible to predict what the costs of regulation and the attendant decline in California production might be, since no methane regulation for dairy has been proposed by CARB. In terms of LCFS credits, it is extremely unlikely that change to LCFS crediting would result in emissions leakage. Emissions leakage is causal[122] and depends on regulatory asymmetries, but LCFS credits are available to dairy operations nationally. This means a change in LCFS crediting would not result in the kind of regulatory asymmetries that cause leakage.

B. Relative Mobility of California Dairies

One study defines mobility as "an inherent characteristic of industry, which is closely related to the industry's own production and technical attributes, and reflects the ability of the industry to transfer flexibly among regions."[123] Measures of industry mobility appear to be relatively less studied than regulatory impacts on competitiveness, but one CARB-commissioned analysis used capital intensity as a proxy for immobility.[124] A study of Chinese industry mobility further identified several key measures of mobility including sunk costs, asset specificity, and difficulty of labor

118 Dr. Stephen F. Hamilton, Dr. Ethan Ligon, Dr. Aric Shafran, and Dr. Sofia Villas-Boas, *Production and Emissions Leakage from California's Cap-and-Trade Program in Food Processing Industries: Case Study of Tomato, Sugar, Wet Corn and Cheese Markets* (May 9, 2016), https://ww2.arb.ca.gov/sites/default/files/cap-and-trade/meetings/20160518/calpoly-food-process-leakage.pdf.

119 The CARB analysis was conducted for food processing sectors, rather than agriculture, because food processing is covered by cap-and-trade. CARB has pioneered efforts to reduce leakage in its cap-and-trade program.

120 Dr. Stephen F. Hamilton, Dr. Ethan Ligon, Dr. Aric Shafran, and Dr. Sofia Villas-Boas, *Production and Emissions Leakage from California's Cap-and-Trade Program in Food Processing Industries: Case Study of Tomato, Sugar, Wet Corn and Cheese Markets* at 43.

121 In the cheese processing plant study, the authors looked at general food processing statistics and assumed that, "[f]or the case of California food processors, the typical plant operates on natural gas; however, global food processing plants including those in other U.S. states rely on other sources such as coal and fuel oil." As a result, the authors suggested generally that food processing outmigration would result in increased net emissions, though they qualified that with the need for more specific data. *Production and Emissions Leakage from California's Cap-and-Trade Program in Food Processing Industries: Case Study of Tomato, Sugar, Wet Corn and Cheese Markets* at 43.

122 *Commentary: What is Carbon Leakage? Clarifying Misconception for a Better Mitigation Effort*, *supra* note 115.

123 Jianmin Dou and Xu Han, *How Does the Industry Mobility Affect Pollution Industry in China: Empirical Test on Pollution Haven Hypothesis and Porter Hypothesis*, 217 J. Cleaner Prod. 105 (April 20, 2019), https://www.sciencedirect.com/science/article/pii/S0959652619301647?casa_token=w8DPvD0fDUEAAAAA:fCh8su48J0KAzSBZXru34w404UX2TyDro5xOoaHLJ6SiVTjZABtruzpOAZ4Afn1xYu6ftyhdXw#bib41 (citing Stem 2007).

124 Fowlie et al., *Measuring Leakage Risk*, *supra* note 109 ("Capital intensity serves as a proxy for immobility; highly capital-intensive firms tend to be harder to relocate.")

force transfer.[125] The same study found generally that more mobile industries are more likely move in response to regulation, while less mobile industries are more likely to innovate.

Industrial-scale confinement dairies are highly capital intensive (and intensification of capital, land, and animals is one of the major trends in dairying in recent decades).[126] Barns and lagoons require significant, long-term investments that become sunk costs. The addition of digesters makes these operations even more capital intensive and less likely to move. Livestock itself is mobile, but like other highly polluting industries, industrial dairies cannot simply pick up and move anywhere. They are limited to areas that are zoned for agriculture and where the addition of thousands of cows and their waste will not be challenged by local communities. Industrial-scale facilities relying on export markets must consider proximity to processing facilities and/or to ports, as well as attendant freight costs. Labor force transfer could impose additional challenges. The National Milk Producers Federation states "[e]ven as technology become a greater park of agriculture, much of dairy farming remains labor-intensive."[127] The dairy labor supply is currently tight. The industry is facing labor shortages "with no foreseeable end in sight."[128]

C. Relative Appeal of Other States

The likelihood of production leakage depends on whether other states' practices and environments—regulatory and otherwise—make them more appealing than California. There is a lot of talk about how challenging the landscape is for California dairies[129]; however, the dairy industry in California is doing relatively well compared to other states. California has remained the top milk producer in the country since 1993.[130] California houses one in five of the nation's cows and produces one fifth of the milk produced in the United States.[131] Dairy farming is the leading agricultural commodity in California, generating $7.57 billion cash receipts from milk (in 2021) and handily sells more milk than any other state.[132] The export value of California dairy was $2.5 billion dollars in 2021.[133] In the most recent agriculture census, Tulare County alone had $1.8 billion in milk sales—5% of milk sales nationally—and four out of five of the top counties for milk sales were in California.[134] None of these statistics suggest a baseline environment that is significantly worse for dairy operators in California than in other states.

There has been a slight decline in California production and cow inventories from 2007-2017

125 Jianmin Dou and Xu Han, *supra* note 123.

126 Sara D. Short, *Characteristics and Production Costs of U.S. Dairy Operations*, US Dep't of Ag. Econ. Res. Service (February 2004), https://www.ers.usda.gov/webdocs/publications/47156/28499_sb974-6_1_.pdf?v=0; Milena Bojovic and Andrew McGregor, *Review of Megatrends in the Global Dairy Sector: What are the Socioecological Implications*, 40 Ag. And Human Values, 373 (2023), https://link.springer.com/article/10.1007/s10460-022-10338-x.

127 Nat'l Milk Prod. Fed., Labor and Immigration, https://www.nmpf.org/issues/labor-rural-policy/labor-and-immigration-reform-efforts/.

128 Taylor Leach, *Dairy Farmers Face Labor Challenges Never Seen Before*, Dairy Herd Mgmt. (Dec 6., 2022), https://www.dairyherd.com/news/labor/dairy-farmers-face-labor-challenges-never-seen.

129 A Congressional Research Service report on emissions leakage explains, "There is every incentive for any industry facing a cost increase from carbon policies to claim that its competitive position could be diminished, thereby justifying special consideration by the government." Larry Parker and John Blodgett, *"Carbon Leakage" and Trade: Issues and Approaches*, Congressional Res. Service (Dec. 19, 2008), https://www.everycrsreport.com/files/20081219_R40100_1464249ac98c462316e637e26ca75217dd95a47c.pdf.

130 Cal. Dep't Food and Ag., California Dairy Pressroom and Resources, Real California Dairy Facts, https://www.californiadairypressroom.com/Press_Kit/Dairy_Industry_Facts.

131 *Id.*

132 *Id.*; U.S. Dep't of Ag., *2017 Ag. Census Highlights: Dairy Cattle and Milk Production*, https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_DairyCattle_and_Milk_Production.pdf.

133 Cal. Dep't of Food and Ag., *California Agricultural Exports 2021-2022*, https://www.cdfa.ca.gov/Statistics/PDFs/2022_Exports_Publication.pdf.

134 U.S. Dep't of Ag., *2017 Ag. Census Highlights: Dairy Cattle and Milk Production*, https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_DairyCattle_and_Milk_Production.pdf.

(the year of the most recent USDA agriculture census), with production and inventory "rising noticeably in Idaho and in the Plains States of Texas, Kansas, and South Dakota."[135] Attrition of California dairy herds and gains in nearby states suggest that California is losing some of the comparative advantage it possessed for the past few decades, but does not validate claims[136] that such migration would be prompted by emissions regulation. Migration is already occurring with no emissions regulations on the books. The fact that the industry is already migrating suggests that hypothetical future emissions regulations would not be the sole cause of such migration, diminishing the case for leakage. There may be broader concerns about the environmental impacts of dairies moving out of state, but these concerns are distinct from the legal concern around emissions leakage.

Some of the commonly identified issues for California dairies include environmental regulation, drought, milk prices, fluctuating demand for dry milk (one of California's major exports),[137] and labor shortages.[138] A 2010 survey found that the top three concerns for both California and Wisconsin dairy operators were: environmental regulations, volatile milk prices, and high prices of inputs.[139] The remainder of this section will briefly survey these concerns.

1. Environmental Quality Regulation

Environmental regulations unrelated to GHG emissions will not influence whether an out-of-state move will result in GHG emissions leakage, but they can impact how appealing that initial move is. California's regulation of air and water quality are comparable to other agricultural states.

Like all states, California is subject to the federal Clean Water Act. At the federal level, the Clean Water Act does not require discharge permits (under the National Pollution Discharge Elimination System (NPDES) program) as a matter of course for agricultural operations.[140] Instead, permits are only federally required where operations are shown to have discharged. It can take extensive documentation of violations of the Clean Water Act and can entail multiple enforcement actions before a NPDES permit is required.

NPDES permitting authority is generally delegated to states. In California, NDPES permits are issued by Regional Water Control Boards. Accord-

135 A Dairy Cares comment letter on LCFS virtual community meetings states, "The regulatory burdens and resulting high cost of doing business in California and resulting economics of dairy production in a national market are driving consolidation, not the presence of LCFS incentives." Michael Boccadero, *Dairy Cares Comments on LCFS Virtual Community Meetings*, *available at* https://ww2.arb.ca.gov/approved-comments?entity_id=28876.

136 A UC Davis report, for example, asserts that "Ongoing attrition and consolidation in the state's dairy sector is evidence of leakage risk." While attrition is an indication of the general health of the industry, that is unrelated to the causal analysis of emissions leakage, which asks whether emissions regulations specifically have shifted or increased net emissions. Ermias Kebreab, Frank Mitloehner, and Daniel A. Sumner, *Meeting the Call: How California is Pioneering a Pathway to Significant Dairy Methane Reduction*, UC Davis CLEAR Center (Dec. 2022), https://clear.ucdavis.edu/sites/g/files/dgvnsk7876/files/inline-files/Meeting-the-Call-California-Pathway-to-Methane-Reduction_0.pdf.

137 Jeff Daniels, *Outside States to California Dairy Farmers: We Have Water*, CNBC (Feb. 10, 2015), https://www.cnbc.com/2015/02/10/california-drought-states-tempt-california-dairy-farms--we-have-water.html ("The USDA economist said it's not just the drought and high cost of feed that has been hurting California dairy producers but a decline in the dry milk market that's been "a big export market for them. They've taken a disproportionate hit on that market. Strong dollar is contributing and China has retreated from the market.")

138 Dave Natzke, *State of the Dairy 2022: California in a 'State' of its Own,* Progressive Dairy (March 10, 2022), https://www.agproud.com/articles/54489-state-of-the-dairy-2022-california-in-a-state-of-its-own ("Outside of milk markets, Raudabaugh splits California dairy farmers into two major burden-carrying groups: those facing water woes and those encountering labor shortages.")

139 Andre de Witte, Jessica Nowak, Frederike Schierholz, and Birthe J. Lassen, *Dairy Farming in Wisconsin and California: Different Challenges –Different Future?* The Snapshot Survey (Spring 2010) http://www.agribenchmark.org/fileadmin/Dateiablage/B-Dairy/Misc/10_Snapshot_USA.pdf.

140 In the early decades of the Clean Water Act, agricultural activities were deemed nonpoint sources. In the early 2000s, CAFOs of a certain size were designated as point sources and therefore were required to seek permits. Prompt litigation brought by the pork industry, however, resulted in a rebuttable presumption that CAFOs do not discharge and are therefore not federally required to obtain National Pollutant Discharge Elimination System (NPDES) permits (though states can still require them). In 2022, a large group of advocates petitioned EPA to rescind the rebuttable presumption that CAFOs do not discharge but EPA did not act on the petition. *Earthjustice Petition to U.S. EPA to Adopt a Rebuttable Presumption that Large CAFOs Using Wet Manure Management Systems Actually Discharge Pollutants Under the Clean Water Act* (October 2022s), *available at* https://earthjustice.org/wp-content/uploads/cafopresumptionpetitionfinal_oct2022.pdf.

ingly, much of the important water quality regulation occurs at the regional level.[141] Today, Central Valley Regional Water Control Board Order No. R5-2013-0122 applies to most dairies.[142] Order No. R5-2013-0122 requires existing dairies to enroll (unless they are not eligible because they have recently expanded). Dairies must submit waste and nutrient management plans and participate in groundwater monitoring to ensure they are in compliance.[143] Since the general order, new and expanding dairies in the region have been issued individual permits.[144] California's Porter-Cologne Water Quality Control Act also requires operations that discharge waste that could impact the quality of state waters to be permitted. (In 2022, only about 7% of California's 1,083 CAFOs were required to have NDPES permits; the rest were permitted under state general orders.)

The Central Valley's water quality permitting is not particularly onerous relative to permitting regimes in other agricultural states. In some respects, it is more lax, particularly given the concentration of CAFOs spreading waste in the Central Valley. For example, Order No. R5-2013-0122 allows dairy operations to apply potassium and phosphorus in excess of agronomic rates unless application causes "adverse impacts," at which point operations are to stop application.[145] This is a weaker standard than under federal regulations and in other states.[146] The Order generally does not require operations to submit their waste management plans to the permitting agency for review; nor are operations required to make their nutrient waste management plans available for public review.[147] By contrast, both Idaho and Texas require nutrient management plans to be approved by a regulating agency and South Dakota requires nutrient management plans to be made available for public review.[148] Industry complaints about water quality permitting are not unique to dairies in California. They are ubiquitous in many western dairying states.[149]

Air emissions like ammonia, volatile organic compounds (VOCs), and particulate matter from

141 Statewide Water Quality Regulations for Confined Animal Facilities, Subchapter 2. Confined Animals, https://www.waterboards.ca.gov/centralvalley/water_issues/confined_animal_facilities/program_regs_requirements/dairy/dairyreg.pdf. The Central Valley Regional Water Control Board had just required NPDES permits for dairies under Order No. R5-2010- 0118, and the order was then revised to reflect the decision in National Pork Producers Council v. Environmental Protection Agency. National Pork Producers Council, et al v. United States Environmental Protection Agency (5th Cir 2011) 635 F 3d 738. It was replaced with Order R5-2011-0091. Cal. Water Boards, Central Valley Region, Confined Animal Facilities – Dairy Program Regulations and Requirements, https://www.waterboards.ca.gov/centralvalley/water_issues/confined_animal_facilities/program_regs_requirements/dairy/.

142 Cal. Regional Water Quality Control Board, Central Valley Region, Order R5-2013-0122, Reissued Waste Discharge Requirements General Order for Existing Milk Cow Dairies.

143 *Id*.

144 Eamon Norman, *Cal. Air Res. Bd. Workshop: Air Quality Regulations for Dairies in the San Joaquin Valley* (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-2-SJVAPCD.pdf; Attachment C: Permitting Requirements for Dairies in California, https://www.waterboards.ca.gov/northcoast/water_issues/programs/dairies/pdf/AttC_Summary_of_Permitting_at_Dairies.pdf; Cal. Regional Water Quality Control Board, Central Valley Region, Order R5-2007-0035: Waste Discharge requirements General Order for Existing Milk Cow Dairies, California Regional Water Quality Control Board.

145 Cal. Regional Water Quality Control Board, Central Valley Region, Order R5-2013-0122, Reissued Waste Discharge Requirements General Order for Existing Milk Cow Dairies at C-11.

146 Earthjustice Petition at 49, *supra* note 140.

147 *Id*.

148 Farmers Assuring Responsible Management, Nutrient Management Fact Sheet: South Dakota (March 2021), https://nationaldairyfarm.com/wp-content/uploads/2023/01/NMP-Fact-Sheet-South-Dakota.pdf; Farmers Assuring Responsible Management, Nutrient Management Fact Sheet: Texas (January 2021) https://nationaldairyfarm.com/wp-content/uploads/2021/09/NMP-Fact-Sheet-Texas.pdf.

149 In Utah: Catherine Merlo, *Western Water Woes: Dairies Grapple with Uncertain Supplies, Ever-Tougher Regulations,* Dairy Herd Management (May 3, 2010), https://www.dairyherd.com/news/western-water-woes-dairies-grapple-uncertain-supplies-ever-tougher-regulations (Mike Kohler, the executive director of Dairy Producers of Utah, which represents 90% of the state's 245 dairies and 90,000 milk cows, argued that water-quality regulations most important issue to dairies there: "The problem isn't obtaining water but managing manure under an increasingly aggressive Environmental Protection Agency."); In New Mexico: *Id.* ("State legislation passed last year required New Mexico's Water Quality Control Commission to identify specific requirements for discharging dairy wastewater to protect groundwater quality. The Environment Department says more than 65% of New Mexico's 150 dairies have polluted groundwater beneath their facilities."; In Texas: Texas Comm'n on Env't Quality, *Interoffice Memorandum: Commission Approval for Proposed Rulemaking Land Application and Disposal of Dairy Waste Docket No: 202301229-RUL* (Oct. 20, 2023), *available at* https://www.tceq.texas.gov/downloads/rules/current/23139321_pex.pdf; In Idaho: *Watering Idaho: Is the Dairy Industry Putting Rural Drinking Water at Risk*, Boise State Public Radio News (Sept. 21, 2016), https://www.boisestatepublicradio.org/environment/2016-09-21/watering-idaho-is-the-dairy-industry-putting-rural-drinking-water-at-risk (On the requirement that dairies have waste management plans); In Washington: Courtney Flatt, *WA Dairies Must Do More to Clean Up Their Act, Judges Rule*, Northwest Public Broadcasting (July 13, 2021), https://crosscut.com/environment/2021/07/wa-dairies-must-do-more-clean-their-act-judges-rule .

dairies are a major concern generally and even more so in the Central Valley.[150] The state regulatory regime for air pollution is entwined with California's State Implementation Plans (SIPs), which are required to remedy the San Joaquin Valley's decades-long nonattainment of federal air quality standards under the Clean Air Act.

In 2003, SB 700 was passed to resolve a conflict between California and federal law. One of the changes the law made was to remove an air permitting exemption for agricultural operations. California now treats large dairy operations like other large sources of air pollutants and makes these farms subject to air district permits if emissions exceed half of a major source threshold.[151] In practice, 96% of dairies in the San Joaquin Valley obtain air permits.[152] The regulation of CAFOs as stationary sources is distinctive and a response to the San Joaquin Valley's severe air quality issues and the dairy industry's role in generating emissions. At least some research suggests that "air quality regulations have not raised farm costs significantly" for California dairies.[153]

California does not currently regulate GHG emissions from dairies, though CARB has the authority to do so as of January 2024. Industry stakeholders and even reporters often describe SB 1383 as imposing a regulatory burden on dairies.[154] But SB 1383 imposes no affirmative obligations on dairies currently. Instead, the law sets industry-wide targets and mandates that *CARB* implement a strategy to meet those targets.[155] Still, the potential for future methane regulations on dairies is viewed as a negative and statewide methane regulations on dairies are undoubtedly less likely to be promulgated in some other major western dairying states than in California.

2. Drought

Drought and overall lack of water resources in California presents serious challenges to the state's dairy industry.[156] Adequate water is important to irrigate feed crops (alfalfa is very water intensive) and to manage the flush systems many California dairies rely on. The lack of water is also a problem for manure spreading at agronomic rates—if there's no water to grow crops, there is no crop to uptake the nutrients and spreading could result in groundwater contamination. Geoff Vanden Heuvel of the California Milk Producer Council observes: "Because the predominant method of manure disposal or utilization as it was, was fertilizer on crops, which if the water supply becomes limited to grow those crops, then that creates a problem."[157]

150 A. Rotz et al., *Environmental Assessments of United States Dairy Farms*, J. of Cleaner Prod. 315 (2021) 128153, https://www.sciencedirect.com/science/article/pii/S0959652621023714 (Ammonia in particular is one of the most serious harms from dairies: "dairy farms may emit as much as 24% of that [ammonia] estimated for the whole country.")

151 SB 700 (Florez, 2003).

152 Eamon Norman, *Cal. Air Res. Bd. Workshop: Air Quality Regulations for Dairies in the San Joaquin Valley* (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-2-SJVAPCD.pdf.

153 Josué Medllín-Azuara et al., *Assessment of California Crop and Livestock Potential to Adapt to Climate Change (Prepare for California's Fourth Climate Change Assessment)*, Publication number: CCCA4-CNRA-2018-018, University of California, Davis and University of California, Merced (2018), https://www.energy.ca.gov/sites/default/files/2019-11/Agriculture_CCCA4-CNRA-2018-018_ADA.pdf.

154 *See, e.g.* A UC Davis blog asserting that the dairy sector "is mandated to reduce methane emissions by 40% by 2030." *California Dairy Sector Poised for Climate Neutrality by 2030, per US Davis Research*, UC Davis CLEAR Center (May 2, 2023) https://clear.ucdavis.edu/news/california-dairy-sector-poised-climate-neutrality-2030-uc-davis-researchers; An agriculture trade publication writes that SB 1383 "require[es] livestock and dairy operations to reduce manure methane emissions by 40% by 2030." Dave Natzke, *State of Dairy 2022: California in a 'State' of its Own*, Progressive Dairy (March 10, 2022), https://www.agproud.com/articles/54489-state-of-the-dairy-2022-california-in-a-state-of-its-own.

155 ENVIRONMENTAL PROTECTION—POLLUTION—REDUCTION, 2016 Cal. Legis. Serv. Ch. 395 (S.B. 1383) (WEST) ("This bill would require the state board, no later than January 1, 2018, to approve and begin implementing that comprehensive strategy to reduce emissions of short-lived climate pollutants to achieve a reduction in methane by 40% ... below 2013 levels by 2030, as specified.")

156 *See, e.g. Are California Farmers Really Leaving for Greener Pastures?* Dairy Herd Management (Dec. 23, 2022), https://www.dairyherd.com/news/business/top-10-stories-2022-are-california-farmers-really-leaving-greener-pastures ("RaboResearch started exploring g the idea of dairy cows migrating toward the center of the country a couple years ago. The Reason? Water issues in the West, as well as a way to be closer to an abundance of feed. And Rabo says today, that scenario is already playing out.")

157 *California Water Crisis Challenges Dairy, Vanden Heuvel Says*, Nat'l Milk Prod. Federal Dairy Defined Podcast (Sept. 12, 2022), https://www.nmpf.org/california-water-crisis-challenges-dairy-vanden-heuvel-says/.

While drought and inadequate water is first and foremast a climactic problem, California's system of water use is often viewed as another source of burdensome regulation by dairy operators.[158] State regulators have to step in in order to manage the water supply and protect the state's water resources. Overdrawn basins have had to submit implementation plans under the Sustainable Groundwater Management Act of 2014.[159] Combined with drought years, this has put increasing pressure on dairies, particularly in the southern San Joaquin Valley.[160]

At least one state (Iowa) touted its "abundant water" at California's dairy expo in an attempt to entice dairy operators to move.[161] But drought and water resources issues generally are also major concerns in many of the western dairying states where California dairy operations might be likely to move.[162]

3. *Milk Prices*

Milk prices are an essential part of what makes a given state more or less appealing to dairy operations. About 75% of U.S. milk production is covered the Federal Milk Marketing order (FMMO).[163] The FMMO applies to and establishes minimum uniform prices for the exchange of milk from dairy operations to dairy processers within specific areas.[164] There are 11 different FMMO regions in the United States. Historically, California set its prices in a separate but similar program,[165] but joined the FMMO in 2018.[166] California comprises its own region in the FMMO. At least some dairy operators seem to think the FMMO has improved California milk prices relative to the old system.[167] There has also been pushback to the new system.[168]

Under both systems, California's milk prices have been relatively low. Daniel Sumner asserts that California's relatively low milk prices stem from its role as a net exporter and the cost pressure on milk processers here. He cautiously predicts that, because these specific pressures are unlikely to change in the near future, "a return to rapid growth of California milk production seems unlikely. However, the inherent strengths of the California dairy industry remain. Therefore, it also seems unlikely that significant aggregate declines in California milk production are on the horizon."

158 *Id.* ("It's a combination of droughts, but also what we call manmade drought.")

159 *Id.* ("And then those agencies in critically overdrafted basins, which is most of the Central Valley, had a requirement that by January 31 of 2020, they had to submit a plan that would show how that area was going to become sustainable by the year 2040.")

160 *Id.* "And in the Southern San Joaquin Valley, south of Fresno is just naturally drier than the northern part of the Central Valley. And so it's facing kind of the crunch quicker than maybe other areas, but we have a lot of dairy in the Southern San Joaquin Valley."

161 Karen Bohnert, *Dairy's Future, Who Will the Top Dairy States Be in the Next Decade*, Dairy Herd Management (August 31, 2021), https://www.dairyherd.com/news/dairy-production/dairys-future-who-will-top-dairy-states-be-next-decade (The Dairy Iowa banner here at the expo touts the state's "abundant land, water, feed and forage supply." It also cites a "positive business climate," among other things."); Jeff Daniels, *Outside States to California: We Have Water,* CNBC (Feb. 10, 2015), https://www.cnbc.com/2015/02/10/california-drought-states-tempt-california-dairy-farms--we-have-water.html.

162 Catherine Merlo, *Western Water Woes: Dairies Grapple with Uncertain Supplies, Ever-Tougher Regulations,* Dairy Herd Management (May 3, 2010) https://www.dairyherd.com/news/western-water-woes-dairies-grapple-uncertain-supplies-ever-tougher-regulations.

163 *Federal Milk Marketing Orders: An Overview,* Cong. Res. Serv. (June 15, 2022), https://sgp.fas.org/crs/misc/R45044.pdf.

164 U.S. Dep't of Ag., *An Oveview of the Federal Milk Marketing Order Program*, https://www.ams.usda.gov/sites/default/files/media/DairyFMMOBooklet.pdf.

165 Cal. Dep't of Food and Ag., *Milk Pricing in California*, https://www.cdfa.ca.gov/dairy/pdf/Milk_Pricing_in_CA.pdf.

166 7 CFR 1051, 26547-26556 *available at* https://www.federalregister.gov/documents/2018/06/08/2018-12245/milk-in-california-federal-milk-marketing-order-promulgation; *USDA to Hear Proposals on Federal Milk Pricing System*, Paso Robles Press (Aug. 18, 2023) https://pasoroblespress.com/special-sections/agriculture/usda-to-hear-proposals-on-federal-milk-pricing-system/. In 2022, the average Class I price in California was $25.74. This was higher than in the Pacific Northwest area (by about 20 cents) and in the Central area (by 12 cents). It was lower than in the Southwest area (by about 90 cents) and in Arizona (by about twenty cents). U.S. Dep't of Ag, Class I Milk Price, https://www.ams.usda.gov/sites/default/files/media/ClassIPrices2022.pdf.

167 Geoff Vanden Heuvel, *California's Milk Price Has Shown Improvement*, Hoard's Dairyman (March 24, 2022), https://hoards.com/article-31723-californias-milk-price-has-shown-improvement.html.

168 Dave Natzke, *State of the Dairy 2022: California in a 'State' of its Own*, Progressive Dairy (March 10, 2022), https://www.agproud.com/articles/54489-state-of-the-dairy-2022-california-in-a-state-of-its-own/ ("Since joining the FMMO system at the end of 2018, dairy cooperatives in California gained far more economic flexibility, especially as it relates to pooling, weakening the farmer safety net, she explained.")

4. *Demand, Trade Exposure, and California's Comparative Advantage*

California carved out its place in the national market by pioneering industrial drylot dairies, but newer dairying states in the West and some older dairying states in the Midwest, like Wisconsin, have now adopted the California model, eroding California's competitive advantage. Traditional dairying states have followed the pattern of consolidation and increased herd sizes to an extent since the early 2000s; however, they've also made greater progress in milk yields. One analysis suggests that traditional dairying states may have focused gains on milk yields rather than increases in herd sizes to the extent of modern states, like California, because of a more stringent regulatory environment:

> *The fact that milk yield in traditional states grew more rapidly after the introduction of genomic testing in dairy genetics suggests that genetics may have played a role in the observed yield increase. It is also possible that, due to zoning and environmental regulations, traditional dairy states are simply more limited in their ability to grow cow numbers. Having exhausted their ability to grow production through cow numbers, they are instead turning to improving yield. This mirrors a larger trend in US crop production where output growth is driven mostly through productivity gains rather than putting more acres into production.*[169]

The overall dairy herd size nationally also appears to be leveling off.[170] Demand for fluid milk is down among younger people[171] and the dairy industry saw a major change[172] in demand nationally and major price fluctuations[173] over the course of the COVID-19 pandemic. This included a "relative shift towards production of storable dairy products." This shift may have helped fuel the gradual move towards the center of the country. Milk production was historically concentrated on the coasts because the perishability of milk required the cows to be near market. This is changing as the dairy industry shifts away from fluid milk.[174]

California's role as a net exporter[175] also results in relatively greater trade exposure and

169 Jared Hutchins and Joe Janzen, *Production Trends in the US Dairy Sector*, FarmDocDaily (Oct. 30, 2023), https://farmdocdaily.illinois.edu/2023/10/production-trends-in-the-us-dairy-sector.html.

170 *Id.* ("In the past two years, cow numbers have begun to level off, perhaps reacting to uncertainty the ability and willingness of the supply chain to continue to accept the volume of milk that it does. It may also be that the total number of dairy cows in the country is reaching a long-run, stable level. This is especially the case if zoning and environmental regulation prevent modern dairy states from expanding cow numbers as they have in the past two decades. If growth in the US dairy herd does level off, we may even see modern dairy states follow the lead of the traditional states and drive growth through yield improvement rather than more cows.")

171 Kim Severson, *Got Milk? Not This Generation*, N.Y. Times (April 4, 2023), https://www.nytimes.com/2023/04/04/dining/milk-dairy-industry-gen-z.html.

172 *Dairy Supply Chains Will Need to Adjust as Consumer Behavior Changes*, Cal. Dairy (July 15, 2020), https://californiadairymagazine.com/2020/07/15/dairy-supply-chains-will-need-to-adjust-as-consumer-behavior-changes/.

173 The large fluctuations in the cheese and all-milk prices seen in Figures 4 and 5 underlie the broader effect of the COVID-19 pandemic on dairy prices. Daniel A. Sumner, Tristan M. Hanon, and Scott Somerville, *Effects of the COVID-19 Pandemic on the Western Dairy Industry,* Western Econ. Forum (June 2021), https://ageconsearch.umn.edu/record/311305/?ln=en.

174 *As California Farmers are Pressed, Dairy Cows Flee for Texas and Arizona,* The Bullvine (Sept. 21, 2022), https://www.thebullvine.com/news/as-california-farmers-are-pressed-dairy-cows-flee-for-texas-and-arizona/. ("According to Boccadoro, milk production has been moved to the Midwestern states as a result of a decline in the demand for fluid milk and a rise in the demand for cheese, yogurt, butter, whey protein, and other milk-related products. Since the pandemic started in 2020, demand for dairy products has grown by 2000%.")

175 This section has focused on inter-state rather than international outmigration. That said, it is notable that the United States is a net exporter of dairy. Int'l Dairy Foods Ass'n, The Importance of Trade for U.S. Dairy, https://www.idfa.org/trade. A UC Davis blog asserts: "While the rise in greenhouse gas emissions in developing countries is largely due to domestic growth, it's no secret that companies from wealthy countries set up factories in foreign countries to cut costs and avoid regulations, thus further contributing to global pollution." In the context of dairy, however, recent years have seen a surge in U.S. dairies catering specifically to the Chinese export market. Agricultural exports to China and the value of agricultural exports has increased every year since 2018, rather than vice versa. U.S. Dep't of Ag. Foreign Ag/Serv., Record U.S. FY 2022 Agriculture Exports to China (Jan. 6, 2023), https://fas.usda.gov/data/record-us-fy-2022-agricultural-exports-china; Amanda Lockwood, *Everything to Know Before Exporting to China*, Dairy Foods, https://www.dairyfoods.com/articles/96607-everything-to-know-before-exporting-to-china. China is the leading importer of nearly every major dairy product. Aidan Connolly, *China is Sneezing, Will it Give the U.S. Dairy Industry a Cold*, Dairy Herd Management (Nov. 29, 2023), https://www.dairyherd.com/news/business/china-sneezing-will-it-give-us-dairy-industry-cold. In recent years, western states have seen the growth of export-only factor dairies. Lynne Terry, *While Small Dairy Farms Shut Down, This Mega-Dairy is Shipping Milk to China*, Civil Easts (Nov. 27, 2018), https://civileats.com/2018/11/27/while-small-dairy-farms-shut-down-this-mega-dairy-is-shipping-milk-to-china/. Moreover, the U.S. dairy industry's major competitors in the Chinese market are the European Union and New Zealand, not developing countries. U.S. Dairy Export Council Staff, *Slow Whey Demand in China Holds Back U.S. Dairy Exports in July*, The U.S. Dairy Exporter Blog (Sept. 7, 2023), https://blog.usdec.org/usdairyexporter/slow-whey-demand-in-china-holds-back-us-dairy-exports-in-july-0. While new emissions regulations could (and probably would) influence these trends, the baseline situation is one in which the U.S. already is better situated to produce and export.

consistently lower prices than the national average.[176] Given this role, tariffs imposed on U.S. dairy products by Mexico and China during the Trump administration may have taken a disproportionate toll on California dairies.[177] As in the discussion of consolidation above, however, the data here is largely from the 2017 USDA Agriculture Census and so will not show the impacts of the LCFS. Additionally, Chinese demand has decreased in recent years, depressing global milk prices.[178] As a net-exporter, California has been particularly impacted as dry milk prices have fallen.[179]

There are also factors that cut against departure for California dairies. California's location on the West Coast and the Central Valley's proximity to urban markets have long been important to the industry. One analyst argued, "California has the second largest population in the country. You need to have milk close to the population, and because there's already infrastructure there, there will always be dairy in California."[180]

The California dairy industry is unlikely to find that other states can replicate the benefits of the Central Valley without any of the perceived challenges. One analyst suggested: "I think we'll continue to see consolidation in the dairy industry in California, the smaller herds are going to really have a tough time of it like they have for the last 10 or 15 years. I still think we'll see some producers migrate out, but it'll continue, I think to be a trickle. I'm not sure that it's going to accelerate significantly."[181]

D. Emissions Implications of Dairies Moving Out of State

Production leakage does not necessarily entail emissions leakage, the focus of the legal leakage concerns. Production leakage only results in emissions leakage where the state that hosts the influx of new dairy operations has a more highly emitting dairy industry and model. Emissions from different dairying models vary based on the regulatory regime, but also from the practices commonly employed, standard operation size, soil characteristics, and regional climate.[182]

Some stakeholders assume that California has a stricter regulatory regime for dairies in California and that California dairies emit fewer GHGs. But California currently does not regulate methane from dairies. Anaerobic digesters capture emissions, but they capture emissions from the high baseline generated by industrial-scale facilities.

There is little evidence that California's baseline model of dairying—confinement-based operations with liquid manure management—emits fewer GHGs than other models. On the contrary, confinement dairies with liquid manure

176 Daniel A. Sumner, California Agriculture: Dimensions and Issues, *Chapter 6: California Dairy: Resilience in a Challenging Environment*, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf ("But, the lower California prices are due to the fact that California is a net exporter of milk products to the rest of the United States and the world, and not because of identified deficiencies in government regulations.")

177 Michael Hiltzik, *Column: California's Dairy Farmers Were Struggling to Regain Profitability. Then Came the Trade Wars*, L.A. Times (October 26, 2018), https://www.latimes.com/business/hiltzik/la-fi-hiltzik-caltrump-dairy-20181026-story.html.

178 Zahra Tayeb, *Economic Slump Means a Glass of Milk Could Soon Cost a Lot Less*, Business Insider (Aug. 3, 2023), https://www.businessinsider.com/china-economy-milk-powder-prices-fall-demand-slump-2023-8.

179 Tracy Withers, *Milk Powder Price Sinks to Three-Year Low as Dairy Demand Wanes*, BNN Bloomberg (Aug. 1, 2023), https://www.bnnbloomberg.ca/milk-powder-price-sinks-to-three-year-low-as-dairy-demand-wanes-1.1953649.

180 *Are California Farmers Leaving for Greener Pastures?* Dairy Herd Management (Dec. 23, 2022), https://www.dairyherd.com/news/business/top-10-stories-2022-are-california-farmers-really-leaving-greener-pastures.

181 *Id. See also* quote from Mike North in the same article ("Mike North of ever.ag says dairy farmers who are in a water deficit area may be forced to relocate, but he says there will always be dairy cows in California. However, consolidation is something he thinks will continue to happen in the state, largely due to the drought. "What's happening is the people that are water threatened may be looking to reduce their herd, but producers who aren't water threatened are buying their cattle and quotas. So, you won't see the number of dairy cattle in California dramatically drop," says North").

182 Rotz et al. ("No clear trends were found that indicated that a given management approach or farm size consistently provided lower environmental footprints. Often differences occurred due to differences in soil characteristics and climate, so a management approach that produces lower footprints for one environmental metric in one region may not function well for other metrics or locations. For example, NH3 and other manure emissions can be a concern for open lot dairies in the west with long-term manure storage, whereas nutrient runoff and water quality issues are often the greater concern for eastern farms using tie stall and free stall barns with less or no storage of manure.")

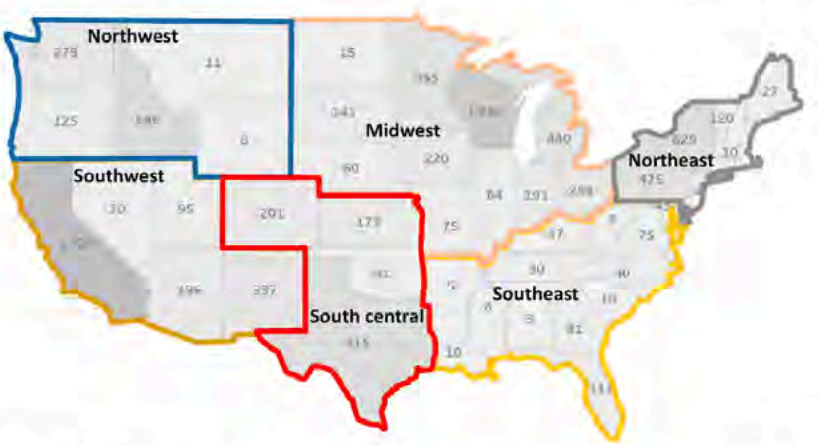

Fig. 1. Dairy regions of the United States used in our evaluation of the environmental footprints of dairy farms. Numbers are thousands of dairy cows in each state (NASS, 2020).

Table 1
Number of each type of dairy farm simulated to represent each region of the U.S.

Region	Amish	Organic	Grazing	Semiconfined	Confined <1000 cows	Confined 1000+ cows
Northeast	1	2	4	6	4	3
Southeast	0	0	5	9	4	2
Midwest	1	2	2	3	8	4
South central	0	1	2	3	6	8
Northwest	0	1	2	0	5	12
Southwest	0	1	1	0	1	17

FIGURE 10 Via A. Rotz et al., Environmental Assessment of U.S. Dairy Farms, supra note 150.

management systems are associated with higher emissions than other dairying systems.[183] This model is more common in the Southwest, and in California in particular, than in other parts of the country.[184] The dairying practices associated with the lowest GHG intensity are smaller grazing operations, which are primarily found in the East and the Midwest.[185]

The adoption of anaerobic digesters significantly reduces the GHG intensity of the California dairying model by capturing emissions generated by the long-term storage of liquified manure in lagoons. But it reduces the emissions from a high baseline relative to other common dairying models. Additionally, while anaerobic digesters capture emissions from manure lagoons, they do not address environmental harms, including but not limited to GHG emissions, beyond the lagoon.

Confinement-based dairies rely heavily on purchased feed. According to the Rotz et al. analysis, about 67% of the total fossil energy consumption by dairies nationally was used to

183 The study also determined that each of these farm management styles resulted in different environmental footprints generally and GHG emissions specifically. The results of the study provide insight into both the leakage discussion and the broader concerns about the LCFS: "Farms with the lowest intensity were often smaller grazing operations with little or no long-term storage of manure. For example, five grazing dairies in the northeast had a mean footprint of 0.88 kg CO2e/kg FPCM. Larger dairies that used an anaerobic digester also had below average intensities (0.69–0.87 kg CO2e/kg FPCM). Dairies with the greater intensity were often confinement operations with long-term liquid manure storage (i.e., large lagoons or retention ponds), particularly in the warmer regions of the country (six operations in the southwest averaged 1.09 kg CO2e/kg FPCM). Often the greatest intensities were associated with dairies that had lower FPCM production per cow along with the use of long-term manure storage." A. Rotz et al., *Environmental Assessments of U.S. Dairy Farms*, J. of Cleaner Prod. 315 (2021) 128153, https://www.sciencedirect.com/science/article/pii/S0959652621023714.

184 One study that determined the environmental footprint of dairy nationally found that the largest confinement dairies were found in the southwest region, where dairies were concentrated in California. The northwest region also had similar concentrations of the largest confinement operations but the other regions had a more varied breakdown, that typically included some smaller confinement operations, semiconfined operations, grazing, and organic operations.

185 A. Rotz et al., *Environmental Assessment of U.S. Dairy Farms*.

produce feed. About 97% of blue water consumption by dairies nationally was used to produce feed. Confinement-based dairies typically lack adequate land to spread manure regularly, necessitating long-term storage of manure which results in greater GHG and ammonia emissions.

The geography and climate of the southwestern region also influences environmental impacts in California, particularly when paired with the dominant model of confinement dairying. The amount of freshwater withdrawals varies regionally, but is highest in the Southwest. Overall, less water is consumed in regions that produce most of their feed on the farm without irrigation. Dairies on the West Coast rely heavily on irrigated feed crops.[186]

In terms of NOx emissions, "portions varied across the country, with less NH3 emission and greater NO3 loss in the eastern regions and greater NH3 emission and less NO3 loss in the dry conditions of the west."[187] In terms of GHG emissions, "manure contributed a lower proportion in the Northeast (17%) due to cooler temperatures and less use of long-term storage, and manure contributed a greater portion in the Southwest (28%) due to warmer temperatures and more use of long-term storage (IPCC, 2006a; Rotz, 2018). The enteric CH4 portion was also greater in the two eastern regions (47%) due to greater use of forage in cow diets."[188]

A comparison between California, as the nation's top dairy producing state, and Wisconsin, the second, illustrates California's role as leading the industrialization of dairy. California dairies are larger and the industry is more consolidated than in Wisconsin. A 2010 survey of California and Wisconsin farmers found that "While farms in Wisconsin are mostly medium-sized family farms, Californian farms operate on a much larger scale but are still owned by the family."[189] In 2014, Wisconsin had almost seven times more licensed dairy herds than California, but the average herd size was about 10 times smaller than the average herd size in California.[190] California first surpassed Wisconsin in dairy production in 1993 after a period of rapid growth and concentration in California (increasing production from 16.6 billion pounds of milk in 1988 to 22.9 billion pounds in 1993).[191] As discussed, the pressures of urbanization in Southern California in the early 1990s resulted in the loss of dairies in that region, but it also allowed them to sell their land at very high prices which they could use to build larger operations in the Central Valley.[192]

There is little evidence to suggest the baseline system of dairying in California is more climate-friendly or environmentally friendly than dairying nationally. However, the states the industry would be most likely to move to may not reflect the national average either. The states that have seen the most dairy growth in recent years are other western states adopting the California model of confinement-based operations with liquid manure management. Therefore, their practices may be similar to the practices of California dairies and, it is likely that they have fewer incentives for digesters, which is the primary method of reducing emissions from these dairies without otherwise altering practices. LCFS credits are available to any operation in the continental

186 Rotz et al. ("The lowest consumers were farms in the Midwest, Northeast, and Southeast regions that produced most of their feed on the farm without irrigation. The greatest consumers were farms in the Northwest and Southwest that relied almost entirely on irrigated feed crops.")

187 *Id.*

188 *Id.*

189 André de Witte, Jessica Novak, Freiderike Schierholz, and Birthe J. Lassen, *Dairy Farming in Wisconsin and California: Different Challenges — Different Future?* Snapshot Survey (Spring 2010), http://www.agribenchmark.org/fileadmin/Dateiablage/B-Dairy/Misc/10_Snapshot_USA.pdf.

190 *Wisconsin vs. California Dairy System Adaption*, University of Wisconsin Food Production Systems and Sustainability, https://kb.wisc.edu/dairynutrient/375fsc/page.php?id=48427.

191 John Oncken, *The Milk Continues to Flow*, Wis. State Farmer (Jan. 27, 2021), https://www.wisfarmer.com/story/opinion/columnists/2021/01/27/milk-continues-flow-california-and-wisconsin/6664991002/.

192 *Id.* ("Of course, they did not just move their 500 to 1000 cows. Instead, they built new and bigger and the strip from Bakersfield north to Sacramento sprouted new dairies, many of them 2,000 to 5,000 cows in size and all housed in freestall barns (copied from the new dairies being built in the Midwest) and away from the mud and rains of the corral type housing used in their former location.").

United States through book-and-claim accounting and federal incentives to support the construction of digesters are available, but California also offers substantial assistance for digester construction in the form of loans and grants.

E. Legal Leakage and Mitigation Measures

The nature of the leakage risk depends on the specific approach to GHG regulation, but several policy tools are available to reduce the likelihood of leakage generally. The primary tools are production incentives/output-based rebating and border climate adjustments.

Border climate adjustments "impose a fee on imported energy-intensive and trade-exposed products and a refund for exports of the same products."[193] They have been challenging to implement in practice.[194] Border climate adjustments are unlikely to be feasible for intra-American leakage, because they would impose a carbon tax on imports from other states, almost certainly generating litigation under the Dormant Commerce Clause.

Output-based rebates "consist of payments to energy-intensive and trade-exposed firms based on their production."[195] They have been found to "significantly reduce simulated emissions leakage."[196] Output-based rebating is similar to free allocations of emissions allowances, such as those used by California's cap-and-trade program.[197] Allocating allowances to regulated industry in the cap-and-trade program is intended to give enterprises time to transfer to less GHG-intensive technologies but also to prevent leakage. The level of allocations "will decline over time to settle at a level needed to prevent leakage."[198]

Output-based rebating has two side effects that make it important to carefully target subsidies to the industries actually at risk of leakage: "First, an opportunity cost is incurred when allowances are allocated for free or tax revenues are recycled to industrial producers. Second, output-based rebating dilutes the carbon price signal received by firms receiving the subsidy."[199]

While these tools have been effective in preventing leakage in other jurisdictions, it's crucial that they accurately target sectors seriously at risk of leakage. It's not clear that this is the case for dairy—further empirical research would be required. Moreover, the effectiveness of these policies in preventing leakage is due to the fact that they shield "key industrial sectors, which is incompatible with deep decarbonization."[200]

In the context of dairies, CARB would have to more deeply analyze how methane regulations would influence dairy operator behavior—in the absence of a specific regulation, it's challenging to determine whether it would actually prompt dairies to leave beyond the pre-existing decline. If it was determined that methane regulations were going to prompt industry departure, this kind of rebate could be carefully tailored to, for example, compensate dairies just enough to make the costs of leaving unappealing. Such rebates could also be tied to ongoing compliance with methane regulations.

In addition to the policy tools designed to address emissions leakage, policymakers should also consider that trade-exposure is one of the major leakage risk factors. The major changes

193 Noah Kaufman, John Larsen, Ben King, and Peter Marsters, *Output-Based Rebates: An Alternative to Border Carbon Adjustments for Preserving US Competitiveness*, Columbia Center on Global Energy Policy, https://www.energypolicy.columbia.edu/wp-content/uploads/2020/12/OBR-commentary-designed-v5-12.01.20.pdf.

194 *Mitigating Emissions Leakage in Incomplete Carbon Markets*, 9 J. of the Ass'n of Env't and Res. Econ. 2, 307-343 (2022).

195 Noah Kaufman, John Larsen, Ben King, and Peter Marsters, *Output-Based Rebates: An Alternative to Border Carbon Adjustments for Preserving US Competitiveness*, Columbia Center on Global Energy Policy, https://www.energypolicy.columbia.edu/wp-content/uploads/2020/12/OBR-commentary-designed-v5-12.01.20.pdf.

196 *Mitigating Emissions Leakage in Incomplete Carbon Markets* at 4, *supra* note 194.

197 Cal. Air Res. Board, *Proposed Regulation to Implement the California Cap-and Trade Program Part I, Vol. 1*, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2010/capandtrade10/capisor.pdf#page=56

198 *Id.*

199 *Id.*

200 Michael Grubb et al., *Carbon Leakage, Consumption, and Trade*, 47 Ann. R. of Env't and Res., 753 (Sept. 2022), https://www.annualreviews.org/doi/pdf/10.1146/annurev-environ-120820-053625.

to the dairy industry's export market over the past few decades have, therefore, increased the risk of leakage. As discussed, the opening of the export market also contributed to price depression and consolidation in the dairy industry. There are several farmer-led movements in the Northeast and the Midwest calling for a return of supply-side management programs specifically in order to preserve a healthy dairy industry and to reduce the environmental harms associated with confinement dairying.[201] This push is in line with the recent political trends, including resurgence in interest in industrial policy[202] and bipartisan pushback[203] against the free-trade line that has dominated U.S. politics for several decades.

The impact of free trade agreements makes it challenging to address the export market and supply-side management issue that has contributed to depressed milk prices, but it should prompt a deeper consideration of how California dairying can both be economically robust and sustainable into the future. These concerns should be especially important given the need to consider food security and the resilience of regional food systems in the face of climate change.

Overall, the likelihood of methane regulation and certainly of any changes to LCFS crediting running afoul of the legal requirement that CARB minimize leakage is low. Each step in the process—that dairies would leave the state in large numbers, that they would generate significantly more emissions out-of-state, and that CARB would not have policy options to minimize these events—is unlikely.

F. Key Takeaways: Emissions Leakage Risk

- **Research tells us that leakage is much less likely in practice than in theory.** Most of the literature on leakage suggests that it is very limited in practice. The textbook economics that envisions leakage imagines a frictionless global market, but uprooting industries incur additional costs that operators may not be willing to bear. Additionally, there are effective mitigation measures available that are commonly employed to reduce leakage risk. Multiple studies have found that while compliance costs can result in small in-state decreases, only a portion of those decreases are accounted for by moves out of state. For more on the risk of leakage in practice, see the CARB-commissioned *Mitigating Leakage Risk.*

- **Leakage risk is also closely tied to industry mobility. Industrial-scale dairying is capital-intensive, requires substantial sunk costs, and is facing a labor shortage, all of which erect barriers to mobility.** Dairy is more mobile than oil and gas production, which requires location at the source of fossil fuels; however, several characteristics of industrial-scale dairies are impediments to mobility.

201 Northeast Farmers Calling for a new supply-side model for organic dairy: *Northeast Dairy Task Force, Recommendations to USDA* (Dec. 16, 2021), https://agriculture.vermont.gov/sites/agriculture/files/Northeast%20Dairy%20Task%20Force%20-%20Recommendations%20to%20USDA.pdf; Wisconsin Farmer Union's Dairy Together advocating for supply management: Sarah E. Loloyd, *Dairy Together: Building a Farmer-Led Movement for Supply Management,* Disparity to Parity, https://disparitytoparity.org/dairy-together-building-a-farmer-led-movement-for-supply-management/ ("The vicious cycle of too much milk, leading to low prices, where only bigger and bigger farms can survive, which then leads to more milk produced, continues to speed up... A coordinated supply response is needed."); National Family Farm Coalition advocating for supply management: Kathryn Anderson, *Supply Management, Parity Prices, and Ecological Thinking as the Foundation for a Practice Agriculture System*, Disparity to Parity, https://disparitytoparity.org/supply-management-parity-prices-and-ecological-thinking-as-the-foundation-for-a-practical-agriculture-system/ ("Supply management and parity pricing directly mitigate environmental impacts by reducing the total volume of production. Importantly, supply management also indirectly improves agriculture's ecological footprint by 1) allowing the small and mid-scale farms that are best suited for diverse and ecological farming to thrive and 2) providing sufficient income for farmers to invest in conservation and regenerative practices.").

202 Anshu Siripurapu and Noah Berman, *Is Industrial Policy Making a Comeback?* Council on Foreign Relations, (Sept. 18, 2023), https://www.cfr.org/backgrounder/industrial-policy-making-comeback.

203 *See, e.g.* John Harwood, *Bipartisan Support for Free Trade Has Been Left Behind as the 2020 Race Barrels Ahead*, CNBC (Sept. 20, 2019), https://www.cnbc.com/2019/09/20/republicans-and-democrats-oppose-free-trade-in-2020-white-house-race.html; Washington Post Editorial Board, *A Bipartisan Retreat on Trade*, Wash. Post (July 31, 2019), https://www.washingtonpost.com/opinions/a-bipartisan-retreat-on-trade/2019/07/31/5473185a-b2f0-11e9-951e-de024209545d_story.html; Mohamed Younis, *Sharply Fewer in U.S. View Foreign Trade as Opportunity,* Gallup (March 31, 2021), https://news.gallup.com/poll/342419/sharply-fewer-view-foreign-trade-opportunity.aspx.

- **California's Central Valley still offers many benefits to dairy operators. Many of the challenges facing California dairies exist nationally or in other western states.** Dairies have struggled nationally for decades, but California has remained the top dairy producer in the country since 1993. On most metrics, California's dairy industry is the most successful in the country. While there are real challenges facing California dairies, many of these challenges are also facing dairies nationwide (like the ongoing trend towards consolidation) or in other western states (like drought and access to adequate water). Dairy operators may find policymakers less likely to directly regulate methane in Texas or in Kansas, but by moving, they would lose benefits like close proximity to urban markets and ports, cheap by-product feed, proximity to major transportation corridors, a milder climate etc.

- **While there has been a decline in California dairy operations in recent years, this movement is caused by a range of pre-existing factors.** Emissions leakage is a causal phenomenon. Outmigration followed by increased net emissions is only leakage if it was caused by emissions regulation. If anything, the fact that the industry has been moving out of state *prior* to any emissions regulations diminishes the likelihood that emissions regulations alone will cause outmigration and attendant emissions leakage. There are other valid and important concerns about the outmigration of dairy operations, but the legal leakage issue is not raised by these departures in the absence of any emissions regulation. Some of the reasons dairies have left California include: California slowly losing its competitive edge as other western states adopt its model of industrial-scale dairying, lack of reliable access to water, increased feed and manure management costs, and increased urbanization pressures.

- **The industry moving out of state ("production leakage") on its own does not necessarily result in emissions leakage. Despite stereotypes of California as a strict environmental regulator, it's not assured that dairies would emit more GHGs if they moved to other states.** Emissions leakage occurs when emissions regulations push and industry and their emissions out of state. This means emissions leakage requires that net emissions stay the same or increase as the result of the move. California-style dairies, however, generally have higher baseline emissions overall and per-cow than small and mid-sized dairies. California pioneered the most industrialized and highest emitting model of dairying in the country. California-style industrialized dairies are proliferating nationally, but they still are not the norm in many "traditional" dairying states, where smaller-scale, lower-emitting models remain more common. It's unlikely that California dairies would move to traditional dairying states, but if they did, net emissions could actually be reduced.

- **Mega-dairies outside of California are increasingly likely to employ anaerobic digesters.** California's main contribution to mitigation of dairy emissions has been the push for dairy digesters. The incentives provided by LCFS credits are available to any dairy operation nationally that plugs into a common carrier pipeline or the grid, however, not just California dairies. This means the LCFS does not incentivize climate-friendly behavior in California more than in any other state. Where California does have an edge is in grant funding for digesters through the

DDRP program. Other states have comparable programs. While other states' programs are less-well funded, this may reflect in part the fact that no state has more industrial dairies than California. Federal funding for digesters is also available, as is private funding.[204]

California dairies are more likely to relocate to other "modern" dairying states in the West, which have generally attempted to replicate California-style mega-dairies. Many of these states are also embracing digesters now, sometimes with the help of California-based companies like Brightmark (which has digester projects in South Carolina, Iowa, Michigan, Washington, Wisconsin, Florida, New York, and South Dakota)[205] and California Bioenergy (which has about 50 projects in California and has recently ventured to South Dakota).[206] A few indications of the surge in digesters in states that would be likely destinations for dairies exiting California:

- In Idaho, a "goldrush" to build dairy digesters specifically due to LCFS credits;
- In Washington, an "explosion of growth" and $22 million public investment in dairy digesters based on a CARB report touting its success;
- In Iowa, a "huge uptick" in dairy digesters from 2022 to 2023
- In Arizona, dairy digesters are a "hot investment;"
- In South Dakota, $150 million in private funding from California Bioenergy goes to three new dairy digester clusters in 2023;
- In Kansas, one of the top states for dairy growth, Shell is constructing a dairy digester;
- In Oregon, where "manure is big business," public funds and a Biomass Tax Credit program have incentivized digesters.

- **California regulators are obligated to minimize emissions leakage to the extent reasonable, not to ensure zero leakage.** Legally, CARB is only required to minimize or mitigate leakage, and there are policy tools available to help do this, like carefully designed output-based rebates. More generally, the dairy market is global, so leakage is possible from virtually any jurisdiction seeking to regulate dairy emissions. The question should be whether the amount of emissions leakage is so great as to frustrate the emissions reductions sought by the regulation.

204 *See, e.g.* Sarah Zimmerman, *Environmental Groups Blast USDA for Extending Climate Funding to Dairy Digesters*, Ag. Dive (Nov. 2, 2023), https://www.agriculturedive.com/news/climate-activists-digesters-dairy-biofuels-usda-ira/698611/; Grace van Deelan, Emma Foehringer Merchant, *Just Two Development Companies Drive One of California's Most Controversial Climate Programs: Manure Digesters*, Inside Climate News (Sept. 20, 2022), https://insideclimatenews.org/news/20092022/just-two-development-companies-drive-one-of-californias-most-controversial-climate-programs-manure-digesters/.

205 *Brightmark Energy to Build Its First Dairy RNG Project in South Dakota*, Bioenergy Int'l (Feb. 6, 2020) https://bioenergyinternational.com/brightmark-energy-to-build-its-first-dairy-rng-project-in-south-dakota/.

206 California Bioenergy, Projects, https://calbioenergy.com/projects/.

207 Michael Boccadero, *Dairy Cares Comment Letter on LCFS Virtual Community Meetings* (June 14, 2023) ("The LCFS is a Necessary Measure to Reach the SB 1383 Targets. Removing Dairies would Lead to Significant, Unavoidable Impacts.").

VI. California's Climate Targets and Credits for Dairy Digesters

Some[207] have argued that California cannot meet its climate targets without LCFS incentives for biogas from dairy manure. The implication is that by eliminating LCFS incentives for biogas, advocates would jeopardize climate progress. More specifically, the argument is that reducing incentives will make dairies less likely to construct biogas control systems and, as a result, methane from existing manure lagoons will continue to be vented. This section examines the two relevant sets of targets—California's overall climate targets established under SB 32 and California's 2030 methane targets set by SB 1383—and evaluates the extent to which this claim is accurate.

A. California's Overall Climate Targets

California's most recent update to the Scoping Plan calls to cut greenhouse gas emissions by 48 percent below 1990 levels by 2030 and 85 percent below 1990 levels by 2045.[208] The Scoping Plan "approaches decarbonization from two perspectives: (1) managing a phasedown of existing energy sources and technology and (2) ramping up, developing, and deploying alternative clean energy sources and technology over time."[209]

Short lived climate pollutants,[210] like methane, account for "about one-third of the cumulative GHG emissions reductions the State is relying on to achieve the statewide 2030 GHG emissions target established under SB 32."[211] The dairy and livestock sectors contribute more than half of the state's methane emissions.

B. California's Dairy Methane Targets

The three largest sources of methane emissions in California are the dairy and livestock industry, landfills, and oil and gas systems.[212] CARB took early action measures to address landfills and oil and gas directly (the Landfill Methane Regulation, Cal. Code of Regs., tit. 17, §§ 95460, et seq. and the Oil and Gas Methane Regulation, Cal. Code of Regs., tit. 17, §§ 95665–77) but declined to do so for the dairy and livestock sectors.

The SLCP Strategy's approach to dairy and livestock was characterized by CARB as a "carrot-then-stick" approach, prioritizing voluntary, incentive-based mechanisms in early years to "overcome technical and market barriers."[213] In the 2022 Scoping Plan CARB explained, "Under this "carrot-then-stick" strategy, incentives are replaced with requirements as the solutions become increasingly feasible and cost-effective."[214] Theoretically, the stick element could be implemented as of January 2024, per SB 1383. However, CARB has not indicated it intends to begin rulemaking on this issue.

SLCP reductions are "necessary to achieve the State's 2030 GHG emissions target, as described in the 2017 Scoping Plan Update, as well as the mid-century carbon neutrality goal."[215] The 2017 Short-Lived Climate Pollutant Reduction Strategy included a target of 40% reduction in total methane emissions as well as a separate 40 percent reduction in methane specifically from dairy and

208 Cal. Air Res. Board, *Press Release 22-44: California releases final proposal for world-leading climate action plan that drastically reduces fossil fuel dependence, slashes pollution* (Nov. 16, 2022), https://ww2.arb.ca.gov/news/california-releases-final-2022-climate-scoping-plan-proposal.

209 Cal. Air Res. Board, *2022 Scoping Plan for Achieving Carbon Neutrality* (November 16, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-11/2022-sp.pdf.

210 Short lived climate pollutants include black carbon (soot), methane (CH4), and fluorinated gases (F-gases, including hydrofluorocarbons [HFCs]). Cal. Air Res. Board, *2022 Scoping Plan* at 222.

211 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target* (Final) (March 2022), https://ww2.arb.ca.gov/sites/default/files/2022-03/final-dairy-livestock-SB1383-analysis.pdf.

212 Cal. Air Res. Board, *2022 Scoping Plan, supra* note 209.

213 *Id.*

214 *Id.*

215 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target, supra* note 211.

livestock operations.[216] California's target of a 40 percent methane reduction below 2013 levels for the dairy and livestock sector by 2030 constitutes a reduction of 9 million metric tons carbon dioxide equivalent (MMTCO2e).[217]

California is not on track to meet these targets for dairy and livestock even with the LCFS incentives. The progress report projects that the dairy and livestock sector will achieve "just over half of the annual methane emissions reductions necessary to achieve the target by 2030 through modifications to manure management systems—primarily using anaerobic digesters—and additional reductions through decreases in animal populations."[218] The SB 1383 progress report concludes that, to meet SB 1383 targets, "approximately 230 additional digesters may be needed, at a cost between $0.7 and $3.9 billion depending on the types of technologies selected."[219] The report also finds, on the other hand, that "based on currently funded projects and reduction trends observed to date, staff's analysis indicates that the State would be unable to achieve the 2030 dairy and livestock sector target through deployment of alternative manure management practices alone."[220] That is, according the CARB's projections, California cannot meet its goals with just digesters or with just alternative manure management practices.

The intra-agency Dairy and Livestock Greenhouse Gas Emissions working group, which consisted of CARB, CDFA, California Energy Commission, and CPUC principals, convened three stakeholder subgroups in 2017 and 2018. Subgroup 1 provided recommendations on non-digester manure management practices, Subgroup 2 provided recommendations on overcoming barriers to implementing livestock digester projects, and Subgroup 3 provided recommendations on research needs related to dairy and livestock emissions reductions. CARB has pursued dairy digester projects as the Board's primary tool to reduce dairy emissions since the recommendations were made final in 2018.[221] Subgroup 3 published a Dairy research Prospectus to Achieve California's SB 1383 Climate Goals.[222]

Beginning January 1, 2024, CARB has authority to regulate GHG emissions from agriculture, "provided that CARB, in consultation with CDFA, determine the regulations are technologically and economically feasible, cost-effective, include provisions to minimize and mitigate potential leakage, and include an evaluation of the achievements made by incentive-based programs."[223] "SB 1383 intends to prioritize the use of voluntary and incentive-based measures to achieve those reductions before regulations are implemented"; however, the progress report projects that California is on track to reach less than half of dairy and livestock reduction targets by 2030.[224] Additionally, the progress report concludes that meeting targets will "require implementation of additional methane emissions reductions strategies, and continued collaboration among agencies and other stakeholders," but the Board has made no indication that it intends to initiate rulemaking.[225]

216 Cal. Air Res. Board, *2022 Scoping Plan, supra* note 209.
217 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target*, *supra* note 211.
218 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target*.
219 *Id.*
220 *Id.*
221 In addition to reductions from digesters, CARB's projections include "a continued annual animal population decrease of 0.5 percent per year through 2030." Cal. Air Res. Board, *2022 Scoping Plan.* A UC Davis report cited *supra* also assumes ongoing herd attrition. It's not clear how assumptions of herd attrition interact with claims that leakage is imminent—this is an area for future research.
222 Cal. Air Res. Board, Dairy and Livestock Subgroup #3, *Dairy Research Prospectus to Achieve California's SB 1383 Climate Goals* (Nov. 26, 2018), https://ww2.arb.ca.gov/sites/default/files/classic/cc/dairy/dsg3/dsg3_final_dairy_air_research_prospectus_11-26-18.pdf.
223 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target*.
224 *Id.*
225 *Id.*

C. Key Takeaways: California's Climate Targets and Credits for Dairy Digesters

- **Dairy digesters are necessary for California to achieve its GHG reduction targets at this point, but so are a range of non-digester interventions that have not been seriously pursued.** Methane captured by digesters accounts for most of the reductions counted towards the methane reduction targets for dairy and livestock, but even with these large reductions California is not on track to meet targets for dairy and livestock. California policymakers should look to the report by the 2018 CARB-convened working group on non-digester tactics to reduce dairy methane emissions to understand alternative, more holistic approaches to reduce GHG emissions from dairies.

- **CARB will not be able to accurately assess and select interventions if it relies on the LCFS life cycle analysis for manure biogas to analyze dairy emissions.** The life cycle analysis CARB uses measures the carbon intensity of transportation fuels produced from manure biogas, not the carbon intensity of milk (this is discussed at length in the carbon intensity discussion). A holistic life cycle analysis of milk produced on California dairies and feed production would prompt different kinds of interventions, since more emissions are generated from enteric fermentation than from manure management. The life cycle analysis for transportation fuels used by the LCFS *assumes* the dairy industry is static—the dependent variable in that analysis is the change in transportation fuel from conventional fuels to manure-derived biogas. This is a valid assumption to make in the context of a transportation program, like the LCFS, but should not drive the broader strategy to achieve emissions reductions from the dairy industry. California policymakers should be considering a suite of options to reform and support the dairy industry transition to a less-emitting model.

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CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

UN environment programme







GLOBAL METHANE ASSESSMENT

Benefits and Costs of Mitigating Methane Emissions



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FOREWORD



Inger Andersen,
Under-Secretary-General of the United Nations and Executive Director of the UN Environment Programme

Today humanity is facing three systemic and escalating planetary crises: the climate crisis, the biodiversity and nature crisis, and the pollution and waste crisis. These crises are not independent but linked and often stem from the same sources and unsustainable models of consumption and production. These links provide an opportunity to identify and deploy solutions which deliver multiple-benefits and the ambitious emissions reductions needed to overcome these crises.

This *Global Methane Assessment* highlights one of the greatest opportunities available today to simultaneously address our interlinked planetary crises and make peace with nature. Methane is a powerful and short-lived climate pollutant which drives climate change and harms human and ecosystem health by contributing to the formation of ground-level ozone. Over the past decade, global methane emissions have risen at a rate faster than at any time in the last 30 years. While methane has both human and natural sources, recent increases are attributed to activity in three anthropogenic sectors, namely fossils fuels, waste and agriculture.

Current methane concentrations are well above those needed to achieve our 2° C target. According to the 2018 Intergovernmental Panel on Climate Change *Global Warming of 1.5° C* report, we cannot achieve the Paris Agreement targets without immediately reducing methane along with carbon dioxide and all other climate forcing emissions.

Fortunately, there are readily available targeted control measures that can reduce more than 30 per cent of projected anthropogenic methane emissions this decade. Most of these technical solutions are in the fossil fuels (oil, gas and coal) and waste sectors, and

can be deployed at low or negative cost. These measures must be implemented urgently and paired with increased efforts to find breakthroughs in agriculture and nature-based solutions. Additional measures that don't specifically target methane, like shifting to renewable energy, residential and commercial energy efficiency, and a reduction in food loss and waste, can reduce methane emissions by a further 15 per cent by 2030.

Readily achievable methane mitigation can deliver nearly 0.3° C of avoided warming over the next two decades while simultaneously reducing ground-level ozone concentrations. Such steps can avoid 255 000 premature deaths and help prevent more than half a million emergency room visits from asthma every year. And because ground level ozone also harms ecosystems and plants, the reduced methane concentrations could increase global crop yields by 26 million tonnes per year.

Fast and ambitious methane mitigation is one of the best strategies available today to deliver immediate and long-lasting multiple benefits for climate, agriculture, human and ecosystem health.

Since its founding in 2012, the Climate and Clean Air Coalition has led on global methane mitigation. As one of its founding partners, the UN Environment Programme (UNEP) has helped lead the Coalition's pioneering oil and gas work through the Oil and Gas Methane Partnership and the Global Methane Alliance. UNEP now hosts the International Methane Emissions Observatory an initiative that will integrate and reconcile methane emissions data, improve reporting and verification of information, and validate monitoring and measurement methodologies and techniques.

This year UNEP launched the UN Decade on Ecosystem Restoration. The next ten years will be paramount in the fight to avert climate change, the loss of nature and biodiversity, and the pollution and waste crisis. Nations, businesses, international organizations and individuals must commit to delivering methane mitigation consistent with the conclusions of this report to make progress towards restoring our degraded ecosystems and secure the future for humanity.



EXECUTIVE SUMMARY

Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5°C. Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45 per cent, or 180 million tonnes a year (Mt/yr) by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts. It would also, each year, prevent 255 000 premature deaths, 775 000 asthma-related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tonnes of crop losses globally (Figure ES1).

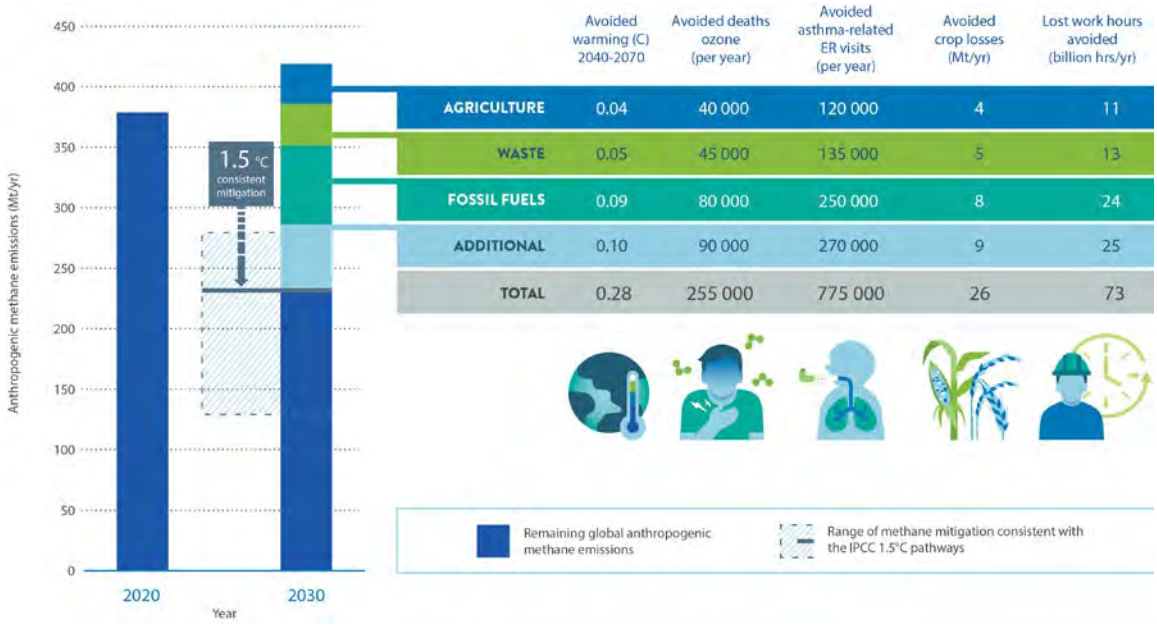

Figure ES1: Current and projected anthropogenic methane emissions and the identified sectoral mitigation potential in 2030 along with several benefits associated with sectoral-level methane emissions mitigation. Avoided warming occurs in the 2040s, other impacts are annual values beginning in 2030 that would continue thereafter.

The findings in this assessment are the result of modelling that uses five state-of-the art global composition-climate models to evaluate changes in the Earth's climate system and surface ozone concentrations from reductions in methane emissions. Results allow for rapid evaluation of impacts from methane emissions and the benefits from mitigation strategies to the climate and ground-level ozone formation and, air quality, public health, agricultural and other development benefits. The assessment results are also available in a web-based decision support tool[1] that allows users to input different methane emissions reduction goals to calculate the multiple benefits at a national level.

THE OPPORTUNITY

- **More than half of global methane emissions stem from human activities in three sectors: fossil fuels (35 per cent of human-caused emissions), waste (20 per cent) and agriculture (40 per cent).** In the fossil fuel sector, oil and gas extraction, processing and distribution account for 23 per cent, and coal mining accounts for 12 per cent of emissions. In the waste sector, landfills and wastewater make up about 20 per cent of global anthropogenic emissions. In the agricultural sector, livestock emissions from manure and enteric fermentation represent roughly 32 per cent, and rice cultivation 8 per cent of global anthropogenic emissions. (Sections 1, 2.1 and 4.1)

- **Currently available measures could reduce emissions from these major sectors by approximately 180 Mt/yr, or as much as 45 per cent, by 2030. This is a cost-effective step required to achieve the United Nations Framework Convention on Climate Change (UNFCCC) 1.5° C target**. According to scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC), global methane emissions must be reduced by between 40–45 per cent by 2030 to achieve least cost-pathways that limit global warming to 1.5° C this century, alongside substantial simultaneous reductions of all climate forcers including carbon dioxide and short-lived climate pollutants. (Section 4.1)

- **There are readily available targeted measures that can reduce 2030 methane emissions by 30 per cent, around 120 Mt/yr**. Nearly half of these technologies are available to the fossil fuel sector in which it is relatively easy

1. http://shindellgroup.rc.duke.edu/apps/methane/

to reduce methane at the point of emission and along production/transmission lines. There are also available targeted solutions in the waste and agricultural sectors. Current targeted solutions alone, however, are not enough to achieve 1.5° C consistent mitigation by 2030. To achieve that, additional measures must be deployed, which could reduce 2030 methane emissions by another 15 per cent, about 60 Mt/yr. (Sections 4.1 and 4.2)

- **Roughly 60 per cent, around 75 Mt/yr, of available targeted measures have low mitigation costs[2], and just over 50 per cent of those have negative costs – the measures pay for themselves quickly by saving money** (Figure SDM2). Low-cost abatement potentials range from 60–80 per cent of the total for oil and gas, from 55–98 per cent for coal, and approximately 30–60 per cent in the waste sector. The greatest potential for negative cost abatement is in the oil and gas subsector where captured methane adds to revenue instead of being released to the atmosphere. (Section 4.2)

- **The mitigation potential in different sectors varies between countries and regions.** The largest potential in Europe and India is in the waste sector; in China from coal production followed by livestock; in Africa from livestock followed by oil and gas; in the Asia-Pacific region, excluding China and India, it is coal and waste; in the Middle East, North America and Russia/Former Soviet Union it is from oil and gas; and in Latin America it is from the livestock subsector. A majority of these major abatement potentials can be achieved at low cost, less than US$ 600 per tonne of methane, especially in the waste sector and the coal subsector in most regions and for the oil and gas subsector in North America. (Section 4)

- **Mitigation potential from all measures is expected to increase between 2030 and 2050, especially in the fossil fuel and waste sectors.** (Section 4.2)

- **The levels of methane mitigation needed to keep warming to 1.5° C will not be achieved by broader decarbonization strategies alone.** The structural changes that support a transformation to a zero-carbon society found in broader strategies will only achieve about 30 per cent of the methane reductions needed over the next 30 years. Focused strategies specifically targeting methane need to be implemented to achieve sufficient methane mitigation. At the same time, without relying on future massive-scale deployment of unproven carbon removal technologies, expansion of natural gas infrastructure and usage is incompatible with keeping warming to 1.5° C. (Sections 4.1, 4.2 and 4.3)

2. Less than US$ 600 per tonne of methane reduced, which would correspond to ~US$ 21 per tonne of carbon dioxide equivalent if converted using the IPCC Fifth Assessment Report's GWP100 value of 28 that excludes carbon-cycle feedbacks.

WHY ACT

- **Methane, a short-lived climate pollutant (SLCP) with an atmospheric lifetime of roughly a decade, is a potent greenhouse gas tens of times more powerful than carbon dioxide at warming the atmosphere.** Methane's atmospheric concentration has more than doubled since pre-industrial times and is second only to carbon dioxide in driving climate change during the industrial era. (Section 1.1)
- **Methane contributes to the formation of ground-level ozone, a dangerous air pollutant.** Ozone attributable to anthropogenic methane emissions causes approximately half a million premature deaths per year globally and harms ecosystems and crops by suppressing growth and diminishing production. (Section 1.1 and 3.3)
- **The atmospheric concentration of methane is increasing faster now than at any time since the 1980s.** In the absence of additional policies, methane emissions are projected to continue rising through at least 2040. Current concentrations are well above levels in the 2° C scenarios used in the IPCC's 2013 Assessment. The Paris Agreement's 1.5° C target cannot be achieved at a reasonable cost without reducing methane emissions by 40–45 per cent by 2030. (Sections 1.1 and 4.1)
- **The growing human-caused emissions come from all three sectors: fossil fuels, agriculture and waste.** (Section 1 and 4.1)
- **Methane's short atmospheric lifetime means taking action now can quickly reduce atmospheric concentrations and result in similarly rapid reductions in climate forcing and ozone pollution.** Lower methane concentrations would rapidly reduce the rate of warming, making methane mitigation one of the best ways of limiting warming in this and subsequent decades. Doing so would also help limit dangerous climate feedback loops, while simultaneously delivering important health and economic benefits from reducing ground-level ozone. (Sections 1.1 and 5)
- **This assessment found that every million tonnes (Mt) of methane reduced:**
  - **prevents approximately 1 430 annual premature deaths due to ozone globally.** Of those, 740 would have died from respiratory disease and 690 from cardiovascular disease. Every million tonnes of reduced methane emissions could also avoid approximately 4 000 asthma-related accident and emergency department visits and 90 hospitalizations per year. (Section 3.4)
  - **avoids losses of 145 000 tonnes of wheat, soybeans, maize and rice ozone exposure every year.** This is roughly equivalent to increased global yields of 55 000 tonnes of wheat, 17 000 tonnes of soybeans, 42 000 tonnes of maize, and 31 000 tonnes of rice annually for every million tonnes of methane reduced. (Section 3.5)
  - **avoids the annual loss of roughly 400 million hours of work, approximately 180 000 years, globally due to extreme heat[3].** Employment within those sectors of the economy that are affected by heat exposure varies between genders, leading to disparities in the impacts for men and women that differ across countries. (Section 3.4)

3. Labour impacts of heat exposure are the most dependent on the size of the methane emission changes, as well as background temperatures, and thus the linear scaling used here to obtain impacts per million tonnes is only approximate.

- **The global monetized benefits for all market and non-market impacts are approximately US$ 4 300 per tonne of methane reduced[4].** When accounting for these benefits nearly 85 per cent of the targeted measures have benefits that outweigh the net costs. The benefits of the annually avoided premature deaths alone from a 1.5°C-consistent-methane mitigation strategy is approximately US$ 450 billion per year. (Sections 3.5 and 3.6)

- **In addition to the benefits quantified here, methane reduction measures also contribute to multiple Sustainable Development Goals (SDGs),** including climate action (SDG13), zero hunger (SDG2), good health and well-being (SDG3). Additionally, they provide cost reductions and efficiency gains in the private sector, create jobs, and stimulate technological innovation. (Sections 1.1, 4.4 and 5)

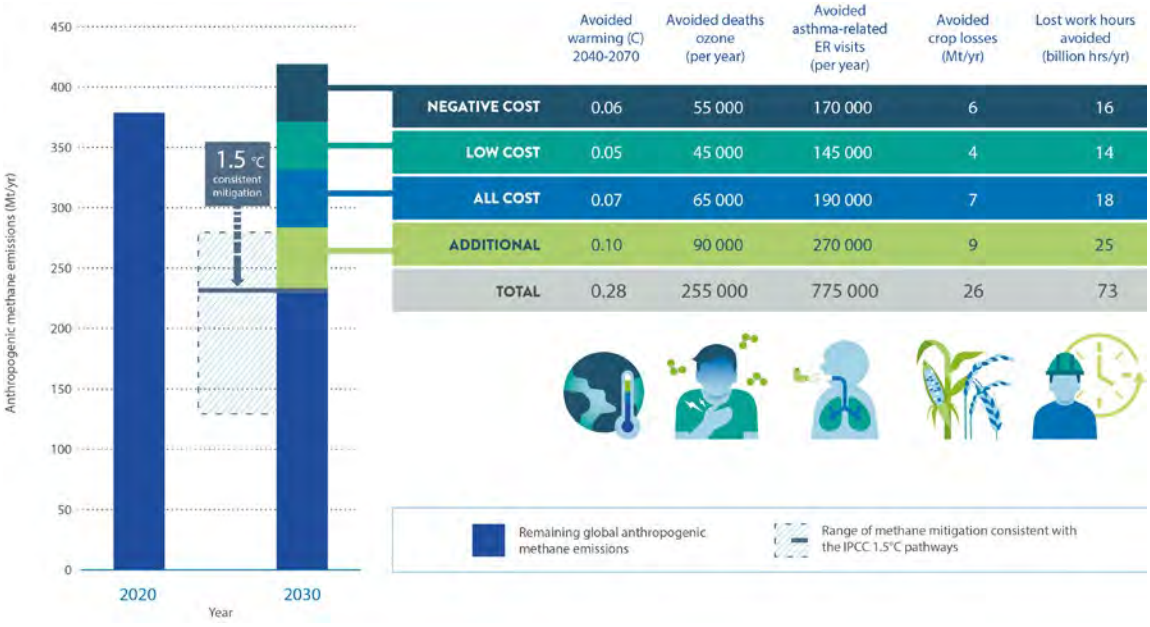

Figure ES2: Current and projected anthropogenic methane emissions and the identified mitigation potential in 2030 of targeted controls and their costs (low cost is greater than zero and less than 2018 US$ 600 per tonne of methane) as well as a set of additional measures, such as energy efficiency and fuel switching, plus behavioural changes, such as reduced food waste, dietary modification and energy demand management, that are consistent with the 1.5° C long-term maximum warming target. The cost of implementation of all-cost measures is more than 2018 US$ 600 per tonne of methane. Avoided warming is in 2040, other impacts are annual values beginning in 2030 that would continue thereafter.

4. Monetary values are in 2018 US$. Fossil methane emissions are valued at ~$4 400 per tonne of methane.

HOW TO DO IT

Trends in methane emissions need to be reversed to achieve a multitude of benefits by 2030. Targeted measures can be rapidly deployed to reduce methane emissions from the fossil fuel and waste sectors, with a majority at negative or low cost. To achieve targets consistent with keeping warming to 1.5° C, a combination of targeted measures and additional measures which reduce methane but do not primarily target it, are needed for all sectors, especially the agricultural one. There are many potential strategies that would facilitate the implementation of these measures including, for example, a price on emissions or an emissions reduction target. There are also barriers. These include addressing the lack of financing, enhancing awareness and improving education, changing production methods, developing new policies and regulations, and changes in consumption and consumer behaviour. Increased political will and private sector engagement and action are needed.

The specific measures include the following.

- **Oil, gas and coal:** the fossil fuel sector has the greatest potential for targeted mitigation by 2030. Readily available targeted measures could reduce emissions from the oil and gas sector by 29–57 Mt/yr and from the coal sector by 12–25 Mt/yr. Up to 80 per cent of oil and gas measures and up to 98 per cent of coal measures could be implemented at negative or low cost. (Section 4.2)

- **Waste:** existing targeted measures could reduce methane emissions from the waste sector by 29–36 Mt/yr by 2030. The greatest potential is in improved treatment and disposal of solid waste. As much as 60 per cent of waste-sector targeted measures have either negative or low cost. (Section 4.2)

- **Agriculture:** existing targeted measures could reduce methane emissions from the agricultural sector by around 30 Mt/yr by 2030. Methane emissions from rice cultivation could be reduced by 6–9 Mt/yr. The targeted mitigation potentials from livestock are less consistent, ranging from 4–42 Mt/yr. Average cost estimates vary across the available analyses. Behavioural change measures and innovative policies are particularly important to prevent emissions from agriculture, given the limited potential to address the sector's methane emissions through technological measures. Three behavioural changes, reducing food waste and loss, improving livestock management, and the adoption of healthy diets (vegetarian or with a lower meat and dairy content) could reduce methane emissions by 65–80 Mt/yr over the next few decades. (Sections 4.2 and 4.4)

- **Additional measures, which reduce methane emissions but do not primarily target methane, could substantially contribute to methane mitigation over the next few decades.** Examples include decarbonization measures – such as a transition to renewable energy and economy-wide energy efficiency improvements. Various implementation levers exist. Emissions pricing, for example, can be an effective policy which could incentivize substantial methane mitigation and support the broad application of methane reduction measures. A rising global tax on methane emissions starting at around US$ 800 per tonne could, for instance, reduce methane emissions by as much as 75 per cent by 2050. (Section 4.3)

- **Incomplete knowledge and monitoring of emissions in some sectors limits the potential for technical mitigation innovation and strategic decision making to efficiently reduce methane emissions.** While there is enough information to act now, addressing emissions at the scale and in the timeframe necessary to meet the 1.5° C target will require an improved understanding of methane emissions levels and sources. Continued and improved cooperation to create transparent and independently verifiable emissions data and mitigation analyses is needed. Such cooperative efforts would enable governments and other stakeholders to develop and assess methane emissions management policies and regulations, verify mitigation reporting and track emissions reductions. (Section 5)

- **Greater regional and global coordination and governance of methane mitigation would support the achievement of the 2030 abatement levels identified here.** While methane reductions are increasingly being addressed through local and national laws and under voluntary programmes, there are few international political agreements with specific targets for methane. The Climate and Clean Air Coalition (CCAC) leads global efforts to drive high-level ambition, and strengthens national actions, polices, planning, and regulations around methane mitigation. (Section 5)

AN INTEGRATED APPROACH

Urgent steps must be taken to reduce methane emissions this decade. Given the wide range of impacts from methane, the societal, economic, and environmental benefits of acting are numerous and far outweigh the costs. The existence of readily available, low-cost, targeted measures, and methane's short-lived atmospheric lifetime means significant climate and clean air benefits can be achieved by 2030. Targets and performance indicators to reduce methane must address the combined and multiple impacts methane has on climate, air quality, public health, agricultural production and ecosystem health. Assessment methodologies should be commonly agreed upon and transparent. An integrated approach to climate and air quality mitigation is required to put the benefits of methane reductions into context. To keep warming to 1.5° C, focused strategies specifically targeting methane emissions need to be implemented alongside substantial and simultaneous mitigation of all other climate pollutants including carbon dioxide and short-lived climate pollutants.



TARGETED MEASURES	
FOSSIL FUEL SECTOR (OIL, GAS, AND COAL)	**Upstream and downstream leak detection and repair**
	Recovery and utilization of vented gas: capture of associated gas from oil wells; blowdown capture; recovery and utilization of vented gas with vapor recovery units and well plungers; Installation of flares.
	Improved control of unintended fugitive emissions from the production of oil and natural gas: regular inspections (and repair) of sites using instruments to detect leaks and emissions due to improper operations; replace pressurized gas pumps and controllers with electric or air systems; replace gas-powered pneumatic devices and gasoline or diesel engines with electric motors; early replacement of devices with lower-release versions; replace compressor seals or rods; cap unused wells.
	Coal mine methane management: pre-mining degasification and recovery and oxidation of ventilation air methane; flooding abandoned coal mines.
WASTE SECTOR	**Solid waste management**: (residential) source separation with recycling/reuse; no landfill of organic waste; treatment with energy recovery or collection and flaring of landfill gas; (industrial) recycling or treatment with energy recovery; no landfill of organic waste.
	Wastewater treatment: (residential) upgrade to secondary/tertiary anaerobic treatment with biogas recovery and utilization; wastewater treatment plants instead of latrines and disposal; (industrial) upgrade to two-stage treatment, i.e., anaerobic treatment with biogas recovery followed by aerobic treatment.
AGRICULTURAL SECTOR	**Improve animal health and husbandry**: reduce enteric fermentation in cattle, sheep and other ruminants through: feed changes and supplements; selective breeding to improve productivity and animal health/fertility
	Livestock manure management: treatment in biogas digesters; decreased manure storage time; improve manure storage covering; improve housing systems and bedding; manure acidification.
	Rice paddies: improved water management or alternate flooding/drainage wetland rice; direct wet seeding; phosphogypsum and sulphate addition to inhibit methanogenesis; composting rice straw; use of alternative hybrids species.
	Agricultural crop residues: prevent burning of agricultural crop residues.
ADDITIONAL BENEFICIAL MEASURES	
FOSSIL FUEL SECTOR (OIL, GAS, AND COAL)	**Renewables for power generation:** use incentives to foster expanded use of wind, solar, and hydro power for electricity generation.
	Improved energy efficiency and energy demand management: (residential) use incentives to improve the energy efficiency of household appliances, buildings, lighting, heating and cooling, encourage rooftop solar installations; (industrial) introduce ambitious energy efficiency standards for industry; improve consumer awareness of cleaner energy options.
WASTE SECTOR	Reduced consumer waste and improved waste separation and recycling, improved sustainable consumption.
AGRICULTURAL SECTOR	**Reduced food waste and loss:** strengthen and expand food cold chains; consumer education campaigns; facilitate donation of unsold or excess food.
	Adoption of healthier diets: decrease intake where consumption of ruminant products is above recommended guidelines.

Table SDM1 Measures To Reduce Methane By 45 Per Cent By 2030

Note: The classification of measures as 'targeted' or 'additional' broadly reflects whether the measure's focus is on methane reductions or whether reductions occur largely as a co-benefit of measures with another primary purpose, but final categorization is governed by the underlying literature on mitigation.



1. INTRODUCTION

CHAPTER FINDINGS

- Methane amounts have risen rapidly over the past decade, reaching five-year average growth rates not seen since the 1980s.
- The increase in atmospheric methane during the 2010s has resulted in its amounts being well above those in the 2° C scenario used in the Intergovernmental Panel on Climate Change's (IPCC) 2013 Assessment.
- There is strong evidence that the increases in methane amounts during the 2010s were primarily attributable to increased emissions from fossil fuel-related, agricultural and waste sources, with fossil fuel-related activities contributing as much as agricultural and waste sources combined.
- Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years.

1.1 IMPORTANCE OF METHANE

Methane (CH_4) is a powerful greenhouse gas, the atmospheric amount of which has more than doubled since pre-industrial times (Nisbet *et al*. 2019). It has been second only to carbon dioxide (CO_2) in driving climate change during the industrial era (Myhre *et al.* 2013). Methane is a short-lived climate pollutant (SLCP) with an atmospheric lifetime of roughly a decade (the perturbation lifetime, relevant for dealing with emission reductions, is 12 years). Methane contributes to the formation of tropospheric ozone (O_3), which, like methane, is a short-lived but powerful greenhouse gas and surface ozone is also an air pollutant with detrimental effects on people, ecosystems and crops.

Emissions of methane to the atmosphere are therefore harmful to society in multiple ways. While methane is not directly dangerous to human health, it does indirectly affect it and agricultural productivity through ozone and climate change. Recent studies have found evidence of these consequences to health and agricultural damage (Shindell *et al.* 2019) to be larger than previously believed. These new studies include the finding that tropospheric ozone may have much higher impacts on public health, particularly respiratory and cardiovascular deaths (Turner *et al.* 2016). In addition, understanding of methane's effect on radiative forcing has recently improved, leading to an upward revision since the Fifth Intergovernmental Panel on Climate Change (IPCC) Assessment (Collins *et al.* 2018; Etminan *et al*. 2016). Taken together, improved understanding suggests that the overall societal impact of methane emissions is likely larger than indicated by prior estimates.

In large part, because of its impacts on public health and agriculture, the broad social cost of methane, that is the monetized societal damage, including climate and air quality related impacts, resulting from a tonne of emissions is 50–100 times greater, depending uon the preferred discount rate (Shindell et al. 2017), than the corresponding social cost of carbon dioxide, before taking into account the recent updates in knowledge.

The amounts of methane in the atmosphere have changed dramatically over the past four decades (Figure 1.1a). Amounts increased sharply in the 1980s but slowed to a near constant level between 2000 and 2005 when emissions and sinks were roughly balanced (Figure 1.2). However, atmospheric methane amounts have increased rapidly again over the past decade (Figure 1.1a). These observations demonstrate that it is crucial to change the trajectory of this greenhouse gas, which in 2020 exhibited the highest growth rate in NOAA's 37-year record (Figure 1.1b). They also shows that atmospheric methane responds quickly to reductions in emissions, as shown by the negative growth rates in the early 2000s (Figure 1.1b).

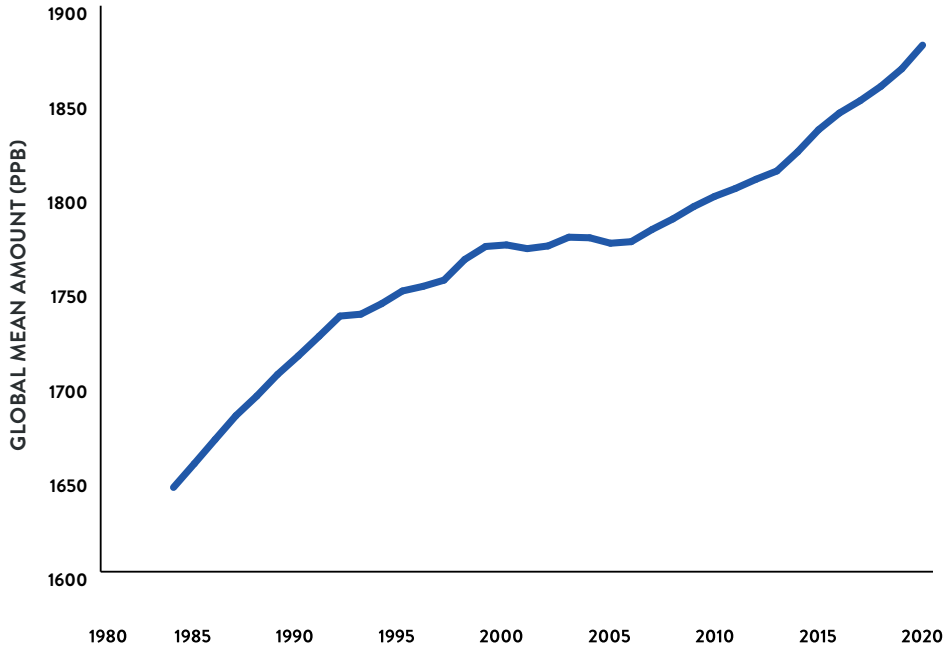

Figure 1.1a Global mean methane amount, 1984–2019, parts per billion

Source: Ed Dlugokencky, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends_ch4/)

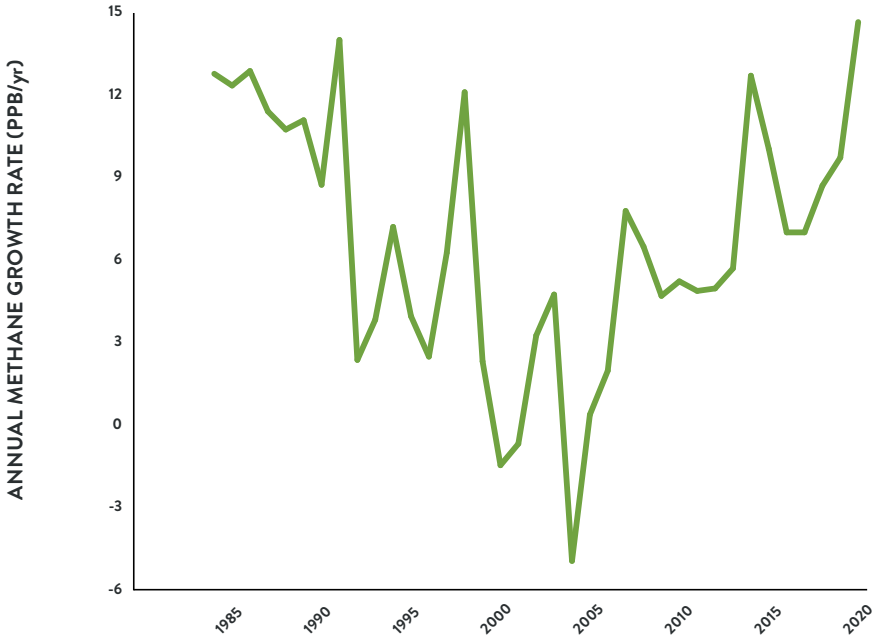

Figure 1.1b Global mean methane annual growth rate, 1984–2019, parts per billion per year

Source: Ed Dlugokencky, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends_ch4/ (accessed 6 February 2021)

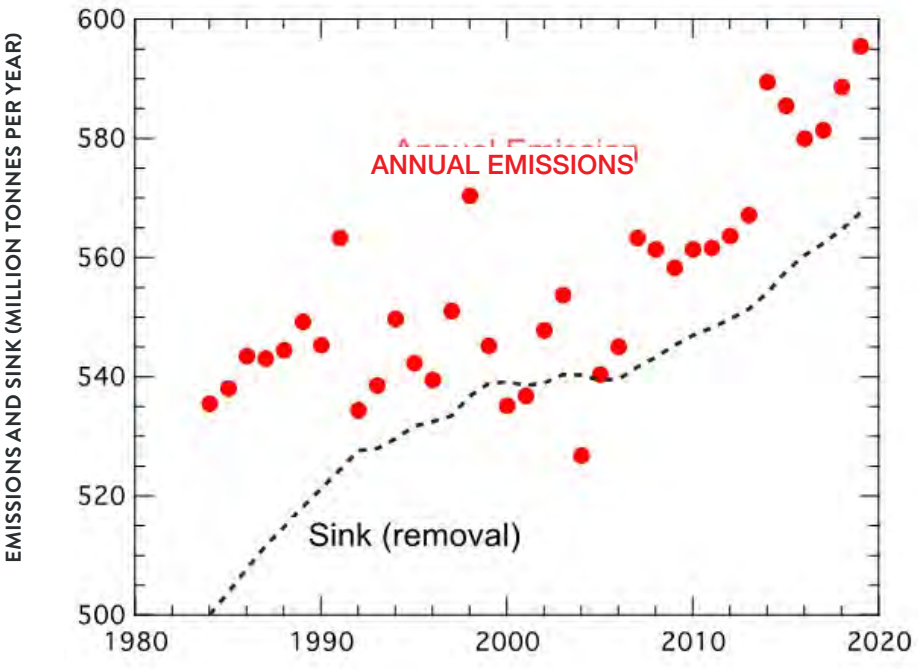

Figure 1.2 Estimated global methane emissions and sinks (removals), 1984–2019, million tonnes per year

Note: Estimated using an inversion from observed amounts based on a constant (time invariant) overall global lifetime of 9.1 years and mass balance (Section 2.1.3).

Source: Ed Dlugokencky, NOAA/ESRL

The possible reasons for these trends have been discussed in a host of newly published papers (Jackson *et al.* 2020; Saunois *et al.* 2020). There is strong evidence that the increases in the abundance of atmospheric methane are due to growth in emissions rather than a slower atmospheric removal rate (Figure 1.2). It appears that increases are due to fossil fuel-related activities and the combined contribution from agricultural and waste sources in roughly equal parts (Jackson *et al.* 2020).

Methane is emitted from both natural and anthropogenic sources, as described more fully in Chapter 2. Humanity has the greatest leverage on anthropogenic sources, though human-induced climate change and land-use changes affect natural sources. Globally, anthropogenic methane emissions are expected to continue to increase. Under current policy scenarios, by 2030 anthropogenic methane emissions are expected to increase by more than 15 per cent over 2010 levels, reaching nearly 380 million tonnes per

year (Mt/yr), an 8 per cent increase on 2020 levels (Höglund-Isaksson *et al.* 2020). Significant emissions growth during the 2020s is expected from all three sectors – fossil fuels, agriculture and waste. The largest increases of about 13 Mt/yr are projected in the waste and wastewater sectors, driven in particular by expected strong growth in the population and income in regions that currently have poorly developed waste management systems. Emissions from the fossil-fuel sector are projected to grow by about 10 Mt/yr, with gas production and distribution being the largest source, followed by oil production whereas emissions related to coal mining are projected to decrease very slightly. The number of uncapped abandoned oil and gas wells and coal mines is increasing and could also continue to contribute to the growth in emissions. In the agriculture sector, continued growth in the number of ruminant animals, due to rising demand for meat from an increasing and increasingly affluent global population, will drive increases in emissions from enteric fermentation and manure management of around 6 Mt/yr. Emissions from rice cultivation are, however, likely to remain approximately constant.

For the 2015 United Nations (UN) Paris Agreement to succeed, reducing anthropogenic methane in addition to carbon dioxide is paramount. Currently the largest contributor to the departure from an idealized path to the 2° C target used in the IPCC's Fifth Assessment Report is the growth in methane amounts (Figure 1.3). Achieving the more stringent 1.5° C target requires even larger decreases in methane. The IPCC's 2018 Special Report concluded that reaching a sustainable mitigation pathway to 1.5° C can only be achieved with deep and simultaneous reductions of carbon dioxide and all non-carbon dioxide climate forcing emissions, including short-lived climate pollutants such as methane. In 1.5° C pathways, global anthropogenic methane emissions fall by an average of 45 per cent by 2040, with the full range showing decreases of 30–65 per cent relative to 2010 by this time. Such trajectories, which imply approximately a 2 per cent annual decrease in emissions over the next 20 years, are in sharp contrast to the current path which shows an increase in the order of 0.5 per cent per year and falls between methane abundance in idealized paths leading to approximately 3–5° C of warming in 2100 (Nisbet *et al*. 2020).

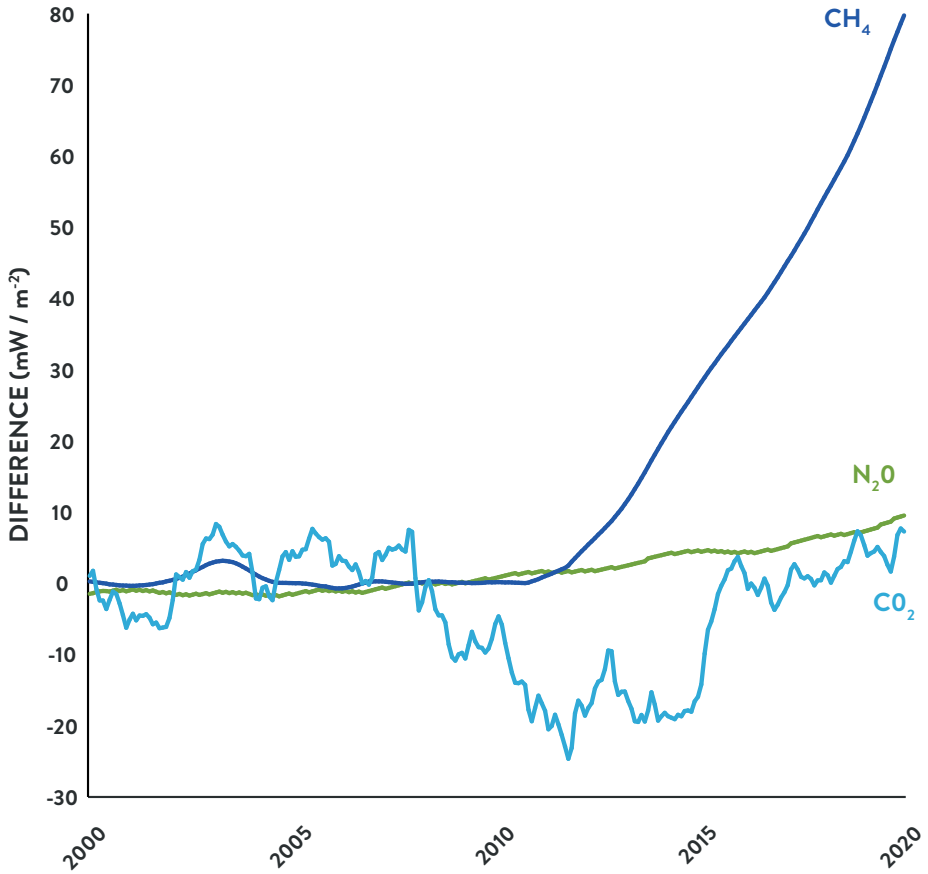

Figure 1.3 Values for the difference between actual global mean annual average radiative forcing from major greenhouse gases and values under Representative Concentration Pathway RCP2.6, 2000–2020, milliWatts per square metre

Note: Representative Concentration Pathway RCP2.6 (Collins et al., 2013) as used in IPCC's Fifth Assessment and consistent with the Paris Agreement.

Source: Nisbet et al. (2020), updated through 2020 courtesy M. Manning

The short lifetime of methane, and the quick response of methane abundance to reduced emissions described earlier, mean that any action taken to reduce emissions will have an immediate pay off for climate in addition to the current and near-future human health and agricultural production. Observations over the past few decades have shown that decreased emissions lead quickly to lower methane levels relative to those that could be expected in the absence of the decreases. That is, there are no mechanisms that offset the decreases even though there are significant natural sources. Simply put, natural emissions do not make up for the decrease in anthropogenic emission. Indeed, the expectation that a reduction in emissions will yield quick results, in the order of a decade, is confirmed and emphasizes the importance of methane.

Methane mitigation offer a way of rapidly reducing the rate of near-term warming. Also, mitigation of methane, along with non-fossil greenhouse gases including some hydroflurocarbons (HFCs) and black carbon-rich sources of particulate matter (PM), is the only plausible way of decreasing warming relative to a reference case with minimal changes in current policies over the next 20 years. This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre *et al*. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman *et al*. 2013)).

Though decarbonization is essential to meeting long-term temperature goals, near-term impacts are also important. Climate changes over the next few decades will limit the ability of human and natural systems to adapt. This is especially problematic for the poorest and women, both groups are particularly vulnerable. Additionally, impacts such as sea-level rise and glacier melting are influenced by cumulative heat uptake, and many impacts may be non-linear. Thus, there is a need for urgent action to reduce damage from ongoing climate change. A prior study (Shindell *et al*. 2017b) listed several reasons for urgency, including stating that early mitigation: *"(i) reduces damage due to climate change over the next few decades, including those dependent on the pace of climate change such as biodiversity losses; … (iii) reduces the risk of potential non-linear changes such as release of carbon from permafrost or ice sheet collapse; (iv) increases the probability of staying below 2° C through mid-century* (Shindell *et al*. 2012; Ramanathan and Xu 2010)*; (v) reduces long-term cumulative climate impacts; (vi) reduces costs of meeting temperature targets relative to late mitigation* (Hamsen *et al*. 2016)*; and (vii) stimulates progress toward the long-term 2° C target through achievement of near-term benefits* (Victor *et al*. 2016)". Reductions in methane emissions can thus provide near-term climate benefits while carbon dioxide emission reductions are implemented for long-term stabilization.

Reducing methane emissions provides an opportunity to rapidly change the environment, both through surface ozone pollution and climate change. Methane mitigation also has clear and immediate economic benefits including improved governance; cost reductions and efficiency in the private sector; job creation, particularly in relation to the leak detection and repair (LDAR) within industry; and technological innovation and entrepreneurship. Mitigating methane emissions directly contributes to the achievement of multiple Sustainable Development Goals (SDGs) (Haines *et al.* 2017), including:

- SDG2 Zero hunger by improving ecosystem health and agricultural yields, thereby helping to end hunger and achieve food security;
- SDG3 Good Health and well-being, SDG11 Sustainable cities and communities and SDG12 Responsible consumption and production by reducing indoor and outdoor air pollution, enabling sustainable food production and helping ensure healthy lives for people across the globe.
- SDG1 No poverty, SDG11 Sustainable cities and communities and SGD13 Climate action by helping reduce the exposure of vulnerable populations to climate-related extreme events.

All 17 SDGs are shown in the Figure 1.4 below:



Figure 1.4 The Sustainable Development Goals established by the United Nations in 2015

Source: United Nations

1.2 PURPOSE OF THIS ASSESSMENT

Despite the well-documented harms resulting from its emissions, efforts thus far to reduce methane have been inadequate given the rapid growth in observed atmospheric methane amounts. This is likely due in part to inadequate awareness of the multiple benefits of emission reductions. Additionally, a lack of adequate policies, institutional structures and governance play important roles. This assessment seeks to better characterize the impacts of methane reductions with state-of-the-art modelling, and to document the multiple benefits that could be realized through methane reductions with an examination of near-term targeted mitigation measures and additional measures which contribute to other development priority goals while also reducing methane emissions. The classification of measures as 'targeted' or 'additional' broadly reflects whether the measure's focus is on methane reductions or whether reductions occur largely as a co-benefit of measures with another primary purpose such as carbon dioxide reduction or health benefits. Such a classification is subjective, however, and the final categorization used in this assessment is governed by achieving consistency with the underlying literature on mitigation options. To better quantify the benefits of methane mitigation, and the uncertainties associated with such a quantification, this work looks at the response to emissions across a variety of impacts using a range of models. The impacts were chosen based on available evidence allowing specific endpoints to be reliably quantified along with an emphasis on links to the SDGs. Previous analyses have shown the multiple benefits of reducing methane emissions (Shindell *et al*. 2012; UNEP/WMO 2011). This assessment adds to those prior analyses by not only including more modelling to better characterize robustness and analyses of additional impacts, but also greatly extends the scope of the associated economic analysis.

In the troposphere, methane plays an important role in regulating both the oxidation capacity as a whole and the amount of ozone in particular. Methane's primary sink is oxidation through the hydroxyl radical. When nitrogen oxides (NO_x) and sunlight are present, this oxidation process leads to the production of ozone (O3). As ozone is also a greenhouse gas, the net impact of methane emissions on climate is larger than the direct impact of the increased methane – ozone adds about 38 per cent to the forcing associated with methane alone (Myhre *et al*. 2013). In addition to the warming caused by direct methane increases and indirect tropospheric ozone increases, there are smaller warming impacts from the oxidation of methane. These include:

1. an increase in carbon dioxide in the atmosphere;
2. an increase in water vapour in the stratosphere; and
3. changes in atmospheric hydroxide (OH) abundance that in turn affect concentrations of radiatively active gases such as HFCs and hydrochlorofluorocarbons.

These complexities mean that to obtain a detailed understanding of the influence of methane emissions requires the use of three-

dimensional composition-climate models capable of representing the most important of these processes, as is done in this assessment.

The physical system modelling examines the worldwide impact of methane emissions, which have virtually the same impact regardless of location (Fiore *et al*. 2008). This is because although methane is a short-lived climate pollutant, a class of pollutants with a lifetime of roughly fifteen years or less, it is a relatively longer-lived one and its atmospheric chemical lifetime of nearly a decade is long compared to atmospheric mixing timescales so that it is a well-mixed gas, in the sense that geographic variations in tropospheric concentrations are relatively small. Impacts of methane emissions include the responses of ozone, temperature and precipitation, as well as subsequent impacts of those changes on human health and crop yields. Full three-dimensional atmospheric composition-climate models are required to capture the response of ozone, which is quite inhomogeneous as it depends on the local availability of other ozone precursors and sunlight, as well as climate responses that are also inhomogeneous.

This new modelling of the composition-climate system is complemented by an analysis of the potential for methane mitigation. This includes both source specific analyses of the potential and cost of targeted methane emissions abatement as well as modelling with integrated assessment models (IAMs) that incorporate such potentials within their representation of the coupled energy-economy-land system. This assessment thus provides information on both the potential for the abatement of methane emissions and the impacts of such controls, both within this document and in an online web-based decision-support tool developed to support it. The potential is compared with reductions in methane emissions under scenarios consistent with avoiding dangerous anthropogenic interference in the climate system, the internationally agreed goal of climate policy. This information can help inform both large-scale efforts to set ambitious goals for the mitigation of methane emissions and detailed analyses of the most cost-effective ways of mitigating emissions at global and regional scales.





2. SOURCES OF METHANE



CHAPTER FINDINGS

- Anthropogenic emissions represent roughly 60 per cent of the total methane emissions.
- Anthropogenic methane emissions come primarily from three sectors: fossil fuels, ~35 per cent; agriculture, ~40 per cent; and waste, ~20 per cent.
- Emissions from livestock are the largest source of agricultural emissions with enteric fermentation the dominant process and cattle the dominant animal causing the emissions.
- The extraction, processing and distribution of the three main fossil fuels lead to comparable emissions: gas and oil each contribute ~34 per cent, followed by coal which contributes ~32 per cent of the fossil fuel methane emissions.
- Emissions vary greatly across regions, with the largest totals in China and South Asia, but there are significant contributions from all regions. Uncertainties in emissions are again largest for China but are also significant for the Americas.
- At subsectoral and regional levels, the largest emissions sources vary markedly. For fossil fuels, they are coal mining in China, ~24 Mt/yr; oil and gas extraction, processing and transport in West Asia, ~18 Mt/yr; in Russia, ~15 Mt/yr; and North America, ~14 Mt/yr. Livestock emissions are highest in Latin America, ~27 Mt/yr, followed by South Asia, ~22 Mt/yr. Emissions from rice cultivation are highest in Southeast Asia+the Republic of Korea+Japan, ~10 Mt/yr, closely followed by South Asia, ~8 Mt/yr, and China, ~8 Mt/yr. Emissions from the waste sector are much more evenly distributed around the world.
- Advances in technology, especially remote sensing, are opening up new opportunities to characterize emission sources more accurately, including high emitters, and highlight substantial biases in much reporting at the facility scale and even at a national scale.
- Changes in emissions from natural sources of methane are likely to create positive feedbacks as emissions increase in a warming climate.

Identifying and quantifying sources of methane is a complex but critical element in understanding atmospheric methane concentrations and their trends. Methane has both natural and anthropogenic sources that can be individually small and geographically dispersed. While most sources have been identified, their relative contributions to atmospheric methane levels remain uncertain. Estimates of global emissions come broadly from two methods:

1. bottom-up which traditionally use some type of activity data representative of the sector, multiplied by an appropriate emission factor;

AND

2. top-down which use atmospheric observations and models to indirectly infer emissions.

Both bottom-up and top-down estimates are discussed in this assessment.

The global methane budget is composed of many sources and a small number of sinks –atmospheric removal processes, primarily oxidation by hydroxyl along with a small contribution from uptake in soils (Table 2.1). This table is based on bottom-up estimates as these currently provide greater detail on specific sources than top-down ones. The sources and sinks are not currently in balance, and the greater emissions flux relative to the sinks drives the ongoing growth in atmospheric amounts.

The anthropogenic methane sources are the focus of this assessment, but natural sources are briefly described in Section 2.1.2 for completeness. Note that this assessment considers fires to be anthropogenic and wetland emissions to be natural although both sources are natural processes that are influenced by human activities. This assessment does not discuss the sinks in further detail as these are relatively well constrained by observations of the abundance of industrial trace gases whose only loss mechanism is oxidation by hydroxyl, the same loss process that dominates the methane sink (Prather *et al*., 2012), and any trends in methane sinks over recent decades are likely to have been very small (Saunois *et al*. 2020). It is noted, however, that there has been some work on the potential for the active removal of methane from the atmosphere in the future, though such studies are at very early stages and are their efficacy and economics remain to be demonstrated (Jackson *et al*. 2020b; Lackner 2020; Jackson *et al*. 2019; Stolaroff *et al*. 2012).

It is important to emphasize that as the atmospheric concentration of methane has been measured to a high degree of precision and the sinks and atmospheric residence time are constrained, the total emissions are also well constrained. This is because the atmospheric abundance times, the removal rate, plus any increase in concentrations, must balance the total emissions flux, allowing the quantification of emissions when the other factors are well-known. Hence, although many individual source strengths are not well known, any upward revision in estimates of the magnitude of one source would necessitate a downward revision in another. Thus, the uncertainty surrounding total emissions is substantially smaller than the sum of uncertainties of individual emissions would imply. Furthermore, isotopic data, in this case the ratio of methane molecules to carbon atoms containing seven neutrons and six protons (13C) to the more common value of six neutrons and six protons (12C)) constrain the apportionment of emissions to fossil and biogenic sources, so that the substantial uncertainties in many individual natural biogenic sources are largely independent from estimates of fluxes from fossil fuel sources.

NATURAL SOURCES	MAGNITUDE (MT/YR)	ANTHROPOGENIC SOURCES	MAGNITUDE (MT/YR)	SINKS	MAGNITUDE (MT/YR)
Wetlands	145 [100–183]	Coal mining	44 [31–63]	Soils	40 [37–47]
Termites	9 [3–15]	Oil and gas industry	84 [72–97]	Total chemical loss	531 [502–540]
Oceans	6 [4–10]	Landfill and waste	68 [64–71]	Total loss	571 [540–585]
Geological	45 [18–65]	Ruminants	115 [110–121]		
Wild animals	2 [1–3]	Rice cultivation	30 [24–40]		
Freshwaters	159 [117–212]	Biomass burning	16 [11–24]		
Permafrost soils	1 [0–1]	Industry	3 [0–8]		
		Biofuels	13 [10–14]		
		Transport	4 [1–13]		
Total natural	367 [243-489]	Total anthropogenic	380 [359–407]		
Total natural (top-down)	232 [194-267]	Total anthropogenic (top-down)	364 [340-381]		

Table 2.1 Estimated natural and anthropogenic sources and sinks of methane, 2017

Note: Values shown are best estimates based on bottom-up studies (except last row), with the minimum and maximum of the studies analyzed in that meta-analysis given in brackets. Natural sources are based on 2000–2006 data as the separation into individual sources was not reported for 2017. The total natural source was evaluated for 2017, however, and was identical to that for the 2000–2006 period. The last row shows natural and anthropogenic totals based on top-down constraints, highlighting how natural sources are substantially lower, based on top-down estimates, likely due to overlap between wetlands and freshwaters, whereas anthropogenic bottom-up and top-down estimates are more consistent.

Source: Jackson et al, (2020)

2.1 ANTHROPOGENIC SOURCES

Approximately 60 per cent of total global methane emissions come from anthropogenic sources. Of these, more than 90 per cent originate from three sectors: fossil fuels, ~35 per cent; agriculture, ~40 per cent; and waste, ~20 per cent.

Fossil fuels: release during oil and gas extraction, pumping and transport of fossil fuels accounts for roughly 23 per cent of all anthropogenic emissions, with emissions from coal mining contributing 12 per cent.

Waste: landfills and waste management represents the next largest component making up about 20 per cent of global anthropogenic emissions.

Agriculture: emissions from enteric fermentation and manure management represent roughly 32 per cent of global anthropogenic emissions. Rice cultivation adds another 8 per cent to anthropogenic emissions. Agricultural waste burning contributes about 1 per cent or less.

These three categories are referred to as sectors in this assessment, with further subdivisions within the three termed subsectors. Biomass burning, which has a mixture of anthropogenic and natural causes, and biofuels are relatively minor sources of methane emissions, as are industry and transport. Emissions from some subsectors show large uncertainties across the existing inventories, in particular for coal mining and rice cultivation (Table 2.1).

2.1.1 BOTTOM-UP ESTIMATES

So called bottom-up emissions inventories are created by compiling activity data and emission factors for individual sectors, with the product of these providing a total sectoral emissions estimate. An example of these is rice cultivation (hectare) for activity, and methane emissions per hectare of rice cultivation for the emission factor. These data are often estimated at the national level. National statistics are frequently used for activity estimates, whereas field and laboratory measurements are generally used as sources of data on emission factors.

Several groups of researchers have assembled global emission inventories for methane covering all sources, whereas other efforts have focused on emissions from specific sectors. A broad overview of available inventories for anthropogenic methane emissions has been assembled by the Global Carbon Project (Saunois *et al*. 2020), incorporating data from the Community Emissions Data System (CEDS) (Hoesly *et al*. 2018), the Emission Database for Global Atmospheric Research (EDGAR) (Janssens-Maenhout *et al*. 2019), the United States Environmental Protection Agency (US EPA) (US EPA 2012), and the Greenhouse Gas – Air Pollution Interactions and Synergies model (GAINS) (Höglund-Isaksson 2020) as well as several estimates for biomass burning emissions. It shows that for all inventories, the two largest sources are agriculture and waste together and fossil fuels, respectively (Figure 2.1).

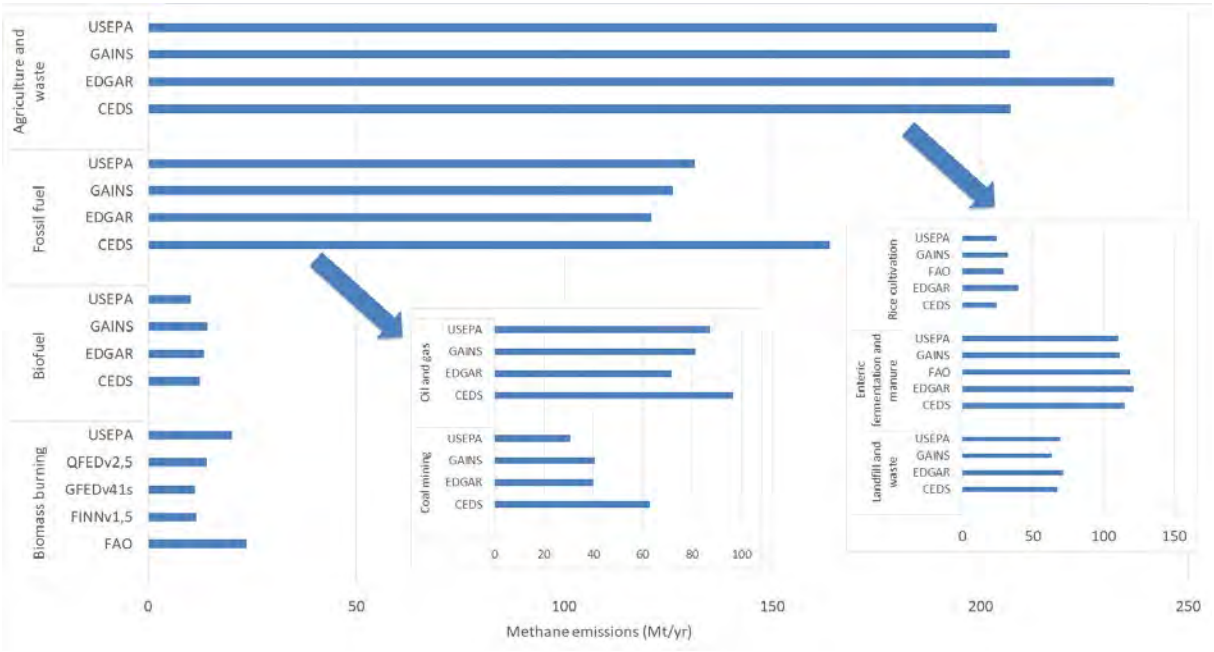

Source: Saunois et al. (2020). Emissions from EDGAR are the V4.3.2 version

Figure 2.1 Estimated anthropogenic methane emissions by sector from global inventories, 2017

Within the fossil fuel sector, the oil and gas subsector is the largest emitter, accounting for roughly two-thirds of the sector's total emissions, with emissions from coal mining making up most of the remainder. Emissions from industry and transport are small, totalling ~7 Mt/yr, less than 2 per cent of anthropogenic emissions, from both categories (averaged across the four inventories). Within the agriculture and waste sectors, emissions related to livestock are the largest source. These include emissions due to enteric fermentation, primarily from cattle, and emissions from manure. Landfills and waste represent the next largest component, followed by rice cultivation. In comparison, biomass burning, which has a mixture of anthropogenic and natural causes, and the use of biofuels are relatively minor sources of methane. Agricultural waste burning, included in the biofuels category in the US EPA inventory and in the agricultural sector in CEDS. GAINS, EDGAR and FAO estimates for this category but not included in Figure 2.1, range from 1 to 3 Mt/yr.

As noted, emissions for some subsectors show large uncertainties across the existing inventories, in particular for coal mining and rice cultivation. Total anthropogenic emissions, excluding biomass burning, are approximately 350–380 Mt/yr. For comparison, emissions from wetlands are estimated to be roughly 160–210 Mt/yr based on biogeochemical models. Hence approximately two-thirds of total emissions are anthropogenic.

The two largest sources are livestock and fossil fuels. Within the livestock subsector, enteric fermentation and manure management are the two processes generating emissions, with the former dominant and cattle the dominant animal (Figure 2.2). Within the manure category, pigs play the largest role though cattle are again important. Within the fossil fuel sector, extraction, processing and distribution of the three main fuels have comparable impacts, with emissions from oil and gas each contributing 34 per cent followed by coal with 32 per cent of sectoral emissions in 2020 (Höglund-Isaksson 2020). Emissions from the coal subsector are entirely from mining-related activities, including both active and abandoned facilities. Within oil and gas, methane emissions associated with onshore conventional extraction along with downstream gas usage are the largest sources (Figure 2.3). Venting, the deliberate release of unwanted gas, is the primary cause of emissions during onshore conventional extraction, whereas fugitive emissions, the inadvertent release or escape of gas from fossil fuel systems, dominate downstream gas emissions. Within the fossil fuel sector, at the national level, emissions from the oil subsector in Russia and the coal subsector in China appear to be far larger than any other national level subsectors (Scarpelli *et al*. 2020). While these types of data based on national inventories are useful, it is important to note that many local measurements show large differences and often substantially higher emissions than conventional reporting, in many cases due to the presence of a small number of super-emitters, and imply these estimates may be too low (Zhang *et al*. 2020; Duren *et al*. 2019; Varon *et al*., 2019; Zavala-Araiza *et al*. 2018). These emissions give a sense of mitigation opportunities by region and sector, which is explored in Chapter 4.

Though some biomass burning is natural, current burning results largely from anthropogenic activities. Large amounts of biomass are burned in the tropics in human induced fires related to shifting cultivation, deforestation, burning of agricultural wastes and the use of biofuels (Dlugokencky and Houweling 2015). Biomass burning remains a relatively small source of methane and it accounts for approximately 5 per cent of global methane emissions, an estimated 10–25 Mt/yr (Figure 2.1) (Saunois *et al*. 2020).

While rice cultivation feeds up to a third of the world's population, rice fields are a significant source of methane (Mbow *et al*. 2019; Dlugokencky and Houweling 2015). Methane is produced through anaerobic decomposition of organic material in flooded rice fields which are responsible for approximately 8–11 per cent of global anthropogenic methane emissions (Saunois *et al*. 2020; Mbow *et al*. 2019).

As noted, there are substantial differences in sector-specific bottom-up methane emissions estimates created by different groups (Figure 2.1). This difference indicates that these estimates could be improved by additional work to better quantify activity levels for each source, and by improved quantification of source-specific emission factors which may vary substantially both between and within nations.

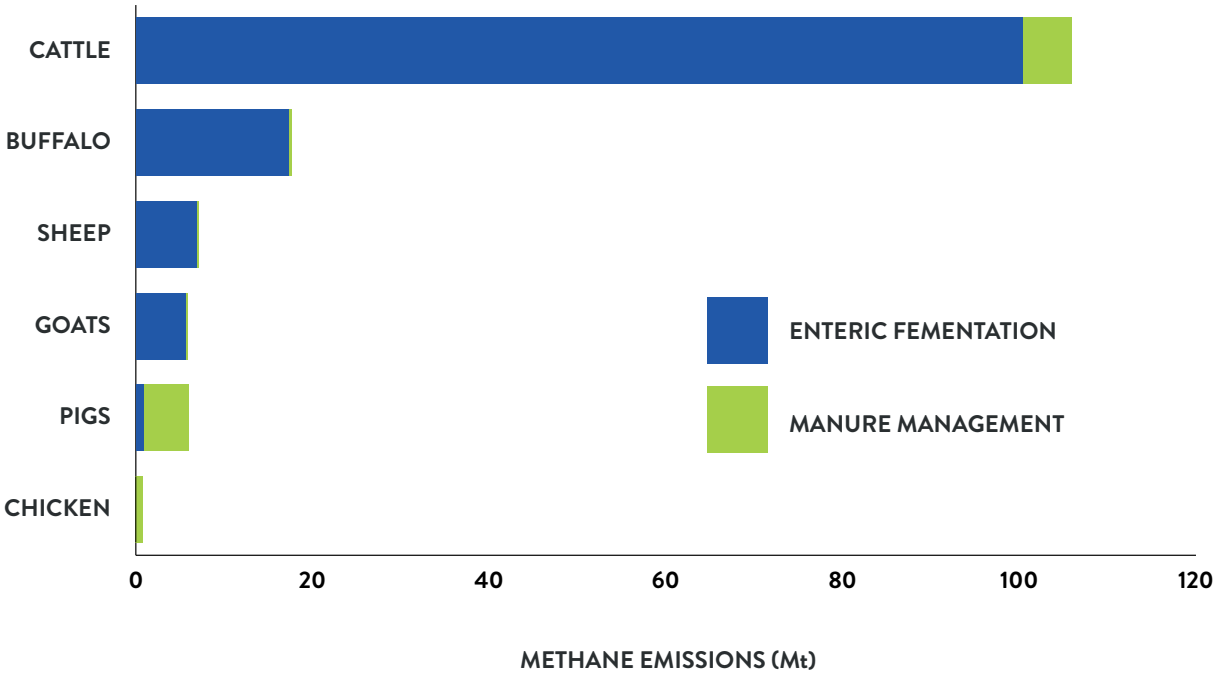

Figure 2.2 Annual livestock methane emissions , million tonnes

Source: FAO (2013; 2017)

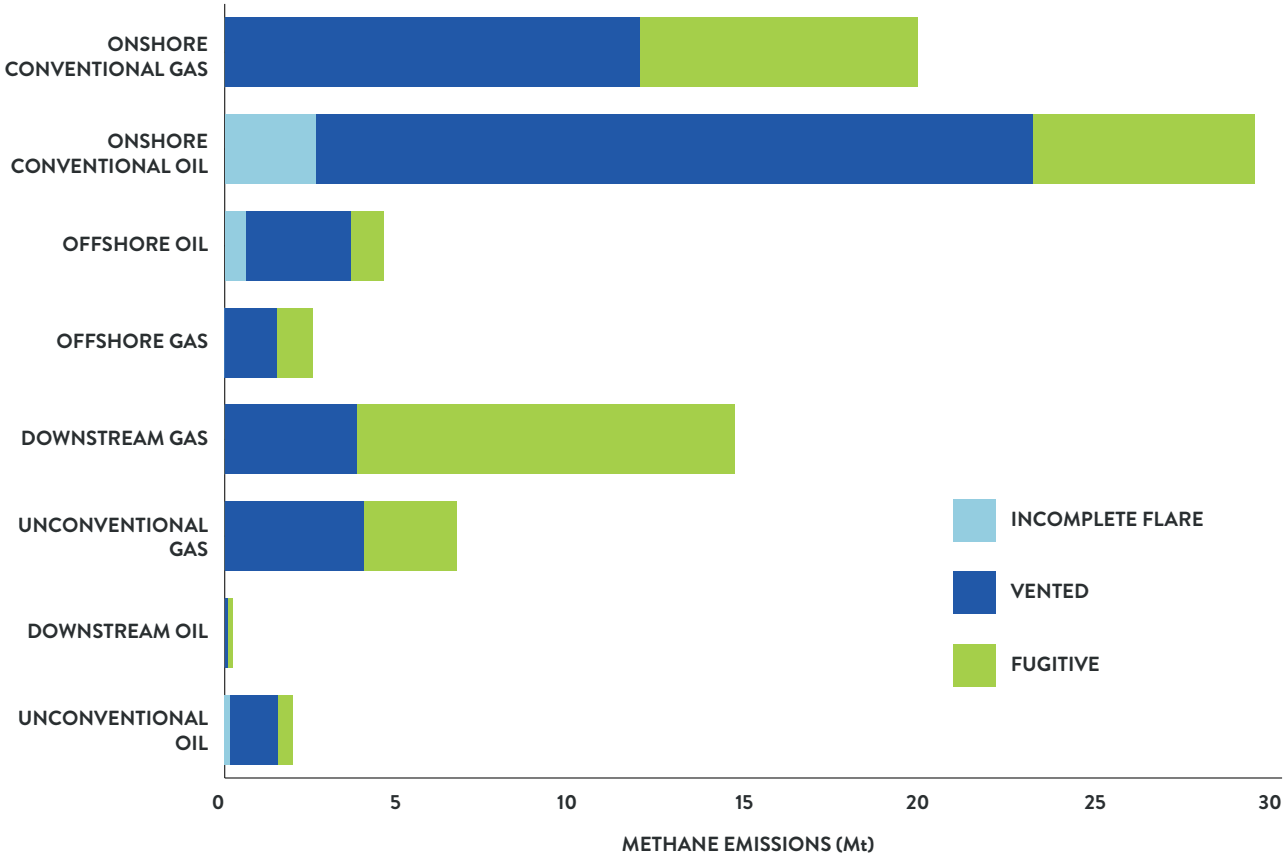

Figure 2.3 Annual oil and gas sector methane emissions by production type and reason, million tonnes

Source IEA (2020)

2.1.2 REGIONAL DIFFERENCES IN BOTTOM-UP ESTIMATES OF EMISSION SOURCES

Across multiple bottom-up inventories, emissions are largest in China, ~46–74 Mt/yr, and South Asia, ~35–50 Mt/yr, but large totals are also emitted from North America, ~35–50 Mt/yr; Latin America, ~50-60 Mt/yr; Southeast Asia+the Republic of Korea+Japan, ~25–35 Mt/yr; Africa, ~45–50 Mt/yr; Russia, ~20–25 Mt/yr; West Asia, ~23–29 Mt/yr; and Europe, ~22–26 Mt/yr (Figure 2.4). Uncertainties about emissions from China are particularly large, but there are also substantial uncertainties about North and Latin America.

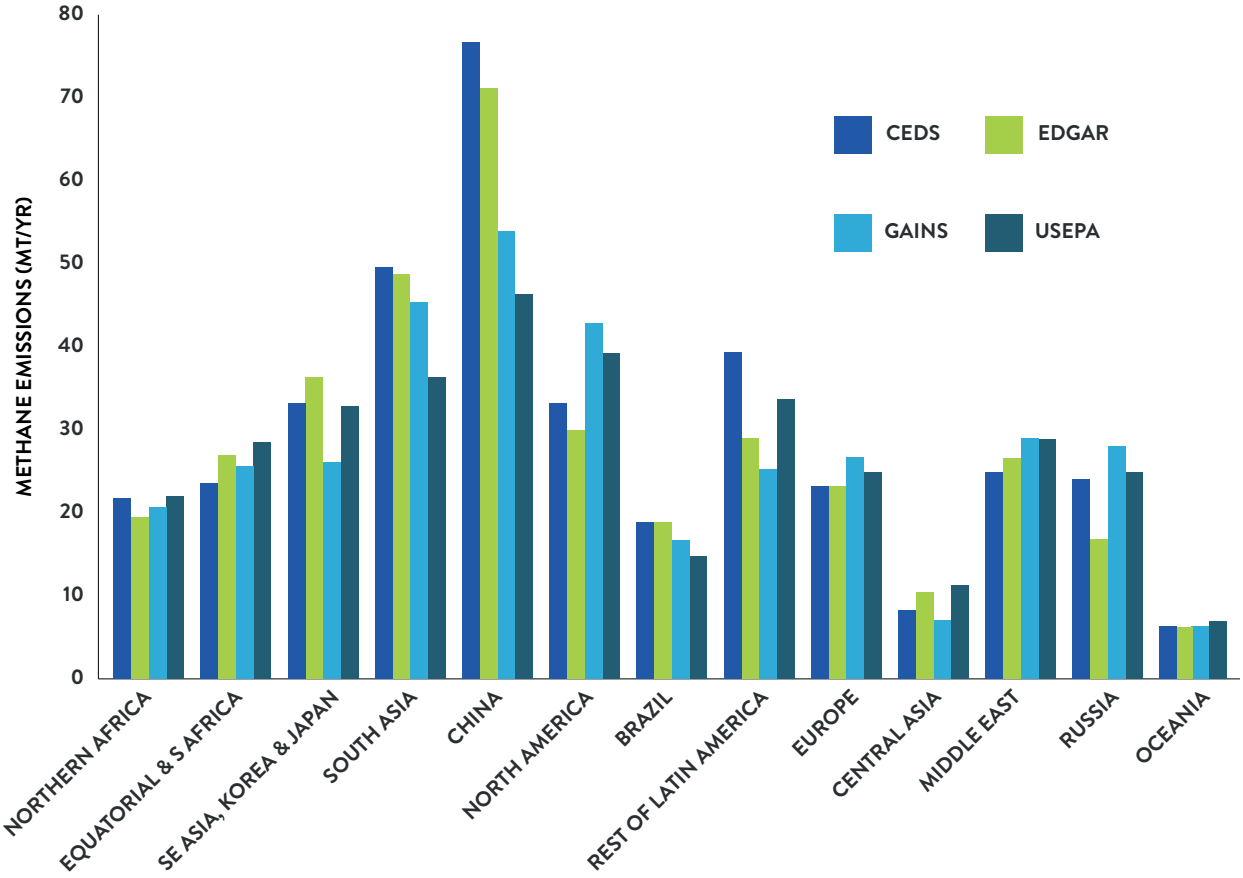

Figure 2.4 Estimated anthropogenic methane emissions by region from global inventories, excluding biomass burning, 2017, million tonnes

Source: Saunois et al. (2020)

While all sources of methane emissions are important in every region, there are some significant regional differences. Emissions from the coal and rice subsectors are particularly important in Asia. Fossil fuel-related emissions are generally a large share of regional emissions throughout the northern hemisphere. Solid waste separation and treatment offers opportunities across all regions. Figure 2.5 shows the global methane emissions for the year 2012 as reported by the EDGARv4.3.2 database, with sector specific shares and total emissions for major world regions.

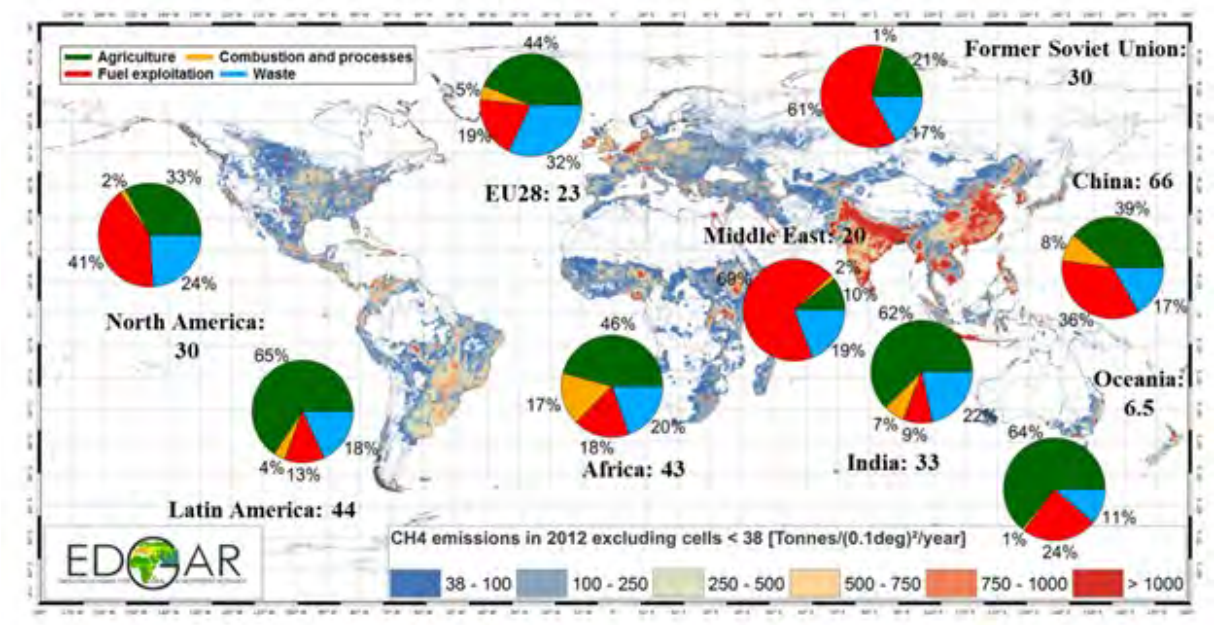

Figure 2.5 Global methane emissions for major world regions, 2012, million tonnes

Source: EDGARv4.3.2

The regional contribution to emissions from individual sectors varies markedly. Within fossil fuels, China is by far the largest source of coal-mining related methane emissions at ~24 Mt/yr; whereas for oil and gas the largest contributions come from West Asia, ~18 Mt/yr; Russia, ~15 Mt/yr; and North America, ~14 Mt/yr (Figure 2.6). Examining emissions related to livestock, the largest contributions comes from Latin America, ~27 Mt/yr, roughly half of which is from Brazil; and South Asia, ~22 Mt/yr; followed by nearly equal contributions from China, Equatorial and Southern Africa; Europe, North Africa and North America, each with 8–11 Mt/yr.

Emissions from rice cultivation are dominated by Southeast Asia+the Republic of Korea+Japan, ~10 Mt/yr; South Asia, ~8 Mt/yr; and China, ~8 Mt/yr, which together account for about 85 per cent of worldwide emissions. In contrast, emissions from landfills and waste are much more evenly distributed across the world. These emissions give a sense of mitigation opportunities by region and sector, which is explored in Chapter 4.

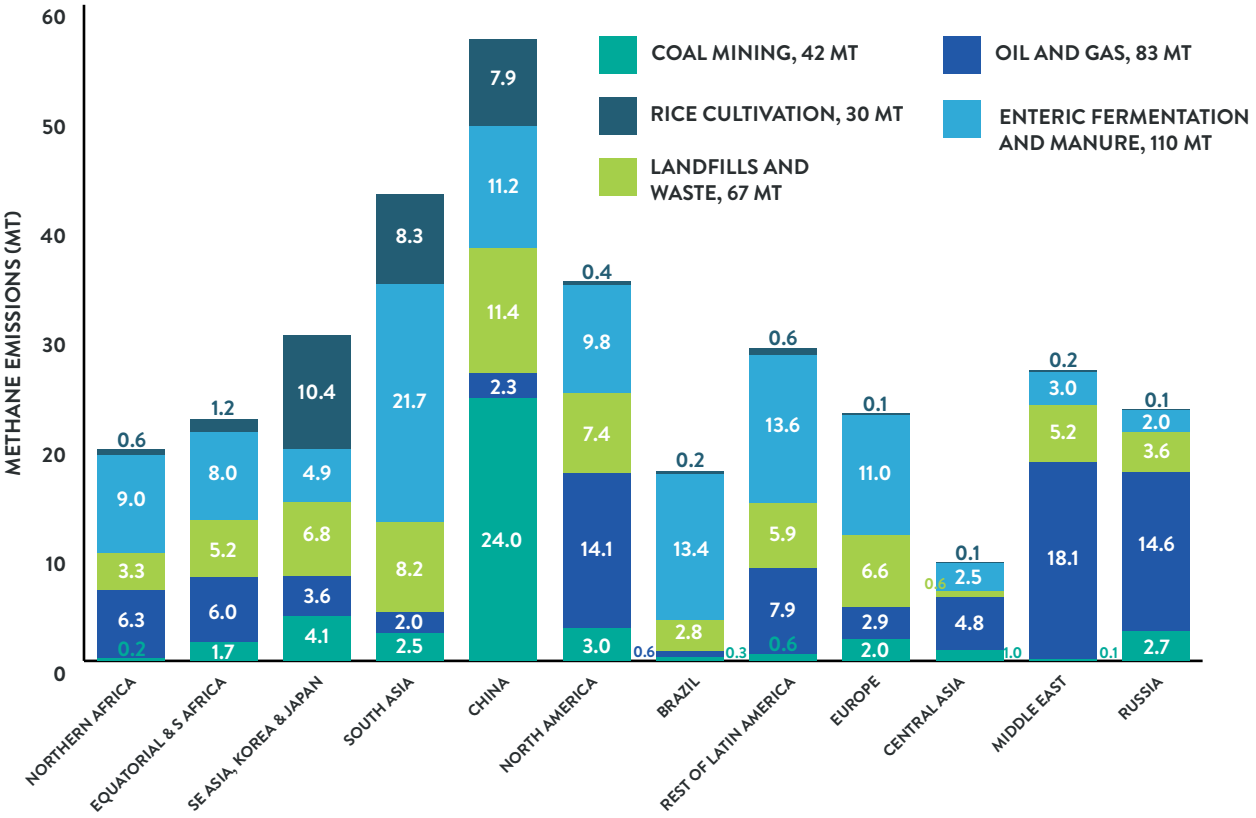

Figure 2.6 Estimated annual sectoral methane emissions by region and global sector totals, excluding Oceania, 2017, million tonnes

Source: Saunois et al. (2020).

2.1.3 ESTIMATING EMISSIONS USING TOP-DOWN METHODS FROM OBSERVED METHANE AMOUNTS

To evaluate bottom-up inventories and obtain a good quantitative understanding of methane sources and sinks, it is critical to monitor and quantify historic and current methane amounts. This section gives a brief description of the different ways of measuring methane amounts and producing emissions estimates, and Table A4 in the Annex gives a summary of each measurement technique available as well as its advantages and disadvantages. Ground-based measurements, ice core data, observations from aircraft, forward and inverse modelling and satellite data are all discussed. Results from such top-down methods generally compare reasonably well with bottom-up estimates such as those shown in Table 2.1 (Jackson *et al*. 2020; Saunois *et al*. 2020).

Ground-based data is highly accurate and now fairly common. The first accurate *in situ* measurements of methane were made in 1978 (Blake *et al*. 1982). In 1983, measurement stations from the National Oceanic and Atmospheric Administration (NOAA/ESRL)[5] and Advanced Global Atmospheric Gases Experiment (AGAGE) (Prinn et al., 2000)[6] had global coverage. As shown in Figure 1.1a, these networks show the amount of methane and its change over time. The latter is proportional to the imbalance between emission sources and sinks. The globally averaged amount, for example, stabilized at approximately 1 770 parts per billion (ppb) around the year 2000, indicating that at that time sources and sinks were equal (Figure 1.1).

To extend the record of methane amounts back in time before ground-based measurements became available, several studies (Bock *et*

5. www.esrl.noaa.gov/gmd/ccgg/trends_ch4/ (accessed 18 February 2021)
6. https://agage.mit.edu/ (accessed 18 February 2021)

al. 2017; Chappellaz *et al*. 2000; Bender *et al*. 1997; Chappellaz *et al*. 1990; Stauffer *et al*. 1985) have been published on atmospheric methane amounts reconstructed from polar ice cores. These records provide further and strong evidence of the predominant role of anthropogenic sources of methane emissions in causing the observed increases over the industrial era. Another important contribution of the evidence from ice cores is the range of emissions during the Holocene[7], which further demonstrates the current rise is well outside natural variability. These measurements significantly improve the quantitative understanding of historic and current changes in the global methane budget. Ice core records published by Etheridge *et al*. (1998), for example, showed that atmospheric methane levels have almost tripled since 1800.

Understanding methane abundances in the atmosphere can help constrain emissions from particular sources. Several studies (Gasbarra *et al*. 2019; Vaughn *et al*. 2018; Lavoie *et al*. 2017; Robertson *et al*. 2017; Sweeney *et al*. 2015; Karion *et al*. 2013) have used aircraft-based measurements to estimate methane emissions from individual facilities including landfills or natural gas production regions, or specific regions such as North America. One typical approach includes transects at multiple altitudes around a source while continuously measuring methane concentrations, and wind speed and direction. Figure 2.7 shows an example of a network that contains measurements from aircraft.

As discussed in the National Academy of Sciences report *Methane Emission Measurement and Monitoring Methods* (2018), following *in situ* sampling, the emission rates are estimated using a mass balance approach in which the concentration differences between the upwind and downwind sections of the flight paths are multiplied by the ventilation rate for the volume enclosed by the flight paths to arrive at the emission estimate (Conley *et al*. 2017; Gvakharia *et al*. 2017).

While these techniques have been applied with success to a variety of methane sources in urban areas (Mehrotra *et al*. 2017; Cambaliza *et al*. 2015) they have limitations and restrictions that need to be further investigated – this approach, for example, can only detect emissions that are encountered at flight elevations at the flight radial distance.

Very recently, remote sensing from aircraft has been used to quantify emissions from specific sources with relatively high accuracy, based on flights of independent instruments on different aircraft (Gorchov Negron *et al*. 2020; Duren *et al*. 2019; Baray *et al*. 2018; Johnson *et al*. 2017; Frankenberg *et al*. 2016; Karion *et al*. 2013). These data have shown that many bottom-up estimates are incorrect. Measurements in California, for example, revealed that multiple landfills that had reported emission rates in the range of 400–800 kilograms (kg) methane per hour in fact had emission rates of ~1 200–2 200 kg methane per hour (Duren *et al*. 2019). Similarly, measurements near offshore drilling platforms in the Gulf of Mexico show that emission rates were roughly double those in standard US EPA inventories (Gorchov Negron *et al*. 2020). These datasets also reveal that a few super-emitting sources typically play an outsized role in the total emissions from a specific source sub-sector. Ground-based studies similarly show that many bottom-up inventories underestimate methane emissions relative to observations (Chen *et al*. 2020; Alvarez *et al*. 2018; Brandt *et al*. 2014). Though valuable, such ground-based and aircraft data are currently available for only a very small area as they require expensive field and flight campaigns.

In addition to aircraft measurements, high altitude platforms can be used to measure methane. High altitude platforms are developmental vehicles typically situated between 20 and 100 kilometres. These platforms combine many of the advantages of satellites and ground-based systems, providing a flexible potential solution to many communications challenges (Wang and Shao 2013).

7. the current geological epoch, which began approximately 11,650 years before present, after the last glacial period

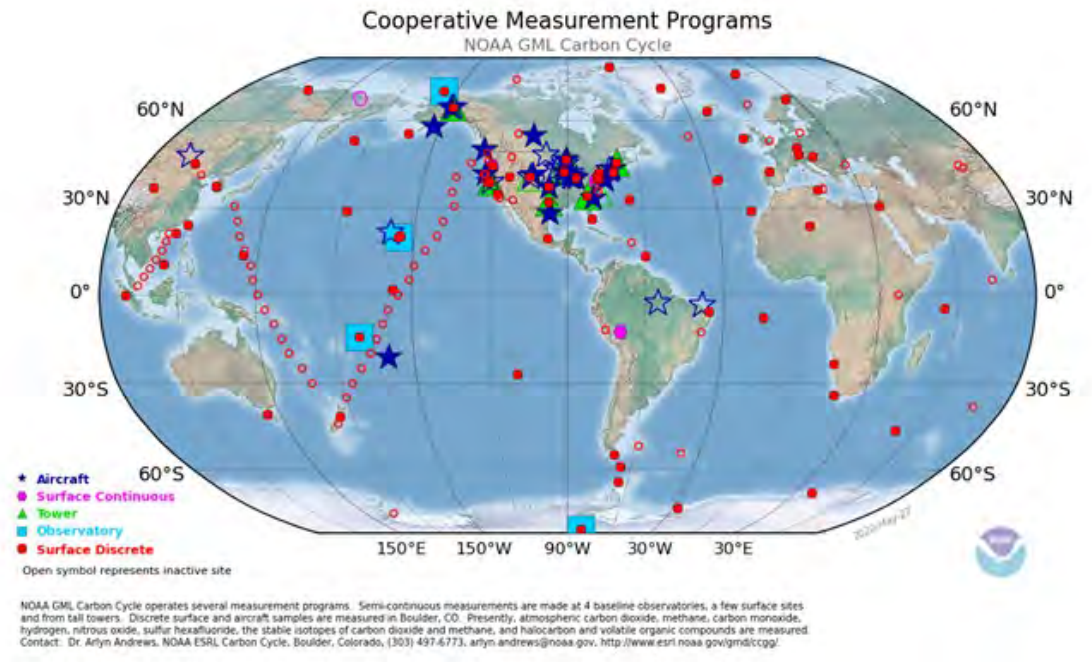

Figure 2.7 Global Monitoring Laboratory network, 2020

Source: NOAA

To understand and quantify global and regional budgets of methane and relate tropospheric measurements to individual sources, forward and inverse modelling can be used. Forward modelling converts an emission source with a certain quantity released per time into atmospheric abundance in specific locations using bottom-up estimates of emissions and sinks, as described in Section 2.1.1, along with an atmospheric transport model to simulate atmospheric methane that can be compared with observations.

Inverse modelling does the reverse where measurements of atmospheric abundance are used to calculate the location of an emission source as well as the emission rate. An inversion is a method that can be used to estimate emissions of a gas at the surface of a domain from atmospheric measurements of these gases usually in mole fractions. Most inverse models are based on Bayesian inference, in which observations are combined with bottom-up estimates (prior) resulting in estimated emissions (posterior). By using inverse modelling to evaluate bottom-up models of emissions, improvements can be made to the bottom-up models.

Though most methane data through the end of the 20th century comes from networks of ground-based and airborne *in-situ* measurements, these ways of measuring methane are generally labour intensive and, in the case of most aircraft data, because of their spatiotemporal scale, can only provide snapshots of emissions. Another limitation of these types of data is the limited spatial coverage. There is great interest in and calls for more satellite measurements of methane to overcome some of these limitations.

Though still a relatively new data source, satellite measurements of atmospheric methane have already been used to detect emission hotspots (Buchwitz *et al*. 2017; Kort *et al*. 2014; Marais *et al*. 2014; Worden *et al*. 2012), to estimate emission trends (Turner *et al*. 2016; Schneising *et al*. 2014) and to derive emissions of large basins with oil and gas extraction activities (Schneising *et al*. 2020; Zhang *et al*. 2020). They have been used in global inverse analyses to estimate emissions on regional scales (Miller *et al*. 2019; Maasakkers *et al*. 2019; Alexe *et al*. 2015; Wecht *et al*. 2014; Bergamaschi *et al*. 2013, 2009, 2007; Monteil *et al*. 2013). In December 2019, satellite data were used to quantify methane emissions from a gas well blowout in Ohio, United States in February–March 2018 (Pandey *et al*. 2019). That study, using data from the Tropospheric Monitoring Instrument (TROPOMI), demonstrated how strong and effective satellite measurements can be in detecting and quantifying methane emissions from unpredictable events. Satellite data from GHGSat and TROPOMI was also used to detect a major continuous methane leak in central Asia which had gone unnoticed (Varon *et al*. 2019).

Table 2.2 lists the types of instruments that have been used to measure methane from satellites in the recent past, along with those proposed for the coming years. Satellite missions tend to be of two types, global monitoring such as SCIAMACHY, GOSAT and TROPOMI, or mission-focused ones including GHGSat and MethaneSAT. The former have very broad spatial coverage at relatively low resolution whereas the latter are at higher resolution but are targeted at specific locations to monitor facility-scale amounts. With the rapid advancements in the ability to monitor methane emissions from space, several commercial enterprises provide or intend to provide facility-scale methane emissions information based on satellite data, either using their own instruments, such as GHGSat, Bluefield Technologies, or combining data from government-launched satellites with bottom-up information to better identify sources, Kayrros, for example.

The overall understanding of methane emissions by source is informed by both bottom-up studies and top-down inversions based on measurements. These provide complementary constraints on the methane budget and are in fairly good agreement for anthropogenic sources though bottom-up estimates for natural sources are generally much larger than top-down values (Jackson *et al*., 2020; Saunois *et al*. 2020).

INSTRUMENT OR SATELLITE	AGENCY	DATA PERIOD	REFERENCE
SCIAMACHY	ESA	2003–2012	Frankenberg *et al.* (2006)
GOSAT	JAXA	2009+	Kuze *et al.* (2016)
TROPOMI	ESA, NSO	2017+	Butz *et al.* (2012)
GHGSat	GHGSat, Inc.	2016+	Varon *et al.* (2018)
GOSAT-2	JAXA	2018+	Glumb *et al.* (2014)
geoCARB	NASA	(2022)	Polonsky *et al.* (2014)
MethaneSAT	EDF	(2022)	Benmergui (2019)
CO2M	ESA	(2025)	Meijer *et al.* (2019)
MERLIN	DLR and CNES	(2021/2022)	
Bluefield	Bluefield Technologies	(2023)	
Sentinel-5	ESA, NSO	(2023, 2030, 2037)	

Table 2.2 Satellite instruments for measuring tropospheric methane

Source: Updated from Jacob et al. (2016). Dates in parentheses are intended launches.

2.2 NATURAL SOURCES

Natural sources of methane include gas hydrates, freshwater bodies, oceans, termites and wetlands as well as other sources such as wildfires. Values for each of these are presented in Table 2.1.

Wetlands are defined as ecosystems in which soils or peats are water saturated or where surface inundation, whether permanent or not, dominates the soil biogeochemistry and determines the ecosystem species composition (US EPA 2012). Examples of wetlands are bogs, fens, marshes, muskegs, peatlands and swamps. Globally, wetlands are the largest natural source of methane with emissions, estimated at 102–200 Mt/yr on average over 2008–2017 (Jackson *et al*. 2020; Saunois *et al*. 2020) which is approximately one quarter of global methane emissions. As can be seen from the range of emissions estimates, however, there is significant uncertainty surrounding methane emissions from wetlands. Key to understanding methane emissions from wetlands are three factors that influence its production which are the spatial and temporal extent of anoxia, linked to water saturation; temperature; and substrate availability (Saunois *et al*. 2020; Wania *et al*. 2010; Whalen 2005; Valentine *et al*. 1994). Wetlands are critical to the current and future global methane budget, but currently significant gaps remain in the understanding of them (Sjögersten *et al*. 2020). Freshwaters are another significant natural source of methane, and in many cases these are similar to wetlands and, as a result, double-counting is a significant issue (Saunois *et al*. 2020).

Geological methane emissions from Earth's degassing are a major source to the atmosphere. These emissions are from gas-oil seeps, microseepage, mud volcanoes and submarine seepage in sedimentary petroleum-bearing basins and geothermal and volcanic manifestations (Etiope and Schwietzke 2019). Bottom-up estimates range from 27–63 Mt/yr, accounting for ~8 per cent of total methane sources, and most top-down estimates are consistent with this range. More recently, however, using an ice core record of the isotopic composition of methane extending back to preindustrial times, it was shown that geological sources were likely to be much lower, in the range of 1–6 Mt/yr (Hmiel *et al*. 2020). This suggests that this source may have been considerably overestimated and that anthropogenic fossil methane sources may be underestimated by a similar amount, given the relatively good constraints on the total emissions of fossil methane.

Termites are a significant source of methane and are responsible for approximately 1–3 per cent of global methane – symbiotic micro-organisms in their digestive parts of termites are responsible for this. Methane emissions from termites in studies conducted between 1982 and 2013 have, however, varied from 0.9 to 150 Mt/yr (Nauer *et al*. 2018) with the most recently reported value being 9 Mt/yr (range [3–15] Mt/yr) (Jackson *et al*. 2020; Saunois *et al*. 2020). This significant uncertainty could be due to several reasons, but the most prominent ones are:

a. lack of data on termite biomass required to upscale (Nauer *et al*. 2018); and
b. a poor understanding of methane turnover in the arboreal, epigeal or hypogeal nests (mounds) of termite colonies (Kirschke *et al*. 2013; Brune *et al*. 2010; Bignell *et al*. 1997).

As discussed in Sjögersten *et al*. (2020), research conducted in 2006–2019 by different groups provides evidence that trees may be an underestimated source of methane. Keppler *et al*. (2006) suggested that plants produce methane in aerobic conditions, and that the fluxes were 62–236 Mt/yr, or approximately 11–46 per cent of the total global methane budget (Nisbet *et al*., 2009; Keppler *et al*., 2006). It is argued that the contribution of vegetation to the methane budget is perhaps the least understood and more recent estimates give a range of methane emissions of 32–143 Mt/yr, approximately 22 per cent of the total annual methane flux (Carmichael *et al*., 2014). Significant uncertainties still remain however, in particular, much of the flux from trees occurs in wetland areas and so is already accounted for in their estimated methane flux.

The ocean is a highly uncertain but small contributor to the global methane budget, emitting 5–25 Mt/yr or 1–13 per cent of natural emissions (Saunois *et al*. 2020; Weber *et al*. 2019). Possible sources of oceanic methane include:

1. leaks from geological marine seepage;
2. production from sediments or thawing sub-sea permafrost;
3. emissions from the destabilization of marine hydrates, crystal water structures that trap methane in sediments deposited on the ocean floor;
4. *in situ* production in the water column, especially in coastal areas because of submarine groundwater discharge (Sharke *et al*. 2014; Saunois *et al*. 2012).

Venting from the seabed usually does not release methane to the atmosphere since it dissolves in the ocean before reaching the surface. There are,

however, two well-known processes that emit methane from the ocean into the atmosphere – diffusive gas transfer and ebullition or bubbling across the air–sea interface (Reeburgh 2007). Further pathways have been identified that may produce methane in the surface ocean mixed layer, providing a more direct pathway for methane to be emitted to the atmosphere (Weber *et al*. 2019; Lenhart *et al*. 2016; Karl *et al*. 2008).

As noted above, several of the natural methane sources potentially overlap with one another, especially freshwaters and wetlands. Presumably because of this, the total from adding up each individual source based on bottom-up estimates is in fact much larger than the total value estimated using top-down methods (Table 2.1). As such, this Assessment relies upon the top-down constraint for the total natural methane emissions, which leads to relative source strengths for anthropogenic and natural methane emissions of ~60 and 40 per cent, respectively. Taking into account the recent findings of Hmiel *et al.* (2020) discussed previously, the balance may be closer to two thirds and one third, however.

Natural sources can also respond to climate change, in which case a portion of the natural flux is indirectly attributable to humans. Examples include increased emissions from wetlands under a warming climate (Shindell *et al*. 2013; Gedney *et al*. 2004) and increased emissions from thawing permafrost (Oh *et al*. 2020; Dean *et al*. 2018; Cooper *et al*. 2017; Zhang *et al*. 2017; Schuur *et al*. 2015). Identified responses of natural methane emissions to climate change overwhelmingly represent positive feedbacks and may be non-linear. An example is evidence that the release of methane from thawing permafrost occurs faster as a result of abrupt rather than gradual thawing (Anthony *et al*. 2018). These feedbacks cannot be mitigated directly but can instead be reduced by the mitigation of anthropogenic methane emissions and emissions of other drivers of warming. It should also be noted that increases in emissions due to these feedbacks would increase methane's lifetime, so that the impact of each tonne of anthropogenic methane would increase slightly. Similarly, potential reductions in emissions of nitrogen oxides, offset in part by reductions in emissions of volatile organic compounds (VOCs), would also increase methane's lifetime. In either case, the benefits of each tonne of methane mitigation would be larger than those analyzed here for current conditions.



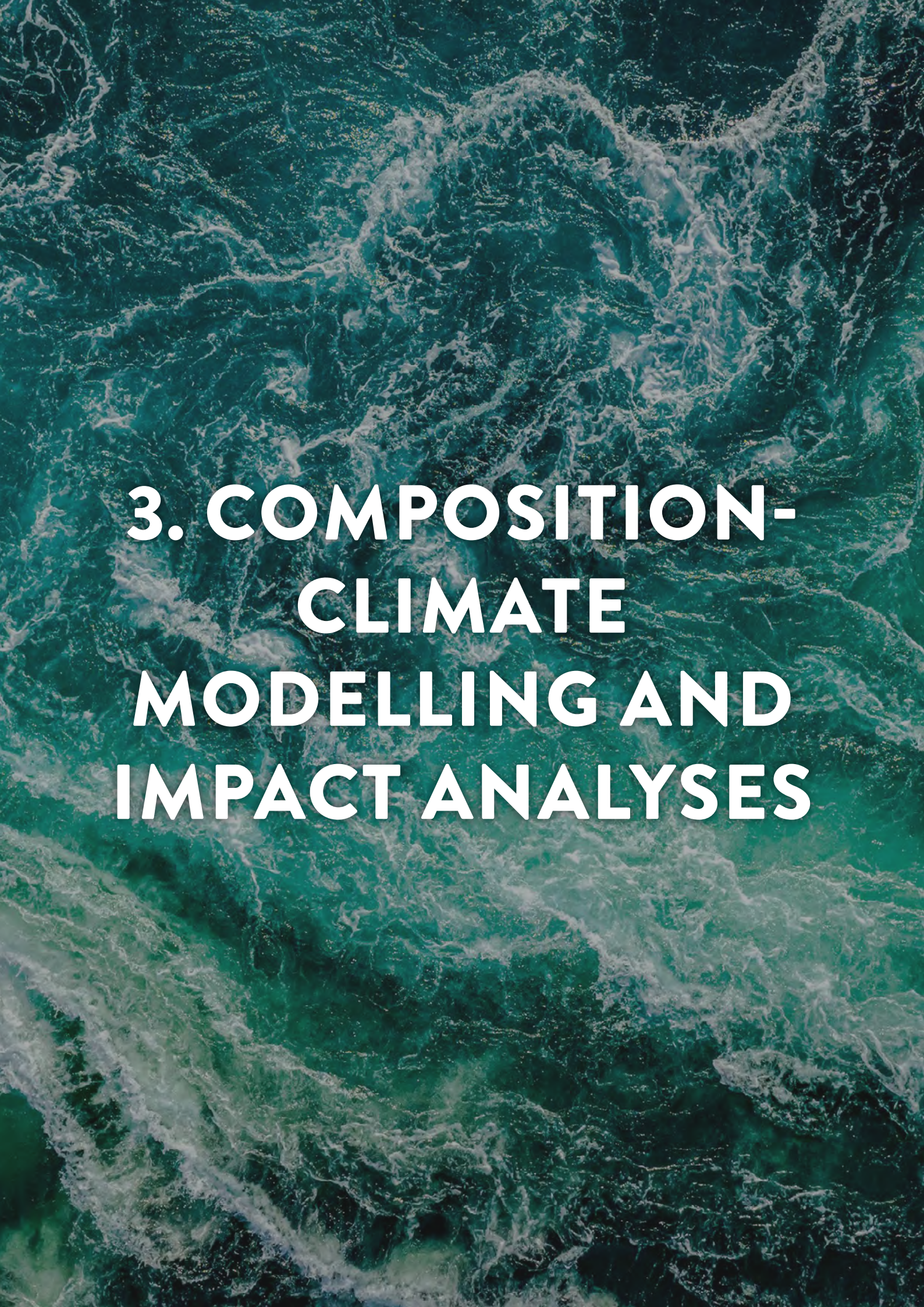

3. COMPOSITION-CLIMATE MODELLING AND IMPACT ANALYSES



CHAPTER FINDINGS

- Coordinated modelling of both composition and climate responses to methane changes was carried out for this assessment by five teams using the models developed by the National Center for Atmospheric Research (NCAR; CESM2; US); the Met Office and academia (UKESM1; UK); the National Oceanic Atmospheric Administration Geophysical Fluid Dynamics Laboratory (NOAA GFDL) (ESM4.1; US); the National Institute for Environmental Studies (NIES), University of Tokyo and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (MIROC: Japan); and the National Aeronautics and Space Administration (NASA) (GISS E2.1; US). This provides improved characterization of responses of ozone and climate and their uncertainties.
- Based upon recently updated epidemiological results, the new modelling indicates that there are 1 430 (670–2 110; 95 per cent confidence interval) premature deaths due to ozone in response to each million tonne of methane emitted, a value considerably higher than prior estimates. Of those, 740 (460–990; 95 per cent confidence interval) are caused by respiratory problems 690 (210–1 120; 95 per cent confidence interval) by cardiovascular ones.
- Roughly 30 per cent of these premature deaths are of people aged less than 70, and just more than 10 per cent of those aged less than 60.
- At the national level, the largest total numbers of premature deaths are in India, China, the US, Russia, and Japan, whereas the largest per person impacts are in Ukraine, Lesotho, Egypt, Georgia and the Democratic People's Republic of Korea.
- There are ~125 (60–185; 95 per cent confidence interval) premature deaths due to heat exposure in China and the United States together per million tonnes of methane emitted, and perhaps ~500 worldwide, though confidence is low for the global values.
- There are approximately 4 000 asthma-related accident and emergency department (A&E) visits and 90 hospitalizations per million tonnes of methane emitted.
- Roughly 300 (210–390; per cent confidence interval) million hours of work are lost globally due to heat per million tonnes of methane emitted.
- 145 (90–200) kilotonnes (kt) of wheat, soybeans, maize and rice are lost per million tonnes of methane emitted. The largest impacts are in Brazil, China, India and the US.
- Mortality impacts are valued at ~US$ 3 200 per tonne of methane using an income elasticity of 1.0 across countries and ~US$ 6 700 using an elasticity of 0.4, both undiscounted.



- **Quantified market costs are comparatively small at ~US$ 122/tonne and stem predominantly from agricultural yield changes, and labour and forestry losses.**
- **The total valuation per tonne of methane is ~US$ 4 300 using a cross-nation income elasticity of 1.0 and US$ 7 900 using an elasticity of 0.4. Valuation is dominated by the effects of ozone, which are only weakly sensitive to discounting, and thus the total valuation does not strongly depend upon the relative weighting of impacts occurring at different times in the future.**
- **Uncertainties in health- or agriculture-related ozone metrics are roughly 25 per cent (95 per cent confidence interval) at the global level whereas for surface temperature response they are ~55 per cent. Responses are nearly linearly proportional to the methane change.**

Modelling was undertaken using five state-of-the art global composition-climate models that evaluate both the changes in surface ozone concentrations and in the Earth's climate system in response to methane reductions. This coordinated comparison allows the investigation of the potential of reducing warming and the impacts associated with ozone formation by decreasing methane emissions, and the characterization of the robustness of these responses.

3.1 EXPERIMENTAL SETUP

The modelling focused on the response to 50 per cent reductions in the anthropogenic increase in methane amounts. A 50 per cent value was chosen as it is large enough to give a clear signal over meteorological noise in the models and is similar in magnitude to what the worldwide application of existing best targeted practices could potentially achieve (Chapter 4). Based on observations reported by NOAA's Earth System Research Laboratory, the 2015 mixing ratio of methane was 1 834 parts per billion by volume (ppbv). Ice core data indicate that the value in 1750 was about 722 ppbv, hence the anthropogenic increase is 1 112 ppbv. A 50 per cent reduction in that increase would therefore lower amounts by 556 ppbv, so that the atmospheric abundance would then be 1 278 ppbv.

The response is evaluated under present day (2015) conditions and for two sets of 2050 emissions following a reference SSP3-7.0 and short-lived climate pollutant control scenarios developed previously by the Asia-Pacific Integrated Model (AIM) group for other pollutants that affect oxidation capacity (Table 3.1; simulations 1–6). The latter cases follow the harmonized Shared Socio-economic Pathway 3 (SSP3) markerscenarios for the baseline (SSP3-7.0) and short-lived climate pollutant controls (SSP3-7.0_lowNTCF) (Fujimori *et al*. 2017). These 2050 cases, with high and low emissions of the non-methane ozone precursors nitrogen oxides, carbon monoxide (CO) and non-methane volatile organic compounds (NMVOCs) (Figure 3.1), are designed to provide information about the sensitivity of the response to methane under most conditions that are likely to be encountered over the next few decades, potentially allowing interpolation of methane responses to any given set of emissions projections. Note that biomass burning emissions were not changed in these simulations.

Aerosol and aerosol precursor emissions increase under the reference SSP3-7.0 case in 2050, but these are unlikely to substantially affect methane. One model performed additional simulations with a 25 per cent decrease and 50 per cent increase in methane to test the linearity of the response (Table 3.1; simulations 7 and 8). Anthropogenic and biomass burning emissions are from the SSP3 dataset produced in support of CMIP6 and the IPCC AR6 cycle assessments. For consistency with 2050 projections, 2015 emissions are taken from the same SSP dataset which has been harmonized to 2015 historical emissions reported by the Community Emissions Data System (CEDS) project (v2017-05-08).

Five state-of-the-art composition-climate models participated in the assessment: the CESM2(WACCM6) model developed at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, US (Danabasoglu *et al*. 2020; Gettelman *et al*. 2020); the GFDL AM4.1/ESM4.1 (Horowitz *et al*. 2020; Dunne *et al*. 2019) model developed by NOAA in Princeton, New Jersey, US; the Goddard Institute of Space Studies (GISS) E2.1/E2.1-G model developed by the NASA in New York, New York, US (Gillet *et al*. 2021; Kelley *et al*. 2020); the MIROC-CHASER model developed jointly by the Atmosphere and Ocean Research Institute, the University of Tokyo, Kashiwa, the National Institute for Environmental Studies (NIES), Tsukuba, the Japan Agency for Marine-Earth Science and Technology, Yokohama, and Nagoya University, Nagoya, Japan (Sekiya *et al*., 2018; Watanabe *et al*. 2011; Sudo *et al*. 2002); and the UKESM1 model developed jointly by the Met Office, Exeter, UK, and the United Kingdom's academic community (Archibald *et al*. 2019; Sellar *et al*. 2019).

To reduce the burden imposed by running these very computationally expensive models, only a single pair of simulations were run with coupled (i.e. responsive) ocean and sea-ice (denoted C1 and C2, with the C indicating coupled). Those runs of 40–45 years length are used to assess climate response to methane reductions. Other runs examining the sensitivity of the ozone response to methane changes were performed in a configuration with fixed ocean boundary conditions and, in most models, with fixed meteorology and were therefore only run from 1–7 years. These shorter simulations include a repeat of the base C1 and C2 simulations in this configuration to assess the impacts of the different experimental setup. Again, for the sake of reduced computational expense, the simulations were amount-driven, with conversion to per million tonne emissions performed afterwards (Section 4.1).

SIMULATION #	METHANE [PPB]	MODELS	CONFIGURATION	ANTHROPOGENIC EMISSIONS	
				CO, NO_x, NMVOC [year]	BC, OC, NH_3, SO_2 [year]
1	1 834	CESM2, GFDL AM4.1, GISS E2.1, MIROC-CHASER, UKESM1	Fixed sea surface Temperatures/sea ice, fixed meteorology	2015	2015
2	1 278				
3	1 834			SSP3-7.0 2050	SSP3-7.0 2050
4	1 278				
5	1 834			SSP3-7.0_lowNTCF 2050	
6	1 278				
7	1 556	GISS E2.1		2015	2015
8	2 390				
C1	1 834	CESM2, GFDL ESM4.1, GISS E2.1-G	Coupled ocean and sea ice	2015	2015
C2	1 278			2015	2015

Table 3.1 Simulations performed for this assessment

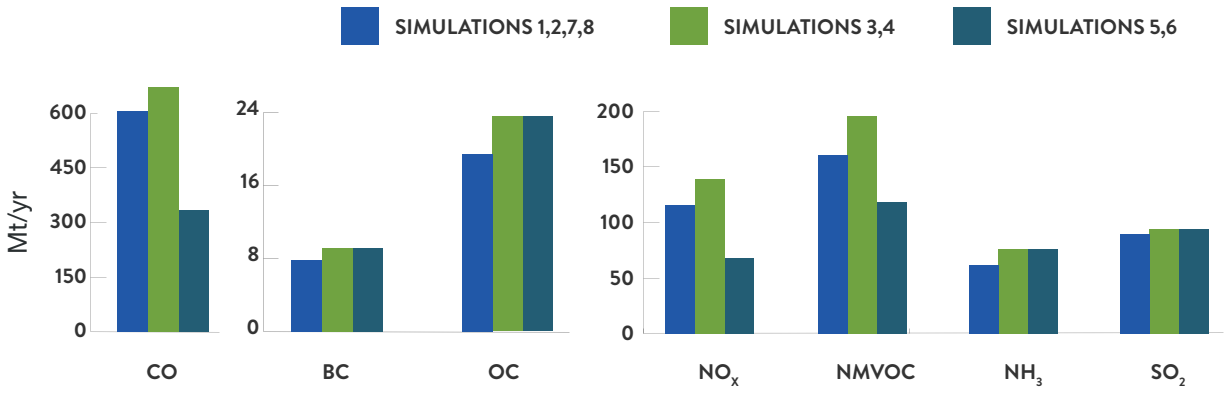

Figure 3.1 Global anthropogenic emissions used in this analysis, million tonnes per year

Note: Simulations C1 and C2 used the emissions shown here for simulations 1 and 2, respectively. Emissions for simulations 1, 2, 7 and 8 are from 2015; emissions for simulations 3 and 4 are from SSP3-7.0 for 2050; and emissions for simulations 5 and 6 are from SSP3-7.0_lowNTCF for ozone precursors and SSP3-7.0 for aerosols, both for 2050 (Table 3.1).

Source: UNEP and CCAC based on Fujimori et al. 2017.

3.2 MODELLED OZONE RESPONSE TO METHANE EMISSIONS CHANGES

Initially, the ozone response under present-day (2015) atmospheric conditions (simulations 1 and 2) was examined. Reducing anthropogenic concentrations by 50 per cent in this case led to a reduction in the global area-weighted annual average surface ozone of ~1.5–2 ppbv. Though a small number, the reduction is larger in the northern than the southern hemisphere and tends to be greatest over land areas where methane catalyzes ozone production more efficiently than over the oceans owing to the presence of anthropogenic nitrogen oxides. Hence the global population-weighted exposure change is ~2–2.5 ppbv. More relevant to human health is the maximum daily 8-hour exposure averaged over the year (MDA8), which is the metric most closely linked to increases in premature deaths from ozone in one of the largest epidemiological studies to date (Turner *et al*. 2016). Changes in this metric have been calculated for all individual models as well as for the multi-model mean (MMM) (Figure 3.2). Changes in this metric are between 2–5 ppbv over much of the northern hemisphere tropical and sub-tropical latitudes. The GFDL AM4.1, GISS E2.1 and CESM2 models are generally quite similar to one another, with the UKESM1 model showing substantially larger responses than those three and the MIROC-CHASER model showing substantially weaker responses.

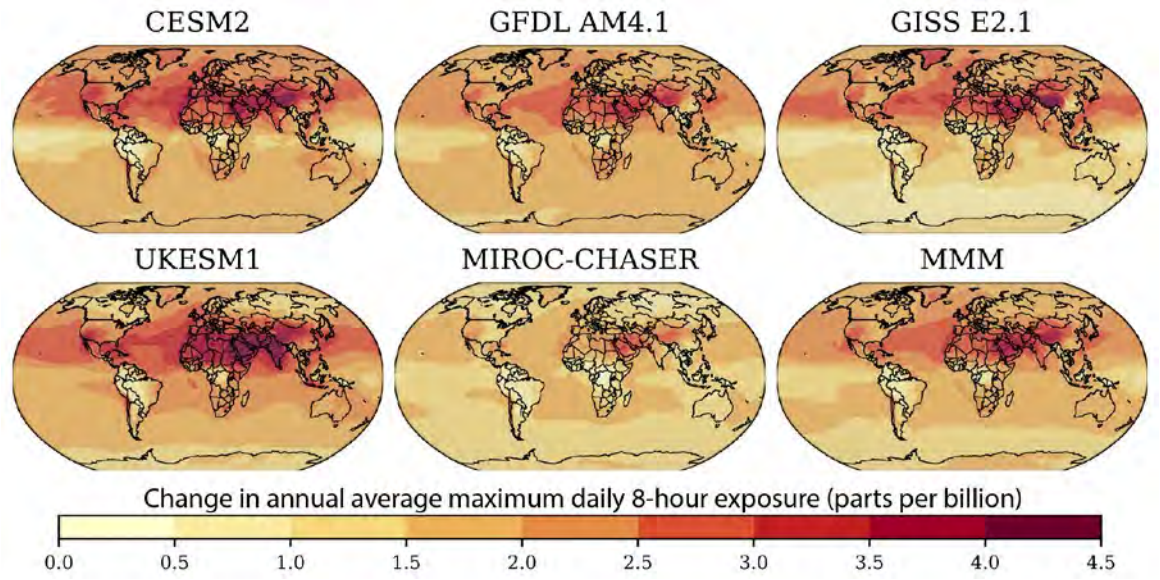

Figure 3.2 Change in annual average maximum daily 8-hour ozone exposure between the present day (2015) and half anthropogenic methane simulations in various models and the multi-model mean (MMM)

Source: UNEP and CCAC

Exploring the sensitivity of the ozone response to the background loading of other pollutants (simulations 1–6), there is a clear dependence of the response on the loading of nitrogen oxides. Throughout the world, the ozone response is larger when methane is altered within a background atmosphere containing higher levels of nitrogen oxides. The sensitivity varies substantially from place to place depending on other factors influencing ozone photochemistry, including the availability of sunlight and of other hydrocarbons or carbon monoxide that can play the same role as methane. Despite the complexity, it appears that this dependence can be represented by a fairly simple logarithmic equation that captures ozone sensitivity to background nitrogen oxide conditions (Figure 3.3). Sensitivity to other pollutants is markedly weaker. This indicates that the dependence of ozone's response to methane on background nitrogen oxides can readily be captured in policy-support tools to allow the estimation of the impacts of changes in methane emissions in any plausible near-future condition. This should provide accurate results for fairly large nations, for which domestic methane emissions dominate nitrogen oxides, and of course requires projected nitrogen oxides emissions levels.

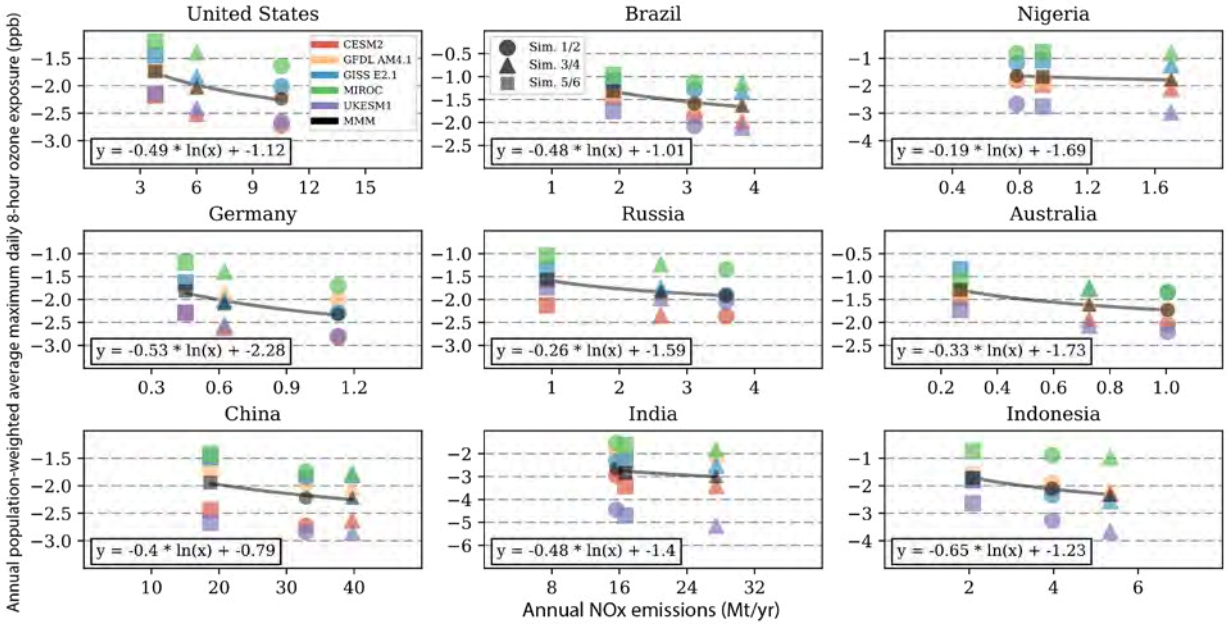

Figure 3.3 Country specific response of annual population-weighted average maximum daily 8-hour ozone exposure due to a 50 per cent reduction in global methane concentrations, parts per billion

Note: The x axis is the country specific anthropogenic land emissions of nitrogen oxides from each simulation pairing. The line is a logarithmic function for the multi-model mean, with the country specific equation displayed in each panel.

Source: UNEP and CCAC

Next, the linearity of the response to different magnitudes of methane concentration change was examined. At the national level, population-weighted ozone changes are extremely linear across a range of methane increases and decreases (Figure 3.4). Though the response itself varies from country to country (i.e. the slopes are different), the ozone change at the national level is directly proportional to the methane concentration change regardless of the ozone metric chosen. This result is consistent with prior studies which also indicate that the ozone/methane relationship is approximately linear (Fiore *et al*. 2008) but its magnitude depends on the local availability of nitrogen oxides, and, through nitrogen oxides, of hydroxyl (West *et al*. 2006; Wang and Jacob 1998).

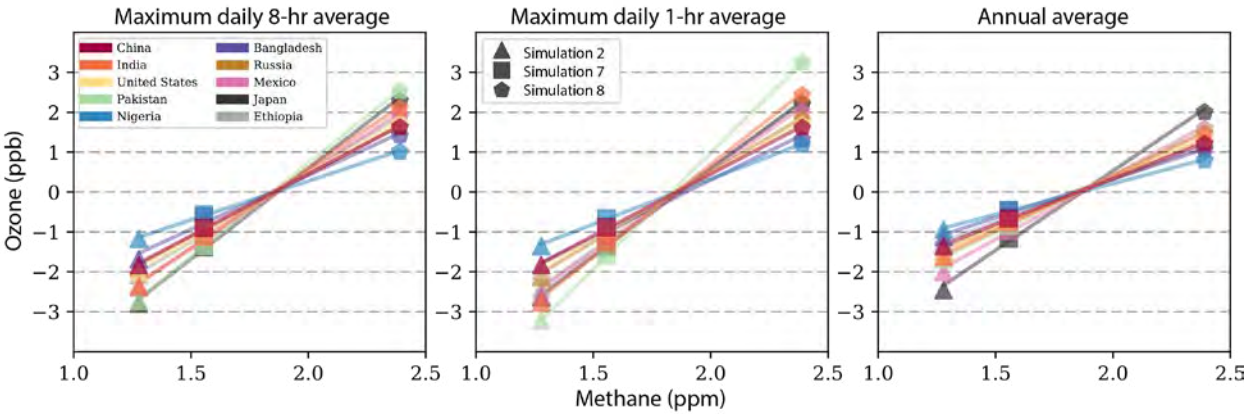

Figure 3.4 Relationship between changing global methane concentrations and the country-level population-weighted ozone metric (parts per billion), with non-methane ozone precursor emissions (carbon dioxide non-methane volatile organic compounds and nitrogen oxides held at 2015 levels (simulations 1, 2, 7 and 8 in Table 3.1)

Note: All results are from the GISS E2.1 model and are plotted as ozone changes relative to the metric values from simulation 1 ([methane] = 1.834 parts per million). The selected countries are the 10 most populous in the northern hemisphere.

Source: UNEP and CCAC

Given that the ozone response to methane concentrations changes is quite linear with the change in methane itself, the response of ozone was converted into the response per unit of methane emission change. For this analysis, the response of methane concentrations per unit methane emission change was first calculated, using the relationship between methane concentrations and emissions derived in prior work (Fiore *et al*., 2008):

$$\frac{C'}{C} = \left(\frac{E'}{E}\right)^{f}$$

where C and C' are initial and perturbed concentrations, E and E' are initial and perturbed emissions, and f is the feedback factor defined as the ratio of the perturbation lifetime to the total atmospheric lifetime. As in Myhre *et al*. (2013), f=1.34 was used and set total present-day annual methane emissions at 568 Mt (Saunois *et al*. 2016). Based on the simulations using values of 1 834 and 1 278 for C and C', E' is found to be 434 Mt/yr. Hence the concentration change between simulations 1 and 2 corresponds to emissions changes of 134 Mt/yr, so that the methane response to emissions changes is 4.1 ppb CH_4/Mt CH_4. Note that using total present-day methane emissions from another estimate would modestly affect this result. For example, using the 550 Mt/yr estimate of Kirschke *et al*. (2013) would lead to emissions changes of 130 Mt/yr in simulations 1 versus 2.

The interannual variability of national and global population-weighted annual MDA8 differences were evaluated between runs 1 and 2 over three years of simulation for the four models with multiple years of simulations, except MIROC-CHASER. At the global level, the standard deviation based on interannual variability driven by year-to-year differences in meteorology for these ozone responses were 8.8, 5.3, 1.0 and 7.6 per cent respectively for CESM2, GFDL AM4.1, GISS E2.1, and UKESM1. Values were even smaller for MDA1. In comparison, the 95 per cent confidence interval, based on the variation across models in the global population-weighted MDA8, was 24 per cent. Values at the national scale showed a similar range, except for some small countries, and were still small in comparison with national level variations between modes. Hence it appears that variability within a model in the fixed Sea Surface Temperature/meteorology setup is relatively small, and hereafter only model-to-model variability is incorporated along with uncertainty in the exposure-response functions in the uncertainty analysis as this provides a good representation of the total. This analysis also supports the inclusion of the MIROC-CHASER single year simulations in this multi-model assessment.

The effect of the model setup on the ozone response was also examined by comparing the changes in the coupled model simulations with those in the simulations with fixed boundary conditions – sea surface temperatures and sea ice, along with meteorology in some models. Again, examining the global population-weighted annual MDA8, the differences between the 50 per cent anthropogenic methane reduction runs including climate (C1 and C2) were found to be very similar to those for the analogous runs without a climate response (simulations 1 and 2). Specifically, responses in the coupled model version were 3 per cent smaller for GFDL, 7 per cent smaller for GISS, and 1 per cent larger for CESM. As in the previous analysis, variability in CESM is largest, but overall there was minimal difference in the response over time in these long simulations. For example, differences in ozone responses over the last 10 years of those simulations were typically within 3 per cent of those in the first 10 years. Variations in response due to setup, as with interannual variability, were similar at the national scale except for some small countries.

3.3 MODELLED CLIMATE RESPONSE TO METHANE EMISSIONS CHANGES

Three of the five participating models were able to complete the long climate simulations, C1 and C2 described in Section 3.1. The response of these three were evaluated separately and for the multi-model mean. Statistical significance was assessed at the grid-point level by evaluating the standard deviation across individual years of model output – years 11–40 in each model's simulation. Temporal autocorrelation was accounted for at each grid point by reducing the sample size to represent an effective number of independent data points, based on the lag-1 autocorrelation (Zwiers and Von Storch 1995). For the multi-model mean, this measure thus includes both variations across the three models and internal variability within the physical climate system as represented by each individual model and has been shown to give reliable statistical ranges for sample sizes larger than about 50, well below the sample size used of 90 (Conley et al., 2018). For zonal and global mean values, statistical significance was assessed

by examining the variability between models in the long-term average surface temperature response. Though atmospheric composition will have largely equilibrated to the perturbed methane within a decade in these experiments, the climate system takes much longer to fully respond. These results thus represent a partial adjustment, as noted averaged over one to three decades following the methane change. To explore this topic further, the GISS E2.1 simulations C1 and C2 were extended by an additional 40 years. Whereas the global mean surface temperature response during years 11–40 was 0.20 ± 0.05° C, the response during the next 40 years was 35 per cent larger with a value of 0.27 ± 0.04° C (total response over years 41–80). This suggests that the evaluation of temperature responses provides a good indication of the near-term impact of methane changes, but that the longer-term changes would be on the order of 35 per cent larger, consistent with the slow response time of the ocean. It is noted also that none of these simulations include either the effect of carbon dioxide produced from methane oxidation or the response of the carbon cycle to methane-induced warming. The former is estimated to add ~2 per cent to the total radiative forcing from methane (Myhre et al. 2013). The latter occurs as the warming induced by methane emissions suppresses carbon uptake, further enhancing the temperature change attributable to methane by ~10 per cent and extending its impact at long timescales (Fu et al. 2020; Gasser et al. 2017).

The results for surface temperature show that methane emissions, which lead to increases in methane, tropospheric ozone and stratospheric water vapour, cause clear and consistent zonal mean, averaged over longitudes, warming over most of the Earth during most seasons (Table 3.2 and Figure 3.5). Impacts are particularly large over the mid-latitudes of the northern hemisphere and especially over the Arctic. The models were most consistent in the response in the tropics. There is substantial variation across the models in the annual mean surface temperature response in the southern hemisphere extratropics, however, especially over the Southern Ocean, and even in parts of the northern hemisphere – eastern Siberia/ Alaska and parts of eastern Europe – when looking at the regional scale. It was noted that the sample size was very small in this analysis with just three models participating, and hence the uncertainty in a quantity, such as the annual global mean surface temperature change over the 11–40-year period following emissions changes, is likely smaller than a broader sampling of models would yield for at least some globally or zonally averaged results. In particular, the 95 per cent confidence interval in climate sensitivity is estimated to be approximately ±34 per cent (Sherwood et al., 2020), which translates into a 95 per cent confidence interval for the global mean annual average surface temperature response to a methane change of ±0.06° C (34 per cent of 0.18° C) rather than the ±0.02° C in this analysis. It is recommended the larger uncertainty range, ~34 per cent relative uncertainty, is used in impact calculations going forward.

Within the tropics, 30° S–30° N, the models give very similar zonal mean responses (Table 3.2 and Figure 3.5). All suggest that warming over the Pacific is less uniform than warming over the Atlantic or especially the Indian Ocean basins (Figure 3.6). Warming over tropical land areas shows fairly good agreement across models except over southernmost Africa. In contrast, the consistently enhanced warming in the Arctic is distributed differently in the three models. It thus becomes difficult to precisely quantify climate responses at national or even continental scales over many parts of the world.

At seasonal timescales, the models are less consistent over northern hemisphere mid-latitude continental areas during boreal winter than other seasons, as expected due to the greater influence of dynamic relative to thermodynamic response in that season (Table 3.2 and Figure 3.7). In the Arctic, however, the models show both stronger and more consistent responses during boreal winter/spring than summer/autumn. Responses in the tropics and southern hemisphere mid-latitudes are quite similar across all seasons. In the Antarctic, there is a high degree of variation across the models in both austral autumn and winter seasons. Seasonal values are often more variable at smaller spatial scales but are nonetheless robust for many large nations such as the Australia, Brazil or the United States, or for some seasons (Figure A1). There is little robust response in precipitation at the local scale (Figure A2) or at the zonal mean scale.

A large body of prior literature has shown that the global mean surface temperature response to well-mixed greenhouse gases scales fairly linearly with the applied forcing (Collins *et al*. 2013; Hansen et al., 2005). Although the response to methane emissions is not exclusively driven by the well-mixed gas methane, roughly three quarters of the forcing comes from non-ozone quasi-uniform forcing, due to methane,

stratospheric water and carbon dioxide; all well-mixed greenhouse gases, and hence it is assumed hereafter that it is a reasonable approximation to scale climate impacts by the methane emission change in a given case relative to that applied in this analysis' modelling.

Although changes in methane forcing are also not perfectly linear with changes in emissions or concentrations, these non-linearities are relatively weak. Furthermore, the non-linearity of forcing relative to concentrations tends to offset the non-linearity in the concentration response to emissions, so that the response of forcing to emissions is closer to linear than either of those relationships. A reduction of one quarter in the concentration, for example, causes 48 per cent as much forcing as reducing the concentration by half rather than the 50 per cent one would obtain with a linear change. Similarly, a reduction in emissions of half the value used in simulations 1 versus 2 yields a concentration change, using the equation given in Section 3.2, that is 51 per cent as large as that in the simulations, again close to the linear value of 50 per cent. Combining these, a reduction in emissions of half the value used in the simulations hence leads to almost exactly half the forcing used in the simulations.

AREA	ANNUAL	DEC-FEB	MAR-MAY	JUN-AUG	SEP-NOV
Global	0.18 (0.02)	0.19 (0.02)	0.18 (0.04)	0.17 (0.03)	0.17 (0.03)
60° N–90° N	0.28 (0.05)	0.56 (0.08)	0.31 (0.22)	0.07 (0.01)	0.19 (0.19)
30° N–60° N	0.22 (0.10)	0.19 (0.09)	0.19 (0.15)	0.25 (0.09)	0.26 (0.07)
30° S–30° N	0.16 (0.02)	0.16 (0.02)	0.16 (0.03)	0.16 (0.03)	0.18 (0.04)
60° S–30° S	0.12 (0.12)	0.13 (0.11)	0.12 (0.02)	0.11 (0.13)	0.12 (0.09)
90° S–60° S	0.19 (0.11)	0.20 (0.09)	0.29 (0.12)	0.24 (0.24)	0.05 (0.22)

Table 3.2. Multi-model mean area-weighted zonal mean temperature response (°C) to the methane increase from one-half present methane to present value, along with the ozone and stratospheric water vapour responses to that methane increase.

Note: values in parentheses are the 95 per cent confidence interval based on the model-to-model variations, with results in bold statistically significant. These values are responses averaged over one to three decades after emissions changes. Values over the subsequent four decades are ~35 per cent larger and values including carbon cycles feedbacks are ~10 per cent larger, as discussed.

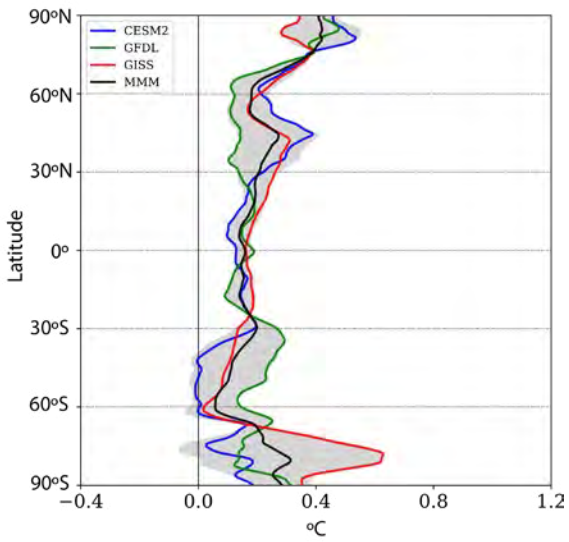

Figure 3.5 Zonal mean annual average temperature response to methane increases from one-half present methane to present value, along with the ozone and stratospheric water vapour responses to that methane increase, degrees centigrade

Note: Shaded area indicated 95 per cent confidence interval based on the three models.

Source: UNEP and CCAC

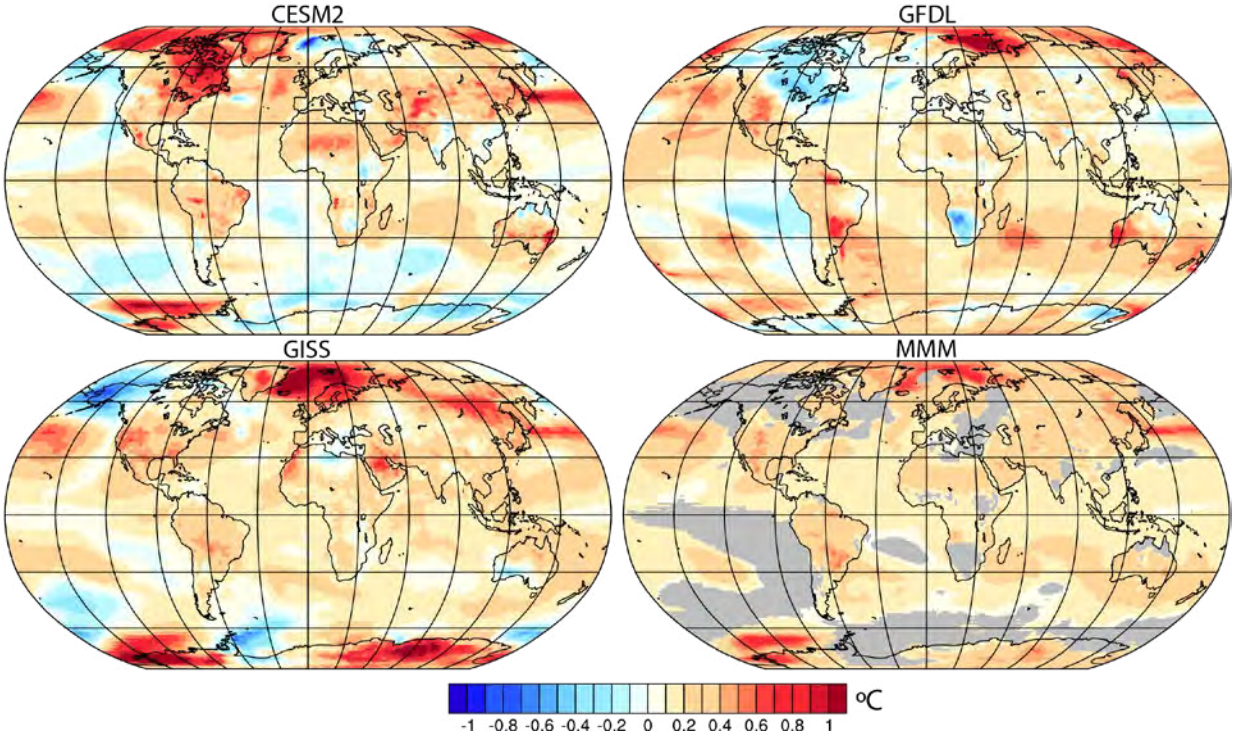

Figure 3.6 Annual average temperature response to methane increases from one-half present methane to present value along with the ozone and stratospheric water vapor responses to that methane increase, degrees centigrade

Note: The multi-model mean (lower right) only includes values for areas in which the value is statistically significant. Non-statistically significant areas are shown in grey.

Source: UNEP and CCAC

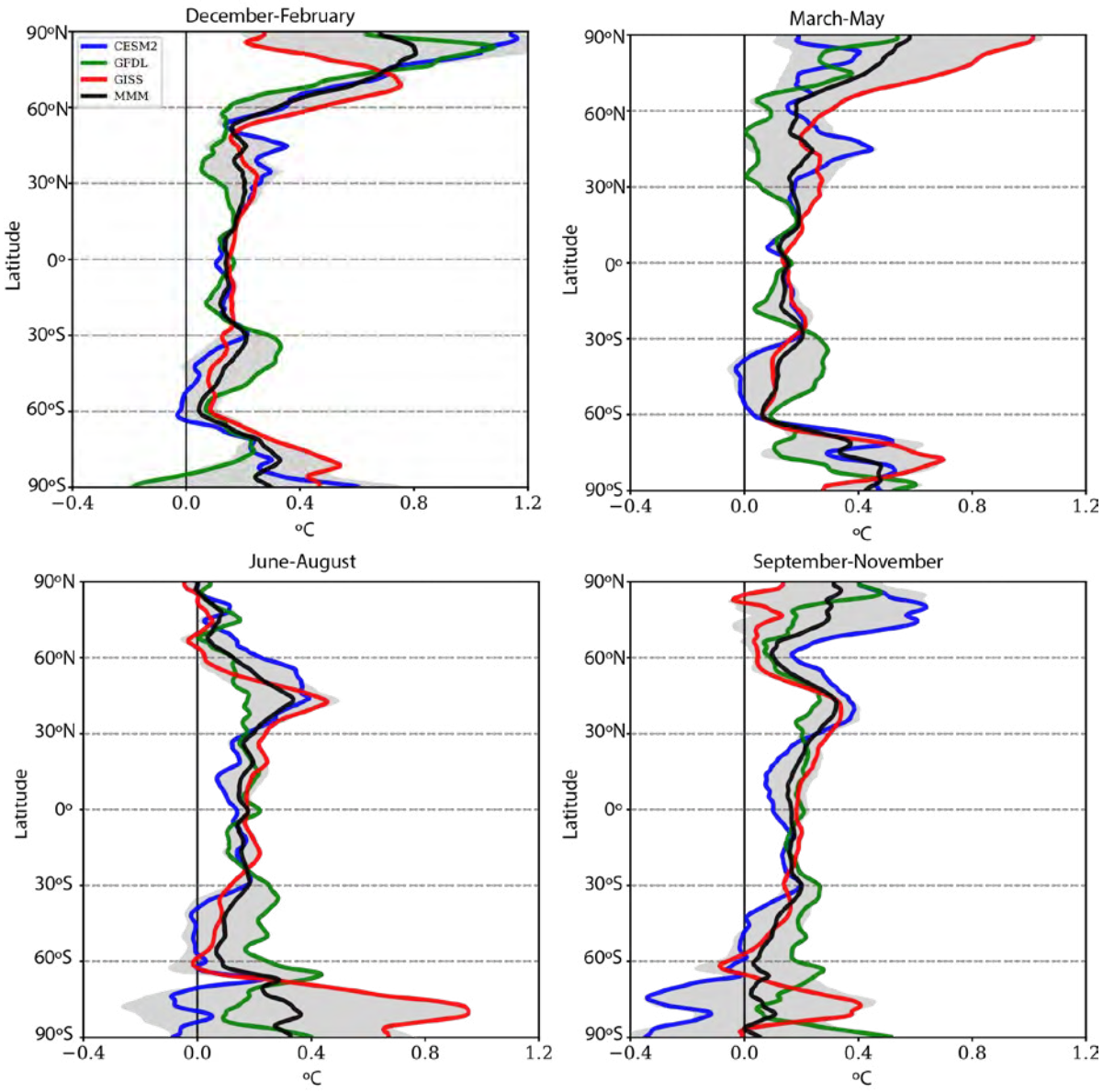

Figure 3.7 Seasonal zonal mean annual average temperature response to methane increases from one-half present methane to present value, along with the ozone and stratospheric water vapor responses to that methane increase, degrees centigrade

Note: Shaded area indicated 95 per cent confidence interval based on the three models.

Source: UNEP and CCAC

3.4 HUMAN HEALTH IMPACTS: METHODS AND RESULTS

Both climate and ozone responses to methane can affect human health through multiple pathways. The relationship between ozone exposure and respiratory mortality and morbidity is well-established. Cardiovascular impacts from ozone exposure have also been identified. Climate change can affect human health in many ways, including the spread of vector- and water-borne diseases, undernutrition and food safety and security-related illnesses, and exposure to weather extremes such as heatwaves, floods and storms. The focus here is on the current impacts and projected risks of changing exposure to high ambient temperatures as this is the best quantified climate-related health impact.

In addition to the ozone and surface temperature related impacts on human health quantified here, other impacts from changes in methane emissions are likely to exist but are not analyzed in this assessment. Changes in stratospheric ozone attributable to methane emissions, for example, could affect human and ecosystem health by altering the flux of ultraviolet (UV) radiation reaching the surface. Policy changes that affect methane emissions could also have indirect effects on well-being. Fuel switching away from natural gas, for example, could reduce injuries related to pipelines. From January 2010 to November 2018, fossil fuel pipelines in the United States are estimated to have resulted in more than 5 500 accidents, with effects including 800 fires, 300 explosions, 600 injuries and 125 fatalities according to an analysis of data from the Pipeline and Hazardous Materials Safety Administration (Kelso 2018). Other potential ways of reducing methane emissions, such as transitioning to healthier diets in areas where consumption of cattle-based products is above recommended guidelines, could have profound health benefits (Springmann *et al*. 2016). Hence the effects reported here are likely to represent a conservative estimate of the overall health impacts of methane emissions or policy/behavioural changes that could lead to methane emissions reductions.

3.4.1 OZONE-RELATED MORTALITY

What are the impacts of ozone and heat exposure on human mortality? Long-term exposure to ozone can cause inflammation and allergic responses leading to respiratory mortality, as well as the development of a systemic oxidative, proinflammatory environment that can increase the risk of cardiovascular diseases. This analysis of the impacts of ozone exposure on premature death is based on the responses reported in one of the largest studies to date that uses the American Cancer Society Cancer Prevention Study-II (ACS CPS-II) cohort (Turner *et al*. 2016). which calculated cause-specific deaths attributable to incremental changes in MDA8 using a version of this cohort that spans 22 years of follow-up and included 669 046 subjects of whom 237 201 died. Here these results are used globally, implicitly assuming that these long-term ozone exposure-response relationships are homogeneous across populations. While there is evidence from other cohort studies in Canada (Crouse et al. 2015) and in the United States, including a cohort of ~61 million elderly people (Di et al. 2017), showing a significant relationship between long-term, seasonal to annual, ozone exposure and premature mortality, none of the smaller cohort studies conducted in European countries have reported a statistically significant relationship between ozone and mortality (Bentayeb et al. 2015; Carey et al. 2013,). This may be due to differences in study design, for example, the study of the French cohort (Bentayeb et al. 2015) has a 95 per cent confidence interval that is more than an order of magnitude larger than other studies, such as exposure estimation methods, length of follow-up and number of events (Jerrett et al. 2013). No studies are available for Africa, Asia, Australia or South America.

Premature mortality attributable to long-term ozone exposure is calculated using well-established methods (Malley *et al*. 2017; Anenberg *et al*. 2010), as described in the equations below.

$$\Delta X = \begin{cases} 0 & if\ [O_3] \le TMREL \\ [O_3] - TMREL & if\ [O_3] > TMREL \end{cases}$$

$$AF = 1 - exp^{-\beta\Delta X}$$

$$\Delta Mort = y_0 \times AF \times Population$$

where TMREL is the theoretical minimum risk exposure level (i.e. the counterfactual) in parts per billion by volume, ΔX is the ozone exposure in a particular grid box above the TMREL, β is the exposure-response function – i.e. the slope of the log-linear relationship between the change in exposure and mortality from the epidemiological study, AF is the attributable fraction of the disease burden related to long-term ozone exposure, y0 is the cause-specific baseline mortality rate, population is the population count in a particular grid box of people aged

30 years or older, and ΔMort is the estimated number of premature, cause-specific mortalities attributable to exposure to ozone levels above TMREL. Note that TMREL is set simply as the minimum ozone exposure reported in the epidemiological study, in this case 26.7 ppbv for the annual maximum daily 8-hour average. There is no compelling evidence that exposure to levels lower than those at which data is available is safe, however. Hence this aspect of the method is a conservative one.

Though the exposure-response function is uniform worldwide, geographic variation in age-binned values of both population and baseline mortality rates is included. Population statistics from the United Nations Population Division for each country[8] for the year 2015 are distributed to grids using population density data from the Gridded Population of the World (GPW) version 4 (CIESIN 2016). Baseline mortality rates, which are the ratio of total deaths within a particular age bin due to a particular cause, such as respiratory deaths, to the total population in a particular age bin, were derived by the Global Burden of Disease (GBD) project (GBD 2017) for each country of the world and the values for 2015 were used for consistency with the population dataset. Global Burden of Disease baseline mortality rates were mapped to best match the current International Classification of Diseases (ICD) codes for respiratory and cardiovascular disease related deaths (respectively ICD-10 Codes: J00-J98; GBD Codes: B.3, A.2.3, A.2.4, and ICD-10 Codes: I20-I25, I30-I51, I60-I69, I70; GBD Codes: B.2.2, B.2.3, B.2.8, B.2.9, B.2.10) for which significant impacts were found in the epidemiological study (Turner *et al*., 2016). In addition to this primary analysis based upon 2015 population and baseline mortality, an analysis focused on the year 2030 was also performed to explore how the benefits of future policies might compare to those from changes in the recent past or present. Projections for 2030 baseline mortality rates are obtained from the International Futures project version 7.53 (International Futures 2020) for respiratory and cardiovascular deaths by age group. Population projections for 2030 were taken from SSP2 though these are fairly similar across the shared socioeconomic pathways at this date (KC and Lutz 2017). The geographic distribution of population is unchanged in the 2030 analysis, so too is the age distribution of the population – only population totals are projected under the shared socioeconomic pathways.

Note that a statistically significant impact on deaths associated with diabetes was also reported but resulted in few total deaths and is not included here. Cause-specific risk increases per 10 ppbv were 1.12 (1.08–1.16; 95 per cent confidence interval) for respiratory diseases and 1.03 (1.01–1.05; 95 per cent confidence interval) for cardiovascular diseases based on the two-pollutant model, accounting for exposure to fine particulate matter, of the epidemiological study (Turner *et al*. 2016). All impacts reported here are based on ozone responses to sustained (rather than pulse) methane emission changes.

Overall, in the primary analysis for 2015 conditions, the 50 per cent reduction in methane leads to 99 000 (62 000–132 000; 95 per cent confidence interval) fewer premature respiratory and 92 000 (28 000–150 000; 95 per cent confidence interval) fewer cardiovascular deaths due to ozone exposure, which corresponds to ~1 400 fewer total deaths per million tonnes of methane emission reductions. Of these, a similar fraction is attributable to respiratory and cardiovascular related deaths, respectively 740 (460–990; 95 per cent confidence interval), and 690 (210–1120; 95 per cent confidence interval), with the uncertainty range on the latter markedly larger. At the national scale, this leads to the largest total impacts occurring in countries with large populations, namely China, India, Japan, Russia and the United States (Figure 3.8). On a per person basis, however, impacts maximize in lower latitude regions where ozone responses are largest and especially in those nations where baseline health conditions are relatively poor. Per person impacts are greatest in Ukraine, Lesotho, Egypt, Georgia, the Democratic People's Republic of Korea, Afghanistan, Bulgaria, Serbia, Uzbekistan and Eritrea (in that order). The United Kingdom, at 13th, is the highest impacted on a per person basis of Organisation for Economic Co-operation and Development (OECD) countries.

In the analysis using 2030 population and baseline mortality, the 50 per cent reduction in methane leads to 105 000 (66 000–140,000; 95 per cent confidence interval) fewer premature respiratory deaths and 81 000 (25 000–132 000; 95 per cent confidence interval) fewer cardiovascular deaths due to ozone exposure. Respiratory-related deaths hence increase by 6 000 relative to the 2015 analysis, due to increases in, for example, India, 1400; the United States, 600; Indonesia, 300; Mexico, 200, and many countries in Western Europe

8. https://esa.un.org/unpd/wpp/DataQuery

that are partially offset by decreases in China, -600, and many countries in Eastern Europe. In contrast, cardiovascular-related deaths for 2030 are 11 000 fewer than those in the 2015 analysis due to decreases in, for example, China, -6 000; Russia -1000; Germany, -400; India, -500; Indonesia, -400; Japan, -400; and the United States, -400, that are offset by increases in some other nations such as Pakistan, +200. There is a divergence in response between respiratory and cardiovascular deaths due to differences in projected changes in baseline mortality rates. In China, for example, mortality rates for cardiovascular disease are projected to decrease across all age groups whereas mortality rates for respiratory disease are projected to drop only for those aged 45–70 and rise for both younger and older populations. In the United States, mortality rates for cardiovascular disease are again projected to decrease across all age groups whereas mortality rates for respiratory disease are projected to drop for those aged less than 80 while rising for the 80+ age group, with a decrease in mortality rates in some younger populations, such as those aged 75–80, being outpaced by the projected growth in the population within that age bin. Similar trends are at work in other nations, for example, in India population is projected to increase by 17 per cent but this is outweighed for cardiovascular deaths by projected reductions in baseline cardiovascular mortality rates which is not the case for respiratory health. Given the generally modest differences between these results, only the primary 2015 analysis is reported hereafter but it should be noted that, in particular for analyses focused only on the better-constrained respiratory-related deaths, the 2030 global impacts are likely to be ~6 per cent larger.

Globally, roughly 40 per cent of avoided respiratory-related premature deaths are in those aged 80+, with about 28 per cent for people in their 70s and 18 per cent for those in their 60s. These values vary substantially, however, at the national level. Two thirds to three quarters of avoided deaths are for 80+ year-olds in many European countries, including France, Sweden, Switzerland and the United Kingdom, whereas that age group experiences less than one third of the total impact in several populous developing countries such as India, Indonesia and Pakistan, which instead see larger effects on populations in their 70s and sometimes in their 60s. Values are similarly distributed for cardiovascular deaths. At the global level, for example, 36 per cent of avoided premature cardiovascular-related deaths are people aged 80+, 36 per cent for those in their 70s and 20 per cent for people in their 60s. Unlike age, current epidemiological studies do not report whether there are gender differences in exposure-response functions.

As shown in Figure 3.4, the ozone exposure metrics respond nearly linearly to methane changes. Using the methods described to calculate premature mortality attributable to long-term ozone exposure, the linearity of this impact to changes in methane were investigated. It was assumed, based on Figure 3.4, that the MDA8 ozone responds linearly to methane changes and so this test examines the linearity of the exposure-response function. Over a wide range of methane emission reductions, national-level responses are highly linear (Figure 3.9). This is because the national average MDA8 ozone changes in response to methane are fairly small, ranging from a 1 to 4 ppbv decrease in response to half anthropogenic emissions reductions –134 Mt. Such small changes in methane do not induce substantial non-linearity through the exposure-response exponential function, nor do they cause national exposures to pass the TMREL threshold. The threshold is not passed as countries in the Northern Hemisphere are typically well above the 26.3 ppbv threshold used here, whereas the few nations with very low exposures, such as New Zealand or Papua New Guinea are already below the threshold. A few countries, including Australia, Colombia and Uruguay, have national exposures within a few parts per billion by volume of the threshold and hence could easily see non-linear behaviour were methane to be reduced in concert with other pollution changes, but with methane changes alone only a few island countries cross the TMREL threshold. These results hold for both respiratory and cardiovascular premature deaths. It can thus be concluded that the modelled response to a 134 Mt change in methane emissions can be linearly scaled to yield a highly accurate estimate of per million tonne responses. Scaled results for the countries most affected are given in Table 3.3 and a full list is given in the Annex.

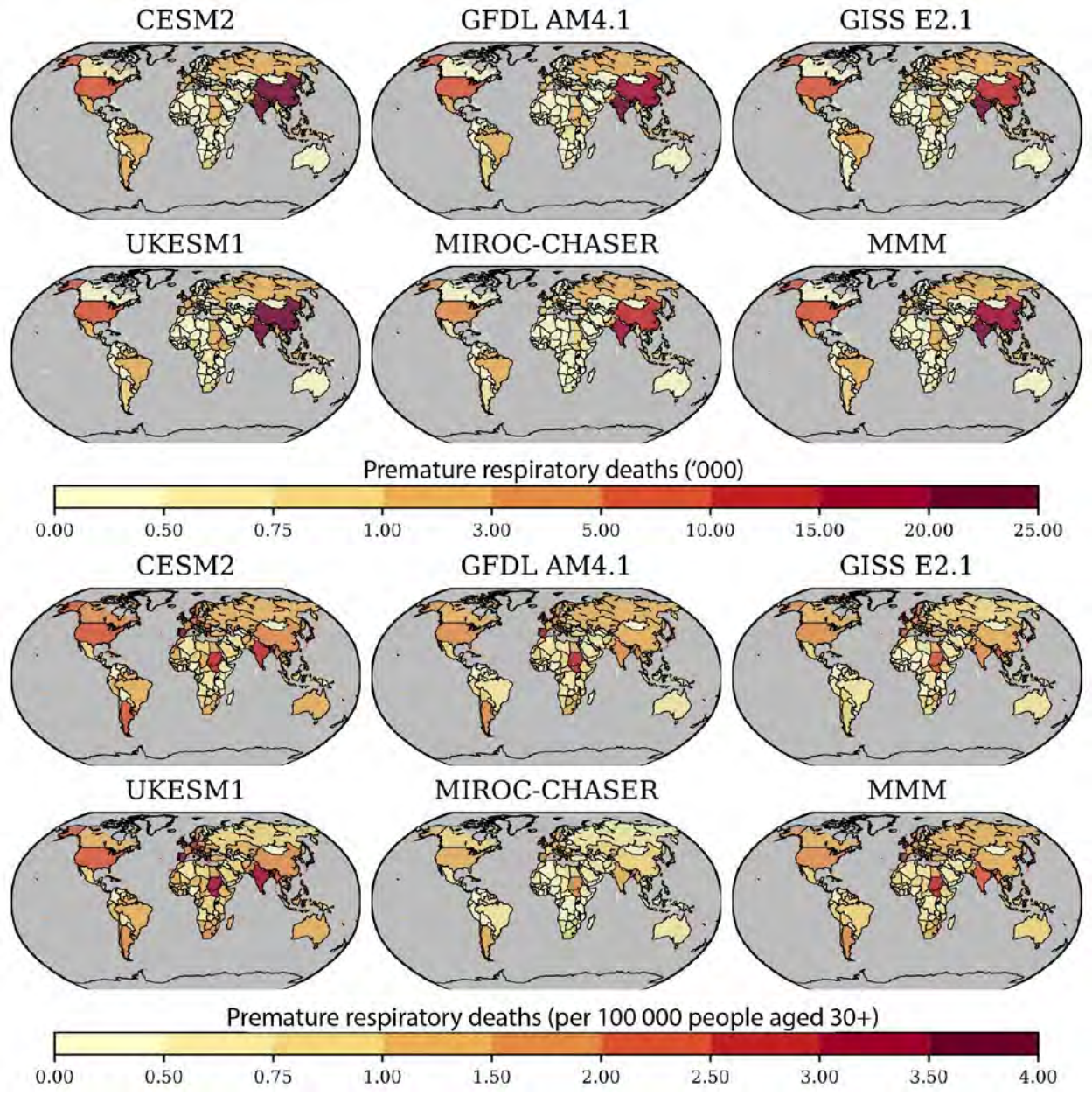

Figure 3.8 National total premature respiratory death changes between present-day (2015) and one-half anthropogenic methane simulations in five different models and the multi-model mean

Note: Values are given as totals and per 100 000 people aged 30 or over.

Source: UNEP and CCAC

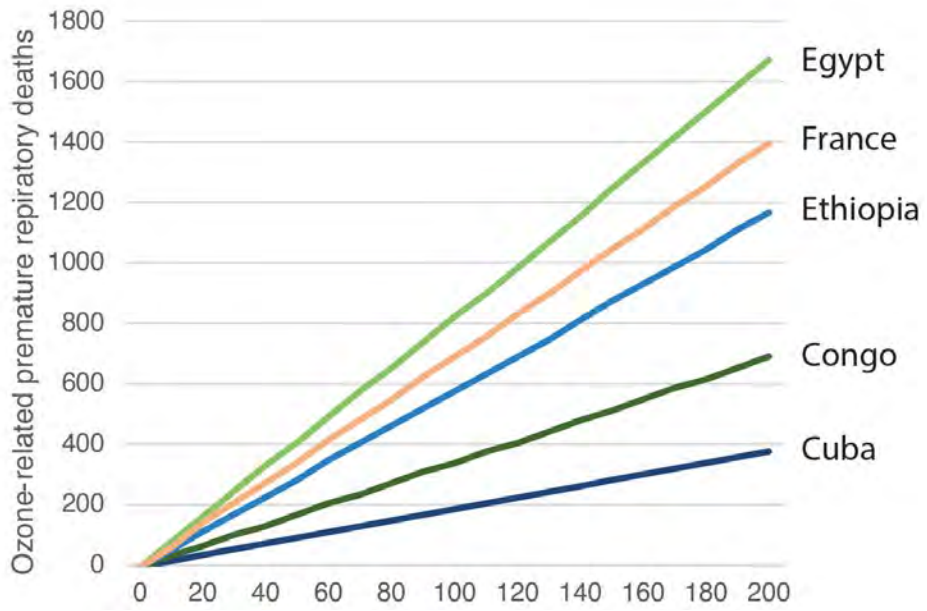

Figure 3.9 National-level reductions in ozone-related premature respiratory deaths associated with the given decrease in methane emissions, 5 selected countries

Note: Developed using the exposure-response function described in the text and assuming a linear response of the maximum daily eight-hour average ozone to methane change.

Source: UNEP and CCAC



Table 3.3 Modelled total deaths and per million people aged 30+ per 10 Mt methane, 10 highest countries

RESPIRATORY							
COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION	LOW	HIGH
India	2 045	1 169	2 863	Lesotho	5.1	3.5	6.5
China	1 419	948	1 831	Korea Dem. People's Rep.	4.5	3.2	5.7
United States	428	287	553	Eritrea	4.1	2.5	5.6
Japan	251	176	316	United Kingdom	3.8	2.5	5.0
Brazil	160	100	216	India	3.5	2.0	4.9
Pakistan	159	98	215	Portugal	3.2	2.1	4.2
United Kingdom	157	102	207	São Tomé and Principe	3.2	2.0	4.3
Indonesia	154	86	219	Guinea-Bissau	3.1	1.6	4.6
Germany	121	79	160	Zimbabwe	3.1	2.0	4.1
Russia	109	71	143	Denmark	3.1	2.1	4.0
CARDIOVASCULAR							
COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION	LOW	HIGH
China	1 566	502	2 522	Ukraine	6.5	2.1	10.8
India	1 122	297	1 844	Georgia	5.4	1.8	8.7
Russia	379	122	624	Uzbekistan	5.3	1.8	8.4
United States	333	108	540	Bulgaria	5.3	1.7	8.6
Pakistan	225	65	365	Egypt	5.1	1.7	8.2
Indonesia	219	57	368	Serbia and Montenegro	4.9	1.6	8.0
Egypt	194	64	310	Belarus	4.8	1.5	7.9
Ukraine	193	61	3`18	Lithuania	4.7	1.5	7.7
Japan	148	50	236	Latvia	4.3	1.4	7.2
Germany	133	42	218	Afghanistan	4.3	1.5	6.9
RESPIRATORY + CARDIOVASCULAR							
COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION	LOW	HIGH
India	3 167	472	5 567	Ukraine	7.6	1.7	13.2
China	2 984	729	5 003	Lesotho	7.5	2.0	12.6
United States	761	189	1 284	Egypt	7.3	1.9	12.1
Russian	488	117	839	Georgia	7.2	1.9	12.1
Japan	399	108	659	Korea Dem. People's Rep.	6.9	1.9	11.4
Pakistan	384	74	659	Afghanistan	6.8	1.9	11.1
Indonesia	373	52	671	Bulgaria	6.7	1.6	11.5
Egypt	276	72	457	Serbia and Montenegro	6.4	1.5	11.0
Brazil	255	54	447	Uzbekistan	6.3	1.7	10.4
Germany	254	60	436	Eritrea	6.1	1.2	10.8

In prior modelling (Shindell *et al*. 2012; UNEP/WMO 2011), each million tonne of methane was estimated to lead to 340 premature deaths per year due to ozone (220–490; central 66 per cent confidence interval). The new value of ~1 400 is roughly four times greater. In large part, the increase in the estimated impact stems from the use of the updated epidemiology based on the extended ACS CPS-II cohort relative to the epidemiology based on the earlier version of this same cohort (Jerrett *et al*. 2009). The newer analysis of this cohort includes not only a greater impact of ozone on respiratory mortality but also the addition of the impact of ozone on cardiovascular mortality. Additional studies on the links between ozone exposure and cardiovascular mortality would be useful as the evidence base for this outcome is less robust than that for respiratory mortality. For example, the US Environmental Protection Agency recently published an *Integrated Science Assessment for Ozone* in which it noted that a limited number of epidemiologic and animal toxicological studies contribute new evidence characterizing the relationship between long-term ozone exposure and cardiovascular health effects. That evidence includes epidemiologic evidence that long-term ozone exposure may be associated with blood pressure changes or hypertension among different life stages or those with pre-existing disease, as well as toxicological evidence of inflammation, oxidative stress, and impaired cardiac contractility in rodents following long-term ozone exposure. Their assessment concluded that the evidence of the relationship between long-term ozone exposure and cardiovascular health effects is suggestive of a causal relationship, but not more definitive. Given the differences in their evidence bases, this assessment presents the results for respiratory and cardiovascular impacts separately.

Additionally, the newer epidemiology uses the metric of the maximum daily 8-hour average over the entire year whereas the older one was based on the warm-season maximum daily 8-hour average. As methane is particularly important during winter months, the response to methane is virtually certain to have been enhanced by the change in the metric. We note that the relationship between ozone exposure and premature death, including exposure timing and ozone-attributable risk, is still an active area of scientific investigation. Total deaths per million tonnes of methane attributable solely to respiratory impacts are, as noted, 740 (460–990; 95 per cent confidence interval). Hence the results here for respiratory impacts are roughly double those found in the earlier work. Previous analyses found a 32–50 per cent increase in respiratory only impacts using the larger, extended cohort relative to the older risk estimates (Seltzer *et al*. 2018) based on observed ozone rather than the response to methane. This suggests that much of the increase may be related to the metric change, with an additional portion potentially due to the use of newer models of atmospheric chemistry and new emissions datasets for non-methane species that affect ozone.

It should be noted that the larger impact of ozone on health has been reported in several previous studies. Malley *et al.* (2017) used the new health exposure relationships (Turner *et al*. 2016) along with modelled ozone distributions, and found a 125 per cent increase in respiratory deaths attributable to ozone exposure in 2010 compared to previous estimates – 1.04–1.23 million deaths compared to 0.40–0.55 million. Using observed ozone data for the China, Europe and the United States, where coverage is fairly complete combined with statistical infilling of missing data, another recent study showed that by including both respiratory and cardiovascular impacts of ozone based on the Turner *et al*. (2016) epidemiology impacts were 153 per cent larger across the three regions than the values with the prior epidemiology, which included respiratory effects only (Seltzer *et al*. 2018). Hence the larger impacts are robust despite the tendency of models to overestimate surface ozone concentrations. Further to this, a bias-adjusted model recently reported total worldwide ozone-related premature deaths of 1.0 ± 0.3 million (Shindell *et al*. 2018). The value for respiratory-related premature deaths due to ozone was 0.6 ± 0.2 million for 2010, and 1.0 ± 0.3 million without bias adjustment, the latter being consistent with the value reported by Malley *et al*. (2017).

3.4.2 HEAT-RELATED MORTALITY

Exposure to heat, even at temperatures that are moderately hot, can compromise the body's ability to regulate its internal temperature, potentially resulting in heat exhaustion, hyperthermia, worsening of chronic conditions and heatstroke, leading to temperature-related deaths

(Sarofim *et al*. 2016; Gasparrini *et al*. 2015; Lee *et al*. 2014). Small temperature changes at mild or moderate temperatures can have larger health impacts than changes at extreme levels, such as during heatwaves or cold snaps, since they occur more frequently (Wellenius *et al*. 2017; Sarofim *et al*. 2016; Gasparrini *et al*.

2015). Heat exposure is currently the primary weather-related illness in the United States, with millions affected annually (Luber and McGeehin 2008). Cold-related mortality is not addressed here given its complexities and uncertainties. In particular, it is unclear to what extent empirically derived cold-related impacts are likely to reflect causal mechanisms given that other confounding affects such as influenza occur with a similar seasonality. Exposure to both heat and high humidity contribute to health impacts (Buzan and Huber 2020; Li *et al*. 2020). Though humidity changes are not explicitly accounted for here, since the epidemiological exposure–response relationships are based on temperature alone, they are implicitly included to some extent as humidity changes are highly correlated with global-scale surface air temperature changes that are included in the long-term epidemiological studies. Epidemiological studies have also reported that despite the known impacts of high humidity on health, there is little evidence that using heat indices that account for both temperature and humidity provides a better fit to the observed mortality data (Armstrong *et al*. 2019).

In the case of premature deaths owing to heat exposure, impacts based on the climate response simulations (C1 and C2) are analyzed here. The analyses are focused on China and the United States as detailed generalized exposure–response relationships have been derived for these two nations from a substantial body of local epidemiological evidence. Most prior studies have relied on city-specific epidemiological studies that created local exposure response functions for the influence of heat exposure on human health (Weinberger *et al*. 2017; Schwartz *et al*. 2015; Honda *et al*. 2014). Based on the available city-specific exposure–response functions for the United States, generalized functions that were shown to be applicable nationwide were recently developed (Shindell *et al*. 2020). These capture the geographic variation in the observed epidemiological functions by including a dependence on local climatic conditions, which may also incorporate at least a portion of localized differences in humidity.

As climate responses are evaluated for one to three decades after emissions reductions take place, the generalized exposure–response functions to the 2030 population were applied together with baseline mortality data using the sources described above for ozone-related deaths. In this instance, based on the underlying epidemiological studies, impacts of heat were applied as an altered all-cause risk rather than cause-specific as for ozone. Hence all-cause all-age mortality projections were used along with projected population changes, again with the geographic distribution of population unchanged. Based on results described in Ma *et al*. (2014), generalized equations have been created for China analogous to those developed previously for the United States (Shindell *et al*. 2020). Briefly, using data from 15 cities in China, relative-risk curves were created from the epidemiological exposure–response functions using a second-order polynomial following the equation $RR = 1 + aT^2 + bT$. The relationship between the coefficients a and b and the local city mean summer temperature (MST) was then derived by linear regression to create a generalized exposure–response function that captured the sensitivity of this function to local climatic conditions, as done for the United States. The result is a generalized polynomial function with the equation:

$$RR = 1 + a_s \times (MST - a_i)T^2 + b_s \times (MST - b_i)T$$

where as and bs were the slopes of the linearly regressed coefficients versus mean summer temperature and ai and bi were the intercepts of the same regressions. The mean summer temperature is unique for each city, and T is the temperature in degrees centigrade above the optimum temperature defined as the value at which relative risk is equal to 1 – set to the 84th percentile of temperatures at a given location.

For the United States, the coefficients are:

$$a_s = -0.0014,\ a_i = 30.9,\ b_s = 0.005,\ b_i = 26.7.$$

For China, the coefficients are:

$$a_s = 0.0037,\ a_i = 21.0,\ b_s = -0.0045,\ b_i = 23.8.$$

Averaged over all available cities, the generalized equations yield results for current conditions (~2010) that are relatively close to those obtained using the local epidemiological results, with values 9 per cent higher for the 15 Chinese cities and 7 per cent lower for the 10 cities in the United States. Hence these generalized equations appear to provide valuable insights into national level impacts of heat exposure. In the analysis conducted for this assessment, the above generalized function at the grid cell level across the China and the United States were applied. As was the case for ozone-related

deaths, epidemiological studies do not provide distinct results according to gender. In the primary calculations, adaptation is not included. In a sensitivity study, the value for the mean summer temperature was allowed to change between the C1 and C2 simulations in order to represent human adaptation to long-term seasonal temperature changes. In a warming climate, for example, United States' cities in cooler regions take on more of the character of warmer cities, becoming less sensitive to heat extremes. In contrast, the optimum temperature is kept fixed at the value from simulation C1 to represent the influence of short-term temperature excursions (see Shindell *et al*., 2020 for additional discussion of adaptation).

It was found that the 50 per cent reduction in methane leads to 2 800 (1 700–3 800; 95 per cent confidence interval) fewer annual heat-related deaths in the United States and 14 000 (6 000–21 000; 95 per cent confidence interval) fewer in China based on the climate response averaged over one to three decades following emissions reductions and accounting for the uncertainty in that national level climate response. For comparison, the total annual ozone-related deaths in these countries are 10 200 for the United States and 40 100 for China. Hence ozone-related reductions in deaths are roughly factors of 3–4 larger. As the ozone-related reductions begin immediately rather than a decade later, they have a larger overall impact on mortality rates in these two countries. Nonetheless, this analysis, especially the results for China, suggests that the human health benefits attributable to reduced climate change are also substantial and that they could contribute a large fraction of total health benefits, in particular in countries with low ozone pollution levels. Based just on these two countries for which data are available, each million tonne of methane emissions mitigation leads to about 125 fewer premature heat-related deaths. The ozone-related deaths in these two countries make up about one quarter of the global total, suggesting that the global total might be roughly 500 fewer premature heat-related deaths per million tonnes of methane if the ratio of China+United States to global heat-related deaths is similar to that for ozone-related deaths.

Potential impacts of adaptation by accounting for the change in summer mean temperatures, as described above, were examined. This led to a reduction in the United States annual heat-related deaths of ~100, or about 2 per cent (0–5 per cent across models). This suggests only weak effects for at least this type of adjustment to mean climatological changes. Warmer cities in the United States experience less increase in the risk of heat-related mortality per degree warming than cooler cities, so that acclimatization to warmer temperatures leads to reduced risk. In China, however, the opposite is true in that warmer cities experience greater risk per degree of warming. Hence this method of accounting for adaptation was not applied to China. Presumably, the difference between these countries is related to the greater wealth in the United States that allows nearly complete use of air conditioning in warm climates, making them better adapted to heat extremes than cooler climates, whereas air conditioning ownership in China has only expanded rapidly very recently, after the epidemiological studies on which the generalized equation for China is based were performed. Given the minimal changes in the United States and lack of an adequate method for China, hereafter only the values without accounting for possible adaptation are reported, though it is noted that a broader exploration of potential adaptation found that it might reduce impacts roughly by half (Shindell *et al*. 2020; Anderson *et al*. 2018; US EPA 2017).

An additional estimate of wider scale heat-related mortality impacts is based on the national-level responses to national average warm-season temperature changes reported in a recent study (Lee *et al*. 2019). This study reported an increase in national level risk for heat-related mortality as a function of national level warming based on averaging across available local datasets, typically from several urban areas within each country. Regional averages were also provided for most parts of the world, with the significant exceptions of Africa and South Asia. The responses were examined using this much rougher relationship with the results from our spatially explicit response to the distribution of daily temperature values in China and the United States. The national-average seasonal-mean method produced an impact that was 55–57 per cent of that found in the more detailed analyses of China and the United States. Based on the consistency across those countries, and assuming the more spatially and temporally explicit method was the more accurate, all national results from the other method were normalized by dividing by 0.56.

Using this normalized national-average seasonal-mean method, the total across regions with data is 53 000 (39 000–74 000 across the three models). This corresponds to about 390 avoided heat-related deaths per million tonnes of methane emissions reduction.

Given the exclusion of Africa, except for Egypt, which is included as part of the Middle East in this analysis, South Asia and this value appears to be fairly consistent with the estimate of 500 deaths per million tonne of methane from the extrapolation of China and the United States results based on the ratio of the ozone-related impacts in those two countries to the global total. More specifically, the World Health Organization estimated worldwide mortality effects of heat exposure, based on data from Japan alone, and reported that 37 per cent of premature deaths due to heat were projected for 2030 in Africa and South Asia (WHO 2014). Applying this same ratio to the results in this analysis would imply ~600 deaths per million tonne of methane.

Though both large-scale estimates are relatively crude and thus confidence in the precise values is low, they provide an indication of a plausible level of worldwide heat-related mortality impacts, adding to a growing body of evidence for such widespread effects (Carleton *et al*. 2020; Lee *et al*. 2019; WHO 2014). It should also be noted that the Lee *et al*. (2019) study reported that impacts were fairly linear with warming, so that the scaling approach used throughout this assessment appears reasonable for this impact as well, although due to data limitations that specifically could not be examined in this analysis. These results suggest that there are, very roughly, three times more ozone-related deaths than heat-related ones. Additionally, ozone-related deaths would decrease immediately in response to reductions in methane emissions, with ozone-related deaths evolving rapidly over time following the ~12 year adjustment time for methane, whereas heat-related deaths would change more slowly as climate responds, with the values estimated here occurring one to three decades after emissions changes.

3.4.3 MORBIDITY AND LABOUR PRODUCTIVITY

The effect of methane emissions reductions is examined here on two non-fatal health impacts in many countries:

1. hospital admissions due to respiratory illness resulting from ozone exposure; and
2. visits accident and emergency departments due to asthma resulting from ozone exposure.

The change in hours of lost labour due to extreme heat is also quantified, but only in the United States due to data limitations.

3.4.3.1 MORBIDITY AND LABOUR PRODUCTIVITY METHODS

Changes in respiratory hospital admission are evaluated for the population aged 65+ based on decreases in ozone exposure in response to methane emissions reductions. Estimates are based on the epidemiological studies of three groups of investigators, in Canada, Europe and the United States, covering 149 cities globally under the Air Pollution and Health: a European and North American Approach (APHENA) project (Katsouyanni *et al*. 2009). Hospital admissions data were collected from medical records for all respiratory diseases, conditions or infections (International Classification of Diseases, Ninth Revision (ICD-9) codes 460–519). This global effort showed a robust relationship between ozone exposures and respiratory hospital admissions for this age group, without distinguishable geographical difference. This relationship was therefore applied worldwide. As with mortality, the epidemiology does not clearly indicate whether there is any differentiation in risk by gender.

A well-established approach (Fann *et al*. 2018; Heroux *et al*. 2015; WHO 2013) was used to estimate respiratory hospital admissions.

$$AF = 1 - exp^{-\beta\Delta[O_3]}$$

$$\Delta Hospital\ admissions = y_0 \times AF \times Population$$

where β is the exposure-response function, that is the slope of the log-linear relationship between unit change in exposure and respiratory hospital admission, developed from APHENA, AF is the attributable fraction of hospital admissions associated with ozone exposure, y_0 is the baseline hospitalization rate of respiratory diseases among the 65+ age group, and population is the count of 65+ year-olds at each 0.5° x 0.5° grid box. This approach is similar to the method used to calculate mortality, except that no lower exposure threshold is applied for morbidity. Given the short-term nature of the link between respiratory hospital admission and ozone exposure, responses in hospital admissions on a daily basis were estimated and the total summed over a year.

National-level variations result from the uneven distribution of ozone changes, country-specific hospitalization admission or discharge rates for those aged 65+ hospitalized due to respiratory diseases, and population distributions of 65+ year-olds. The exposure–response functions studied in APHENA have used both penalized

spline and natural spline models. For this analysis the average of the two exposure–response functions was calculated, and a relative risk of 1.006 (0.0008–1.012) used for per 10 ppbv of ozone maximum daily 8-hour average (i.e. β is 0.00063 (0.000087–0.0012)). Data on the post-65 population were again from GPW version 4 (CIESIN, 2016), the same dataset used for mortality estimation. Baseline hospital admission data are compiled from multiple datasets. Efforts were made to include all the available datasets representing a baseline level of respiratory hospitalization. The baseline rate of respiratory hospital admissions for the United States was obtained from Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE) (US EPA 2015), which calculated the baseline respiratory hospital admission rate by age-groups from the Healthcare Cost and Utilization Project (HCUP) 2014. This is also the only available dataset that reports age-specific rates. The all-age rate for respiratory hospital admissions for China was obtained from China's *2016 Health and Family Planning Statistics Yearbook* (NHFPC, 2016) while the all-age hospital discharge rate for respiratory diseases for European countries came from Eurostat (Eurostat, 2016). Hospital discharge rates here, which are virtually the same as the hospital admission rates, include "*finalisation of treatment, signing out against medical advice, transfer to another healthcare institution, or because of death*". To transform the all-age rate to the 65+ rate in China and Europe, a ratio of 3.30:1 was applied, which was the average ratio of hospital admissions between those aged 65+ and all-age groups that was calculated from the United States dataset. Finally, the annual hospital admission rates were divided by 365 to obtain a daily average hospitalization rate. Given the limited availability of data, this compiled dataset of 35 countries from multiple sources was not ideal and may have introduced heterogeneity. In particular, it assumes the ratio between those aged 65+ and all-age groups in China and Europe is the same as that in the United States. It also assumes that there are no seasonal variations in respiratory hospital admissions over the year. The impacts of these heterogeneity and assumptions are, however, likely to be significantly lower than the uncertainty associated with the exposure–response function. Ozone responses are based upon the modelling in simulations 1 and 2.

Asthma-related accident and emergency department visit changes were evaluated for the entire population based upon decreases in ozone exposure in response to methane emissions reductions. Results are based upon the average of epidemiological relationships across three meta-analyses of existing literature that reviewed 22, 26 and 50 studies (Orellano et al. 2017; Zhang *et al*. 2016; Zheng *et al*. 2015). These reviews cover studies in the Asia, Europe and the United States. The approach developed in Anenberg *et al.* (2018) was used to estimate the global asthma accident and emergency department visits due to ozone exposure.

$$AF = 1 - exp^{-\beta\Delta[O_3]}$$

$$\Delta Hospital\ admissions = y_0 \times \mathrm{A\&EV} \times AF \times Population$$

where, again, β is the exposure–response function, that is the slope of the log-linear relationship between unit change in ozone exposure and asthma emergency room visits, AF is the attributable fraction, y0 is the country-specific baseline prevalence rate of asthma for the all-age population, accident and emergency department visits (A&EV) is the fraction of individuals with asthma visiting accident and emergency departments in each country, and population is the all-age population count in each grid box. Note that although accident and emergency department visits are a short-term morbidity impact, estimation is usually based on the relationship with an annual change of ozone exposure. As such, an annual average of ozone exposure changes was calculated using annual maximum daily 8-hour average and the above method applied.

Exposure response functions were applied from the three meta-analyses respectively: Orellano *et al*. (2017): 1.03 (1.01–1.06); Zhang *et al*. (2016): 1.05 (1.04–1.07) and Zheng *et al*. (2015): 1.02 (1.01–1.02). An average of the three results for estimated asthma-related accident and emergency department visits was then calculated. Annual country-specific baseline asthma prevalence rate for the all-age group was collected from the GBD 2018 (Global Burden of Disease Collaborative Network, 2018). The A&EV for available countries compiled by Anenberg *et al*. (2018) was used, which includes multiple national data sources. The final results here are for 56 countries and territories, due to data availability in A&EV . The gridded all-age population was again from GPW version 4 (CIESIN 2016). Ozone responses were again based on the modelling in simulations 1 and 2. As both ozone morbidity impacts are based upon the maximum daily 8-hour average, and prior studies have shown that a sum of daily maximum daily 8-hour averages is very close

to the annual maximum daily 8-hour average (Anenberg *et al*. 2018), the analysis presented previously regarding the linearity of the annual maximum daily 8-hour average (Figure 4.3) applies to these endpoints as well and hence hereafter it is assumed these impacts can be represented by a linear scaling from the results explicitly modelled in this assessment.

Labour losses due to exposure to extreme heat are evaluated using two distinct methods. The first is based on an empirically established exposure–response function for the United States (Graff Zivin and Neidell 2014). To evaluate this exposure–response relationship, nationally representative survey data from 2003–2006 and daily weather observations from roughly 8 000 weather stations were used to investigate how Americans allocate their work and leisure time as a function of ambient temperatures. The authors found a statistically significant approximately linear decrease in the time allocated to labour with increasing temperatures above a threshold of about 29° C for high-risk sectors. This relationship has been used in several recent studies of the United States (Hsiang *et al*. 2017; USGCRP 2018). In the calculations for this assessment, the value of time lost is calculated using county-level annual employment, covering 15–64 year-olds, and annual average weekly wages from the Quarterly Census of Employment and Wages, U.S. Bureau of Labor Statistics. The North American Industry Classification System was used to determine the number of workers in high-risk industries/sectors – largely those that cannot readily be air-conditioned: agriculture, forestry, fishing and hunting; construction; manufacturing; mining; transportation: and utilities. The 2016 fraction of workers in high-risk industries was used for each county. The analysis covers the contiguous United States, that is, excluding Alaska and Hawaii. Surface temperature changes in response to methane emissions reductions are based upon the daily temperature values modelled in simulations C1 and C2. Ninety years of data were used, years 11–40 from each of the three models that performed the C1 and C2 simulations, giving adequate data to establish a clear signal despite the noise inherent in daily temperatures.

The second method is based on a publication (Knittel *et al*. 2020) that appeared after the modelling to support this assessment was already largely completed. The relationship between heat and labour productivity in this study has the advantage of being applicable globally, but it relates productivity to relative humidity as well as temperature and daily humidity data was only available from an extension of the simulations performed for 20 years with one model as the need for this output had not been anticipated (thought the study that brought this method to our attention relied upon older methods). In the analysis using this method, following Knittel *et al*. and Kjellstrom *et al.* (2018), daily mean and max surface air temperature and daily mean relative humidity were used to represent the wet bulb globe temperature (WGBT) or heat index using the following equation:

$$\mathrm{WBGT} = 0.567\times T + 0.393\times \mathrm{Vapour} + 3.94$$

with T as either the daily mean, daily max or the average of those (daily halfmeanmax) 2-metre air temperature, in °C, and Vapour as the water vapour partial pressure in kilopascals9. This equation is representative for light wind conditions and moderately high heat radiation levels typically experienced by outdoor workers. The WBGT minus 4 is used to represent conditions experienced by indoor workers (Knittel *et al*. 2020).

Vapour was calculated using the daily means of relative humidity (RH) and T using:

$$Vapour = \frac{RH}{100}\times 6.105 \times \exp\left(\frac{17.27\times Tavg}{237.7\times Tavg}\right)$$

The WBGT was then related to work ability (WA) following Knittel *et al*. (2020) based on the work of Bröde *et al*. (2017) and Kjellstrom et al. (2014):

$$WA = 0.1+0.9/(1+(WBGT/\alpha 1)^{\alpha 2})$$

where and are unitless coefficients derived for the three different work intensity categories: light, 24.64 and 22.72; medium, 32.98 and 17.81; and heavy work, 30.94 and 16.64. Light work includes all the service sectors, such as retail sales, wholesale trade, hotels and restaurants, post and telecoms, financial services and insurance, and public administration, and is assumed to be indoors. Medium work includes such sectors as food, textile and wood industries, machinery and electronic equipment, and transport and is

9. Kilopascal = 1000 pascals

likewise assumed to be indoors (i.e. in a shaded or air conditioned space rather than direct sunlight). Heavy work includes the agriculture, forestry and fishery, extraction and construction sectors and is assumed to be outdoors.

Work ability is assumed to be limited to 0.1 to 0.9 (in portion of an hour) to allow for some minimal work and acknowledge that breaks are needed even under optimal conditions. The calculated fractional work loss, WL=1-WA, is then multiplied by the working population, adults aged 15–64, in each country in each work category to get the annual total labour loss due to heat. The lost hours are based on 12 months multiplied by 30 days per month multiplied by 12 hours per day, with a distribution of work that has 4 hours each at daily maximum, daily half mean max and daily mean temperatures; these assumptions have been shown to provide a good approximation of the hourly temperature distribution during the day (Kjellstrom *et al.* 2018). This leads to 4 320 potential work hours per year. The country-specific working population in 2018 for each labour category was based on data from the International Labour Organization (ILO), which includes gender-specific information (ILO, 2020). As in Knittel *et al*. (2020) and Kjellstrom *et al.* (2018), the relationship between WA and WBGT is assumed to be applicable worldwide although the underlying data is largely from more developed nations.

3.4.3.2 MORBIDITY AND LABOUR PRODUCTIVITY RESULTS

The ozone decreases in response to reductions in methane emissions lead to an estimated reduction of 855 annual hospitalizations for persons aged 65+ per 10 Mt of methane in countries for which sufficient data is available. Among those nations, the largest values are seen in China, followed by the United States (Table 3.4; Figure 3.10). Effects are larger than in either of those nations, however, for Europe. Note that data is unavailable to allow these effects to be quantified outside of China, Europe and the United States. In addition, the overall uncertainty range for this impact is quite large, ±84 per cent, owing primarily to the uncertainty in the exposure–response relationship.

The ozone decreases in response to reductions in methane emissions also lead to a decrease in asthma-related accident and emergency department visits, with a response of 43050 fewer cases per 10 Mt methane emission cuts. Note that in comparison with respiratory hospitalizations, there is much more data available and so the impact on asthma-related accident and emergency department visits is quantified for many more nations (Table 3.5a; Figure 3.11). In addition, the epidemiological relationship has a much narrower uncertainty range, so that the overall uncertainty in the change in number of accident and emergency department visits is much smaller at ±37 per cent. Among the many countries for which impacts were estimated, benefits in India are far larger than in any other nation, with more than half the avoided cases taking place there. China ranks second and the benefits distinctly larger than in countries ranking third and lower. Several other countries do see substantial benefits, however, including both developed ones such as the Republic of Korea, Japan and the United States as well as developing countries including Brazil, Ethiopia and Nigeria, all of which see more than 500 fewer accident and emergency department visits per 10 Mt of methane emissions decrease.

As described above, the change in labour losses due to exposure to extreme heat was calculated for the United States only using the first method applied to multiple models. Based on the simulations of the climate response to methane emissions changes, the cooler climate resulting from the methane emission reduction between simulations C2 and C1 leads to 13.6 million (2.2–18.2; 95 per cent confidence interval) fewer lost work hours annually in the United States. This translates to approximately 1.0 (0.2–1.4) million hours per 10 Mt of methane.

The second method provided work loss estimates for most of the world, but in this case from a single model only. It is noted that the second method finds a much larger loss for the United States, namely 44 million fewer lost work hours annually in the United States. The second method is based on the temperature changes simulated in the GISS model and using the first method that model produced an estimate of just 4.8 million lost work hours rather than the 13.6 million lost work hours for the multi-model mean. Hence a multi-model mean with the second method would be likely to find larger impacts than the results based on the GISS model alone. Using the GISS climate simulations, the second method finds that the cooler climate resulting from the methane emission reduction between simulations C2 and C1 leads to 55 billion lost work hours annually (±38 billion based on the

GISS model's interannual variability over the 20 year simulation). Using this global method, effects tend to be greatest in low latitude, humid countries in which the daily heat index or WBGT frequently reaches high values (Table 3.5b; Figure 3.12). This corresponds to ~410 million lost work hours per million tonne of methane emitted, assuming responses are again quasi-linear. Employment within those sectors of the economy that are affected by heat exposure varies across gender, leading to disparities in the impacts for men and women in most countries. While in a few, such as Angola, Uganda, Cambodia, Viet Nam, Azerbaijan, Brazil and Kenya, there is nearly an even split between lost hours for men and women, in most the majority of the lost hours are for male labour, with female labour losses often accounting for only 20–35 per cent of the total (Table 3.5b). Nepal stands out as the only country with substantial losses, millions of hours lost in response to a 134 Mt decrease in emissions, for which the loss of labour is substantially higher amongst women, 59 per cent, while globally 66 per cent of impacts are felt by men and 34 per cent by women.

In a related analysis, the ILO reports that increased heat projected for 2030 could bring productivity losses equivalent to 80 million jobs (ILO 2019). Converting 80 million jobs to hours lost, assuming 50 weeks of 40 hours are worked per year, this translates to roughly 160 billion lost work hours annually. Their analysis hence similarly identifies the potential for large impacts. It also indicates substantial non-linearities in response, with impacts in 2030 nearly 10 times greater than those in 1995 despite 2030 warming being only roughly double the 1995 value. This makes it difficult to compare the results here directly with the ILO's, and also suggests that assuming a linear response as in this assessment provides only a very rough measure of impacts and that the non-linearity of this response merits further characterization.

Table 3.4 Respiratory hospital admissions due to ozone exposure per 10 Mt methane emissions for countries with available data

Note: other countries are likely have impacts as well, though these are not quantified here.

COUNTRY	CASES	COUNTRY	CASES
China	247	Norway	5.7
United States	145	Denmark	4.7
Italy	96	Czechia	4.5
Germany	78	Serbia and Montenegro	4.5
France	59	Slovakia	3.0
Spain	51	Finland	2.5
United Kingdom	45	Croatia	2.4
Poland	21	Slovenia	2.4
Greece	13	Ireland	2.1
Romania	9.9	Lithuania	1.2
Belgium	9.9	Estonia	0.9
Portugal	8.3	Cyprus	0.7
Sweden	8.1	Malta	0.5
Bulgaria	7.2	Luxembourg	0.3
Austria	7.2	Latvia	0.3
Netherlands	6.7	Iceland	0.2
Hungary	6.2	**TOTAL**	**855**

The uncertainty range is ±84 per cent.

Figure 3.10 Change in respiratory hospital admissions for people aged 65+ due to ozone exposure change resulting from a 134 Mt change in methane emissions, China, Europe and United States

Note: Based on the multi-model mean ozone change. Values are for China, the US, Europe and China only; although other countries are likely have impacts, these have not been quantified here due to data limitations – grey indicates no quantification.

Source: UNEP and CCAC

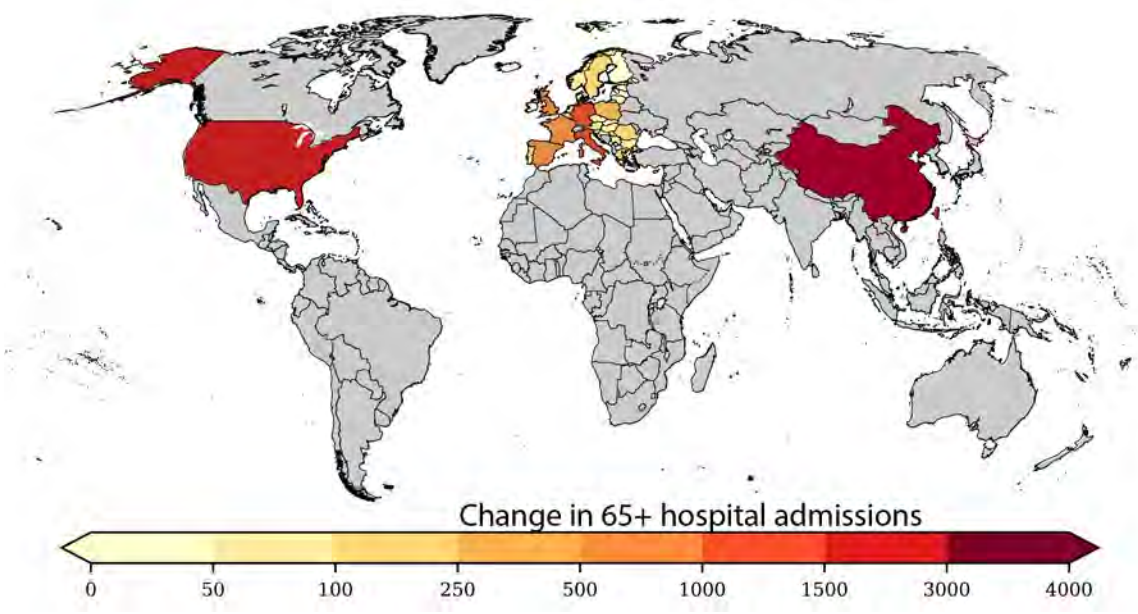

Figure 3.11 Change in asthma-related visits to accident and emergency departments due to ozone exposure change resulting from a 134 Mt increase in methane emissions, all ages, selected countries

Note: Based on the multi-model mean ozone change. Values given for countries with available underlying data – grey indicates no quantification.

Source: UNEP and CCAC

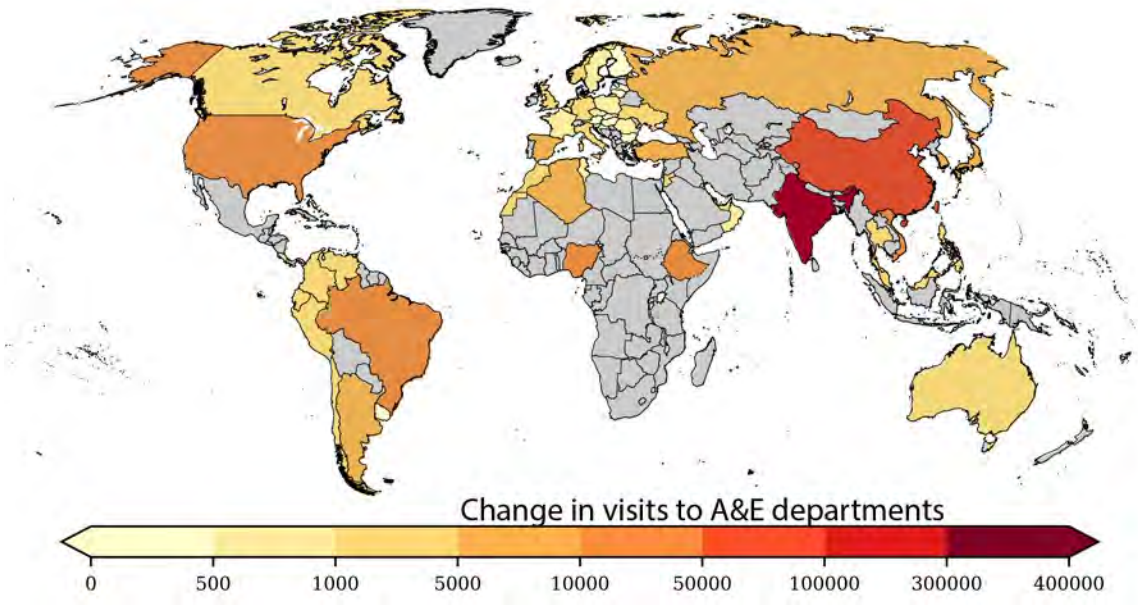

Figure 3.12 Change in lost labour hours due to heat exposure resulting from a 134 Mt increase in methane emissions, selected countries, million hours

Note: Values given for countries with available underlying data and statistically significant temperature responses – grey indicates no quantification.

Source: UNEP and CCAC

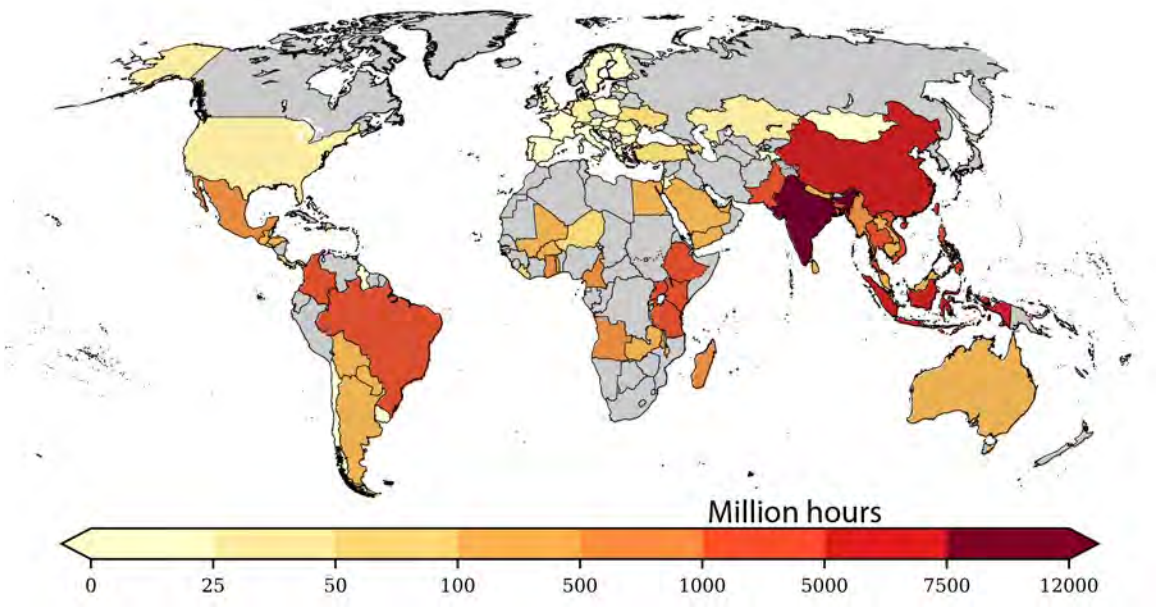

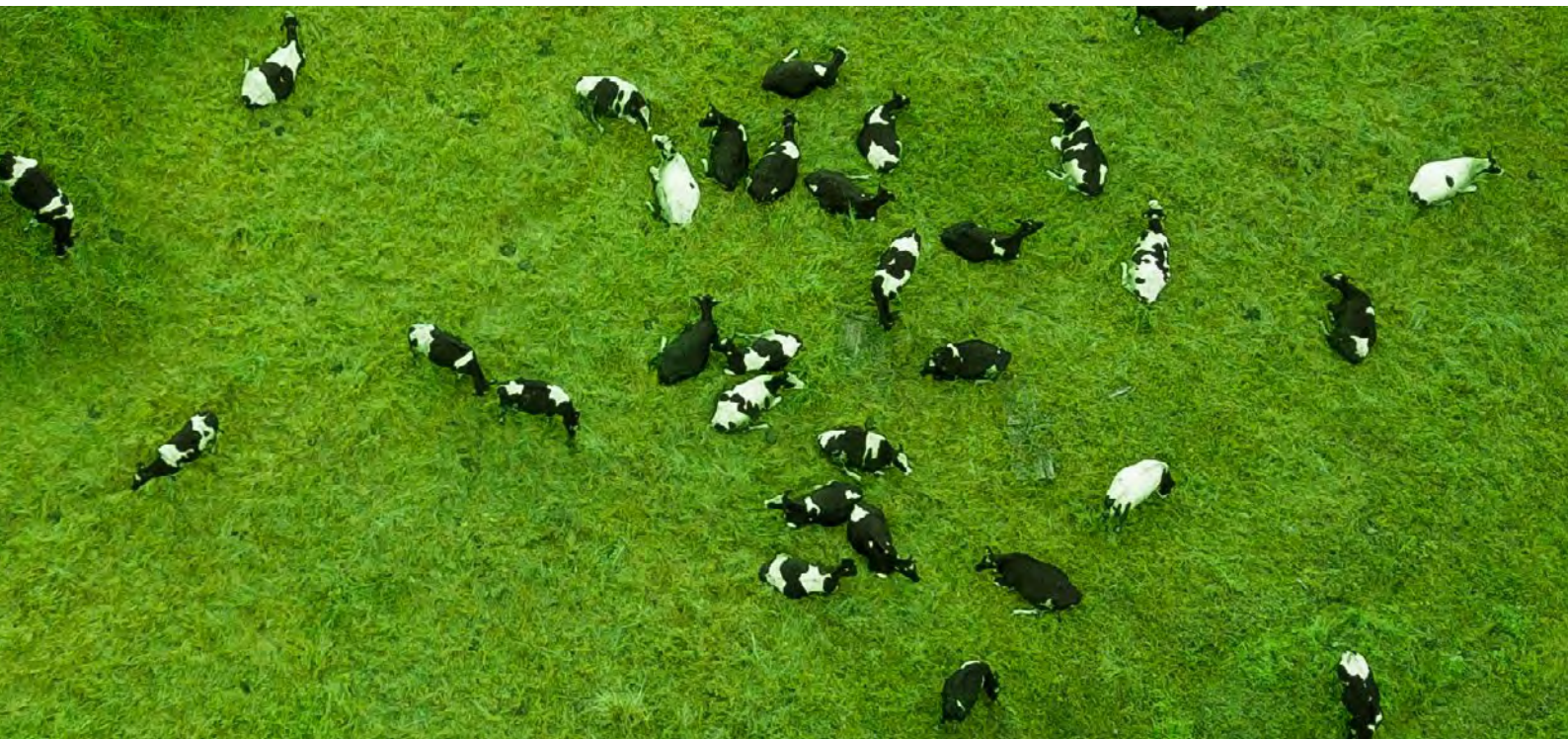

Table 3.5a. Asthma-related accident and emergency department visits due to ozone exposure, all age groups, per 10 Mt of methane emissions

COUNTRY	CASES	COUNTRY	CASES
India	23 000	Australia	110
China	7 200	Norway	108
United States	1 500	Jordan	95
Brazil	1 100	Italy	83
Ethiopia	1 100	United Arab Emirates	81
Nigeria	1 100	Poland	69
Viet Nam	860	Sweden	64
Turkey	580	Lebanon	63
Russia	570	France	63
Korea, Rep.	530	Costa Rica	56
Japan	510	Czechia	51
Argentina	410	Romania	47
Algeria	380	Oman	46
Spain	380	Belgium	46
Colombia	360	Tunisia	40
Thailand	345	Kuwait	38
Peru	308	Hungary	35
Morocco	261	Austria	26
Venezuela	246	Finland	23
Canada	224	Croatia	23
Ukraine	220	Uruguay	18
Philippines	161	Bulgaria	17
Germany	150	Singapore	17
Ecuador	133	Slovakia	15
United Kingdom	121	Latvia	12
Netherlands	114	Slovenia	12
Malaysia	113	Lithuania	10
Chile	111	**TOTAL**	**43 050**

The uncertainty range is ± 37 per cent.

Table 3.5b. Reduced labour losses due to heat exposure resulting from a 134 Mt decrease in methane emissions for the nations with the 15 largest number of hours lost

COUNTRY	LOST WORK HOURS (MILLION)	LOSSES FOR WOMEN (%)
India	12 000	22
China	6 700	39
Indonesia	5 900	32
Brazil	4 900	44
Viet Nam	2 300	45
Ethiopia	2 200	41
Philippines	1 700	19
Bangladesh	1 600	32
Thailand	1 400	42
Tanzania	1 200	47
Uganda	1 200	51
Pakistan	1 200	23
Colombia	1 100	36
Kenya	1 100	50
Mexico	800	17
GLOBAL TOTAL	**55 000**	**34**

The uncertainty range is ± 70 per cent.

3.5 CROP IMPACTS: METHODS AND RESULTS

Methane also plays a significant role in reducing crop yields and the quality of vegetation. Ozone exposure is estimated to result in yield losses in wheat, 7.1 per cent; soybean,12.4 per cent; maize, 6.1 per cent; and rice, 4.4 per cent for near present-day global totals (Mills *et al*. 2018; Shindell *et al*. 2016; Avnery *et al*. 2011a). Impacts on these four crops for which robust ozone concentration-response functions are available, were evaluated using an empirical crop model based on statistical relationships for the impacts of temperature, precipitation, carbon dioxide concentrations, and ozone, rather than plant level simulations (Shindell *et al*. 2019). Wheat, maize and rice responses to changes in meteorological variables are based on a meta-analysis of more than 1 000 modelling studies (Challinor *et al*. 2014), incorporating relationships observed in field studies. Responses for soybeans to temperature are based upon a separate study (Zhao *et al*. 2017) as those were not included in the meta-analysis. Separate temperature response coefficients for wheat, maize, and rice are included according to temperate or tropical conditions. For ozone, the M7 and M12 exposure metrics, the mean 7- or 12-hour daylight exposure during the growing season, depending on the crop, are used. These affect yields based on the response reported in field studies (Wang and Mauzerall 2004), and have been used previously for global crop modelling (Van Dingenen *et al*. 2009). The growing season is locally defined based on Van Dingenen *et al*. (2009). Changes in temperature, precipitation

and ozone in response to methane emissions changes are taken from the simulations performed for this assessment. In addition, a small amount of carbon dioxide is formed when methane is oxidized. This carbon dioxide response fertilizes crop growth, especially for C3 plants such as wheat, soybeans and rice with only very small effects for maize, a C4 plant (C3 and C4 refer to the type of photosynthesis used by the plant to create energy, with the first carbon compound produced containing either 3 or 4 carbon atoms). These effects are included here based on relationships described previously (Tebaldi and Lobell 2018). Crop distributions for 2010 were taken from the Food and Agricultural Organization of the United Nations (FAO) data sets[10] and are maintained at those levels in all calculations of impacts – no projected changes in crop areas are included. It is noted that ozone has additional detrimental impacts on ecosystems, including the loss of protein content in grains, loss of forage quality in grasslands, and losses in forest productivity and carbon uptake.

The effects of ozone and temperature dominate the response, with only minimal impact from projected changes in precipitation or carbon dioxide at large scales, as in prior analyses (Shindell *et al*. 2019). The relative importance of temperature change versus ozone change varies across crops and locations. They are, for example, similar in importance for maize, but temperature has a much larger impact than ozone on tropical wheat, whereas ozone dominates for soybeans in most locations and is larger for rice in many nations. Based on the quasi-linearity of the responses of both ozone and temperature to methane emissions changes, the modelled impacts were converted to crop impacts per unit methane emission.

The global totals for a 50 reduction in anthropogenic-related methane increases, a 134 Mt decrease in methane emissions, are avoided yield losses of 7.46 Mt of wheat, 2.23 Mt of soybeans, 5.58 Mt of maize and 4.20 Mt of rice, with uncertainty ranges of roughly 36 per cent based on the Monte-Carlo sampling performed previously (Shindell *et al*. 2019). National level totals are reported in Tables 3.6a–3.6d and shown in Figure 3.13. Losses in terms of total tonnage are naturally heavily weighted towards nations with large baseline yields as those vary across countries much more than the relative yield changes due to methane emissions. Relative yield losses tend to be greatest in low latitude countries, predominantly those in South Asia, the Middle East and Africa.

The total effects reported here, avoided yield losses of ~20 Mt, are slightly smaller than the value of 27 Mt in response to a very similar methane emissions reduction that was reported in prior modelling using just two models (Shindell *et al*. 2012; UNEP 2011). This is at first somewhat surprising given that these new estimates include both ozone and climate whereas the earlier results were for ozone alone. As the ozone exposure–response functions have not changed, this suggests that the multi-model analysis has produced a slightly smaller crop-related ozone response (M7 or M12) than in the prior study. The range given in the prior work, however, was very large spanning 7–69 million tonnes, as the two models differed markedly. The prior studies used the GISS and ECHAM models, with nearly a factor of two larger response in the latter and the current analysis reporting a multi-model mean close to the earlier low-end model (GISS). Using several models this time, the current results provide a substantially better constrained value that is well within the large range in the earlier analysis. Differences may also stem in part from changes in background conditions in predominantly rural areas where crops are grown.

As with health-related impacts, the linearity of crop impacts was examined across the various prescribed changes in methane concentrations. Responses are again relatively linear in nearly all cases at the national level for countries with substantial impacts (Figure 3.14). Significant deviations are seen for maize in China and rice in Bangladesh, with weaker responses to an increase than a decrease in methane in the former and vice-versa in the latter. Even in these cases, however, a linear approximation yields a fairly close result over the 0–134 Mt decrease range. Hence as with health impacts, hereafter it is assumed that crop responses can be well approximated with a linear scaling of the multi-model mean response from the half anthropogenic methane simulations.

10. faostat.fao.org

Table 3.6a Total (Mt) and relative (per cent) losses in yield of maize per 134 Mt methane emissions for countries with losses greater than 0.040 Mt and the top 14 countries for relative yield losses

COUNTRY	YIELD LOSS (MT)	COUNTRY	YIELD LOSS (%)
United States	2.345	Bangladesh	3.1
China	1.554	Nepal	3.1
Brazil	0.214	Jordan	2.9
India	0.147	Tajikistan	2.9
Mexico	0.134	Iraq	2.8
Egypt	0.115	Pakistan	2.7
Italy	0.107	India	2.6
France	0.078	Iran	2.6
South Africa	0.060	Afghanistan	2.3
Argentina	0.059	Uzbekistan	2.2
Romania	0.050	Egypt	2.1
Hungary	0.047	Syria	2.0
Indonesia	0.043	Turkmenistan	2.0
Canada	0.040	Angola	1.8
GLOBAL	**5.580**	**GLOBAL**	**1.2**

The uncertainties are ~40 per cent.

Table 3.6b Total (Mt) and relative (%) losses in yield of wheat per 134 Mt methane emissions for countries losses greater than 0.075 Mt and the top 16 countries for relative yield losses

COUNTRY	YIELD LOSS (MT)	COUNTRY	YIELD LOSS (%)
India	2.700	United Arab Emirates	5.9
China	1.324	Saudi Arabia	5.8
Pakistan	0.556	Brazil	5.7
United States	0.449	Oman	5.2
France	0.203	Paraguay	5.1
Australia	0.200	Qatar	4.6
Turkey	0.186	Bahrain	4.6
Egypt	0.148	Bolivia	4.5
Iran	0.142	Madagascar	4.3
Germany	0.139	Yemen	4.2
Russia	0.115	India	4.2
Argentina	0.085	Sudan	4.1
Saudi Arabia	0.083	Eritrea	3.6
United Kingdom	0.076	Tanzania	3.5
Canada	0.076	Niger	3.5
Ukraine	0.075	Myanmar	3.3
GLOBAL	**7.460**	**GLOBAL**	**1.7**

The uncertainties are ~30 per cent.

Table 3.6c Total (Mt) and relative (%) losses in yield of rice per 134 Mt methane emissions (for countries with losses greater than 0.020 Mt and the top 16 countries for relative yield losses

COUNTRY	YIELD LOSS (MT)	COUNTRY	YIELD LOSS (%)
India	1.432	Uzbekistan	1.8
China	1.252	Nepal	1.7
Bangladesh	0.360	Tajikistan	1.7
Indonesia	0.173	Afghanistan	1.6
Myanmar	0.119	Iraq	1.5
Thailand	0.102	Kyrgyzstan	1.4
United States	0.085	Bhutan	1.4
Viet Nam	0.075	Pakistan	1.3
Pakistan	0.071	Turkmenistan	1.3
Japan	0.071	Kazakhstan	1.2
Korea, Rep.	0.061	India	1.2
Nepal	0.053	Bangladesh	1.1
Egypt	0.053	United States	1.1
Brazil	0.038	Iran	1.1
Philippines	0.038	Australia	1.0
Angola	0.027	Rwanda	1.0
GLOBAL	**4.202**	**GLOBAL**	**0.8**

The uncertainties are ~40 per cent.

Table 3.6d Total (Mt) and relative (%) losses in yield of soy per 134 Mt methane emission for countries with losses greater than 0.010 Mt and the top 11 countries for relative yield losses

COUNTRY	YIELD LOSS (MT)	COUNTRY	YIELD LOSS (%)
United States	1.054	Iran	3.4
Brazil	0.412	Iraq	3.3
Argentina	0.231	Nepal	2.8
Congo, Dem. Rep.	0.182	India	2.8
India	0.077	Zambia	2.7
Australia	0.061	Tanzania	2.6
China	0.047	Kazakhstan	2.5
Paraguay	0.030	Korea, Rep.	2.4
Gabon	0.016	Zimbabwe	2.3
Canada	0.012	Angola	2.2
Italy	0.010	Mozambique	2.2
GLOBAL	**2.232**	**GLOBAL**	**1.7**

The uncertainties are ~40 per cent.

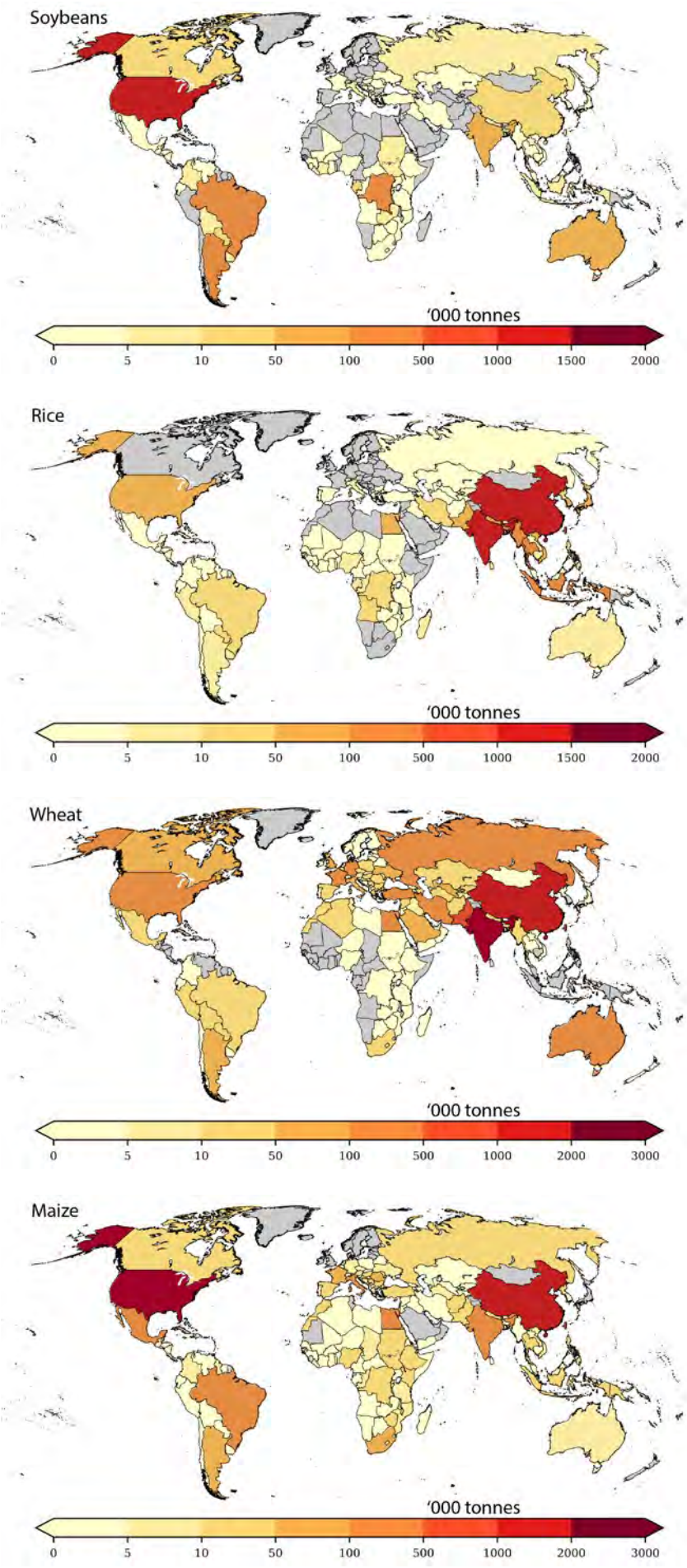

Figure 3.13 Annual change in soybean, rice, wheat and maize yields due to ozone exposure, climate and carbon dioxide changes resulting from a 134 Mt change in methane emissions, thousand tonnes

Note: Based on the multi-model mean changes – grey indicates no quantification.

Source: UNEP and CCAC

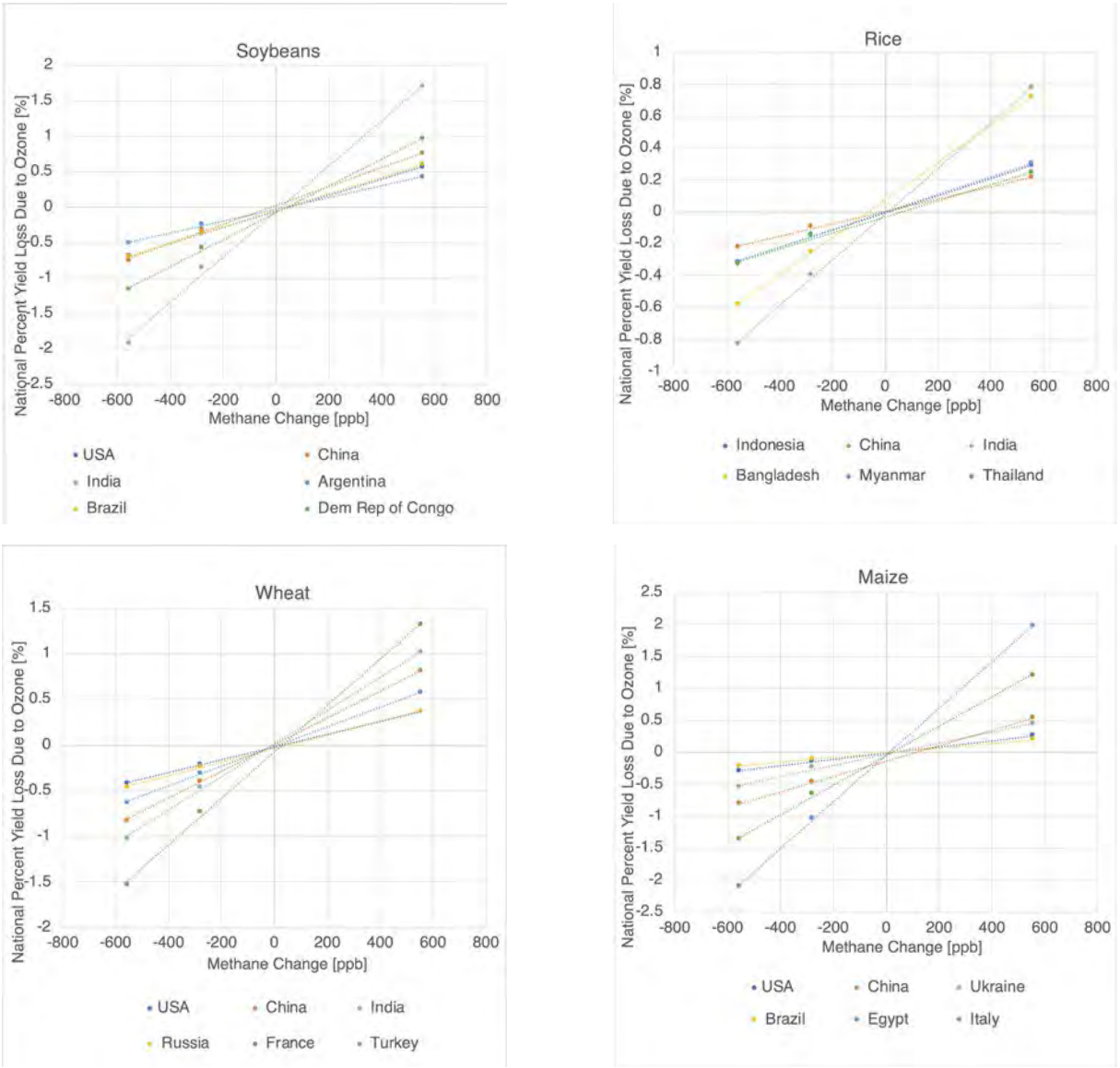

Figure 3.14 Change in wheat, soybean, maize and rice yields versus change in methane amounts, selected countries, per cent

Note: Responses are shown for countries with the largest impacts for each crop based on GISS-E2 simulations. The charts include points from individual simulations along with linear fits for each country. Negative losses represent gains.

Source: UNEP and CCAC

3.6 MONETIZATION OF IMPACTS: METHODS AND RESULTS

Both market and non-market costs associated with the impacts described above are evaluated. All values are in constant 2018 US dollars. Non-market values include those associated with premature death and many of the effects of climate change. Market costs include direct spending on health care and the effects of environmental changes on labour productivity.

Monetized benefits associated with avoided mortality are evaluated using a willingness-to-pay (WTP) measure of the value societies place upon reduced risk of premature death. This measure is often referred to as the value of a statistical life (VSL) though it is in fact an expression of the value that people affix to small changes in mortality risks in monetary terms rather than the value of any individual's life. Health literature often uses disability adjusted life years (DALYs), which are arguably more informative since they incorporate the age of the affected individuals and years with disabilities as well as premature deaths. Monetization is virtually always based on VSL, however, which is a better-established metric in the economics literature (Viscusi and Aldy 2003). Here the societal willingness-to-pay based is evaluated on national level gross domestic product (GDP) using data from the World Bank based upon national accounts data (World Bank, 2019). Gross domestic product values are used for 2018 except in the few cases for which they are unavailable in which case the most recent year is used – 2017 for Iran and 2011 for Eritrea. The WTP here is based on the mean of 26 peer-reviewed studies evaluated by the United States Environmental Protection Agency (US EPA 1997) and used by that agency to derive its official recommended VSL of US$ 7.4 million in 2006 US dollars. That value is then inflated to represent the year 2018 using an economic growth rate of 2.6 per cent per year and an elasticity for WTP with income growth for any specific country of 0.4, as in prior studies (Shindell *et al*. 2012; UNEP 2011). To account for the fact that WTP is a function of income across countries, monetized benefits are evaluated using both the same elasticity of 0.4, a value typically used to account for differential income levels within a country or region, and also using an elasticity of 1.0 as recommended by Hammitt and Robinson (2011) for across country analyses and used in the work of OECD (2018) and the World Bank and the Institute for Health Metrics and Evaluation (IHME) (2016) for both high-to-low income and low-to-high income comparisons. In other words, in this analysis, for country a,

$$VSL_a = VSL_{US} \times (Income_a/Income_{US})^{ß}$$

where ß is either 1.0 or 0.4. Both sets of values are presented (Tables 3.7a and 3.7b).
The results for ozone-related deaths show that national level values are greatest for countries with either or both large populations and high per person GDP, including China, India, Japan and the United States (Table 3.7 and Figure 3.15). It is important to emphasize that the WTP does not reflect an ethical judgement about the comparative value of the life of any individual, but simply that the willingness to pay to reduce risk is naturally a function of income. Hence the larger valuation associated with lives lost in wealthier nations merely reflects their wealth and does not imply a greater value for their citizens.

Values in countries with lower per person income are larger with the smaller value of income elasticity, as is the global total for ozone-related deaths which is approximately US$ 2500 (US$ 600–4 300; 95 per cent confidence interval here and hereafter) per tonne of methane emitted for an across country income elasticity of 1.0 and US$ 5 300 (US$ 1 200–9 100) per tonne for across country income elasticity of 0.4. Additional mortality-related benefits owing to reduced heat-related deaths are US$ 110 (US$ 75–150) for impacts in the United States, and US$ 120 (US$ 75–160) for China with income elasticity of 1.0 and US$ 360 (US$ 230–490) for China with income elasticity of 0.4. Using the results from the national-average seasonal-mean method to evaluate a broader set of countries (Section 3.4.2), the valuation rises to US$ 700 (US$ 200–1 100) per tonne for an elasticity of 1.0 and US$ 1 400 (US$ 300–2 500) per tonne for an elasticity of 0.4 and adopting the better characterized uncertainty range associated with ozone-related mortalities. These values are used hereafter, noting again that they do not include South Asia or Africa and are hence conservative. The total worldwide mortality valuation of all quantified impacts using an income elasticity of 1.0 is thus US$ 3 200 (US$ 800–5 400) per tonne of methane.

As described in the previous section, several additional impacts that can be readily monetized, including health morbidity outcomes, labour productivity in the United States, and crop yield changes have been quantified. First, morbidity changes associated with ozone exposure, for which values are calculated for two health impacts: hospital admissions and asthma-related accident and emergency department visits. For both end points, valuations are calculated only

for countries where baseline hospital admission data for respiratory conditions are available – China, Europe and the United States – or accident and emergency department visits – a broader set of countries.

First, the unit costs associated with each type of morbidity burdens are estimated. However, unit cost data is limited, as a result of which the cost estimation involves data collection and imputation, the latter for cases when actual data are not available. In the data collection, one important source was compiled by the CaRBonH calculation tool (Spadaro 2018). It estimated unit costs of several major morbidity endpoints for 53 countries, mostly in Europe. Since the target pollutant for CaRBonH was PM instead of ozone, the unit costs of morbidity endpoints studied were not, however, immediately usable in this project. CaRBonH reported country-specific average costs of cardiovascular and respiratory hospital admissions, for example, rather than reporting respiratory hospital admission separately. In addition, it reported the unit cost of each asthma symptom day for those between the ages of 5–20, rather than costs for asthma accident and emergency department visits for all age groups. This analysis took advantage of the broad coverage of CaRBonH's country-level data but made several adjustments to obtain estimates for unit costs of ozone-related morbidity.

For hospital admissions, most countries for which morbidity burdens could be estimated are in Europe, due to the availability of baseline hospitalization rates, except for China and the United States and China. Thus the average unit costs of hospital admissions for cardiovascular (ICD-9 codes 390–459; ICD-10 codes I00–I99) and respiratory (ICD-9 codes 460–519; ICD-10 codes J00–J99) concerns were collected for all age groups from CaRBonH for all the European countries in this analysis' morbidity estimates, and adjusted for respiratory issues as a single cause, and for the post-65 age group. Detailed cost information was used from the Healthcare Cost and Utilization Project (HCUP) for the United States to make the adjustment – the HCUP's dataset is the most comprehensive for inpatients in the United States. The same ICD-9 codes from CaRBonH were used to locate the diseases in HCUP dataset. The ratio of the mean hospital costs for all (age) discharges between cardiovascular and respiratory diseases, were found to be 1.43, and the ratio of the mean hospital costs for respiratory diseases between those aged 65+ and all age groups was 0.98. The unit costs for European countries were adjusted using a scaling factor of 0.69 (= 0.98/1.43), to obtain the estimated unit costs for respiratory hospital admissions of those aged 65+. The unit cost from HCUP for the United States was used directly. To estimate the unit cost for China, the average costs were calculated for three respiratory diseases reported in China's 2016 *Health and Family Planning Statistical Yearbook*, weighted by the number of hospitalizations for each disease. This estimate was not strictly equivalent to all respiratory diseases considered for other countries and was not specific to the 65+ population. Nonetheless, it is likely to be a good approximation, since the three most prevalent respiratory diseases in China were selected, and the ratio between those aged 65+ and all age groups from HCUP, 0.98, indicated that the hospitalization costs were likely to be very similar between the two age-groups.

For the cost of visits to accident and emergency departments for asthma, it was first note that there is a highly linear relationship (R-square = 0.96) between the cost of asthma symptom days and of income per person across the 53 countries in CaRBonH. The cost of asthma symptom days of children aged 5–19 analyzed in CaRBonH is based upon health treatment expenditures. Hence, here both the different age groups were considered for the impact and the difference between accident and emergency department visits and general health treatment for asthma. Since the cost for an accident and emergency department visit is a proportion of all treatment expenditure, it was assumed that there was also a good correlation between the cost of an accident and emergency department visit and income per person worldwide. Secondly, it was assumed that the correlation for children aged 5–19 holds for all age groups. Thus the cost estimate utilized for each asthma accident and emergency department visit for all age groups in the United States, US$ 1 501 in 2008 US dollars (Wang *et al*. 2014). As with mortality valuations, income comparisons are made based on:

$$\text{Cost}_a = \text{Cost}_{US} \times (\text{Income}_a/\text{Income}_{US})^{ß}$$

In this case, the income elasticity (ß) follows that used in CaRBonH, which is 0.8, 0.9, and 1.0 for high, upper-middle, and lower-middle income countries, respectively. Income data was obtained from the World Bank (World Bank 2020).

For respiratory hospital admissions, the largest economic impact is in the United States, followed by Germany, Italy, France and China within the relatively limited set of countries (Table 3.8). The

total across all countries for which estimates were made is US$ 0.36 per tonne. Values are generally larger for the healthcare costs of asthma-related accident and emergency department visits, with highest expenditures in the United States, Japan, India and China, respectively (Table 3.9; Figure 3.16). The total across all countries for which estimates were made is US$ 0.92 per tonne. Hence, as expected, these healthcare expenditures are comparatively small relative to mortality-related valuations.

As previously discussed, labour losses due to exposure to extreme heat were calculated using two distinct methodologies. The first was applied only for the United States and, using this method, a 50 per cent reduction in anthropogenic methane concentrations led to a reduction in lost labour of 13.6 million work hours. To estimate the value associated with the time lost, 2016 county-level annual employment for those of working ages, 15–64 year-olds, and annual average weekly wages from the Quarterly Census of Employment and Wages (U.S. Bureau of Labor Statistics 2020a; accessed 10 January 2019) were used. The following North American Industry Classification System (NAICS) codes were used to determine the number of workers in high-risk industries/sectors: NAICS 11 for agriculture, forestry, fishing and hunting; NAICS 23 for construction; NAICS 31-33 for manufacturing; NAICS 21 for mining; NAICS 48–49 for transport, and NAICS 22 for utilities (U.S. Bureau of Labor Statistics 2020b; accessed 10 January 2019). The 2016 fraction of workers in high-risk industries was used for each county. National average wages range from US$ 19.0 per hour for agriculture to US$ 44.90 per hour for utilities and are spatially heterogeneous across the United States. Accounting for the affected economic sectors, largely manufacturing and construction, these losses are valued at US$ 449 (73–601; 95 per cent confidence interval) million. At the state level, the largest impacts are in Texas, US$ 141 million; Arizona, US$ 32 million; and Florida, US$ 24 million, with impacts generally larger in warmer states.

The second method for estimating of labour losses due to extreme heat was applied globally. Hours of reduced work availability calculated using this method were valued based on hourly wage data for the affected work areas from the ILO (ILO 2020; accessed 2 September 2020). This dataset provided enough detail to attribute wages to the three labour categories described previously (light, medium and heavy) for 131 countries. The hourly wage data provided by ILO varies from country to country, ranging from 2014 to 2018, and were converted to US dollars based on national purchasing power parity. For the United States, the latest year, 2015, as reported by ILO was used, adjusted to 2018 US dollars. For the United States, the labour loss reductions from a 50 per cent decrease in anthropogenic methane concentrations were 44.1 million hours. These losses are valued at US$ 531 million per year (360–702; 95 per cent confidence interval), similar to the results using the first method. This similarity, however, is largely coincidental as the labour losses are much larger in the second method but that is offset by markedly lower hourly wages across all sectors in the United States in the ILO dataset relative to government statistics. There are also differences in the employment sectors affected. The strongest effects in the first method are in the manufacturing, construction and transport sectors. In the second method, there are again significant impacts in construction which is considered part of the heavy outdoor work category, the category that represents the vast majority of impacts, but there are no impacts on manufacturing or transport due to the assumption of a lower WBGT for these sectors as they are considered indoor medium work. Hence the labour loss results are quite sensitive to the wage dataset used and the methodology employed.

The global total using this second method was a value of US$ 8.5 billion (3.1–13.8; 95 per cent confidence interval) for the half anthropogenic methane reduction, corresponding to value of US$ 63 per tonne of methane (US$ 23–103 per tonne). Effects are large in both hot and humid countries where the hours lost are greatest such as Brazil, China, India and Indonesia, but also in some less sensitive but wealthier countries such as Australia, the United States and the United Arab Emirates (Table 3.10; Figure 3.17). The total is substantially larger than valuations associated with ozone-related morbidity outcomes across all countries with estimates of accident and emergency department visits for asthma and hospital admissions but is similarly much less than the value associated with ozone-related or heat-related mortalities. There would be differences in the valuation of the lost labour for men and women, as was seen for the labour hours lost (Table 3.5b). These are not quantified here as the ILO dataset underlying these calculations does not include wage differences by gender.

For changes in crop production, valuation is based upon yield changes multiplied by the 2018 global market prices per tonne from the

United States Department of Agriculture (USDA) and World Bank11 which gives US$ 210 for wheat, US$ 394 for soybeans, US$ 164 for maize and US$ 421 for rice. This provides a fairly simplistic measure of the value of yield changes, as it clearly does not account for benefits such as those to subsistence farmers or national food security. The valuation per tonne of methane is then US$ 11.7 for wheat, US$ 6.6 for soybeans, US$ 6.8 for maize and US$ 13.2 for rice leading to a valuation summing over these four crops of just more than US$ 38 per tonne of methane. For comparison, in prior studies that only accounted for the effects of ozone on yields, the value was US$ 29 per tonne of methane (Shindell *et al*. 2012; UNEP 2011). As climate impacts, predominantly from temperature change, are now included it seems reasonable that the new values is roughly one third larger. While at the global level valuation of reduced risk of premature death dominates all other impacts, crop changes can be of comparable magnitude in some areas depending on the income elasticity used to account for differential income levels across countries. Using an elasticity of 1.0, for example, leads to agricultural impacts in India having a larger valuation than that of the reduced risk of premature death, and a valuation for Brazil that is more than half that of the reduced risk of premature death (Figures 3.15 and 3.18). It should be note that there are additional potential effects from air quality that were not included here, such as changes in forestry yields, tourism or depreciation of man-made materials. The valuation of the impacts of ozone resulting from methane emissions on forestry have been evaluated as ~US$ 20 per tonne of methane, based on a global extrapolation of a United States analysis (West and Fiore 2005).

Finally, the effects of climate change using a social cost framework was assessed. Social costs of climate change attempt to account for all the effects of climate, including both market and non-market costs, but ignore the effects of air pollution. This makes it challenging to compare with the values in this analysis as the agricultural impacts included, for example, are the result of both climate and air pollution changes. There was a clear rationale for excluding air pollution in the original development of social costs for carbon dioxide given that emissions of carbon dioxide and co-emitted air pollutants are not necessarily correlated. For example, two similar coal-fired power plants or motor vehicles (with internal combustion engines) could have quite different air pollutant emissions depending on the efficiency of any applied pollution controls such as scrubbers or catalytic converters. Hence conventional practice has been to include the response of air pollutants such as ozone to carbon dioxide emissions when this takes place due to climate change but to exclude the response to co-emissions that takes place via atmospheric chemistry. This has extended not only to social costs, but to broader evaluations of the societal impacts of greenhouse gas emissions such as the US EPA's Climate Change Impacts and Risk Analysis project (US EPA 2015a). With methane, however, this rationale breaks down as methane affects ozone both via climate change and atmospheric chemistry. Following conventional practice and leaving out atmospheric chemical responses therefore means that an intrinsic effect of methane emissions themselves is neglected rather than an effect of a potentially co-emitted pollutant.

Prior analyses of the climate impacts of methane yield a per tonne social cost of US$ 810 (Marten and Newbold 2012) or US$ 910 (Shindell 2015) in 2007 US dollars and using a 3 per cent economic discount rate. Values without discounting, as in the VSL analyses here, would of course be larger but are not standard in the existing literature. The largest climate-related impact in the analysis was the finding that the reduced risk of heat-related premature mortalities in China and the United States alone were valued at ~US$ 230 per tonne, and that a rough estimate of the worldwide valuation was US$ 700 per tonne. Applying 3 per cent discounting to that estimate would reduce the US$ 700 per tonne to US$ 580 per tonne. This analysis therefore suggests that prior estimates of the climate-only social cost of methane are potentially too low. As such, this analysis includes the valuation of heat-related health impacts along with these social costs as they account for damage associated with all other impacts and appear to underestimate the effects of climate change on human health (Carleton *et al*. 2020; Shindell 2015). Here, the mean of the studies mentioned above is used, which is US$ 1 100 per tonne converted to 2018 US dollars and rounded to the nearest hundred. Note that values for fossil methane are slightly higher, by ~US$ 150 per tonne with a 3 per cent discount rate (Shindell *et al*. 2017), due to the climate impacts of the carbon dioxide that is eventually produced by the oxidation of the carbon within the emitted methane.

11. indexmundi.com/commodities

The total valuation per tonne of methane for all market and non-market impacts assessed here is roughly US$ 4 300 using a cross-nation income elasticity for WTP of 1.0 and US$ 7 900 using an elasticity of 0.4 (Figure 3.19) – values are ~US$ 150 per tonne larger for fossil-related emissions. This value is dominated by mortality effects, of which US$ 2 500 are due to ozone and ~US$ 700 are due to heat using the more conservative 500 deaths per million tonnes of methane of this analysis' two global-scale estimates and a WTP income elasticity of 1.0, followed by climate impacts. These numbers are comparable to those reported previously using a social cost framework that incorporated both climate and air pollution related impacts (Shindell *et al*. 2017), though slightly larger as a result of the updated epidemiology underlying the estimates of ozone-attributable premature deaths. Given the dominance of ozone-related impacts that occur immediately in response to methane changes, decaying thereafter with the residence time of methane, these impacts are only weakly sensitive to discounting. For example, the ozone-related impacts over the first 25 years following methane emissions, using 5 per cent annual discounting, are 83 per cent of the value using 2 per cent discounting and the value is 80 per cent over the first 50 years. In contrast, the valuation of a specific impact 25 years in the future using 5 per cent discounting is only 50 per cent of the value using 2 per cent discounting, a proportionality more applicable to the effect of temperature change based on the evaluation of the response averaged over 10–40 years after emissions. Hence roughly two thirds of the total valuation has minimal sensitivity to discounting whereas the remainder would be substantially affected were future benefits to be discounted at a rate other than the 3 per cent assumed here for climate, which is the dominant contributor to the third of impacts sensitive to discounting. Using a discount rate of 5 per cent, for example, the value of benefits would be ~US$ 700 less whereas using a discount rate of 1.4 per cent it would be ~US$ 700 greater.

The total market costs are comparatively small at ~US$ 122 per tonne and stem predominantly from labour losses, agricultural yield changes and forestry losses. In contrast, healthcare costs related to morbidity effects associated with ozone were relatively small, about US$ 1 per tonne, though there are likely to be additional non-fatal health outcomes associated with ozone. It was noted that although discounting is conventionally applied to estimates of mitigation costs (Section 5), the valuation of impacts does not discount future benefits. This is consistent with the usage of impact valuations to assess effects on future generations, especially in the case of climate change related impacts that occur over many decades, and the desire to value welfare of future generations similarly to that of today's population, which implies a near-zero discount rate. This is in contrast to the use of mitigation costs to compare options for the use of capital that employ a variety of discount rates that are not near zero. This issue is discussed further in Section 5. As the valuation of benefits is dominated by the effects of air pollution, and this responds immediately to changes in methane emissions, with impacts tapering off according to the ~12-year methane residence time, these benefits are in any case much less sensitive to the choice of discounting rate than are climate-related benefits.

A prior valuation of the impacts of methane through ozone on agriculture, forestry, and non-fatal health endpoints found a monetized impact of ~US$ 80 per tonne (West and Fiore 2005). This resulted from estimated impacts of roughly US$ 30 per tonne due to both agricultural losses and non-fatal human health effects, along with the ~US$ 20 per tonne due to forestry losses. The agricultural impacts shown in this analysis are larger, consistent with the prior study not including climate impacts – it should also be noted that West and Fiore (2005) also extrapolated globally from limited regional studies in the United States, Europe and East Asia. Their valuation of non-mortality human health effects is markedly greater, however. They again extrapolated from limited studies, in this case in the United States and Europe only, but more importantly included different impacts, namely avoided minor restricted activity days and worker productivity changes in the United States and morbidity impacts in Europe associated with ozone exposure, for both of which there is some, but limited, evidence. Hence the results here are larger for market valuations because this analysis found larger impacts for crops and included impacts on labour, which had a larger influence than not including several of the impacts that contributed most strongly in West and Fiore's 2005 analysis.

Table 3.7a Value of reduced risk of ozone-related deaths per tonne of methane for countries with values greater US$ 10*

COUNTRY	US$ (MILLION)	LOW	HIGH
United States	639	159	1 077
China	390	95	653
Japan	210	57	346
Germany	161	38	278
United Kingdom	133	32	229
India	85	13	149
Italy	74	18	126
Russia	74	18	127
France	72	16	124
Spain	59	14	100
Canada	39	10	67
Netherlands	32	7	56
Brazil	30	6	53
Australia	27	6	48
Korea, Rep.	27	7	45
Belgium	23	5	40
Poland	21	5	37
Indonesia	19	3	35
Mexico	18	4	31
Switzerland	17	4	29
Sweden	17	4	30
Turkey	15	4	25
Argentina	14	3	25
Saudi Arabia	14	4	23
Denmark	14	3	23
Norway	13	3	22
Austria	13	3	22
Portugal	12	3	21
Romania	12	3	21
Greece	11	3	18
Ireland	10	2	17
Czechia	10	2	17
GLOBAL	**2 511**	**598**	**4 264**

Note: income elasticity of 1.0 across countries

Table 3.7b Value of reduced risk of ozone-related deaths per tonne of methane for countries with values greater than US$ 10*

COUNTRY	US$ (MILLION)	LOW	HIGH
China	1 189	291	1 994
India	671	100	1 179
United States	639	159	1 077
Japan	278	75	459
Russia	206	49	354
Germany	191	45	328
United Kingdom	168	40	288
Italy	107	26	180
Indonesia	103	14	185
Brazil	98	21	172
France	92	21	159
Spain	91	22	154
Pakistan	72	14	124
Egypt	64	17	106
Ukraine	57	13	98
Mexico	56	13	94
Poland	49	11	85
Canada	47	12	80
Turkey	47	12	79
Korea, Rep.	41	11	68
Philippines	41	9	72
Argentina	39	9	69
Iran, Islamic Rep.	36	10	60
Netherlands	36	8	62
Bangladesh	35	7	59
Romania	32	7	55
Viet Nam	30	6	51
Australia	29	6	51
Thailand	28	5	50

COUNTRY	US$ (MILLION)	LOW	HIGH
Belgium	27	6	47
Saudi Arabia	25	6	42
South Africa	25	6	43
Portugal	22	5	38
Morocco and Western Sahara	22	5	37
Greece	21	5	35
Sweden	19	4	32
Czechia	18	4	31
Kazakhstan	18	4	30
Malaysia	17	3	31
Myanmar	17	4	29
Algeria	16	4	28
Uzbekistan	16	4	26
Hungary	16	4	27
Nigeria	15	2	27
Switzerland	15	4	25
Austria	14	3	24
Denmark	14	3	24
Serbia and Montenegro	14	3	23
Cuba	14	3	24
Bulgaria	13	3	22
Sri Lanka	13	2	23
Chile	12	3	21
Ethiopia	12	2	22
Peru	12	2	22
Belarus	11	3	20
Norway	11	3	19
Israel	11	2	18
GLOBAL	**5 315**	**1 193**	**9 073**

Note: income elasticity of 0.4 across countries

Table 3.8 Country-specific cost of respiratory hospital admissions attributable to ozone exposure, 2018 US$ per '000 tonnes, 65+ age group

COUNTRY	COST (2018 US$)
United States	83
Germany	54
Italy	46
France	37
China	31
United Kingdom	26
Spain	25
Belgium	6.2
Greece	5.5
Netherlands	5.4
Austria	5.3
Poland	5.2
Norway	4.9
Sweden	4.8
Portugal	3.6
Denmark	3.1
Hungary	1.6
Czechia	1.5
Ireland	1.4
Finland	1.3
Bulgaria	1.2
Romania	1.1
Slovakia	1.0
Slovenia	1.0
Croatia	0.6
Serbia and Montenegro	0.4
Luxembourg	0.3
Lithuania	0.3
Estonia	0.2
Cyprus	0.2
Malta	0.2
Iceland	0.1
Latvia	0.05
TOTAL	**358**

The uncertainty range is ± 84 per cent.

Table 3.9 Cost of asthma-related accident and emergency department visits attributable to ozone exposure, US$ per '000 tonnes for countries with values greater than US$ 5 per '000 tones, all age groups

COUNTRY	US$ PER '000 TONNES
United States	278
Japan	78
India	66
China	52
Spain	49
Korea, Rep.	41
Norway	39
Canada	33
Germany	26
Netherlands	24
Brazil	22
United Kingdom	19
Turkey	18
Australia	15
Sweden	14
United Arab Emirates	13
Russian	13
Italy	12
France	11
Argentina	8.6
Belgium	8.4
Kuwait	5.6
Venezuela	5.5
Colombia	5.1
Austria	5.0
TOTAL	**924**

The uncertainty range is ± 37 per cent.

Table 3.10 Value of labour losses due to heat exposure, 2018 US$, top 15 countries

COUNTRY	COST PER TONNE (2018 US$)
China	32.7
Brazil	5.3
Australia	4.7
United States	3.7
India	2.4
Indonesia	1.7
Viet Nam	1.4
United Arab Emirates	1.1
Philippines	1.0
Thailand	0.8
Qatar	0.6
Malaysia	0.5
Mexico	0.5
Pakistan	0.5
Saudi Arabia	0.5
Global	63

The uncertainty range is ± 62 per cent.

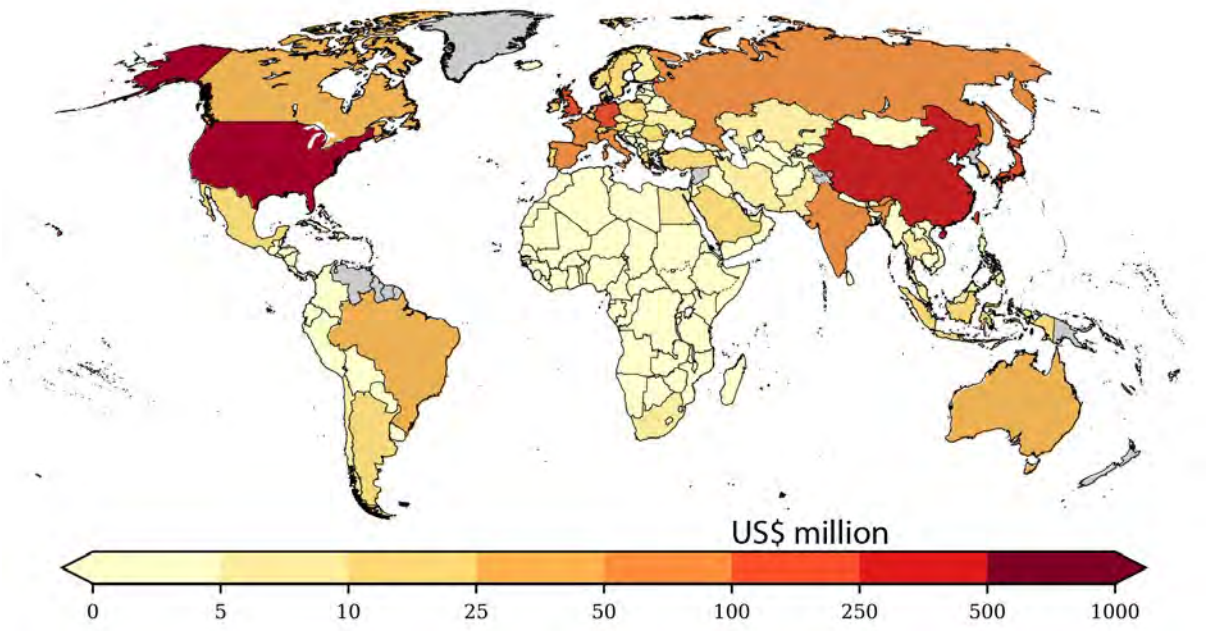

Figure 3.15 Valuation of reduced risk of premature death due to respiratory and cardiovascular illnesses caused by ozone, people aged 30+ per million tonnes of methane emission, US$ millions

Note: Grey indicates no quantification.

Source: UNEP and CCAC

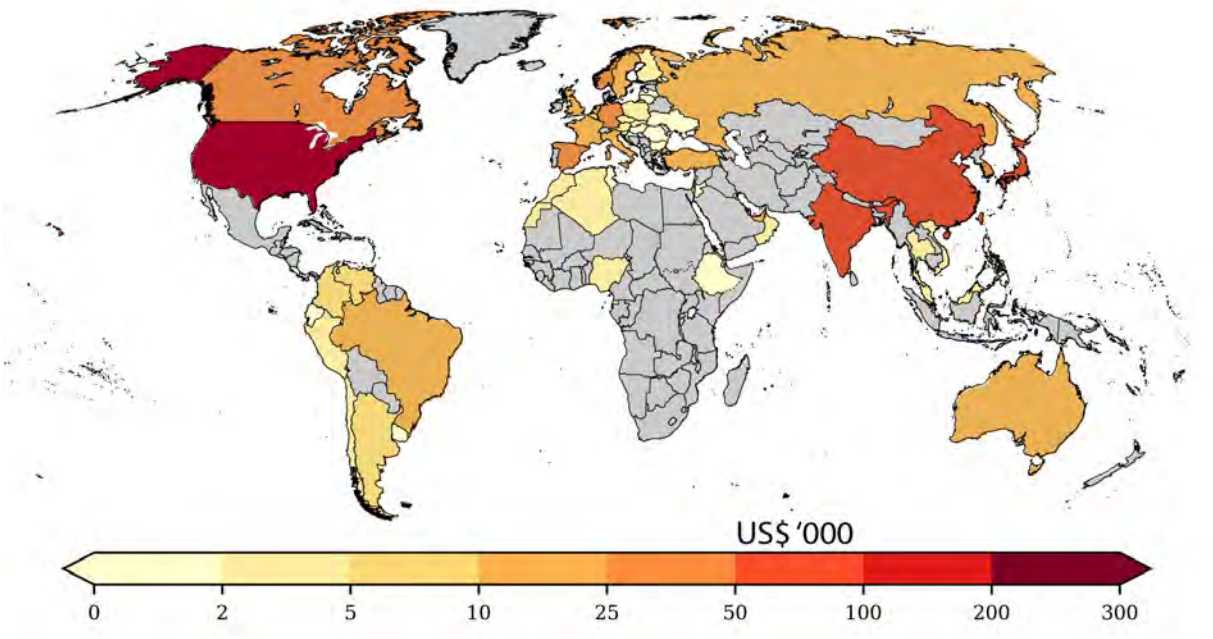

Figure 3.16 Valuation of the change in asthma-related accident and emergency department visits due to ozone exposure change per million tonne increase in methane emissions, 2018 US$ '000

Note: Based on the scaled multi-model mean ozone change. Grey indicates no quantification.

Source: UNEP and CCAC

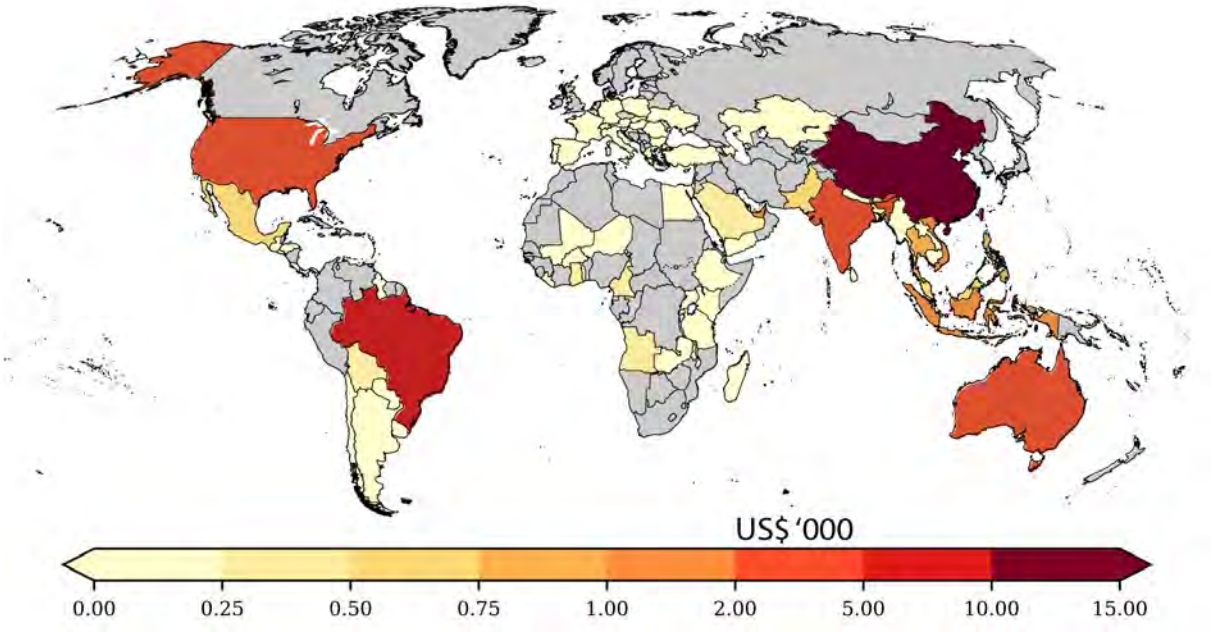

Figure 3.17 Valuation of labour productivity gains due to reduced heat exposure per million tonne reduction in methane emissions, 2018 US$ '000

Note: Grey indicates no quantification.

Source: UNEP and CCAC

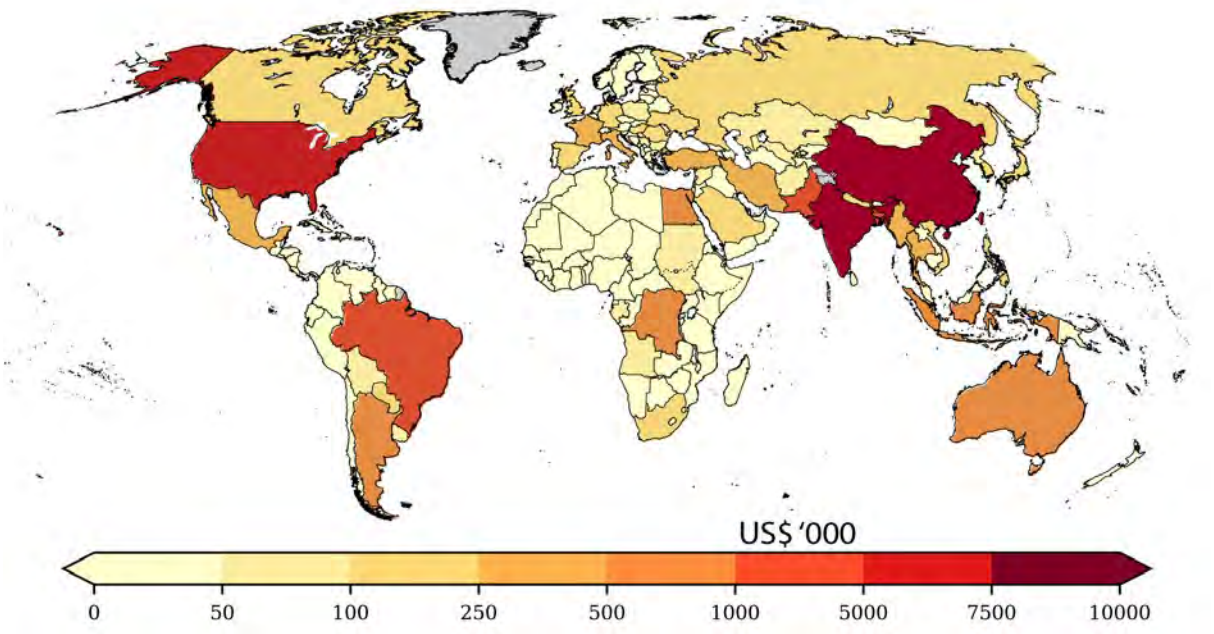

Figure 3.18 Valuation of the avoided yield losses of soybeans rice, wheat and maize per million tonne reduction in methane emissions, 2018 US$ '000

Note: Grey indicates no quantification.

Source: UNEP and CCAC

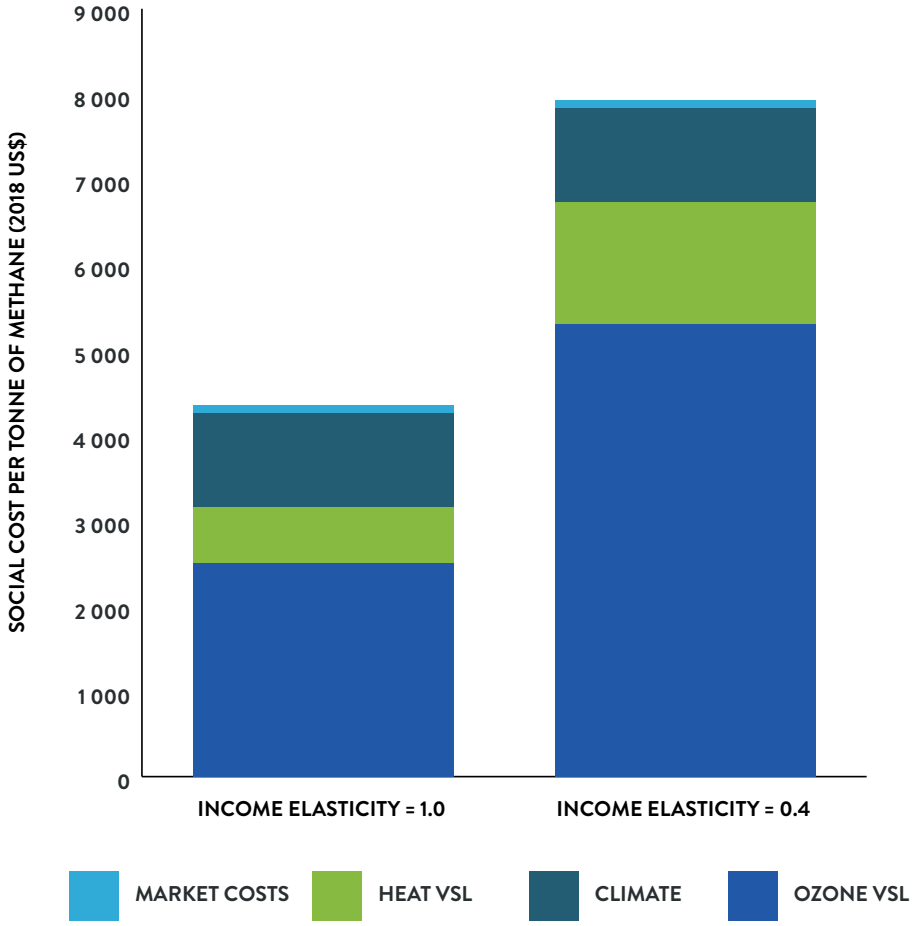

Figure 3.19. Valuation per tonne of emitted methane apportioned to the various impacts quantified in this assessment for the indicated elasticity in cross-nation income comparisons, 2018 US$

Note: Heat VSL and climate impacts are strongly sensitive to the assumed discount rate. Market costs are dominated by agricultural and labour impacts, which are moderately sensitive to discounting.

Source: UNEP and CCAC



4. METHANE EMISSIONS MITIGATION

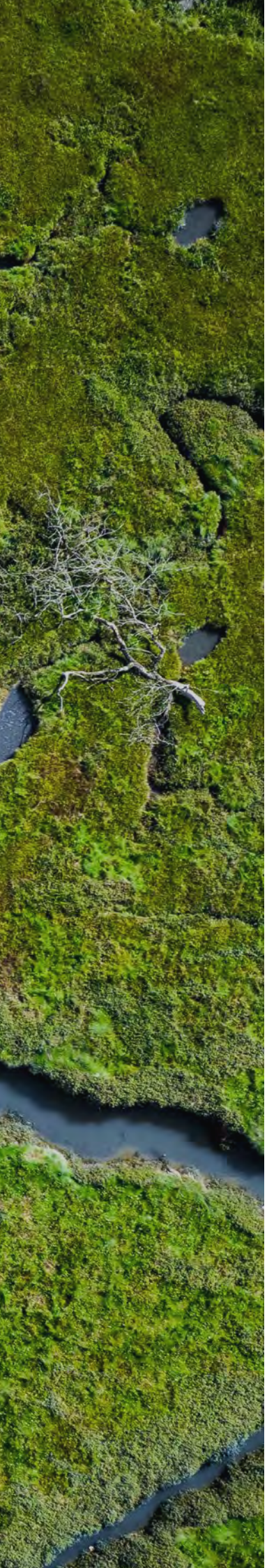

CHAPTER FINDINGS

- In the absence of additional policies, methane emissions are projected to continue to rise through at least 2040 with emissions at the end of the century higher than at present in all but one socio-economic pathway.
- In modelled scenarios consistent with keeping global mean temperatures below the 1.5ºC target, methane emissions are reduced in response to targeted and additional measures by around 100–150 Mt/yr from the fossil fuel and waste sectors combined and by about 30–80 Mt/yr from the agricultural sector in 2030 relative to reference case emissions, with a substantial range across models and across baseline socio-economic pathways.
- Analysis of the technical potential to mitigate methane from four separate studies shows that for 2030, reductions of 29–57 Mt/yr could be made in the oil and gas subsector, 12–25 Mt/yr from coal mining, 29–36 Mt/yr in the waste sector and 6–9 Mt/yr from rice cultivation. Values for the livestock subsector are less consistent, ranging from 4–42 Mt/yr. Average cost estimates vary greatly across the analyses, not only in amounts but even as to whether they are net expenditures or savings for some sectors.
- Targeted abatement measures with a negative cost could reduce total emissions by ~40 Mt/yr with the greatest potential for abatement coming from the oil and gas subsector and the waste sector. Considering only low-cost targeted controls, defined here as less than US$ 600 per tonne of methane, abatement potentials still typically represent a substantial fraction of the total potential, from 60–80 per cent for oil and gas in three of the four analyses, but 36 per cent in the fourth which does not consider negative costs, from 55–98 per cent for coal, and from ~30–60 per cent in the waste sector.
- Considering the potential for mitigation in different sectors and regions, the largest potential in Europe and India is in the waste sector, in China from coal production followed by livestock, in Africa from livestock followed by oil and gas, in the Asia-Pacific region, excluding China and India, from the coal subsector and the waste sector, in the Middle East, North America and Former Soviet Union it is from the oil and gas subsector, and in Latin America from the livestock subsector. A majority of these major abatement potentials can be achieved at low cost, less than US$ 600 per tonne of methane, especially in the waste sector and coal subsector in most regions and for the oil and gas subsector in North America.
- Within the oil and gas subsector, across available analyses mitigation potentials are greatest for oil production, followed by natural gas production and then downstream gas. With regard to reducing emissions from the waste sector, most of the potential is from changes in the treatment and disposal of solid waste.

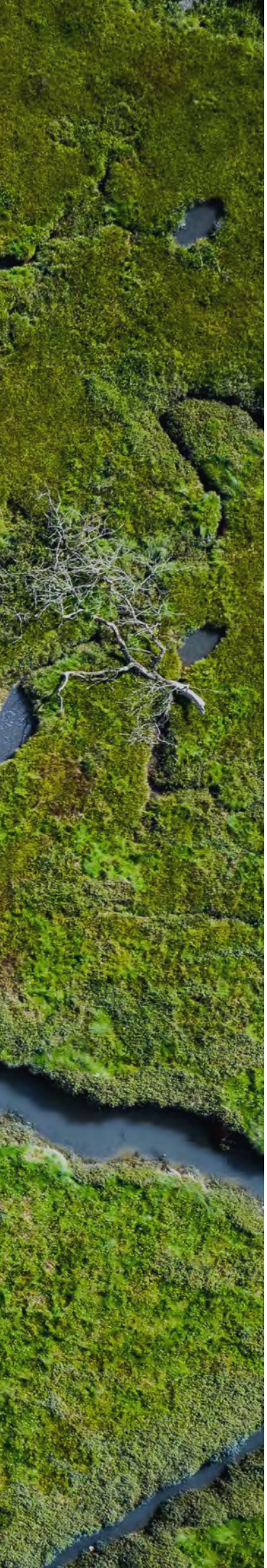

- Achieving climate stabilization at levels that avoid dangerous anthropogenic interference with the climate requires the decarbonizing of economies, which will affect methane emissions. Decarbonization of the economy results in only about 30 per cent of the methane abatement seen under a broad multi-pollutant, multi-policy 2ºC scenario in 2050, however, highlighting the role of methane-specific policies.
- By 2050, emissions from enteric fermentation, especially from cattle, are by far the dominant remaining source of methane emissions in under 2ºC scenarios produced by IAMs as emissions from other sources have been substantially reduced.
- There are numerous financial, legislative and regulatory mechanisms available to support implementation of the identified targeted and additional measures at scale. One commonly employed in IAMs is the imposition of a fairly modest methane tax, which could lead to rapid and substantial decreases in methane emissions, especially from coal, gas and landfills, with abatement of livestock-related emissions highly model-dependent.
- Given the limited technical potential to address agricultural sector methane emissions, behavioural change and policy innovation are particularly important for this sector.
- A relatively robust evidence base indicates that three behavioural changes, reduced food waste and loss, improved livestock management, and adoption of healthier diets, have the potential to reduce methane emissions by 65–80 Mt/yr over the next few decades.
- A web-based decision support tool has been created that allows users to input a level of methane emissions mitigation or select from the analyzed abatement options and view the national and global values for all impacts included in this assessment.

As discussed in Chapter 3, the modelling performed for this assessment quantifies many physical and societal impacts associated with potential changes in methane concentrations. Those changes are evaluated in terms of the corresponding change in emissions using the well-established relationship between methane emissions and concentrations, and the analysis presented in Chapter 3 shows that the impacts are generally well-represented by assuming a linear relationship between emissions changes and impact responses. This chapter examines changes in methane emissions both in scenarios consistent with low warming targets and in response to specific methane reduction policies or technologies. The impacts analyzed in Chapter 3 can then be related to the methane abatement potentials explored here, as is primarily done in Chapter 5.

4.1 METHANE EMISSIONS UNDER BASELINE AND ALL-SECTOR ALL-POLLUTANT MITIGATION SCENARIOS

There are a multitude of internally consistent projections of future methane emissions. Among those, the SSPs that are the result of a coordinated effort by the research community to generate consistent future scenarios that span a broad range of possible societal developments with a variety of IAMs are emphasized (Riahi *et al*. 2016). The underlying storylines include developments in socioeconomics, demographics, technology, lifestyle, policy and institutions. They consist of five distinct narratives, referred to as sustainability (SSP1), middle-of-the-road (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fueled development (SSP5). These scenarios are intended to span a range of challenge levels for both mitigation and adaptation. For mitigation, challenges are rated as relatively small for SSP1 and SSP4, medium for SSP2, and high for SSP3 and SSP5. Each scenario includes a baseline case as well as scenarios with increasingly stringent climate change mitigation goals. To examine the question of how much methane mitigation is achievable and how much is consistent with worldwide targets for climate change mitigation, this analysis is particularly interested in scenarios consistent with the 1.5ºC target as assessed in the 2018 IPCC *Special Report on Global Warming of 1.5ºC* (IPCC 2018; Rogelj *et al*. 2018). Here those scenarios classified by IPCC as either having at least a 50 per cent likelihood of keeping temperatures below 1.5ºC throughout the 21st century and those with a median temperature below 1.5ºC in 2100 but with a 50–66 per cent change of overshooting that value during the century, typically by no more than 0.1ºC, are considered. Many, but not all, of these scenarios were generated within the SSP framework.

Given the wide range of socio-economic assumptions, it is not surprising that projected methane emissions over the remainder of this century vary markedly across the baseline cases for the SSPs (Figure 4.1). Through 2060, emissions are greatest for SSP3 and SSP5, but from 2070 onward they are largest in SSP3 as emissions in some regions continue to grow rapidly throughout the century. This increase is largely driven by agriculture as food demands increase with an ever-growing population that exceeds 12 billion by 2100. Under SSP3, no models were able to produce a 1.5ºC scenario. Models were able to generate 1.5ºC and 2ºC scenarios for the other four SSPs, though not all models could. Given the difference in baseline emissions across those four SSPs, evaluation of methane mitigation under the 1.5ºC or 2ºC scenarios as a fraction of projected emissions therefore depends greatly on the reference pathway. Even for 2030, there are substantial differences across the baselines with SSP4 and SSP5 having emissions of about 490–500 Mt/yr whereas SSP1 and SSP2 have emissions of about 390 Mt/yr. It should be noted that these also diverge by around 40 Mt/yr in 2020, reflecting uncertainties in current methane sources, as discussed in Chapter 2, and that the divergence is substantially larger in 2030.

Most 1.5ºC scenarios are in agreement with recent observations for methane amounts (Figure 4.2). This is in contrast to the older representative concentration pathways (RCPs) that do not capture recent trends (Nisbet *et al*. 2020), with the better performance of the SSPs unsurprising as they were created later when these observations were known. This analysis has screened out the few scenarios that do not agree with observations made in the past decade for methane. The scenarios included in this assessment come from seven distinct IAMs, though not all provided all diagnostic outputs.

The 1.5ºC scenarios show marked declines in methane amounts over the coming 20 years (Figure 4.2). These are achieved by lowering emissions in the current decade from the agriculture, forestry and other land-use category, the waste sector and especially the energy sector (Figure 4.3). All decrease energy- and waste-related emissions and all but one decrease emissions from agriculture, forestry and other land-use. In all three sectors there are large variation across models and scenarios. For the agriculture, forestry and other land-use, the average reduction in emissions in 2030 is 22 per cent compared with 2020, with a standard deviation of 18 per cent across models and a full range of 0–51 per cent. For the energy sector, the average reduction of emissions in 2030 is much larger at 59 per cent relative to 2020, with a smaller standard deviation of 14 per cent across models and a full range of -29 per cent to -82 per cent. For the waste sector, the average reduction of emissions in 2030 is between the other two at 34 per cent relative to 2020, with a substantial standard deviation of 23 per cent across models and a full range of -6 per cent to -78 per cent. The average reduction in the total from these three sectors is 37 per cent reduction in anthropogenic methane emissions in 2030 relative to 2020. Hence the 1.5ºC

scenarios provide a wide range of estimates of potential methane mitigation relative to the present. Assuming the relative mitigation across subsectors is similar to that reported for most of these same IAMs under 2ºC scenarios in 2050, this translates to average 2030 reductions of about 20 per cent for enteric fermentation, 22 per cent for manure management and 30 per cent for rice cultivation. For energy and waste, estimated reductions are about 75 per cent for coal mining related emissions, 60 per cent for oil and natural gas, 65 per cent for landfills and 45 per cent for sewage.

Analysis of the SSPs, which include some 1.5ºC scenarios but not the full dataset shown in Figures 4.2 and 4.3, provides estimates of mitigation potential in a given future year relative to the reference case emissions for that year. Despite reference emissions varying greatly across the SSPs, mitigation in 2030 is fairly consistent across them (Figure 4.4). Examining the mean across IAMs, excepting SSP4, for which there is only one model that produced a 1.5ºC scenario and that model's results also do not vary greatly across SSPs, methane abatement is around 50–70 Mt/yr- for land-use, primarily agriculture, and around 120–130 Mt/yr for the energy and waste sectors combined. There is a large range of results across the different IAMs, however, which show mitigation levels that differ by up to a factor of about seven in land-use and about two and a half in the energy and waste sectors combined. For SSP1 and SSP2, for which at least four models produced 1.5ºC scenarios, the range for land-use mitigation in 2030 is in the range of 17–125 Mt/yr whereas for the energy and waste sectors combined the range is 69–192 Mt/yr.

Fuel switching plays an important role in the decreases in methane emissions from the energy sector in most of the IAMs. Transitioning to renewables, for example, would in the long term remove the bulk of methane emissions, and is what happens in most IAMs in order to achieve stringent mitigation targets. This does not happen, however, in all pathways consistent with low warming targets. The scenarios examined in 2018 IPCC *Special Report on Global Warming of 1.5ºC* and classified as having no or limited overshoot, for example, found the 25th percentile showed a decrease of 26 per cent in primary energy from gas whereas the 75th percentile suggested an increase of 21 per cent in 2030 relative to 2010 (IPCC 2018). The full range across those scenarios shows a median decrease of 15 per cent in primary energy from gas between 2020 and 2030, but the range is extremely broad, expanding from 105–153 exajoules (EJ) in 2020 to 17–174 EJ in 2030 (Rogelj *et al*. 2018). As a result, there is a possibility that the use of gas, and hence fugitive methane emissions from the gas subsector as well as emissions associated with its extraction, will increase even under aggressive climate change mitigation policies. This is quite distinct from the use of coal or oil, which drop much more uniformly across all potential scenarios. Most of the scenarios that include increases in gas use over the next decades maintain consistency with the stringent climate targets by relying on large-scale negative-emissions technologies in the future to compensate for their high early emissions. This is primarily biofuel energy with carbon capture and storage (BECCS), which does not currently exist at scale, is currently quite expensive though the models project that it might be inexpensive many decades into the future, and requires converting large areas of land to growing biofuel crops rather than food with associated issues around food security, water usage, fertilizer application and biodiversity, which has led to popular protests against even the limited current deployment of biofuel plants without carbon capture and storage. Biofuel energy with carbon capture and storage is also not carbon negative in the short-term and can in fact lead to temporarily increased carbon, when, for example, a forest is cut down for biofuel use (Sterman *et al*. 2018; Holtsmark 2012). Many of these barriers also exist for the carbon capture and storage portion alone, as it similarly does not currently exist at scale and remains expensive. Hence there are multiple risks that this technology will not work, will be too expensive, and/or will have so many side effects that society will not want to use it. Those scenarios also generally overshoot the 1.5ºC target substantially, only returning to an appropriate level towards the very end of this century.

Scenarios that do not overshoot the target or rely heavily on biofuel energy with carbon capture and storage generally feature a shift away from gas to renewables, but in a small number of those use of gas goes up over the current decade as well. In those pathways, afforestation can be very large and carbon capture and storage is eventually applied to natural gas plants, turning them in to approximately carbon neutral power sources. This technology does not raise the issues of water and land use associated with biofuel energy with carbon capture and storage, but does still assume that carbon capture and storage technology drops dramatically in price so that it becomes fairly inexpensive to have gas with carbon capture and storage before mid-century. Thus, there is still a range from

steep declines in gas usage for primary energy to substantial increases through 2030, though the typical values across those scenarios are decreases of ~15–30 per cent, with the largest decreases being about 85 per cent. When the analysis is restricted to only those scenarios in which the average 2040-2060 BECCS and afforestation values are fairly low (less than 5.0 Gt CO_2/yr and 3.6 Gt CO_2/yr, respectively), global production of gas has to decline annually by ~3% over 2020-2030 to be consistent with a 1.5° C pathway (SEI *et al.* 2020). This corresponds to a decrease in gas usage by roughly one-third by 2030, whereas current plans and projections are for an increase of ~20 per cent relative to 2020 usage (SEI *et al.* 2020).

It is worth emphasizing the dramatic changes required in scenarios that do not rely on large-scale future deployment of carbon capture and storage, whether for bio or fossil fuels. Analyses show that without large amounts of carbon removal, given the large reduction in gas usage required under low warming pathways even the current fossil fuel infrastructure is incompatible with the world's climate targets, with the situation much worse when planned additional fossil fuel energy sector infrastructure is also considered (Shearer *et al*. 2020; Pfeiffer *et al*. 2018). This implies that use of current power plants would have to be curtailed either by early retirement or a reduction in usage and construction of additional fossil capacity halted in the absence of large-scale carbon removal in order to meet the well-below 2°C target.

In addition, a transition away from fossil fuels could still leave abandoned infrastructure. There were more than 3.2 million abandoned oil and gas wells in the United States alone in 2018, which emit ~0.3 Mt/yr of methane according to the US EPA (US EPA report to UNFCCC; 2020). That agency acknowledges that this figure is likely a large underestimate due to incomplete data. Similarly, The International Institute for Applied Systems Analysis (IIASA) estimates that 2020 emissions of methane from abandoned coal mines around the world are just over 3.5 Mt/yr (Höglund-Isaksson 2020).

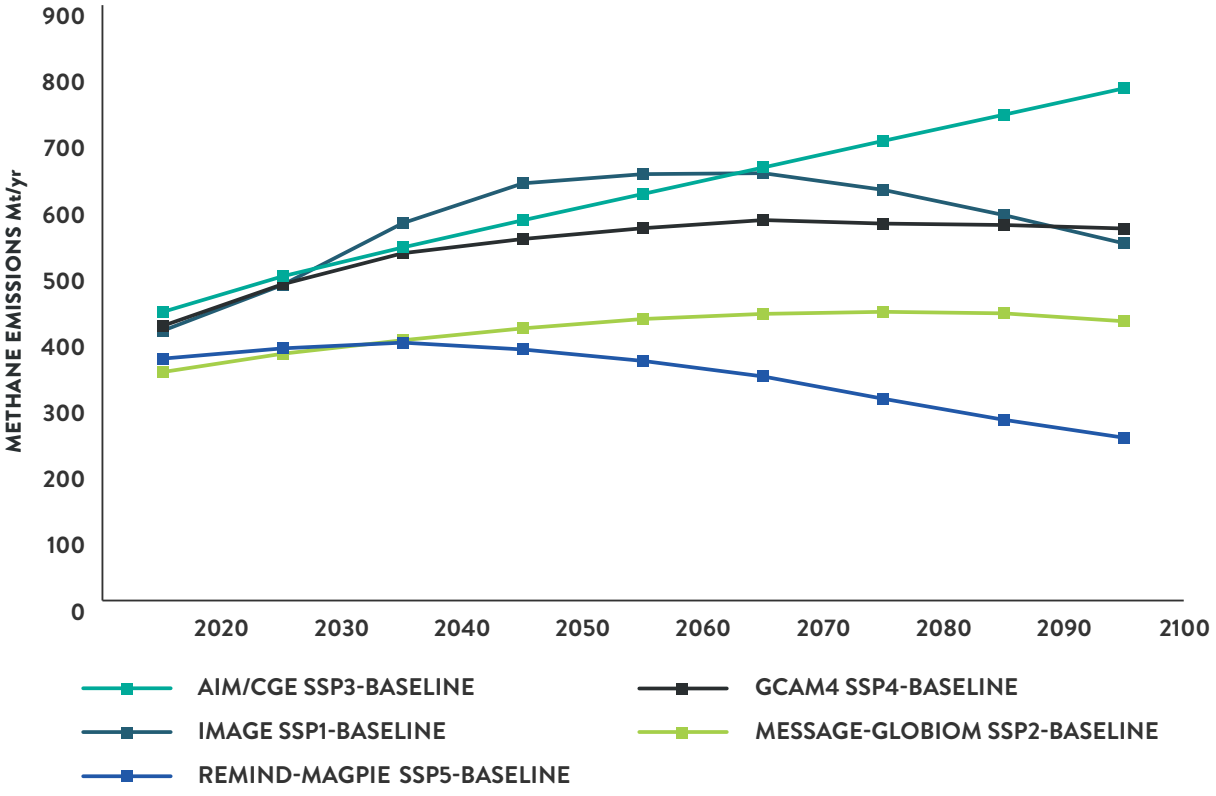

Figure 4.1 Estimated global total anthropogenic methane emissions under the five shared socioeconomic pathway baseline scenarios, 2020–2100, million tonnes per year

Values are shown for the marker scenario with a particular integrated assessment model's results chosen as a representative example for each shared socioeconomic pathway.

Source: UNEP and CCAC

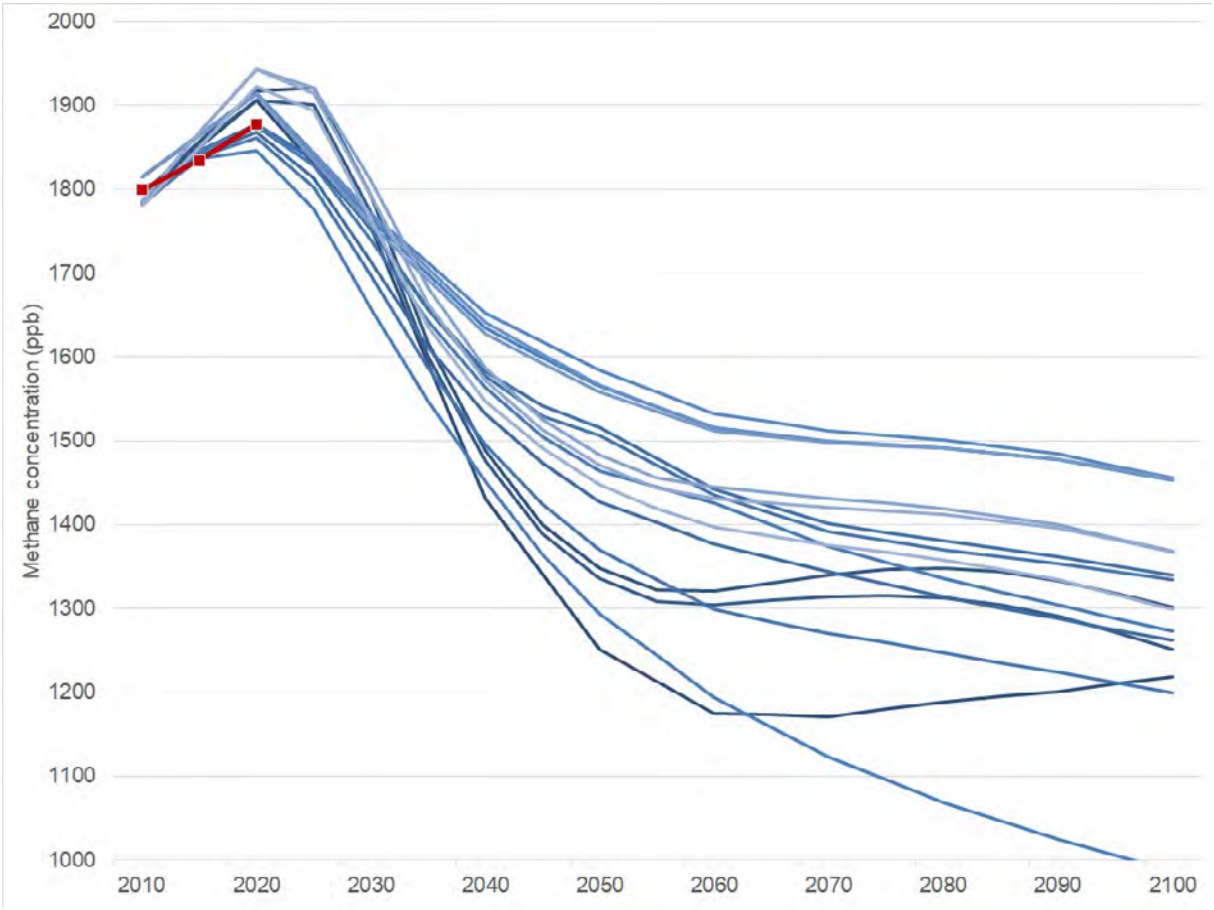

Figure 4.2 Estimated global average methane amounts under scenarios consistent with 1.5°C, and as observed for 2010–2020, parts per billion

Source: UNEP and CCAC



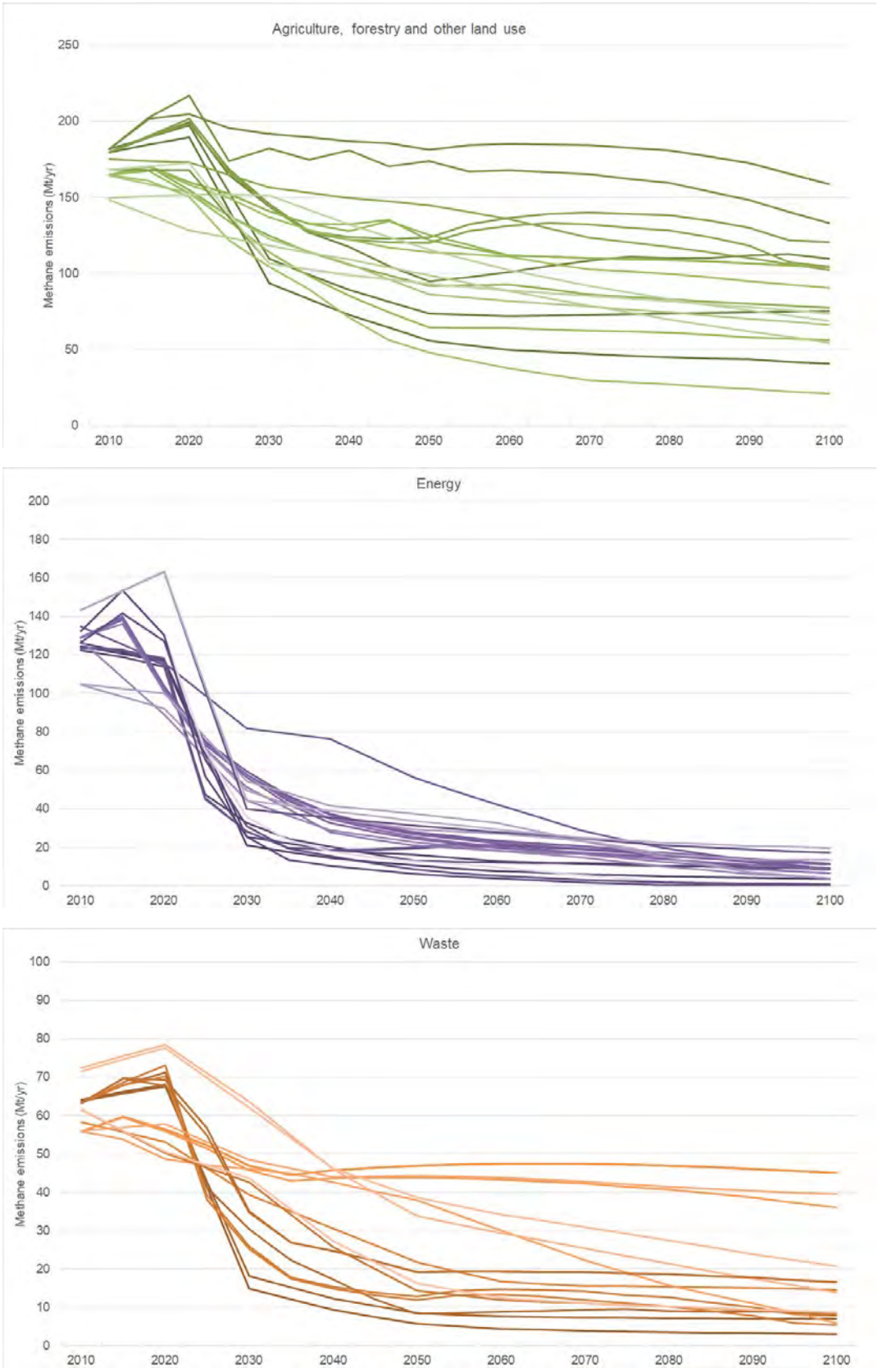

Figure 4.3 Estimated total global anthropogenic methane emissions under scenarios consistent with 1.5°C from the land-use (top), energy (middle) and waste (bottom) sectors, 2010–2100, million tonnes per year

Note: All available scenarios that included all three sectors are shown.

Source: UNEP and CCAC

AGRICULTURE, FORESTRY AND OTHER LAND USE

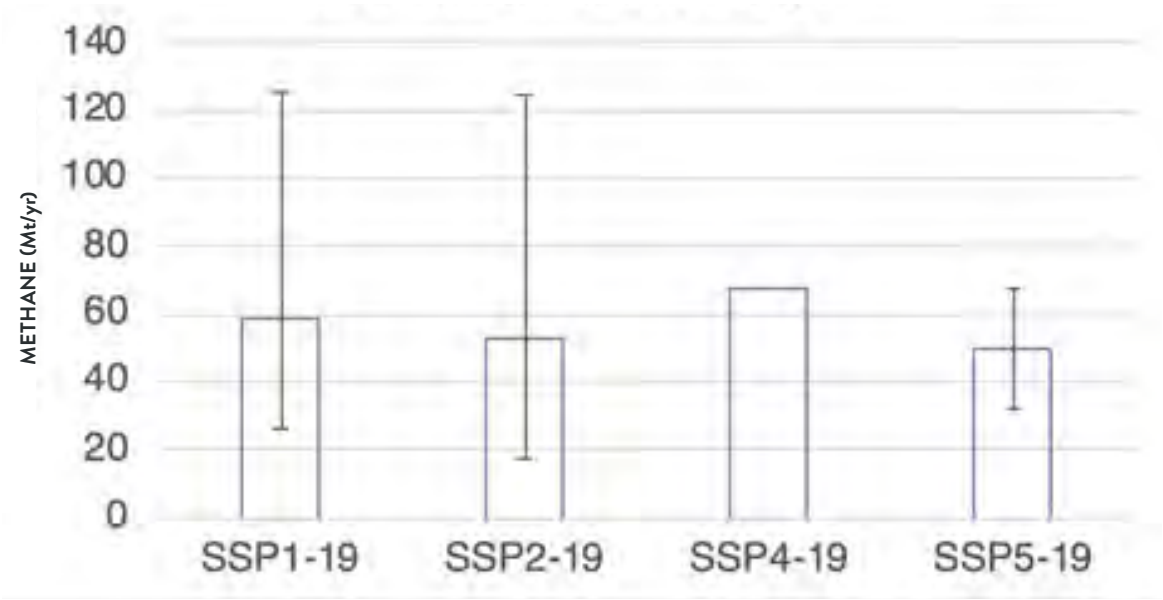

ENERGY AND WASTE

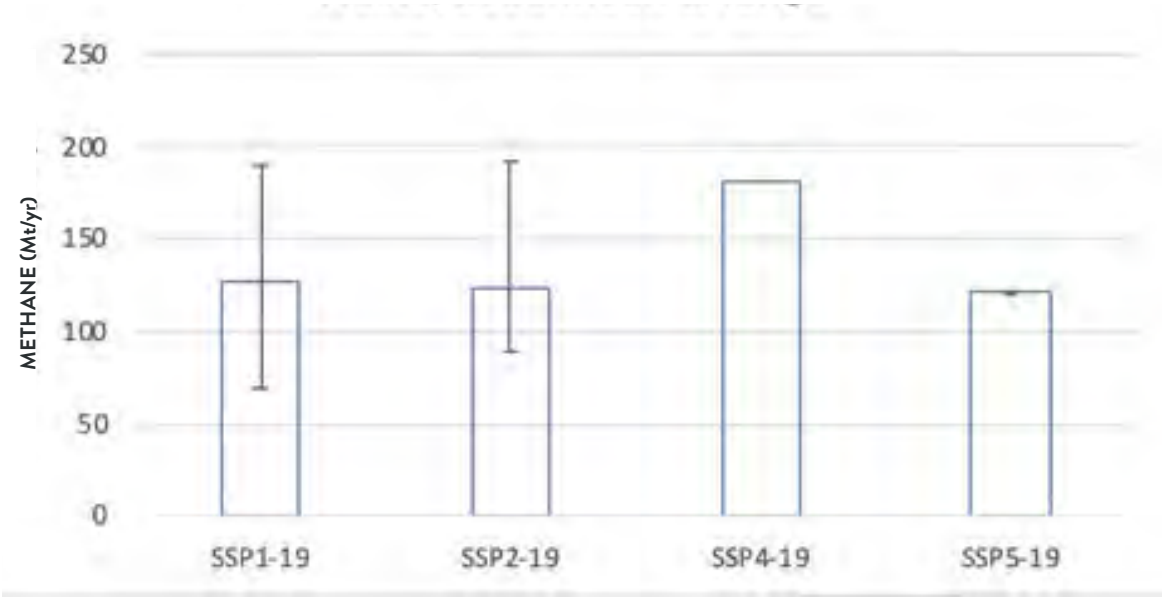

Figure 4.4 Estimates of methane mitigation potential for the land-use (top) and the energy and waste (bottom) sectors under the four shared socioeconomic pathways for which at least one model produced a 1.5°C scenario, 2030, million tonnes of methane per year

Note: Bars show the mean across integrated assessment models and ranges indicate maximum and minimum values – there is no range for SSP4 as only one produced a 1.5°C scenario under that pathway. Similarly, the range is very small for SSP5 as only two models produced a 1.5° C scenario. Agriculture, forestry and other land use includes biomass burning. Energy and Waste includes small contributions from biofuels and transportation.

Source: UNEP and CCAC

4.2 MARGINAL ABATEMENT POTENTIALS AND COSTS BY SECTOR

The methane abatement that takes place in the all-sector all-pollutant climate change mitigation scenarios discussed in Section 4.1 is based in part on abatement cost curves that are incorporated within the IAMs. These encompass methane mitigation opportunities in multiple sectors at a variety of costs, which are examined in detail in this section. Abatement potentials have been analyzed by several teams, including IIASA, US EPA, the International Energy Agency (IEA) and in a literature review by Harmsen *et al*. (2019). These analyses are similar in their aims but differ in coverage and methodology. In particular, the IEA analysis includes only the oil and gas subsector and analyzes present-day abatement potentials associated with targeted control measures (IEA 2020). In contrast, the IIASA analysis covers all sectors and include time-dependent estimates of both changes in baseline emissions and mitigation in which the latter include sector-specific assumptions about technology turnover times, based on the literature, improvements in technology over time and the achievable pace of regulations (Höglund-Isaksson 2020). The IIASA analysis, furthermore, includes discount rates of 4 and 10 per cent in their cost evaluation and extends to 2050. The US EPA produced analyses in 2019 that similarly include projected changes in baseline emissions, extend to 2050, and use a discount rate of 10 per cent in cost estimates (US EPA 2019). Finally, the Harmsen *et al*. (2019) analysis covers all sectors, includes estimates of technology development and the removal of implementation barriers through 2050 as implemented in the Integrated Model to Assess the Global Environment (IMAGE) IAM following SSP2, and uses a discount rate of 5 per cent. This analysis is not entirely independent of the others as it relies upon IIASA data for the fossil fuel sector and earlier US EPA data (US EPA 2013) for the waste sector but implements different projections of future development and so obtains different results even in those sectors as well as in the agricultural sector for which it provides an independent analysis. Note that the IEA documentation does not describe the discount rate used in its analysis.

To create compatible regional analyses, the following changes were made relative to regional results reported by these groups: for the IIASA analyses, Oceanian OECD, China, India, and the rest of Southeast Asia were added to create an Asia-Pacific group; for the IEA analyses, Ukraine was moved from Europe to Russia and the Former Soviet Union and Mexico was moved from North America to Latin and Central America. The data from Harmsen *et al*. and the US EPA was provided at relatively high resolution, allowing its (re)assembly into the regions used in this assessment. Total anthropogenic emissions are estimated to be around 364–380 Mt/yr based on the central values of bottom-up and top-down estimates (Chapter 2). The IEA analysis does not have total baseline emissions as it does not include all sectors. The Harmsen analysis, using the IMAGE model with all sectors, has a value ~390 Mt/yr, similar to the Chapter 2 estimates. The IIASA analyses, without emissions from forest fires and savannah burning or transport, has baseline emissions of ~345 Mt/yr, similar to the analogous value of ~355 Mt/yr based on the source estimates described in Chapter 2. The US EPA baseline emissions, with the same sectors as IIASA, other than the very small source from agricultural waste burning, are substantially lower at ~325 Mt/yr. This value is based on national reporting to the UNFCCC, supplemented with IPCC Tier 1 methods, and this methodological difference is likely the main driver of this much lower baseline. In order to increase comparability across the mitigation analyses and to bring the US EPA estimates in line with the source estimates of Chapter 2, the US EPA baseline and mitigation has been scaled up by 7 per cent uniformly across all sectors, which brings the total to the same amount as the IIASA analysis, the next lowest baseline. Given the large uncertainties in emission source strengths discussed in Chapter 2, it is difficult to classify a particular baseline as inconsistent with observations however, and so this should be regarded as primarily a method to enhance comparability across the analyses. Based on the findings of potential underestimates of fossil-related methane sources based on ice cores discussed in Chapter 2 (Hmiel *et al*. 2020), it is noted that even the scaled US EPA baseline estimates and the IIASA baseline estimates may be biased low, with similar biases carrying over to mitigation.

4.2.1 BROAD SECTORAL ANALYSES

To analyze the abatement potential across broad sectors, these are grouped into five categories for ease of visualization: all oil and gas, coal, all livestock, rice, and all waste. Groups beginning with *all* include multiple subsectors, whereas rice is self standing and coal is related to mining alone, though some analyses do divide this by active and abandoned coal mines. These groupings

are somewhat arbitrary and were chosen in part to reflect data availability – the IEA, for example, does not include coal, precluding their inclusion in a fossil fuel sector. Analysis of results within these groupings is presented in Section 4.2.2.

At the global scale and considering abatement measures regardless of costs, the four analyses all find the greatest potential within the oil and gas subsector, for which 2030 (2020 for IEA) the maximum abatement range is 29–57 Mt/yr. There is greater divergence in the cost estimates than in the mitigation potential, with the average abatement cost being around US$ 1 000 per tonne of methane in the Harmsen analyses, near zero in the IEA analysis, and having a net negative cost of roughly US$ 700 per tonne methane in the IIASA analysis. The average cost in the US EPA analysis is nearly US$ 30 000 per tonne of methane, but this very high value results from a small number of very expensive measures. Restricting the analysis to those measures with costs of less than US$ 25 000 (2018 US dollars) per tonne of methane, which would be US$ 1 000 per tonne carbon dioxide equivalent if using a global warming potential over 100 years (GWP100) of 25, as in the US EPA analysis, reveals 85 per cent of the total abatement potential is available at an average cost of US$2 300 per tonne of methane (Figure 4.5). Though this cost is much lower, it is still higher than those of the other three analyses, which do not incorporate abatement measures costing more than US$ 25 000 per tonne of methane.

The three analyses that included the waste sector find very similar mitigation potentials of 29–36 Mt/yr but very different cost estimates that range from the most expensive (Harmsen) to the largest net negative costs (IIASA), for which there are several reasons. Firstly, IIASA's mitigation potential considers almost full source separation of organic waste with recycling or energy recovery possible globally. US EPA assumes a gradual shift away from open dumps in developing countries but this appears to be at a slower rate than in the IIASA analysis. Secondly, in the cost estimates, IIASA considers the cost-savings from recycling, energy recovery and use, and the opportunity cost of avoided landfilling. The cost-savings are subtracted from the investment and maintenance costs to arrive at net costs. Average world market prices for recycled materials are used to value cost savings of recycling and expected future gas and electricity prices from IEA are used to reflect the benefit of energy recovery in the waste sector. The US EPA uses generally similar methods, but the larger discount rate in their analysis would make net costs higher. Note that the range quoted above is for all measures regardless of costs, but, as with the oil and gas subsector, the US EPA analysis includes a small number of very expensive measures in the wastewater subsector. When these are excluded, the mitigation potential in that analysis decreases from 36 to 32 Mt/yr and the costs become similar to the other analyses for the waste sector (Figure 4.5).

As a result of the above, extremely large discrepancies in the cost estimates result from the use of differing boundaries within the sector, different assumptions about global capacities, potentially different timescales for phasing in mitigation measures, and the inclusion of a small set of extremely expensive controls. It should also be noted that in the case of paper recycling, in the IIASA estimate this is reflected as a gain based the average global market price of recycled paper, but this may inflate the benefits because the market price of recycled paper is often distorted by the pulp and paper industry intervening in the market to keep the price of both recycled and virgin pulp high and stable, at least in some regions. The US EPA analysis also includes a price for scrap paper of US$ 140 per tonne.

In contrast, estimates of mitigation options for livestock are in fairly good agreement as to the costs but differ markedly in magnitude. In the Harmsen analysis, the mitigation potential is 42 Mt/yr, making it the second largest potential, the IIASA analysis is only 4 Mt/yr making it the group with the smallest potential among the five considered here, the US EPA analysis is in between at 12 Mt/yr (Figure 4.5). Average costs are similar at ~US$ 600 (IIASA) or ~US$ 1 000 (Harmsen and US EPA) per tonne of methane. Results for abatement from coal mining are relatively similar across the analyses in both potential and costs, with values of 12–25 Mt/yr[1] and average costs of ~US$ 100–700 per tonne. Finally, the mitigation potential is similar in the three analyses for rice cultivation at 6–9 Mt/yr but, as with waste, costs diverge greatly with the average value being ~US$ 150 per tonne in the IIASA analysis and about 20 times that, ~US$ 3 000 per tonne of methane, in the Harmsen analysis and the US EPA in between at US$ 1 700 per tonne.

The analysis of abatement potential available at all costs is a useful way of characterizing the maximum potential through targeted measures. These results can be highly influenced by a

small subset of very expensive measures, however, as noted previously for the US EPA's oil and gas subsector and wastewater results, and as such it is also useful to examine those measures that can be put into place at a low cost, which is defined here as less than US$ 600 per tonne methane, which would correspond to ~US$ 21 per tonne of carbon dioxide equivalent if converted using the IPCC Fifth Assessment Report's GWP100 value of 28 that excludes carbon-cycle feedbacks.

The abatement potential of low-cost controls is naturally smaller than the all-cost potential, but the difference varies by source group and across the four analyses. For oil and gas subsector, the low-cost measures make up ~80 per cent of the all-cost measures in the IIASA analyses, but only ~60 per cent in the US EPA and IEA analysis and just 36% in the Harmsen analysis. This leads to a large range of mitigation potentials, as in the all-cost case, with low-cost abatement in oil and gas ranging from 18 to 32 Mt/yr. Average costs remain positive in the Harmsen analysis despite the imposition of a low-cost threshold that removes the most abatement, which presumably largely accounts for its much smaller fraction of the total abatement potential falling within the low-cost threshold for the average costs. Average costs are slightly negative in the US EPA and IEA analyses, with IEA having the largest mitigation potential, and strongly negative for the IIASA analysis (Figure 4.6). Around 10–20 Mt/yr in the waste sector can be abated at low cost, though, as with all costs, the differences in scope lead to a large divergence in average costs across the analyses. They are, however, consistent in finding that most coal-related methane emissions abatement comes at low cost, though the values range from 55 to 98 per cent of the total potential. In contrast, the divergence between the three analyses expands for the mitigation potential for livestock when a low-cost threshold is imposed. Computing the mean across the available analyses for each subsector, the total mitigation potential available at low cost is estimated to be about 73 Mt/yr. This is a large fraction of the ~120 Mt/yr available at all costs.

Including only those abatement measures with negative costs reveals that the greatest potential for net economic benefits without accounting for environmental impacts comes from mitigating emissions from the oil and gas subsector and the waste sector (Figure 4.7). This is unsurprising given that many of the control measures for these two sources consist of capture and use of natural gas. Potentials are smaller in the coal, rice and livestock subsectors and as noted previously, divergences in average cost estimates are large for livestock.

Analysis of the nine regions used in this assessment shows marked differences in mitigation potentials. For the all-cost analysis, the largest abatement potentials are as follows: for Europe and India in the waste sector; for China in the coal subsector, followed by livestock; for Africa livestock, followed by oil and gas; for Asia Pacific, excluding China and India, the coal subsector and the waste sector, for the Middle East, North America and Russia/Former Soviet Union (FSU) the oil and gas subsector; and for Latin America the livestock subsector. As with the global analysis, a large majority of these major abatement potentials can generally be achieved at low cost. This is especially the case for waste and the coal subsector, whereas for livestock the costs are quite dependent on the abatement analysis. The bulk of the abatement in the oil and gas subsector can also be achieved at low cost for North America in all four analyses, but for Russia and the Former Soviet Union this is the case in three of the four with one finding only about a third of all cost mitigation is available at low cost. For the Middle East, two of the analyses found 70–80 per cent of mitigation is available at low cost whereas the other two found less than half was available. Hence there are varying degrees of consistency across the analyses, but in most regions, it is clear where the largest methane abatement potential lies.

The total mitigation potentials analyzed here are a large fraction of the total emissions. For waste, the ~30 Mt/yr all-cost reductions represent roughly 40 per cent of the estimated 2030 emissions. For fossil fuels, the ~60 Mt/yr all-cost mitigation potential is likewise about 40 per cent of the estimated 2030 total. For agriculture, however, targeted measures make a smaller and less robust percentage contribution, with the analyses providing estimates of about 10, 15 and 35 per cent of estimated 2030 emissions from this sector (~10–50 M/yr).

This assessment focuses on the abatement potential for methane in 2030. The mitigation potential analyses of IIASA, Harmsen and the US EPA extend further into the future, and we also compare worldwide potentials in 2030 with those estimated for 2050. Though all three analyses include projected changes in baseline emissions and technological progress, there are much larger differences in 2050 values relative to their 2030 equivalents in the IIASA analysis than

in the Harmsen or US EPA analyses (Figure 4.8). The greatest differences are seen in the waste sector, in which, in particular for solid waste, the IIASA analysis reports a more than three-fold growth in low cost abatement potential between 2030 and 2050, whereas the growth is only 18 per cent in the Harmsen analysis that is based on the 2013 US EPA estimates and 41 per cent in the 2019 US EPA estimates. As noted previously, this is primarily related to the assumption that regions outside of Europe will continue to landfill waste rather than use source separation. For fossil fuels, there is again an 18 per cent growth in the estimated low-cost abatement potential over between 2030 and 2050 in the Harmsen analysis and a similar 17 per cent growth in the US EPA analysis whereas the growth is 67 per cent in the IIASA analysis.

The IIASA analysis also includes more than a tripling of the all-cost agricultural sector abatement potential between 2030 and 2050, which instead decreases slightly in the Harmsen and US EPA analyses, bringing the results of the IIASA and Harmsen analyses for this sector closer together in 2050. The three analyses still diverge substantially – 20 Mt in the US EPA analysis, 35 Mt of methane according to IIASA and 68 Mt according to Harmsen. They are closer for rice cultivation with 8 Mt in the US EPA analysis, 15 Mt in Harmsen, and 16 Mt in IIASA, but there are large differences in the abatement of livestock emissions; 11 Mt in the US EPA and 16 Mt in IIASA while Harmsen suggests 53 Mt. The difference is in the assessment of the feasible abatement potential for enteric fermentation in ruminants. While Harmsen sees a large potential from replacing low-productivity indigenous cows and cattle globally with imported highly productive breeds, the other analyses only see this as a feasible solution for large industrial farms. For smallholder farmers in Africa and Southeast Asia, they do not see this as a feasible targeted solution without first implementing institutional and social reforms. This is because of the important role that keeping livestock plays in poor farmers' risk management; as assets when access to credits and health insurance schemes is missing.

Changes in average abatement costs for the low-cost measures are small over the 2030–2050 period in all three analyses for the fossil fuel and waste sectors, as well as their underlying subsectors. Projected changes in low-cost abatement potentials are substantial in the agricultural sector in the IIASA analysis while they are small for the other two, but costs in this sector are also not projected to change greatly over time. The large divergence in costs therefore remains with the average costs of low-cost measures across all sectors having fairly small positive values, from US$ 15–200 per tonne of methane, in the Harmsen study which had a minimum cost of zero whereas they are negative in the IIASA and US EPA analyses in which the range is about -US$ 1 000–10 000 per tonne for the global sectoral averages for waste, fossil fuels and agriculture. In 2050, the total low-cost abatement potential is estimated to be about 110 Mt/yr for the average of the three analyses, roughly 50 per cent larger than the 2030 potential.



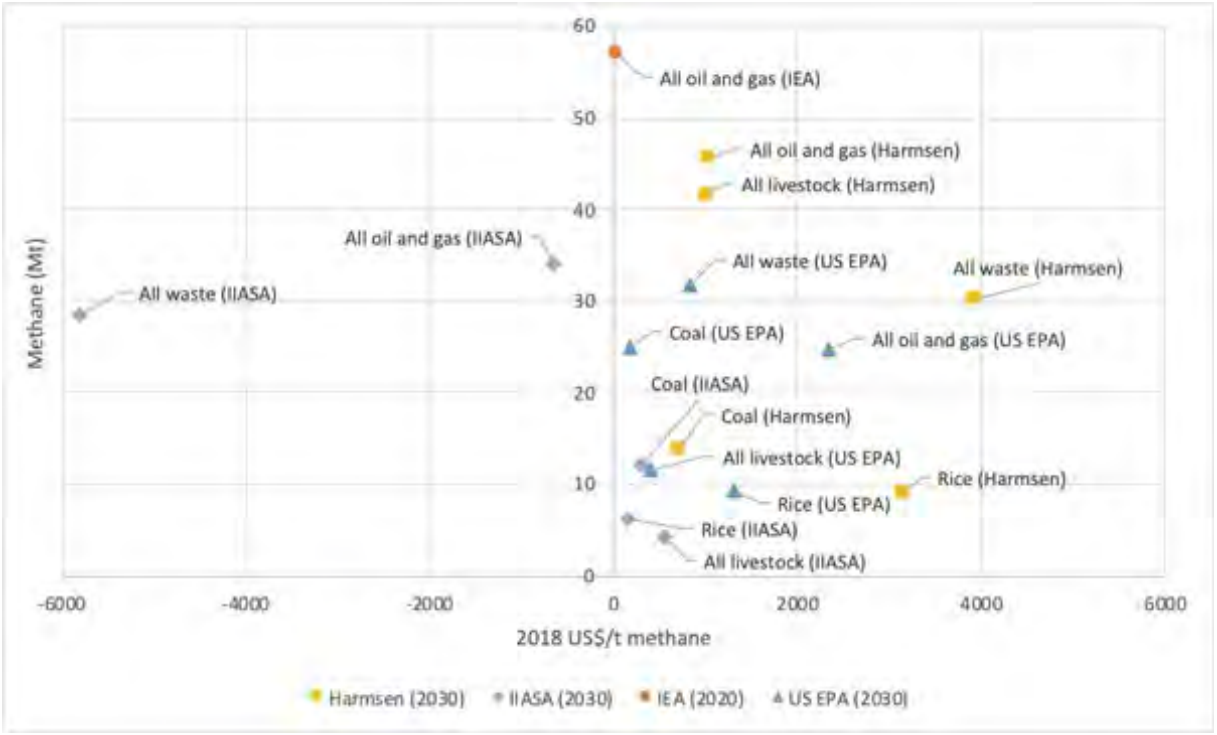

Figure 4.5 Worldwide methane mitigation potential by sector, million tonnes, versus average mitigation cost, 2018 US$ per tonne, from the indicated analyses

Note: All costs of mitigation are included below a US$ 25 000 per tonne of methane exclusion threshold.

Source: UNEP and CCAC

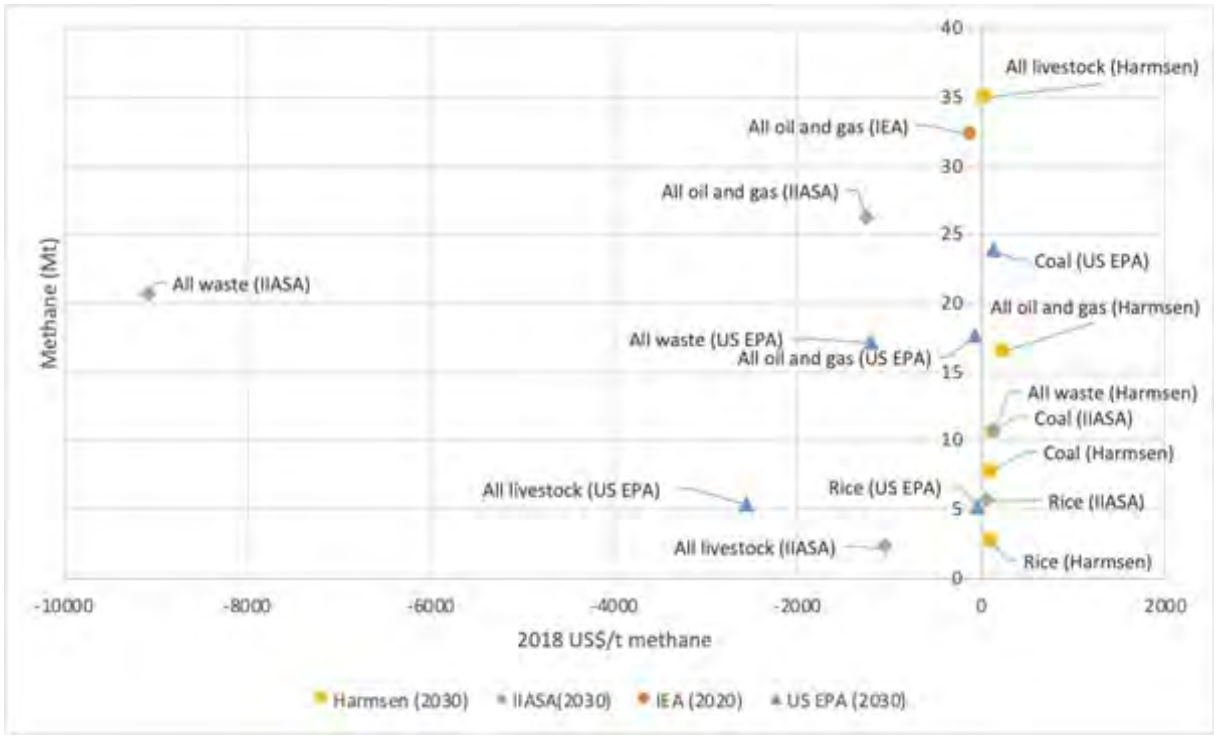

Figure 4.6 Worldwide methane mitigation potential by sector, million tonnes, versus average mitigation cost, 2018 US$ per tonne, from the indicated analyses

Note: Only includes abatement measures that cost less than 2018 US$ 600 per tonne of methane.

Source: UNEP and CCAC

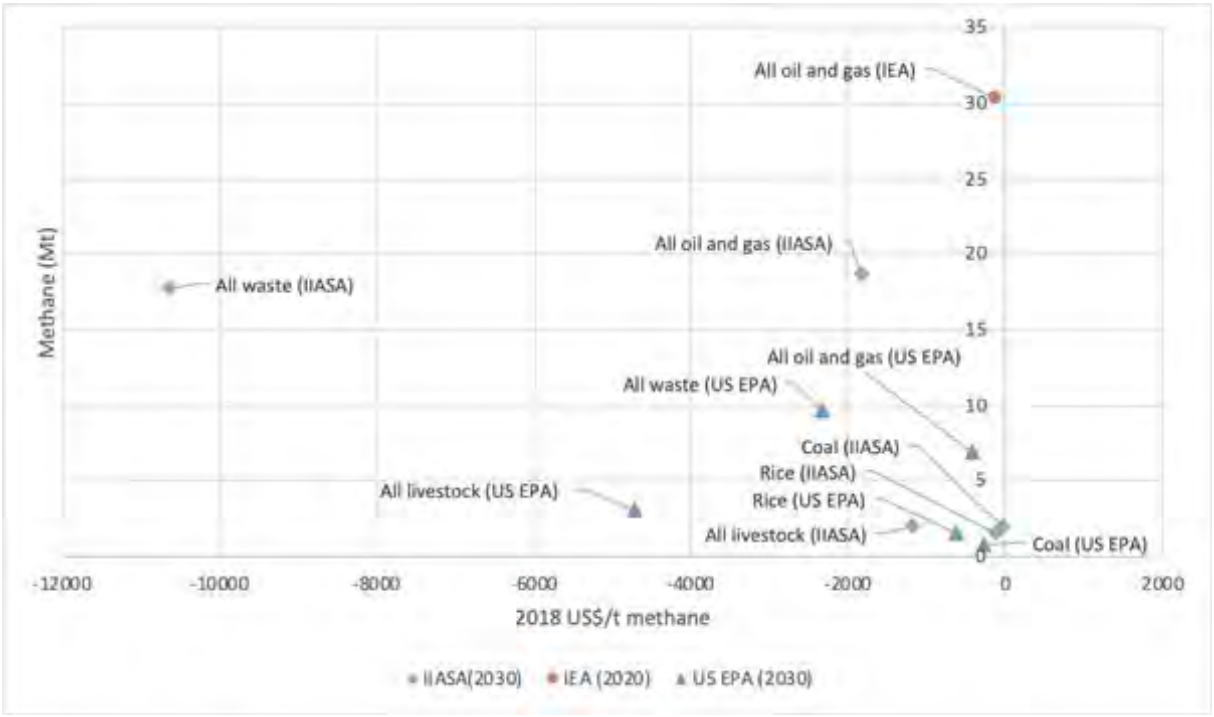

Figure 4.7 Worldwide methane mitigation potential by sector, million tonnes, versus average mitigation cost, 2018 US$ per tonne, from the indicated analyses

Note: Only includes abatement measures with negative net costs.

Source: UNEP and CCAC

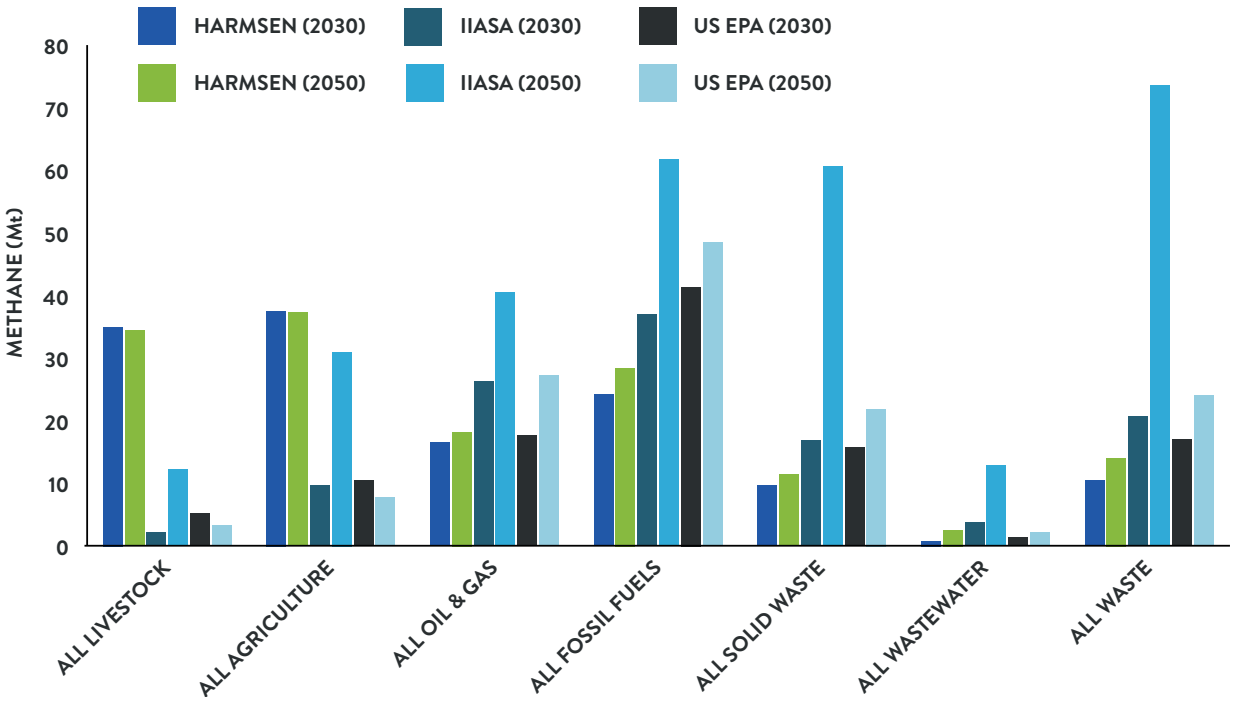

Figure 4.8 Comparison of mitigation potentials in the Harmsen, IIASA and US EPA analyses by sector for measures costing less than 2018 US$ 600 per tonne methane, 2030 and 2050

Source: UNEP and CCAC

4.2.2 DETAILED SUBSECTOR ANALYSES

Within the three of the five categories examined in the previous section, all oil and gas, all livestock, and all waste, there are several subsectors with different abatement potential, techniques and costs. These are explored here, beginning with oil and gas, putting this into context with the fossil sector as a whole, followed by waste and then livestock, similarly putting this into context with the agricultural sector as a whole.

The IEA analysis, which is only available for the oil and gas subsector, estimates that the full application of best available abatement technologies could reduce the oil and gas subsector's methane emissions by approximately 57 Mt annually, 72 per cent of its current emissions. These results are similar to those reported in the Harmsen study with substantially lower potential according to the IIASA and US EPA analyses (Figure 4.9). Within the oil and gas subsector, the IEA analysis finds larger potential in gas whereas the Harmsen and IIASA analyses find larger potential in oil, in the Harmsen case substantially so. The US EPA analysis does not separate oil and gas.

In comparison, mitigation options in the coal sector are slightly smaller than in either the oil or gas subsectors in the IIASA and Harmsen analyses, but the coal subsector potential is larger in the US EPA analysis than in either of those studies. The average of these leads to roughly comparable contributions from oil, gas and coal in the total abatement potential. The total fossil fuel mitigation potential is fairly robust across the three analyses, with the full range captured as 53 ± 7 Mt/yr. The average of the three coal subsector mitigation analyses and the four oil and gas analyses is higher at 58 Mt/yr. This represents from roughly 30 per cent to just over half of projected 2030 emissions from this sector. Looking at only the low-cost measures, the total fossil fuel abatement potential differs more sharply across the three analyses, with values of 24–42 Mt/yr (Figure 4.10) and an average based on the three coal subsector mitigation analyses and the four oil and gas analyses of 37 Mt/yr. Again, it seems that the abatement potential for the low-cost subset of all controls is similar for the three fossil fuels, except in the Harmsen analysis which includes little low-cost abatement within the oil subsector. Specific controls for all sectors applied in the various analyses are listed in Table 4.1.

The IEA, IIASA and US EPA analyses, but not the Harmsen study, all analyzed the portion of identified emissions reductions that could be achieved at a net cost savings. These are particularly large for the oil and gas subsector in which there is a net saving to operators through reduced losses. For this subsector, the portion of total reductions (Figure 4.9) that can be realized at negative cost is 53 per cent in the IEA analysis, 55 per cent in the IIASA analysis, and 25 per cent in the US EPA analysis for the global total in 2030. Though the IEA and IIASA analyses are similar for the global total, they vary substantially for some regions. In Europe, for example, the portion of abatement available at negative cost is only 31 per cent in the IEA analysis, but 87 per cent in IIASA's analysis. The spread is also large for North America, with values of 56 per cent in the IEA analysis and 92 per cent in the IIASA analysis. Russia and the Former Soviet Union has a generally smaller percentage of abatement potential with negative costs, 45–59 per cent, whereas all other regions have more than 70 per cent of emissions abatable at negative costs in at least one analysis. For the coal subsector, IIASA and US EPA, the two analyses with results for the subsector, find that 3 (US EPA) to 17 (IIASA) per cent of identified global emissions reductions can be achieved at negative costs, and again results are more variable at the regional level. For the waste sector, these two analyses differ considerably, with 27 per cent of global emissions reductions having negative costs according to the US EPA analysis and 62 per cent in the IIASA analysis, due to the differing scope of their economic analysis previously discussed.

Additional detail is provided for the oil and gas subsector within both the IEA and IIASA analyses. As shown in Figure 4.9, the IIASA analysis finds substantially less mitigation potential in the oil and gas subsector than the other three analyses, including the IEA. Examination of the components of this subsector shows that the differences are consistent across the components, but the relative differences are largest for natural gas production and smallest for oil production with downstream gas in the middle (Figure 4.11). Some of this discrepancy comes from the inclusion of technology turnover times by the IIASA that is not included in the IEA analysis, as can be seen by examining the IIASA abatement potential in 2050 which is substantially larger as roughly two thirds of the total mitigation potential in that analysis takes place in the 2030s with only on third in the 2020s. The difference between the oil and gas totals in the IIASA and US EPA results relative to the Harmsen results may also be linked to

turnover times, as the Harmsen analyses are based on assessments that are 5–10 years older than the IIASA and US EPA assessments. Harmsen is a review of assessments produced around 2012–2016 while the US EPA and IIASA studies were for 2019 to 2020. This leaves only a ~10-year horizon until 2030 in those analyses versus 15–18 years in the Harmsen study.

Individual abatement technologies were examined at a very detailed level in the IEA analysis. The IEA classifies all emissions from production, gathering and processing of fuels as upstream and all emissions from refining, transmission and distribution as downstream. Their analysis shows that the category with the largest mitigation potential, upstream leak detection and repair (LDAR), is also the cheapest. The bulk of the negative cost benefits are obtained from five abatement technologies, each of which contributes substantial health and climate benefits while simultaneously leading to economic gains even when the value of the environmental impacts is not included (Figure 4.12). The majority of the negative cost options occur in four source categories, onshore conventional oil and gas and offshore oil and gas, whereas abatement within the unconventional oil and gas and downstream categories typically have positive costs. Full application of all abatement technology in the offshore and onshore conventional categories, including individual applications with positive costs, would result in abatement of ~40 Mt/yr of methane emissions, leading to a reduction in global mean surface warming of ~0.05 C and ~45 000 avoided premature deaths annually with an overall negative cost for each of these four production sources – Chapter 5 includes more discussion of socio-economic impacts of abatement. Accounting for the environmental benefits of emissions reductions, all the identified IEA targeted measures have negative net costs. It should be note, however, that the most costly of the measures analyzed by IEA, the installation of flares, would likely lead to increased emissions of black carbon that would have damaging health and climate impacts (Stohl *et al*. 2015).

Within the waste sector, all cost abatement potential is concentrated within the solid waste subsector which has three to six times the potential found in the wastewater (sewage) subsector (Figure 4.9). Totals in the three available analyses are very similar for the full waste sector, so that the full range is captured by 32 ± 4 Mt/yr. Hence this sector has about half the potential of the fossil sector for all cost measures and a much narrower uncertainty range. Evaluating this mitigation potential as a share of projected 2030 waste sector emissions is complicated by a large divergence between them, which were ~70 Mt/yr in the Harmsen and US EPA analyses, whereas there was a much larger value of 114 Mt/yr in the IIASA analysis. Hence although all the studies find similar abatement potential, the share of 2030 emissions from waste estimated to be abatable ranges from just 25 per cent in the IIASA analysis to ~40-50 per cent in the US EPA and Harmsen analyses. For low-cost measures in the waste sector, the analyses are again fairly consistent with all falling within the range 16 ±5 Mt/yr.

Within the waste sector, the IIASA analysis provides additional detail on specific measures. The largest abatement within the analysis is for municipal waste, for which the separation and treatment of biodegradable municipal waste with no biodegradable waste being sent to landfill forms the primary component of the estimated potential abatement. The separation of biodegradable waste is another measure with a negative cost, even without accounting for environmental impacts, with an estimated average value per tonne of methane of ~US$ 8 500 per tonne methane and a global mitigation potential of ~16 Mt/yr. Industrial solid waste also shows significant potential for abatement, ~5 Mt/yr, with again a large majority of that able to be achieved at zero or net negative costs – the average cost is -US$ 6 800 per tonne of methane. It should be noted that, in the IIASA analysis, the vast majority of the waste sector's methane emissions, other than the relatively small subsector of domestic wastewater, can be eliminated by targeted control measures by 2040. The US EPA analysis categorizes waste sector measures differently, but similarly finds many with negative cost. The largest mitigation potential with a negative net cost is nearly 9 Mt/yr for gas capture and usage for electricity generation at an average cost -US$ 1 750 per tonne methane. The largest of the negative costs is for landfill gas recovery for direct use, with an average value of -US$ 3 100 per tonne and an estimated mitigation potential of 2.2 Mt/yr. Among other waste sector measures in the US EPA analysis, flaring of landfill gas and composting are on average low-cost measures, whereas anaerobic digestion, waste to energy, mechanical biological treatment and paper recycling all have average costs higher than this assessment's low cost threshold.

Three of the analyses included the agriculture sector, and as noted previously they differ greatly

from one another. These large differences stem from livestock, as the analyses are in fairly close agreement with mitigation potentials for rice of 6, 9 and 9 Mt/yr for the all-cost abatement potential (Figure 4.9), corresponding to ~20–30 per cent of emissions from this subsector. The analyses differ markedly on the costs associated with rice methane mitigation measures, however, with nearly all the identified potential achievable at low cost in the IIASA analysis, 55 per cent in the US EPA analysis, and less than a third of them in the Harmsen analysis (Figure 4.10). For livestock, the all-cost emissions reductions represent 3 per cent of that subsector's projected 2030 emissions in the IIASA analysis, 8 per cent in the US EPA analysis and 30 per cent in Harmsen's (Figure 4.9), with the differences arising primarily from differing assumptions about the previously discussed plausibility of introducing high productivity breeds to Africa and Southeast Asia as for both rice and livestock the three analyses project similar 2030 baseline emissions. For the small agricultural waste-burning subsector within agriculture, targeted measures are estimated to be able to eliminate emissions completely at no cost in the IIASA analysis, but they will require regulation and enforcement.

Within the livestock subsector, the analyses include changes in management practices and in animal feed. Changes in management may include improving herd health, breeding for improved productivity, and shifts from pastoral to intensive systems for cattle. In the last, additional impacts on biodiversity, those living near intensive operations, and the treatment of the animals themselves need to be considered and are likely to be highly regionally dependent (Gerber *et al*. 2013). In the case of animal feed, options include processing feed grain to improve digestibility and feed supplements including nitrate and tannins (as antimethanogens). Additional feed supplements offer potential for reducing methane emissions from the livestock sector but are currently considered experimental and are therefore not included in most abatement potential analyses. In one study, an artificial supplement given to dairy cows reduces methane production from enteric fermentation by 30 per cent with no adverse effects on milk production and a gain in overall cattle growth (Hristov *et al*., 2015). Widespread application of this practice could lead to significant abatement of methane, potentially of up to 20 Mt/yr (Shindell *et al*. 2017), though the supplement has thus far been tested in only a single small herd. Adding small quantities of the seaweed *Asparagopsis taxiformis*, potentially in combination with *Oedogonium* sp., to ruminant feed has also been found to greatly reduce methane production from enteric fermentation, with decreases of 80 per cent in sheep and up to 99 per cent in cows based on *in vitro* trials (Roque *et al*. 2021; Abbott *et al*. 2020; Vijn *et al*. 2020; Kinley *et al*., 2016; Li *et al*., 2016; Machado *et al*., 2016; 2018). In both cases, further studies are needed to confirm benefits and explore the potential for scaling up these practices as well as fully characterizing potential effects on animal health and the long-term persistence of the identified potential benefits.

All three mitigation analyses for the livestock sector include methane emissions abatement through improved manure management. The primary policy in this area is the adoption of farm-scale anaerobic digesters for manure from cattle and pigs. There have also been analyses of the potential of additives mixed into the manure slurry ponds to reduce emissions, with both widely available acids such as sulfuric or lactic acid (Sokolov *et al*. 2019; Sommer *et al*. 2017; Petersen *et al*. 2014) and commercial products (Peterson *et al*. 2020; Borgonovo *et al*. 2019) having been explored. Both seem to offer the potential to greatly reduce both methane and ammonia emissions based on field studies and sulfuric acidification has been widely used in Denmark primarily to control ammonia. In the rest of the world, however, there has been limited use of such techniques, primarily owing to concerns over the safe handling of the acids and uncertainty regarding the long-term impacts on soils. In terms of mitigation potential, it appears that such practices are likely to achieve roughly the same methane reductions as the application of well-managed anaerobic digestion with biogas recovery that is included in current mitigation analyses. These are therefore not included as separate measures in the IIASA analysis, although they are included in the Harmsen analysis, along with anaerobic digesters, decreased manure storage time, improved manure storage covering and improved housing systems and bedding (Table 4.1).

It is noted that many emissions abatement measures are expected to affect methane while leaving other emissions virtually unchanged; such measures include capture of fugitive emissions or controls on landfills, use of anaerobic digestion for manure, and introducing intermittent irrigation practices for rice. Other measures, however, in particular those that affect people's diets or, especially, livestock are likely to affect emissions of carbon dioxide and nitrous oxide, both greenhouse gases – for example,

the slurry acidification of manure discussed previously may increase nitrous oxide emissions. The impacts of those additional greenhouse gas emissions on global climate could be accounted for fairly easily based on prior modelling of the response to well-mixed greenhouse gases. Changes such as fuel switching or efficiency increases would also affect multiple pollutant emissions, and hence are typically studies with IAMs rather than using MAC curve analyses – efficiency is discussed further in Section 4.3.1. In addition to methane, fuel switching from coal or increasing energy efficiency would reduce carbon dioxide and volatile organic compound emissions and air pollution, switching away from gas would reduce carbon dioxide and volatile organic compound emissions (Fann et al. 2018), and reducing consumption of cattle-based foods would be likely to reduce both carbon dioxide emissions by reducing deforestation, and nitrous oxide emissions through reducing fertilizer use, and hence all these measures would be expected to yield addition benefits through non-methane emissions changes rather than having additional impacts that offset some of those related to planetary warming described in Chapter 3.

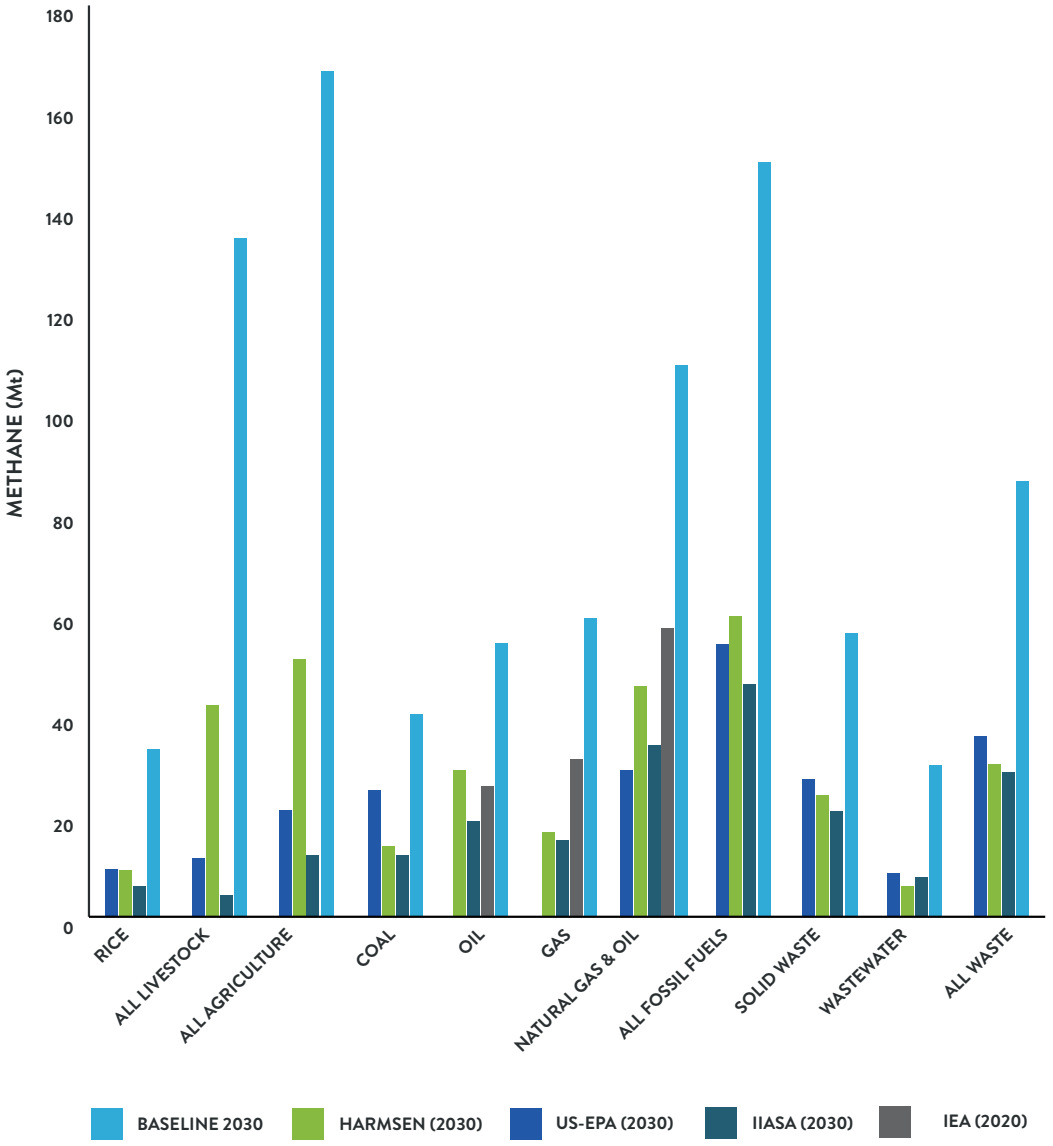

Figure 4.9 Methane emissions mitigation potentials for 2020 for the IEA analysis and 2030 in the Harmsen, IIASA and US EPA analyses including all cost measures as well as the average baseline 2030 emission projected in the IIASA, Harmsen and US EPA analyses

Note: The potential in the IIASA and US EPA studies is based on a 10 year time horizon whereas the Harmsen study has an ~15 year horizon.

Source: UNEP and CCAC

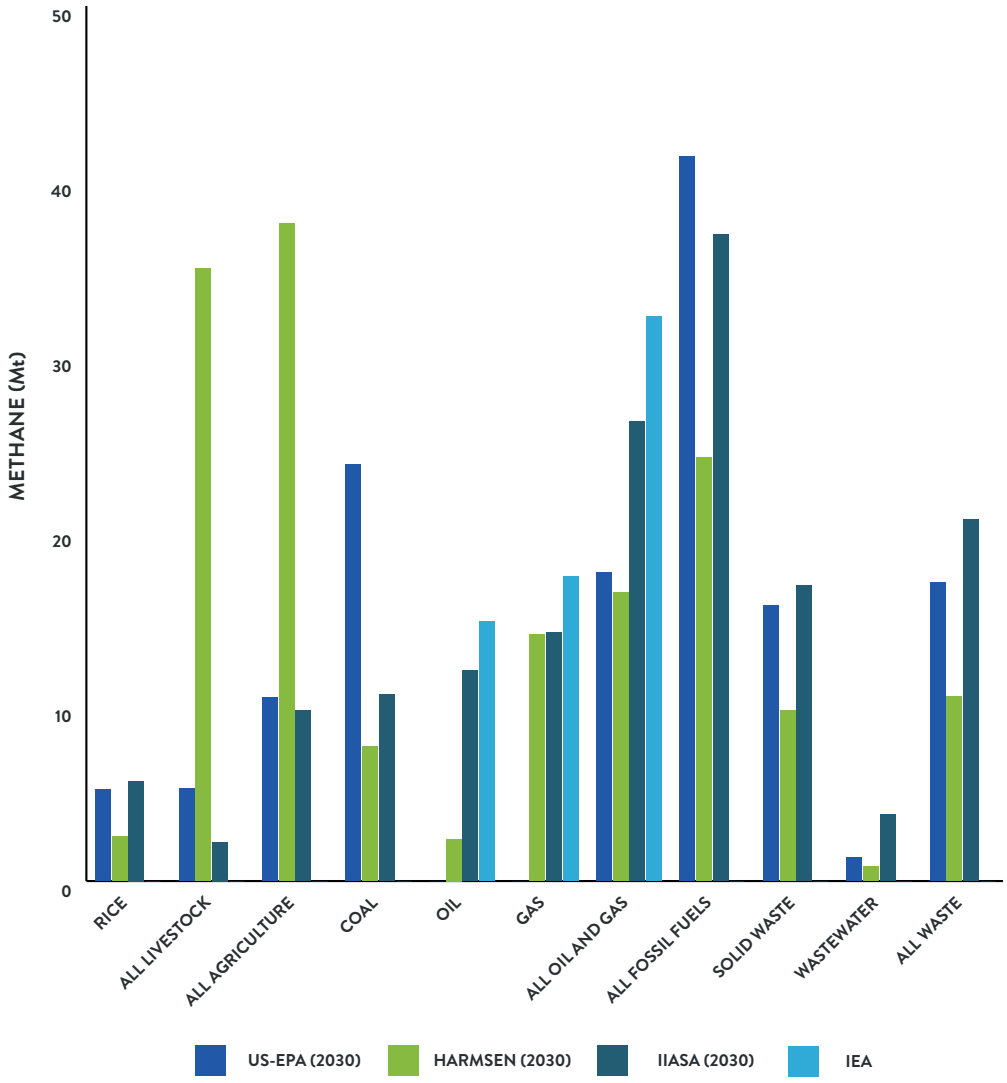

Figure 4.10 Methane emissions mitigation potentials for 2020 for the IEA analysis and 2030 in the Harmsen, IIASA and US EPA analyses for measures costing less than 2018 US$ 600 per tonne of methane

Source: UNEP and CCAC

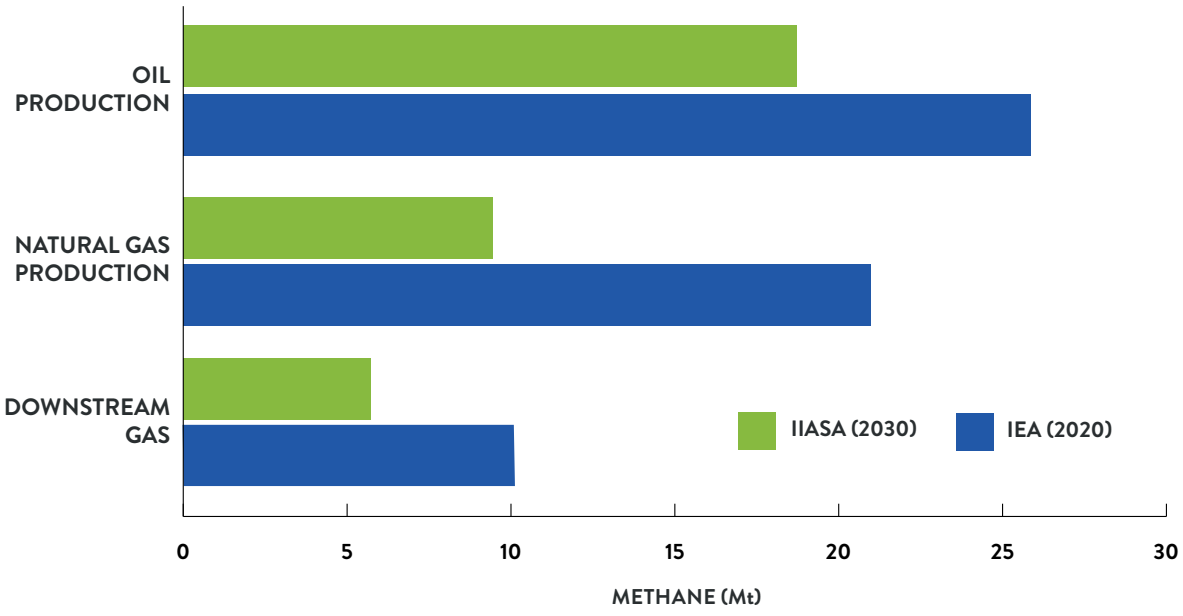

Figure 4.11 IEA estimated mitigation potentials in the oil and gas sectors, million tonnes of methane

Note: IEA potentials are estimated for 2020 while the IIASA values are shown for 2030.

Source: UNEP and CCAC

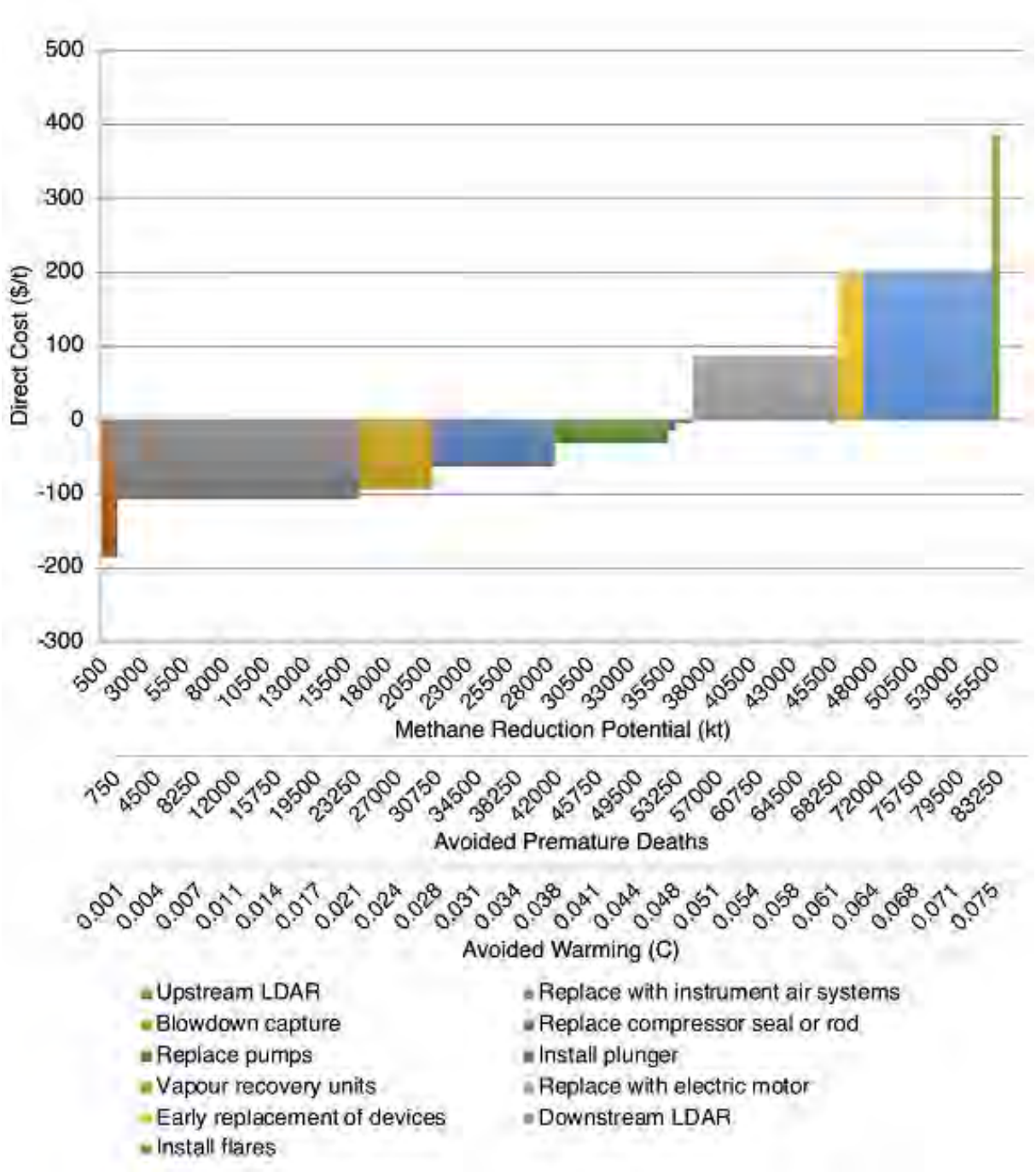

Figure 4.12 Relative savings/costs (2018 US$ per tonne) of targeted methane abatement measures in the oil and gas sector identified by the IEA showing the reduction potential, '000 tonnes; impacts on premature deaths and global mean surface temperature, degrees Centigrade

Source: UNEP and CCAC

Table 4.1 Emissions control measures included in at least one of the mitigation analyses

TECHNICAL CONTROLS		
FOSSIL FUELS	**WASTE**	**AGRICULTURE**
Oil and gas: upstream and downstream leak detection and repair (LDAR).	Municipal solid waste: source separation with recycling/reuse; no landfill of organic waste; treatment with energy recovery or collection and flaring of landfill gas.	Cattle, sheep and other ruminants through enteric fermentation: feed changes and supplements; breeding to improve productivity and animal health/fertility.
Oil and gas: blowdown capture; recovery and utilization of vented gas with vapour recovery units and well plungers; installation of flares.	Industrial solid waste: recycling or treatment with energy recovery; no landfill of organic waste.	Ruminants and pigs through manure management: treatment in biogas digesters; decreased manure storage time; improved manure storage covering; improved housing systems and bedding; manure acidification.
Oil and gas by existing devices: replace pressurized gas pumps and controllers with electric or air systems; replace gas-powered pneumatic devices and gasoline or diesel engines with electric motors; early replacement of devices with lower-release versions; replace compressor seals or rods; cap unused wells.	Residential wastewater: upgrade of primary treatment to secondary/ tertiary anaerobic treatment with biogas recovery and utilization. Wastewater treatment plants instead of latrines and disposal.	Rice cultivation: improved water management or alternate flooding/ drainage wetland rice; direct wet seeding; phosphogypsum and sulphate addition to inhibit methanogenesis; composting rice straw; use of alternative hybrids.
Coal mining: pre-mining degasification; air methane oxidation with improved ventilation.	Industrial wastewater: upgrade of treatment to two-stage treatment, i.e., anaerobic treatment with biogas recovery followed by aerobic treatment.	Agricultural waste burning: ban and enforcement of existing bans.
Coal mining: flooding abandoned mines.		
BEHAVIOURAL AND TECHNOLOGICAL CHANGES		
FOSSIL FUELS	**WASTE**	**AGRICULTURE**
Fuel switching from fossil fuels to renewables/nuclear.		Reduced food waste.
Energy demand management.		Dietary change.
Energy efficiency improvement.		
Emissions pricing.	Emissions pricing.	Emissions pricing.

4.3 ABATEMENT IN RESPONSE TO METHANE-SPECIFIC POLICIES

4.3.1 MULTIPLE INTEGRATED ASSESSMENT MODEL 2050 ANALYSES

The IAMs used to generate scenarios consistent with particular warming targets are designed to achieve those targets at the lowest possible cost considering all sectors, usually all pollutants, and all mitigation options including targeted controls, behavioural changes and directed policies such as taxes. They therefore include many methane abatement measures, as discussed in Section 4.1. Here the methane abatement in those scenarios are compared with the total potential from the analyses discussed in Section 4.2 and with the response seen in IAMs to methane-specific policies.

An analysis of nine IAMs has probed their changes in methane emissions in response to various policies, focusing on the year 2050 (Harmsen *et al*. 2019b), and here the impact of low carbon scenarios on methane in 2050 is also discussed. In the reference cases used in the Harmsen *et al*. (2019b) study, which follow SSP2, anthropogenic emissions are projected to rise from 2010 levels of about 360 Mt/yr to about 460 Mt/yr in 2050. Transitioning to the least-cost mitigation pathway consistent with the 2ºC climate target in those models leads to a decrease in emissions to about 185 Mt/yr in 2050 to, a reduction of about 275 Mt/yr, 60 per cent. This is towards the high end of the emissions consistent with 1.5ºC scenarios shown in Section 4.1, which range from about 60 to 200 Mt/yr in 2050. In contrast, were a climate policy to consider mitigation of carbon dioxide alone, i.e. following a 2ºC-like scenario but imposing an emissions price only on carbon dioxide, the reduction would be only about 80 Mt/yr. Comparison of these results demonstrates that the bulk of the methane reductions under a 2ºC scenario come about from policies targeted directly at methane as opposed to being merely a co-benefit of a strategy focused of carbon dioxide. This highlights that general measures to decarbonize the economy result in only a modest reduction in methane emissions over the near term. In the case of SSP2, the carbon dioxide focused mitigation policies lead to only ~30 per cent of the methane abatement in 2050 seen under a broad 2ºC scenario, and a similar fraction over the longer term with values of 22–48 per cent of the 2ºC abatement in 2100 (Harmsen *et al*. 2019b). This stems from the limited impact of carbon dioxide-focussed mitigation policies on waste and agricultural sector methane emissions as a whole and on end-of-pipe controls for methane on remaining fossil fuel use within the energy sector.

Across sectors, under a 2ºC climate policy the models produce reductions in methane emissions from fossil fuels that are essentially as large as their maximum reduction potential. In contrast, reductions in emissions from agricultural subsectors – manure, enteric fermentation and rice cultivation – are lower than the maximum potential, whereas those for waste – sewage and landfills – are at the maximum in some models but lower in others. Reductions are typically greater than 50 per cent for fossil fuels and landfills, and they extend as high as 95 per cent, but smaller for other sectors, with 25–55 per cent for manure, 15–80 per cent for sewage, 25–65 per cent for rice and about 15–45 per cent for enteric fermentation. Along with these percentage changes, it is important to consider the overall magnitude of each source. Along a 2ºC pathway in the IAMs, emissions from manure, oil, coal and landfills are nearly always 20 Mt/yr or less each by 2050, and emissions from sewage, rice and natural gas are nearly always 35 Mt/yr or less respectively, whereas emissions from enteric fermentation primarily range from about 80 to 140 Mt/yr. Hence enteric fermentation, especially from cattle, becomes by far the dominant remaining source of methane emissions in the IAMs under 2ºC scenarios, even in those with the largest estimates of reduction in that sector – emissions in the very lowest emission example for this sub-sector are slightly more than 60 Mt/yr.

The analysis of methane emissions in IAMs not only explored the response in least-cost multi-pollutant pathways and in the carbon dioxide tax only pathways, but also examined the role of a cross-sector focus on methane (Harmsen *et al*. 2019b). This was accomplished by imposing an economy-wide tax on methane emissions and examining how the models responded. In principle, this is similar to imposing a cap on methane and allowing markets to find the least-cost way of staying within that cap. The tax was imposed from 2020 at a value of 2018 US$ 2 100 × 1.05 to the power of (year-2040) per tonne of methane. This leads to ~US$ 790 in 2020 and ~US$ 1 300 in 2030 greater than the low-cost threshold. Hence these analyses encompass reductions larger than those included in these analyses of marginal abatement potential available at low cost and that covering all costs reported in Section 4.2.

The results show that the models generally respond to a methane tax by most strongly reducing emissions from the energy sector, followed by

land use, largely agriculture, and lastly the waste sector (Figure 4.13, top). Differences between the models are very large, however, especially for the land-use and waste sectors. Delving more deeply into the IAM responses to a methane tax shows that the models typically produce the largest total abatement from the coal subsector, followed, in order, by enteric fermentation, landfills, gas, sewage, rice and oil (Figure 4.13, bottom). Contributions from reductions in energy demand, manure management and agricultural waste burning are small in nearly all models. Model-to-model differences are considerable, however, especially for the fossil fuel subsectors, enteric fermentation and sewage. The AIM model is particularly distinct, with far larger mitigation, ~20–30 Mt/yr in the enteric fermentation, sewage, oil and agricultural waste burning subsectors than any other IAM.

Across sectors, the models on average reduce 2050 emissions by a total of 209 Mt/yr in response to the imposed tax, representing a reduction of about 50–75 per cent in the projected 2050 emissions. The upper end of this range is consistent with the methane reductions in 2°C pathways in these same models, though on average the tax produces a smaller reduction than that which occurs in the 2°C pathways. Naturally these results would be sensitive to the level of the tax imposed in the models, though it is expected that the relative sectoral contributions are fairly robust to the level of the tax.

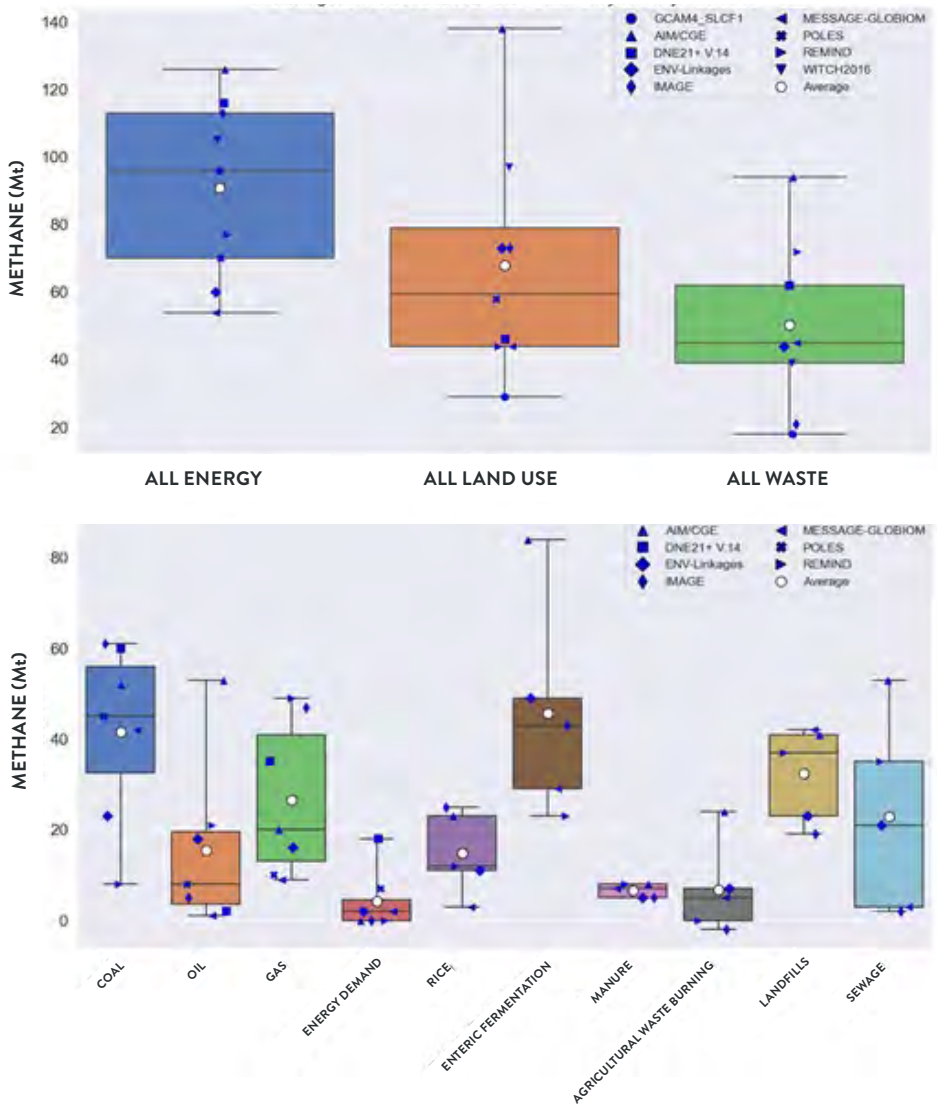

Figure 4.13 Abatement in 2050, relative to the baseline, by sector in integrated assessment model simulations that imposed a methane tax, million tonnes of methane

Note: The horizontal lines within each box are the median values, open circles are average values, filled symbols are individual integrated assessment model results, and the box and uncertainty bar show the 25–75th percentile and full range, respectively.

Source: UNEP and CCAC

4.3.2 2030 ANALYSIS USING THE GLOBAL CHANGE ASSESSMENT MODEL

Though the use of multiple IAMs in Harmsen *et al*. (2019b) provides valuable information about the relative ease of reducing methane emissions from different sectors, that analysis is restricted to 2050 and 2100 and only explored SSP2. Here, additional analyses were therefore performed using an updated version of one of the IAMs included in that study, the Global Change Assessment Model (GCAM), to examine the response in 2030 across multiple SSPs for consistency with the mitigation potential analyses. The GCAM is an IAM that is capable of simulating the dynamics of human-Earth systems and how those systems respond to global changes, such as in population, economic output, energy resource availability, technology performance and climate. The version used was GCAM5.2, as opposed to the version in Harmsen *et al*., GCAM4, that was also used to generate SSPs. The GCAM5.2 is an updated version of GCAM5.1, described in Calvin *et al*. (2019). While earlier versions of the GCAM model focussed more heavily on the energy sector, GCAM 5.2 contains additional detail in other sectors and can better reflect the reality of human-Earth systems. Compared to GCAM4, GCAM5.2 includes a new climate model, new land region and new representations of water supply and demand, regional agricultural markets, and depletable energy resources.

In this study, the environmental and socioeconomic impacts of a global tax on methane are explored. Two baseline scenarios that assume no specific climate policy is in effect were simulated, as well as versions of those scenarios in which the same global methane tax as in Harmsen *et al*. (2019b) is imposed. The differences between baseline and tax scenarios show the effects of the imposed tax for each baseline. The first baseline scenario follows the second shared socioeconomics pathway (SSP2), as in the IAM simulations in Harmsen *et al*. (2019b). No major changes from historical patterns in social, economic and technological trends are assumed in SSP2. To examine the sensitivity to the choice of baseline scenario, the second baseline follows SSP1, a sustainability scenario.

Differing from many other climate policy scenarios that either impose a tax on carbon dioxide or carbon dioxide equivalent, the methane policy scenario involves a global tax specifically on methane that increases by 5 per cent annually. The GCAM separates methane emissions into three categories:

1. methane emissions from agricultural production, including but not limited to rice cultivation and livestock;
2. methane emissions from agricultural waste, including the burning of crop residues; and
3. a general category which covers all other methane emissions.

The methane tax is applied to all three categories simultaneously. The GCAM includes marginal abatement curves for many methane sources, allowing the methane emission factor to be reduced as a function of the magnitude of the methane tax. It also has an option that allows the effectiveness of controls to improve time, representing technological improvement. This analysis opted not to use this option as the resulting removal efficiencies for some control options approached 100 per cent for future years, exceeding what was believed to be reasonable. As a result, it is expected that the scenarios used here may have underestimated methane mitigation potential and overestimated costs. To analyze the results, methane emissions were aggregated into seven groups: agriculture, fossil-fuel extraction, buildings, electricity, industry, transportation and waste, allowing the exploration of the tax's effect on different sectors.

It was found that implementing the methane tax described above (2018 US$ 2 100 rising by 5 per cent a year up to 2040 per tonne of methane) in GCAM to represent a policy specifically designed to reduce methane emissions causes an immediate drop in anthropogenic methane emissions in the implementation year, 2025, and, under the conditions of SSP2, a fairly constant emission rate thereafter (Figure 4.14). As emissions continue to grow in the reference case, the influence of the tax grows with time, so that anthropogenic emissions are reduced by 20 per cent in 2030, 25 per cent in 2050 and 40 per cent in 2100.

The abatement in response to the economy-wide methane tax under SSP2 comes primarily from the fossil-fuel sector in the GCAM (Figure 4.15). Within this sector, abatement through 2030 is largely achieved by reductions in emissions related to coal which provide 43 Mt/yr of abatement relative to 15 Mt/yr for gas and 6 Mt/yr for oil. Reductions in emissions in the agricultural and waste sectors are also substantial, though smaller. Within agriculture, these come primarily from abatement of emissions related to rice cultivation, 10 Mt/yr of abatement, with an additional 7 Mt/yr from cattle and 4 Mt/yr each from smaller ruminants –pigs, sheep and goats.

The waste sector has a total reduction of 9 Mt/yr entirely from municipal landfills. An additional minor contribution of less than 1 Mt/yr globally in 2030, comes from reductions in the building sector. The total drop in 2030 in response to the tax is 92 Mt/yr. Examining the regional breakdown of responses to the tax, the largest share of the reductions takes place in China, 24 per cent; and Russia and the Former Soviet Union, 24 per cent; followed by Europe, 20 per cent. In contrast, 4 per cent or less each of the reductions come from North America, South and Central America, India and the Middle East, with Africa and Asia Pacific in between at 11 per cent and 12 per cent, respectively.

In contrast, under SSP1, emissions of methane are markedly lower in the baseline scenario and the imposition of the methane-specific tax has less impact on the emissions, decreasing them by 70 Mt/yr in 2030. Under SSP1, the majority of the emissions reductions again come from the fossil-fuel sector, which provides 58 Mt/yr of the 70 Mt/yr reduction. This is 91 per cent of the reduction under SSP2 but represents 83 per cent of the total reductions, a larger fraction than the 70 per cent contribution from the fossil sector under SSP2. The larger fraction of the total coming from the fossil-fuel sector under SSP1 largely stems from the greater baseline reductions in the agricultural sector under that scenario. Those remove nearly all the methane abatement potential in that sector that responded to the methane tax under SSP2, i.e. the rice and livestock abatement, so that under SSP1 the agricultural sector emissions are largely unchanged by the imposition of the methane tax (Figure 4.15). Note that the methane reduction under the baseline SSP1 scenario in the GCAM is slightly greater than that in the SSP1 marker scenario (Figure 4.1), but only marginally so. Methane emissions reductions in the waste sector in response to the tax are 9 Mt/yr- in 2030 under SSP1, equal to those under SSP2.

For comparison with the analysis from Harmsen *et al*. (2019b), presented in Section 4.3.1, the sectoral contributions in 2050 were also examined. Under SSP2, GCAM5.2 produces methane emissions abatements of 81 Mt/yr in the fossil fuel sector, 32 Mt/yr- in the agricultural sector and 15 Mt/yr in the waste sector. In response to the same tax and using the same SSP2 baseline, GCAM4 produced abatement values of 96, 29 and 18 Mt/yr in the fossil-fuel, agriculture and waste sectors, respectively. Hence overall the updated version of GCAM behaves fairly similarly to the prior version, though GCAM4 appears to have included more use of coal in its baseline scenario. As shown in Figure 4.13, the abatement within the fossil fuel sector in response to a methane tax in the GCAM is right in the middle of that obtained across the many IAMs that performed these simulations. In 2050, the abatement within the fossil-fuel subsectors is 58 Mt/yr from coal, 16 Mt/yr from gas and 6 Mt/yr from oil, the latter two being almost the same as the 2030 values. In comparison with other IAMs, these results put GCAM5.2 towards the high-end for coal abatement but at the low end for the other fuels. The abatement in the agricultural. Land-use and waste sectors, however, is the lowest of all the participating models with a value roughly half the multi-model mean and less than a quarter of the highest value. Still examining 2050, GCAM5.2 produces an abatement of emissions in response to the methane tax of 85 Mt/yr under SSP1, only two thirds of that seen under SSP2. Hence, unsurprisingly, the influence of the baseline scenario becomes progressively more important over time.

In addition to evaluating the emission impacts of a global methane tax, the control cost of the policy in each model year was also evaluated. The GCAM reports the marginal cost of control, which is equivalent to the tax. Many of the resulting emission reductions, however, may have been achieved for less. Therefore, to estimate the policy cost in a particular year, five additional scenarios were created with taxes that were 10, 20, 40, 60, and 80 per cent of the original methane tax trajectory. Integrating these under the resulting curve for a particular year produced an estimate of the control cost for that year. Note that the control cost is not intended to represent the overall policy cost, the calculation of which would include economic feedbacks.

Analysis of the costs in GCAM5.2 show that measures considered low cost, less than US$ 600 per tonne of methane, in this assessment can abate roughly 72 Mt/yr (Figure 4.16), which corresponds to about 16 per cent of anthropogenic methane emissions under SSP2. Under SSP1, the abatement is reduced to ~54 Mt/yr, though this represents a fairly similar 15 per cent of anthropogenic methane emissions as those are reduced relative to SSP2 under that scenario's baseline. These values are fairly similar to the sum of the low-cost sectoral abatement potential estimated in the analyses by Harmsen *et al*., IIASA and the US EPA (Figure 4.10). The mitigation across sectors, however, being heavily weighted towards abatement within the fossil-fuel sector, is similar only to that in the US EPA analysis and differs substantially

from the other two. With the full tax implemented in 2030, ~US$ 1 300 per tonne of methane, roughly 21 per cent or 91 Mt/yr of emissions are abated under SSP2, a value again fairly similar to that found in the US EPA analysis (Figure 4.9). Within the fossil-fuel subsectors, however, the GCAM's abatement is overwhelmingly in coal whereas the Harmsen *et al*., IIASA and the US EPA analyses all show greater abatement potential within oil and gas than within coal.

Overall, there is broad consistency in the proportion of anthropogenic emissions that can be abated by targeted measures in approximately a decade between GCAM5.2 and the bottom-up sectoral analyses of abatement potentials. There are marked differences in the proportion within each of the three main anthropogenic methane emission sectors, and indeed the GCAM is an outlier within IAMs in producing minimal abatement within the agricultural and waste sectors. In addition, the balance of abatement potential across the three main fossil fuels is quite different in GCAM5.2 with respect to the abatement potential analyses of the Harmsen *et al*., IIASA and the US EPA. Nonetheless, all these analyses indicate that roughly 20 per cent of anthropogenic emissions could be eliminated through targeted control measures that cost less than ~US$ 1 200 per tonne of methane, a value less than a third the societal benefit of ~US$ 4 300 per tonne based on the evaluation in Section 3.5.

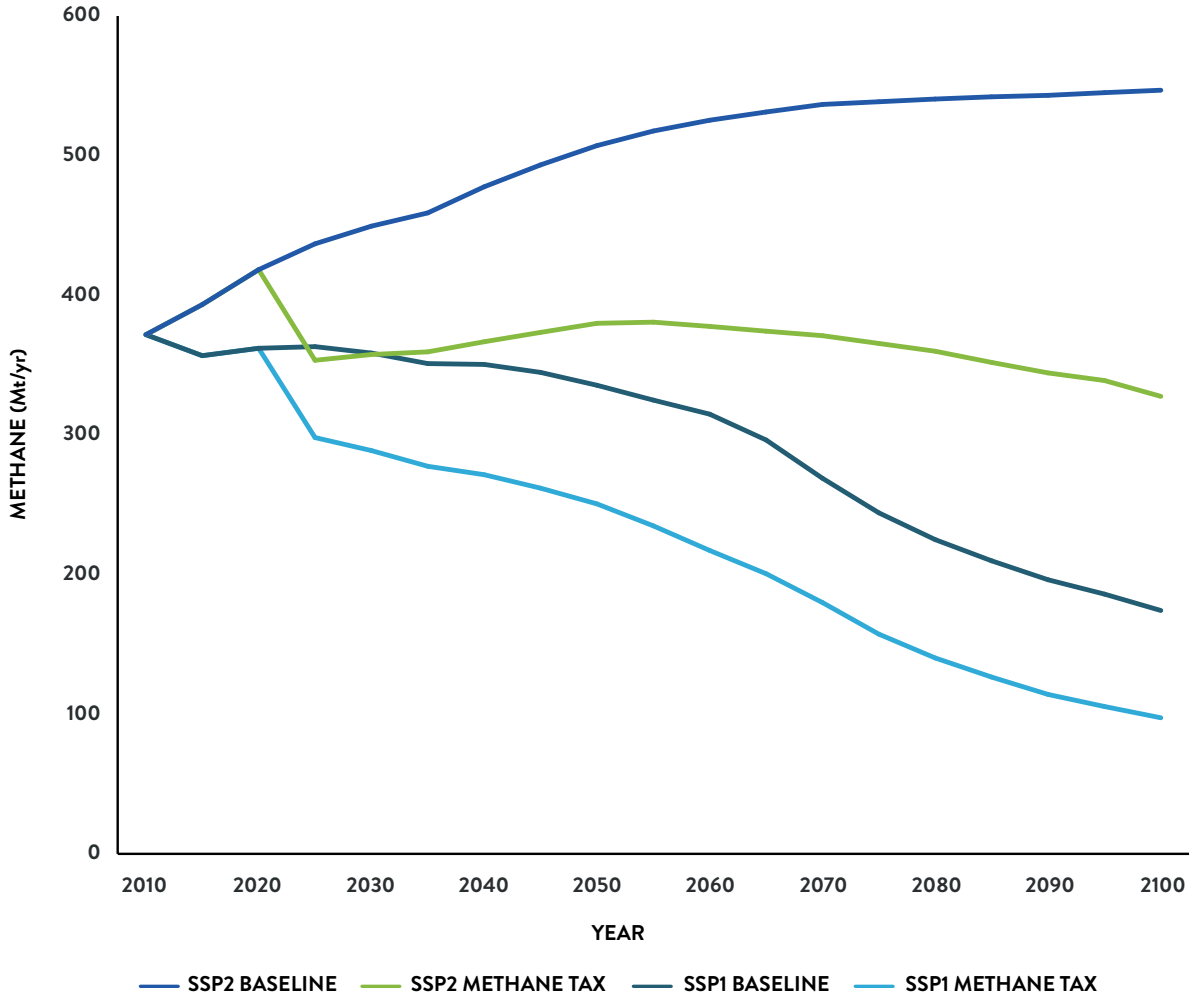

Figure 4.14 Anthropogenic methane emissions in Global Change Assessment Model 5.2, in baseline shared socioeconomic pathways 1 and 2 simulations and in the same simulations but with an economy-wide methane tax of 2018 US$ 2 100 per tonne of methane, increasing annually by 5 per cent to 2040, 2010–2100, million tonnes

Source: UNEP and CCAC

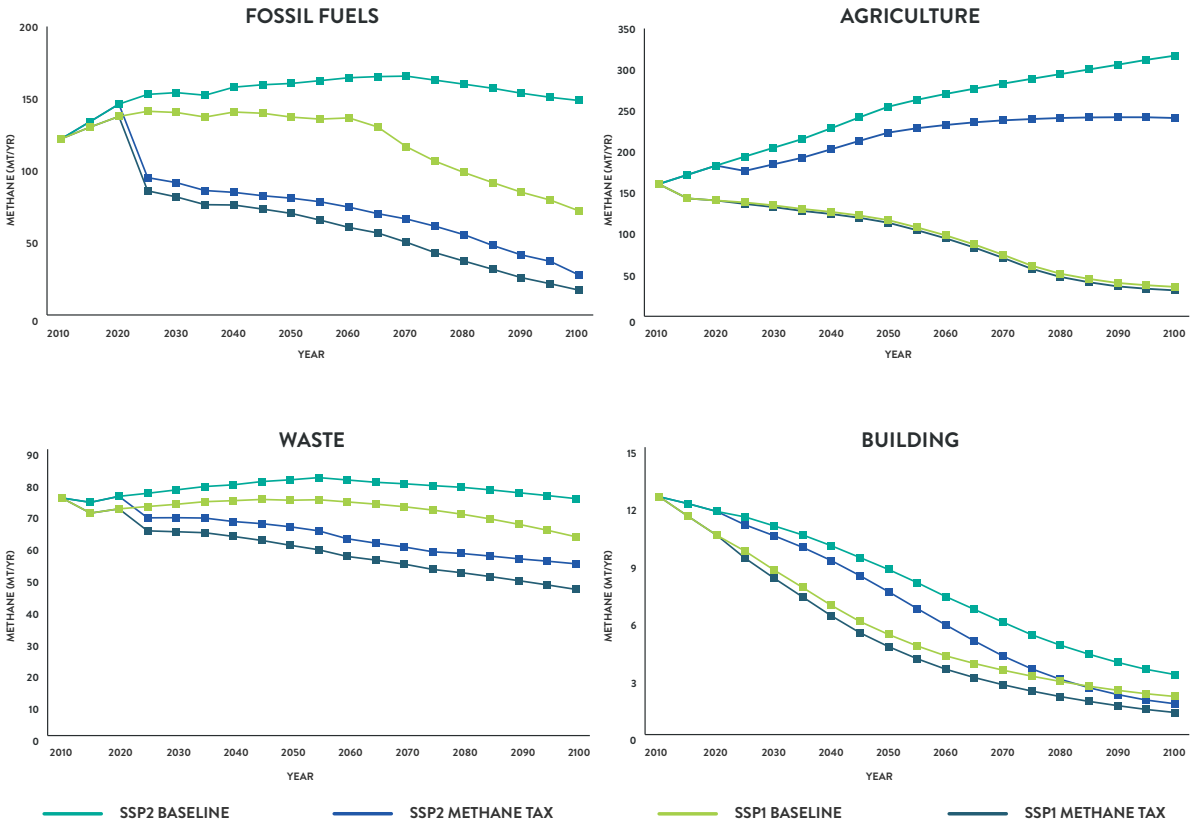

Figure 4.15 Methane emissions in Global Change Assessment Model 5.2 as in Figure 4.14 but by sector, 2010–2100, million tonnes

Source: UNEP and CCAC

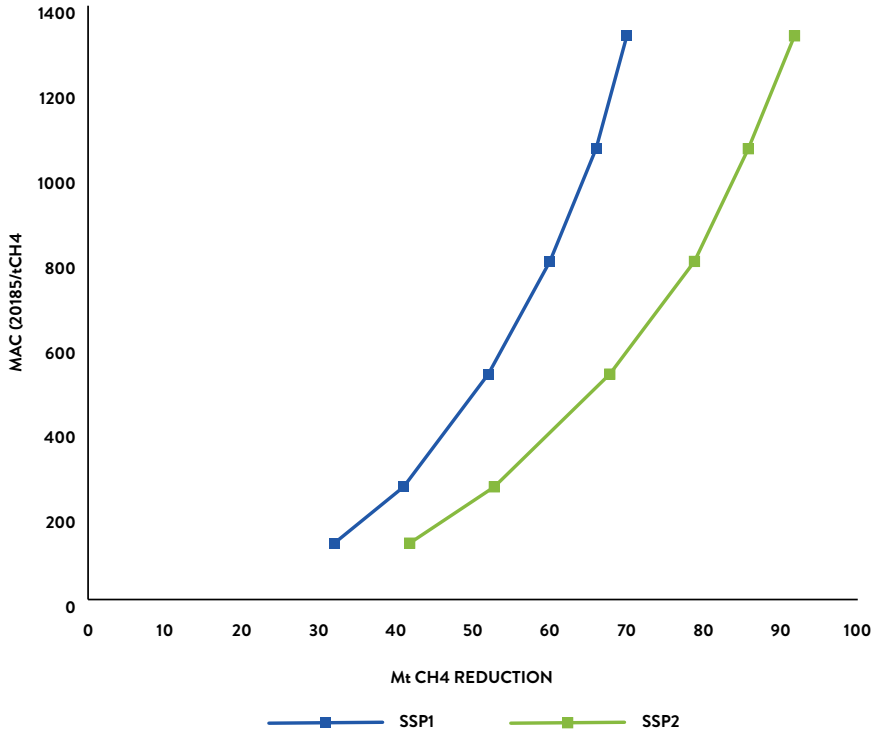

Figure 4.16 Marginal abatement cost for economy-wide methane reductions relative to the percentage of anthropogenic emissions abated in 2030, 2018 US$ per tonne of methane.

Note: The Global Change Assessment Model 5.2 under a shared socioeconomic pathway 1 and 2 projections

Source: UNEP and CCAC

4.4 METHANE MITIGATION AND FOOD

Behavioural changes are an important component of climate change mitigation according to the IPCC (Mbow *et al*. 2019; Field *et al*. 2014), though solutions presented in the literature are overwhelmingly focused on their technological aspects (van de Ven *et al*. 2017). Along with options such as fuel switching and increased efficiency discussed in the previous section, demand management can play a substantial role and may be especially relevant in the agricultural sector in which targeted mitigation options leave a large share of methane emissions unabated (Sections 4.2 and 4.3). This section therefore focuses on those options that are directly relevant to methane emissions from the food supply chain. Values quoted in this analysis are largely based on the FAO's GLEAM dataset (Gerber *et al*. 2013). This includes methane emissions associated with enteric fermentation and manure management, as well as a small component from animal feed, primarily for pigs and chickens.

4.4.1 REDUCING FOOD WASTE

Food loss and waste (FLW) is linked to environmental, social and economic impacts (FAO, 2019; Ishangulyyev *et al*. 2019; Mbow *et al*. 2019; Abiad *et al*. 2018; FUSIONS 2016) including substantial methane emissions. According to the FAO (2019) food loss is defined as loss occurring in the food supply chain from harvest up to, but not including, the retail level, while food waste is defined as loss occurring at the retail and consumption levels (FAO, 2019). There is no consensus to-date, however, on separate definitions of food loss and food waste (Ishangulyyev *et al*. 2019; Abdelradi *et al*. 2018). Food that ends up in landfills with other municipal solid waste is a source of methane.

While it occurs at various points along the supply chain there are differences in food loss and waste produced at different points between developing and developed countries. In developing regions most food waste occurs on-farm and during distribution while in developed countries, food is much more likely to be wasted because certain foods are unappealing to consumers or because they have passed their use-by dates (Porter *et al*. 2018; Garrone *et al*. 2014; Parfitt *et al*. 2010).

While more than 10 per cent of the global population lives in hunger (FAO 2017) roughly a third of all food produced for human consumption turns into lost or wasted at some point along the food supply chain (Porter *et al*. 2018; Gustavsson *et al*. 2011). Many studies highlight the mitigation benefits of reducing this large volume and indicate that the potential reductions of emissions can be substantial but also diverse (FAO 2019; Springmann *et al*. 2018; Wollenberg *et al*. 2015; Bajželi *et al*. 2014). Most of these provide both base case emissions and emissions reductions estimates only in terms of carbon dioxide equivalent rather than separating the various greenhouse gases. For example, an FAO report (2019) suggests that the global carbon footprint of food loss and waste, excluding emissions from land-use change, is 3.3 gigatonnes[12] of carbon dioxide equivalent (Gt CO_2e). Similarly, an earlier report from the FAO estimated total emissions related to food loss and waste of 2.7 Gt CO_2e (FAO, 2014). Based on the source data reported in Chapter 2, methane emissions from ruminants and rice cultivation are ~145 Mt/yr. Hence if it is assumed here that loss and waste in these two categories is similar to the total across all food types, methane emissions associated with food loss and waste would be nearly 50 Mt/yr.

A prior study explored the implications of reducing food loss and waste to reduce total agricultural losses by 15 per cent by 2030, representing roughly a 50–75 per cent decrease in food loss and waste (Stehfest *et al*. 2013). Using two models, the study found that this led to a reduction in ruminant products of ~3–4 per cent and in crops of ~6–9 per cent. These values are lower than the theoretical maximum as prices decline for these commodities with increased supply, leading to a rebound effect that offsets some of the 15 per cent reduction in food loss and waste. Such decreases would lead to an abatement of ~5–7 Mt/yr of methane emissions. Larger reductions could potentially be achieved with policies focussed on preventing loss and waste of cattle products, potentially including price adjustments to prevent the rebound effects, as these have the largest associated methane emissions. Food loss and waste reductions would provide additional benefits through reductions in carbon dioxide and nitrous oxide emissions, though prior valuation of the benefits of food loss and waste reductions found that approximately two-thirds of the benefits of such agricultural sector changes are attributable to methane (Shindell *et al*. 2017) – including the updates presented in Chapter 3 the portion attributable to methane would be even higher. Similarly, another study estimated a 2.2

12. Gigatonne = 109 tonnes

per cent reduction in 2020 total greenhouse gas emissions could be achieved by reducing food waste (van de Ven *et al*. 2017). This translates to about 1.3 Gt CO_2e or about 40–50 per cent of the food loss and waste total. Based on the 50 Mt/yr of methane associated with food loss and waste, this suggests reductions of as high as ~20 Mt/yr.

There are many potential strategies to reduce food loss and waste for the different stages of production, handling and storage, processing and packaging, distribution and marketing, and consumption. Table 4.2 presents a list of strategies related to the distribution and marketing, and consumption stages (Ishangulyyev *et al*. 2019). Targeting behavioural change to women is particularly important for the consumption stage since women generally bear primary responsibility for food purchase and preparation. Reductions in food loss and waste can also come in part from improvements in the cold food chain – storage and transport – which not only influences methane emissions but includes opportunities to mitigate climate change by replacement of hydrofluorocarbons with more climate friendly substances.

Table 4.2 Potential strategies for reductions in food loss and waste

DISTRIBUTION AND MARKETING	CONSUMPTION
Improve inventory systems	
Establish online marketplaces to facilitate sale (donation) of perishable products	Facilitate increased donation of unsold foods from cafeterias and restaurants
Change food date labelling practices and in-store promotions	Implement consumer education and campaigns, both nationally and regionally
Improve institutions related to this stage	Reduce portion sizes
Improve distribution vehicles	Provide education about home economics in educational institutions and communities
Provide guidance on storage and preparation of food to consumers	Involve women in food safe campaigns
Improve the knowledge and ability of workers	Effective use of leftovers
Improve marketplaces – storage, covered areas	Training for restaurant, cafeteria, and supermarket management to forecast customer demand and reflect demand in food purchasing to avoid bulk purchases
Deevelop links with research institutions to predict consumer demand changes	Implement good storage practices
Improve the cold-storage food chain	Correctly interpret label dates
	Distribution of excess food to charitable groups

4.4.2 IMPROVING LIVESTOCK MANAGEMENT

Farm management practices vary widely around the world, and hence in regions with greater emissions per unit of animal protein produced there are substantial mitigation opportunities through the adoption of best practices. This issue was recently assessed by the FAO (Gerber *et al*. 2013), which reported wide disparities in emissions per kilogram of protein using the Global Livestock Environmental Assessment Model (GLEAM) framework. That dataset was analyzed to explore the abatement potential if the livestock production chain worldwide were to match the practices of the most efficient producers, where the latter were assessed based on the 10th percentile of the lowest emission intensity – i.e. a high-performing value, but not an extreme case. In such an instance, methane emissions from ruminants could be reduced by ~31 Mt/yr. By far the largest share of this abatement would come from cattle, which contribute ~28 Mt/yr- – ~20 Mt/yr from meat and ~8 Mt/yr from dairy. Another 5 Mt/yr might be abated by the adoption of best management practices for buffalo, which were not included in this analysis due to a lack of data specifying the 10th percentile of emissions per kilogram of protein in the FAO dataset.

Achieving very low emissions per kilogram of protein may involve large-scale industrialized agriculture, which can have other social and environmental impacts beyond greenhouse gas emissions and hence such policies need to be considered with care. It should also be noted that improved livestock management is sometimes considered in the targeted mitigation options discussed previously (Section 4.2), though clearly some of those analyses estimate much lower potential for this as they find less total mitigation potential across the entire agricultural sector than that estimated here for livestock management alone. In addition, changes to livestock feed are commonly included in the targeted analyses (Section 4.2) and constitute another component of livestock management.

4.4.3 DIETARY CHANGE

According to the FAO (2019) between 2007–2016 current food consumption patterns were responsible for 21–37 per cent of total greenhouse gas emissions. The FAO furthermore estimates that the world will need to produce about 50 percent more food by 2050 to feed the growing world population (FAO 2017). Unless current dietary patterns and food systems change, this would result in significant increases in greenhouse gas emissions (Drew *et al*. 2020; FAO 2019; Poore and Nemecek 2018; Alexandrowicz *et al*. 2016).

As described in Chapter 2, both rice cultivation and especially ruminant animals are large sources of methane emissions. It is therefore not surprising that several studies suggest that dietary shifts could significantly contribute to reducing greenhouse gas emissions, including methane (Clark *et al*. 2019; Springmann *et al*. 2018; Bryngelson *et al*. 2016; Springmann *et al*. 2016; Bajželj *et al*. 2014; Hedenus *et al*. 2014; Pradhan *et al*. 2013).

Poor diet is also itself a major global health concern, resulting in an estimated 11 million premature deaths in 2017. Consequently, setting dietary and nutritional goals would have great benefits for human health through reducing the incidence of non-communicable diseases such as type 2 diabetes and cardiovascular disease (Afhsin *et al*. 2019). It is important, however, to mention that setting both dietary and nutritional goals without considering the environmental cost associated with them could in fact result in an increase of greenhouse gas emissions (Torero 2020). Recent studies also demonstrate the multiple benefits of healthier and more sustainable diets, including benefits to human health and land use (Gao *et al*., 2018; Springmann *et al*., 2016; Tilman *et al*. 2014; Popp *et al*. 2010; Stehfest *et al*. 2009). The IPCC Synthesis Report provides further detailed analysis in relation to food systems, food security, greenhouse gas emissions, and land degradation (Pauchari *et al*. 2014).

There are three types of diets described by the FAO in terms of the nutrients received by each diet:

1. energy sufficient diet: provides adequate calories for energy balance for work each day;
2. nutrient adequate diet: provides adequate calories and relevant nutrient intake values;
3. healthy diet: provides adequate calories and nutrients, but also includes a more diverse intake of foods from several different food groups.

While each of these diets comes with a climate-related cost, a critical point presented in the FAO report (2020) is that not all healthy diets are sustainable and not all diets designed for sustainability are always healthy. The FAO highlights, “this important nuance is not well understood and is missing from ongoing

discussions and debates on the potential contribution of healthy diets to environmental *sustainability*" (FAO 2020).

Policies that integrate and combine environmental and nutritional priorities are limited (Aleksandrowicz *et al*. 2016; Watts *et al*. 2015). Furthermore, as is highlighted in Gao *et al*. (2018), several studies suggest that combining health, air pollution and greenhouse gas benefits can lead to more attractive strategies that encourage implementation of mitigation measures related to dietary choices (Gao *et al*. 2018; Watts *et al*. 2017; Edenhofer *et al*. 2014; Field *et al*. 2014; Haines *et al*. 2012; Shindell *et al*. 2012; Chae *et al*. 2011; Watts *et al*. 2009; Aunan *et al*. 2006; Cifuentes *et al*. 2001).

As with food waste reduction, most of the studies of dietary change provide emissions reductions estimates only in terms of carbon dioxide equivalent rather than separating out the various greenhouse gases. Several, however, provide estimates of the change in consumption of cattle-based foods, for which the impact on methane emissions can readily be evaluated. For example, a study of diets in the United Kingdom explored how alterations could both optimize nutrition and maximize greenhouse gas reductions without drastically changing overall dietary patterns. This study found that a reduction of 34 per cent in the consumption of both beef and dairy products (average for men and women) was ideal (Green *et al*. 2015). If extended across the European Union, and assuming a similar percentage decrease was ideal across that region, this would lead to a reduction in methane emissions of ~6 Mt/yr based on the full lifecycle emissions associated with livestock (Weiss and Leip 2012).

In a broader study, it was estimated that the adoption of healthy diets globally would entail approximately a 50 per cent reduction in beef consumption in 2050 (Stehfest *et al*. 2009). Accomplishing such as shift in the near term would lead to a reduction in methane emissions from beef cattle of ~14 Mt/yr based on current consumption. As demand for red meat is projected to roughly double by the middle of this century, the overall benefits in the future would be larger, though obviously they would depend on a reduction that could be achieved by a target year such as 2030. Including such a dietary shift in climate change mitigation policies is also estimated to greatly reduce the costs of achieving low-warming targets (Stehfest *et al*. 2009). These results seem generally comparable to the overall greenhouse gas reductions estimated for dietary change, which are in the range of 4.4 per cent for healthy diets and ~6–7 per cent for vegetarian or vegan diets in 2030 (van de Ven *et al*. 2017). Given that livestock accounts for roughly 18 per cent of total greenhouse gas emissions (Stehfest *et al*. 2009), the healthy diet reductions translate to a decrease in livestock-related emissions of about 25 per cent. Based on total ruminant emissions of 115 Mt/yr of methane (Chapter 2), this corresponds to diet-related reductions of ~29 Mt/yr of methane if the reductions are comparable across consumption of the various potential animal products.

These estimates provide a rough idea of the emissions reductions that could be achieved by a reduction in the consumption of ruminant-based foods, primarily from cattle through the adoption of either healthy or vegetarian/vegan diets. Reductions associated with healthy diets are likely to represent the majority of those that would come from vegetarian diets, with lower barriers to adoption. Healthy diets might achieve reductions in methane emissions in the range of 15–30 Mt/yr, with additional climate benefits from reductions in carbon dioxide and nitrous oxide – the IPCC, for example, estimates a total mitigation potential from healthier and more sustainable diets of 0.7-8.0 Gt CO_2e/yr by 2050 (Mbow *et al*. 2019).

4.4.4 CONCLUSION ON METHANE MITIGATION AND FOOD

Additional possibilities for mitigation of the large methane emissions from agriculture, especially livestock, exist and some cannot be easily characterized as solely targeted or additional. For instance, substitution of cultured meat for traditional livestock products could substantially reduce associated greenhouse gas emissions, especially methane (Post 2012; Tuomisto and Teixeira de Mattos 2011). Such technologies are not yet commercially viable, however, and may not gain widespread consumer acceptance.

Overall, while individual behaviour cannot address the scale of greenhouse gas emissions, literature suggests that including behavioural change in a broad portfolio of policies could help address and mitigate emissions and also support top-down policies (IPCC 2018; van de Ven *et al*. 2017; Watts *et al*. 2015; Gilligan *et al*. 2010). Implementing these changes, however, may be challenging for several reasons. There will be a clear discrepancy in the priorities, needs and abilities of different national governments to assist with these changes. Taking the example

of diets, many developed countries have an obesity epidemic, while in some developing ones, hunger and malnutrition, through having too little or not enough of the right types of food, is a severe problem. Switching diet to more sustainable sources will have co-benefits for reducing greenhouse gas emissions, particularly methane, and improving health (Willet *et al*. 2019). Implement structural and long-lasting changes in individual dietary intake, however, will likely require strong intervention, mitigation and incentivisation by governments through innovative policies. Social influence approaches can be an effective way of encouraging resource conservation (Camilleri *et al*. 2019; Abrahamse and Steg 2013), as part of either government or non-governmental programmes. Similarly, interventions in livestock management practices or efforts to reduce food loss and waste face considerable barriers in terms of institutional capacity, education and societal reluctance to change traditional habits as well as economic barriers. Nevertheless, given that the impact of the three elements with the strongest evidence base – reduced food loss and waste, improved livestock management, and change to healthier diets – is estimated here to have the potential to reduce methane emissions by up to 65–80 Mt/yr over the next few decades, the impact of behavioural change and innovative policies on agricultural methane emissions should not be ignored. The full abatement potential identified here for these elements is unlikely to be realized by 2030, so that abatement at these levels is perhaps an appropriate target for 2050.

4.5 WEB-BASED DECISION SUPPORT TOOL

A web-based decision support tool that allows users to input a level of methane emissions mitigation and easily determine the national values for the response of all impacts included in this analysis has been developed. This can be used to evaluate the benefits to climate, health and, through environmental changes, the economy of a wide range of action, ranging from individual mitigation projects to national pledges under the Paris Agreement or international targets for methane controls.

The tool also allows the user to view the impacts of methane mitigation options based on the four mitigation potential analyses described in this assessment – Harmsen *et al*., IEA, IIASA, and the US EPA. The user can select broad sectors or more detailed subsectors and can choose to view impacts of worldwide or regional mitigation.

For example, a user wanting to examine mitigation potential of methane emissions from the fossil-fuel sector based on the IIASA analysis, can select low-cost measures only, and the global total, and get the impact on respiratory health from the associated methane emissions reductions. By placing the cursor over a country a panel will pop up showing the reduction in national-level deaths per million persons and the numerical value for that country's results will be displayed. Worldwide totals and the associated mitigation costs and benefits will be displayed below the interactive maps.

Note that the temperature responses in the tool include the estimated carbon cycle response enhancement of 10 per cent (Section 3.3), though this has not been applied to heat-related labour productivity changes, for which a 10 per cent change would be far less than the associated 70 per cent uncertainty. This tool can be found at: http://shindellgroup.rc.duke.edu/apps/methane/

An archive of the hourly ozone produced by the modelling described in Chapter 3 has also been created. This will allow calculation of any new health or agriculture metrics should the finding for which metric is most appropriate change again. This repository is available at https://doi.org/10.7924/r4qn65b0z and can be cited as:

Shindell, D., Zhang, Y., Seltzer, K., Faluvegi, G., Naik, V., Horowitz, L., He, J., Lamarque, J.-F., Sudo, K., and Collins, B. 2020. *Data from modelling in support of the Global Methane Assessment*, UN Environment and Duke Research Data Repository. https://doi.org/10.7924/r4qn65b0z



5. CONCLUSIONS: MITIGATION OPPORTUNITIES, IMPACTS AND UNCERTAINTIES

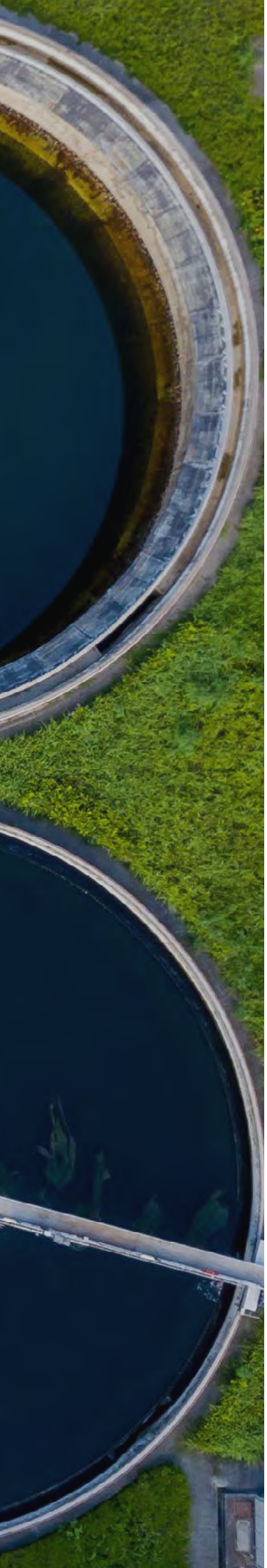

CHAPTER FINDINGS

- Implementation of identified targeted control measures with costs less than the estimated societal benefits could abate ~100 Mt/yr of methane emissions by 2030 and provide benefits including reducing global warming by ~0.15ºC over the 2040–2070 period, and by ~0.2º C over the longer term (2070–2100); preventing premature deaths due to ozone exposure immediately with annual totals reaching ~140 000 per year in 2030; preventing ~40 billion lost work hours annually due to heat exposure annually by ~2045; and preventing ~15 Mt tonnes of crop losses due primarily to ozone exposure each year by 2030. The crop yield increases would be worth approximately US$ 4 billion per year, the increased labour productivity about US$ 6.3 billion per year, and the valuation of the reduced risk of premature deaths is ~US$ 250 billion (US$60–420; 95 per cent confidence interval).

- The greatest targeted abatement potential very likely lies within the fossil-fuel sector, for which average mitigation costs range from a high of ~US$1 250 per tonne of methane in the US EPA analysis to a net savings of ~US$ 400 per tonne in the IIASA analysis, with values in between those for the Harmsen and IEA analyses, the latter of which only considers the oil and gas subsectors. All these average costs are much lower than the per tonne societal benefits.

- Examining only targeted controls in the relatively robustly characterized fossil-fuel and waste sectors that cost less than the estimated societal benefits per tonne, the abatement potential is about 75 ±2 Mt/yr. Benefits from this level of abatement include ~0.13ºC warming avoided in the 2040–2070 period, ~105 000 avoided premature deaths due to ozone exposure annually by 2030, and 11 Mt of avoided crop losses due primarily to ozone exposure each year. The benefits of the annually avoided premature deaths alone are estimated at US$ 190 billion (US$ 40–310 billion; 95 per cent confidence interval).

- Targeted measures alone are not enough to reach emissions levels seen in 1.5ºC scenarios over the next several decades, which require both targeted and additional measures to achieve ~180 Mt/yr of methane abatement by 2030. Behavioural measures include fuel switching, energy efficiency, improved waste separation, reducing food waste, dietary change and transport demand management. Both targeted and additional measures face implementation barriers including financing, a lack of awareness/education, governance and consumer preferences.

- Uncertainties exist along the entire chain from mitigation potential through physical responses to societal impacts. Overall uncertainties are likely to be primarily driven by limited understanding of climate sensitivity and of the effects of ozone exposure on human health, with generally small contributions from incomplete knowledge of mitigation potentials or in an understanding of the ozone response to methane emissions reductions. In some specific sectors or regions, however, limited knowledge of current emissions is probably a major driver of uncertainties in benefit-potential estimates.

It has been clear to the scientific community for some time that reducing methane emissions would contribute to both improved air quality and climate change mitigation (Shindell *et al*. 2012; UNEP 2011; UNEP/WMO 2011; Fiore *et al*. 2002). There are substantial uncertainties, however, in the characterization of each step along the pathway from mitigation to impacts, including the methane emissions themselves, the responses of the physical system to changes in emissions, and the potential for emissions reductions in the various sectors that emit large amounts of methane. Prior analyses have typical relied on the results of one or two models for physical responses, used a single set of emissions data and a single set of mitigation potentials. This assessment, however, provides a more thorough analysis of robustness for each step by analyzing results from multiple models of the composition-climate system, multiple models of the energy-economy-land system, and multiple analyses of methane mitigation potentials. It also incorporates recent advances in understanding of the societal impacts of physical system responses to methane emissions, including not only climate and composition responses of the physical system, but many downstream impacts of both ozone and climate change on human health and crops. This provides a robust characterization of the overall societal costs and benefits of methane mitigation.

The analysis shows that there is great potential to mitigate methane emissions over the current decade, 2020–2030, using existing targeted control measures. Such measures could abate roughly 125 Mt/yr of methane emissions, about 30 per cent of the projected 2030 anthropogenic emissions. Taking the average across the various available analyses of abatement potentials and costs, targeted control measures with costs of less than the estimated societal benefits could abate 101 Mt/yr of methane emissions by 2030 and achieving such abatement would have enormous societal benefits. These include climate-related benefits of reducing warming by ~0.15ºC by 2040, with a value of 0.2ºC over the longer term (~2070–2100), and the associated prevention of ~40 billion lost work hours, roughly 30 per cent of which are for women and 70 per cent for men, due to heat exposure annually, starting around 2040. They also include air pollution-related benefits starting immediately after emissions are reduced and continuing each year thereafter. Increasing through the 2020s, benefits for 2030 and subsequent years include preventing annually ~140 000 premature deaths due to ozone exposure, ~430 000 accident and emergency department visits due to asthma and ~9 000 hospitalizations of elderly people due to ozone, and ~15 Mt of crop losses due to ozone exposure. The crop yield increases would be worth approximately US$ 4 billion per year, the increased labour productivity about US$ 6.4 billion per year, while the valuation of the reduced risk of premature deaths is ~US$ 250 billion annually (US$ 60–420; 95 per cent confidence interval).

The discussion of climate change responses to methane mitigation in Chapter 3 focussed on the response averaged over 1–3 decades after potential cuts. It is useful to also characterize the potential impact of methane mitigation on global mean temperature as a function of time. Therefore the response was evaluated using absolute global temperature potentials (AGTPs), as in prior Assessments (UNEP 2017; UNEP/WMO 2011). In brief, the yearly AGTPs represent the global mean temperature change per kilogram of emission each year subsequent to those emissions based on an impulse-response function for the climate system, as is used in IPCC for selected example years, for example, AGTP50 or AGTP100 (Myhre *et al*. 2013). In the calculations in this assessment, the transient climate response is based on analysis of the last generation of climate models (CMIP5) (Geoffroy *et al*. 2013). The AGTPs include the carbon-cycle response to the temperature change induced by the emitted species including the impact of ozone generated by methane on carbon uptake (Gasser *et al*. 2017; Collins *et al*. 2010) as described in Shindell *et al*. (2017). Temperature responses are also provided averaged over latitude bands based on analogous absolute regional temperature potentials (Collins *et al*. 2013; Shindell 2012). To take advantage of the new results from simulations in support of this assessment, the responses have been calibrated to match the global climate impacts reported in Chapter 3, including the estimated carbon cycle response enhancement of 10 per cent (Section 3.3), though this changes the AGTPs only minimally.

To illustrate the evolution of temperature responses over time, the temperature response to the methane mitigation seen in 1.5ºC scenarios is evaluated, based on IAMs that included targeted controls, behavioural change, emissions pricing and other developments such as decarbonization. The average mitigation across the available scenarios is 180 Mt/yr in 2030, 240 Mt/yr in 2040 and 280 Mt/yr in 2050. Avoided warming reaches 0.3ºC towards the

end of the 2040s in response to those emissions reductions (Figure 5.1). In comparison with prior studies, the 2050 value of 0.32ºC is slightly greater than the impact of methane mitigation estimated in Shindell *et al*. (2012)/ UNEP/WMO (2011) for 2050, 0.28ºC, but is substantially so when comparing both results for period 30 years after abatement begins – 2040 in the earlier scenarios, for which time the response was 0.24ºC in response to abatement of 139 Mt yr in 2030. The greater 2050 value in this analysis stems primarily from the greater abatement amounts which have a larger impact than the later start of abatement. The Arctic response is 60 per cent larger than the global mean value, in good agreement with the results found here in the full climate model simulations (Chapter 3; Table 3.2).

Comparisons are also drawn with the 2017 UNEP *Emissions Gap Report* that estimated that the response to the full application of targeted methane mitigation options identified by IIASA would lead to avoided warming of 0.09ºC in 2030 and 0.30±0.12ºC in 2050 using a similar method to that used here (UNEP 2017). Methane mitigation analyzed in that report was 152 Mt/yr by 2030 and 171 Mt/yr in 2050. Those are greater values for 2030 than reported here from the IIASA bottom-up analyses as the older ones used in the UNEP report had an earlier abatement starting date. The results presented here exhibit a slightly smaller response per million tonnes of emissions mitigation based upon the latest climate modelling, though well within the uncertainty range. Of note is that, based on both the new modelling and updated constraints on climate sensitivity, the uncertainty ranges are slightly reduced in the new analyses: 95 per cent confidence intervals were 40 per cent in the 2017 UNEP report and 36 per cent in Shindell *et al*. (2012)/UNEP/WMO (2011), whereas now they are estimated at 33 per cent (Chapter 3).

In addition to this analysis of the impact of emissions changes through 2050, the impact of methane emissions changes through 2100 were also explored, again using AGTP. In 1.5º C scenarios generated by IAMs, methane emissions fall rapidly in the first half of the century but thereafter decline only modestly through 2100 (Rogelj *et al*. 2018). As discussed in Chapter 4, this is primarily due to emissions from agriculture which are not abated given the cost curves, abatement options and pricing mechanisms used in most of the IAMs. As such, the longer-term climate impact of aggressive methane abatement becomes highly dependent upon the reference case against which the fairly steady post-2050 are compared (Figure 4.1). Relative to the high baseline methane emissions under SSP3's marker scenario, the 2100 impact of 1.5º C methane reductions is a reduction in warming of 0.77º C. Relative to the lower baseline emissions of SSP1's marker scenario, the reduction is much less at -0.42º C, with the mid-range (for methane) SSP4 and SSP5 having value of about -0.6º C.

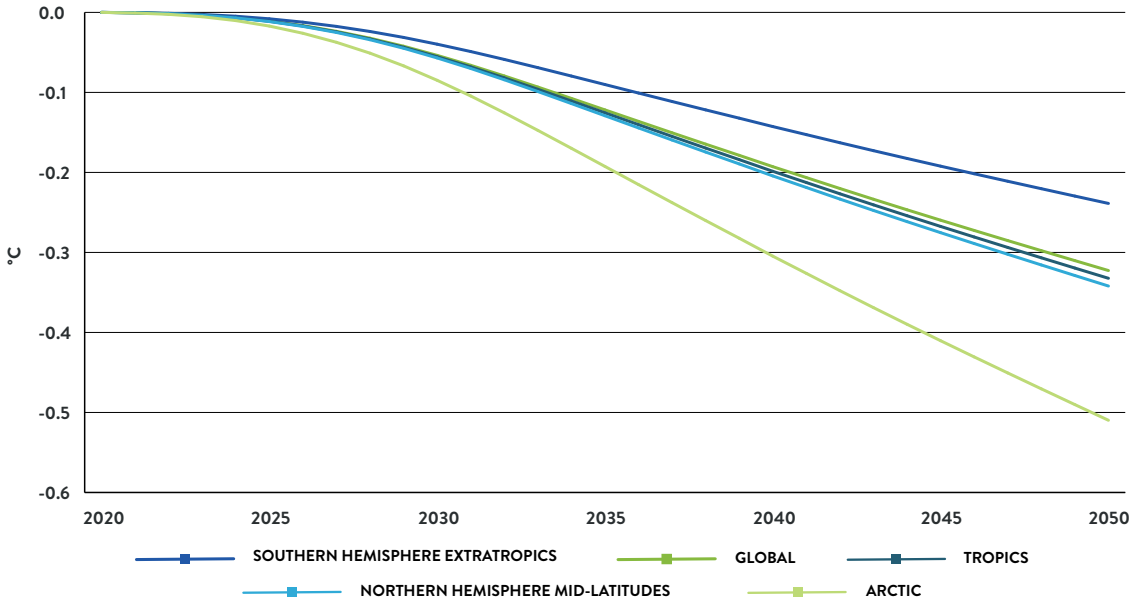

Figure 5.1. Temperature response to methane abatement from 2020–2050 based on mitigation levels consistent with 1.5º C scenarios, 2020–2050, degrees centigrade

Note: In addition to global mean responses, values are given for the southern hemisphere extratropics (90–28º S), the tropics (28º S–28º N), the northern hemisphere mid-latitudes (28–60º N) and the Arctic (60–90º N).

Source: UNEP and CCAC

The identified targeted abatement measures reduce emissions in the fossil fuel sector by ~58 ±12 Mt/yr and those in the waste sector by ~32 ±4 Mt/yr when examining all controls regardless of cost for 2030. The targeted abatement potential within the agricultural sector is not as robustly characterized as the estimates are very different at ~10, 20 and 50 Mt/yr. Hence this analysis reveals that the greatest targeted potential very likely lies within the fossil-fuel sector, whereas there is the greatest agreement on the abatement potential in the waste sector. Delving further into the emission sources, this assessment finds that within the fossil-fuel sector there is a comparable magnitude abatement potential in each the three subsectors coal, gas and oil. In contrast, within the waste sector the abatement potential is largely concentrated within the solid waste subsector with a relatively small amount within the wastewater subsector. These results consider all abatement measures regardless of cost and show substantial differences in the average value, weighted by mitigation potential at each cost value, across the various analyses. For the fossil-fuel sector, average mitigation costs range from a high of US$1 240 in the US EPA analysis for measures costing less than US$ 25 000 per tonne of methane), a middle value of US$ 960 per tonne of methane in the Harmsen *et al.* analysis to -US$ 400 in the IIASA analysis, with values in between those from IEA, US$ 10 for the oil and gas subsectors only. Although the mitigation potential for the waste sector is more consistent across the various analyses, the costs are more divergent, with an average cost range of US$ 3 930 per tonne of methane in the Harmsen *et al*. analysis, $840 in the US EPA analysis for measures costing less than US$ 25 000 per tonne of methane, to -US$ 5 800 in the IIASA analysis. In comparison, average costs for the agricultural sector are more consistent at US$ 1 390 in Harmsen *et al*., US$ 800 in the US EPA analysis and US$ 270 in IIASA, despite the large divergence in the abatement potential itself for this sector. As discussed in Section 4.2.1, abatement potentials vary greatly across regions. The largest potential in the waste sector is for Europe and India; the coal subsector followed by livestock for China; in livestock for Africa, followed by oil and gas, in the coal subsector and the waste sector for Asia and the Pacific (excluding China and India); in the oil and gas subsector for the Middle East, North America, and Russia and the Former Soviet Union; and in the livestock subsector for Latin America.

The targeted mitigation potential was examined for only those measures with costs of less than the US$ 4 300 per tonne of methane in estimated societal benefits found in Chapter 3. The total abatement potential in the three cross-sector analyses are 85 Mt/yr in IIASA, 93 Mt/yr in US EPA and 121 Mt/yr in Harmsen *et al*., for an average of 100 Mt/yr. In that same order, potentials are 46, 44, and 59 Mt/yr for the fossil-fuel sector, 27, 30 and 18 Mt/y for the waste sector, and 12, 19 and 44 Mt/yr for the agricultural sector. Hence the totals across the more robust fossil-fuel and waste sectors are 73, 74 and 77 Mt/yr, for a range of 75 ±2 Mt/yr. The benefits from this level of abatement (75 Mt/yr) are also substantial: just over 0.1°C of warming avoided a decade after these reductions are achieved, and benefits immediately following reductions, and continuing each year thereafter, that include about 105 000 avoided premature deaths due to ozone exposure, about 325 000 fewer accident and emergency department visits due to asthma, and ~11 Mt of crop losses due to avoided ozone exposure. The benefits of the avoided premature deaths alone are estimated at US$ 190 billion per year. It is emphasized that these benefits all come at a net gain to society as even the most expensive controls within this analysis have costs of less than the societal benefits, and hence the average costs of controls are far less than the average benefit per tonne of emissions abatement.

It is also informative to examine the total cost of implementing all targeted methane measures. The IEA analysis is excluded here as it does not encompass the full fossil-fuel sector, and the IIASA and US EPA analyses are relied on since the Harmen *et al.* analysis does not include negative costs. For the fossil fuel sector, the total cost based on the US EPA analysis is US$ 62 billion for measures costing less than US$ 25 000 per tonne of methane, whereas the total is a savings of US$ 18 billion in the IIASA analysis. Similarly for waste, the total cost based on the US EPA analysis is US$ 27 billion whereas the total is a saving of US$ 166 billion in the IIASA analysis. The differences in both sectors are partly attributable to the much higher discount rate used in the US EPA analysis –10 per cent versus 4 per cent in the IIASA analysis – which greatly reduces the value of gas that is captured and utilized – net costs will also depend on the estimated future price of natural gas. In the waste sector, the inclusion of substantial revenue from recycled paper in the IIASA waste

analysis, as discussed in Chapter 4, is another major source of differences. Hence the total cost for all targeted measures across these two sectors ranges from ~US$ 90 billion to a savings of ~US$ 185 billion. For the agricultural sector, the total cost based on the IIASA analysis is US$ 3 billion whereas the total is US$ 17 billion in the US EPA analysis. Thus the spending in the agricultural sector is more consistent, even though the mitigation potential differs strongly – see Chapter 4 for further discussion on the agricultural sector in these two analyses. This is likely due to the reduced influence of the discount rate differences as less of the methane abatement is used in this sector. Hence it is very difficult to estimate the total spending required to implement the targeted measures. Averaging across these two analyses for all three sectors, the total spending is negative. In all sectors the total cost seems likely to be relatively small or negative but will depend on the chosen discount rate and prices of natural gas. As the total costs include both measures with net savings and those with net costs, sometimes large costs, it is important to keep in mind that even when total costs are large, they are sensitive to the costs of the most expensive measures along the cost curves. Thus the conclusions regarding the portion of targeted measures available at negative or low costs are typically emphasized in this assessment.

The uncertainty in the fossil-fuel plus waste sector, the methane mitigation potential is about 17–20 per cent, though it is larger for some subsectors within those general sectors. Considering the all-cost measures, the uncertainty is about 25 per cent for the total from fossil fuels and about 10 per cent for the total from waste. The variation in these mitigation potentials can be compared with the uncertainties in climate, health and crop responses. For climate, there is about a 34 per cent uncertainty in the global mean temperature change, based on current understanding of climate sensitivity, with a slightly smaller value for the tropics and a larger one for the Arctic, here 60–90° N, where the response is largest. For premature deaths, uncertainties for those related to respiratory effects are ~35 per cent and those for cardiovascular-related effects are ~65 per cent, both for the 95 per cent confidence interval. Uncertainties in heat-related deaths, for China and the United States only, are about 48 per cent with a 95 per cent confidence interval, whereas those for crop yield impacts are roughly 36 per cent. These impact uncertainties reflect the fact that the temperature response to methane emissions changes, ~34 per cent, is more uncertain than the ozone response, ~24 per cent. In general, it was found that uncertainties in the impacts of methane mitigation are likely to be driven most strongly by uncertainties in climate sensitivity and in the effects of ozone exposure on human health, with relatively small contributions from uncertainties in the mitigation potential or ozone response to methane emissions reductions. It is also noted that there likely are additional effects of ozone on human health, as recent research indicates that exposure to air pollution affects nearly every organ in the human body (Andrade *et al*., 2019), and hence additional impacts are likely to be present beyond those quantified here, so that health benefits of mitigation should be considered conservative.

Considering the low-cost measures, defined here as those costing less than US$ 600 per tonne of methane, the different analyses vary more as they are sensitive to the use of a cost threshold at this level since it falls within a range encompassing many mitigation measures. For mitigation within the fossil-fuel sector, low-cost mitigation potentials range from 32 to 66 Mt/yr in the two analyses finding that the average cost of the low-cost measures is negative, -US$ 120 and -US$ 851 per tonne of methane in the IEA and IIASA analyses, respectively. The Harmsen *et al*. and US EPA analyses, however, find low-cost potentials of 24 and 42 Mt/yr and average costs that are positive at US$ 182 and US$ 38 per tonne of methane, respectively. For the waste and agricultural sectors, the average costs of the low-cost measures is negative in some analyses and very low in others, always less than US$ 140 per tonne of methane and typically less than US$ 60 per tonne of methane. Magnitudes vary by nearly a factor of two in the waste sector, 11–21 Mt/yr, and nearly a factor of four in the agricultural sector, 10 to 38 Mt/yr. Hence the low-cost measures are generally beneficial from an economic standpoint even without accounting for the environmental benefits, or when only accounting for market costs, primarily crop yield and labour productivity increases, when evaluating environmental impacts, but the potential available at these low costs is quite sensitive to the particular analysis used. As discussed previously, when environmental benefits are accounted for, slightly more than 80 per cent of identified targeted potential for methane controls lead to net societal benefits.

Though significant, a reduction of either ~100 or ~125 Mt/yr, which represents ~25 or 30 per cent in anthropogenic methane emissions by 2030 is less than that seen in 1.5°C scenarios.

Examining estimated targeted mitigation potential over a longer timescale provides valuable insights into the potential for targeted controls to provide abatement consistent with low warming scenarios. Looking at the total assessed mitigation potential across all sectors, IIASA concluded that maximum feasible reductions would reduce 2050 methane emissions by 242 Mt/yr whereas Harmsen *et al*. found a 2050 total abatement potential of 185 Mt/yr. These analyses account for the time required for technological turnover and for phasing in new regulations, and also include changes in baseline emissions based on projected energy demand and population growth, which affects generation of waste and food production. Baseline 2050 anthropogenic emissions were projected to be 450 Mt/yr in the IIASA analysis, a large increase over the 355 Mt/yr in 2020 in its model. The reduction of 242 Mt/yr thus represents a decrease of 54 per cent. The reduction is similar in the Harmsen *et al*. analysis at 47 per cent despite the smaller abatement as that analysis had a smaller projected growth in baseline methane emissions. An equivalent percentage reduction today would translate to about 190 Mt/yr of methane mitigation. That level of reduction would be almost exactly equal to the mean methane mitigation in 2030 seen in 1.5ºC scenarios. On the one hand, this indicates that full implementation of targeted mitigation measures in a single decade could potentially lead to methane reductions consistent with the magnitude required in 2030 for such a low warming pathway. On the other hand, this indicates that were targeted measures to be the only policies employed, full application of all technologies, even those with very high mitigation costs, would be required at an exceptionally fast rate of deployment and that even with targeted measures across the full cost range, the additional methane mitigation after 2030 needed to stay on a 1.5ºC pathway would require additional measures which contribute to other priority development goals with benefits for methane. The additional measures examined in this assessment include several that might be widely considered part of climate policy, such as switching to renewable energy, and others that might not, such as reducing food waste or improving waste separation. Such categorizations are highly subjective, but in general the additional measures in the fossil-fuel sector are more closely aligned with policies commonly viewed as part of a climate portfolio. Those constitute roughly 40 per cent of the additional measures included in this assessment. Roughly 43 per cent come from changes in the agricultural sector and 17 per cent from the waste sector, both of which include measures associated with consumption or disposal practices that are less consistently currently viewed as part of climate policies.

Behavioural changes have the potential to substantially augment targeted methane controls. These are especially important for the agricultural sector, where targeted measures have the smallest relative impact. The analysis presented here suggests that behavioural changes, reducing food loss and waste, improving livestock management and shifting to healthier diets that at the global level include reduced consumption of ruminant-based foods, have the potential to provide up to 65–80 Mt/yr of additional methane emissions mitigation. Though these face substantial structural barriers, widespread adoption of such measures alongside targeted controls could bring anthropogenic methane emissions in line with those in 1.5ºC scenarios. Additional progress in targeted measures including feed supplements for livestock and alternatives to animal protein (Section 4.4.4) as well as diverting organic material that would otherwise lead to methane release from landfills to make useful products also have potential if they prove economically feasible and societally acceptable, and hence can be scaled up.

Policy ambition to date has thus far fallen short of mitigation consistent with 1.5ºC scenarios, and, as discussed in Chapter 1, atmospheric methane amounts are continuing to increase. Some steps have been taken, however. The countries of North America pledged to reduced methane emissions from oil and gas by 45 per cent by 2025, and the Climate and Clean Air Coalition (CCAC) Mineral Methane Initiative is aiming for a reduction of 60–75 per cent from the oil and gas subsector by 2030 among participants. These would provide substantial sector and region-specific mitigation. For example, were the low end of the 2030 Oil and Gas Initiative goal to be achieved across all CCAC partner countries, that would correspond to mitigation of about 30 Mt/yr of methane emissions based on projected 2030 baseline emissions, or ~28 Mt/yr based upon current 2020 emissions. Several sub-national jurisdictions have also put ambitious methane reduction laws into place. These include the US states of California and New York, with a 40 per cent reduction from 2013 methane emissions by 2030 in the former and a 40 per cent reduction from 1990 emissions by 2030 in the latter for all greenhouse gases including methane – using a 20-year methane global warming potential to emphasize the importance of reducing this gas as outlined in the New York's Methane Reduction Plan. Such steps are, however, only a partial recipe for achieving a 1.5ºC pathway.

Achieving a 1.5ºC pathway would require not only reversing the current rising trend in methane emissions but also greatly reducing anthropogenic methane emissions by 2030. This could be accomplished by policies targeted at implementing targeted controls on specific sectors, policies to bring about behavioural change, policies to bring about broad, cross-sectoral emissions reductions such as ambitious international agreements, following, for example, the pattern of the Kigali Amendments to reduce hydrofluorocarbon emissions, imposition of emissions caps or taxes, such as in the modelling presented in Section 4.3, or a combination of such policies. Implemented policies should be gender responsive, especially those promoting behavioural change. Achieving methane reductions also requires increased education and information about the economic and societal impacts of mitigation, something this assessment aims to provide, along with additional infrastructure to make use of abated emissions in some sectors and a change in economic incentives that may be misaligned and prevent even action with overall negative costs from being taken up (IEA 2020). It is also worth pointing out that due to the removal of co-emitted aerosols that accompanies a realistically paced phase-out of fossil fuels, even aggressive decarbonization will tend to have minimal net impacts on near-term, the first 20 years, temperatures. (Shindell and Smith, 2019). Prior research has therefore pointed out that the only plausible way of decreasing warming relative to the reference case during the next 20 years is through reductions in greenhouse gases from non-fossil sources including methane and nitrous oxide from agriculture and waste as well as fluorinated gases (Shindell and Smith 2019).

Prior analyses have shown the multiple benefits of reducing methane emissions (Shindell *et al*. 2012; UNEP/WMO 2011). This work adds to those prior analyses by both including more modelling to better characterize robustness and analyses of additional impacts, and also by greatly extending the scope of the associated economic analysis. A prior economic analysis by UNEP (UNEP 2011) included results from a single analysis of mitigation costs, whereas this study includes multiple such analyses and finds that the variation across them of mitigation potentials is large, leading to greater uncertainty than in the analyses of physical system responses, especially for the agricultural sector. Results are relatively robust for the fossil fuel and waste sectors and indicate clearly that there is an enormous potential for methane emissions mitigation with benefits that greatly outweigh implementation costs.



6. REFERENCES

Abbott, D.W., Aasen, I.M., Beauchemin, K.A., Grondahl, F., Gruninger, R., Hayes, M., Huws, S., Kenny, D.A., Krizsan, S.J., Kirwan, S.F., Lind, V., Meyer, U., Ramin, M., Theodoridou, K., von Soosten, D., Walsh, P.J., Waters, S., and Xing, X. (2020) Seaweed and Seaweed Bioactives for Mitigation of Enteric Methane: Challenges and Opportunities. *Animals*, 10(12), 2432.

Abdelradi, F. (2018). Food waste behaviour at the household level: A conceptual framework. *Waste Manag*., 71, 485-493.

Abiad M.G. and Meho L.I. (2018). Food loss and food waste research in the Arab world: A systematic review. *Food Security*, 1–12.

Abrahamse, W. and Steg, L. (2013). Social influence approaches to encourage resource conservation: A meta-analysis. *Global Environ. Change*, 23, 1773–85.

Academy of Science of South Africa, Brazilian Academy of Sciences, German National Academy of Sciences Leopoldina, U.S. National Academy of Medicine and U.S. National Academy of Sciences. (2019). Air Pollution and Health – A Science-Policy Initiative. *Annals of Global Health*, 85, 140, 1-9.

Afhsin, A., et al. (2017). Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study. *The Lancet*, 393, 1958-1972.

Alexandrowicz, L., Green, R., Joy. E.J.M., Smith, P. and Haines, A. (2016). The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PloS ONE*, 11(11): e0165797.

Alexe, M., Bergamaschi, P., Segers, A., Detmers, R., Butz, A., Hasekamp, O., Guerlet, S., Parker, R., Boesch, H., Frankenberg, C., Scheepmaker, R.A., Dlugokencky, E., Sweeney, C., Wofsy, S.C., and Kort, E.A. (2015). Inverse modelling of CH_4 emissions for 2010–2011 using different satellite retrieval products from GOSAT and SCIAMACHY. *Atmos. Chem. Phys*., 15, 113–133, doi:10.5194/acp-15-113-2015.

Alvarez, R.A., Zavala-Araiza, D., Lyon, D.R., Allen, D.T., Barkley, Z.R., Brandt, A.R., Davis, K.J., Herndon, S.C., Jacob, D.J., Karion, A. and Kort, E.A. (2018). Assessment of methane emissions from the US oil and gas supply chain. *Science*, 361, 186-188.

Anderson, G.B., Oleson, K.W., Jones, B. and Peng, R.D. (2018). Projected trends in high-mortality heatwaves under different scenarios of climate, population, and adaptation in 82 US communities. *Climatic Change*, 146, 455–470.

Anenberg, S.C., Horowitz, L.W., Tong, D.Q. and West J.J. (2010). An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human Mortality using atmospheric modeling. *Env. Health Persp*., 118, 1189–1195.

Anenberg, S.C., Henze, D.K., Tinney, V., Kinney, P.L., Raich, W., Fann, N., Malley, C.S., Roman, H., Lamsal, L., Duncan, B. and Martin, R.V. (2018). Estimates of the global burden of ambient PM 2.5, ozone, and NO2 on asthma incidence and emergency room visits. *Environmental Health Perspectives*, 126(10), p.107004.

Anthony, K.W., von Deimling, T.S., Nitze, I., Frolking, S., Emond, A., Daanen, R., Anthony, P., Lindgren, P., Jones, B. and Grosse, G. (2018). 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes. *Nature Communications*, 9, 1-11.

Archibald, A., O'Connor, F., Archer-Nicholls, S., Chipperfield, M., Dalvi, M., Folberth, G., Dennison, F., Dhomse, S., Griffiths, P., Hardacre, C., Hewitt, A., Hill, R., Johnson, C., Keeble, J., Köhler, M., Morgenstern, O., Mulchay, J., Ordóñez, C., Pope, R., Rumbold, S., Russo, M., Savage, N., Sellar, A., Stringer, M., Turnock, S., Wild, O. and Zeng, G. (2019). Description and evaluation of the UKCA stratosphere-troposphere chemistry scheme (StratTrop vn 1.0) implemented in UKESM1. *Geosci. Model Dev. Discuss*., doi:10.5194/gmd-2019-246.

Armstrong, B., Sera, F., Vicedo-Cabrera, A.M., Abrutzky, R., Åström, D.O., Bell, M.L.,

Chen, B-Y., de Sousa Zanotti Stagliorio Coelho, M., Correa, P.M., Dang, T.N., Diaz, M.H., Dung,

D.V., Forsberg, B., Goodman, P., Guo, Y-L.L., Guo, Y., Hashizume, M., Honda, Y., Indermitte, E., Íñiguez, C., Kan, H., Kim, H., Kyselý, J., Lavigne, E., Michelozzi, P., Orru, H., Ortega, N.V., Pascal, M., Ragettli, M.S., Saldiva, P.H.N., Schwartz, J., Scortichini, M., Seposo, X., Tobias, A., Tong, S., Urban, A., De la Cruz Valencia, C., Zanobetti, A., Zeka, A. and Gasparrini, A. (2019). The role of humidity in associations of high temperature with mortality: a multicountry, multicity study. *Environmental Health Perspectives*, 127(9), 097007.

Aunan, K., Fang, J., Hu, T., Seip, H.M., and Vennemo, H. (2006). Climate change and air quality-measures with co-benefits in China. *Environ. Sci. Technol*., 40, 4822-4829.

Avnery, S., Mauzerall, D.L., Liu, J. and Horowitz, L.W. (2011). Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage, *Atmospheric Environment*, 45, 2284-2296.

Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E. and Gilligan, C.A. (2014). Importance of food-demand management for climate mitigation. *Nature Climate Change*, 4, 924–929.

Baray, S., Darlington, A., Gordon, M., Hayden, K.L., Leithead, A., Li, S.M., Liu, P.S.K., Mittermeier, R.L., Moussa, S.G., O'Brien, J., Staebler, R., Wolde, M., Worthy, D., McLaren, R. (2018). Quantification of Methane Sources in the Athabasca Oil Sands Region of Alberta by Aircraft Mass Balance. *Atmos. Chem. Phys*., 18, 7361– 7378.

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., Eom, J., Krey, V., Kriegler, E., Mouratiadou, I. and de Boer, H.S. (2017). Shared socio-economic pathways of the energy sector–quantifying the narratives. *Global Environmental Change*, 42, pp.316-330.

Bender, M., Sowers, T. and Brook, E. (1997). Ice core isotope data constrain methane emissions. *Proceedings of the National Academy of Sciences*, 94 (16), 8343-8349.

Benmergui, J.S. (2019). *Innovations in Modeling and Statistical Analysis for Greenhouse Gas Flux Monitoring*. Doctoral dissertation, Harvard University, Graduate School of Arts & Sciences.

Bentayeb, M., Wagner, V., Stempfelet, M., Zins, M., Goldberg, M., Pascal, M., Larrieu, S., Beaudeau, P., Cassadou, S., Eilstein, D., Filleul, L., Le Tertre, A., Medinaa, S., Pascal, L., Prouvost, H., Quénel, P., Zeghnoun, A. and Lefranc, A. (2015). Association between long-term exposure to air pollution and mortality in France: a 25-year follow-up study. *Environ Int*., 85, 5–14.

Bergamaschi, P., Frankenberg, C., Meirink, J.F., Krol, M., Dentener, F., Wagner, T., Platt, U., Kaplan, J.O., Körner, S., Heimann, M., Dlugokencky, E.J. and Goede, A. (2007). Satellite chartography of atmospheric CH_4 from SCIAMACHY on board ENVISAT: 2. Evaluation based on inverse model simulations. *J. Geophys. Res.-Atmos*., 112, D02304.

Bergamaschi, P., Frankenberg, C., Meirink, J.F., Krol, M., Villani, M.G., Houweling, S., Dentener, F., Dlugokencky, E.J., Miller, J.B., Gatti, L.V., Engel, A., and Levin, I. (2009). Inverse modeling of global and regional CH_4 emissions using SCIAMACHY satellite retrievals. *J. Geophys. Res*., 114, D22301.

Bergamaschi, P., Houweling, S., Segers, A., Krol, M., Frankenberg, C., Scheepmaker, R.A., Dlugokencky, E., Wofsy, S.C., Kort, E.A., Sweeney, C., Schuck, T., Brenninkmeijer, C., Chen, H., Beck, V. and Gerbig, C. (2013). Atmospheric CH_4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements. *J. Geophys. Res.-Atmos*., 118, 7350–7369.

Bignell, D.E., Eggleton, P., Nunes, L., Thomas, K.L. (2017). Termites as mediators of carbon fluxes in tropical forest: Budgets for carbon dioxide and methane emissions. In Watt, A.D., Stork, N.E. and Hunter, M.D. (eds.). *Forests and Insects*. Chapman & Hall, London, UK.

Blake, D.R., Mayer, E.W., Tyler, S.C., Makide, Y., Montague, D.C. and Rowland, F.S. (1982). Global increase in atmospheric methane concentrations between 1978 and 1980. *Geophys. Res. Lett*., 9: 477-480.

Bock, M., Schmitt, J., Beck, J., Seth, B., Chappellaz, J. and Fischer, H. (2017). Glacial/interglacial wetland, biomass burning, and geologic methane emissions constrained by dual stable isotopic

CH_4 ice core records. *Proceedings of the National Academy of Sciences*, 114 (29) E5778-E5786.

Borgonovo, F., Conti, C., Lovarelli, D., Ferrante, V. and Guarino, M. (2019). Improving the sustainability of dairy slurry by a commercial additive treatment. *Sustainability*, 11, 4998.

Brandt, A.R., Heath, G.A., Kort, E.A., O'Sullivan, F., Pétron, G., Jordaan, S.M., Tans, P., Wilcox, J., Gopstein, A.M., Arent, D., Wofsy, S., Brown, N.J., Bradley, R., Stucky, G.D., Eardley, D. and Harriss, R. (2014). Methane Leaks from North American Natural Gas Systems, *Science*, 343, 733–735.

Bröde, P., Fiala, D., Lemke, B. and Kjellstrom, T. (2017). Estimated work ability in warm outdoor environments depends on the chosen heat stress assessment metric. *Int J Biometeorol*. https://doi.org/10.1007/s00484-017-1346-9 (accessed 6 March 2021).

Brune, A. (2010). Methanogenesis in the digestive tracts of insects. In Timmis, K.N. (ed.). *Handbook of Hydrocarbon and Lipid Microbiology, Vol 8*. Springer Verlag, Berlin, Germany.

Bryngelsson, D., Wirsenius, S., Hedenus, F. and Sonesson, U. (2016). How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture. *Food Policy*, 59, 152–164.

Buchwitz, M., Schneising, O., Reuter, M., Heymann, J., Krautwurst, S., Bovensmann, H., Burrows, J.P., Boesch, H., Parker, R.J., Somkuti, P. and Detmers, R.G. (2017). Satellite-derived methane hotspot emission estimates using a fast data-driven method. *Atmospheric Chemistry and Physics*, 17, 5751.

Buzan, J.R. and Huber, M. (2020). Moist heat stress on a hotter Earth. *Annual Review of Earth and Planetary Sciences*, 48.

Calvin, K.V., Patel, P.L., Clarke, L.E., Asrar, G.R., Bond-Lamberty, B., Cui, Y., Di Vittorio, A., Dorheim, K.R., Edmonds, J.A., (2019). GCAM v5.1: Representing the linkages between energy, water, land, climate, and economic systems. *Geoscientific Model Development*, 12, 1–22.

Cambaliza, M.O.L., Bogner, J.E., Green, R.B., Shepson, P.B., Harvey, T.A., Spokas. K.A., Stirm, B.H., Corcoran, M., Hartin, C., Hejazi, M., Horowitz, R., Iyer. G., Kyle, P., Kim, S., Link, R., McJeon, H., Smith, S.J., Snyder, A., Waldhoff, S. and Wise, M. (2017). Field measurements and modeling to resolve m2 to km2 CH_4 emissions for a complex urban source: An Indiana landfill study, *Elementa: Science of the Anthropocene*, 5(36).

Camilleri, A.R., Larrick, R.P., Hossain, S. and Patino-Echeverri, D. (2017). Consumers underestimate the emissions associated with food but are aided by labels. *Nat. Clim. Change*, 9, 53–8.

Carey, I.M., Atkinson, R.W., Kent, A.J., van Staa, T., Cook, D.G. and Anderson, H.R. (2013). Mortality Associations with Long-Term Exposure to Outdoor Air Pollution in a National English Cohort. *Am J Respir Crit Care Med*., 187, 1226–123.

Carleton, T.A., Jina, A., Delgado, M.T., Greenstone, M., Houser, T., Hsiang, S.M., Hultgren, A., Kopp, R.E., McCusker, K.E., Nath, I.B., Rising, J., Rode, A., Seo, H.K., Viaene, A., Yuan, J, and Zhang, A.T. (2020). *Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits*. NBER Working Paper No. 27599. National Bureau of Economc Research, Cambridge, MA, US. http://www.nber.org/papers/w27599 (accessed 6 March 2020)

Carmichael, M.J., Bernhardt, E.S., Bräuer, S.L. and Smith, W.K. (2014). The role of vegetation in methane flux to the atmosphere: should vegetation be included as a distinct category in the global methane budget? *Biogeochemistry*, 119(1-3), 1-24.

Center for International Earth Science Information Network, Columbia University, Food and Agriculture Programme of the United Nations, and Centro Internacional de Agricultura Tropical (2016). *Gridded Population of the World, Version 4 (GPWv4): Population Count Grid*. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY, US.

Chae, Y. and J. Park. (2011). Quantifying costs and benefits of integrated environmental strategies of air quality management and greenhouse gas reduction in the Seoul Metropolitan Area. *Energy Policy*, 39, 5296-5308.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R. and Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, 4, 287–291.

Chappellaz J., Raynaud D., Blunier T. and Stauffer B. (2000) The Ice Core Record of Atmospheric Methane. In Khalil M.A.K. (ed.). *Atmospheric Methane*. Springer Verlag, Berlin, Germany.

Chappellaz, J., Barnola, J., Raynaud, D., Korotkevich, Y.S. and Lorius, C. (1990). Ice-core record of atmospheric methane over the past 160,000 years. *Nature*, 345, 127–131.

Chan, E., Worthy, D.E., Chan, D., Ishizawa, M., Moran, M.D., Delcloo, A. and Vogel, F. (2020). Eight-Year Estimates of Methane Emissions from Oil and Gas Operations in Western Canada are Nearly Twice those Reported in Inventories. *Environmental Science & Technology*, 54, 23, 14899–14909.

Cifuentes, L., Borja-Aburto, V.H., Gouveia, N., Thurston, G. and Davis, D.L. (2001). Hidden health benefits of greenhouse gas mitigation. *Science*, 293.

Clark, M.A., Springmann, M., Hill, J. and Tilman, D. (2019). Multiple health and environmental impacts of foods, *Proceedings of the National Academy of Sciences*, 116(46), 23357–23362.

Collins, W.J., Sitch, S. and Boucher, O. (2010). How vegetation impacts affect climate metrics for ozone precursors. *J. Geophys. Res*., 115, D23308.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J. and Wehner, M. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. In Stocker, T.F., Qin, D.. Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Climate Change 2013: *The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Collins, W.J., Fry, M.M., Yu, H., Fuglestvedt, J.S., Shindell, D.T. and West, J.J. (2013). Global and regional temperature-change potentials for near-term climate forcers. *Atmos. Chem. Phys*., 13, 2471–2485.

Collins, W.J., Webber, C.P., Cox, P.M., Huntingford, C., Lowe, J., Sitch, S., Chadburn, S.E., Comyn-Platt, E., Harper, A.B., Hayman, G. and Powell, T. (2018). Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters*, 13, 054003.

Conley, A.J., Westervelt, D.M., Lamarque, J.-F., Fiore, A.M., Shindell, D., Correa, G., Faluvegi, G. and Horowitz, L.W. (2018). Multimodel surface temperature responses to removal of U.S. sulfur dioxide emissions. *J. Geophys. Res*., 123, 2773–2796.

Conley, S., Faloona, I., Mehrotra, S., Suard, M., Lenschow, D.H., Sweeney, C., Herndon, S., Schwietzke, S., Pétron, G., Pifer, J. and Kort, E.A. (2017). Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases. *Atmospheric Measurement Techniques*, 10(9).

Cooper, M.D., Estop-Aragonés, C., Fisher, J.P., Thierry, A., Garnett, M.H., Charman, D.J., Murton, J.B., Phoenix, G.K., Treharne, R., Kokelj, S.V. and Wolfe, S.A. (2017). Limited contribution of permafrost carbon to methane release from thawing peatlands. *Nature Climate Change*, 7, 507-511.

Crouse, D.L., Peters, P.A., Hystad, P., Brook, J.R., van Donkelaar, A., Martin, R.V.,

Villeneuve, P.J., Jerrett, M., Goldberg, M.S., Arden Pope III, C., Brauer, M., Robert D. Brook, R.D., Robichaud, A., Richard Menard, R. and Burnett, R.T. (2015). Ambient PM2.5, O3, and NO2 exposures and associations with mortality over 16 years of follow-up in the Canadian Census Health and Environment Cohort (CanCHEC). *Environ. Health Persp*., 123, 1180–1186.

Danabasoglu, G., Lamarque, J.-F., Bacmeister, J., Bailey, D.A., DuVivier, A.K., Edwards, J., Emmons, L., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M.M., Large, W.G., Lawrence, D., Lenaerts, J., Lindsay, K., Lipscomb, W., Lofverstrom, M., Mills, M., Neale, R., Oleson, K., Otto-Bleisner, B., Phillips, A., Sacks, W., Tilmes, S., Vertenstein, M., Bertini, A., Deser, C., Fox-Kemper, B., Kay, J.E., Kushner, P., Long, M.C., Mickelson, S., Moore, J.K., Nienhouse, E., Polvani, L., Rasch,

P.J., and Strand, W.G. (2020). The Community Earth System Model version 2 (CESM2). Accepted for publication in *JAMES*.

Dean, J.F., Middelburg, J.J., Röckmann, T., Aerts, R., Blauw, L.G., Egger, M., Jetten, M.S., de Jong, A.E., Meisel, O.H., Rasigraf, O. and Slomp, C.P. (2018). Methane feedbacks to the global climate system in a warmer world. *Reviews of Geophysics*, 56, 207-250.

Di, Q., Wang, Y., Zanobetti, A., Wang, Y., Koutrakis, P., Choirat C., Dominici, F. and Schwartz, J.D. (2017). Air pollution and mortality in the Medicare population, *N Engl J Med*., 376, 2513–2522.

Dlugokencky E. and Houweling S. (2015). *Chemistry of the Atmosphere: Methane, In Encyclopedia of Atmospheric Sciences*, 2nd. Edition. Academic Press, Cambridge, MA, US.

Drew, J., Cleghorn, C., Macmillan, A. and Mizdrak, A. (2020). Healthy and Climate-Friendly Eating Patterns in the New Zealand Context. *Environmental Health Perspectives*, 128,1, 17007.

Dunne, J.P., Horowitz, L.W., Adcroft, A.J., Ginoux, P., Held, I.M., John, J.G., Krasting, J.P., Malyshev, S., Naik, V., Paulot, F., Shevliakova, E., Stock, C. A., Zadeh, N., Balaji, V., Blanton, C., Dunne, K.A., Dupuis, C., Durachta, J., Dussin, R., Gauthier, P.P.G., Griffies, S.M., Guo, H., Hallberg, R.W., Harrison, M., He, J., Hurlin, W., McHugh, C., Menzel, R., Milly, P.C.D., Nikonov, S., Paynter, D. J., Ploshay, J., Radhakrishnan, A., Rand, K., Reichl, B.G., Robinson, T., Schwarzkopf, D.M., Sentman, L.T., Underwood, S., Vahlenkamp, H., Winton, M., Wittenberg, A.T., Wyman, B., Zeng, Y. and Zhao, M. (2020). The GFDL Earth System Model version 4.1 (GFDL-ESM4.1): Model description and simulation characteristics. *J. Adv. Modeling Earth Sys*. https://doi.org/10.1029/2019MS002015 (accessed 6 March 2021).

Duren, R.M., Thorpe, A.K., Foster, K.T., Rafiq, T., Hopkins, F.M., Yadav, V., Bue, B.D..Thimpson, D.R., Conley, S., Colombi, N.K., Frankenberg, C., McCubbin, I.B., Eastwood, M.L. Falk, M., Herner, J.D., Croes, B.E., Green, R.D. and Miller, C.E. (2019). California's methane super-emitters. *Nature,* 575, 180-185.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K. Adler, A., Baum, I., Brunner, S., Eikemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C. and Zwickel, T. (2014). *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Etheridge, D.M., Steele, L.P., Francey, R.J. and Langenfeld, R.L. (1998). Atmospheric methane between 1000 A.D. and present: Evidence of anthropogenic emissions and climatic variability. *J. Geophys. Res*., 103, D13, 15,979-15,993.

Etiope, G. and Schwietzke, S. (2019). Global geological methane emissions: an update of top-down and bottom-up estimates. *Elem. Sci. Anth*., 7, 47.

Etminan, M., Myhre, G., Highwood, E.J. and Shine, K.P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, 43, 12-614.

EUROSTAT. (2016). *Hospital discharges by diagnosis*. Publications Office of the European Union, Luxembourg.

Fann, N., Coffman, E., Timin, B. and Kelly, J.T. (2018). The estimated change in the level and distribution of PM2.5-attributable health impacts in the United States: 2005-2014. *Environ Res*., 167, 506-514.

Fann, N., Baker, K.R., Chan, E.A.W., Eyth, A., Macpherson, A., Miller, E. and Snyder, J. (2018) Assessing Human Health PM 2.5 and Ozone Impacts from U.S. Oil and Natural Gas Sector Emissions in 2025. *Environ. Sci. Technol., 52, 8095*–8103.

Food and Agriculture Organization (2014). *Food wastage footprint: Full cost accounting*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Food and Agriculture Organization of the United Nations (2017). *Global Livestock Environmental Assessment Model (GLEAM)*. Food and Agriculture Organization of the United Nations, Rome, Italy. www.fao.org/gleam/en/ (accessed 6 March 2021).

Food and Agriculture Organization of the United Nations (2019). *State of Food and Agriculture (SOFA), 2019*. Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/state-of-food-agriculture/2019/en/ (accessed 6 March 2021)

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme and World Health Organization (2017). *The State of Food Security and Nutrition in the World: Building Resilience for Peace and Food Security*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme and World Health Organization (2020). *The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets*. Food and Agriculture Organization of the United Nations, Rome, Italy. https://doi.org/10.4060/ca9692en (accessed 6 March 2021).

Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E.

Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N.. MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds.). (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Fiore, A.M., Jacob, D.J., Field, B.D., Streets, D.G., Fernandes, S.D. and Jang, C. (2002). Linking ozone pollution and climate change: The case for controlling methane. *Geophysical Research Letters*, 29, 25-1.

Fiore, A.M., West, J.J., Horowitz, L.W., Naik, V. and Schwarzkopf, M.D. (2008). Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality. *J. Geophys. Res*., 113, 1–16.

Frankenberg, C., Meiring, J.F., Bergamaschi, P., Goede, A.P.H., Heimann, M., Korner, S., Platt, U., van Weele, M., and Wagner, T. (2006). Satellite chartography of atmospheric methane from SCIAMACHY on board ENVISAT: Analysis of the years 2003 and 2004. *JGR: Atmospheres*. Doi:10.1029/2005JD006235.

Frankenberg, C., Thorpe, A.K., Thompson, D.R., Hulley, G., Kort, E.A., Vance, N., Borchardt, J., Krings, T., Gerilowski, K., Sweeney, C., Conley, S., Bue, B.D., Aubrey, A.D., Hook, S. and Green, R.O. (2016). Airborne methane remote measurements reveal heavy-tail flux

distribution in Four Corners region. *Proc. Natl Acad. Sci*., 113, 9734–9739.

Fu, B., Gasser, T., Li, B. and Tao, S. (2020) Short-lived climate forcers have long-term climate impacts via the carbon–climate feedback. *Nat. Clim. Chang*., 10, 851–855.

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D. S., Dai, H., Hijioka, Y. and Kainuma, M. (2017). SSP3: AIM implementation of Shared Socioeconomic Pathways. *Global Environmental Change*, 42, 268–283.

FUSIONS. (2016). *Estimates of European food waste levels*. IVL Swedish Environmental Research Institute, Stockholm, Sweden. http://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf (accessed 6 March 2021).

Gao, J., Kovats, S., Vardoulakis, S., Wilkinson, P., Woodward, A., Li, J., Gu, S., Liu, X., Wu, H., Wang, J., Song, X., Zhai, Y., Zhao, J. and Liu, Q. (2018). Public health co-benefits of greenhouse gas emissions reduction: A systematic review. *Science of the Total Environment*, 627, 388-402.

Garrone, P., Melacini, M. and Perego, A. (2014). Opening the black box of food waste reduction. *Food Pol*., 46, 129-139.

Gasbarra, D., Toscano, P., Famulari, D., Finardi, S., Di Tommasi, P., Zaldei, A., Carlucci, P., Magliulo, E. and Gioli, B. (2019). Locating and quantifying multiple landfills methane emissions using aircraft data. *Environmental Pollution*, 254, Part B, 112987, ISSN 0269-7491.

Gasser, T., Peters, G.P., Fuglestvedt, J.S., Collins, W.J., Shindell, D.T. and Ciais, P. (2017). Accounting for the climate-carbon feedback in emission metrics. *Earth System Dynamics*, 8(2), 235-253.

Gasparrini, A., Guo, Y.M., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S.L., Rocklov, J., Forsberg, B., Leone, M., De Sario, M., Bell, M.L., Guo, Y.L.L., Wu, C.F., Kan, H., Yi, S.M., Coelho, M., Saldiva, P.H.N., Honda, Y., Kim, H. and Armstrong, B. (2015). Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet*, 386, 369–375.

Gedney, N., Cox, P.M. and Huntingford, C. (2004). Climate feedback from wetland methane emissions. *Geophysical Research Letters*, 31(20).

Geoffroy, O., Saint-Martin, D., Bellon, G., Voldoire, A., Olivié, D.J.L. and Tytéca, S. (2013). Transient climate response in a two-layer energy-balance model. Part II: Representation of the efficacy of deep-ocean heat uptake and validation for CMIP5 AOGCMs. *J. Climate*., 26, 1859-1876.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. and Tempio, G. (2013). *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Gettelman, A., Mills, M.J., Kinnison, D.E., Garcia, R.R., Smith, A.K., Marsh, D.R., Tilmes, S., Vitt, F., Bardeen, C.G., McInerny, J., Liu, H.-L., Solomon, S.C., Polvani, L.M., Emmons, L.K., Lamarque, J.-F., Richter, J.H., Glanville, A.S., Bacmeister, J.T., Phillips, A.S., Neale, R.B., Simpson, I.R., DuVivier, A.K., Hodzic, A. and Randel, W.J. (2019). The Whole Atmosphere Community Climate Model Version 6 (WACCM6). *J. Geophys. Res*. https://doi.org/10.1029/2019JD030943 (accessed 6 March 2021).

Gillett, N.P., Kirchmeier-Young, M., Ribes, A., Shiogama, H., Hegerl, G.C., Knutti, R., Gastineau, G., John, J.G., Li, L., Larissa Nazarenko, L., Rosenbloom, N., Seland, Ø., Wu, T., Yukimoto, S. and Ziehn, T. 2021. Constraining human contributions to observed warming since the pre-industrial period. *Nature Climate Change*. https://doi.org/10.1038/s41558-020-00965-9 (accessed 19 Feb. 2021).

Gilligan, J., Dietz, T., Gardner, G., Stern, P. and Vandenbergh, M. (2010). The behavioural wedge. *Significance*, 7: 17–20.

Global Burden of Disease Collaborative Network. (2017). *Global Burden of Disease Study 2017 (GBD 2017) Results*. The Institute for Health Metrics and Evaluation, Seattle, WA, US.

Gorchov Negron, A.M., Kort, E.A., Conley, S.A. and Smith, M.L. (2020). Airborne Assessment of Methane Emissions from Offshore Platforms in the US Gulf of Mexico. *Environmental Science & Technology*, 54, 5112–5120.

Graff Zivin, J. and Neidell, M. (2014). Temperature and the Allocation of Time: Implications for Climate Change. *J. Labor Econ*., 32(1), 1–26.

Green, R., Milner, J., Dangour, A.D. and Haines, A. (2015). The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. *Climatic Change*, 129, 253.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R. and Meybeck, A. (2011). *Global Food Losses and Food Waste – Extent, Causes and Prevention*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Gvakharia, A., Kort, E.A., Brandt, A., Peischl, J., Ryerson, T.B., Schwarz, J.P., Smith. M.L. and Sweeney, C. (2017). Methane, black carbon, and ethane emissions from natural gas flares in the Bakken Shale, North Dakota. *Environmental Science & Technology*, 51(9), 5317–5325.

Haines, A. (2012). Health benefits of a low carbon economy. *Public Health*, 126 (Suppl. 1), pp. S33-9.

Haines, A., Amann, M., Borgford-Parnell, N., Leonard, S., Kuylenstierna, J.C.I. and Shindell, D. (2017). Short-lived climate pollutant mitigation and the sustainable development goals. *Nature Climate*

Change, 7, 863–869.

Hammitt, J.K. and Robinson, L.A. (2011). The income elasticity of the value per statistical life: transferring estimates between high and low income populations. *Journal of Benefit-Cost Analysis*, 2(1), 1–29.

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G.A., Russell, G., Aleinov, I., Bauer, M., Bauer, S.E., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, N., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, H., Kelley, M., Kiang, N., Koch, D., Lean, J., Lo, K., Menn, S., Miller, R.L., Minnis, P., Novakov, T., Oinas, V., Perlwitz, Ja., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielieki, D., Wong, T., Yao, M. and Zhang, S. (2005). Efficacy of climate forcings. J. Geophys. Res., 110, D18104.

Harmsen, M.J.H.M., van Den Berg, M., Krey, V., Luderer, G., Marcucci, A., Strefler, J. and Van Vuuren, D.P. (2016). How climate metrics affect global mitigation strategies and costs: a multi-model study. *Climatic Change*, 136, 203–216.

Harmsen, M.J.H.M., van Vuuren, D.P., Nayak, D.R., Hof, A.F., Höglund-Isaksson, L., Lucas, P.L., Nielsen, J.B., Smith, P. and Stehfest, E., (2019). Long-term marginal abatement cost curves of non-CO_2 greenhouse gases. *Environmental Science & Policy*, 99, 136–149.

Harmsen, M.J.H.M., van Vuuren, D.P., Bodirsky B.L., Chateau, J., Durand-Lasserve, O., Drouet, L., Fricko, O., Fujimori, S., Gernaat, D.E.H.J., Hanaoka, T., Hilaire, J., Keramidas, K., Luderer, G., Moura, M.C.P., Sano, F., Smith, S.J. and Wada, K. (2019b). The role of methane in future climate strategies: mitigation potentials and climate impacts. *Climatic Change*, 163:1409–1425.

https://doi.org/10.1007/s10584-019-02437-2 (accessed 6 March 2021).

Hedenus, F., Wirsenius, S. and Johansson, D.J.A. (2014). The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Climatic Change*, 124(1–2): 79–91.

Héroux, M.E., Anderson, H.R., Atkinson, R., Brunekreef, B., Cohen, A., Forastiere, F., Hurley, F., Katsouyanni, K., Krewski, D., Krzyzanowski, M. and Künzli, N. (2015). Quantifying the health impacts of ambient air pollutants: recommendations of a WHO/Europe project. *Int J Public Health*, 60, 619–27.

Hmiel, B., Petrenko, V.V., Dyonisius, M.N., Buizert, C., Smith, A.M., Place, P.F., Harth, C., Beaudette, R., Hua, Q., Yang, B., Vimont, I., Michel, S.E., Severinghaus, J.P., Etheridge, D., Bromley, T., Schmitt, J., Faïn, X., Weiss, R.F. and Dlugokencky, E. (2020). Preindustrial 14 CH_4 indicates greater anthropogenic fossil CH_4 emissions. *Nature*, 578, 409–412.

Höglund-Isaksson, L., Gómez-Sanabria, A. Klimont, Z., Rafaj, P. and Schöpp, W. (2020). Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. *Environ. Res. Comm*., 2, 025004.

Holtsmark, B. (2012). Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, 112, 415–428.

Honda, Y., Kondo, M., McGregor, G., Kim, H., Guo, Y.L., Hijioka, Y., Yoshikawa, M., Oka, K., Takano, S., Hales, S. and Kovats, R. (2014). Heat-related mortality risk model for climate change impact projection. *Environmental Health and Preventive Medicine*, 19, 56–63.

Horowitz, L.W., Naik, V., Paulot, F., Ginoux, P.A., Dunne, J.P., Mao, J., Schnell, J., Chen, X., He, J., John, J.G. and Lin, M. (2020). The GFDL global atmospheric chemistry-climate model AM4. 1: Model description and simulation characteristics. *Journal of Advances in Modeling Earth Systems*, 12(10), e2019MS00203.

Hristov, A.N., Oh, J., Giallongo, F., Frederick, T.W., Harper, M.T., Weeks, H.L., Branco, A.F., Moate, P.J., Deighton, M.H., Williams, S.R.O. and Kindermann, M. (2015). An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. *Proceedings of the National Academy of Sciences*, 112, 10663–10668.

Hsiang, S., Kopp, R., Jina, A., Hsiang, S., Kopp, R., Jina, A., Rising, A., Delgado, M., Mohan, S.,

Rasmussen, D.J., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen, K. and Houser, T. (2017). Estimating economic damage from climate change in the United States. *Science*, 356(6345), 1362–1369.

International Energy Agency (2020). *Methane Tracker*. International Energy Agency, Paris, France. https://www.iea.org/reports/methane-tracker (accessed 6 March 2021).

International Labour Organization (2019). *Working on a warmer planet: The impact of heat stress on labour productivity and decent work*. International Labour Office, Geneva, Switzerland.

International Labour Organization (2020). *ILOSTAT explorer: Statutory nominal gross monthly minimum wage – Harmonized series – Annual, 2020*. International Labour Office, Geneva, Switzerland. https://www.ilo.org/shinyapps/bulkexplorer0/?lang=en&segment=indicator&id=EAR_4MMN_CUR_NB_A (accessed 6 March 2021).

International Futures (Ifs) modeling system, Version 7.58. Frederick S. Pardee Center for International Futures, Josef Korbel School of International Studies, University of Denver, Denver, CO. http://www.ifs.du.edu/ifs/frm_MainMenu.aspx (accessed 6 March 2021).

Intergovernmental Panel on Climate Change (2018). Summary for Policymakers. In Masson-Delmotte, V., Masson Delmotte, V., Zhai, P., Portner, H.O., Roberts, D.C., Skea, J., Shukla, P.R., Pirani, A., Mouffouma-Okia, W., Pean, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. World Meteorological Organisation, Geneva, Switzerland.

Ishangulyyev, R., Kim, S. and Lee, S.H. (2019). Understanding Food Loss and Waste-Why Are We Losing and Wasting Food? *Foods*, 8, 297.

Jackson, R.B., Saunois, M., Bousquet, P., Canadell, J.G., Poulter, B., Stavert, A.R., Bergamaschi, P., Niwa, Y., Segers, A. and Tsuruta, A. (2020). Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. *Environ. Res. Lett*., 15, 071002.

Jackson R.B., Solomon E.I., Canadell J.G., Cargnello M. and Field C.B. (2019). Comment, Methane Removal and Atmospheric Restoration. *Nature Sustainability*, 2, 436–438.

Jackson R.B., Solomon E.I., Canadell J.G., Cargnello M., Field C.B. and Abernethy S. (2020). Reply to: Practical constraints on atmospheric methane removal. *Nature Sustainability*, 3, 358–359.

Jacob, D., Turner, A., Maasakkers, J., Sheng, J-X., Sun, K., Liu, X., Chance, K., Aben, I., McKeever, J. and Frankenberg, C. (2016). Satellite observations of atmospheric methane and their value for quantifying methane emissions. *Atmospheric Chemistry and Physics*, 16. 14371–14396. 10.5194/acp-16-14371-2016.

Jerrett, M., Burnett, R.T., Beckerman, B.S., Turner, M.C., Krewski, D., Thurston, G., Martin,R.V., van Donkelaar, A., Hughes, E., Shi, Y., Gapstur, S.M., Thun, M.J and Arden Pope III, C. (2013). Spatial analysis of air pollution and mortality in California. *Am J Respir Crit Care Med*., 188, 593–599.

Johnson, M.R., Tyner, D.R., Conley, S., Schwietzke, S. and Zavala-Araiza, D. (2017). Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector. *Environ. Sci. Technol*., 51, 13008–13017.

Karion, A., Sweeney, C., Pétron, G., Frost, G., Hardesty, R.M., Kofler, J., Miller, B.M., Newberger, T., Wolter, S., Banta, R., Brewer, A., Dlugokencky, E., Lang, P., Montzka, S.A., Schnell, R., Tans, P., Trainer, M., Zamora, R. and Conley, S. (2013). Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophys. Res. Lett*., 40, 4393–4397.

Karl, D.M., Beversdorf, L., Björkman, K.M., Church, M.J., Martinez, A. and Delong, E.F. (2008). Aerobic production of methane in the sea. *Nature Geosci*., 1, 473–478.

Katsouyanni, K., Samet, J.M., Anderson, H.R., Atkinson, R., Le, A.T., Medina, S., Samoli, E., Touloumi, G., Burnett, R.T., Krewski, D. and Ramsay, T. (2009). *Air pollution and health: a European and North American approach (APHENA)*. Research report. Health Effects Institute, Boston, MA, US.

Kelley, M., Schmidt, G.A., Nazarenko, L.S., Bauer, S.E., Ruedy, R., Russell, G.L., Ackerman, A.S., Aleinov, I., Bauer, M., Bleck, R., Canuto, V., Cesana, G., Cheng, Y., Clune, T.L., Cook, B.I., Cruz, C.A., Del Genio, A.D., Elsaesser, G.S., Faluvegi, G., Kiang, N.Y., Kim, D., Lacis, A.A., Leboissetier, A., LeGrande, A.N., Lo, K.K., Marshall, J., Matthews, E.E., McDermid, S., Mezuman, K., Miller, R.L., Murray, L.T., Oinas, V., Orbe, C., García-Pando, C.P., Perlwitz, J.P., Puma, M.J., Rind, D., Romanou, A., Shindell, D.T., Sun, S., Tausnev, N., Tsigaridis, K., Tselioudis, G., Weng, E., Wu, J. and Yao, M.S. (2020). GISS-E2.1: Configurations and Climatology. *J. Adv. Modeling Earth Sys*., 12(8), e2019MS002025.

Kelso, M. (2018). Pipeline Incidents Continue to Impact Residents. *Fractracker Alliance*, 7. https://www.fractracker.org/2018/12/pipeline-incidents-impact-residents/ (accessed 9 March 2021).

Keppler, F., Hamilton, J.T., Brass, M. and Röckmann, T. (2006). Methane emissions from terrestrial plants under aerobic conditions. *Nature*, 439,187–91.

Kinley, R.D., de Nys, R., Vucko, M.J., Machado, L. and Tomkins, N.W. (2016). The red macroalgae Asparagopsis taxiformis is a potent natural antimethanogenic that reduces methane production during in vitro fermentation with rumen fluid. *Animal Production Science*, 56, 282–289.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, S., Canadell, J.G., Dlugokencky, E.J., Bergamaschi, P., Bergmann, D., Blake, D.R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E.L., Houweling, S., Josse, B., Fraser, P.J., Krummel, P.B., Lamarque, J-F., Langenfelds, R.L., Le Quéré, C., Naik, V., O'Doherty, S., Palmer, P.I., Pison, I., Plummer, D., Poulter, B., Prinn, R.G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D.T., Simpson, I.J., Spahni, R., Steele. L.P., Strode, S.A., Sudo, K., Szopa, S., van der Werf, G.R., Voulgarakis, A., van Weele, M., Weiss, R.F., Williams, J.E. and Zeng, G.(2013). Three decades of global methane sources and sinks. Nature Geoscience, 6, 813–823.

Kirtman, B., Power, S.B., Adedoyin, J.A., Boer, G.J., Bojariu, R., Camilloni, I., Doblas-Reyes, F.J., Fiore, A.M., Kimoto, M., Meehl, G.A., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenborgh, G.J., Vecchi, G. and Wang, H.J. (2013). Near-term Climate Change: Projections and Predictability. In Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K.

Kjellstrom, T., Freyberg, C., Lemke, B., Otto, M. and Briggs, D. (2018) Estimating population heat exposure and impacts on working people in conjunction with climate change. *Int J Biometeorol, 62, 291–306.*

Kjellstrom, T., Lemke, B., Otto, M., Hyatt, O. and Dear, K. (2014). Occupational Heat Stress. Contribution to WHO project on Global assessment of the health impacts of climate change. Technical Report 2014:4, 1–52. *Climate CHIP*.

Knittel, N., Jury, M.W., Bednar-Friedl, B., Bachner, G. and Steiner, A.K. (2020). A global analysis of heat-related labour productivity losses under climate change – implications for Germany's foreign trade. *Climatic Change*, 1–19.

Kort, E.A., Frankenberg, C., Costigan, K.R., Lindenmaier, R., Dubey, M.K. and Wunch, D. (2014). Four corners: The largest US methane anomaly viewed from space. *Geophys. Res. Lett*., 41, 6898–6903.

Lackner, K.S. (2020). Practical Constraints on Atmospheric Methane Removal. *Nature Sustainability*, 3, 357.

Lavoie, T. N., Paul B. Shepson, Maria O. L. Cambaliza, Brian H. Stirm, Stephen Conley, Shobhit Mehrotra, Ian C. Faloona, and David Lyon, Spatiotemporal Variability of Methane Emissions at Oil and Natural Gas Operations in the Eagle Ford Basin. *Environmental Science & Technology*, 51 (14), 8001-8009, 2017.

Lee, M., Nordio, F., Zanobetti, A., Kinney, P., Vautard, R. and Schwartz, J. (2014). Acclimatization across space and time in the effects of temperature on mortality: a time-series analysis. *Environmental Health*, 13, doi: 10.1186/1476-069x-13-89.

Lee, J.Y., Kim, H., Gasparrini, A., Armstrong, B., Bell, M.L., Lavigne, F.S.E., Abrutzky, R., Tong, S., de Sousa Zanotti Stagliorio Coelho, M., Hilario, P., Matus Correal Nicolas Valdes Ortega, N.S.P., Kan, H., Osorio Garcia., S., Kyselý, J., Urban,, A., Orru, H., Indermitte, E., Jaakkola, J.J.K., Ryti, N.R.I., Pascal, M., Goodman, P.G., Zeka, A., Michelozzi, P., Scortichini, M., Hashizume, M., Honda, Y., Hurtado, M., Cruz, J., Seposo., Nunes, B., Teixeira, J.P., Tobias, A., Íñiguez, C., Forsberg, B., Åström, C., Vicedo-Cabrera, A.M., Ragettli, M.S., Guo, Y-L,L, Chen, B-Y., Zanobetti, A., Schwartz, J., Dang, T.N., Van, D.D., Mayvaneh, F., Overcenco, A., Li, S. and Guo,, Y..(2019). Predicted temperature-increase-induced global health burden and its regional variability. *Env. Intl*., 131, 105027.

Lenhart, K., Klintzsch, T., Langer, G., Nehrke, G., Bunge, M., Schnell, S. and Keppler, F. (2016). Evidence for methane production by the marine algae Emiliania huxleyi. *Biogeosciences*, 13, 3163–3174.

Li, D., Yuan, J. and Kopp, R.B. (2020). Escalating global exposure to compound heat-humidity extremes with warming. *Environmental Research Letters*.

Li, X., Norman, H.C., Kinley, R.D., Laurence, M., Wilmot, M., Bender, H., de Nys, R. and Tomkins, N. (2016). Asparagopsis taxiformis decreases enteric methane production from sheep. *Animal Production Science*, 58, 681–688.

Luber, G. and McGeehin, M. (2008). Climate Change and Extreme Heat Events. *American Journal of Preventive Medicine*, 35, 429–435.

Ma, W., Chen, R. and Kan, H. (2014). Temperature-related mortality in 17 large Chinese cities: How heat and cold affect mortality in China. *Environmental Research*, 134, 127–133.

Maasakkers, J.D., Jacob, D., Sulprizio, M.P., Scarpelli, T.R., Nesser, H., Sheng, J.X., Zhang, Y., Hersher, M., Bloom, A.A., Bowman, K.W., Worden, J.R., Janssens-Maenhout, G. and Parker, R.J. (2019). Global distribution of methane emissions, emission trends, and OH concentrations and trends inferred from an inversion of GOSAT satellite data for 2010-2015. *Atmos. Chem. Phys*., 19, 7859–7881.

Machado, L., Magnusson, M., Paul, N.A., Kinley, R., de Nys, R. and Tomkins, N. (2016). Dose-response effects of Asparagopsis taxiformis and Oedogonium sp. On in vitro fermentation and methane production. *J Appl Phycol*., 28, 1443–1452.

Machado, L., Tomkins, N., Magnusson, M., Midgley, D.J., de Nys, R. and Rosewarne, C.P. (2018). In Vitro Response of Rumen Microbiota to the Antimethanogenic Red Macroalga Asparagopsis taxiformis, *Microb. Ecol*., 75, 811–818.

Malley, C.S., Henze, D.K., Kuylenstierna, J.C.I., Vallack, H.W., Davila, Y., Anenberg S.C., Turner, M.C. and Ashmore, M.R. (2017). Updated global estimates of respiratory mortality in adults ≥ 30 years of age attributable to long-term ozone exposure. *Env. Health Persp*., 125, 087021.

Marais, E.A., Jacob, D.J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Kurosu, T.P., Chance, K., and Sauvage, B. (2014). Anthropogenic emissions in Nigeria and implications for ozone air quality: a view from space. *Atmos. Environ*., 99, 32–40.

Marten, A. and Newbold, S. (2012). Estimating the social cost of non-CO_2 GHG emissions: Methane and nitrous oxide. *Energy Policy*, 51, 957.

Mbow, C., Rosenzweig, C. ., Barioni, L.G., Benton, T.G., Herrero, M, Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M.G., Sapkota, T., Tubiello, F.N. and Xu, Y. (2019). Food Security. In Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J. (eds.). *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security,*

and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Mehrotra, S., Faloona, I., Suard, M., Conley, S. and Fischer, M.L. (2017). Airborne methane emission measurements for selected oil and gas facilities across California. Environmental *Science & Technology*, 51, 12981–12987.

Meijer, Y. *et al*. (2019). Copernicus Mission Requirements Document, EOP-SM/3088/YM-ym, Issue 2.0.

Miller, S.M., Michalak, A.M., Detmers, R.G., Hasekamp, O.P., Bruhwiler, L.M.P., and Schwietzke, S. (2019). China's coal mine methane regulations have not curbed growing emissions. *Nature Communications*, doi:10.1038/s41467-018-07891-7.

Mills, G., Sharps, K., Simpson, D., Pleijel, H., Frei, M., Burkey, K., Emberson, L., Uddling, J., Broberg, M., Feng, Z., Kobayashi, K. and Agrawal, M. (2018). Closing the global ozone yield gap: Quantification and cobenefits for multistress tolerance. *Glob Change Biol*., 24, 4869–4893.

Monteil, G., Houweling, S., Butz, A., Guerlet, S., Schepers, D., Hasekamp, O., Frankenberg, C., Scheepmaker, R., Aben, I. and Röckmann, T. (2013). Comparison of CH_4 inversions based on 15 months of GOSAT and SCIAMACHY observations. *J. Geophys. Res.-Atmos*., 118, 11807–11823, doi:10.1002/2013JD019760.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, ., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. and Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. Midgley, P.M. (eds.). *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Naik, V., Voulgarakis, A., Fiore, A.M., Horowitz, L.W., Lamarque, J.-F., Lin, M., Prather, M.J., Young, P.J., Bergmann, D., Cameron-Smith, P.J., Cionni, I., Collins, W.J., Dalsøren, S. B., Doherty, R., Eyring, V., Faluvegi, G., Folberth, G.A., Josse, B., Lee, Y.H., MacKenzie, I. A., Nagashima, T., van Noije, T.P.C., Plummer, D.A., Righi, M., Rumbold, S.T., Skeie, R., Shindel, D.T., Stevenson, D.S., Strode, S., Sudo, K., Szopa, S. and Zeng, G. (2013). Preindustrial to present-day changes in tropospheric hydroxyl radical and methane lifetime from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmos. Chem. Phys*., 13, 5277–5298.

National Academies of Sciences, Engineering and Medicine. (2018). *Improving Characterization of Anthropogenic Methane Emissions in the United States*. National Academies Press, Washington, DC, U.S. https://www.ncbi.nlm.nih.gov/books/NBK519293/ (accessed 22 March 2021).

Nauer, P.A., Hutley, L.B. and Arndt, S.K. (2018). Termite mounds mitigate half of termite methane emissions. *Proceedings of the National Academy of Sciences*, 115, 13306–13311.

Nisbet, R.E., Fisher, R., Nimmo, R.H., Bendall, D.S., Crill, P.M., Gallego-Sala, A.V., Hornibrook, E.R., López-Juez, E., Lowry, D., Nisbet, P.B., Shuckburgh, E.F., Sriskantharajah, S., Howe, C.J. and Nisbet, E. G. (2009). Emission of methane from plants. *Proceedings Biological Sciences*, 276, 1347–1354.

Nisbet, E.G., Manning, M.R., Dlugokencky, E J., Fisher, R.E., Lowry, D., Michel, S.E., (2019). Very strong atmospheric methane growth in the 4 Years 2014–2017: Implications for the Paris Agreement. *Global Biogeochemical Cycles*, 33, 318–342.

Nisbet, E. G., Fisher, R. E., Lowry, D., France, J. L., Allen, G., Bakkaloglu, S., Lund Myhre, C., Platt, S.M., Allen, G., Bousquet, P., Brownlow, R., Cain, M., France, J.L., Hermansen, O., Hossaini, R., Jones, A.E., Levin, I., Manning, A.C., Myhre, G., Pyle, J.A., Vaughn, B.H., Warwick, N.J. and White, J.W.C. (2020). Methane mitigation: methods to reduce emissions, on the path to the Paris agreement. *Reviews of Geophysics*, 58, e2019RG000675.

National Health and Family Planning Commission (2016), *China health and family planning statistical yearbook*. Peking Union Medical College Publishing House, Beijing, China.

Organisation for Economic Co-operation and Development (2018). *Cost-Benefit Analysis and the*

Environment: Further Developments and Policy Use. Organisation for Economic Co-operation and Development Publishing, Paris, France. https://doi.org/10.1787/9789264085169-en (accessed 9 March 2021).

Oh, Y., Zhuang, Q., Liu, L., Welp, L.R., Lau, M.C.Y., Onstott, T.C., Medvigy, D., Bruhwiler, L., Dlugokencky, E.J., Hugelius, G., D'Imperio, L. and Elberling, B. (2020). Reduced net methane emissions due to microbial methane oxidation in a warmer Arctic, *Nat. Clim. Chang*. 10, 317–321, 2020.

Orellano, P., Quaranta, N., Reynoso, J., Balbi, B. and Vasquez, J. (2017). Effect of outdoor air pollution on asthma exacerbations in children and adults: Systematic review and multilevel meta-analysis. *PloS One*, 12, e0174050.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., Edenhofer, O., Elgizouli, I., Field, C.B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneros, B., Kattsov, V., Lee, H., Mach, K.J., Marotzke, J., Mastrandrea, M.D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J.J., Pichs-Madruga, R., Plattner, G-K., Pörtner, H-O., Power, S.B., Preston, B., Ravindranath, N.H., Reisinger,A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T.F., Tschakert, P., van Vuuren, D. and van Ypersele, J-P. (2014). *Climate change 2014: synthesis report*. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Pandey, S., Gautam, R., Houweling, S., van der Gon, H.D., Sadavarte, P., Borsdorff, T., Hasekamp, O., Landgraf, J., Tol, P., van Kempen, T., Hoogeveen, R., van Hees, R., Hamburg, S.P., Maasakkers, J.D., Aben, I. (2019) Satellite observations reveal extreme methane leakage from a natural gas well blowout. *Proc. National Acad. Sci*., 116, 26376–26381.

Parfitt, J., Barthel, M. and Macnaughton, S. (2010). Food waste within food supply chains: quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365, 3065–3081.

Petersen, S.O., Højberg, O., Poulsen, M., Schwab, C. and Eriksen, J. (2014). Methanogenic community changes, and emissions of methane and other gases, during storage of acidified and untreated pig slurry. *Journal of Applied Microbiology*, 117, 160–172.

Peterson, C.B., El Mashad, H.M., Zhao, Y., Pan, Y. and Mitloehner, F.M. (2020). Effects of SOP Lagoon Additive on Gaseous Emissions from Stored Liquid Dairy Manure. *Sustainability*, 12, 1393.

Pfeiffer, A., Hepburn, C., Vogt-Schilb, A. and Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*, 13(5), p.054019.

Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360, 987–992.

Popp, A., Lotze-Campen, H. and Bodirsky, B. (2010). Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. *Global Environmental Change*, 20(3): 451–462.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M. and Hasegawa, T. (2017). Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, 42, 331–345.

Porter, S.D., Reay, D.S., Bomberg, E. and Higgins, P. (2018). Avoidable food losses and associated production-phase greenhouse gas emissions arising from application of cosmetic standards to fresh fruit and vegetables in Europe and the UK. *Journal of Cleaner Production*, 201, 869–878.

Post, M.J. (2012). Cultured meat from stem cells: Challenges and prospects. *Meat Science*, 92(3), 297–301.

Pradhan, P., Reusser, D.E. and Kropp, J.P. (2013). Embodied greenhouse gas emissions in diets. *PloS*

ONE, 8(5), e62228.

Prather, M.J., Holmes, C.D. and Hsu, J. (2012). Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry. *Geophys. Res. Lett.*, 39, L09803, doi:10.1029/2012gl051440.

Prinn, R.G., Weiss, R.F., Fraser, P.J., Simmonds, P.G., Cunnold, D.M., Alyea, F.N., O'Doherty, S., Salameh, P., Miller, B.R., Huang, J. and Wang, R.H.J. (2000). A history of chemically and radiatively important gases in air deduced from ALE/GAGE/AGAGE. *Journal of Geophysical Research: Atmospheres*, 105(D14), 17751–17792.

Ramanathan, V. and Xu, Y. (2010). The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues. *Proc Natl Acad Sci USA*., 107, 8055–8062.

Reeburgh, W. S. (2007). Oceanic methane biogeochemistry. *Chemical Reviews*, 107, 486–513.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Crespo Cuaresma, J., Samir, K. C., Leimback, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. and Tavoni, M. (2016). Shared socioeconomic pathways: an overview. Global Environ. Change, 42, 153–168.

Robertson, A.M., Edie, R., Snare, D., Soltis, J., Field, R.A., Burkhart, M.D., Bell, C.S., Zimmerle, D. and Murphy, S.M. (2017). Variation in Methane Emission Rates from Well Pads in Four Oil and Gas Basins with Contrasting Production Volumes and Compositions. *Environmental Science & Technology*, 51, 8832–8840.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R. and Vilariño, M.V. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Cambridge University Press, Cambridge, UK.

Roque, B.M., Venegas, M., Kinley, R.D., De Nys, R., Duarte, T.L., Yang, X., and Kebreab, E. (2021) Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 in beef steers, *PLoS One*, 16, e0247820.

Samir, K.C. and Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Env. Change*, 42, 181–192.

Sarofim, M.C., Saha, S., Hawkins, M.D., Mills, D.M., Hess, J., Horton, R., Kinney, P., Schwartz, J. and St. Juliana, A. (2016). Temperature-Related Death and Illness, In Crimmins, A., Balbus, J., Gamble, J.L., Beard, C.B., Bell, J.E., Dodgen, D., Eisen, R.J., Fann, N., Hawkins, M.D., Herring, S.C., Jantarasami, L., Mills, D.M., Saha, S., Sarofim, M.C., Trtanj, J.and Ziska, L. (eds.). *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. US Global Change Research Program, Washington, DC, US.

Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J.G., Dlugokencky, E.J., Etiope, G., Bastviken, D., Houweling, S., Janssens-Maenhout, G., Tubiello, F.N., Castaldi, S., Jackson, R.B., Alexe, M., Arora, V.K., Beerling, D.J., Bergamaschi, P., Blake, D.R., Brailsford, G., Brovkin, V., Bruhwiler, L., Crevoisier, C., Crill, P., Covey, K., Curry, C., Frankenberg, C., Gedney, N., Höglund-Isaksson, L., Ishizawa, M., Ito, A., Joos, F., Kim, H-S., Kleinen, T., Krummel, P., Lamarque, J-F., Langenfelds, R., Locatelli, R., Machida, T., Maksyutov, S., McDonald, K.C., Marshall, J., Melton, J.R., Morino, I., Naik, V., O'Doherty, S., Parmentier, F-J,W, Patra, P.K., Peng, C., Peng, S., Peters, G.P., Pison, I., Prigent, C., Prinn, R., Ramonet, M., Riley, W.J., Saito, M., Santini, M., Schroeder, R.,

Simpson, I.J., Spahni, R., Steele, P., Takizawa, A., Thornton, B. F., Tian, H., Tohjima, Y., Viovy, N., Voulgarakis, A., van Weele, M., van der Werf, G.R., Weiss, R., Wiedinmyer, C., Wilton, D.J., Wiltshire, A., Worthy, D., Wunch, D., Xu, X., Yoshida, Y., Zhang, B., Zhang, Z. and Zhu, Q. (2016). The global methane budget 2000–2012. *Earth System Science Data*, 8, 2.

Saunois, M., Stavert, A.R., Poulter, B., Bousquet, P., Canadell, J.G., Jackson, R.B., Raymond, P.A., Dlugokencky, E.J., Houweling, S., Patra, P.K., Ciais, P., Arora, V.K., Bastviken, D., Bergamaschi, P., Blake, D.R., Brailsford, G., Bruhwiler, L., Carlson, K.M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P.M., Covey, K., Curry, C.L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M.I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K.M., Joos, F., Kleinen, T., Krummel, P.B., Langenfelds, R.L., Laruelle, G.G., Liu, L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R.J., Peng, C., Peng, S., Peters, G.P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W.J., Rosentreter, J.A., Segers, A., Simpson, I.J., Shi, H., Smith, S.J., Steele, L.P., Thornton, B.F., Tian, H., Tohjima, Y., Tubiello, F.N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T.S., van Weele, M., van der Werf, G.R., Weiss, R.F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., and Zhuang, Q. (2020). The Global Methane Budget 2000–2017, Earth Syst. Sci. Data, 12, 1561–1623.

Scarpelli, T.R., Jacob, D.J., Maasakkers, J.D., Sulprizio, M.P., Sheng, J-X., Rose, K., Romeo, L., Worden, J.R. and Janssens-Maenhout, G. (2020). A global gridded (0.1°×0.1°) inventory of methane emissions from oil, gas, and coal exploitation based on national reports to the United Nations Framework Convention on Climate Change. Earth Syst. Sci. Data, 12, 563–575.

Schneising, O., Burrows, J.P., Dickerson, R.R., Buchwitz, M., Reuter, M. and Bovensmann, H. (2014). Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations. *Earth's Future*, 2, 548–558.

Schneising, O., Buchwitz, M., Reuter, M., Vanselow, S., Bovensmann, H. and Burrows, J.P. (2020). Remote sensing of methane leakage from natural gas and petroleum systems revisited. *Atmos. Chem. Phys*., 20, 9169-9281.

Schuur, E.A., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M. and Natali, S.M. (2015). Climate change and the permafrost carbon feedback. *Nature*, 520, 171–179.

Schwartz, J.D., Lee, M., Kinney, P.L., Yang, S.J., Mills, D., Sarofim, M.C., Jones, R., Streeter, R., St Juliana, A., Peers, J. and Horton, R.M. (2015). Projections of temperature-attributable premature deaths in 209 US cities using a cluster-based Poisson approach. *Environmental Health*, 14.

Stockholm Environment Institute, International Institute for Sustainable Development, Overseas Development Institute, E3G, and United Nations Environment Programme (2020). *The Production Gap Report: 2020 Special Report*. http://productiongap.org/2020report.

Sekiya, T., Miyazaki, K., Ogochi, K., Sudo, K. and Takigawa, M. (2018). Global high-resolution simulations of tropospheric nitrogen dioxide using CHASER V4. 0. *Geoscientific Model Development*, 11.

Sellar, A.A., Jones, C.G., Mulcahy, J., Tang, Y., Yool, A., Wiltshire, A., O'Connor, F.M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., Mora, L., Kuhlbrodt, T., Rumbold, S., Kelley, D.I., Ellis, R., Johnson, C.E., Walton, J., Abraham, N.L., Andrews, M.B., Andrews, T., Archibald, A.T., Berthou, S., Burke, E., Blockley, E., Carslaw, K., Dalvi, M., Edwards, J., Folberth, G.A., Gedney, N., Griffiths, P.T., Harper, A.B., Hendry, M.A., Hewitt, A.J., Johnson, B., Jones, A., Jones, C.D., Keeble, J., Liddicoat, S., Morgenstern, O., Parker, R.J., Predoi, V., Robertson, E., Siahaan, A., Smith, R.S., Swaminathan, R., Woodhouse, M.T., Zeng, G. and Zerroukat, M. (2019). UKESM1: Description and evaluation of the UK Earth System Model. *J. Adv. Model. Earth Syst*., doi:10.1029/2019ms001739.

Seltzer, K., Shindell, D. and Malley, C. (2018). Measurement-based assessment of health burdens from long-term ozone exposure in the United States, Europe, and China. *Env. Res. Lett*., 13, 104018.

Shearer, C., Tong, D., Fofrich, R. and Davis, S.J. (2020). Committed emissions of the U.S. power sector, 2000–2018. *AGU Advances*, 1, e2020AV000162.

Sherwood, S., Webb, M.J., Annan, J.D., Armour, K.C., Forster, P.M., Hargreaves, J.C., Hegerl, G., Klein, S.A., Marvel, K.D., Rohling, E.J. and Watanabe, M. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, e2019RG000678.

Shindell, D.T. (2012). Evaluation of the Absolute Regional Temperature Potential. *Atmos. Chem. Phys*., 12, 7955–7960.

Shindell, D.T., Borgford-Parnell, N., Brauer, M., Haines, A., Kuylenstierna, J.C.I., Leonard, S.A., Ramanathan, V., Ravishankara, A., Amann, M. and Srivastava, L. (2017b). A climate policy pathway for near- and long-term benefits. *Science*, 356, 493–494.

Shindell, D., Faluvegi, G., Kasibhatla, P. and Van Dingenen, R. (2019). Spatial patterns of crop yield change by emitted pollutant. *Earth's Future*, 7, 101–112.

Shindell, D., Faluvegi, G., Seltzer, K. and Shindell, C. (2018). Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nat. Clim. Change*, 8, 291–295.

Shindell, D., Fuglestvedt, J.S. and Collins, W.J. (2017). The Social Cost of Methane: Theory and Applications. *Faraday Disc.,* 200, 429–451.

Shindell, D., Kuylenstierna, J.C.I., Vignati, E., Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N.., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, K., Milly, G., Williams, M., Demkine, V. and Fowler, D. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, 335, 183–189.

Shindell, D. and Smith, C.J. (2019). Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature*, 573, 408–411.

Shindell, D., Zhang, Y., Scott, M., Ru, M., Stark, K. and Ebi, K.L. (2020). The Effects of Heat Exposure on Human Mortality Throughout the US. *GeoHealth*, 3. https://doi.org/10.1029/ 2019GH000234 (accessed 22 March 2021).

Sjögersten, S., Siegenthaler, A., Lopez, O.R., Aplin, P., Turner, B. and Gauci, V. (2020). Methane emissions from tree stems in neotropical peatlands. *The New Phytologist*, 225,2, 769–781.

Skarke, A., Ruppel, C., Kodis, M., Brothers, D. and Lobecker, E.. (2014). Widespread methane leakage from the sea floor on the northern US Atlantic margin. *Nature Geosci.,* 7, 657–661.

Sokolov, V., VanderZaag, A., Habtewold, J., Dunfield, K., Wagner-Riddle, C., Venkiteswaran, J.J. and Gordon, R. (2019). Greenhouse gas mitigation through dairy manure acidification. *Journal of environmental quality*, 48, 1435–1443.

Sommer, S.G., Clough, T.J., Balaine, N., Hafner, S.D. and Cameron, K.C. (2017). Transformation of organic matter and the emissions of methane and ammonia during storage of liquid manure as affected by acidification. *Journal of Environmental Quality*, 46, 514–521.

Spadaro, J.V., Kendrovski, V. and Sanchez Martinez, G. (2018). *Achieving health benefits from carbon reductions: Manual for CaRBonH calculation tool*. World Health Organization, Geneva, Switzerland. https://core.ac.uk/reader/189891440 (accessed 9 March 2021).

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J. and Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature*, 562, 519–525.

Springmann, M., Godfray, H.C.J., Rayner, M. and Scarborough, P. (2016). Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, 113(15), 4146–4151.

Stauffer, B., Fischer, G., Neftel, A. and Oeschger, H. (1985). Increase of Atmospheric Methane Recorded in Antarctic Ice Core. *Science*, 1386–1388.

Stehfest, E., Bouwman, L., Van Vuuren, D.P., Den Elzen, M.G.J., Eickhout, B. and Kabat, P. (2009). Climate benefits of changing diet. *Clim. Change*, 95, 83–102.

Stehfest, E., van den Berg, M., Woltjer, G. and Msangi, S. (2013). Options to reduce the environmental effects of livestock production – Comparison of two economic models. *Agr. Syst*., 114, 38–53.

Sterman J. D., Siegel, L. and Pooney-Varga, J.N. (2018). Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Env. Res. Lett*., 13, 1–10.

Stohl, A., Aamaas, B., Amann, M., Baker, L., Bellouin, N., Berntsen, T.K., Boucher, O., Cherian, R., Collins, W., Daskalakis, N. and Dusinska, M., Evaluating the climate and air quality impacts of short-lived pollutants, Atmos. Chem. Phy., 15,10529-10566, 2015.

Stolaroff J.K., Bhattacharyya S., Smith C.A., Bourcier W.L., Cameron-Smith P.J. and Aines R.D. (2012). Review of Methane Mitigation Technologies with Application to Rapid Release of Methane from the Arctic. *Env. Sci. Tech*., 46, 6455–6469.

Sudo, K., Takahashi, M., Kurokawa, J.-i., and Akimoto, H. (2002). CHASER: A global chemical model of the troposphere 1. Model description. *J. Geophys. Res*., 107, ACH–7.

Sweeney, C., Karion, A., Wolter, S., Newberger, T., Guenther, D., Higgs, J.A., Andrews, A.E., Lang, P.M., Neff, D., Dlugokencky, E., Miller, J.B., Montzka, S.A., Miller, J.B., Masarie, K.A., Biraud, S.C., Novelli, P.C., Crotwell, M., Crotwell, A.M., Thoning, K. and Tans, P.P. (2015).Seasonal climatology of CO_2 across North America from aircraft measurements in the NOAA/ESRL Global Greenhouse Gas Reference Network. *J. Geophys. Res. Atmos*., 120, 5155–5190.

Tebaldi, C. and Lobell, D. (2018). Estimated impacts of emission reductions on wheat and maize crops. *Climatic Change*, 146(3-4), 533–545.

Tilman, D. and Clark, M. (2014). Global diets link environmental sustainability and human health, *Nature*, 515, 518–522.

Torero, M. (2020). Without food, there can be no exit from the pandemic. *Nature*, 580, 588–589.

Tuomisto, H.L. and M.J. Teixeira de Mattos. (2011). Environmental Impacts of Cultured Meat Production. *Environmental Science & Technology*, 45(14), 6117–6123.

Turner, M.C., Jerrett, M., Pope, C.A., Krewski, D., Gapstur, S.M., Diver, W.R., Beckerman, B.S., Marshall, J.D., Su, J., Crouse, D.L. and Burnett, R.T. (2016). Long-term ozone exposure and mortality in a large prospective study. *Am. J. Respir. Crit. Care Med*., 193, 1134–42.

Turner, A.J., Jacob, D.J., Benmergui, J., Wofsy, S.C., Maasakkers, J.D., Butz, A., Hasekamp, O., Biraud, S.C. and Duglokencky, E. (2016). A large increase in US methane emissions over the past decade inferred from satellite data. *Geophys. Res. Lett*., 43, 2218–2224.

United Nations Environment Programme and World Meteorological Organization (2011). *Integrated Assessment of Black Carbon and Tropospheric Ozone*. United Nations Environment Programme, Nairobi, Kenya and World Meteorological Organization, Geneva, Switzerland.

United Nations Environment Programme (2011). *Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers*. United Nations Environment Programme, Nairobi, Kenya.

United Nations Environment Programme (2017). *The Emissions Gap Report 2017*. United Nations Environment Programme, Nairobi, Kenya..

United States Bureau of Labor Statistics. (2020a). *Quarterly Census of Employment and Wages*. U.S. Bureau of Labor Statistics, Washington, DC, US. https://www.bls.gov/cew/datatoc.htm (accessed 9 March 2021).

United States Bureau of Labor Statistics. (2020b). *Quarterly Census of Employment and Wages: QCEW Industry Codes and Titles*. U.S. Bureau of Labor Statistics, Washington, DC, US. https://data.bls.gov/cew/doc/titles/industry/industry_titles.htm (accessed 9 March 2021).

United States Environmental Protection Agency. (1997). *The Benefits and Costs of the Clean Air Act 1970-1990. Prepared for Congress by Office of Air and Radiation and Office of Policy, Planning and Evaluation*. United States Environment Protection Agency, Washington, DC, US. https://www.epa.gov/environmental-economics/benefits-and-costs-clean-air-act-1970-1990-1997 (accessed 9 March 2021).

United States Environmental Protection Agency. (2013). *Global Mitigation of Non-CO_2 Greenhouse Gases: 2010-2030*. United States Environment Protection Agency, Washington, DC, US. EPA 430-R-13-011.

United States Environmental Protection Agency. (2015). *Environmental Benefits Mapping and Analysis Program–Community Edition (BenMAP-CE)*. United States Environment Protection Agency, Washington, DC, US.

United States Environmental Protection Agency (2015a) *Climate Change in the United States: Benefits of Global Action. United States Environmental Protection Agency, Office of Atmospheric Programs,* Washington, DC, US. EPA 430-R-15-001.

United States Environmental Protection Agency. (2017). *Multi-model framework for quantitative sectoral impacts analysis: A technical report for the Fourth National Climate Assessment*. United States Environment Protection Agency, Washington, DC, US.

United States Environmental Protection Agency (2019). *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation Potential: 2015-2050*. United States Environment Protection Agency, Washington, DC, US. EPA 430-R-19-010.

United States Global Change Research Program (2018). *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B.C. and Maycock, T.K. (eds.). U.S. Global Change Research Program, Washington, DC, US.

Valentine, D.W., Holland, E.A. and Schimel, D.S. (1994). Ecosystem and physiological controls over methane production in northern wetlands. *J. Geophys. Res*., 99, 1563–1571.

van de Ven, D.-J., González-Eguino, M. and Arto, I. (2018). The potential of behavioural change for climate change mitigation: a case study for the European Union. *Mitigation and Adaptation Strategies for Global Change*, 23, 853–886.

Van Dingenen, R., Dentener, F.J., Raes, F., Krol, M.C., Emberson, L. and Cofala, J. (2009). The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment*, 43, 604–618.

Varon, D.J., Jacob, D.J., McKeever, J., Jervis, D., Durak, B.O.A., Xia, Yan, and Huang, Y.,(2018) Quantifying methane point sources from fine-scale satellite observations of atmospheric methane plumes, *Atmos. Meas. Tech*., 11, 5673–5686.

Varon, D.J., McKeever, J., Jervis, D., Maasakkers, J.D., Pandey, S., Houweling, S., Aben, I., Scarpelli, T. and Jacob, D.J. (2019). Satellite discovery of anomalously large methane point sources from oil/gas production. *Geophysical Research Letters*, 46, 13507–13516.

Vaughn, T.L., Bell, C.C., Pickering, C.K., Schwietzke, S., Heath, G.A., Pétron, G., Zimmerle, D.J., Schnell, R.C. and Nummedal, D. (2018). Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region. *Proceedings of the National Academy of Sciences*, 115, 11712–11717.

Victor, D.G., Zaelke, D. and Ramanathan, V. (2015). Soot and short-lived pollutants provide political opportunity. *Nature Climate Change*, 5, 796–798.

Vijn, S., Compart D.P., Dutta, N., Foukis, A., Hess, M., Hristov, A.N., Kalscheur, K.F., Kebreab, E., Nuzhdin, S.V., Price, N.N., Sun, Y., Tricarico, J.M., Turzillo, A., Weisbjerg, W.R., Yarish, C., and Kurt, T.D. (2020) Key considerations for the Use of Seaweed to Reduce Enteric Methane Emissions From Cattle, *Front. Vet. Sci*., 7, 597430.

Viscusi, W.K. and Aldy, J.E. (2003). The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World. *J. Risk Uncert*., 27, 5–76.

Wania, R., Melton, J.R., Hodson, E.L., Poulter, B., Ringeval, B., Spahni, R., Bohn, T., Avis, C. A., Chen, G., Eliseev, A.V., Hopcroft, P.O., Riley, W.J., Subin, Z.M., Tian, H., van Bodegom, P.M., Kleinen, T., Yu, Z.C., Singarayer, J.S., Zürcher, S., Lettenmaier, D.P., Beerling, D.J., Denisov, S.N., Prigent, C., Papa, F. and Kaplan, J.O. (2013). Present state of global wetland extent and wetland methane modelling: methodology of a model inter-comparison project (WETCHIMP). *Geosci. Model Dev*., 6, 617–641.

Wang, Y., and Jacob, D.J. (1998). Anthropogenic forcing on tropospheric ozone and OH since preindustrial times. *J. Geophys. Res*., 103, 31123–31135.

Wang, X. and Mauzerall, D.L. (2004). Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. *Atmospheric Environment*, 38, 4383–4402.

Wang, T., Srebotnjak, T., Brownell, J. and Hsia, R.Y. (2014). Emergency department charges for asthma-related outpatient visits by insurance status, *J Health Care Poor Underserved*, 25, 396–405.

Wang, W-Q. and Shao, H. (2013). Azimuth-variant signal processing in high-altitude platform passive SAR with spaceborne/airborne transmitter. *Remote Sensing*, 5, 1292–1310.

Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takemura, T., Okajima, H., Nozawa, T., Kawase, H., Abe, M., Yokohata, T., Ise (, T., Sato, H., Kato, E., Takata, K., Emori, S. and Kawamiya, M. (2011). MIROC-ESM 2010: Model description and basic results of CMIP5-20c3m experiments. *Geoscientific Model Development*, 4, 845.

Watts, G. (2009). *The Health Benefits of Tackling Climate Change: An Executive Summary*. The Lancet, London, UK.

Watts, N, Adger, W.N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., Cox, P.M., Depledge, J., Drummond, P., Ekins, P., Galaz, V., Grace, D., Graham, H., Grubb, M., Haines, A., Hamilton, I., Hunter, A., Jiang, X., Li, M., Kelman, I., Liang, L., Lott, M., Lowe, R., Luo, Y., Mace, G., Maslin, M., Nilsson, M., Oreszczyn, T., Pye, S., Quinn, T., Svensdotter, M., Venevsky, S., Warner, K., Xu, B., Yang, J., Yin, Y., Yu, C., Zhang, Q., Gong, P., Montgomery, H. and Costello, A. (2015). Health and climate change: policy responses to protect public health. *The Lancet*, 386, 1861–914.

Watts, N., Amann, M., Ayeb-Karlsson, S., Belesova, K., Bouley, T., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Chambers, J., Cox, P.M., Daly, M., Dasandi, N., Davies, M., Depledge, M., Depoux, A., Dominguez-Salas, P., Drummond P., Ekins, P., Flahault, A., Frumkin, H., Georgeson, L., Ghanei, M., Grace, D., Graham, H., Grojsman, R., Haines, A., Hamilton, I., Hartinger, S., Johnson, A., Kelman, I., Kiesewetter, G., Kniveton, .C., 26, Liang, L., Lott, M., Lowe, R., Mace, G., Sewe, M.O., Maslin, M., Mikhaylov, S., Milner, J., Latifi, A.M., Moradi-Lakeh, M., Morrissey, K., Murray, K., Neville, T., Nilsson, M., Oreszczyn, T., Owfi, F., Pencheon, D., Pye, S., Rabbaniha, M., Robinson, E., Rocklöv, J., Schütte, S., Shumake-Guillemot, J., Steinbach, R., Tabatabaei, M., Wheeler, N., Wilkinson, P., Gong, P., Montgomery, H. and Costello, A. (2017). The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *The Lancet*, pii: S0140-6736 (17), 32464–32469.

Weber, T., Wiseman, N.A. and Kock, A. (2019). Global ocean methane emissions dominated by shallow coastal waters. *Nat Commun*., 10, 4584.

Wecht, K.J., Jacob, D.J., Frankenberg, C., Jiang, Z. and Blake, D.R. (2014). Mapping of North America methane emissions with high spatial resolution by inversion of SCIAMACHY satellite data. *J. Geophys. Res*., 119, 7741–7756.

Weinberger, K.R., Haykin, L., Eliot, M.N., Schwartz, J.D., Gasparrini, A. and Wellenius, G.A. (2017). Projected temperature-related deaths in ten large US metropolitan areas under different climate change scenarios. *Environment International*, 107, 196–204.

Weiss, F. and Leip, A. (2012). Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model. *Agriculture, Ecosystems & Environment*, 149, 124–134.

Wellenius, G.A., Eliot, M.N., Bush, K.F., Holt, D., Lincoln, R.A., Smith, A.E. and Gold, J. (2017). Heat-related morbidity and mortality in New England: Evidence for local policy. *Environmental Research*, 156, 845–853.

West, J.J. and Fiore, A.M. (2005). Management of tropospheric ozone by reducing methane emissions. *Environ. Sci. Technol*., 39, 4685.

West, J.J., Fiore, A.M., Horowitz, L.W. and Mauzerall, D.L. (2006). Global health benefits of mitigating ozone pollution with methane emission controls. *Proc. National Acad. Sci*., 103, 3988–3993.

Whalen, S.C. (2005). Biogeochemistry of Methane Exchange between Natural Wetlands and the Atmosphere. Environ. *Eng. Sci*., 22, 73–94.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Sibanda, L.M., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S., Narain, S., Nishtar, S. and Murray, C.J.L.

(2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393, no. 10170, 447–492.

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D.P., Dickie, A., Neufeldt, H., Sander, B.O., Wassmann, R., Sommer, R., Amonette, J.E., Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R.M., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F., Baedeker, T., Sadler, M., Vermeulen, S. and Campbell, B.M. (2016). Reducing emissions from agriculture to meet the 2 °C target. *Glob. Change Biol*., 22, 3859–3864.

Worden, J., Kulawik, S., Frankenberg, C., Payne, V., Bowman, K., Cady-Peirara, K., Wecht, K., Lee, J.-E. and Noone, D. (2012). Profiles of CH_4, HDO, H2O, and N2O with improved lower tropospheric vertical resolution from Aura TES radiances. *Atmospheric Measurement Techniques*, 5, 397–411.

World Health Organization (2013). *Health risks of air pollution in Europe—HRAPIE project recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide*. World Health Organization, Copenhagen, Denmark.

World Health Organization (2014). *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s*. World Health Organization, Geneva, Switzerland,

World Bank. 2020. *World Development Indicators*. The World Bank, Washington, DC, US. https://databank.worldbank.org/home.aspx (accessed 18 March 2020).

World Bank and Institute for Health Metrics and Evaluation (2016). *The Cost of Air Pollution: Strengthening the Economic Case for Action*. The World Bank, Washington, DC, US and Institute for Health Medicine, https://openknowledge.worldbank.org/handle/10986/25013 (accessed 10 March 2021).

Zavala-Araiza, D., Herndon, S.C., Roscioli, J.R., Yacovitch, T.I., Johnson, M.R., Tyner, D.R., Omara, M. and Knighton, B. (2018). Methane emissions from oil and gas production sites in Alberta, Canada. *Elem Sci Anth*., 6(1).

Zhang, S., Li, G., Tian, L., Guo, Q. and Pan, X. (2016). Short-term exposure to air pollution and morbidity of COPD and asthma in East Asian area: A systematic review and meta-analysis. *Environ Res*., 148, 15–23.

Zhang, Y., Gautam, R., Pandey, S., Omara, M., Maasakkers, J.D., Sadavarte, P., Lyon, D., Nesser, H., Sulprizio, M.P., Varon, D.J., Zhang, R., Houweling, S., Zavala-Araiza, D., Alvarez, R.A., Lorente, A., Hamburg, S.P., Aben, I. and Jacob, D. (2020). Quantifying methane emissions from the largest oil-producing basin in the United States from Space. *Science Advances*, doi:10.1126/sciadv.aaz5120.

Zhang, Z., Zimmermann, N.E., Stenke, A., Li, X., Hodson, E.L., Zhu, G., Huang, C. and Poulter, B. (2017). Emerging role of wetland methane emissions in driving 21st century climate change. *Proceedings of the National Academy of Sciences*, 114, 9647–9652.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J-L., Elliott, J., Ewert, F., Janssens, I.A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., Peng, S., Peñuelas, J., Ruane, A.C., Wallach, D., Wang, T., Wu, D., Liu, Z., Zhu, Y., Zhu, Z. and Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, 114, 9326–9331.

Zheng, X.Y., Ding, H., Jiang, L.N., Chen, S.W., Zheng, J.P., Qiu, M., Zhou, Y.X., Chen, Q. and Guan, W.J. (2015). Association between Air Pollutants and Asthma Emergency Room Visits and Hospital Admissions in Time Series Studies: A Systematic Review and Meta-Analysis. *PloS One*, 10, e0138146.

Zhu, Y., Purdy, K.J., Eyice, Ö. and Shen, L. (2020). Disproportionate increase in freshwater methane emissions induced by experimental warming. *Nat. Clim. Chang*., 10, 685–690.

Zwiers, F.W and von Storch, H. (1995). Taking serial correlation into account in tests of the mean. *Journal of Climate*, 8, 336–351.



7. ABBREVIATIONS

A&E	Hospital accident and emergency departments
A&EV	Hospital accident and emergency department visits
ACS	American Cancer Society
AFOLU	Agriculture, forestry and other land use
AGAGE	Advanced Global Atmospheric Gases Experiment
AGTPs	Absolute global temperature potentials
AIM	Asia-Pacific Integrated Model
APHENA	Air Pollution and Health: a European and North American Approach
BC	Black carbon
BECCS	Biofuel energy with carbon capture and storage
C	centigrade
CaRBonH	Carbon reduction benefits on health
CCAC	Climate and Clean Air Coalition
CCS	Carbon capture and storage
CEDS	Community Emissions Data System
CESM	Community Earth System Model
CGE	Computable general equilibrium
C_2H_2	Acetylene
CH_4	Methane
CMIP	Coupled Model Intercomparison Project
CNES	Centre national d'études spatiales (French National Centre for Space Studies)
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DALY	Disability adjusted life year
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospece Centre)
DRC	Democratic Republic of the Congo
EDF	Environmental Defense Fund
EDGAR	Emissions Database for Global Atmospheric Research
e.g.	*exempli gratia* (for example)
EJ	Exajoules (10^{18} joules)
EPA	Environment Protection Agency
ESA	European Space Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FINN	Fire INventory from the National Center for Atmospheric Research
FLW	Food loss and waste

FSU	Former Soviet Union
GAINS	Greenhouse Gas – Air Pollution Interactions and Synergies
GBD	Global burden of disease
GCAM	Global Change Assessment Model
GDP	Gross domestic product
GFDL	Geophysical Fluid Dynamics Laboratory
GFED	Global Fire Emissions Database
GHG	Greenhouse gas
GISS	Goddard Institute of Space Studies
GLEAM	Global Livestock Environmental Assessment Model
GLOBIOM	Global Biosphere Management Model
GOSAT	Greenhouse Gases Observing Satellite
GPW	Gridded Population of the World
Gt	Gigatonne (10^9 tonnes)
GWP	Global warming potential
GWP100	Global warming potential over 100 years
HCUP	Healthcare Cost and Utilization Project
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
hrs/yr	Hours per year
IAM	Integrated assessment model
ICD	International Classification of Diseases
i.e.	*id est* (that is)
IEA	International Energy Agency
IGSD	Institute for Governance & Sustainable Development
IHME	Institute for Health Metrics and Evaluation
IIASA	International Institute for Applied Systems Analysis
ILO	International Labour Organization
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JAXA	Japan Aerospace Exploration Agency
kg	Kilogram
kt	Kilotonne (1 000 tonnes)
LDAR	Leak detection and repair
M	Metre

m^2	Square metre
mm	Millimetre
MAC	Marginal abatement cost
MDA	Maximum daily average
MDA8	Maximum daily 8-hour exposure averaged over the year
MESSAGE	Model of Energy Supply Systems and their General Environmental Impact
Met Office	The United Kingdom's Meteorological Office
MIROC	Model for Interdisciplinary Research on Climate
MMM	Multi-model mean
MST	Mean summer temperature
Mt	Million tonnes
Mt/yr	Million tonnes per year
mW	MilliWatts
N	North
NAICS	North American Industry Classification System
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NH_3	Ammonia
NHml	Northern hemisphere mid-latitudes
NIES	National Institute for Environmental Studies, Japan
NMVOC	Non-methane volatile organic compound
NOAA	National Oceanic and Atmospheric Administration
NO_x	Nitrogen oxides
N_2O	Nitrous oxide
NTCF	Near-term climate forcers
NSO	Netherlands Space Organisation
O_3	Ozone
OC	Organic carbon
OECD	Organisation for Economic Co-operation and Development
OH	Hydroxide
PBL	Netherlands Environmental Assessment Agency
PM	Particulate matter
ppb	Parts per billion
ppbv	Parts per billion by volume
QFED	Quick Fire Emissions Dataset
RCP	Representative concentration pathway

REMIND	REgional *Model* of INvestments and Development
RR	Relative Risk
S	South
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SDG	Sustainable Development Goal
SEI	Stockholm Environment Institute
SHext	Southern hemisphere extratropics
SLCP	Short-lived climate pollutant
SO_2	Sulphur dioxide
SSP	Shared socioeconomic pathway
t	Tonne
Tg	Teragram (10^{12} grams)
TMREL	Theoretical minimum risk exposure level
TROPOMI	Tropospheric Monitoring Instrument
UK	United Kingdom
UKESM	United Kingdom Earth System Model
UN	United Nations
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
US$	United States dollar
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
UV	Ultraviolet
VOC	Volatile organic compound
VSL	Value of statistical life
WA	Work availability
WBGT	Wet bulb globe temperature
WITCH	World Induced Technical Change Hybrid model
WL	Work loss
WMO	World Meteorological Organization
WTP	Willingness to pay
yr	Year

Note Throughout this assessment 1 billion = 1 000 000 000 (10^9)



8. ANNEX – ADDITIONAL FIGURES AND TABLES

Figures A1 and A2 and Tables A1–A3 report values from the modelling performed in support of this assessment described in Chapter 3.

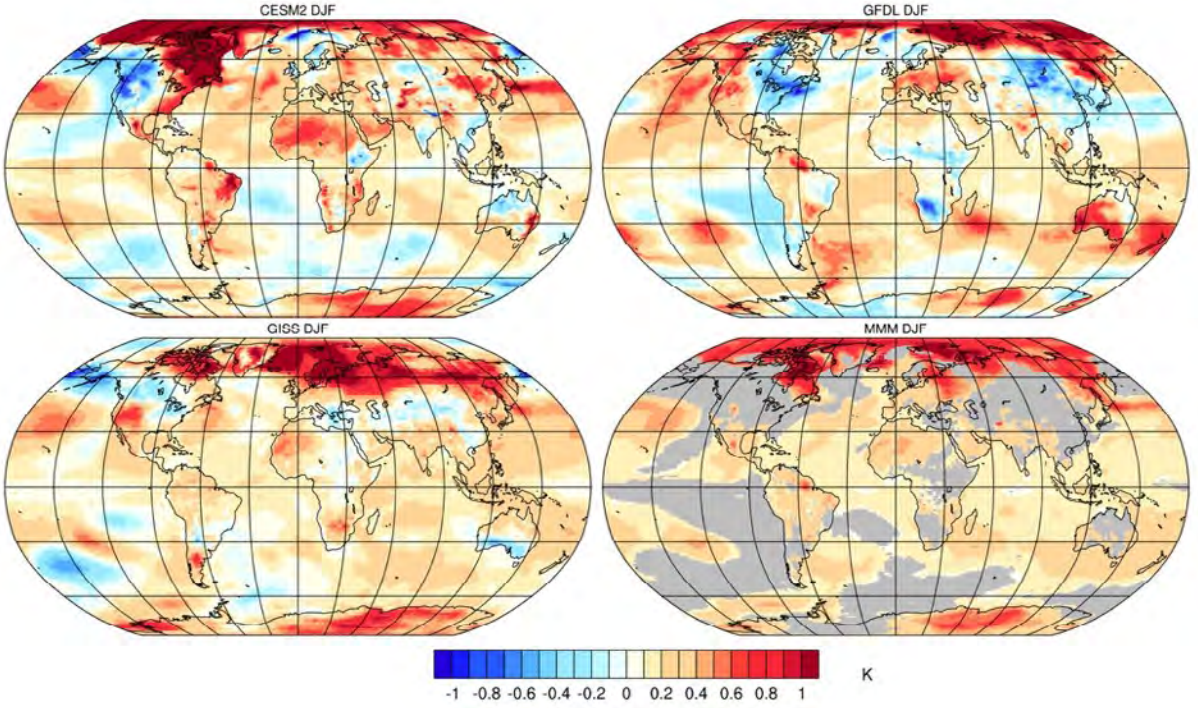

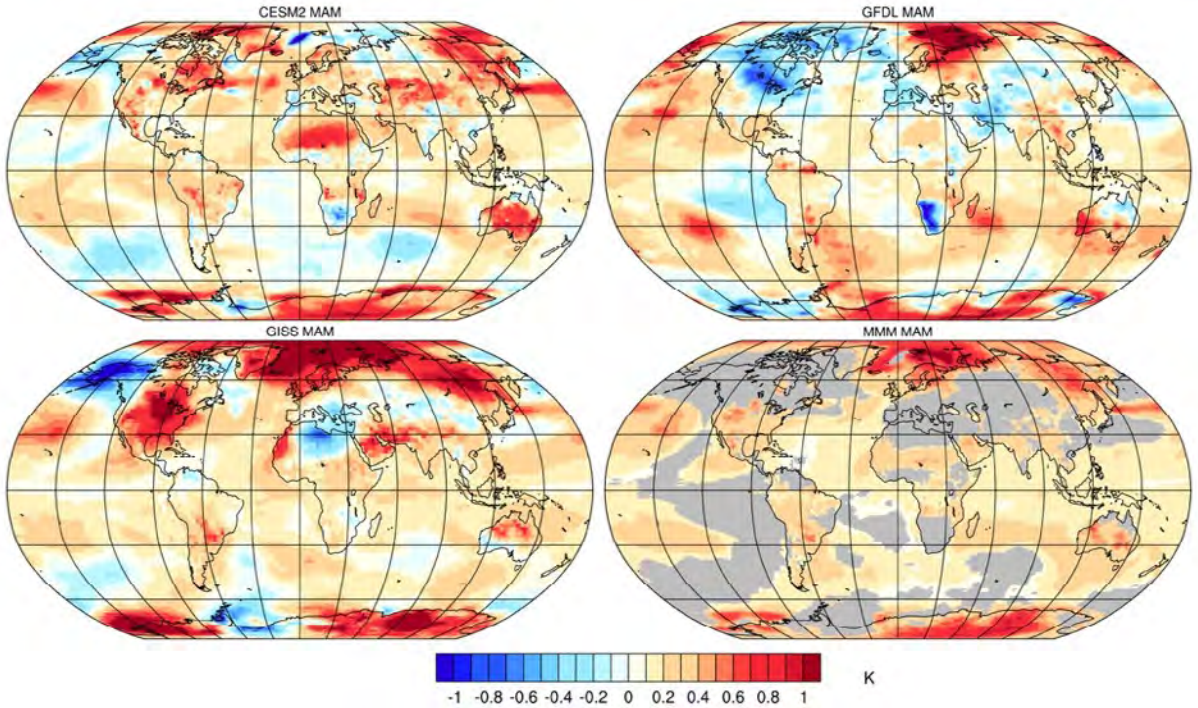

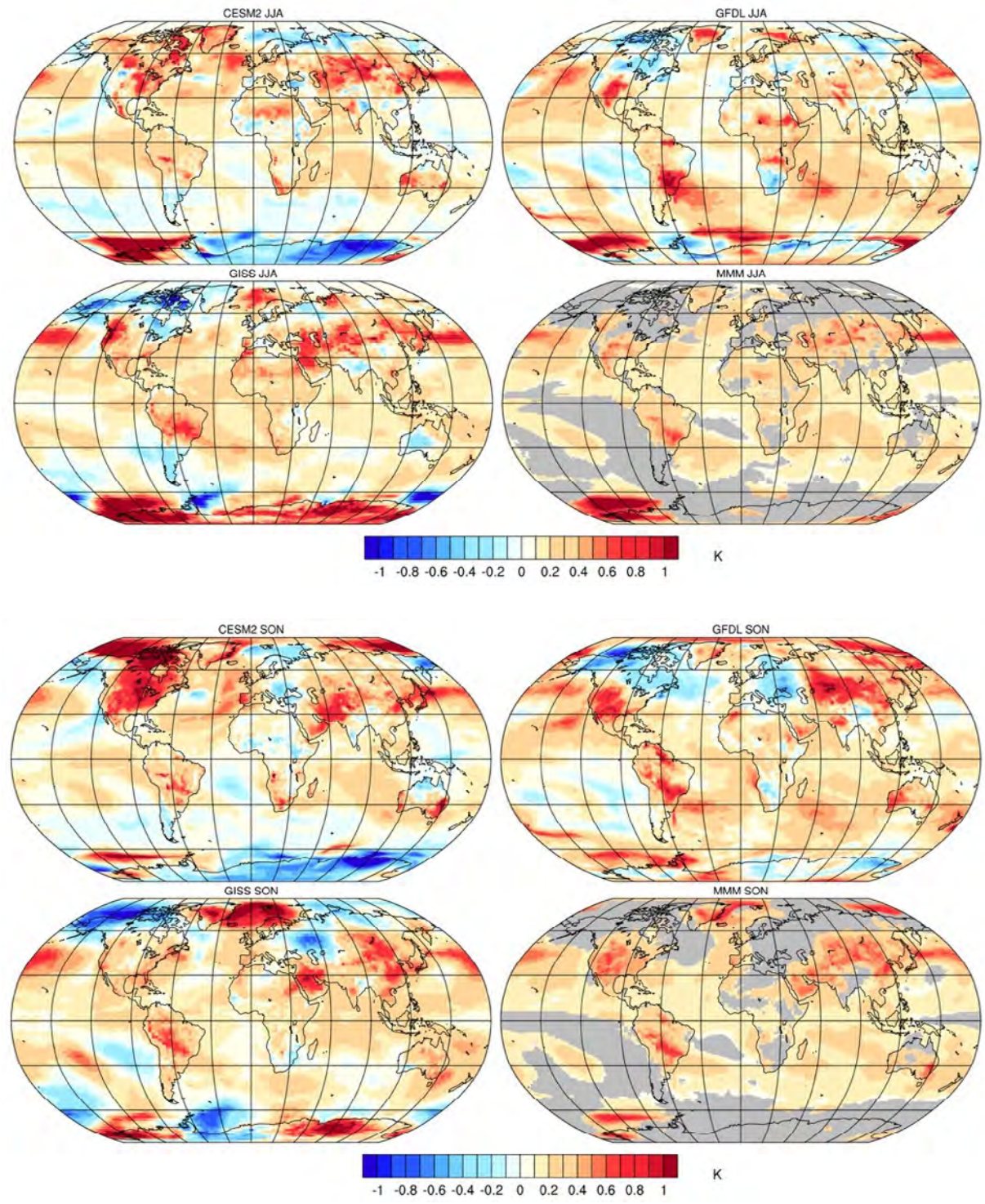

Figure A1 Average temperature responses to methane increase from one-half present methane to the present value, along with the ozone and stratospheric water vapour responses to that methane increase, for the indicated seasons, degrees Centigrade

Note: The multi-model mean is shown in the lower right map for each season, with values included only for areas in which the value is statistically significant – grey indicates no quantification.

Source: UNEP and CCAC

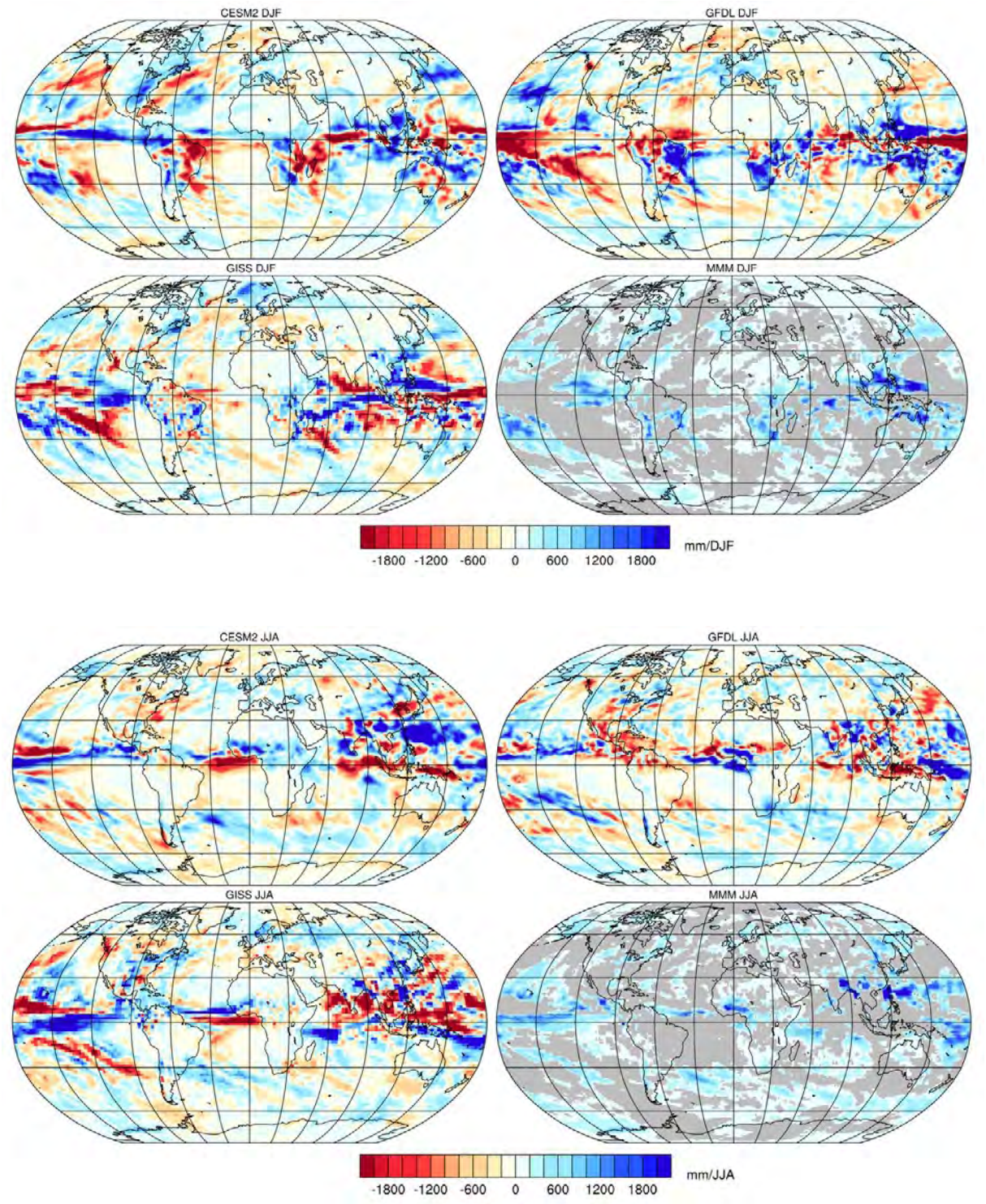

Figure A2 As Figure A1 but showing precipitation for solstice seasons only, millimetres

Note: The multi-model mean is shown in the lower right map for each season, with values included only for areas in which the value is statistically significant – grey indicates no quantification.

Source: UNEP and CCAC

Table A1 Total and per person respiratory deaths per 10 Mt of methane for all countries with non-zero values

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
India	2 045	1 169	2 863	Lesotho	5	4	7
China	1 419	948	1 831	Korea, Dem People's Rep.	5	3	6
United States	428	287	553	Eritrea	4	2	6
Japan	251	176	316	United Kingdom	4	2	5
Brazil	160	100	216	India	4	2	5
Pakistan	159	98	215	Portugal	3	2	4
United Kingdom	157	102	207	São Tome and Principe	3	2	4
Indonesia	154	86	219	Guinea-Bissau	3	2	5
Germany	121	79	160	Zimbabwe	3	2	4
Russia	109	71	143	Denmark	3	2	4
Philippines	101	64	137	Belgium	3	2	4
Spain	89	59	116	Somalia	3	2	4
Bangladesh	82	51	111	Myanmar	3	2	4
Egypt	82	57	104	Nepal	3	2	4
Mexico	77	50	100	Argentina	3	2	4
Italy	74	49	96	Swaziland	3	2	4
Myanmar	72	45	97	Spain	3	2	4
France	69	45	92	Japan	3	2	3
Korea, Dem Peoples Rep.	64	45	80	Netherlands	3	2	4
Argentina	63	40	86	Gambia	3	1	4
Turkey	61	42	79	Chad	3	1	4
Viet Nam	61	38	82	Cuba	3	2	3
Ethiopia	58	35	80	Haiti	3	2	3
Thailand	52	31	72	Sri Lanka	3	1	4
South Africa	51	34	67	Philippines	2	2	3
Nigeria	42	22	61	Afghanistan	2	2	3
Korea, Rep.	39	27	49	Guinea	2	1	3
Iran, Islamic Rep.	38	27	47	Senegal	2	1	4
Poland	37	24	50	Djibouti	2	1	3
Canada	35	24	46	Grenada	2	2	3
DRC	34	21	46	Central African Rep.	2	1	3
Ukraine	33	21	44	Pakistan	2	1	3
Nepal	32	20	42	Niger	2	1	3
Netherlands	29	19	39	Mozambique	2	1	3
Sri Lanka	28	15	40	Barbados	2	1	3
Peru	27	15	37	Norway	2	1	3

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Malaysia	26	15	36	Uruguay	2	1	3
Kenya	25	15	36	United States	2	1	3
Tanzania	25	15	35	Greece	2	1	3
Portugal	23	15	31	Egypt	2	1	3
Morocco and Western Sahara	23	15	31	South Africa	2	1	3
Afghanistan	23	16	28	Cape Verde	2	1	3
Belgium	23	14	30	Germany	2	1	3
Australia	21	13	28	Israel	2	1	3
Romania	20	13	26	St. Lucia	2	1	3
Cuba	19	12	25	Malta	2	1	3
Sudan	18	11	25	Namibia	2	1	3
Mozambique	18	11	24	Mauritania	2	1	3
Ghana	18	9	26	Ireland	2	1	3
Greece	17	11	23	Burundi	2	1	3
Algeria	17	11	23	Puerto Rico and the Virgin Islands	2	1	3
Saudi Arabia	17	11	21	Ethiopia	2	1	3
Chile	16	11	21	Benin	2	1	3
Kazakhstan	15	10	19	Ghana	2	1	3
Zimbabwe	14	9	19	Cameroon	2	1	3
Colombia	14	8	19	Sweden	2	1	2
Uzbekistan	13	9	17	Malawi	2	1	3
Uganda	13	7	19	Peru	2	1	3
Venezuela	13	8	18	Malaysia	2	1	3
Cameroon	13	7	17	Georgia	2	1	2
Yemen	12	8	16	Armenia	2	1	2
Niger	12	6	17	Comoros	2	1	2
Czechia	12	8	15	Kenya	2	1	3
Sweden	12	8	15	El Salvador	2	1	2
Angola	12	7	15	Burkina Faso	2	1	3
Côte d'Ivoire	11	6	16	Italy	2	1	2
Denmark	11	7	15	Luxembourg	2	1	2
Somalia	11	7	15	Bahamas	2	1	2
Senegal	11	6	16	Sierra Leone	2	1	2
Hungary	10	7	14	China	2	1	2
Haiti	10	6	13	Zambia	2	1	2
Cambodia	10	6	13	Jamaica	2	1	2
Serbia and Montenegro	9	6	12	Tanzania	2	1	2

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Chad	9	5	13	France	2	1	2
Madagascar	9	0	0	Mali	2	1	3
Guinea	9	5	13	Kazakhstan	2	1	2
Israel	9	6	11	Côte d'Ivoire	2	1	2
Malawi	9	5	12	Bolivia	2	1	2
Burkina Faso	8	4	13	Timor-Leste	2	1	2
Guatemala	8	5	11	Bhutan	2	1	2
Mali	8	4	11	DRC	2	1	2
Syrian Arab Rep.	7	5	10	Czechia	2	1	2
Bulgaria	7	5	10	Chile	2	1	2
Switzerland	7	5	10	Botswana	2	1	2
Norway	7	5	10	Cyprus	2	1	2
Bolivia	7	5	9	Hungary	2	1	2
Zambia	7	5	10	St.Vincent and			
the Grenadines	2	1	2				
Austria	7	5	9	Turkey	2	1	2
Tunisia	7	5	9	Yemen	2	1	2
Ecuador	6	4	9	Cambodia	2	1	2
Benin	6	3	9	Angola	2	1	2
Dominican Rep.	6	4	8	Togo	2	1	2
Eritrea	6	4	8	Serbia and Montenegro	2	1	2
Ireland	6	4	8	Congo	2	1	2
Burundi	6	3	8	Iceland	2	1	2
Rwanda	5	3	8	Canada	2	1	2
Azerbaijan	5	4	7	Romania	2	1	2
Iraq	5	4	7	Guatemala	1	1	2
Singapore	5	3	7	Brazil	1	1	2
El Salvador	5	3	7	Bulgaria	1	1	2
Belarus	5	3	6	Poland	1	1	2
Georgia	4	3	6	Rwanda	1	1	2
Slovakia	4	3	6	Croatia	1	1	2
United Arab Emirates	4	3	6	Australia	1	1	2
Puerto Rico and the Virgin Islands	4	3	6	Morocco and Western Sahara	1	1	2
Uruguay	4	3	6	Antigua and Barbuda	1	1	2
Croatia	4	3	5	Lao People's Dem Rep.	1	1	2
Tajikistan	4	3	5	Singapore	1	1	2
Lebanon	4	2	5	Uganda	1	1	2

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Sierra Leone	4	2	5	Liberia	1	1	2
Lesotho	4	2	5	Lebanon	1	1	2
Togo	4	2	5	Tajikistan	1	1	2
Honduras	3	2	5	Switzerland	1	1	2
Finland	3	2	5	Mexico	1	1	2
Lao People's Dem Rep.	3	2	5	Bosnia and Herzegovina	1	1	2
Libyan Arab Jamahiriya	3	2	4	Slovenia	1	1	2
Central African Rep.	3	2	4	Dominican Rep.	1	1	2
Bosnia and Herzegovina	3	2	4	Viet Nam	1	1	2
Armenia	3	2	4	Indonesia	1	1	2
Kyrgyzstan	3	2	4	Gabon	1	1	2
Mauritania	3	2	4	Belize	1	1	2
Moldova	3	2	4	Slovakia	1	1	2
Jordan	2	2	3	Thailand	1	1	2
Congo	2	1	3	Kyrgyzstan	1	1	2
Jamaica	2	2	3	Madagascar	1	1	2
Costa Rica	2	1	3	Bangladesh	1	1	2
Lithuania	2	1	3	Tunisia	1	1	2
Nicaragua	2	1	3	Austria	1	1	2
Liberia	2	1	3	Lithuania	1	1	2
Slovenia	2	1	2	Russia	1	1	2
Paraguay	2	1	2	Sudan	1	1	2
Panama	2	1	2	Korea, Rep.	1	1	1
Guinea-Bissau	2	1	2	Libyan Arab Jamahiriya	1	1	1
Namibia	2	1	2	Syria	1	1	1
Albania	2	1	2	Moldova	1	1	1
Gambia	1	1	2	Ukraine	1	1	1
Botswana	1	1	2	Azerbaijan	1	1	1
Turkmenistan	1	1	2	Saudi Arabia	1	1	1
Latvia	1	1	2	Trinidad and Tobago	1	1	2
Oman	1	1	2	Honduras	1	1	1
Cyprus	1	1	1	Uzbekistan	1	1	1
Swaziland	1	1	1	Iran, Islamic Rep.	1	1	1
North Macedonia	1	1	1	Algeria	1	1	1
Gabon	1	1	1	Finland	1	1	1
Trinidad and Tobago	1	0	1	Equatorial Guinea	1	1	1
Djibouti	1	1	1	Albania	1	1	1
Estonia	1	0	1	Latvia	1	1	1
Kuwait	1	0	1	Costa Rica	1	1	1
Mongolia	1	0	1	Panama	1	1	1

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
				Venezuela	1	1	1
				Maldives	1	1	1
				Estonia	1	1	1
				Ecuador	1	0	1
				Nigeria	1	0	1
				Nicaragua	1	1	1
				United Arab Emirates	1	1	1
				Belarus	1	0	1
				Jordan	1	0	1
				North Macedonia	1	0	1
				Brunei Darussalam	1	0	1
				Paraguay	1	0	1
				Oman	1	0	1
				Turkmenistan	1	0	1
				Colombia	1	0	1
				Mongolia	1	0	1

Table A2 Total and per person cardiovascular deaths per 10 Mt of methane for all countries with non-zero values

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
China	1 566	502	2 522	Ukraine	7	2	11
India	1 122	297	1 844	Georgia	5	2	9
Russia	379	122	624	Uzbekistan	5	2	8
United States	333	108	540	Bulgaria	5	2	9
Pakistan	225	65	365	Egypt	5	2	8
Indonesia	219	57	368	Serbia and Montenegro	5	2	8
Egypt	194	64	310	Belarus	5	2	8
Ukraine	193	61	318	Lithuania	5	1	8
Japan	148	50	236	Latvia	4	1	7
Germany	133	42	218	Afghanistan	4	1	7
Brazil	95	29	159	Russia	4	1	7
Bangladesh	93	27	151	Romania	4	1	7
Italy	88	28	142	Armenia	4	1	6
United Kingdom	76	24	125	Azerbaijan	4	1	6
Iran, Islamic Rep.	76	25	120	Kyrgyzstan	4	1	6
Uzbekistan	70	23	112	Turkmenistan	4	1	6
Viet Nam	66	20	108	Bosnia and Herzegovina	4	1	6
Poland	65	21	108	Morocco and Western Sahara	4	1	6

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Mexico	63	20	103	Moldova	4	1	6
Morocco and Western Sahara	62	19	101	Croatia	4	1	6
Philippines	61	19	102	Kazakhstan	3	1	6
France	60	19	99	Yemen	3	1	5
Turkey	59	19	96	Pakistan	3	1	5
Spain	56	18	90	Hungary	3	1	5
Romania	53	17	87	Syria	3	1	5
Algeria	41	13	67	Albania	3	1	5
Afghanistan	40	13	63	North Macedonia	3	1	5
Sudan	39	11	65	Lebanon	3	1	5
Korea, Dem People's Rep.	34	11	54	Tajikistan	3	1	5
Kazakhstan	30	10	48	Slovakia	3	1	5
Belarus	29	9	48	Czechia	3	1	5
Serbia and Montenegro	29	9	48	Tunisia	3	1	5
Argentina	28	9	48	Greece	3	1	5
Canada	28	9	46	Malta	3	1	4
Thailand	28	8	46	Poland	3	1	4
Saudi Arabia	28	9	44	Haiti	3	1	4
Nigeria	27	7	46	Estonia	3	1	4
Ethiopia	27	8	44	Sudan	3	1	4
Bulgaria	26	8	43	Lesotho	2	1	4
Korea, Rep.	26	9	41	Korea, Dem People's Rep.	2	1	4
Yemen	25	8	41	Mongolia	2	1	4
South Africa	23	7	38	Cuba	2	1	4
Myanmar	22	7	36	Germany	2	1	4
Greece	22	7	35	Algeria	2	1	4
Hungary	22	7	35	Dominican Rep.	2	1	4
Iraq	21	7	33	Jamaica	2	1	4
Syria	21	7	33	Libyan Arab Jamahiriya	2	1	4
Czechia	21	7	34	Portugal	2	1	4
DRC	19	6	32	Italy	2	1	3
Azerbaijan	19	6	31	Eritrea	2	1	3
Nepal	19	6	30	Bahamas	2	1	3
Sri Lanka	18	5	30	Iran, Islamic Rep.	2	1	3
Cuba	17	5	28	Austria	2	1	3
Venezuela	17	5	28	India	2	1	3
Tunisia	17	5	27	Sweden	2	1	3
Netherlands	16	5	27	Finland	2	1	3

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Portugal	16	5	26	Grenada	2	1	3
Australia	15	5	25	China	2	1	3
Malaysia	15	4	25	St. Vincent and the Grenadines	2	1	3
Belgium	14	4	22	Belgium	2	1	3
Georgia	13	4	21	Guinea-Bissau	2	0	3
Tanzania	12	4	21	United Kingdom	2	1	3
Sweden	12	4	20	Indonesia	2	0	3
Mozambique	12	4	19	Iraq	2	1	3
Austria	11	4	19	Trinidad and Tobago	2	0	3
Kenya	11	3	18	Saudi Arabia	2	1	3
Dominican Rep.	10	3	17	United States	2	1	3
Slovakia	10	3	17	Barbados	2	1	3
Haiti	10	3	17	Slovenia	2	1	3
Croatia	10	3	16	Spain	2	1	3
Colombia	10	3	17	St. Lucia	2	1	3
Ghana	10	2	17	Cyprus	2	1	3
Chile	10	3	16	Nepal	2	1	3
Kyrgyzstan	9	3	15	Somalia	2	1	3
Moldova	9	3	15	Israel	2	1	3
Lithuania	9	3	15	Japan	2	1	3
Tajikistan	9	3	14	Sri Lanka	2	0	3
Turkmenistan	9	3	14	Gambia	2	0	3
Bosnia and Herzegovina	9	3	15	Djibouti	2	0	3
Lebanon	8	3	13	Cape Verde	2	0	3
Switzerland	8	3	13	Turkey	2	0	2
Peru	8	2	13	Timor-Leste	1	0	3
Côte d'Ivoire	7	2	12	Denmark	1	0	2
Finland	7	2	11	Netherlands	1	0	2
Israel	7	2	11	Philippines	1	0	2
Angola	6	2	11	Mozambique	1	0	2
Armenia	6	2	10	Switzerland	1	0	2
Uganda	6	1	11	Luxembourg	1	0	2
Somalia	6	2	10	France	1	0	2
Libyan Arab Jamahiriya	6	2	10	Norway	1	0	2
Cambodia	6	2	10	Central African Rep.	1	0	2
Zimbabwe	6	2	10	Oman	1	0	2
Latvia	6	2	10	Viet Nam	1	0	2
Senegal	6	1	10	Bangladesh	1	0	2

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Denmark	5	2	9	Jordan	1	0	2
Albania	5	2	9	Lao People's Dem Rep.	1	0	2
Niger	5	1	9	Iceland	1	0	2
Madagascar	5	1	9	Swaziland	1	0	2
Cameroon	5	1	8	Ireland	1	0	2
Guinea	5	1	8	Puerto Rico and the Virgin Islands	1	0	2
United Arab Emirates	5	1	8	Uruguay	1	0	2
Norway	5	1	8	Antigua and Barbuda	1	0	2
Mali	5	1	8	Guinea	1	0	2
Jordan	5	1	7	Senegal	1	0	2
Burkina Faso	5	1	8	Zimbabwe	1	0	2
Chad	4	1	7	Argentina	1	0	2
Honduras	4	1	7	Chad	1	0	2
Malawi	4	1	7	Honduras	1	0	2
Guatemala	4	1	7	El Salvador	1	0	2
North Macedonia	4	1	6	Canada	1	0	2
Ireland	4	1	6	Venezuela	1	0	2
Zambia	4	1	6	Mauritania	1	0	2
Bolivia	3	1	6	Mexico	1	0	2
Ecuador	3	1	6	São Tome and Principe	1	0	2
El Salvador	3	1	6	Ghana	1	0	2
Lao People's Dem Rep.	3	1	5	Malaysia	1	0	2
Jamaica	3	1	5	Bhutan	1	0	2
Mongolia	3	1	5	Niger	1	0	2
Eritrea	3	1	5	Australia	1	0	2
Puerto Rico and the Virgin Islands	3	1	5	Sierra Leone	1	0	2
Benin	3	1	5	Namibia	1	0	2
Singapore	3	1	5	Mali	1	0	2
Oman	3	1	4	Comoros	1	0	2
Burundi	3	1	4	Côte d'Ivoire	1	0	2
Uruguay	3	1	4	South Africa	1	0	2
Slovenia	2	1	4	Chile	1	0	2
Estonia	2	1	4	Cambodia	1	0	2
Sierra Leone	2	1	4	Burundi	1	0	2
Togo	2	0	4	Burkina Faso	1	0	2
Nicaragua	2	1	3	DRC	1	0	2
Costa Rica	2	1	3	Ethiopia	1	0	2

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Central African Rep.	2	1	3	Liberia	1	0	2
Rwanda	2	0	3	Myanmar	1	0	1
Paraguay	2	0	3	Togo	1	0	2
Lesotho	2	1	3	Malawi	1	0	1
Mauritania	2	0	3	Benin	1	0	2
Panama	1	0	2	Brazil	1	0	1
Congo	1	0	2	Angola	1	0	1
Trinidad and Tobago	1	0	2	Congo	1	0	1
Kuwait	1	0	2	Botswana	1	0	1
Liberia	1	0	2	Zambia	1	0	1
Cyprus	1	0	2	United Arab Emirates	1	0	1
Guinea-Bissau	1	0	2	Tanzania	1	0	1
Gambia	1	0	1	Bolivia	1	0	1
Namibia	1	0	1	Nicaragua	1	0	1
Botswana	1	0	1	Singapore	1	0	1
Malta	1	0	1	Kenya	1	0	1
				Korea, Rep.	1	0	1
				Costa Rica	1	0	1
				Belize	1	0	1
				Cameroon	1	0	1
				Maldives	1	0	1
				Panama	1	0	1
				Guatemala	1	0	1
				Gabon	1	0	1
				Madagascar	1	0	1
				Paraguay	1	0	1
				Thailand	1	0	1
				Uganda	1	0	1
				Bahrain	1	0	1
				Kuwait	1	0	1
				Peru	1	0	1
				Nigeria	1	0	1
				Rwanda	1	0	1

Table A3 Total and per person respiratory + cardiovascular deaths per 10 Mt of methane for all countries with non-zero values

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
India	3 167	472	5 567	Ukraine	8	2	13
China	2 984	729	5 003	Lesotho	8	2	13
United States	761	189	1 284	Egypt	7	2	12
Russian	488	117	839	Georgia	7	2	12
Japan	399	108	659	Korea, Dem People's Rep.	7	2	11
Pakistan	384	74	659	Afghanistan	7	2	11
Indonesia	373	52	671	Bulgaria	7	2	12
Egypt	276	72	457	Serbia and Montenegro	6	2	11
Brazil	255	54	447	Uzbekistan	6	2	10
Germany	254	60	436	Eritrea	6	1	11
United Kingdom	233	55	400	Lithuania	6	1	10
Ukraine	226	51	390	Armenia	6	2	10
Bangladesh	176	34	300	United Kingdom	6	1	10
Philippines	162	35	285	Pakistan	6	1	10
Italy	162	39	273	Belarus	6	1	10
Spain	145	35	245	Romania	6	1	10
Mexico	140	33	237	India	5	1	10
France	130	29	223	Portugal	5	1	9
Viet Nam	127	27	219	Russia	5	1	9
Turkey	121	31	203	Latvia	5	1	9
Iran, Islamic Rep.	114	31	186	Morocco and Western Sahara	5	1	9
Poland	103	23	178	Bosnia and Herzegovina	5	1	9
Korea, Dem People's Rep.	97	27	160	Haiti	5	1	9
Myanmar	94	20	163	Kyrgyzstan	5	1	8
Argentina	92	20	161	Kazakhstan	5	1	9
Morocco and Western							
Sahara	85	19	145	Greece	5	1	8
Ethiopia	84	16	149	Guinea-Bissau	5	0	9
Uzbekistan	83	22	138	Azerbaijan	5	1	8
Thailand	80	14	141	Croatia	5	1	8
South Africa	75	18	127	Belgium	5	1	9
Romania	73	17	125	Moldova	5	1	8
Nigeria	69	8	128	Yemen	5	1	8
Korea, Rep.	65	17	107	Cuba	5	1	9
Canada	64	16	108	Hungary	5	1	8
Afghanistan	62	17	102	Malta	5	1	8
Algeria	58	14	99	Somalia	5	1	8
Sudan	57	10	102	Denmark	5	1	8

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
DRC	54	10	94	Nepal	5	1	8
Nepal	50	11	84	Czechia	4	1	8
Netherlands	45	10	79	Germany	4	1	8
Sri Lanka	45	6	82	Spain	4	1	8
Saudi Arabia	44	11	74	Turkmenistan	4	1	7
Kazakhstan	44	11	75	Zimbabwe	4	1	8
Malaysia	40	6	72	Lebanon	4	1	7
Portugal	39	9	67	Tajikistan	4	1	7
Greece	39	9	66	Japan	4	1	7
Serbia and Montenegro	39	9	66	Syria	4	1	7
Tanzania	38	7	67	São Tome and Principe	4	1	7
Yemen	37	9	64	Grenada	4	1	7
Kenya	36	6	66	Slovakia	4	1	7
Belgium	36	8	63	Gambia	4	0	8
Cuba	36	7	63	Netherlands	4	1	7
Australia	36	8	63	Argentina	4	1	7
Peru	34	5	62	Swaziland	4	1	7
Belarus	34	8	59	Sri Lanka	4	1	7
Bulgaria	34	8	58	Poland	4	1	7
Czechia	32	7	56	Albania	4	1	7
Hungary	32	7	55	Tunisia	4	1	7
Venezuela	30	6	53	Barbados	4	1	7
Mozambique	29	7	51	Philippines	4	1	7
Syria	28	7	47	United States	4	1	7
Ghana	28	2	52	Djibouti	4	1	7
Iraq	26	7	43	Jamaica	4	1	7
Chile	26	6	44	Myanmar	4	1	7
Azerbaijan	24	6	41	Chad	4	1	7
Tunisia	24	5	40	St. Lucia	4	1	7
Sweden	24	6	41	Sweden	4	1	7
Colombia	24	4	43	Italy	4	1	6
Haiti	20	4	35	Mozambique	4	1	7
Zimbabwe	20	5	34	Central African Rep.	4	1	7
Uganda	19	2	36	Guinea	4	1	7
Austria	18	5	31	Israel	4	1	6
Côte d'Ivoire	18	3	33	Senegal	4	0	7
Angola	18	4	31	North Macedonia	4	1	6
Cameroon	18	3	31	Bahamas	4	1	6
Georgia	17	5	29	Sudan	4	1	7
Niger	17	2	32	Cape Verde	4	1	6
Somalia	17	3	30	Norway	4	1	6
Denmark	17	4	29	Dominican Rep.	4	1	6
Dominican Rep.	16	3	29	Uruguay	4	1	6

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Senegal	16	2	30	China	4	1	6
Switzerland	16	4	27	St. Vincent and the Grenadines	3	1	6
Cambodia	16	3	27	Estonia	3	1	6
Israel	15	3	26	Niger	3	0	6
Slovakia	15	3	26	Ireland	3	1	6
Madagascar	14	0	0	Puerto Rico and the Virgin Islands	3	1	6
Croatia	14	3	24	Libyan Arab Jamahiriya	3	1	6
Guinea	14	2	25	Cyprus	3	1	5
Chad	13	2	24	Algeria	3	1	6
Tajikistan	13	4	22	Mauritania	3	1	6
Burkina Faso	13	1	25	Luxembourg	3	1	6
Malawi	13	3	22	Timor-Leste	3	1	6
Guatemala	12	3	21	South Africa	3	1	5
Mali	12	1	23	Austria	3	1	5
Kyrgyzstan	12	3	20	France	3	1	5
Lebanon	12	3	20	Namibia	3	1	5
Moldova	12	3	21	Turkey	3	1	5
Bosnia and Herzegovina	12	3	20	Indonesia	3	0	6
Norway	12	3	20	Slovenia	3	1	5
Lithuania	11	3	20	El Salvador	3	1	5
Zambia	11	2	19	Ghana	3	0	6
Bolivia	11	3	18	Burundi	3	0	5
Turkmenistan	10	3	17	Iran, Islamic Rep.	3	1	5
Finland	10	2	18	Malaysia	3	0	5
Ecuador	10	2	18	Ethiopia	3	1	5
Ireland	10	2	16	Iceland	3	1	5
Armenia	9	3	16	Mongolia	3	1	5
Libyan Arab Jamahiriya	9	2	16	Trinidad and Tobago	3	0	5
United Arab Emirates	9	2	15	Saudi Arabia	3	1	5
Benin	9	1	17	Benin	3	0	5
Eritrea	9	2	16	Comoros	3	1	5
El Salvador	8	2	14	Finland	3	1	5
Burundi	8	1	15	Switzerland	3	1	5
Singapore	8	1	14	Lao People's Dem Rep.	3	1	5
Honduras	8	2	13	Malawi	3	1	5
Puerto Rico and the Virgin Islands	7	2	12	Canada	3	1	5
Rwanda	7	1	13	Antigua and Barbuda	3	1	5
Jordan	7	2	12	Sierra Leone	3	0	5
Latvia	7	2	12	Bhutan	3	1	4
Albania	7	2	12	Mali	3	0	5

COUNTRY	TOTAL	LOW	HIGH	COUNTRY	PER MILLION PEOPLE	LOW	HIGH
Uruguay	7	1	12	Viet Nam	3	1	5
Lao People's Dem Rep.	7	1	11	Côte d'Ivoire	3	0	5
Sierra Leone	6	1	10	Burkina Faso	3	0	5
Togo	6	0	11	Cameroon	3	0	5
Jamaica	5	1	9	Chile	3	1	4
Lesotho	5	1	9	Bangladesh	3	0	4
Central African Rep.	5	1	8	Kenya	3	0	5
North Macedonia	5	1	8	DRC	3	0	4
Slovenia	4	1	7	Cambodia	3	1	4
Mauritania	4	1	8	Zambia	3	1	4
Costa Rica	4	1	7	Tanzania	3	0	4
Nicaragua	4	1	7	Bolivia	2	1	4
Oman	4	1	7	Australia	2	1	4
Congo	4	1	7	Botswana	2	1	4
Mongolia	4	1	6	Togo	2	0	5
Paraguay	4	1	6	Angola	2	1	4
Liberia	3	1	5	Mexico	2	1	4
Panama	3	1	6	Congo	2	0	4
Estonia	3	1	5	Peru	2	0	4
Guinea-Bissau	3	0	5	Brazil	2	1	4
Namibia	2	1	4	Honduras	2	0	4
Gambia	2	0	4	Liberia	2	0	4
Trinidad and Tobago	2	0	4	Iraq	2	1	4
Cyprus	2	1	4	Guatemala	2	0	4
Kuwait	2	0	4	Singapore	2	0	4
Botswana	2	1	4	Jordan	2	1	4
Swaziland	2	0	3	Venezuela	2	0	4
Gabon	1	0	3	Uganda	2	0	4
Djibouti	1	0	2	Belize	2	0	4
Malta	1	0	2	Oman	2	0	3
Luxembourg	1	0	2	Rwanda	2	0	4
Timor-Leste	1	0	2	Gabon	2	0	4
Bhutan	1	0	1	Korea, Rep.	2	1	3
Qatar	1	0	1	Madagascar	2	0	0
Bahamas	1	0	1	Thailand	2	0	3
Bahrain	1	0	1	Costa Rica	2	0	3
Cape Verde	1	0	1	Panama	2	0	3
Barbados	1	0	1	Maldives	2	0	3
Comoros	1	0	1	United Arab Emirates	2	0	3
Iceland	1	0	1	Nicaragua	2	0	3
Mauritius	1	0	0	Ecuador	1	0	2
Equatorial Guinea	1	0	1	Equatorial Guinea	1	0	2
				Paraguay	1	0	2

Table A4 Methane measurement techniques, the methods used by each technique and the advantages and disadvantages of each method

Source: Methane Emission Measurement and Monitoring Methods, National Academies of Sciences, Engineering, and Medicine (2018)

TECHNIQUE	METHOD	ADVANTAGES	DISADVANTAGES
Ground-based measurements	Measurement of emissions from fixed points based on flow rate and methane composition.	Measures total methane emissions from individual point sources (e.g., stacks, animals).	Limited number of methane sources are emitted as point sources.
		Captures temporal trends if deployed for extended time periods.	Labour intensive to quantify spatial and temporal variability (requires a large number of individual measurements to capture variability).
			Often limited to measurements from normaloperations or where there are no safety concerns.
External tracer	Release of tracer gas (C2H2, N2O) at known rate from source area.	Measures total methane emissions from source area.	Difficult to isolate individual sources within source area depending on layout and meteorological conditions.
	Measurement of methane and tracer concentrations across well-mixed downwind plumes to derive emission rate.	Measures complex sources or quantifies the uncertainty in the emission estimate (multiple tracers).	Appropriate meteorological conditions are necessary for technique to work properly.
			Vulnerable to bias if the locations of tracer release differ significantly from the location of methane release.
			Labour intensive to measure the spatial and temporal variability of emissions over many sources.
			Difficult to isolate various sources within the source area depending on source layout and meteorological conditions.
Facility-scale in situ aircraft measurements	Multiple vertical measurements of atmospheric methane and wind-speed gradients above a source area to derive an emission rate.	Remotely measures total methane emissions from a source area/ facility regardless of the operational status or safety conditions at the facility.	Generally, cannot isolate individual sources within source area unless useful source-specific tracers can be co-quantified.
		Captures temporal trends with repeated overflights.	Appropriate meteorological conditions (sufficient vertical mixing of surface emissions at flyover elevations, typically midday conditions) are necessary.
			Requires multiple flights to capture temporal trends in emissions.
			Generally limited to higher-emitting sources (lower detection limits are much higher than point-source techniques).
			Labour intensive to measure the spatial and temporal variability of emissions over many sources.

Towers	Methane by infrared spectrometry at precise infrared wavelengths.	High precision.	Sparse spatial coverage, potential small-sensitivity footprint.
	Time-series measurements of concentrations, analyzed by eddy covariance or by inverse modeling.	Consistent measurements across multiple sites.	Methods are not fully developed.
		Long time series.	Challenging to apply to individual facilities and distinguish confounding sources.
Aircraft mass balance measurements	Measurements upwind and downwind of source region.	Ability to target specific emission source regions and obtain vertical profiles of methane concentrations.	Limited spatial coverage; temporal coverage limited to a snapshot.
	High time-resolution instruments.	Analyzed using simple flow-through models and/or sophisticated inversion modelling.	Challenging to account for transient plumes through the box.
	Infrared spectrometry at precise infrared wavelengths.		Labour intensive to measure the spatial and temporal variability of emissions.
Aircraft remote-sensing measurements	Absorption spectroscopy using reflected sunlight or thermal emissions.	Ability to map methane plumes at the 1–5 m scale, direct source attribution.	Limited spatial and temporal coverage.
			Not as accurate as in situ data.
Satellites – global coverage	Absorption spectroscopy using reflected sunlight (sensitive to entire atmospheric column) or thermal emissions (less sensitive to boundary layer).	Global, complete spatial coverage, frequent revisit time with a single instrument (e.g., TROPOMI, GOSAT).	Coarse spatial resolution with current instruments (~10 km).
			Not as accurate as in situ data, emissions not cleanly resolved.
			Limited to sunlit, cloud-free, snow-free scenes.
Satellites – targeted monitoring	Absorption spectroscopy using reflected sunlight (sensitive to entire atmospheric column) or thermal emissions (less sensitive to boundary layer).	Relatively high resolution (~50 m x 50 m) (e.g., GHGsat).	Limited spatial coverage (targeted facilities or locations).

CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

UN environment programme







For more information, contact:
The Climate and Clean Air Coalition
Hosted by the United Nations Environment Programme
1 rue Miollis, 75015 Paris, France
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Website: www.ccacoalition.org

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Methane emissions are driving climate change. Here's how to reduce them.

unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them

https://www.facebook.com/unep

A recent assessment from the United Nations Environment Programme (UNEP) and the Climate and Clean Air Coalition found that cutting farming-related methane emissions would be key in the battle against climate change. But how can the world do that? Read on for the answers.

Where does methane come from?

Agriculture is the predominant source.

Livestock emissions – from manure and gastroenteric releases – account for roughly 32 per cent of human-caused methane emissions. Population growth, economic development and urban migration have stimulated unprecedented demand for animal protein and with the global population approaching 10 billion, this hunger is expected to increase by up to 70 per cent by 2050.

Agricultural methane doesn't only come from animals, though. Paddy rice cultivation – in which flooded fields prevent oxygen from penetrating the soil, creating ideal conditions for methane-emitting bacteria – accounts for another 8 per cent of human-linked emissions.

What's the big deal about methane?

Methane is the primary contributor to the formation of ground-level ozone, a hazardous air pollutant and greenhouse gas, exposure to which causes 1 million premature deaths every year. Methane is also a powerful greenhouse gas. Over a 20-year period, it is 80 times more potent at warming than carbon dioxide.

Methane has accounted for roughly 30 per cent of global warming since pre-industrial times and is proliferating faster than at any other time since record keeping began in the 1980s. In fact, according to data from the United States National Oceanic and Atmospheric Administration, even as carbon dioxide emissions decelerated during the pandemic-related lockdowns of 2020, atmospheric methane shot up.

How can we reduce methane emissions?

UNEP Food Systems and Agriculture Advisor James Lomax says the world needs to begin by "rethinking our approaches to agricultural cultivation and livestock production." That includes leveraging new technology, shifting towards plant-rich diets and embracing

alternative sources of protein. Lomax says that will be key if humanity is to slash greenhouse gas emissions and limit global warming to 1.5°C, a target of the Paris climate change agreement.

Can farmers help in the campaign to cut methane emissions?

Yes. They can provide animals with more nutritious feed so that they are larger, healthier and more productive, effectively producing more with less. Scientists are also experimenting with alternative types of feed to reduce the methane produced by cows and looking at ways to manage manure more efficiently by covering it, composting it, or using it to produce biogas.

When it comes to staple crops like paddy rice, experts recommend alternate wetting and drying approaches that could halve emissions. Rather than allowing the continuous flooding of fields, paddies could be irrigated and drained two to three times throughout the growing season, limiting methane production without impacting yield. That process would also require one-third less water, making it more economical.

Will reducing methane really help counter climate change?

Yes. Carbon dioxide remains in the atmosphere for hundreds to thousands of years. This means that even if emissions were immediately and dramatically reduced it would not have an effect on the climate until later in the century. But it takes only about a decade for methane to break down. So, reducing methane emissions now would have an impact in the near term and is critical for helping keep the world on a path to 1.5°C.

How much methane can we really cut?

Human-caused methane emissions could be reduced by as much as 45 per cent within the decade. This would avert nearly 0.3°C of global warming by 2045, helping to limit global temperature rise to 1.5˚C and putting the planet on track to achieve the Paris Agreement targets. Every year, the subsequent reduction in ground-level ozone would also prevent 260,000 premature deaths, 775,000 asthma-related hospital visits, 73 billion hours of lost labour from extreme heat and 25 million tonnes of crop losses.

What is the United Nations doing to help limit methane emissions?

A lot. UN Secretary-General António Guterres will convene the UN Food Systems Summit in September 2021, which aims to help make farming and food production more environmentally friendly.

In the meantime, the UN's Koronivia Joint Work on Agriculture initiative is supporting the transformation of agricultural and food systems, focusing on how to maintain productivity amid a changing climate. Representatives are also working to mainstream agriculture into the UN Framework Convention on Climate Change and will hold discussions at the UN Climate Change Conference (COP26), later this year.

For more information about agriculture and clean air, contact Tiy Chung: tiy.chung@un.org

Every year, on 7 September, the world celebrates the International Day of Clean Air for Blue Skies. The day aims to raise awareness and facilitate actions to improve air quality. It is a global call to find new ways of doing things, to reduce the amount of air pollution we cause, and ensure that everyone, everywhere can enjoy their right to breathe clean air. The theme of the second annual International Day of Clear Air for blue skies, facilitated by the United Nations Environment Programme (UNEP), is "Healthy Air, Healthy Planet."

Managing grazing livestock during wet weather

extension.umn.edu/beef-cow-calf/managing-grazing-livestock-during-wet-weather

Quick facts

To manage grazing livestock during wet weather:

- Check your feed supply and options.
- Have alternative feedstuffs, appropriate housing, and a culling plan ready if necessary.
- Plan for the worst in the case of a flood.
- Monitor livestock for disease and control pests.



Dense stands of perennial forage withstand weather extremes and livestock pressure better than sparse stands. Rotational grazing, overseeding, soil testing, fertilizing, and preventing overgrazing can all promote healthy pastures.

During wet weather, the following steps can further limit livestock damage to pastures:

- Rotate livestock to new pastures more often to limit soil compaction and damage to plants or roots. You may need to move livestock multiple times a day. Resting pastures allows plants time to recover.
- Move waterers, feeders, and mineral supplements often to prevent damage and excess mud around these areas if possible.

- Remove livestock from pastures that are too wet to graze to avoid creating mud.

How pastures respond to flooding depends on the forage species. Check your forage species' flooding tolerance to help guide decisions.

Remove livestock from pastures

Sometimes your best option is to remove livestock from pastures until conditions dry out.

- Have a backup plan for grazing. The plan should include options like a sacrifice lot, concrete holding pad, or holding building. Select a sacrifice lot that has well-draining soils.
- Make sure you have enough stored feed to provide livestock when they can't graze.
- Prepare for the worst and have a culling strategy. You may need to cull livestock if wet conditions worsen and you lack feed inventory.

Protect livestock from flood contamination

Protect the health of your livestock if forage ground floods:

- Provide a fresh, clean water source.
- Don't allow livestock to graze in or near actively flooding pastures. Soil, fecal matter, bacteria, and other debris can contaminate forages during a flood.
- Don't feed dry hay that was impacted by flood waters.
- Sample standing flood waters for nitrates, coliform bacteria, or toxins such as pesticides.

Once flood waters recede, remove debris and repair fences and water lines. You may also need to manage affected forages.

- If pastures have been contaminated by flowing flood waters, cut standing forage to a 4-inch height and allow the cut forage to decompose. Do not graze or harvest this forage. Once the forage regrows to 12 inches, grazing may resume.
- Roll out flood-water-contaminated hay and allow it to decompose. Place decomposing hay bales in fields that need additional fertility.

Repair sacrifice areas or damaged pastures

Healthy perennial pastures can recover from spring flooding if you limit damage from grazing. When possible, delay grazing until plants recover from wet weather and flooding. Keep livestock in a sacrifice paddock and feed stored forages. You can rotate sacrifice areas on your farm yearly to allow repair and recovery.

Allow areas to rest

If you have enough land and feed resources available, allow sacrifice areas and damaged pastures to regrow.. Weed species will be quick to fill in the area. Consider mowing the weeds before they head out to limit the competition for the grasses and legumes. It may be possible to graze these paddocks once during the grazing season depending on weather conditions and timing.

Replant pastures

Once pastures dry out, decide if replanting is worthwhile.

Before replanting, take a soil sample to ensure the soil pH is above 6 and that soil fertility is adequate. Use a no-till planter to limit further soil disturbance and damage to the soil structure.

If needed, level off pastures with a harrow before planting. You could also broadcast seed and do a pass with a cultipacker.

You can plant a fast-growing summer annual or cover crop from early to mid-summer to prevent weed pressure. You can graze or harvest the summer annual depending on the timing of planting and species planted.

Once grazed or harvested, you can then plant a perennial pasture mix. The ideal time to plant a perennial pasture in the Midwest is between August 1 and September 15.

Spending time and money to repair damaged paddocks is an investment in future forage inventory, grazing capacity, ecosystem functioning and productivity.

Alternative feedstuffs

Like drought, wet weather can lead to feedstuff shortages. You can prepare for weather events by checking your forage supply and the needs of your livestock. Other options include reducing livestock numbers or purchasing forages or alternative feedstuffs.
See Feeding dairy cattle in a drought.

Alternative feed options to purchase or plant as emergency forage:

- BMR Sorghum
- Sudangrass
- Sorghum-sudangrass
- Japanese millet
- Hybrid pearl millet
- Barley
- Barley and pea mix
- Oat and pea mix
- Forage brassicas like rape, kale, and turnips

These resources can help determine which alternative might best fit your system and needs:

- Alternative annual forages: Warm-season grasses
- Alternative feedstuffs for horses
- Ten ways to stretch your horse's hay supply
- Pricing and using alternative forages
- Alternative Feeds for Ruminants-NDSU Extension
- Emergency Forage Options- Wisconsin Extension
- Use of Brassica Crops in Grazing Systems- Wisconsin Extension

Manage wet feed

Wet weather and flooding can affect the quality of feedstuffs like grain and silage.

- Storing wet feed can be a fire hazard. Always move wet feed away from buildings.
- Moldy feed can be toxic and lead to death or abortions in livestock.
- Never feed hay or grain that has been in contact with flood waters.
- Grain affected by ponded water and not flood waters with no risk of contamination may be ensiled similar to high-moisture corn. Always test the grain for mycotoxins first.

Always determine the nutritional value of rained-on hay. Depending on the timing and intensity of the rain event, forage may still be of high quality. Generally, rainfall on cut forages will reduce dry matter yield and digestibility. When concerned about the quality of forages, have them tested.

Housing livestock

Manage manure

- Develop a manure management plan when confining livestock during long stretches of wet weather.
- Reduce risks of manure application during wet weather, especially in the spring and fall.
- Keep track of your available manure storage. Have a plan in case there is a risk of manure overflow.

The Minnesota Pollution Control Agency (MPCA) has other manure management plan tools. If manure storage facilities are in danger of overflowing, contact the MPCA or your local county feedlot officer.

It is important to prevent manure contamination of streams, rivers, and lakes. If your manure storage facility overflows, you must contact the Minnesota Duty Officer at 800-422-0798.

Prevent mud

Managing mud on horse and livestock farms requires preventive measures.

- Install alternative footing and temporary drainage systems in chronic problem areas.
- Move feeders to dry spots. You may also provide bedding around feeders to maintain good footing and keep livestock as clean and dry as possible.
- Scrape livestock pens often, if possible, and maintain a slope away from feeding areas.

Develop an emergency flood plan

- Horse and livestock owners should have emergency flood plans. Plans may include an evacuation outline, backup generators, and livestock pens on higher ground.
- Never store fertilizers, herbicides, pesticides and treated seeds near livestock. Place these items where flood water will not reach them and possibly contaminate feed or water.
- Move livestock out of barns and enclosed areas if floodwaters start approaching these structures. If you need help moving livestock, contact your local county emergency managers or local county feedlot officer.
    - Preparing for a barn disaster: flood
    - Flood Resources MDA

Injury, disease and pest concerns

- Wet weather can chill livestock during cool temperatures, especially in the fall and spring.
- Wet and muddy hair poorly insulates livestock.
- Added stress can compromise their immune systems and mud and manure can harbor bacteria and other pathogens leading to disease.
- Young livestock can be especially susceptible.

Monitor for disease

- Always contact your veterinarian if you suspect disease in your livestock.
- In flood conditions, injuries and disease can occur from livestock eating debris.
- Soil-borne pathogen risk increases during floods with the movement of soil.
- Livestock exposed to flooding conditions, or that will be sent to pastures affected by flooding, should be vaccinated against clostridial diseases and tetanus. Discuss with your veterinarian the available vaccination options.

Diseases to monitor include:

Liver flukes and redwater disease in Minnesota beef cattle — Snails spread liver flukes and often live near water. Cattle can ingest liver flukes when grazing near surface water or eating hay stored in wet conditions, where snails live. Limit grazing near wet areas and feeding stored forage possibly contaminated by snails.

Foot rot can occur from bacteria that thrive in wet conditions. Prolonged moisture can damage skin between the toes of livestock and lead to infection.

Post-flood neurologic disorders in horses — After a flood horses may be more likely to develop neurologic disorders due to increased parasite pressure, ingestion of toxic plants, and stressed immune systems.

Scratches is a skin condition that can be caused by long-term exposure to wet bedding or mud. It causes an irritated or infected area of skin on the pastern or heel bulb of horses.

In wet conditions, mosquitos are more frequent, which can increase the risk of horse diseases like West Nile Virus.

Horses are at a greater risk of developing cellulitis in wet, muddy conditions, where bacteria thrive. Cellulitis is a bacterial infection in connective tissue under the skin of the lower leg characterized by heat, swelling and tenderness. Consult with your veterinarian if you suspect your horse has cellulitis.

Other diseases to be aware of during wet weather and flooding include:

- Leptospirosis, E. coli and salmonella from untreated water
- Parasites like roundworms, hookworms, giardia and fleas
- Clostridial diseases like blackleg and malignant edema
- Anthrax
- Mastitis
- Tetanus
- Botulism
- Brooder Pneumonia
- Erysipelas

Control pests

Fly and mosquito populations increase during and after wet weather. Pest control plans can help limit irritation, stress and disease pressure on livestock. Frequent clean-up and removal of manure and bedding can reduce breeding sites for pests like stable and house flies.

Additional pest control resources:

Author: Sabrina Florentino, Extension educator

Reviewed in 2024

Climate Change in Minnesota

climate.umn.edu/climate-change-minnesota-0

University of Minnesota Climate Adaptation Partnership



Changes we've already observed

Between 1895 and 2024, the average annual temperature in Minnesota has increased by 3.2°F. This increase in accumulated heat is driving changes in our seasonal high and low temperatures, decreasing the length of snow cover, increasing heavy rain events, and altering ecosystems across Minnesota. Warming has also accelerated in recent years[3].

Most of the warming since 1985 has been concentrated during the coldest months of the year, with the state's average winter temperatures increasing by 5.4°F and average winter low temperatures increasing by 6.8°F. Average daily low temperatures have increased at more than twice the rate of the average daily high temperatures. In recent decades, winter warming has also accelerated significantly, with average daily low temperatures in winter rising over 15 times faster than summer high temperatures between 1970 and 2024[4].

Minnesota also experienced, on average, an increase of 3.5 inches of precipitation per year between 1895 and 2024. The largest single rain event has grown by 13%[1], and the state is now experiencing more frequent and intense heavy rainfall events than ever recorded. At the same time, Minnesota has experienced a rise in rapid transitions between wet and dry periods, resulting in flash drought conditions that increase moisture stress on both agricultural crops and native vegetation[5].

Projected changes in temperature

Future climate projections indicate Minnesota's average temperatures will continue to rise, accompanied by increased humidity (making it feel even warmer) and greater seasonal variability.

By mid-century (2040-2059), the **annually averaged daily maximum temperature in Minnesota is projected to increase between 3.6°F under an intermediate emissions scenario and 4.2°F under a very high emissions scenario**.

Similarly to observed trends, projected increases in wintertime lows are greater than projected increases in summertime highs. On average, daily minimum temperatures in the winter are projected to increase by 6°F and daily maximum temperatures in the summer are projected to increase by 4.9°F by mid-century under a very high emissions scenario.

Warming could fuel significant shifts in the state's seasonal extremes. The number of days per year with minimum temperatures below freezing (32°F) could decline by nearly a month by mid-century (2040-2059), and by two months by the end of the century (2080-2099). Meanwhile, temperatures exceeding 100°F are expected to increase significantly by the end of the century, with the state projected to experience 20 days per year above 100°F under a very high emissions scenarios.

Projected changes in precipitation

Precipitation patterns across Minnesota are expected to become more intense, with more rainfall occurring in a single event and longer dry periods in between.

Seasonal precipitation trends are projected to vary significantly, **often with wintertime and springtime averages projected to *increase*, and summertime averages projected to *decrease***. In some cases, summertime averages are expected to decrease so much that they can lower annual average values overall. Additionally, due to warming temperatures, by mid-century, the number of days per year with snow cover depth greater than 1 inch is expected to decline by 12 (intermediate emissions) to 15 (very high emissions) days.

Precipitation changes are expected to vary by region, with the southeastern part of the state expected to see the largest increase — an additional 4.4 inches of annual precipitation compared to historical simulations (1995–2014) by the end of the century (see figure below).

Future droughts in Minnesota are expected to become more severe due to rising temperatures accelerating soil moisture loss. Regionally, the Midwest is projected to experience the greatest increase in consecutive dry days in the U.S., with durations potentially extending by up to 25% by 2100[5].

United States Government Accountability Office

GAO

Report to Congressional Requesters

September 2008

CONCENTRATED ANIMAL FEEDING OPERATIONS

EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern

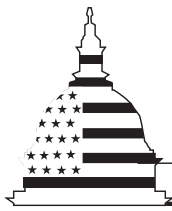

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GAO-08-944

September 2008

CONCENTRATED ANIMAL FEEDING OPERATIONS

EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern

GAO Accountability • Integrity • Reliability

Highlights

Highlights of GAO-08-944, a report to congressional requesters

Why GAO Did This Study

Concentrated Animal Feeding Operations (CAFO) are large livestock and poultry operations that raise animals in a confined situation. CAFOs can improve the efficiency of animal production but large amounts of manure produce can, if not properly managed, degrade air and water quality. The Environmental Protection Agency (EPA) is responsible for regulating CAFOs and requires CAFOs that discharge certain pollutants to obtain a permit.

This report discusses the (1) trends in CAFOs over the past 30 years, (2) amounts of waste they generate, (3) findings of key research on CAFOs' health and environmental impacts, (4) EPA's progress in developing CAFO air emissions protocols, and (5) effect of recent court decisions on EPA's regulation of CAFO water pollutants. GAO analyzed U.S. Department of Agriculture's (USDA) data from 1982 through 2002, for large farms as a proxy for CAFOs; reviewed studies, EPA documents, laws, and regulations; and obtained the views of federal and state officials.

What GAO Recommends

To more effectively regulate CAFOs, GAO recommends that EPA complete its inventory of permitted CAFOs, reassess the current nationwide air emissions monitoring study, and establish a strategy and timetable for developing a process-based model for measuring CAFO air emissions. EPA partially agreed with GAO's recommendations.

To view the full product, including the scope and methodology, click on GAO-08-944. For more information, contact Anu Mittal (202) 512-3841, mittala@gao.gov.

What GAO Found

Because no federal agency collects consistent, reliable data on CAFOs, GAO could not determine the trends in these operations over the past 30 years. However, using USDA data for large farms that raise animals as a proxy for CAFOs, it appears that the number of these operations increased by about 230 percent, going from about 3,600 in 1982 to almost 12,000 in 2002. Also, during this 20-year period the number of animals per farm had increased, although it varied by animal type. Moreover, GAO found that EPA does not have comprehensive, accurate information on the number of permitted CAFOs nationwide. As a result, EPA does not have the information it needs to effectively regulate these CAFOs. EPA is currently working with the states to establish a new national data system.

The amount of manure generated by large farms that raise animals depends on the type and number of animals raised, but large operations can produce more than 1.6 million tons of manure a year. Some large farms that raise animals can generate more raw waste than the populations of some U.S. cities produce annually. In addition, according to some agricultural experts, the clustering of large operations in certain geographic areas may result in large amounts of manure that cannot be effectively used as fertilizer on adjacent cropland and could increase the potential of pollutants reaching nearby waters and degrading water quality.

Since 2002, at least 68 government-sponsored or peer-reviewed studies have been completed that examined air and water quality issues associated with animal feeding operations and 15 have directly linked air and water pollutants from animal waste to specific health or environmental impacts. EPA has not yet assessed the extent to which these pollutants may be impairing human health and the environment because it lacks key data on the amount of pollutants that are being emitted from animal feeding operations.

As a first step in developing air emissions protocols for animal feeding operations, in 2007, a 2-year nationwide air emissions monitoring study, largely funded by industry, was initiated. However, as currently structured, the study may not provide the scientific and statistically valid data it was intended to provide and that EPA needs to develop air emissions protocols. Furthermore, EPA has not established a strategy or timetable for developing a more sophisticated process-based model that considers the interaction and implications of all emission sources at an animal feeding operation.

Two recent federal court decisions have affected EPA's ability to regulate water pollutants discharged by CAFOs. The 2005 *Waterkeeper* case required EPA to abandon the approach that it had proposed in 2003 for regulating CAFO water discharges. Similarly, the 2006 *Rapanos* case has complicated EPA's enforcement of CAFO discharges because EPA believes that it must now gather significantly more evidence to establish which waters are subject to the Clean Water Act's permitting requirements.

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Abbreviations

CAFO	Concentrated Animal Feeding Operation
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act of 1980
EPA	Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-to-Know Act of 1986
NAS	National Academy of Sciences
NPDES	National Pollutant Discharge Elimination System
USDA	U.S. Department of Agriculture

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GAO
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Congressional Requesters

Over the last 40 years, diversified, independent, family-owned-and-operated farms that produce a variety of crops and a few animals are becoming a smaller share of the agricultural sector and are being replaced by fewer, much larger farms. For animal production, this change has meant a movement to significantly larger operations that can raise, for example, as many as 2 million chickens or 800,000 hogs at one facility at one time.

These large-scale livestock and poultry operations are generally referred to as animal feeding operations. An animal feeding operation is one that (1) raises animals in a confined situation for a total of 45 days or more during a 12-month period and (2) brings feed to the animals rather than having the animals graze or seek feed in pastures and fields or on rangeland. Concentrated animal feeding operations (CAFO) are a subset of animal feeding operations and usually operate on a much larger scale. Generally, a CAFO is an animal feeding operation that raises enough animals to meet or exceed certain minimum thresholds, depending upon the type of livestock being raised. For example, as defined in Clean Water Act regulations, an animal feeding operation would be considered a CAFO if it raised 1,000 or more beef cattle, 2,500 hogs weighing more than 55 pounds, or 125,000 broiler chickens.[1] In addition, an animal feeding operation of any size can be designated a CAFO if it meets certain conditions, such as being a significant contributor of pollutants to federally regulated waters.[2]

While CAFOs may have improved the efficiency of the animal production industry, they have also raised environmental and health concerns because of the large amounts of manure they produce. Generally, to minimize potential environmental problems, these operations retain the manure that they produce in storage facilities onsite and periodically dispose of it by spreading it on nearby or adjacent cropland as fertilizer. If the manure is properly contained and managed, it can benefit crop production; if improperly contained and managed, it can degrade air and

[1]40 C.F.R. § 122.23(b).

[2]Federally regulated waterways include waters of the United States as defined in 33 C.F.R. § 328.3(a)(1)-(7) and may include rivers, wetlands, impoundments, the territorial seas, and waters used in interstate commerce.

water quality, thereby potentially impairing human health and damaging the environment. Specifically, these operations can potentially degrade air quality because large amounts of manure may emit unsafe quantities of ammonia, hydrogen sulfide, and particulate matter,[3] and they can potentially degrade water quality because pollutants in manure such as nitrogen, phosphorus, bacteria, and organic matter could enter nearby water bodies.

Several federal laws provide the Environmental Protection Agency (EPA) with the authority to regulate water and air pollutants from CAFOs. The Clean Water Act specifically addresses CAFOs by requiring EPA to consider CAFOs like any other industry if they discharge pollutants into federally regulated waters. As a result, CAFOs that have such discharges must obtain a permit that establishes design standards and management practices for retaining and disposing of manure in such a way as to limit the amounts and types of pollutants from manure that are released into federally regulated waters. EPA, or the states that have been authorized by EPA to administer the Clean Water Act, are responsible for issuing these permits. In contrast, three other acts provide EPA with certain authorities related to air emissions from these operations, although they do not specifically cite CAFOs as regulated entities. Under the Clean Air Act, any animal feeding operation, regardless of size, that exceeds established air emission thresholds for certain pollutants can be regulated. For example, pollutants such as particulate matter that are emitted by animal feeding operations are regulated under the Clean Air Act and other pollutants such as hydrogen sulfide or ammonia may be regulated under the act in certain circumstances. Similarly, the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and the Emergency Planning and Community Right-to-Know Act of 1986 (EPCRA) do not specifically mention CAFOs, but they do require owners or operators of these facilities to report to federal or state and local authorities when a "reportable quantity" of certain hazardous substances, such as hydrogen sulfide or ammonia,[4] is released into the environment. Together, CERCLA's and EPCRA's reporting requirements provide government authorities, emergency management agencies, and citizens the ability to

[3]Particulate matter is a complex mixture of extremely small particles and liquid droplets. Particulate matter can be made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles.

[4]Each of these hazardous substances has a reportable quantity of 100 pounds in a 24-hour period.

know about the source and magnitude of hazardous releases into the environment.

In light of the growing concerns regarding the potential human health and environmental impacts of CAFOs, you asked us to determine the (1) trends in CAFOs over the past 30 years; (2) amount of waste they generate; (3) findings of recent key academic, industry, and government research on the impacts of CAFOs on human health and the environment, and the extent to which EPA has assessed the nature and severity of such impacts; (4) progress that EPA and the states have made in regulating and controlling the emissions of, and in developing protocols to measure, air pollutants from CAFOs that could affect air quality; and (5) extent to which recent court decisions have affected EPA and the states' ability to regulate CAFO discharges that impair water quality.

In conducting our work, we reviewed laws and regulations and federal and state agencies' documents; met with officials from EPA and the U.S. Department of Agriculture (USDA), industry, citizen and environmental groups, and academia. We also spoke with state officials and visited CAFOs in eight states. These states were Arkansas, California, Colorado, Iowa, Maryland, Minnesota, North Carolina, and Texas. We chose these states because they were geographically dispersed and contained numerous CAFOs representing various animal types. In addition, to determine trends in CAFOs over the past 30 years, from 1974 through 2002, we obtained the most recent data available from USDA on large farms that raise animals to use as a proxy for CAFO data. However, because of limitations in USDA's data for 1974 through 1982, we could not determine from these data which farms prior to 1982 would meet EPA's minimum size thresholds for CAFOs. Consequently, our analysis of trends in CAFOs focuses on the 20-year period between 1982 and 2002. We also obtained and reviewed the data that EPA compiled over the last 5 years from each of its regions on the number of CAFOs that were issued a permit. To identify the amount of waste CAFOs generate, we estimated the amounts of manure generated by various size farms that raise animals. To provide a perspective of the amount of waste that large farms that raise animals can generate, we selected certain cities based on their population and estimated the amount of sanitary waste generated by the human population and compared these amounts with the amount of waste generated by three different sizes of large farms.[5] To report on key research on the impacts of CAFOs on human health and the environment,

[5]Human sanitary waste includes feces and urine but does not include wastes such as water from showers, washing dishes and clothes, and flushing toilets.

we reviewed EPA's 2003 Rule regulating discharges from CAFOs under the Clean Water Act and the National Academy of Sciences study on air emissions from animal feeding operations.[6] We also conducted library and Internet searches to identify key studies completed since 2002 on air and water pollutants from waste generated by animal feeding operations. We compared the findings from these studies with EPA assessments to date and interviewed EPA officials regarding these assessments. To assess the progress that EPA and the states have made in regulating and controlling the air emissions of, and in developing protocols to measure, air pollutants from CAFOs, we reviewed relevant documents and interviewed EPA officials, as well as officials responsible for an ongoing national air emissions monitoring study. In addition, we contacted state officials in all 50 states to determine which states had developed air emission regulations applicable to CAFOs. Finally, to determine the extent to which recent court decisions have affected EPA and the states' ability to regulate CAFO discharges that impair water quality, we reviewed the results of recent federal and state court decisions. We also interviewed EPA and state officials on how the court decisions have affected their ability to regulate CAFOs. A more detailed description of our scope and methodology is presented in appendix I.

We conducted this performance audit between July 2007 and August 2008, in accordance with generally accepted government auditing standards. These standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Results in Brief

No federal agency collects accurate and consistent data on the number, size, and location of CAFOs. However, according to USDA officials, the data USDA collects for large farms that raise animals can serve as a proxy in estimating trends in CAFOs nationwide from 1982 through 2002. Using these data, we found that the number of large farms that raise animals has increased 234 percent, from about 3,600 in 1982 to almost 12,000 in 2002. We found that the number of animals raised on these large farms had also increased, but the rate of increase varied greatly by animal type. For example, the average number of hogs raised on large farms increased by 37 percent, from about 3,400 in 1982 to nearly 4,600 in 2002. In contrast,

[6]National Academy of Sciences, *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs* (Washington, D.C.: National Academies Press, 2003).

during the same time period, the average number of broiler chickens raised on large farms only increased by about 3 percent, from approximately 155,000 to nearly 160,000. Furthermore, almost half of the livestock and poultry raised in the United States in 2002, about 43 percent, were raised on large farms. Over the last 5 years, EPA has been compiling data from its regions in an effort to develop information on the number of permitted CAFOs nationwide. However, we determined that these data are inconsistent and inaccurate and do not provide necessary information on the characteristics of these CAFOs. Without a systematic and coordinated process for collecting and maintaining accurate and complete information on the number, size, and location of permitted CAFOs, EPA does not have the information that it needs to effectively regulate these operations. EPA has indicated that it is working with the states to develop and implement a new national system to collect and maintain these data.

The amount of manure that a large farm raising animals can generate depends on the types and numbers of animals being raised at a specific operation; such farms can produce from over 2,800 tons to more than 1.6 million tons of manure annually. For example, a layer farm that meets EPA's minimum large CAFO threshold of 82,000 laying hens could produce more than 2,800 tons of manure a year, while a farm with 10,000 beef cattle (cattle fattened with feed) could produce about 117,000 tons of manure a year. In fact, some large farms can produce more raw waste than the human population of a large U.S. city. For example, a very large hog farm, with as many as 800,000 hogs, generates more than 1.6 million tons of manure annually—more than one and a half times the sanitary waste produced by the about 1.5 million residents of Philadelphia, Pennsylvania in 1 year. Furthermore, while manure is a valuable resource often used as fertilizer, agricultural experts and government officials have raised concerns about the large amounts of manure produced by animal feeding operations that are increasingly clustered within specific geographic areas within a state. For example, five contiguous North Carolina counties had an estimated hog population of over 7.5 million hogs in 2002 and the hog operations in these counties could have produced as much as 15.5 million tons of manure that year. According to agricultural experts and government officials that we spoke to, such clustering of operations raises concerns that the amount of manure produced could result in the overapplication of manure to croplands in these areas and the release of excessive levels of some pollutants that could potentially damage water quality.

At least 68 government-sponsored or peer-reviewed studies have been completed on air and water quality issues associated with animal waste since 2002 and 15 of these studies have directly linked pollutants from

animal waste to specific health or environmental impacts. Of the remaining 53 studies, 7 found no impacts, 12 made indirect linkages between these pollutants and health and environmental impacts, and 34 of the studies focused on measuring the amount of water or air pollutants emitted by animal feeding operations. However, EPA has not yet assessed the extent to which air and water pollution from CAFOs may be impairing human health and the environment because it lacks key data on the amount of pollutants that CAFOs are discharging. Of the 15 studies we found directly linking pollutants from animal waste to human health or environmental impacts, 8 focused on water pollutants and 7 on air pollutants. Most of the water studies found that nutrients or hormones released from animal feeding operations were causing environmental harm, such as reproductive disorders in fish and degraded water quality. One water study found that animal feeding operations were causing pathogens such as *E. coli* to contaminate drinking water, which were then causing gastrointestinal illnesses in humans. Similarly, all seven air studies linked air emissions from animal feeding operations to adverse human health effects. Specifically, six found exposure to these emissions caused respiratory inflammation and one found an increased incidence of headaches, eye irritation, and nausea in people working at or living near these operations. According to EPA officials, although the agency has long recognized the potential impacts that water pollutants from CAFOs can have on human health and the environment, it has not yet assessed these impacts because it lacks information on the extent to which water pollutants are actually being discharged by CAFOs. According to other officials at EPA, the agency does not have the resources needed to conduct a study that would provide this information. Likewise, EPA has not yet assessed the air quality impacts from animal feeding operation emissions because, according to agency officials, it lacks key data on the extent to which these operations are emitting pollutants. To gather this information, EPA entered into a series of agreements with animal feeding operations to implement a national air emissions monitoring study that is currently ongoing and is being funded by the industry and will measure and quantify air emissions from animal feeding operations.

The ongoing national air emissions monitoring study is considered a first step in EPA's efforts to develop protocols for measuring and quantifying air contaminants from animal feeding operations; however, it is not clear if the study will provide EPA the data that it needs to develop these protocols. EPA believes that this 2-year study, initiated in 2007, will provide a scientific basis for estimating air emissions from animal feeding operations so that the agency can develop protocols that these operations can use to more quickly determine if they exceed regulatory thresholds. However, concerns have been raised that the animal feeding operations

being monitored in the study do not represent a valid sample of all animal feeding operations and that the data collected during the early phases of the study may be incomplete. As a result, it is uncertain whether the study will ultimately provide data of sufficient quantity and quality that will enable the agency to develop its planned protocols. In addition, it is uncertain if and when EPA will develop a process-based model that considers the interaction and implications of all sources of emissions at an animal feeding operation. Furthermore, other EPA actions make it unclear at this time how the agency intends to regulate air emissions from animal feeding operations once the data collection effort is complete. For example, EPA has not yet decided if it will aggregate the emissions occurring on an animal feeding operation or if the emissions from barns and manure storage areas will be considered separately when determining if an operation has exceeded air emissions thresholds. Moreover, in December 2007, EPA proposed a rule to exempt releases to the air of hazardous substances, such as ammonia and hydrogen sulfide, from manure at farms, including animal feeding operations, which meet or exceed their reportable quantity from both CERCLA and EPCRA notification requirements. EPA stated that, in all instances, the source and nature of the release make emergency responses unnecessary, impractical, and unlikely for these operations, and hence it found notifications to be unnecessary. It is unclear to us how EPA made this determination when it has not yet completed its data collection effort and does not yet know the extent to which animal feeding operations are emitting these pollutants. In the absence of federal guidance on how to regulate air emissions from animal feeding operations, officials in six states told us that they are regulating some emissions covered under the Clean Air Act, CERCLA, and EPCRA. For example, Minnesota has established state emissions thresholds for hydrogen sulfide that apply to CAFOs and the state requires CAFO operators to develop an air emissions plan specifying how they will control these emissions.

Two recent federal court decisions have affected EPA's and some states' ability to regulate CAFOs for pollutants that may impair water quality. Specifically:

- In 2005, in *Waterkeeper Alliance Inc. v. EPA* (*Waterkeeper*), the U.S. Court of Appeals for the Second Circuit set aside key provisions of a CAFO rule EPA had issued in 2003. This rule would have provided EPA with comprehensive information on the universe of CAFOs and their operations and would have subjected large numbers of previously unregulated CAFOs to monitoring and reporting requirements, as well as periodic inspections. However, the court concluded that EPA did not have the authority under the Clean Water Act to require CAFOs that were not discharging pollutants

into federally regulated waters to apply for permits. As a result, CAFO operators currently determine for themselves whether they need to apply for a federal permit, and EPA must rely on other means of acquiring information about CAFOs that are illegally discharging pollutants, such as through citizens' reports. EPA has developed proposed revisions to its 2003 rule in response to the court's ruling. The resulting rule is currently awaiting the Office of Management and Budget's approval, but EPA is not certain when that review will be completed and the final rule issued. The *Waterkeeper* decision has had mixed impacts on states' regulation of CAFOs. Some states have not been affected by the *Waterkeeper* decision because they have used their own authorities to adopt regulations more stringent than federal regulations. As a result, these states, such as Minnesota, have continued to require all CAFOs to obtain state permits. In contrast, officials in those states, such as Colorado, that base their regulations on the Clean Water Act and federal regulations told us that their programs will remain in limbo until EPA issues its final revised rule.

- The Supreme Court's 2006 decision—*Rapanos v. United States* (*Rapanos*)—has also complicated EPA's enforcement of CAFO regulations. The Court's decision has raised questions that have not yet been resolved about which "waters" are considered federal waters and, therefore, fall under the jurisdiction of the Clean Water Act. According to EPA enforcement officials, the agency may be less likely to seek enforcement against a CAFO that it believes is discharging pollutants into a water body because it is now more difficult to prove that the water body is federally regulated. Congress is considering legislation that seeks to clearly define the scope of the Clean Water Act and resolve the questions raised by the *Rapanos* decision.

To more effectively regulate CAFOs, we are recommending that the Administrator of EPA direct the agency to complete its efforts to develop a comprehensive national inventory of permitted CAFOs that incorporates appropriate internal controls to ensure the quality of the data collected. To ensure that the national air emissions monitoring study will provide the scientific and statistically valid data that EPA needs for developing its air emissions protocols, we are recommending that EPA reassess the current data collection efforts, including its internal controls. We are also recommending that EPA establish a strategy and timetable for developing a process-based model that will provide more sophisticated air emissions estimating methodologies for animal feeding operations. In commenting on a draft of this report, EPA partially agreed with our recommendations.

Background

The livestock and poultry industry is vital to our nation's economy, supplying meat, milk, eggs, and other animal products; however, the past several decades have seen substantial changes in America's animal production industries. As a result of domestic and export market forces, technological changes, and industry adaptations, food animal production that was integrated with crop production has given way to fewer, larger farms that raise animals in confined situations. These large-scale animal production facilities are generally referred to as animal feeding operations. CAFOs are a subset of animal feeding operations and generally operate on a larger scale. While CAFOs may have improved the efficiency of the animal production industry, their increased size and the large amounts of manure they generate have resulted in concerns about the management of animal waste and the potential impacts this waste can have on environmental quality and public health.

Animal manure can be, and frequently is, used beneficially on farms to fertilize crops and to restore nutrients to soil. However, if improperly managed, manure and wastewater from animal feeding operations can adversely impact water quality through surface runoff and erosion, direct discharges to surface water, spills and other dry-weather discharges, and leaching into the soil and groundwater. Excess nutrients in water can result in or contribute to low levels of oxygen in the water and toxic algae blooms, which can be harmful to aquatic life. Improperly managed manure can also result in emissions to the air of particles and gases, such as ammonia, hydrogen sulfide, and volatile organic compounds, which may also result in a number of potentially harmful environmental and human health effects.

Most agricultural activities are considered to be nonpoint sources of pollution because the pollution that occurs from these activities is in conjunction with soil erosion caused by water and surface runoff of rainfall or snowmelt from diffuse areas such as farms and rangeland. However, section 502(14) of the Clean Water Act specifically defines point sources of pollution to include CAFOs, which means that under the act, CAFOs that discharge into federally regulated waters are required to obtain a federal permit called a National Pollutant Discharge Elimination System (NPDES) permit. These permits generally allow a point source to discharge specified pollutants into federally regulated waters under specific limits and conditions. These permits are issued by EPA or a state agency authorized by EPA to implement the NPDES program for that state. Currently, 45 states are authorized to administer the NPDES permit program, and their programs must be at least as stringent as the federal

program.[7] In 1976, in accordance with the Clean Water Act's designation of CAFOs as point sources, EPA defined which poultry and livestock facilities constituted a CAFO and established permitting regulations for CAFOs. According to EPA regulations issued in 1976, to be considered a CAFO a facility must first be considered an animal feeding operation. Animal feeding operations are agricultural operations where the following conditions are met:

- animals are fed or maintained in a confined situation for a total of 45 days or more in any 12-month period, and
- crops, vegetation, forage growth, or post harvest residues are not sustained during normal growing seasons over any portion of the lot.

If an animal feeding operation met EPA's criteria and either met or exceeded minimum size thresholds based on the type of animals being raised, EPA considered the operation to be a CAFO. For example, an animal feeding operation would be considered a CAFO if it raised 1,000 or more beef cattle, 2,500 pigs weighing more than 55 pounds, or 125,000 chickens. In addition, EPA could designate an animal feeding operation of any size as a CAFO under certain circumstances. For example, if an animal feeding operation was a significant contributor of pollutants to federally regulated water, EPA could designate the operation as a CAFO. Appendix II lists the full text of EPA's current CAFO definition, including the size thresholds established for small, medium, and large CAFOs.

Under EPA's 1976 CAFO regulations, certain animal feeding operations did not require permits. These included (1) those animal feeding operations that only discharged during a 25-year, 24-hour storm event—which is the amount of rainfall during a 24-hour period that occurs on average once every 25 years or more and (2) chicken operations that use dry manure-handling systems—systems that do not use water to handle their waste. In addition, EPA generally did not regulate animal waste that was applied to cropland or pastureland.

In January 2003, we reported that although EPA believed that many animal feeding operations degrade water quality, it had placed little emphasis on its permit program and that exemptions in its regulations allowed as many as 60

[7]EPA has retained program authority for Alaska, Idaho, Massachusetts, New Hampshire, and New Mexico. Oklahoma has been authorized to issue permits for most sources but not for CAFOs.

percent of the largest operations to avoid obtaining permits.[8] In its response to our 2003 report, EPA acknowledged that the CAFO program was hampered by outdated regulations and incomplete attention by EPA and the states. EPA pointed out that it had revised its permitting regulations for CAFOs to eliminate the exemptions that allowed most animal feeding operations to avoid regulation. The revisions, issued in February 2003 and known as the 2003 CAFO rule, resulted, in part, from the settlement of a 1989 lawsuit by the Natural Resources Defense Council and Public Citizen, in which these groups alleged that EPA had failed to comply with the Clean Water Act. EPA's 2003 CAFO rule included the following key provisions:

- *Duty to apply*. All CAFOs were required to apply for an NPDES permit unless the permitting authority determined that the CAFO had no potential to discharge to federally regulated waters.

- *Expanded CAFO definitions to include all poultry operations and stand-alone operations raising immature animals.* The previous rule had applied only to poultry operations that used a liquid manure-handling system. The 2003 rule expanded the CAFO definition to all types of poultry operations, and EPA officials estimated that this revision could result in almost 2,200 additional poultry operations requiring a permit.

- *More stringent design standard for new facilities in the swine, poultry, and veal categories.* Under the previous rule, facilities were to be designed, constructed, and operated to contain runoff from a 25-year, 24-hour rainfall event; this continues to be the rule for existing facilities. For new facilities, the 2003 rule established a no-discharge standard that can be met if the facilities are designed, constructed, and operated to contain the runoff from a 100-year, 24-hour storm event.

- *Best management practices*. Operations would be required to implement best management practices for applying manure to cropland and for animal production areas. The rule required, among other things, specified setbacks from streams, vegetated buffers, depth markers in lagoons, and other impoundments for production areas to prevent or reduce pollution from the operation.

- *Nutrient management plans.* CAFO operations would be required to develop a plan for managing the nutrient content of animal manure as well

[8]GAO, *Livestock Agriculture: Increased EPA Oversight Will Improve Environmental Program for Concentrated Animal Feeding Operations*, GAO-03-285 (Washington, D.C.: Jan. 16, 2003).

as the wastewater resulting from CAFO operations, such as water used to flush manure from barns.

- *Compliance schedule.* The 2003 rule required newly defined CAFOs to apply for permits by April 2006 and existing CAFOs to develop and implement nutrient management plans by December 31, 2006.[9]

  According to EPA officials, the 2003 rule was expected to ultimately lead to better water quality because the revised regulations would extend coverage to more animal feeding operations that could potentially discharge and contaminate water bodies and subject these operations to periodic inspections.

Three laws provide EPA with certain authorities related to air emissions from animal feeding operations: the Clean Air Act,[10] the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), and the Emergency Planning and Community Right-to-Know Act of 1986 (EPCRA).[11] Although these laws provide EPA with authority related to air emissions from various sources, they do not expressly identify animal feeding operations as a regulated entity. Specifically:

- The Clean Air Act authorizes EPA to regulate stationary and mobile sources of air pollution and emphasizes controlling sources that emit more than threshold quantities of regulated pollutants. Livestock producers and other agricultural sources whose emissions meet or exceed specific statutory or regulatory thresholds are therefore subject to Clean Air Act requirements. Although EPA has authorized states and local governments to carry out certain portions of the act, EPA retains concurrent enforcement authority.

- Taken together, CERCLA and EPCRA require owners or operators of a facility to report to federal or state authorities the release of hazardous substances that meet or exceed their reportable quantities so as to alert federal, state, and local agencies, as well as the public, to the release of these substances. Section 103 of CERCLA requires that the person in charge of a facility notify the National Response Center of any non-permitted release of "hazardous

[9]In July 2007, EPA extended these deadlines to February 27, 2009.

[10]The Clean Air Act, 42 U.S.C. §§7401-7671q.

[11]CERCLA, Pub. L. No. 96-510, 94 Stat. 2767 (codified as amended at 42 U.S.C. §§9601-9675) and EPCRA, Pub. L. No. 99-499, Tit. III, 100 Stat. 1728 (codified as amended at 42 U.S.C. §§11001-11050).

substances" in a reportable quantity as soon as he or she has knowledge of that release. Section 304 of EPCRA requires that the owner or operator of a facility at which a hazardous chemical is produced, used, or stored give immediate notice of a release of any "extremely hazardous substance" to the community emergency coordinator. Among the reportable substances that could be released by livestock facilities are hydrogen sulfide and ammonia. The reportable quantity for each of these hazardous substances is 100 pounds in a 24-hour period. Under these acts, EPA can assess civil penalties for failure to report releases of hazardous substances or extremely hazardous substances that equal or exceed their reportable quantities—up to $32,500 per day or $32,500 per violation for first time offenders.

EPA is also working with USDA to address the impacts of animal feeding operations on air and water quality and public health. In 1998, EPA entered into a memorandum of understanding with USDA that calls for the agencies to coordinate on air quality issues relating to agriculture and share information. In addition, in 1999, the two agencies issued a unified national strategy aimed at having the owners and operators of animal feeding operations take actions to minimize water pollution from confinement facilities and land application of manure and in 2001 adopted an agreement to develop a process for working together constructively. To help minimize water pollution from animal feeding operations and meet EPA's regulatory requirements, USDA, through its Natural Resources Conservation Service, provides financial and technical assistance to CAFO operators in developing and implementing nutrient management plans.

The Number of Large Farms Raising Animals Has Increased, but Specific Data on CAFOs Are Not Available

Because no federal agency collects accurate and consistent data on the number, size, and location of CAFOs nationwide, it is difficult to determine precise trends in CAFOs over the last 30 years. According to USDA officials, the data USDA collects for large farms raising animals can be used as a proxy for estimating trends in CAFOs nationwide. Using these data, we determined that between 1982 and 2002, the number of large farms raising animals has increased sharply, from about 3,600 to almost 12,000. Moreover, EPA has compiled some data from its regions on the number of CAFOs that have been issued permits; however, these data are inconsistent and inaccurate. As a result, EPA does not have a systematic way of identifying and inspecting all of the CAFOs nationwide that have been issued permits.

Since 1982 the Number of Large Farms Raising Animals Has Increased as Has the Average Number of Animals on Farms

We found that the number of large farms raising animals for all animal types increased by 234 percent between 1982 and 2002. Table 1 shows the changes in the number of large farms by animal type for 1982 through 2002.

Table 1: Nationwide Trends in the Number of Large Farms Raising Animals for All Animal Types, 1982 through 2002

Type of animal farm	1982	1987	1992	1997	2002	Percentage change, 1982-2002
Beef cattle[a]	966	1,014	1,004	958	982	2
Dairy cow	541	712	1,009	1,445	1,939	258
Hog[b]	916	1,257	2,061	4,170	5,571	508
Layer	720	808	788	788	706	(2)
Broiler	173	357	737	1,331	2,227	1,187
Turkey	278	437	504	577	570	105
Total of all animal types[c]	**3,594**	**4,585**	**6,103**	**9,269**	**11,995**	**234**

Source: GAO analysis of USDA data.

Notes: The phrase "all animal types" refers to the following animals: beef cattle, dairy cows, hogs, layers, broilers, and turkeys.

The criteria for a large farm varied by animal type, consistent with EPA's CAFO thresholds, and represent the average number of animals on a farm per day.

[a]Beef cattle includes only cattle on feed, not grazing on pasture, and sold weighing 500 pounds or more.

[b]Hogs include swine of all sizes from birth to market size.

[c]The number of large farms for all animal types is the total of large farms for each animal type and may include some farms multiple times if they were considered large for more than one animal type.

As table 1 shows, large broiler and hog farms experienced the largest increase, with large farms raising broilers increasing by 1,187 percent and large farms raising hogs increasing by 508 percent. Large farms raising layers and large farms raising beef cattle remained relatively stable over these 20 years, while layer farms were the only farms that experienced an overall decrease in number over the period, declining by 2 percent. In contrast, while the number of large farms raising animals has increased, the number of all farm raising animals has decreased. Appendix III presents trends in the number of all farms raising animals, from 1982 to 2002.

Just as the number of large farms for almost all animal types increased between 1982 and 2002, so did the size of these farms as illustrated by the

median number of animals raised on each farm.[12] Table 2 shows the trends in the median number of animals raised on large farms for all animal types from 1982 through 2002.

Table 2: Median Number of Animals Raised on Large Farms, by Animal Type, 1982 through 2002

Animal type	1982	1987	1992	1997	2002	Percentage change, 1982-2002
Beef cattle[a]	2,820	2,950	2,919	3,308	3,424	21
Dairy cows	910	988	1,020	1,100	1,200	32
Hogs[b]	3,350	3,500	3,778	4,334	4,588	37
Layers	131,530	146,383	155,319	168,000	180,000	37
Broilers	154,830	168,593	159,840	161,820	159,840	3
Turkeys	80,000	79,500	81,000	79,697	80,491	1

Source: GAO's analysis of USDA data.

Note: We used the median number of animals raised on large farms to represent the average concentration of animals raised on large farms per day.

The criteria for a large farm varied by animal type, consistent with EPA's CAFO thresholds, and represent the average number of animals on a farm per day.

The median is the point above and below which half of the cases exist. For large animal farms, half of the farms of a particular animal type have more animals than the median farm and half have fewer animals. For example, in the table above, half of large layer farms in 2002 have more than 180,000 layers and half have less than 180,000 layers.

[a]Beef cattle includes only cattle on feed, not grazing on pasture, and sold weighing 500 pounds or more.

[b]Hogs include swine of all sizes from birth to market size.

The layer and hog sectors had the largest increases in the median number of animals raised per farm, both growing by 37 percent between 1982 and 2002. Specifically, for layers, large farms increased the number of birds they raised from 131,530 in 1982 to 180,000 in 2002 and for hogs, large farms increased the number of animals they raised from 3,350 in 1982 to 4,588 in 2002. In contrast, large farms that raised either broilers or turkeys only increased slightly in size with an overall increase of 3 and 1 percent, respectively, from 1982 to 2002.

[12]The median is the point above and below which half of the cases exist. For large farms that raise animals, half of the farms of a particular animal type have more animals than the median farm and half have fewer animals.

The increases in the number of large farms for almost all animal types, as well as the increases in the median number of animals raised on these farms, are also reflected in the percentage of animals raised on large farms as compared with animals raised on all farms. Specifically, the number of animals raised on large farms increased from over 257 million in 1982 to over 890 million in 2002—an increase of 246 percent. In contrast, the number of animals raised on all farms increased from over 1,145 million in 1982 to 2,072 million in 2002—an increase of 81 percent. This is particularly noteworthy because the number of animals raised on large farms only accounted for 22 percent of animals raised on all farms in 1982; yet, the number of animals raised on large farms accounted for 43 percent of animals raised on all farms in 2002. Table 3 shows the trends in the number of animals raised on large farms and the number of animals raised on all farms from 1982 to 2002.

Table 3: Nationwide Trends in the Number of Animals Raised on Large Farms as a Proportion of the Number of Animals Raised on All Farms, by Animal Type, 1982 and 2002

Animal type	Number of animals raised on all animal farms		Percent change, 1982-2002	Number of animals raised on large farms		Percent change, 1982-2002	The number of animals raised on large farms as a percentage of the number of animals raised on all animal farms	
	1982	2002		1982	2002		1982	2002
Beef cattle[a]	11,064,096	11,264,122	2	6,601,928	8,677,892	31	60	77
Dairy cows	10,849,880	9,103,959	(16)	632,583	3,183,086	403	6	35
Hogs[b]	45,944,318	66,318,763	44	4,176,477	47,789,951	1,044	9	72
Layers	386,638,856	420,742,205	9	160,005,126	304,500,225	90	41	72
Broilers	612,092,410	1,440,501,856	135	52,140,827	457,461,691	777	9	32
Turkeys	78,550,564	124,152,525	58	33,443,754	68,417,853	105	43	55
Total of all animal types[c]	**1,145,140,124**	**2,072,083,430**	**81**	**257,000,695**	**890,030,698**	**246**	**22**	**43**

Source: GAO analysis of USDA data.

Note: The phrase “all animal types” refers to the following animals: beef cattle, dairy cows, hogs, layers, broilers, and turkeys.

A farm was included in all farms, for a particular animal type, only if it had one or more animals of that type. For example, if a farm had broilers only, it would not be counted in all farms for other animal types. If a farm raised no animals of any type, then it would also not be included in all farms.

Reported percentages have been rounded to the nearest whole number but calculations involving percentages used non-rounded percentages.

[a]Beef cattle includes only cattle on feed, not grazing on pasture, and sold weighing 500 pounds or more.

[b]Hogs include swine of all sizes from birth to market size.

[c]The number of large farms for all animal types is the total number of large farms for each animal type and may include some farms multiple times if they were considered large for more than one animal type.

As table 3 shows, most of the beef cattle, hogs, and layers raised in the United States in 2002 were raised on large farms. Specifically, 77 percent of beef cattle and 72 percent of both hogs and layers were raised on large farms.

EPA Does Not Have a Systematic Means of Identifying Permitted CAFOs Because It Lacks Accurate Data

EPA does not have its own data collection process to determine the number, size, and location of CAFOs that have been issued permits nationwide. Since 2003, the agency has compiled quarterly estimates from its regions on the number of permits that have been issued to CAFOs. These data are developed by EPA's regional offices or originates with the state permitting authority. However, we determined that these data are inconsistent and inaccurate and do not provide EPA with the reliable data that it needs to identify and inspect permitted CAFOs nationwide. For example, according to EPA some uncertainty in the data exists because some states may be using general permits to cover more than one operation. In addition, EPA has not established adequate internal controls to ensure that the data are correctly reported. For example, officials from 17 states told us that data reported by EPA for their states were inaccurate. In one case, when we asked a state official for the number of CAFOs in his state, the official realized that the CAFO numbers reported by EPA's regional office were incorrect because of a clerical error, which resulted in some CAFO statistics for the state being doubled. After the state official discovered this error the state's data were corrected and resubmitted to EPA. Without a systematic and coordinated process for collecting and maintaining accurate and complete information on the number, size, and location of permitted CAFOs nationwide, EPA does not have the information it needs to effectively regulate these operations.

In commenting on a draft of this report, EPA stated that the information from permit files is available to EPA upon request; however, the information is currently not readily compiled in a national database. EPA is currently working with the states to develop and implement a new national data system to collect and record operation-specific information. As part of this effort, the agency plans to develop national requirements for data that should be collected and entered into the database by the states. According to EPA, it may require the states to provide data that identifies operations that have been issued or applied for a CAFO permit

as well as operations that should have applied for a permit based on an inspection or enforcement action.

Large Farms That Raise Animals Can Produce Thousands of Tons of Manure Each Year, and Regional Clustering of Farms Can Exacerbate Manure Management Problems

The amount of manure a large farm that raises animals can generate primarily depends on the types and numbers of animals raised on that farm, and the amount of manure produced can range from over 2,800 tons to more than 1.6 million tons a year. To further put this in perspective, the amount of manure produced by large farms that raise animals can exceed the amount of waste produced by some large U.S. cities. In addition, multiple large farms that raise animals may be located in a relatively small area, such as two or more adjacent counties, which raises additional concerns about the potential impacts of the manure produced, stored, and disposed of by these farms.

Table 4 shows the estimated number of animals and the typical amounts of manure produced each year, by type of animal, for three different sizes of large farms: (1) large farms that meet EPA's thresholds for each animal type, (2) large farms that raise the median number of animals according to our analysis of USDA farm census data, and (3) large farms that fell into the 75th percentile based on our analysis. As table 4 shows, a dairy farm that meets the minimum threshold of 700 dairy cows could produce almost 17,800 tons of manure a year; a median-sized dairy farm with 1,200 dairy cows could produce about 30,500 tons of manure a year; and a larger dairy farm with 1,900 dairy cows could produce almost 48,300 tons of manure a year.

Table 4: Estimated Typical Manure Production for Three Different Sizes of Large Farms That Raise Animals, 2002

Animal type	EPA's minimum thresholds for large CAFOs[a]	Estimated tons of manure produced annually by large CAFOs meeting EPA's minimum threshold	Median number of animals raised on large farms[b]	Estimated tons of manure produced annually by large farms that raised median number of animals	Number of animals raised on large farms in the 75th percentile[c]	Estimated tons of manure produced annually by large farms in the 75th percentile
Beef cattle[d]	1,000	11,690	3,424	40,025	10,000	116,895
Dairy cows	700	17,793	1,200	30,502	1,900	48,295
Hogs[e]	2,500	5,100	4,588	9,360	7,700	15,708
Layers	82,000	2,843	180,000	6,242	400,000	13,870
Broilers	125,000	4,125	159,840	5,275	195,383	6,448
Turkeys	55,000	3,633	80,491	5,317	124,500	7,719

Source: GAO analyses based on EPA CAFO definitions, USDA data, and standards for manure production cited by the American Society of Agricultural and Biological Engineers, "Manure Production and Characteristics," March 2005.

Note: The amounts of manure reported are estimates. The actual amount of manure produced by an animal will vary based on, among other things, feeding programs, feeds used, climatic conditions, production techniques, and animal genetics.

EPA reports its minimum thresholds for large CAFOs in terms of inventory data for all the animal types included in table 4. To be able to compare the annual manure estimates for EPA's thresholds, the median, and 75th percentile animal counts, we used USDA data on animal sales, inventories, and production cycles, and adjusted these to determine typical inventory during a year.

The criteria for a large farm varied by animal type, consistent with EPA's CAFO thresholds, and represent the average number of animals on a farm per day.

[a]This category captures the minimum inventory threshold that an animal feeding operation must meet to be designated as a large CAFO by EPA and the Clean Water Act.

[b]This column represents the median-sized animal farm in 2002, for each animal type. The median is the point above and below which half of the cases exist. For large farms that raise animals, half of the farms of a particular animal type have more animals than the median farm and half have fewer animals. For example, in table 4, half of large layer farms have more than 180,000 layers and half have less than 180,000 layers.

[c]This column represents the farms ranked in the 75th percentile for the amount of animals raised per farm in 2002, for each animal type. The 75th percentile is the point where 25 percent of the cases are larger and 75 percent are smaller. For large farms that raise animals, the 75th percentile indicates the larger of the large farms. The 75th percentile gives a more complete picture of how big a large farm can be. For example, for beef cattle the 75th percentile farm is about 3 times larger than the median-size farm and 25 percent of the beef cattle farms are larger than 10,000 cattle.

[d]Beef cattle includes only cattle on feed, not grazing on pasture, and sold weighing 500 pounds or more. The beef cattle manure estimates are for cattle fed from about 700 pounds to about 1,200 pounds.

[e]Hogs include swine of all sizes from birth to market size. The hog manure estimates are for hogs fed from about 27 pounds to about 260 pounds.

Additionally, individual large farms that raise animals can generate as much waste as certain U.S. cities.[13] For example, a dairy farm meeting EPA's large CAFO threshold of 700 dairy cows can create about 17,800 tons of manure annually, which is more than the about 16,000 tons of sanitary waste per year generated by the almost 24,000 residents of Lake Tahoe, California. Likewise, a median-sized beef cattle operation with 3,423 head of beef cattle can produce more than 40,000 tons of manure annually, which is more than the almost 38,900 tons of sanitary waste per year generated by the nearly 57,000 residents of Galveston, Texas. Similarly, some larger farms can produce more waste than some large U.S. cities. For example, a large farm with 800,000 hogs could produce over 1.6 million tons of manure per year, which is one and a half times more than the annual sanitary waste produced by the city of Philadelphia, Pennsylvania—about 1 million tons—with a population of almost 1.5

[13]Human sanitary waste includes urine and feces only; it does not include any other household sewage wastes such as water from washing dishes or clothes or water used for showers or flushing.

million.[14] Moreover, a beef cattle farm with 140,000 head of cattle could produce over 1.6 million tons of manure annually, more than the almost 1.4 million tons of sanitary waste generated by the more than 2 million residents of Houston, Texas.[15]

Although manure is considered a valuable commodity, especially in states with large amounts of farmland, like Iowa, where it is used as fertilizer for field crops, in some parts of the country, large farms that raise animals are clustered in a few contiguous counties. This collocation of large farms that raise animals has resulted in a separation of animal production from crop production because many of these operations purchase feed rather than grow it on adjacent cropland. As a result, there is much less cropland on which the manure can be applied as fertilizer. This clustering of large farms that raise animals has occurred because of structural changes in the farming sector. According to agricultural experts and USDA officials, the overall decrease in the number of farms and increase in the average number of animals raised on a farm may have occurred because these operations wanted to achieve economies of size. To achieve these economies, operators often need significant amounts of capital, which they obtain through production contracts with large processing companies.

A USDA report identified this concern as early as 2000 when it found that between 1982 and 1997 as livestock production became more spatially concentrated that when manure was applied to cropland, crops were not fully using the nutrients in manure and this could result in ground and surface water pollution from the excess nutrients.[16] According to the report, the number of counties where farms produced more manure nutrients, primarily nitrogen and phosphorus, than could be applied to the land without accumulating nutrients in the soil increased. Specifically, the numbers of counties with excess manure nitrogen increased by 103 percent, from 36 counties in 1982 to 73 counties in 1997. Similarly, the number of counties with excess manure phosphorous increased by 57 percent, from 102 counties in 1982 to 160 counties in 1997. As a result, the potential for runoff and leaching of these nutrients from the soil was high, and water quality could be impaired, according to USDA. Agricultural

[14]EPA officials told us that the agency has identified a hog farm of this size.

[15]EPA officials told us that the agency has identified a cattle farm of this size.

[16]R. L. Kellogg, C.H. Lander, D. C. Moffitt, and N. Gollehon. *Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States*. (Washington, D.C.: December 2000).

experts and government officials who we spoke to during our review echoed the findings of USDA's report and provided several examples of more recent clustering trends that have resulted in degraded water quality, including the following:

- As a result of adopting the poultry industry's approach of developing close ties between producers and processors,[17] North Carolina experienced a rapid growth in the number of hog CAFOs, primarily in five contiguous counties. Based on our analysis of 2002 USDA data, we estimated that the hog population of the five North Carolina counties was more than 7.5 million hogs in 2002 and that hog operations in these counties produced as much as 15.5 million tons of manure that year. Figure 1 shows the geographic concentration of hog farms in North Carolina in 2002.

Figure 1: Geographic Concentration of Hogs in Five Contiguous North Carolina Counties, 2002

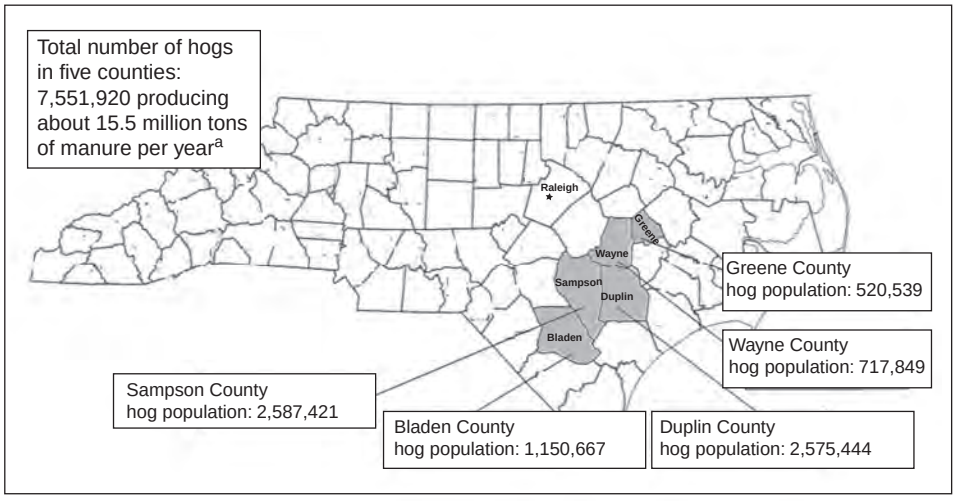

Source: GAO analysis of USDA data.

Note: Hog populations are the number of hogs on a typical day per county in 2002. The number of hogs was estimated by dividing hogs-to-market sales by two production cycles and adjusting for inventory on hand at the end of the year.

[17]GAO, *Animal Agriculture: Information on Waste Management and Water Quality Issues*, GAO/RCED-95-200BR (Washington, D.C.: June 1995).

[a]This is the amount of manure that would be produced if all of these hogs were in the feeder-finish production phase where they start at about 27 pounds and are marketed at about 260 pounds. The amount of manure would be less if a large percentage of these hogs were nursery pigs (up to about 27 pounds). Although we were unable to determine what percentage of hogs in these counties was not in the feeder-finish production cycle, we adjusted our estimates based on 1997 USDA data that showed that 25 percent of swine sold were not in the feeder-finish production cycle.

According to North Carolina agricultural experts, excessive manure production has contributed to the contamination of some of the surface and well water in these counties and the surrounding areas. According to these experts, this contamination may have occurred because the hog farms are attempting to dispose of excess manure but have little available cropland that can effectively use it. According to state officials, partly out of concern for the potential contamination of waterways and surface water from manure, in 1997, North Carolina placed a moratorium on new swine farms and open manure lagoons, which was subsequently continued through 2007. While the moratorium included exceptions that could allow a new swine farm to begin operations in this area, according to state officials, the requirements for these exceptions are so stringent that they effectively have prevented the construction of new swine operations or the expansion of existing operations.

- Similarly, a California water official told us that the geographic clustering of large farms that raise animals is causing concern in his state as well. Our analysis of USDA data shows that in 2002 two counties in the San Joaquin Valley in California had 535,443 dairy cows that produced about 13.6 million tons of manure that year. According to the official, because of the limited flow of water through the Valley, once pollutants reach the water, they do not dissipate, resulting in a long-term accumulation of these pollutants.

- Regional clustering is also occurring in Arkansas. Two counties in northwest Arkansas, located on the Arkansas-Oklahoma border, raised 14,264,828 broiler chickens that produced over 471,000 tons of manure that year. According to EPA Region 6 officials, the Arkansas-Oklahoma border is an area of concern due to the number of poultry operations (primarily broilers, but also turkeys and layers) within this area. Furthermore, region 6 officials identified numerous water bodies in northwest Arkansas and northeast Oklahoma that have been impaired by manure from animal feeding operations and identified these locations as "areas of general ground water concern."

  While USDA officials acknowledge that regional clustering of large animal feeding operations has occurred, they told us that they believe the nutrient management plans that they have helped livestock and poultry producers develop and implement have reduced the likelihood that pollutants from manure are entering ground and surface water. They also believe that as a

result of new technologies such as calibrated manure spreaders, improved animal feeds, and systems that convert manure into electricity, large animal feeding operations are able to more effectively use the manure being generated. However, USDA could not provide information on the extent to which these techniques are being utilized or their effectiveness in reducing water pollution from animal waste.

Studies Have Identified Impacts of Pollutants from Animal Waste, but EPA Has Not Assessed the Extent of Such Impacts

Since 2002, at least 68 government-sponsored or peer-reviewed studies have been completed on air and water pollutants from animal feeding operations. Of these 68 studies, 15 have directly linked pollutants from animal waste generated by these operations to specific health or environmental impacts, 7 have found no impacts, and 12 have made indirect linkages between these pollutants and health and environmental impacts. In addition, 34 of the studies have focused on measuring the amount of certain pollutants emitted by animal feeding operations that are known to cause human health or environmental impacts at certain concentrations. Appendix IV presents information, including the sponsor, the pollutants, and impacts, identified for each of the 68 studies we reviewed.[18] Although EPA is aware of the potential impacts of air and water pollutants from animal feeding operations, it lacks data on the number of animal feeding operations and the amount of discharges actually occurring. Without such data, according to EPA officials, the agency is unable to assess the extent to which these pollutants are harming human health and the environment.

Some Recent Studies Directly Link Pollutants from Animal Waste to Health and Environmental Impacts

Of the 15 studies completed since 2002 that we reviewed that directly link pollutants from animal waste to human health or environmental impacts, 8 focused on water pollutants and 7 on air pollutants. Academic experts and industry and EPA officials told us that only a few studies directly link CAFOs with health or environmental impacts because the same pollutants that CAFOs discharge also often come from other sources including smaller livestock operations; row crops using commercial fertilizers; and wastes from humans, municipalities, or wildlife, making it difficult to distinguish the actual source of pollution. Table 5 shows the eight government-sponsored or peer-reviewed studies completed since 2002 that found direct links between water pollutants from animal waste and impacts on human health or the environment.

[18]Sponsors are agencies, organizations, or universities responsible for conducting the study and not necessarily the group funding the study.

Table 5: Studies Completed Since 2002 Linking Water Pollutants from Animal Feeding Operations with Impacts on Human Health or the Environment

Study title	Sponsor[a]	Pollutant(s) studied	Impact identified
Effects of the Feedlot Contaminant 17α-Trenbolone on Reproductive Endocrinology of the Fathead Minnow	EPA	Hormones	Adverse effects to reproductive system of aquatic life
Endocrine-Disrupting Effects of Cattle Feedlot Effluent on an Aquatic Sentinel Species, the Fathead Minnow	University of Florida, St. Mary's College of Maryland, University of Nebraska, EPA, Tufts University	Hormones	Adverse effects to reproductive system of aquatic life
Effects of the Androgenic Growth Promoter 17ß-Trenbolone on Fecundity and Reproductive Endocrinology of the Fathead Minnow	EPA, University of Minnesota	Hormones	Adverse effects to reproductive system of aquatic life
In Vitro and in Vivo Effects of 17ß-Trenbolone: A Feedlot Effluent Contaminant	EPA	Hormones	Reproductive malformations in laboratory rats and human cells
Characterization of Waterborne Outbreak-associated *Campylobacter jejuni*, Walkerton, Ontario	Health Canada	Bacteria	Gastrointestinal illness and death in humans
Impact of Animal Waste Application on Runoff Water Quality in Field Experimental Plots	Jackson State University, National Institutes of Health-Center for Environmental Health, Louisiana State University	Nutrients, bacteria	Water degradation
Nutrient Loading Patterns on an Agriculturally Impacted Stream System in Huntingdon County Pennsylvania over Three Summers	Juniata College	Nutrients	Water degradation; unable to sustain aquatic life
Concentrated Animal Feeding Operations, Row Crops, and Their Relationship to Nitrate in Eastern Iowa Rivers	University of Iowa	Nutrients	Water degradation

Source: GAO's analysis of identified studies.

[a]Sponsor refers to the organization under whose auspices the research was conducted or with whom the primary researchers were affiliated.

As table 5 shows, EPA sponsored four of the water quality studies that identified reproductive alterations in aquatic species caused by hormones in discharges from animal feeding operations. Two of these studies found that hormones from these discharges caused a significant decline in the fertility of female fish in nearby water bodies. Similarly, three other studies found water bodies impaired by higher nitrogen and phosphorus levels from manure runoff from animal feeding operations. For example, the study by Juniata College found that the runoff resulted in nutrient

concentrations in the water that were too high to sustain fish populations. Only one of the eight water pollutant studies linked pollutants from animal feeding operations to human health effects. This study, conducted by Health Canada, directly linked water discharges from a cattle farm to bacteria found in nearby waters. These bacteria, which included *Campylobacter* and *E. coli*, caused gastrointestinal illnesses in more than 2,300 residents and 7 deaths in a nearby community.

Table 6 shows the seven government-sponsored or peer-reviewed studies completed since 2002 that we reviewed that directly link air pollutants from animal feeding operations with human health effects.

Table 6: Studies Completed Since 2002 Directly Linking Air Pollutants from Animal Feeding Operations to Impacts on Human Health

Study title	Sponsor[a]	Pollutant(s) studied	Impact identified
Feedlot Dust Stimulation of Interleukin-6 and 8 Requires Protein Kinase C-Epsilon Human Bronchial Epithelial Cells	Nebraska Medical Center, Department of Veterans Affairs Medical Center, Texas A&M	Dust	Respiratory inflammation
Farm Residence and Exposures and the Risk of Allergic Diseases In New Zealand Children	University of Otago, New Zealand	Dust	Greater prevalence of allergies in children living on farms
Exhaled Nitric Oxide and Bronchial Responsiveness in Healthy Subjects Exposed to Organic Dust	National Institute of Environmental Medicine, Sweden	Dust	Respiratory inflammation (occupational)
Hog Barn Dust Extract Augments Lymphocyte Adhesion to Human Airway Epithelial Cells	Department of Veterans Affairs Medical Center, University of Nebraska Medical Center	Dust	Respiratory inflammation (occupational)
Hog Barn Dust Extract Stimulates IL-8 And IL-6 Release in Human Bronchial Epithelial Cells Via PKC Activation	Department of Veterans Affairs Medical Center, University of Nebraska Medical Center	Dust	Respiratory inflammation (occupational)
Experimental Human Exposure to Inhaled Grain Dust and Ammonia: Towards a Model of Concentrated Animal Feeding Operations	University of Iowa	Dust, ammonia	Tightening of airway in asthmatics (occupational)
Symptomatic Effects of Exposure to Diluted Air Sampled from a Swine Confinement Atmosphere on Healthy Human Subjects	Duke University	Hydrogen sulfide, ammonia, endotoxin, dust, odor	Headaches, eye irritation, nausea

Source: GAO's analysis of identified studies.

[a]Sponsor refers to the organization under whose auspices the research was conducted or with whom the primary researchers were affiliated.

As table 6 shows, six of these studies identified airway inflammation or wheezing in people working at or living on an animal feeding operation.

For example, the studies conducted by the Department of Veterans Affairs show that the dust of hog confinement facilities induces airway inflammation in workers. The seventh study, completed by Duke University in a laboratory setting, exposed healthy volunteers to air emissions consistent with those that would occur downwind from animal feeding operations. These volunteers reported headaches, eye irritation, and nausea following this exposure. According to experts who we spoke with, the effects of air emissions from animal feeding operations on workers are well known, but the impacts of these emissions on nearby communities are still uncertain, and more research is needed to identify these impacts. Additionally, experts said it is difficult to determine which specific contaminant or mixture of contaminants causes particular health symptoms. For example, while hydrogen sulfide causes respiratory and other health problems, other contaminants emitted from animal feeding operations, such as ammonia, can also cause similar symptoms.

Some Studies Found No Links between Pollutants from Animal Feeding Operations and Harm to Human Health or the Environment

We found seven government-sponsored or peer-reviewed studies that have been completed since 2002 that found no impact on human health or the environment from pollutants released by animal feeding operations. These seven studies are shown in table 7.

Table 7: Studies Completed Since 2002 Finding No Links between Pollutants from Animal Feeding Operations and Impacts on Human Health or the Environment

Study title	Sponsor[a]	Pollutant(s) studied	Finding(s)
Prevalence of *Escherichia coli O157:H7* Bacterial Infections Associated with the Use of Animal Wastes in Louisiana for the Period 1996-2004	Grambling State University, Louisiana State University, Jackson State University	*Escherichia coli*	No clear indication that any cases of *E. coli* infection are related to animal waste
Prevalence of Selected Bacterial Infections Associated with the Use of Animal Waste in Louisiana	Jackson State University, Louisiana State University	*Escherichia coli*	No clear indication that any cases of *E. coli* infection are related to animal waste
Impacts of Swine Manure Pits on Groundwater Quality	Illinois State Geological Survey, University of Illinois, Illinois Department of Agriculture	Chloride, ammonium, phosphate, potassium, nitrate, bacteria	Manure seepage from swine facilities has had limited impacts on groundwater

Study title	Sponsor[a]	Pollutant(s) studied	Finding(s)
Ground-Water Quality and Effects of Poultry Confined Animal Feeding Operations on Shallow Ground Water, Upper Shoal Creek Basin, Southwest Missouri, 2000	U.S. Geological Survey	Nutrients, bacteria	The results do not indicate that poultry CAFOs are affecting the shallow ground water with respect to nutrients and fecal bacteria
Environmental Exposure to Endotoxin and Its Relation to Asthma in School-Age Children	Institute of Social and Preventive Medicine (Switzerland), Children's Hospital (Austria), Philipps University (Germany), Ruhr University (Germany), University Children's Hospital (Switzerland), University of Munich (Germany	Dust	Decreased risk of hay fever, asthma, and wheeze in children exposed to high levels of endotoxin in dust
Ecological Associations between Asthma Prevalence and Potential Exposure to Farming	University of North Carolina	Farm air	Farm exposures may be protective against childhood asthma.
Atmospheric Pollutants and Trace Gases: Atmospheric Ammonia, Volatile Fatty Acids, and Other Odorants near Beef Feedlots	Research Centre, Agriculture and Agri-Food Canada	Ammonia, odor, organic compounds, dust	Odorants from feedlots were effectively dispersed. Emitted ammonia was deposited to the soil downwind.

Source: GAO's analysis of identified studies.

[a]Sponsor refers to the organization under whose auspices the research was conducted or with whom the primary researchers were affiliated.

As table 7 shows, the results of a U.S. Geological Survey study did not indicate that poultry animal feeding operations were causing an increase of nutrient concentrations and fecal bacteria in groundwater. Similarly, another study by Agriculture and Agri-Food Canada found that odorants, including ammonia and dust emitted by animal feeding operations, never exceeded the established irritation threshold. According to EPA and academic experts we spoke with, the concentrations of air pollutants and water pollutants emitted by animal feeding operations can vary, which may account for the differences in the findings of these studies. These variations may be the result of numerous factors, including the type of animals being raised, feed being used, and manure management system being employed, as well as the climate and time of day when the emissions occur.

Some Recent Studies Indirectly Link Pollutants from Animal Feeding Operations with Human Health and Environmental Impacts

We also identified 12 government-sponsored or peer-reviewed studies completed since 2002 that indirectly link pollutants from animal feeding operations to human health or environmental impacts. While these studies found that animal feeding operations were the likely cause of human health or environmental impacts occurring in areas near the operations, they could not conclusively link waste from animal feeding operations to the impacts, often because other sources of pollutants could also be contributing. For example, 5 of these 12 studies found an increased incidence of asthma or respiratory problems in people living or attending school near animal feeding operations, compared with a control group. These studies hypothesized that the pollutants emitted from animal feeding operations were likely the cause of the increased incidence of asthma, but some of these studies acknowledged that pollutants from other sources could also be contributing to the increased incidence. Table 8 lists the 12 studies that have been completed since 2002 that made indirect links between emissions from animal feeding operations and human health and environmental impacts.

Table 8: Studies Completed Since 2002 That Found an Indirect Link between Pollutants from Animal Feeding Operations and Human Health or Environmental Impacts

Study title	Sponsor[a]	Impact(s)
Associations between Indicators of Livestock Farming Intensity and Incidence of Human Shiga Toxin-Producing *Escherichia coli* Infection	University of Guelph; Université de Montréal; Centre for Infectious Disease Prevention and Control – Health Canada	The strongest associations with human *Escherichia coli* infection were the ratio of beef cattle to human population and the application of manure to the surface of agricultural land by a solid spreader and by a liquid spreader.
The Potential Impact of Flooding on Confined Animal Feeding Operations in Eastern North Carolina	University of North Carolina	Flood events have a significant potential to degrade environmental health because of dispersion of wastes from industrial animal operations in areas with vulnerable populations.
Odor from Industrial Hog Farming Operations and Mucosal Immune Function in Neighbors	University of North Carolina, Duke University	This study suggests that malodor from industrial swine operations can affect the secretory immune system, although the reduced levels reported are still within normal range.
Environmental Stressors, Perceived Control, and Health: The Case of Residents Near Large-Scale Hog Farms in Eastern North Carolina	University of North Carolina Wilmington	Residents living near large-scale hog farms in eastern North Carolina report symptoms related to respiratory, sinus, and nausea problems.

Study title	Sponsor[a]	Impact(s)
Asthma Prevalence and Morbidity Among Rural Iowa Schoolchildren	University of Iowa, EPA	Among children who wheeze, farm and nonfarm children were equally likely to have been given a diagnosis of asthma and had comparable morbidity. Asthma in rural schoolchildren was comparable to schoolchildren in large cities.
Occupational Asthma in Newly Employed Workers in Intensive Swine Confinement Facilities	Institute of Agricultural Rural and Environmental Health, University of Saskatchewan, Laval University	Newly employed workers in intensive swine confinement facilities reported development of acute onset of wheezing and cough suggestive of asthma.
Asthma and Farm Exposures in a Cohort of Rural Iowa Children	University of Iowa, EPA, Colorado State University, Kaiser Permanente	There was a high prevalence of asthma health outcome among farm children living on farms that raise swine and raise swine and add antibiotics.
Asthma Symptoms among Adolescents Who Attend Public Schools That Are Located Near Confined Swine Feeding Operations	University of North Carolina, RTI International	Estimated exposure to airborne pollution from confined swine feeding operations is associated with adolescents' wheezing symptoms.
Airway Responses of Healthy Farmers and Nonfarmers to Exposure in a Swine Confinement Building	National Institute of Environmental Medicine (Sweden), National Institute for Working Life (Sweden)	Altered lung function and bronchial responsiveness was found in nonfarming subjects. Only minor alterations were found in the farmers.
Environmental Exposure to Confined Animal Feeding Operations and Respiratory Health of Neighboring Residents	Institute for Occupational and Environmental Medicine (Germany), National Research Centre for Environment and Health (Germany), Boston University, Municipal Health Service Amsterdam	Respiratory disease was found among residents living near confined animal feeding operations.
School Proximity to Concentrated Animal Feeding Operations and Prevalence of Asthma in Students	University of Iowa Carver College of Medicine, University of Iceland	Children in the study school, located one-half mile from a CAFO, had a significantly increased prevalence of physician-diagnosed asthma.
Lung Function and Farm Size Predict Healthy Worker Effect in Swine Farmers	University of Saskatchewan (Canada)	Some swine workers are less affected by swine air and continue in the profession. Other workers are more affected.

Source: GAO's analysis of identified studies.

[a]Sponsor refers to the organization under whose auspices the research was conducted or with whom the primary researchers were affiliated.

Many Recent Studies Have Measured the Level of Pollutants Emitted by Animal Feeding Operations

Thirty-four government-sponsored or peer-reviewed studies completed since 2002 have focused on measuring the amounts of water or air pollutants emitted by animal feeding operations that are known to cause harm to humans or the environment. Specifically:

- Nineteen of the 34 studies focused on water pollutants. Four studies found increased levels of phosphorus or nitrogen in surface water and groundwater near animal feeding operations. According to EPA, excessive amounts of these nutrients can deplete oxygen in water, which could result in fish deaths, reduced aquatic diversity, and illness in infants. The other 15 studies measured water pollutants such as pathogens, hormones, and antibiotics.

- Fifteen of the 34 studies focused on measuring air emissions from animal feeding operations. Seven of the 15 studies found high levels of ammonia surrounding animal feeding operations. EPA considers ammonia a hazardous substance that may harm human health or the environment, and that must be reported when emissions exceed its reportable quantity. The other eight studies measured the levels of other air pollutants, such as hydrogen sulfide, particulate matter, and carbon dioxide.

Appendix IV provides additional details about each of the 34 studies.

EPA Has Not Yet Assessed the Extent of the Human Health and Environmental Impacts of Pollutants from Animal Feeding Operations

While EPA recognizes the potential impacts that water and air pollutants from animal feeding operations can have on human health and the environment, it lacks the data necessary to assess how widespread these impacts are and has limited plans to collect the data it needs.

Water quality. EPA has long recognized the impacts of pollution from CAFOs on water quality. For example, almost a decade ago, in its 1998 study on feedlot point sources, EPA documented environmental impacts that may be attributed to these operations.[19] This report identified pollutants from animal feeding operations and listed about 300 spills and runoff events that were attributable to animal feeding operations from 1985 through 1997. More recently when developing the 2003 CAFO rule, EPA documented the potential water quality impacts from CAFOs. It reported that contaminants in manure will have an impact on water quality if significant amounts reach surface water or groundwaters. Moreover, as discussed above, numerous studies completed since 2002 have provided

[19]EPA, Office of Water, *Feedlots Point Source Category Study* (Washington, D.C.: 1999).

additional information on the direct and indirect impacts of discharges from animal feeding operations on human health and the environment, and many more studies have been completed that have measured the amounts of pollutants being discharged.

EPA officials we spoke with acknowledged that the potential human health and environmental impacts of some CAFO water pollutants, such as nitrogen, phosphorus, and pathogens, are well known. They told us that the agency has recently focused its research efforts on obtaining more information on emerging pollutants, such as hormones and antibiotics, and on how the concentrations of nutrients and pathogens differ among the various types of animal feeding operations. However, these officials also stated that EPA does not have data on the number and location of CAFOs nationwide and the amount of discharges from these operations. Without this information and data on how pollutant concentrations vary by type of operation, it is difficult to estimate the actual discharges occurring and to assess the extent to which CAFOs may be contributing to water pollution. According to agency officials, because of a lack of resources, the agency currently has no plans for a national study to collect information on CAFO water discharges. However, the agency has recently taken the following three steps that may help gather additional data on CAFO pollutants that affect water quality:

- EPA has begun research to determine (1) how the concentration of pathogens and nutrients vary in manure on the basis of certain characteristics, such as animal type and animal feed, and (2) how manure management techniques can reduce the amount of pathogens and nutrients in runoff.

- EPA has set a long-term research goal, as part of its *Multi-Year Plan for Endocrine Disruptors (FY2007-2013)*, to characterize the magnitude and extent of the impact of hormones released by CAFOs and to determine the impact of management strategies on the fate and effects of hormones. At the time of our review, according to an EPA official, the agency had only limited preliminary findings because it has just recently begun this work.

- EPA and the U.S. Geological Survey have discussed a joint project to identify (1) the location of CAFOs nationwide and (2) those watersheds where many CAFOs might be located. According to EPA officials, this project is still in the discussion phase.

Air quality. More recently, EPA has recognized concerns about the possible health impacts from air emissions produced by animal feeding operations. Prompted in part by public concern, EPA and USDA

commissioned a 2003 study by the National Academy of Sciences (NAS) to evaluate the scientific information needed to support the regulation of air emissions from animal feeding operations.[20] The NAS report identified several air pollutants from animal feeding operations and their potential impacts. For example, the study identified ammonia and hydrogen sulfide as two air pollutants emitted from animal feeding operations that can impair human health. According to the study, ammonia can cause eye, nose, and throat irritation at certain concentrations, and hydrogen sulfide can cause respiratory distress. While such effects are known to occur, the study noted that additional research is warranted to determine if air emissions from animal feeding operations are occurring in high enough concentrations to cause these effects. The NAS report also concluded that in order to determine the human health and environmental effects of air emissions from animal feeding operations, EPA and USDA would first need to obtain accurate estimates of emissions and their concentrations from animal feeding operations with varying characteristics, such as animal type, animal feed, manure management techniques, and climate.

Since the NAS report was issued, EPA has conducted one hypothetical assessment of the impacts of air emissions from animal feeding operations. In 2004, EPA updated a preliminary analysis to estimate the levels of emissions of ammonia and hydrogen sulfide that occur downwind from a manure lagoon and that could pose a risk to human health. EPA found that ammonia would not reach levels associated with respiratory irritation if emitted at the reportable quantity of 100 pounds per day.[21] On the other hand, the agency found that hydrogen sulfide could cause respiratory irritation and central nervous system effects about one mile downwind if emitted at the reportable quantity of 100 pounds per day.[22] EPA officials who conducted this analysis told us that there have been no documented cases of hydrogen sulfide emissions from animal feeding operations exceeding the reportable quantity. However, other officials noted that the agency does not know exactly what type of species and what size of operations are likely to have emissions above the reportable quantity, and, as noted in the NAS report, accurate measurements of the

[20]National Academies of Sciences, *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs* (Washington, D.C.: National Academies Press, 2003).

[21]Section 302.4 of title 40 of the Code of Federal Regulations notes that the reportable quantity for ammonia is 100 pounds per 24 hours.

[22]Section 302.4 of title 40 of the Code of Federal Regulations notes that the reportable quantity for hydrogen sulfide is 100 pounds per 24 hours.

air pollutants being emitted by animal feeding operations are currently not known.

In 2007, a national air emissions monitoring study to collect data on air emissions from animal feeding operations was undertaken as part of a series of consent agreements EPA entered into with individual animal feeding operations. This study, funded by industry and approved by EPA, is intended to help the agency determine how to measure and quantify air emissions from animal feeding operations. The data collected will in turn be used to estimate air emissions from animal feeding operations with varying characteristics, and, according to EPA officials, it is only the first step in a long-term effort to accurately quantify air emissions from animal feeding operations. According to agency officials, until EPA can determine the actual level of emissions occurring, it will be unable to assess the extent to which these emissions are affecting human health and the environment. Progress in conducting the national air emissions monitoring study is discussed in greater detail in the following section.

It Is Unclear If EPA's Efforts to Develop Air Emissions Protocols for Animal Feeding Operations Will Be Effective and How EPA Intends to Regulate These Emissions in the Future

The National Air Emissions Monitoring Study—a 2-year effort to collect data on air emissions from animal feeding operations—is intended to provide a scientific basis for estimating air emissions from these operations. The results of this study were intended to help EPA develop protocols that will allow it to determine which operations do not comply with applicable federal laws. As currently structured, however, the study may not provide the quantity and quality of data needed for developing appropriate methods for estimating emissions. Furthermore, it is uncertain if and when EPA will develop a process-based model that considers the interaction and implications of all sources of emissions at an animal feeding operation. Also, other more recent decisions suggest that the agency has not yet determined how it intends to regulate air emissions from animal feeding operations. In the absence of federal guidance on how to regulate air emissions from animal feeding operations, a few states have developed their own regulations.

A National Air Emissions Monitoring Study Has Begun, but the Study May Not Provide the Data EPA Needs to Develop Air Emissions Protocols

According to EPA, although it has the authority to require animal feeding operations to monitor their emissions and come into compliance with the Clean Air Act on a case-by-case basis, this approach has proven to be time and labor intensive. As an alternative to the case-by-case approach, in January 2005, EPA offered animal feeding operations an opportunity to sign a voluntary consent agreement and final order, known as the Air Compliance Agreement. To participate in the agreement, animal feeding operations were required to take the following actions:

- Pay a civil penalty ranging from $200 to $1,000 per animal feeding operation, depending on the number of animals at the operation and the number of operations that each participant signed up.[23]
- Pay up to $2,500 per farm to help fund a nationwide emissions monitoring study and make their facilities available as a monitoring site for emissions testing.
- Once emission protocols are published, apply for all applicable air permits and comply with permit conditions, if deemed necessary.
- Once emission protocols are published, report any releases of ammonia and hydrogen sulfide above the threshold levels established by CERCLA and EPCRA.[24, 25]

[23]The total penalty is capped at $10,000 for a participant having 10 or fewer farms to $100,000 for a participant having over 200 farms.

[24]Since announcing the Air Compliance Agreement, EPA has proposed exempting such releases from the CERCLA and EPCRA reporting requirements. The exemption, proposed in December 2007, has not been finalized.

[25]Any farm more than 10 times larger than EPA's established size thresholds for CAFOs must, within 120 days of receiving an executed copy of the agreement, provide the National Response Center with a written statement noting the facility's location, estimating air emissions of ammonia, and stating that it will notify the Center of reportable releases when emission rates are determined by the monitoring study.

In return for meeting these requirements, EPA agreed not to sue participating animal feeding operations for certain past violations or violations occurring during the emissions monitoring study.[26]

Almost 13,900 animal feeding operations were approved for participation in the agreement, representing the egg, broiler chicken, dairy, and swine industries. Some turkey operations volunteered but were not approved because there were too few operations to fund a monitoring site, and the beef cattle industry chose not to participate. EPA collected a total of $2.8 million in civil penalties from participating animal feeding operations and deposited these funds into the U.S. Treasury. An additional $14.8 million was collected by a nonprofit, industry-established organization to fund the national air emissions monitoring study. Industry groups representing the participating operations provided the funding for the study as was called for under the agreement. Table 9 shows the level of participation by type of operation and the amount of funding provided by different industry groups for the national air emissions monitoring study.

Table 9: Number of Participants in the Air Compliance Agreement, Funding Provided by Animal Type, and Source of the Funding for the National Air Emissions Monitoring Study

(Dollars in millions)

	Air Compliance Agreement		National Air Emissions Monitoring Study	
Animal type	Number of participants	Number of animal feeding operations	Funding provided	Funding source
Swine	1,878	4,865	$6.0	National Pork Board
Dairy	474	573	5.0	National Milk Producers Council
Layers	218	2,693	2.8	United Egg Producers
Broilers	41	5,752	1.0	National Chicken Council
Total	**2,611**	**13,883**	**$14.8**	

Source: EPA.

The purpose of the National Air Emissions Monitoring Study is to collect data that will provide a scientific basis for measuring and estimating air

[26]EPA placed certain conditions and limits on its agreement not to sue animal feeding operations participating in the Air Compliance Agreement. For example, EPA can continue to pursue cases that present an imminent and substantial endangerment to public health, welfare, or the environment. In addition, EPA's agreement not to sue only covers emissions from agricultural livestock and livestock waste and does not extend to generators or land application of animal waste.

emissions from animal feeding operations and will help EPA to determine operations' compliance status. To provide a framework for the monitoring study and develop a sampling plan that was representative of animal feeding operations in the United States, in 2003 EPA convened a panel of industry experts, university and government scientists, and other stakeholders knowledgeable in the field. In 2004, the nonprofit organization founded by the various livestock sectors selected an independent science adviser to oversee the data collection at 20 of the 13,883 animal feeding operations that were selected to participate in the study. Their selection was submitted to and approved by EPA. Data collection began in May 2007. Once 2 years of data has been collected, EPA will use these data to develop air emissions protocols. Figure 6 shows EPA's expected timeline for the development of air emissions protocols.

Figure 2: EPA Timeline for Development of Air Emission Protocols for Animal Feeding Operations

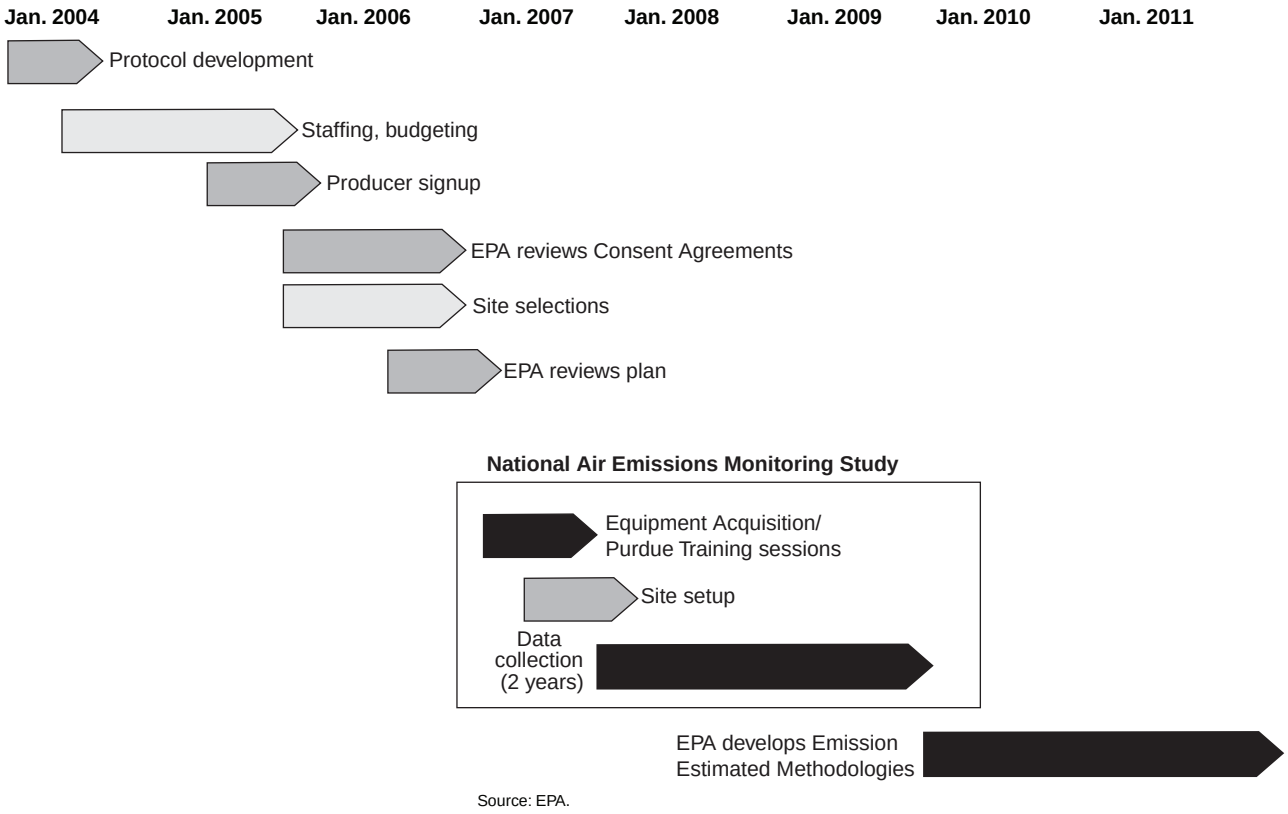

Source: EPA.

However, the National Air Emissions Monitoring Study may not provide the data that EPA needs to develop comprehensive protocols for quantifying air emissions from animal feeding operations for a variety of reasons. First, the monitoring study does not include the 16 combinations of animal types and geographic regional pairings recommended by EPA's expert panel. The panel recommended this approach so that the study sample would be representative of the vast majority of participating animal feeding operations, accounting for differences in climatic conditions, manure-handling methods, and density of operations. However, EPA approved only 12 of the 16 combinations recommended by the expert panel, excluding southeastern broiler, eastern layer, midwestern turkey, and southern dairy operations. Second, site selection for the study has been a concern since the plan to select monitoring sites for the monitoring study was announced in 2005. At that time, many agricultural experts, environmental groups, and industry and state officials disagreed with the site selection methodology. In commenting on EPA's *Federal Register* notice of the Animal Feeding Operation Consent

Agreement and Final Order, these experts and officials stated that the study did not include a sufficient number of monitoring sites to establish a statistically valid sample. Without such a sample, we believe that EPA will not be able to accurately estimate emissions for all types of operations. More recently, in June 2008, the state of Utah reached an agreement with EPA to separately study animal feeding operations in the state because of the state's continuing concerns that the National Air Emissions Monitoring Study will not collect information on emissions from operations in Rocky Mountain states and therefore may not be meaningful for those operations that raise animals in arid areas. Finally, agricultural experts have raised concerns that the National Air Emissions Monitoring Study does not include other sources that can contribute significantly to emissions from animal feeding operations. For example, these experts have noted that the monitoring study will not capture data on ammonia emissions from feedlots and manure applied to fields. According to these experts, feedlots and manure on fields, as well as other excluded sources, account for approximately half of the total ammonia emissions from animal feeding operations.

Furthermore, USDA's Agricultural Air Quality Task Force has also recently raised concerns about the quantity and quality of the data being collected during the early phases of the study and how EPA will eventually use the information.[27] In particular, the task force expressed concern that the technologies used to collect emissions data were not functioning reliably. For example, according to data provided by EPA, almost one-third of the preliminary data from one site were incomplete during a 2-month data collection period. The task force was also concerned about EPA's plans to extrapolate the data across a variety of CAFO operating configurations. At its May 2008 task force meeting, the members requested that the Secretary of Agriculture ask EPA to review the first 6 months of the study's data to determine if the study needs to be revised in order to yield more useful information.

EPA acknowledged that emissions data should be collected for every type of animal feeding operation and practice, but EPA officials stated that such an extensive study is impractical. According to EPA officials, the industry identified those monitoring sites that they believed best represented the type of operations and manure management practices that

[27]The Agricultural Air Quality Task Force, created in accordance with the 1996 farm bill, is charged with advising the Secretary of Agriculture with respect to providing oversight and coordination related to agricultural air quality, and consists of leaders in farming, industry, health, and science.

are in their various animal sectors. EPA reviewed and approved these site selections. According to EPA, it believes that the selected sites provide a reasonable representation of the various animal sectors. EPA has also indicated that it plans to use other relevant information to supplement the study data and has identified some potential additional data sources. For example, a study conducted at two broiler facilities in Kentucky has been accepted as meeting the emissions study's requirements. However, according to agricultural experts, until EPA identifies all the supplemental data that it plans to use, it is not clear if these data, together with the emissions study data, will enable EPA to develop comprehensive air emissions protocols.

Furthermore, EPA has also indicated that completing the National Air Emissions Monitoring Study is only the first step in a multiyear effort to develop a process-based model for predicting overall emissions for animal feeding operations. A process-based model would capture emissions data from all sources and use these data to assess the interaction of all sources and the impact that different manure management techniques have on air emissions for the entire operation. For example, technologies are available to decrease emissions from manure lagoons by, among other things, covering the lagoon to capture the ammonia. However, if an operation spreads the lagoon liquid as fertilizer for crops, ammonia emissions could increase on the field. According to NAS, a process-based model is needed to provide scientifically sound estimates of air emissions from animal feeding operations that can be used to develop management and regulatory programs. Although EPA plans to develop a process-based model after 2011, it has not yet established a timetable for completing this model and, therefore, it is uncertain when EPA will have more sophisticated approaches that will more accurately estimate emissions from animal feeding operations.

Recent EPA Decisions Suggest That the Agency Has Not Yet Determined How It Plans to Regulate Air Emissions from Animal Feeding Operations

Two recent decisions by EPA suggest that the agency has not yet determined how it intends to regulate air emissions from animal feeding operations. EPA's first decision in this context was made in December 2007. At that time EPA proposed to exempt releases to the air of hazardous substances from manure at farms that meet or exceed the reportable quantities from both CERCLA and EPCRA notification requirements. According to EPA, this decision was in response to language that was contained in congressional committee reports related to EPA's appropriations legislation for 2005 and 2006. EPA was directed to promptly and expeditiously provide clarification on the application of these laws to poultry, livestock, and dairy operations. In addition, the agency received a petition from the National Chicken Council, the

National Turkey Federation, and the U.S. Poultry and Egg Association seeking an exemption from the CERLA and EPCRA reporting requirements for ammonia emissions from poultry operations. The petition argued that ammonia emissions from poultry operations pose little or no risk to public health, and emergency response is inappropriate. In proposing the rule, EPA noted that the agency would not respond to releases from animal wastes under CERCLA or EPCRA nor would it expect state and local governments to respond to such releases because the source and nature of these releases are such that emergency response is unnecessary, impractical, and unlikely. It also noted that it had received 26 comment letters from state and local response agencies supporting the exemption for ammonia from poultry operations. However, during the public comment period ending on March 27, 2008, a national association representing state and local emergency responders with EPCRA responsibilities questioned whether EPA had the authority to exempt these operations until the agency had data from its monitoring study to demonstrate actual levels of emissions from animal feeding operations. This national association further commented that EPA should withdraw the proposal because it denied responders and the public the information necessary to protect themselves from dangerous releases.[28] The timing of this proposed exemption, before the National Air Emissions Monitoring Study has been completed, we believe calls into question the basis for EPA's decision.

The second decision that EPA has recently made that calls into question how the agency intends to regulate air emissions from animal feeding operations involves the timing of key regulatory decisions. EPA has stated that it will not make key regulatory decisions on how federal air regulations apply to animal feeding operations until after 2011, when the monitoring study is completed. According to EPA, the agency will issue guidance defining the scope of the term "source" as it relates to animal agriculture and farm activities. As a result, EPA has not decided if it will aggregate the emissions occurring on an animal feeding operation as one source or if the emissions from the barns, lagoons, feed storage, and fields will each be considered as a separate source when determining if an operation has exceeded air emissions' reportable quantities. Depending on the approach EPA takes, how emissions are calculated could differ significantly. For example, according to preliminary data EPA has received from an egg-laying operation in Indiana, individual chicken barns may

[28]The National Association of SARA Title III Program Officials. The Superfund Amendments and Reauthorization Act (SARA) amended CERCLA on October 17, 1986, after the first 6 years of the program.

exceed the CERCLA reportable quantities for ammonia. Moreover, if emissions from all of the barns on the operation are aggregated, they might be more than 500 times the CERCLA reportable quantities. In addition, EPA does not intend to issue guidance to address emissions, and sources of emissions, that cannot reasonably pass through a stack, chimney, or other functionally equivalent opening, i.e., fugitive emissions, until after the conclusion of the monitoring study.

EPA has already been asked to clarify what it considers a source on an animal feeding operation but has declined to do so. In a 2004 ruling on an appeal of a civil suit against a swine operation, the U.S. Court of Appeals for the 10th Circuit overturned a 2002 federal district court ruling that a farm's individual barns, lagoons, and land application areas could be considered separate "sources" for purposes of CERCLA reporting requirements.[29] The Court of Appeals ruled that the whole farm site was the proper entity to be assessed for purposes of CERCLA reporting. The Court invited EPA to file a friend-of-the-court brief in order to clarify the government's position on this issue, but EPA declined to do so within the court-specified time frame.[30] Another court reached similar conclusions in 2003.[31] Despite these court rulings, EPA has indicated that it will not decide on what it considers a source until the National Air Emissions Monitoring Study is completed.

Lacking Federal Guidance, Some States Have Begun to Regulate Air Emissions from Animal Feeding Operations

In the absence of federal guidance on how to regulate air emissions from animal feeding operations, officials in 6 states, out of the 47 states that responded to our survey, are regulating some emissions covered under the Clean Air Act, CERCLA and EPCRA. As table 10 shows, state officials in California, Idaho, Minnesota, Missouri, Nebraska, and North Dakota reported that they have developed state air regulations for certain pollutants that are emitted by CAFOs.

[29]*Sierra Club v. Seaboard Farms Inc.*, 387 F.3d 1167 (10th Cir. 2004).

[30]In commenting on a draft of this report, EPA noted that it had a very limited time to respond to the court's request.

[31]*Sierra Club v. Tyson Foods, Inc.*, 299 F. Supp. 2d 693 (W.D. Ky. 2003).

Table 10: States That Reported Having Regulations for Air Emissions from Animal Feeding Operations, 2008

	Hydrogen sulfide	Ammonia	Particulate matter	Volatile organic compounds
California	X	X	X	X
Idaho		X		
Minnesota	X			
Missouri	X		X	
Nebraska	X			
North Dakota	X			

Source: State officials, as reported to GAO.

Specific examples of the types of regulations that the states have developed include the following:

- Minnesota has established state emissions thresholds for hydrogen sulfide that apply to CAFOs. CAFO operators in the state must develop an air emissions control plan and must implement it if the Minnesota Pollution Control Agency detects elevated levels of hydrogen sulfide. According to state officials, once an operator reduces emissions, the agency re-monitors to ensure the emission levels remained below the state-established threshold.[32] Minnesota may take legal action against CAFO operators violating this standard. For example, in June 2008, monitoring by the Minnesota Pollution Control Agency at a dairy operation recorded hydrogen sulfide levels above the state threshold and in cooperation with the State Attorney General, the agency, using state authorities, filed a lawsuit against the dairy's operator.

- In 2003, California passed a law that authorized the state and local air districts to require animal feeding operations above a certain size to apply for clean air permits and develop a plan to decrease air emissions. For example, one air district in California—the San Joaquin Valley Air Pollution Control District with large clusters of animal feeding operations—developed a rule in 2006 to implement the law that required large animal feeding operations to apply for a permit that includes a plan for mitigating their emissions. According to air district officials, the district

[32]The standard is: 50 ppb average over 1/2 hour not to be exceeded more than two times per year; 30 ppb average over 1/2 hour not to be exceeded more than two times in any 5 consecutive days.

has implemented specific regulations for dairy animal feeding operations that require these operations to obtain five separate permits for components of their operations, including barns and land application of manure. The officials told us that these regulations were put in place, in part because the area is designated as a severe nonattainment area under the Clean Air Act and they are required to regulate a broader range of emission sources. According to state officials we spoke with, as a result of these more stringent state regulations, CAFOs in California may be relocating to other states—such as Texas and Iowa.

Two Federal Court Decisions Have Affected EPA's and Some States' Ability to Regulate Water Pollutants Discharged by CAFOs

Two federal court decisions have affected EPA and some states' abilities to regulate CAFOs for water pollutants. The 2005 *Waterkeeper Alliance Inc. v. EPA* decision forced EPA to revise its 2003 rule for permitting CAFOs and abandon its approach of requiring all CAFO operators to obtain a permit. Although this court decision affected EPA's ability to regulate CAFOs, states' reaction to the *Waterkeeper* decision has varied: some states such as Minnesota continue to require all CAFOs to obtain permits while others such as Colorado have delayed developing new rules until EPA issues its final revised rule. In addition, the Supreme Court's 2006 decision—*Rapanos v. United State*s—has made determination of Clean Water Act jurisdiction over certain types of waters more complex. According to EPA, this has required the agency to gather significantly more evidence to establish Clean Water Act jurisdiction in some enforcement cases.

The *Waterkeeper* Decision Has Impacted EPA's Ability to Regulate CAFOs, but Has Not Had a Similar Impact on Some States

In its 2005 *Waterkeeper* decision, the U.S. Court of Appeals for the Second Circuit set aside a key provision of EPA's 2003 CAFO rule requiring every CAFO to apply for a NPDES permit. Under the 2003 rule, large numbers of previously unregulated CAFOs were required to apply for permits and would have been subject to monitoring and reporting requirements imposed by the permit as well as periodic inspections. According to EPA, the 2003 rule would have expanded the number of CAFOs requiring permits from an estimated 12,500 to an estimated 15,300, an increase of about 22 percent. According to EPA officials, when fully implemented, this requirement for all CAFOs with a potential to discharge to apply for permits would have provided EPA with more comprehensive information on the number and location of CAFOs and how they are operated and managed, thus allowing EPA to more effectively locate and inspect CAFOs nationwide.

However, in 2003, both environmental and agricultural groups challenged EPA's 2003 rule. In the *Waterkeeper* case, environmental groups argued,

among other things, that EPA's 2003 rule did not adequately provide for (1) public review and comment on a CAFO's nutrient management plan and (2) permitting authorities to review the CAFO's nutrient management plan. The court agreed with the environmental groups and instructed EPA to revise the rule accordingly. The agricultural groups challenged the 2003 rule's CAFO permitting requirement, arguing that the agency exceeded its authority under the Clean Water Act by requiring CAFOs that were not discharging pollutants into federally regulated waters to apply for permits or demonstrate that they had no potential to discharge. The court also agreed with the agricultural groups and set aside the permitting requirements for CAFOs that did not actually discharge. Following the court's decision, many aspects of the 2003 rule remained in effect, including EPA's revised regulatory definition of CAFOs and the expansion of the number of CAFOs needing permits by deleting a significant exception.

In effect, the *Waterkeeper* decision returned EPA's permitting program to one in which CAFO operators are not required to apply for a NPDES permit unless they discharge, or propose discharging, into federally regulated waters. As a result, EPA must identify and prove that an operation has discharged or is discharging pollutants in order to require the operator to apply for a permit. To help identify unpermitted discharges from CAFOs, EPA officials stated that they have to rely on other methods that are not necessarily all-inclusive, such as citizens' complaints, drive-by observations, aerial flyovers, and state water quality assessments that identify water bodies impaired by pollutants associated with CAFOs. According to EPA officials, these methods have helped the agency identify some CAFOs that may be discharging as well as targeting inspections to such CAFOs.

In response to the *Waterkeeper* decision, EPA proposed a new rule in June 2006 requiring that (1) only CAFO operators that discharge, or propose to discharge, apply for a permit; (2) permitting authorities review CAFO nutrient management plans and incorporate the terms of these plans into the permits; and (3) permitting authorities provide the public with an opportunity to review and comment on the nutrient management plans. According to EPA officials, the final rule is currently being reviewed by the Office of Management and Budget before it is formally published in the *Federal Register*. These officials said it is uncertain when the OMB review will be completed and the final rule issued. Estimates vary on how this rule, when implemented, will affect the number of CAFOs that will obtain a permit. EPA estimates that 25 percent fewer CAFOs will need to apply for a permit under the new rule than would have been required to apply for a permit under the 2003 rule. In contrast, an association representing

state water program officials believes that many fewer CAFOs than EPA estimates will voluntarily apply for a permit under the new 2006 rule, when it is finalized.

The need to develop and implement a new rule that meets the *Waterkeeper* requirements has also resulted in delays in implementing the provisions of the 2003 rule that the Court upheld. Specifically, EPA has not yet implemented, among other things the expanded CAFO definitions, which cover operations such as dry-manure poultry operations. This is particularly significant since, according to a USDA official with extensive knowledge of the poultry industry and another agricultural expert that we spoke to, at least 90 percent of poultry operations use a dry-manure management system. An EPA Region 6 official told us that in Texas alone this expanded definition would result in about 1,500 additional dry-manure poultry operations being covered under the new CAFO definition.

Although the *Waterkeeper* decision has affected EPA's ability to regulate CAFOs' water pollutant discharges, this decision has not had the same impact on the ability of some of the states to regulate these operations. According to officials in the 47 states responding to our survey, the impact of the *Waterkeeper* decision on their ability to regulate water pollution from CAFOs has been mixed. As table 11 shows, the impacts of the *Waterkeeper* decision ranged from having little impact on state regulation of CAFOs to impairing state CAFO programs.

Table 11: State Officials' Views of the Impact of the *Waterkeeper* Decision on Their CAFO Programs

Impact of *Waterkeeper*	Number of states reporting impact
Waterkeeper had little or no impact	16
Reduced the number of CAFOs with permits	15
Impaired state program	10
Waiting for EPA to issue revised rule	9
Prompted state legislation to require permits for CAFOs	1

Source: GAO analysis of state official responses.

Note: Some state officials identified more than one impact.

Officials from several of the states that told us that the *Waterkeeper* decision had little impact on their regulation of CAFOs, saying that this was primarily because their states had implemented CAFO regulations that were more stringent than those required under the Clean Water Act. For example, Minnesota officials stated that the *Waterkeeper* decision had

no impact on their state's regulations because the state used its own authority to adopt regulations more stringent than EPA's regulations. Moreover, according to Minnesota officials, even after the *Waterkeeper* decision, the state has continued to require all CAFOs to obtain permits from the state environmental agency. Similarly, Kansas officials stated that the *Waterkeeper* decision had only minimal effects because the state has regulated CAFOs since the 1960s.

However, 34 states indicated that the *Waterkeeper* decision directly affected their state programs. Officials from 15 states told us that the number of CAFOs that had obtained permits since the *Waterkeeper* decision had decreased although none provided us with numbers on what this decrease had been. Similarly, officials in 10 states told us that the *Waterkeeper* decision had impaired their state's ability to regulate CAFOs because it discredited the program, created confusion or uncertainty, or made it difficult for them to determine which operations needed a permit. For example, according to the state official responsible for Indiana's CAFO permitting program, although the state has had a CAFO permitting program since 1971, it adopted EPA's 2003 CAFO Rule because the rule was more protective. However, when the *Waterkeeper* decision set aside portions of the 2003 rule, this official told us that the decision, in effect, discredited the state's regulatory program. In addition, officials from nine states who are responsible for their state's permitting program told us that their programs remain in limbo while they wait for EPA to issue its final revised rule. These state officials, including officials in Colorado, said that they will update their state rules once EPA's final rule is issued.

Finally, state water pollution control officials have expressed some concerns that EPA's new 2006 rule will place a greater administrative burden on states than the 2003 rule would have. In an August 2006 letter to EPA, the Association of State and Interstate Water Pollution Control Administrators noted that the "reactive" enforcement that EPA will now follow will require permitting authorities to significantly increase their enforcement efforts to achieve the level of environmental benefit that would have been provided by the 2003 rule. These officials believe that requiring EPA and the states to identify CAFOs that actually discharge pollutants into federally regulated water bodies will consume more resources than requiring all CAFOs to apply for a permit.

The *Rapanos* Decision Has Affected EPA's Overall Ability to Regulate Pollutants Entering Federally Regulated Waters

The Supreme Court's 2006 *Rapanos* decision has also affected EPA's enforcement of the Clean Water Act because the agency believes that it must gather significantly more evidence to establish which waters are subject to the act's permitting requirements. At issue in the *Rapanos* decision was whether the Clean Water Act's wetlands permitting program applied to four specific wetlands that were adjacent to non-navigable tributaries of traditional navigable waters. The Court rejected the standards applied by the lower courts in determining whether wetlands at issue fell under the act's jurisdiction and, therefore, could be subject to permitting requirements. Although a majority of the justices rejected the standards applied by the lower courts, a majority could not agree on how to determine which waters would fall under the act's jurisdiction, and thus how far EPA could reach to regulate discharges of pollutants under the act.

Although the *Rapanos* case arose in the context of a different permit program, the scope of EPA's pollutant discharge permit program originates in the same Clean Water Act definition that was discussed in the decision. According to EPA enforcement officials, the agency may now be less likely to seek enforcement against a CAFO that it believes is discharging pollutants into a water body because it may be more difficult to prove that the water body is federally regulated. According to EPA officials, as a result of the *Rapanos* decision, the agency must now spend more resources developing an enforcement case because the agency must gather proof that the CAFO not only has illegally discharged pollutants, but that those discharges ultimately entered a federally regulated water body. These officials told us that the farther a CAFO is from a regulated water body, the more evidence they will need to prove that the discharges entered that water body. To ensure "nationwide consistency, reliability, and predictability in their administration of the statute," EPA has issued national guidance to clarify the agency's responsibilities in light of the Supreme Court's decision. However, in a March 4, 2008, memorandum, EPA's Assistant Administrator for Enforcement and Compliance Assurance stated that the *Rapanos* decision and EPA's guidance has resulted in significant adverse impacts to the clean water enforcement program. According to the memorandum, the *Rapanos* decision and guidance negatively affected approximately 500 enforcement cases, including as many as 187 cases involving NPDES permits. In May 2007, Members of Congress, in both the House and Senate, introduced a bill entitled the Clean Water Restoration Act of 2007 to clearly define the scope of the Clean Water Act. As of August 2008, neither bill had been reported out of committee.

Conclusions

For more than 30 years, EPA has regulated CAFOs under the Clean Water Act and during this time it has amassed a significant body of knowledge about the pollutants discharged by animal feeding operations and the potential impacts of these pollutants on human health and the environment. Despite its long-term regulation of CAFOs, EPA still lacks comprehensive and reliable data on the number, location, and size of the operations that have been issued permits and the amounts of discharges they release. As a result, EPA has neither the information it needs to assess the extent to which CAFOs may be contributing to water pollution, nor the information it needs to ensure compliance with the Clean Water Act. More recently, EPA has also begun to address concerns about air pollutants that are emitted by animal feeding operations. The Nationwide Air Emissions Monitoring Study, along with EPA's plans to develop air emissions estimating protocols, are important steps in providing much needed information on the amount of air pollutants emitted from animal feeding operations. However, questions about the sufficiency of the sites selected for the air emissions study and the quantity and quality of the data being collected could undermine EPA's efforts to develop air emissions protocols by 2011 as planned. Finally, while the study and resulting protocols are important first steps, a process-based model that more accurately predicts the total air emissions from an animal feeding operation is still needed. While EPA has indicated it intends to develop such a model, it has not yet established a strategy and timeline for this activity.

Recommendations for Executive Action

In order to more effectively monitor and regulate CAFOs, we recommend that the Administrator of the Environmental Protection Agency should complete the agency's effort to develop a national inventory of permitted CAFOs and incorporate appropriate internal controls to ensure the quality of the data.

In order to more effectively determine the extent of air emissions from animal feeding operations, the Administrator of the Environmental Protection Agency should

- reassess the current data collection efforts, including its internal controls, to ensure that the National Air Emissions Monitoring Study will provide the scientific and statistically valid data that EPA needs for developing its air emissions protocols;
- provide stakeholders with information on the additional data that it plans to use to supplement the National Air Emissions Monitoring Study; and

- establish a strategy and timetable for developing a process-based model that will provide more sophisticated air emissions estimating methodologies for animal feeding operations.

Agency Comments and Our Evaluation

We provided a draft of this report for review and comment to the EPA and the Secretary of USDA. We received written comments from EPA. USDA did not provide written comments, but did provide technical comments and clarifications, which we incorporated, as appropriate.

EPA partially concurred with our conclusions and recommendations. In its written comments, EPA acknowledged that currently no national inventory of permitted CAFOs exists. The agency stated that it is currently working with its regions and the states to develop and implement a new national data system to collect and record facility-specific information on permitted CAFOs. We have revised our recommendation to reflect the actions that EPA has underway. In response to our recommendations that EPA reassess the current data collection effort, EPA stated that the agency has developed a quality assurance plan for the study and is continuously evaluating the National Air Emissions Monitoring Study. We are aware that EPA has developed a quality assurance plan for the data collected during the study. However, our recommendation also reflects other concerns with the study. For example, the monitoring sites selected may not represent a statistically valid sample or animal feeding operations that account for the differences in climatic conditions, manure-handling methods, and density of operations; and the study does not address other sources that can contribute significantly to emissions from animal feeding operations. EPA did not address these issues in its comments. Therefore, we continue to believe that EPA should reassess the ongoing effort to ensure that the study, as currently structured, will provide the data that EPA needs.

In response to our recommendation that the agency identify the information that it plans to use to supplement the National Air Emissions Monitoring Study, EPA stated that it cannot yet identify the data that it will use to augment the data collected during the monitoring study. However, the agency indicated that it has begun discussions with USDA to identify ongoing research that is focused on agricultural air emissions and gaps that may still exist, but did not provide any additional information on when it plans to identify the supplemental data that it plans to use to augment the monitoring study. Until it does so, neither EPA nor stakeholders can be assured that these data, in combination with the emissions study data, will enable EPA to develop the planned protocols. The agency also agreed with our recommendation to establish a strategy

and timetable for developing a process-based model and said that it has begun to evaluate what is needed to develop such a model. However, the agency did not provide any information on when it expects to complete plans for developing a process-based model. EPA also provided technical comments, which we have incorporated, as appropriate. EPA's written comments are provided in appendix V.

As agreed with your offices, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the report date. At that time, we will send copies to interested congressional committees, the Administrator of the Environmental Protection Agency, the Secretary of the United States Department of Agriculture and other interested parties. We also will make copies available to others upon request. In addition, the report will be available at no charge on GAO's Web site at http://www.gao.gov.

If you or your staff have any questions regarding this report, please contact me at (202) 512-3841 or mittala@gao.gov. Contact points for our Office of Congressional Relations and Public Affairs may be found on the last page of this report. Key contributors to this report are listed in appendix VI.



Anu Mittal
Director, Natural Resources
and Environment

List of Requesters

The Honorable John D. Dingell
Chairman
Committee on Energy and Commerce
House of Representatives

The Honorable James L. Oberstar
Chairman
Committee on Transportation and Infrastructure
House of Representatives

The Honorable Gene Green
Chairman
Subcommittee on Environment and Hazardous Materials
Committee on Energy and Commerce
House of Representatives

The Honorable Eddie Bernice Johnson
Chairwoman
Subcommittee on Water Resources and Environment
Committee on Transportation and Infrastructure
House of Representatives

The Honorable Hilda L. Solis
House of Representatives

Appendix I: Objectives, Scope, and Methodology

For this report we were asked to determine the (1) trends in concentrated animal feeding operations (CAFOs) over the past 30 years; (2) amount of waste they generate; (3) findings of recent key academic, industry, and government research of the potential impacts of CAFOs on human health and the environment, and the extent to which the Environmental Protection Agency (EPA) has assessed the nature and severity of these identified impacts; (4) progress that EPA and states have made in regulating and controlling the air emissions of, and in developing protocols to measure, air pollutants from CAFOs that could affect air quality; and (5) extent to which recent court decisions have affected EPA and the states' ability to regulate CAFO discharges that impair water quality.

In conducting our work, we reviewed laws and regulations and federal and state agencies' documents. We met with officials from EPA, the U.S. Department of Agriculture (USDA), the National Pork Producers Council, the National Pork Board, the National Cattlemen's Beef Association, the Environmental Integrity Project (a nonpartisan, nonprofit environmental advocacy group), the Sierra Club, California Association of Irritated Residents, Waterkeeper Alliance, Iowa Citizens for Community Improvement, Environmental Defense, National Association of Clean Air Agencies, Association of State and Interstate Water Pollution Control Administrators, as well as state officials. The National Chicken Council did not respond to our requests for information. Additionally, we visited CAFOs in eight states: Arkansas, California, Colorado, Iowa, Maryland, Minnesota, North Carolina, and Texas. We chose these states because they were geographically dispersed and contained numerous CAFOs representing multiple types of animals.

For our analysis of trends in CAFOs over the past 30 years, we used USDA's Census of Agriculture data. We assessed the reliability of these data by reviewing USDA's documentation on the development, administration, and data quality program for the Census of Agriculture. We also electronically tested the data used in this study to determine if there were any missing data or anomalies in the dataset. Furthermore, we compared the results of our nationwide results for each year by animal sector to USDA's published reports. On the basis of these assessments, we determined the data to be sufficiently reliable for the purposes for which it was used in this report. In addition, respecting USDA's requirement to protect the privacy of individual farmers responding to the Census of Agriculture surveys, we conducted these analyses at USDA and worked

with USDA to review our results and verify that no single operation could be identified from our analysis.[1]

From USDA's Census of Agriculture data, we analyzed the most recent data available for large farms raising animals from 1974 through 2002.[2] We used these data on large farms as a proxy for CAFOs because no federal agency collects consistent data on these types of operations. USDA has periodically collected data on farms nationwide using the Census of Agriculture survey. Prior to 1982, these surveys were conducted every four years; whereas since 1982, the agency has administered the survey every five years (the most recent survey results, conducted in 2007, will not be available until February 2009). In analyzing Census data prior to 1982, we found that the categories reported by USDA were not consistent with EPA's minimum size threshold for large CAFOs: 2,500 hogs, 700 dairy or milk cows, 55,000 turkeys, 1,000 beef cattle, 82,000 layers, and 125,000 broilers.[3] For instance, the largest farm categories USDA reported for broilers prior to 1982 was farms with sales of 100,000 and more. Since sales data must be converted to an inventory number, we had to make adjustments for production cycles to determine the number of animals on a farm per day.[4] Broiler farms complete six production cycles per year therefore, when we divided the USDA provided number of 100,000 in broiler sales by 6 to account for the total number of possible production cycles, the USDA reported broiler sales represent a farm with an inventory of about 17,000 broilers. Farms of this size are much smaller than the

[1]In order to adjust the data for survey undercoverage and nonresponse, we used the official USDA statistical weights. However, we were unable to calculate the confidence intervals around the reported estimates because the Census of Agriculture's documentation does not provide the necessary information to determine the statistical error associated with subpopulation estimates.

[2]We included a farm, for the purposes of calculating the number of farms overall and for each animal type, only when it reported, on the Census of Agriculture survey, either sales or inventory numbers for a particular animal type.

[3]By minimum size threshold, we mean the minimum number of animals required for classification as a large CAFO without consideration of other factors, such as whether the animal feeding operation is a significant contributor of pollutants to federally regulated waters, or whether pollutants are discharged into federally regulated waters from the operation through a manmade ditch.

[4]A production cycle is the length of time an animal is fed before being sold plus time between "crops." For example, the feeding period for a broiler is about 48 days. Including time for cleaning barns between cycles, restocking, etc., a broiler farm has about 6 production cycles per year. We used the number of cycles per animal type provided in "Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients," USDA, December 2000.

125,000 broiler CAFO threshold defined by EPA. Similarly, categories for farms raising other types of animals, in the pre-1982 USDA data, were also different than the EPA CAFO definitions for these types of operations. As a result, we used the time frame of 1982 through 2002 because USDA could provide us with detailed electronic data that allowed us to apply EPA's CAFO thresholds to determine the trends in the overall number of large farms that raised animals and could be potentially considered a CAFO. For broilers and layers/pullets,[5] we used EPA's CAFO minimum size threshold for dry-litter manure handling systems because these systems represent the majority of poultry operations. These thresholds are larger than for those poultry operations that have liquid manure handling systems.

Because USDA does not report the average number of animals on a farm, we used USDA Census of Agriculture inventory, sales, and inventory plus sales data for this purpose. The choice of using inventory only, sales only, or inventory and sales data for a particular animal type depended on the wording of Census survey questions during the years we analyzed. When only sales data or inventory plus sales data were used, we adjusted these data using the appropriate USDA formulas to determine the average number of animals on a farm.[6] When both inventory and sales were used for an animal type, we applied an approved USDA approach to determine the average number of animals on a farm. As a result, we made the following adjustments for each animal type:

- For beef cattle, USDA only collected sales data for 1982 through 1997. As a result, for beef cattle, we used sales of cattle on feed (2002 survey) or sales of fattened cattle (1982 through 1997 surveys) adjusted for the number of production cycles. This increased the likelihood that we were including cattle raised on CAFOs instead of operations that allow the cattle to graze on pastureland.

- For dairy cows, we used the inventory of animals as of December 31 for each Census year since these animals are maintained to produce milk and not specifically for slaughter. For dairy cows, we included the categories: lactating and nonlactating cows.

[5]A pullet is a replacement hen for laying eggs that is less than 1 year of age.

[6]"Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients," USDA, December 2000.

- For hogs, the Census of Agriculture reported both inventory and sales data for hogs and pigs.[7] These data were not reported by either the weight or age, so we used the total for all hogs and pigs of all ages. We used both the inventory and sales data for hogs and adjusted for the number of production or finish cycles. Hogs may be sold more than once because of the practice of selling feeder pigs at about 10-12 weeks of age to producers to be grown to typical slaughter size. For example, in 1997, about 25 percent of all hog and pig sales reported on the Census of Agriculture were feeder pigs.[8] We adjusted the hog data to factor out these multiple sales.

- For layers, we used survey responses of inventory as of December 31 for layers 20 weeks old and older plus pullets for laying flock replacement.

- For broilers, we used inventory and sales data from the categories: broilers, fryers, capons, roaster and other chickens raised for meat.

- For turkeys, both inventory and sales data were used and included both hens and tom turkeys.

We also reviewed EPA's data on the number of CAFOs that had been issued permits—these data are either collected by EPA's regional offices or from the states—for the period 2003 to 2008. We assessed the accuracy and reliability of these data by interviewing officials in 47 states and we asked them to verify the information that EPA had for the numbers of CAFOs permitted in their state.[9] Based on the information we obtained from the state officials, we determined that EPA's data for permitted CAFOs was not reliable and could not be used to identify trends in permitted CAFOs over the 5-year period.

To identify the amount of manure, including urine, a large CAFO is estimated to generate for each animal type, we used EPA's thresholds for the minimum number of animals that constitute a CAFO. To illustrate the size of a "typical" large farm for each animal type, we used the median for

[7]The term "hogs" includes all production stages unless otherwise stated.

[8]1997 was the last Census of Agriculture survey that asked for sales of feeder pigs. The 2002 survey asked for hogs "sold or moved from this operation, including feeder pigs." In many hog contract operations, the farmer does not own the pigs being fed. GAO did not determine what effect changing the survey wording had on the change in total hogs sold between 1997 and 2002 nor whether the sales of feeder pigs as a percentage of total swine sales changed from 1997 to 2002.

[9]The three states that did not provide information on their state CAFO programs were Connecticut, Nevada, and Vermont.

a large-sized farm. We used the median instead of the mean because we believe it provides a more representative measure for a typical large farm. We also present information on farms at the 75th percentile of all large farms for a particular animal type to represent larger farms.[10]

To estimate the amount of manure produced by each type of animal, we used engineering standards for manure production cited by the American Society of Agricultural and Biological Engineers (ASABE).[11] These standards report the total amount of manure over the production cycle for hogs, beef cattle, turkeys, and broilers. In order to estimate the average pounds of manure per day, we divided the total manure produced over the production cycle by the number of days in the production cycle. Further, we converted the pounds of manure into tons of manure per farm per year. We adjusted the manure calculations for the following animal types:

- For layers, the standards provided the average daily pounds of manure produced by layers. We multiplied the average pounds of manure per day times the average number of animals times 365 days to get manure produced per year.
- For broilers, we determined the average daily pound of manure from the information provided in the standards. We multiplied the average pound of manure per day times the average number of animals times 365 days to get manure per year.
- For dairy cows, the standards provided the average daily pounds of manure produced by dairy cows. We multiplied the average pounds of manure per day times the average number of animals times 365 days to get manure per year. However, we adjusted the data to take into account the typical percentage of cows that are either lactating or dry (nonlactating) and applied the different amounts of manure produced by each type of dairy cow.
- For turkeys, we adjusted the turkey statistics based on the ratio of hens to tom turkeys raised on farms and applied different amounts of manure due to the different sizes of the animals.

[10]We do not report the largest farm for each particular animal type to avoid disclosing information that would allow the identification of the person who supplied the particular information to USDA. Federal law prohibits such disclosure.

[11]"Manure Production and Characteristics" (St. Joseph, Mich.: March 2005). Manure is "as-excreted" and excludes bedding, waste feed, dilution water, biochemical degradation of solids, or dissipation of gases.

- For hogs, the manure standards report manure produced by hogs covering a specific stage of production: feeder-pig-to-finish pigs—beginning with a pig weighing on average about 27 pounds and resulting in a hog weighing 154 pounds. Estimates for other hog operation types such as nursery, farrow to feeder, and farrow to finish would therefore differ. Census of Agriculture data for 2002 indicate that about a third of all hogs sold were from the grow-to-finish (called finish only on the survey) operation type. The ASABE manure standards for this type of operation use 154 pounds as the finish weight. However, USDA reports that typical hog finish (slaughter) weights at the time of the 2002 Census were about 260 pounds. For hogs only, we adjusted the ASABE manure estimates by 1.7 to account for the larger finish weights reported by USDA. We believe this is a conservative adjustment because manure produced by hogs weighing 154 to 260 pounds will be the maximum amount per day that ASABE used to calculate the average pounds produced for the hogs growing from about 27 pounds to 154 pounds.

- For beef cattle, we used the manure standard for "beef-finishing cattle." This standard is for cattle fattened from about 740 pounds to about 1,200 pounds at marketing. Beef cattle (listed as cattle on feed) data from the Census are for cattle sold for slaughter and thus similar in weight to those for the standard. The reported manure results for beef cattle are for operations of this type only.

  In addition, the number of days on feed for hogs, turkeys, and broilers used for the ASABE manure standards does not take into account time between herds or flocks entering and leaving an operation; therefore, we adjusted the manure generated to account for the time between cycles.

  We recognize that all amounts of manure reported are estimates because amounts of manure per animal type vary by feeding programs, feeds used, climatic conditions, production techniques, and animal genetics, among other things. As feeds, animal genetics, and production techniques change in the future, these estimates might change—and may have changed since 2002—but USDA did not provide specific information on what changes have occurred and how those changes may have impacted the manure production on farms. We did not estimate the ability of the farm or surrounding farms to assimilate the manure if applied to pastures and crop land nor did we take into account various technologies to process and/or convert manure. Reported estimates of manure are for amounts produced. We did not determine whether these amounts were discharged into the air or streams and wetlands. Manure harvested from CAFOs for application to land might be less than that excreted by animals because of shrinkage due to evaporation.

To provide a perspective of the amount of wastes generated by these large farms, we compared them with the amount of human sanitary waste generated in various cities. We selected certain cities on the basis of their population, as reported by the U.S. Census Bureau's Population Estimates for 2002, and calculated the amount of sanitary waste generated by the human population of those cities by applying estimates for human sanitary waste production. Human sanitary waste includes feces and urine but does not include wastes such as water from showers, washing dishes and clothes, and flushing toilets. We found two sources of information for average daily human sanitary waste.[12] Because these sources provided different estimates (2.68 and 4.76 pounds per person per day), we averaged the two amounts to use in our calculations of human sanitary waste produced for cities (3.72 pounds per person per day). All amounts of human sanitary waste reported are estimates because amounts will vary based on differences in age, dietary habits, activity levels, and climatic conditions, among other things. Human sanitary waste is a small portion of human discharge into sewage systems. Our reported estimates of human sanitary waste for a city are illustrative only and are not intended to be estimates of actual human sanitary waste entering a particular city's waste treatment system. These estimates are for a population the size of selected cities assuming that the residents do not commute outside the city boundaries and that nonresidents do not enter the city for work or other reasons.

To identify the findings of recent key academic, industry, and government research on the potential impacts of CAFOs on human health and the environment, and the extent to which EPA has assessed the nature and severity of such impacts, we reviewed EPA's 2003 CAFO rule (for water impact studies) and the findings and supporting documents of the National Academy of Sciences study on air emissions from animal feeding operations (for air impact studies).[13] In addition, we

- conducted library, online journal and Internet searches to identify recent studies;

[12]Metcalf and Eddy, Inc., "Wastewater Engineering: Treatment, Disposal, and Reuse," 3rd Edition, (New York, N.Y..: 1991) and Parker, D. and Gallagher, S. K., "Distribution of Human Waste Samples in Relation to Sizing Waste Processing in Space," in "Second Conference on Lunar Bases and Space Activities of the 21st Century," Volume 2 (NASA Conferences Publication 3166: 1992).

[13]National Academy of Sciences, *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs* (Washington, D.C.: National Academies Press, 2003).

- consulted with EPA, USDA, state agencies, industry groups, environmental groups, and academia to help identify additional studies; and
- identified studies through citations in previously identified studies.

We only included in our review studies that (1) were peer-reviewed or produced by a federal agency, (2) were new and original research completed since 2002, (3) had a clearly defined methodology, and (4) identified pollutants found in animal waste and/or their impacts. Through this effort, we found over 200 studies and identified 68 studies that examined air and water quality issues associated with animal waste and met our criteria. We also classified these studies according to whether they

- found a direct link between pollutants from animal waste and impacts on human health or the environment;
- did not find any impacts on human health or the environment from pollutants from animal waste;
- found an indirect link between animal waste and human health or environmental impacts; or
- measured pollutants from animal waste otherwise known to cause human health or environmental impacts.

The classification for each study involved two reviewers. If the reviewers disagreed on the classification, they turned to a third reviewer for resolution. Finally, we compared the findings from these studies with EPA assessments to date and interviewed EPA officials regarding these assessments.

To determine the progress that EPA and states have made in regulating and controlling the air emissions of, and in developing protocols to measure, air pollutants from CAFOs, we reviewed relevant documents, interviewed officials responsible for the ongoing air monitoring study and visited several National Air Emissions Monitoring Study sites in North Carolina. Additionally, we interviewed industry and environmental groups, the umbrella association for state and local clean air agencies, and citizen groups about how EPA air emissions protocols affect them. Finally, we contacted state CAFO officials in all 50 states to determine which states had developed air emission regulations applicable to CAFOs. Officials in

47 states responded.[14] These 47 states account for an estimated 99 percent of large animal feeding operations that could be defined as CAFOs under EPA's 2003 rule.

Finally, to determine the extent to which recent court decisions have affected EPA and the states' ability to regulate CAFO discharges that impair water quality, we examined recent federal decisions, including the *Waterkeeper Alliance Inc. v. EPA* (*Waterkeeper*), and the Supreme Court's 2006 decision in *Rapanos v. United State*s. We interviewed EPA officials about how these court decisions have affected their regulations. To better understand the bases for the lawsuits and what has occurred since the court decisions, we contacted plaintiffs and defendants involved in *Waterkeeper* and other court cases, including industry and environmental groups. To identify the impact of these cases on states regulations, we contacted state CAFO officials in all 50 states to determine how the *Waterkeeper* decision affected their regulations. We asked the states if the *Waterkeeper* decision had affected their state's CAFO program. Using the responses we received from 47 states, we conducted content analyses and classified them into six categories, including if the decision (1) had little impact on the state program, (2) caused the state to wait for EPA guidance (3) impaired the state program, (4) proactively changed legislation, (5) reduced the number of CAFOs with permits, or (6) other. Some officials identified more than one impact. The responses in the "other" category included such responses as "not applicable," "because the state does not have delegated authority," and "we have spent a large amount of time studying the ruling and commenting on EPA proposed rules that were developed to satisfy the ruling."

We conducted this performance audit between July 2007 and August 2008, in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[14]The three states that did not provide information on their CAFO programs were Connecticut, Nevada, and Vermont.

Appendix II: EPA's Definition of Concentrated Animal Feeding Operations

EPA's National Pollutant Discharge Elimination System (NPDES) permit program regulates the discharge of pollutants from point sources to waters of the United States. The Clean Water Act defines point sources to include CAFOs. To be considered a CAFO, a facility must first be defined as an animal feeding operation, which is a lot or facility (other than an aquatic animal production facility) where the following conditions are met:

- Animals have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period.
- Crops, vegetation, forage growth, or post-harvest residues are not sustained in the normal growing season over any portion of the lot or facility.

Generally CAFOs must meet the above definition of an animal feeding operation and stable or confine a certain minimum number of animals at the operation. EPA classifies CAFOs as large, medium, or small, based on size. Table 12 shows the number of animals at a farm that meet EPA's definition of a large, medium, and small CAFO.

Table 12: EPA Designation of Large, Medium, and Small CAFOs for Various Size Thresholds by Animal Type

	Size thresholds (number of animals)		
Animal type	**Large CAFOs**	**Medium CAFOs[a]**	**Small CAFOs[b]**
Cattle or cow/calf pairs	1,000 or more	300 - 999	less than 300
Mature dairy cows	700 or more	200 - 699	less than 200
Veal calves	1,000 or more	300 - 999	less than 300
Swine (weighing over 55 pounds)	2,500 or more	750 - 2,499	less than 750
Swine (weighing less than 55 pounds)	10,000 or more	3,000 - 9,999	less than 3,000
Horses	500 or more	150 - 499	less than 150
Sheep or lambs	10,000 or more	3,000 - 9,999	less than 3,000
Turkeys	55,000 or more	16,500 - 54,999	less than 16,500
Laying hens or broilers (liquid manure handling systems)	30,000 or more	9,000 - 29,999	less than 9,000
Chickens other than laying hens (other than a liquid manure handling system)	125,000 or more	37,500 - 124,999	less than 37,500
Laying hens (other than a liquid manure handling system)	82,000 or more	25,000 - 81,999	less than 25,000
Ducks (other than a liquid manure handling system)	30,000 or more	10,000 - 29,999	less than 10,000
Ducks (liquid manure handling systems)	5,000 or more	1,500 - 4,999	less than 1,500

Source: EPA.

[a]Must also meet one of two "method of discharge" criteria to be defined as a CAFO or may be designated.

[b]May be designated as a CAFO on a case-by-case basis.

In addition to size, EPA uses the following criteria to determine if a CAFO operator needs to apply for a NPDES permit.

- A large CAFO confines at least the number of animals described in table 12.
- A medium CAFO falls within the size range in table 12 and either:
  - discharged pollutants into federally regulated waters through a manmade ditch, flushing system, or similar manmade device;
  - discharged pollutants directly into federally regulated waters that originate outside of and pass over, across, or through the facility or otherwise come into contact with animals confined in the operation; or
  - is designated as a CAFO by the permitting authority as a significant contributor of pollutants.
- A small CAFO confines the number of animals described in table 12 and has been designated as a CAFO by the permitting authority as a significant contributor of pollutants.

Appendix III: Nationwide Trends in the Number of All Animal Farms and the Number of Animals Raised on Large Farms, 1982-2002

This appendix provides our analysis of USDA's data for trends on the number of all animal farms and the number of animals raised on large farms per day for all animal types for the period from 1982 through 2002.

Table 13: Nationwide Trends in the Number of All Farms That Raise Animals for All Animal Types, 1982 through 2002

Type of animal farm	1982	1987	1992	1997	2002	Percentage change, 1982-2002
Beef cattle[a]	215,465	173,961	133,795	99,654	98,061	(54)
Dairy cow	277,762	202,068	155,339	116,874	91,989	(67)
Hog[b]	347,699	256,595	202,811	114,289	89,542	(74)
Layer	218,114	146,056	89,507	74,073	104,974	(52)
Broiler	52,890	41,097	31,427	30,979	41,572	(21)
Turkey	24,701	19,195	13,767	12,129	16,999	(31)
Total of all animal farms[c]	**1,136,631**	**838,972**	**626,646**	**447,998**	**443,137**	**(61)**

Source: GAO analysis of USDA data.

Notes: The phrase "all animal types" refers to the following animals: beef cattle, dairy cows, hogs, layers, broilers, and turkeys.

The criteria for a large farm varied by animal type, consistent with EPA's CAFO thresholds, and represent the average number of animals on a farm per day.

[a]Beef cattle includes only cattle on feed, not grazing on pasture, and sold weighing 500 pounds or more.

[b]Hogs include swine of all sizes from birth to market size.

[c]The number of large farms for all animal types is the total of large farms for each animal type and may include some farms multiple times if they were considered large for more than one animal type.

Table 14: Nationwide Trends in the Number of Animals Raised on Large Farms per Day for All Animal Types, 1982 through 2002

Type of animal farm	1982	1987	1992	1997	2002	Percentage change, 1982-2002
Beef cattle[a]	6,601,928	7,368,109	7,533,708	8,598,508	8,677,892	31
Dairy cow	632,583	860,878	1,300,616	2,049,814	3,183,086	403
Hog[b]	4,176,477	6,275,200	12,133,231	32,412,839	47,789,951	1,044
Layer	160,005,126	212,871,326	229,959,901	263,660,262	304,500,225	90
Broiler	52,140,827	102,198,894	170,873,560	298,222,567	457,461,691	777
Turkey	33,443,754	52,905,796	62,042,552	73,029,156	68,417,853	105
Total of all animal types[c]	**257,000,695**	**382,480,203**	**483,843,568**	**677,973,146**	**890,030,698**	**246**

Source: GAO analysis of USDA data.

Notes: The phrase “all animal types” refers to the following animals: beef cattle, dairy cows, hogs, layers, broilers, and turkeys.

The criteria for a large farm varied by animal type, consistent with EPA’s CAFO thresholds, and represent the number of animals on a farm per production day.

[a]Beef cattle include only cattle on feed, not grazing on pasture, and sold weighing 500 pounds or more.

[b]Hogs include swine of all sizes from birth to market size.

[c]The number of large farms for all animal types is the total of large farms for each animal type and may include some farms multiple times if they were considered large for more than one animal type.

Appendix IV: Government-Sponsored or Peer-Reviewed Studies Completed Since 2002 on the Impacts of Pollutants from Animal Waste

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Studies showing a direct impact				
Ankley, Gerald T., Kathleen M. Jensen, Elizabeth A. Makynen, Michael D. Kahl, Joseph J. Korte, Michael W. Hornung, Tala R. Henry, Jeffrey S. Denny, Richard L. Leino, Vickie S. Wilson, et al. "Effects of the Androgenic Growth Promoter 17β-trenbolone on Fecundity and Reproductive Endocrinology of the Fathead Minnow." Environmental Toxicology and Chemistry. Vol. 22, no. 6 (2003):1,350–1,360.	EPA, University of Minnesota	Water	Hormones	Fertility of fish was significantly reduced by hormones and female fish developed male sex characteristics.
Clark, Clifford G., Lawrence Price, Rafiq Ahmed, David L. Woodward, Pasquale L. Melito, Frank G. Rodgers, Frances Jamieson, Bruce Ciebin, Aimin Li, and Andrea Ellis. "Characterization of Waterborne Outbreak–Associated Campylobacter jejuni, Walkerton, Ontario." Emerging Infectious Diseases. Vol. 9, no. 10 (2003):1,232-1,241.	Health Canada, Ontario Ministry of Health	Water	Bacteria	Cattle manure from a nearby farm entered the groundwater system and caused gastrointestinal illness and death in residents.
Diesel, Elizabeth A., Melissa L. Wilson, Ryan Mathur, Evan Teeters, David Lehmann, and Caitlan Ziatos. "Nutrient Loading Patterns on an Agriculturally Impacted Stream System in Huntingdon County Pennsylvania Over Three Summers." Northeastern Geology & Environmental Sciences. Vol. 29, no. 1 (2007):25-33.	Juniata College	Water	Nutrients	Excess nutrients from CAFO manure contributed significantly to impaired water quality and resulted in the inability to sustain fish populations.
Hill, Dagne D., William E. Owens, and Paul B. Tchounwou. "Impact of Animal Application on Runoff Water Quality in Field Experimental Plots." International Journal of Environmental Research and Public Health. Vol. 2, no. 2 (2005):314–321.	Jackson State University, NIH-Center for Environmental Health, Louisiana State University	Water	Nutrients, bacteria	Nutrients from manure spread on fields contributed to water pollution.
Jensen, Kathleen M., Elizabeth A. Makynen, Michael D. Kahl, and Gerald T. Ankley. "Effects of the Feedlot Contaminant 17α-Trenbolone on Reproductive Endocrinology of the Fathead Minnow." Environmental Science & Technology. Vol. 40, no. 9 (2006): 3,112-3,117.	EPA	Water	Hormones	Fertility of fish was significantly reduced by hormones and female fish developed male sex characteristics.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Orlando, Edward F., Alan S. Kolok, Gerry A. Binzcik, Jennifer L. Gates, Megan K. Horton, Christy S. Lambright, L. Earl Gray, Jr., Ana M. Soto, and Louis J. Guillette, Jr. "Endocrine-Disrupting Effects of Cattle Feedlot Effluent on an Aquatic Sentinel Species, the Fathead Minnow." Environmental Health Perspectives. Vol. 112, no. 3 (2004):353–358.	University of Florida; St. Mary's College of Maryland, University of Nebraska, EPA, Tufts University.	Water	Hormones	Male fish were demasculinized and there was defeminization of female fish.
Weldon, Mark B. and Keri C. Hornbuckle. "Concentrated Animal Feeding Operations, Row Crops, and Their Relationship to Nitrate in Eastern Iowa Rivers." Environmental Science & Technology. Vol. 40, no. 10 (2006): 3,168-3,173.	University of Iowa	Water	Nitrogen	High concentrations of nutrients in waters are a result of CAFO manure and degrade water quality.
Mathisen, T., S. G. Von Essen, T. A. Wyatt, and D. J. Romberger. "Hog Barn Dust Extract Augments Lymphocyte Adhesion to Human Airway Epithelial Cells." Journal of Applied Physiology. Vol. 96, no. 5 (2004):1,738–1,744.	Department of Veterans Affairs Medical Center, University of Nebraska Medical Center	Air	Dust	Dust from hog confinement facilities induces airway inflammation.
Romberger, D. J., V. Bodlak, S. G. Von Essen, T. Mathisen, and T. A. Wyatt. "Hog Barn Dust Extract Stimulates IL-8 And IL-6 Release in Human Bronchial Epithelial Cells Via PKC Activation." Journal of Applied Physiology. Vol. 93, no. 1 (2002):289–296.	Department of Veterans Affairs Medical Center, University of Nebraska Medical Center	Air	Dust	Dust from hog confinement facilities induces airway inflammation.
Schiffman, Susan S., Clare Studwell, Lawrence R. Landerman, Katherine Berman, and John S. Sundy. "Symptomatic Effects of Exposure to Diluted Air Sampled from a Swine Confinement Atmosphere on Healthy Human Subjects." Environmental Health Perspectives. Vol. 113, no. 5 (2005):567-576.	Duke University	Air	Hydrogen sulfide, ammonia, total suspended particulates, endotoxin, odor, dust	Short-term exposure to emissions expected downwind from a swine confinement facility can induce headaches, eye irritation, and nausea.
Sigurdarson, Sigurdur T., Patrick T. O'Shaughnessy, Janet A. Watt, and Joel N. Kline. "Experimental Human Exposure Inhaled Grain Dust and Ammonia: Towards a Model of Concentrated Animal Feeding Operations." American Journal of Industrial Medicine.Vol. 46, issue 5 (2004):345:348.	University of Iowa	Air	Dust, ammonia	Exposure to endotoxin-rich dust from CAFOs causes airflow obstruction in subjects with mild asthma.
Sundblad, B-M., B-M. Larsson, L. Palmberg, and K. Larsson. "Exhaled Nitric Oxide and Bronchial Responsiveness in Healthy Subjects Exposed to Organic Dust." European Respiratory Journal. Vol. 20, no. 2 (2002): 426–431.	National Institute of Environmental Medicine, Sweden	Air	Dust	Airway inflammation is induced by exposure to a farming environment.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Wickens, K., et. Al. "Farm Residence and Exposures and the Risk of Allergic Diseases in New Zealand Children." Allergy. Vol. 57, no. 12 (2002): 1,171-1,179.	University of Otago (New Zealand) Utrecht University (The Netherlands)	Air	Dust	There was a greater prevalence of allergic disease for children on farms.
Wilson, Vickie S., Christy Lambright, Joe Ostby, and L.E. Gray, Jr. "In Vitro and in Vivo Effects of 17β-Trenbolone: A Feedlot Effluent Contaminant." Toxicological Sciences. Vol. 70, no. 2 (2002): 202-211.	EPA	Water	Hormones	Hormones found in feedlot effluent caused reproductive malformations in laboratory rats and human cells.
Wyatt, Todd A., Rebecca E. Slager, Jane DeVasure, Brent W. Auvermann, Michael L. Mulhern, Susanna Von Essen, Tracy Mathisen, Anthony A. Floreani, and Debra J. Romberger. "Feedlot Dust Stimulation of Interleukin-6 And 8 Requires Protein Kinase C-Epsilon Human Bronchial Epithelial Cells." American Journal of Physiology-Lung Cellular and Molecular Physiology. Vol. 293, no. 5 (2007):1,163-1,170.	Nebraska Medical Center, Department of Veterans Affairs Medical Center, Texas A&M	Air	Dust	Dust extract from cattle feedlots stimulates airway inflammation at concentrations found downwind from the operation.
Studies indicating no impact				
Hill, Dagne D., William E. Owens, and Paul B. Tchounwou. "Prevalence of *Escherichia coli O157:H7* Bacterial Infections Associated With the Use of Animal Wastes in Louisiana for the Period 1996-2004." International Journal of Environmental Research and Public Health. Vol. 3, no. 1 (2006): 107-113.	Grambling State University, Louisiana State University, Jackson State University	Water	*Escherichia coli* (not measured)	Although some of the parishes surveyed had large amounts of animal waste generated each year, statistics did not show a correlations with *Escherichia coli 0157:H7* bacterial infections.
Hill, Dagne D., William E. Owens, and Paul B. Tchounwou. "Prevalence of Selected Bacterial Infections Associated with the Use of Animal Waste in Louisiana." International Journal of Environmental Research and Public Health. Vol. 2, no. 1 (2005): 84–93.	Jackson State University, Louisiana State University,	Water	*Escherichia coli* (not measured)	Although the four parishes surveyed had large amounts of animal waste generated, statistics does not show a correlation between this and bacterial infections.
Krapac, I.G., W.S. Dey, W.R. Roy, C.A. Smyth, E. Storment, S.L. Sargent, and J.D. Steele. "Impacts of Swine Manure Pits on Groundwater Quality." Environmental Pollution. Vol. 120, issue 2 (2002): 475-492.	Illinois State Geological Survey, University of Illinois, Illinois Department of Agriculture	Water	Chloride, ammonium, phosphate, potassium, nitrate, bacteria	Groundwater near swine CAFOs has not been significantly impacted.
Mugel, Douglas N. "Ground-Water Quality and Effects of Poultry Confined Animal Feeding Operations on Shallow Ground Water, Upper Shoal Creek Basin, Southwest Missouri, 2000." U.S. Geological Survey Water-Resources Investigations Report 02-4125 (2002).	United States Geological Survey	Water	Nutrients, bacteria	The results do not indicate that poultry CAFOs are affecting the shallow ground water with respect to nutrients and fecal bacteria.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Braun-Fahrlander, Charlotte, Josef Riedler, Udo Herz, Waltraud Eder, Marco Waster, Leticia Grize, Soyoun Maisch, David Carr, Florian Gerlach, Albrecht Bufe. "Environmental Exposure to Endotoxin and its Relation to Asthma in School-Age Children." The New England Journal of Medicine. Vol. 347, no. 12 (2002): 869-877.	Institute of Social and Preventive Medicine (Switzerland), Children's Hospital (Austria), Philipps University (Germany), Ruhr University (Germany), University Children's Hospital (Switzerland), University of Munich (Germany)	Air	Dust	Decreased risk of hay fever, asthma, and wheeze in children exposed to high levels of endotoxin in dust.
Elliott, L., K. Yeatts, and D. Loomis. "Ecological Associations Between Asthma Prevalence And Potential Exposure to Farming." European Respiratory Journal. Vol. 24, no. 6 (2004): 938–941.	University of North Carolina, Chapel Hill	Air	N/A	Findings are consistent with the hypothesis that certain farm exposures are protective against childhood asthma.
McGinn, S. M., H. H. Janzen, and T. Coates. "Atmospheric Pollutants and Trace Gases: Atmospheric Ammonia, Volatile Fatty Acids, and Other Odorants near Beef Feedlots." Journal of Environmental Quality. Vol. 32, no. 4 (2003):1,173–1,182.	Research Centre, Agriculture and Agri-Food Canada	Air	Ammonia, odor, organic compounds, total suspended particulates, dust	Odorants from feedlots were effectively dispersed. Emitted ammonia was deposited to the soil downwind.
Studies showing an indirect link between pollutants and impacts				
Valcour, James E., Pascal Michel, Scott A. McEwen, and Jeffrey B. Wilson. "Associations between Indicators of Livestock Farming Intensity and Incidence of Human Shiga Toxin-Producing *Escherichia coli* Infection." Emerging Infectious Diseases. Vol. 8, no. 3 (2002): 252-257.	University of Guelph; Université de Montréal; Centre for Infectious Disease Prevention and Control-Health Canada	Water	*Escherichia coli* (not measured)	The strongest associations with human *Escherichia coli* infection were the ratio of beef cattle to human population and the application of manure to the surface of agricultural land by a solid spreader and by a liquid spreader.
Wing, Steve, Stephanie Freedman, and Lawrence Band. "The Potential Impact of Flooding on Confined Animal Feeding Operations in Eastern North Carolina." Environmental Health Perspectives. Vol. 110, no. 4 (2002): 387–391.	University of North Carolina	Water	N/A	Flood events have a significant potential to degrade environmental health because of dispersion of wastes from industrial animal operations in areas with vulnerable populations.
Avery, Rachel C., Steve Wing, Stephen W. Marshall, and Susan S. Schiffman. "Odor from Industrial Hog Farming Operations and Mucosal Immune Function in Neighbors." Archives of Environmental Health. Vol. 59, no. 2 (2004): 101-108.	University of North Carolina, Duke University	Air	N/A	This study suggests that malodor from industrial swine operations can affect the secretory immune system, although the reduced levels reported are still within normal range.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Bullers, Susan. "Environmental Stressors, Perceived Control, and Health: The Case of Residents Near Large-Scale Hog Farms in Eastern North Carolina." Human Ecology. Vol. 33, no. 1 (2005): 1-16.	University of North Carolina Wilmington	Air/Water	N/A	Residents living near large-scale hog farms in eastern North Carolina report symptoms related to respiratory and sinus problems and nausea.
Chénard, Liliane, Ambikaipakan Senthilselvan, Vaneeta K. Grover, Shelley P. Kirychuk, Joshua A. Lawson, Thomas S. Hurst, and James A. Dosman. "Lung Function and Farm Size Predict Healthy Worker Effect in Swine Farmers." Chest. Vol. 131, no. 1 (2007): 245-254.	Institute of Agriculture Rural and Environmental Health, University of Saskatchewan (Canada), University of Alberta (Canada), Canadian Institute of Health Research	Air	N/A	Some swine workers are less affected by swine air and continue in the profession. Other workers are more affected.
Chrischilles, Elizabeth, Richard Ahrens, Angela Kuehl, Kevin Kelly, Peter Thorne, Leon Burmeister, and James Merchant. "Asthma Prevalence and Morbidity Among Rural Iowa Schoolchildren." Journal of Allergy and Clinical Immunology. Vol. 113, no. 1 (2004): 66-71.	University of Iowa, EPA	Air	N/A	Among children who wheeze, farm and nonfarm children were equally likely to have been given a diagnosis of asthma and had comparable morbidity.
Dosman, J.A., J.A. Lawson, S.P. Kirychuk, Y. Cormier, J. Biem, and N. Koehncke. "Occupational Asthma in Newly Employed Workers in Intensive Swine Confinement Facilities." European Respiratory Journal. Vol. 24, no. 6 (2004): 698–702.	Institute of Agricultural Rural and Environmental Health, University of Saskatchewan (Canada), Laval University (Canada)	Air	N/A	Newly employed workers in intensive swine confinement facilities reported development of acute onset of wheezing and cough suggestive of asthma.
Merchant, James A., Allison L. Naleway, Erik R. Svendsen, Kevin M. Kelly, Leon F. Burmeister, Ann M. Stromquist, Craig D. Taylor, Peter S. Thorne, Stephen J. Reynolds, Wayne T. Sanderson, and Elizabeth A. Chrischilles. "Asthma and Farm Exposures in a Cohort of Rural Iowa Children." Environmental Health Perspectives. Vol. 113, No. 3 (2005): 350-356.	University of Iowa, EPA, Colorado State University, Kaiser Permanente	Air	N/A	There was a high prevalence of asthma health outcome among farm children living on farms that raise swine and raise swine and add antibiotics.
Mirabelli, Maria C., Steve Wing, Stephen W. Marshall, and Timothy C. Wilcosky. "Asthma Symptoms Among Adolescents Who Attend Public Schools That Are Located Near Confined Swine Feeding Operations." Pediatrics. Vol. 118, no. 1 (2006): 66-75.	University of North Carolina, RTI International	Air	N/A	Estimated exposure to airborne pollution from confined swine feeding operations is associated with adolescents' wheezing symptoms.
Palmberg, Lena, Britt-Marie Larsson, Per Malmberg, and Kjell Larsson. "Airway Responses of Healthy Farmers and Nonfarmers to Exposure in a Swine Confinement Building." Scandinavian Journal of Work, Environment, and Health. Vol. 28, no. 4 (2002): 256-263.	National Institute of Environmental Medicine (Sweden), National Institute for Working Life (Sweden)	Air	N/A	Altered lung function and bronchial responsiveness was found in nonfarming subjects. Only minor alterations were found in the farmers.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Radon, Katja, Anja Schulze, Vera Ehrenstein, Rob T. van Strien, Georg Praml, and Dennis Nowak. "Environmental Exposure to Confined Animal Feeding Operations and Respiratory Health of Neighboring Residents." Epidemiology. Vol. 18, no. 3 (2007): 300-308.	Institute for Occupational and Environmental Medicine (Germany), National Research Centre for Environment and Health (Germany), Boston University, Municipal Health Service Amersterdam	Air	N/A	Respiratory disease was found among resident living near confined animal feeding operations.
Sigurdarson, Sigurdur T. and Joel N. Kline. "School Proximity to Concentrated Animal Feeding Operations and Prevalence of Asthma in Students." Chest. Vol. 129, no. 6 (2006):1,486–1,491.	University of Iowa Carver College of Medicine, University of Iceland	Air	N/A	Children in the study school, located one-half mile from a CAFO, had a significantly increased prevalence of physician-diagnosed asthma.
Studies measuring pollutants				
Anderson, M.E. and M.D. Sobsey. "Detection And Occurrence of Antimicrobially Resistant E. Coli In Groundwater on or Near Swine Farms In Eastern North Carolina." Water Science & Technology. Vol. 54, no. 3 (2006): 211-218.	University of North Carolina	Water	Antibiotics	Antibiotic-resistant *E. coli* strains are present in groundwaters of swine farms.
Batt, Angela L., Daniel D. Snow, and Diana S. Aga. "Occurrence of Sulfonamide Antimicrobials in Private Water Wells in Washington Country, Idaho, USA." Chemosphere. Vol. 64, issue 11 (2006): 1,963-1,971.	State University of New York at Buffalo, University of Nebraska	Water	Antimicrobials, nitrate, ammonium	All six sampled wells were contaminated by veterinary antimicrobials and had elevated concentrations of nitrate and ammonium. Three wells had nitrate levels exceeding EPA thresholds.
Campagnolo, Enzo R., Kammy R. Johnson, Adam Karpati, Carol S. Rubin, Dana W. Kolpin, Michael T. Meyer, J. Emilio Esteban, Russell W. Currier, Kathleen Smith, Kendall M. Thu, and Michael McGeehin. "Antimicrobial Residues in Animal Waste and Water Resources Proximal to Large-Scale Swine and Poultry Feeding Operations." The Science of the Total Environment. Vol. 299, no. 1 (2002): 89-95.	CDC, U.S. Geological Survey, Iowa Department of Public Health, Ohio Department of Health, University of Iowa	Water	Antimicrobials	Multiple classes of antimicrobial compounds were detected in surface and groundwater samples collected proximal to the swine and poultry farms.
Durhan, Elizabeth J., Christy S. Lambright, Elizabeth A. Makynen, James Lazorchak, Phillip C. Hartig, Vickie S. Wilson, L. Earl Gray, and Gerald T. Ankley. "Identification of Metabolites of Trenbolone Acetate in Androgenic Runoff from a Beef Feedlot." Environmental Health Perspectives. Vol. 114, supp. 1 (2006):65–68.	EPA	Water	Hormones	Whole-water samples from the discharge contained detectible concentrations of hormones.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Gessel, Peter D., Neil C. Hansen, Sagar M. Goyal, Lee J. Johnston, and Judy Webb. "Persistence Of Zoonotic Pathogens in Surface Soil Treated With Different Rates of Liquid Pig Manure." Applied Soil Ecology. Vol. 25, issue 23 (2004): 237-243.	University of Minnesota	Water	Pathogens	Manure application rate was correlated positively with the persistence of fecal indicators but did not relate to survival of indicators with short survival times.
Haggard, Brian E. , Paul B. DeLaune, Douglas R. Smith, and Philip A. Moore, Jr. "Nutrient and B17-Estradiol Loss in Runoff Water From Poultry Litters." Journal of the American Water Resources Association. Vol. 41, no. 2 (2005):245-256.	USDA, University of Arkansas	Water	Nutrients, hormones	In general, poultry litter applications increased nutrient and hormone concentrations in runoff water.
Hutchins, Stephen R., Mark V. White, Felisa M. Hudson, and Dennis D. Fine. "Analysis of Lagoon Samples from Different Concentrated Animal Feeding Operations for Estrogens and Estrogen Conjugates." Environmental Science & Technology. Vol. 41, no. 3 (2007): 738-744.	EPA, Shaw Environmental and Infrastructure	Water	Hormones	Estrogen conjugates contribute significantly to the overall estrogen load, even in different types of CAFO lagoons.
Koike, S., I.G. Krapac, H.D. Oliver, A.C. Yannarell, J.C. Chee-Sanford, R.I. Aminov, and R.I. Makie. "Monitoring and Source Tracking of Tetracycline Resistance Genes in Lagoons and Groundwater Adjacent to Swine Production Facilities over a 3-Year Period." Applied and Environmental Microbiology. Vol. 73, no. 15 (2007): 4,813-4,823.	University of Illinois, USDA, Illinois State Geological Survey, Rowett Research Institute (UK)	Water	Antibiotics	Antibiotic resistance genes in groundwater are affected by swine manure and also part of the indigenous gene pool.
Miller, David H. and Gerald T. Ankley. "Modeling Impacts On Populations: Fathead Minnow (Pimephales Promelas) Exposure to the Endocrine Disruptor 17ß-Trenbolone as a Case Study." Ecotoxicology and Environmental Safety. Vol. 59, issue 1 (2004): 1-9.	EPA	Water	Hormones	Model shows that if fathead minnow is exposed to continuous concentrations of hormone, there will be a risk of extinction.
Nelson, Nathan O., John E. Parsons, and Robert L. Mikkelsen. "Field-Scale Evaluation of Phosphorus Leaching in Acid Sandy Soils Receiving Swine Waste." Journal of Environmental Quality. Vol. 34, no. 6 (2005): 2,024-2,035.	USDA, North Carolina State University	Water	Phosphorus	The results show that substantial quantities of phosphorus can be leached through soils with low phosphorus sorption capacities.
Peak, Nicholas, Knapp, Charles W, Richard K. Yang, Margery M. Hanfelt, Marilyn S. Smith, Diana S. Aga, and David W. Graham. "Abundance of Six Tetracycline Resistance Genes in Wastewater Lagoons at Cattle Feedlots With Different Antibiotic Use Strategies." Environmental Microbiology. Vol. 9, no. 1 (2007): 143-151.	University of Kansas, Kansas State University, State University of New York at Buffalo	Water	Antibiotic resistant genes	CAFOs using larger amounts of antibiotics had significantly higher detected resistance gene levels.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Sapkota, Amy R., Frank C. Curriero, Kristen E. Gibson, and Kellogg J. Schwab. "Antibiotic-Resistant Enterococci and Fecal Indicators in Surface Water and Groundwater Impacted by a Concentrated Swine Feeding Operation." Environmental Health Perspectives. Vol. 115, no. 7 (2007):1,040–1,045.	Johns Hopkins Bloomberg School of Public Health; University of Maryland	Water	Antibiotic resistant bacteria, fecal indicators	Detected elevated levels of fecal indicators and antibiotic-resistant bacteria in water sources down gradient from a swine facility.
Soto, Ana M., Janine M. Calabro, Nancy V. Prechtl, Alice Y. Yau, Edward F. Orlando, Andreas Daxenberger, Alan S. Kolok, Louis J. Guillette, Jr., Bruno le Bizec, Iris G. Lange, and Carlos Sonnenschein. "Androgenic and Estrogenic Activity in Water Bodies Receiving Cattle Feedlot Effluent in Eastern Nebraska, USA." Environmental Health Perspectives. Vol. 112, no. 3 (2004):346–352.	Tufts University; Southwest Research Institute; St. Mary's College of Maryland; Universität München-Weihenstephan, Germany; University of Nebraska; University of Florida; Ecole Nationale Vétérinaire de Nantes, France	Water	Hormones	Feedlot effluents contain sufficient levels of hormonally active agents to warrant further investigation of possible effects on aquatic ecosystem health.
Thorsten, Christiana, Rudolf J. Schneider, Harald A. Farber, Dirk Skutlarek, Michael T. Meyer, and Heiner E. Goldbach. "Determination of Antibiotic Residues in Manure, Soil, and Surface Waters." Acta hydrochimica et hydrobiologica. Vol. 31, no. 1 (2003):36–44.	University of Bonn, Germany; U.S. Geological Survey	Water	Antibiotics	In each of the surface waters tested antibiotics could be detected.
Thurston-Enriquez, Jeanette A., John E. Gilley, and Bahman Eghball. "Microbial Quality of Runoff Following Land Application of Cattle Manure And Swine Slurry." Journal of Water and Health. vol. 3, no. 2 (2005): 157-171.	University of Nebraska	Water	Microbials	Large microbial loads could be released via heavy precipitation events and could have a significant impact on water bodies.
Toetz, Dale. "Nitrate in Ground and Surface Waters in the Vicinity of a Concentrated Animal Feeding Operation." Archives of Hydrobiology. Vol. 166, no. 1 (2006): 67-77.	Oklahoma State University	Water	Nitrogen	Drinking water was contaminated with CAFOs as the suspected source.
U.S. Department of Interior. U.S. Geological Survey. In cooperation with U.S. Environmental Protection Agency, National Exposure Research Laboratory. Geochemistry and Characteristics of Nitrogen Transport at a Confined Animal Feeding Operations in a Coastal Plain Agricultural Watershed, and Implications for Nutrient Loading in the Neuse River Basin, North Carolina, 1999-2002. Scientific Investigations Report 2004-5283, Reston, Va.: (2004).	U.S. Geological Survey, EPA	Water	Nitrogen	Large amounts of nitrogen moving in the estuary as a result of extreme events may potentially cause algal growths.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
United State Geological Survey in cooperation with Virginia Department of Health. Water-Quality Data from Ground- and Surface-Water Sites near Concentrated Animal Feeding Operations (CAFOs) and non-CAFOs in the Shenandoah Valley and Eastern Shore of Virginia, January-February, 2004. Reston, Va (2005).	United State Geological Survey in cooperation with Virginia Department of Health	Water	Bacteria, antibiotics, trace metals, biological oxygen demand, nitrogen	N/A
United States Geological Survey. Fractionation and Characterization of Organic Matter in Wastewater from a Swine Waste-Retention Basin. Scientific Investigations Report 2004-5217 (2004).	United States Geological Survey	Water	Organic matter	The bulk of the organic matter consists of microbial cellular constituents and their degradation products.
Chapin, Amy, Ana Rule, Kristen Gibson, Timothy Buckley, and Kellogg Schwab. “Airborne Multidrug-Resistant Bacteria Isolated from a Concentrated Swine Feeding Operation.” Environmental Health Perspectives. Vol. 113, no. 2 (2005):137-142.	Johns Hopkins University	Air	Antibiotic resistant bacterial pathogens	Multidrug-resistant bacterial pathogens were detected in the air of a swine CAFO.
Donham, Kelley. J., Joung Ae Lee, Kendall Thu, and Stephen J. Reynolds. “Assessment of Air Quality at Neighbor Residences in the Vicinity Of Swine Production Facilities.” Journal of Agromedicine. Vol. 11, no. 3-4 (2006): 15-24.	University of Iowa, Northern Illinois University, and Colorado State University	Air	Hydrogen sulfide, ammonia, carbon dioxide, particulate matter	Average concentration of hydrogen sulfide exceeded EPA recommended community standards in all three areas assessed.
Gibbs, Shawn G., Christopher F. Green, Patrick M. Tarwater, Linda C. Mota, Kristina D. Mena, and Pasquale V. Scarpino. “Isolation of Antibiotic-Resistant Bacteria from the Air Plume Downwind of a Swine Confined or Concentrated Animal Feeding Operation.” Environmental Health Perspectives. Vol. 114, no. 7 (2006):1,032–1,037.	University of Texas, University of Cincinnati	Air	Antibiotic-resistant bacteria	Bacterial concentrations with multiple antibiotic resistances or multidrug resistance were recovered inside and outside to 150 m downwind of a facility, even after antibiotic use was discontinued.
Harper, Lowry A., Ron R. Sharpe, Tim B. Parkin, Alex De Visscher, Oswald van Cleemput, and F. Michael Byers. “Nitrogen Cycling through Swine Production Systems: Ammonia, Dinitrogen, and Nitrous Oxide Emissions.” Journal of Environmental Quality. Vol. 33, no. 4 (2004): 1,189-1,201.	USDA, Ghent University (Belgium)	Air	Nitrogen	In contrast with previous and current estimates of ammonia emissions from CAFOs, this study found smaller ammonia emissions from animal housing, lagoons, and fields.
Hamscher, Gerd, Heike Theresia Pawelzick, Silke Sczesny, Heinz Nau, and Jörg Hartung. “Antibiotics in Dust Originating from a Pig-Fattening Farm: A New Source of Health Hazard for Farmers?” Environmental Health Perspectives. Vol. 111, no. 13 (2003):1,590–1,594.	School of Veterinary Medicine Hannover, Germany	Air	Antibiotics	Five different antibiotics were detected in dust samples swine feeding operation.

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Hoff, Steven J., Dwaine S. Bundy, Minda A. Nelson, Brian C. Zelle, Larry D. Jacobson, Albert J. Heber, Jinqin Ni, Yuanhui Zhang, Jacek A. Koziel, and David B. Beasley. "Emissions of Ammonia, Hydrogen Sulfide, and Odor before, during, and after Slurry Removal from a Deep-Pit Swine Finisher." Journal of the Air & Waste Management Association. Vol. 56, no. 5 (2006): 581-590.	Iowa State University, University of Minnesota, Purdue University, University of Illinois, North Carolina State University	Air	Ammonia, hydrogen sulfide, odor	Emissions of ammonia, hydrogen sulfide, and odor had large increases during slurry removal. A slurry removal even will result in acute exposure for animals and workers.
O'Connor, Rod, Mark O'Connor, Kurt Irgolic, Justin Sabrsula, Hakan Gurleyuk, Robert Brunette, Crystal Howard, Jennifer Garcia, John Brien, June Brien, and Jessica Brien. "Transformations, Air Transport, and Human Impact of Arsenic from Poultry Litter." Environmental Forensics. Vol. 6, no. 1 (2005): 83-89.	Chenard Consulting Services, Karl-Franzeas University (Austria), University of North Carolina, Frontier Geosciences, Aqua-Tech Laboratories	Air	Arsenic	Levels of arsenic found in homes. This could represent a significant health risk.
Radon, Katja, Brigitta Danuser, Martin Iversen, Eduard Monso, Christoph Weber, Jorg Hartung, Kelley J. Donham, Urban Palmgren, and Dennis Nowak. "Air Contaminants in Different European Farming Environments." Annals of Agriculture and Environmental Medicine. Vol. 9, no. 1 (2002): 41-48.	Ludwig-Maximilians-University (Germany), Swiss Federal Institute of Technology, Aarhus University Hospital (Denmark), Hospital Germans Trial I Pujol (Spain), School of Veterinary Medicine (Germany), University of Iowa, Pegasus Labor GmbH (Germany)	Air	Dust, endotoxin, fungi	The exposure level found in this study might put the farmers at risk from respiratory diseases.
Razote, E.B., R.G. Maghirang, B.Z. Predicala, J.P. Murphy, B.W. Auvermann, J.P. Harner III, and W.L. Hargrove. "Laboratory Evaluation of the Dust-Emission Potential of Cattle Feedlot Surfaces." Transactions of the ASABE. Vol. 49, no. 4 (2006): 1,117-1,124.	Kansas State University, Prairie Swine Center, Inc. (Canada), Texas A&M University	Air	Particulate Matter	N/A
Robarge, Wayne P., John T. Walker, Ronald B. McCulloch, and George Murray. "Atmospheric Concentrations of Ammonia and Ammonium at an Agricultural Site in the Southeast United States." Atmospheric Environment. Vol. 36, no. 10 (2002): 1,661-1,674.	North Carolina State University, EPA, URS Corporation, North Carolina Department of Environmental and Natural Resources	Air	Ammonia	Elevated ambient ammonia concentrations near an agricultural site.
United State Environmental Protection Agency. National Emission Inventory – Ammonia Emissions from Animal Husbandry Operations, Draft Report. Washington, D.C. (2004).	EPA	Air	Ammonia	N/A

Study	Sponsor[a]	Medium	Pollutant(s)	Impact
Walker, J.T., W.P. Robarge, Y. Wu, and T.P. Meyers. "Measurement of Bi-Directional Ammonia Fluxes Over Soybean Using Themodified Bowen-Ratio Technique." Agricultural and Forest Meteorology. Vol. 138, no. 1-4 (2006): 54-68.	EPA, North Carolina State University, NASA, NOAA	Air	Ammonia	In general, the net deposition flux was lower than expected.
Walker, John T., Wayne P. Robarge, Arun Shendrikar, and Hoke Kimball. "Inorganic Pm2.5 at a U.S. Agricultural Site." Environmental Pollution. Vol. 139, no. 2 (2006): 258-271.	EPA, North Carolina State University, North Carolina Department of Environment and Natural Resources	Air	Particulate matter	Model results show that reductions in atmospheric ammonia will have minimal effect on organic PM2.5 during summer and a moderate effect during winter.
Walker, J.T., Dave R. Whitall, Wayne P. Robarge, and Hans W. Pearl. "Ambient Ammonia and Ammonium Aerosol Across a Region of Variable Ammonia Emission Density." Atmospheric Environment. Vol. 38, no. 9 (2004): 1,235-1,246.	EPA, NOAA, North Carolina State University, University of North Carolina	Air	Ammonia, ammonium	Agricultural ammonia emissions influence local ambient concentrations of ammonia and PM2.5.
Wilson, Sacoby M. and Marc L. Serre. "Examination of Atmospheric Ammonia Levels Near Hog Cafos, Homes, and Schools In Eastern North Carolina." Atmospheric Environment. Vol. 41, issue 23 (2007): 4,977–4,987.	University of Michigan, Ann Arbor; University of North Carolina at Chapel Hill	Air	Ammonia	Distance to one or more CAFOs is the key variable in controlling atmospheric ammonia at the community level in Eastern N.C.
Muller-Suur, C., P.H. Larsson, K. Larsson, J. Grunewald. "Lymphocyte Activation After Exposure to Swine Dust: A Role Of Humoral Mediators and Phagocytic Cells." European Respiratory Journal. Vol. 19, issue 1 (2002): 104-107.		Air	Dust	About immune system response.
Charavaryamath, Chandrashekhar, Kyathanahalli S Janardhan, Hugh G Townsend, Philip Willson, and Baljit Singh. "Multiple Exposures to Swine Barn Air Induce Lung Inflammation and Airway Hyper-Responsiveness." Respiratory Research. Vol. 6, no. 1 (2005):50-66.	University of Saskatchewan, Canada	Air	Endotoxin	Does not address human impacts.
Eduard, Wijnand, Ernst Omenaas, Per Sigvald Bakke, Jeroen Douwes, and Dick Heederik. "Atopic and Non-atopic Asthma in a Farming and a General Population." American Journal of Industrial Medicine. Vol. 46, issue 4 (2004): 396-399.	National Institute of Ocupational Health (Norway), University of Bergen (Norway), University of Wellington (New Zealand)	Air	N/A	Protective effect of the farm environment on asthma.

Source: GAO's analysis of identified studies.

[a]Sponsor refers to the organization under whose auspices the research was conducted or with whom the primary researchers were affiliated.

Appendix V: Comments from the Environmental Protection Agency

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

AUG 2 6 2008

OFFICE OF
AIR AND RADIATION

Ms. Anu K. Mittal
Director, Natural Resources and Environment
U. S. Government Accountability Office
Washington, DC 20548

Dear Ms. Mittal:

The U. S. Environmental Protection Agency (EPA) appreciates the opportunity to review and comment on the Government Accountability Office (GAO) draft report, "*Concentrated Animal Feeding Operations: EPA Needs More Information and a Clearly Defined Strategy to Protect Air and Water Quality from Pollutants of Concern*" (GAO-08-944). EPA agrees in part with the conclusions and recommendations in the draft report. Below I provide brief comments and clarification on EPA's position regarding the recommendations. Additional technical comments and clarifications on draft report language have been provided in a separate document.

Recommendation 1:

In order to more effectively monitor and regulate CAFOs, we recommend that the Administrator of the Environmental Protection Agency develop a comprehensive inventory of CAFOs nationwide and incorporate appropriate internal controls to ensure the quality of data. The inventory should be periodically updated to capture changes that have occurred in the animal production industry.

In Waterkeeper Alliance v. EPA, the Second Circuit Court of Appeals found that EPA did not have the authority to permit non-discharging CAFOs. EPA is finalizing amendments to a rule that would require CAFOs that discharge to apply for National Pollutant Discharge Elimination System (NPDES) permits. EPA's Office of Water has supported the Office of Enforcement and Compliance Assurance in working with EPA Regions and States to develop and implement a new national NPDES data system to collect and record facility-specific information on permitted CAFOs. This data system, called the Integrated Compliance Information System (ICIS), allows EPA to have an updated national inventory of permitted CAFOs, including number, location, size, and permitted discharges. National data on inspections, enforcement actions, and other NPDES program information will also be collected. Although this information is currently collected by permitting authorities for permitted CAFOs, there is no

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comprehensive national database where the information is stored. While ICIS-NPDES has the functionality to provide complete data on the CAFO universe, the data must be consistently collected and entered into ICIS by states and EPA regions. Thus, EPA is developing a proposed rule package that would set national requirements for certain NPDES program information being provided by authorized states to ICIS. This information may include an obligation for authorized states to provide national data for identifying facilities that have been issued, or applied for, a CAFO permit, as well as facilities that should have applied for a CAFO permit based on an inspection or enforcement action.

Recommendation 2:

In order to more effectively determine the extent of air emissions from animal feeding operations, the Administrator of the Environmental Protection Agency should:

a. reassess the current data collection efforts, including its internal controls, to ensure that the national air emissions monitoring study will provide the scientific and statistically valid data that EPA needs for developing its air emissions protocols;

The Agency is continuously evaluating the national air monitoring study, both the data that are being collected, and the methods that are being used to collect these data. This continuous evaluation has resulted in changes being made and documented in numerous Standard Operating Procedures and also to the overall project Quality Assurance Plan. These changes range from items such as utilization of a different instrument than originally intended to changes in the maintenance schedule for certain items. All these changes have been identified through discussions with the monitoring contractor or through the audits described below.

The Agency is currently involved in a program of conducting Technical Systems Audits at each monitoring site to ensure the contractor is performing according to the approved Quality Assurance Project Plan. Each site is scheduled to be audited once during the first year of data collection and once during the second year. To date, the Agency has performed the first year audits at all but six of the monitoring sites with those remaining sites scheduled to be audited by the end of September 2008.

b. Provide information to stakeholders on the additional data that it plans to use to supplement the national air emissions monitoring study

With respect to the supplemental data that will be used to augment the data collected from the national air emissions monitoring study, we are not able to identify at this time which individual studies we plan to use. However, the Agency has been meeting with the Department of Agriculture (USDA), with representatives from their offices of Agricultural Research Service, Cooperative State Research, Education, and

Extension Service, and the Economic Research Service to help identify what research is ongoing and where gaps may still exist. We recently held a two-day workshop in Research Triangle Park, North Carolina with USDA representatives that focused on agricultural air emissions. Day 2 of the workshop focused exclusively on CAFO research.

c. Establish a strategy and timetable for developing a process-based model that will provide more sophisticated air emissions estimating methodologies for animal feeding operations.

The Agency has begun to evaluate what is necessary to develop a process-based model for estimating emissions from animal feeding operations. The emissions estimating methodology that will be developed from the monitoring study will assess the wide range of process information that is being collected in the monitoring study. To the extent that these parameters have a significant and logical impact on emissions, they will be included in the development of a process-based model. This will be performed through the use of a statistical software application that performs a multiple regression analysis of the process parameters and the measured emissions.

As part of the joint EPA/USDA workshop, there were several presentations on process based models that are currently being developed throughout the country and discussions on what data needs still exist to complete these models. These discussions with both USDA and modeling experts will continue as we flesh out our plans for developing a process based model.

Once again, thank you for the opportunity to respond.

Sincerely,

for Elizabeth Craig

Robert J. Meyers
Principal Deputy Assistant Administrator

Appendix VI: GAO Contact and Staff Acknowledgments

GAO Contact

Anu Mittal (202) 512-3841 or mittala@gao.gov

Staff Acknowledgments

In addition to the individual named above, Sherry L. McDonald, Assistant Director; Kevin Bray; Yecenia C. Camarillo; Wendy Dye; Paul Hobart; Cathy Hurley; Holly L. Sasso; James W. Turkett; and Greg Wilmoth made key contributions to this report. Also contributing to this report were Elizabeth Beardsley, Ben N. Shouse, and Carol Herrnstadt Shulman.

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Appendix A.
Census of Agriculture Methodology

The purpose of a census is to enumerate all objects with a defined characteristic. For the census of agriculture, that goal is to account for "any place from which $1,000 or more of agricultural products were produced and sold, or normally would have been sold, during the census year." To do this, NASS creates a Census Mail List (CML) of agricultural operations that potentially meet the farm definition, collects agricultural information from those operations, reviews the data, corrects or completes the requested information, and combines the data to provide information on the characteristics of farm operations and farm producers at the national, State, and county levels. In this appendix, these census processes are described.

THE CENSUS POPULATION

The Census Mail List

The National Agricultural Statistics Service (NASS) maintains a list of farmers and ranchers from which the CML is compiled. The goal is to build as complete a list as possible of agricultural places that meet the farm definition. The CML compilation begins with the list used to define sampling populations for NASS surveys conducted for the agricultural estimates program. Each record on the list includes name, address, telephone number, and email plus additional information that is used to efficiently administer the census of agriculture and agricultural estimates programs.

NASS builds and improves the list on an ongoing basis by obtaining outside source lists. Sources include State and federal government lists, producer association lists, seed grower lists, pesticide applicator lists, veterinarian lists, marketing association lists, and a variety of other agriculture-related lists. NASS also obtains special commodity lists to address specific list deficiencies. These outside source lists are matched to the NASS list using record linkage programs. Most names on newly acquired sources are already on the NASS list. Records not on the NASS list are treated as potential farms until NASS can confirm their existence as a qualifying farm. Staff in NASS regional and field offices routinely contact these potential farms to determine whether they meet the farm definition. For the 2022 Census of Agriculture, NASS made a concerted effort to work with community-based organizations not only to improve list coverage for minorities but also to increase census awareness and participation.

List building activities for developing the 2022 CML started in 2019 by updating list information from respondents to the 2017 Census of Agriculture. Between 2017 and 2022, NASS conducted a series of National Agricultural Classification Surveys (NACS) on over 2.1 million records, which included nonrespondents from the 2017 census and newly added records from outside list sources. The NACS report forms collected information that was used to determine whether an operation met the farm definition. If the definition was met, the operation was added to the NASS list and subsequently to the CML. Addressees that were nonrespondents to a NACS were also added to the CML and identified with a special status code.

Measures were taken to improve name and address quality. Additional record linkage programs were run to detect and remove duplicate records both within each State and across States. List addresses were processed through software programs that utilize the United States Postal Service's National Change of Address System and the Locatable Address Conversion System to improve mail delivery. Records on the list with missing or invalid phone numbers were matched against a nationally available telephone database to obtain as many phone numbers as possible. To reduce costs, operations with characteristics that indicated they were unlikely to be farms, according to the farm definition, were removed from the list.

The official CML for the 2022 Census of Agriculture was established on September 3, 2022. The list contained 2,879,343 records. Of these, 2,079,333 records were thought to meet the NASS farm definition and 800,010 were potential farm records, which included NACS nonrespondents, other records added to the CML by the NASS regional field offices after the record linkage process, and late adds to the CML that were not included in any previous NACS or State screening survey.

Not on the Mail List (NML)

Extensive efforts are directed toward developing a CML that includes all farms in the U.S. However, some farms are not on the list, and some agricultural operations on the list are not farms. NASS uses its June Area Survey (JAS) to

quantify the number and types of farms not on the CML. The records in the JAS that are not on the CML are said to be in the Not-on-the-Mail List (NML) domain. If a JAS record in the NML domain is determined to be a farm during the census, it is an NML farm. The NML farms are used to measure coverage associated with the grown crops, farm numbers, and inventories of cattle. Sampled segments in the JAS are personally enumerated. Each operation identified within a segment boundary is known as a tract.

The 2022 JAS sample was increased to improve the farm counts for operations that produced specialty commodities or had socially disadvantaged or minority producers. The total JAS sample consisted of 14,015 segments of which 4,933 were additional ACES segments. This set of additional segments is referred to as the Agricultural Coverage Evaluation Survey (ACES) segments. The ACES segments were selected using a multivariate sampling design that targeted specific items at the U.S. level. The 2022 JAS consisted of sample segments from all States, with the exception of Alaska where NASS does not maintain an area frame.

During the JAS/ACES enumeration process, each tract is identified as either agricultural or non-agricultural. Each JAS/ACES agricultural tract is identified as a farm or non-farm in June based on the farm definition of $1,000 of sales or potential sales of agricultural products. Non-agricultural tracts are further classified into categories: with farm potential, with unknown farm potential, or with no farm potential. The names and addresses collected in the 2022 JAS/ACES were matched to the CML. Those from the 2022 JAS/ACES that did not match were determined to be in the NML domain and sent a yellow census report form so that they could be differentiated from the green report form sent to those addressees on the CML. Instructions on the census report form directed any respondent who received duplicate forms to complete the CML form and to mail all duplicate forms back together. Those who returned a CML and an NML form had been misclassified as NML and were removed from the NML domain.

The initial NML mailout consisted of 41,273 records. A total of 40,775 NML records were analyzed, of which 1,913 records were confirmed to be NML and in-scope.

The farm/nonfarm status of each NML domain operation was determined based on the reported data in the census form. An operation in the NML domain that was determined to be a farm is referred to as an NML farm. Characteristics of NML farms and their producers provided a measure of the undercoverage of farms present in the CML.

The percentage of farms not represented on the CML varied by State. In general, NML farms tended to be small in acreage, production, and sales of agricultural products. Farm operations were missing from the CML for various reasons, including the possibility that the operation started after development of the CML, the operation was so small that it did not appear in any agriculture-related source list, or the operation was misclassified as a nonfarm prior to census mailout. The CML was used with the NML in a capture-recapture framework to represent all farming operations across all States in the JAS sample.

DATA COLLECTION OUTREACH AND PROMOTIONAL EFFORTS

NASS planned and executed a multi-phase strategic communications campaign for the 2022 Census of Agriculture, to increase the level of awareness and response among all U.S. agricultural producers.

- Phase 1 ran from April 2021 − June 2022. It raised awareness about the census and list building, encouraged producers to sign up in response to NASS mailings and at community, association, and other stakeholder meetings where NASS partners reached out.

- Phase 2 ran from July 2022 − October 2022. It notified farm producers and agricultural organizations that the census would be mailed in November and encouraged communications regarding the census.

- Phase 3 ran from November 2022 – May 2023. It focused on census data collection with messaging urging response to remind producers that it was not too late to respond.

- Phase 4 ran from August 2023 – February 2024. It thanked producers for their participation and NASS partners for their support and informed everyone of the February 2024 data release plan.

The communications campaign focused on these primary areas: partnership building, local-level outreach, public relations, media relations, paid media, social media and some paid advertising. Some external support was provided by a private communications agency (i.e. primarily assisted with design and paid advertising).

The unifying force behind the 2022 communications campaign was the theme “Your Voice. Your Future. Your Opportunity.” This was accompanied by supporting messages and artwork that created a consistent look and feel for all census communications. All messages and materials served the purpose of inspiring action: Sign Up to Be Counted - Show the Value of Your Work - *Grow Your*

Farm Future - Shape Farm Policy/Programs - Respond to the Census of Agriculture - Be counted - The Census of Agriculture is Your Voice, Your Future, Your Opportunity.

Partnership and Local-Level Outreach

At the national level, NASS officials met with leaders from dozens of agricultural organizations, State Departments of Agriculture, and other USDA agencies to successfully secure their support in promoting the census among their constituencies. Stakeholders partnered with NASS to promote the 2022 Census of Agriculture through publications (e.g. newsletters), special mailings, speeches, social media, websites, and other communications. In addition, through grassroots-level outreach and efforts, NASS partnered with a number of community-based organizations to reach minority and limited-resource farmers and ranchers. National-level outreach was encouraged and mirrored at the regional, State, and local levels. Among the highlights of these partnership efforts was the production of multiple television and radio public service announcements featuring the U.S. Secretary of Agriculture, State secretaries, directors, and commissioners of agriculture and leaders from community-based organizations.

Coverage of American Indian and Alaska Native Farm Producers

To maximize coverage of American Indian and Alaska Native agricultural producers, special procedures were followed in the census. A concerted effort was made to get individual reports from every American Indian and Alaska Native farm or ranch producer in the country. If this was not possible within some reservations, a single reservation-level census report was obtained from knowledgeable reservation officials. These reports covered agricultural activity on the entire reservation. NASS staff reviewed these data and removed duplication with any data reported by American Indian or Alaska Native producers who responded on an individual census report form. Additionally, NASS obtained, from knowledgeable reservation officials, the count of American Indian and Alaska Native producers (on reservations) who were not counted through individual census report forms, but whose agricultural activity was included in the reservation-level report form.

Table D, **American Indian and Alaska Native Producers:** 2022 provides the number of producers (1) reported as American Indian or Alaska Native in the race category, either as a single race or in combination with other races, on the individual census report forms (for up to four per farm) and (2) identified as American Indian or Alaska Native producers farming on reservations by reservation officials. The count from the individual report forms is summarized in the "Individually reported" column. It includes up to four producers on or off reservations. The "Other" column provides counts of producers on reservations as reported by a reservation or tribal official. The "Total" column is simply a sum of the "Individually reported" and the "Other" columns. Tables in other parts of the publication count the reservation-level reports as single farms.

Public Relations

In the public relations arena, NASS worked with internal and external, national, regional, and local stakeholders to equip them with communications tools and resources to deliver the census communications message to their audiences. NASS utilized its Intranet, the Partner Tools section on the census webpage, and a regularly scheduled, newsletter-type email update to deliver materials to staff across its 12 regions, other USDA agencies and external stakeholders. The materials included but were not limited to: customizable news releases, public service announcement scripts, and a PowerPoint template; Secretary of Agriculture video public service announcements, and drop-in advertisements; informational, instructional, and testimonial videos; website buttons and banners; brochures in multiple languages; social media posts; flyers; posters; FAQ sheets, talking points, and more. In addition, at the national level, NASS issued six news releases during data collection (three more were produced before data collection to inform and prepare producers) citing department and agency spokespeople, published half a dozen timely and relevant pieces to the USDA blog highlighting the census, and conducted three social media campaigns. These public relations efforts at the national and local-levels helped ensure that NASS' message about the census was continually in the media, including print and online publications, a variety of social media, radio, and some television programs. Media outlets included both those specializing in agriculture and more general outlets.

Paid Media

With a very limited budget, NASS was able to apply a small portion of funds toward paid advertising. For the 2022 Census of Agriculture, NASS strategically advertised in regional print publications, online, and with national agriculture news services (i.e., TV, radio) to bolster reach both in general and within geographically specific, previously under-represented populations and lower response areas.

DATA COLLECTION

Method of Enumeration

Data collection was accomplished primarily by mail, Computer-Assisted Self Interview (CASI) on the Internet, and personal enumeration for special classes of records in the census operations. Personal enumeration (interviewing) involved the use of both Computer-Assisted Telephone Interview (CATI) and Computer-Assisted Personal Interview (CAPI) data collection instruments. Enumerators at the five NASS Data Collection Centers conducted CATI data collection. In addition, enumerators under contract with NASS through the National Association of State Departments of Agriculture (NASDA) conducted phone and personal interviews with respondents. For the 2022 Census of Agriculture, NASS implemented a pre-notification strategy to increase awareness, improve overall responses, and encourage respondents to report early to avoid continued correspondence. All records with an e-mail address received an e-mail message marketing the improved web form and announcing the census mail packets were coming.

Report Forms

Four versions of report forms were used for the 2022 Census of Agriculture:

- General form (22 - A100)
- Hawaii form (22 - A101)
- American Indian form (22 - A300)
- Farm Status form (22 - A400)

The general form facilitated reporting crops and livestock most commonly grown and raised in the U.S. The short form expedited reporting specific crops or livestock for pre-identified farms and ranches in the U.S. The Hawaii form targeted crops and livestock specifically grown or raised on farms and ranches in Hawaii. The American Indian form focused on crops and livestock for farms and ranches on reservations in Arizona, New Mexico, and Utah. All report forms allowed respondents to write in specific commodities that were not prelisted on their report form.

Report Form Mailings

Census data collection began on November 22, 2022. Nearly all producers on the CML received a letter inviting them to report online. They received a unique survey code and instructions for completing their census online. The letter encouraged producers to report online early to avoid receiving mail and phone follow-up. Approximately 3 million mail packets were mailed in December 2022. Each packet contained a cover letter, instruction sheet, a labeled report form, and a return envelope. The Census Bureau's National Processing Center (NPC) in Jeffersonville, IN was contracted to perform mail packet preparation, initial mailout, and two follow-up mailings to nonrespondents.

The initial mailout was followed by a thank-you reminder correspondence in January 2023. This pressure-sealed envelope reminded respondents of the approaching deadline and that they could report online. First follow-up mail packets were mailed in mid-February 2023 to approximately 1.5 million nonrespondents. Second follow-up mail packets were mailed in mid-March 2023 to approximately 1 million nonrespondents. A final mailing went to approximately 800,000 non-respondents. This mailing included a drastically reduced four-page questionnaire designed to primarily determine if the operation was a farm or not in business.

Nonresponse Follow-up

Operating concurrently with NPC's mail data collection efforts, NASS Data Collection Centers targeted selected groups of census nonrespondents for telephone enumeration. NASS regional field offices targeted selected groups of census nonrespondents for in-person enumeration. These efforts were referred to as:

- Must Case Follow-up
- American Indian Producer Follow-up
- National Nonresponse Follow-up
- Not on Mail List (NML) Follow-up

Must Case Follow-up. Must cases are known large or unique operations, the absence of which could have significantly affected the accuracy of census results. For the 2022 Census of Agriculture, 125,697 records were categorized as Must cases. Each active Must operation was accounted for by mail receipt, phone interview, or personal enumeration; if an operation was no longer in business, its nonfarm status was documented. Call centers conducted CATI calling of nonrespondent Must cases from March 2023 through May 2023, after the initial and first follow-up mailings. Following the CATI calling, the remaining nonresponse Must cases were assigned to regional field offices for personal enumeration. Because of the potential importance of Must cases, they were all accounted for and therefore not eligible for nonresponse weighting adjustment.

American Indian Producer Follow-up. The American Indian report form (22-A300) was mailed to all operations in Arizona, New Mexico and Utah thought to have an American Indian producer. It was included in the initial

mailout, but due to poor mail response, a personal enumeration data collection strategy was utilized with no additional mail follow-up. A concerted effort was made to get individual reports from every American Indian farm producer in the country. If this was not possible within a reservation, a single reservation-level census report was obtained from knowledgeable reservation officials. These reports covered agricultural activity on the entire reservation. NASS staff reviewed these data and removed any duplicate data reported by American Indian producers from that reservation who responded on an individual census report form. Additionally, NASS obtained, from knowledgeable reservation officials, the count of American Indian farm producers (on the reservations) who were not counted through individual census report forms, but whose agricultural activity was included in the reservation-level report form.

National Nonresponse Follow-up (Excludes Must Records). In April 2023, a group of records that were not part of other nonresponse data collection efforts were identified for additional phone contacts. In total, 82,237 records with specified demographics and/or eligibility for Census Special Studies (follow-ons) were made available for nonresponse Computer-Assisted Telephone Interviews (CATI).

Not-on-the-Mail List (NML) Follow-up. To account for farming operations not on the CML, NASS used its 2022 JAS sample from the NASS area frame, augmented with the ACES segments. Because the NASS area frame covers all land in the U.S. with the exception of Alaska, it includes all farms. As previously described, NASS conducted a record linkage operation between the CML records and the records from the 2022 JAS/ACES. Those 2022 JAS records that did not match records on the CML were designated as "Not-on-the-Mail List" (NML) records. These records were mailed a yellow census form so that it could be differentiated from the green forms mailed to CML records. The NML records were mailed at the same time as the census mailing and received the same follow-up procedures as the census mailing through the first follow-up in mid-February 2023. Beginning in March 2023, CATI was used for nonresponse follow-up for NML nonrespondents.

REPORT FORM PROCESSING

Data Capture

The Census Bureau's National Processing Center (NPC) in Jeffersonville, IN was contracted to process returned mail packets. NASS staff on site at the NPC provided technical guidance and monitored NPC processing activities. All report forms returned to the NPC were immediately checked in, using bar codes printed on the mailing label, and removed from follow-up report form mailings. All forms with any data were scanned and an image was made of each page of a report form. Optical Mark Recognition (OMR) was used to capture categorical responses and to identify the other answer zones in which some type of mark was present.

Data entry operators keyed data from the scanned images using OMR results that highlighted the areas of the report forms with respondent entries. The keyer evaluated the contents and captured pertinent responses. Ten percent of the captured data were keyed a second time for quality control. If differences existed between the first keyed value and the second, an adjudicator handled resolution. The decision of the adjudicator was used to grade the performance of the keyers, who were required to maintain a certain accuracy level.

The images and the captured data were transferred to NASS's centralized network and became available to NASS analysts on a flow basis. The images were available for use in all stages of review.

Editing Data

Captured data were processed through a computer formatting program that verified that records were valid – that the record ID number was on the list of census records, that the reported counties of operation and production were valid, and other related criteria. Rejected records were referred to analysts for correction. Accepted records were sent to a complex computer batch edit process. Each execution of the computer edit in batch mode consisted of records from only one State and flowed as the data were received from NPC, the NASS Computer-Assisted Self Interview (CASI), or the Computer-Assisted Telephone Interview (CATI) applications.

The computer edit determined whether a reporting operation met the qualifying criteria to be counted as a farm (in-scope). The edit examined each in-scope record for reasonableness and completeness and determined whether to accept the recorded value for each data item or take corrective action. Such corrective actions included removing erroneously reported values, replacing an unreasonable value with one consistent with other reported data, or providing a value for an item omitted by the respondent. To the extent possible, the computer edit determined a replacement value. Strategies for determining replacement values are discussed in the next section. Operations failing to meet the qualifying criteria for being classified as a farm were categorized as out-of-scope for the census. Records that NASS had reason to believe might have been erroneously classified as out-of-

scope (indications of recent and/or significant agricultural activity reported on NASS surveys, for example) were referred to analysts for verification.

The edit systematically checked reported data section-by-section with the overall objective of achieving an internally consistent and complete report. NASS subject-matter experts had previously defined the criteria for acceptable data. Problems that could not be resolved within the edit were referred to an analyst for intervention. Prior to the census mail-out, NASS established a group of analysts in a Census Editing Unit in the National Operations Center in St. Louis, MO who examined the scanned images, consulted additional sources of information, and determined an appropriate action. Regional field office analysts also participated using an interactive version of the edit program to submit corrected data and immediately re-edit the record to ensure a satisfactory solution.

Farm Status Form Editing

From the CML, 883,732 records were selected to receive a Farm Status form as a final follow-up form; this form was derived from the full census report form by selecting a subset of the questions on the full form. Since these questions were also asked on the general form, the edit was able to treat the Farm Status form responses as though they were incomplete general forms, as described in the previous paragraphs.

Imputing Data

The edit determined the best value to impute for reported responses that were deemed unreasonable and for required responses that were absent. If an item could not be calculated directly from other current responses, the edit determined whether acreage, production, or inventory items had been reported for that farm on a recent NASS crop or livestock survey. For producers who had not changed in five years, demographics such as race and gender were taken from the previous census. Administrative data from the Farm Service Agency were used for a few items, such as Conservation Reserve Program acreage. When deterministic edit logic and previously-reported data sources were unable to provide a current value, data from a reporting farm of similar type, size, and location were considered. In cases where automated imputation was unable to provide a consistent report, the record was referred to an analyst for resolution.

Separate system processes were established to efficiently provide data from a similar farm to the edit when donor imputation was required. The farm characteristics used to define similarity between a recipient record and its donor record were determined dynamically by the edit logic. Euclidean distance was used for similarity computations, with each contributing similarity characteristic scaled appropriately. The most similar farm based on this criterion (the "nearest neighbor") was identified and returned to the edit for use as a donor. The calculated distance between the centroids of the principal counties of production of the donor and recipient was always included as one of the measures of similarity.

To provide donors to the automated edit, a pool of successfully edited records was maintained for each section of the report form. These donor pools began with 2017 census data, reconfigured to emulate 2022 data and then edited using 2022 logic. Data from the 2020 Census Content Test were similarly remapped and edited before being added to the original donor pools. As 2022 records were successfully processed, they were added to the donor pools, which maintained the most recent data for each farm. Donor pools were updated approximately every other week, as determined by edit processing schedules. After several updates, all initial data records were dropped, leaving only 2022 records in the donor pools. After each update, donor pool records were grouped into strata containing farms in the same State of similar type and size, using a data-driven algorithm to define strata. Certain American Indian farms were treated as a separate group, effectively having their own donor pool.

In response to each donor request issued by the edit, a dedicated system process would search the appropriate stratum and respond with the most similar donor, while giving preference to more recent donors. In relatively rare instances where it was unable to provide a donor, the donor selection process issued an appropriate failure message to the edit. Imputation failures occurred for several different reasons. The requirement that an imputed value be positive could have ruled out all available donors, as could have the necessity for the donor record to satisfy a particular constraint – say, that the donor record has cattle, but no milk cows. In general, an imputation failure occurred if there were no satisfactory donors in the same profile as the report being edited. Records with imputation failures were either held until more records were available in the donor pool or referred to an analyst. In addition, when such a failure occurred in finding a donor for expenditure data, donor pool averages were provided in lieu of an individual donor, wherever possible. This "failover" utility was first introduced for the 2012 census imputation process, and significantly reduced the number of imputation failures among the expenditure and labor variables. During the early stages of editing, records requiring imputation for production (and hence yields) of field crops or hay, land values, or certain expenditure variables, were set aside or "parked." These records were edited when the donor pools contained only 2022 records, ensuring that 2022 data were

used in the imputations for the variables.

After receiving a donor's data, the edit substituted the values into the edited record. In many cases, the donor record's data value was scaled using another data field specified in the edit logic. In such cases, the size of the auxiliary field's value in the edited record, relative to its value in the donor record, was used to appropriately scale the donor record's value for the field to be imputed. The imputed data were then validated by the same edit logic to which reported data were subject. Since imputation was conducted independently for each occurrence, reports requiring multiple imputations may have drawn from multiple donors.

As was done for the 2017 Census, for records reporting three or more persons as producers, a different imputation process was used for certain items (specifically the items in question 3) in the Personal Characteristics Section. Records with one or two persons reported as producers had these data edited and imputed using the decision logic table edit and donor pool imputation process. Records with three or more persons reported as producers, and for which it was determined that these data were inconsistent or missing, had these data imputed using a fully conditional specification method. During the edit for records reporting three or more producers, the items needing imputation were marked, and the record was flagged. At the end of the data collection period, the data for these records (both the items needing to be imputed and the other variables needed by the model) were pulled and run through the imputation program. The resulting imputed values were loaded back to the records, and the records were made available for review.

Data Analysis

The complex edit ensured the full internal consistency of the record. Successfully completing the edit did not provide insight as to whether the report was reasonable compared to other reports in the county. Analysts were provided an additional set of tools, in the form of listings and graphs, to review record-level data across farms. These examinations revealed extreme outliers, large and small, or unique data distribution patterns that were possibly a result of reporting, recording, or handling errors. Potential problems were investigated and, when necessary, corrections were made, and the record interactively edited again.

When NASS summarizes data from the census of agriculture, each individual report is typically assigned to a single “principal” county. The principal county is the county in which the majority of an operation’s agricultural products are produced, as reported by the producer. For large operations that have significant production in multiple counties, their reports may be broken up into multiple source counties to more accurately summarize the data. Similarly, for large farms operating in more than one State, separate report forms are completed by State in order to assign the proper portion of the farm’s total agricultural production to each State in which the farm operates.

ACCOUNTING FOR UNDERCOVERAGE, NONRESPONSE, AND MISCLASSIFICATION

Although much effort has been expended making the CML as complete and accurate as possible, it does not include all U.S. farm operations, resulting in list undercoverage. Additionally, some farm operations on the CML did not respond to the census, despite numerous contact attempts. Finally, although each operation was classified as a farm or a nonfarm based on their census responses, some were misclassified; that is, some nonfarms were classified as farms and some farms were classified as nonfarms. NASS’s goal is to produce agricultural census totals for publication at the county level that are fully adjusted for these factors: list undercoverage, nonresponse, and misclassification.

In 2017, NASS used a series of models based on a subset of the responding census and all the JAS records in a capture-recapture framework to separately adjust for undercoverage, nonresponse, and misclassification. For the 2022 Census of Agriculture, the capture-recapture methodology was extended to model the probability of capture with a single model, thereby allowing the utilization of all census responses and JAS records in the adjustments. To implement capture-recapture methods, two independent samples are required. The 2022 Census of Agriculture (based on the CML) and the 2022 JAS (based on the area frame) were those two samples. Historically, NASS has been careful to maintain the independence of the CML and the area frame. Thus, the Census of Agriculture and the JAS were assumed to be independent after accounting for heterogeneity in the capture probabilities based on characteristics of records.

For a farm to be identified as a farm, and thus captured by the census, it must be on the CML, respond to the census report form, and be classified as a farm on the form. Thus, the capture probability π_C is of interest:

$\pi_C = \pi(\text{CML, Responded, Farm on Census}|\text{Farm})$

Two types of classification error can occur. First, a farm can be misclassified as a nonfarm. This type of misclassification is accounted for in determining the probability of capture π_C. The second type of classification

error results when a response to the census is classified as a farm operation when it does not meet the definition of a farm. That is, some farms on the CML may be misclassified from their census report response and may be nonfarms. To account for the misclassification of nonfarms as farms, the probability of a farm on the census being classified correctly must be estimated; that is,

$\pi_{CCFC} = \pi(\text{Farm} \mid \text{Farm on Census})$

where *CCFC* represents Correct Census Farm Classification. To adjust for undercoverage, nonresponse, and misclassification, each CML record classified as a farm based on its response to the census report form was given a weight of the ratio of the estimated probability of correct classification of a farm on the census and the estimated probability of capture $(\hat{\pi}_{CCFC}/\hat{\pi}_C$ where the hat symbol ($\hat{}$) denotes an estimate). To estimate the number of farms with a given set of characteristics, the weights of CML records responding as farms on the census and having that set of characteristics were summed.

This estimator is referred to as the capture-recapture estimator (*CR*):

$$CR = \sum_{i \in F} \frac{\hat{\pi}_{CCFC,i}}{\hat{\pi}_{C,i}}$$

where *F* is the set of all CML records classified as farms based on their responses to the census report form.

To estimate these probabilities $(\hat{\pi}_C \text{ and } \hat{\pi}_{CCFC})$, the records in the 2022 JAS sample were matched to the 2022 CML using probabilistic record linkage allowing the records only on the CML, JAS, and on both the CML and JAS to be identified. All CML records and JAS tracts were used to estimate the capture-recapture probabilities jointly.

Resolving Farm Status

The farm status based on census responses to either the CML or NML census data collection and the response on the JAS agreed in most cases; these records are referred to as having resolved farm status. However, in other cases, a record was identified as a farm (nonfarm) on the JAS and as a nonfarm (farm) on the CML or the NML. Such records are said to have conflicting or unresolved farm status. An operation identified as a farm is referred to as in-scope; an operation identified as a nonfarm is referred to as out-of-scope. From the set of matched records, two groups with conflicting farm status were identified: 1) in-scope JAS records that were out-of-scope on the census and 2) census in-scope and JAS out-of-scope records. The records with conflicting farm status were sent to NASS regional field offices for review. In each case, efforts were made to determine whether (1) the status had changed between June and December when the census was conducted, (2) the JAS farm status was correct, (3) the census farm status was correct, (4) the records were incorrectly matched, or (5) the farm status could not be resolved.

The probability that an operation is a farm was estimated for census and JAS by using a conditional logistic model. Only those records identified as a farm based on either their JAS response or their Census response were used to develop the model for estimating the probability a record is associated with a farm. Operations with matching farm status were considered as certain if the farm status agreed between the JAS and the CML. If the status between the JAS and CML was conflicting, then the operation was treated as uncertain during the modeling stages. Characteristics of the operations were considered as potential covariates in the model. Variable selection was conducted using a stepwise algorithm to maximize the conditional likelihood. The probability of being a farm is estimated for each record classified as a farm based on their JAS or census response. The estimated probability is used as a weight in all subsequent modeling.

Capture Probabilities

Recall that, for a farm to be identified as a farm, and thus captured, by the census, it must be on the CML, respond to either the census or JAS report form and, based on that response, be classified as a farm. Therefore, the probability of capture π_C may be written as

$\pi_C = \pi(\text{CML, Responded, Farm on Census}|\text{Farm})$
$= \pi(\text{CML}|\text{Farm})\pi(\text{Responded}|\text{CML, Farm})\pi(\text{Farm on Census}|\text{CML, Responded, Farm})$

Terms in the probability of capturing a farm depend on characteristics of the farm. These terms, as well as the corresponding terms associated with a farm being captured by the JAS, were jointly estimated from a single model. Using all Census and JAS data, model variables were selected by applying a stepwise variable selection algorithm and expert opinion. Estimation was based on a conditional weighted likelihood. The events of a farm being included in the CML, the JAS or both were included in the likelihood. The event of a farm not being included in either the JAS or the CML was excluded from the likelihood but was accounted for through the model's capture-recapture properties. Although the probability of capture is estimated for both CML and JAS records, only CML records with a census response are given a census weight; records with only a JAS response are not given a census weight or used further to produce census estimates.

Because Alaska is not included in the JAS and thus has no area frame, the Alaskan agricultural operations were not

included in the capture-recapture process. No adjustments were made for undercoverage or misclassification. To account for nonresponse, the CML records were divided into three groups: (1) the Must records, (2) the Criteria Records, and (3) the remaining CML records. The must records received a weight of one, thereby receiving no adjustment for nonresponse. The probability of response for each of the other two groups was the proportion of responders within the group. Each record within the group was then given a weight equal to the reciprocal of the probability of response.

Misclassification

An operation is misclassified if: (1) it meets the definition of a farm but is classified as a nonfarm on the census or (2) it does not meet the definition of a farm but is classified as a farm on the census. The first type of misclassification is accounted for when modeling the probability of capture. An adjustment is still needed for the misclassification of nonfarms as farms. As with farm status and capture, the probability of this misclassification depends on an operation's characteristics. Thus, a conditional logistic model was developed. Given that a farm on the CML was classified as a farm in the census, the probability of its being a farm was modeled based on its characteristics.

CALIBRATION

Each operation identified as being in-scope on the CML was given a weight equal to the probability of misclassifying a nonfarm as a farm on the census divided by the probability of capture. This weight accounted for undercoverage, nonresponse, and both types of misclassification.

The record weighting processes were initially applied at the State level to produce adjusted estimates of farm numbers, land in farms, and for 64 different categories of characteristics of the farm operation or the farm producer -- value of agricultural sales (10); age (2); female; race (3); Hispanic origin; 4 sales categories for each of 10 major commodities (40); and farm type groups (7). The State-level number of farms and land in farms were two additional adjusted estimates, resulting in 66 categories. To reduce the intercensal variation at the State level, the State targets were smoothed by averaging the 2022 estimates from capture-recapture and the published 2017 State estimates.

These State estimates were general purpose in that they did not provide any control over expected levels of commodity production of the individual farm operation. As a result of this limitation, the procedures could have over-adjusted or under-adjusted for commodity production. To address this, a second set of variables, known as commodity targets, was added to the calibration algorithm. These targets were commodity totals from administrative sources or from NASS surveys of nonfarm populations (e.g., USDA Farm Service Agency program data, Agricultural Marketing Service market orders, livestock slaughter data, cotton ginning data). The introduction of these commodity coverage targets strengthened the overall adjustment procedure by ensuring that major commodity totals remained within reasonable bounds of established benchmarks.

Each State was calibrated separately. The calibration algorithm addressed commodity coverage. The algorithm was controlled by the 65 State farm operation coverage targets and the State commodity coverage targets. Because calibration targets are estimates subject to uncertainty, NASS allowed some tolerance in the determination of the adjusted weights. Rather than forcing the total for each calibration variable computed using the adjusted weights to equal a specific amount, NASS allowed the estimated total to fall within a tolerance range.

To ensure that all subdomains for which NASS publishes summed to their grand total, integer weights were produced by a discrete calibration algorithm. This eliminated the need for rounding individual cell values and ensured that marginal totals always added correctly to the grand total. If a weight was initially not in the interval [1,6], it was trimmed so that it was in that interval. That is, adjusted weights less than 1 were set to 1, and those greater than 6 were set to 6. The remaining non-integer weights were then rounded sequentially to reduce the distance of the estimated totals from the targets.

Calibration adjustments began with the computation of a priority index for each record. The priority index was the absolute value of the gradient of the relative error associated with increasing or decreasing a record's weight by one. The record with the highest priority index was then selected as a candidate to increase or decrease its weight by one to reduce the cumulative distance from the targets as measured by the relative error. If the new value produced an improvement and satisfied the range restrictions, the weight was updated and new priorities were assigned; otherwise, the record with the next highest priority index was processed. This process was iteratively performed until convergence was attained. Because census data collection was assumed to be complete for very large and unique farms, their weights were set to 1 during the calibration adjustment process. For all other farms, the final census record weights were forced to be an integer number in the interval [1, 6]. The calibration process considered all targets simultaneously through the priority index. Although calibration was seldom able to adjust

weights so that all State targets were met, all targets were brought collectively as close to the targets as possible.

The proportions of selected census data items that were due to coverage, response, and classification adjustments are displayed in Tables A and C.

DISCLOSURE REVIEW

After tabulation and review of the aggregates, a comprehensive disclosure review was conducted. NASS is obligated to withhold, under Title 7, U.S. Code, any total that would reveal an individual's information or allow it to be closely estimated by the public. Farm counts are not considered sensitive and are not subject to disclosure controls. Cell suppression was used to protect the cells that were determined to be sensitive to a disclosure of information.

Based on agency standards, data cells were determined to be sensitive to a disclosure of information if they failed either of two rules. The threshold rule failed if the data cell contained less than three operations. For example, if only one farmer produced turkeys in a county, NASS could not publish the county total for turkey inventory without disclosing that individual's information. The dominance rule failed if the distribution of the data within the cell allowed a data user to estimate any respondent's data too closely. For example, if there are many farmers producing turkeys in a county and some of them were large enough to dominate the cell total, NASS could not publish the county total for turkey inventory without risking disclosing an individual respondent's data. In both of these situations, the data were suppressed and a "(D)" was placed in the cell in the census publication table. These data cells are referred to as primary suppressions.

Since most items were summed to marginal totals, primary suppressions within these summation relationships were protected by ensuring that there were additional suppressions within the linear relationship that provided adequate protection for the primary. A detailed computer routine selected additional data cells for suppression to ensure all primary suppressions were properly protected. These data cells are referred to as complementary suppressions. These cells are not themselves sensitive to a disclosure of information but were suppressed to protect other primary suppressions. A "(D)" was also placed in the cell of the census publication table to indicate a complementary suppression. A data user cannot determine whether a cell with a (D) represents a primary or a complementary suppression.

Regional field office analysts reviewed all complementary suppressions to ensure no cells had been withheld that were vital to the data users. In instances where complementary suppressions were deemed critically important to a State or county, analysts requested an override, and a different complementary cell was chosen.

CENSUS QUALITY

The purpose of the census of agriculture is to account for "any place from which $1,000 or more of agricultural products were produced and sold, or normally would have been sold, during the census year." To accomplish this, NASS develops a CML that contains identifying information for operations that have an indication of meeting the census definition, develops procedures to collect agricultural information from those records, establishes criteria for analyst review of the data, creates computer routines to correct or complete the requested information, and provides census estimates of the characteristics of farms and farm producers with associated measures of uncertainty.

It is not likely that either the CML includes all operations that meet the definition of a farm or that all those that do meet the definition of a farm respond to the census inquiry. The goal is to publish data with a high level of quality. The quality of a census may be measured in many ways. One of the first indicators used is a measure of the response to the census data collection as it has generally been thought that a high response rate indicates more complete coverage of the population of interest. This is a valid assumption if the enumeration list, the CML here, has complete coverage of the population of interest. In the case of the census of agriculture, the definition requiring advance knowledge of sales makes achieving a high level of coverage difficult. To ensure that the census of agriculture is as complete as possible, records are included that might not meet the census definition of a farm – in fact, almost 50 percent more records than the anticipated number of qualifying farm operations were included in the 2022 CML. A second indicator of quality then is the coverage of the farm population by the CML. Other indicators of quality relate to the accuracy and completeness of the data, and the validity of the procedures used in processing the data.

In some cases, NASS was able to produce measures of quality – such as the response rate to the data collection, the coverage of the census mail list, and the variability of the final adjusted estimates. In other cases, measures were not produced but descriptions of procedures that NASS used to reduce errors from the procedures were subsequently provided.

Census Response Rate

The response rate is one indicator of the quality of a data

collection. It is generally assumed that if a response rate is close to a full participation level of 100 percent, the potential for nonresponse bias is small, although this has been questioned in the literature. The response rate for the 2022 Census of Agriculture CML was 61.0 percent, as compared with the 2017 Census of Agriculture's response rate of 71.8 percent and 74.6 percent for the 2012 Census of Agriculture.

The 2022 Census of Agriculture's response rate used the fourth response rate formula (RR4) from the American Association of Public Opinion Research's Response Rate Standard Definitions manual:

$$RR4 = \frac{C_{adj}}{C_{adj} + R + NC + O + Replicated + e(U)}(100)$$

where
C_{adj} = number of fully and partially completed records, excluding replicated records
R = number of explicit refusals
NC = number of non-contacted operations known to be eligible
O = number of other types of nonrespondents
Replicated = number of replicated records
U = number of operations of unknown eligibility
$e(U)$ = estimated number of operations of unknown eligibility assumed to be eligible

Records were classified into the above variables based on the combination of their active status (AS) codes, in-scope status, and replication status. Active status refers to the eligibility status of records for selection on the CML. All replicated records were considered a form of nonresponse and were classified into other nonrespondents; in-scope status was considered immaterial.

Certain active status classifications indicated records of unknown agricultural status. These classifications included records to be removed from the CML but had data from outside sources indicating agricultural activity, new records from outside data sources, nonrespondents and refusals to the NACS, records for regional office handling only, and records with Farm Service Agency or Conservation Reserve Program data on operations that are not owned by the principal producer. These records were stratified (grouped) based on their probabilities of being in-scope had they responded. The estimated number of in-scope nonrespondents was calculated for the *h*th stratum (group) by the following formula:

$$e(U_h) = \left(\frac{C_{in-scope,h}}{C_h}\right)U_h$$

where
$e(U_h)$ = estimated number of operations of unknown eligibility assumed to be eligible in the *h*th group
$C_{in-scope,h}$ = the number of completed and in-scope census records in the *h*th group
C_h = the number of completed census records in the *h*th group
U_h = number of operations of unknown eligibility in the *h*th group

Census Coverage

As a side-product of the statistical adjustment used to account for undercoverage, nonresponse of farms on the CML, and misclassification of responses to the census, the proportion of the adjustments due to each of those factors can be derived. The percentage of final census estimates due to adjustments for undercoverage, nonresponse, and misclassification as well as the total percent adjustment for selected items are displayed in Tables A and C.

MEASURED ERRORS IN THE CENSUS PROCESS

NASS uses statistical procedures in compiling the CML, in its data collection procedures, in data editing and processing, and in compiling the final data. Additionally, it uses statistical procedures to both measure errors in the various processes when adjusting for those errors in the final data. One example is the statistical process used to account for undercoverage, nonresponse of farms on the CML, and misclassification of responses to the census. The basis of the undercoverage adjustment is the capture-recapture procedure that uses the area sample enumeration from the JAS. The largest contributors to error in the census estimates are due to the adjustments for nonresponse, undercoverage, misclassification, and integer calibration.

Variability in Census Estimates due to Statistical Adjustment

In conducting the 2022 Census of Agriculture, efforts were initiated to measure error associated with the adjustments for farm operations that were not on the CML; for farm operations that were on the CML but did not respond to the census report form; for farms and nonfarms that were misclassified as nonfarms and farms, respectively; and for integer calibration. These error measurements were developed from the standard error of the estimates at the national, State, and county levels and were expressed as coefficients of variation (CVs) at the national and State levels and as generalized coefficients of variation (GCVs) at the county levels.

The standard error of an estimate is an estimate of the

standard deviation of the sampling distribution of the estimator. In each case, standard errors were computed using an approach based on a delete-a-group jackknife methodology. To conduct the jackknifing, $k = 10$ mutually exclusive and exhaustive groups of records were formed. The groups were selected using a stratified random design so that each group reflected capture status by the CML and the JAS. Based on estimated weights for records in each group, a delete-a-group jackknife estimator of the variance would account for the uncertainty associated with modeling the capture-recapture probabilities and the uncertainty due to integer calibration. Therefore, the weights within each jackknife group were computed using the group-specific models and calibrated to match group-specific targets. For a given data item *i*, such as the number of farms, the estimate was computed at the specified geographical level, such as nation, State, or county, using the weights obtained for group *j*. Estimates of the variance and standard error associated with the estimator T_i are then, respectively,

$$\sigma_i^2 = \frac{k-1}{k}\sum_{j=1}^{k}\left(T_i^{(j)} - \sum_{l=1}^{k}\frac{T_i^{(l)}}{k}\right)^2; \quad SE(T_i) = \sqrt{\sigma_i^2}$$

Ten (10) calibration-adjusted jackknife groups were used to provide standard errors for 2022 State and national estimates (i.e., $k=10$). For the estimate of the number of farms with a given set of characteristics, only the CML records with those characteristics were used to obtain the overall estimate as well as the estimates from each calibrated jackknife group.

Note that the calibrated jackknife groups were only constructed once, and different subsets of the records were used to compute estimates and standard errors for the data items.

The CV is a measure of the relative amount of error associated with the sample estimate:

$$\mathrm{CV}_i = \frac{SE(T_i)}{T_i}100\%$$

where $SE(T_i)$ is the standard error of the capture-recapture estimate for data item *i*. This relative measure allows the reliability of a range of estimates to be compared. For example, the standard error is often larger for large population estimates than for small population estimates, but the large population estimates may have a smaller CV, indicating a more reliable estimate. For county-level estimates, a generalized coefficient of variation (GCV) was determined for each estimate within a State. A generalized variance function relates a function of the variance of an estimator to a function of the estimator. Within a State, the standard error of an estimate for a data item was often found to be linearly related to the estimate of that item with an intercept of zero. Based on this modeled relationship, the GCV is the slope of the line relating the standard error to the estimate, multiplied times 100 to represent the GCV as a percentage.

The standard error is the product of the CV (or GCV for county estimates) and the estimate divided by 100. As an example, if the GCV for a State is 25 percent and a county's estimate is 4, then the standard error is 25(4)/100 = 1. The standard error of an estimated data item from the census provides a measure of the uncertainty associated with that estimated data item due to the possible outcomes of the census collection, including incompleteness of the CML, nonresponse to the census, misclassification either as a farm or as a nonfarm, and the integer calibration. With 95 percent confidence, an estimate is within two standard errors of the true value being estimated. For this example, with 95 percent confidence, the estimate of 4 is within 2(1) = 2 of the true county value.

Note: The standard errors and consequently, the CVs tend to be substantially smaller than those reported for the 2017 Census of Agriculture. For 2017, the model of the probability of capture incorporated information from the approximately 40,000 respondents to the 2017 JAS and the census records matching a JAS record. In contrast, the models for the 2022 Census of Agriculture relied on information from the approximately 1 million responding CML records and the 2022 JAS, some of which were on both the CML and the JAS. The large increase in the number of records used in the modeling process led to a major decrease in the measures of uncertainty (standard errors and CVs).

Table B presents the fully adjusted estimates with the coefficient of variation for selected items.

NONMEASURED ERRORS IN THE CENSUS PROCESS

As noted in the previous section, errors can be introduced from adjustments for coverage, nonresponse, and misclassification and from integer calibration. These errors are measurable. However, nonsampling errors are imbedded in the census process that cannot be directly measured as part of the design of the census but must be contained to ensure an accurate count. Extensive efforts were made to compile a complete and accurate mail list for the census, to elicit response to the census, to design an understandable report form with clear instructions, to minimize processing errors through the use of quality control measures, to reduce matching error associated with the capture-recapture estimation process, and to minimize

error associated with identification of a respondent as a farm operation (referred to as classification error). The weight adjustment and tabulation processes recognize the presence of nonsampling errors; however, it is assumed that these errors are small and that, in total, the net effect is zero. In other words, the positive errors cancel the negative errors.

Respondent and Enumerator Error

Incorrect or incomplete responses to the census report form or to the questions posed by an enumerator can introduce error into the census data. Steps were taken in the design and execution of the Census of Agriculture to reduce errors from respondent reporting. Poor instructions and ambiguous definitions lead to misreporting. Respondents may not remember accurately, may estimate responses, or may record an item in the wrong cell. To reduce reporting and recording errors, the report form was tested prior to the census using industry-accepted cognitive testing procedures. Detailed instructions for completing the report form were provided to each respondent. Questions were phrased as clearly as possible based on previous tests of the report form. Computer-assisted telephone interviewing software included immediate integrity checks of recorded responses so suspect data could be verified or corrected. In addition, each respondent's answers were checked for completeness and consistency by the complex edit and imputation system.

Processing Error

Processing of each census report form was another potential source of nonsampling error. All mail returns that included multiple reports, respondent remarks, or that were marked out of business and report forms with no reported data were sent to an analyst for verification and appropriate action. Integrity checks were performed by the imaging system and data transfer functions. Standard quality control procedures were in place that required that randomly selected batches of data keyed from image be re-entered by a different operator to verify the work and evaluate key entry operators. All systems and programs were thoroughly tested before going on-line and were monitored throughout the processing period.

Developing accurate processing methods is complicated by the complex structure of agriculture. Among the complexities are the many places to be included, the variety of arrangements under which farms are operated, the continuing changes in the relationship of producers to the farm operated, the expiration of leases and the initiation or renewal of leases, the problem of obtaining a complete list of agriculture operations, the difficulty of contacting and identifying some types of contractor/contractee relationships, the producer's absence from the farm during the data collection period, and the producer's opinion that part or all of the operation does not qualify and should not be included in the census. During data collection and processing of the census, all operations underwent a number of quality control checks to ensure results were as accurate as possible.

Item Nonresponse

All item nonresponse actions provide another opportunity to introduce measurement errors. Regardless of whether previously reported data, administrative data, the nearest neighbor algorithm, the fully conditional specification method, or manual imputation is used to complete a nonresponse item, some risk exists that the imputed value does not equal the actual value. Previously reported and administrative data were used only when they related to the census reference period. A new nearest neighbor was randomly selected for each incident to eliminate the chance of a consistent bias.

Record Matching Error

The process of building and expanding the CML involves finding new list sources and checking for names not on the list. An automated processing system compared each new name to the existing CML names and "linked" like records for the purpose of preventing duplication. New names with strong links to a CML name were discarded and those with no links were added as potential farms. Names with weak links, possible matches, were reviewed by staff to determine whether the new name should be added. Despite this thorough review, some new names may have been erroneously added or deleted. Additions could contribute to duplication (overcoverage) whereas deletions could contribute to undercoverage. As a result, some names received more than one report form, and some farm producers did not receive a report form. Respondents were instructed to complete one form and return all forms so the duplication could be removed.

Another chance for error came when comparing June Area Survey tract producer names to the CML. Area producers whose names were not found on the CML were part of the measure of list incompleteness, or NML. Mistakes in determining overlap status resulted in overcounts (including a tract whose producer was on the CML) or undercounts (excluding a tract whose producer was not on the CML). All tracts determined to not be on the list were triple checked to eliminate, or at least minimize, any error. NML tract producers were mailed a report form printed in a different color. To identify duplication, all respondents who received multiple report forms were instructed to complete the CML version and return all forms so

duplication could be removed.

Records in the 2022 JAS were matched to the 2022 census using probabilistic record linkage. The records of operations with differing farm status were sent out to be reviewed by NASS regional field offices. If farm status could not be resolved, the probability of an operation being a farm was imputed using a missing data model. The uncertainty associated with this estimate apart from model uncertainty was accounted for, but errors not found through this process were not.

Table A. **Summary of U.S. Coverage, Nonresponse, and Misclassification Adjustments: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
Farms	number	1,900,487	36,680	44.5	15.7	15.4	13.4
Land in farms	acres	880,100,848	19,889,860	27.7	3.0	10.3	14.4
Farms by size:							
1 to 9 acres	farms	234,592	11,486	57.8	29.7	16.8	11.3
	acres	1,084,341	52,987	57.0	29.8	16.4	10.8
10 to 49 acres	farms	566,912	14,586	50.7	23.3	16.1	11.3
	acres	14,193,479	357,922	49.2	21.3	16.3	11.6
50 to 69 acres	farms	130,096	2,830	44.0	15.5	15.3	13.1
	acres	7,553,962	162,416	43.9	15.4	15.3	13.2
70 to 99 acres	farms	153,239	3,782	41.7	12.5	14.5	14.6
	acres	12,601,546	305,221	41.6	12.4	14.5	14.6
100 to 139 acres	farms	138,398	2,236	40.0	10.7	14.0	15.3
	acres	16,045,194	257,848	39.9	10.6	14.0	15.3
140 to 179 acres	farms	108,796	1,843	39.7	8.9	15.6	15.1
	acres	17,126,924	292,176	39.7	8.9	15.6	15.1
180 to 219 acres	farms	69,602	1,496	37.7	8.2	14.2	15.3
	acres	13,747,397	298,052	37.7	8.2	14.2	15.3
220 to 259 acres	farms	52,177	1,319	36.5	7.0	14.1	15.4
	acres	12,415,492	312,408	36.5	7.0	14.1	15.4
260 to 499 acres	farms	166,600	2,842	37.3	5.5	15.7	16.2
	acres	59,494,534	991,299	37.3	5.4	15.7	16.3
500 to 999 acres	farms	120,456	2,337	37.4	3.9	17.3	16.3
	acres	83,738,842	1,567,226	37.3	3.8	17.3	16.2
1,000 to 1,999 acres	farms	76,311	2,320	34.6	2.7	15.4	16.5
	acres	105,224,602	3,289,192	34.4	2.6	15.3	16.4
2,000 acres or more	farms	83,308	2,430	29.8	1.9	11.2	16.7
	acres	536,874,535	16,985,268	21.4	1.4	7.0	13.1
Irrigated land use:							
Harvested cropland	farms	254,574	7,709	41.3	13.3	14.8	13.2
	acres	51,155,829	1,510,122	26.6	2.6	8.4	15.5
Pastureland and other land	farms	55,833	1,585	47.3	19.0	15.7	12.7
	acres	3,774,534	172,674	27.1	3.7	12.7	10.8
Market value of agricultural products sold	$1,000	543,087,166	9,776	22.7	4.2	5.5	12.9
Farms by value of sales:							
Less than $1,000	farms	499,816	13,150	57.1	23.2	17.7	16.2
	$1,000	56,798	2	62.7	36.2	16.0	10.5
$1,000 to $2,499	farms	179,054	8,076	52.4	23.7	18.0	10.7
	$1,000	292,472	13	52.1	23.6	17.9	10.6
$2,500 to $4,999	farms	166,149	6,257	47.2	21.9	15.2	10.1
	$1,000	593,713	22	47.0	21.8	15.2	10.1
$5,000 to $9,999	farms	191,688	6,923	45.2	19.2	14.9	11.1
	$1,000	1,359,995	49	45.0	19.0	14.8	11.2
$10,000 to $19,999	farms	168,876	3,843	35.1	12.4	12.7	10.0
	$1,000	2,386,213	56	35.0	12.3	12.7	10.0
$20,000 to $24,999	farms	53,378	1,327	35.6	11.3	13.4	10.9
	$1,000	1,180,735	30	35.5	11.3	13.4	10.8
$25,000 to $39,999	farms	100,390	3,925	36.1	10.5	13.2	12.4
	$1,000	3,162,262	127	36.1	10.4	13.2	12.5
$40,000 to $49,999	farms	43,657	2,163	37.6	10.0	14.2	13.4
	$1,000	1,938,084	97	37.6	10.0	14.2	13.3
$50,000 to $99,999	farms	116,220	3,968	35.9	8.3	13.7	13.9
	$1,000	8,237,216	290	36.0	8.2	13.8	14.0
$100,000 to $249,999	farms	122,968	4,859	35.5	5.7	13.7	16.1
	$1,000	19,715,890	765	35.4	5.5	13.8	16.1
$250,000 to $499,999	farms	85,266	4,871	39.5	4.1	20.5	14.9
	$1,000	30,549,461	1,744	39.7	4.1	20.7	14.9
$500,000 to $999,999	farms	67,641	1,712	35.2	3.9	17.5	13.8
	$1,000	48,248,980	1,155	35.4	3.9	17.5	14.1
$1,000,000 or more	farms	105,384	3,643	26.9	4.6	6.7	15.6
	$1,000	425,365,347	10,445	18.8	3.7	3.5	11.6
Farms by legal status for tax purposes:							
Family or individual	farms	1,609,899	33,964	44.8	17.8	15.0	12.0
	acres	508,952,143	9,940,625	32.2	4.5	12.2	15.5
Partnership	farms	125,457	1,972	42.9	7.4	17.8	17.7
	acres	157,864,970	3,465,598	23.8	1.7	9.0	13.1
Corporation:							
Family held	farms	108,693	1,933	41.6	8.5	15.5	17.7
	acres	134,277,030	3,998,735	24.1	1.7	7.9	14.5
Other than family held	farms	18,955	504	48.3	8.4	18.9	21.0
	acres	16,586,984	523,257	20.9	1.6	9.3	10.0
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc	farms	37,483	689	44.2	10.8	13.0	20.5
	acres	62,419,721	3,612,878	10.3	1.1	3.3	5.9
Tenure:							
Full owners	farms	1,356,796	30,698	47.3	19.0	15.4	12.9
	acres	311,935,837	7,843,514	29.0	5.0	10.3	13.7
Part owners	farms	423,889	6,543	35.1	4.9	15.2	15.0
	acres	489,711,406	10,768,105	26.3	1.5	9.2	15.6
Tenants	farms	119,802	2,652	46.4	9.5	18.4	18.5
	acres	78,453,605	2,369,235	31.6	2.2	16.2	13.2
Producers characteristics by- [1] (see text)							
Sex of operator:							
Male	farms	1,757,655	34,110	44.4	15.0	16.1	13.3
	acres	844,939,806	17,575,966	27.7	2.9	10.5	14.3
Female	farms	1,110,546	24,161	46.1	18.1	16.9	11.2
	acres	407,340,844	10,453,012	29.0	3.9	12.8	12.3
Primary occupation:							
Farming	farms	1,415,315	22,990	41.6	11.9	15.3	14.3
Other	farms	1,958,729	40,935	49.6	15.0	19.6	15.0

See footnote(s) at end of table.

--continued

Table A. **Summary of U.S. Coverage, Nonresponse, and Misclassification Adjustments: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
Producers characteristics by- [1] (see text) - Con.							
Hispanic, Latino, or Spanish origin	farms	83,505	2,844	53.5	20.7	18.9	13.9
	acres	36,866,263	2,645,621	26.4	2.4	10.2	13.7
Race:							
American Indian or Alaska Native	farms	40,621	2,213	52.5	19.4	12.2	21.0
	acres	55,781,477	3,406,570	14.2	1.5	5.6	7.1
Asian	farms	16,072	500	46.1	19.4	13.1	13.7
	acres	2,608,401	186,323	28.0	4.8	10.7	12.5
Black or African American	farms	28,723	1,029	58.8	25.5	17.3	15.9
	acres	4,318,741	237,837	53.2	8.8	21.9	22.5
Native Hawaiian or Other Pacific Islander	farms	2,779	161	48.6	22.5	13.7	12.4
	acres	799,151	172,632	23.7	5.9	7.3	10.4
White	farms	1,829,449	36,736	44.1	15.5	15.5	13.1
	acres	823,942,903	18,144,054	28.5	3.1	10.6	14.8
More than one race reported	farms	24,990	832	48.6	15.0	19.1	14.5
	acres	9,661,430	496,631	33.3	3.1	18.7	11.5
Military service:							
Never served or only on active duty for training in the Reserves or National Guard (see text)	producers	3,068,291	56,215	46.3	13.6	18.0	14.7
Active duty now or in the past (see text)	producers	305,753	6,572	45.8	15.2	16.8	13.7
All producers by age group [1]:							
Under 25 years	farms	57,000	3,134	61.2	12.4	29.6	19.2
25 to 34 years	farms	239,480	13,724	60.1	15.1	26.9	18.1
35 to 44 years	farms	426,616	8,577	52.2	13.0	23.1	16.0
45 to 54 years	farms	519,430	7,585	47.8	14.0	18.7	15.2
55 to 64 years	farms	837,525	16,665	45.2	14.0	16.5	14.7
65 to 74 years	farms	826,931	11,553	41.9	14.1	14.0	13.7
75 years and over	farms	467,062	6,465	39.7	14.5	12.9	12.3
Net cash farm income of operations:							
Farms with gains of- [2]							
Less than $1,000	farms	49,749	1,906	44.2	17.2	16.3	10.7
	$1,000	23,703	1	43.4	17.1	16.1	10.3
$1,000 to $4,999	farms	124,479	4,546	41.1	14.6	14.2	12.3
	$1,000	344,589	12	40.6	14.1	14.1	12.5
$5,000 to $9,999	farms	85,880	2,687	37.5	11.6	13.7	12.1
	$1,000	625,404	19	37.3	11.5	13.7	12.1
$10,000 to $24,999	farms	130,660	3,486	36.3	9.7	13.4	13.2
	$1,000	2,150,109	60	36.2	9.6	13.3	13.4
$25,000 to $49,999	farms	99,992	2,301	35.7	8.2	13.7	13.7
	$1,000	3,592,062	83	35.6	8.1	13.7	13.8
$50,000 or more	farms	324,637	5,129	33.5	5.0	13.1	15.3
	$1,000	175,933,735	2,671	24.2	4.5	6.0	13.7
Farms with losses of-							
Less than $1,000	farms	62,687	1,732	49.0	21.0	15.0	13.0
	$1,000	31,899	1	49.3	21.2	15.4	12.7
$1,000 to $4,999	farms	267,812	5,810	51.3	23.4	16.1	11.9
	$1,000	790,294	16	51.6	23.7	16.1	11.8
$5,000 to $9,999	farms	236,036	4,562	52.2	23.9	16.3	12.0
	$1,000	1,718,557	32	52.2	24.0	16.2	12.0
$10,000 to $24,999	farms	292,088	6,002	51.4	22.4	16.8	12.2
	$1,000	4,633,969	94	51.3	22.2	17.0	12.1
$25,000 to $49,999	farms	122,322	2,859	49.7	18.3	17.1	14.3
	$1,000	4,229,039	99	49.6	18.1	17.1	14.4
$50,000 or more	farms	104,145	2,130	44.8	10.3	17.4	17.1
	$1,000	19,626,105	704	39.1	6.3	15.1	17.7
Livestock and poultry:							
Cattle and calves inventory	farms	732,123	10,470	38.2	25.1	7.0	6.1
	number	87,954,742	1,577,554	25.0	9.3	4.6	11.1
Beef cows inventory	farms	622,162	7,989	37.8	24.4	7.1	6.3
	number	29,214,479	434,384	31.4	11.5	9.2	10.8
Milk cows inventory	farms	36,024	490	28.6	17.4	6.8	4.3
	number	9,309,855	206,563	12.2	4.7	1.4	6.2
Hog and pigs inventory	farms	60,809	3,353	48.4	17.1	17.5	13.8
	number	73,817,751	13,682,264	25.0	3.5	5.3	16.2
Layers inventory	farms	240,530	11,966	51.9	22.4	19.2	10.3
	number	388,509,039	10,505,439	11.5	3.1	1.7	6.7
Broilers sold	farms	31,877	1,554	46.3	16.8	17.8	11.7
	number	9,176,809,391	320,913,347	33.1	9.2	5.6	18.4
Aquaculture sold	farms	5,961	320	38.3	10.0	12.9	15.4
	$1,000	2,270,147	51	17.3	2.4	0.9	14.0
Selected crops harvested:							
Corn for grain	farms	289,382	13,624	34.8	5.1	12.6	17.0
	acres	80,597,963	2,096,870	27.7	1.7	8.6	17.4
Durum wheat for grain	farms	2,179	291	36.8	1.4	26.2	9.2
	acres	1,611,312	180,842	26.7	0.9	16.5	9.4
Other spring wheat for grain	farms	17,307	2,799	38.3	2.0	18.9	17.3
	acres	10,406,490	1,393,355	33.0	0.7	11.6	20.7
Winter wheat for grain	farms	81,601	5,016	33.5	3.9	17.4	12.2
	acres	25,194,192	1,116,052	26.4	1.3	14.3	10.8
Sorghum for grain	farms	13,591	593	35.7	3.3	18.3	14.2
	acres	4,692,243	89,710	26.9	1.6	14.2	11.1
Soybeans for beans	farms	270,851	10,262	31.6	5.5	17.4	8.7
	acres	84,599,236	3,817,578	28.5	2.5	12.4	13.6
Rice	farms	3,824	454	31.1	1.8	12.4	16.8
	acres	2,279,958	194,244	22.9	1.7	5.8	15.4
Cotton	farms	14,283	1,705	36.5	2.3	15.1	19.1
	acres	7,740,383	492,954	18.2	0.9	5.3	12.0

See footnote(s) at end of table.

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Table A. **Summary of U.S. Coverage, Nonresponse, and Misclassification Adjustments: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
Selected crops harvested: - Con.							
Peanuts	farms	4,919	790	33.5	3.2	13.5	16.8
	acres	1,425,267	200,271	21.3	1.7	7.6	12.0
Barley	farms	9,112	482	33.1	4.0	16.9	12.2
	acres	2,430,308	151,793	29.0	1.3	13.7	14.0
Oats	farms	15,538	2,027	39.8	11.4	16.0	12.4
	acres	914,059	71,019	37.9	4.0	16.3	17.6
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	694,318	13,624	38.1	19.0	12.2	6.9
	acres	54,159,397	692,839	33.0	9.2	13.2	10.5
Land in vegetables (see text)	farms	69,452	9,225	39.7	13.7	15.2	10.7
	acres	3,927,522	350,868	14.9	1.3	2.5	11.2
Potatoes	farms	15,099	1,933	35.1	12.1	12.8	10.1
	acres	1,076,285	48,022	8.3	0.3	0.6	7.3
Tomatoes in the open	farms	25,997	3,986	38.5	13.9	14.7	9.9
	acres	323,808	176,612	10.5	3.1	3.6	3.8
Sweet corn (see text)	farms	17,768	2,837	34.3	10.7	14.2	9.3
	acres	467,542	31,026	14.1	1.7	2.9	9.6
Lettuce	farms	11,187	1,459	38.6	13.4	14.8	10.4
	acres	367,432	25,947	17.5	2.3	3.8	11.4
Land in orchards (see text)	farms	110,544	4,245	45.1	18.0	15.7	11.4
	acres	6,203,085	482,919	25.0	8.0	6.6	10.4
Apples	farms	27,463	834	45.5	15.9	15.9	13.7
	acres	411,262	11,567	23.8	4.1	3.1	16.6
Grapes (including muscadine) (see text)	farms	27,951	895	44.6	15.5	14.9	14.1
	acres	1,108,161	194,002	28.9	9.8	6.6	12.5
Oranges	farms	7,010	668	45.8	22.0	18.0	5.8
	acres	(D)	(D)	(D)	(D)	(D)	(D)
Almonds	farms	8,586	550	35.3	22.9	8.0	4.4
	acres	1,632,710	141,363	26.5	11.6	5.5	9.4
Land in berries	farms	35,331	2,057	46.3	15.2	16.7	14.5
	acres	356,896	31,554	27.4	3.6	4.7	19.1

[1] Data were collected for a maximum of four producers per farm.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.

Table B. **Reliability Estimates of U.S. Totals: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Coefficient of variation (percent)
Farms ..... number	1,900,487	1.9
Land in farms ..... acres	880,100,848	2.3
Farms by size:		
1 to 9 acres ..... farms	234,592	4.9
acres	1,084,341	4.9
10 to 49 acres ..... farms	566,912	2.6
acres	14,193,479	2.5
50 to 69 acres ..... farms	130,096	2.2
acres	7,553,962	2.2
70 to 99 acres ..... farms	153,239	2.5
acres	12,601,546	2.4
100 to 139 acres ..... farms	138,398	1.6
acres	16,045,194	1.6
140 to 179 acres ..... farms	108,796	1.7
acres	17,126,924	1.7
180 to 219 acres ..... farms	69,602	2.1
acres	13,747,397	2.2
220 to 259 acres ..... farms	52,177	2.5
acres	12,415,492	2.5
260 to 499 acres ..... farms	166,600	1.7
acres	59,494,534	1.7
500 to 999 acres ..... farms	120,456	1.9
acres	83,738,842	1.9
1,000 to 1,999 acres ..... farms	76,311	3.0
acres	105,224,602	3.1
2,000 acres or more ..... farms	83,308	2.9
acres	536,874,535	3.2
Irrigated land use:		
Harvested cropland ..... farms	254,574	3.0
acres	51,155,829	3.0
Pastureland and other land ..... farms	55,833	2.8
acres	3,774,534	4.6
Market value of agricultural products sold $1,000	543,087,166	1.8
Farms by value of sales:		
Less than $1,000 ..... farms	499,816	2.6
$1,000	56,798	4.0
$1,000 to $2,499 ..... farms	179,054	4.5
$1,000	292,472	4.3
$2,500 to $4,999 ..... farms	166,149	3.8
$1,000	593,713	3.8
$5,000 to $9,999 ..... farms	191,688	3.6
$1,000	1,359,995	3.6
$10,000 to $19,999 ..... farms	168,876	2.3
$1,000	2,386,213	2.3
$20,000 to $24,999 ..... farms	53,378	2.5
$1,000	1,180,735	2.5
$25,000 to $39,999 ..... farms	100,390	3.9
$1,000	3,162,262	4.0
$40,000 to $49,999 ..... farms	43,657	5.0
$1,000	1,938,084	5.0
$50,000 to $99,999 ..... farms	116,220	3.4
$1,000	8,237,216	3.5
$100,000 to $249,999 ..... farms	122,968	4.0
$1,000	19,715,890	3.9
$250,000 to $499,999 ..... farms	85,266	5.7
$1,000	30,549,461	5.7
$500,000 to $999,999 ..... farms	67,641	2.5
$1,000	48,248,980	2.4
$1,000,000 or more ..... farms	105,384	3.5
$1,000	425,365,347	2.5
Farms by legal status for tax purposes:		
Family or individual ..... farms	1,609,899	2.1
acres	508,952,143	2.0
Partnership ..... farms	125,457	1.6
acres	157,864,970	2.2
Corporation:		
Family held ..... farms	108,693	1.8
acres	134,277,030	3.0
Other than family held ..... farms	18,955	2.7
acres	16,586,984	3.2
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc ..... farms	37,483	1.8
acres	62,419,721	5.8
Tenure:		
Full owners ..... farms	1,356,796	2.3
acres	311,935,837	2.5
Part owners ..... farms	423,889	1.5
acres	489,711,406	2.2
Tenants ..... farms	119,802	2.2
acres	78,453,605	3.0
Producers characteristics by- [1] (see text)		
Sex of operator:		
Male ..... farms	1,757,655	1.9
acres	844,939,806	2.1
Female ..... farms	1,110,546	2.2
acres	407,340,844	2.6
Primary occupation:		
Farming ..... farms	1,415,315	1.6
Other ..... farms	1,958,729	2.1

Item	Total	Coefficient of variation (percent)
Producers characteristics by- [1] (see text) - Con.		
Hispanic, Latino, or Spanish origin ..... farms	83,505	3.4
acres	36,866,263	7.2
Race:		
American Indian or Alaska Native ..... farms	40,621	5.4
acres	55,781,477	6.1
Asian ..... farms	16,072	3.1
acres	2,608,401	7.1
Black or African American ..... farms	28,723	3.6
acres	4,318,741	5.5
Native Hawaiian or Other Pacific Islander ..... farms	2,779	5.8
acres	799,151	21.6
White ..... farms	1,829,449	2.0
acres	823,942,903	2.2
More than one race reported ..... farms	24,990	3.3
acres	9,661,430	5.1
Military service:		
Never served or only on active duty for training in the Reserves or National Guard (see text) ..... producers	3,068,291	1.8
Active duty now or in the past (see text) ..... producers	305,753	2.1
All producers by age group [1]:		
Under 25 years ..... farms	57,000	5.5
25 to 34 years ..... farms	239,480	5.7
35 to 44 years ..... farms	426,616	2.0
45 to 54 years ..... farms	519,430	1.5
55 to 64 years ..... farms	837,525	2.0
65 to 74 years ..... farms	826,931	1.4
75 years and over ..... farms	467,062	1.4
Net cash farm income of operations:		
Farms with gains of- [2]		
Less than $1,000 ..... farms	49,749	3.8
$1,000	23,703	4.5
$1,000 to $4,999 ..... farms	124,479	3.7
$1,000	344,589	3.5
$5,000 to $9,999 ..... farms	85,880	3.1
$1,000	625,404	3.1
$10,000 to $24,999 ..... farms	130,660	2.7
$1,000	2,150,109	2.8
$25,000 to $49,999 ..... farms	99,992	2.3
$1,000	3,592,062	2.3
$50,000 or more ..... farms	324,637	1.6
$1,000	175,933,735	1.5
Farms with losses of-		
Less than $1,000 ..... farms	62,687	2.8
$1,000	31,899	2.1
$1,000 to $4,999 ..... farms	267,812	2.2
$1,000	790,294	2.0
$5,000 to $9,999 ..... farms	236,036	1.9
$1,000	1,718,557	1.9
$10,000 to $24,999 ..... farms	292,088	2.1
$1,000	4,633,969	2.0
$25,000 to $49,999 ..... farms	122,322	2.3
$1,000	4,229,039	2.3
$50,000 or more ..... farms	104,145	2.0
$1,000	19,626,105	3.6
Livestock and poultry:		
Cattle and calves inventory ..... farms	732,123	1.4
number	87,954,742	1.8
Beef cows inventory ..... farms	622,162	1.3
number	29,214,479	1.5
Milk cows inventory ..... farms	36,024	1.4
number	9,309,855	2.2
Hog and pigs inventory ..... farms	60,809	5.5
number	73,817,751	18.5
Layers inventory ..... farms	240,530	5.0
number	388,509,039	2.7
Broilers sold ..... farms	31,877	4.9
number	9,176,809,391	3.5
Aquaculture sold ..... farms	5,961	5.4
$1,000	2,270,147	2.3
Selected crops harvested:		
Corn for grain ..... farms	289,382	4.7
acres	80,597,963	2.6
Durum wheat for grain ..... farms	2,179	13.4
acres	1,611,312	11.2
Other spring wheat for grain ..... farms	17,307	16.2
acres	10,406,490	13.4
Winter wheat for grain ..... farms	81,601	6.1
acres	25,194,192	4.4
Sorghum for grain ..... farms	13,591	4.4
acres	4,692,243	1.9
Soybeans for beans ..... farms	270,851	3.8
acres	84,599,236	4.5
Rice ..... farms	3,824	11.9
acres	2,279,958	8.5

See footnote(s) at end of table.

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Table B. **Reliability Estimates of U.S. Totals: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Coefficient of variation (percent)
Selected crops harvested: - Con.			
Cotton	farms	14,283	11.9
	acres	7,740,383	6.4
Peanuts	farms	4,919	16.1
	acres	1,425,267	14.1
Barley	farms	9,112	5.3
	acres	2,430,308	6.2
Oats	farms	15,538	13.0
	acres	914,059	7.8
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	694,318	2.0
	acres	54,159,397	1.3
Land in vegetables (see text)	farms	69,452	13.3
	acres	3,927,522	8.9
Potatoes	farms	15,099	12.8
	acres	1,076,285	4.5
Tomatoes in the open	farms	25,997	15.3
	acres	323,808	54.5
Selected crops harvested: - Con. Land in vegetables (see text) - Con.			
Sweet corn (see text)	farms	17,768	16.0
	acres	467,542	6.6
Lettuce	farms	11,187	13.0
	acres	367,432	7.1
Land in orchards (see text)	farms	110,544	3.8
	acres	6,203,085	7.8
Apples	farms	27,463	3.0
	acres	411,262	2.8
Grapes (including muscadine) (see text)	farms	27,951	3.2
	acres	1,108,161	17.5
Oranges	farms	7,010	9.5
	acres	(D)	(D)
Almonds	farms	8,586	6.4
	acres	1,632,710	8.7
Land in berries	farms	35,331	5.8
	acres	356,896	8.8

[1] Data were collected for a maximum of four producers per farm.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.

Table C. **Summary of Coverage, Nonresponse, and Misclassification Adjustments by State: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Total (number)	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
ALL FARMS (NUMBER)						
United States Total						
United States	1,900,487	36,680	44.5	15.7	15.4	13.4
States						
Alabama	37,362	1,408	48.7	11.8	17.6	19.3
Alaska	1,173	2	7.7	(NA)	7.7	(NA)
Arizona	16,710	2,892	61.0	21.8	10.5	28.8
Arkansas	37,756	1,863	42.3	13.5	14.5	14.2
California	63,134	4,099	46.7	26.4	11.7	8.7
Colorado	36,056	3,988	44.5	15.5	17.3	11.8
Connecticut	5,058	339	56.1	25.0	13.1	18.0
Delaware	2,158	75	50.8	19.8	17.1	13.9
Florida	44,703	2,861	57.9	24.0	18.7	15.2
Georgia	39,264	2,072	47.4	12.3	19.4	15.7
Hawaii	6,569	647	49.9	20.4	15.1	14.4
Idaho	22,877	1,266	42.7	15.1	19.1	8.5
Illinois	71,123	3,161	37.1	10.4	13.0	13.7
Indiana	53,599	993	40.9	17.4	14.7	8.9
Iowa	86,911	5,597	32.9	8.8	10.3	13.8
Kansas	55,734	3,554	44.2	7.9	20.2	16.1
Kentucky	69,425	6,407	44.0	15.5	16.2	12.2
Louisiana	25,006	1,878	52.1	19.4	18.2	14.5
Maine	7,036	389	53.9	25.1	8.5	20.4
Maryland	12,550	523	41.3	14.0	10.9	16.5
Massachusetts	7,083	387	52.3	23.7	13.8	14.8
Michigan	45,581	6,043	47.5	23.0	16.3	8.2
Minnesota	65,531	4,913	35.6	11.1	12.8	11.7
Mississippi	31,290	1,577	46.9	13.4	15.8	17.6
Missouri	87,887	1,967	41.5	15.9	15.7	10.0
Montana	24,266	4,530	44.7	10.6	21.7	12.4
Nebraska	44,479	1,964	45.7	7.9	17.7	20.1
Nevada	3,122	147	45.8	16.8	15.0	14.0
New Hampshire	3,949	532	58.2	21.1	7.7	29.4
New Jersey	9,998	396	46.5	17.3	10.5	18.8
New Mexico	20,976	1,660	54.5	20.1	15.5	18.9
New York	30,650	994	43.6	15.7	10.8	17.1
North Carolina	42,817	3,598	45.2	13.1	17.9	14.2
North Dakota	25,068	2,281	48.2	4.9	25.9	17.4
Ohio	76,009	892	43.2	17.4	14.8	11.1
Oklahoma	70,378	2,177	44.5	13.4	22.1	9.0
Oregon	35,547	2,043	45.8	23.0	9.4	13.4
Pennsylvania	49,053	1,303	45.8	18.3	11.7	15.8
Rhode Island	1,054	83	46.3	22.1	9.5	14.8
South Carolina	22,633	1,239	53.8	12.8	20.6	20.4
South Dakota	28,299	1,690	44.6	5.5	21.9	17.3
Tennessee	63,105	4,120	42.2	14.8	15.6	11.8
Texas	230,662	10,786	48.3	20.2	14.0	14.1
Utah	17,386	608	42.3	19.1	15.2	7.9
Vermont	6,537	700	53.4	15.8	24.0	13.6
Virginia	38,995	4,076	42.9	14.2	16.1	12.6
Washington	32,076	2,278	48.4	23.7	9.8	14.9
West Virginia	22,787	1,578	40.1	16.4	13.6	10.1
Wisconsin	58,521	4,272	37.5	17.5	14.1	5.9
Wyoming	10,544	281	43.9	15.8	17.1	11.0
LAND IN FARMS (ACRES)						
United States Total						
United States	880,100,848	19,889,860	27.7	3.0	10.3	14.4
States						
Alabama	8,629,101	659,543	39.2	4.9	13.2	21.1
Alaska	869,852	(L)	0.6	(NA)	0.6	(NA)
Arizona	25,525,087	1,787,679	6.4	0.5	1.0	4.9
Arkansas	13,722,525	882,987	31.2	4.3	6.5	20.5
California	24,190,604	3,158,639	19.9	6.5	7.1	6.3
Colorado	30,213,899	4,681,646	26.1	2.7	12.1	11.3
Connecticut	372,014	31,368	36.3	14.7	7.3	14.3
Delaware	522,834	16,821	29.8	6.3	8.4	15.0
Florida	9,701,400	1,486,112	25.8	3.1	3.6	19.1
Georgia	9,939,313	2,713,044	34.4	3.8	9.9	20.8
Hawaii	1,053,302	155,904	6.2	0.7	4.2	1.2
Idaho	11,547,963	897,873	18.9	1.3	11.4	6.2
Illinois	26,292,041	464,910	27.1	2.6	10.5	14.0
Indiana	14,602,240	336,018	27.0	2.9	8.2	15.9
Iowa	29,978,165	769,892	29.7	2.0	7.2	20.6
Kansas	44,794,702	1,079,764	33.4	2.3	18.1	13.1
Kentucky	12,431,190	656,869	33.9	7.5	12.0	14.4
Louisiana	7,986,381	1,296,701	37.7	5.2	8.5	24.0
Maine	1,225,046	65,109	38.4	16.6	5.6	16.2
Maryland	1,978,036	50,262	25.1	5.2	6.1	13.8
Massachusetts	464,451	35,383	34.9	15.5	7.6	11.8
Michigan	9,472,069	4,493,603	27.2	5.2	7.9	14.0
Minnesota	25,442,625	7,766,836	31.9	1.6	5.7	24.5
Mississippi	10,251,497	1,069,522	37.2	3.7	8.3	25.2
Missouri	27,026,243	653,952	33.3	5.7	9.4	18.3
Montana	57,601,320	7,185,564	24.0	1.3	10.6	12.1

--continued

Table C. **Summary of Coverage, Nonresponse, and Misclassification Adjustments by State: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Total (number)	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
LAND IN FARMS (ACRES) - Con.						
States - Con.						
Nebraska	43,975,693	814,578	31.8	3.3	14.3	14.1
Nevada	5,896,654	255,058	9.3	0.5	6.9	2.0
New Hampshire	417,187	64,721	42.4	13.5	6.8	22.2
New Jersey	711,502	16,084	26.6	6.4	3.8	16.4
New Mexico	39,128,563	8,449,483	22.6	2.4	7.8	12.4
New York	6,502,286	125,847	29.6	8.2	5.6	15.8
North Carolina	8,128,136	562,053	29.3	3.8	9.2	16.3
North Dakota	38,537,022	1,193,151	40.2	3.1	25.8	11.4
Ohio	13,652,346	195,852	27.7	4.1	9.1	14.5
Oklahoma	32,897,563	1,345,687	31.5	3.6	17.9	9.9
Oregon	15,295,779	795,173	16.4	2.2	7.2	7.0
Pennsylvania	7,058,325	181,053	36.9	9.5	7.8	19.6
Rhode Island	59,076	2,310	16.4	6.4	2.0	8.0
South Carolina	4,553,922	281,360	40.1	5.0	15.4	19.7
South Dakota	42,304,601	1,311,508	34.0	2.4	18.3	13.3
Tennessee	10,732,951	462,250	34.5	5.6	11.8	17.1
Texas	125,471,325	7,392,284	26.8	2.6	8.4	15.8
Utah	10,494,923	1,812,347	11.3	1.8	5.3	4.2
Vermont	1,173,890	104,541	36.0	11.6	12.9	11.5
Virginia	7,309,687	654,280	30.7	6.8	10.1	13.8
Washington	13,855,414	1,461,196	16.4	3.0	5.0	8.5
West Virginia	3,549,104	97,794	31.0	9.8	11.3	9.9
Wisconsin	13,784,678	1,381,602	28.1	7.2	11.8	9.1
Wyoming	28,776,321	2,171,042	18.3	2.4	8.4	7.5
SALES ($1,000)						
United States Total						
United States	543,087,166	9,776	22.7	4.2	5.5	12.9
States						
Alabama	9,035,897	348	32.9	7.8	5.7	19.4
Alaska	90,850	(L)	1.2	(NA)	1.2	(NA)
Arizona	5,202,714	145	11.3	2.0	1.5	7.8
Arkansas	13,899,149	648	27.7	3.3	4.7	19.8
California	59,005,675	3,381	24.7	5.3	6.2	13.2
Colorado	9,222,516	544	11.4	3.7	3.8	3.8
Connecticut	704,034	32	12.6	8.5	2.2	1.8
Delaware	2,095,755	69	37.9	11.8	13.1	12.9
Florida	10,224,600	499	26.4	6.4	4.7	15.3
Georgia	13,239,372	934	27.8	7.9	3.8	16.2
Hawaii	673,776	54	13.0	2.5	6.7	3.8
Idaho	10,892,201	232	11.1	2.1	3.5	5.4
Illinois	26,417,147	190	21.4	3.2	8.1	10.1
Indiana	18,029,033	397	23.3	4.5	8.0	10.7
Iowa	43,935,488	1,728	26.3	5.6	7.2	13.4
Kansas	23,985,145	301	16.5	2.8	3.1	10.7
Kentucky	8,005,745	479	18.8	3.2	5.0	10.6
Louisiana	4,807,123	1,026	25.8	4.1	3.7	18.1
Maine	869,526	38	15.7	7.8	2.7	5.2
Maryland	3,378,072	101	21.7	3.6	4.3	13.8
Massachusetts	607,161	57	22.1	10.5	6.1	5.6
Michigan	12,212,745	4,353	16.7	3.4	2.4	10.9
Minnesota	28,482,097	6,450	29.9	2.3	5.9	21.7
Mississippi	8,247,775	674	28.0	1.8	3.3	23.0
Missouri	14,697,022	370	23.8	4.7	5.0	14.1
Montana	4,544,537	698	23.2	1.1	9.7	12.4
Nebraska	29,413,398	740	23.5	3.6	5.0	14.9
Nevada	959,681	15	12.1	1.4	3.4	7.3
New Hampshire	249,304	16	17.0	8.9	1.9	6.2
New Jersey	1,487,751	32	15.5	1.1	0.6	13.7
New Mexico	2,949,036	125	7.2	2.9	1.4	2.8
New York	8,037,292	153	17.1	2.0	1.1	14.1
North Carolina	18,692,574	2,909	29.0	4.3	9.4	15.3
North Dakota	12,138,799	296	32.2	3.0	20.3	8.9
Ohio	15,412,137	251	20.9	2.8	11.0	7.1
Oklahoma	8,540,529	168	17.4	4.3	5.3	7.8
Oregon	6,771,166	248	14.9	1.3	1.3	12.4
Pennsylvania	10,282,392	214	22.7	3.3	4.0	15.4
Rhode Island	92,830	8	16.9	9.0	4.7	3.2
South Carolina	4,427,204	267	25.1	7.1	6.5	11.5
South Dakota	12,935,225	365	26.7	4.1	12.3	10.3
Tennessee	5,161,034	182	20.9	5.0	6.0	9.9
Texas	32,166,561	960	19.9	7.3	3.3	9.3
Utah	2,341,598	108	10.4	3.8	3.7	3.0
Vermont	1,033,194	49	17.5	7.8	6.4	3.3
Virginia	5,491,996	446	18.9	5.4	4.9	8.6
Washington	12,751,572	703	14.1	1.7	1.4	11.1
West Virginia	947,765	21	14.0	5.6	3.5	5.0
Wisconsin	16,698,780	1,231	18.4	4.7	6.6	7.1
Wyoming	1,600,189	77	15.4	3.4	5.5	6.5

Table D. **American Indian or Alaska Native Producers: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	American Indian or Alaska Native farm producers		
	Total	Individually reported [1]	Other [2]
United States Total			
United States	78,854	78,316	538
States			
Alabama	1,253	1,253	-
Alaska	123	123	-
Arizona	17,402	17,087	315
Arkansas	1,363	1,363	-
California	2,398	2,397	1
Colorado	1,205	983	222
Connecticut	48	48	-
Delaware	11	11	-
Florida	913	913	-
Georgia	556	556	-
Hawaii	264	264	-
Idaho	517	517	-
Illinois	373	373	-
Indiana	344	344	-
Iowa	288	288	-
Kansas	1,195	1,195	-
Kentucky	739	739	-
Louisiana	509	509	-
Maine	123	123	-
Maryland	150	150	-
Massachusetts	83	83	-
Michigan	747	747	-
Minnesota	467	467	-
Mississippi	295	295	-
Missouri	1,689	1,689	-
Montana	1,796	1,796	-
Nebraska	261	261	-
Nevada	447	447	-
New Hampshire	48	48	-
New Jersey	85	85	-
New Mexico	8,479	8,479	-
New York	400	400	-
North Carolina	1,219	1,219	-
North Dakota	475	475	-
Ohio	578	578	-
Oklahoma	18,211	18,211	-
Oregon	1,318	1,318	-
Pennsylvania	335	335	-
Rhode Island	13	13	-
South Carolina	355	355	-
South Dakota	1,265	1,265	-
Tennessee	952	952	-
Texas	5,640	5,640	-
Utah	1,177	1,177	-
Vermont	109	109	-
Virginia	526	526	-
Washington	1,130	1,130	-
West Virginia	312	312	-
Wisconsin	354	354	-
Wyoming	314	314	-

[1] Data were collected for a maximum of four producers per farm.
[2] Data represent American Indian or Alaska Native farm or ranch producers on reservations who did not report individually. Data obtained by reservation officials.

2022 CENSUS OF AGRICULTURE

Minnesota

State and County Data

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Acknowledgments

The U.S. Department of Agriculture's National Agricultural Statistics Service (NASS) conducted the 2022 Census of Agriculture, analyzed the data, and prepared this and other reports. The census provides a comprehensive picture of U.S. agriculture in 2022, and NASS recognizes and appreciates that many individuals and organizations contributed to the effort.

Most importantly, the success of the agriculture census depends directly on the cooperation of farmers and ranchers across the country. Agricultural producers took the time to provide the information requested, recognizing that participating in the census is their responsibility and gives them a voice in their future. We are grateful to every producer who participated in the 2022 census.

Also essential were the many partners who communicated about the census and encouraged producers to respond. Farm organizations, stakeholder groups, agriculture media, community-based organizations, and land grant and other universities helped build awareness of the census and its importance to producers, their communities, and U.S. agriculture as a whole. We appreciate their help in reaching all kinds of agricultural operations, thereby ensuring a comprehensive census.

Various USDA agencies and State departments of agriculture provided valuable advice during the planning, data collection, and processing phases of the census, as well as critical assistance at the local level to farmers and ranchers completing census forms. Our thanks to them and to the enumerators who collected data locally through NASS' cooperative agreement with the National Association of State Departments of Agriculture.

Members of the Advisory Committee on Agriculture Statistics offered advice on census questions, as well as their strong and consistent support and thoughtful recommendations for census and other programs. Representatives of public and private organizations provided input as well.

Finally, we acknowledge and appreciate the support services of the U.S. Department of Commerce National Processing Center in Jeffersonville, IN.

To learn more about the census of agriculture, visit www.nass.usda.gov/AgCensus, where you can access new and historic data in a variety of formats, including the Quick Stats database. To learn about other NASS reports and activities, visit www.nass.usda.gov. For additional information, contact NASS Customer Service through email (nass@usda.gov) or phone (800-727-9540).

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Introduction

HISTORY

The 2022 Census of Agriculture is the 30th Federal census of agriculture and the sixth conducted by the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS). The U.S. Department of Commerce, Bureau of the Census conducted the census of agriculture for 156 years (1840-1996). The 1997 Appropriations Act contained a provision that transferred the responsibility for the census of agriculture to NASS.

The history of collecting data on U.S. agriculture dates back as far as President George Washington, who kept meticulous statistical records describing his own and other farms. In 1791, President Washington wrote to farmers requesting information on land values, crop acreages, crop yields, livestock prices, and taxes. Washington compiled the results on an area extending roughly 250 miles from north to south and 100 miles from east to west which today lies in Maryland, Pennsylvania, Virginia, West Virginia, and the District of Columbia, where most of the young country's population lived. In effect, Washington's inquiry was an attempt to fulfill the need for sound agricultural data for a nation that was heavily reliant on the success of agriculture. Such informal inquiries worked while the Nation was young, but were insufficient as the country expanded.

In 1839, Congress appropriated $1,000 for "carrying out agricultural investigations, and procuring agricultural statistics." The first agriculture census was taken in 1840 as part of the sixth decennial census of population. As the country expanded and agriculture evolved, the decade between agriculture censuses became too long an interval to capture the changes in agricultural production. After the 1920 census, the census interval was changed to every five years resulting in a separate, mid-decade census of agriculture that was conducted in 1925, 1935, and 1945. The agriculture census continued as part of the decennial census through 1950. From 1954 to 1974, the census was taken for the years ending in 4 and 9. In 1976, Congress authorized the census of agriculture for 1978 and 1982 to adjust the data reference year so it coincided with other economic censuses. This adjustment in timing established the census of agriculture on a 5-year cycle collecting data for years ending in 2 and 7.

USES OF CENSUS DATA

The census of agriculture provides a detailed picture of U.S. farms and ranches every five years. It is the leading source of uniform, comprehensive agricultural data for every State and county or county equivalent. Census of agriculture data are routinely used by agriculture organizations, businesses, State departments of agriculture, elected representatives, and legislative bodies at all levels of government, public and private sector analysts, the news media, and colleges and universities. census of agriculture data are frequently used to:

- Show the importance and value of agriculture at the county, State, and national levels;
- Provide agricultural news media and agricultural associations benchmark statistics for stories and articles on U.S. agriculture and the foods produced;
- Compare the income and costs of production;
- Provide important data about the demographics and financial well-being of producers;
- Evaluate historical agricultural trends to formulate farm and rural policies and develop programs that help agricultural producers;
- Allocate local and national funds for farm programs, e.g. extension service projects, agricultural research, soil conservation programs, and land-grant colleges and universities;
- Identify the assets needed to support agricultural production such as land, buildings, machinery, and other equipment;
- Create an extensive database of information on uncommon crops and livestock and the value of those commodities for assessing the need to develop policies and programs to support those commodities;
- Provide geographic data on production so agribusinesses will locate near major production areas for efficiencies for both producers and agribusinesses;

- Measure the usage of modern technologies such as conservation practices, organic production, renewable energy systems, internet access, and specialized marketing strategies;

- Develop new and improved methods to increase agricultural production and profitability;

- Plan for operations during drought and emergency outbreaks of diseases or infestations of pests;

- Analyze and report the current state of food, fuel, and fiber production in the United States; and

- Make energy projections and forecast needs for agricultural producers and their communities.

LEGAL AUTHORITY

The 2022 Census of Agriculture is required by law under the "Census of Agriculture Act of 1997," Public Law 105-113 (Title 7, United States Code, Section 2204g). The law directs the Secretary of Agriculture to conduct a census of agriculture every fifth year. The census of agriculture includes every State, Puerto Rico, Guam, the U.S. Virgin Islands, the Commonwealth of Northern Mariana Islands, and American Samoa.

FARM DEFINITION

The agriculture census definition of a farm is any place from which $1,000 or more of agricultural products were produced and sold, or normally would have been sold, during the census year. The definition has changed nine times since it was established in 1850. The current definition was first used for the 1974 Census of Agriculture and was used in each subsequent census of agriculture. This definition is consistent with the definition used for current USDA surveys. The farm definition used for each U.S. territory varies. The report for each territory includes a discussion of its farm definition.

DATA COMPARABILITY

Most commodity data are comparable between the 2022 and 2017 censuses. Changes were made to the 2022 census that affect the comparability for some data items. Demographic data for the 2022 Census of Agriculture are not fully comparable to 2017 and earlier census data due to terminology and definition changes. Dollar figures are expressed in current dollars and have not been adjusted for inflation or deflation. In general, data for censuses since 1974 are not fully comparable with data for 1969 and earlier censuses due to changes in the farm definition. See Appendix B, General Explanation and Census of Agriculture Report Form, Data Changes for a detailed discussion of these changes.

REFERENCE PERIOD

Reference periods for the 2022 Census of Agriculture were similar to those used in the 2017 Census of Agriculture. Reference periods used were:

- Crop production is measured for the calendar year, except for a few crops such as avocados, citrus, and olives for which the production year overlaps the calendar year. See Appendix B, General Explanation and Census of Agriculture Report Form for details.

- Livestock, poultry, machinery and equipment inventories, and market value of land and buildings are measured as of December 31 of the census year.

- Crop and livestock sales, other farm-related income, direct sales income, income from federal farm programs, Commodity Credit Corporation loans, Conservation Reserve, Farmable Wetlands, Conservation Reserve Enhancement, and Wetlands Reserve Program participation, farm expenses, chemical and fertilizer use, irrigated acreage, and hired farm labor data are measured for the calendar year.

TABLES AND APPENDICES

Chapter 1. Table 1 shows State-level historical data through the 1992 census and tables 2 through 51 show detailed State-level data usually accompanied by historical data from the 2017 census. Tables 52 through 70 show detailed producer and farm operation data compared to the previous census when applicable. Tables 71 through 77 show detailed State-level data cross-tabulated by several categories for the 2022 census only.

Chapter 2. County-level data are presented in 57 tables in 2 different table formats - county and county summary. Most tables include 2017 historical data. County tables include general data for all counties within the State. The county names are listed in alphabetical order in the column headings. County summary tables provide comprehensive data for all counties reporting a data item.

Appendix A. Provides information about data collection and data processing activities and discusses the statistical methodology used in conducting and evaluating the census. Table A summarizes coverage, nonresponse, and misclassification adjustment for selected items for the United States. Table B provides reliability estimates of U.S. totals for selected items. Table C summarizes coverage, nonresponse, and misclassification adjustment

for selected items at the State/county level. Table D provides total number of American Indian or Alaska Native farm producers both on and off reservations by State.

Appendix B. Includes definitions of specific terms and phrases used in this publication, including items in the publication tables that carry the note "see text." It also provides facsimiles of the report form and instruction sheet used to collect data.

RESPONDENT CONFIDENTIALITY

In keeping with the provisions of Title 7 of the United States Code, no data are published that would disclose information about the operations of an individual farm or ranch. All tabulated data are subjected to an extensive disclosure review prior to publication. Any tabulated item that identifies data reported by a respondent or allows a respondent's data to be accurately estimated or derived, was suppressed and coded with a 'D'. However, the number of farms reporting an item is not considered confidential information and is provided even though other information is withheld.

SPECIAL EFFORTS DIRECTED AT MINORITIES

NASS implemented several activities to improve coverage of minority farm producers. These activities included, but were not limited to:

- Obtaining mail lists from organizations likely to contain names and addresses of historically underserved farm producers;
- Conducting pre-census promotion activities that targeted historically underserved audiences including women, American Indian and Alaska Native, Asian, Black and African American, and Hispanic, Latino, or Spanish origin farm producers.

SPECIAL STUDIES AND CUSTOM TABULATIONS

Special studies such as the 2023 Irrigation and Water Management Survey and the 2023 Census of Aquaculture are part of the census program and provide supplemental information to the 2022 Census of Agriculture in the respective subject area. Results are published on the internet.

Custom-designed tabulations may be developed when data are not published elsewhere. These tabulations are developed to individual user specifications on a cost reimbursable basis and shared with the public. Quick Stats, NASS's online database that allows data users to build customized queries, should be investigated before requesting a custom tabulation.

All special tabulations are subject to a thorough disclosure review prior to release to prevent the disclosure of any individual respondent data. Instructions to request a special tabulation can be found on the NASS website, including information about timing, fees, and the submission form. Questions can be directed to SM.NASS.Data.Lab@usda.gov.

ABBREVIATIONS AND SYMBOLS

The following abbreviations and symbols are used throughout the tables:

- Represents zero.

(D) Withheld to avoid disclosing data for individual farms.

(H) Coefficient of variation is greater than or equal to 99.95 percent or the standard error is greater than or equal to 99.95 percent of mean.

(IC) Independent city.

(L) Coefficient of variation is less than 0.05 percent or the standard error is less than 0.05 percent of the mean.

(NA) Not available.

(X) Not applicable.

(Z) Less than half of the unit shown.

cwt Hundredweight.

sq ft Square feet.

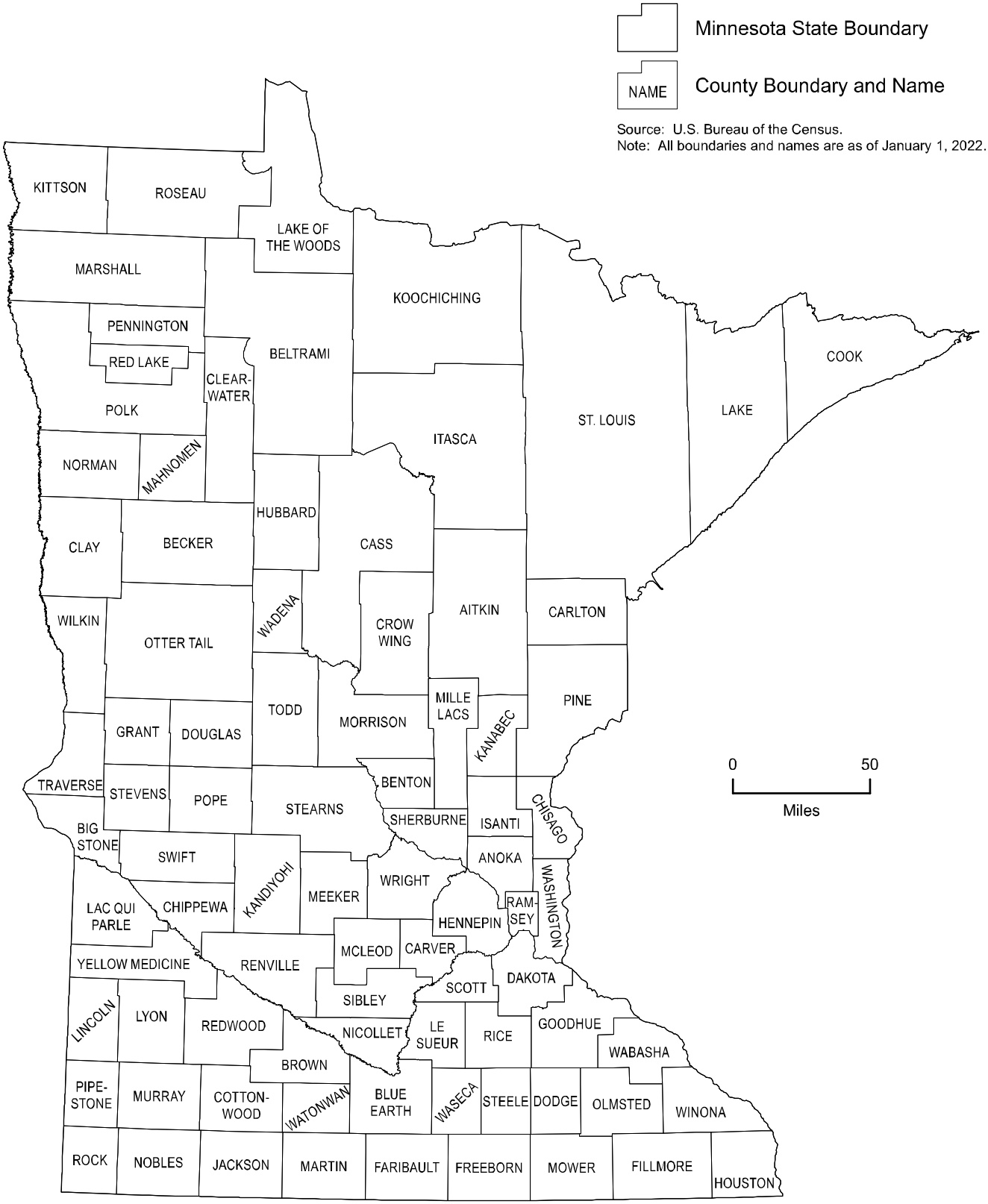
Minnesota State Boundary
NAME
County Boundary and Name
Source: U.S. Bureau of the Census.
Note: All boundaries and names are as of January 1, 2022.
KITTSON
ROSEAU
LAKE OF THE WOODS
MARSHALL
KOOCHICHING
PENNINGTON
RED LAKE
BELTRAMI
CLEAR-WATER
POLK
ITASCA
ST. LOUIS
LAKE
COOK
NORMAN
MAHNOMEN
HUBBARD
CASS
CLAY
BECKER
WILKIN
OTTER TAIL
WADENA
CROW WING
AITKIN
CARLTON
TODD
MORRISON
MILLE LACS
KANABEC
PINE
GRANT
DOUGLAS
TRAVERSE
STEVENS
POPE
STEARNS
BENTON
SHERBURNE
ISANTI
CHISAGO
BIG STONE
SWIFT
KANDIYOHI
MEEKER
WRIGHT
ANOKA
WASHINGTON
LAC QUI PARLE
CHIPPEWA
HENNEPIN
RAM-SEY
YELLOW MEDICINE
RENVILLE
MCLEOD
CARVER
SCOTT
DAKOTA
SIBLEY
LINCOLN
LYON
REDWOOD
NICOLLET
LE SUEUR
RICE
GOODHUE
WABASHA
BROWN
PIPE-STONE
MURRAY
COTTON-WOOD
WATONWAN
BLUE EARTH
WASECA
STEELE
DODGE
OLMSTED
WINONA
ROCK
NOBLES
JACKSON
MARTIN
FARIBAULT
FREEBORN
MOWER
FILLMORE
HOUSTON
0
50
Miles

Table 1. **Historical Highlights: 2022 and Earlier Census Years**

[For meaning of abbreviations and symbols, see introductory text.]

All farms	2022	2017	2012	2007	2002	1997	Not adjusted for coverage	
							1997	1992
Farms ..... number	65,531	68,822	74,542	80,992	80,839	78,755	73,367	75,079
Land in farms ..... acres	25,442,625	25,516,982	26,035,838	26,917,962	27,512,270	27,560,621	25,994,621	25,666,944
Average size of farm ..... acres	388	371	349	332	340	350	354	342
Estimated market value of land and buildings [1]:								
Average per farm ..... dollars	2,371,007	1,799,201	1,474,057	853,968	517,132	398,576	407,863	310,612
Average per acre ..... dollars	6,107	4,853	4,220	2,569	1,513	1,148	1,164	910
Estimated market value of all machinery and equipment [1] $1,000	17,904,134	15,385,551	14,737,084	10,664,895	6,665,874	6,440,856	6,208,376	5,239,930
Average per farm ..... dollars	273,216	223,666	197,715	131,698	86,369	81,809	84,613	69,859
Farms by size:								
1 to 9 acres	4,401	5,234	3,488	3,687	3,591	3,722	3,090	3,517
10 to 49 acres	15,218	14,618	15,292	16,927	16,546	12,005	10,104	8,927
50 to 179 acres	18,844	19,456	24,129	25,679	23,955	23,374	21,535	20,967
180 to 499 acres	14,183	15,923	18,074	20,188	21,372	23,747	23,365	26,395
500 to 999 acres	6,421	7,164	7,293	8,323	8,986	9,831	9,781	10,497
1,000 to 1,999 acres	3,752	4,182	4,081	4,264	4,554	4,605	4,251	3,913
2,000 acres or more	2,712	2,245	2,185	1,924	1,835	1,471	1,241	863
Total cropland ..... farms	58,762	61,686	67,285	71,970	73,458	71,153	67,545	69,866
acres	21,544,060	21,786,756	21,597,136	21,948,603	22,729,158	22,583,431	21,491,743	21,387,063
Harvested cropland..... farms	47,549	50,272	53,891	53,943	57,323	62,760	60,726	66,549
acres	19,662,443	20,054,132	19,807,839	19,267,018	19,398,309	19,794,078	18,968,607	18,201,061
Irrigated land ..... farms	3,625	3,220	2,853	2,918	2,433	2,265	2,193	2,368
acres	648,313	611,621	524,016	506,357	454,850	403,289	380,394	370,404
Market value of agricultural products sold $1,000	28,482,097	18,395,390	21,280,184	13,180,466	8,575,627	8,404,722	8,290,264	6,477,004
Average per farm ..... dollars	434,635	267,289	285,479	162,738	106,083	106,720	112,997	86,269
Crops, including nursery and greenhouse crops $1,000	17,143,767	10,191,518	13,879,211	7,048,913	4,562,882	4,312,433	4,200,970	3,054,747
Livestock, poultry, and their products $1,000	11,338,329	8,203,872	7,400,974	6,131,554	4,012,745	4,092,288	4,089,293	3,422,257
Farms by value of sales:								
Less than $2,500	18,998	21,107	21,188	30,678	29,024	19,153	14,647	9,725
$2,500 to $4,999	3,533	3,833	4,047	4,451	4,417	5,783	5,260	5,387
$5,000 to $9,999	4,091	4,385	4,552	4,795	5,491	6,431	6,179	7,028
$10,000 to $24,999	5,562	5,822	6,022	6,677	8,099	9,481	9,207	11,187
$25,000 to $49,999	4,268	4,737	5,630	5,737	7,242	7,855	8,033	10,168
$50,000 to $99,999	5,328	6,467	8,112	6,490	8,024	9,595	9,402	12,482
$100,000 to $499,999	12,139	13,374	14,632	15,738	14,917	17,660	17,885	17,774
$500,000 or more	11,612	9,097	10,359	6,426	3,625	2,797	2,754	1,328
Farms by legal status for tax purposes:								
Family or individual	55,532	59,322	65,530	70,055	73,018	69,320	64,428	66,068
Partnership	5,022	4,566	4,668	6,227	5,056	6,486	6,174	6,800
Corporation	3,803	3,549	3,215	2,848	2,342	2,583	2,442	1,982
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	1,174	1,385	1,129	1,862	423	366	323	229
Total farm production expenses [1] $1,000	20,780,603	15,133,150	15,520,275	10,320,405	7,288,947	6,508,683	6,362,110	5,244,708
Selected farm production expenses [1]:								
Livestock and poultry purchased or leased $1,000	1,926,426	1,649,648	1,301,768	1,304,042	836,490	642,827	639,336	607,096
Feed purchased $1,000	3,890,272	2,668,319	2,961,840	1,944,488	1,271,172	1,311,135	1,301,623	919,271
Fertilizer, lime, and soil conditioners purchased [2] $1,000	2,325,700	1,374,497	1,967,178	999,236	493,994	509,578	491,584	405,097
Gasoline, fuels, and oils purchased $1,000	956,802	630,623	798,828	618,971	322,649	314,563	306,292	298,913
Hired farm labor $1,000	1,320,974	832,429	692,816	521,852	459,332	342,722	334,790	261,649
Interest expense $1,000	702,889	666,967	655,486	584,665	546,747	515,473	499,899	449,417
Chemicals purchased $1,000	1,161,099	797,679	783,570	449,837	350,354	419,612	406,227	301,155
Livestock and poultry:								
Cattle and calves inventory ..... farms	16,823	20,969	23,702	24,685	28,034	32,148	30,913	34,501
number	2,121,625	2,337,505	2,412,684	2,395,217	2,265,997	2,399,617	2,395,456	2,543,373
Beef cows ..... farms	11,691	13,339	13,547	14,410	15,565	16,208	15,745	15,101
number	364,629	368,214	357,826	399,768	403,594	395,059	409,184	381,869
Milk cows ..... farms	2,185	3,644	4,746	5,148	6,474	9,910	9,603	13,380
number	459,536	457,801	463,312	459,752	478,248	554,274	541,650	609,034
Cattle and calves sold ..... farms	14,649	18,474	20,383	22,122	22,961	31,162	30,320	33,852
number	1,599,910	1,683,259	1,537,782	1,586,705	1,356,142	1,334,446	1,339,902	1,388,581
Hogs and pigs inventory ..... farms	2,928	3,225	3,355	4,382	5,628	7,765	7,512	13,125
number	8,873,776	8,467,361	7,606,785	7,652,284	6,440,067	5,665,364	5,722,460	4,668,590
Hogs and pigs sold ..... farms	3,352	3,562	3,420	4,748	6,390	7,892	7,717	13,749
number	28,535,462	27,228,111	22,154,443	22,815,512	18,618,300	12,814,319	12,943,053	9,141,699
Layers inventory ..... farms	6,146	5,245	4,501	3,760	2,859	(NA)	(NA)	(NA)
number	14,553,497	10,849,607	9,693,648	10,596,573	11,876,411	(NA)	(NA)	(NA)
Broilers and other meat-type chickens sold ..... farms	1,028	1,049	1,157	940	1,036	686	621	679
number	41,793,592	60,397,850	45,037,969	47,948,383	31,138,768	28,483,244	28,456,532	36,828,542
Selected crops harvested:								
Corn for grain ..... farms	24,697	28,086	33,198	30,976	31,782	37,619	37,630	42,961
acres	7,732,455	7,790,541	8,316,822	7,801,001	6,556,082	6,338,175	6,227,640	6,123,731
bushels	1,478,451,268	1,494,241,562	1,297,767,570	1,138,660,229	989,887,877	796,829,406	783,739,207	669,550,546
Corn for silage or greenchop ..... farms	2,768	4,606	6,746	7,998	8,889	12,425	12,373	(NA)
acres	313,974	330,543	361,189	433,506	367,455	442,835	438,176	(NA)
tons	6,334,518	6,702,696	6,160,112	5,791,485	6,230,527	6,542,513	6,482,293	(NA)
Wheat for grain, all ..... farms	3,669	4,284	5,499	6,727	7,023	9,819	9,518	12,753
acres	1,268,681	1,197,036	1,354,928	1,718,565	1,920,238	2,699,818	2,391,598	2,609,161
bushels	82,039,945	79,313,793	76,133,135	82,488,109	64,609,805	83,878,930	74,531,074	126,255,763
Durum wheat for grain ..... farms	31	14	-	64	27	33	30	(NA)
acres	(D)	1,413	-	(D)	4,156	4,344	3,823	(NA)
bushels	54,556	85,479	-	(D)	147,547	161,464	142,151	(NA)

See footnote(s) at end of table.

--continued

Table 1. **Historical Highlights: 2022 and Earlier Census Years** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

All farms	2022	2017	2012	2007	2002	1997	Not adjusted for coverage	
							1997	1992
Selected crops harvested: - Con.								
Wheat for grain, all - Con.								
Other spring wheat for grain ..... farms	3,557	4,130	5,243	6,217	6,688	9,331	9,051	(NA)
acres	1,261,299	1,190,554	1,319,274	1,646,309	1,887,131	2,628,165	2,329,490	(NA)
bushels	81,643,094	78,976,826	74,557,255	79,279,840	63,465,505	81,749,420	72,702,523	(NA)
Winter wheat for grain ..... farms	102	161	377	683	475	(NA)	(NA)	(NA)
acres	(D)	5,069	35,654	(D)	28,951	(NA)	(NA)	(NA)
bushels	342,295	251,488	1,575,880	(D)	996,753	(NA)	(NA)	(NA)
Oats for grain ..... farms	2,329	2,532	4,665	5,499	7,464	10,324	10,122	16,658
acres	126,011	84,616	130,729	180,942	231,859	306,040	296,188	465,846
bushels	9,470,546	6,494,938	7,812,393	10,494,120	12,958,117	16,667,790	16,179,495	29,142,473
Barley for grain ..... farms	336	552	1,003	1,126	1,462	4,136	3,910	(NA)
acres	55,330	67,521	99,643	108,268	139,739	496,702	433,610	(NA)
bushels	4,011,381	5,369,559	6,052,695	5,800,659	5,661,303	25,015,257	21,915,338	(NA)
Sorghum for grain ..... farms	12	12	10	3	13	41	41	(NA)
acres	364	526	147	36	185	2,188	2,267	(NA)
bushels	24,260	44,880	2,761	360	7,942	104,501	109,199	(NA)
Sorghum for silage or greenchop ..... farms	54	41	15	13	80	180	174	(NA)
acres	1,394	850	880	145	1,529	3,366	2,993	(NA)
tons	11,883	7,990	5,319	1,716	13,755	33,144	30,155	(NA)
Soybeans for beans ..... farms	25,337	27,865	28,783	27,040	29,347	31,148	31,292	33,581
acres	7,597,171	8,142,472	7,005,764	6,273,919	7,068,452	6,351,840	6,174,563	5,078,066
bushels	373,669,175	376,505,537	293,830,150	259,891,979	303,069,928	239,041,962	233,714,926	162,137,215
Dry edible beans, excluding chickpeas and limas ..... farms	573	506	555	526	665	879	833	(NA)
acres	210,162	160,604	155,154	145,422	156,707	176,016	163,716	(NA)
cwt	5,278,245	3,520,202	3,189,208	2,638,507	2,683,985	2,683,152	2,514,605	(NA)
Forage - land used for all hay and haylage, grass silage, and greenchop ..... farms	23,394	25,835	26,994	29,844	33,574	(NA)	(NA)	(NA)
acres	1,392,072	1,448,195	1,499,586	1,716,693	2,112,533	(NA)	(NA)	(NA)
tons, dry equivalent	3,565,994	3,877,087	3,998,940	4,392,567	5,741,264	(NA)	(NA)	(NA)
Sunflower seed, all ..... farms	221	165	242	505	367	667	588	1,131
acres	66,924	36,214	47,725	126,552	65,514	(D)	99,245	202,025
pounds	151,726,117	74,066,478	95,684,515	190,298,028	84,268,425	(D)	106,405,806	278,550,934
Sugarbeets for sugar ..... farms	1,106	1,107	1,226	1,247	1,369	1,536	1,622	(NA)
acres	446,627	423,096	480,847	485,650	476,617	445,986	456,360	(NA)
tons	11,642,041	12,544,950	12,300,781	11,432,253	8,793,583	8,092,386	8,269,808	(NA)
Vegetables harvested for sale [4] ..... farms	2,620	2,840	2,623	2,720	2,639	3,064	3,002	(NA)
acres	205,632	212,474	227,641	247,099	225,640	223,281	219,881	(NA)
Potatoes ..... farms	509	577	559	478	284	366	348	(NA)
acres	49,008	46,278	48,212	49,935	58,107	75,168	72,434	(NA)
Sweet potatoes ..... farms	58	82	6	-	-	(NA)	(NA)	(NA)
acres	23	33	3	-	-	(NA)	(NA)	(NA)
Land in orchards [5] ..... farms	1,174	1,061	881	814	569	596	533	(NA)
acres	5,049	4,767	5,043	4,979	4,148	4,538	4,390	(NA)

[1] Data for 2002 and prior years are based on a sample of farms.
[2] Data for 1997 and prior years exclude cost of lime and manure.
[3] Data for 2017 and prior years exclude sugarcane for seed.
[4] Data for 2002 and prior years exclude potatoes, sweet potatoes, and ginseng.
[5] Data for 2012 and prior years exclude pineapples.

Table 2. **Market Value of Agricultural Products Sold Including Landlord's Share, Food Marketing Practices, and Value-Added Products: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		2022	Percent of total in 2022	2017
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD				
Total sales	farms	65,531	100.0	68,822
	$1,000	28,482,097	100.0	18,395,390
Average per farm	dollars	434,635	(X)	267,289
By value of sales:				
Less than $1,000	farms	15,502	23.7	17,597
	$1,000	1,169	(Z)	2,048
$1,000 to $2,499	farms	3,496	5.3	3,510
	$1,000	5,706	(Z)	5,839
$2,500 to $4,999	farms	3,533	5.4	3,833
	$1,000	12,660	(Z)	13,846
$5,000 to $9,999	farms	4,091	6.2	4,385
	$1,000	29,240	0.1	31,180
$10,000 to $19,999	farms	4,177	6.4	4,270
	$1,000	59,970	0.2	61,573
$20,000 to $24,999	farms	1,385	2.1	1,552
	$1,000	30,596	0.1	34,560
$25,000 to $39,999	farms	2,858	4.4	3,195
	$1,000	90,565	0.3	102,282
$40,000 to $49,999	farms	1,410	2.2	1,542
	$1,000	62,843	0.2	68,897
$50,000 to $99,999	farms	5,328	8.1	6,467
	$1,000	386,353	1.4	469,267
$100,000 to $249,999	farms	6,767	10.3	7,597
	$1,000	1,101,110	3.9	1,248,260
$250,000 to $499,999	farms	5,372	8.2	5,777
	$1,000	1,930,062	6.8	2,070,536
$500,000 to $999,999	farms	4,483	6.8	4,689
	$1,000	3,183,211	11.2	3,324,186
$1,000,000 or more	farms	7,129	10.9	4,408
	$1,000	21,588,612	75.8	10,962,917
$1,000,000 to $2,499,999	farms	4,057	6.2	3,302
	$1,000	6,359,113	22.3	5,034,592
$2,500,000 to $4,999,999	farms	2,424	3.7	763
	$1,000	8,002,062	28.1	2,537,450
$5,000,000 or more	farms	648	1.0	343
	$1,000	7,227,437	25.4	3,390,875
Value of sales by commodity or commodity group:				
Crops, including nursery and greenhouse crops	farms	43,821	66.9	46,722
	$1,000	17,143,767	60.2	10,191,518
Grains, oilseeds, dry beans, and dry peas	farms	32,075	48.9	35,101
	$1,000	15,268,581	53.6	8,843,440
Corn	farms	25,230	38.5	28,902
	$1,000	9,045,595	31.8	4,766,809
Wheat	farms	3,668	5.6	4,284
	$1,000	735,504	2.6	440,555
Soybeans	farms	25,334	38.7	27,864
	$1,000	5,087,514	17.9	3,447,327
Sorghum	farms	53	0.1	28
	$1,000	437	(Z)	219
Barley	farms	336	0.5	536
	$1,000	27,673	0.1	23,008
Rice	farms	-	-	-
	$1,000	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms	3,613	5.5	3,577
	$1,000	371,859	1.3	165,523
Tobacco	farms	-	-	-
	$1,000	-	-	-
Cotton and cottonseed	farms	-	-	-
	$1,000	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms	2,648	4.0	2,860
	$1,000	446,099	1.6	383,264
Fruits, tree nuts, and berries	farms	1,212	1.8	1,118
	$1,000	48,717	0.2	25,839
Fruits and tree nuts	farms	944	1.4	833
	$1,000	30,052	0.1	21,398
Berries	farms	489	0.7	544
	$1,000	18,665	0.1	4,441
Nursery, greenhouse, floriculture, and sod	farms	1,051	1.6	920
	$1,000	391,444	1.4	277,254
Cultivated Christmas trees and short rotation woody crops	farms	244	0.4	228
	$1,000	7,578	(Z)	5,895
Cultivated Christmas trees	farms	243	0.4	208
	$1,000	(D)	(D)	5,800
Short rotation woody crops	farms	1	(Z)	28
	$1,000	(D)	(D)	95
Other crops and hay	farms	16,722	25.5	18,158
	$1,000	981,348	3.4	655,825
Maple syrup	farms	364	0.6	289
	$1,000	869	(Z)	758
Livestock, poultry, and their products	farms	22,770	34.7	26,062
	$1,000	11,338,329	39.8	8,203,872
Poultry and eggs	farms	4,445	6.8	4,175
	$1,000	1,943,207	6.8	1,285,951
Cattle and calves	farms	14,649	22.4	18,474
	$1,000	2,094,135	7.4	1,886,939

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Table 2. **Market Value of Agricultural Products Sold Including Landlord's Share, Food Marketing Practices, and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		2022	Percent of total in 2022	2017
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.				
Total sales - Con.				
Value of sales by commodity or commodity group: - Con.				
Livestock, poultry, and their products - Con.				
Milk from cows	farms	1,893	2.9	3,349
	$1,000	2,504,638	8.8	1,737,886
Hogs and pigs	farms	3,352	5.1	3,562
	$1,000	4,666,832	16.4	3,165,075
Sheep, goats, wool, mohair, and milk	farms	2,604	4.0	2,673
	$1,000	33,457	0.1	26,154
Horses, ponies, mules, burros, and donkeys	farms	1,247	1.9	1,414
	$1,000	18,147	0.1	14,189
Aquaculture	farms	98	0.1	60
	$1,000	19,763	0.1	11,474
Other animals and other animal products (see text)	farms	1,405	2.1	1,209
	$1,000	58,149	0.2	76,204
LANDLORD'S SHARE OF TOTAL SALES				
Value of landlord's share of total sales	farms	1,294	2.0	1,409
	$1,000	118,307	0.4	74,786
FOOD MARKETING PRACTICES				
Value of food sold directly to consumers	farms	3,339	5.1	3,533
	$1,000	44,673	0.2	39,117
Average per farm	dollars	13,379	(X)	11,072
By value of sales:				
$1 to $499	farms	610	0.9	703
	$1,000	130	(Z)	148
$500 to $999	farms	366	0.6	494
	$1,000	247	(Z)	337
$1,000 to $4,999	farms	1,174	1.8	1,229
	$1,000	2,665	(Z)	2,968
$5,000 to $9,999	farms	454	0.7	435
	$1,000	2,976	(Z)	2,923
$10,000 to $24,999	farms	396	0.6	396
	$1,000	6,140	(Z)	5,905
$25,000 to $49,999	farms	149	0.2	133
	$1,000	5,066	(Z)	4,691
$50,000 or more	farms	190	0.3	143
	$1,000	27,449	0.1	22,144
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms	1,026	1.6	637
	$1,000	108,704	0.4	68,637
Average per farm	dollars	105,950	(X)	107,750
By value of sales:				
$1 to $499	farms	140	0.2	100
	$1,000	33	(Z)	24
$500 to $999	farms	96	0.1	50
	$1,000	66	(Z)	34
$1,000 to $4,999	farms	305	0.5	174
	$1,000	753	(Z)	397
$5,000 to $9,999	farms	112	0.2	87
	$1,000	759	(Z)	584
$10,000 to $24,999	farms	168	0.3	86
	$1,000	2,573	(Z)	1,383
$25,000 to $49,999	farms	70	0.1	33
	$1,000	2,475	(Z)	1,143
$50,000 or more	farms	135	0.2	107
	$1,000	102,046	0.4	65,071
VALUE-ADDED PRODUCTS SOLD				
Value of processed or value-added agricultural products sold	farms	1,058	1.6	1,046
	$1,000	47,262	0.2	30,035
Average per farm	dollars	44,671	(X)	28,714
By value of sales:				
$1 to $499	farms	205	0.3	211
	$1,000	40	(Z)	44
$500 to $999	farms	141	0.2	120
	$1,000	93	(Z)	76
$1,000 to $4,999	farms	301	0.5	343
	$1,000	671	(Z)	840
$5,000 to $9,999	farms	94	0.1	129
	$1,000	606	(Z)	880
$10,000 to $24,999	farms	150	0.2	113
	$1,000	2,337	(Z)	1,708
$25,000 to $49,999	farms	54	0.1	47
	$1,000	1,780	(Z)	1,519
$50,000 or more	farms	113	0.2	83
	$1,000	41,735	0.1	24,969

Table 3. **Economic Class of Farms by Market Value of Agricultural Products Sold and Government Payments: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022			2017		
	Market value of agricultural products sold and government payments	Market value of agricultural products sold	Government payments	Market value of agricultural products sold and government payments	Market value of agricultural products sold	Government payments
Total ..... farms	65,531	65,531	31,583	68,822	68,822	41,230
$1,000	29,066,202	28,482,097	584,106	18,789,881	18,395,390	394,491
Average per farm ..... dollars	443,549	434,635	18,494	273,021	267,289	9,568
By economic class:						
Less than $1,000 ..... farms	6,079	6,079	549	7,503	7,503	694
$1,000	1,327	1,009	319	2,109	1,786	323
$1,000 to $2,499 ..... farms	6,033	6,033	3,063	6,259	6,259	3,306
$1,000	9,997	5,126	4,871	10,428	5,269	5,159
$2,500 to $4,999 ..... farms	5,681	5,681	2,758	6,284	6,284	3,205
$1,000	20,425	11,572	8,853	22,629	12,692	9,937
$5,000 to $9,999 ..... farms	6,141	6,141	2,839	6,565	6,565	3,197
$1,000	43,879	27,576	16,304	46,593	29,480	17,113
$10,000 to $24,999 ..... farms	7,125	7,125	3,051	7,422	7,422	3,826
$1,000	114,738	85,636	29,102	121,069	90,273	30,797
$25,000 to $49,999 ..... farms	4,813	4,813	2,168	5,363	5,363	3,193
$1,000	172,312	145,284	27,028	192,929	165,477	27,451
$50,000 to $99,999 ..... farms	5,488	5,488	2,639	6,659	6,659	4,716
$1,000	396,767	368,451	28,316	485,434	459,523	25,911
$100,000 to $249,999 ..... farms	6,899	6,899	3,590	7,646	7,646	6,083
$1,000	1,119,898	1,069,643	50,255	1,257,769	1,214,718	43,051
$250,000 to $499,999 ..... farms	5,477	5,477	3,064	5,816	5,816	5,025
$1,000	1,970,453	1,910,838	59,615	2,080,629	2,028,919	51,711
$500,000 to $999,999 ..... farms	4,529	4,529	2,937	4,778	4,778	4,192
$1,000	3,226,615	3,137,939	88,675	3,383,045	3,308,321	74,724
$1,000,000 or more ..... farms	7,266	7,266	4,925	4,527	4,527	3,793
$1,000	21,989,791	21,719,022	270,768	11,187,246	11,078,932	108,314
$1,000,000 to $2,499,999 ..... farms	4,148	4,148	2,817	3,403	3,403	2,915
$1,000	6,507,437	6,377,759	129,678	5,185,426	5,106,651	78,774
$2,500,000 to $4,999,999 ..... farms	2,458	2,458	1,695	779	779	656
$1,000	8,153,343	8,055,372	97,971	2,592,772	2,571,455	21,317
$5,000,000 or more ..... farms	660	660	413	345	345	222
$1,000	7,329,011	7,285,891	43,119	3,409,048	3,400,826	8,222

Table 4. **Farm Production Expenses: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Expenses ($1,000)	Farms	Expenses ($1,000)
Total farm production expenses [1] ..... farms	65,531	(X)	68,822	(X)
$1,000	(X)	20,780,603	(X)	15,133,150
Average per farm ..... dollars	(X)	317,111	(X)	219,888
Farms with expenses of-				
$1 to $4,999	8,552	24,447	12,008	32,131
$5,000 to $9,999	8,540	62,622	9,240	67,081
$10,000 to $24,999	12,171	198,377	11,753	189,148
$25,000 to $49,999	7,761	278,500	7,288	262,188
$50,000 to $99,999	6,336	451,129	7,100	507,675
$100,000 to $249,999	8,033	1,309,141	8,439	1,369,989
$250,000 to $499,999	5,006	1,801,872	5,474	1,952,442
$500,000 or more	9,132	16,654,516	7,520	10,752,496
$500,000 to $999,999	3,621	2,574,256	4,184	2,939,071
$1,000,000 to $2,499,999	4,177	6,416,721	2,590	3,878,255
$2,500,000 or more	1,334	7,663,539	746	3,935,169
Fertilizer, lime, and soil conditioners purchased ..... farms	36,421	(X)	40,476	(X)
$1,000	(X)	2,325,700	(X)	1,374,497
percent of total	(X)	11.2	(X)	9.1
Farms with expenses of-				
$1 to $499	2,951	640	3,963	824
$500 to $999	1,601	1,115	2,440	1,674
$1,000 to $4,999	5,977	15,246	7,963	20,305
$5,000 to $9,999	3,837	27,070	5,146	36,235
$10,000 to $24,999	5,873	94,798	7,839	124,458
$25,000 to $49,999	5,102	180,829	5,374	187,890
$50,000 to $99,999	4,358	304,986	4,128	283,755
$100,000 or more	6,722	1,701,014	3,623	719,356
Chemicals purchased ..... farms	37,339	(X)	38,474	(X)
$1,000	(X)	1,161,099	(X)	797,679
percent of total	(X)	5.6	(X)	5.3
Farms with expenses of-				
$1 to $499	5,389	1,095	6,290	1,161
$500 to $999	2,359	1,604	2,271	1,553
$1,000 to $4,999	7,312	18,984	8,213	21,919
$5,000 to $9,999	4,589	32,390	5,393	37,644
$10,000 to $24,999	6,904	109,918	7,423	117,234
$25,000 to $49,999	4,407	153,642	4,705	163,777
$50,000 or more	6,379	843,466	4,179	454,391
$50,000 to $99,999	3,571	246,699	2,692	183,247
$100,000 or more	2,808	596,767	1,487	271,144
Seeds, plants, vines, and trees purchased ..... farms	36,437	(X)	36,673	(X)
$1,000	(X)	1,772,341	(X)	1,516,361
percent of total	(X)	8.5	(X)	10.0
Farms with expenses of-				
$1 to $499	3,240	756	3,268	721
$500 to $999	2,103	1,398	1,678	1,118
$1,000 to $4,999	6,157	15,534	5,103	13,234
$5,000 to $9,999	3,683	26,867	3,930	28,455
$10,000 to $24,999	6,607	107,342	8,162	130,929
$25,000 or more	14,647	1,620,445	14,532	1,341,905
$25,000 to $49,999	5,582	190,996	5,675	199,702
$50,000 or more	9,065	1,429,449	8,857	1,142,203
Cover crop seed purchased ..... farms	4,909	(X)	4,084	(X)
$1,000	(X)	20,527	(X)	12,103
percent of total	(X)	0.1	(X)	0.1
Farms with expenses of-				
$1 to $499	1,505	307	1,631	318
$500 to $999	671	443	680	450
$1,000 to $4,999	1,610	3,639	1,282	2,769
$5,000 to $9,999	564	3,754	235	1,545
$10,000 to $24,999	459	6,122	183	2,582
$25,000 or more	100	6,261	73	4,439
$25,000 to $49,999	45	1,513	40	1,330
$50,000 or more	55	4,748	33	3,109
Livestock and poultry purchased or leased ..... farms	13,933	(X)	16,345	(X)
$1,000	(X)	1,926,426	(X)	1,649,648
percent of total	(X)	9.3	(X)	10.9
Farms with expenses of-				
$1 to $999	2,886	1,020	3,584	1,309
$1,000 to $4,999	3,772	9,456	4,874	11,885
$5,000 to $9,999	1,708	11,877	1,697	11,482
$10,000 to $24,999	1,453	22,393	1,766	27,864
$25,000 to $49,999	719	24,814	837	28,671
$50,000 to $99,999	653	46,431	830	59,853
$100,000 to $249,999	912	154,129	1,104	177,203
$250,000 or more	1,830	1,656,305	1,653	1,331,381
$250,000 to $499,999	800	290,769	747	262,116
$500,000 to $999,999	591	407,940	562	396,225
$1,000,000 or more	439	957,596	344	673,040
Breeding livestock purchased or leased ..... farms	5,904	(X)	7,659	(X)
$1,000	(X)	171,016	(X)	141,885
percent of total	(X)	0.8	(X)	0.9
Farms with expenses of-				
$1 to $999	1,051	448	1,502	614
$1,000 to $4,999	2,371	6,002	3,487	8,385
$5,000 to $9,999	976	6,392	975	6,518
$10,000 to $24,999	771	11,598	933	14,383
$25,000 to $49,999	279	9,504	301	10,413

See footnote(s) at end of table.

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Table 4. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Expenses ($1,000)	Farms	Expenses ($1,000)
Total farm production expenses [1] - Con.				
Livestock and poultry purchased or leased - Con.				
Breeding livestock purchased or leased - Con.				
Farms with expenses of- - Con.				
$50,000 to $99,999	146	9,962	220	14,667
$100,000 to $249,999	146	22,059	135	20,714
$250,000 or more	164	105,050	106	66,191
$250,000 to $499,999	87	30,001	50	18,021
$500,000 to $999,999	49	34,903	44	31,678
$1,000,000 or more	28	40,145	12	16,493
Other livestock and poultry purchased or leased ... farms	9,786	(X)	11,036	(X)
$1,000	(X)	1,755,410	(X)	1,507,763
percent of total	(X)	8.4	(X)	10.0
Farms with expenses of-				
$1 to $999	2,525	791	3,199	1,026
$1,000 to $4,999	2,134	5,095	2,273	5,375
$5,000 to $9,999	888	6,327	875	5,910
$10,000 to $24,999	787	12,298	921	14,598
$25,000 to $49,999	470	16,191	567	19,241
$50,000 to $99,999	503	36,161	672	48,566
$100,000 to $249,999	795	136,871	970	156,156
$250,000 or more	1,684	1,541,676	1,559	1,256,889
$250,000 to $499,999	725	265,233	715	251,185
$500,000 to $999,999	548	377,348	519	364,965
$1,000,000 or more	411	899,094	325	640,739
Feed purchased ... farms	26,145	(X)	29,902	(X)
$1,000	(X)	3,890,272	(X)	2,668,319
percent of total	(X)	18.7	(X)	17.6
Farms with expenses of-				
$1 to $999	4,339	2,047	6,345	2,902
$1,000 to $4,999	8,699	21,528	10,709	25,438
$5,000 to $9,999	3,425	23,293	3,384	22,689
$10,000 to $24,999	3,419	50,680	2,937	44,722
$25,000 to $49,999	1,345	46,588	1,543	53,818
$50,000 to $99,999	1,004	69,557	1,429	100,289
$100,000 or more	3,914	3,676,580	3,555	2,418,461
$100,000 to $249,999	1,155	188,636	1,353	212,069
$250,000 to $499,999	1,030	378,362	1,040	380,200
$500,000 to $999,999	953	680,232	672	467,216
$1,000,000 or more	776	2,429,350	490	1,358,976
Gasoline, fuels, and oils purchased ... farms	61,621	(X)	63,964	(X)
$1,000	(X)	956,802	(X)	630,623
percent of total	(X)	4.6	(X)	4.2
Farms with expenses of-				
$1 to $999	18,613	7,321	23,727	8,552
$1,000 to $4,999	19,101	44,274	18,497	43,394
$5,000 to $9,999	6,688	45,662	7,300	50,102
$10,000 to $24,999	8,072	123,363	8,220	126,820
$25,000 to $49,999	4,270	146,689	3,621	122,809
$50,000 or more	4,877	589,492	2,599	278,947
Utilities ... farms	48,636	(X)	51,248	(X)
$1,000	(X)	400,978	(X)	305,957
percent of total	(X)	1.9	(X)	2.0
Farms with expenses of-				
$1 to $499	4,981	1,257	6,823	1,667
$500 to $999	4,942	3,279	6,717	4,470
$1,000 to $4,999	24,023	57,560	23,311	55,402
$5,000 to $9,999	6,661	44,962	7,152	48,189
$10,000 to $24,999	5,416	85,017	5,540	79,296
$25,000 or more	2,613	208,902	1,705	116,934
$25,000 to $49,999	1,626	57,039	1,111	37,458
$50,000 or more	987	151,863	594	79,476
Repairs, supplies, and maintenance costs ... farms	55,660	(X)	58,445	(X)
$1,000	(X)	1,322,234	(X)	889,519
percent of total	(X)	6.4	(X)	5.9
Farms with expenses of-				
$1 to $999	9,145	3,827	12,377	5,153
$1,000 to $4,999	16,664	40,723	18,075	42,115
$5,000 to $9,999	8,260	55,861	8,091	54,849
$10,000 to $24,999	9,239	146,723	10,137	156,471
$25,000 to $49,999	5,425	193,109	5,525	189,440
$50,000 or more	6,927	881,989	4,240	441,491
$50,000 to $99,999	3,645	245,957	2,924	193,342
$100,000 or more	3,282	636,032	1,316	248,149
Hired farm labor ... farms	17,399	(X)	19,374	(X)
$1,000	(X)	1,320,974	(X)	832,429
percent of total	(X)	6.4	(X)	5.5
Farms with expenses of-				
$1 to $999	1,987	949	3,586	1,633
$1,000 to $4,999	3,957	10,307	5,000	12,067
$5,000 to $9,999	1,858	13,102	2,289	15,414
$10,000 to $24,999	2,608	41,121	3,058	48,392
$25,000 to $49,999	1,908	68,332	2,161	76,460

See footnote(s) at end of table.

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Table 4. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Expenses ($1,000)	Farms	Expenses ($1,000)
Total farm production expenses [1] - Con.				
Hired farm labor - Con.				
Farms with expenses of- - Con.				
$50,000 to $99,999	1,841	126,210	1,577	110,069
$100,000 or more	3,240	1,060,953	1,703	568,394
$100,000 to $249,999	2,234	315,409	1,053	162,274
$250,000 to $499,999	518	176,398	429	142,754
$500,000 or more	488	569,147	221	263,366
Contract labor ... farms	4,311	(X)	4,724	(X)
$1,000	(X)	152,565	(X)	82,304
percent of total	(X)	0.7	(X)	0.5
Farms with expenses of-				
$1 to $999	452	216	824	396
$1,000 to $4,999	1,452	3,802	1,388	3,460
$5,000 to $9,999	631	4,320	783	5,413
$10,000 to $24,999	838	12,325	931	14,235
$25,000 to $49,999	315	10,970	423	14,482
$50,000 or more	623	120,933	375	44,318
$50,000 to $99,999	410	28,066	243	16,210
$100,000 or more	213	92,867	132	28,108
Customwork and custom hauling ... farms	19,181	(X)	21,712	(X)
$1,000	(X)	425,172	(X)	310,122
percent of total	(X)	2.0	(X)	2.0
Farms with expenses of-				
$1 to $999	2,876	1,351	4,432	2,047
$1,000 to $4,999	6,088	15,216	7,392	18,296
$5,000 to $9,999	2,933	20,602	3,438	24,008
$10,000 to $24,999	3,607	55,472	3,690	58,050
$25,000 to $49,999	2,030	72,451	1,594	54,055
$50,000 or more	1,647	260,080	1,166	153,666
$50,000 to $99,999	1,033	73,171	707	48,005
$100,000 or more	614	186,910	459	105,661
Cash rent for land, buildings, and grazing fees ... farms	24,199	(X)	24,769	(X)
$1,000	(X)	2,302,712	(X)	1,851,799
percent of total	(X)	11.1	(X)	12.2
Farms with expenses of-				
$1 to $499	780	214	1,158	297
$500 to $999	909	619	1,002	700
$1,000 to $4,999	3,600	9,232	3,641	9,210
$5,000 to $9,999	2,314	16,493	2,358	16,787
$10,000 to $24,999	4,009	66,459	4,203	69,507
$25,000 to $49,999	3,281	117,749	3,540	126,574
$50,000 or more	9,306	2,091,946	8,867	1,628,724
Rent and lease expenses for machinery, equipment, and farm share of vehicles ... farms	6,598	(X)	7,187	(X)
$1,000	(X)	182,357	(X)	130,176
percent of total	(X)	0.9	(X)	0.9
Farms with expenses of-				
$1 to $499	672	158	1,084	256
$500 to $999	561	379	730	505
$1,000 to $4,999	1,683	3,802	1,981	4,549
$5,000 to $9,999	810	5,571	892	6,301
$10,000 to $24,999	1,358	21,103	1,289	19,823
$25,000 to $49,999	538	18,579	626	21,039
$50,000 or more	976	132,765	585	77,704
Interest expense ... farms	27,274	(X)	31,165	(X)
$1,000	(X)	702,889	(X)	666,967
percent of total	(X)	3.4	(X)	4.4
Farms with expenses of-				
$1 to $999	2,468	1,158	3,401	1,581
$1,000 to $4,999	6,848	18,125	8,345	22,508
$5,000 to $9,999	5,113	35,654	5,531	38,871
$10,000 to $24,999	6,142	96,483	6,822	107,228
$25,000 to $49,999	3,278	112,614	3,686	128,235
$50,000 to $99,999	2,038	140,093	2,236	153,021
$100,000 or more	1,387	298,762	1,144	215,523
Secured by real estate ... farms	20,348	(X)	24,135	(X)
$1,000	(X)	467,669	(X)	452,333
percent of total	(X)	2.3	(X)	3.0
Farms with expenses of-				
$1 to $999	1,511	721	2,176	1,055
$1,000 to $4,999	5,125	14,629	6,854	18,604
$5,000 to $9,999	4,292	29,546	4,917	34,273
$10,000 to $24,999	4,835	74,617	5,347	82,065
$25,000 to $49,999	2,363	80,847	2,678	92,488
$50,000 to $99,999	1,380	92,639	1,487	100,501
$100,000 or more	842	174,670	676	123,348
Not secured by real estate ... farms	16,953	(X)	19,739	(X)
$1,000	(X)	235,219	(X)	214,634
percent of total	(X)	1.1	(X)	1.4
Farms with expenses of-				
$1 to $999	2,836	1,334	4,365	1,758
$1,000 to $4,999	6,264	14,749	6,738	16,290
$5,000 to $9,999	2,577	17,178	2,955	19,922
$10,000 to $24,999	2,823	43,593	3,557	53,694
$25,000 to $49,999	1,506	48,026	1,342	44,859
$50,000 to $99,999	543	35,988	544	36,013
$100,000 or more	404	74,352	238	42,098

See footnote(s) at end of table.

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Table 4. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Expenses ($1,000)	Farms	Expenses ($1,000)
Total farm production expenses [1] - Con.				
Property taxes paid ..... farms	61,644	(X)	64,702	(X)
$1,000	(X)	482,443	(X)	403,333
percent of total	(X)	2.3	(X)	2.7
Farms with expenses of-				
$1 to $499	2,889	821	4,901	1,296
$500 to $999	4,279	3,165	6,343	4,718
$1,000 to $4,999	32,157	88,155	33,305	84,673
$5,000 to $9,999	11,291	76,795	10,476	71,621
$10,000 to $24,999	7,298	109,878	6,820	102,714
$25,000 or more	3,730	203,628	2,857	138,310
Medical supplies, veterinary, and custom services for livestock ..... farms	19,351	(X)	24,677	(X)
$1,000	(X)	255,043	(X)	189,609
percent of total	(X)	1.2	(X)	1.3
Farms with expenses of-				
$1 to $999	8,101	3,424	12,609	4,734
$1,000 to $4,999	6,158	13,241	7,186	15,243
$5,000 to $9,999	1,713	11,886	1,916	13,076
$10,000 to $24,999	1,605	24,648	1,733	25,904
$25,000 to $49,999	674	23,530	549	18,183
$50,000 to $99,999	623	41,596	333	23,137
$100,000 or more	477	136,718	351	89,332
$100,000 to $249,999	272	38,565	236	35,831
$250,000 or more	205	98,153	115	53,501
All other production expenses ..... farms	44,226	(X)	38,536	(X)
$1,000	(X)	1,200,596	(X)	833,806
percent of total	(X)	5.8	(X)	5.5
Farms with expenses of-				
$1 to $999	7,576	3,213	5,557	2,565
$1,000 to $4,999	14,638	37,020	12,970	31,941
$5,000 to $9,999	5,771	39,171	6,167	42,140
$10,000 to $24,999	7,254	106,640	6,898	106,273
$25,000 to $49,999	3,867	126,637	3,486	119,959
$50,000 to $99,999	3,372	242,990	2,077	143,744
$100,000 or more	1,748	644,925	1,381	387,185
$100,000 to $249,999	1,197	172,716	1,024	145,317
$250,000 or more	551	472,209	357	241,868
Production expenses paid by landlords [1] ..... farms	2,062	(X)	1,960	(X)
$1,000	(X)	65,113	(X)	40,456
percent of total	(X)	0.3	(X)	0.3
Farms with expenses of-				
$1 to $499	165	38	242	56
$500 to $999	107	75	143	105
$1,000 to $4,999	463	1,134	505	1,309
$5,000 to $9,999	279	1,964	263	1,823
$10,000 to $24,999	371	6,097	401	6,358
$25,000 or more	677	55,805	406	30,805
$25,000 to $49,999	286	9,800	197	6,973
$50,000 to $99,999	277	17,934	140	9,513
$100,000 or more	114	28,072	69	14,319
Depreciation expenses claimed ..... farms	41,075	(X)	37,853	(X)
$1,000	(X)	2,240,389	(X)	1,467,973
percent of total	(X)	10.8	(X)	9.7
Farms with expenses of-				
$1 to $499	1,520	381	1,508	379
$500 to $999	1,725	1,211	1,572	1,085
$1,000 to $4,999	8,519	22,410	8,958	23,999
$5,000 to $9,999	5,663	39,251	5,344	36,630
$10,000 to $24,999	8,494	134,687	7,757	123,223
$25,000 or more	15,154	2,042,449	12,714	1,282,657
$25,000 to $49,999	5,394	188,447	5,348	186,016
$50,000 to $99,999	4,095	283,445	3,808	259,518
$100,000 or more	5,665	1,570,557	3,558	837,123

[1] Landlord production expenses are included within total farm production expenses.

Table 5. **Net Cash Farm Income of the Operations and Producers: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Income ($1,000)	Farms	Income ($1,000)
Net cash farm income of the operations	65,531	9,296,848	68,822	4,525,276
Average per farm ..... dollars	(X)	141,869	(X)	65,753
Farms with net gains [1]	41,496	10,071,273	42,786	5,100,329
Average per farm ..... dollars	(X)	242,705	(X)	119,206
Farms with gains of-				
less than $1,000	1,541	775	1,917	923
$1,000 to $4,999	4,053	11,280	5,221	14,625
$5,000 to $9,999	3,053	22,351	4,060	29,640
$10,000 to $24,999	5,680	95,057	7,351	123,483
$25,000 to $49,999	5,396	196,292	6,627	240,042
$50,000 or more	21,773	9,745,519	17,610	4,691,615
Farms with net losses	24,035	774,425	26,036	575,053
Average per farm ..... dollars	(X)	32,221	(X)	22,087
Farms with losses of-				
less than $1,000	1,786	856	2,178	1,072
$1,000 to $4,999	6,380	18,668	7,839	22,256
$5,000 to $9,999	5,021	36,645	5,495	39,508
$10,000 to $24,999	5,999	95,543	5,737	90,319
$25,000 to $49,999	2,539	87,840	2,455	85,017
$50,000 or more	2,310	534,873	2,332	336,882
Net cash farm income of producers	65,531	8,390,544	68,822	3,899,993
Average per farm ..... dollars	(X)	128,039	(X)	56,668
Producers reporting net gains [1]	41,274	9,202,183	42,429	4,514,250
Average per farm ..... dollars	(X)	222,954	(X)	106,395
Farms with gains of-				
less than $1,000	1,557	788	1,930	926
$1,000 to $4,999	4,059	11,301	5,254	14,723
$5,000 to $9,999	3,084	22,642	4,093	29,859
$10,000 to $24,999	5,726	95,839	7,402	124,239
$25,000 to $49,999	5,475	199,308	6,785	246,188
$50,000 or more	21,373	8,872,304	16,965	4,098,314
Producers reporting net losses	24,257	811,639	26,393	614,258
Average per farm ..... dollars	(X)	33,460	(X)	23,274
Farms with losses of-				
less than $1,000	1,780	852	2,188	1,074
$1,000 to $4,999	6,394	18,720	7,877	22,383
$5,000 to $9,999	5,032	36,678	5,475	39,334
$10,000 to $24,999	6,008	95,604	5,838	91,999
$25,000 to $49,999	2,576	89,435	2,527	87,378
$50,000 or more	2,467	570,351	2,488	372,090

[1] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.

Table 6. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Value ($1,000)	Farms	Value ($1,000)
Government payments	31,583	584,106	41,230	394,491
Average per farm ..... dollars	(X)	18,494	(X)	9,568
Farms with receipts of-				
$1 to $999	3,767	1,892	8,056	3,244
$1,000 to $4,999	11,126	28,642	15,224	39,365
$5,000 to $9,999	5,331	37,978	7,103	50,419
$10,000 to $24,999	5,641	89,143	6,764	105,179
$25,000 to $49,999	2,851	100,229	2,866	100,444
$50,000 or more	2,867	326,221	1,217	95,841
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	19,069	126,510	19,972	107,308
Average per farm ..... dollars	(X)	6,634	(X)	5,373
Farms with receipts of-				
$1 to $999	3,060	1,603	4,378	2,147
$1,000 to $4,999	9,032	22,651	9,662	23,760
$5,000 to $9,999	3,408	23,971	3,103	21,738
$10,000 to $24,999	2,601	39,698	2,123	31,924
$25,000 or more	968	38,586	706	27,739
Amount from other Federal farm programs	16,968	457,596	33,153	287,183
Average per farm ..... dollars	(X)	26,968	(X)	8,662

Item	2022		2017	
	Farms	Value ($1,000)	Farms	Value ($1,000)
Government payments - Con.				
Amount from other Federal farm programs - Con.				
Farms with receipts of-				
$1 to $999	2,302	1,013	9,577	3,749
$1,000 to $4,999	4,064	10,733	10,973	27,576
$5,000 to $9,999	2,498	18,008	4,907	34,791
$10,000 to $24,999	3,481	55,527	4,626	72,265
$25,000 or more	4,623	372,316	3,070	148,801
Commodity Credit Corporation Loans	990	197,241	2,777	414,580
Average per farm ..... dollars	(X)	199,233	(X)	149,291
Farms with receipts of-				
$1 to $999	38	13	98	36
$1,000 to $4,999	43	101	127	368
$5,000 to $9,999	50	336	84	602
$10,000 to $19,999	61	853	184	2,675
$20,000 to $24,999	32	692	76	1,668
$25,000 to $49,999	137	4,911	397	14,604
$50,000 or more	629	190,335	1,811	394,627
Amount spent to repay CCC loans	1,256	195,908	2,618	357,144

Table 7. **Income from Farm-Related Sources: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Value ($1,000)	Farms	Value ($1,000)
Total income from farm-related sources	38,287	1,011,249	42,569	868,545
Average per farm ... dollars	(X)	26,412	(X)	20,403
Farms with receipts of-				
$1 to $999	7,561	2,740	9,957	3,466
$1,000 to $4,999	9,733	23,830	11,255	27,957
$5,000 to $9,999	4,662	32,444	5,526	39,042
$10,000 to $24,999	6,494	104,520	6,896	110,738
$25,000 to $49,999	4,514	159,280	4,380	153,966
$50,000 or more	5,323	688,435	4,555	533,376
Customwork and other agricultural services	4,779	144,025	5,718	119,832
Average per farm ... dollars	(X)	30,137	(X)	20,957
Farms with receipts of-				
$1 to $999	518	238	664	311
$1,000 to $4,999	1,303	3,235	1,715	4,386
$5,000 to $9,999	740	4,921	976	6,581
$10,000 to $24,999	914	14,130	1,131	17,711
$25,000 to $49,999	561	18,839	612	20,623
$50,000 or more	743	102,663	620	70,221
Gross cash rent or share payments	15,680	479,289	16,598	420,859
Average per farm ... dollars	(X)	30,567	(X)	25,356
Farms with receipts of-				
$1 to $999	1,292	693	1,508	796
$1,000 to $4,999	3,654	9,336	4,162	10,643
$5,000 to $9,999	2,155	15,405	2,393	17,159
$10,000 to $24,999	3,365	54,943	3,641	59,086
$25,000 or more	5,214	398,913	4,894	333,175
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	619	5,384	670	4,701
Average per farm ... dollars	(X)	8,698	(X)	7,017
Farms with receipts of-				
$1 to $999	196	79	223	80
$1,000 to $4,999	205	460	218	502
$5,000 to $9,999	86	600	113	775
$10,000 to $24,999	83	1,306	76	1,196
$25,000 or more	49	2,938	40	2,150
Agri-tourism and recreational services	509	13,615	473	13,217
Average per farm ... dollars	(X)	26,748	(X)	27,943
Farms with receipts of-				
$1 to $999	144	45	180	59
$1,000 to $4,999	146	333	136	301
Total income from farm-related sources - Con.				
Agri-tourism and recreational services - Con.				
Farms with receipts of- - Con.				
$5,000 to $9,999	45	300	36	237
$10,000 to $24,999	67	1,005	56	888
$25,000 or more	107	11,931	65	11,732
Patronage dividends and refunds from cooperatives	23,672	126,183	27,504	115,527
Average per farm ... dollars	(X)	5,330	(X)	4,200
Farms with receipts of-				
$1 to $999	10,382	3,386	13,471	4,147
$1,000 to $4,999	7,959	18,030	8,937	20,196
$5,000 to $9,999	2,464	16,108	2,600	17,197
$10,000 to $24,999	1,871	27,947	1,737	25,645
$25,000 or more	996	60,711	759	48,342
Crop and livestock insurance payments	5,882	171,530	5,640	125,828
Average per farm ... dollars	(X)	29,162	(X)	22,310
Farms with receipts of-				
$1 to $999	500	239	673	352
$1,000 to $4,999	1,332	3,382	1,811	4,628
$5,000 to $9,999	889	6,227	960	6,696
$10,000 to $24,999	1,381	22,101	1,070	16,626
$25,000 or more	1,780	139,581	1,126	97,526
Amount from State and local government agricultural program payments	1,422	7,129	1,190	5,819
Average per farm ... dollars	(X)	5,013	(X)	4,890
Farms with receipts of-				
$1 to $999	301	144	405	196
$1,000 to $4,999	819	2,065	523	1,243
$5,000 to $9,999	138	921	121	840
$10,000 to $24,999	104	1,543	73	1,114
$25,000 or more	60	2,456	68	2,426
Other farm-related income sources	2,557	64,095	3,475	62,761
Average per farm ... dollars	(X)	25,066	(X)	18,061
Farms with receipts of-				
$1 to $999	623	197	1,041	298
$1,000 to $4,999	706	1,801	926	2,242
$5,000 to $9,999	279	1,804	374	2,615
$10,000 to $24,999	390	5,788	535	8,396
$25,000 or more	559	54,504	599	49,210

Table 8. **Land: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

All farms	2022		2017
	Total	Percent of total in 2022	
LAND USE			
Farms ... number	65,531	100.0	68,822
Land in farms ... acres	25,442,625	100.0	25,516,982
Total cropland ... farms	58,762	89.7	61,686
acres	21,544,060	84.7	21,786,756
Harvested cropland ... farms	47,549	72.6	50,272
acres	19,662,443	77.3	20,054,132
Farms by acres harvested:			
1 to 49 acres	16,934	25.8	16,471
1 to 9 acres	6,328	9.7	6,092
10 to 19 acres	4,271	6.5	3,923
20 to 29 acres	2,676	4.1	2,718
30 to 49 acres	3,659	5.6	3,738
50 to 99 acres	5,412	8.3	5,609
100 to 199 acres	6,580	10.0	7,345
200 to 499 acres	8,316	12.7	9,769
500 to 999 acres	4,858	7.4	5,555
1,000 to 1,999 acres	3,081	4.7	3,603
2,000 acres or more	2,368	3.6	1,920
Other pasture and grazing land that could have been used for crops without additional improvement ... farms	3,908	6.0	3,907
acres	174,215	0.7	161,930
Other cropland ... farms	25,702	39.2	25,085
acres	1,707,402	6.7	1,570,694
Cropland idle or used for cover crops or soil-improvement, but not harvested and not pastured or grazed ... farms	22,588	34.5	21,950
acres	1,546,009	6.1	1,458,432
LAND USE - Con.			
Total cropland - Con.			
Other cropland - Con.			
Cropland on which all crops failed or were abandoned ... farms	2,413	3.7	2,288
acres	110,013	0.4	56,872
Cropland in summer fallow ... farms	2,242	3.4	2,185
acres	51,380	0.2	55,390
Total woodland ... farms	23,960	36.6	24,988
acres	1,446,600	5.7	1,392,385
Woodland pastured ... farms	7,908	12.1	8,836
acres	315,103	1.2	345,599
Woodland not pastured ... farms	19,456	29.7	19,859
acres	1,131,497	4.4	1,046,786
Permanent pasture and rangeland, other than cropland and woodland pastured ... farms	19,837	30.3	22,224
acres	1,031,215	4.1	1,073,788
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc ... farms	42,652	65.1	45,547
acres	1,420,750	5.6	1,264,053
CONSERVATION AND CROP INSURANCE			
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs ... farms	19,069	(X)	19,972
acres	951,335	(X)	1,073,549
Land enrolled in crop insurance programs ... farms	27,305	(X)	29,578
acres	18,167,226	(X)	17,684,964

Table 9. **Land in Farms, Harvested Cropland, and Irrigated Land by Size of Farm: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

All farms	Farms		Land in farms (acres)		Harvested cropland (acres)		Irrigated land (acres)	
	2022	2017	2022	2017	2022	2017	2022	2017
Land in farms	65,531	68,822	25,442,625	25,516,982	19,662,443	20,054,132	648,313	611,621
Farms by size:								
1 to 9 acres	4,401	5,234	22,106	26,402	5,447	6,902	799	627
10 to 49 acres	15,218	14,618	398,319	396,828	116,138	110,999	3,844	2,415
50 to 69 acres	3,598	3,712	211,291	217,056	67,610	70,295	1,403	1,328
70 to 99 acres	5,575	5,741	455,348	467,485	163,112	168,375	4,129	2,455
100 to 139 acres	4,857	5,087	567,895	594,116	230,286	237,404	6,061	3,976
140 to 179 acres	4,814	4,916	757,338	773,134	356,651	371,727	6,927	6,626
180 to 219 acres	2,981	3,253	588,138	643,027	292,947	352,517	7,815	9,359
220 to 259 acres	2,503	2,916	594,776	691,707	322,004	415,194	7,323	13,809
260 to 499 acres	8,699	9,754	3,130,858	3,494,375	2,022,637	2,348,311	53,545	53,865
500 to 999 acres	6,421	7,164	4,468,495	5,002,107	3,462,397	4,029,020	105,801	113,182
1,000 to 1,999 acres	3,752	4,182	5,173,695	5,720,340	4,417,695	5,107,505	150,689	159,593
2,000 to 4,999 acres	2,430	1,998	6,977,216	5,635,726	6,362,106	5,147,421	198,550	153,628
5,000 acres or more	282	247	2,097,150	1,854,679	1,843,413	1,688,462	101,427	90,758
Farms with harvested cropland	47,549	50,272	23,754,389	23,898,864	19,662,443	20,054,132	647,985	611,292
Farms by size:								
1 to 9 acres	1,928	2,155	9,424	10,822	5,447	6,902	747	549
10 to 49 acres	8,326	7,685	221,792	214,051	116,138	110,999	3,741	2,219
50 to 69 acres	2,150	2,178	126,171	127,873	67,610	70,295	1,397	1,325
70 to 99 acres	3,531	3,663	289,247	298,986	163,112	168,375	4,124	2,443
100 to 139 acres	3,351	3,485	392,452	407,625	230,286	237,404	6,015	3,936
140 to 179 acres	3,598	3,719	566,694	585,812	356,651	371,727	6,923	6,626
180 to 219 acres	2,357	2,690	465,678	531,961	292,947	352,517	7,815	9,359
220 to 259 acres	2,054	2,553	487,920	605,857	322,004	415,194	7,211	13,809
260 to 499 acres	7,726	8,864	2,792,101	3,184,121	2,022,637	2,348,311	53,545	53,865
500 to 999 acres	6,142	6,909	4,285,833	4,837,286	3,462,397	4,029,020	105,801	113,182
1,000 to 1,999 acres	3,693	4,142	5,095,013	5,667,735	4,417,695	5,107,505	150,689	159,593
2,000 to 4,999 acres	2,412	1,985	6,931,164	5,601,143	6,362,106	5,147,421	198,550	153,628
5,000 acres or more	281	244	2,090,900	1,825,592	1,843,413	1,688,462	101,427	90,758
Farms with irrigated land	3,625	3,220	2,331,272	2,142,296	1,948,596	1,859,878	648,313	611,621
Farms by size:								
1 to 9 acres	559	394	2,123	1,546	958	727	799	627
10 to 49 acres	723	528	17,151	12,956	6,238	4,047	3,844	2,415
50 to 69 acres	104	118	6,114	6,883	2,481	2,738	1,403	1,328
70 to 99 acres	176	134	14,425	10,980	6,471	3,869	4,129	2,455
100 to 139 acres	158	113	18,501	13,124	10,172	7,046	6,061	3,976
140 to 179 acres	121	112	19,079	17,508	12,080	10,908	6,927	6,626
180 to 219 acres	111	112	22,087	22,446	14,710	15,373	7,815	9,359
220 to 259 acres	98	140	23,275	32,967	14,583	23,664	7,323	13,809
260 to 499 acres	423	443	152,441	161,863	112,051	117,864	53,545	53,865
500 to 999 acres	478	469	340,343	329,768	280,421	278,078	105,801	113,182
1,000 to 1,999 acres	368	398	514,342	560,277	436,882	490,165	150,689	159,593
2,000 to 4,999 acres	257	219	754,191	633,398	688,631	581,908	198,550	153,628
5,000 acres or more	49	40	447,200	338,580	362,918	323,491	101,427	90,758

Table 10. **Irrigation: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Farms with irrigation		2022	2017
Irrigated farms (see text)	number	3,625	3,220
Proportion of farms	percent	5.5	4.7
Irrigated land	acres	648,313	611,621
Average per farm	acres	179	190
Acres irrigated:			
1 to 9 acres	farms	1,494	1,163
	acres	3,052	2,352
10 to 49 acres	farms	474	360
	acres	12,271	9,938
50 to 99 acres	farms	379	385
	acres	27,028	27,806
100 to 199 acres	farms	491	545
	acres	66,577	75,447
200 to 499 acres	farms	490	499
	acres	150,657	154,065
500 to 999 acres	farms	168	154
	acres	120,182	108,999

Farms with irrigation		2022	2017
Irrigated land - Con.			
Acres irrigated: - Con.			
1,000 to 1,999 acres	farms	92	77
	acres	131,888	100,746
2,000 acres or more	farms	37	37
	acres	136,658	132,268
Irrigated land use:			
Harvested cropland	farms	3,551	3,131
	acres	644,857	609,225
Pastureland and other land	farms	160	132
	acres	3,456	2,396
Land in irrigated farms	acres	2,331,272	2,142,296
Cropland	acres	2,041,793	1,937,288
Harvested cropland	acres	1,948,596	1,859,878
Land with irrigation systems or equipment present (see text)	farms	3,968	(NA)
	acres	709,449	(NA)

Table 11. **Selected Characteristics of Irrigated and Nonirrigated Farms: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Characteristics	All farms		Irrigated farms				Nonirrigated farms	
			Any land irrigated		All harvested cropland irrigated			
	2022	2017	2022	2017	2022	2017	2022	2017
Farms ..... number	65,531	68,822	3,625	3,220	1,066	800	61,906	65,602
Land in farms ..... acres	25,442,625	25,516,982	2,331,272	2,142,296	140,400	114,142	23,111,353	23,374,686
Estimated market value of land and buildings:								
Average per farm ..... dollars	2,371,007	1,799,201	3,800,588	3,246,486	920,251	699,972	2,287,296	1,728,163
Average per acre ..... dollars	6,107	4,853	5,910	4,880	6,987	4,906	6,127	4,850
Irrigated land ..... acres	648,313	611,621	648,313	611,621	97,986	78,281	(X)	(X)
Land in farms according to use:								
Total cropland ..... farms	58,762	61,686	3,609	3,188	1,066	800	55,153	58,498
acres	21,544,060	21,786,756	2,041,793	1,937,288	110,788	87,244	19,502,267	19,849,468
Harvested cropland ..... farms	47,549	50,272	3,575	3,180	1,066	800	43,974	47,092
acres	19,662,443	20,054,132	1,948,596	1,859,878	97,236	78,099	17,713,847	18,194,254
Pastureland, excluding woodland pastured ..... farms	21,619	23,997	992	979	221	181	20,627	23,018
acres	1,205,430	1,235,718	75,308	63,468	5,734	4,446	1,130,122	1,172,250
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs ..... farms	19,069	19,972	527	591	69	65	18,542	19,381
acres	951,335	1,073,549	22,131	22,353	2,346	3,001	929,204	1,051,196
Owned and rented land in farms:								
Owned land in farms ..... farms	60,960	63,700	3,273	2,896	941	692	57,687	60,804
acres	13,006,137	13,626,270	1,126,810	1,051,066	105,532	90,619	11,879,327	12,575,204
Rented or leased land in farms ..... farms	25,135	27,345	1,799	1,681	241	177	23,336	25,664
acres	12,436,488	11,890,712	1,204,462	1,091,230	34,868	23,523	11,232,026	10,799,482
Market value of agricultural products sold $1,000	28,482,097	18,395,390	3,153,936	1,934,634	403,356	240,584	25,328,161	16,460,756
Average per farm ..... dollars	434,635	267,289	870,051	600,818	378,383	300,730	409,139	250,919
Crops, including nursery and greenhouse crops ..... farms	43,821	46,722	3,495	3,128	1,021	776	40,326	43,594
$1,000	17,143,767	10,191,518	2,305,507	1,382,194	383,641	231,714	14,838,260	8,809,323
Livestock, poultry, and their products ..... farms	22,770	26,062	1,248	1,255	208	206	21,522	24,807
$1,000	11,338,329	8,203,872	848,429	552,439	19,714	8,870	10,489,900	7,651,433
Total farm production expenses $1,000	20,780,603	15,133,150	2,211,130	1,537,564	260,494	176,607	18,569,473	13,595,586
Average per farm ..... dollars	317,111	219,888	609,967	477,504	244,366	220,759	299,962	207,243
Fertilizer, lime, and soil conditioners purchased ..... farms	36,421	40,476	2,924	2,855	685	586	33,497	37,621
$1,000	2,325,700	1,374,497	276,895	163,269	22,788	10,520	2,048,805	1,211,228
Chemicals purchased ..... farms	37,339	38,474	2,835	2,551	584	456	34,504	35,923
$1,000	1,161,099	797,679	145,944	86,667	16,229	7,087	1,015,155	711,013
Seeds, plants, vines, and trees purchased ..... farms	36,437	36,673	3,217	2,804	882	612	33,220	33,869
$1,000	1,772,341	1,516,361	223,480	183,670	24,975	29,675	1,548,861	1,332,691
Cover crop seed purchased ..... farms	4,909	4,084	642	538	145	119	4,267	3,546
$1,000	20,527	12,103	2,352	1,295	189	125	18,175	10,807
Livestock and poultry purchased or leased ..... farms	13,933	16,345	785	827	133	159	13,148	15,518
$1,000	1,926,426	1,649,648	121,776	82,428	2,654	1,946	1,804,650	1,567,220
Feed purchased ..... farms	26,145	29,902	1,302	1,314	263	231	24,843	28,588
$1,000	3,890,272	2,668,319	250,641	164,916	8,176	2,740	3,639,631	2,503,403
Gasoline, fuels, and oils purchased ..... farms	61,621	63,964	3,495	3,153	976	764	58,126	60,811
$1,000	956,802	630,623	106,317	68,574	11,381	8,332	850,485	562,050
Utilities ..... farms	48,636	51,248	3,083	2,916	764	645	45,553	48,332
$1,000	400,978	305,957	53,419	38,810	14,621	8,955	347,559	267,148
Repairs, supplies, and maintenance costs ..... farms	55,660	58,445	3,349	3,045	883	698	52,311	55,400
$1,000	1,322,234	889,519	145,039	94,646	19,768	9,957	1,177,195	794,874
Hired farm labor ..... farms	17,399	19,374	1,639	1,732	377	358	15,760	17,642
$1,000	1,320,974	832,429	274,729	183,409	76,911	57,653	1,046,245	649,020
Contract labor ..... farms	4,311	4,724	450	439	131	87	3,861	4,285
$1,000	152,565	82,304	28,965	11,376	14,461	2,709	123,600	70,928
Customwork and custom hauling ..... farms	19,181	21,712	1,282	1,304	129	126	17,899	20,408
$1,000	425,172	310,122	48,504	32,764	2,880	2,975	376,668	277,357
Cash rent for land, buildings, and grazing fees ..... farms	24,199	24,769	1,795	1,587	239	139	22,404	23,182
$1,000	2,302,712	1,851,799	247,642	186,670	11,044	4,905	2,055,070	1,665,129
Rent and lease expenses for machinery, equipment, and farm share of vehicles ..... farms	6,598	7,187	587	618	98	67	6,011	6,569
$1,000	182,357	130,176	23,716	18,022	4,290	1,161	158,641	112,154
Interest expense ..... farms	27,274	31,165	1,874	1,894	348	283	25,400	29,271
$1,000	702,889	666,967	72,265	69,250	5,248	5,813	630,624	597,717
Property taxes paid ..... farms	61,644	64,702	3,330	2,962	945	700	58,314	61,740
$1,000	482,443	403,333	40,238	31,508	5,694	3,907	442,205	371,825
Medical supplies, veterinary, and custom services for livestock ..... farms	19,351	24,677	974	1,082	134	141	18,377	23,595
$1,000	255,043	189,609	22,001	16,734	771	210	233,042	172,875
All other production expenses ..... farms	44,226	38,536	2,940	2,472	687	457	41,286	36,064
$1,000	1,200,596	833,806	129,559	104,852	18,602	18,060	1,071,037	728,954
Commodity Credit Corporation loans ..... farms	990	2,777	107	245	13	8	883	2,532
$1,000	197,241	414,580	27,882	60,675	2,149	1,218	169,359	353,906
Government payments ..... farms	31,583	41,230	1,535	1,789	157	166	30,048	39,441
$1,000	584,106	394,491	49,359	22,141	2,150	1,269	534,747	372,350
Total income from farm-related sources ..... farms	38,287	42,569	2,070	2,024	367	309	36,217	40,545
$1,000	1,011,249	868,545	81,359	61,358	9,590	7,040	929,890	807,187
Estimated market value of all machinery and equipment ..... farms	65,531	68,788	3,625	3,220	1,066	800	61,906	65,568
$1,000	17,904,134	15,385,551	1,654,556	1,443,618	155,339	116,646	16,249,578	13,941,933
Average per farm ..... dollars	273,216	223,666	456,429	448,329	145,721	145,808	262,488	212,633
Livestock inventory:								
Cattle and calves ..... farms	16,823	20,969	812	880	74	81	16,011	20,089
number	2,121,625	2,337,505	219,780	192,832	2,985	3,683	1,901,845	2,144,673
Milk cows ..... farms	2,185	3,644	203	287	8	17	1,982	3,357
number	459,536	457,801	60,504	48,378	334	685	399,032	409,423
Hogs and pigs ..... farms	2,928	3,225	147	151	29	8	2,781	3,074
number	8,873,776	8,467,361	396,189	397,006	(D)	(D)	8,477,587	8,070,355

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Table 11. **Selected Characteristics of Irrigated and Nonirrigated Farms: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Characteristics	All farms		Irrigated farms				Nonirrigated farms	
			Any land irrigated		All harvested cropland irrigated			
	2022	2017	2022	2017	2022	2017	2022	2017
Livestock inventory: - Con.								
Sheep and lambs ..... farms	2,137	2,248	103	92	20	24	2,034	2,156
number	109,592	116,311	9,299	3,771	614	499	100,293	112,540

Table 12. **Cattle and Calves - Inventory: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Number	Farms	Number
Cattle and calves	16,823	2,121,625	20,969	2,337,505
Farms with-				
1 to 9	3,446	17,165	4,141	20,640
10 to 19	2,534	34,775	3,109	42,745
20 to 49	4,022	126,869	5,084	160,321
50 to 99	2,582	177,582	3,336	232,916
100 to 199	1,927	263,233	2,715	370,565
200 to 499	1,348	397,131	1,682	499,079
500 to 999	659	461,186	665	447,167
1,000 to 2,499	255	351,621	180	257,081
2,500 to 4,999	32	109,999	39	131,400
5,000 or more	18	182,064	18	175,591
Cows and heifers that calved	13,439	824,165	16,346	826,015
Farms with-				
1 to 9	3,791	17,945	4,520	20,775
10 to 19	2,649	36,250	3,246	44,175
20 to 49	3,629	109,738	4,508	140,233
50 to 99	1,745	118,910	2,517	165,917
100 to 199	878	114,311	988	125,806
200 to 499	541	162,238	428	126,514
500 to 999	145	92,953	85	55,840
1,000 to 2,499	48	70,923	43	59,569
2,500 or more	13	100,897	11	87,186
Beef cows	11,691	364,629	13,339	368,214
Farms with-				
1 to 9	3,718	17,682	4,408	20,482
10 to 19	2,619	35,814	3,154	42,742
20 to 49	3,494	104,830	3,882	117,841
50 to 99	1,205	79,467	1,369	86,828
100 to 199	470	59,183	357	46,152
200 to 499	149	41,955	150	40,269
500 to 999	33	21,398	17	(D)
1,000 to 2,499	3	4,300	2	(D)
2,500 or more	-	-	-	-

Item	2022		2017	
	Farms	Number	Farms	Number
Cattle and calves - Con.				
Cows and heifers that calved - Con.				
Milk cows	2,185	459,536	3,644	457,801
Farms with-				
1 to 9	328	966	483	1,361
10 to 19	82	1,107	199	2,788
20 to 49	233	8,110	800	27,928
50 to 99	573	41,268	1,160	78,673
100 to 199	418	54,967	612	77,100
200 to 499	390	119,479	275	84,557
500 to 999	103	66,159	63	41,084
1,000 to 2,499	45	66,583	41	57,124
2,500 or more	13	100,897	11	87,186
Other cattle	14,574	1,297,460	18,140	1,511,490
Farms with-				
1 to 9	4,477	20,327	5,477	24,730
10 to 19	2,483	33,446	3,046	41,039
20 to 49	3,199	97,678	3,906	120,933
50 to 99	1,799	122,364	2,486	168,002
100 to 199	1,173	156,424	1,559	203,419
200 to 499	859	256,663	1,045	322,447
500 to 999	401	283,569	472	314,240
1,000 to 2,499	157	213,771	115	169,209
2,500 or more	26	113,218	34	147,471
Cattle on feed	2,553	520,056	3,220	596,367
Farms with-				
1 to 19	317	4,493	432	6,256
20 to 49	750	23,213	927	28,634
50 to 99	528	35,398	659	44,070
100 to 199	338	44,618	487	64,480
200 to 499	300	88,605	409	125,467
500 to 999	236	171,740	229	154,918
1,000 to 2,499	69	90,823	54	77,412
2,500 or more	15	61,166	23	95,130

Table 13. **Cattle and Calves - Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Number sold	2022			2017		
	Farms	Number	Value ($1,000)	Farms	Number	Value ($1,000)
Cattle and calves	14,649	1,599,910	2,094,135	18,474	1,683,259	1,886,939
Farms by number sold-						
1 to 9	4,154	19,214	21,444	5,330	24,738	23,288
10 to 19	2,404	32,563	36,567	3,303	45,090	41,516
20 to 49	3,610	112,647	126,051	4,699	146,126	135,405
50 to 99	1,896	129,777	143,720	2,287	153,752	139,651
100 to 199	1,147	151,529	175,661	1,187	159,430	166,245
200 to 499	827	244,770	312,218	1,004	305,567	355,058
500 to 999	327	222,190	338,644	421	290,752	369,728
1,000 to 2,499	209	305,170	469,541	181	249,465	296,951
2,500 to 4,999	54	172,598	246,487	43	139,372	185,456
5,000 or more	21	209,452	223,801	19	168,967	173,643
Cattle weighing 500 pounds or more	13,933	1,254,841	(NA)	17,228	1,393,743	(NA)
Farms by number sold-						
1 to 9	4,363	19,343	(NA)	5,698	25,113	(NA)
10 to 19	2,440	32,731	(NA)	3,255	44,191	(NA)
20 to 49	3,462	105,838	(NA)	4,189	126,303	(NA)
50 to 99	1,615	108,535	(NA)	1,719	113,808	(NA)
100 to 199	923	122,548	(NA)	923	124,247	(NA)
200 to 499	633	190,849	(NA)	871	261,960	(NA)
500 to 999	261	176,819	(NA)	367	255,831	(NA)
1,000 to 2,499	176	262,073	(NA)	159	223,185	(NA)
2,500 to 4,999	49	150,483	(NA)	35	114,088	(NA)
5,000 or more	11	85,622	(NA)	12	105,017	(NA)
Cattle on feed	2,685	636,782	(NA)	3,434	708,257	(NA)
Farms by number sold-						
1 to 19	420	6,010	(NA)	583	8,245	(NA)
20 to 49	831	25,602	(NA)	1,078	33,642	(NA)
50 to 99	457	31,055	(NA)	571	38,817	(NA)
100 to 199	341	44,451	(NA)	443	61,210	(NA)
200 to 499	313	94,435	(NA)	417	126,722	(NA)
500 to 999	181	126,311	(NA)	236	170,181	(NA)
1,000 to 2,499	112	174,185	(NA)	71	105,004	(NA)
2,500 to 4,999	23	75,721	(NA)	25	82,110	(NA)
5,000 or more	7	59,012	(NA)	10	82,326	(NA)
Calves weighing less than 500 pounds	4,938	345,069	(NA)	6,226	289,516	(NA)
Farms by number sold-						
1 to 9	1,922	8,142	(NA)	2,377	10,465	(NA)
10 to 19	892	11,721	(NA)	1,302	16,969	(NA)
20 to 49	1,142	34,096	(NA)	1,581	46,701	(NA)
50 to 99	440	28,293	(NA)	534	34,308	(NA)
100 to 199	299	40,976	(NA)	244	32,387	(NA)
200 to 499	169	46,929	(NA)	129	37,663	(NA)
500 to 999	36	25,517	(NA)	28	20,110	(NA)
1,000 or more	38	149,395	(NA)	31	90,913	(NA)

Table 14. **Cattle and Calves Herd Size by Inventory and Sales: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Herd size	Cattle and calves inventory						Cattle and calves sales		
	Total		Cows and heifers that calved		Other cattle				
	Farms	Number	Farms	Number	Farms	Number	Farms	Number	Value ($1,000)
Farms with December 31, 2022 herd size of-									
1 to 9	3,446	17,165	2,335	8,890	2,274	8,275	1,773	10,886	12,559
10 to 19	2,534	34,775	2,144	19,817	1,900	14,958	1,793	17,821	21,401
20 to 49	4,022	126,869	3,425	66,028	3,662	60,841	3,512	75,808	81,575
50 to 99	2,582	177,582	2,235	83,257	2,548	94,325	2,550	110,657	123,802
100 to 199	1,927	263,233	1,633	115,480	1,913	147,753	1,908	147,215	170,959
200 to 499	1,348	397,131	1,042	149,170	1,323	247,961	1,341	253,691	340,219
500 to 999	659	461,186	427	137,385	654	323,801	659	400,398	575,453
1,000 to 2,499	255	351,621	158	103,879	250	247,742	255	323,347	461,080
2,500 to 4,999	32	109,999	25	36,462	32	73,537	32	86,374	135,372
5,000 or more	18	182,064	15	103,797	18	78,267	18	146,626	136,654
All farms with December 31, 2022 inventory	16,823	2,121,625	13,439	824,165	14,574	1,297,460	13,841	1,572,823	2,059,074
Farms with no cattle and calves inventory, on December 31, 2022	-	-	-	-	-	-	808	27,087	35,061
Total	16,823	2,121,625	13,439	824,165	14,574	1,297,460	14,649	1,599,910	2,094,135

Table 15. **Cow Herd Size by Inventory and Sales: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Cow herd [1]	Cattle and calves inventory						Cattle and calves sales		
	Total		Cows and heifers that calved		Other cattle				
	Farms	Number	Farms	Number	Farms	Number	Farms	Number	Value ($1,000)
Farms with December 31, 2022 cow herd size of-									
1 to 9	3,791	44,352	3,791	17,945	2,619	26,407	2,232	27,508	35,003
10 to 19	2,649	76,717	2,649	36,250	2,015	40,467	2,128	37,545	45,065
20 to 49	3,629	227,864	3,629	109,738	3,269	118,126	3,489	139,947	166,081
50 to 99	1,745	253,196	1,745	118,910	1,711	134,286	1,745	137,928	179,006
100 to 199	878	243,761	878	114,311	864	129,450	878	137,391	173,441
200 to 499	541	304,199	541	162,238	516	141,961	541	142,829	152,404
500 to 999	145	174,052	145	92,953	140	81,099	145	107,108	121,954
1,000 to 2,499	48	124,564	48	70,923	43	53,641	48	64,250	59,742
2,500 or more	13	149,740	13	100,897	13	48,843	13	107,329	54,721
All farms with December 31, 2022 cow inventory	13,439	1,598,445	13,439	824,165	11,190	774,280	11,219	901,835	987,415
Farms with no cow inventory, on December 31, 2022	3,384	523,180	-	-	3,384	523,180	3,430	698,075	1,106,720
Total	16,823	2,121,625	13,439	824,165	14,574	1,297,460	14,649	1,599,910	2,094,135

[1] Cow herd includes beef cows, milk cows, and heifers that calved.

Table 16. **Beef Cow Herd Size by Inventory and Sales: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Beef cow herd	Cattle and calves inventory							
	Total		Cows and heifers that calved		Beef cows		Other cattle	
	Farms	Number	Farms	Number	Farms	Number	Farms	Number
Farms with December 31, 2022 beef cow herd size of-								
1 to 9	3,718	57,474	3,718	25,288	3,718	17,682	2,573	32,186
10 to 19	2,619	85,123	2,619	40,705	2,619	35,814	1,999	44,418
20 to 49	3,494	237,306	3,494	116,516	3,494	104,830	3,142	120,790
50 to 99	1,205	180,530	1,205	82,218	1,205	79,467	1,204	98,312
100 to 199	470	145,440	470	63,971	470	59,183	462	81,469
200 to 499	149	85,797	149	44,132	149	41,955	147	41,665
500 to 999	33	47,911	33	21,398	33	21,398	33	26,513
1,000 to 2,499	3	18,500	3	4,300	3	4,300	3	14,200
2,500 or more	-	-	-	-	-	-	-	-
All farms with December 31, 2022 beef cow inventory	11,691	858,081	11,691	398,528	11,691	364,629	9,563	459,553
Farms with no beef cow inventory, on December 31, 2022	5,132	1,263,544	1,748	425,637	-	-	5,011	837,907
Total	16,823	2,121,625	13,439	824,165	11,691	364,629	14,574	1,297,460

Beef cow herd	Cattle and calves sales								
	Total			Cattle				Calves	
				Total		Cattle on feed			
	Farms	Number	Value ($1,000)	Farms	Number	Farms	Number	Farms	Number
Farms with December 31, 2022 beef cow herd size of-									
1 to 9	2,236	32,134	38,657	2,005	24,490	111	10,060	585	7,644
10 to 19	2,123	41,057	48,258	1,925	32,199	149	9,714	707	8,858
20 to 49	3,359	145,598	172,391	3,261	121,213	462	34,713	1,284	24,385
50 to 99	1,205	110,540	155,783	1,205	98,007	239	37,550	396	12,533
100 to 199	470	101,222	144,306	470	91,330	112	39,823	165	9,892
200 to 499	149	53,904	71,185	148	47,019	38	13,472	59	6,885
500 to 999	33	50,231	75,273	33	46,084	16	25,579	10	4,147
1,000 to 2,499	3	11,150	24,500	3	11,150	3	9,500	-	-
2,500 or more	-	-	-	-	-	-	-	-	-
All farms with December 31, 2022 beef cow inventory	9,578	545,836	730,355	9,050	471,492	1,130	180,411	3,206	74,344
Farms with no beef cow inventory, on December 31, 2022	5,071	1,054,074	1,363,780	4,883	783,349	1,555	456,371	1,732	270,725
Total	14,649	1,599,910	2,094,135	13,933	1,254,841	2,685	636,782	4,938	345,069

Table 17. **Milk Cow Herd Size by Inventory and Sales: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Milk cow herd	Cattle and calves inventory							
	Total		Cows and heifers that calved		Milk cows		Other cattle	
	Farms	Number	Farms	Number	Farms	Number	Farms	Number
Farms with December 31, 2022 milk cow herd size of-								
1 to 9	328	6,281	328	3,118	328	966	241	3,163
10 to 19	82	2,881	82	1,592	82	1,107	72	1,289
20 to 49	233	21,571	233	9,280	233	8,110	220	12,291
50 to 99	573	86,333	573	44,514	573	41,268	540	41,819
100 to 199	418	112,765	418	59,420	418	54,967	400	53,345
200 to 499	390	224,491	390	122,367	390	119,479	371	102,124
500 to 999	103	117,932	103	66,335	103	66,159	99	51,597
1,000 to 2,499	45	106,064	45	66,623	45	66,583	40	39,441
2,500 or more	13	149,740	13	100,897	13	100,897	13	48,843
All farms with December 31, 2022 milk cow inventory	2,185	828,058	2,185	474,146	2,185	459,536	1,996	353,912
Farms with no milk cow inventory, on December 31, 2022	14,638	1,293,567	11,254	350,019	-	-	12,578	943,548
Total	16,823	2,121,625	13,439	824,165	2,185	459,536	14,574	1,297,460

Milk cow herd	Cattle and calves sales							Milk sales	
	Total			Cattle		Calves			
	Farms	Number	($1,000)	Farms	Number	Farms	Number	Farms	($1,000)
Farms with December 31, 2022 milk cow herd size of-									
1 to 9	183	2,831	2,805	170	2,031	69	800	39	718
10 to 19	63	1,222	1,373	60	831	34	391	65	4,496
20 to 49	228	6,814	6,930	228	5,152	133	1,662	233	35,091
50 to 99	573	32,515	29,227	573	21,145	391	11,370	573	196,245
100 to 199	418	44,044	37,079	418	27,484	293	16,560	418	275,537
200 to 499	390	93,367	86,391	390	54,586	289	38,781	390	656,713
500 to 999	103	51,362	40,768	103	25,888	92	25,474	103	379,977
1,000 to 2,499	45	53,100	35,242	45	22,110	40	30,990	45	376,758
2,500 or more	13	107,329	54,721	13	34,142	13	73,187	13	572,830
All farms with December 31, 2022 milk cow inventory	2,016	392,584	294,535	2,000	193,369	1,354	199,215	1,879	2,498,365
Farms with no milk cow inventory, on December 31, 2022	12,633	1,207,326	1,799,600	11,933	1,061,472	3,584	145,854	14	6,273
Total	14,649	1,599,910	2,094,135	13,933	1,254,841	4,938	345,069	1,893	2,504,638

Table 18. **Cattle and Calves - Number Sold per Farm by Sales: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Number sold	Cattle and calves			Cattle weighing 500 pounds or more		Calves weighing less than 500 pounds	
	Farms	Number	Value ($1,000)	Farms	Number	Farms	Number
Total	14,649	1,599,910	2,094,135	13,933	1,254,841	4,938	345,069
Farms by number of cattle and calves sold-							
1 to 9	4,154	19,214	21,444	3,703	15,827	961	3,387
10 to 19	2,404	32,563	36,567	2,237	26,431	786	6,132
20 to 49	3,610	112,647	126,051	3,551	92,638	1,300	20,009
50 to 99	1,896	129,777	143,720	1,884	101,695	855	28,082
100 to 199	1,147	151,529	175,661	1,136	119,145	505	32,384
200 to 499	827	244,770	312,218	818	191,024	355	53,746
500 to 999	327	222,190	338,644	327	189,378	109	32,812
1,000 to 2,499	209	305,170	469,541	205	265,140	46	40,030
2,500 or more	75	382,050	470,289	72	253,563	21	128,487

Table 19. **Hogs and Pigs - Inventory: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Hogs and pigs	2022		2017		Hogs and pigs	2022		2017	
	Farms	Number	Farms	Number		Farms	Number	Farms	Number
Total hogs and pigs	2,928	8,873,776	3,225	8,467,361	Total hogs and pigs - Con.				
Farms with-					Farms with- - Con.				
1 to 24	893	6,064	1,036	6,989					
25 to 49	93	3,051	131	4,217	500 to 999	154	104,640	200	136,876
50 to 99	71	4,708	84	5,596	1,000 to 1,999	293	403,858	332	463,514
100 to 199	65	8,229	89	12,738	2,000 to 4,999	824	2,592,075	759	2,325,970
200 to 499	116	35,806	137	44,021	5,000 or more	419	5,715,345	457	5,467,440

Table 20. **Hogs and Pigs - Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Hogs and pigs	2022			2017		
	Farms	Number	Value ($1,000)	Farms	Number	Value ($1,000)
Total hogs and pigs sold	3,352	28,535,462	4,666,832	3,562	27,228,111	3,165,075
Farms with sales of-						
1 to 24	1,015	7,215	1,717	1,226	8,465	1,405
25 to 49	134	4,264	879	164	5,628	780
50 to 99	80	5,560	1,058	85	5,435	793
100 to 199	67	10,110	2,285	76	10,208	1,385
200 to 499	83	26,276	5,459	108	37,225	5,462
500 to 999	63	44,352	9,368	104	73,119	11,915
1,000 to 1,999	162	227,004	49,590	181	250,873	39,417
2,000 to 4,999	522	1,868,795	428,429	514	1,784,590	284,862
5,000 or more	1,226	26,341,886	4,168,048	1,104	25,052,568	2,819,056

Table 21. **Hogs and Pigs Herd Size by Inventory and Sales: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Herd size	Hogs and pigs inventory		Hogs and pigs sales		
	Farms	Number	Farms	Number	Value ($1,000)
Farms with December 31, 2022 herd size of-					
1 to 24	893	6,064	610	9,104	1,881
25 to 49	93	3,051	91	3,849	786
50 to 99	71	4,708	70	10,418	2,074
100 to 199	65	8,229	63	18,053	3,216
200 to 499	116	35,806	111	109,970	21,251
500 to 999	154	104,640	153	349,979	72,794
1,000 to 1,999	293	403,858	293	1,266,301	266,072
2,000 to 4,999	824	2,592,075	822	7,907,099	1,496,461
5,000 or more	419	5,715,345	418	17,306,170	2,472,411
All farms with December 31, 2022 inventory	2,928	8,873,776	2,631	26,980,943	4,336,948
Farms with no hog or pig inventory, on December 31, 2022	-	-	721	1,554,519	329,885
Total	2,928	8,873,776	3,352	28,535,462	4,666,832

Table 22. **Hogs and Pigs - Inventory and Sales by Number Sold per Farm: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Hogs and pigs	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
Farms with sales of-					
1 to 24	551	5,179	1,015	7,215	1,717
25 to 49	121	3,115	134	4,264	879
50 to 99	72	4,814	80	5,560	1,058
100 to 199	65	8,263	67	10,110	2,285
200 to 499	68	26,462	83	26,276	5,459
500 to 999	51	21,317	63	44,352	9,368
1,000 to 1,999	136	93,721	162	227,004	49,590
2,000 to 4,999	455	840,410	522	1,868,795	428,429
5,000 or more	1,112	7,856,612	1,226	26,341,886	4,168,048
All farms with sales	2,631	8,859,893	3,352	28,535,462	4,666,832
Farms with December 31, 2022 inventory and no sales	297	13,883	-	-	-
Total	2,928	8,873,776	3,352	28,535,462	4,666,832

Table 23. **Hogs and Pigs - Inventory by Type of Producer: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Herd size	Independent grower		Contractor or integrator		Contract grower (Contractee)	
	Farms	Number	Farms	Number	Farms	Number
Total inventory	1,718	3,057,726	110	2,209,435	1,100	3,606,615
Farms with-						
1 to 24	893	6,064	-	-	-	-
25 to 49	93	3,051	-	-	-	-
50 to 99	67	4,466	-	-	4	242
100 to 199	54	6,987	-	-	11	1,242
200 to 499	65	19,037	2	(D)	49	(D)
500 to 999	62	43,876	3	(D)	89	(D)
1,000 to 1,999	121	173,306	10	11,335	162	219,217
2,000 to 4,999	200	673,718	22	70,829	602	1,847,528
5,000 or more	163	2,127,221	73	2,123,901	183	1,464,223

Table 24. **Hogs and Pigs - Number Sold by Type of Producer: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Hogs and pigs	Independent grower		Contractor or integrator		Contract grower (Contractee)	
	Farms	Number	Farms	Number	Farms	Number
Total hogs and pigs sold	1,957	9,114,151	108	7,541,308	1,287	11,880,003
Farms with-						
1 to 24	1,014	(D)	-	-	1	(D)
25 to 49	132	(D)	-	-	2	(D)
50 to 99	80	5,560	-	-	-	-
100 to 199	59	8,658	-	-	8	1,452
200 to 499	63	19,278	-	-	20	6,998
500 to 999	38	26,414	-	-	25	17,938
1,000 to 1,999	58	(D)	9	(D)	95	138,887
2,000 to 4,999	140	(D)	6	(D)	376	1,370,931
5,000 or more	373	8,494,228	93	7,503,943	760	10,343,715

Table 25. **Hogs and Pigs - Inventory by Type of Operation: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Herd size	Farrow to wean		Farrow to finish		Finish only		Farrow to feeder		Nursery		Other	
	Farms	Number	Farms	Number	Farms	Number	Farms	Number	Farms	Number	Farms	Number
Total inventory	161	1,125,017	659	2,051,153	1,547	4,095,522	124	300,735	128	539,770	309	761,579
Farms with-												
1 to 24	47	297	291	2,337	373	2,300	59	586	-	-	123	544
25 to 49	1	(D)	52	1,744	21	675	17	(D)	-	-	2	(D)
50 to 99	1	(D)	37	2,568	11	762	15	906	-	-	7	(D)
100 to 199	3	455	40	5,003	13	1,678	5	573	-	-	4	520
200 to 499	10	2,650	27	8,079	50	16,320	4	1,364	6	1,700	19	5,693
500 to 999	3	1,900	23	17,225	110	72,478	-	-	11	8,198	7	4,839
1,000 to 1,999	7	(D)	42	56,168	204	288,667	2	(D)	10	11,442	28	35,755
2,000 to 4,999	28	109,714	67	216,384	583	1,790,216	10	25,200	60	205,468	76	245,093
5,000 or more	61	1,000,201	80	1,741,645	182	1,922,426	12	269,441	41	312,962	43	468,670

Table 26. **Hogs and Pigs - Number Sold by Type of Operation: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Hogs and pigs	Farrow to wean		Farrow to finish		Finish only		Farrow to feeder		Nursery		Other	
	Farms	Number	Farms	Number	Farms	Number	Farms	Number	Farms	Number	Farms	Number
Total hogs and pigs sold	157	6,665,715	611	4,193,604	2,073	11,243,594	118	1,231,763	143	2,930,856	250	2,269,930
Farms with-												
1 to 24	33	(D)	211	1,949	696	4,291	29	(D)	2	(D)	44	337
25 to 49	8	256	63	2,017	41	1,326	19	560	-	-	3	105
50 to 99	1	(D)	36	2,427	14	908	25	(D)	-	-	4	318
100 to 199	2	(D)	39	6,137	15	2,022	6	(D)	-	-	5	760
200 to 499	2	(D)	30	9,054	30	10,340	7	2,010	2	(D)	12	3,278
500 to 999	-	-	10	6,935	41	30,117	2	(D)	2	(D)	8	4,500
1,000 to 1,999	6	(D)	30	43,649	100	140,214	1	(D)	13	16,766	12	15,375
2,000 to 4,999	6	13,568	47	151,637	396	1,430,472	10	37,674	11	36,545	52	198,899
5,000 or more	99	6,640,217	145	3,969,799	740	9,623,904	19	1,186,279	113	2,875,329	110	2,046,358

Table 27. **Sheep and Lambs Flock Size by Inventory, Sales, and Wool Production: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Flock size	Sheep and lambs inventory		Sheep and lambs sold			Wool production		
	Farms	Number	Farms	Number	Value ($1,000)	Farms	Pounds	Value ($1,000)
Farms with December 31, 2022 flock size of-								
1 to 24	1,328	13,576	643	7,152	1,294	371	29,794	23
25 to 99	574	27,026	482	19,867	3,636	399	134,839	90
100 to 299	181	27,203	181	22,623	4,388	167	139,222	86
300 to 999	43	23,042	43	20,395	4,454	39	119,754	57
1,000 to 2,499	11	18,745	11	17,883	3,805	11	119,002	(D)
2,500 to 4,999	-	-	-	-	-	-	-	-
5,000 or more	-	-	-	-	-	-	-	-
All farms with December 31, 2022 inventory	2,137	109,592	1,360	87,920	17,577	987	542,611	(D)
Farms with no sheep or lamb inventory, on December 31, 2022	-	-	140	4,592	1,264	9	9,515	(D)
Total	2,137	109,592	1,500	92,512	18,840	996	552,126	259

Table 28. **Goats, Kids, and Mohair - Inventory, Mohair Production, and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Inventory				Sales					
	2022		2017		2022			2017		
	Farms	Number	Farms	Number	Farms	Number	Value ($1,000)	Farms	Number	Value ($1,000)
Goats, all	2,326	50,691	1,996	36,312	1,215	38,339	8,735	1,072	20,644	3,082
Angora goats and kids	117	1,274	157	1,095	33	378	45	29	222	20
Milk goats and kids	734	14,638	698	13,342	389	8,331	2,127	368	5,854	1,083
Meat goats and other goats and kids	1,726	34,779	1,362	21,875	870	29,630	6,563	758	14,568	1,979
Mohair clipped ... pounds	(X)	(X)	(X)	(X)	39	8,636	7	42	4,105	27

Table 29. **Equine - Inventory and Sales: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Equine	Farms	Number	Value ($1,000)	Equine	Farms	Number	Value ($1,000)
INVENTORY				**SALES**			
Total horses and ponies	6,988	40,131	(X)	Total horses and ponies	1,171	4,403	18,000
Farms with-				Farms by number sold-			
1 to 24	6,794	31,891	(X)	1 to 24	1,159	3,683	17,249
25 to 49	148	5,126	(X)	25 to 49	9	270	331
50 to 99	41	2,549	(X)	50 to 99	-	-	-
100 or more	5	565	(X)	100 or more	3	450	420
Total mules, burros, and donkeys	1,319	3,060	(X)	Total mules, burros, and donkeys	135	325	147
Farms with-				Farms by number sold-			
1 to 24	1,318	(D)	(X)	1 to 24	134	(D)	(D)
25 to 49	-	-	(X)	25 to 49	1	(D)	(D)
50 or more	1	(D)	(X)	50 or more	-	-	-

Table 30. **Poultry - Inventory and Number Sold: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Number	Farms	Number
INVENTORY				
Layers	6,146	14,553,497	5,245	10,849,607
Farms with inventory of-				
1 to 49	5,412	93,685	4,577	79,677
50 to 99	472	28,191	409	25,480
100 to 399	161	24,770	175	26,119
400 to 3,199	36	49,047	42	37,790
3,200 to 9,999	8	46,070	3	22,945
10,000 to 19,999	24	332,590	13	185,050
20,000 to 49,999	4	124,303	3	97,503
50,000 to 99,999	5	396,210	4	315,210
100,000 or more	24	13,458,631	19	10,059,833
Pullets for laying flock replacement	723	4,185,443	615	4,636,614
Broilers and other meat-type chickens	1,285	7,767,645	1,290	11,068,267
Turkeys	623	14,927,734	666	18,110,298
Chukars	28	35,131	20	22,951
Ducks	834	18,056	718	24,337
Emus	31	117	24	87
Geese	354	2,700	320	2,417
Guineas	518	5,198	436	3,619
Hungarian partridge	1	(D)	2	(D)
Ostriches	6	8	5	9
Peacocks or peahens	197	1,331	194	1,143
Pheasants	105	145,319	92	159,951
Pigeons or squab	44	2,224	67	4,468
Quail	83	268,222	26	16,133
Rheas	-	-	4	20
Roosters	689	114,472	485	38,609
Other poultry	-	-	7	30
NUMBER SOLD				
Layers	664	7,016,481	702	4,223,081
Farms by number sold-				
1 to 99	549	(D)	617	11,976
100 to 399	40	7,804	38	5,794
400 to 3,199	20	24,205	17	15,108
3,200 to 9,999	9	48,085	3	22,683
10,000 to 19,999	25	325,894	13	172,550
20,000 to 49,999	4	103,800	2	(D)
50,000 to 99,999	1	(D)	1	(D)
100,000 or more	16	6,436,346	11	3,884,970

Item	2022		2017	
	Farms	Number	Farms	Number
NUMBER SOLD - Con.				
Pullets for laying flock replacement	102	8,319,040	93	9,562,724
Farms by number sold-				
1 to 1,999	78	(D)	72	(D)
2,000 to 15,999	3	26,000	3	37,000
16,000 to 29,999	2	(D)	3	78,000
30,000 to 59,999	5	194,000	1	(D)
60,000 to 99,999	-	-	-	-
100,000 or more	14	8,036,916	14	9,400,039
Broilers and other meat-type chickens	1,028	41,793,592	1,049	60,397,850
Farms by number sold-				
1 to 1,999	900	109,073	822	81,596
2,000 to 15,999	4	(D)	10	37,200
16,000 to 29,999	-	-	1	(D)
30,000 to 59,999	7	270,499	2	(D)
60,000 to 99,999	-	-	1	(D)
100,000 to 199,999	2	(D)	16	2,508,000
200,000 to 299,999	63	15,167,700	142	35,714,800
300,000 to 499,999	37	17,172,000	45	15,961,000
500,000 or more	15	8,719,000	10	5,924,000
Turkeys	379	39,460,145	486	48,194,708
Farms by number sold-				
1 to 1,999	202	(D)	200	(D)
2,000 to 7,999	2	(D)	4	18,036
8,000 to 15,999	8	94,626	2	(D)
16,000 to 29,999	14	296,361	20	481,971
30,000 to 59,999	31	1,303,786	85	3,807,700
60,000 to 99,999	24	1,889,873	71	5,517,506
100,000 or more	98	35,857,241	104	38,344,252
Chukars	31	188,427	21	68,805
Ducks	191	41,771	203	52,635
Emus	1	(D)	8	32
Geese	57	637	67	706
Guineas	65	1,261	54	1,247
Hungarian partridge	-	-	1	(D)
Ostriches	-	-	-	-
Peacocks or peahens	23	192	34	183
Pheasants	67	368,058	63	572,704
Pigeons or squab	14	794	21	1,790
Quail	39	232,512	15	(D)
Rheas	-	-	-	-
Roosters	143	120,655	113	32,204
Other poultry	5	19	-	-
Poultry hatched	933	163,542,456	865	155,673,316

Table 31. **Aquaculture Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017	
	Farms	Value ($1,000)	Farms	Value ($1,000)
Catfish	-	-	1	(D)
Trout	10	1,728	9	741
Other food fish	4	(D)	4	144
Baitfish	27	4,425	18	4,344
Crustaceans	6	(D)	1	(D)
Mollusks	-	-	-	-
Ornamental fish	6	20	3	205
Sport or game fish	51	13,480	29	6,028
Other aquaculture products	8	11	-	-

Table 32. **Other Animals - Inventory: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022		2017		Item	2022		2017	
	Farms	Number	Farms	Number		Farms	Number	Farms	Number
Colonies of honey bees	1,398	121,824	1,063	45,905	Llamas	122	872	139	679
Bison	53	3,109	67	2,897	Mink, live	7	8,151	13	50,774
Deer in captivity	93	3,057	138	4,186	Rabbits, live	153	4,328	189	5,663
Elk in captivity	62	2,773	89	3,858	Other livestock	38	(X)	62	(X)
Alpacas	214	2,266	211	2,014					

Table 33. **Other Animals and Animal Products - Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022			2017		
	Farms	Number	Value ($1,000)	Farms	Number	Value ($1,000)
Honey collected [1] (pounds)	1,075	8,865,510	23,517	830	7,653,535	14,148
Milk from sheep and goats	152	(NA)	5,616	158	(NA)	3,741
Bison	35	1,349	2,854	50	779	1,660
Deer in captivity	62	717	1,422	67	698	1,196
Elk in captivity	39	557	1,484	57	755	1,921
Alpacas	49	308	202	46	239	338
Llamas	28	121	131	16	39	26
Mink, live	1	(D)	(D)	1	(D)	(D)
Rabbits, live	59	6,851	106	88	4,960	66
Equine products	185	(X)	1,113	211	(X)	1,947
Other livestock	10	(X)	44	10	(X)	31,655
Other livestock products [1]	185	(X)	27,256	136	(X)	23,230

[1] Data are for farms with production, not necessarily sold.

Table 34. **Specified Crops Harvested - Yield per Acre Irrigated and Nonirrigated: 2022**

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	Entire crop irrigated			Part of crop irrigated				None of crop irrigated		
	Farms	Acres	Average yield per acre	Farms	Acres irrigated	Acres not irrigated	Average yield per acre	Farms	Acres	Average yield per acre
Barley for grain (bushels)	2	(D)	(D)	8	(D)	(D)	(D)	326	54,935	72.6
Corn for grain (bushels)	228	60,618	203.8	1,113	242,279	472,365	189.3	23,356	6,957,193	191.3
Corn for silage or greenchop (tons)	31	3,804	25.3	77	9,331	15,353	20.0	2,660	285,486	20.1
Cotton, all (bales)	-	-	-	-	-	-	-	-	-	-
Upland cotton (bales)	-	-	-	-	-	-	-	-	-	-
Pima cotton (bales)	-	-	-	-	-	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas (cwt)	36	17,088	27.0	59	22,843	19,486	25.5	478	150,745	24.8
Oats for grain (bushels)	24	1,347	76.3	42	1,847	1,550	54.0	2,263	121,267	75.7
Peanuts for nuts (pounds)	-	-	-	-	-	-	-	-	-	-
Rice (cwt)	-	-	-	-	-	-	-	-	-	-
Sorghum for grain (bushels)	-	-	-	-	-	-	-	12	364	66.6
Soybeans for beans (bushels)	170	26,421	47.2	722	96,313	238,415	48.4	24,445	7,236,022	49.2
Sugarbeets for sugar (tons)	1	(D)	(D)	30	(D)	(D)	(D)	1,075	425,333	26.0
Sugarcane for sugar or seed (tons) (see text)	-	-	-	-	-	-	-	-	-	-
Tobacco (pounds)	-	-	-	-	-	-	-	-	-	-
Wheat for grain, all (bushels)	20	4,144	64.1	32	2,107	7,566	63.6	3,617	1,254,864	64.7
Winter wheat for grain (bushels)	-	-	-	1	(D)	(D)	(D)	101	(D)	(D)
Durum wheat for grain (bushels)	-	-	-	-	-	-	-	31	(D)	33.9
Other spring wheat for grain (bushels)	20	4,144	64.1	31	(D)	(D)	63.6	3,506	1,247,505	64.7
Forage - land used for all hay and haylage, grass silage, and greenchop (tons, dry equivalent)	255	11,573	(X)	420	21,381	42,815	(X)	22,719	1,316,303	(X)
Alfalfa hay (tons, dry)	179	7,341	3.3	242	8,608	14,879	3.0	14,912	713,289	2.6
Other dry hay (tons, dry)	96	2,139	2.5	57	1,519	3,166	1.4	8,403	383,597	1.7
Haylage or greenchop from alfalfa or alfalfa mixtures (tons, green)	47	3,266	8.0	102	8,792	13,189	6.9	1,965	190,847	7.0
All other haylage, grass silage, and greenchop (tons, green)	50	1,716	2.9	17	543	1,041	8.5	2,243	86,605	4.1
Land in vegetables	618	36,355	(X)	146	18,285	14,494	(X)	1,856	127,584	(X)
Land in orchards	155	419	(X)	49	360	392	(X)	970	3,879	(X)
Land in berries	171	407	(X)	14	19	47	(X)	393	656	(X)

Table 35. **Specified Crops by Acres Harvested: 2022 and 2017**

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	2022					2017				
	Farms	Acres	Quantity	Irrigated land		Farms	Acres	Quantity	Irrigated land	
				Farms	Acres				Farms	Acres
FIELD CROPS										
Barley for grain (bushels)	336	55,330	4,011,381	10	116	552	67,521	5,369,559	8	886
1 to 14 acres	35	233	10,348	6	27	108	837	42,806	-	-
15 to 24 acres	37	690	33,295	1	(D)	73	1,374	86,052	1	(D)
25 to 49 acres	53	1,908	102,740	-	-	122	4,299	239,473	1	(D)
50 to 99 acres	43	3,046	201,056	1	(D)	58	4,045	300,173	-	-
100 to 249 acres	94	15,614	1,200,492	2	(D)	105	17,001	1,349,270	3	(D)
250 to 499 acres	53	18,156	1,288,138	-	-	57	19,397	1,661,529	3	649
500 to 999 acres	17	11,179	848,952	-	-	26	16,966	1,440,923	-	-
1,000 acres or more	4	4,504	326,360	-	-	3	3,602	249,333	-	-
Camelina (pounds)	2	(D)	(D)	-	-	-	-	-	-	-
Canola (pounds)	184	65,913	147,784,049	1	(D)	112	32,391	67,729,542	-	-
1 to 14 acres	3	12	11,550	-	-	2	(D)	(D)	-	-
15 to 24 acres	-	-	-	-	-	-	-	-	-	-
25 to 49 acres	1	(D)	(D)	-	-	4	(D)	(D)	-	-
50 to 99 acres	8	638	1,139,530	-	-	8	593	1,060,251	-	-
100 to 249 acres	75	13,052	24,701,796	-	-	42	7,090	14,601,304	-	-
250 to 499 acres	57	20,899	42,636,936	1	(D)	38	11,976	24,566,880	-	-
500 to 999 acres	33	22,240	55,719,265	-	-	15	9,375	20,642,028	-	-
1,000 acres or more	7	(D)	(D)	-	-	3	3,200	6,620,000	-	-
Chickpeas, all (cwt) (see text)	1	(D)	(D)	-	-	3	180	3,856	2	(D)
Corn for grain (bushels)	24,697	7,732,455	1,478,451,268	1,341	302,897	28,086	7,790,541	1,494,241,562	1,417	288,250
1 to 14 acres	1,739	12,527	1,724,201	18	106	2,051	14,825	1,990,944	15	83
15 to 24 acres	1,124	21,580	3,192,873	22	395	1,186	22,873	3,349,405	18	296
25 to 49 acres	2,603	92,971	14,988,360	64	2,054	3,010	108,881	17,836,941	51	1,730
50 to 99 acres	4,264	303,390	52,807,782	166	9,041	5,021	356,439	62,356,734	191	10,430
100 to 249 acres	6,444	1,029,080	189,376,012	323	30,538	7,612	1,204,422	222,024,514	380	35,872
250 to 499 acres	4,136	1,446,320	273,244,161	299	55,296	4,875	1,712,023	327,153,590	352	63,768
500 to 999 acres	2,538	1,729,126	331,668,138	236	65,405	2,896	1,978,681	388,286,930	226	62,386
1,000 acres or more	1,849	3,097,461	611,449,741	213	140,062	1,435	2,392,397	471,242,504	184	113,685
1,000 to 1,999 acres	1,495	2,038,908	405,336,073	136	68,962	1,161	1,527,523	303,834,223	133	61,000
2,000 to 2,999 acres	245	573,904	112,462,651	52	45,116	179	421,335	84,786,271	33	23,096
3,000 to 4,999 acres	87	310,813	59,893,956	18	15,348	73	266,432	51,069,729	13	16,087
5,000 acres or more	22	173,836	33,757,061	7	10,636	22	177,107	31,552,281	5	13,502
Corn for silage or greenchop (tons)	2,768	313,974	6,334,518	108	13,135	4,606	330,543	6,702,696	176	15,332
1 to 14 acres	516	4,191	63,266	2	(D)	985	8,543	137,698	5	40
15 to 24 acres	332	6,201	100,920	1	(D)	756	14,405	261,815	13	240
25 to 49 acres	550	19,174	331,782	15	464	1,142	39,001	748,923	31	940
50 to 99 acres	583	39,519	738,402	26	1,122	917	61,114	1,189,154	58	2,842
100 to 249 acres	452	67,325	1,440,439	29	2,385	559	80,064	1,696,951	34	3,574
250 to 499 acres	218	75,557	1,530,689	14	3,515	157	50,867	1,038,672	14	2,423
500 to 999 acres	86	56,977	1,120,009	15	3,308	70	45,570	960,671	16	3,897
1,000 acres or more	31	45,030	1,009,011	6	2,310	20	30,979	668,812	5	1,376
Dry edible beans, excluding chickpeas and limas (cwt)	573	210,162	5,278,245	95	39,931	506	160,604	3,520,202	101	41,653
1 to 14 acres	28	136	2,717	1	(D)	23	127	3,744	-	-
15 to 24 acres	6	128	7,136	1	(D)	12	234	5,731	-	-
25 to 49 acres	17	592	17,839	-	-	27	929	22,831	1	(D)
50 to 99 acres	101	7,496	237,671	13	(D)	74	5,377	138,767	8	(D)
100 to 249 acres	146	24,557	649,077	23	3,370	161	26,992	636,549	41	6,957
250 to 499 acres	140	50,746	1,205,191	18	4,327	124	43,771	886,738	17	5,784
500 to 999 acres	100	66,049	1,766,841	24	10,172	54	36,509	712,097	17	7,143
1,000 to 1,999 acres	27	37,162	829,697	9	(D)	26	34,757	769,681	12	(D)
2,000 acres or more	8	23,296	562,076	6	(D)	5	11,908	344,064	5	(D)
Dry edible peas (cwt)	35	5,781	148,841	7	1,230	66	11,187	302,729	5	2,591
Flaxseed (bushels)	19	2,215	49,189	-	-	23	2,709	78,848	-	-
Hemp for fiber (pounds) (see text)	1	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Hemp for floral (CBD and other cannabinoid usage) (pounds) (see text)	72	195	126,586	41	69	(NA)	(NA)	(NA)	(NA)	(NA)
Other hemp usage (pounds) (see text)	2	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Hops (pounds)	20	12	10,797	17	12	37	59	79,260	26	48
Lentils (cwt)	-	-	-	-	-	3	241	2,952	1	(D)
Mint for oil, all (pounds of oil)	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Mint, peppermint for oil, (pounds of oil) (see text)	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Oats for grain (bushels)	2,329	126,011	9,470,546	66	3,194	2,532	84,616	6,494,938	24	891
1 to 14 acres	548	4,586	292,527	8	35	874	7,285	503,361	2	(D)
15 to 24 acres	358	6,774	444,371	10	115	638	12,180	879,323	8	132
25 to 49 acres	530	17,967	1,178,626	15	425	587	19,763	1,460,711	9	256
50 to 99 acres	567	39,650	2,759,473	14	824	286	18,133	1,331,884	2	(D)
100 to 249 acres	286	38,005	3,008,637	16	1,627	127	17,691	1,344,716	2	(D)
250 to 499 acres	29	9,301	777,320	3	168	11	3,671	330,910	-	-
500 to 999 acres	8	5,697	624,732	-	-	9	5,893	644,033	1	(D)
1,000 acres or more	3	4,031	384,860	-	-	-	-	-	-	-
Popcorn (pounds, shelled)	5	11	2,485	1	(D)	5	15	(D)	-	-
Proso millet (bushels)	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Rye for grain (bushels)	580	37,506	2,020,506	18	787	404	20,301	837,792	5	265
Sorghum for grain (bushels)	12	364	24,260	-	-	12	526	44,880	2	(D)

--continued

Table 35. **Specified Crops by Acres Harvested: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	2022					2017				
	Farms	Acres	Quantity	Irrigated land		Farms	Acres	Quantity	Irrigated land	
				Farms	Acres				Farms	Acres
FIELD CROPS - Con.										
Sorghum for silage or greenchop (tons)	54	1,394	11,883	2	(D)	41	850	7,990	-	-
Soybeans for beans (bushels)	25,337	7,597,171	373,669,175	892	122,734	27,865	8,142,472	376,505,537	950	128,172
1 to 14 acres	1,306	10,476	444,387	19	115	1,145	9,209	359,853	5	43
15 to 24 acres	1,001	19,093	810,030	12	216	1,142	22,272	948,527	8	135
25 to 49 acres	2,682	96,092	4,443,839	75	2,319	2,837	103,407	4,680,887	59	1,813
50 to 99 acres	4,663	333,800	16,244,681	137	7,895	5,378	386,197	18,082,765	188	10,423
100 to 249 acres	6,879	1,098,331	54,268,259	252	21,598	7,568	1,209,805	57,742,526	225	21,745
250 to 499 acres	4,297	1,493,758	73,494,093	177	25,578	5,043	1,762,510	85,771,518	242	37,416
500 to 999 acres	2,864	1,983,275	98,047,509	136	35,488	3,255	2,233,314	104,663,897	154	36,767
1,000 acres or more	1,645	2,562,346	125,916,377	84	29,525	1,497	2,415,758	104,255,564	69	19,830
1,000 to 1,999 acres	1,399	1,856,638	92,174,807	66	22,035	1,221	1,610,554	71,530,684	55	12,820
2,000 to 2,999 acres	176	405,360	19,908,963	11	5,351	191	437,607	18,487,522	10	6,306
3,000 to 4,999 acres	58	217,095	10,157,378	4	1,815	68	257,428	10,044,994	2	(D)
5,000 acres or more	12	83,253	3,675,229	3	324	17	110,169	4,192,364	2	(D)
Sugarbeets for sugar (tons)	1,106	446,627	11,642,041	31	10,798	1,107	423,096	12,544,950	32	8,808
1 to 14 acres	15	133	3,296	-	-	19	163	5,031	1	(D)
15 to 24 acres	20	424	11,919	-	-	14	292	6,681	-	-
25 to 49 acres	45	1,649	42,993	-	-	35	1,320	39,202	-	-
50 to 99 acres	113	8,566	231,199	-	-	153	11,127	321,257	2	(D)
100 to 249 acres	312	52,864	1,353,124	10	1,001	283	49,069	1,429,385	10	(D)
250 to 499 acres	281	105,242	2,838,955	3	(D)	321	114,666	3,399,128	6	1,081
500 to 999 acres	238	155,118	3,986,581	10	(D)	220	148,489	4,483,311	2	(D)
1,000 to 1,999 acres	68	86,992	2,287,947	7	5,490	49	62,448	1,784,113	7	3,919
2,000 acres or more	14	35,639	886,027	1	(D)	13	35,522	1,076,842	4	(D)
Sunflower seed, all (pounds)	221	66,924	151,726,117	2	(D)	165	36,214	74,066,478	4	266
1 to 14 acres	7	39	(D)	1	(D)	13	39	75,624	-	-
15 to 24 acres	1	(D)	(D)	-	-	6	106	120,880	-	-
25 to 49 acres	24	884	1,374,648	-	-	20	704	945,479	1	(D)
50 to 99 acres	29	2,080	3,948,534	-	-	21	1,560	2,913,502	2	(D)
100 to 249 acres	62	(D)	21,517,630	1	(D)	51	8,272	14,892,970	-	-
250 to 499 acres	49	17,893	39,742,205	-	-	37	12,284	27,316,335	1	(D)
500 to 999 acres	44	29,248	72,479,807	-	-	13	8,103	15,442,974	-	-
1,000 acres or more	5	5,700	12,606,593	-	-	4	5,146	12,358,714	-	-
Sunflower seed - oil varieties (pounds)	207	62,065	139,161,307	2	(D)	148	33,562	70,823,217	3	(D)
1 to 14 acres	7	39	(D)	1	(D)	9	33	71,024	-	-
15 to 24 acres	1	(D)	(D)	-	-	6	106	120,880	-	-
25 to 49 acres	21	(D)	(D)	-	-	14	489	753,220	1	(D)
50 to 99 acres	26	1,801	3,298,464	-	-	20	(D)	(D)	2	(D)
100 to 249 acres	62	(D)	21,517,630	1	(D)	49	(D)	(D)	-	-
250 to 499 acres	46	16,525	34,344,205	-	-	35	(D)	(D)	-	-
500 to 999 acres	39	26,180	66,233,067	-	-	11	(D)	(D)	-	-
1,000 acres or more	5	5,700	12,606,593	-	-	4	5,146	12,358,714	-	-
Sunflower seed - non-oil varieties (pounds)	15	4,859	12,564,810	-	-	17	2,652	3,243,261	1	(D)
1 to 14 acres	-	-	-	-	-	4	6	4,600	-	-
15 to 24 acres	-	-	-	-	-	-	-	-	-	-
25 to 49 acres	3	(D)	(D)	-	-	6	215	192,259	-	-
50 to 99 acres	3	279	650,070	-	-	1	(D)	(D)	-	-
100 to 249 acres	1	(D)	(D)	-	-	2	(D)	(D)	-	-
250 to 499 acres	4	(D)	5,470,000	-	-	2	(D)	(D)	1	(D)
500 to 999 acres	4	2,468	5,694,740	-	-	2	(D)	(D)	-	-
1,000 acres or more	-	-	-	-	-	-	-	-	-	-
Triticale for grain (bushels) (see text)	10	284	15,214	1	(D)	(NA)	(NA)	(NA)	(NA)	(NA)
Wheat for grain, all (bushels)	3,669	1,268,681	82,039,945	52	6,251	4,284	1,197,036	79,313,793	45	6,999
1 to 14 acres	194	1,330	52,150	2	(D)	277	2,443	116,646	2	(D)
15 to 24 acres	222	4,231	182,103	6	37	325	6,121	292,290	1	(D)
25 to 49 acres	468	16,801	793,283	3	(D)	622	22,276	1,159,010	5	150
50 to 99 acres	555	38,330	2,009,554	11	485	721	50,767	2,883,212	9	260
100 to 249 acres	809	133,715	7,610,938	15	1,120	876	139,539	8,511,733	11	1,121
250 to 499 acres	544	189,696	11,623,432	9	1,553	735	254,584	16,426,837	11	2,455
500 to 999 acres	557	379,162	24,315,733	3	2,181	493	343,575	23,770,524	2	(D)
1,000 acres or more	320	505,416	35,452,752	3	(D)	235	377,731	26,153,541	4	2,088
1,000 to 1,999 acres	265	354,456	24,562,617	2	(D)	189	253,219	17,262,910	3	(D)
2,000 to 2,999 acres	40	94,150	6,606,340	1	(D)	33	76,225	5,395,453	-	-
3,000 to 4,999 acres	14	(D)	(D)	-	-	11	(D)	(D)	-	-
5,000 acres or more	1	(D)	(D)	-	-	2	(D)	(D)	1	(D)
Winter wheat for grain (bushels)	102	(D)	342,295	1	(D)	161	5,069	251,488	1	(D)
1 to 14 acres	20	(D)	5,258	-	-	48	382	19,682	1	(D)
15 to 24 acres	12	228	7,437	1	(D)	32	589	20,621	-	-
25 to 49 acres	30	1,074	65,901	-	-	49	1,679	83,985	-	-
50 to 99 acres	22	1,607	100,671	-	-	29	1,815	85,486	-	-
100 to 249 acres	18	2,753	163,028	-	-	3	604	41,714	-	-
250 to 499 acres	-	-	-	-	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-	-	-	-	-
Durum wheat for grain (bushels)	31	(D)	54,556	-	-	14	1,413	85,479	-	-
Other Spring wheat for grain (bushels)	3,557	1,261,299	81,643,094	51	(D)	4,130	1,190,554	78,976,826	45	(D)
1 to 14 acres	179	1,250	48,461	2	(D)	231	2,064	97,379	2	(D)
15 to 24 acres	216	4,098	177,865	5	(D)	300	5,658	277,517	1	(D)
25 to 49 acres	422	15,104	707,912	3	(D)	573	20,567	1,075,407	5	147
50 to 99 acres	530	36,619	1,923,637	11	485	693	49,028	2,801,226	9	260
100 to 249 acres	790	130,874	7,443,045	15	1,120	870	138,288	8,438,509	11	1,121
250 to 499 acres	544	189,676	11,627,529	9	1,553	735	254,432	16,419,237	11	2,455
500 to 999 acres	556	378,612	24,288,143	3	2,181	493	343,180	23,739,724	2	(D)
1,000 acres or more	320	505,066	35,426,502	3	(D)	235	377,337	26,127,827	4	2,088
1,000 to 1,999 acres	266	356,288	24,709,101	2	(D)	189	253,069	17,248,908	3	(D)
2,000 to 2,999 acres	39	91,968	6,433,606	1	(D)	33	76,225	5,395,453	-	-

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Table 35. **Specified Crops by Acres Harvested: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	2022					2017				
	Farms	Acres	Quantity	Irrigated land		Farms	Acres	Quantity	Irrigated land	
				Farms	Acres				Farms	Acres
FIELD CROPS - Con.										
Wheat for grain, all (bushels) - Con.										
Other Spring wheat for grain (bushels) - Con.										
3,000 to 4,999 acres	14	(D)	(D)	-	-	11	(D)	(D)	-	-
5,000 acres or more	1	(D)	(D)	-	-	2	(D)	(D)	1	(D)
FIELD AND GRASS SEEDS, FORAGE, AND HAY										
Field and grass seed crops, all	155	66,601	(X)	6	505	137	37,056	(X)	4	535
1 to 14 acres	6	33	(X)	-	-	10	(D)	(X)	-	-
15 to 24 acres	9	190	(X)	-	-	2	(D)	(X)	-	-
25 to 49 acres	8	274	(X)	3	90	24	891	(X)	1	(D)
50 to 99 acres	28	1,862	(X)	-	-	12	904	(X)	-	-
100 to 249 acres	32	5,958	(X)	2	(D)	46	7,965	(X)	2	(D)
250 to 499 acres	29	9,795	(X)	1	(D)	21	6,917	(X)	-	-
500 to 999 acres	22	15,856	(X)	-	-	17	11,765	(X)	1	(D)
1,000 to 1,999 acres	17	22,710	(X)	-	-	3	4,030	(X)	-	-
2,000 acres or more	4	9,923	(X)	-	-	2	(D)	(X)	-	-
Fescue seed (pounds)	12	5,119	5,604,932	-	-	5	675	(D)	1	(D)
Ryegrass seed (pounds)	112	53,935	51,155,950	-	-	93	27,908	27,187,045	-	-
Forage - land used for all hay and all haylage, grass silage, and greenchop (tons, dry equivalent)	23,394	1,392,072	3,565,994	675	32,954	25,835	1,448,195	3,877,087	479	26,872
1 to 14 acres	7,582	55,246	105,256	142	850	7,990	58,241	126,680	70	(D)
15 to 24 acres	3,524	65,843	127,486	66	960	3,927	73,401	168,950	36	589
25 to 49 acres	4,513	155,930	340,549	91	2,211	5,188	179,873	458,319	68	2,063
50 to 99 acres	3,666	248,896	618,438	153	7,151	4,702	316,005	864,032	121	5,758
100 to 249 acres	3,115	457,723	1,257,874	147	11,276	3,192	462,009	1,275,419	124	9,577
250 to 499 acres	780	253,498	693,244	47	5,088	635	209,395	600,153	46	6,144
500 to 999 acres	188	120,948	312,249	22	3,884	171	108,824	282,557	12	2,121
1,000 acres or more	26	33,988	110,898	7	1,534	30	40,447	100,977	2	(D)
1,000 to 1,999 acres	25	(D)	(D)	7	1,534	28	(D)	(D)	2	(D)
2,000 to 2,999 acres	1	(D)	(D)	-	-	2	(D)	(D)	-	-
3,000 to 4,999 acres	-	-	-	-	-	-	-	-	-	-
5,000 acres or more	-	-	-	-	-	-	-	-	-	-
Hay - All hay including alfalfa and other dry (tons, dry)	21,207	1,134,538	2,629,928	530	19,607	23,737	1,210,924	3,002,173	386	17,270
1 to 14 acres	7,034	51,295	103,217	130	826	7,621	55,507	126,519	68	(D)
15 to 24 acres	3,327	62,097	130,378	61	949	3,817	71,428	170,238	39	592
25 to 49 acres	4,304	148,636	329,204	81	2,029	5,027	174,244	450,707	65	1,976
50 to 99 acres	3,304	223,988	526,008	131	5,697	4,072	271,936	702,079	110	5,413
100 to 249 acres	2,552	371,979	909,395	99	7,059	2,555	364,050	915,965	73	5,294
250 to 499 acres	547	177,237	390,647	19	1,899	494	161,623	393,811	24	2,907
500 to 999 acres	124	79,975	173,080	6	633	130	82,995	174,956	5	473
1,000 acres or more	15	19,331	67,999	3	515	21	29,141	67,898	2	(D)
1,000 to 1,999 acres	14	(D)	(D)	3	515	19	(D)	(D)	2	(D)
2,000 to 2,999 acres	1	(D)	(D)	-	-	2	(D)	(D)	-	-
3,000 to 4,999 acres	-	-	-	-	-	-	-	-	-	-
5,000 acres or more	-	-	-	-	-	-	-	-	-	-
Alfalfa hay (tons, dry)	15,333	744,117	1,971,568	421	15,949	17,865	828,937	2,345,020	338	15,364
1 to 14 acres	5,194	37,693	83,768	85	(D)	5,926	42,829	107,363	58	383
15 to 24 acres	2,520	47,121	113,490	49	755	2,921	54,686	148,248	38	573
25 to 49 acres	3,140	108,052	276,721	81	2,291	3,876	134,376	396,304	57	1,761
50 to 99 acres	2,371	160,188	422,654	107	4,584	3,001	198,770	576,807	101	5,175
100 to 249 acres	1,715	243,022	678,436	84	5,937	1,756	244,126	687,833	61	4,576
250 to 499 acres	332	107,031	266,287	10	888	316	104,245	295,893	19	2,555
500 to 999 acres	55	33,142	82,666	3	(D)	62	39,705	103,605	4	341
1,000 acres or more	6	7,868	47,546	2	(D)	7	10,200	28,967	-	-
Other dry hay (tons, dry)	8,556	390,421	658,360	153	3,658	9,043	381,987	657,153	80	1,906
1 to 14 acres	3,228	23,591	40,957	68	468	3,608	25,165	47,953	25	(D)
15 to 24 acres	1,513	28,078	47,891	19	(D)	1,659	30,772	55,412	20	344
25 to 49 acres	1,734	60,157	97,549	33	869	1,720	59,054	108,316	13	272
50 to 99 acres	1,085	72,711	120,087	17	749	1,131	75,233	132,456	18	814
100 to 249 acres	766	111,131	194,712	13	1,222	721	104,903	175,455	3	192
250 to 499 acres	177	57,070	94,076	2	(D)	154	51,325	77,502	1	(D)
500 to 999 acres	46	29,461	54,304	-	-	41	24,170	45,238	-	-
1,000 acres or more	7	8,222	8,784	1	(D)	9	11,365	14,821	-	-
All haylage, grass silage, and greenchop (tons, green)	4,152	305,999	1,893,891	211	14,317	4,365	284,273	1,770,188	160	11,280
1 to 14 acres	1,148	8,200	20,885	26	154	1,027	7,266	20,885	13	68
15 to 24 acres	553	10,276	29,819	15	193	550	10,216	37,036	13	227
25 to 49 acres	711	24,556	118,413	37	1,004	926	32,339	163,179	24	826
50 to 99 acres	758	51,961	294,778	39	2,283	1,051	71,051	424,455	49	2,769
100 to 249 acres	734	106,362	723,882	59	4,505	647	94,002	590,174	42	3,464
250 to 499 acres	196	65,814	465,027	25	3,776	128	42,955	350,168	14	2,388
500 to 999 acres	45	29,286	178,483	6	1,592	31	19,925	150,806	5	1,538
1,000 acres or more	7	9,544	62,604	4	810	5	6,519	33,485	-	-
Haylage or greenchop from alfalfa or alfalfa mixtures (tons, green)	2,114	216,094	1,522,392	149	12,058	2,736	216,829	1,542,528	146	9,924
1 to 14 acres	270	2,170	7,796	10	53	346	2,382	10,499	10	43
15 to 24 acres	197	3,682	18,115	3	(D)	271	5,109	26,887	12	204
25 to 49 acres	374	13,330	93,888	26	775	629	21,938	138,700	20	678
50 to 99 acres	528	36,689	241,213	25	1,433	844	57,642	389,272	48	2,679
100 to 249 acres	548	79,612	574,030	53	4,055	517	74,656	525,779	39	3,096
250 to 499 acres	160	54,199	393,523	26	3,788	101	33,924	300,035	14	2,256
500 to 999 acres	32	19,431	147,684	3	1,183	24	15,784	124,674	3	968
1,000 acres or more	5	6,981	46,143	3	(D)	4	5,394	26,682	-	-

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Table 35. **Specified Crops by Acres Harvested: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	2022					2017				
	Farms	Acres	Quantity	Irrigated land		Farms	Acres	Quantity	Irrigated land	
				Farms	Acres				Farms	Acres
FIELD AND GRASS SEEDS, FORAGE, AND HAY - Con.										
All haylage, grass silage, and greenchop (tons, green) - Con.										
All other haylage, grass silage, and greenchop (tons, green)	2,310	89,905	371,499	67	2,259	1,953	67,444	227,660	25	1,356
1 to 14 acres	958	6,601	15,184	17	(D)	832	5,576	13,145	8	28
15 to 24 acres	397	7,413	17,668	13	182	323	6,001	14,759	1	(D)
25 to 49 acres	440	14,754	45,514	17	389	396	13,895	43,156	8	276
50 to 99 acres	279	18,815	86,595	13	817	261	16,817	57,751	4	246
100 to 249 acres	205	28,016	153,622	6	690	120	16,289	52,938	1	(D)
250 to 499 acres	21	6,766	25,383	-	-	14	4,640	20,916	2	(D)
500 to 999 acres	10	7,540	27,533	1	(D)	7	4,226	24,995	1	(D)
1,000 acres or more	-	-	-	-	-	-	-	-	-	-
OTHER SPECIFIED CROPS										
Land in vegetables	2,620	196,718	(X)	764	54,640	2,840	207,071	(X)	706	51,939
0.1 to 0.9 acres	568	249	(X)	206	101	504	230	(X)	143	63
1.0 to 4.9 acres	787	1,506	(X)	294	508	764	1,426	(X)	272	456
5.0 to 14.9 acres	169	1,300	(X)	53	307	223	1,734	(X)	63	370
15.0 to 24.9 acres	56	1,103	(X)	16	219	65	1,260	(X)	17	205
25.0 to 49.9 acres	173	6,362	(X)	18	501	249	9,594	(X)	19	603
50.0 to 99.9 acres	322	23,382	(X)	35	2,341	408	29,533	(X)	36	2,660
100.0 to 249.9 acres	364	56,336	(X)	70	9,961	447	66,689	(X)	84	10,840
250.0 to 499.9 acres	125	42,610	(X)	45	13,460	129	44,931	(X)	49	14,585
500.0 to 749.9 acres	23	13,932	(X)	11	6,607	28	16,408	(X)	11	5,607
750.0 to 999.9 acres	13	10,981	(X)	5	4,118	8	6,523	(X)	4	2,645
1,000.0 acres or more	20	38,956	(X)	11	16,517	15	28,745	(X)	8	13,905
Land in orchards	1,174	5,049	(X)	204	778	1,061	4,767	(X)	154	891
Land in berries	578	1,129	(X)	185	426	638	1,002	(X)	196	440

Table 36. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017**

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
Vegetables harvested for sale	2,620	205,632	1,632	23,564	1,026	182,068	2,840	212,474	1,634	28,581	1,257	183,892
0.1 to 0.9 acres	534	235	519	230	17	5	468	225	464	222	12	3
1.0 to 4.9 acres	805	1,575	805	1,569	20	7	788	1,576	787	1,566	15	10
5.0 to 14.9 acres	179	1,344	173	1,293	10	51	233	1,817	225	1,719	9	98
15.0 to 24.9 acres	56	1,076	38	(D)	18	(D)	64	1,234	41	759	26	475
25.0 to 49.9 acres	177	6,485	27	858	150	5,627	242	9,291	27	853	216	8,437
50.0 to 99.9 acres	299	21,834	23	1,444	279	20,391	406	29,334	25	1,419	391	27,915
100.0 to 249.9 acres	369	57,045	13	1,324	360	55,722	448	66,993	25	2,481	430	64,512
250.0 to 499.9 acres	141	48,279	21	7,867	122	40,413	137	47,845	22	8,220	117	39,624
500.0 to 749.9 acres	24	14,289	8	4,230	17	10,059	30	17,333	13	6,684	19	10,649
750.0 to 999.9 acres	16	13,641	1	(D)	15	(D)	8	6,665	-	-	8	6,665
1,000.0 acres or more	20	39,827	4	3,216	18	36,611	16	30,161	5	4,657	14	25,504
1,000.0 to 1,999.9 acres	16	23,072	4	3,216	14	19,856	11	16,027	1	(D)	10	(D)
2,000.0 to 2,999.9 acres	2	(D)	-	-	2	(D)	4	(D)	3	(D)	3	5,731
3,000.0 to 4,999.9 acres	1	(D)	-	-	1	(D)	-	-	-	-	-	-
5,000.0 acres or more	1	(D)	-	-	1	(D)	1	(D)	1	(D)	1	(D)
Artichokes (excluding Jerusalem)	3	(Z)	3	(Z)	-	-	12	1	12	1	-	-
Asparagus, bearing age	194	141	193	(D)	1	(D)	215	128	215	128	-	-
Beans, lima	20	505	14	1	6	504	5	(D)	3	1	2	(D)
Beans, snap (bush and pole)	390	2,553	370	276	22	2,278	529	4,465	497	461	32	4,005
0.1 to 0.9 acres	344	60	343	(D)	2	(D)	453	85	452	(D)	1	(D)
1.0 to 4.9 acres	22	38	22	(D)	1	(D)	42	72	42	72	-	-
5.0 to 14.9 acres	3	(D)	1	(D)	2	(D)	-	-	-	-	-	-
15.0 to 24.9 acres	1	(D)	1	(D)	-	-	2	(D)	-	-	2	(D)
25.0 to 49.9 acres	5	148	2	(D)	3	(D)	5	155	1	(D)	4	(D)
50.0 to 99.9 acres	11	785	1	(D)	10	(D)	8	540	-	-	8	540
100.0 to 249.9 acres	1	(D)	-	-	1	(D)	16	2,418	2	(D)	14	(D)
250.0 to 499.9 acres	2	(D)	-	-	2	(D)	2	(D)	-	-	2	(D)
500.0 acres or more	1	(D)	-	-	1	(D)	1	(D)	-	-	1	(D)
Beets	305	595	303	(D)	3	(D)	322	351	319	(D)	3	(D)
Broccoli	254	(D)	254	(D)	-	-	306	170	306	170	-	-
Brussels sprouts	101	25	101	25	-	-	142	44	142	44	-	-
Cabbage, Chinese (nappa, bok choy, etc.)	108	28	108	28	-	-	157	35	157	35	-	-
Cabbage, head	290	309	290	308	3	(Z)	304	421	302	(D)	3	(D)
Cabbage, mustard	17	3	17	3	(X)	(X)	15	4	15	4	(X)	(X)
Cantaloupes and muskmelons	155	124	155	124	-	-	170	117	170	117	-	-
Carrots	336	1,194	332	512	4	682	364	947	359	398	5	548
Cauliflower	145	47	145	47	-	-	179	59	179	59	-	-
Celery	105	22	105	22	-	-	88	16	88	16	-	-
Chicory	5	1	5	1	-	-	3	(Z)	3	(Z)	(X)	(X)
Collards	53	14	53	14	-	-	33	9	33	9	-	-
Cucumbers and pickles	425	200	417	198	13	3	549	326	539	323	17	3
Daikon	34	6	34	6	-	-	41	9	41	9	-	-
Eggplant	169	50	169	50	-	-	192	59	192	59	-	-
Escarole and endive	8	1	8	1	(X)	(X)	6	1	6	1	(X)	(X)
Garlic	316	81	316	78	7	3	224	52	221	51	4	(Z)
Ginger root	8	1	8	1	-	-	6	1	6	1	-	-
Ginseng, (cultivated only)	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Gourds (see text)	138	84	138	84	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Herbs, fresh cut	219	49	219	49	(X)	(X)	247	80	247	80	(X)	(X)
Honeydew melons	38	8	38	8	-	-	51	7	51	7	(X)	(X)
Horseradish	29	(D)	28	3	1	(D)	28	3	27	(D)	1	(D)
Kale	242	52	242	52	-	-	230	80	230	80	-	-
Lettuce, all	322	94	322	94	(X)	(X)	289	97	289	97	(X)	(X)
Lettuce, head	163	30	163	30	(X)	(X)	96	22	96	22	(X)	(X)
Lettuce, leaf	221	41	221	41	(X)	(X)	232	54	232	54	(X)	(X)
Lettuce, romaine	152	23	152	23	(X)	(X)	111	22	111	22	(X)	(X)
Mustard greens	43	14	43	14	-	-	51	12	51	12	-	-
Okra	44	11	43	(D)	1	(D)	48	16	48	16	-	-
Onions, dry	292	308	290	(D)	2	(D)	340	292	340	292	-	-
Onions, green	209	60	209	60	-	-	230	67	230	67	-	-
Parsley	110	20	110	20	-	-	108	20	108	20	-	-

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Table 36. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
Parsnips (see text)	21	2	21	2	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Peas, Chinese (sugar, snow)	121	671	111	28	10	644	159	1,030	142	235	17	795
Peas, green	599	47,364	108	20	491	47,345	697	44,463	163	53	536	44,410
0.1 to 0.9 acres	105	(D)	105	(D)	-	-	155	29	153	(D)	2	(D)
1.0 to 4.9 acres	3	(D)	3	(D)	-	-	7	17	7	17	-	-
5.0 to 14.9 acres	1	(D)	-	-	1	(D)	6	65	1	(D)	5	(D)
15.0 to 24.9 acres	15	(D)	-	-	15	(D)	21	416	-	-	21	416
25.0 to 49.9 acres	107	4,119	-	-	107	4,119	198	7,487	-	-	198	7,487
50.0 to 99.9 acres	222	15,664	-	-	222	15,664	186	12,842	2	(D)	186	(D)
100.0 to 249.9 acres	119	16,719	-	-	119	16,719	111	16,605	-	-	111	16,605
250.0 to 499.9 acres	21	6,433	-	-	21	6,433	9	2,962	-	-	9	2,962
500.0 acres or more	6	4,068	-	-	6	4,068	4	4,039	-	-	4	4,039
Peas, southern (cowpeas) - blackeyed, crowder, etc.	4	(Z)	4	(Z)	-	-	8	2	8	2	-	-
Peppers, Bell (excluding pimientos)	439	348	434	347	5	1	489	391	487	390	5	1
Peppers, other than Bell (including chile)	294	79	280	77	14	1	305	(D)	303	(D)	3	(D)
Potatoes	509	49,008	474	13,882	39	35,127	577	46,278	526	16,942	57	29,336
0.1 to 0.9 acres	370	92	370	92	-	-	362	96	362	96	-	-
1.0 to 4.9 acres	51	81	51	81	-	-	100	187	100	(D)	1	(D)
5.0 to 14.9 acres	4	(D)	4	(D)	-	-	14	119	13	(D)	1	(D)
15.0 to 24.9 acres	1	(D)	1	(D)	-	-	4	77	4	77	-	-
25.0 to 49.9 acres	7	261	6	(D)	1	(D)	6	192	5	(D)	1	(D)
50.0 to 99.9 acres	13	973	12	(D)	1	(D)	14	1,267	5	(D)	9	(D)
100.0 to 249.9 acres	8	1,098	4	(D)	4	(D)	20	3,287	6	766	15	2,521
250.0 to 499.9 acres	30	11,100	17	6,219	15	4,881	31	11,906	17	6,307	15	5,599
500.0 to 749.9 acres	9	5,423	5	(D)	4	(D)	14	8,085	11	5,972	4	2,113
750.0 to 999.9 acres	6	4,965	1	(D)	5	(D)	4	3,329	-	-	4	3,329
1,000.0 acres or more	10	24,974	3	2,120	9	22,854	8	17,734	3	2,853	7	14,881
1,000.0 to 1,999.9 acres	8	(D)	3	2,120	7	(D)	4	(D)	-	-	4	(D)
2,000.0 to 2,999.9 acres	-	-	-	-	-	-	3	6,799	2	(D)	2	(D)
3,000.0 acres or more	2	(D)	-	-	2	(D)	1	(D)	1	(D)	1	(D)
Pumpkins	627	2,018	621	2,018	6	1	569	1,827	569	(D)	1	(D)
0.1 to 0.9 acres	375	99	369	98	6	1	357	90	357	90	-	-
1.0 to 4.9 acres	173	362	173	362	-	-	140	273	140	(D)	1	(D)
5.0 to 14.9 acres	53	401	53	401	-	-	48	370	48	370	-	-
15.0 to 24.9 acres	11	201	11	201	-	-	10	176	10	176	-	-
25.0 to 49.9 acres	9	283	9	283	-	-	7	260	7	260	-	-
50.0 to 99.9 acres	3	166	3	166	-	-	4	256	4	256	-	-
100.0 acres or more	3	508	3	508	-	-	3	405	3	405	-	-
Radishes	206	(D)	206	(D)	-	-	270	(D)	270	(D)	-	-
Rhubarb	216	73	210	72	6	2	193	72	192	(D)	1	(D)
Spinach	155	31	155	31	-	-	163	44	163	44	-	-
Squash, all (including zucchini) (see text)	539	652	539	652	-	-	682	921	682	920	1	(D)
Sweet corn (see text)	1,243	96,990	496	2,453	750	94,536	1,531	107,955	557	3,447	985	104,508
0.1 to 0.9 acres	264	77	264	77	-	-	334	90	334	90	-	-
1.0 to 4.9 acres	163	316	163	316	-	-	133	267	133	(D)	1	(D)
5.0 to 14.9 acres	47	366	47	366	-	-	59	474	53	406	6	68
15.0 to 24.9 acres	15	299	7	130	8	169	32	625	10	186	22	439
25.0 to 49.9 acres	143	5,449	4	128	139	5,321	219	8,675	3	(D)	217	(D)
50.0 to 99.9 acres	271	19,783	4	275	268	19,508	388	27,585	15	789	380	26,796
100.0 acres or more	340	70,699	7	1,161	335	69,538	366	70,239	9	1,649	359	68,590
100.0 to 249.9 acres	268	40,036	5	(D)	265	(D)	297	43,193	5	(D)	293	(D)
250.0 to 499.9 acres	57	18,096	2	(D)	55	(D)	58	18,574	3	894	55	17,680
500.0 to 749.9 acres	8	4,828	-	-	8	4,828	8	4,777	1	(D)	8	(D)
750.0 to 999.9 acres	4	3,441	-	-	4	3,441	1	(D)	-	-	1	(D)
1,000.0 acres or more	3	4,298	-	-	3	4,298	2	(D)	-	-	2	(D)
Sweet potatoes	58	23	58	23	-	-	82	33	82	33	-	-
Tomatoes in the open	592	300	581	298	18	2	670	350	663	348	11	2
Turnip greens	19	4	19	4	-	-	30	6	30	6	-	-
Turnips	90	18	90	18	-	-	102	16	102	16	-	-
Watercress	2	(D)	2	(D)	(X)	(X)	6	1	6	1	(X)	(X)
Watermelons	209	237	209	237	-	-	253	136	253	136	-	-
Other vegetables	123	184	123	184	-	-	167	336	167	336	-	-

Table 37. **Specified Fruits and Nuts by Acres: 2022 and 2017**

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
Noncitrus fruit, all	1,126	4,724	931	3,739	588	985	1,028	4,589	814	3,687	556	903
Apples	751	3,219	600	2,567	393	651	706	3,600	545	2,931	394	669
0.1 to 0.9 acres	320	118	233	(D)	151	(D)	292	97	200	60	137	37
1.0 to 4.9 acres	302	595	246	416	167	178	273	577	209	357	168	221
5.0 to 14.9 acres	83	641	75	506	40	135	83	600	78	481	43	119
15.0 to 24.9 acres	16	292	16	234	9	58	23	418	23	338	20	80
25.0 to 49.9 acres	21	730	21	573	19	157	24	775	24	660	19	115
50.0 to 99.9 acres	6	403	6	351	6	52	6	387	6	(D)	5	(D)
100.0 acres or more	3	440	3	(D)	1	(D)	5	746	5	(D)	2	(D)
Apricots	22	(D)	13	3	11	(D)	22	11	10	5	19	7
Cherries, sweet	52	12	22	6	33	6	24	15	9	3	19	12
Cherries, tart	123	54	77	42	58	12	103	40	65	26	49	14
Grapes (including muscadine) (see text)	433	1,290	361	1,045	173	246	327	816	261	657	138	160
Kiwifruit	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Peaches, all	17	(D)	5	1	13	(D)	19	3	2	(D)	17	(D)
Peaches, clingstone	10	(D)	4	(D)	7	(D)	6	1	2	(D)	4	(D)
Peaches, freestone	11	(D)	2	(D)	9	(D)	13	2	-	-	13	2
Pears, all	156	70	93	32	100	37	91	36	47	20	50	16
Pears, Bartlett	45	14	20	7	27	8	11	2	7	1	4	(Z)
Pears, other than Bartlett	127	56	74	26	80	30	84	34	42	18	48	16
Persimmons	6	3	-	-	6	3	-	-	-	-	-	-
Plums and prunes	150	64	93	42	90	22	135	48	80	28	69	19
Plums	150	64	93	42	90	22	134	(D)	79	(D)	68	(D)
Prunes	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Other noncitrus fruit (see text)	20	5	5	2	16	3	10	21	8	(D)	4	(D)
Nuts, all	109	325	55	102	72	223	65	177	28	119	49	58
Chestnuts	24	(D)	5	(D)	21	54	8	(D)	1	(D)	8	4
Hazelnuts (Filberts)	63	123	43	(D)	31	(D)	47	131	18	99	36	32
Pecans, all	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Pecans, improved	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Walnuts, English	29	142	8	26	24	115	14	26	7	7	10	19
Other nuts	2	(D)	2	(D)	1	(D)	15	(D)	6	(D)	12	(D)

Table 38. **Berries by Acres: 2022 and 2017**

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Crop	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
Berries, all (see text)	578	1,129	494	872	231	257	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Aronia berries	49	30	44	26	11	4	65	93	52	46	36	47
Blackberries and dewberries (including marionberries)	33	13	22	9	16	4	23	37	19	(D)	7	(D)
Blueberries, all	174	340	111	296	87	44	180	124	137	91	66	34
Blueberries, tame	165	292	103	(D)	84	(D)	169	121	132	89	60	32
Blueberries, wild	16	48	8	(D)	9	(D)	13	3	5	1	8	2
Cranberries	10	(D)	5	(D)	8	4	9	(D)	4	(D)	8	4
Currants (black or red)	44	17	42	(D)	6	(D)	59	31	52	17	34	14
Elderberries	91	51	55	18	40	34	46	(D)	28	9	26	(D)
Gooseberries (see text)	11	4	6	(D)	8	(D)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Loganberries	3	(D)	1	(D)	2	(D)	1	(D)	-	-	1	(D)
Mulberries (see text)	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Raspberries, all	270	177	242	137	80	40	312	196	264	138	107	58
Strawberries	218	401	184	308	85	93	232	423	193	329	104	94
Other berries (see text)	30	44	19	13	19	31	51	29	32	14	27	15

Table 39. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Crop		Under glass or other protection		In the open		Value of sales	
		Farms	Square feet	Farms	Acres	Farms	Dollars
FLORICULTURE AND BEDDING CROPS							
Bedding/Garden plants, cut flowers and cut florist greens, foliage plants, potted flowering plants, and other floriculture and bedding crops, total	2022	376	13,099,758	351	528	605	139,921,406
	2017	350	14,692,175	245	416	490	136,247,594
Bedding/Garden plants - annuals, herbaceous perennials, vegetable plants (include hanging baskets)	2022	321	8,459,412	136	229	391	95,906,823
	2017	306	9,771,478	123	226	364	98,198,865
Cut flowers and cut florist greens	2022	61	394,932	188	178	218	9,190,414
	2017	24	404,204	86	118	99	5,979,762
Foliage plants, indoor (include hanging baskets)	2022	51	1,070,501	19	5	69	6,635,408
	2017	31	908,430	8	3	36	9,654,688
Potted flowering plants	2022	85	2,981,019	42	34	121	23,692,175
	2017	72	3,323,647	23	24	85	20,069,757
Other floriculture and bedding crops	2022	13	193,894	21	83	32	4,496,586
	2017	18	284,416	22	46	37	2,344,522
NURSERY CROPS							
Nursery stock crops	2022	60	1,497,053	297	6,690	325	146,712,916
	2017	56	646,291	236	5,271	263	79,870,101
Aquatic plants	2022	3	400	5	1	8	8,682
	2017	5	(D)	4	3	7	184,140
HEMP							
Hemp clones or transplants sold for transplants to others (see text)	2022	9	2,500	(X)	(X)	9	13,750
	2017	(NA)	(NA)	(X)	(X)	(NA)	(NA)
Hemp complete grows (see text)	2022	38	61,906	(X)	(X)	38	640,128
	2017	(NA)	(NA)	(X)	(X)	(NA)	(NA)
Hemp seeds (see text)	2022	8	2,400	-	-	8	27,600
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
PROPAGATIVE MATERIALS SOLD							
Bulbs, corms, rhizomes, and tubers - dry	2022	7	(D)	12	20	18	108,378
	2017	11	1,575	21	29	30	122,703
Cuttings, seedlings, liners, and plugs	2022	15	394,871	3	(D)	18	9,921,875
	2017	10	534,684	6	6	15	6,915,175
Flower seeds	2022	7	(D)	14	451	21	767,180
	2017	9	(D)	19	545	27	1,981,576
Tobacco transplants to farm fields	2022	1	(D)	-	-	1	(D)
	2017	-	-	-	-	-	-
SOD							
Sod harvested or intended for sale in future years (see text)	2022	(X)	(X)	52	8,604	52	47,606,894
	2017	(X)	(X)	(NA)	(NA)	(NA)	(NA)
2022 farms by area:							
0.1 to 14.9 acres		(X)	(X)	8	(D)	8	(D)
15.0 to 49.9 acres		(X)	(X)	14	432	14	2,821,506
50.0 to 99.9 acres		(X)	(X)	7	544	7	1,350,272
100.0 to 249.9 acres		(X)	(X)	12	1,853	12	9,734,842
250.0 to 399.9 acres		(X)	(X)	5	1,449	5	10,367,825
400.0 to 749.9 acres		(X)	(X)	4	2,309	4	12,832,675
750.0 acres or more		(X)	(X)	2	(D)	2	(D)
FOOD CROPS GROWN UNDER GLASS OR OTHER PROTECTION							
Total greenhouse vegetables and fresh cut herbs	2022	275	3,709,397	(X)	(X)	275	39,093,358
	2017	304	2,504,364	(X)	(X)	304	26,773,375
2022 farms by area:							
1 to 999 square feet		81	31,207	(X)	(X)	81	107,608
1,000 to 1,999 square feet		53	78,976	(X)	(X)	53	324,480
2,000 to 2,999 square feet		33	82,383	(X)	(X)	33	363,824
3,000 to 3,999 square feet		22	71,808	(X)	(X)	22	365,257
4,000 to 5,999 square feet		33	159,834	(X)	(X)	33	1,511,712
6,000 to 9,999 square feet		28	197,987	(X)	(X)	28	865,271
10,000 or more square feet		25	3,087,202	(X)	(X)	25	35,555,206
10,000 to 19,999 square feet		12	147,892	(X)	(X)	12	591,361
20,000 to 39,999 square feet		5	119,650	(X)	(X)	5	(D)
40,000 or more square feet		8	2,819,660	(X)	(X)	8	(D)
Greenhouse tomatoes	2022	226	2,697,020	(X)	(X)	226	(D)
	2017	227	1,956,248	(X)	(X)	227	24,435,860
2022 farms by area:							
1 to 999 square feet		109	41,587	(X)	(X)	109	255,392
1,000 to 1,999 square feet		35	49,956	(X)	(X)	35	325,934
2,000 to 2,999 square feet		24	59,772	(X)	(X)	24	363,445
3,000 to 3,999 square feet		18	60,231	(X)	(X)	18	362,263
4,000 to 5,999 square feet		16	75,228	(X)	(X)	16	468,046
6,000 to 9,999 square feet		11	86,056	(X)	(X)	11	570,329
10,000 or more square feet		13	2,324,190	(X)	(X)	13	(D)
10,000 to 19,999 square feet		5	58,250	(X)	(X)	5	421,740

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Table 39. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Crop		Under glass or other protection		In the open		Value of sales	
		Farms	Square feet	Farms	Acres	Farms	Dollars
FOOD CROPS GROWN UNDER GLASS OR OTHER PROTECTION - Con.							
Total greenhouse vegetables and fresh cut herbs - Con.							
Greenhouse tomatoes - Con.							
2022 farms by area: - Con.							
20,000 to 39,999 square feet		7	(D)	(X)	(X)	7	1,084,813
40,000 or more square feet		1	(D)	(X)	(X)	1	(D)
Other greenhouse vegetables and fresh cut herbs	2022	199	1,012,377	(X)	(X)	199	(D)
	2017	220	548,116	(X)	(X)	220	2,337,515
2022 farms by area:							
1 to 999 square feet		87	41,767	(X)	(X)	87	81,381
1,000 to 1,999 square feet		39	53,633	(X)	(X)	39	113,529
2,000 to 2,999 square feet		21	52,422	(X)	(X)	21	118,916
3,000 to 3,999 square feet		12	40,820	(X)	(X)	12	83,918
4,000 to 5,999 square feet		14	66,937	(X)	(X)	14	957,933
6,000 to 9,999 square feet		12	83,283	(X)	(X)	12	198,397
10,000 or more square feet		14	673,515	(X)	(X)	14	(D)
10,000 to 19,999 square feet		11	(D)	(X)	(X)	11	504,370
20,000 to 39,999 square feet		-	-	(X)	(X)	-	-
40,000 or more square feet		3	(D)	(X)	(X)	3	(D)
Vegetable seeds (see text)	2022	41	25,833	(X)	(X)	41	39,172
	2017	11	15,218	(X)	(X)	25	99,846
Vegetable transplants to farm fields	2022	105	121,962	(X)	(X)	105	292,388
	2017	50	64,655	(X)	(X)	61	235,148
Greenhouse fruits and berries	2022	53	207,992	(X)	(X)	53	673,700
	2017	38	68,997	(X)	(X)	38	213,825
2022 farms by area:							
1 to 999 square feet		21	7,540	(X)	(X)	21	26,443
1,000 to 1,999 square feet		13	19,669	(X)	(X)	13	66,875
2,000 to 2,999 square feet		5	10,742	(X)	(X)	5	36,523
3,000 to 3,999 square feet		7	21,525	(X)	(X)	7	73,185
4,000 to 5,999 square feet		4	18,516	(X)	(X)	4	54,674
6,000 to 9,999 square feet		-	-	(X)	(X)	-	-
10,000 or more square feet		3	130,000	(X)	(X)	3	416,000
10,000 to 19,999 square feet		2	(D)	(X)	(X)	2	(D)
20,000 to 39,999 square feet		-	-	(X)	(X)	-	-
40,000 or more square feet		1	(D)	(X)	(X)	1	(D)
MUSHROOM CROPS							
Mushrooms	2022	34	85,172	(X)	(X)	34	5,940,836
	2017	7	11,145	(X)	(X)	7	1,041,917
Mushroom spawn	2022	2	(X)	(X)	(X)	2	(D)
	2017	-	(X)	(X)	(X)	-	-

Table 40. **Woodland Crops Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Crop		Acres in production		Trees cut		Irrigated		Value of sales ($1,000)
		Farms	Acres	Farms	Number	Farms	Acres	
Cultivated Christmas trees	2022	378	7,127	243	153,600	41	626	(D)
	2017	321	7,337	209	182,532	18	230	5,800
2022 farms by acres in production:								
1 to 2 acres		100	126	57	580	11	(D)	(D)
3 to 4 acres		26	87	16	701	-	-	22
5 to 9 acres		53	306	30	2,522	6	23	105
10 to 19 acres		104	1,304	63	10,268	2	(D)	508
20 to 49 acres		72	2,123	58	42,678	15	334	2,820
50 to 99 acres		15	955	11	17,225	4	75	1,141
100 acres or more		8	2,226	8	79,626	3	170	2,964
2017 farms by acres in production:								
1 to 2 acres		75	107	36	788	1	(D)	19
3 to 4 acres		41	137	26	2,877	4	12	73
5 to 9 acres		52	312	25	2,194	2	(D)	67
10 to 19 acres		56	678	38	7,499	1	(D)	221
20 to 49 acres		67	2,045	56	29,337	5	76	1,107
50 to 99 acres		18	1,248	16	24,940	2	(D)	1,159
100 acres or more		12	2,810	12	114,897	3	80	3,155

Crop		Acres in production		Harvested		Irrigated		Value of sales ($1,000)
		Farms	Acres	Farms	Acres	Farms	Acres	
Short rotation woody crops	2022	5	290	1	(D)	-	-	(D)
	2017	77	1,808	28	110	6	24	95
2022 farms by acres in production:								
1 to 9 acres		-	-	-	-	-	-	-
10 to 49 acres		3	(D)	1	(D)	-	-	(D)
50 to 99 acres		-	-	-	-	-	-	-
100 to 249 acres		2	(D)	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-	-
500 acres or more		-	-	-	-	-	-	-
2017 farms by acres in production:								
1 to 9 acres		31	(D)	13	(D)	1	(D)	(D)
10 to 49 acres		37	899	13	74	5	(D)	65
50 to 99 acres		7	498	2	(D)	-	-	(D)
100 to 249 acres		2	(D)	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-	-
500 acres or more		-	-	-	-	-	-	-

Crop		Taps set		Syrup produced		Value of sales ($1,000)
		Farms	Number	Farms	Gallons	
Maple syrup	2022	364	97,822	364	21,507	869
	2017	291	99,205	291	19,102	758
2022 farms by number of taps:						
1 to 99 taps		237	(D)	237	(D)	(D)
100 to 499 taps		85	16,607	85	3,553	156
500 to 999 taps		22	15,028	22	3,541	168
1,000 to 1,999 taps		11	15,236	11	3,961	170
2,000 to 2,999 taps		3	6,701	3	1,225	56
3,000 to 4,999 taps		1	(D)	1	(D)	(D)
5,000 to 9,999 taps		5	34,300	5	6,618	213
10,000 taps or more		-	-	-	-	-
10,000 to 14,999 taps		-	-	-	-	-
15,000 to 19,999 taps		-	-	-	-	-
20,000 taps or more		-	-	-	-	-
2017 farms by number of taps:						
1 to 99 taps		169	6,204	169	1,165	47
100 to 499 taps		91	16,530	91	2,983	130
500 to 999 taps		12	6,975	12	1,315	(D)
1,000 to 1,999 taps		10	14,044	10	2,429	137
2,000 to 2,999 taps		3	(D)	3	(D)	71
3,000 to 4,999 taps		1	(D)	1	(D)	(D)
5,000 to 9,999 taps		4	20,500	4	2,610	66
10,000 taps or more		1	(D)	1	(D)	(D)
10,000 to 14,999 taps		(NA)	(NA)	(NA)	(NA)	(NA)
15,000 to 19,999 taps		(NA)	(NA)	(NA)	(NA)	(NA)
20,000 taps or more		(NA)	(NA)	(NA)	(NA)	(NA)

Table 41. **Farms by Concentration of Market Value of Agricultural Products Sold: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Characteristics		All farms	Fewest number of farms accounting for-			
			10 percent of sales	25 percent of sales	50 percent of sales	75 percent of sales
Farms	number	65,531	91	627	2,690	6,907
	percent	100.0	0.1	1.0	4.1	10.5
Land in farms	acres	25,442,625	328,163	1,861,028	6,611,300	12,505,878
Average size of farm	acres	388	3,606	2,968	2,458	1,811
Estimated market value of land and buildings	farms	65,531	91	627	2,690	6,907
	$1,000	155,374,449	2,015,928	12,122,096	44,839,810	83,239,001
Average per farm	dollars	2,371,007	22,153,051	19,333,486	16,669,074	12,051,397
Average per acre	dollars	6,107	6,143	6,514	6,782	6,656
Estimated market value of all machinery and equipment	$1,000	17,904,134	266,135	1,298,695	4,506,978	8,725,995
	percent	100.0	1.5	7.3	25.2	48.7
Land in farms according to use:						
Total cropland	acres	21,544,060	298,147	1,764,427	6,345,068	11,931,591
Harvested cropland	acres	19,662,443	295,712	1,723,520	6,198,921	11,616,068
Pastureland, excluding woodland pastured	acres	1,205,430	5,289	19,494	58,140	148,465
Market value of agricultural products sold	$1,000	28,482,097	2,856,486	7,121,364	14,242,412	21,362,489
Average per farm	dollars	434,635	31,389,956	11,357,838	5,294,577	3,092,875
Grains, oilseeds, dry beans, and dry peas	farms	32,075	41	428	2,275	6,040
	$1,000	15,268,581	262,996	1,504,204	5,539,478	9,941,475
Tobacco	farms	-	-	-	-	-
	$1,000	-	-	-	-	-
Cotton and cottonseed	farms	-	-	-	-	-
	$1,000	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms	2,648	7	65	222	551
	$1,000	446,099	52,236	179,339	262,762	353,754
Fruits, tree nuts, and berries	farms	1,212	-	2	9	25
	$1,000	48,717	-	(D)	7,760	15,885
Fruits and tree nuts	farms	944	-	1	7	18
	$1,000	30,052	-	(D)	(D)	7,761
Berries	farms	489	-	2	5	11
	$1,000	18,665	-	(D)	(D)	8,124
Nursery, greenhouse, floriculture, and sod	farms	1,051	4	15	29	73
	$1,000	391,444	131,431	209,283	250,377	314,380
Cultivated Christmas trees and short rotation woody crops	farms	244	-	1	4	6
	$1,000	7,578	-	(D)	(D)	1,798
Cultivated Christmas trees	farms	243	-	1	4	6
	$1,000	(D)	-	(D)	(D)	1,798
Short rotation woody crops	farms	1	-	-	-	-
	$1,000	(D)	-	-	-	-
Other crops and hay	farms	16,722	12	116	686	1,607
	$1,000	981,348	(D)	121,240	421,149	689,013
Maple syrup	farms	364	-	-	1	2
	$1,000	869	-	-	(D)	(D)
Cattle and calves	farms	14,649	25	186	650	1,814
	$1,000	2,094,135	161,249	571,920	1,071,476	1,526,734
Milk from cows	farms	1,893	17	94	271	746
	$1,000	2,504,638	615,615	1,105,124	1,567,788	2,128,629
Hogs and pigs	farms	3,352	33	231	804	1,641
	$1,000	4,666,832	780,142	1,989,703	3,419,387	4,478,593
Sheep, goats, wool, mohair, and milk	farms	2,604	-	2	26	69
	$1,000	33,457	-	(D)	852	3,351
Horses, ponies, mules, burros, and donkeys	farms	1,247	-	1	3	20
	$1,000	18,147	-	(D)	(D)	111
Poultry and eggs	farms	4,445	26	100	193	359
	$1,000	1,943,207	824,312	1,417,154	1,675,237	1,881,590
Aquaculture	farms	98	-	-	-	-
	$1,000	19,763	-	-	-	-
Other animals and other animal products	farms	1,405	2	16	30	77
	$1,000	58,149	(D)	(D)	24,741	27,177
Value of organically produced commodities	farms	577	2	8	25	70
	$1,000	121,783	(D)	10,402	17,381	56,933
Value of landlords' share of total sales	farms	1,294	4	37	137	377
	$1,000	118,307	2,300	15,943	42,143	75,627
Total farm production expenses	farms	65,531	91	627	2,690	6,907
	$1,000	20,780,603	2,017,965	5,357,941	10,008,664	15,065,623
Selected farm production expenses:						
Fertilizer, lime, and soil conditioners purchased	farms	36,421	49	462	2,331	6,167
	$1,000	2,325,700	40,452	221,849	779,071	1,425,674
Chemicals purchased	farms	37,339	53	476	2,355	6,205
	$1,000	1,161,099	26,931	127,424	403,828	721,376
Livestock and poultry purchased or leased	farms	13,933	62	386	1,224	2,703
	$1,000	1,926,426	229,337	732,372	1,268,116	1,721,501
Feed purchased	farms	26,145	76	469	1,496	3,519
	$1,000	3,890,272	1,007,945	1,881,208	2,748,401	3,498,972
Gasoline, fuels, and oils purchased	farms	61,621	91	625	2,683	6,891
	$1,000	956,802	57,598	171,066	366,665	599,844
Utilities	farms	48,636	91	627	2,690	6,903
	$1,000	400,978	41,258	106,487	171,971	250,972
Hired farm labor	farms	17,399	90	593	2,398	5,736
	$1,000	1,320,974	155,899	491,870	760,184	1,080,984
Interest expense	farms	27,274	72	528	2,308	5,790
	$1,000	702,889	24,126	109,881	270,301	433,290
Government payments	farms	31,583	42	386	1,788	4,627
	$1,000	584,106	9,086	38,545	118,680	249,673
Inventory of selected livestock:						
Cattle and calves	farms	16,823	25	188	664	1,838
	number	2,121,625	187,690	457,950	801,522	1,254,529
Milk cows	farms	2,185	17	93	269	744
	number	459,536	108,131	191,089	273,320	377,665
Hogs and pigs	farms	2,928	33	230	709	1,457
	number	8,873,776	1,722,891	4,176,315	6,296,947	8,358,670

Table 42. **Commodities Raised and Delivered Under Production Contracts: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Commodity	2022		2017	
	Farms	Number	Farms	Number
Broilers and other meat-type chickens	119	41,480,700	214	60,121,600
Eggs, chicken (dozens)	39	51,924,410	25	33,865,703
Layers	36	1,727,454	21	1,008,905
Pullets for laying flock replacement	13	3,754,000	14	5,082,000
Turkeys	60	5,699,214	102	10,482,477
Custom fed cattle shipped directly for slaughter	59	44,297	99	60,537
Hogs and pigs	1,294	12,102,347	1,172	11,152,573
Replacement dairy heifers	122	58,947	172	55,107
Other cattle, sheep, livestock, or poultry	25	(X)	56	(X)
Grains, oilseeds, vegetables, melons, potatoes, and other crops	951	(X)	1,120	(X)
Value of commodities ($1,000)	2,605	3,271,269	2,842	2,402,259
Total payments received ($1,000)	2,605	340,513	2,842	282,496

Table 43. **Value of Land and Buildings: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Value of land and buildings	2022		2017	
	Farms	Value ($1,000)	Farms	Value ($1,000)
Estimated market value of land and buildings	65,531	155,374,449	68,822	123,824,645
Average per farm ....dollars	(X)	2,371,007	(X)	1,799,201
Average per acre ....dollars	(X)	6,107	(X)	4,853
By value group:				
$1 to $49,999	1,819	48,342	3,041	76,641
$50,000 to $99,999	2,318	169,705	3,260	239,528
$100,000 to $199,999	5,817	864,280	8,202	1,212,542
$200,000 to $499,999	17,490	5,802,780	19,305	6,160,821
$500,000 to $999,999	13,050	9,011,795	11,198	7,831,538
$1,000,000 to $1,999,999	8,615	11,984,344	8,858	12,423,871
$2,000,000 to $4,999,999	8,631	27,138,814	8,415	26,528,189
$5,000,000 to $9,999,999	3,992	27,916,231	4,229	29,353,285
$10,000,000 or more	3,799	72,438,158	2,314	39,998,230

Table 44. **Value of Machinery and Equipment on Operation: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Value of machinery and equipment	2022		2017	
	Farms	Value ($1,000)	Farms	Value ($1,000)
Estimated market value of machinery and equipment	65,531	17,904,134	68,788	15,385,551
Average per farm ....dollars	(X)	273,216	(X)	223,666
By value group:				
$1 to $4,999	3,305	9,564	4,441	12,536
$5,000 to $9,999	3,816	26,415	4,382	30,052
$10,000 to $19,999	6,447	88,044	7,585	103,852
$20,000 to $29,999	5,450	127,733	6,334	148,290
$30,000 to $49,999	6,933	260,018	7,589	282,153
$50,000 to $69,999	5,828	326,452	5,747	323,066
$70,000 to $99,999	4,678	378,832	4,827	391,523
$100,000 to $199,999	9,020	1,205,267	8,734	1,168,952
$200,000 to $499,999	9,719	2,959,132	9,982	3,031,054
$500,000 to $999,999	5,346	3,618,414	5,455	3,714,721
$1,000,000 or more	4,989	8,904,263	3,712	6,179,352

Table 45. **Selected Machinery and Equipment on Operation: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Selected machinery and equipment	2022						2017			
	Total		Manufactured 2018 to 2022		Manufactured prior to 2018		Total		Manufactured 2013 to 2017	
	Farms	Number	Farms	Number	Farms	Number	Farms	Number	Farms	Number
Trucks, including pickups	51,156	127,301	13,424	17,745	46,077	109,556	54,590	127,910	13,543	17,341
Tractors	52,770	184,473	7,605	12,615	50,098	171,858	56,422	198,583	8,769	14,490
2 or 3	17,211	41,967	1,820	4,111	16,806	41,063	18,845	46,376	2,456	5,624
4 or more	21,942	128,889	616	3,335	20,353	117,856	24,064	138,694	605	3,158
Less than 40 horsepower (PTO)	22,815	36,863	2,008	2,302	21,180	34,561	25,328	40,957	1,790	2,034
40 to 99 horsepower (PTO)	35,619	60,537	2,626	3,059	33,666	57,478	39,967	70,470	2,684	3,138
100 horsepower (PTO) or more	31,912	87,073	4,117	7,254	30,494	79,819	34,377	87,156	5,664	9,318
Grain and bean combines, self-propelled	21,753	25,736	2,584	2,858	19,502	22,878	24,390	27,944	2,974	3,244
Cotton pickers and strippers, self-propelled	-	-	-	-	-	-	-	-	-	-
Forage harvesters, self-propelled	2,195	2,384	175	191	2,027	2,193	2,854	3,075	249	263
Hay balers	19,296	24,300	1,673	1,791	17,962	22,509	22,933	29,164	2,201	2,326

Table 46. **Fertilizers and Chemicals Applied: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	2022	2017
Any fertilizer, manure, or chemicals used ... farms	40,094	42,180
Any fertilizer or chemical expenses ... farms	40,780	43,318
$1,000	3,486,799	2,172,176
Commercial fertilizer, lime, and soil conditioners used ... farms	34,208	37,969
acres treated	14,076,782	14,641,179
Manure used ... farms	13,721	16,229
acres treated	1,453,615	1,690,674
Organic fertilizer used ... farms	1,053	1,123
acres treated	135,551	139,319
Commercial fertilizer, lime, and soil conditioners expenses ... farms	36,421	40,476
$1,000	2,325,700	1,374,497

Item	2022	2017
Chemical expenses ... farms	37,339	38,474
$1,000	1,161,099	797,679
Acres treated to control-		
Insects ... farms	13,847	18,339
acres	5,229,304	7,867,716
Weeds, grass, or brush ... farms	34,397	34,699
acres	17,661,145	18,000,973
Nematodes ... farms	3,288	2,707
acres	977,113	786,555
Diseases in crops and orchards ... farms	5,080	4,417
acres	2,350,398	2,183,439
Chemicals used to control growth, thin fruit, ripen, or defoliate ... farms	1,762	655
acres on which used	318,341	182,352

Table 47. **Land Use Practices: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Land use practices	2022		2017	
	Farms	Acres	Farms	Acres
Land drained by tile	19,088	8,247,260	21,249	8,079,984
Average per farm	(X)	432	(X)	380
Acres drained:				
1 to 9 acres	1,429	6,185	1,522	6,549
10 to 49 acres	3,392	84,915	3,669	93,222
50 to 99 acres	2,279	158,346	2,550	175,730
100 to 199 acres	2,909	402,834	3,454	478,068
200 to 499 acres	4,222	1,322,127	4,894	1,523,162
500 to 999 acres	2,533	1,733,744	3,027	2,078,694
1,000 to 1,999 acres	1,469	1,986,151	1,607	2,141,243
2,000 acres or more	855	2,552,958	526	1,583,316
Land artificially drained by ditches	9,435	4,560,910	10,845	4,674,449
Average per farm	(X)	483	(X)	431
Acres drained by ditches:				
1 to 9 acres	1,091	4,745	1,121	4,784
10 to 49 acres	2,409	57,911	2,815	65,658
50 to 99 acres	1,128	76,060	1,331	90,128
100 to 199 acres	1,177	159,159	1,450	190,783
200 to 499 acres	1,374	420,936	1,695	525,048
500 to 999 acres	894	625,217	1,031	710,688
1,000 to 1,999 acres	712	1,004,234	832	1,158,735
2,000 acres or more	650	2,212,648	570	1,928,625
Land under conservation easement	4,909	282,171	2,522	218,215
Average per farm	(X)	57	(X)	87
Acres under easement:				
1 to 9 acres	1,209	5,636	528	(D)
10 to 49 acres	2,252	52,483	1,004	24,276
50 to 99 acres	728	49,188	418	28,901
100 to 199 acres	481	64,122	316	43,327
200 to 499 acres	191	53,442	192	57,493
500 to 999 acres	29	19,921	40	27,707
1,000 to 1,999 acres	15	19,234	22	28,537
2,000 acres or more	4	18,145	2	(D)
Cropland on which no-till practices were used	6,845	1,194,987	5,815	1,091,337
Average per farm	(X)	175	(X)	188
No-till practices used:				
1 to 9 acres	1,152	4,400	902	3,685
10 to 49 acres	1,942	51,133	1,557	42,780
50 to 99 acres	1,112	79,359	938	67,847
100 to 199 acres	1,013	138,819	946	131,524
200 to 499 acres	986	301,650	950	291,581
500 to 999 acres	420	293,861	321	219,649
1,000 to 1,999 acres	196	256,643	155	208,595
2,000 acres or more	24	69,122	46	125,676
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	15,574	7,881,385	16,704	8,214,896
Average per farm	(X)	506	(X)	492
Conservation or reduced tillage used (see text):				
1 to 9 acres	1,201	4,975	814	3,335
10 to 49 acres	2,465	64,681	2,168	61,389
50 to 99 acres	1,900	136,089	1,920	139,563
100 to 199 acres	2,298	331,196	2,998	431,480
200 to 499 acres	3,420	1,101,154	3,962	1,264,537
500 to 999 acres	2,004	1,406,015	2,548	1,805,550
1,000 to 1,999 acres	1,334	1,847,821	1,486	2,033,130
2,000 acres or more	952	2,989,454	808	2,475,912
Cropland on which intensive or conventional tillage practices were used (see text)	22,330	9,573,777	22,993	9,499,259
Average per farm	(X)	429	(X)	413
Intensive or conventional tillage used (see text):				
1 to 9 acres	2,060	9,183	2,086	8,841
10 to 49 acres	4,341	107,675	4,204	108,562
50 to 99 acres	2,969	212,683	2,991	215,086
100 to 199 acres	3,531	503,436	3,946	564,690
200 to 499 acres	4,338	1,379,703	4,620	1,464,437
500 to 999 acres	2,497	1,751,643	2,596	1,832,503
1,000 to 1,999 acres	1,568	2,179,770	1,674	2,326,232
2,000 acres or more	1,026	3,429,684	876	2,978,908
Cropland planted to a cover crop (excluding CRP)	6,050	760,423	5,302	579,147
Average per farm	(X)	126	(X)	109
Cover crop acres (excluding CRP):				
1 to 9 acres	1,285	4,823	1,183	4,611
10 to 49 acres	1,981	48,326	2,053	48,509
50 to 99 acres	933	63,769	779	52,846
100 to 199 acres	781	102,351	524	68,657
200 to 499 acres	701	214,430	488	142,880
500 to 999 acres	274	179,695	193	127,312
1,000 to 1,999 acres	77	101,893	64	82,432
2,000 acres or more	18	45,136	18	51,900
Use of precision agriculture practices (see text)	15,460	(X)	(NA)	(X)

Table 48. **Selected Characteristics of Farms by North American Industry Classification System: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

NAICS code (see text)	Farms	Land in farms (acres)	Harvested cropland (acres)	Estimated market value of selected capital assets, average per farm (dollars)		Market value of agricultural products sold ($1,000)		
				Land and buildings	Machinery and equipment	Total	Crops	Livestock, poultry, and their products
Total	65,531	25,442,625	19,662,443	2,371,007	273,216	28,482,097	17,143,767	11,338,329
Crop production (111)	47,434	21,616,513	17,363,576	2,753,917	295,675	16,428,614	15,680,687	747,927
Oilseed and grain farming (1111)	26,315	18,449,252	16,406,107	4,421,589	475,221	15,109,533	14,424,684	684,849
Soybean farming (11111)	5,720	1,938,124	1,496,082	1,756,769	222,090	952,182	941,361	10,821
Oilseed (except soybean) farming (11112)	28	22,090	15,965	2,337,439	246,813	10,507	10,399	108
Dry pea and bean farming (11113)	91	64,051	50,031	3,540,320	513,611	57,873	57,838	35
Wheat farming (11114)	691	530,558	412,739	2,703,346	377,560	223,204	222,564	640
Corn farming (11115)	15,899	11,425,895	10,461,606	5,095,290	517,371	10,268,496	10,087,795	180,700
Rice farming (11116)	-	-	-	-	-	-	-	-
Other grain farming (11119)	3,886	4,468,534	3,969,684	5,928,911	693,475	3,597,271	3,104,726	492,545
Vegetable and melon farming (1112)	1,072	174,341	131,044	1,136,172	138,387	338,324	336,981	1,343
Potato farming (111211)	58	74,884	66,629	6,565,034	1,089,317	209,152	(D)	(D)
Other vegetable (except potato) and melon farming (111219)	1,014	99,457	64,415	825,645	83,994	129,172	(D)	(D)
Fruit and tree nut farming (1113)	972	89,074	7,882	538,040	45,151	41,845	41,208	638
Orange groves (11131)	-	-	-	-	-	-	-	-
Citrus (except orange) groves (11132)	-	-	-	-	-	-	-	-
Noncitrus fruit and tree nut farming (11133)	972	89,074	7,882	538,040	45,151	41,845	41,208	638
Apple orchards (111331)	370	21,390	3,674	494,941	46,424	18,081	17,711	370
Grape vineyards (111332)	258	7,424	1,322	425,613	39,200	4,738	4,706	32
Strawberry farming (111333)	97	3,577	1,274	388,992	66,861	13,371	13,219	152
Berry (except strawberry) farming (111334)	106	(D)	631	1,187,035	32,725	2,851	2,828	23
Tree nut farming (111335)	34	2,694	237	568,927	35,537	218	(D)	(D)
Fruit and tree nut combination farming (111336)	7	(D)	63	191,914	19,583	13	(D)	(D)
Other noncitrus fruit farming (111339)	100	(D)	681	457,936	52,969	2,572	2,513	59
Greenhouse, nursery, and floriculture production (1114)	971	73,678	27,478	721,352	131,089	395,981	395,167	814
Food crops grown under cover (11141)	112	3,419	438	439,247	79,817	43,837	43,818	19
Nursery and floriculture production (11142)	859	70,259	27,040	758,134	137,774	352,144	351,349	795
Nursery and tree production (111421)	526	57,807	23,643	876,580	138,694	215,422	214,778	644
Floriculture production (111422)	333	12,452	3,397	571,039	136,322	136,722	136,572	151
Other crop farming (1119)	18,104	2,830,168	791,065	653,657	66,289	542,930	482,647	60,283
Tobacco farming (11191)	-	-	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-	-	-
Sugarcane farming (11193)	-	-	-	-	-	-	-	-
Hay farming (11194)	6,492	1,022,699	406,051	634,632	74,129	140,430	126,274	14,156
All other crop farming (11199)	11,612	1,807,469	385,014	664,293	61,906	402,500	356,373	46,127
Animal production and aquaculture (112)	18,097	3,826,112	2,298,867	1,367,362	214,349	12,053,483	1,463,080	10,590,402
Cattle ranching and farming (1121)	9,358	2,571,938	1,467,248	1,481,913	241,599	4,752,939	692,449	4,060,490
Beef cattle ranching and farming, including feedlots (11211)	7,645	1,550,640	668,739	993,195	142,506	1,699,407	358,500	1,340,907
Beef cattle ranching and farming (112111)	6,753	1,197,691	405,425	772,458	107,120	614,644	131,623	483,021
Cattle feedlots (112112)	892	352,949	263,314	2,664,308	410,397	1,084,763	226,877	857,886
Dairy cattle and milk production (11212)	1,713	1,021,298	798,509	3,663,027	683,845	3,053,532	333,949	2,719,583
Hog and pig farming (1122)	1,855	682,599	611,116	3,658,976	485,883	4,930,446	605,254	4,325,192
Poultry and egg production (1123)	1,724	166,005	76,977	756,410	170,440	1,975,640	64,795	1,910,846
Chicken egg production (11231)	1,162	53,143	9,995	423,557	92,638	567,225	4,908	562,316
Broilers and other meat-type chicken production (11232)	166	28,009	20,372	1,096,202	218,811	220,789	15,838	204,951
Turkey production (11233)	169	69,815	43,163	3,035,513	736,671	1,113,098	42,384	1,070,714
Poultry hatcheries (11234)	13	414	-	478,695	400,886	57,232	-	57,232
Other poultry production (11239)	214	14,624	3,447	517,208	94,217	17,297	1,664	15,633
Sheep and goat farming (1124)	1,456	59,864	11,232	362,359	55,482	25,104	(D)	(D)
Sheep farming (11241)	820	36,695	6,261	394,983	58,161	13,365	1,521	11,843
Goat farming (11242)	636	23,169	4,971	320,297	52,027	11,740	(D)	(D)
Aquaculture (1125)	81	30,695	(D)	898,288	220,175	19,729	(D)	(D)
Other animal production (1129)	3,623	315,011	(D)	603,260	89,546	349,623	98,329	251,294
Apiculture (11291)	302	9,811	481	249,842	64,487	23,239	143	23,095
Horse and other equine production (11292)	2,388	110,144	20,300	452,747	68,337	17,196	823	16,372
Fur-bearing animal and rabbit production (11293)	11	693	(D)	406,720	31,645	1,178	12	1,167
All other animal production (11299)	922	194,363	111,407	1,111,200	153,375	308,011	97,351	210,660

Table 49. **Renewable Energy: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		2022	2017
Renewable energy producing systems (see text)	farms	4,247	3,591
Solar panels	farms	2,063	1,107
Wind turbines	farms	819	888
Methane digesters	farms	15	9
Renewable energy producing systems (see text) - Con.			
Geothermal/geoexchange systems	farms	1,695	1,822
Small hydro systems	farms	24	11
Wind rights leased to others	farms	1,189	1,202

Table 50. **Institutional, Research, Experimental, and American Indian Reservation Farms: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Characteristics		2022	2017
Farms	number	85	63
Land in farms	acres	106,825	73,031
Average size of farm	acres	1,257	1,159
Estimated market value of land and buildings	$1,000	405,427	323,595
Average per farm	dollars	4,769,728	5,136,422
Average per acre	dollars	3,795	4,431
Estimated market value of all machinery and equipment	$1,000	24,559	26,609
Land in farms according to use:			
Total cropland	farms	39	43
	acres	39,074	54,120
Harvested cropland	farms	36	36
	acres	37,292	48,409
Other pasture and grazing land that could have been used for crops without additional improvements	farms	2	3
	acres	(D)	(D)
Other cropland	farms	10	21
	acres	(D)	(D)
Total woodland	farms	12	12
	acres	(D)	3,547
Woodland pastured	farms	4	2
	acres	122	(D)
Woodland not pastured	farms	11	11
	acres	(D)	(D)
Permanent pasture and rangeland other than cropland and woodland pastured	farms	13	11
	acres	(D)	3,201
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	74	50
	acres	26,886	12,163
Irrigated land	farms	18	17
	acres	22,960	23,466
Market value of agricultural products sold	$1,000	38,141	119,483
Average per farm	dollars	448,715	1,896,555
Market value of agricultural products sold - Con.			
Crops, including nursery and greenhouse crops	$1,000	16,134	(D)
Livestock, poultry, and their products	$1,000	22,007	(D)
Total farm production expenses [1]	$1,000	37,530	107,827
Average per farm	dollars	441,530	1,711,545
Government payments	farms	4	22
	$1,000	304	378
Average per farm	dollars	75,995	17,171
Total income from farm-related sources	farms	11	28
	$1,000	835	1,574
Average per farm	dollars	75,871	56,210
Tenure:			
Full owners		66	48
Part owners		16	12
Tenants		3	3
Farms by North American Industry Classification System:			
Oilseed and grain farming (1111)		19	22
Vegetable and melon farming (1112)		1	1
Fruit and tree nut farming (1113)		3	1
Greenhouse, nursery, and floriculture production (1114)		-	-
Other crop farming (1119)		9	8
Tobacco farming (11191)		-	-
Cotton farming (11192)		-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)		9	8
Beef cattle ranching and farming (112111)		-	1
Cattle feedlots (112112)		-	-
Dairy cattle and milk production (11212)		2	3
Hog and pig farming (1122)		-	-
Poultry and egg production (1123)		-	-
Sheep and goat farming (1124)		1	1
Aquaculture and other animal production (1125, 1129)		50	26

[1] Landlord production expenses are included within total farm production expenses.

Table 51. **Organic Agriculture: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		2022	2017
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES			
Total organic product sales	farms	577	639
	$1,000	121,783	101,325
Average per farm	dollars	211,063	158,568
By value of sales:			
$1 to $4,999	farms	65	116
	$1,000	131	227
$5,000 to $9,999	farms	25	61
	$1,000	159	408
$10,000 to $24,999	farms	64	90
	$1,000	1,012	1,637
$25,000 to $49,999	farms	94	67
	$1,000	3,441	2,306
$50,000 or more	farms	329	305
	$1,000	117,039	96,747
TYPE OF PRODUCTION			
USDA National Organic Program certified organic production	farms	582	647
USDA National Organic Program organic production exempt from certification	farms	55	88
Acres transitioning into USDA National Organic Program organic production	farms	121	167
ALL PRODUCERS' CHARACTERISTICS FOR FARMS WITH CERTIFIED OR EXEMPT ORGANIC PRODUCTION [1]			
Sex of producers:			
Male		816	893
Female		438	511
Primary occupation:			
Farming		800	897
Other		454	507

Item	2022	2017
ALL PRODUCERS' CHARACTERISTICS FOR FARMS WITH CERTIFIED OR EXEMPT ORGANIC PRODUCTION [1] (SEE TEXT) - Con.		
Place of residence:		
On farm operated	927	1,135
Not on farm operated	327	269
Days worked off farm:		
None	572	677
Any	682	727
1 to 49 days	145	160
50 to 99 days	60	75
100 to 199 days	93	118
200 days or more	384	374
Years on present farm:		
2 years or less	58	65
3 or 4 years	113	189
5 to 9 years	276	217
10 years or more	807	933
Average years on present farm	20.6	20.1
Age group:		
Under 25 years	31	45
25 to 34 years	182	203
35 to 44 years	300	255
45 to 54 years	172	263
55 to 64 years	287	365
65 to 74 years	236	219
75 years and over	46	54
Average age	50.7	50.7
Military service:		
Never served or only on active duty for training in Reserves or National Guard (see text)	1,191	1,324
Active duty now or in the past (see text)	63	80

[1] Data were collected for a maximum of four producers per farm.

Table 52. **Selected Producer Characteristics: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
Producers ..... number	114,868	111,760
Sex of producers:		
Male	79,245	77,243
Female	35,623	34,517
Hired managers	6,902	6,449
Primary occupation:		
Farming	51,122	51,657
Other	63,746	60,103
Place of residence:		
On farm operated	79,195	83,850
Not on farm operated	35,673	27,910
Days of work off farm:		
None	46,862	45,391
Any	68,006	66,369
1 to 49 days	9,840	9,133
50 to 99 days	4,745	4,327
100 to 199 days	8,361	8,771
200 days or more	45,060	44,138
Years on present farm:		
2 years or less	4,867	4,695
3 or 4 years	7,650	6,687
5 to 9 years	18,524	13,070
10 years or more	83,827	87,308
Average years on present farm	24.2	24.9
Years operating any farm:		
5 years or less	13,846	11,946
6 to 10 years	15,740	11,401
11 years or more	85,282	88,413
Average years on any farm	26.1	26.7
Age group:		
Under 25 years	1,900	1,418
25 to 34 years	9,374	8,789
35 to 44 years	16,237	13,351
45 to 54 years	16,743	21,142
55 to 64 years	29,818	33,914
65 to 74 years	27,187	22,149
75 years and over	13,609	10,997
Average age	57.1	56.5
Young producers (see text)	11,274	(NA)
Producers of Hispanic, Latino, or Spanish origin	754	651
Producers by race:		
American Indian or Alaska Native	244	180
Asian	306	399
Black or African American	61	39
Native Hawaiian or Other Pacific Islander	43	22
White	113,864	110,824
More than one race reported	350	296
Military service:		
Never served or only on active duty for training in the Reserves or National Guard (see text)	105,603	100,608
Active duty now or in the past (see text)	9,265	11,152
Number of persons living in producers' households	228,210	223,722
On farm involvement in decisionmaking:		
Day-to-day decisions	98,292	97,014
Land use and/or crop decisions	83,860	84,087
Livestock decisions	49,585	54,954
Marketing decisions (see text)	68,020	(NA)
Record keeping and/or financial management	84,043	86,235
Estate planning or succession planning	64,079	65,971

Table 53. **Selected Farm Characteristics by Producers' Involvement in Decisionmaking: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Day-to-day decisions		Land use and/or crop decisions		Livestock decisions	
	2022	2017	2022	2017	2022	2017
FARMS AND LAND IN FARMS						
Farms ..... number	62,481	66,125	55,746	60,525	32,472	38,426
Land in farms ..... acres	24,948,306	25,076,601	23,853,589	24,131,458	10,707,258	11,954,212
FARMS BY SIZE						
1 to 9 acres	4,185	4,941	3,118	3,906	2,736	3,354
10 to 49 acres	14,196	13,742	11,835	11,931	8,252	8,785
50 to 179 acres	17,665	18,499	15,679	16,876	8,571	10,362
180 to 499 acres	13,720	15,530	12,827	14,745	7,187	9,389
500 acres or more	12,715	13,413	12,287	13,067	5,726	6,536
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	58,029	61,089	51,554	55,744	30,821	36,236
acres	12,619,280	13,294,246	11,884,800	12,668,978	5,890,572	6,941,483
Rented or leased land in farms ..... farms	24,758	26,985	23,725	26,075	12,668	15,285
acres	12,329,026	11,782,355	11,968,789	11,462,480	4,816,686	5,012,729
TENURE						
Full owners ..... farms	37,723	39,140	32,021	34,450	19,804	23,141
acres	5,352,366	5,726,377	4,825,884	5,281,793	2,495,188	3,087,087
Part owners ..... farms	20,306	21,949	19,533	21,294	11,017	13,095
acres	17,705,156	17,338,172	17,184,894	16,897,882	7,599,674	8,194,810
Tenants ..... farms	4,452	5,036	4,192	4,781	1,651	2,190
acres	1,890,784	2,012,052	1,842,811	1,951,783	612,396	672,315
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	62,481	66,125	55,746	60,525	32,472	38,426
$1,000	28,710,900	18,617,449	26,252,387	17,219,907	16,249,045	11,345,784
Market value of agricultural products sold ..... farms	62,481	66,125	55,746	60,525	32,472	38,426
$1,000	28,143,585	18,236,682	25,721,478	16,859,033	16,017,535	11,185,708
Crops, including nursery and greenhouse crops ..... farms	42,645	45,763	40,359	43,896	20,790	25,535
$1,000	16,951,910	10,079,154	16,492,478	9,789,668	6,223,748	4,103,005
Livestock, poultry, and their products ..... farms	22,428	25,731	19,928	23,605	20,103	23,775
$1,000	11,191,675	8,157,528	9,229,001	7,069,364	9,793,786	7,082,703
Government payments ..... farms	29,575	39,257	26,612	36,561	12,906	19,046
$1,000	567,315	380,767	530,909	360,875	231,510	160,077
FARMS BY ECONOMIC CLASS						
Less than $1,000	5,760	7,204	4,706	6,185	3,804	5,283
$1,000 to $2,499	5,485	5,708	4,379	4,772	2,514	2,923
$2,500 to $4,999	5,176	5,812	4,346	5,085	2,560	3,251
$5,000 to $9,999	5,694	6,153	4,821	5,448	3,011	3,621
$10,000 to $24,999	6,664	7,059	5,879	6,357	3,808	4,320
$25,000 to $49,999	4,627	5,179	4,147	4,854	2,535	2,969
$50,000 or more	29,075	29,010	27,468	27,824	14,240	16,059
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS						
CCC loans ..... farms	978	2,751	943	2,680	460	1,345
$1,000	196,439	410,839	190,692	400,007	77,816	175,906
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	17,241	18,342	14,779	16,335	5,639	7,257
$1,000	114,067	98,731	97,935	87,223	33,252	35,404
Other Federal farm program payments ..... farms	16,624	32,052	15,861	30,499	9,057	16,406
$1,000	453,248	282,036	432,974	273,652	198,259	124,673
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	25,569	26,352	24,540	25,518	9,302	11,038
Vegetable and melon farming (1112)	1,037	1,248	985	1,216	404	595
Fruit and tree nut farming (1113)	959	706	897	681	361	262
Greenhouse, nursery, and floriculture production (1114)	948	839	879	762	246	250
Other crop farming (1119)	16,196	16,369	13,518	14,180	6,166	7,030
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	16,196	16,369	13,518	14,180	6,166	7,030
Beef cattle ranching and farming (112111)	6,597	8,449	5,730	7,502	6,293	8,172
Cattle feedlots (112112)	875	1,302	774	1,204	860	1,266
Dairy cattle and milk production (11212)	1,700	2,795	1,656	2,731	1,667	2,741
Hog and pig farming (1122)	1,836	1,618	1,399	1,344	1,472	1,359
Poultry and egg production (1123)	1,697	1,060	1,246	821	1,330	833
Sheep and goat farming (1124)	1,429	1,476	1,169	1,214	1,360	1,411
Aquaculture and other animal production (1125, 1129)	3,638	3,911	2,953	3,352	3,011	3,469
OTHER FARM CHARACTERISTICS						
Farms by-						
Type of organization:						
Operation more than 50 percent owned by one producer's household and/or extended family	59,338	63,788	52,985	58,435	31,109	37,347
Limited Liability Company	4,627	3,025	4,119	2,785	2,522	1,787
Operation's legal status for tax purposes:						
Family or individual	53,105	57,118	47,259	52,224	28,197	33,925

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Table 53. **Selected Farm Characteristics by Producers' Involvement in Decisionmaking: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Item	Marketing decisions (see text)		Record keeping and financial management		Estate or succession planning	
	2022	2017	2022	2017	2022	2017
FARMS AND LAND IN FARMS						
Farms ..... number	45,960	(NA)	57,329	62,492	41,043	45,498
Land in farms ..... acres	21,980,256	(NA)	23,937,371	24,171,789	18,701,450	18,660,268
FARMS BY SIZE						
1 to 9 acres	2,848	(NA)	3,690	4,481	2,210	2,835
10 to 49 acres	8,544	(NA)	12,302	12,729	8,224	8,933
50 to 179 acres	11,706	(NA)	16,101	17,371	11,443	12,468
180 to 499 acres	11,123	(NA)	12,922	14,854	9,459	11,013
500 acres or more	11,739	(NA)	12,314	13,057	9,707	10,249
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	42,025	(NA)	53,105	57,725	38,699	42,797
acres	10,490,483	(NA)	11,986,191	12,737,681	9,512,540	9,970,266
Rented or leased land in farms ..... farms	22,493	(NA)	23,729	26,047	16,988	18,804
acres	11,489,773	(NA)	11,951,180	11,434,108	9,188,910	8,690,002
TENURE						
Full owners ..... farms	23,467	(NA)	33,600	36,445	24,055	26,694
acres	3,712,214	(NA)	4,952,312	5,386,807	3,823,627	4,137,249
Part owners ..... farms	18,558	(NA)	19,505	21,280	14,644	16,103
acres	16,483,192	(NA)	17,148,559	16,849,547	13,648,265	13,227,942
Tenants ..... farms	3,935	(NA)	4,224	4,767	2,344	2,701
acres	1,784,850	(NA)	1,836,500	1,935,435	1,229,558	1,295,077
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	45,960	(NA)	57,329	62,492	41,043	45,498
$1,000	25,245,502	(NA)	27,257,788	17,916,670	21,832,246	13,947,910
Market value of agricultural products sold ..... farms	45,960	(NA)	57,329	62,492	41,043	45,498
$1,000	24,776,123	(NA)	26,716,782	17,548,897	21,421,351	13,658,456
Crops, including nursery and greenhouse crops ..... farms	35,876	(NA)	39,893	43,456	28,819	31,783
$1,000	15,684,351	(NA)	16,453,507	9,769,339	13,016,542	7,689,230
Livestock, poultry, and their products ..... farms	18,967	(NA)	21,032	24,741	15,362	18,113
$1,000	9,091,773	(NA)	10,263,275	7,779,558	8,404,809	5,969,226
Government payments ..... farms	20,777	(NA)	27,624	37,596	20,619	28,193
$1,000	469,378	(NA)	541,006	367,773	410,895	289,454
FARMS BY ECONOMIC CLASS						
Less than $1,000	3,104	(NA)	4,726	6,353	3,360	4,551
$1,000 to $2,499	2,479	(NA)	4,657	5,234	3,156	3,667
$2,500 to $4,999	2,724	(NA)	4,517	5,412	3,124	3,849
$5,000 to $9,999	3,340	(NA)	5,088	5,799	3,491	4,178
$10,000 to $24,999	4,556	(NA)	6,124	6,671	4,189	4,799
$25,000 to $49,999	3,506	(NA)	4,248	4,909	2,956	3,415
$50,000 or more	26,251	(NA)	27,969	28,114	20,767	21,039
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS						
CCC loans ..... farms	921	(NA)	961	2,678	749	2,061
$1,000	186,291	(NA)	191,829	399,148	157,029	328,602
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	9,634	(NA)	15,834	17,416	12,102	13,433
$1,000	60,833	(NA)	105,750	94,373	82,700	73,660
Other Federal farm program payments ..... farms	14,735	(NA)	15,865	30,889	11,752	23,054
$1,000	408,545	(NA)	435,256	273,400	328,195	215,794
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	22,750	(NA)	24,367	25,222	17,655	18,386
Vegetable and melon farming (1112)	851	(NA)	961	1,178	577	827
Fruit and tree nut farming (1113)	738	(NA)	880	669	592	410
Greenhouse, nursery, and floriculture production (1114)	774	(NA)	903	789	533	513
Other crop farming (1119)	7,211	(NA)	14,143	15,110	10,337	11,347
Tobacco farming (11191)	-	(NA)	-	-	-	-
Cotton farming (11192)	-	(NA)	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	7,211	(NA)	14,143	15,110	10,337	11,347
Beef cattle ranching and farming (112111)	5,260	(NA)	6,088	8,059	4,235	5,692
Cattle feedlots (112112)	804	(NA)	842	1,261	654	938
Dairy cattle and milk production (11212)	1,570	(NA)	1,643	2,737	1,284	2,026
Hog and pig farming (1122)	1,438	(NA)	1,708	1,548	1,276	1,158
Poultry and egg production (1123)	1,084	(NA)	1,403	949	950	647
Sheep and goat farming (1124)	1,123	(NA)	1,317	1,373	829	882
Aquaculture and other animal production (1125, 1129)	2,357	(NA)	3,074	3,597	2,121	2,672
OTHER FARM CHARACTERISTICS						
Farms by-						
Type of organization:						
Operation more than 50 percent owned by one producer's household and/or extended family	43,772	(NA)	54,335	60,268	39,056	43,977
Limited Liability Company	3,666	(NA)	4,396	2,921	3,014	2,095
Operation's legal status for tax purposes:						
Family or individual	38,804	(NA)	48,237	53,763	34,458	38,890

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Table 53. **Selected Farm Characteristics by Producers' Involvement in Decisionmaking: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Day-to-day decisions		Land use and/or crop decisions		Livestock decisions	
	2022	2017	2022	2017	2022	2017
OTHER FARM CHARACTERISTICS - Con.						
Farms by- - Con.						
Operation's legal status for tax purposes: - Con.						
Partnership	4,741	4,378	4,369	4,088	2,212	2,283
Corporation	3,642	3,418	3,303	3,156	1,700	1,726
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	993	1,211	815	1,057	363	492
Number of producers:						
1 producer	26,800	32,248	23,672	29,513	12,885	17,792
2 producers	27,826	28,315	24,796	25,801	15,543	17,368
3 producers	4,277	3,485	4,000	3,299	2,324	2,127
4 producers	2,349	1,455	2,183	1,350	1,238	812
5 or more producers	1,229	622	1,095	562	482	327
Number of male producers:						
1 producer	47,792	53,583	42,314	48,911	25,293	31,425
2 producers	8,237	7,081	7,814	6,758	4,120	3,947
3 producers	2,496	1,665	2,342	1,573	1,209	907
4 producers	700	331	646	297	294	152
5 or more producers	423	175	364	158	123	87
Number of female producers:						
1 producer	28,605	29,299	25,232	26,492	16,379	18,393
2 producers	2,222	1,604	1,980	1,494	1,214	973
3 producers	413	260	353	209	218	125
4 producers	128	95	107	73	39	40
5 or more producers	76	35	70	32	22	22
Farms reporting-						
Internet access	51,937	52,578	46,769	48,558	27,273	30,956
Dial-up	1,791	2,066	1,606	1,892	981	1,263
Broadband (DSL, cable, fiber optic) (see text)	32,132	(NA)	29,115	(NA)	16,515	(NA)
Cellular data plan (see text)	31,127	19,654	28,514	18,416	16,435	11,705
Satellite	8,181	8,192	7,342	7,571	4,514	5,136
Don't know	2,682	4,596	2,352	4,221	1,288	2,770
Other	335	1,201	307	1,102	188	593
Farms by number of households sharing in net income of operation:						
1 household	50,044	54,281	44,499	49,509	26,717	32,033
2 households	8,609	8,747	7,853	8,206	4,175	4,914
3 households	2,168	1,775	1,973	1,660	951	888
4 households	903	765	765	659	344	327
5 or more households	757	557	656	491	285	264

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Table 53. **Selected Farm Characteristics by Producers' Involvement in Decisionmaking: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Item	Marketing decisions (see text)		Record keeping and financial management		Estate or succession planning	
	2022	2017	2022	2017	2022	2017
OTHER FARM CHARACTERISTICS - Con.						
Farms by- - Con.						
Operation's legal status for tax purposes: - Con.						
Partnership	3,671	(NA)	4,582	4,236	3,166	3,041
Corporation	2,993	(NA)	3,553	3,319	2,672	2,568
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	492	(NA)	957	1,174	747	999
Number of producers:						
1 producer	19,736	(NA)	24,024	29,989	16,749	21,981
2 producers	20,193	(NA)	25,638	27,018	18,565	19,486
3 producers	3,467	(NA)	4,196	3,430	3,143	2,506
4 producers	1,771	(NA)	2,300	1,434	1,758	1,089
5 or more producers	793	(NA)	1,171	621	828	436
Number of male producers:						
1 producer	34,969	(NA)	43,394	50,412	31,037	36,739
2 producers	6,730	(NA)	7,931	6,827	5,660	4,918
3 producers	2,005	(NA)	2,399	1,633	1,849	1,190
4 producers	474	(NA)	675	332	490	221
5 or more producers	235	(NA)	379	173	225	100
Number of female producers:						
1 producer	20,243	(NA)	26,448	27,976	19,427	20,479
2 producers	1,557	(NA)	2,173	1,613	1,603	1,211
3 producers	283	(NA)	410	258	308	192
4 producers	74	(NA)	130	90	92	61
5 or more producers	43	(NA)	71	45	56	24
Farms reporting-						
Internet access	39,625	(NA)	48,232	50,110	34,538	36,346
Dial-up	1,360	(NA)	1,657	1,951	1,220	1,468
Broadband (DSL, cable, fiber optic) (see text)	24,598	(NA)	30,083	(NA)	21,352	(NA)
Cellular data plan (see text)	24,585	(NA)	29,287	18,965	21,141	13,843
Satellite	6,445	(NA)	7,595	7,827	5,689	5,892
Don't know	1,879	(NA)	2,386	4,340	1,654	3,071
Other	271	(NA)	308	1,128	249	830
Farms by number of households sharing in net income of operation:						
1 household	36,727	(NA)	45,649	51,086	32,827	37,219
2 households	6,652	(NA)	7,980	8,342	5,761	6,097
3 households	1,613	(NA)	2,086	1,772	1,433	1,277
4 households	567	(NA)	888	742	558	511
5 or more households	401	(NA)	726	550	464	394

Table 54. **Involvement in Decisionmaking by Selected Producer Characteristics: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Day-to-day decisions		Land use and/or crop decisions		Livestock decisions	
	2022	2017	2022	2017	2022	2017
Producers ..... number	98,292	97,014	83,860	84,087	49,585	54,954
Sex of producers:						
Male	71,699	71,479	64,945	66,029	35,528	40,315
Female	26,593	25,535	18,915	18,058	14,057	14,639
Hired managers	6,235	5,754	5,295	4,860	2,896	2,918
Primary occupation:						
Farming	47,511	48,165	42,014	43,274	24,255	27,498
Other	50,781	48,849	41,846	40,813	25,330	27,456
Place of residence:						
On farm operated	71,196	75,282	59,925	64,577	40,921	46,913
Not on farm operated	27,096	21,732	23,935	19,510	8,664	8,041
Days of work off farm:						
None	40,702	40,473	34,279	35,195	19,289	21,899
Any	57,590	56,541	49,581	48,892	30,296	33,055
1 to 49 days	8,432	7,969	7,317	6,920	3,685	3,984
50 to 99 days	4,198	3,823	3,614	3,364	2,044	2,154
100 to 199 days	7,346	7,606	6,264	6,543	3,931	4,661
200 days or more	37,614	37,143	32,386	32,065	20,636	22,256
Years on present farm:						
2 years or less	3,790	3,853	3,129	3,329	1,939	2,346
3 or 4 years	6,335	5,658	5,455	4,878	3,363	3,454
5 to 9 years	15,643	11,029	13,632	9,737	8,666	6,490
10 years or more	72,524	76,474	61,644	66,143	35,617	42,664
Years operating any farm:						
5 years or less	11,054	9,960	9,415	8,527	5,847	5,917
6 to 10 years	13,341	9,561	11,513	8,361	7,311	5,626
11 years or more	73,897	77,493	62,932	67,199	36,427	43,411
Age group:						
Under 25 years	1,444	1,076	1,184	934	1,044	894
25 to 34 years	8,062	7,675	7,189	6,738	4,755	4,890
35 to 44 years	14,163	11,793	12,480	10,382	8,185	7,495
45 to 54 years	14,602	18,531	12,461	16,006	7,953	11,186
55 to 64 years	25,797	29,573	21,757	25,675	13,010	16,586
65 to 74 years	23,147	19,132	19,774	16,538	10,601	9,831
75 years and over	11,077	9,234	9,015	7,814	4,037	4,072
Average age	56.9	56.4	56.6	56.2	54.8	54.8
Young producers (see text)	9,506	(NA)	8,373	(NA)	5,799	(NA)
Producers of Hispanic, Latino, or Spanish origin	623	566	507	474	324	331
Producers by race:						
American Indian or Alaska Native	226	151	186	147	125	102
Asian	251	334	210	296	65	152
Black or African American	53	33	37	31	21	9
Native Hawaiian or Other Pacific Islander	31	18	20	12	14	13
White	97,438	96,222	83,161	83,362	49,208	54,509
More than one race reported	293	256	246	239	152	169
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	90,204	86,962	76,802	74,977	45,861	49,484
Active duty now or in the past (see text)	8,088	10,052	7,058	9,110	3,724	5,470
Number of persons living in producers' households	204,418	204,743	183,725	186,304	105,287	119,127

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Table 54. **Involvement in Decisionmaking by Selected Producer Characteristics: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Item	Marketing decisions (see text)		Record keeping and financial management		Estate or succession planning	
	2022	2017	2022	2017	2022	2017
Producers ..... number	68,020	(NA)	84,043	86,235	64,079	65,971
Sex of producers:						
Male	51,932	(NA)	58,938	61,005	44,084	46,191
Female	16,088	(NA)	25,105	25,230	19,995	19,780
Hired managers	4,955	(NA)	5,131	4,937	4,125	3,943
Primary occupation:						
Farming	37,922	(NA)	40,999	42,509	32,064	33,240
Other	30,098	(NA)	43,044	43,726	32,015	32,731
Place of residence:						
On farm operated	51,485	(NA)	61,005	67,084	47,958	52,402
Not on farm operated	16,535	(NA)	23,038	19,151	16,121	13,569
Days of work off farm:						
None	28,745	(NA)	34,595	35,516	28,360	28,829
Any	39,275	(NA)	49,448	50,719	35,719	37,142
1 to 49 days	5,714	(NA)	7,234	7,065	5,505	5,157
50 to 99 days	3,002	(NA)	3,544	3,444	2,650	2,631
100 to 199 days	5,366	(NA)	6,347	6,910	4,622	5,248
200 days or more	25,193	(NA)	32,323	33,300	22,942	24,106
Years on present farm:						
2 years or less	2,278	(NA)	2,982	3,283	1,849	1,941
3 or 4 years	4,314	(NA)	5,238	4,810	3,178	2,993
5 to 9 years	10,892	(NA)	13,080	9,768	8,627	6,341
10 years or more	50,536	(NA)	62,743	68,374	50,425	54,696
Years operating any farm:						
5 years or less	7,166	(NA)	8,987	8,488	5,469	5,019
6 to 10 years	9,119	(NA)	11,149	8,415	7,344	5,539
11 years or more	51,735	(NA)	63,907	69,332	51,266	55,413
Age group:						
Under 25 years	950	(NA)	838	758	425	390
25 to 34 years	6,292	(NA)	6,746	6,707	4,071	4,028
35 to 44 years	10,724	(NA)	12,243	10,516	8,182	6,417
45 to 54 years	10,152	(NA)	12,505	16,455	8,461	12,017
55 to 64 years	17,545	(NA)	22,156	26,535	17,308	21,105
65 to 74 years	15,710	(NA)	20,097	17,098	17,047	14,765
75 years and over	6,647	(NA)	9,458	8,166	8,585	7,249
Average age	56.0	(NA)	57.1	56.5	59.0	58.3
Young producers (see text)	7,242	(NA)	7,584	(NA)	4,496	(NA)
Producers of Hispanic, Latino, or Spanish origin	375	(NA)	470	456	347	362
Producers by race:						
American Indian or Alaska Native	138	(NA)	182	130	130	111
Asian	144	(NA)	181	260	120	196
Black or African American	34	(NA)	41	27	31	21
Native Hawaiian or Other Pacific Islander	23	(NA)	16	14	18	13
White	67,471	(NA)	83,387	85,569	63,593	65,450
More than one race reported	210	(NA)	236	235	187	180
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	62,799	(NA)	77,389	77,649	58,505	58,779
Active duty now or in the past (see text)	5,221	(NA)	6,654	8,586	5,574	7,192
Number of persons living in producers' households	148,588	(NA)	173,513	179,281	127,016	131,766

Table 55. **Selected Farm Characteristics - Farms with Male Producers: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
FARMS AND LAND IN FARMS		
Farms ..... number	62,332	65,159
Land in farms ..... acres	25,033,191	25,044,003
FARMS BY SIZE		
1 to 9 acres	3,985	4,823
10 to 49 acres	14,017	13,190
50 to 179 acres	17,824	18,264
180 to 499 acres	13,774	15,469
500 acres or more	12,732	13,413
OWNED AND RENTED LAND IN FARMS		
Owned land in farms ..... farms	57,892	60,248
acres	12,674,383	13,254,566
Rented or leased land in farms ..... farms	24,708	26,747
acres	12,358,808	11,789,437
TENURE		
Full owners ..... farms	37,624	38,412
acres	5,386,834	5,686,435
Part owners ..... farms	20,268	21,836
acres	17,761,659	17,355,006
Tenants ..... farms	4,440	4,911
acres	1,884,698	2,002,562
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS		
Total ..... farms	62,332	65,159
$1,000	28,737,552	18,560,471
Market value of agricultural products sold ..... farms	62,332	65,159
$1,000	28,166,412	18,177,728
Crops, including nursery and greenhouse crops ..... farms	42,512	45,192
$1,000	17,004,526	10,090,624
Livestock, poultry, and their products ..... farms	21,948	25,058
$1,000	11,161,886	8,087,104
Government payments ..... farms	30,133	39,377
$1,000	571,141	382,744
FARMS BY ECONOMIC CLASS		
Less than $1,000	5,492	6,676
$1,000 to $2,499	5,514	5,692
$2,500 to $4,999	5,236	5,741
$5,000 to $9,999	5,676	6,082
$10,000 to $24,999	6,708	6,949
$25,000 to $49,999	4,580	5,122
$50,000 or more	29,126	28,897
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS		
CCC loans ..... farms	976	2,754
$1,000	194,590	413,433
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	17,845	18,577
$1,000	118,316	99,827
Other Federal farm program payments ..... farms	16,632	32,069
$1,000	452,825	282,917
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)		
Oilseed and grain farming (1111)	25,748	26,322
Vegetable and melon farming (1112)	992	1,132
Fruit and tree nut farming (1113)	922	672

Characteristics	2022	2017
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS) - Con.		
Greenhouse, nursery, and floriculture production (1114)	895	792
Other crop farming (1119)	16,684	16,537
Tobacco farming (11191)	-	-
Cotton farming (11192)	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	16,684	16,537
Beef cattle ranching and farming (112111)	6,483	8,252
Cattle feedlots (112112)	873	1,304
Dairy cattle and milk production (11212)	1,684	2,781
Hog and pig farming (1122)	1,833	1,607
Poultry and egg production (1123)	1,629	990
Sheep and goat farming (1124)	1,322	1,310
Aquaculture and other animal production (1125, 1129)	3,267	3,460
OTHER FARM CHARACTERISTICS		
Farms by-		
Type of organization:		
Operation more than 50 percent owned by one producer's household and/or extended family	59,055	62,761
Limited Liability Company	4,571	2,938
Operation's legal status for tax purposes:		
Family or individual	52,707	56,064
Partnership	4,902	4,425
Corporation	3,703	3,444
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	1,020	1,226
Number of producers:		
1 producer	25,523	30,588
2 producers	28,579	28,849
3 producers	4,429	3,554
4 producers	2,488	1,504
5 or more producers	1,313	664
Number of male producers:		
1 producer	49,913	55,574
2 producers	8,598	7,301
3 producers	2,596	1,743
4 producers	766	344
5 or more producers	459	197
Number of female producers:		
1 producer	27,111	(NA)
2 producers	2,087	(NA)
3 producers	415	(NA)
4 producers	119	(NA)
5 or more producers	73	(NA)
Farms reporting-		
Internet access	51,554	51,777
Dial-up	1,783	2,023
Broadband (DSL, cable, fiber optic) (see text)	32,016	(NA)
Cellular data plan (see text)	30,681	19,179
Satellite	8,037	8,050
Don't know	2,705	4,546
Other	327	1,190
Farms by number of households sharing in net income of operation:		
1 household	49,427	53,038
2 households	8,808	8,876
3 households	2,267	1,855
4 households	1,003	783
5 or more households	827	607

Table 56. **Male Producers - Selected Producer Characteristics: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
Producers ..... number	79,245	77,243
Hired managers	5,298	4,675
Primary occupation:		
Farming	39,670	40,475
Other	39,575	36,768
Place of residence:		
On farm operated	52,544	56,281
Not on farm operated	26,701	20,962
Days of work off farm:		
None	32,824	32,901
Any	46,421	44,342
1 to 49 days	7,122	6,503
50 to 99 days	3,284	2,923
100 to 199 days	5,398	5,416
200 days or more	30,617	29,500
Years on present farm:		
2 years or less	3,101	3,000
3 or 4 years	4,985	4,385
5 to 9 years	12,436	8,712
10 years or more	58,723	61,146
Years operating any farm:		
5 years or less	8,843	7,642
6 to 10 years	10,413	7,585
11 years or more	59,989	62,016
Age group:		
Under 25 years	1,423	1,007
25 to 34 years	6,581	6,156
35 to 44 years	11,261	9,256
45 to 54 years	11,594	14,313
Age group - Con.		
55 to 64 years	20,162	23,088
65 to 74 years	18,832	15,601
75 years and over	9,392	7,822
Average age	57.0	56.5
Young producers (see text)	8,004	(NA)
Producers of Hispanic, Latino, or Spanish origin	496	436
Producers by race:		
American Indian or Alaska Native	151	117
Asian	133	178
Black or African American	31	21
Native Hawaiian or Other Pacific Islander	21	9
White	78,683	76,732
More than one race reported	226	186
Military service:		
Never served or only on active duty for training in the Reserves or National Guard (see text)	70,435	66,464
Active duty now or in the past (see text)	8,810	10,779
Number of persons living in producers' households	197,823	195,289
On farm involvement in decisionmaking:		
Day-to-day decisions	71,699	71,479
Land use and/or crop decisions	64,945	66,029
Livestock decisions	35,528	40,315
Marketing decisions (see text)	51,932	(NA)
Record keeping and/or financial management	58,938	61,005
Estate planning or succession planning	44,084	46,191

Table 57. **Selected Farm Characteristics - Farms with Female Producers: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics		2022	2017
FARMS AND LAND IN FARMS			
Farms	number	32,729	32,384
Land in farms	acres	9,634,361	9,747,291
FARMS BY SIZE			
1 to 9 acres		2,729	2,743
10 to 49 acres		9,314	8,494
50 to 179 acres		9,801	9,316
180 to 499 acres		6,139	6,722
500 acres or more		4,746	5,109
OWNED AND RENTED LAND IN FARMS			
Owned land in farms	farms	31,204	30,841
	acres	5,407,386	5,617,353
Rented or leased land in farms	farms	9,997	10,768
	acres	4,226,975	4,129,938
TENURE			
Full owners	farms	22,732	21,616
	acres	2,661,853	2,691,056
Part owners	farms	8,472	9,225
	acres	6,381,901	6,484,491
Tenants	farms	1,525	1,543
	acres	590,607	571,744
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS			
Total	farms	32,729	32,384
	$1,000	11,017,353	6,970,806
Market value of agricultural products sold	farms	32,729	32,384
	$1,000	10,785,939	6,812,185
Crops, including nursery and greenhouse crops	farms	19,669	20,032
	$1,000	5,991,419	3,659,637
Livestock, poultry, and their products	farms	12,954	13,793
	$1,000	4,794,520	3,152,548
Government payments	farms	14,627	17,654
	$1,000	231,414	158,621
FARMS BY ECONOMIC CLASS			
Less than $1,000		3,842	4,507
$1,000 to $2,499		3,673	3,404
$2,500 to $4,999		3,333	3,365
$5,000 to $9,999		3,527	3,509
$10,000 to $24,999		3,984	3,657
$25,000 to $49,999		2,526	2,298
$50,000 or more		11,844	11,644
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS			
CCC loans	farms	366	1,042
	$1,000	79,415	162,452
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments	farms	9,345	9,327
	$1,000	63,736	47,974
Other Federal farm program payments	farms	7,077	13,638
	$1,000	167,678	110,647
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)			
Oilseed and grain farming (1111)		9,856	9,851
Vegetable and melon farming (1112)		680	736
Fruit and tree nut farming (1113)		711	492
Greenhouse, nursery, and floriculture production (1114)		647	512
Other crop farming (1119)		9,589	8,892
Tobacco farming (11191)		-	-
Cotton farming (11192)		-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)		9,589	8,892
Beef cattle ranching and farming (112111)		3,897	4,643
Cattle feedlots (112112)		406	539
Dairy cattle and milk production (11212)		948	1,449
Hog and pig farming (1122)		826	725
Poultry and egg production (1123)		1,307	647
Sheep and goat farming (1124)		1,093	1,088
Aquaculture and other animal production (1125, 1129)		2,769	2,810
OTHER FARM CHARACTERISTICS			
Farms by-			
Type of organization:			
Operation more than 50 percent owned by one producer's household and/or extended family		31,493	31,477
Limited Liability Company		2,621	1,595
Operation's legal status for tax purposes:			
Family or individual		28,347	28,248
Partnership		1,967	1,730
Corporation		1,757	1,647
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.		658	759
Number of producers:			
1 producer		2,825	3,305
2 producers		23,994	24,677
3 producers		3,024	2,607
4 producers		2,070	1,325
5 or more producers		816	470
Number of female producers:			
1 producer		29,809	30,295
2 producers		2,322	1,692
3 producers		426	270
4 producers		109	96
5 or more producers		63	31
Number of male producers:			
1 producer		24,396	(NA)
2 producers		3,728	(NA)
3 producers		1,139	(NA)
4 producers		166	(NA)
5 or more producers		109	(NA)
Farms reporting-			
Internet access		27,849	26,785
Dial-up		944	1,000
Broadband (DSL, cable, fiber optic) (see text)		17,618	(NA)
Cellular data plan (see text)		16,633	9,993
Satellite		4,410	4,258
Don't know		1,307	2,130
Other		192	611
Farms by number of households sharing in net income of operation:			
1 household		26,631	26,918
2 households		4,256	4,063
3 households		985	811
4 households		466	334
5 or more households		391	258

Table 58. **Female Producers - Selected Producer Characteristics: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
Producers ..... number	35,623	34,517
Hired managers	1,604	1,774
Primary occupation:		
Farming	11,452	11,182
Other	24,171	23,335
Place of residence:		
On farm operated	26,651	27,569
Not on farm operated	8,972	6,948
Days of work off farm:		
None	14,038	12,490
Any	21,585	22,027
1 to 49 days	2,718	2,630
50 to 99 days	1,461	1,404
100 to 199 days	2,963	3,355
200 days or more	14,443	14,638
Years on present farm:		
2 years or less	1,766	1,695
3 or 4 years	2,665	2,302
5 to 9 years	6,088	4,358
10 years or more	25,104	26,162
Years operating any farm:		
5 years or less	5,003	4,304
6 to 10 years	5,327	3,816
11 years or more	25,293	26,397
Age group:		
Under 25 years	477	411
25 to 34 years	2,793	2,633
35 to 44 years	4,976	4,095
45 to 54 years	5,149	6,829
Age group - Con.		
55 to 64 years	9,656	10,826
65 to 74 years	8,355	6,548
75 years and over	4,217	3,175
Average age	57.3	56.3
Young producers (see text)	3,270	(NA)
Producers of Hispanic, Latino, or Spanish origin	258	215
Producers by race:		
American Indian or Alaska Native	93	63
Asian	173	221
Black or African American	30	18
Native Hawaiian or Other Pacific Islander	22	13
White	35,181	34,092
More than one race reported	124	110
Military service:		
Never served or only on active duty for training in the Reserves or National Guard (see text)	35,168	34,144
Active duty now or in the past (see text)	455	373
Number of persons living in producers' households	30,387	28,433
On farm involvement in decisionmaking:		
Day-to-day decisions	26,593	25,535
Land use and/or crop decisions	18,915	18,058
Livestock decisions	14,057	14,639
Marketing decisions (see text)	16,088	(NA)
Record keeping and/or financial management	25,105	25,230
Estate planning or succession planning	19,995	19,780

Table 59. **Selected Farm Characteristics - Farms with Hispanic, Latino, or Spanish Origin Producers: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
FARMS AND LAND IN FARMS		
Farms ..... number	607	583
Land in farms ..... acres	287,887	268,129
FARMS BY SIZE		
1 to 9 acres	61	62
10 to 49 acres	176	133
50 to 179 acres	160	130
180 to 499 acres	76	125
500 acres or more	134	133
OWNED AND RENTED LAND IN FARMS		
Owned land in farms ..... farms	565	538
acres	136,389	122,287
Rented or leased land in farms ..... farms	214	246
acres	151,498	145,842
TENURE		
Full owners ..... farms	393	337
acres	44,395	41,793
Part owners ..... farms	172	201
acres	230,786	199,900
Tenants ..... farms	42	45
acres	12,706	26,436
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS		
Total ..... farms	607	583
$1,000	365,745	215,054
Market value of agricultural products sold ..... farms	607	583
$1,000	359,285	211,819
Crops, including nursery and greenhouse crops ..... farms	371	422
$1,000	210,944	136,354
Livestock, poultry, and their products ..... farms	254	240
$1,000	148,341	75,465
Government payments ..... farms	276	335
$1,000	6,460	3,235
FARMS BY ECONOMIC CLASS		
Less than $1,000	65	76
$1,000 to $2,499	87	57
$2,500 to $4,999	65	38
$5,000 to $9,999	28	75
$10,000 to $24,999	85	57
$25,000 to $49,999	37	26
$50,000 or more	240	254
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS		
CCC loans ..... farms	13	35
$1,000	7,323	9,973
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	170	147
$1,000	1,032	746
Other Federal farm program payments ..... farms	146	286
$1,000	5,428	2,489
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)		
Oilseed and grain farming (1111)	194	191
Vegetable and melon farming (1112)	16	15
Fruit and tree nut farming (1113)	13	12
Greenhouse, nursery, and floriculture production (1114)	8	13

Characteristics	2022	2017
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS) - Con.		
Other crop farming (1119)	170	153
Tobacco farming (11191)	-	-
Cotton farming (11192)	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	170	153
Beef cattle ranching and farming (112111)	41	64
Cattle feedlots (112112).....	6	5
Dairy cattle and milk production (11212)	21	50
Hog and pig farming (1122)	35	14
Poultry and egg production (1123)	50	25
Sheep and goat farming (1124)	27	1
Aquaculture and other animal production (1125, 1129)	26	40
OTHER FARM CHARACTERISTICS		
Farms by-		
Type of organization:		
Operation more than 50 percent owned by one producer's household and/or extended family	565	569
Limited Liability Company	90	52
Operation's legal status for tax purposes:		
Family or individual	503	476
Partnership	59	58
Corporation	33	39
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	12	10
Number of producers:		
1 producer	139	219
2 producers	299	277
3 producers	53	66
4 producers	73	16
5 or more producers	43	5
Number of male producers:		
1 producer	394	436
2 producers	100	84
3 producers	36	27
4 producers	31	4
5 or more producers	23	1
Number of female producers:		
1 producer	310	294
2 producers	66	25
3 producers	8	2
4 producers	5	1
5 or more producers	2	-
Farms reporting-		
Internet access	491	458
Dial-up	15	16
Broadband (DSL, cable, fiber optic) (see text)	321	(NA)
Cellular data plan (see text)	277	150
Satellite	72	104
Don't know	29	49
Other	12	9
Farms by number of households sharing in net income of operation:		
1 household	442	465
2 households	90	80
3 households	29	30
4 households	35	4
5 or more households	11	4

Table 60. **Hispanic, Latino, or Spanish Origin Producers - Selected Producer Characteristics: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
Producers ..... number	754	651
Sex of producers:		
Male	496	436
Female	258	215
Hired managers	68	57
Primary occupation:		
Farming	317	319
Other	437	332
Place of residence:		
On farm operated	473	503
Not on farm operated	281	148
Days of work off farm:		
None	269	280
Any	485	371
1 to 49 days	66	50
50 to 99 days	42	22
100 to 199 days	58	42
200 days or more	319	257
Years on present farm:		
2 years or less	50	42
3 or 4 years	98	42
5 to 9 years	132	64
10 years or more	474	503
Years operating any farm:		
5 years or less	161	84
6 to 10 years	103	55
11 years or more	490	512

Characteristics	2022	2017
Age group:		
Under 25 years	37	21
25 to 34 years	46	49
35 to 44 years	182	99
45 to 54 years	148	119
55 to 64 years	164	206
65 to 74 years	110	109
75 years and over	67	48
Average age	52.1	54.3
Young producers (see text)	83	(NA)
Producers by race:		
American Indian or Alaska Native	18	8
Asian	5	-
Black or African American	7	10
Native Hawaiian or Other Pacific Islander	6	4
White	703	625
More than one race reported	15	4
Military service:		
Never served or only on active duty for training in the Reserves or National Guard (see text)	685	549
Active duty now or in the past (see text)	69	102
Number of persons living in producers' households	1,596	1,292
On farm involvement in decisionmaking:		
Day-to-day decisions	623	566
Land use and/or crop decisions	507	474
Livestock decisions	324	331
Marketing decisions (see text)	375	(NA)
Record keeping and/or financial management	470	456
Estate planning or succession planning	347	362

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Table 61. **Selected Farm Characteristics by Race: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	All farms		Any producer reporting race as -					
			American Indian or Alaska Native only		Asian only		Black or African American only	
	2022	2017	2022	2017	2022	2017	2022	2017
FARMS AND LAND IN FARMS								
Farms ..... number	65,531	68,822	207	151	240	311	46	35
Land in farms ..... acres	25,442,625	25,516,982	117,541	76,848	40,554	35,235	5,943	3,166
FARMS BY SIZE								
1 to 9 acres	4,401	5,234	12	4	68	139	6	8
10 to 49 acres	15,218	14,618	66	48	76	83	14	5
50 to 179 acres	18,844	19,456	67	50	54	56	18	20
180 to 499 acres	14,183	15,923	29	20	28	19	6	1
500 acres or more	12,885	(NA)	33	29	14	14	2	1
OWNED AND RENTED LAND IN FARMS								
Owned land in farms ..... farms	60,960	63,700	197	147	174	165	37	30
acres	13,006,137	13,626,270	104,397	68,314	20,769	18,606	3,026	2,474
Rented or leased land in farms ..... farms	25,135	27,345	42	20	101	188	15	10
acres	12,436,488	11,890,712	13,144	8,534	19,785	16,629	2,917	692
TENURE								
Full owners ..... farms	40,396	41,477	165	131	139	123	31	25
acres	5,657,674	5,981,683	97,910	62,597	11,542	10,485	2,061	1,977
Part owners ..... farms	20,564	22,223	32	16	35	42	6	5
acres	17,880,717	17,512,421	17,891	9,471	26,206	22,498	2,798	1,012
Tenants ..... farms	4,571	5,122	10	4	66	146	9	5
acres	1,904,234	2,022,878	1,740	4,780	2,806	2,252	1,084	177
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS								
Total ..... farms	65,531	68,822	207	151	240	311	46	35
$1,000	29,066,202	18,789,881	24,241	14,450	38,562	60,681	5,414	6,353
Market value of agricultural products sold ..... farms	65,531	68,822	207	151	240	311	46	35
$1,000	28,482,097	18,395,390	23,512	13,781	37,145	60,105	5,214	6,292
Crops, including nursery and greenhouse crops ..... farms	43,821	46,722	126	88	178	262	34	19
$1,000	17,143,767	10,191,518	20,667	8,386	28,622	19,913	3,164	6,223
Livestock, poultry, and their products ..... farms	22,770	26,062	71	64	56	70	17	8
$1,000	11,338,329	8,203,872	2,845	5,394	8,523	40,191	2,050	70
Government payments ..... farms	31,583	41,230	65	54	64	82	13	13
$1,000	584,106	394,491	729	670	1,417	577	200	61
FARMS BY ECONOMIC CLASS								
Less than $1,000	6,079	7,503	40	26	22	60	6	10
$1,000 to $2,499	6,033	6,259	33	20	13	34	4	4
$2,500 to $4,999	5,681	6,284	29	15	32	40	6	-
$5,000 to $9,999	6,141	6,565	17	22	33	32	8	4
$10,000 to $24,999	7,125	7,422	34	21	42	51	4	7
$25,000 to $49,999	4,813	5,363	10	15	27	34	5	2
$50,000 or more	29,659	(NA)	44	32	71	60	13	8
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS								
CCC loans ..... farms	990	2,777	1	1	1	11	-	-
$1,000	197,241	414,580	(D)	(D)	(D)	1,619	-	-
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	19,069	19,972	39	35	40	34	2	5
$1,000	126,510	107,308	249	147	221	220	(D)	16
Other Federal farm program payments ..... farms	16,968	33,153	32	37	30	71	11	9
$1,000	457,596	287,183	480	523	1,197	357	(D)	44
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)								
Oilseed and grain farming (1111)	26,315	26,958	27	30	32	37	10	6
Vegetable and melon farming (1112)	1,072	1,258	10	18	70	160	1	9
Fruit and tree nut farming (1113)	972	732	7	2	12	17	-	1
Greenhouse, nursery, and floriculture production (1114)	971	855	4	7	28	13	4	2
Other crop farming (1119)	18,104	18,088	97	42	52	35	20	14
Tobacco farming (11191)	-	-	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	18,104	18,088	97	42	52	35	20	14
Beef cattle ranching and farming (112111)	6,753	8,636	17	26	14	23	3	2
Cattle feedlots (112112)	892	1,312	2	-	-	-	-	-
Dairy cattle and milk production (11212)	1,713	2,808	-	-	3	2	-	-
Hog and pig farming (1122)	1,855	1,636	1	2	6	5	-	-
Poultry and egg production (1123)	1,724	1,068	19	6	9	2	2	-
Sheep and goat farming (1124)	1,456	1,486	7	11	6	6	3	1
Aquaculture and other animal production (1125, 1129)	3,704	3,985	16	7	8	11	3	-
OTHER FARM CHARACTERISTICS								
Farms by-								
Type of organization:								
Operation more than 50 percent owned by one producer's household and/or extended family	62,111	66,299	188	134	233	292	46	33
Limited Liability Company	4,803	3,147	35	7	26	22	18	3

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Table 61. **Selected Farm Characteristics by Race: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Any producer reporting race as - con.				Any producer reporting more than one race	
	Native Hawaiian or Other Pacific Islander only		White only			
	2022	2017	2022	2017	2022	2017
FARMS AND LAND IN FARMS						
Farms ..... number	39	22	65,219	68,436	305	270
Land in farms ..... acres	9,191	2,884	25,312,777	25,436,544	162,218	78,020
FARMS BY SIZE						
1 to 9 acres	1	6	4,323	5,090	50	5
10 to 49 acres	20	6	15,124	14,530	79	72
50 to 179 acres	8	2	18,783	19,356	78	117
180 to 499 acres	5	8	14,139	15,899	45	46
500 acres or more	5	-	12,850	13,561	53	30
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	38	22	60,717	63,458	280	264
acres	4,505	2,884	12,907,107	13,559,543	105,506	55,613
Rented or leased land in farms ..... farms	10	-	24,997	27,142	115	86
acres	4,686	-	12,405,670	11,877,001	56,712	22,407
TENURE						
Full owners ..... farms	29	22	40,222	41,294	190	184
acres	(D)	2,884	5,571,902	5,927,606	69,438	30,181
Part owners ..... farms	9	-	20,495	22,164	90	80
acres	6,849	-	17,838,787	17,489,432	90,375	46,847
Tenants ..... farms	1	-	4,502	4,978	25	6
acres	(D)	-	1,902,088	2,019,506	2,405	992
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	39	22	65,219	68,436	305	270
$1,000	6,992	732	29,021,808	18,765,992	93,516	32,236
Market value of agricultural products sold ..... farms	39	22	65,219	68,436	305	270
$1,000	6,815	678	28,439,262	18,372,561	89,414	30,869
Crops, including nursery and greenhouse crops ..... farms	31	16	43,593	46,416	194	172
$1,000	6,659	645	17,104,415	10,174,812	83,106	23,497
Livestock, poultry, and their products ..... farms	14	5	22,700	25,982	103	111
$1,000	156	32	11,334,847	8,197,749	6,308	7,372
Government payments ..... farms	19	8	31,501	41,119	131	118
$1,000	177	54	582,546	393,430	4,102	1,367
FARMS BY ECONOMIC CLASS						
Less than $1,000	6	3	6,042	7,431	37	34
$1,000 to $2,499	9	8	5,997	6,213	42	17
$2,500 to $4,999	2	-	5,644	6,226	31	50
$5,000 to $9,999	5	2	6,096	6,518	34	41
$10,000 to $24,999	1	2	7,092	7,368	31	32
$25,000 to $49,999	2	3	4,785	5,316	25	20
$50,000 or more	14	4	29,563	29,364	105	76
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS						
CCC loans ..... farms	1	2	990	2,773	-	8
$1,000	(D)	(D)	197,241	414,422	-	232
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	11	7	19,019	19,918	78	51
$1,000	37	14	126,238	106,954	469	332
Other Federal farm program payments ..... farms	10	6	16,928	33,067	77	93
$1,000	141	40	456,309	286,476	3,633	1,035
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	11	10	26,258	26,904	72	58
Vegetable and melon farming (1112)	1	-	1,005	1,089	13	16
Fruit and tree nut farming (1113)	-	1	960	730	5	4
Greenhouse, nursery, and floriculture production (1114)	1	-	951	837	16	8
Other crop farming (1119)	17	10	18,007	18,008	110	95
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	17	10	18,007	18,008	110	95
Beef cattle ranching and farming (112111)	3	-	6,739	8,611	28	42
Cattle feedlots (112112)	-	-	891	1,312	1	2
Dairy cattle and milk production (11212)	-	-	1,711	2,808	4	6
Hog and pig farming (1122)	-	-	1,855	1,630	-	5
Poultry and egg production (1123)	6	-	1,707	1,061	25	8
Sheep and goat farming (1124)	-	-	1,446	1,468	8	14
Aquaculture and other animal production (1125, 1129)	-	1	3,689	3,978	23	12
OTHER FARM CHARACTERISTICS						
Farms by-						
Type of organization:						
Operation more than 50 percent owned by one producer's household and/or extended family	37	21	61,813	65,936	292	258
Limited Liability Company	6	2	4,759	3,124	44	12

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Table 61. **Selected Farm Characteristics by Race: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	All farms		Any producer reporting race as -					
			American Indian or Alaska Native only		Asian only		Black or African American only	
	2022	2017	2022	2017	2022	2017	2022	2017
OTHER FARM CHARACTERISTICS - Con.								
Farms by- - Con.								
Operation's legal status for tax purposes:								
Family or individual	55,532	59,322	170	113	200	272	37	27
Partnership	5,022	4,566	10	5	11	21	9	2
Corporation	3,803	3,549	11	11	28	12	-	2
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	1,174	1,385	16	22	1	6	-	4
Number of producers:								
1 producer	28,348	33,893	54	41	60	135	16	13
2 producers	28,866	29,111	114	91	132	141	23	17
3 producers	4,480	3,627	20	9	10	22	2	2
4 producers	2,500	1,513	14	6	16	8	5	1
5 or more producers	1,337	678	5	4	22	5	-	2
Number of male producers:								
1 producer	49,919	55,583	154	114	180	210	35	26
2 producers	8,600	7,302	23	17	24	22	6	3
3 producers	2,596	1,743	8	7	10	5	-	-
4 producers	766	344	7	-	8	-	-	2
5 or more producers	459	197	3	1	2	3	-	-
Number of female producers:								
1 producer	29,936	30,333	141	103	160	212	28	17
2 producers	2,374	1,715	7	5	16	16	3	3
3 producers	466	283	2	1	12	4	1	2
4 producers	138	103	-	2	-	-	1	-
5 or more producers	90	47	-	-	3	3	-	-
Farms reporting-								
Internet access	53,964	54,361	158	123	175	197	31	21
Dial-up	1,876	2,132	8	6	4	-	-	-
Broadband (DSL, cable, fiber optic) (see text)	33,399	(NA)	102	(NA)	93	(NA)	16	(NA)
Cellular data plan (see text)	32,121	20,213	107	49	100	74	22	9
Satellite	8,385	8,416	33	21	24	27	4	1
Don't know	2,877	4,775	3	7	19	22	3	1
Other	346	1,247	-	2	-	17	-	-
Farms by number of households sharing in net income of operation:								
1 household	52,287	56,324	148	121	198	249	41	27
2 households	9,039	9,114	36	25	24	50	3	8
3 households	2,321	1,929	9	1	10	6	2	-
4 households	1,024	822	12	3	6	-	-	-
5 or more households	860	633	2	1	2	6	-	-

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Table 61. **Selected Farm Characteristics by Race: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Any producer reporting race as - con.				Any producer reporting more than one race	
	Native Hawaiian or Other Pacific Islander only		White only			
	2022	2017	2022	2017	2022	2017
OTHER FARM CHARACTERISTICS - Con.						
Farms by- - Con.						
Operation's legal status for tax purposes:						
Family or individual	35	20	55,261	58,987	259	236
Partnership	1	1	5,010	4,541	9	15
Corporation	3	1	3,786	3,542	28	13
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	-	-	1,162	1,366	9	6
Number of producers:						
1 producer	1	7	28,133	33,613	84	84
2 producers	29	15	28,794	29,031	157	151
3 producers	5	-	4,463	3,612	26	22
4 producers	4	-	2,495	1,508	23	8
5 or more producers	-	-	1,334	672	15	5
Number of male producers:						
1 producer	26	22	49,668	55,320	208	209
2 producers	11	-	8,589	7,285	57	39
3 producers	2	-	2,595	1,737	12	5
4 producers	-	-	765	344	7	-
5 or more producers	-	-	458	196	3	-
Number of female producers:						
1 producer	31	15	29,812	30,167	175	167
2 producers	1	-	2,365	1,700	29	11
3 producers	1	-	461	278	2	2
4 producers	-	-	137	101	1	4
5 or more producers	-	-	90	47	2	-
Farms reporting-						
Internet access	34	14	53,754	54,135	255	209
Dial-up	2	-	1,870	2,128	6	8
Broadband (DSL, cable, fiber optic) (see text)	19	(NA)	33,287	(NA)	157	(NA)
Cellular data plan (see text)	14	5	32,002	20,143	163	55
Satellite	3	1	8,349	8,389	50	26
Don't know	6	1	2,852	4,753	12	13
Other	-	-	345	1,233	1	5
Farms by number of households sharing in net income of operation:						
1 household	32	20	52,000	56,010	249	232
2 households	6	2	9,016	9,060	32	32
3 households	-	-	2,320	1,920	20	5
4 households	1	-	1,024	821	2	-
5 or more households	-	-	859	625	2	1

Table 62. **Selected Producer Characteristics by Race: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	All producers		All producers reporting race as -					
			American Indian or Alaska Native only		Asian only		Black or African American only	
	2022	2017	2022	2017	2022	2017	2022	2017
Producers ..... number	114,868	111,760	244	180	306	399	61	39
Sex of producers:								
Male	79,245	77,243	151	117	133	178	31	21
Female	35,623	34,517	93	63	173	221	30	18
Hired managers	6,902	6,449	9	14	14	8	3	3
Primary occupation:								
Farming	51,122	51,657	65	50	134	150	30	19
Other	63,746	60,103	179	130	172	249	31	20
Place of residence:								
On farm operated	79,195	83,850	162	126	169	173	41	24
Not on farm operated	35,673	27,910	82	54	137	226	20	15
Days of work off farm:								
None	46,862	45,391	64	44	103	76	29	17
Any	68,006	66,369	180	136	203	323	32	22
1 to 49 days	9,840	9,133	26	20	27	31	1	7
50 to 99 days	4,745	4,327	11	8	38	94	-	2
100 to 199 days	8,361	8,771	23	16	24	78	15	1
200 days or more	45,060	44,138	120	92	114	120	16	12
Years on present farm:								
2 years or less	4,867	4,695	12	3	42	65	4	11
3 or 4 years	7,650	6,687	38	11	32	79	12	6
5 to 9 years	18,524	13,070	43	15	73	107	24	11
10 years or more	83,827	87,308	151	151	159	148	21	11
Years operating any farm:								
5 years or less	13,846	11,946	55	9	79	143	16	20
6 to 10 years	15,740	11,401	37	12	71	77	18	6
11 years or more	85,282	88,413	152	159	156	179	27	13
Age group:								
Under 25 years	1,900	1,418	-	-	5	16	-	1
25 to 34 years	9,374	8,789	20	4	45	58	17	10
35 to 44 years	16,237	13,351	39	9	68	76	23	6
45 to 54 years	16,743	21,142	51	42	43	93	3	9
55 to 64 years	29,818	33,914	67	78	89	101	8	4
65 to 74 years	27,187	22,149	48	41	51	49	4	8
75 years and over	13,609	10,997	19	6	5	6	6	1
Average age	57.1	56.5	55.2	58.3	50.2	49.0	45.7	48.7
Young producers (see text)	11,274	(NA)	20	(NA)	50	(NA)	17	(NA)
Producers of Hispanic, Latino, or Spanish origin	754	651	18	8	5	-	7	10
Military service:								
Never served or only on active duty for training in the Reserves or National Guard (see text)	105,603	100,608	208	160	303	386	52	29
Active duty now or in the past (see text)	9,265	11,152	36	20	3	13	9	10
Number of persons living in producers' households	228,210	223,722	536	404	570	1,047	115	73
On farm involvement in decisionmaking:								
Day-to-day decisions	98,292	97,014	226	151	251	334	53	33
Land use and/or crop decisions	83,860	84,087	186	147	210	296	37	31
Livestock decisions	49,585	54,954	125	102	65	152	21	9
Marketing decisions (see text)	68,020	(NA)	138	(NA)	144	(NA)	34	(NA)
Record keeping and/or financial management	84,043	86,235	182	130	181	260	41	27
Estate planning or succession planning	64,079	65,971	130	111	120	196	31	21

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Table 62. **Selected Producer Characteristics by Race: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	All producers reporting race as - con.				All producers reporting more than one race	
	Native Hawaiian or Other Pacific Islander only		White only			
	2022	2017	2022	2017	2022	2017
Producers ..... number	43	22	113,864	110,824	350	296
Sex of producers:						
Male	21	9	78,683	76,732	226	186
Female	22	13	35,181	34,092	124	110
Hired managers	4	-	6,853	6,419	19	5
Primary occupation:						
Farming	15	6	50,753	51,313	125	119
Other	28	16	63,111	59,511	225	177
Place of residence:						
On farm operated	26	15	78,550	83,284	247	228
Not on farm operated	17	7	35,314	27,540	103	68
Days of work off farm:						
None	14	8	46,548	45,149	104	97
Any	29	14	67,316	65,675	246	199
1 to 49 days	5	4	9,746	9,039	35	32
50 to 99 days	-	-	4,680	4,214	16	9
100 to 199 days	7	1	8,253	8,647	39	28
200 days or more	17	9	44,637	43,775	156	130
Years on present farm:						
2 years or less	-	-	4,785	4,600	24	16
3 or 4 years	10	1	7,506	6,561	52	29
5 to 9 years	12	3	18,310	12,874	62	60
10 years or more	21	18	83,263	86,789	212	191
Years operating any farm:						
5 years or less	21	3	13,608	11,724	67	47
6 to 10 years	4	1	15,541	11,258	69	47
11 years or more	18	18	84,715	87,842	214	202
Age group:						
Under 25 years	4	-	1,869	1,391	22	10
25 to 34 years	3	9	9,251	8,672	38	36
35 to 44 years	4	3	16,034	13,200	69	57
45 to 54 years	17	1	16,567	20,957	62	40
55 to 64 years	11	3	29,569	33,644	74	84
65 to 74 years	4	3	27,020	22,003	60	45
75 years and over	-	3	13,554	10,957	25	24
Average age	48.7	49.9	57.1	56.5	51.1	52.7
Young producers (see text)	7	(NA)	11,120	(NA)	60	(NA)
Producers of Hispanic, Latino, or Spanish origin	6	4	703	625	15	4
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	43	22	104,686	99,746	311	265
Active duty now or in the past (see text)	-	-	9,178	11,078	39	31
Number of persons living in producers' households	53	19	226,235	221,558	701	621
On farm involvement in decisionmaking:						
Day-to-day decisions	31	18	97,438	96,222	293	256
Land use and/or crop decisions	20	12	83,161	83,362	246	239
Livestock decisions	14	13	49,208	54,509	152	169
Marketing decisions (see text)	23	(NA)	67,471	(NA)	210	(NA)
Record keeping and/or financial management	16	14	83,387	85,569	236	235
Estate planning or succession planning	18	13	63,593	65,450	187	180

Table 63. **Selected Farm Characteristics by Race and Ethnicity: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Any producer reporting race as -					
	American Indian or Alaska Native alone or in combination with other races		Asian alone or in combination with other races		Black or African American alone or in combination with other races	
	2022	2017	2022	2017	2022	2017
FARMS AND LAND IN FARMS						
Farms ..... number	401	357	294	336	75	55
Land in farms ..... acres	208,783	135,515	48,965	41,340	17,555	13,091
FARMS BY SIZE						
1 to 9 acres	34	7	82	139	7	8
10 to 49 acres	106	107	97	84	21	15
50 to 179 acres	125	137	62	70	28	25
180 to 499 acres	64	58	33	23	12	2
500 acres or more	72	48	20	20	7	5
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	377	347	226	190	66	50
acres	150,348	106,305	25,182	24,457	10,792	12,179
Rented or leased land in farms ..... farms	127	89	114	194	22	17
acres	58,435	29,210	23,783	16,883	6,763	912
TENURE						
Full owners ..... farms	274	268	180	142	53	38
acres	113,255	77,260	13,056	15,677	4,554	11,043
Part owners ..... farms	103	79	46	48	13	12
acres	91,609	52,483	33,073	23,411	11,917	1,871
Tenants ..... farms	24	10	68	146	9	5
acres	3,919	5,772	2,836	2,252	1,084	177
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	401	357	294	336	75	55
$1,000	100,281	39,600	43,478	65,081	12,290	6,763
Market value of agricultural products sold ..... farms	401	357	294	336	75	55
$1,000	96,187	37,984	41,802	64,340	11,468	6,505
Crops, including nursery and greenhouse crops ..... farms	251	223	208	281	56	30
$1,000	88,707	25,842	32,138	23,951	9,171	6,290
Livestock, poultry, and their products ..... farms	136	159	76	76	23	14
$1,000	7,480	12,142	9,664	40,389	2,297	215
Government payments ..... farms	155	136	84	102	27	20
$1,000	4,094	1,616	1,676	741	822	258
FARMS BY ECONOMIC CLASS						
Less than $1,000	66	51	28	60	10	14
$1,000 to $2,499	46	35	24	34	9	7
$2,500 to $4,999	48	51	44	48	7	3
$5,000 to $9,999	42	57	36	32	13	6
$10,000 to $24,999	59	47	46	53	7	9
$25,000 to $49,999	26	27	29	36	6	6
$50,000 or more	114	89	87	73	23	10
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS						
CCC loans ..... farms	1	7	1	11	-	-
$1,000	(D)	217	(D)	1,619	-	-
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	91	67	52	40	11	11
$1,000	627	352	272	235	37	110
Other Federal farm program payments ..... farms	90	104	40	88	18	12
$1,000	3,467	1,264	1,404	506	784	149
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	84	76	38	46	21	9
Vegetable and melon farming (1112)	15	28	76	166	3	9
Fruit and tree nut farming (1113)	10	6	12	17	-	1
Greenhouse, nursery, and floriculture production (1114)	12	12	29	14	5	2
Other crop farming (1119)	168	115	69	38	30	24
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	168	115	69	38	30	24
Beef cattle ranching and farming (112111)	32	59	22	27	5	4
Cattle feedlots (112112)	3	-	-	2	-	-
Dairy cattle and milk production (11212)	2	6	5	2	-	-
Hog and pig farming (1122)	1	7	6	5	-	-
Poultry and egg production (1123)	30	12	15	2	4	3
Sheep and goat farming (1124)	15	19	6	6	3	1
Aquaculture and other animal production (1125, 1129)	29	17	16	11	4	2
OTHER FARM CHARACTERISTICS						
Farms by-						
Type of organization:						
Operation more than 50 percent owned by one producer's household and/or extended family	376	337	285	311	72	52
Limited Liability Company	55	17	44	22	19	3

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Table 63. **Selected Farm Characteristics by Race and Ethnicity: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Any producer reporting race as - con.				Any producer reporting ethnicity as Hispanic, Latino, or Spanish origin	
	Native Hawaiian or Other Pacific Islander alone or in combination with other races		White alone or in combination with other races			
	2022	2017	2022	2017	2022	2017
FARMS AND LAND IN FARMS						
Farms ..... number	67	36	65,324	68,544	607	583
Land in farms ..... acres	18,211	5,351	25,396,498	25,470,260	287,887	268,129
FARMS BY SIZE						
1 to 9 acres	9	6	4,339	5,092	61	62
10 to 49 acres	28	13	15,157	14,563	176	133
50 to 179 acres	15	6	18,805	19,403	160	130
180 to 499 acres	7	10	14,156	15,913	76	125
500 acres or more	8	1	12,867	13,573	134	133
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	57	36	60,808	63,564	565	538
acres	10,777	(D)	12,969,505	13,584,054	136,389	122,287
Rented or leased land in farms ..... farms	23	3	25,046	27,176	214	246
acres	7,434	(D)	12,426,993	11,886,206	151,498	145,842
TENURE						
Full owners ..... farms	44	33	40,278	41,368	393	337
acres	7,464	3,581	5,623,916	5,942,292	44,395	41,793
Part owners ..... farms	13	3	20,530	22,196	172	201
acres	10,536	1,770	17,869,952	17,508,442	230,786	199,900
Tenants ..... farms	10	-	4,516	4,980	42	45
acres	211	-	1,902,630	2,019,526	12,706	26,436
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	67	36	65,324	68,544	607	583
$1,000	9,906	2,110	29,045,173	18,775,335	365,745	215,054
Market value of agricultural products sold ..... farms	67	36	65,324	68,544	607	583
$1,000	9,566	1,997	28,461,506	18,381,376	359,285	211,819
Crops, including nursery and greenhouse crops ..... farms	44	19	43,661	46,482	371	422
$1,000	8,994	1,589	17,125,384	10,179,732	210,944	136,354
Livestock, poultry, and their products ..... farms	22	10	22,740	26,025	254	240
$1,000	572	409	11,336,123	8,201,644	148,341	75,465
Government payments ..... farms	34	18	31,541	41,163	276	335
$1,000	340	112	583,666	393,959	6,460	3,235
FARMS BY ECONOMIC CLASS						
Less than $1,000	7	4	6,051	7,449	65	76
$1,000 to $2,499	19	9	6,011	6,218	87	57
$2,500 to $4,999	3	4	5,656	6,252	65	38
$5,000 to $9,999	7	5	6,114	6,544	28	75
$10,000 to $24,999	3	4	7,102	7,370	85	57
$25,000 to $49,999	9	3	4,792	5,328	37	26
$50,000 or more	19	7	29,598	29,383	240	254
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS						
CCC loans ..... farms	1	4	990	2,777	13	35
$1,000	(D)	104	197,241	414,580	7,323	9,973
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	23	15	19,046	19,943	170	147
$1,000	71	32	126,441	107,188	1,032	746
Other Federal farm program payments ..... farms	14	13	16,946	33,100	146	286
$1,000	270	80	457,225	286,771	5,428	2,489
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	14	11	26,284	26,921	194	191
Vegetable and melon farming (1112)	1	-	1,007	1,089	16	15
Fruit and tree nut farming (1113)	1	1	962	732	13	12
Greenhouse, nursery, and floriculture production (1114)	2	-	956	841	8	13
Other crop farming (1119)	34	18	18,041	18,058	170	153
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	34	18	18,041	18,058	170	153
Beef cattle ranching and farming (112111)	7	3	6,747	8,620	41	64
Cattle feedlots (112112)	-	-	891	1,312	6	5
Dairy cattle and milk production (11212)	-	-	1,713	2,808	21	50
Hog and pig farming (1122)	-	-	1,855	1,635	35	14
Poultry and egg production (1123)	6	-	1,719	1,066	50	25
Sheep and goat farming (1124)	-	-	1,452	1,482	27	1
Aquaculture and other animal production (1125, 1129)	2	3	3,697	3,980	26	40
OTHER FARM CHARACTERISTICS						
Farms by-						
Type of organization:						
Operation more than 50 percent owned by one producer's household and/or extended family	64	33	61,913	66,042	565	569
Limited Liability Company	6	2	4,772	3,132	90	52

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Table 63. **Selected Farm Characteristics by Race and Ethnicity: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Any producer reporting race as -					
	American Indian or Alaska Native alone or in combination with other races		Asian alone or in combination with other races		Black or African American alone or in combination with other races	
	2022	2017	2022	2017	2022	2017
OTHER FARM CHARACTERISTICS - Con.						
Farms by- - Con.						
Operation's legal status for tax purposes:						
Family or individual	333	298	251	290	61	44
Partnership	19	11	11	27	9	4
Corporation	30	21	30	13	2	2
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	19	27	2	6	3	5
Number of producers:						
1 producer	121	110	66	137	23	25
2 producers	209	208	171	155	38	24
3 producers	33	20	14	31	3	2
4 producers	31	12	20	8	8	2
5 or more producers	7	7	23	5	3	2
Number of male producers:						
1 producer	297	283	220	222	53	41
2 producers	58	38	36	33	10	7
3 producers	10	8	10	7	3	-
4 producers	7	-	8	-	-	2
5 or more producers	4	1	2	3	-	-
Number of female producers:						
1 producer	252	236	198	225	49	22
2 producers	26	12	22	18	4	4
3 producers	3	3	12	4	1	2
4 producers	-	4	1	-	2	-
5 or more producers	-	-	3	3	2	-
Farms reporting-						
Internet access	322	282	218	215	58	34
Dial-up	12	14	4	-	2	-
Broadband (DSL, cable, fiber optic) (see text)	209	(NA)	123	(NA)	31	(NA)
Cellular data plan (see text)	213	82	129	83	35	13
Satellite	60	44	27	29	15	4
Don't know	7	17	20	22	5	3
Other	1	5	-	19	-	-
Farms by number of households sharing in net income of operation:						
1 household	308	303	248	268	63	46
2 households	56	45	28	54	8	9
3 households	21	4	10	8	2	-
4 households	14	3	6	-	1	-
5 or more households	2	2	2	6	1	-

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Table 63. **Selected Farm Characteristics by Race and Ethnicity: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	Any producer reporting race as - con.				Any producer reporting ethnicity as Hispanic, Latino, or Spanish origin	
	Native Hawaiian or Other Pacific Islander alone or in combination with other races		White alone or in combination with other races			
	2022	2017	2022	2017	2022	2017
OTHER FARM CHARACTERISTICS - Con.						
Farms by- - Con.						
Operation's legal status for tax purposes:						
Family or individual	62	32	55,353	59,084	503	476
Partnership	1	3	5,011	4,547	59	58
Corporation	3	1	3,792	3,544	33	39
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	1	-	1,168	1,369	12	10
Number of producers:						
1 producer	7	10	28,215	33,696	139	219
2 producers	39	25	28,806	29,050	299	277
3 producers	14	1	4,471	3,615	53	66
4 producers	4	-	2,495	1,508	73	16
5 or more producers	3	-	1,337	675	43	5
Number of male producers:						
1 producer	34	34	49,750	55,406	394	436
2 producers	21	-	8,597	7,288	100	84
3 producers	9	1	2,595	1,740	36	27
4 producers	-	-	766	344	31	4
5 or more producers	1	-	459	196	23	1
Number of female producers:						
1 producer	35	26	29,842	30,200	310	294
2 producers	4	-	2,368	1,702	66	25
3 producers	1	-	462	279	8	2
4 producers	1	-	137	103	5	1
5 or more producers	1	-	90	47	2	-
Farms reporting-						
Internet access	53	25	53,835	54,210	491	458
Dial-up	2	-	1,872	2,132	15	16
Broadband (DSL, cable, fiber optic) (see text)	24	(NA)	33,332	(NA)	321	(NA)
Cellular data plan (see text)	27	10	32,044	20,161	277	150
Satellite	13	1	8,365	8,399	72	104
Don't know	6	1	2,862	4,757	29	49
Other	-	-	346	1,236	12	9
Farms by number of households sharing in net income of operation:						
1 household	50	34	52,098	56,106	442	465
2 households	14	2	9,021	9,068	90	80
3 households	2	-	2,321	1,923	29	30
4 households	1	-	1,024	821	35	4
5 or more households	-	-	860	626	11	4

Table 64. **Selected Producer Characteristics by Race and Ethnicity: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	All producers reporting race as -					
	American Indian or Alaska Native alone or in combination with other races		Asian alone or in combination with other races		Black or African American alone or in combination with other races	
	2022	2017	2022	2017	2022	2017
Producers ..... number	467	408	373	433	95	60
Sex of producers:						
Male	303	260	167	198	47	37
Female	164	148	206	235	48	23
Hired managers	19	16	21	11	5	3
Primary occupation:						
Farming	156	153	153	161	43	25
Other	311	255	220	272	52	35
Place of residence:						
On farm operated	331	316	207	198	64	35
Not on farm operated	136	92	166	235	31	25
Days of work off farm:						
None	120	126	130	79	33	24
Any	347	282	243	354	62	36
1 to 49 days	54	32	29	41	5	11
50 to 99 days	21	15	40	94	4	4
100 to 199 days	45	36	33	84	21	2
200 days or more	227	199	141	135	32	19
Years on present farm:						
2 years or less	23	11	49	71	7	13
3 or 4 years	69	37	40	79	19	9
5 to 9 years	85	55	81	115	29	13
10 years or more	290	305	203	168	40	25
Years operating any farm:						
5 years or less	90	45	91	149	24	25
6 to 10 years	78	38	86	85	27	9
11 years or more	299	325	196	199	44	26
Age group:						
Under 25 years	12	8	10	18	3	1
25 to 34 years	43	28	55	62	18	14
35 to 44 years	74	57	77	82	32	9
45 to 54 years	91	66	57	103	7	10
55 to 64 years	112	147	109	108	18	8
65 to 74 years	96	81	57	50	8	12
75 years and over	39	21	8	10	9	6
Average age	54.3	55.3	50.0	49.1	47.7	51.6
Young producers (see text)	55	(NA)	65	(NA)	21	(NA)
Producers of Hispanic, Latino, or Spanish origin	27	10	8	-	13	10
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	402	362	366	420	80	44
Active duty now or in the past (see text)	65	46	7	13	15	16
Number of persons living in producers' households	1,000	895	692	1,117	185	116
On farm involvement in decisionmaking:						
Day-to-day decisions	422	352	309	366	84	53
Land use and/or crop decisions	356	335	255	326	62	45
Livestock decisions	216	249	97	161	32	19
Marketing decisions (see text)	279	(NA)	185	(NA)	52	(NA)
Record keeping and/or financial management	352	307	222	292	62	44
Estate planning or succession planning	259	257	159	214	51	32

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Table 64. **Selected Producer Characteristics by Race and Ethnicity: 2022 and 2017** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	All producers reporting race as - con.				All producers reporting ethnicity as Hispanic, Latino, or Spanish origin	
	Native Hawaiian or Other Pacific Islander alone or in combination with other races		White alone or in combination with other races			
	2022	2017	2022	2017	2022	2017
Producers ..... number	94	41	114,199	111,117	754	651
Sex of producers:						
Male	56	19	78,905	76,916	496	436
Female	38	22	35,294	34,201	258	215
Hired managers	6	-	6,872	6,424	68	57
Primary occupation:						
Farming	22	9	50,875	51,431	317	319
Other	72	32	63,324	59,686	437	332
Place of residence:						
On farm operated	58	22	78,791	83,510	473	503
Not on farm operated	36	19	35,408	27,607	281	148
Days of work off farm:						
None	35	16	46,650	45,245	269	280
Any	59	25	67,549	65,872	485	371
1 to 49 days	7	12	9,780	9,069	66	50
50 to 99 days	6	-	4,696	4,223	42	22
100 to 199 days	13	2	8,288	8,675	58	42
200 days or more	33	11	44,785	43,905	319	257
Years on present farm:						
2 years or less	4	-	4,809	4,616	50	42
3 or 4 years	19	1	7,557	6,590	98	42
5 to 9 years	27	13	18,369	12,934	132	64
10 years or more	44	27	83,464	86,977	474	503
Years operating any farm:						
5 years or less	41	3	13,674	11,771	161	84
6 to 10 years	12	11	15,606	11,305	103	55
11 years or more	41	27	84,919	88,041	490	512
Age group:						
Under 25 years	13	-	1,891	1,401	37	21
25 to 34 years	7	13	9,289	8,708	46	49
35 to 44 years	24	4	16,100	13,256	182	99
45 to 54 years	24	6	16,626	20,997	148	119
55 to 64 years	20	9	29,635	33,726	164	206
65 to 74 years	6	6	27,080	22,048	110	109
75 years and over	-	3	13,578	10,981	67	48
Average age	44.9	50.1	57.1	56.5	52.1	54.3
Young producers (see text)	20	(NA)	11,180	(NA)	83	(NA)
Producers of Hispanic, Latino, or Spanish origin	12	6	711	629	754	651
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	92	41	104,983	100,008	685	549
Active duty now or in the past (see text)	2	-	9,216	11,109	69	102
Number of persons living in producers' households	124	48	226,919	222,169	1,596	1,292
On farm involvement in decisionmaking:						
Day-to-day decisions	59	27	97,720	96,475	623	566
Land use and/or crop decisions	38	22	83,398	83,600	507	474
Livestock decisions	36	19	49,359	54,677	324	331
Marketing decisions (see text)	42	(NA)	67,673	(NA)	375	(NA)
Record keeping and/or financial management	29	29	83,616	85,801	470	456
Estate planning or succession planning	30	21	63,770	65,628	347	362

Table 65. **Selected Farm Characteristics - Farms with Producers with Military Service: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics		2022	2017
FARMS AND LAND IN FARMS			
Farms	number	8,801	10,771
Land in farms	acres	2,540,720	2,943,726
FARMS BY SIZE			
1 to 9 acres		535	827
10 to 49 acres		2,250	2,423
50 to 179 acres		3,103	3,689
180 to 499 acres		1,808	2,466
500 acres or more		1,105	1,366
OWNED AND RENTED LAND IN FARMS			
Owned land in farms	farms	8,418	10,285
	acres	1,599,917	1,946,249
Rented or leased land in farms	farms	2,198	2,755
	acres	940,803	997,477
TENURE			
Full owners	farms	6,603	8,016
	acres	949,324	1,185,731
Part owners	farms	1,815	2,269
	acres	1,444,076	1,582,935
Tenants	farms	383	486
	acres	147,320	175,060
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS			
Total	farms	8,801	10,771
	$1,000	2,099,989	1,644,245
Market value of agricultural products sold	farms	8,801	10,771
	$1,000	2,045,584	1,592,776
Crops, including nursery and greenhouse crops	farms	5,280	6,595
	$1,000	1,398,087	961,674
Livestock, poultry, and their products	farms	2,485	3,393
	$1,000	647,497	631,102
Government payments	farms	4,357	6,252
	$1,000	54,406	51,469
FARMS BY ECONOMIC CLASS			
Less than $1,000		956	1,430
$1,000 to $2,499		1,038	1,284
$2,500 to $4,999		982	1,236
$5,000 to $9,999		1,112	1,298
$10,000 to $24,999		1,136	1,369
$25,000 to $49,999		674	920
$50,000 or more		2,903	3,234
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS			
CCC loans	farms	94	250
	$1,000	16,960	31,598
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments	farms	3,150	3,663
	$1,000	20,925	20,943
Other Federal farm program payments	farms	1,705	4,532
	$1,000	33,481	30,526
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)			
Oilseed and grain farming (1111)		2,810	3,401
Vegetable and melon farming (1112)		122	164
Fruit and tree nut farming (1113)		193	165
Greenhouse, nursery, and floriculture production (1114)		115	167
Other crop farming (1119)		3,458	4,015
Tobacco farming (11191)		-	-
Cotton farming (11192)		-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)		3,458	4,015
Beef cattle ranching and farming (112111)		839	1,336
Cattle feedlots (112112)		75	131
Dairy cattle and milk production (11212)		85	170
Hog and pig farming (1122)		108	116
Poultry and egg production (1123)		281	151
Sheep and goat farming (1124)		164	185
Aquaculture and other animal production (1125, 1129)		551	770
OTHER FARM CHARACTERISTICS			
Farms by-			
Type of organization:			
Operation more than 50 percent owned by one producer's household and/or extended family		8,299	10,350
Limited Liability Company		568	446
Operation's legal status for tax purposes:			
Family or individual		7,408	9,294
Partnership		749	764
Corporation		442	454
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.		202	259
Number of producers:			
1 producer		3,144	4,685
2 producers		4,151	4,836
3 producers		773	727
4 producers		443	337
5 or more producers		290	186
Number of male producers:			
1 producer		6,614	8,739
2 producers		1,306	1,426
3 producers		531	372
4 producers		148	92
5 or more producers		103	63
Number of female producers:			
1 producer		4,102	4,656
2 producers		381	296
3 producers		93	50
4 producers		27	33
5 or more producers		22	21
Farms reporting-			
Internet access		6,777	7,820
Dial-up		287	391
Broadband (DSL, cable, fiber optic) (see text)		4,055	(NA)
Cellular data plan (see text)		3,674	2,676
Satellite		1,020	1,238
Don't know		494	735
Other		37	173
Farms by number of households sharing in net income of operation:			
1 household		6,708	8,536
2 households		1,343	1,601
3 households		404	339
4 households		172	148
5 or more households		174	147

Table 66. **Producers with Military Service - Selected Producer Characteristics: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
Producers ..... number	9,265	11,152
Sex of producers:		
Male	8,810	10,779
Female	455	373
Hired managers	248	270
Primary occupation:		
Farming	4,795	6,119
Other	4,470	5,033
Place of residence:		
On farm operated	6,478	8,459
Not on farm operated	2,787	2,693
Days of work off farm:		
None	5,289	6,292
Any	3,976	4,860
1 to 49 days	783	995
50 to 99 days	302	486
100 to 199 days	520	685
200 days or more	2,371	2,694
Years on present farm:		
2 years or less	251	287
3 or 4 years	375	402
5 to 9 years	966	756
10 years or more	7,673	9,707
Years operating any farm:		
5 years or less	675	696
6 to 10 years	829	662
11 years or more	7,761	9,794

Characteristics	2022	2017
Age group:		
Under 25 years	8	2
25 to 34 years	172	219
35 to 44 years	546	352
45 to 54 years	741	895
55 to 64 years	1,247	1,336
65 to 74 years	3,007	5,125
75 years and over	3,544	3,223
Average age	68.8	68.4
Young producers (see text)	180	(NA)
Producers of Hispanic, Latino, or Spanish origin	69	102
Producers by race:		
American Indian or Alaska Native	36	20
Asian	3	13
Black or African American	9	10
Native Hawaiian or Other Pacific Islander	-	-
White	9,178	11,078
More than one race reported	39	31
Number of persons living in producers' households	18,817	22,625
On farm involvement in decisionmaking:		
Day-to-day decisions	8,088	10,052
Land use and/or crop decisions	7,058	9,110
Livestock decisions	3,724	5,470
Marketing decisions (see text)	5,221	(NA)
Record keeping and/or financial management	6,654	8,586
Estate planning or succession planning	5,574	7,192

Table 67. **Selected Farm Characteristics - Farms with Young Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022
FARMS AND LAND IN FARMS	
Farms ..... number	8,554
Land in farms ..... acres	3,762,834
FARMS BY SIZE	
1 to 9 acres	816
10 to 49 acres	1,984
50 to 179 acres	2,042
180 to 499 acres	1,642
500 acres or more	2,070
OWNED AND RENTED LAND IN FARMS	
Owned land in farms ..... farms	7,224
acres	1,509,617
Rented or leased land in farms ..... farms	4,728
acres	2,253,217
TENURE	
Full owners ..... farms	3,826
acres	412,978
Part owners ..... farms	3,398
acres	2,880,411
Tenants ..... farms	1,330
acres	469,445
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS	
Total ..... farms	8,554
$1,000	5,111,693
Market value of agricultural products sold ..... farms	8,554
$1,000	5,032,096
Crops, including nursery and greenhouse crops ... farms	6,194
$1,000	2,788,231
Livestock, poultry, and their products ..... farms	4,022
$1,000	2,243,865
Government payments ..... farms	3,558
$1,000	79,597
FARMS BY ECONOMIC CLASS	
Less than $1,000	634
$1,000 to $2,499	593
$2,500 to $4,999	539
$5,000 to $9,999	591
$10,000 to $24,999	800
$25,000 to $49,999	640
$50,000 or more	4,757
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS	
CCC loans ..... farms	145
$1,000	33,780
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	1,438
$1,000	7,633
Other Federal farm program payments ..... farms	2,633
$1,000	71,964
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)	
Oilseed and grain farming (1111)	3,664
Vegetable and melon farming (1112)	171
Fruit and tree nut farming (1113)	126

Characteristics	2022
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS) - Con.	
Greenhouse, nursery, and floriculture production (1114)	166
Other crop farming (1119)	1,297
Tobacco farming (11191)	-
Cotton farming (11192)	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	1,297
Beef cattle ranching and farming (112111)	1,091
Cattle feedlots (112112)	171
Dairy cattle and milk production (11212)	433
Hog and pig farming (1122)	467
Poultry and egg production (1123)	271
Sheep and goat farming (1124)	328
Aquaculture and other animal production (1125, 1129)	369
OTHER FARM CHARACTERISTICS	
Farms by-	
Type of organization:	
Operation more than 50 percent owned by one producer's household and/or extended family	8,028
Limited Liability Company	995
Operation's legal status for tax purposes:	
Family or individual	6,865
Partnership	907
Corporation	662
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	120
Number of producers:	
1 producer	1,899
2 producers	3,293
3 producers	1,789
4 producers	1,071
5 or more producers	502
Number of male producers:	
1 producer	4,232
2 producers	2,631
3 producers	1,096
4 producers	264
5 or more producers	149
Number of female producers:	
1 producer	3,793
2 producers	893
3 producers	205
4 producers	22
5 or more producers	17
Farms reporting-	
Internet access	7,604
Dial-up	216
Broadband (DSL, cable, fiber optic) (see text)	4,956
Cellular data plan (see text)	5,093
Satellite	1,213
Don't know	249
Other	55
Farms by number of households sharing in net income of operation:	
1 household	6,130
2 households	1,434
3 households	572
4 households	239
5 or more households	179

Table 68. **Young Producers - Selected Producer Characteristics: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022
Producers ..... number	11,274
Sex of producers:	
Male	8,004
Female	3,270
Hired managers	1,160
Primary occupation:	
Farming	4,401
Other	6,873
Place of residence:	
On farm operated	6,959
Not on farm operated	4,315
Days of work off farm:	
None	2,471
Any	8,803
1 to 49 days	1,080
50 to 99 days	620
100 to 199 days	989
200 days or more	6,114
Years on present farm:	
2 years or less	1,763
3 or 4 years	2,673
5 to 9 years	4,616
10 years or more	2,222
Years operating any farm:	
5 years or less	5,127
6 to 10 years	3,973
11 years or more	2,174
Producers of Hispanic, Latino, or Spanish origin	83
Producers by race:	
American Indian or Alaska Native	20
Asian	50
Black or African American	17
Native Hawaiian or Other Pacific Islander	7
White	11,120
More than one race reported	60
Military service:	
Never served or only on active duty for training in the Reserves or National Guard (see text)	11,094
Active duty now or in the past (see text)	180
Number of persons living in producers' households	22,228
On farm involvement in decisionmaking:	
Day-to-day decisions	9,506
Land use and/or crop decisions	8,373
Livestock decisions	5,799
Marketing decisions (see text)	7,242
Record keeping and/or financial management	7,584
Estate planning or succession planning	4,496

Table 69. **Selected Farm Characteristics - Farms with New and Beginning Producers: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
FARMS AND LAND IN FARMS		
Farms ..... number	18,914	16,132
Land in farms ..... acres	5,184,617	4,456,912
FARMS BY SIZE		
1 to 9 acres	2,189	1,974
10 to 49 acres	5,672	4,365
50 to 179 acres	5,305	4,741
180 to 499 acres	3,149	2,869
500 acres or more	2,599	2,183
OWNED AND RENTED LAND IN FARMS		
Owned land in farms ..... farms	16,642	13,560
acres	2,328,371	2,068,610
Rented or leased land in farms ..... farms	7,301	6,817
acres	2,856,246	2,388,302
TENURE		
Full owners ..... farms	11,613	9,315
acres	1,072,776	989,916
Part owners ..... farms	5,029	4,245
acres	3,439,099	2,752,462
Tenants ..... farms	2,272	2,572
acres	672,742	714,534
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS		
Total ..... farms	18,914	16,132
$1,000	6,377,717	3,535,157
Market value of agricultural products sold ..... farms	18,914	16,132
$1,000	6,262,382	3,466,371
Crops, including nursery and greenhouse crops ... farms	11,897	10,434
$1,000	3,569,139	1,785,579
Livestock, poultry, and their products ..... farms	7,289	6,395
$1,000	2,693,244	1,680,792
Government payments ..... farms	7,264	7,980
$1,000	115,335	68,786
FARMS BY ECONOMIC CLASS		
Less than $1,000	2,218	2,336
$1,000 to $2,499	2,077	1,703
$2,500 to $4,999	1,876	1,577
$5,000 to $9,999	1,920	1,700
$10,000 to $24,999	2,209	1,800
$25,000 to $49,999	1,491	1,341
$50,000 or more	7,123	5,675
COMMODITY CREDIT CORPORATION (CCC) LOANS AND FEDERAL FARM PROGRAM PAYMENTS		
CCC loans ..... farms	190	530
$1,000	31,665	75,575
Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Program payments ..... farms	4,116	3,524
$1,000	24,238	17,182
Other Federal farm program payments ..... farms	3,940	6,481
$1,000	91,097	51,604
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)		
Oilseed and grain farming (1111)	6,494	5,748
Vegetable and melon farming (1112)	537	523
Fruit and tree nut farming (1113)	489	318

Characteristics	2022	2017
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS) - Con.		
Greenhouse, nursery, and floriculture production (1114)	457	242
Other crop farming (1119)	4,603	3,802
Tobacco farming (11191)	-	-
Cotton farming (11192)	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	4,603	3,802
Beef cattle ranching and farming (112111)	2,065	2,276
Cattle feedlots (112112)	195	259
Dairy cattle and milk production (11212)	430	611
Hog and pig farming (1122)	680	461
Poultry and egg production (1123)	913	364
Sheep and goat farming (1124)	733	564
Aquaculture and other animal production (1125, 1129)	1,318	964
OTHER FARM CHARACTERISTICS		
Farms by-		
Type of organization:		
Operation more than 50 percent owned by one producer's household and/or extended family	17,789	15,425
Limited Liability Company	2,345	1,282
Operation's legal status for tax purposes:		
Family or individual	15,624	13,504
Partnership	1,725	1,290
Corporation	1,175	986
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	390	352
Number of producers:		
1 producer	5,496	5,780
2 producers	8,719	7,255
3 producers	2,340	1,754
4 producers	1,572	935
5 or more producers	787	408
Number of male producers:		
1 producer	12,199	11,168
2 producers	3,823	2,912
3 producers	1,384	826
4 producers	446	208
5 or more producers	229	102
Number of female producers:		
1 producer	9,529	7,972
2 producers	1,438	987
3 producers	314	184
4 producers	63	62
5 or more producers	46	21
Farms reporting-		
Internet access	16,125	13,243
Dial-up	442	320
Broadband (DSL, cable, fiber optic) (see text)	10,428	(NA)
Cellular data plan (see text)	10,138	5,479
Satellite	2,467	2,019
Don't know	607	975
Other	105	299
Farms by number of households sharing in net income of operation:		
1 household	14,404	12,643
2 households	2,712	2,296
3 households	932	665
4 households	489	307
5 or more households	377	221

Table 70. **New and Beginning Producers - Selected Producer Characteristics: 2022 and 2017**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Characteristics	2022	2017
Producers ..... number	29,586	23,347
Sex of producers:		
Male	19,256	15,227
Female	10,330	8,120
Hired managers	1,524	1,266
Primary occupation:		
Farming	7,700	6,289
Other	21,886	17,058
Place of residence:		
On farm operated	17,330	14,176
Not on farm operated	12,256	9,171
Days of work off farm:		
None	6,381	4,641
Any	23,205	18,706
1 to 49 days	2,591	2,067
50 to 99 days	1,294	983
100 to 199 days	2,423	2,109
200 days or more	16,897	13,547
Years operating any farm:		
5 years or less	13,846	(NA)
6 to 10 years	15,740	(NA)
11 years or more	(X)	(X)
Age group:		
Under 25 years	1,900	1,418
25 to 34 years	7,200	6,810
35 to 44 years	7,930	5,730
45 to 54 years	4,729	4,102
Age group: - Con.		
55 to 64 years	4,678	3,643
65 to 74 years	2,603	1,383
75 years and over	546	261
Average age	43.9	42.4
Young producers (see text)	9,100	(NA)
Producers of Hispanic, Latino, or Spanish origin	264	139
Producers by race:		
American Indian or Alaska Native	92	21
Asian	150	220
Black or African American	34	26
Native Hawaiian or Other Pacific Islander	25	4
White	29,149	22,982
More than one race reported	119	83
Military service:		
Never served or only on active duty for training in the Reserves or National Guard (see text)	28,082	21,989
Active duty now or in the past (see text)	1,504	1,358
Number of persons living in producers' households	62,790	51,055
On farm involvement in decisionmaking:		
Day-to-day decisions	24,395	19,521
Land use and/or crop decisions	20,928	16,888
Livestock decisions	13,158	11,543
Marketing decisions (see text)	16,285	(NA)
Record keeping and/or financial management	20,136	16,903
Estate planning or succession planning	12,813	10,558

Table 71. **Summary by Size of Farm: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
FARMS AND LAND IN FARMS						
Farms ..... number	65,531	4,401	15,218	3,598	5,575	4,857
percent	100.0	6.7	23.2	5.5	8.5	7.4
Land in farms ..... acres	25,442,625	22,106	398,319	211,291	455,348	567,895
Average size of farm ..... acres	388	5	26	59	82	117
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	65,531	4,401	15,218	3,598	5,575	4,857
$1,000	29,066,202	1,006,625	1,922,644	338,141	428,952	594,322
Average per farm ..... dollars	443,549	228,726	126,340	93,980	76,942	122,364
Farms by economic class:						
Less than $1,000	6,079	962	3,035	413	585	334
$1,000 to $2,499	6,033	976	3,127	451	544	375
$2,500 to $4,999	5,681	596	2,608	562	649	499
$5,000 to $9,999	6,141	533	2,258	613	839	651
$10,000 to $24,999	7,125	455	2,103	674	1,000	767
$25,000 to $49,999	4,813	223	902	461	686	620
$50,000 to $99,999	5,488	119	370	261	915	987
$100,000 to $249,999	6,899	104	240	67	215	484
$250,000 to $499,999	5,477	110	133	19	43	42
$500,000 to $999,999	4,529	63	86	16	26	26
$1,000,000 or more	7,266	260	356	61	73	72
$1,000,000 to $2,499,999	4,148	158	167	38	38	44
$2,500,000 to $4,999,999	2,458	73	111	11	24	10
$5,000,000 or more	660	29	78	12	11	18
Total sales ..... farms	65,531	4,401	15,218	3,598	5,575	4,857
$1,000	28,482,097	998,181	1,904,525	329,366	413,899	577,737
Grains, oilseeds, dry beans, and dry peas ..... farms	32,075	343	2,689	1,030	1,917	2,042
$1,000	15,268,581	1,071	34,969	29,486	85,950	124,673
Sales of $50,000 or more ..... farms	23,618	-	30	193	842	1,168
$1,000	15,113,786	-	1,814	12,362	61,591	105,334
Corn ..... farms	25,230	207	1,428	637	1,238	1,467
$1,000	9,045,595	694	20,376	17,237	49,150	72,845
Sales of $50,000 or more ..... farms	18,777	-	26	121	380	662
$1,000	8,908,714	-	1,577	7,929	28,914	53,106
Wheat ..... farms	3,668	4	97	27	75	82
$1,000	735,504	1	509	(D)	(D)	1,620
Sales of $50,000 or more ..... farms	2,125	-	-	-	4	7
$1,000	707,000	-	-	-	254	423
Soybeans ..... farms	25,334	142	1,372	584	1,189	1,385
$1,000	5,087,514	363	13,629	11,701	33,360	48,071
Sales of $50,000 or more ..... farms	17,131	-	2	31	190	308
$1,000	4,898,487	-	(D)	(D)	11,680	21,460
Sorghum ..... farms	53	-	10	4	1	-
$1,000	437	-	27	9	(D)	-
Sales of $50,000 or more ..... farms	1	-	-	-	-	-
$1,000	(D)	-	-	-	-	-
Barley ..... farms	336	-	5	1	1	12
$1,000	27,673	-	5	(D)	(D)	86
Sales of $50,000 or more ..... farms	151	-	-	-	-	-
$1,000	24,984	-	-	-	-	-
Rice ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	3,613	17	157	39	123	179
$1,000	371,859	13	422	154	2,192	2,052
Sales of $50,000 or more ..... farms	1,013	-	-	-	16	7
$1,000	342,531	-	-	-	1,673	655
Tobacco ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	2,648	518	684	77	125	89
$1,000	446,099	4,924	16,966	3,810	3,659	2,802
Sales of $50,000 or more ..... farms	994	7	89	19	20	15
$1,000	424,789	572	10,724	3,183	2,114	1,882
Fruits, tree nuts, and berries ..... farms	1,212	293	608	54	79	53
$1,000	48,717	3,964	13,826	1,636	4,989	3,149
Sales of $50,000 or more ..... farms	178	17	81	9	21	14
$1,000	38,977	1,760	8,892	1,204	4,342	2,766
Fruits and tree nuts ..... farms	944	207	484	42	69	38
$1,000	30,052	1,493	9,421	1,147	3,723	2,789
Sales of $50,000 or more ..... farms	116	3	55	7	15	13
$1,000	22,967	173	5,728	824	3,111	2,536
Berries ..... farms	489	139	232	21	28	22
$1,000	18,665	2,471	4,405	489	1,265	359
Sales of $50,000 or more ..... farms	66	14	23	4	7	2
$1,000	15,470	1,566	2,879	380	1,061	(D)
Nursery, greenhouse, floriculture, and sod ..... farms	1,051	362	406	44	60	40
$1,000	391,444	39,291	59,759	30,888	14,601	54,782
Sales of $50,000 or more ..... farms	343	91	105	17	22	16
$1,000	381,613	35,551	55,573	30,431	14,186	54,375

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
FARMS AND LAND IN FARMS							
Farms ..... number	4,814	2,981	2,503	8,699	6,421	3,752	2,712
percent	7.3	4.5	3.8	13.3	9.8	5.7	4.1
Land in farms ..... acres	757,338	588,138	594,776	3,130,858	4,468,495	5,173,695	9,074,366
Average size of farm ..... acres	157	197	238	360	696	1,379	3,346
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS							
Total ..... farms	4,814	2,981	2,503	8,699	6,421	3,752	2,712
$1,000	606,365	463,224	488,832	2,959,362	4,918,850	6,031,057	9,307,828
Average per farm ..... dollars	125,959	155,392	195,299	340,196	766,057	1,607,425	3,432,090
Farms by economic class:							
Less than $1,000	296	142	87	172	45	8	-
$1,000 to $2,499	227	122	68	109	32	2	-
$2,500 to $4,999	322	130	111	174	29	1	-
$5,000 to $9,999	446	251	157	340	48	5	-
$10,000 to $24,999	742	386	297	556	122	21	2
$25,000 to $49,999	533	316	228	619	199	23	3
$50,000 to $99,999	817	506	299	841	305	62	6
$100,000 to $249,999	1,222	880	890	2,102	568	110	17
$250,000 to $499,999	89	118	261	2,853	1,575	210	24
$500,000 to $999,999	48	65	61	533	2,531	984	90
$1,000,000 or more	72	65	44	400	967	2,326	2,570
$1,000,000 to $2,499,999	43	42	25	273	664	1,830	826
$2,500,000 to $4,999,999	21	19	10	101	251	379	1,448
$5,000,000 or more	8	4	9	26	52	117	296
Total sales ..... farms	4,814	2,981	2,503	8,699	6,421	3,752	2,712
$1,000	582,181	447,991	473,636	2,890,563	4,818,054	5,910,213	9,135,752
Grains, oilseeds, dry beans, and dry peas ..... farms	2,513	1,726	1,559	6,400	5,628	3,557	2,671
$1,000	223,051	178,454	212,146	1,413,997	2,621,025	3,460,580	6,883,179
Sales of $50,000 or more ..... farms	1,787	1,235	1,258	5,619	5,337	3,485	2,664
$1,000	206,253	167,608	205,526	1,396,880	2,614,381	3,459,042	6,882,994
Corn ..... farms	1,925	1,378	1,300	5,474	4,885	2,989	2,302
$1,000	130,694	108,539	126,592	866,342	1,601,974	2,035,555	4,015,598
Sales of $50,000 or more ..... farms	1,176	916	966	4,692	4,629	2,927	2,282
$1,000	111,639	97,207	117,688	846,268	1,595,238	2,033,995	4,015,153
Wheat ..... farms	111	96	107	581	804	810	874
$1,000	3,287	1,891	3,507	24,683	67,439	168,342	462,602
Sales of $50,000 or more ..... farms	21	10	25	164	441	644	809
$1,000	1,927	578	2,068	16,696	59,637	164,570	460,848
Soybeans ..... farms	1,850	1,307	1,235	5,396	5,026	3,305	2,543
$1,000	86,973	65,679	79,037	504,896	915,139	1,187,901	2,140,764
Sales of $50,000 or more ..... farms	717	629	742	4,167	4,610	3,213	2,522
$1,000	54,177	47,375	64,628	468,352	903,675	1,185,153	2,140,109
Sorghum ..... farms	4	3	2	14	6	3	6
$1,000	13	31	(D)	58	49	(D)	138
Sales of $50,000 or more ..... farms	-	-	-	-	-	1	-
$1,000	-	-	-	-	-	(D)	-
Barley ..... farms	13	6	9	48	72	69	100
$1,000	53	153	(D)	1,162	4,186	(D)	17,060
Sales of $50,000 or more ..... farms	-	-	-	8	32	33	78
$1,000	-	-	-	867	3,535	4,198	16,385
Rice ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	192	208	158	740	715	545	540
$1,000	2,031	2,162	2,923	16,856	32,237	63,799	247,017
Sales of $50,000 or more ..... farms	6	4	16	90	166	270	438
$1,000	659	484	1,824	10,040	23,785	58,687	244,724
Tobacco ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	63	42	48	244	260	294	204
$1,000	2,510	4,318	2,964	39,822	59,913	153,153	151,257
Sales of $50,000 or more ..... farms	16	23	16	140	203	258	188
$1,000	1,698	3,998	2,239	37,313	58,124	152,247	150,695
Fruits, tree nuts, and berries ..... farms	38	16	13	29	15	9	5
$1,000	(D)	4,607	(D)	7,405	1,207	5,465	(D)
Sales of $50,000 or more ..... farms	9	8	1	9	3	4	2
$1,000	945	4,489	(D)	7,086	1,035	5,352	(D)
Fruits and tree nuts ..... farms	34	13	9	24	14	6	4
$1,000	868	2,298	330	6,813	(D)	599	(D)
Sales of $50,000 or more ..... farms	8	4	1	6	2	2	-
$1,000	729	(D)	(D)	6,520	(D)	(D)	-
Berries ..... farms	12	9	5	12	2	5	2
$1,000	(D)	2,309	(D)	592	(D)	4,866	(D)
Sales of $50,000 or more ..... farms	1	5	-	4	1	3	2
$1,000	(D)	2,240	-	542	(D)	(D)	(D)
Nursery, greenhouse, floriculture, and sod ..... farms	21	16	12	49	26	10	5
$1,000	7,498	8,848	(D)	18,014	42,291	109,279	(D)
Sales of $50,000 or more ..... farms	12	10	6	31	21	10	2
$1,000	7,381	8,803	5,379	17,665	(D)	109,279	(D)

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.						
Total - Con.						
Total sales - Con.						
Cultivated Christmas trees and short rotation woody crops ..... farms	244	17	101	28	17	21
$1,000	7,578	6	1,514	1,003	463	811
Sales of $50,000 or more ..... farms	27	-	4	6	3	5
$1,000	6,051	-	900	879	299	692
Cultivated Christmas trees ..... farms	243	17	101	28	16	21
$1,000	(D)	6	1,514	1,003	(D)	811
Sales of $50,000 or more ..... farms	27	-	4	6	3	5
$1,000	6,051	-	900	879	299	692
Short rotation woody crops ..... farms	1	-	-	-	1	-
$1,000	(D)	-	-	-	(D)	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other crops and hay ..... farms	16,722	464	3,467	882	1,515	1,385
$1,000	981,348	1,432	10,761	4,230	12,300	16,586
Sales of $50,000 or more ..... farms	2,437	5	14	3	49	69
$1,000	867,179	396	1,080	296	4,329	6,352
Maple syrup ..... farms	364	39	146	25	33	35
$1,000	869	67	179	37	144	(D)
Sales of $50,000 or more ..... farms	3	-	-	-	1	2
$1,000	191	-	-	-	(D)	(D)
Cattle and calves ..... farms	14,649	604	2,187	634	985	1,038
$1,000	2,094,135	34,227	163,057	29,576	91,382	44,362
Sales of $50,000 or more ..... farms	4,609	77	222	59	122	135
$1,000	1,933,030	29,272	144,882	23,260	80,409	32,098
Milk from cows ..... farms	1,893	27	68	37	44	63
$1,000	2,504,638	12,365	350,612	25,746	25,024	18,947
Sales of $50,000 or more ..... farms	1,826	27	55	27	34	44
$1,000	2,503,304	12,365	350,485	25,564	24,787	(D)
Hogs and pigs ..... farms	3,352	519	783	114	167	132
$1,000	4,666,832	699,413	964,677	92,310	96,120	173,727
Sales of $50,000 or more ..... farms	2,034	293	346	31	57	40
$1,000	4,660,288	698,798	963,485	91,986	95,791	173,390
Sheep, goats, wool, mohair, and milk ..... farms	2,604	434	1,088	170	195	153
$1,000	33,457	2,710	11,128	1,385	2,347	1,788
Sales of $50,000 or more ..... farms	120	5	29	6	12	11
$1,000	19,839	1,075	6,684	484	1,230	880
Horses, ponies, mules, burros, and donkeys ..... farms	1,247	124	541	125	122	96
$1,000	18,147	2,283	6,942	2,112	1,647	1,030
Sales of $50,000 or more ..... farms	76	8	32	8	6	3
$1,000	8,302	1,471	2,980	599	744	218
Poultry and eggs ..... farms	4,445	699	1,891	293	356	301
$1,000	1,943,207	167,628	244,352	106,254	72,204	131,766
Sales of $50,000 or more ..... farms	447	41	119	24	39	25
$1,000	1,935,336	166,447	240,739	105,699	71,630	131,349
Aquaculture ..... farms	98	41	8	7	5	5
$1,000	19,763	7,873	2,941	378	443	1,761
Sales of $50,000 or more ..... farms	62	29	7	2	2	5
$1,000	19,502	7,766	(D)	(D)	(D)	1,761
Other animals and other animal products ..... farms	1,405	391	528	90	71	89
$1,000	58,149	20,995	23,020	552	2,769	1,552
Sales of $50,000 or more ..... farms	154	58	32	2	11	7
$1,000	52,455	19,274	20,979	(D)	2,462	1,320
Value of-						
Government payments ..... farms	31,583	552	4,604	1,617	2,586	2,360
$1,000	584,106	8,444	18,119	8,775	15,054	16,585
Landlord's share of total sales ..... farms	1,294	4	58	18	41	64
$1,000	118,307	6	165	116	632	1,073
FOOD MARKETING PRACTICES						
Value of food sold directly to-						
Consumers ..... farms	3,339	702	1,387	170	224	199
$1,000	44,673	3,014	16,173	3,057	3,818	1,691
Retail markets, institutions, and food hubs for local or regionally branded products ..... farms	1,026	199	386	67	87	58
$1,000	108,704	5,539	25,300	(D)	1,135	1,264
FARM PRODUCTION EXPENSES						
Total farm production expenses [1] ..... farms	65,531	4,401	15,218	3,598	5,575	4,857
$1,000	20,780,603	825,200	1,588,034	285,935	355,856	459,859
Average per farm ..... dollars	317,111	187,503	104,352	79,470	63,831	94,680
Fertilizer, lime, and soil conditioners purchased ..... farms	36,421	960	4,066	1,295	2,269	2,304
$1,000	2,325,700	1,785	10,241	5,761	15,327	22,985
Farms with expenses of-						
$1 to $4,999	10,529	887	3,580	895	1,222	912
$5,000 to $24,999	9,710	56	468	377	982	1,203
$25,000 to $49,999	5,102	14	8	22	52	171
$50,000 or more	11,080	3	10	1	13	18
Chemicals purchased ..... farms	37,339	940	4,402	1,446	2,528	2,497
$1,000	1,161,099	858	5,270	3,438	8,543	11,509
Farms with expenses of-						
$1 to $4,999	15,060	909	4,241	1,263	2,069	1,648

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.								
Total - Con.								
Total sales - Con.								
Cultivated Christmas trees and short rotation woody crops	farms	10	11	8	26	4	1	-
	$1,000	(D)	(D)	(D)	(D)	1,115	(D)	-
Sales of $50,000 or more	farms	-	-	2	3	3	1	-
	$1,000	-	-	(D)	697	(D)	(D)	-
Cultivated Christmas trees	farms	10	11	8	26	4	1	-
	$1,000	(D)	(D)	(D)	(D)	1,115	(D)	-
Sales of $50,000 or more	farms	-	-	2	3	3	1	-
	$1,000	-	-	(D)	697	(D)	(D)	-
Short rotation woody crops	farms	-	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-	-
Sales of $50,000 or more	farms	-	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-	-
Other crops and hay	farms	1,321	928	743	2,472	1,635	885	1,025
	$1,000	17,294	13,889	13,968	73,968	95,396	134,934	586,592
Sales of $50,000 or more	farms	68	55	56	405	492	452	769
	$1,000	6,283	5,005	6,521	47,073	78,619	128,262	582,962
Maple syrup	farms	19	15	9	30	9	1	3
	$1,000	57	21	(D)	57	5	(D)	(D)
Sales of $50,000 or more	farms	-	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-	-
Cattle and calves	farms	1,072	803	790	2,894	2,241	1,019	382
	$1,000	48,216	40,355	43,736	262,702	462,583	530,639	343,299
Sales of $50,000 or more	farms	175	167	191	1,019	1,312	803	327
	$1,000	33,720	28,945	32,170	221,952	439,164	524,929	342,229
Milk from cows	farms	70	126	85	517	508	283	65
	$1,000	20,257	66,216	33,047	270,807	562,669	615,333	503,616
Sales of $50,000 or more	farms	66	122	82	514	507	283	65
	$1,000	20,199	66,206	32,952	270,735	(D)	615,333	503,616
Hogs and pigs	farms	139	119	78	390	399	339	173
	$1,000	160,178	69,147	57,464	434,815	673,789	754,107	491,085
Sales of $50,000 or more	farms	70	58	39	266	350	315	169
	$1,000	159,861	68,518	57,024	433,547	673,186	753,728	490,976
Sheep, goats, wool, mohair, and milk	farms	100	45	54	185	109	57	14
	$1,000	1,882	592	422	4,142	2,584	3,727	749
Sales of $50,000 or more	farms	7	1	-	22	12	12	3
	$1,000	1,408	(D)	-	2,677	1,372	3,172	(D)
Horses, ponies, mules, burros, and donkeys	farms	52	29	20	67	25	41	5
	$1,000	731	613	112	1,745	443	436	54
Sales of $50,000 or more	farms	1	5	-	9	1	3	-
	$1,000	(D)	467	-	1,185	(D)	(D)	-
Poultry and eggs	farms	239	131	102	235	133	40	25
	$1,000	98,986	59,319	102,709	359,491	292,782	139,441	168,276
Sales of $50,000 or more	farms	32	20	17	52	42	17	19
	$1,000	98,569	59,118	102,472	359,061	292,572	139,410	168,269
Aquaculture	farms	2	5	3	7	5	3	7
	$1,000	(D)	(D)	(D)	(D)	803	(D)	2,595
Sales of $50,000 or more	farms	-	1	2	1	3	3	7
	$1,000	-	(D)	(D)	(D)	(D)	(D)	2,595
Other animals and other animal products	farms	46	42	28	65	33	13	9
	$1,000	362	1,117	639	1,614	1,454	718	3,356
Sales of $50,000 or more	farms	2	5	4	15	11	2	5
	$1,000	(D)	865	520	1,311	1,386	(D)	3,311
Value of-								
Government payments	farms	2,471	1,576	1,324	5,126	4,349	2,817	2,201
	$1,000	24,184	15,232	15,197	68,799	100,796	120,844	172,076
Landlord's share of total sales	farms	66	59	46	220	290	224	204
	$1,000	1,369	894	2,154	10,103	20,091	30,197	51,507
FOOD MARKETING PRACTICES								
Value of food sold directly to-								
Consumers	farms	157	99	76	183	78	50	14
	$1,000	1,959	3,864	2,131	6,217	1,020	1,463	266
Retail markets, institutions, and food hubs for local or regionally branded products	farms	39	31	30	70	43	13	3
	$1,000	3,303	(D)	805	5,815	38,437	2,975	(D)
FARM PRODUCTION EXPENSES								
Total farm production expenses [1]	farms	4,814	2,981	2,503	8,699	6,421	3,752	2,712
	$1,000	454,239	361,936	368,731	2,101,954	3,411,818	4,291,080	6,275,961
Average per farm	dollars	94,358	121,414	147,316	241,632	531,353	1,143,678	2,314,145
Fertilizer, lime, and soil conditioners purchased	farms	2,767	1,907	1,751	6,908	5,867	3,640	2,687
	$1,000	35,919	30,450	34,843	232,089	419,921	544,290	972,089
Farms with expenses of-								
$1 to $4,999		859	526	403	915	270	51	9
$5,000 to $24,999		1,506	961	785	2,288	843	204	37
$25,000 to $49,999		359	344	440	2,174	1,224	262	32
$50,000 or more		43	76	123	1,531	3,530	3,123	2,609
Chemicals purchased	farms	2,852	1,928	1,747	6,868	5,833	3,616	2,682
	$1,000	18,083	15,166	17,006	113,261	201,859	267,230	498,877
Farms with expenses of-								
$1 to $4,999		1,401	812	618	1,453	502	125	19

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Chemicals purchased - Con.						
Farms with expenses of- - Con.						
$5,000 to $24,999	11,493	24	153	178	425	826
$25,000 to $49,999	4,407	6	7	3	30	14
$50,000 or more	6,379	1	1	2	4	9
Seeds, plants, vines, and trees purchased ... farms	36,437	1,321	4,228	1,234	2,214	2,239
$1,000	1,772,341	5,687	15,231	9,712	13,671	24,674
Farms with expenses of-						
$1 to $999	5,343	806	2,061	369	557	424
$1,000 to $4,999	6,157	357	1,702	526	774	652
$5,000 to $24,999	10,290	105	374	297	812	1,037
$25,000 to $49,999	5,582	36	63	17	43	86
$50,000 or more	9,065	17	28	25	28	40
Cover crop seed purchased ... farms	4,909	115	528	158	258	266
$1,000	20,527	26	193	179	301	389
Livestock and poultry purchased or leased ... farms	13,933	1,693	3,547	644	859	760
$1,000	1,926,426	165,325	309,091	41,463	67,366	46,341
Farms with expenses of-						
$1 to $4,999	6,658	1,021	2,326	407	525	410
$5,000 to $24,999	3,161	299	679	133	183	227
$25,000 to $99,999	1,372	115	161	49	73	56
$100,000 to $249,999	912	80	124	19	29	17
$250,000 or more	1,830	178	257	36	49	50
Breeding livestock purchased or leased ... farms	5,904	560	1,189	301	417	392
$1,000	171,016	18,514	31,097	4,776	5,211	7,937
Other livestock and poultry purchased or leased ... farms	9,786	1,367	2,782	465	558	496
$1,000	1,755,410	146,811	277,993	36,687	62,155	38,403
Feed purchased ... farms	26,145	2,686	7,152	1,320	1,754	1,621
$1,000	3,890,272	342,185	662,520	92,371	92,996	146,142
Farms with expenses of-						
$1 to $4,999	13,038	1,754	4,709	829	1,071	947
$5,000 to $24,999	6,844	481	1,714	340	466	480
$25,000 to $99,999	2,349	103	262	65	107	102
$100,000 to $249,999	1,155	77	80	23	28	21
$250,000 or more	2,759	271	387	63	82	71
Gasoline, fuels, and oils purchased ... farms	61,621	3,989	13,875	3,242	5,009	4,529
$1,000	956,802	15,171	40,366	10,428	14,545	21,310
Farms with expenses of-						
$1 to $4,999	37,714	3,502	12,754	2,868	4,372	3,739
$5,000 to $24,999	14,760	384	917	319	569	722
$25,000 to $49,999	4,270	61	105	40	50	42
$50,000 or more	4,877	42	99	15	18	26
Utilities ... farms	48,636	2,759	8,732	2,139	3,436	3,205
$1,000	400,978	18,937	38,880	14,125	9,359	13,681
Farms with expenses of-						
$1 to $999	9,923	1,050	3,384	669	1,094	879
$1,000 to $4,999	24,023	1,209	4,334	1,240	1,987	1,972
$5,000 to $24,999	12,077	390	802	182	329	321
$25,000 to $49,999	1,626	48	110	31	16	11
$50,000 or more	987	62	102	17	10	22
Repairs, supplies, and maintenance costs ... farms	55,660	3,380	11,271	2,749	4,292	3,972
$1,000	1,322,234	48,887	68,277	21,592	27,383	28,310
Farms with expenses of-						
$1 to $4,999	25,809	2,539	8,752	1,938	2,972	2,453
$5,000 to $24,999	17,499	617	2,163	688	1,192	1,351
$25,000 to $49,999	5,425	123	176	72	80	115
$50,000 or more	6,927	101	180	51	48	53
Hired farm labor ... farms	17,399	818	2,092	496	769	808
$1,000	1,320,974	72,277	135,201	25,037	29,663	45,873
Farms with expenses of-						
$1 to $4,999	5,944	366	1,130	282	496	479
$5,000 to $24,999	4,466	162	464	108	161	212
$25,000 to $99,999	3,749	178	304	70	68	79
$100,000 to $249,999	2,234	50	96	14	25	13
$250,000 or more	1,006	62	98	22	19	25
Contract labor ... farms	4,311	271	709	158	243	258
$1,000	152,565	10,963	13,062	5,623	4,332	2,216
Farms with expenses of-						
$1 to $999	452	55	153	27	50	40
$1,000 to $4,999	1,452	89	310	71	109	133
$5,000 to $24,999	1,469	80	176	31	69	70
$25,000 to $49,999	315	24	42	21	7	8
$50,000 or more	623	23	28	8	8	7
Customwork and custom hauling ... farms	19,181	664	2,439	700	1,232	1,235
$1,000	425,172	24,285	32,351	4,976	9,607	7,477
Farms with expenses of-						
$1 to $999	2,876	232	899	170	297	254
$1,000 to $4,999	6,088	157	1,042	376	589	576
$5,000 to $24,999	6,540	133	313	121	294	356
$25,000 to $49,999	2,030	78	88	12	27	29
$50,000 or more	1,647	64	97	21	25	20

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
FARM PRODUCTION EXPENSES - Con.							
Total farm production expenses [1] - Con.							
Chemicals purchased - Con.							
Farms with expenses of- - Con.							
$5,000 to $24,999	1,401	1,037	1,011	4,059	1,974	356	49
$25,000 to $49,999	42	71	104	1,068	2,108	831	123
$50,000 or more	8	8	14	288	1,249	2,304	2,491
Seeds, plants, vines, and trees purchased ... farms	2,688	1,853	1,709	6,814	5,825	3,632	2,680
$1,000	30,279	25,851	27,481	170,425	304,445	404,971	739,914
Farms with expenses of-							
$1 to $999	341	184	138	345	95	22	1
$1,000 to $4,999	531	377	241	668	249	73	7
$5,000 to $24,999	1,593	1,100	1,031	2,700	924	246	71
$25,000 to $49,999	172	145	253	2,570	1,810	320	67
$50,000 or more	51	47	46	531	2,747	2,971	2,534
Cover crop seed purchased ... farms	274	196	188	793	829	701	603
$1,000	480	352	324	2,277	3,794	6,046	6,167
Livestock and poultry purchased or leased ... farms	715	548	418	1,861	1,635	879	374
$1,000	57,584	34,453	40,882	209,838	330,982	366,377	256,724
Farms with expenses of-							
$1 to $4,999	387	255	165	656	394	80	32
$5,000 to $24,999	171	165	133	548	430	158	35
$25,000 to $99,999	69	58	55	267	270	143	56
$100,000 to $249,999	33	35	36	151	182	144	62
$250,000 or more	55	35	29	239	359	354	189
Breeding livestock purchased or leased ... farms	323	300	206	911	805	368	132
$1,000	6,753	5,071	2,305	17,064	27,812	26,471	18,002
Other livestock and poultry purchased or leased ... farms	459	324	262	1,157	999	629	288
$1,000	50,831	29,381	38,577	192,775	303,170	339,906	238,721
Feed purchased ... farms	1,482	1,073	945	3,535	2,682	1,354	541
$1,000	108,539	83,215	84,620	452,055	645,376	635,803	544,451
Farms with expenses of-							
$1 to $4,999	753	478	441	1,248	561	190	57
$5,000 to $24,999	473	331	292	1,150	800	248	69
$25,000 to $99,999	127	139	110	524	479	228	103
$100,000 to $249,999	41	44	48	257	297	155	84
$250,000 or more	88	81	54	356	545	533	228
Gasoline, fuels, and oils purchased ... farms	4,451	2,835	2,414	8,490	6,350	3,729	2,708
$1,000	22,420	17,874	17,501	101,687	160,259	207,019	328,221
Farms with expenses of-							
$1 to $4,999	3,257	1,777	1,379	3,061	795	166	44
$5,000 to $24,999	1,121	962	939	4,622	3,258	811	136
$25,000 to $49,999	52	73	68	608	1,628	1,258	285
$50,000 or more	21	23	28	199	669	1,494	2,243
Utilities ... farms	3,478	2,349	2,068	7,849	6,201	3,712	2,708
$1,000	13,953	9,436	9,370	47,729	62,734	70,974	91,800
Farms with expenses of-							
$1 to $999	827	446	349	871	266	66	22
$1,000 to $4,999	2,192	1,471	1,368	4,696	2,637	751	166
$5,000 to $24,999	420	389	327	2,042	2,824	2,350	1,701
$25,000 to $49,999	20	33	11	175	351	348	472
$50,000 or more	19	10	13	65	123	197	347
Repairs, supplies, and maintenance costs ... farms	4,056	2,652	2,293	8,245	6,310	3,729	2,711
$1,000	34,839	31,250	28,442	155,531	239,427	270,675	367,621
Farms with expenses of-							
$1 to $4,999	2,147	1,158	903	2,175	606	118	48
$5,000 to $24,999	1,689	1,211	1,130	4,222	2,409	677	150
$25,000 to $49,999	175	201	181	1,212	1,791	999	300
$50,000 or more	45	82	79	636	1,504	1,935	2,213
Hired farm labor ... farms	765	609	562	2,408	2,915	2,708	2,449
$1,000	17,522	25,805	18,240	85,337	159,808	282,517	423,697
Farms with expenses of-							
$1 to $4,999	428	323	287	941	770	332	110
$5,000 to $24,999	241	173	186	887	966	676	230
$25,000 to $99,999	75	64	66	439	814	887	705
$100,000 to $249,999	14	23	12	93	265	610	1,019
$250,000 or more	7	26	11	48	100	203	385
Contract labor ... farms	240	131	141	573	552	549	486
$1,000	6,062	2,429	8,370	19,066	12,770	36,389	31,283
Farms with expenses of-							
$1 to $999	39	14	9	30	18	13	4
$1,000 to $4,999	120	59	58	214	168	94	27
$5,000 to $24,999	66	41	62	243	268	217	146
$25,000 to $49,999	5	8	4	51	35	46	64
$50,000 or more	10	9	8	35	63	179	245
Customwork and custom hauling ... farms	1,411	988	882	3,517	2,974	1,895	1,244
$1,000	12,641	10,760	10,608	49,948	75,702	85,405	101,412
Farms with expenses of-							
$1 to $999	220	122	101	320	170	74	17
$1,000 to $4,999	526	389	308	1,001	685	282	157
$5,000 to $24,999	575	384	387	1,601	1,323	728	325
$25,000 to $49,999	56	62	63	421	424	386	384
$50,000 or more	34	31	23	174	372	425	361

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Cash rent for land, buildings, and grazing fees ..... farms	24,199	420	1,500	596	997	1,229
$1,000	2,302,712	7,458	11,230	5,432	10,438	13,871
Farms with expenses of-						
$1 to $4,999	5,289	324	1,102	364	482	565
$5,000 to $9,999	2,314	35	236	112	192	210
$10,000 to $24,999	4,009	26	92	89	268	307
$25,000 or more	12,587	35	70	31	55	147
Rent and lease expenses for machinery, equipment, and farm share of vehicles ..... farms	6,598	231	740	192	293	342
$1,000	182,357	2,544	6,632	949	1,265	2,046
Farms with expenses of-						
$1 to $999	1,233	101	259	93	102	99
$1,000 to $4,999	1,683	88	298	56	113	128
$5,000 to $24,999	2,168	28	140	36	73	103
$25,000 to $49,999	538	6	16	2	5	5
$50,000 or more	976	8	27	5	-	7
Interest expense ..... farms	27,274	1,125	3,920	1,012	1,602	1,558
$1,000	702,889	8,951	31,264	7,611	11,207	12,958
Farms with expenses of-						
$1 to $4,999	9,316	728	2,154	569	851	788
$5,000 to $24,999	11,255	342	1,547	398	708	688
$25,000 to $99,999	5,316	43	189	42	40	73
$100,000 or more	1,387	12	30	3	3	9
Secured by real estate ..... farms	20,348	797	3,098	755	1,217	1,121
$1,000	467,669	3,858	19,626	5,535	8,469	8,936
Farms with expenses of-						
$1 to $999	1,511	170	482	76	120	94
$1,000 to $4,999	5,125	354	1,255	341	504	431
$5,000 to $24,999	9,127	260	1,235	309	561	552
$25,000 to $49,999	2,363	13	105	23	25	33
$50,000 or more	2,222	-	21	6	7	11
Not secured by real estate ..... farms	16,953	654	2,079	542	850	908
$1,000	235,219	5,093	11,638	2,076	2,737	4,023
Farms with expenses of-						
$1 to $999	2,836	191	635	145	244	256
$1,000 to $4,999	6,264	348	1,089	292	448	471
$5,000 to $24,999	5,400	84	267	97	150	153
$25,000 to $49,999	1,506	10	53	6	7	20
$50,000 or more	947	21	35	2	1	8
Property taxes paid ..... farms	61,644	3,985	14,460	3,390	5,240	4,539
$1,000	482,443	10,957	45,142	12,219	17,753	19,341
Farms with expenses of-						
$1 to $4,999	39,325	3,552	12,516	2,794	4,382	3,450
$5,000 to $9,999	11,291	318	1,456	446	669	818
$10,000 to $24,999	7,298	101	415	116	154	217
$25,000 or more	3,730	14	73	34	35	54
Medical supplies, veterinary, and custom services for livestock ..... farms	19,351	1,735	4,544	889	1,168	1,149
$1,000	255,043	22,614	43,786	4,929	5,822	7,601
Farms with expenses of-						
$1 to $4,999	14,259	1,385	3,936	767	1,045	1,007
$5,000 to $24,999	3,318	208	379	89	79	112
$25,000 to $49,999	674	41	63	17	18	15
$50,000 to $99,999	623	47	62	11	16	2
$100,000 or more	477	54	104	5	10	13
All other production expenses ..... farms	44,226	2,081	6,908	1,907	3,040	2,908
$1,000	1,200,596	66,316	119,489	20,270	16,580	33,523
Farms with expenses of-						
$1 to $4,999	22,214	1,506	5,688	1,575	2,418	2,149
$5,000 to $24,999	13,025	367	923	266	538	664
$25,000 to $49,999	3,867	100	118	35	51	59
$50,000 to $99,999	3,372	50	88	18	21	16
$100,000 or more	1,748	58	91	13	12	20
Production expenses paid by landlords [1] ..... farms	2,062	34	164	36	87	78
$1,000	65,113	79	444	2,152	526	684
Depreciation expenses claimed ..... farms	41,075	1,989	6,378	1,673	2,645	2,549
$1,000	2,240,389	44,378	93,165	25,297	31,758	43,909
NET CASH FARM INCOME						
Net cash farm income of operations ..... farms	65,531	4,401	15,218	3,598	5,575	4,857
$1,000	9,296,848	207,302	460,365	97,799	125,885	190,424
Average per farm ..... dollars	141,869	47,103	30,251	27,182	22,580	39,206
Farms with net gains [2] ..... number	41,496	1,616	6,011	1,850	3,158	3,031
Average net gain ..... dollars	242,705	172,093	103,459	70,600	52,103	74,875
Gain of-						
Less than $1,000	1,541	145	637	122	230	117
$1,000 to $4,999	4,053	306	1,398	387	498	446
$5,000 to $9,999	3,053	204	790	258	419	344
$10,000 to $24,999	5,680	250	1,196	450	794	737
$25,000 to $49,999	5,396	152	816	325	607	675
$50,000 or more	21,773	559	1,174	308	610	712

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
FARM PRODUCTION EXPENSES - Con.							
Total farm production expenses [1] - Con.							
Cash rent for land, buildings, and grazing fees ..... farms	1,291	1,123	999	5,001	5,008	3,432	2,603
$1,000	19,398	18,020	19,846	157,114	358,310	560,601	1,120,994
Farms with expenses of-							
$1 to $4,999	416	352	287	941	379	68	9
$5,000 to $9,999	201	225	145	576	305	69	8
$10,000 to $24,999	407	296	251	1,258	754	208	53
$25,000 or more	267	250	316	2,226	3,570	3,087	2,533
Rent and lease expenses for machinery, equipment, and farm share of vehicles ..... farms	340	293	214	1,019	1,130	909	895
$1,000	2,058	3,077	1,800	13,181	21,443	38,453	88,909
Farms with expenses of-							
$1 to $999	86	71	50	188	123	40	21
$1,000 to $4,999	125	91	57	234	287	132	74
$5,000 to $24,999	122	109	97	451	488	318	203
$25,000 to $49,999	4	12	8	90	119	153	118
$50,000 or more	3	10	2	56	113	266	479
Interest expense ..... farms	1,710	1,162	1,052	4,488	4,345	2,961	2,339
$1,000	16,849	13,519	12,066	72,449	116,776	151,720	247,517
Farms with expenses of-							
$1 to $4,999	800	465	376	1,312	810	330	133
$5,000 to $24,999	770	582	561	2,365	1,979	926	389
$25,000 to $99,999	132	103	112	759	1,408	1,341	1,074
$100,000 or more	8	12	3	52	148	364	743
Secured by real estate ..... farms	1,247	860	755	3,298	3,268	2,201	1,731
$1,000	11,681	8,972	8,657	50,160	81,413	97,138	163,224
Farms with expenses of-							
$1 to $999	109	59	38	173	126	44	20
$1,000 to $4,999	407	271	189	670	452	189	62
$5,000 to $24,999	629	465	459	1,918	1,576	809	354
$25,000 to $49,999	86	42	53	387	671	553	372
$50,000 or more	16	23	16	150	443	606	923
Not secured by real estate ..... farms	987	705	670	2,869	2,857	2,103	1,729
$1,000	5,168	4,548	3,409	22,289	35,363	54,582	84,293
Farms with expenses of-							
$1 to $999	271	155	112	439	237	108	43
$1,000 to $4,999	467	349	326	1,141	800	395	138
$5,000 to $24,999	230	174	211	1,138	1,445	908	543
$25,000 to $49,999	11	11	19	109	272	466	522
$50,000 or more	8	16	2	42	103	226	483
Property taxes paid ..... farms	4,500	2,815	2,353	8,204	6,076	3,564	2,518
$1,000	21,332	14,904	14,344	62,807	77,440	74,588	111,615
Farms with expenses of-							
$1 to $4,999	3,178	1,792	1,335	3,686	1,785	638	217
$5,000 to $9,999	980	722	690	2,620	1,580	706	286
$10,000 to $24,999	292	262	288	1,655	2,005	1,190	603
$25,000 or more	50	39	40	243	706	1,030	1,412
Medical supplies, veterinary, and custom services for livestock ..... farms	1,093	839	745	3,029	2,415	1,259	486
$1,000	6,253	5,514	5,081	25,813	41,134	48,729	37,767
Farms with expenses of-							
$1 to $4,999	929	661	619	2,121	1,251	423	115
$5,000 to $24,999	137	131	99	697	756	458	173
$25,000 to $49,999	11	30	12	105	179	120	63
$50,000 to $99,999	10	11	8	76	185	142	53
$100,000 or more	6	6	7	30	44	116	82
All other production expenses ..... farms	3,280	2,174	1,935	7,464	6,113	3,707	2,709
$1,000	30,507	20,214	18,231	133,625	183,430	245,340	313,071
Farms with expenses of-							
$1 to $4,999	2,089	1,230	967	2,838	1,337	323	94
$5,000 to $24,999	1,070	816	869	3,633	2,504	1,008	367
$25,000 to $49,999	83	77	71	671	1,442	856	304
$50,000 to $99,999	16	33	16	195	587	1,100	1,232
$100,000 or more	22	18	12	127	243	420	712
Production expenses paid by landlords [1] ..... farms	69	74	61	290	449	338	382
$1,000	895	519	1,000	5,270	9,950	16,530	27,063
Depreciation expenses claimed ..... farms	2,811	1,931	1,736	6,937	6,023	3,695	2,708
$1,000	46,429	43,072	36,352	231,565	403,636	483,939	756,890
NET CASH FARM INCOME							
Net cash farm income of operations ..... farms	4,814	2,981	2,503	8,699	6,421	3,752	2,712
$1,000	213,410	140,481	154,539	998,161	1,654,804	1,882,702	3,170,975
Average per farm ..... dollars	44,331	47,125	61,742	114,744	257,718	501,786	1,169,238
Farms with net gains [2] ..... number	3,321	2,065	1,837	7,033	5,645	3,398	2,531
Average net gain ..... dollars	72,899	84,523	93,922	155,504	308,697	581,784	1,282,835
Gain of-							
Less than $1,000	119	54	28	61	24	3	1
$1,000 to $4,999	361	149	137	275	78	14	4
$5,000 to $9,999	358	188	128	273	58	25	8
$10,000 to $24,999	602	356	247	751	206	80	11
$25,000 to $49,999	691	406	325	904	371	106	18
$50,000 or more	1,190	912	972	4,769	4,908	3,170	2,489

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
NET CASH FARM INCOME - Con.						
Net cash farm income of operations - Con.						
Farms with net losses ..... number	24,035	2,785	9,207	1,748	2,417	1,826
Average net loss ..... dollars	32,221	25,422	17,544	18,770	15,993	20,001
Loss of-						
Less than $1,000	1,786	208	717	147	218	152
$1,000 to $4,999	6,380	839	2,800	485	739	502
$5,000 to $9,999	5,021	684	2,174	401	531	358
$10,000 to $24,999	5,999	721	2,323	426	596	469
$25,000 to $49,999	2,539	221	816	193	216	211
$50,000 or more	2,310	112	377	96	117	134
Net cash farm income of producers ..... farms	65,531	4,401	15,218	3,598	5,575	4,857
$1,000	8,390,544	115,151	325,040	57,867	87,409	166,907
Average per farm ..... dollars	128,039	26,165	21,359	16,083	15,679	34,364
Producers reporting net gains [2] ..... farms	41,274	1,587	5,947	1,839	3,157	3,032
Average net gain ..... dollars	222,954	122,387	83,635	49,034	40,445	67,359
Gain of-						
Less than $1,000	1,557	148	637	123	234	119
$1,000 to $4,999	4,059	310	1,404	387	504	443
$5,000 to $9,999	3,084	213	801	258	420	356
$10,000 to $24,999	5,726	271	1,215	449	802	752
$25,000 to $49,999	5,475	174	851	324	614	672
$50,000 or more	21,373	471	1,039	298	583	690
Producers reporting net losses ..... farms	24,257	2,814	9,271	1,759	2,418	1,825
Average net loss ..... dollars	33,460	28,102	18,589	18,367	16,656	20,452
Loss of-						
Less than $1,000	1,780	204	718	147	217	150
$1,000 to $4,999	6,394	841	2,801	487	736	498
$5,000 to $9,999	5,032	682	2,185	399	534	362
$10,000 to $24,999	6,008	725	2,328	425	594	468
$25,000 to $49,999	2,576	224	809	197	208	210
$50,000 or more	2,467	138	430	104	129	137
COMMODITY CREDIT CORPORATION LOANS						
Total ..... farms	990	1	3	7	2	8
$1,000	197,241	(D)	(D)	67	(D)	185
INCOME FROM FARM-RELATED SOURCES						
Total income from farm-related sources ..... farms	38,287	1,324	6,350	1,976	2,950	2,970
$1,000	1,011,249	25,877	125,755	45,593	52,789	55,960
Customwork and other agricultural services ..... farms	4,779	137	418	134	207	204
$1,000	144,025	2,921	6,358	1,787	3,414	3,148
Gross cash rent or share payments ..... farms	15,680	579	4,080	1,311	1,669	1,691
$1,000	479,289	15,376	95,741	36,083	41,941	45,496
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products ..... farms	619	18	129	31	61	59
$1,000	5,384	(D)	576	135	311	428
Agri-tourism and recreational services ..... farms	509	54	164	22	36	27
$1,000	13,615	(D)	4,628	333	808	502
Patronage dividends and refunds from cooperatives ..... farms	23,672	528	2,054	729	1,341	1,445
$1,000	126,183	770	2,268	802	1,884	1,984
Crop and livestock insurance payments ..... farms	5,882	75	246	93	200	260
$1,000	171,530	756	2,115	2,083	1,472	2,134
Amount from State and local government agricultural program payments ..... farms	1,422	35	170	55	88	90
$1,000	7,129	167	377	154	249	237
Other farm-related income sources ..... farms	2,557	160	502	143	133	149
$1,000	64,095	5,371	13,691	4,216	2,708	2,032
LAND USE						
Total cropland ..... farms	58,762	2,489	12,305	3,217	5,127	4,490
acres	21,544,060	8,511	205,090	115,778	262,470	337,348
Harvested cropland ..... farms	47,549	1,928	8,326	2,150	3,531	3,351
acres	19,662,443	5,447	116,138	67,610	163,112	230,286
Farms by acres harvested:						
1 to 49 acres	16,934	1,928	8,326	1,550	1,872	1,221
50 to 99 acres	5,412	-	-	600	1,659	1,034
100 to 199 acres	6,580	-	-	-	-	1,096
200 to 499 acres	8,316	-	-	-	-	-
500 to 999 acres	4,858	-	-	-	-	-
1,000 to 1,999 acres	3,081	-	-	-	-	-
2,000 acres or more	2,368	-	-	-	-	-
Cropland-						
Other pasture and grazing land that could have been used for crops without additional improvements ..... farms	3,908	130	829	181	314	301
acres	174,215	297	5,709	2,742	5,342	6,889
On which all crops failed or were abandoned ..... farms	2,413	39	344	108	195	203
acres	110,013	59	2,163	1,177	2,597	3,599
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed ..... farms	22,588	550	4,759	1,410	2,280	1,862
acres	1,546,009	2,576	77,210	41,829	87,147	92,447
In summer fallow ..... farms	2,242	51	467	164	223	189
acres	51,380	132	3,870	2,420	4,272	4,127

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
NET CASH FARM INCOME - Con.							
Net cash farm income of operations - Con.							
Farms with net losses ..... number	1,493	916	666	1,666	776	354	181
Average net loss ..... dollars	19,216	37,183	27,020	57,323	113,131	266,098	419,233
Loss of-							
Less than $1,000	129	63	48	77	25	2	-
$1,000 to $4,999	323	211	150	248	64	8	11
$5,000 to $9,999	294	170	106	226	63	14	-
$10,000 to $24,999	432	235	196	433	131	33	4
$25,000 to $49,999	185	98	87	294	131	63	24
$50,000 or more	130	139	79	388	362	234	142
Net cash farm income of producers ..... farms	4,814	2,981	2,503	8,699	6,421	3,752	2,712
$1,000	174,072	110,979	126,073	877,270	1,500,902	1,773,545	3,075,330
Average per farm ..... dollars	36,160	37,229	50,369	100,847	233,749	472,693	1,133,971
Producers reporting net gains [2] ..... farms	3,304	2,044	1,834	7,011	5,633	3,367	2,519
Average net gain ..... dollars	61,532	71,447	78,895	139,157	282,732	555,995	1,252,148
Gain of-							
Less than $1,000	118	55	29	65	26	1	2
$1,000 to $4,999	360	151	131	274	79	13	3
$5,000 to $9,999	360	186	126	275	56	25	8
$10,000 to $24,999	606	344	255	744	209	69	10
$25,000 to $49,999	699	405	334	917	365	103	17
$50,000 or more	1,161	903	959	4,736	4,898	3,156	2,479
Producers reporting net losses ..... farms	1,510	937	669	1,688	788	385	193
Average net loss ..... dollars	19,358	37,417	27,833	58,268	116,403	255,822	408,449
Loss of-							
Less than $1,000	129	65	47	77	24	2	-
$1,000 to $4,999	329	214	154	250	63	11	10
$5,000 to $9,999	291	159	103	233	67	17	-
$10,000 to $24,999	438	245	198	421	127	37	2
$25,000 to $49,999	190	109	87	309	137	66	30
$50,000 or more	133	145	80	398	370	252	151
COMMODITY CREDIT CORPORATION LOANS							
Total ..... farms	41	29	18	201	190	224	266
$1,000	648	473	605	10,512	16,152	38,337	130,169
INCOME FROM FARM-RELATED SOURCES							
Total income from farm-related sources ..... farms	2,906	1,991	1,687	6,482	5,031	2,894	1,726
$1,000	61,285	39,193	34,438	140,753	147,772	142,726	139,108
Customwork and other agricultural services ..... farms	258	198	195	957	986	691	394
$1,000	6,383	3,131	3,873	26,703	33,883	27,842	24,581
Gross cash rent or share payments ..... farms	1,283	821	635	1,746	998	527	340
$1,000	43,547	26,717	23,129	59,376	40,640	23,798	27,445
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products ..... farms	55	54	34	95	52	23	8
$1,000	913	272	231	1,166	819	287	(D)
Agri-tourism and recreational services ..... farms	36	24	16	70	43	13	4
$1,000	289	1,298	540	1,550	2,853	137	(D)
Patronage dividends and refunds from cooperatives ..... farms	1,798	1,306	1,151	4,970	4,316	2,586	1,448
$1,000	2,725	2,792	2,590	16,093	26,820	33,040	34,416
Crop and livestock insurance payments ..... farms	325	251	203	1,281	1,389	944	615
$1,000	4,384	3,294	2,975	23,746	34,635	46,632	47,302
Amount from State and local government agricultural program payments ..... farms	102	71	47	314	243	141	66
$1,000	277	332	117	1,156	1,666	1,646	749
Other farm-related income sources ..... farms	145	112	88	444	341	211	129
$1,000	2,766	1,357	983	10,964	6,455	9,344	4,207
LAND USE							
Total cropland ..... farms	4,581	2,847	2,422	8,488	6,362	3,730	2,704
acres	491,297	382,534	403,884	2,359,078	3,791,068	4,691,498	8,495,504
Harvested cropland ..... farms	3,598	2,357	2,054	7,726	6,142	3,693	2,693
acres	356,651	292,947	322,004	2,022,637	3,462,397	4,417,695	8,205,519
Farms by acres harvested:							
1 to 49 acres	790	409	235	488	95	19	1
50 to 99 acres	843	415	274	491	74	20	2
100 to 199 acres	1,965	1,237	675	1,284	279	38	6
200 to 499 acres	-	296	870	5,463	1,536	133	18
500 to 999 acres	-	-	-	-	4,158	670	30
1,000 to 1,999 acres	-	-	-	-	-	2,813	268
2,000 acres or more	-	-	-	-	-	-	2,368
Cropland-							
Other pasture and grazing land that could have been used for crops without additional improvements ..... farms	256	216	241	766	398	211	65
acres	7,424	7,416	7,082	39,888	36,243	28,587	26,596
On which all crops failed or were abandoned ..... farms	212	159	91	399	347	191	125
acres	4,128	4,615	3,064	16,906	27,036	20,877	23,792
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed ..... farms	1,875	1,107	910	2,827	2,198	1,435	1,375
acres	118,887	74,992	69,308	271,439	257,575	218,943	233,656
In summer fallow ..... farms	185	119	81	331	232	133	67
acres	4,207	2,564	2,426	8,208	7,817	5,396	5,941

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
LAND USE - Con.							
Total woodland	farms	23,960	661	5,597	1,609	2,661	2,321
	acres	1,446,600	1,604	58,095	38,438	84,539	101,933
Woodland pastured	farms	7,908	258	1,803	434	735	710
	acres	315,103	574	13,383	6,486	14,362	19,258
Woodland not pastured	farms	19,456	460	4,352	1,355	2,224	1,920
	acres	1,131,497	1,030	44,712	31,952	70,177	82,675
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	19,837	1,266	5,368	1,175	1,707	1,475
	acres	1,031,215	4,002	54,834	23,100	41,976	51,410
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	42,652	2,702	10,277	2,401	3,739	3,243
	acres	1,420,750	7,989	80,300	33,975	66,363	77,204
Irrigated land	farms	3,625	559	723	104	176	158
	acres	648,313	799	3,844	1,403	4,129	6,061
Harvested cropland	farms	3,551	534	711	98	171	149
	acres	644,857	(D)	3,699	1,356	4,027	5,913
Pastureland and other land	farms	160	26	28	12	9	14
	acres	3,456	(D)	145	47	102	148
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	19,069	410	3,891	1,293	1,989	1,703
	acres	951,335	2,347	62,740	35,587	73,156	78,020
Land enrolled in crop insurance programs	farms	27,305	136	1,472	673	1,458	1,553
	acres	18,167,226	625	33,678	30,846	91,737	139,222
ORGANIC AGRICULTURE							
Total organic product sales	farms	577	32	90	23	34	52
	$1,000	121,783	1,931	10,794	1,391	1,076	3,695
VALUE OF LAND AND BUILDINGS							
Estimated market value of land and buildings	farms	65,531	4,401	15,218	3,598	5,575	4,857
	$1,000	155,374,449	1,059,036	5,080,787	1,581,143	2,746,237	3,161,149
Average per farm	dollars	2,371,007	240,635	333,867	439,450	492,599	650,844
Average per acre	dollars	6,107	47,907	12,756	7,483	6,031	5,566
Farms by value group:							
$1 to $49,999		1,819	1,086	699	17	6	2
$50,000 to $99,999		2,318	558	1,521	139	61	13
$100,000 to $199,999		5,817	834	3,197	519	798	360
$200,000 to $499,999		17,490	1,413	6,969	1,808	2,488	1,838
$500,000 to $999,999		13,050	396	2,423	946	1,851	1,819
$1,000,000 to $1,999,999		8,615	88	301	139	336	749
$2,000,000 to $4,999,999		8,631	22	100	27	25	63
$5,000,000 to $9,999,999		3,992	4	8	3	10	13
$10,000,000 or more		3,799	-	-	-	-	-
VALUE OF MACHINERY AND EQUIPMENT							
Estimated market value of all machinery and equipment	farms	65,531	4,401	15,218	3,598	5,575	4,857
	$1,000	17,904,134	303,341	908,036	263,754	414,758	520,892
Farms by value group:							
$1 to $4,999		3,305	538	1,511	247	348	233
$5,000 to $9,999		3,816	492	1,637	313	437	304
$10,000 to $19,999		6,447	757	2,509	586	814	539
$20,000 to $49,999		12,383	1,178	4,404	1,011	1,538	1,235
$50,000 to $99,999		10,506	729	2,860	706	1,190	1,099
$100,000 to $199,999		9,020	390	1,463	436	798	798
$200,000 to $499,999		9,719	241	674	223	363	521
$500,000 or more		10,335	76	160	76	87	128
SELECTED MACHINERY AND EQUIPMENT							
Trucks, including pickups	farms	51,156	2,927	10,215	2,412	3,767	3,502
	number	127,301	4,589	15,442	3,881	6,056	5,955
Tractors, all	farms	52,770	2,545	10,422	2,648	4,131	3,833
	number	184,473	4,348	20,780	6,381	10,277	10,734
Less than 40 horsepower (PTO)	farms	22,815	1,426	5,415	1,363	1,959	1,711
	number	36,863	1,864	7,939	2,097	3,025	2,776
40 to 99 horsepower (PTO)	farms	35,619	1,311	6,629	1,800	2,853	2,724
	number	60,537	1,679	9,245	2,790	4,469	4,533
100 horsepower (PTO) or more	farms	31,912	510	2,444	934	1,690	1,967
	number	87,073	805	3,596	1,494	2,783	3,425
Grain and bean combines, self-propelled	farms	21,753	139	943	424	892	1,006
	number	25,736	153	1,037	465	971	1,119
Cotton pickers and strippers, self-propelled	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	2,195	47	215	77	95	134
	number	2,384	51	234	87	109	148
Hay balers	farms	19,296	492	3,355	975	1,416	1,533
	number	24,300	563	3,923	1,210	1,798	1,966

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
LAND USE - Con.								
Total woodland	farms	2,058	1,406	1,094	3,370	1,969	836	378
	acres	119,923	94,174	82,782	328,175	254,944	140,990	141,003
Woodland pastured	farms	660	509	378	1,299	730	309	83
	acres	24,749	18,669	15,991	78,136	65,041	34,481	23,973
Woodland not pastured	farms	1,699	1,128	914	2,737	1,645	691	331
	acres	95,174	75,505	66,791	250,039	189,903	106,509	117,030
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	1,415	1,025	854	2,727	1,812	739	274
	acres	61,730	47,355	46,387	203,239	211,153	154,562	131,467
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	3,172	2,013	1,751	5,702	3,965	2,204	1,483
	acres	84,388	64,075	61,723	240,366	211,330	186,645	306,392
Irrigated land	farms	121	111	98	423	478	368	306
	acres	6,927	7,815	7,323	53,545	105,801	150,689	299,977
Harvested cropland	farms	113	110	94	421	477	368	305
	acres	6,686	(D)	6,999	52,425	105,020	150,416	299,762
Pastureland and other land	farms	10	1	12	14	20	5	9
	acres	241	(D)	324	1,120	781	273	215
CONSERVATION AND CROP INSURANCE								
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	1,577	880	721	2,281	1,803	1,272	1,249
	acres	95,614	55,571	53,042	186,694	137,028	93,620	77,916
Land enrolled in crop insurance programs	farms	2,060	1,391	1,310	5,706	5,395	3,514	2,637
	acres	249,733	207,653	238,983	1,681,371	3,182,314	4,289,947	8,021,117
ORGANIC AGRICULTURE								
Total organic product sales	farms	39	29	23	121	63	45	26
	$1,000	2,112	1,742	3,285	25,262	27,245	28,499	14,750
VALUE OF LAND AND BUILDINGS								
Estimated market value of land and buildings	farms	4,814	2,981	2,503	8,699	6,421	3,752	2,712
	$1,000	3,935,526	3,122,724	3,170,860	17,434,007	26,707,052	32,467,510	54,908,417
Average per farm	dollars	817,517	1,047,542	1,266,824	2,004,139	4,159,329	8,653,388	20,246,466
Average per acre	dollars	5,197	5,310	5,331	5,568	5,977	6,275	6,051
Farms by value group:								
$1 to $49,999		6	2	-	1	-	-	-
$50,000 to $99,999		16	6	-	2	2	-	-
$100,000 to $199,999		84	17	3	3	2	-	-
$200,000 to $499,999		1,490	702	367	409	6	-	-
$500,000 to $999,999		1,693	990	779	1,808	344	1	-
$1,000,000 to $1,999,999		1,373	986	853	2,618	1,057	114	1
$2,000,000 to $4,999,999		141	265	500	3,657	2,850	859	122
$5,000,000 to $9,999,999		11	9	1	201	2,020	1,396	316
$10,000,000 or more		-	4	-	-	140	1,382	2,273
VALUE OF MACHINERY AND EQUIPMENT								
Estimated market value of all machinery and equipment	farms	4,814	2,981	2,503	8,699	6,421	3,752	2,712
	$1,000	544,877	452,342	415,375	2,286,574	3,338,674	3,482,396	4,973,115
Farms by value group:								
$1 to $4,999		148	100	42	102	32	4	-
$5,000 to $9,999		257	107	75	167	20	6	1
$10,000 to $19,999		388	215	188	352	84	14	1
$20,000 to $49,999		1,064	524	379	817	202	22	9
$50,000 to $99,999		1,162	641	492	1,149	371	81	26
$100,000 to $199,999		994	668	607	1,902	764	161	39
$200,000 to $499,999		660	556	564	2,864	2,150	730	173
$500,000 or more		141	170	156	1,346	2,798	2,734	2,463
SELECTED MACHINERY AND EQUIPMENT								
Trucks, including pickups	farms	3,661	2,400	2,098	7,746	6,081	3,664	2,683
	number	6,666	4,546	4,252	18,341	19,966	17,676	19,931
Tractors, all	farms	3,933	2,535	2,229	7,987	6,163	3,659	2,685
	number	12,106	8,791	8,040	33,028	30,857	21,387	17,744
Less than 40 horsepower (PTO)	farms	1,758	1,086	941	3,114	2,212	1,114	716
	number	2,860	1,899	1,511	5,286	3,956	2,173	1,477
40 to 99 horsepower (PTO)	farms	2,880	1,836	1,683	5,831	4,319	2,304	1,449
	number	4,985	3,334	3,120	10,894	8,263	4,610	2,615
100 horsepower (PTO) or more	farms	2,311	1,740	1,587	6,672	5,815	3,588	2,654
	number	4,261	3,558	3,409	16,848	18,638	14,604	13,652
Grain and bean combines, self-propelled	farms	1,340	1,010	908	4,411	4,826	3,288	2,566
	number	1,482	1,115	995	4,860	5,572	4,021	3,946
Cotton pickers and strippers, self-propelled	farms	-	-	-	-	-	-	-
	number	-	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	133	100	89	467	452	264	122
	number	142	108	107	507	478	277	136
Hay balers	farms	1,572	1,134	970	3,579	2,565	1,183	522
	number	1,995	1,432	1,312	4,656	3,274	1,516	655

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
FERTILIZERS AND CHEMICALS						
Commercial fertilizer, lime, and soil conditioners used ..... farms	34,208	636	3,316	1,149	2,038	2,133
acres treated	14,076,782	1,952	51,816	37,987	99,106	147,856
Manure used ..... farms	13,721	391	2,142	582	886	914
acres treated	1,453,615	1,084	22,711	11,443	23,270	32,742
Organic fertilizer used ..... farms	1,053	149	253	52	56	79
acres treated	135,551	231	1,967	1,358	1,928	3,842
Acres treated to control-						
Insects ..... farms	13,847	368	1,322	409	698	691
acres	5,229,304	1,018	17,721	14,616	34,372	48,291
Weeds, grass, or brush ..... farms	34,397	532	3,386	1,263	2,202	2,266
acres	17,661,145	1,761	55,338	44,749	113,486	165,670
Nematodes ..... farms	3,288	50	260	113	183	194
acres	977,113	177	3,837	3,484	9,552	12,847
Diseases in crops and orchards ..... farms	5,080	147	455	127	217	214
acres	2,350,398	408	5,899	4,073	10,814	14,908
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	1,762	64	215	63	94	89
acres on which used	318,341	122	3,006	1,903	3,603	4,420
LAND USE PRACTICES						
Land drained by tile ..... farms	19,088	273	1,887	643	1,050	1,080
acres	8,247,260	989	29,551	19,859	54,330	76,279
Land artificially drained by ditches ..... farms	9,435	181	1,124	359	529	553
acres	4,560,910	763	16,528	9,383	20,519	28,319
Land under conservation easement ..... farms	4,909	29	841	335	548	451
acres	282,171	72	8,632	6,341	14,694	15,333
Cropland on which no-till practices were used ..... farms	6,845	238	895	263	412	468
acres	1,194,987	496	9,404	5,929	14,615	20,906
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ..... farms	15,574	193	1,267	429	786	818
acres	7,881,385	584	17,296	13,468	35,367	50,374
Cropland on which intensive or conventional tillage practices were used (see text) ..... farms	22,330	395	2,510	896	1,522	1,517
acres	9,573,777	1,324	38,567	28,304	72,858	106,942
Cropland planted to a cover crop (excluding CRP) ..... farms	6,050	169	781	201	369	348
acres	760,423	320	6,235	3,449	9,038	12,683
Use of precision agriculture practices (see text) ..... farms	15,460	196	942	380	742	730
RENEWABLE ENERGY						
Renewable energy producing systems (see text) ..... farms	4,247	245	880	207	266	253
Solar panels ..... farms	2,063	166	543	132	146	144
Wind turbines ..... farms	819	16	53	20	32	28
Methane digesters ..... farms	15	6	-	-	-	-
Geothermal/geoexchange systems ..... farms	1,695	78	331	74	111	97
Small hydro systems ..... farms	24	7	3	-	1	1
Wind rights leased to others ..... farms	1,189	37	127	43	74	69
TENURE						
Full owners ..... farms	40,396	3,949	13,313	2,884	4,471	3,504
Part owners ..... farms	20,564	79	1,175	461	731	982
Tenants ..... farms	4,571	373	730	253	373	371
OWNED AND RENTED LAND						
Land owned ..... farms	61,213	4,028	14,546	3,363	5,231	4,516
acres	15,768,785	97,713	892,494	383,958	631,244	734,119
Owned land in farms ..... farms	60,960	4,028	14,488	3,345	5,202	4,486
acres	13,006,137	20,626	361,687	183,268	395,951	468,324
Land rented or leased from others ..... farms	25,328	463	1,949	720	1,121	1,367
acres	12,515,140	1,941	45,237	29,788	63,221	104,321
Rented or leased land in farms ..... farms	25,135	452	1,905	714	1,104	1,353
acres	12,436,488	1,480	36,632	28,023	59,397	99,571
Land rented or leased to others ..... farms	15,946	703	4,339	1,382	1,651	1,686
acres	2,841,300	77,548	539,412	202,455	239,117	270,545
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS						
Total producers	118,256	7,723	27,153	6,589	10,030	8,684
Farms by number of producers:						
1 producer	28,348	1,797	6,071	1,462	2,383	2,214
2 producers	28,866	2,178	7,757	1,701	2,520	2,109
3 producers	4,480	250	700	229	326	249
4 producers	2,500	109	438	128	228	179
5 or more producers	1,337	67	252	78	118	106
Total male producers	81,062	4,740	16,826	4,213	6,748	5,774
Farms by number of male producers:						
1 producer	49,919	3,458	12,262	2,803	4,357	3,857
2 producers	8,600	377	1,236	425	517	512
3 producers	2,596	110	313	100	233	124
4 producers	766	19	122	32	85	58
5 or more producers	459	22	86	21	54	36
Total female producers	37,193	2,983	10,327	2,376	3,282	2,910
Farms by number of female producers:						
1 producer	29,936	2,542	8,629	1,835	2,752	2,290
2 producers	2,374	139	575	162	176	162
3 producers	466	39	105	41	35	39

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
FERTILIZERS AND CHEMICALS							
Commercial fertilizer, lime, and soil conditioners used ..... farms	2,636	1,810	1,670	6,724	5,790	3,624	2,682
acres treated	246,193	205,098	224,700	1,479,303	2,584,427	3,307,675	5,690,669
Manure used ..... farms	963	731	634	2,564	2,194	1,160	560
acres treated	45,037	39,073	36,569	225,321	345,133	352,146	319,086
Organic fertilizer used ..... farms	62	25	32	138	128	58	21
acres treated	4,267	1,627	2,836	20,561	37,377	28,719	30,838
Acres treated to control-							
Insects ..... farms	843	582	528	2,530	2,694	1,920	1,262
acres	79,974	61,390	69,364	491,805	993,912	1,308,371	2,108,470
Weeds, grass, or brush ..... farms	2,671	1,836	1,661	6,613	5,717	3,587	2,663
acres	281,137	230,612	257,921	1,713,229	3,102,800	4,142,143	7,552,299
Nematodes ..... farms	219	143	137	562	626	468	333
acres	19,639	15,135	16,053	99,614	203,212	243,760	349,803
Diseases in crops and orchards ..... farms	284	141	170	731	981	885	728
acres	27,333	15,311	22,082	148,090	353,802	596,848	1,150,830
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	88	69	78	244	242	278	238
acres on which used	5,868	5,631	8,232	35,548	41,944	78,304	129,760
LAND USE PRACTICES							
Land drained by tile ..... farms	1,418	872	907	3,741	3,442	2,207	1,568
acres	140,257	108,124	139,386	878,122	1,626,472	2,034,030	3,139,861
Land artificially drained by ditches ..... farms	622	428	358	1,573	1,522	1,180	1,006
acres	44,996	37,618	38,894	282,566	566,005	1,073,600	2,441,719
Land under conservation easement ..... farms	486	246	243	704	537	324	165
acres	25,417	15,492	16,406	56,546	41,073	37,647	44,518
Cropland on which no-till practices were used ..... farms	409	323	274	1,114	1,231	761	457
acres	26,623	22,124	23,685	141,121	295,176	350,974	283,934
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ..... farms	997	743	701	3,112	2,875	1,993	1,660
acres	87,155	79,088	93,859	697,119	1,300,429	1,785,809	3,720,837
Cropland on which intensive or conventional tillage practices were used (see text) ..... farms	1,847	1,207	1,086	4,170	3,394	2,184	1,602
acres	180,084	142,643	156,365	957,665	1,643,778	2,128,320	4,116,927
Cropland planted to a cover crop (excluding CRP) ..... farms	337	250	215	1,003	1,030	788	559
acres	15,072	12,989	12,918	77,867	141,953	214,608	253,291
Use of precision agriculture practices (see text) ..... farms	947	626	621	2,922	3,464	2,414	1,476
RENEWABLE ENERGY							
Renewable energy producing systems (see text) ..... farms	224	178	118	594	552	428	302
Solar panels ..... farms	88	86	43	263	196	142	114
Wind turbines ..... farms	56	40	25	163	175	125	86
Methane digesters ..... farms	-	-	-	-	3	5	1
Geothermal/geoexchange systems ..... farms	91	62	57	223	225	203	143
Small hydro systems ..... farms	-	1	3	3	3	1	1
Wind rights leased to others ..... farms	88	71	44	217	224	142	53
TENURE							
Full owners ..... farms	3,453	1,808	1,489	3,651	1,418	337	119
Part owners ..... farms	995	974	821	4,336	4,528	3,114	2,368
Tenants ..... farms	366	199	193	712	475	301	225
OWNED AND RENTED LAND							
Land owned ..... farms	4,472	2,794	2,330	8,018	5,959	3,463	2,493
acres	868,732	615,674	590,486	2,485,410	2,733,332	2,356,967	3,378,656
Owned land in farms ..... farms	4,448	2,782	2,310	7,987	5,946	3,451	2,487
acres	622,133	459,800	452,729	2,099,770	2,469,146	2,222,555	3,250,148
Land rented or leased from others ..... farms	1,386	1,187	1,021	5,075	5,012	3,427	2,600
acres	141,413	132,597	144,613	1,038,789	2,008,080	2,963,905	5,841,235
Rented or leased land in farms ..... farms	1,361	1,173	1,014	5,048	5,003	3,415	2,593
acres	135,205	128,338	142,047	1,031,088	1,999,349	2,951,140	5,824,218
Land rented or leased to others ..... farms	1,264	809	623	1,678	987	499	325
acres	252,807	160,133	140,323	393,341	272,917	147,177	145,525
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS							
Total producers	8,499	5,149	4,442	15,325	11,510	7,419	5,733
Farms by number of producers:							
1 producer	2,203	1,437	1,152	4,157	2,985	1,499	988
2 producers	2,009	1,202	1,069	3,404	2,463	1,451	1,003
3 producers	333	166	155	628	598	456	390
4 producers	184	108	69	350	255	223	229
5 or more producers	85	68	58	160	120	123	102
Total male producers	5,867	3,635	3,122	11,165	8,639	5,742	4,591
Farms by number of male producers:							
1 producer	3,729	2,375	1,950	6,682	4,677	2,298	1,471
2 producers	628	338	340	1,276	1,212	942	797
3 producers	171	110	80	369	305	366	315
4 producers	55	21	18	110	82	84	80
5 or more producers	29	29	25	53	45	19	40
Total female producers	2,632	1,514	1,320	4,160	2,871	1,677	1,141
Farms by number of female producers:							
1 producer	2,078	1,252	1,045	3,310	2,307	1,174	722
2 producers	179	109	78	278	201	148	167
3 producers	32	12	27	53	32	37	14

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS - Con.						
Total producers - Con.						
Total female producers - Con.						
Farms by number of female producers: - Con.						
4 producers	138	4	32	3	10	21
5 or more producers	90	5	16	12	6	17
PRODUCERS' CHARACTERISTICS [3]						
Sex of producers:						
Male	79,245	4,661	16,392	4,123	6,591	5,576
Female	35,623	2,946	10,053	2,252	3,194	2,743
Hired managers	6,902	307	608	151	178	161
Primary occupation:						
Farming	51,122	2,286	7,222	2,029	3,150	2,899
Other	63,746	5,321	19,223	4,346	6,635	5,420
Place of residence:						
On farm operated	79,195	5,602	19,240	4,008	5,880	5,189
Not on farm operated	35,673	2,005	7,205	2,367	3,905	3,130
Days of work off farm:						
None	46,862	2,264	8,401	2,287	3,680	3,303
Any	68,006	5,343	18,044	4,088	6,105	5,016
1 to 49 days	9,840	582	2,066	584	894	680
50 to 99 days	4,745	331	968	209	356	298
100 to 199 days	8,361	547	1,860	498	702	628
200 days or more	45,060	3,883	13,150	2,797	4,153	3,410
Years on present farm:						
2 years or less	4,867	619	1,637	347	401	361
3 or 4 years	7,650	1,003	2,402	486	660	532
5 to 9 years	18,524	2,110	5,642	1,124	1,684	1,233
10 years or more	83,827	3,875	16,764	4,418	7,040	6,193
Average years on present farm	24.2	16.0	19.6	21.8	23.0	24.3
Years operating any farm:						
5 years or less	13,846	1,845	4,399	919	1,261	867
6 to 10 years	15,740	1,667	5,069	1,013	1,455	1,119
11 years or more	85,282	4,095	16,977	4,443	7,069	6,333
Average years on any farm	26.1	18.2	21.4	23.7	24.9	26.4
Age group:						
Under 25 years	1,900	200	506	93	114	100
25 to 34 years	9,374	975	2,253	491	734	489
35 to 44 years	16,237	1,568	4,259	833	1,082	1,002
45 to 54 years	16,743	1,337	4,082	889	1,244	1,090
55 to 64 years	29,818	1,661	6,530	1,628	2,612	2,132
65 to 74 years	27,187	1,354	5,934	1,556	2,519	2,178
75 years and over	13,609	512	2,881	885	1,480	1,328
Average age	57.1	52.0	56.0	58.1	59.2	59.7
Young producers (see text)	11,274	1,175	2,759	584	848	589
Producers of Hispanic, Latino, or Spanish origin	754	68	206	55	45	38
Producers by race:						
American Indian or Alaska Native	244	15	71	14	14	16
Asian	306	80	114	11	35	10
Black or African American	61	6	22	4	12	5
Native Hawaiian or Other Pacific Islander	43	1	20	8	1	2
White	113,864	7,455	26,126	6,317	9,695	8,265
More than one race reported	350	50	92	21	28	21
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	105,603	7,049	24,082	5,756	8,836	7,521
Active duty now or in the past (see text)	9,265	558	2,363	619	949	798
Number of persons living in producers' households	228,210	15,270	49,515	12,108	18,273	15,997
On farm involvement in decisionmaking:						
Day-to-day decisions	98,292	6,599	22,421	5,274	8,197	6,884
Land use and/or crop decisions	83,860	4,766	17,866	4,377	6,949	5,826
Livestock decisions	49,585	4,372	12,766	2,665	3,644	3,308
Marketing decisions (see text)	68,020	4,279	12,660	3,038	4,867	4,410
Record keeping and/or financial management	84,043	5,344	17,653	4,365	6,758	5,928
Estate planning or succession planning	64,079	3,467	12,768	3,288	5,066	4,554
FARMS BY TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	62,111	4,188	14,668	3,424	5,298	4,631
Operation more than 50 percent owned by one producer's household and/or extended family — acres	22,990,670	21,153	384,376	201,042	432,873	541,791
Limited Liability Company — farms	4,803	584	1,132	233	284	285
Limited Liability Company — acres	2,179,815	2,461	27,682	13,699	22,939	33,516

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS - Con.							
Total producers - Con.							
Total female producers - Con.							
Farms by number of female producers: - Con.							
4 producers	17	2	5	18	4	14	8
5 or more producers	5	-	2	7	10	8	2
PRODUCERS' CHARACTERISTICS [3]							
Sex of producers:							
Male	5,785	3,555	3,007	10,939	8,489	5,658	4,469
Female	2,511	1,488	1,256	3,950	2,716	1,495	1,019
Hired managers	157	164	169	715	1,329	1,562	1,401
Primary occupation:							
Farming	3,265	2,217	1,996	8,276	7,812	5,512	4,458
Other	5,031	2,826	2,267	6,613	3,393	1,641	1,030
Place of residence:							
On farm operated	5,047	3,387	2,913	10,439	8,468	5,313	3,709
Not on farm operated	3,249	1,656	1,350	4,450	2,737	1,840	1,779
Days of work off farm:							
None	3,274	2,079	1,698	6,624	5,792	4,143	3,317
Any	5,022	2,964	2,565	8,265	5,413	3,010	2,171
1 to 49 days	707	427	399	1,330	1,076	652	443
50 to 99 days	364	243	186	727	506	324	233
100 to 199 days	646	358	363	1,187	846	430	296
200 days or more	3,305	1,936	1,617	5,021	2,985	1,604	1,199
Years on present farm:							
2 years or less	354	173	146	400	226	145	58
3 or 4 years	448	244	190	754	428	230	273
5 to 9 years	1,138	719	476	1,883	1,198	832	485
10 years or more	6,356	3,907	3,451	11,852	9,353	5,946	4,672
Average years on present farm	25.7	26.6	28.2	27.9	29.3	28.7	27.9
Years operating any farm:							
5 years or less	950	490	380	1,288	693	439	315
6 to 10 years	908	581	418	1,496	1,041	638	335
11 years or more	6,438	3,972	3,465	12,105	9,471	6,076	4,838
Average years on any farm	27.6	28.6	29.9	29.8	31.2	30.8	30.2
Age group:							
Under 25 years	86	73	51	233	204	155	85
25 to 34 years	563	410	242	1,106	963	651	497
35 to 44 years	841	609	447	1,913	1,537	1,199	947
45 to 54 years	1,075	606	540	1,982	1,631	1,159	1,108
55 to 64 years	2,117	1,287	1,201	3,957	3,159	1,998	1,536
65 to 74 years	2,245	1,283	1,117	3,892	2,663	1,451	995
75 years and over	1,369	775	665	1,806	1,048	540	320
Average age	60.0	58.7	60.0	58.0	56.4	54.6	53.8
Young producers (see text)	649	483	293	1,339	1,167	806	582
Producers of Hispanic, Latino, or Spanish origin	73	20	12	63	48	75	51
Producers by race:							
American Indian or Alaska Native	31	11	10	11	21	16	14
Asian	11	11	6	14	4	4	6
Black or African American	2	5	1	2	1	1	-
Native Hawaiian or Other Pacific Islander	1	-	-	5	1	4	-
White	8,230	5,003	4,232	14,831	11,161	7,107	5,442
More than one race reported	21	13	14	26	17	21	26
Military service:							
Never served or only on active duty for training in the Reserves or National Guard (see text)	7,419	4,586	3,871	13,787	10,610	6,818	5,268
Active duty now or in the past (see text)	877	457	392	1,102	595	335	220
Number of persons living in producers' households	16,157	9,753	8,336	29,588	23,365	16,671	13,177
On farm involvement in decisionmaking:							
Day-to-day decisions	6,951	4,261	3,572	12,923	9,913	6,359	4,938
Land use and/or crop decisions	6,189	3,787	3,258	11,489	8,892	5,860	4,601
Livestock decisions	3,153	2,214	1,846	6,420	4,847	2,780	1,570
Marketing decisions (see text)	4,700	3,050	2,710	10,111	8,385	5,519	4,291
Record keeping and/or financial management	6,111	3,754	3,304	11,585	8,943	5,803	4,495
Estate planning or succession planning	4,664	2,861	2,601	9,025	7,206	4,845	3,734
FARMS BY TYPE OF ORGANIZATION							
Operation more than 50 percent owned by one producer's household and/or extended family — farms	4,569	2,827	2,400	8,273	6,025	3,439	2,369
Operation more than 50 percent owned by one producer's household and/or extended family — acres	718,749	557,577	570,219	2,977,165	4,187,604	4,725,841	7,672,280
Limited Liability Company — farms	244	189	147	580	493	350	282
Limited Liability Company — acres	37,854	37,094	34,917	210,365	351,113	482,035	926,140

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
LEGAL STATUS FOR TAX PURPOSES							
Family or individual	farms	55,532	3,795	13,808	3,194	4,933	4,311
	acres	17,410,756	19,512	362,247	187,534	402,547	504,220
Partnership	farms	5,022	252	610	190	303	270
	acres	4,452,974	1,097	16,334	11,308	24,854	31,521
Registered under State law	farms	4,156	214	494	162	231	205
	acres	3,904,476	928	13,041	9,643	18,895	24,059
Corporation	farms	3,803	274	526	123	218	170
	acres	3,244,861	1,181	12,612	7,145	18,025	19,783
Family held	farms	3,375	231	408	97	181	143
	acres	3,085,380	1,026	9,871	5,585	15,043	16,698
More than 10 stockholders	farms	34	7	-	4	-	1
10 or less stockholders	farms	3,341	224	408	93	181	142
Other than family held	farms	428	43	118	26	37	27
	acres	159,481	155	2,741	1,560	2,982	3,085
More than 10 stockholders	farms	67	3	28	5	6	1
10 or less stockholders	farms	361	40	90	21	31	26
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	farms	1,174	80	274	91	121	106
	acres	334,034	316	7,126	5,304	9,922	12,371
HIRED FARM LABOR							
Hired farm labor	farms	17,399	818	2,092	496	769	808
	workers	72,097	4,331	7,848	2,046	2,291	2,870
Workers by days worked:							
150 days or more	farms	9,054	408	912	228	332	348
	workers	30,983	1,965	3,331	733	840	1,387
Less than 150 days	farms	12,949	610	1,564	371	552	611
	workers	41,114	2,366	4,517	1,313	1,451	1,483
Migrant farm labor on farms with hired labor	farms	573	26	44	8	8	12
Migrant farm labor on farms reporting only contract labor	farms	41	4	9	3	2	1
Unpaid workers	farms	17,519	1,373	4,292	965	1,444	1,331
	workers	40,333	3,205	10,182	2,205	3,229	3,244
FARMS BY SIZE							
1 to 9 acres		4,401	4,401	-	-	-	-
10 to 49 acres		15,218	-	15,218	-	-	-
50 to 69 acres		3,598	-	-	3,598	-	-
70 to 99 acres		5,575	-	-	-	5,575	-
100 to 139 acres		4,857	-	-	-	-	4,857
140 to 179 acres		4,814	-	-	-	-	-
180 to 219 acres		2,981	-	-	-	-	-
220 to 259 acres		2,503	-	-	-	-	-
260 to 499 acres		8,699	-	-	-	-	-
500 to 999 acres		6,421	-	-	-	-	-
1,000 to 1,999 acres		3,752	-	-	-	-	-
2,000 acres or more		2,712	-	-	-	-	-
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)							
Oilseed and grain farming (1111)		26,315	262	2,239	854	1,631	1,706
Vegetable and melon farming (1112)		1,072	331	402	47	60	43
Fruit and tree nut farming (1113)		972	248	509	42	74	33
Greenhouse, nursery, and floriculture production (1114)		971	300	358	56	69	55
Other crop farming (1119)		18,104	623	5,447	1,570	2,522	1,971
Tobacco farming (11191)		-	-	-	-	-	-
Cotton farming (11192)		-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)		18,104	623	5,447	1,570	2,522	1,971
Beef cattle ranching and farming (112111)		6,753	676	2,127	445	649	557
Cattle feedlots (112112)		892	66	136	45	47	62
Dairy cattle and milk production (11212)		1,713	37	72	35	37	52
Hog and pig farming (1122)		1,855	389	433	48	77	60
Poultry and egg production (1123)		1,724	346	852	90	115	77
Sheep and goat farming (1124)		1,456	425	739	86	75	63
Aquaculture and other animal production (1125,1129)		3,704	698	1,904	280	219	178
FARM TYPOLOGY (SEE TEXT)							
Farms by typology group:							
Small family farms							
Gross cash farm income less than $150,000		41,924	3,866	14,140	3,281	5,070	4,278
Gross cash farm income $150,000 to $349,999		7,074	156	271	86	159	271
Midsize family farms							
Gross cash farm income $350,000 to $999,999		7,367	91	110	28	40	50
Large family farms							
Gross cash farm income $1,000,000 to $4,999,999		5,311	55	104	23	19	18
Gross cash farm income $5,000,000 or more		435	20	43	6	10	14
Non-family farms		3,420	213	550	174	277	226
OTHER FARM CHARACTERISTICS							
Farms reporting-							
Internet access		53,964	3,733	12,255	2,838	4,238	3,741
Dial-up		1,876	112	439	106	174	123
Broadband (DSL, cable, fiber optic) (see text)		33,399	2,269	7,553	1,813	2,616	2,243
Cellular data plan (see text)		32,121	2,160	6,938	1,545	2,441	2,145
Satellite		8,385	562	1,881	396	596	482
Don't know		2,877	179	627	162	245	273
Other		346	31	69	21	18	20

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
LEGAL STATUS FOR TAX PURPOSES								
Family or individual	farms	4,196	2,632	2,188	7,449	5,030	2,543	1,453
	acres	660,652	519,500	519,714	2,678,241	3,471,537	3,461,198	4,623,854
Partnership	farms	349	193	167	713	704	558	713
	acres	54,472	37,821	39,898	259,511	496,988	781,175	2,697,995
Registered under State law	farms	262	166	129	579	595	490	629
	acres	40,863	32,598	30,688	212,127	420,829	683,576	2,417,229
Corporation	farms	159	90	94	398	610	609	532
	acres	24,949	17,758	22,338	145,234	446,112	873,228	1,656,496
Family held	farms	140	77	84	337	583	577	517
	acres	21,995	15,093	20,025	123,386	427,757	827,213	1,601,688
More than 10 stockholders	farms	-	1	-	6	13	1	1
10 or less stockholders	farms	140	76	84	331	570	576	516
Other than family held	farms	19	13	10	61	27	32	15
	acres	2,954	2,665	2,313	21,848	18,355	46,015	54,808
More than 10 stockholders	farms	2	1	2	3	5	9	2
10 or less stockholders	farms	17	12	8	58	22	23	13
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	farms	110	66	54	139	77	42	14
	acres	17,265	13,059	12,826	47,872	53,858	58,094	96,021
HIRED FARM LABOR								
Hired farm labor	farms	765	609	562	2,408	2,915	2,708	2,449
	workers	1,927	2,047	1,484	7,660	10,582	13,211	15,800
Workers by days worked:								
150 days or more	farms	331	258	255	1,136	1,449	1,643	1,754
	workers	678	731	560	3,097	4,252	6,160	7,249
Less than 150 days	farms	575	452	403	1,733	2,142	2,035	1,901
	workers	1,249	1,316	924	4,563	6,330	7,051	8,551
Migrant farm labor on farms with hired labor	farms	3	10	5	48	94	114	201
Migrant farm labor on farms reporting only contract labor	farms	-	1	3	5	9	3	1
Unpaid workers	farms	1,265	754	663	2,440	1,750	871	371
	workers	2,789	1,705	1,595	5,600	3,899	1,910	770
FARMS BY SIZE								
1 to 9 acres		-	-	-	-	-	-	-
10 to 49 acres		-	-	-	-	-	-	-
50 to 69 acres		-	-	-	-	-	-	-
70 to 99 acres		-	-	-	-	-	-	-
100 to 139 acres		-	-	-	-	-	-	-
140 to 179 acres		4,814	-	-	-	-	-	-
180 to 219 acres		-	2,981	-	-	-	-	-
220 to 259 acres		-	-	2,503	-	-	-	-
260 to 499 acres		-	-	-	8,699	-	-	-
500 to 999 acres		-	-	-	-	6,421	-	-
1,000 to 1,999 acres		-	-	-	-	-	3,752	-
2,000 acres or more		-	-	-	-	-	-	2,712
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)								
Oilseed and grain farming (1111)		2,129	1,409	1,287	5,053	4,447	2,870	2,428
Vegetable and melon farming (1112)		22	15	11	58	33	38	12
Fruit and tree nut farming (1113)		21	12	9	19	3	1	1
Greenhouse, nursery, and floriculture production (1114)		26	22	10	49	19	7	-
Other crop farming (1119)		1,691	948	712	1,730	635	168	87
Tobacco farming (11191)		-	-	-	-	-	-	-
Cotton farming (11192)		-	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)		1,691	948	712	1,730	635	168	87
Beef cattle ranching and farming (112111)		508	266	248	725	377	135	40
Cattle feedlots (112112)		50	33	49	178	129	82	15
Dairy cattle and milk production (11212)		65	118	82	479	440	251	45
Hog and pig farming (1122)		64	52	33	235	251	162	51
Poultry and egg production (1123)		71	25	24	57	45	14	8
Sheep and goat farming (1124)		34	7	4	16	3	3	1
Aquaculture and other animal production (1125,1129)		133	74	34	100	39	21	24
FARM TYPOLOGY (SEE TEXT)								
Farms by typology group:								
Small family farms								
Gross cash farm income less than $150,000		3,796	1,994	1,403	3,130	838	123	5
Gross cash farm income $150,000 to $349,999		665	713	848	2,907	838	142	18
Midsize family farms								
Gross cash farm income $350,000 to $999,999		90	90	132	2,029	3,590	1,032	85
Large family farms								
Gross cash farm income $1,000,000 to $4,999,999		13	28	14	197	730	2,061	2,049
Gross cash farm income $5,000,000 or more		5	2	3	10	29	81	212
Non-family farms		245	154	103	426	396	313	343
OTHER FARM CHARACTERISTICS								
Farms reporting-								
Internet access		3,785	2,331	2,024	7,228	5,744	3,507	2,540
Dial-up		125	81	63	268	210	99	76
Broadband (DSL, cable, fiber optic) (see text)		2,298	1,409	1,216	4,447	3,468	2,349	1,718
Cellular data plan (see text)		2,215	1,368	1,183	4,336	3,713	2,391	1,686
Satellite		514	368	302	1,092	1,019	641	532
Don't know		233	141	121	412	280	107	97
Other		10	13	6	52	44	23	39

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
OTHER FARM CHARACTERISTICS - Con.						
Farms by number of households sharing in net income of operation:						
1 household	52,287	3,811	13,067	2,932	4,511	3,939
2 households	9,039	398	1,481	446	689	612
3 households	2,321	106	316	97	177	151
4 households	1,024	51	188	49	106	84
5 or more households	860	35	166	74	92	71
LIVESTOCK						
Cattle and calves inventory ... farms	16,823	851	2,984	802	1,141	1,249
number	2,121,625	27,463	171,743	30,230	49,412	57,330
Farms with-						
1 to 9	3,446	491	1,471	272	315	257
10 to 49	6,556	273	1,247	413	632	717
50 to 99	2,582	48	143	73	128	189
100 to 199	1,927	16	54	25	36	58
200 to 499	1,348	11	21	9	13	15
500 or more	964	12	48	10	17	13
Cows and heifers that calved ... farms	13,439	567	2,162	651	959	1,053
number	824,165	6,841	85,105	12,826	19,010	22,508
Beef cows ... farms	11,691	508	2,063	613	908	982
number	364,629	4,382	23,553	7,605	14,120	18,579
Farms with-						
1 to 9	3,718	365	1,277	326	397	349
10 to 49	6,113	139	757	270	482	592
50 to 99	1,205	2	20	17	24	33
100 to 199	470	2	4	-	4	4
200 to 499	149	-	3	-	1	3
500 or more	36	-	2	-	-	1
Milk cows ... farms	2,185	75	153	56	78	98
number	459,536	2,459	61,552	5,221	4,890	3,929
Farms with-						
1 to 9	328	42	86	31	41	43
10 to 49	315	21	29	5	19	35
50 to 99	573	5	16	9	8	14
100 to 199	418	4	4	-	7	4
200 to 499	390	3	4	10	2	1
500 or more	161	-	14	1	1	1
Other cattle ... farms	14,574	641	2,228	648	931	1,061
number	1,297,460	20,622	86,638	17,404	30,402	34,822
Cattle and calves sold ... farms	14,649	604	2,187	634	985	1,038
number	1,599,910	25,434	167,582	21,503	86,600	40,234
$1,000	2,094,135	34,227	163,057	29,576	91,382	44,362
Calves weighing less than 500 pounds ... farms	4,938	152	674	201	319	363
number	345,069	5,991	60,924	4,032	45,957	4,990
Cattle weighing 500 pounds or more ... farms	13,933	551	1,969	589	909	967
number	1,254,841	19,443	106,658	17,471	40,643	35,244
Cattle on feed ... farms	2,685	76	148	49	70	128
number	636,782	13,820	48,417	9,088	11,906	9,454
Hogs and pigs inventory ... farms	2,928	443	712	109	137	134
number	8,873,776	1,334,904	1,872,396	249,668	201,771	481,552
Farms with-						
1 to 24	893	143	352	70	77	87
25 to 49	93	17	20	4	3	9
50 to 99	71	4	5	7	5	3
100 to 199	65	1	5	3	-	2
200 to 499	116	6	23	-	5	-
500 or more	1,690	272	307	25	47	33
Hogs and pigs sold ... farms	3,352	519	783	114	167	132
number	28,535,462	4,048,949	7,868,737	581,716	806,227	1,458,936
$1,000	4,666,832	699,413	964,677	92,310	96,120	173,727
Sheep and lambs inventory ... farms	2,137	338	905	133	172	119
number	109,592	6,291	31,597	5,876	5,963	5,278
Sheep and lambs sold ... farms	1,500	238	610	89	116	70
number	92,512	3,848	23,040	3,555	5,589	3,648
Total horses and ponies inventory ... farms	6,988	591	2,958	566	627	517
number	40,131	2,806	16,959	3,545	3,743	3,278
Total horses and ponies sold ... farms	1,171	114	502	123	118	92
number	4,403	260	1,364	516	433	448
Goats, all inventory ... farms	2,326	430	1,024	164	162	153
number	50,691	7,214	16,522	3,285	5,522	4,113
Goats, all sold ... farms	1,215	221	531	97	85	82
number	38,339	4,540	19,150	1,913	2,983	1,936
POULTRY						
Layers inventory ... farms	6,146	979	2,697	407	515	408
number	14,553,497	2,711,693	1,136,671	63,870	65,700	(D)
Farms with-						
1 to 399	6,045	965	2,661	400	502	407
400 to 3,199	36	3	15	2	10	-
3,200 to 9,999	8	-	6	2	-	-
10,000 to 19,999	24	5	7	3	3	-
20,000 to 49,999	4	-	1	-	-	1
50,000 to 99,999	5	1	-	-	-	-
100,000 or more	24	5	7	-	-	-

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
OTHER FARM CHARACTERISTICS - Con.							
Farms by number of households sharing in net income of operation:							
1 household	3,786	2,410	1,992	6,786	4,799	2,522	1,732
2 households	711	380	364	1,378	1,157	831	592
3 households	165	92	86	290	327	272	242
4 households	97	65	14	136	76	77	81
5 or more households	55	34	47	109	62	50	65
LIVESTOCK							
Cattle and calves inventory ... farms	1,221	908	857	3,087	2,303	1,032	388
number	63,192	61,873	56,825	326,185	483,039	470,793	323,540
Farms with-							
1 to 9	184	109	75	177	73	14	8
10 to 49	693	426	408	1,126	468	117	36
50 to 99	221	206	200	752	476	122	24
100 to 199	78	116	121	621	573	168	61
200 to 499	31	41	48	343	459	263	94
500 or more	14	10	5	68	254	348	165
Cows and heifers that calved ... farms	1,070	772	701	2,531	1,857	830	286
number	25,593	29,569	23,016	123,539	181,184	164,528	130,446
Beef cows ... farms	992	659	621	2,082	1,439	590	234
number	21,126	16,562	16,037	69,045	77,804	55,382	40,434
Farms with-							
1 to 9	291	154	118	275	133	25	8
10 to 49	637	431	434	1,400	704	211	56
50 to 99	60	59	50	339	394	168	39
100 to 199	2	12	19	60	174	130	59
200 to 499	1	3	-	7	32	42	57
500 or more	1	-	-	1	2	14	15
Milk cows ... farms	103	138	88	537	512	281	66
number	4,467	13,007	6,979	54,494	103,380	109,146	90,012
Farms with-							
1 to 9	37	16	3	22	6	-	1
10 to 49	29	42	20	83	27	4	1
50 to 99	24	49	41	223	151	28	5
100 to 199	13	18	21	161	135	46	5
200 to 499	-	9	3	45	168	125	20
500 or more	-	4	-	3	25	78	34
Other cattle ... farms	1,031	802	795	2,867	2,195	998	377
number	37,599	32,304	33,809	202,646	301,855	306,265	193,094
Cattle and calves sold ... farms	1,072	803	790	2,894	2,241	1,019	382
number	39,321	36,120	35,242	216,000	332,292	354,383	245,199
$1,000	48,216	40,355	43,736	262,702	462,583	530,639	343,299
Calves weighing less than 500 pounds ... farms	361	312	280	1,009	792	352	123
number	6,786	8,406	6,576	46,662	54,031	48,607	52,107
Cattle weighing 500 pounds or more ... farms	1,004	761	765	2,813	2,215	1,016	374
number	32,535	27,714	28,666	169,338	278,261	305,776	193,092
Cattle on feed ... farms	133	104	151	638	659	384	145
number	9,687	9,122	11,599	74,866	139,634	183,182	116,007
Hogs and pigs inventory ... farms	112	112	68	322	321	303	155
number	331,318	142,084	118,452	649,824	1,007,124	1,330,730	1,153,953
Farms with-							
1 to 24	35	32	19	57	18	1	2
25 to 49	11	6	6	7	1	9	-
50 to 99	5	8	2	20	10	1	1
100 to 199	3	11	13	11	7	8	1
200 to 499	7	10	3	23	27	9	3
500 or more	51	45	25	204	258	275	148
Hogs and pigs sold ... farms	139	119	78	390	399	339	173
number	1,410,867	363,142	506,688	2,240,653	3,301,387	3,423,477	2,524,683
$1,000	160,178	69,147	57,464	434,815	673,789	754,107	491,085
Sheep and lambs inventory ... farms	83	31	33	168	90	55	10
number	3,312	2,672	1,716	18,255	12,667	13,240	2,725
Sheep and lambs sold ... farms	60	23	35	124	79	47	9
number	2,062	2,088	1,522	16,491	12,246	15,192	3,231
Total horses and ponies inventory ... farms	384	215	199	455	272	142	62
number	2,065	1,443	837	2,676	1,744	724	311
Total horses and ponies sold ... farms	49	27	19	66	25	31	5
number	183	104	69	737	164	99	26
Goats, all inventory ... farms	98	44	34	130	42	34	11
number	4,642	1,070	775	4,116	2,043	1,114	275
Goats, all sold ... farms	48	20	23	61	31	11	5
number	3,565	730	347	1,203	1,245	618	109
POULTRY							
Layers inventory ... farms	333	176	128	294	158	39	12
number	50,267	140,422	2,482,214	4,744,928	3,012,328	(D)	(D)
Farms with-							
1 to 399	330	172	121	286	152	38	11
400 to 3,199	-	1	3	2	-	-	-
3,200 to 9,999	-	-	-	-	-	-	-
10,000 to 19,999	3	-	-	1	1	1	-
20,000 to 49,999	-	2	-	-	-	-	-
50,000 to 99,999	-	1	-	1	1	-	1
100,000 or more	-	-	4	4	4	-	-

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
POULTRY - Con.						
Pullets for laying flock replacement inventory ..... farms	723	169	298	25	65	60
number	4,185,443	472,614	950,426	414	(D)	201,385
Layers sold ..... farms	664	129	326	44	46	21
number	7,016,481	1,203,683	297,998	773,124	39,947	(D)
Pullets for laying flock replacement sold ..... farms	102	32	47	-	2	-
number	8,319,040	1,162,825	2,400,906	-	(D)	-
Broilers and other meat-type chickens sold ..... farms	1,028	171	402	71	78	80
number	41,793,592	1,855,647	6,195,915	4,033,214	3,260,171	3,675,278
Farms with-						
1 to 1,999	900	164	379	60	71	67
2,000 to 59,999	11	1	2	2	-	-
60,000 to 99,999	-	-	-	-	-	-
100,000 or more	117	6	21	9	7	13
Turkeys inventory ..... farms	623	89	263	35	56	34
number	14,927,734	278,323	1,794,313	415,078	658,831	1,431,911
Turkeys sold ..... farms	379	43	133	25	27	25
number	39,460,145	655,715	4,267,246	1,575,395	1,834,566	3,698,465
CROPS						
Barley for grain ..... farms	336	-	5	1	1	12
acres	55,330	-	(D)	(D)	(D)	262
bushels	4,011,381	-	(D)	(D)	(D)	12,296
Irrigated ..... farms	10	-	-	-	-	2
acres	116	-	-	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	72	-	5	1	1	6
25 to 99 acres	96	-	-	-	-	6
100 to 249 acres	94	-	-	-	-	-
250 to 499 acres	53	-	-	-	-	-
500 acres or more	21	-	-	-	-	-
Corn for grain ..... farms	24,697	204	1,365	610	1,194	1,424
acres	7,732,455	770	21,401	17,313	47,095	70,645
bushels	1,478,451,268	117,101	3,374,176	2,858,541	8,157,101	12,266,737
Irrigated ..... farms	1,341	-	24	15	29	37
acres	302,897	-	496	494	1,181	1,894
Farms by acres harvested:						
1 to 24 acres	2,863	204	1,080	271	346	277
25 to 99 acres	6,867	-	285	339	848	1,032
100 to 249 acres	6,444	-	-	-	-	115
250 to 499 acres	4,136	-	-	-	-	-
500 acres or more	4,387	-	-	-	-	-
Corn for silage or greenchop ..... farms	2,768	5	82	50	85	131
acres	313,974	19	1,092	808	1,930	2,443
tons	6,334,518	106	16,272	12,651	31,408	45,265
Irrigated ..... farms	108	-	2	-	1	-
acres	13,135	-	(D)	-	(D)	-
Farms by acres harvested:						
1 to 24 acres	848	5	71	35	57	100
25 to 99 acres	1,133	-	11	15	28	31
100 to 249 acres	452	-	-	-	-	-
250 to 499 acres	218	-	-	-	-	-
500 acres or more	117	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas ..... farms	573	5	12	2	24	15
acres	210,162	(D)	156	(D)	1,259	722
cwt	5,278,245	(D)	8,445	(D)	46,810	33,158
Irrigated ..... farms	95	-	1	-	-	4
acres	39,931	-	(D)	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	34	5	8	2	9	2
25 to 99 acres	118	-	4	-	15	12
100 to 249 acres	146	-	-	-	-	1
250 to 499 acres	140	-	-	-	-	-
500 acres or more	135	-	-	-	-	-
Oats for grain ..... farms	2,329	2	104	38	85	136
acres	126,011	(D)	1,053	(D)	1,424	3,734
bushels	9,470,546	(D)	67,070	(D)	83,392	203,728
Irrigated ..... farms	66	-	1	-	-	2
acres	3,194	-	(D)	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	906	2	100	29	63	80
25 to 99 acres	1,097	-	4	9	22	53
100 to 249 acres	286	-	-	-	-	3
250 to 499 acres	29	-	-	-	-	-
500 acres or more	11	-	-	-	-	-
Sorghum for grain ..... farms	12	-	3	2	-	-
acres	364	-	5	(D)	-	-
bushels	24,260	-	430	(D)	-	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	7	-	3	2	-	-
25 to 99 acres	4	-	-	-	-	-
100 to 249 acres	1	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
POULTRY - Con.							
Pullets for laying flock replacement inventory ..... farms	23	16	17	36	13	1	-
number	2,491	(D)	533	1,188,060	907,361	(D)	-
Layers sold ..... farms	31	11	15	24	13	3	1
number	42,931	53,046	2,363,505	1,586,788	(D)	(D)	(D)
Pullets for laying flock replacement sold ..... farms	6	3	1	9	1	1	-
number	(D)	(D)	(D)	4,293,303	(D)	(D)	-
Broilers and other meat-type chickens sold ..... farms	54	30	22	70	39	10	1
number	5,082,182	(D)	1,979,423	8,470,809	4,791,889	1,266,010	(D)
Farms with-							
1 to 1,999	38	25	17	46	26	6	1
2,000 to 59,999	3	2	-	1	-	-	-
60,000 to 99,999	-	-	-	-	-	-	-
100,000 or more	13	3	5	23	13	4	-
Turkeys inventory ..... farms	26	27	15	21	28	11	18
number	912,968	548,662	702,555	2,072,106	1,802,250	1,972,172	2,338,565
Turkeys sold ..... farms	27	13	12	22	23	11	18
number	2,618,860	1,572,806	1,170,397	6,338,620	5,408,637	4,496,931	5,822,507
CROPS							
Barley for grain ..... farms	13	6	9	48	72	69	100
acres	170	325	268	3,405	9,180	9,687	31,979
bushels	6,793	24,200	10,681	181,692	660,483	705,578	2,408,114
Irrigated ..... farms	3	-	1	-	4	-	-
acres	(D)	-	(D)	-	86	-	-
Farms by acres harvested:							
1 to 24 acres	12	-	6	12	12	15	2
25 to 99 acres	1	6	3	28	22	19	11
100 to 249 acres	-	-	-	2	28	25	39
250 to 499 acres	-	-	-	6	10	7	30
500 acres or more	-	-	-	-	-	3	18
Corn for grain ..... farms	1,869	1,344	1,274	5,350	4,824	2,948	2,291
acres	121,580	101,001	116,694	789,095	1,421,075	1,749,336	3,276,450
bushels	21,635,996	18,129,604	21,187,686	145,365,091	269,508,521	335,608,340	640,242,374
Irrigated ..... farms	45	56	56	249	332	265	233
acres	2,429	4,114	3,814	23,294	52,314	71,669	141,198
Farms by acres harvested:							
1 to 24 acres	212	147	91	175	41	13	6
25 to 99 acres	1,398	859	600	1,158	268	52	28
100 to 249 acres	259	338	578	3,603	1,325	179	47
250 to 499 acres	-	-	5	414	2,899	679	139
500 acres or more	-	-	-	-	291	2,025	2,071
Corn for silage or greenchop ..... farms	147	166	133	633	700	397	239
acres	4,638	6,067	4,737	34,413	69,016	94,498	94,313
tons	75,992	107,659	87,843	649,149	1,398,577	1,955,521	1,954,075
Irrigated ..... farms	2	4	3	19	23	38	16
acres	(D)	170	105	763	1,892	6,458	3,580
Farms by acres harvested:							
1 to 24 acres	87	88	66	193	110	23	13
25 to 99 acres	53	65	61	339	351	128	51
100 to 249 acres	7	13	6	92	179	96	59
250 to 499 acres	-	-	-	9	56	102	51
500 acres or more	-	-	-	-	4	48	65
Dry edible beans, excluding chickpeas and limas ..... farms	13	5	7	44	95	109	242
acres	611	280	1,027	5,930	14,131	33,725	152,295
cwt	18,048	13,430	34,615	182,045	354,971	900,061	3,685,718
Irrigated ..... farms	1	-	-	5	20	12	52
acres	(D)	-	-	519	2,671	3,198	33,345
Farms by acres harvested:							
1 to 24 acres	4	2	-	1	-	-	1
25 to 99 acres	8	2	2	23	34	14	4
100 to 249 acres	1	1	5	14	53	32	39
250 to 499 acres	-	-	-	6	6	39	89
500 acres or more	-	-	-	-	2	24	109
Oats for grain ..... farms	160	172	125	568	515	287	137
acres	4,221	5,893	4,913	26,084	32,734	22,928	22,473
bushels	266,930	311,715	309,480	1,696,121	2,298,157	2,031,057	2,171,412
Irrigated ..... farms	1	2	1	11	23	15	10
acres	(D)	(D)	(D)	146	1,298	632	970
Farms by acres harvested:							
1 to 24 acres	104	81	55	231	111	38	12
25 to 99 acres	50	82	58	292	293	172	62
100 to 249 acres	6	9	12	39	102	71	44
250 to 499 acres	-	-	-	6	9	6	8
500 acres or more	-	-	-	-	-	-	11
Sorghum for grain ..... farms	-	-	-	3	2	1	1
acres	-	-	-	38	(D)	(D)	(D)
bushels	-	-	-	(D)	(D)	(D)	(D)
Irrigated ..... farms	-	-	-	-	-	-	-
acres	-	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres	-	-	-	2	-	-	-
25 to 99 acres	-	-	-	1	2	-	1
100 to 249 acres	-	-	-	-	-	1	-
250 to 499 acres	-	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
CROPS - Con.							
Soybeans for beans	farms	25,337	142	1,372	584	1,189	1,385
	acres	7,597,171	554	23,725	19,133	51,669	75,353
	bushels	373,669,175	27,446	1,029,872	868,770	2,509,937	3,619,090
Irrigated	farms	892	4	31	5	19	33
	acres	122,734	4	673	124	889	1,945
Farms by acres harvested:							
1 to 24 acres		2,307	142	1,022	206	247	222
25 to 99 acres		7,345	-	350	378	942	1,011
100 to 249 acres		6,879	-	-	-	-	152
250 to 499 acres		4,297	-	-	-	-	-
500 acres or more		4,509	-	-	-	-	-
Sugarbeets for sugar	farms	1,106	3	22	3	16	18
	acres	446,627	27	514	163	1,238	1,544
	tons	11,642,041	621	13,649	4,564	32,484	42,582
Irrigated	farms	31	-	-	-	-	-
	acres	10,798	-	-	-	-	-
Sunflower seed, all	farms	221	-	2	-	2	3
	acres	66,924	-	(D)	-	(D)	119
	pounds	151,726,117	-	(D)	-	(D)	118,800
Irrigated	farms	2	-	-	-	-	1
	acres	(D)	-	-	-	-	(D)
Farms by acres harvested:							
1 to 24 acres		8	-	2	-	2	1
25 to 99 acres		53	-	-	-	-	2
100 to 249 acres		62	-	-	-	-	-
250 to 499 acres		49	-	-	-	-	-
500 acres or more		49	-	-	-	-	-
Wheat for grain, all	farms	3,669	4	97	27	75	82
	acres	1,268,681	6	1,449	834	2,804	3,570
	bushels	82,039,945	148	55,825	41,234	132,910	173,999
Irrigated	farms	52	-	2	-	2	1
	acres	6,251	-	(D)	-	(D)	(D)
Farms by acres harvested:							
1 to 24 acres		416	4	78	12	30	23
25 to 99 acres		1,023	-	19	15	45	52
100 to 249 acres		809	-	-	-	-	7
250 to 499 acres		544	-	-	-	-	-
500 acres or more		877	-	-	-	-	-
Forage-land used for all hay and haylage, grass silage, and greenchop	farms	23,394	673	5,043	1,283	1,985	1,909
	acres	1,392,072	2,224	59,029	26,830	51,556	67,643
	tons, dry equivalent	3,565,994	4,180	96,388	43,129	94,628	129,056
Irrigated	farms	675	4	94	20	33	24
	acres	32,954	12	824	361	871	822
Farms by acres harvested:							
1 to 24 acres		11,106	673	4,590	848	1,078	809
25 to 99 acres		8,179	-	453	435	907	1,013
100 to 249 acres		3,115	-	-	-	-	87
250 to 499 acres		780	-	-	-	-	-
500 acres or more		214	-	-	-	-	-
Alfalfa hay	farms	15,333	385	2,915	830	1,184	1,190
	acres	744,117	1,283	31,979	14,697	27,588	36,028
	tons, dry	1,971,568	2,503	59,521	27,124	58,668	76,572
Irrigated	farms	421	3	26	6	16	20
	acres	15,949	7	189	98	374	533
Other dry hay	farms	8,556	216	1,850	478	784	749
	acres	390,421	639	20,787	9,168	18,329	23,008
	tons, dry	658,360	1,214	29,650	12,432	25,474	31,439
Irrigated	farms	153	3	50	11	8	6
	acres	3,658	5	401	134	296	135
Field and grass seed crops, all	farms	155	-	4	-	1	1
	acres	66,601	-	16	-	(D)	(D)
Irrigated	farms	6	-	-	-	-	-
	acres	505	-	-	-	-	-
Land in vegetables	farms	2,620	506	671	77	123	88
	acres	196,718	625	1,918	680	1,806	1,377
Irrigated	farms	764	210	247	22	45	29
	acres	54,640	237	540	173	474	436
Farms by acres harvested:							
0.1 to 4.9 acres		1,355	497	564	48	77	58
5.0 to 24.9 acres		225	9	101	21	17	11
25.0 to 99.9 acres		495	-	6	8	29	17
100.0 to 249.9 acres		364	-	-	-	-	2
250.0 acres or more		181	-	-	-	-	-
Beans, snap	farms	390	97	170	16	29	13
	acres	2,553	18	49	7	10	8
Harvested for processing	farms	22	1	3	-	-	1
	acres	2,278	(D)	(D)	-	-	(D)
Peas, green	farms	599	29	44	5	18	8
	acres	47,364	(D)	27	(D)	289	251
Harvested for processing	farms	491	-	1	1	7	4
	acres	47,345	-	(D)	(D)	287	249
Potatoes	farms	509	92	186	27	39	23
	acres	49,008	22	72	14	69	174
Harvested for processing	farms	39	-	-	-	-	-
	acres	35,127	-	-	-	-	-

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
CROPS - Con.								
Soybeans for beans	farms	1,852	1,307	1,235	5,396	5,027	3,305	2,543
	acres	131,664	101,899	116,911	764,017	1,381,598	1,798,433	3,132,215
	bushels	6,515,791	4,973,432	5,855,055	37,435,581	67,938,272	87,715,188	155,180,741
Irrigated	farms	32	42	29	176	205	171	145
	acres	2,194	1,792	1,613	14,173	19,999	34,543	44,785
Farms by acres harvested:								
1 to 24 acres		136	77	56	140	46	9	4
25 to 99 acres		1,386	876	633	1,265	412	73	19
100 to 249 acres		330	354	543	3,649	1,536	272	43
250 to 499 acres		-	-	3	342	2,881	926	145
500 acres or more		-	-	-	-	152	2,025	2,332
Sugarbeets for sugar	farms	8	10	18	73	160	226	549
	acres	688	729	2,136	8,159	27,911	61,812	341,706
	tons	17,984	18,056	52,994	228,466	678,977	1,604,069	8,947,595
Irrigated	farms	-	-	-	1	6	2	22
	acres	-	-	-	(D)	780	(D)	9,910
Sunflower seed, all	farms	6	1	3	26	28	61	89
	acres	292	(D)	(D)	2,582	2,401	15,303	46,038
	pounds	428,400	(D)	(D)	5,311,606	5,211,910	30,547,540	109,801,211
Irrigated	farms	-	-	-	-	-	1	-
	acres	-	-	-	-	-	(D)	-
Farms by acres harvested:								
1 to 24 acres		-	-	2	1	-	-	-
25 to 99 acres		6	1	1	12	19	7	5
100 to 249 acres		-	-	-	13	9	29	11
250 to 499 acres		-	-	-	-	-	23	26
500 acres or more		-	-	-	-	-	2	47
Wheat for grain, all	farms	111	96	107	582	804	810	874
	acres	6,575	4,868	7,129	51,211	133,976	312,769	743,490
	bushels	371,993	238,064	406,655	2,808,904	7,538,895	19,165,260	51,106,058
Irrigated	farms	2	-	-	14	9	7	15
	acres	(D)	-	-	513	790	1,905	2,885
Farms by acres harvested:								
1 to 24 acres		37	17	20	95	56	34	10
25 to 99 acres		51	74	64	282	252	113	56
100 to 249 acres		23	5	23	192	293	149	117
250 to 499 acres		-	-	-	13	185	214	132
500 acres or more		-	-	-	-	18	300	559
Forage-land used for all hay and haylage, grass silage, and greenchop	farms	1,883	1,315	1,071	3,753	2,600	1,217	662
	acres	82,425	66,852	63,693	305,173	309,962	218,909	137,776
	tons, dry equivalent	162,695	142,853	133,448	728,682	858,574	688,749	483,612
Irrigated	farms	30	36	24	140	127	92	51
	acres	912	1,439	824	5,709	7,089	7,530	6,561
Farms by acres harvested:								
1 to 24 acres		669	402	273	887	521	207	149
25 to 99 acres		1,051	740	583	1,625	870	346	156
100 to 249 acres		163	173	211	1,081	874	354	172
250 to 499 acres		-	-	4	160	299	214	103
500 acres or more		-	-	-	-	36	96	82
Alfalfa hay	farms	1,227	887	718	2,673	1,932	881	511
	acres	45,522	38,477	34,856	164,706	165,726	111,041	72,214
	tons, dry	98,523	86,634	79,948	417,724	458,979	334,813	270,559
Irrigated	farms	24	21	15	104	91	59	36
	acres	551	753	482	3,401	3,626	3,425	2,510
Other dry hay	farms	774	491	410	1,340	880	362	222
	acres	29,311	20,970	20,499	92,192	81,683	47,292	26,543
	tons, dry	41,993	35,159	29,972	151,377	138,729	105,863	55,058
Irrigated	farms	2	12	3	25	13	11	9
	acres	(D)	461	(D)	617	752	368	336
Field and grass seed crops, all	farms	3	8	7	10	25	36	60
	acres	123	468	199	784	4,946	9,292	50,734
Irrigated	farms	-	-	-	-	6	-	-
	acres	-	-	-	-	505	-	-
Land in vegetables	farms	63	42	48	244	260	294	204
	acres	1,866	1,976	1,904	20,011	35,464	60,868	68,223
Irrigated	farms	9	7	7	47	51	59	31
	acres	490	(D)	(D)	4,979	9,403	21,412	16,085
Farms by acres harvested:								
0.1 to 4.9 acres		35	10	14	30	8	11	3
5.0 to 24.9 acres		5	8	6	30	9	6	2
25.0 to 99.9 acres		17	18	23	109	115	97	56
100.0 to 249.9 acres		6	6	5	60	95	113	77
250.0 acres or more		-	-	-	15	33	67	66
Beans, snap	farms	9	11	5	11	7	17	5
	acres	(D)	5	1	(D)	186	972	1,201
Harvested for processing	farms	-	-	-	-	4	10	3
	acres	-	-	-	-	162	903	1,200
Peas, green	farms	9	9	7	74	147	135	114
	acres	241	357	(D)	4,474	10,289	12,762	18,389
Harvested for processing	farms	4	6	5	69	147	133	114
	acres	240	357	(D)	4,473	10,289	12,762	18,389
Potatoes	farms	14	13	6	32	17	33	27
	acres	(D)	11	(D)	2,906	5,181	16,900	23,581
Harvested for processing	farms	-	-	1	7	8	11	12
	acres	-	-	(D)	(D)	3,394	11,470	18,501

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	1 to 9 acres	10 to 49 acres	50 to 69 acres	70 to 99 acres	100 to 139 acres
CROPS - Con.							
Land in vegetables - Con.							
Potatoes - Con.							
Farms by acres harvested:							
0.1 to 4.9 acres		421	92	186	27	37	20
5.0 to 24.9 acres		5	-	-	-	1	-
25.0 to 99.9 acres		20	-	-	-	1	2
100.0 to 249.9 acres		8	-	-	-	-	1
250.0 acres or more		55	-	-	-	-	-
Sweet corn (see text)	farms	1,243	109	204	31	59	34
	acres	96,990	98	463	236	979	757
Harvested for processing	farms	750	-	4	3	14	11
	acres	94,536	-	143	142	832	688
Sweet potatoes	farms	58	15	32	3	2	-
	acres	23	4	6	(D)	(D)	-
Harvested for processing	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Tomatoes in the open	farms	592	205	262	24	31	19
	acres	300	45	116	34	11	16
Harvested for processing	farms	18	8	10	-	-	-
	acres	2	1	1	-	-	-
Land in orchards	farms	1,174	247	598	57	95	47
	acres	5,049	390	2,019	202	605	472
Irrigated	farms	204	50	88	12	17	11
	acres	778	57	288	49	89	24
Farms by bearing and nonbearing acres:							
0.1 to 4.9 acres		927	236	468	46	64	28
5.0 to 24.9 acres		212	11	121	9	26	12
25.0 to 99.9 acres		32	-	9	2	5	7
100.0 to 249.9 acres		3	-	-	-	-	-
250.0 acres or more		-	-	-	-	-	-
Apples	farms	751	152	380	36	67	36
	bearing and nonbearing acres	3,219	202	1,026	150	404	346
Grapes (including muscadine) (see text)	farms	433	91	248	9	29	12
	bearing and nonbearing acres	1,290	148	769	17	150	(D)
Peaches, all	farms	17	6	9	1	-	1
	bearing and nonbearing acres	(D)	1	3	(D)	-	(D)
Walnuts, English	farms	29	-	16	1	2	1
	bearing and nonbearing acres	142	-	44	(D)	(D)	(D)
Land in berries	farms	578	164	271	26	40	24
	acres	1,129	117	374	47	79	39

See footnote(s) at end of table.

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Table 71. **Summary by Size of Farm: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		140 to 179 acres	180 to 219 acres	220 to 259 acres	260 to 499 acres	500 to 999 acres	1,000 to 1,999 acres	2,000 or more acres
CROPS - Con.								
Land in vegetables - Con.								
Potatoes - Con.								
Farms by acres harvested:								
0.1 to 4.9 acres		14	13	5	18	2	5	2
5.0 to 24.9 acres		-	-	-	2	-	2	-
25.0 to 99.9 acres		-	-	1	4	3	8	1
100.0 to 249.9 acres		-	-	-	1	2	-	4
250.0 acres or more		-	-	-	7	10	18	20
Sweet corn (see text)	farms	38	34	32	169	184	216	133
	acres	1,620	1,370	1,369	12,746	20,577	30,560	26,216
Harvested for processing	farms	21	16	22	145	180	204	130
	acres	1,584	1,261	1,339	12,326	20,180	29,832	26,209
Sweet potatoes	farms	1	1	-	4	-	-	-
	acres	(D)	(D)	-	(D)	-	-	-
Harvested for processing	farms	-	-	-	-	-	-	-
	acres	-	-	-	-	-	-	-
Tomatoes in the open	farms	9	10	8	12	2	9	1
	acres	(D)	8	4	16	(D)	43	(D)
Harvested for processing	farms	-	-	-	-	-	-	-
	acres	-	-	-	-	-	-	-
Land in orchards	farms	40	16	13	37	14	6	4
	acres	199	173	80	661	171	67	10
Irrigated	farms	8	3	1	7	5	2	-
	acres	18	90	(D)	149	10	(D)	-
Farms by bearing and nonbearing acres:								
0.1 to 4.9 acres		29	9	10	20	9	4	4
5.0 to 24.9 acres		9	5	2	12	4	1	-
25.0 to 99.9 acres		2	2	1	3	-	1	-
100.0 to 249.9 acres		-	-	-	2	1	-	-
250.0 acres or more		-	-	-	-	-	-	-
Apples	farms	28	13	7	22	6	3	1
	bearing and nonbearing acres	138	132	58	557	(D)	(D)	(D)
Grapes (including muscadine) (see text)	farms	12	3	4	9	9	4	3
	bearing and nonbearing acres	33	(D)	4	24	24	10	9
Peaches, all	farms	-	-	-	-	-	-	-
	bearing and nonbearing acres	-	-	-	-	-	-	-
Walnuts, English	farms	1	-	-	8	-	-	-
	bearing and nonbearing acres	(D)	-	-	72	-	-	-
Land in berries	farms	13	10	6	14	3	5	2
	acres	13	182	11	47	(D)	120	(D)

[1] Landlord production expenses are included with total farm production expenses.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.
[3] Data were collected for a maximum of four producers per farm.

Table 72. **Summary by Market Value of Agricultural Products Sold: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
FARMS AND LAND IN FARMS						
Farms ..... number	65,531	7,129	4,483	5,372	6,767	5,328
percent	100.0	10.9	6.8	8.2	10.3	8.1
Land in farms ..... acres	25,442,625	12,748,488	3,636,577	2,582,955	1,953,889	1,056,363
Average size of farm ..... acres	388	1,788	811	481	289	198
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	65,531	7,129	4,483	5,372	6,767	5,328
$1,000	29,066,202	21,845,670	3,274,458	1,987,913	1,148,573	407,689
Average per farm ..... dollars	443,549	3,064,339	730,417	370,051	169,732	76,518
Farms by economic class:						
Less than $1,000	6,079	-	-	-	-	-
$1,000 to $2,499	6,033	-	-	-	-	-
$2,500 to $4,999	5,681	-	-	-	-	-
$5,000 to $9,999	6,141	-	-	-	-	-
$10,000 to $24,999	7,125	-	-	-	-	-
$25,000 to $49,999	4,813	-	-	-	-	-
$50,000 to $99,999	5,488	-	-	-	-	4,953
$100,000 to $249,999	6,899	-	-	-	6,480	374
$250,000 to $499,999	5,477	-	-	5,189	287	1
$500,000 to $999,999	4,529	-	4,346	183	-	-
$1,000,000 or more	7,266	7,129	137	-	-	-
$1,000,000 to $2,499,999	4,148	4,011	137	-	-	-
$2,500,000 to $4,999,999	2,458	2,458	-	-	-	-
$5,000,000 or more	660	660	-	-	-	-
Total sales ..... farms	65,531	7,129	4,483	5,372	6,767	5,328
$1,000	28,482,097	21,588,612	3,183,211	1,930,062	1,101,110	386,353
Grains, oilseeds, dry beans, and dry peas ..... farms	32,075	6,250	4,199	4,948	5,972	3,968
$1,000	15,268,581	10,109,905	2,432,359	1,524,410	844,009	247,486
Sales of $50,000 or more ..... farms	23,618	6,091	4,068	4,794	5,566	3,099
$1,000	15,113,786	10,106,177	2,429,131	1,520,650	834,190	223,639
Corn ..... farms	25,230	5,733	3,763	4,423	5,047	2,772
$1,000	9,045,595	6,130,855	1,390,209	878,238	474,787	122,424
Sales of $50,000 or more ..... farms	18,777	5,567	3,610	4,216	4,317	1,067
$1,000	8,908,714	6,126,620	1,386,306	873,087	452,751	69,949
Wheat ..... farms	3,668	1,131	676	650	531	295
$1,000	735,504	510,702	118,736	66,365	26,171	8,833
Sales of $50,000 or more ..... farms	2,125	935	506	425	200	59
$1,000	707,000	506,472	114,980	62,061	19,051	4,436
Soybeans ..... farms	25,334	5,671	3,902	4,466	4,881	2,761
$1,000	5,087,514	3,167,116	878,302	551,801	327,255	110,308
Sales of $50,000 or more ..... farms	17,131	5,416	3,673	4,071	3,052	919
$1,000	4,898,487	3,160,493	871,718	539,228	264,798	62,250
Sorghum ..... farms	53	6	4	5	21	6
$1,000	437	107	150	30	91	29
Sales of $50,000 or more ..... farms	1	-	1	-	-	-
$1,000	(D)	-	(D)	-	-	-
Barley ..... farms	336	125	48	80	33	23
$1,000	27,673	17,970	3,637	4,277	1,414	285
Sales of $50,000 or more ..... farms	151	80	28	34	8	1
$1,000	24,984	16,917	3,392	3,588	(D)	(D)
Rice ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	3,613	866	524	532	608	400
$1,000	371,859	283,155	41,324	23,698	14,290	5,609
Sales of $50,000 or more ..... farms	1,013	551	195	153	87	27
$1,000	342,531	277,659	35,733	18,989	8,370	1,780
Tobacco ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	2,648	558	208	203	255	203
$1,000	446,099	354,878	32,104	22,157	18,539	7,605
Sales of $50,000 or more ..... farms	994	485	177	121	131	80
$1,000	424,789	352,594	31,080	19,993	15,929	5,193
Fruits, tree nuts, and berries ..... farms	1,212	25	13	36	84	117
$1,000	48,717	15,885	3,863	6,319	8,831	5,723
Sales of $50,000 or more ..... farms	178	10	8	22	63	75
$1,000	38,977	15,630	3,766	6,094	8,475	5,013
Fruits and tree nuts ..... farms	944	18	10	26	62	89
$1,000	30,052	7,761	2,379	3,739	6,516	3,660
Sales of $50,000 or more ..... farms	116	5	4	12	46	49
$1,000	22,967	7,591	2,280	3,562	6,306	3,229
Berries ..... farms	489	11	6	20	44	53
$1,000	18,665	8,124	1,484	2,580	2,316	2,063
Sales of $50,000 or more ..... farms	66	8	4	10	20	24
$1,000	15,470	8,039	(D)	2,353	2,065	(D)
Nursery, greenhouse, floriculture, and sod ..... farms	1,051	73	47	77	117	149
$1,000	391,444	314,380	28,870	20,857	13,508	6,312
Sales of $50,000 or more ..... farms	343	73	44	68	86	72
$1,000	381,613	314,380	(D)	20,677	(D)	4,847

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
FARMS AND LAND IN FARMS						
Farms ..... number	4,268	5,562	4,091	3,533	3,496	15,502
percent	6.5	8.5	6.2	5.4	5.3	23.7
Land in farms ..... acres	628,036	573,857	303,852	221,424	195,939	1,541,245
Average size of farm ..... acres	147	103	74	63	56	99
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	4,268	5,562	4,091	3,533	3,496	15,502
$1,000	165,359	99,424	33,955	15,563	8,001	79,597
Average per farm ..... dollars	38,744	17,875	8,300	4,405	2,289	5,135
Farms by economic class:						
Less than $1,000	-	-	-	-	-	6,079
$1,000 to $2,499	-	-	-	-	3,117	2,916
$2,500 to $4,999	-	-	-	3,139	211	2,331
$5,000 to $9,999	-	-	3,721	279	106	2,035
$10,000 to $24,999	-	5,170	308	94	53	1,500
$25,000 to $49,999	3,894	354	48	13	6	498
$50,000 to $99,999	357	28	10	6	2	132
$100,000 to $249,999	17	10	4	2	1	11
$250,000 to $499,999	-	-	-	-	-	-
$500,000 to $999,999	-	-	-	-	-	-
$1,000,000 or more	-	-	-	-	-	-
$1,000,000 to $2,499,999	-	-	-	-	-	-
$2,500,000 to $4,999,999	-	-	-	-	-	-
$5,000,000 or more	-	-	-	-	-	-
Total sales ..... farms	4,268	5,562	4,091	3,533	3,496	15,502
$1,000	153,407	90,566	29,240	12,660	5,706	1,169
Grains, oilseeds, dry beans, and dry peas ..... farms	2,430	2,123	1,088	654	317	126
$1,000	71,724	29,128	6,793	2,174	520	74
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Corn ..... farms	1,494	1,063	470	247	137	81
$1,000	33,400	12,119	2,519	788	206	50
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Wheat ..... farms	165	101	57	40	18	4
$1,000	3,092	1,162	293	119	27	4
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Soybeans ..... farms	1,418	1,156	575	332	147	25
$1,000	33,153	14,701	3,582	1,040	243	12
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sorghum ..... farms	4	2	2	-	3	-
$1,000	10	(D)	(D)	-	4	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Barley ..... farms	13	5	2	3	4	-
$1,000	78	(D)	(D)	2	2	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Rice ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	256	198	95	80	36	18
$1,000	1,992	1,127	392	224	39	8
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Tobacco ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	258	398	231	157	120	57
$1,000	5,264	3,895	1,093	397	141	27
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Fruits, tree nuts, and berries ..... farms	156	316	212	109	98	46
$1,000	3,139	3,304	1,234	269	128	22
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Fruits and tree nuts ..... farms	115	247	176	87	77	37
$1,000	2,088	2,582	978	228	103	19
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Berries ..... farms	83	138	65	32	28	9
$1,000	1,050	722	256	42	25	3
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Nursery, greenhouse, floriculture, and sod ..... farms	198	192	97	69	30	2
$1,000	4,463	2,311	502	193	(D)	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.						
Total - Con.						
Total sales - Con.						
Cultivated Christmas trees and short rotation woody crops ... farms	244	6	3	17	12	16
$1,000	7,578	1,798	(D)	1,703	1,930	502
Sales of $50,000 or more ... farms	27	3	1	5	11	7
$1,000	6,051	(D)	(D)	1,396	(D)	425
Cultivated Christmas trees ... farms	243	6	3	17	12	16
$1,000	(D)	1,798	(D)	1,703	1,930	502
Sales of $50,000 or more ... farms	27	3	1	5	11	7
$1,000	6,051	(D)	(D)	1,396	(D)	425
Short rotation woody crops ... farms	1	-	-	-	-	-
$1,000	(D)	-	-	-	-	-
Sales of $50,000 or more ... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other crops and hay ... farms	16,722	1,655	888	1,058	1,622	1,694
$1,000	981,348	695,932	79,064	50,495	56,913	42,076
Sales of $50,000 or more ... farms	2,437	1,057	372	290	369	349
$1,000	867,179	688,834	72,839	41,812	40,456	23,239
Maple syrup ... farms	364	2	6	3	8	19
$1,000	869	(D)	(D)	2	4	217
Sales of $50,000 or more ... farms	3	-	-	-	-	3
$1,000	191	-	-	-	-	191
Cattle and calves ... farms	14,649	1,877	1,389	1,655	1,999	1,758
$1,000	2,094,135	1,536,787	190,343	132,225	105,600	60,748
Sales of $50,000 or more ... farms	4,609	1,627	849	775	818	540
$1,000	1,933,030	1,531,158	176,026	111,515	79,075	35,257
Milk from cows ... farms	1,893	784	460	394	151	67
$1,000	2,504,638	2,154,436	223,468	104,121	18,387	3,885
Sales of $50,000 or more ... farms	1,826	784	459	391	145	47
$1,000	2,503,304	2,154,436	(D)	104,026	18,231	(D)
Hogs and pigs ... farms	3,352	1,656	285	192	183	94
$1,000	4,666,832	4,490,194	135,578	31,252	6,300	1,225
Sales of $50,000 or more ... farms	2,034	1,623	248	117	37	9
$1,000	4,660,288	4,489,857	135,050	30,187	4,550	645
Sheep, goats, wool, mohair, and milk ... farms	2,604	73	94	120	191	167
$1,000	33,457	3,617	7,534	5,545	4,795	3,692
Sales of $50,000 or more ... farms	120	14	24	20	26	36
$1,000	19,839	2,721	6,801	4,403	3,377	2,537
Horses, ponies, mules, burros, and donkeys ... farms	1,247	20	19	46	74	107
$1,000	18,147	111	(D)	2,619	3,986	2,926
Sales of $50,000 or more ... farms	76	-	1	10	32	33
$1,000	8,302	-	(D)	(D)	3,653	2,264
Poultry and eggs ... farms	4,445	365	104	143	194	255
$1,000	1,943,207	1,883,512	33,651	13,470	4,692	1,705
Sales of $50,000 or more ... farms	447	314	46	41	32	14
$1,000	1,935,336	1,883,420	33,545	13,191	4,228	952
Aquaculture ... farms	98	-	14	19	28	8
$1,000	19,763	-	9,043	5,571	4,405	520
Sales of $50,000 or more ... farms	62	-	13	15	27	7
$1,000	19,502	-	(D)	5,559	(D)	(D)
Other animals and other animal products ... farms	1,405	77	29	55	101	82
$1,000	58,149	27,177	6,366	9,321	9,216	1,949
Sales of $50,000 or more ... farms	154	33	11	28	59	23
$1,000	52,455	26,569	6,217	9,117	8,961	1,591
Value of-						
Government payments ... farms	31,583	4,788	2,891	2,959	3,458	2,479
$1,000	584,106	257,057	91,247	57,851	47,463	21,336
Landlord's share of total sales ... farms	1,294	396	225	208	173	105
$1,000	118,307	78,755	20,425	11,616	4,922	1,680
FOOD MARKETING PRACTICES						
Value of food sold directly to-						
Consumers ... farms	3,339	64	67	110	237	264
$1,000	44,673	6,049	3,935	5,827	8,739	5,633
Retail markets, institutions, and food hubs for local or regionally branded products ... farms	1,026	30	31	56	116	97
$1,000	108,704	84,135	7,333	3,991	6,051	2,501
FARM PRODUCTION EXPENSES						
Total farm production expenses [1] ... farms	65,531	7,129	4,483	5,372	6,767	5,328
$1,000	20,780,603	15,233,603	2,274,738	1,370,537	881,989	345,206
Average per farm ... dollars	317,111	2,136,850	507,414	255,126	130,337	64,791
Fertilizer, lime, and soil conditioners purchased ... farms	36,421	6,380	4,266	5,104	6,228	4,266
$1,000	2,325,700	1,450,907	397,795	250,272	148,191	46,028
Farms with expenses of-						
$1 to $4,999 ...	10,529	127	97	213	677	1,201
$5,000 to $24,999 ...	9,710	433	435	1,047	3,233	2,697
$25,000 to $49,999 ...	5,102	499	653	1,777	1,754	340
$50,000 or more ...	11,080	5,321	3,081	2,067	564	28
Chemicals purchased ... farms	37,339	6,419	4,290	5,114	6,238	4,310
$1,000	1,161,099	733,389	192,422	123,136	71,626	23,051
Farms with expenses of-						
$1 to $4,999 ...	15,060	267	190	404	1,415	2,571

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.							
Total - Con.							
Total sales - Con.							
Cultivated Christmas trees and short rotation woody crops	farms	20	35	20	37	28	50
	$1,000	481	299	93	(D)	(D)	(D)
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Cultivated Christmas trees	farms	20	35	20	36	28	50
	$1,000	481	299	93	(D)	(D)	(D)
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Short rotation woody crops	farms	-	-	-	1	-	-
	$1,000	-	-	-	(D)	-	-
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Other crops and hay	farms	1,511	2,080	1,627	1,623	1,588	1,376
	$1,000	23,415	18,356	7,688	4,521	2,189	699
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Maple syrup	farms	26	72	32	59	81	56
	$1,000	151	246	132	44	52	18
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Cattle and calves	farms	1,599	1,963	1,248	725	391	45
	$1,000	35,940	22,891	6,793	2,167	609	32
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Milk from cows	farms	16	14	3	1	1	2
	$1,000	303	32	6	(D)	(D)	(D)
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Hogs and pigs	farms	122	212	259	172	137	40
	$1,000	451	745	663	260	141	23
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Sheep, goats, wool, mohair, and milk	farms	187	417	392	405	345	213
	$1,000	2,574	2,860	1,413	878	451	98
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Horses, ponies, mules, burros, and donkeys	farms	144	314	226	142	129	26
	$1,000	3,001	3,411	1,174	391	189	(D)
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Poultry and eggs	farms	303	626	588	670	925	272
	$1,000	1,060	1,705	1,153	1,046	1,092	121
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Aquaculture	farms	6	7	11	2	1	2
	$1,000	96	58	63	(D)	(D)	(D)
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Other animals and other animal products	farms	100	298	192	165	182	124
	$1,000	1,496	1,572	572	287	150	43
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Value of-							
Government payments	farms	1,623	1,488	789	610	526	9,972
	$1,000	11,952	8,857	4,716	2,902	2,296	78,428
Landlord's share of total sales	farms	79	56	37	9	6	-
	$1,000	592	230	73	9	4	-
FOOD MARKETING PRACTICES							
Value of food sold directly to-							
Consumers	farms	360	665	552	448	407	165
	$1,000	5,487	4,880	2,726	926	403	68
Retail markets, institutions, and food hubs for local or regionally branded products	farms	127	217	113	98	110	31
	$1,000	1,843	2,137	378	222	101	12
FARM PRODUCTION EXPENSES							
Total farm production expenses [1]	farms	4,268	5,562	4,091	3,533	3,496	15,502
	$1,000	173,241	144,378	70,339	48,868	41,346	196,358
Average per farm	dollars	40,591	25,958	17,194	13,832	11,827	12,667
Fertilizer, lime, and soil conditioners purchased	farms	2,678	2,555	1,335	995	765	1,849
	$1,000	15,174	7,931	2,436	1,448	897	4,621
Farms with expenses of-							
$1 to $4,999		1,487	2,094	1,253	956	740	1,684
$5,000 to $24,999		1,151	448	76	35	21	134
$25,000 to $49,999		38	10	4	4	3	20
$50,000 or more		2	3	2	-	1	11
Chemicals purchased	farms	2,811	2,691	1,430	983	691	2,362
	$1,000	8,075	3,928	1,362	629	316	3,166
Farms with expenses of-							
$1 to $4,999		2,368	2,566	1,391	972	683	2,233

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Chemicals purchased - Con.						
Farms with expenses of- - Con.						
$5,000 to $24,999	11,493	865	1,111	2,827	4,296	1,685
$25,000 to $49,999	4,407	969	1,501	1,407	443	44
$50,000 or more	6,379	4,318	1,488	476	84	10
Seeds, plants, vines, and trees purchased ... farms	36,437	6,357	4,275	5,110	6,096	3,893
$1,000	1,772,341	1,136,475	280,059	172,363	110,894	39,631
Farms with expenses of-						
$1 to $999	5,343	15	12	18	100	270
$1,000 to $4,999	6,157	64	60	156	536	1,026
$5,000 to $24,999	10,290	387	538	1,554	4,156	2,363
$25,000 to $49,999	5,582	604	986	2,614	1,107	157
$50,000 or more	9,065	5,287	2,679	768	197	77
Cover crop seed purchased ... farms	4,909	1,209	594	632	633	421
$1,000	20,527	11,152	3,758	2,274	1,682	750
Livestock and poultry purchased or leased ... farms	13,933	2,753	1,027	1,089	1,299	1,024
$1,000	1,926,426	1,727,796	93,711	43,606	25,345	9,161
Farms with expenses of-						
$1 to $4,999	6,658	114	157	287	481	511
$5,000 to $24,999	3,161	159	255	339	503	420
$25,000 to $99,999	1,372	254	255	337	285	93
$100,000 to $249,999	912	487	279	116	30	-
$250,000 or more	1,830	1,739	81	10	-	-
Breeding livestock purchased or leased ... farms	5,904	726	428	538	686	637
$1,000	171,016	124,496	14,139	8,910	6,905	4,374
Other livestock and poultry purchased or leased ... farms	9,786	2,265	719	674	784	532
$1,000	1,755,410	1,603,300	79,571	34,696	18,441	4,787
Feed purchased ... farms	26,145	3,596	1,745	2,006	2,413	2,055
$1,000	3,890,272	3,509,805	168,326	82,122	42,676	22,980
Farms with expenses of-						
$1 to $4,999	13,038	124	208	439	851	937
$5,000 to $24,999	6,844	164	456	749	1,049	850
$25,000 to $99,999	2,349	310	475	554	480	263
$100,000 to $249,999	1,155	473	409	235	27	5
$250,000 or more	2,759	2,525	197	29	6	-
Gasoline, fuels, and oils purchased ... farms	61,621	7,113	4,472	5,338	6,636	5,180
$1,000	956,802	610,119	126,080	81,436	57,786	25,463
Farms with expenses of-						
$1 to $4,999	37,714	292	270	763	2,397	3,500
$5,000 to $24,999	14,760	1,181	1,932	3,781	3,948	1,609
$25,000 to $49,999	4,270	1,472	1,780	661	232	58
$50,000 or more	4,877	4,168	490	133	59	13
Utilities ... farms	48,636	7,125	4,470	5,358	6,395	4,449
$1,000	400,978	254,246	42,758	30,469	24,616	13,063
Farms with expenses of-						
$1 to $999	9,923	67	107	314	669	758
$1,000 to $4,999	24,023	630	1,290	2,931	4,432	3,092
$5,000 to $24,999	12,077	4,175	2,868	2,027	1,251	582
$25,000 to $49,999	1,626	1,360	151	62	31	16
$50,000 or more	987	893	54	24	12	1
Repairs, supplies, and maintenance costs ... farms	55,660	7,117	4,468	5,357	6,556	4,998
$1,000	1,322,234	777,742	188,090	126,701	93,646	42,248
Farms with expenses of-						
$1 to $4,999	25,809	223	175	508	1,611	2,097
$5,000 to $24,999	17,499	819	1,281	3,043	4,076	2,592
$25,000 to $49,999	5,425	1,254	1,699	1,318	645	271
$50,000 or more	6,927	4,821	1,313	488	224	38
Hired farm labor ... farms	17,399	5,909	2,381	1,956	1,933	1,141
$1,000	1,320,974	1,093,930	89,186	47,555	37,718	15,546
Farms with expenses of-						
$1 to $4,999	5,944	400	530	674	871	633
$5,000 to $24,999	4,466	870	769	794	692	387
$25,000 to $99,999	3,749	1,814	897	394	307	103
$100,000 to $249,999	2,234	1,900	147	75	56	12
$250,000 or more	1,006	925	38	19	7	6
Contract labor ... farms	4,311	1,279	415	423	446	335
$1,000	152,565	125,792	8,100	5,978	5,077	1,823
Farms with expenses of-						
$1 to $999	452	14	9	4	30	55
$1,000 to $4,999	1,452	121	94	148	161	158
$5,000 to $24,999	1,469	454	228	205	201	115
$25,000 to $49,999	315	150	47	46	36	7
$50,000 or more	623	540	37	20	18	-
Customwork and custom hauling ... farms	19,181	4,248	2,168	2,506	3,010	2,037
$1,000	425,172	296,066	43,629	34,488	26,596	11,168
Farms with expenses of-						
$1 to $999	2,876	99	80	179	239	281
$1,000 to $4,999	6,088	389	415	631	1,014	989
$5,000 to $24,999	6,540	1,216	1,197	1,286	1,584	740
$25,000 to $49,999	2,030	1,230	305	303	141	16
$50,000 or more	1,647	1,314	171	107	32	11

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Chemicals purchased - Con.						
Farms with expenses of- - Con.						
$5,000 to $24,999	429	116	37	9	8	110
$25,000 to $49,999	14	9	1	2	-	17
$50,000 or more	-	-	1	-	-	2
Seeds, plants, vines, and trees purchased ...farms	2,529	2,509	1,452	1,099	875	2,242
$1,000	14,682	9,157	2,478	2,029	1,081	3,492
Farms with expenses of-						
$1 to $999	448	884	818	693	640	1,445
$1,000 to $4,999	1,272	1,297	540	332	199	675
$5,000 to $24,999	725	287	83	68	32	97
$25,000 to $49,999	49	23	11	4	4	23
$50,000 or more	35	18	-	2	-	2
Cover crop seed purchased ...farms	292	346	169	126	124	363
$1,000	298	201	92	55	33	232
Livestock and poultry purchased or leased ...farms	1,027	1,512	1,204	908	942	1,148
$1,000	6,887	8,337	4,047	2,054	1,637	3,843
Farms with expenses of-						
$1 to $4,999	563	1,007	969	811	859	899
$5,000 to $24,999	431	446	210	90	79	229
$25,000 to $99,999	33	59	25	7	4	20
$100,000 to $249,999	-	-	-	-	-	-
$250,000 or more	-	-	-	-	-	-
Breeding livestock purchased or leased ...farms	564	799	492	313	296	425
$1,000	3,249	4,231	1,777	721	754	1,458
Other livestock and poultry purchased or leased ...farms	611	970	909	713	746	863
$1,000	3,639	4,106	2,269	1,333	883	2,385
Feed purchased ...farms	1,974	2,912	2,149	1,739	1,820	3,736
$1,000	16,131	17,012	8,721	5,217	4,335	12,946
Farms with expenses of-						
$1 to $4,999	1,011	1,779	1,577	1,429	1,579	3,104
$5,000 to $24,999	837	1,053	547	307	238	594
$25,000 to $99,999	125	78	25	3	3	33
$100,000 to $249,999	1	2	-	-	-	3
$250,000 or more	-	-	-	-	-	2
Gasoline, fuels, and oils purchased ...farms	4,138	5,351	3,916	3,319	3,270	12,888
$1,000	13,829	11,699	6,246	4,497	3,702	15,944
Farms with expenses of-						
$1 to $4,999	3,299	4,821	3,684	3,156	3,157	12,375
$5,000 to $24,999	818	517	227	158	107	482
$25,000 to $49,999	18	11	5	5	6	22
$50,000 or more	3	2	-	-	-	9
Utilities ...farms	3,283	3,983	2,682	2,067	1,943	6,881
$1,000	7,929	7,718	4,474	2,921	2,579	10,206
Farms with expenses of-						
$1 to $999	744	1,311	1,129	1,003	974	2,847
$1,000 to $4,999	2,238	2,368	1,412	963	893	3,774
$5,000 to $24,999	297	304	141	101	76	255
$25,000 to $49,999	2	-	-	-	-	4
$50,000 or more	2	-	-	-	-	1
Repairs, supplies, and maintenance costs ...farms	3,886	4,871	3,430	2,815	2,620	9,542
$1,000	23,347	20,343	10,512	7,567	6,108	25,931
Farms with expenses of-						
$1 to $4,999	2,109	3,597	2,839	2,393	2,298	7,959
$5,000 to $24,999	1,670	1,204	564	406	314	1,530
$25,000 to $49,999	89	60	27	13	6	43
$50,000 or more	18	10	-	3	2	10
Hired farm labor ...farms	668	863	505	379	335	1,329
$1,000	10,540	8,585	3,459	3,052	1,859	9,545
Farms with expenses of-						
$1 to $4,999	382	555	383	293	261	962
$5,000 to $24,999	227	232	83	64	52	296
$25,000 to $99,999	42	61	34	14	22	61
$100,000 to $249,999	6	15	5	8	-	10
$250,000 or more	11	-	-	-	-	-
Contract labor ...farms	236	284	143	130	102	518
$1,000	1,500	1,280	432	394	218	1,970
Farms with expenses of-						
$1 to $999	37	43	34	39	37	150
$1,000 to $4,999	116	168	83	61	53	289
$5,000 to $24,999	73	60	26	30	12	65
$25,000 to $49,999	7	12	-	-	-	10
$50,000 or more	3	1	-	-	-	4
Customwork and custom hauling ...farms	1,358	1,235	647	438	334	1,200
$1,000	4,677	3,390	1,285	688	728	2,458
Farms with expenses of-						
$1 to $999	356	467	317	229	188	441
$1,000 to $4,999	759	620	276	187	121	687
$5,000 to $24,999	226	136	51	20	20	64
$25,000 to $49,999	16	4	3	2	5	5
$50,000 or more	1	8	-	-	-	3

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Cash rent for land, buildings, and grazing fees ..... farms	24,199	6,107	3,848	3,954	3,847	2,311
$1,000	2,302,712	1,679,364	331,837	167,675	81,662	22,931
Farms with expenses of-						
$1 to $4,999	5,289	85	145	315	721	942
$5,000 to $9,999	2,314	120	123	310	585	562
$10,000 to $24,999	4,009	303	445	925	1,364	633
$25,000 or more	12,587	5,599	3,135	2,404	1,177	174
Rent and lease expenses for machinery, equipment, and farm share of vehicles ..... farms	6,598	1,950	874	865	829	450
$1,000	182,357	133,316	20,008	13,303	8,068	2,715
Farms with expenses of-						
$1 to $999	1,233	63	72	117	162	122
$1,000 to $4,999	1,683	232	179	218	222	161
$5,000 to $24,999	2,168	601	398	370	408	153
$25,000 to $49,999	538	281	111	99	22	5
$50,000 or more	976	773	114	61	15	9
Interest expense ..... farms	27,274	5,971	3,261	3,408	3,447	2,230
$1,000	702,889	439,762	93,016	55,858	41,819	18,766
Farms with expenses of-						
$1 to $4,999	9,316	483	479	915	1,275	1,092
$5,000 to $24,999	11,255	1,461	1,524	1,810	1,801	982
$25,000 to $99,999	5,316	2,814	1,157	658	339	148
$100,000 or more	1,387	1,213	101	25	32	8
Secured by real estate ..... farms	20,348	4,528	2,430	2,447	2,423	1,606
$1,000	467,669	279,613	63,725	39,971	28,465	13,480
Farms with expenses of-						
$1 to $999	1,511	80	75	132	158	149
$1,000 to $4,999	5,125	297	300	429	645	566
$5,000 to $24,999	9,127	1,361	1,197	1,427	1,390	798
$25,000 to $49,999	2,363	1,129	552	310	178	75
$50,000 or more	2,222	1,661	306	149	52	18
Not secured by real estate ..... farms	16,953	4,163	2,236	2,226	2,239	1,331
$1,000	235,219	160,150	29,291	15,887	13,354	5,286
Farms with expenses of-						
$1 to $999	2,836	154	162	259	399	369
$1,000 to $4,999	6,264	533	472	846	992	690
$5,000 to $24,999	5,400	1,503	1,319	1,040	781	245
$25,000 to $49,999	1,506	1,137	224	70	40	19
$50,000 or more	947	836	59	11	27	8
Property taxes paid ..... farms	61,644	6,734	4,195	4,902	6,086	4,816
$1,000	482,443	188,513	57,388	45,069	41,446	23,278
Farms with expenses of-						
$1 to $4,999	39,325	1,313	1,115	1,762	3,070	3,294
$5,000 to $9,999	11,291	1,088	1,017	1,570	1,958	1,166
$10,000 to $24,999	7,298	1,915	1,516	1,333	907	278
$25,000 or more	3,730	2,418	547	237	151	78
Medical supplies, veterinary, and custom services for livestock ..... farms	19,351	3,438	1,609	1,770	1,947	1,598
$1,000	255,043	209,935	15,990	8,658	6,039	3,798
Farms with expenses of-						
$1 to $4,999	14,259	557	765	1,214	1,635	1,427
$5,000 to $24,999	3,318	1,320	713	527	292	155
$25,000 to $49,999	674	524	94	15	14	10
$50,000 to $99,999	623	568	32	13	4	6
$100,000 or more	477	469	5	1	2	-
All other production expenses ..... farms	44,226	7,117	4,467	5,357	6,385	4,381
$1,000	1,200,596	866,445	126,345	81,847	58,784	23,555
Farms with expenses of-						
$1 to $4,999	22,214	445	561	1,232	2,443	2,952
$5,000 to $24,999	13,025	1,399	1,655	3,245	3,593	1,316
$25,000 to $49,999	3,867	1,121	1,618	682	253	91
$50,000 to $99,999	3,372	2,595	517	141	82	22
$100,000 or more	1,748	1,557	116	57	14	-
Production expenses paid by landlords [1] ..... farms	2,062	715	341	284	183	138
$1,000	65,113	42,705	11,149	6,012	2,459	1,308
Depreciation expenses claimed ..... farms	41,075	7,074	4,445	5,243	5,305	3,579
$1,000	2,240,389	1,426,475	302,028	206,784	126,402	55,854
NET CASH FARM INCOME						
Net cash farm income of operations ..... farms	65,531	7,129	4,483	5,372	6,767	5,328
$1,000	9,296,848	6,896,285	1,114,233	720,228	366,033	138,444
Average per farm ..... dollars	141,869	967,357	248,546	134,071	54,091	25,984
Farms with net gains [2] ..... number	41,496	6,706	4,173	4,878	5,708	4,240
Average net gain ..... dollars	242,705	1,065,153	282,924	158,867	77,604	43,803
Gain of-						
Less than $1,000	1,541	6	3	10	20	15
$1,000 to $4,999	4,053	4	8	30	115	132
$5,000 to $9,999	3,053	10	7	37	130	243
$10,000 to $24,999	5,680	30	56	104	466	1,035
$25,000 to $49,999	5,396	48	93	261	1,138	1,561
$50,000 or more	21,773	6,608	4,006	4,436	3,839	1,254

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Cash rent for land, buildings, and grazing fees ..... farms	1,465	1,220	539	302	202	404
$1,000	8,078	4,472	1,474	558	549	4,112
Farms with expenses of-						
$1 to $4,999	903	992	484	282	170	250
$5,000 to $9,999	340	149	30	13	24	58
$10,000 to $24,999	193	59	16	4	4	63
$25,000 or more	29	20	9	3	4	33
Rent and lease expenses for machinery, equipment, and farm share of vehicles ..... farms	339	262	196	137	135	561
$1,000	1,352	1,090	546	469	340	1,150
Farms with expenses of-						
$1 to $999	132	116	96	57	53	243
$1,000 to $4,999	120	93	60	51	70	277
$5,000 to $24,999	83	44	39	26	8	38
$25,000 to $49,999	2	7	1	3	4	3
$50,000 or more	2	2	-	-	-	-
Interest expense ..... farms	1,574	1,694	1,068	717	720	3,184
$1,000	10,563	9,913	5,751	3,892	3,651	19,897
Farms with expenses of-						
$1 to $4,999	860	985	616	420	436	1,755
$5,000 to $24,999	659	683	437	272	272	1,354
$25,000 to $99,999	54	23	14	25	12	72
$100,000 or more	1	3	1	-	-	3
Secured by real estate ..... farms	1,136	1,298	805	551	550	2,574
$1,000	7,534	7,423	4,192	3,079	2,993	17,195
Farms with expenses of-						
$1 to $999	144	168	130	91	93	291
$1,000 to $4,999	434	629	355	230	215	1,025
$5,000 to $24,999	526	484	308	214	234	1,188
$25,000 to $49,999	24	13	11	14	5	52
$50,000 or more	8	4	1	2	3	18
Not secured by real estate ..... farms	976	965	603	401	357	1,456
$1,000	3,029	2,490	1,560	812	659	2,702
Farms with expenses of-						
$1 to $999	288	290	202	131	120	462
$1,000 to $4,999	505	532	321	237	220	916
$5,000 to $24,999	180	138	77	27	13	77
$25,000 to $49,999	2	4	-	6	4	-
$50,000 or more	1	1	3	-	-	1
Property taxes paid ..... farms	3,908	5,189	3,850	3,372	3,376	15,216
$1,000	15,182	17,357	11,050	9,766	9,950	63,445
Farms with expenses of-						
$1 to $4,999	3,003	4,375	3,410	3,017	2,977	11,989
$5,000 to $9,999	715	610	356	288	312	2,211
$10,000 to $24,999	157	184	75	57	78	798
$25,000 or more	33	20	9	10	9	218
Medical supplies, veterinary, and custom services for livestock ..... farms	1,480	2,073	1,407	977	1,021	2,031
$1,000	2,357	2,814	1,382	834	888	2,349
Farms with expenses of-						
$1 to $4,999	1,390	1,976	1,373	949	993	1,980
$5,000 to $24,999	87	88	34	28	28	46
$25,000 to $49,999	3	9	-	-	-	5
$50,000 to $99,999	-	-	-	-	-	-
$100,000 or more	-	-	-	-	-	-
All other production expenses ..... farms	3,091	3,233	1,991	1,438	1,352	5,414
$1,000	12,940	9,351	4,685	2,855	2,505	11,283
Farms with expenses of-						
$1 to $4,999	2,464	2,737	1,772	1,322	1,249	5,037
$5,000 to $24,999	565	473	212	112	102	353
$25,000 to $49,999	49	23	7	4	1	18
$50,000 to $99,999	10	-	-	-	-	5
$100,000 or more	3	-	-	-	-	1
Production expenses paid by landlords [1] ..... farms	103	83	57	37	42	79
$1,000	559	465	125	52	84	194
Depreciation expenses claimed ..... farms	2,622	2,892	1,831	1,379	1,247	5,458
$1,000	32,008	26,102	13,438	8,459	6,773	36,066
NET CASH FARM INCOME						
Net cash farm income of operations ..... farms	4,268	5,562	4,091	3,533	3,496	15,502
$1,000	29,707	-4,231	-19,611	-22,405	-21,946	100,112
Average per farm ..... dollars	6,960	-761	-4,794	-6,342	-6,277	6,458
Farms with net gains [2] ..... number	2,912	3,029	1,476	898	625	6,851
Average net gain ..... dollars	23,444	14,405	9,918	9,153	11,245	29,526
Gain of-						
Less than $1,000	73	184	177	201	178	674
$1,000 to $4,999	290	728	686	405	184	1,471
$5,000 to $9,999	391	801	325	104	80	925
$10,000 to $24,999	1,140	985	161	100	110	1,493
$25,000 to $49,999	770	198	81	56	46	1,144
$50,000 or more	248	133	46	32	27	1,144

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
NET CASH FARM INCOME - Con.						
Net cash farm income of operations - Con.						
Farms with net losses ..... number	24,035	423	310	494	1,059	1,088
Average net loss ..... dollars	32,221	583,059	214,221	110,785	72,646	43,458
Loss of-						
Less than $1,000	1,786	1	3	13	28	23
$1,000 to $4,999	6,380	12	9	25	83	138
$5,000 to $9,999	5,021	9	5	23	82	123
$10,000 to $24,999	5,999	15	30	92	247	266
$25,000 to $49,999	2,539	42	51	78	185	266
$50,000 or more	2,310	344	212	263	434	272
Net cash farm income of producers ..... farms	65,531	7,129	4,483	5,372	6,767	5,328
$1,000	8,390,544	6,042,586	1,075,063	708,356	364,172	138,064
Average per farm ..... dollars	128,039	847,606	239,809	131,861	53,816	25,913
Producers reporting net gains [2] ..... farms	41,274	6,548	4,124	4,859	5,694	4,243
Average net gain ..... dollars	222,954	965,119	277,901	157,550	77,556	43,624
Gain of-						
Less than $1,000	1,557	7	2	9	20	17
$1,000 to $4,999	4,059	9	7	34	121	132
$5,000 to $9,999	3,084	29	16	38	128	247
$10,000 to $24,999	5,726	57	63	115	452	1,046
$25,000 to $49,999	5,475	102	106	276	1,139	1,553
$50,000 or more	21,373	6,344	3,930	4,387	3,834	1,248
Producers reporting net losses ..... farms	24,257	581	359	513	1,073	1,085
Average net loss ..... dollars	33,460	476,783	197,769	111,459	72,163	43,349
Loss of-						
Less than $1,000	1,780	-	3	9	29	24
$1,000 to $4,999	6,394	19	8	24	92	140
$5,000 to $9,999	5,032	17	12	23	84	125
$10,000 to $24,999	6,008	25	36	90	243	259
$25,000 to $49,999	2,576	62	68	82	193	262
$50,000 or more	2,467	458	232	285	432	275
COMMODITY CREDIT CORPORATION LOANS						
Total ..... farms	990	475	181	168	108	46
$1,000	197,241	166,345	17,570	9,260	3,151	850
INCOME FROM FARM-RELATED SOURCES						
Total income from farm-related sources ..... farms	38,287	4,970	3,621	4,247	5,180	3,756
$1,000	1,011,249	284,218	114,513	102,852	99,449	75,960
Customwork and other agricultural services ..... farms	4,779	1,253	740	738	618	383
$1,000	144,025	64,272	27,230	22,872	11,833	8,308
Gross cash rent or share payments ..... farms	15,680	872	626	696	1,273	1,390
$1,000	479,289	52,370	23,249	29,204	48,913	47,516
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products ..... farms	619	3	14	26	36	36
$1,000	5,384	(D)	157	433	588	186
Agri-tourism and recreational services ..... farms	509	15	15	44	55	63
$1,000	13,615	(D)	146	2,443	1,823	1,443
Patronage dividends and refunds from cooperatives ..... farms	23,672	4,241	3,280	3,740	4,232	2,612
$1,000	126,183	70,194	22,608	15,538	9,154	3,862
Crop and livestock insurance payments ..... farms	5,882	1,450	1,042	995	1,062	578
$1,000	171,530	73,642	34,741	23,967	18,749	9,697
Amount from State and local government agricultural program payments ..... farms	1,422	164	159	187	182	145
$1,000	7,129	1,960	1,197	1,063	799	374
Other farm-related income sources ..... farms	2,557	415	241	298	322	232
$1,000	64,095	19,967	5,184	7,331	7,590	4,573
LAND USE						
Total cropland ..... farms	58,762	6,578	4,363	5,199	6,575	5,154
acres	21,544,060	12,158,816	3,320,097	2,205,314	1,524,110	690,687
Harvested cropland ..... farms	47,549	6,483	4,335	5,161	6,546	5,091
acres	19,662,443	11,835,744	3,165,996	2,072,905	1,354,719	577,816
Farms by acres harvested:						
1 to 49 acres	16,934	144	68	126	302	663
50 to 99 acres	5,412	93	39	71	372	1,890
100 to 199 acres	6,580	141	149	269	2,882	2,009
200 to 499 acres	8,316	548	714	3,504	2,842	491
500 to 999 acres	4,858	992	2,563	1,113	144	38
1,000 to 1,999 acres	3,081	2,225	776	78	2	-
2,000 acres or more	2,368	2,340	26	-	2	-
Cropland-						
Other pasture and grazing land that could have been used for crops without additional improvements ..... farms	3,908	222	235	297	530	440
acres	174,215	29,900	16,408	15,690	31,466	25,695
On which all crops failed or were abandoned ..... farms	2,413	234	203	219	312	251
acres	110,013	26,872	15,515	16,997	12,602	9,843
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed ..... farms	22,588	2,524	1,436	1,478	1,758	1,325
acres	1,546,009	260,051	116,309	94,311	120,500	72,101
In summer fallow ..... farms	2,242	132	126	174	208	217
acres	51,380	6,249	5,869	5,411	4,823	5,232

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
NET CASH FARM INCOME - Con.						
Net cash farm income of operations - Con.						
Farms with net losses ..... number	1,356	2,533	2,615	2,635	2,871	8,651
Average net loss ..... dollars	28,437	18,897	13,097	11,622	10,092	11,810
Loss of-						
Less than $1,000	53	158	210	227	242	828
$1,000 to $4,999	253	569	700	831	1,051	2,709
$5,000 to $9,999	216	467	576	661	669	2,190
$10,000 to $24,999	417	789	775	620	664	2,084
$25,000 to $49,999	239	366	284	235	192	601
$50,000 or more	178	184	70	61	53	239
Net cash farm income of producers ..... farms	4,268	5,562	4,091	3,533	3,496	15,502
$1,000	29,779	-4,003	-19,552	-22,362	-21,866	100,307
Average per farm ..... dollars	6,977	-720	-4,779	-6,330	-6,255	6,471
Producers reporting net gains [2] ..... farms	2,916	3,029	1,479	903	625	6,854
Average net gain ..... dollars	23,406	14,460	9,900	9,115	11,250	29,520
Gain of-						
Less than $1,000	77	190	175	206	178	676
$1,000 to $4,999	290	715	691	406	184	1,470
$5,000 to $9,999	391	801	325	103	80	926
$10,000 to $24,999	1,140	988	161	100	110	1,494
$25,000 to $49,999	768	202	83	56	46	1,144
$50,000 or more	250	133	44	32	27	1,144
Producers reporting net losses ..... farms	1,352	2,533	2,612	2,630	2,871	8,648
Average net loss ..... dollars	28,456	18,872	13,091	11,632	10,065	11,798
Loss of-						
Less than $1,000	52	157	211	224	244	827
$1,000 to $4,999	246	572	704	832	1,050	2,707
$5,000 to $9,999	211	468	571	658	670	2,193
$10,000 to $24,999	430	784	772	620	662	2,087
$25,000 to $49,999	234	366	284	235	195	595
$50,000 or more	179	186	70	61	50	239
COMMODITY CREDIT CORPORATION LOANS						
Total ..... farms	8	3	-	1	-	-
$1,000	48	(D)	-	(D)	-	-
INCOME FROM FARM-RELATED SOURCES						
Total income from farm-related sources ..... farms	2,780	2,969	1,625	1,214	1,188	6,737
$1,000	37,589	40,723	16,773	10,900	11,398	216,874
Customwork and other agricultural services ..... farms	267	231	96	135	118	200
$1,000	3,252	1,965	663	682	592	2,355
Gross cash rent or share payments ..... farms	1,225	1,465	969	795	758	5,611
$1,000	23,420	22,184	12,242	9,053	9,090	202,048
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products ..... farms	63	75	61	48	80	177
$1,000	1,111	553	222	(D)	375	1,251
Agri-tourism and recreational services ..... farms	53	73	41	20	29	101
$1,000	741	3,114	750	(D)	124	1,496
Patronage dividends and refunds from cooperatives ..... farms	1,595	1,486	619	346	311	1,210
$1,000	1,457	1,204	244	224	191	1,505
Crop and livestock insurance payments ..... farms	310	203	72	50	19	101
$1,000	3,536	4,543	516	199	92	1,847
Amount from State and local government agricultural program payments ..... farms	125	131	79	31	27	192
$1,000	442	315	250	67	93	566
Other farm-related income sources ..... farms	196	272	95	77	106	303
$1,000	3,628	6,844	1,885	445	842	5,804
LAND USE						
Total cropland ..... farms	3,964	4,915	3,435	2,907	2,717	12,955
acres	342,161	270,777	121,815	78,681	64,504	767,098
Harvested cropland ..... farms	3,879	4,708	3,225	2,723	2,330	3,068
acres	266,468	188,362	82,048	50,125	31,133	37,127
Farms by acres harvested:						
1 to 49 acres	1,639	3,416	2,791	2,538	2,254	2,993
50 to 99 acres	1,420	898	349	160	64	56
100 to 199 acres	674	337	74	22	11	12
200 to 499 acres	140	57	11	3	1	5
500 to 999 acres	6	-	-	-	-	2
1,000 to 1,999 acres	-	-	-	-	-	-
2,000 acres or more	-	-	-	-	-	-
Cropland-						
Other pasture and grazing land that could have been used for crops without additional improvements ..... farms	370	474	239	253	221	627
acres	13,087	12,416	4,290	3,934	5,430	15,899
On which all crops failed or were abandoned ..... farms	175	234	163	131	142	349
acres	5,694	4,991	3,295	1,501	2,582	10,121
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed ..... farms	951	1,060	757	606	788	9,905
acres	53,324	60,905	28,956	21,198	23,179	695,175
In summer fallow ..... farms	164	253	222	149	168	429
acres	3,588	4,103	3,226	1,923	2,180	8,776

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
LAND USE - Con.							
Total woodland	farms	23,960	998	879	1,243	1,916	1,919
	acres	1,446,600	108,970	72,306	123,409	142,417	127,783
Woodland pastured	farms	7,908	239	282	420	737	841
	acres	315,103	24,152	19,736	24,385	50,365	49,530
Woodland not pastured	farms	19,456	873	744	1,028	1,496	1,416
	acres	1,131,497	84,818	52,570	99,024	92,052	78,253
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	19,837	923	823	1,250	1,863	1,811
	acres	1,031,215	126,107	97,721	113,594	157,067	143,346
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	42,652	4,369	2,616	3,054	4,092	3,175
	acres	1,420,750	354,595	146,453	140,638	130,295	94,547
Irrigated land	farms	3,625	750	358	361	485	354
	acres	648,313	435,918	86,855	55,607	46,188	13,464
Harvested cropland	farms	3,551	749	357	361	483	349
	acres	644,857	435,175	86,467	55,374	45,484	12,942
Pastureland and other land	farms	160	25	12	8	17	14
	acres	3,456	743	388	233	704	522
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	19,069	2,277	1,131	1,076	1,245	969
	acres	951,335	86,222	45,372	39,710	61,028	43,364
Land enrolled in crop insurance programs	farms	27,305	6,235	4,033	4,647	5,308	3,074
	acres	18,167,226	11,486,597	3,031,661	1,917,657	1,120,779	353,064
ORGANIC AGRICULTURE							
Total organic product sales	farms	577	71	62	81	109	94
	$1,000	121,783	57,011	26,956	20,667	10,332	4,498
VALUE OF LAND AND BUILDINGS							
Estimated market value of land and buildings	farms	65,531	7,129	4,483	5,372	6,767	5,328
	$1,000	155,374,449	84,814,088	22,405,493	15,381,761	10,386,862	5,023,388
Average per farm	dollars	2,371,007	11,897,053	4,997,879	2,863,321	1,534,929	942,828
Average per acre	dollars	6,107	6,653	6,161	5,955	5,316	4,755
Farms by value group:							
$1 to $49,999		1,819	49	16	47	61	75
$50,000 to $99,999		2,318	43	21	16	30	48
$100,000 to $199,999		5,817	67	21	16	100	191
$200,000 to $499,999		17,490	174	73	150	524	1,133
$500,000 to $999,999		13,050	303	128	322	1,447	2,063
$1,000,000 to $1,999,999		8,615	387	356	1,116	2,979	1,419
$2,000,000 to $4,999,999		8,631	1,031	1,844	3,218	1,540	369
$5,000,000 to $9,999,999		3,992	1,572	1,778	458	80	28
$10,000,000 or more		3,799	3,503	246	29	6	2
VALUE OF MACHINERY AND EQUIPMENT							
Estimated market value of all machinery and equipment	farms	65,531	7,129	4,483	5,372	6,767	5,328
	$1,000	17,904,134	8,896,616	2,685,531	1,998,661	1,484,363	792,311
Farms by value group:							
$1 to $4,999		3,305	-	2	1	10	66
$5,000 to $9,999		3,816	7	10	10	66	109
$10,000 to $19,999		6,447	23	7	44	192	279
$20,000 to $49,999		12,383	106	57	195	535	868
$50,000 to $99,999		10,506	237	116	381	1,069	1,330
$100,000 to $199,999		9,020	381	371	911	2,012	1,509
$200,000 to $499,999		9,719	1,030	1,412	2,421	2,297	944
$500,000 or more		10,335	5,345	2,508	1,409	586	223
SELECTED MACHINERY AND EQUIPMENT							
Trucks, including pickups	farms	51,156	6,913	4,378	5,173	6,275	4,510
	number	127,301	37,921	15,799	14,399	14,450	8,682
Tractors, all	farms	52,770	6,802	4,322	5,045	6,159	4,639
	number	184,473	40,512	22,201	22,787	24,698	16,100
Less than 40 horsepower (PTO)	farms	22,815	1,981	1,515	1,859	2,424	1,904
	number	36,863	3,956	2,569	3,246	4,239	3,070
40 to 99 horsepower (PTO)	farms	35,619	4,091	2,928	3,406	4,404	3,335
	number	60,537	7,834	5,539	6,108	8,127	6,157
100 horsepower (PTO) or more	farms	31,912	6,475	4,179	4,734	5,357	3,462
	number	87,073	28,722	14,093	13,433	12,332	6,873
Grain and bean combines, self-propelled	farms	21,753	5,465	3,677	3,771	3,664	2,114
	number	25,736	7,209	4,295	4,287	4,144	2,415
Cotton pickers and strippers, self-propelled	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	2,195	551	234	259	286	201
	number	2,384	581	242	288	308	220
Hay balers	farms	19,296	1,740	1,509	1,818	2,499	2,156
	number	24,300	2,139	1,898	2,294	3,272	2,825

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
LAND USE - Con.							
Total woodland	farms	1,838	2,521	2,031	1,842	1,856	6,917
	acres	111,345	129,388	88,143	70,842	70,416	401,581
Woodland pastured	farms	852	1,014	796	667	605	1,455
	acres	37,352	29,819	18,352	12,595	10,723	38,094
Woodland not pastured	farms	1,371	1,951	1,592	1,464	1,480	6,041
	acres	73,993	99,569	69,791	58,247	59,693	363,487
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	1,726	2,579	1,823	1,532	1,493	4,014
	acres	101,920	95,360	42,016	29,255	21,388	103,441
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	2,737	3,854	2,949	2,703	2,635	10,468
	acres	72,610	78,332	51,878	42,646	39,631	269,125
Irrigated land	farms	345	401	171	182	133	85
	acres	4,717	2,683	663	803	536	879
Harvested cropland	farms	338	393	169	179	106	67
	acres	4,508	2,419	656	792	399	641
Pastureland and other land	farms	10	13	4	4	31	22
	acres	209	264	7	11	137	238
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	621	685	495	442	438	9,690
	acres	33,798	28,875	21,549	16,404	15,797	559,216
Land enrolled in crop insurance programs	farms	1,560	1,080	383	196	119	670
	acres	110,225	61,881	10,701	4,778	3,451	66,432
ORGANIC AGRICULTURE							
Total organic product sales	farms	69	43	17	17	10	4
	$1,000	1,787	413	55	47	13	4
VALUE OF LAND AND BUILDINGS							
Estimated market value of land and buildings	farms	4,268	5,562	4,091	3,533	3,496	15,502
	$1,000	2,864,037	2,881,614	1,680,481	1,376,879	1,345,735	7,214,111
Average per farm	dollars	671,049	518,090	410,775	389,720	384,936	465,366
Average per acre	dollars	4,560	5,021	5,531	6,218	6,868	4,681
Farms by value group:							
$1 to $49,999		81	169	213	199	225	684
$50,000 to $99,999		97	286	228	233	206	1,110
$100,000 to $199,999		362	665	649	554	613	2,579
$200,000 to $499,999		1,559	2,268	1,900	1,696	1,624	6,389
$500,000 to $999,999		1,438	1,637	871	678	670	3,493
$1,000,000 to $1,999,999		579	423	200	141	127	888
$2,000,000 to $4,999,999		122	103	27	28	25	324
$5,000,000 to $9,999,999		26	9	3	4	6	28
$10,000,000 or more		4	2	-	-	-	7
VALUE OF MACHINERY AND EQUIPMENT							
Estimated market value of all machinery and equipment	farms	4,268	5,562	4,091	3,533	3,496	15,502
	$1,000	452,282	389,484	237,955	173,792	158,913	634,226
Farms by value group:							
$1 to $4,999		100	217	275	327	400	1,907
$5,000 to $9,999		157	340	319	333	409	2,056
$10,000 to $19,999		322	714	625	581	587	3,073
$20,000 to $49,999		942	1,645	1,248	1,093	995	4,699
$50,000 to $99,999		1,167	1,413	962	718	674	2,439
$100,000 to $199,999		991	826	458	368	311	882
$200,000 to $499,999		471	372	185	99	113	375
$500,000 or more		118	35	19	14	7	71
SELECTED MACHINERY AND EQUIPMENT							
Trucks, including pickups	farms	3,486	4,411	3,132	2,570	2,531	7,777
	number	6,166	7,061	4,666	3,731	3,520	10,906
Tractors, all	farms	3,677	4,577	3,284	2,696	2,586	8,983
	number	11,670	11,877	7,693	6,009	4,997	15,929
Less than 40 horsepower (PTO)	farms	1,612	2,179	1,796	1,539	1,414	4,592
	number	2,763	3,492	2,802	2,355	2,043	6,328
40 to 99 horsepower (PTO)	farms	2,714	3,343	2,323	1,842	1,704	5,529
	number	5,075	5,560	3,633	2,830	2,389	7,285
100 horsepower (PTO) or more	farms	2,172	1,889	917	608	446	1,673
	number	3,832	2,825	1,258	824	565	2,316
Grain and bean combines, self-propelled	farms	1,092	810	367	216	137	440
	number	1,221	895	392	234	144	500
Cotton pickers and strippers, self-propelled	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	165	159	104	68	65	103
	number	185	182	110	81	73	114
Hay balers	farms	1,780	2,161	1,466	1,208	1,067	1,892
	number	2,345	2,768	1,874	1,493	1,235	2,157

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
FERTILIZERS AND CHEMICALS						
Commercial fertilizer, lime, and soil conditioners used ..... farms	34,208	6,344	4,247	5,076	6,135	4,100
acres treated	14,076,782	8,378,467	2,431,314	1,612,633	1,006,520	363,377
Manure used ..... farms	13,721	2,368	1,440	1,563	1,860	1,438
acres treated	1,453,615	841,955	204,582	149,132	110,534	56,754
Organic fertilizer used ..... farms	1,053	91	83	100	123	126
acres treated	135,551	56,605	29,074	22,022	11,398	7,433
Acres treated to control-						
Insects ..... farms	13,847	3,301	2,184	2,342	2,268	1,245
acres	5,229,304	3,226,208	943,409	589,364	308,342	92,794
Weeds, grass, or brush ..... farms	34,397	6,336	4,219	5,026	6,117	4,136
acres	17,661,145	10,930,226	2,983,162	1,912,520	1,154,691	389,558
Nematodes ..... farms	3,288	852	493	556	540	318
acres	977,113	579,567	180,393	115,855	65,978	22,134
Diseases in crops and orchards ..... farms	5,080	1,572	861	770	718	414
acres	2,350,398	1,650,514	369,892	197,328	90,500	29,195
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	1,762	487	245	218	279	159
acres on which used	318,341	195,684	47,216	35,476	24,502	8,515
LAND USE PRACTICES						
Land drained by tile ..... farms	19,088	4,268	2,819	3,138	3,340	1,651
acres	8,247,260	5,271,054	1,359,542	890,773	470,956	123,054
Land artificially drained by ditches ..... farms	9,435	1,810	1,153	1,187	1,245	840
acres	4,560,910	2,914,456	714,323	406,910	224,943	99,352
Land under conservation easement ..... farms	4,909	434	323	322	424	297
acres	282,171	57,042	19,493	18,529	19,657	16,646
Cropland on which no-till practices were used ..... farms	6,845	1,233	812	919	956	769
acres	1,194,987	566,266	251,985	178,228	109,694	45,552
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ..... farms	15,574	3,703	2,150	2,404	2,581	1,658
acres	7,881,385	5,280,266	1,186,742	772,610	414,307	141,179
Cropland on which intensive or conventional tillage practices were used (see text) ..... farms	22,330	3,727	2,587	3,025	3,942	2,701
acres	9,573,777	5,769,918	1,652,275	1,042,955	688,891	237,748
Cropland planted to a cover crop (excluding CRP) ..... farms	6,050	1,275	722	733	782	515
acres	760,423	417,432	122,875	88,859	55,767	25,925
Use of precision agriculture practices (see text) ..... farms	15,460	4,034	2,824	2,696	2,482	1,259
RENEWABLE ENERGY						
Renewable energy producing systems (see text) ..... farms	4,247	807	424	413	386	246
Solar panels ..... farms	2,063	282	159	172	171	124
Wind turbines ..... farms	819	231	126	137	105	46
Methane digesters ..... farms	15	14	-	1	-	-
Geothermal/geoexchange systems ..... farms	1,695	364	178	139	141	88
Small hydro systems ..... farms	24	3	1	5	-	2
Wind rights leased to others ..... farms	1,189	243	138	175	191	81
TENURE						
Full owners ..... farms	40,396	1,148	721	1,468	3,004	2,933
Part owners ..... farms	20,564	5,413	3,336	3,274	2,868	1,785
Tenants ..... farms	4,571	568	426	630	895	610
OWNED AND RENTED LAND						
Land owned ..... farms	61,213	6,577	4,072	4,761	5,930	4,764
acres	15,768,785	4,906,462	1,808,901	1,607,507	1,564,785	1,024,103
Owned land in farms ..... farms	60,960	6,561	4,057	4,742	5,872	4,718
acres	13,006,137	4,675,445	1,673,210	1,451,671	1,292,144	768,318
Land rented or leased from others ..... farms	25,328	6,009	3,770	3,911	3,786	2,423
acres	12,515,140	8,100,762	1,974,407	1,136,044	671,412	294,948
Rented or leased land in farms ..... farms	25,135	5,981	3,762	3,904	3,763	2,395
acres	12,436,488	8,073,043	1,963,367	1,131,284	661,745	288,045
Land rented or leased to others ..... farms	15,946	870	612	703	1,272	1,367
acres	2,841,300	258,736	146,731	160,596	282,308	262,688
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS						
Total producers	118,256	14,912	7,885	9,108	11,362	9,098
Farms by number of producers:						
1 producer	28,348	2,547	2,116	2,682	3,391	2,491
2 producers	28,866	2,737	1,726	2,016	2,608	2,282
3 producers	4,480	1,027	396	441	479	309
4 producers	2,500	567	175	158	210	184
5 or more producers	1,337	251	70	75	79	62
Total male producers	81,062	11,512	5,988	6,894	8,368	6,342
Farms by number of male producers:						
1 producer	49,919	4,078	3,270	4,090	5,310	4,276
2 producers	8,600	1,926	894	909	997	670
3 producers	2,596	809	208	230	249	153
4 producers	766	178	48	46	49	35
5 or more producers	459	75	18	18	17	22
Total female producers	37,193	3,399	1,897	2,214	2,994	2,756
Farms by number of female producers:						
1 producer	29,936	2,324	1,535	1,869	2,454	2,301
2 producers	2,374	367	148	121	198	156
3 producers	466	65	14	19	34	30

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
FERTILIZERS AND CHEMICALS						
Commercial fertilizer, lime, and soil conditioners used ..... farms	2,452	2,180	1,086	749	551	1,288
acres treated	132,148	72,050	21,363	11,128	6,756	41,026
Manure used ..... farms	1,129	1,267	679	494	441	1,042
acres treated	31,429	24,420	9,387	5,759	3,736	15,927
Organic fertilizer used ..... farms	136	139	62	72	56	65
acres treated	3,020	2,914	703	453	316	1,613
Acres treated to control-						
Insects ..... farms	767	682	389	255	110	304
acres	29,085	14,226	4,979	2,357	1,294	17,246
Weeds, grass, or brush ..... farms	2,578	2,287	1,097	680	463	1,458
acres	132,525	66,954	19,883	9,540	5,818	56,268
Nematodes ..... farms	206	133	87	49	37	17
acres	7,791	3,563	1,016	476	227	113
Diseases in crops and orchards ..... farms	239	197	143	82	50	34
acres	7,587	2,934	1,752	318	215	163
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	140	88	48	59	23	16
acres on which used	4,059	1,449	776	366	185	113
LAND USE PRACTICES						
Land drained by tile ..... farms	948	770	380	280	231	1,263
acres	40,592	20,499	6,394	4,313	3,422	56,661
Land artificially drained by ditches ..... farms	530	579	351	242	272	1,226
acres	50,393	39,582	10,839	5,608	6,689	87,815
Land under conservation easement ..... farms	239	325	174	161	174	2,036
acres	14,030	13,283	8,940	6,297	7,878	100,376
Cropland on which no-till practices were used ..... farms	542	576	351	230	176	281
acres	20,280	11,713	4,363	2,218	1,131	3,557
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ..... farms	967	817	474	331	182	307
acres	46,755	21,070	8,264	3,692	1,527	4,973
Cropland on which intensive or conventional tillage practices were used (see text) ..... farms	1,815	1,796	1,006	666	492	573
acres	87,327	50,231	18,085	7,857	5,296	13,194
Cropland planted to a cover crop (excluding CRP) ..... farms	416	451	253	205	205	493
acres	12,538	18,907	2,990	2,157	1,899	11,074
Use of precision agriculture practices (see text) ..... farms	656	463	234	132	97	583
RENEWABLE ENERGY						
Renewable energy producing systems (see text) ..... farms	256	321	239	192	265	698
Solar panels ..... farms	151	203	164	128	158	351
Wind turbines ..... farms	27	13	21	8	10	95
Methane digesters ..... farms	-	-	-	-	-	-
Geothermal/geoexchange systems ..... farms	98	118	84	66	111	308
Small hydro systems ..... farms	6	3	-	-	3	1
Wind rights leased to others ..... farms	44	43	28	14	12	220
TENURE						
Full owners ..... farms	2,676	3,990	3,283	3,036	3,199	14,938
Part owners ..... farms	1,185	1,185	564	359	200	395
Tenants ..... farms	407	387	244	138	97	169
OWNED AND RENTED LAND						
Land owned ..... farms	3,877	5,211	3,864	3,401	3,406	15,350
acres	661,500	630,515	356,881	275,524	246,575	2,686,032
Owned land in farms ..... farms	3,861	5,175	3,847	3,395	3,399	15,333
acres	502,818	481,253	270,390	205,334	186,811	1,498,743
Land rented or leased from others ..... farms	1,615	1,580	823	506	302	603
acres	130,368	95,412	34,944	18,001	10,435	48,407
Rented or leased land in farms ..... farms	1,592	1,572	808	497	297	564
acres	125,218	92,604	33,462	16,090	9,128	42,502
Land rented or leased to others ..... farms	1,174	1,498	1,039	873	801	5,737
acres	163,832	152,070	87,973	72,101	61,071	1,193,194
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS						
Total producers	7,529	9,774	7,073	6,142	6,161	29,212
Farms by number of producers:						
1 producer	1,871	2,365	1,705	1,354	1,296	6,530
2 producers	1,901	2,671	2,049	1,922	1,956	6,998
3 producers	288	249	180	152	131	828
4 producers	152	180	114	84	77	599
5 or more producers	56	97	43	21	36	547
Total male producers	5,082	6,313	4,484	3,760	3,686	18,633
Farms by number of male producers:						
1 producer	3,392	4,606	3,400	2,970	2,963	11,564
2 producers	477	511	354	281	189	1,392
3 producers	154	127	58	57	46	505
4 producers	26	47	19	3	17	298
5 or more producers	24	22	18	3	17	225
Total female producers	2,447	3,461	2,589	2,382	2,475	10,579
Farms by number of female producers:						
1 producer	2,020	2,811	2,272	2,078	2,193	8,079
2 producers	146	209	122	105	110	692
3 producers	26	35	19	23	19	182

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS - Con.						
Total producers - Con.						
Total female producers - Con.						
Farms by number of female producers: - Con.						
4 producers	138	21	-	10	7	7
5 or more producers	90	10	4	1	2	2
PRODUCERS' CHARACTERISTICS [3]						
Sex of producers:						
Male	79,245	11,298	5,914	6,828	8,280	6,274
Female	35,623	3,076	1,822	2,141	2,920	2,692
Hired managers	6,902	3,726	1,091	699	524	299
Primary occupation:						
Farming	51,122	11,379	5,704	5,849	6,426	4,371
Other	63,746	2,995	2,032	3,120	4,774	4,595
Place of residence:						
On farm operated	79,195	9,846	5,956	6,590	7,926	6,254
Not on farm operated	35,673	4,528	1,780	2,379	3,274	2,712
Days of work off farm:						
None	46,862	8,654	4,088	4,197	4,545	3,443
Any	68,006	5,720	3,648	4,772	6,655	5,523
1 to 49 days	9,840	1,216	701	788	1,007	778
50 to 99 days	4,745	531	417	382	539	445
100 to 199 days	8,361	726	568	714	958	740
200 days or more	45,060	3,247	1,962	2,888	4,151	3,560
Years on present farm:						
2 years or less	4,867	264	135	244	392	306
3 or 4 years	7,650	679	288	456	641	604
5 to 9 years	18,524	1,782	895	1,215	1,562	1,394
10 years or more	83,827	11,649	6,418	7,054	8,605	6,662
Average years on present farm	24.2	26.7	28.4	28.0	27.1	26.0
Years operating any farm:						
5 years or less	13,846	1,077	494	770	1,108	966
6 to 10 years	15,740	1,234	761	1,026	1,361	1,092
11 years or more	85,282	12,063	6,481	7,173	8,731	6,908
Average years on any farm	26.1	29.2	30.4	29.9	29.3	28.2
Age group:						
Under 25 years	1,900	291	158	144	205	153
25 to 34 years	9,374	1,582	715	872	1,061	842
35 to 44 years	16,237	2,637	1,150	1,411	1,614	1,268
45 to 54 years	16,743	2,595	1,243	1,203	1,445	1,091
55 to 64 years	29,818	3,964	2,254	2,396	2,799	2,037
65 to 74 years	27,187	2,538	1,728	2,117	2,702	2,266
75 years and over	13,609	767	488	826	1,374	1,309
Average age	57.1	52.8	54.9	55.7	56.9	57.6
Young producers (see text)	11,274	1,873	873	1,016	1,266	995
Producers of Hispanic, Latino, or Spanish origin	754	122	32	42	44	41
Producers by race:						
American Indian or Alaska Native	244	7	11	10	19	11
Asian	306	12	3	24	22	39
Black or African American	61	1	5	1	4	4
Native Hawaiian or Other Pacific Islander	43	1	4	-	3	6
White	113,864	14,318	7,703	8,903	11,135	8,886
More than one race reported	350	35	10	31	17	20
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	105,603	13,851	7,427	8,479	10,368	8,168
Active duty now or in the past (see text)	9,265	523	309	490	832	798
Number of persons living in producers' households	228,210	34,238	16,619	18,811	22,713	17,556
On farm involvement in decisionmaking:						
Day-to-day decisions	98,292	12,771	6,890	7,929	9,800	7,699
Land use and/or crop decisions	83,860	11,063	6,234	7,096	8,977	6,924
Livestock decisions	49,585	6,424	3,037	3,527	4,481	3,900
Marketing decisions (see text)	68,020	10,631	6,027	6,924	8,479	6,384
Record keeping and/or financial management	84,043	11,427	6,367	7,277	9,114	6,944
Estate planning or succession planning	64,079	9,446	5,025	5,650	6,793	5,154
FARMS BY TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	62,111	6,314	4,193	5,135	6,434	5,135
Operation more than 50 percent owned by one producer's household and/or extended family — acres	22,990,670	11,079,759	3,385,115	2,430,903	1,849,102	1,015,752
Limited Liability Company — farms	4,803	910	314	356	450	325
Limited Liability Company — acres	2,179,815	1,417,160	223,223	155,531	118,332	53,446

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS - Con.						
Total producers - Con.						
Total female producers - Con.						
Farms by number of female producers: - Con.						
4 producers	2	15	4	-	-	72
5 or more producers	8	12	-	5	1	45
PRODUCERS' CHARACTERISTICS [3]						
Sex of producers:						
Male	4,993	6,235	4,409	3,711	3,596	17,707
Female	2,376	3,327	2,562	2,363	2,457	9,887
Hired managers	148	149	44	57	29	136
Primary occupation:						
Farming	3,153	3,568	2,228	1,690	1,519	5,235
Other	4,216	5,994	4,743	4,384	4,534	22,359
Place of residence:						
On farm operated	5,295	7,264	5,614	4,910	5,141	14,399
Not on farm operated	2,074	2,298	1,357	1,164	912	13,195
Days of work off farm:						
None	2,551	2,969	2,204	1,687	1,671	10,853
Any	4,818	6,593	4,767	4,387	4,382	16,741
1 to 49 days	630	800	625	523	498	2,274
50 to 99 days	361	428	303	271	248	820
100 to 199 days	692	865	654	517	508	1,419
200 days or more	3,135	4,500	3,185	3,076	3,128	12,228
Years on present farm:						
2 years or less	469	492	305	336	390	1,534
3 or 4 years	573	756	520	673	573	1,887
5 to 9 years	1,130	1,905	1,640	1,271	1,373	4,357
10 years or more	5,197	6,409	4,506	3,794	3,717	19,816
Average years on present farm	23.5	21.9	21.0	19.8	18.6	22.5
Years operating any farm:						
5 years or less	1,123	1,464	961	1,067	1,046	3,770
6 to 10 years	961	1,585	1,339	1,099	1,285	3,997
11 years or more	5,285	6,513	4,671	3,908	3,722	19,827
Average years on any farm	25.6	23.9	23.0	21.6	20.4	24.1
Age group:						
Under 25 years	111	229	162	135	102	210
25 to 34 years	702	815	535	469	485	1,296
35 to 44 years	1,064	1,444	1,021	956	1,060	2,612
45 to 54 years	1,052	1,404	1,155	932	996	3,627
55 to 64 years	1,820	2,359	1,736	1,638	1,547	7,268
65 to 74 years	1,703	2,246	1,543	1,331	1,254	7,759
75 years and over	917	1,065	819	613	609	4,822
Average age	56.7	56.3	56.4	56.0	55.6	61.3
Young producers (see text)	813	1,044	697	604	587	1,506
Producers of Hispanic, Latino, or Spanish origin	37	103	21	46	90	176
Producers by race:						
American Indian or Alaska Native	12	34	8	22	33	77
Asian	34	56	29	29	8	50
Black or African American	4	9	13	6	5	9
Native Hawaiian or Other Pacific Islander	2	1	2	1	7	16
White	7,295	9,434	6,895	5,986	5,963	27,346
More than one race reported	22	28	24	30	37	96
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	6,750	8,740	6,272	5,519	5,457	24,572
Active duty now or in the past (see text)	619	822	699	555	596	3,022
Number of persons living in producers' households	14,341	17,822	13,077	11,496	11,379	50,158
On farm involvement in decisionmaking:						
Day-to-day decisions	6,341	8,319	6,163	5,316	5,410	21,654
Land use and/or crop decisions	5,610	7,221	5,133	4,394	4,342	16,866
Livestock decisions	3,617	5,357	4,060	3,452	3,359	8,371
Marketing decisions (see text)	4,970	6,174	4,158	3,436	3,066	7,771
Record keeping and/or financial management	5,531	7,113	4,996	4,206	4,105	16,963
Estate planning or succession planning	3,920	5,015	3,524	3,066	2,916	13,570
FARMS BY TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	4,128	5,401	3,988	3,452	3,426	14,505
Operation more than 50 percent owned by one producer's household and/or extended family — acres	601,328	548,520	292,883	216,043	189,840	1,381,425
Limited Liability Company — farms	302	442	297	216	257	934
Limited Liability Company — acres	38,995	32,721	17,187	9,892	12,669	100,659

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
LEGAL STATUS FOR TAX PURPOSES						
Family or individual ... farms	55,532	4,196	3,544	4,488	5,877	4,760
acres	17,410,756	6,932,411	2,851,922	2,093,940	1,664,721	921,242
Partnership ... farms	5,022	1,460	428	490	542	290
acres	4,452,974	3,352,870	371,035	239,609	170,906	72,615
Registered under State law ... farms	4,156	1,317	370	415	440	199
acres	3,904,476	3,012,658	323,864	195,702	130,406	48,220
Corporation ... farms	3,803	1,436	463	342	234	211
acres	3,244,861	2,404,606	386,086	180,743	73,614	45,007
Family held ... farms	3,375	1,347	436	316	193	188
acres	3,085,380	2,319,813	367,960	174,284	60,849	41,601
More than 10 stockholders ... farms	34	10	1	6	3	1
10 or less stockholders ... farms	3,341	1,337	435	310	190	187
Other than family held ... farms	428	89	27	26	41	23
acres	159,481	84,793	18,126	6,459	12,765	3,406
More than 10 stockholders ... farms	67	22	-	7	-	4
10 or less stockholders ... farms	361	67	27	19	41	19
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. ... farms	1,174	37	48	52	114	67
acres	334,034	58,601	27,534	68,663	44,648	17,499
HIRED FARM LABOR						
Hired farm labor ... farms	17,399	5,909	2,381	1,956	1,933	1,141
workers	72,097	41,319	7,599	6,214	5,585	2,858
Workers by days worked:						
150 days or more ... farms	9,054	4,144	1,226	909	821	485
workers	30,983	21,529	2,740	1,946	1,664	772
Less than 150 days ... farms	12,949	4,332	1,755	1,453	1,427	865
workers	41,114	19,790	4,859	4,268	3,921	2,086
Migrant farm labor on farms with hired labor ... farms	573	444	45	31	32	7
Migrant farm labor on farms reporting only contract labor ... farms	41	5	7	6	5	2
Unpaid workers ... farms	17,519	1,273	1,228	1,456	1,805	1,548
workers	40,333	2,728	2,538	3,129	4,008	3,652
FARMS BY SIZE						
1 to 9 acres	4,401	260	63	103	104	122
10 to 49 acres	15,218	356	86	132	226	354
50 to 69 acres	3,598	61	16	18	64	253
70 to 99 acres	5,575	72	27	43	207	888
100 to 139 acres	4,857	72	26	39	454	971
140 to 179 acres	4,814	72	48	86	1,148	787
180 to 219 acres	2,981	63	67	110	853	490
220 to 259 acres	2,503	44	58	243	881	292
260 to 499 acres	8,699	400	518	2,735	2,112	826
500 to 999 acres	6,421	943	2,438	1,616	587	277
1,000 to 1,999 acres	3,752	2,241	1,028	222	112	63
2,000 acres or more	2,712	2,545	108	25	19	5
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	26,315	4,166	3,489	4,357	5,288	3,426
Vegetable and melon farming (1112)	1,072	69	17	42	98	109
Fruit and tree nut farming (1113)	972	5	6	19	57	85
Greenhouse, nursery, and floriculture production (1114)	971	64	42	64	87	90
Other crop farming (1119)	18,104	107	73	119	375	598
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	18,104	107	73	119	375	598
Beef cattle ranching and farming (112111)	6,753	127	73	124	384	670
Cattle feedlots (112112)	892	270	94	108	120	127
Dairy cattle and milk production (11212)	1,713	706	409	354	139	63
Hog and pig farming (1122)	1,855	1,280	193	84	33	12
Poultry and egg production (1123)	1,724	295	44	41	31	16
Sheep and goat farming (1124)	1,456	-	9	12	25	43
Aquaculture and other animal production (1125,1129)	3,704	40	34	48	130	89
FARM TYPOLOGY (SEE TEXT)						
Farms by typology group:						
Small family farms						
Gross cash farm income less than $150,000	41,924	133	82	68	2,202	4,883
Gross cash farm income $150,000 to $349,999	7,074	279	90	2,054	4,132	227
Midsize family farms						
Gross cash farm income $350,000 to $999,999	7,367	426	3,757	3,010	99	23
Large family farms						
Gross cash farm income $1,000,000 to $4,999,999	5,311	5,042	264	3	1	1
Gross cash farm income $5,000,000 or more	435	434	-	-	-	1
Non-family farms	3,420	815	290	237	333	193
OTHER FARM CHARACTERISTICS						
Farms reporting-						
Internet access	53,964	6,727	4,147	4,769	5,694	4,339
Dial-up	1,876	231	111	158	204	156
Broadband (DSL, cable, fiber optic) (see text)	33,399	4,281	2,599	2,886	3,418	2,632
Cellular data plan (see text)	32,121	4,497	2,737	3,000	3,435	2,639
Satellite	8,385	1,401	771	831	911	594
Don't know	2,877	237	171	254	325	265
Other	346	86	35	35	30	15

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
LEGAL STATUS FOR TAX PURPOSES							
Family or individual	farms	3,860	5,056	3,795	3,333	3,276	13,347
	acres	553,338	511,587	278,479	206,841	179,082	1,217,193
Partnership	farms	204	237	145	96	74	1,056
	acres	42,087	28,460	11,962	4,266	6,507	152,657
Registered under State law	farms	159	175	111	74	55	841
	acres	31,585	17,736	10,653	3,119	5,633	124,900
Corporation	farms	134	186	94	61	104	538
	acres	20,243	21,189	7,725	4,858	7,476	93,314
Family held	farms	109	162	70	44	85	425
	acres	17,817	18,875	5,304	3,681	5,075	70,121
More than 10 stockholders	farms	-	2	-	-	-	11
10 or less stockholders	farms	109	160	70	44	85	414
Other than family held	farms	25	24	24	17	19	113
	acres	2,426	2,314	2,421	1,177	2,401	23,193
More than 10 stockholders	farms	-	-	-	1	5	28
10 or less stockholders	farms	25	24	24	16	14	85
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	farms	70	83	57	43	42	561
	acres	12,368	12,621	5,686	5,459	2,874	78,081
HIRED FARM LABOR							
Hired farm labor	farms	668	863	505	379	335	1,329
	workers	1,744	1,941	967	828	596	2,446
Workers by days worked:							
150 days or more	farms	314	388	133	87	99	448
	workers	532	562	217	160	153	708
Less than 150 days	farms	477	642	407	317	254	1,020
	workers	1,212	1,379	750	668	443	1,738
Migrant farm labor on farms with hired labor	farms	2	10	-	-	1	1
Migrant farm labor on farms reporting only contract labor	farms	2	1	-	2	-	11
Unpaid workers	farms	1,296	1,805	1,377	1,154	1,167	3,410
	workers	3,219	4,233	3,362	2,976	2,771	7,717
FARMS BY SIZE							
1 to 9 acres		218	446	519	587	673	1,306
10 to 49 acres		862	2,011	1,800	1,604	1,743	6,044
50 to 69 acres		439	528	344	320	216	1,339
70 to 99 acres		641	684	434	342	260	1,977
100 to 139 acres		544	541	338	242	223	1,407
140 to 179 acres		470	447	242	180	144	1,190
180 to 219 acres		270	249	130	74	82	593
220 to 259 acres		171	192	81	66	51	424
260 to 499 acres		478	366	174	104	83	903
500 to 999 acres		154	83	26	14	19	264
1,000 to 1,999 acres		20	13	3	-	2	48
2,000 acres or more		1	2	-	-	-	7
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)							
Oilseed and grain farming (1111)		1,967	1,746	930	590	296	60
Vegetable and melon farming (1112)		151	224	152	106	77	27
Fruit and tree nut farming (1113)		87	210	169	80	71	183
Greenhouse, nursery, and floriculture production (1114)		124	177	81	71	52	119
Other crop farming (1119)		696	1,155	1,072	1,233	1,317	11,359
Tobacco farming (11191)		-	-	-	-	-	-
Cotton farming (11192)		-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)		696	1,155	1,072	1,233	1,317	11,359
Beef cattle ranching and farming (112111)		874	1,351	992	613	376	1,169
Cattle feedlots (112112)		116	52	3	2	-	-
Dairy cattle and milk production (11212)		10	-	1	-	-	31
Hog and pig farming (1122)		4	32	60	65	78	14
Poultry and egg production (1123)		14	67	109	269	748	90
Sheep and goat farming (1124)		69	173	188	250	258	429
Aquaculture and other animal production (1125,1129)		156	375	334	254	223	2,021
FARM TYPOLOGY (SEE TEXT)							
Farms by typology group:							
Small family farms							
Gross cash farm income less than $150,000		4,081	5,357	3,970	3,447	3,421	14,280
Gross cash farm income $150,000 to $349,999		46	33	17	5	5	186
Midsize family farms							
Gross cash farm income $350,000 to $999,999		1	11	1	-	-	39
Large family farms							
Gross cash farm income $1,000,000 to $4,999,999		-	-	-	-	-	-
Gross cash farm income $5,000,000 or more		-	-	-	-	-	-
Non-family farms		140	161	103	81	70	997
OTHER FARM CHARACTERISTICS							
Farms reporting-							
Internet access		3,488	4,471	3,363	2,889	2,880	11,197
Dial-up		124	163	123	124	124	358
Broadband (DSL, cable, fiber optic) (see text)		2,084	2,732	2,109	1,740	1,811	7,107
Cellular data plan (see text)		2,123	2,607	1,908	1,601	1,606	5,968
Satellite		517	646	480	435	379	1,420
Don't know		215	219	172	169	114	736
Other		17	25	10	14	13	66

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
OTHER FARM CHARACTERISTICS - Con.						
Farms by number of households sharing in net income of operation:						
1 household	52,287	4,652	3,392	4,145	5,376	4,302
2 households	9,039	1,515	809	938	1,060	795
3 households	2,321	613	208	207	233	127
4 households	1,024	199	39	51	63	51
5 or more households	860	150	35	31	35	53
LIVESTOCK						
Cattle and calves inventory ... farms	16,823	1,900	1,407	1,727	2,107	1,848
number	2,121,625	1,270,602	235,261	189,626	162,957	102,387
Farms with-						
1 to 9	3,446	30	48	93	129	166
10 to 49	6,556	170	216	429	775	827
50 to 99	2,582	97	201	436	630	581
100 to 199	1,927	172	459	556	434	243
200 to 499	1,348	543	439	189	131	31
500 or more	964	888	44	24	8	-
Cows and heifers that calved ... farms	13,439	1,345	1,042	1,301	1,665	1,632
number	824,165	455,697	87,854	70,414	71,750	54,119
Beef cows ... farms	11,691	659	648	975	1,529	1,562
number	364,629	73,204	43,589	45,679	66,030	52,789
Farms with-						
1 to 9	3,718	69	71	133	188	200
10 to 49	6,113	258	285	533	856	1,021
50 to 99	1,205	122	154	199	341	291
100 to 199	470	111	91	84	131	50
200 to 499	149	68	44	25	12	-
500 or more	36	31	3	1	1	-
Milk cows ... farms	2,185	782	462	400	163	102
number	459,536	382,493	44,265	24,735	5,720	1,330
Farms with-						
1 to 9	328	-	4	11	15	45
10 to 49	315	5	13	100	117	57
50 to 99	573	40	252	255	26	-
100 to 199	418	188	191	34	5	-
200 to 499	390	388	2	-	-	-
500 or more	161	161	-	-	-	-
Other cattle ... farms	14,574	1,819	1,348	1,635	1,995	1,698
number	1,297,460	814,905	147,407	119,212	91,207	48,268
Cattle and calves sold ... farms	14,649	1,877	1,389	1,655	1,999	1,758
number	1,599,910	1,110,682	148,237	116,005	95,359	58,415
$1,000	2,094,135	1,536,787	190,343	132,225	105,600	60,748
Calves weighing less than 500 pounds ... farms	4,938	725	474	573	596	639
number	345,069	250,916	24,389	20,678	19,596	12,305
Cattle weighing 500 pounds or more ... farms	13,933	1,856	1,375	1,626	1,962	1,689
number	1,254,841	859,766	123,848	95,327	75,763	46,110
Cattle on feed ... farms	2,685	797	510	490	457	230
number	636,782	519,408	56,495	33,684	17,679	5,971
Hogs and pigs inventory ... farms	2,928	1,472	243	175	140	77
number	8,873,776	8,385,131	347,012	103,142	23,542	5,039
Farms with-						
1 to 24	893	10	7	35	56	49
25 to 49	93	6	6	12	8	8
50 to 99	71	4	7	14	20	6
100 to 199	65	7	7	15	23	5
200 to 499	116	24	31	26	24	7
500 or more	1,690	1,421	185	73	9	2
Hogs and pigs sold ... farms	3,352	1,656	285	192	183	94
number	28,535,462	27,499,478	769,278	203,756	45,441	5,782
$1,000	4,666,832	4,490,194	135,578	31,252	6,300	1,225
Sheep and lambs inventory ... farms	2,137	69	79	95	130	134
number	109,592	11,452	19,068	16,774	10,931	11,133
Sheep and lambs sold ... farms	1,500	61	69	81	98	113
number	92,512	15,372	21,062	12,979	8,476	8,794
Total horses and ponies inventory ... farms	6,988	145	154	230	348	377
number	40,131	545	593	1,664	2,729	2,742
Total horses and ponies sold ... farms	1,171	18	13	45	71	106
number	4,403	63	35	368	731	436
Goats, all inventory ... farms	2,326	37	51	65	130	105
number	50,691	734	4,244	2,866	7,195	5,243
Goats, all sold ... farms	1,215	12	38	34	91	69
number	38,339	188	14,535	2,979	4,774	3,499
POULTRY						
Layers inventory ... farms	6,146	114	108	151	265	350
number	14,553,497	14,054,047	249,279	43,496	59,292	23,149
Farms with-						
1 to 399	6,045	76	89	143	247	337
400 to 3,199	36	-	1	2	15	13
3,200 to 9,999	8	-	-	5	3	-
10,000 to 19,999	24	5	18	1	-	-
20,000 to 49,999	4	4	-	-	-	-
50,000 to 99,999	5	5	-	-	-	-
100,000 or more	24	24	-	-	-	-

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
OTHER FARM CHARACTERISTICS - Con.						
Farms by number of households sharing in net income of operation:						
1 household	3,530	4,701	3,630	3,083	3,114	12,362
2 households	550	655	361	354	292	1,710
3 households	110	96	53	55	40	579
4 households	46	70	22	21	32	430
5 or more households	32	40	25	20	18	421
LIVESTOCK						
Cattle and calves inventory ... farms	1,611	2,081	1,315	852	649	1,326
number	63,362	49,588	17,311	8,932	5,564	16,035
Farms with-						
1 to 9	164	444	589	500	444	839
10 to 49	989	1,433	710	342	203	462
50 to 99	415	188	16	10	-	8
100 to 199	35	16	-	-	2	10
200 to 499	8	-	-	-	-	7
500 or more	-	-	-	-	-	-
Cows and heifers that calved ... farms	1,416	1,778	1,050	704	503	1,003
number	32,587	27,452	9,567	4,858	3,162	6,705
Beef cows ... farms	1,386	1,753	1,028	691	489	971
number	32,236	27,203	9,460	4,811	3,115	6,513
Farms with-						
1 to 9	240	601	599	524	382	711
10 to 49	1,070	1,129	427	167	107	260
50 to 99	76	20	2	-	-	-
100 to 199	-	3	-	-	-	-
200 to 499	-	-	-	-	-	-
500 or more	-	-	-	-	-	-
Milk cows ... farms	58	81	42	22	30	43
number	351	249	107	47	47	192
Farms with-						
1 to 9	50	75	42	22	30	34
10 to 49	8	6	-	-	-	9
50 to 99	-	-	-	-	-	-
100 to 199	-	-	-	-	-	-
200 to 499	-	-	-	-	-	-
500 or more	-	-	-	-	-	-
Other cattle ... farms	1,438	1,745	999	611	435	851
number	30,775	22,136	7,744	4,074	2,402	9,330
Cattle and calves sold ... farms	1,599	1,963	1,248	725	391	45
number	35,717	24,249	7,547	2,708	918	73
$1,000	35,940	22,891	6,793	2,167	609	32
Calves weighing less than 500 pounds ... farms	522	671	400	215	107	16
number	7,716	6,084	2,224	836	287	38
Cattle weighing 500 pounds or more ... farms	1,531	1,824	1,089	627	325	29
number	28,001	18,165	5,323	1,872	631	35
Cattle on feed ... farms	143	53	3	2	-	-
number	2,706	800	(D)	(D)	-	-
Hogs and pigs inventory ... farms	96	170	186	140	124	105
number	1,340	3,148	2,432	929	781	1,280
Farms with-						
1 to 24	80	143	159	138	117	99
25 to 49	9	12	24	2	5	1
50 to 99	4	10	3	-	2	1
100 to 199	3	3	-	-	-	2
200 to 499	-	2	-	-	-	2
500 or more	-	-	-	-	-	-
Hogs and pigs sold ... farms	122	212	259	172	137	40
number	2,223	4,148	3,182	1,375	654	145
$1,000	451	745	663	260	141	23
Sheep and lambs inventory ... farms	144	306	278	233	252	417
number	6,917	13,046	7,896	4,641	3,256	4,478
Sheep and lambs sold ... farms	104	257	218	244	161	94
number	6,739	9,773	4,720	3,025	1,279	293
Total horses and ponies inventory ... farms	448	851	706	595	748	2,386
number	3,659	5,600	3,433	2,755	2,867	13,544
Total horses and ponies sold ... farms	137	304	221	139	111	6
number	784	1,093	488	240	159	6
Goats, all inventory ... farms	147	276	306	297	401	511
number	4,823	6,392	5,435	4,031	5,042	4,686
Goats, all sold ... farms	87	182	190	202	204	106
number	2,846	3,165	2,543	1,917	1,554	339
POULTRY						
Layers inventory ... farms	404	799	820	863	1,151	1,121
number	15,204	24,864	24,008	22,771	25,328	12,059
Farms with-						
1 to 399	399	799	820	863	1,151	1,121
400 to 3,199	5	-	-	-	-	-
3,200 to 9,999	-	-	-	-	-	-
10,000 to 19,999	-	-	-	-	-	-
20,000 to 49,999	-	-	-	-	-	-
50,000 to 99,999	-	-	-	-	-	-
100,000 or more	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
POULTRY - Con.						
Pullets for laying flock replacement inventory ..... farms	723	16	6	20	21	35
number	4,185,443	3,788,035	120	115,212	64,270	201,177
Layers sold ..... farms	664	28	23	26	39	42
number	7,016,481	6,667,242	248,340	36,765	37,571	3,981
Pullets for laying flock replacement sold ..... farms	102	14	-	9	8	2
number	8,319,040	8,036,916	-	196,300	77,550	(D)
Broilers and other meat-type chickens sold ..... farms	1,028	128	21	40	36	63
number	41,793,592	41,400,984	156,266	56,471	88,685	12,726
Farms with-						
1 to 1,999	900	11	16	37	33	63
2,000 to 59,999	11	-	5	3	3	-
60,000 to 99,999	-	-	-	-	-	-
100,000 or more	117	117	-	-	-	-
Turkeys inventory ..... farms	623	147	16	24	10	16
number	14,927,734	14,696,951	128,159	89,455	9,612	193
Turkeys sold ..... farms	379	147	22	21	3	14
number	39,460,145	38,777,969	518,704	146,519	14,154	439
CROPS						
Barley for grain ..... farms	336	125	48	80	33	23
acres	55,330	33,624	7,625	9,093	3,839	633
bushels	4,011,381	2,517,290	562,185	656,588	210,962	44,445
Irrigated ..... farms	10	-	5	-	-	2
acres	116	-	92	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	72	9	8	18	4	16
25 to 99 acres	96	27	11	23	19	6
100 to 249 acres	94	39	21	31	2	1
250 to 499 acres	53	30	7	8	8	-
500 acres or more	21	20	1	-	-	-
Corn for grain ..... farms	24,697	5,706	3,745	4,372	4,945	2,657
acres	7,732,455	5,001,120	1,242,224	816,061	474,825	133,002
bushels	1,478,451,268	985,726,950	232,092,248	149,887,712	81,051,897	21,135,453
Irrigated ..... farms	1,341	514	243	219	230	89
acres	302,897	207,992	48,237	24,903	15,929	4,922
Farms by acres harvested:						
1 to 24 acres	2,863	46	32	43	143	352
25 to 99 acres	6,867	246	232	446	2,753	2,180
100 to 249 acres	6,444	523	774	3,038	1,974	120
250 to 499 acres	4,136	1,025	2,219	812	75	5
500 acres or more	4,387	3,866	488	33	-	-
Corn for silage or greenchop ..... farms	2,768	940	434	437	391	251
acres	313,974	233,086	32,127	23,127	14,179	6,770
tons	6,334,518	4,910,079	616,113	418,675	233,076	103,738
Irrigated ..... farms	108	65	19	12	4	5
acres	13,135	11,184	907	716	133	98
Farms by acres harvested:						
1 to 24 acres	848	56	56	123	196	147
25 to 99 acres	1,133	264	292	261	172	100
100 to 249 acres	452	308	72	45	22	4
250 to 499 acres	218	198	11	8	1	-
500 acres or more	117	114	3	-	-	-
Dry edible beans, excluding chickpeas and limas ..... farms	573	339	73	60	51	23
acres	210,162	182,097	13,528	8,638	4,534	1,018
cwt	5,278,245	4,530,279	320,458	229,661	144,123	41,704
Irrigated ..... farms	95	68	5	15	5	1
acres	39,931	36,880	654	2,134	(D)	(D)
Farms by acres harvested:						
1 to 24 acres	34	-	-	1	4	8
25 to 99 acres	118	17	23	22	36	14
100 to 249 acres	146	69	35	30	11	1
250 to 499 acres	140	126	7	7	-	-
500 acres or more	135	127	8	-	-	-
Oats for grain ..... farms	2,329	313	324	367	472	332
acres	126,011	31,823	21,062	17,931	24,577	14,836
bushels	9,470,546	2,946,337	1,759,424	1,467,823	1,607,303	918,532
Irrigated ..... farms	66	22	18	12	8	3
acres	3,194	1,300	1,190	305	239	126
Farms by acres harvested:						
1 to 24 acres	906	44	80	139	188	139
25 to 99 acres	1,097	190	180	183	203	163
100 to 249 acres	286	61	57	45	69	27
250 to 499 acres	29	8	6	-	12	3
500 acres or more	11	10	1	-	-	-
Sorghum for grain ..... farms	12	1	1	2	4	-
acres	364	(D)	(D)	(D)	39	-
bushels	24,260	(D)	(D)	(D)	1,470	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	7	-	-	-	3	-
25 to 99 acres	4	1	-	2	1	-
100 to 249 acres	1	-	1	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
POULTRY - Con.						
Pullets for laying flock replacement inventory ..... farms	55	114	101	131	147	77
number	3,179	4,317	2,580	2,443	2,190	1,920
Layers sold ..... farms	36	129	106	116	72	47
number	4,493	10,773	2,352	3,174	1,254	536
Pullets for laying flock replacement sold ..... farms	6	23	10	14	16	-
number	(D)	256	131	1,375	(D)	-
Broilers and other meat-type chickens sold ..... farms	74	180	170	158	95	63
number	11,736	41,034	10,162	7,844	4,218	3,466
Farms with-						
1 to 1,999	74	180	170	158	95	63
2,000 to 59,999	-	-	-	-	-	-
60,000 to 99,999	-	-	-	-	-	-
100,000 or more	-	-	-	-	-	-
Turkeys inventory ..... farms	24	68	97	80	75	66
number	632	639	686	677	463	267
Turkeys sold ..... farms	23	40	46	25	28	10
number	729	509	437	225	372	88
CROPS						
Barley for grain ..... farms	13	5	2	3	4	-
acres	355	54	(D)	40	(D)	-
bushels	16,945	1,760	(D)	(D)	566	-
Irrigated ..... farms	2	-	1	-	-	-
acres	(D)	-	(D)	-	-	-
Farms by acres harvested:						
1 to 24 acres	5	4	1	3	4	-
25 to 99 acres	8	1	1	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Corn for grain ..... farms	1,400	996	449	228	127	72
acres	41,132	17,430	4,403	1,596	488	174
bushels	5,763,260	2,134,741	458,218	146,918	42,303	11,568
Irrigated ..... farms	20	21	2	1	2	-
acres	497	348	(D)	(D)	(D)	-
Farms by acres harvested:						
1 to 24 acres	600	796	431	221	127	72
25 to 99 acres	786	199	18	7	-	-
100 to 249 acres	14	1	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Corn for silage or greenchop ..... farms	163	82	24	21	14	11
acres	2,895	1,224	198	185	131	52
tons	35,223	14,412	1,503	975	562	162
Irrigated ..... farms	2	1	-	-	-	-
acres	(D)	(D)	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	135	65	24	21	14	11
25 to 99 acres	27	17	-	-	-	-
100 to 249 acres	1	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas ..... farms	3	9	5	7	2	1
acres	138	162	23	(D)	(D)	(D)
cwt	2,632	8,362	492	302	(D)	(D)
Irrigated ..... farms	-	-	-	-	-	1
acres	-	-	-	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	1	5	5	7	2	1
25 to 99 acres	2	4	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Oats for grain ..... farms	204	166	77	52	18	4
acres	7,878	4,806	2,132	842	113	11
bushels	395,985	229,139	97,149	43,177	5,067	610
Irrigated ..... farms	1	-	1	-	1	-
acres	(D)	-	(D)	-	(D)	-
Farms by acres harvested:						
1 to 24 acres	112	92	45	45	18	4
25 to 99 acres	71	68	32	7	-	-
100 to 249 acres	21	6	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Sorghum for grain ..... farms	2	-	-	-	2	-
acres	(D)	-	-	-	(D)	-
bushels	(D)	-	-	-	(D)	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	2	-	-	-	2	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
CROPS - Con.							
Soybeans for beans	farms	25,337	5,672	3,902	4,466	4,881	2,761
	acres	7,597,171	4,492,757	1,379,752	876,014	537,683	198,581
	bushels	373,669,175	229,559,120	65,306,461	41,502,590	24,698,694	8,446,051
Irrigated	farms	892	304	152	158	147	72
	acres	122,734	71,605	19,814	15,760	9,972	3,821
Farms by acres harvested:							
1 to 24 acres		2,307	56	34	32	107	232
25 to 99 acres		7,345	304	291	588	2,518	1,929
100 to 249 acres		6,879	640	784	2,789	2,008	567
250 to 499 acres		4,297	1,001	2,081	947	236	29
500 acres or more		4,509	3,671	712	110	12	4
Sugarbeets for sugar	farms	1,106	723	172	108	60	23
	acres	446,627	396,618	31,287	12,880	4,721	773
	tons	11,642,041	10,416,358	753,644	318,665	124,337	20,614
Irrigated	farms	31	31	-	-	-	-
	acres	10,798	10,798	-	-	-	-
Sunflower seed, all	farms	221	100	43	38	21	6
	acres	66,924	46,998	12,671	4,416	2,122	387
	pounds	151,726,117	113,469,955	25,063,340	8,016,566	4,143,814	731,250
Irrigated	farms	2	-	1	-	-	-
	acres	(D)	-	(D)	-	-	-
Farms by acres harvested:							
1 to 24 acres		8	-	-	-	1	1
25 to 99 acres		53	10	3	20	8	5
100 to 249 acres		62	14	20	16	12	-
250 to 499 acres		49	32	15	2	-	-
500 acres or more		49	44	5	-	-	-
Wheat for grain, all	farms	3,669	1,131	676	650	531	296
	acres	1,268,681	811,687	227,470	135,693	58,086	22,389
	bushels	82,039,945	56,136,896	13,578,645	7,692,257	3,033,109	1,055,855
Irrigated	farms	52	18	5	11	1	6
	acres	6,251	3,105	355	2,177	(D)	133
Farms by acres harvested:							
1 to 24 acres		416	34	38	60	59	54
25 to 99 acres		1,023	157	126	154	225	161
100 to 249 acres		809	155	137	219	206	78
250 to 499 acres		544	169	170	161	41	3
500 acres or more		877	616	205	56	-	-
Forage-land used for all hay and haylage, grass silage, and greenchop	farms	23,394	2,014	1,465	1,762	2,499	2,357
	acres	1,392,072	311,358	132,233	133,450	196,525	191,807
	tons, dry equivalent	3,565,994	1,250,003	419,330	386,792	490,389	404,351
Irrigated	farms	675	152	83	76	111	56
	acres	32,954	14,581	3,557	3,737	4,129	2,917
Farms by acres harvested:							
1 to 24 acres		11,106	440	375	578	870	725
25 to 99 acres		8,179	545	630	775	1,019	960
100 to 249 acres		3,115	633	365	327	436	515
250 to 499 acres		780	295	68	55	146	132
500 acres or more		214	101	27	27	28	25
Alfalfa hay	farms	15,333	1,359	1,085	1,422	1,933	1,757
	acres	744,117	148,913	75,236	83,185	117,831	110,885
	tons, dry	1,971,568	561,005	247,473	249,784	309,613	253,686
Irrigated	farms	421	91	54	57	89	43
	acres	15,949	4,957	1,944	2,365	2,707	2,003
Other dry hay	farms	8,556	545	431	524	804	875
	acres	390,421	34,322	27,333	30,847	52,746	67,839
	tons, dry	658,360	98,697	57,766	62,603	103,443	112,185
Irrigated	farms	153	21	10	17	11	20
	acres	3,658	735	143	762	129	767
Field and grass seed crops, all	farms	155	54	31	34	11	14
	acres	66,601	48,730	8,246	6,758	1,673	824
Irrigated	farms	6	-	-	5	1	-
	acres	505	-	-	(D)	(D)	-
Land in vegetables	farms	2,620	558	208	203	248	199
	acres	196,718	138,548	26,620	15,633	10,897	2,727
Irrigated	farms	764	113	39	48	71	72
	acres	54,640	42,812	6,058	3,145	1,666	402
Farms by acres harvested:							
0.1 to 4.9 acres		1,355	10	5	24	74	112
5.0 to 24.9 acres		225	16	3	37	57	52
25.0 to 99.9 acres		495	186	95	88	77	35
100.0 to 249.9 acres		364	202	80	42	40	-
250.0 acres or more		181	144	25	12	-	-
Beans, snap	farms	390	31	3	21	34	57
	acres	2,553	2,452	(D)	11	14	19
Harvested for processing	farms	22	17	-	-	-	-
	acres	2,278	(D)	-	-	-	-
Peas, green	farms	599	278	112	70	39	28
	acres	47,364	32,499	8,044	4,527	1,607	621
Harvested for processing	farms	491	275	110	62	30	12
	acres	47,345	32,498	8,041	4,525	1,605	617
Potatoes	farms	509	70	17	32	59	49
	acres	49,008	46,934	1,503	351	103	25
Harvested for processing	farms	39	34	3	2	-	-
	acres	35,127	34,342	(D)	(D)	-	-

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
CROPS - Con.						
Soybeans for beans ..... farms	1,418	1,156	575	332	147	27
acres	65,517	33,076	9,717	3,028	873	173
bushels	2,583,100	1,178,381	286,405	84,550	18,652	5,171
Irrigated ..... farms	22	24	2	6	5	-
acres	908	750	(D)	(D)	76	-
Farms by acres harvested:						
1 to 24 acres	346	538	473	319	145	25
25 to 99 acres	990	606	102	13	2	2
100 to 249 acres	79	12	-	-	-	-
250 to 499 acres	3	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Sugarbeets for sugar ..... farms	7	13	-	-	-	-
acres	181	167	-	-	-	-
tons	4,566	3,857	-	-	-	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Sunflower seed, all ..... farms	6	4	3	-	-	-
acres	135	156	39	-	-	-
pounds	60,800	193,592	46,800	-	-	-
Irrigated ..... farms	1	-	-	-	-	-
acres	(D)	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	2	1	3	-	-	-
25 to 99 acres	4	3	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Wheat for grain, all ..... farms	165	101	57	40	18	4
acres	7,875	3,578	1,210	538	115	40
bushels	354,742	131,549	39,333	13,802	2,847	910
Irrigated ..... farms	8	-	1	-	2	-
acres	446	-	(D)	-	(D)	-
Farms by acres harvested:						
1 to 24 acres	46	28	36	39	18	4
25 to 99 acres	107	71	21	1	-	-
100 to 249 acres	12	2	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Forage-land used for all hay and haylage, grass silage, and greenchop ..... farms	2,057	2,782	2,090	1,913	1,830	2,625
acres	135,513	124,636	62,579	42,602	28,209	33,160
tons, dry equivalent	246,716	190,551	76,848	46,618	27,513	26,883
Irrigated ..... farms	49	32	17	38	18	43
acres	1,675	784	337	597	183	457
Farms by acres harvested:						
1 to 24 acres	661	1,172	1,152	1,276	1,518	2,339
25 to 99 acres	930	1,277	860	612	302	269
100 to 249 acres	401	316	73	23	10	16
250 to 499 acres	59	17	5	2	-	1
500 acres or more	6	-	-	-	-	-
Alfalfa hay ..... farms	1,481	1,831	1,218	1,035	884	1,328
acres	73,322	62,916	27,821	18,422	10,870	14,716
tons, dry	152,273	109,258	40,166	22,845	11,860	13,605
Irrigated ..... farms	36	18	8	15	5	5
acres	1,295	284	131	203	54	6
Other dry hay ..... farms	780	1,139	840	822	814	982
acres	51,160	52,170	27,382	19,616	13,519	13,487
tons, dry	78,483	69,891	31,417	20,105	12,802	10,968
Irrigated ..... farms	12	9	4	18	7	24
acres	223	342	65	108	87	297
Field and grass seed crops, all ..... farms	4	2	-	5	-	-
acres	145	(D)	-	(D)	-	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Land in vegetables ..... farms	253	397	229	152	117	56
acres	1,115	679	288	104	86	20
Irrigated ..... farms	105	162	81	42	27	4
acres	220	184	99	35	17	2
Farms by acres harvested:						
0.1 to 4.9 acres	210	376	221	152	115	56
5.0 to 24.9 acres	29	21	8	-	2	-
25.0 to 99.9 acres	14	-	-	-	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 acres or more	-	-	-	-	-	-
Beans, snap ..... farms	54	110	48	11	15	6
acres	10	19	7	(D)	14	1
Harvested for processing ..... farms	-	3	-	-	2	-
acres	-	1	-	-	(D)	-
Peas, green ..... farms	23	22	18	6	3	-
acres	42	23	2	1	(Z)	-
Harvested for processing ..... farms	1	1	-	-	-	-
acres	(D)	(D)	-	-	-	-
Potatoes ..... farms	76	96	63	17	21	9
acres	32	37	18	3	3	2
Harvested for processing ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
CROPS - Con.							
Land in vegetables - Con.							
Potatoes - Con.							
Farms by acres harvested:							
0.1 to 4.9 acres	farms	421	6	3	25	57	49
5.0 to 24.9 acres	farms	5	2	-	2	-	-
25.0 to 99.9 acres	farms	20	3	11	4	2	-
100.0 to 249.9 acres	farms	8	6	1	1	-	-
250.0 acres or more	farms	55	53	2	-	-	-
Sweet corn (see text)	farms	1,243	377	157	141	160	92
	acres	96,990	57,669	17,789	10,854	8,456	1,562
Harvested for processing	farms	750	353	151	113	100	24
	acres	94,536	56,182	17,664	10,743	8,238	1,371
Sweet potatoes	farms	58	-	1	12	10	13
	acres	23	-	(D)	9	4	5
Harvested for processing	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Tomatoes in the open	farms	592	15	5	31	53	58
	acres	300	58	15	41	70	25
Harvested for processing	farms	18	-	-	-	-	-
	acres	2	-	-	-	-	-
Land in orchards	farms	1,174	19	11	28	65	97
	acres	5,049	530	282	565	921	563
Irrigated	farms	204	9	2	5	12	27
	acres	778	197	(D)	36	112	155
Farms by bearing and nonbearing acres:							
0.1 to 4.9 acres		927	13	5	11	16	49
5.0 to 24.9 acres		212	1	2	8	34	47
25.0 to 99.9 acres		32	3	4	8	15	1
100.0 to 249.9 acres		3	2	-	1	-	-
250.0 acres or more		-	-	-	-	-	-
Apples	farms	751	8	8	19	50	70
	bearing and nonbearing acres	3,219	504	266	443	662	363
Grapes (including muscadine) (see text)	farms	433	11	4	9	18	35
	bearing and nonbearing acres	1,290	26	10	107	196	182
Peaches, all	farms	17	-	-	1	-	2
	bearing and nonbearing acres	(D)	-	-	(D)	-	(D)
Walnuts, English	farms	29	-	-	1	1	-
	bearing and nonbearing acres	142	-	-	(D)	(D)	-
Land in berries	farms	578	11	6	21	44	55
	acres	1,129	280	87	146	130	147

See footnote(s) at end of table.

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Table 72. **Summary by Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
CROPS - Con.							
Land in vegetables - Con.							
Potatoes - Con.							
Farms by acres harvested:							
0.1 to 4.9 acres		76	95	63	17	21	9
5.0 to 24.9 acres		-	1	-	-	-	-
25.0 to 99.9 acres		-	-	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-	-
250.0 acres or more		-	-	-	-	-	-
Sweet corn (see text)	farms	90	109	57	31	20	9
	acres	492	89	44	15	18	3
Harvested for processing	farms	9	-	-	-	-	-
	acres	338	-	-	-	-	-
Sweet potatoes	farms	7	7	7	-	1	-
	acres	(D)	2	1	-	(D)	-
Harvested for processing	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Tomatoes in the open	farms	100	173	84	40	31	2
	acres	34	36	13	5	(D)	(D)
Harvested for processing	farms	1	5	3	6	3	-
	acres	(D)	(D)	(Z)	(D)	(Z)	-
Land in orchards	farms	127	271	200	101	89	166
	acres	411	669	416	118	176	398
Irrigated	farms	30	59	22	15	15	8
	acres	46	91	23	15	49	(D)
Farms by bearing and nonbearing acres:							
0.1 to 4.9 acres		100	237	178	97	83	138
5.0 to 24.9 acres		27	33	22	4	6	28
25.0 to 99.9 acres		-	1	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-	-
250.0 acres or more		-	-	-	-	-	-
Apples	farms	99	189	121	43	44	100
	bearing and nonbearing acres	241	368	169	23	50	130
Grapes (including muscadine) (see text)	farms	34	94	86	51	43	48
	bearing and nonbearing acres	88	187	196	80	105	112
Peaches, all	farms	3	10	1	-	-	-
	bearing and nonbearing acres	(Z)	3	(D)	-	-	-
Walnuts, English	farms	1	7	2	2	-	15
	bearing and nonbearing acres	(D)	14	(D)	(D)	-	110
Land in berries	farms	88	151	72	41	29	60
	acres	92	107	54	34	13	40

[1] Landlord production expenses are included with total farm production expenses.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.
[3] Data were collected for a maximum of four producers per farm.

Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
FARMS AND LAND IN FARMS						
Farms ..... number	65,531	7,266	4,529	5,477	6,899	5,488
percent	100.0	11.1	6.9	8.4	10.5	8.4
Land in farms ..... acres	25,442,625	12,948,517	3,596,804	2,586,162	1,950,490	1,092,854
Average size of farm ..... acres	388	1,782	794	472	283	199
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	65,531	7,266	4,529	5,477	6,899	5,488
$1,000	29,066,202	21,989,791	3,226,615	1,970,453	1,119,898	396,767
Average per farm ..... dollars	443,549	3,026,396	712,434	359,769	162,328	72,297
Farms by economic class:						
Less than $1,000	6,079	-	-	-	-	-
$1,000 to $2,499	6,033	-	-	-	-	-
$2,500 to $4,999	5,681	-	-	-	-	-
$5,000 to $9,999	6,141	-	-	-	-	-
$10,000 to $24,999	7,125	-	-	-	-	-
$25,000 to $49,999	4,813	-	-	-	-	-
$50,000 to $99,999	5,488	-	-	-	-	5,488
$100,000 to $249,999	6,899	-	-	-	6,899	-
$250,000 to $499,999	5,477	-	-	5,477	-	-
$500,000 to $999,999	4,529	-	4,529	-	-	-
$1,000,000 or more	7,266	7,266	-	-	-	-
$1,000,000 to $2,499,999	4,148	4,148	-	-	-	-
$2,500,000 to $4,999,999	2,458	2,458	-	-	-	-
$5,000,000 or more	660	660	-	-	-	-
Total sales ..... farms	65,531	7,266	4,529	5,477	6,899	5,488
$1,000	28,482,097	21,719,022	3,137,939	1,910,838	1,069,643	368,451
Grains, oilseeds, dry beans, and dry peas ..... farms	32,075	6,384	4,247	5,033	6,030	3,936
$1,000	15,268,581	10,220,541	2,391,017	1,509,272	814,768	232,482
Sales of $50,000 or more ..... farms	23,618	6,225	4,109	4,878	5,579	2,827
$1,000	15,113,786	10,216,812	2,387,642	1,505,442	803,550	200,340
Corn ..... farms	25,230	5,834	3,792	4,489	5,056	2,725
$1,000	9,045,595	6,181,280	1,372,869	870,569	459,649	115,914
Sales of $50,000 or more ..... farms	18,777	5,668	3,635	4,273	4,232	969
$1,000	8,908,714	6,177,045	1,368,882	865,117	434,580	63,089
Wheat ..... farms	3,668	1,185	679	650	547	252
$1,000	735,504	525,797	111,686	62,932	25,004	5,970
Sales of $50,000 or more ..... farms	2,125	985	500	421	187	32
$1,000	707,000	521,509	107,854	58,390	17,130	2,117
Soybeans ..... farms	25,334	5,794	3,942	4,538	4,872	2,725
$1,000	5,087,514	3,206,990	865,457	546,900	315,342	105,042
Sales of $50,000 or more ..... farms	17,131	5,537	3,708	4,109	2,940	837
$1,000	4,898,487	3,200,291	858,689	533,266	250,021	56,221
Sorghum ..... farms	53	7	3	5	21	6
$1,000	437	187	70	30	91	29
Sales of $50,000 or more ..... farms	1	1	-	-	-	-
$1,000	(D)	(D)	-	-	-	-
Barley ..... farms	336	129	52	78	33	19
$1,000	27,673	18,451	3,396	4,709	896	167
Sales of $50,000 or more ..... farms	151	84	27	37	3	-
$1,000	24,984	17,398	3,134	4,037	415	-
Rice ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	3,613	901	517	537	610	400
$1,000	371,859	287,836	37,539	24,132	13,786	5,360
Sales of $50,000 or more ..... farms	1,013	577	175	159	81	21
$1,000	342,531	282,240	31,831	19,361	7,737	1,361
Tobacco ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	2,648	565	215	198	256	197
$1,000	446,099	356,808	32,437	21,257	17,570	7,264
Sales of $50,000 or more ..... farms	994	492	180	119	125	78
$1,000	424,789	354,525	31,266	19,225	14,738	5,035
Fruits, tree nuts, and berries ..... farms	1,212	25	13	39	82	117
$1,000	48,717	15,885	3,863	6,947	8,244	5,684
Sales of $50,000 or more ..... farms	178	10	8	25	60	75
$1,000	38,977	15,630	3,766	6,722	7,846	5,013
Fruits and tree nuts ..... farms	944	18	10	28	60	89
$1,000	30,052	7,761	2,379	4,160	6,094	3,660
Sales of $50,000 or more ..... farms	116	5	4	14	44	49
$1,000	22,967	7,591	2,280	3,984	5,884	3,229
Berries ..... farms	489	11	6	21	44	53
$1,000	18,665	8,124	1,484	2,787	2,150	2,024
Sales of $50,000 or more ..... farms	66	8	4	11	19	24
$1,000	15,470	8,039	(D)	2,560	1,858	(D)
Nursery, greenhouse, floriculture, and sod ..... farms	1,051	74	46	80	118	145
$1,000	391,444	315,337	27,913	21,262	13,174	6,240
Sales of $50,000 or more ..... farms	343	74	43	70	84	72
$1,000	381,613	315,337	(D)	21,072	(D)	4,847

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
FARMS AND LAND IN FARMS						
Farms ..... number	4,813	7,125	6,141	5,681	6,033	6,079
percent	7.3	10.9	9.4	8.7	9.2	9.3
Land in farms ..... acres	769,147	837,123	553,204	396,776	329,898	381,650
Average size of farm ..... acres	160	117	90	70	55	63
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	4,813	7,125	6,141	5,681	6,033	6,079
$1,000	172,312	114,738	43,879	20,425	9,997	1,327
Average per farm ..... dollars	35,801	16,104	7,145	3,595	1,657	218
Farms by economic class:						
Less than $1,000	-	-	-	-	-	6,079
$1,000 to $2,499	-	-	-	-	6,033	-
$2,500 to $4,999	-	-	-	5,681	-	-
$5,000 to $9,999	-	-	6,141	-	-	-
$10,000 to $24,999	-	7,125	-	-	-	-
$25,000 to $49,999	4,813	-	-	-	-	-
$50,000 to $99,999	-	-	-	-	-	-
$100,000 to $249,999	-	-	-	-	-	-
$250,000 to $499,999	-	-	-	-	-	-
$500,000 to $999,999	-	-	-	-	-	-
$1,000,000 or more	-	-	-	-	-	-
$1,000,000 to $2,499,999	-	-	-	-	-	-
$2,500,000 to $4,999,999	-	-	-	-	-	-
$5,000,000 or more	-	-	-	-	-	-
Total sales ..... farms	4,813	7,125	6,141	5,681	6,033	6,079
$1,000	145,284	85,636	27,576	11,572	5,126	1,009
Grains, oilseeds, dry beans, and dry peas ..... farms	2,393	2,051	1,034	604	259	104
$1,000	65,922	26,151	6,071	1,890	408	59
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Corn ..... farms	1,452	1,010	456	237	111	68
$1,000	31,205	10,836	2,357	717	159	41
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Wheat ..... farms	142	99	65	35	10	4
$1,000	2,600	1,115	294	89	13	4
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Soybeans ..... farms	1,409	1,106	511	295	125	17
$1,000	30,549	13,128	3,008	889	201	8
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sorghum ..... farms	4	2	2	-	3	-
$1,000	10	(D)	(D)	-	4	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Barley ..... farms	13	4	1	3	4	-
$1,000	42	(D)	(D)	2	2	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Rice ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	245	188	99	71	29	16
$1,000	1,516	1,055	405	193	30	7
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Tobacco ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	267	403	224	156	114	53
$1,000	5,361	3,848	1,018	381	133	23
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Fruits, tree nuts, and berries ..... farms	164	320	208	104	95	45
$1,000	3,227	3,315	1,156	251	123	22
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Fruits and tree nuts ..... farms	120	254	172	83	74	36
$1,000	2,160	2,606	902	213	99	18
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Berries ..... farms	86	136	64	31	28	9
$1,000	1,068	709	253	38	25	3
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Nursery, greenhouse, floriculture, and sod ..... farms	201	190	98	67	30	2
$1,000	4,497	2,284	503	185	(D)	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.						
Total - Con.						
Total sales - Con.						
Cultivated Christmas trees and short rotation woody crops ... farms	244	6	3	17	12	18
$1,000	7,578	1,798	(D)	1,703	1,930	517
Sales of $50,000 or more ... farms	27	3	1	5	11	7
$1,000	6,051	(D)	(D)	1,396	(D)	425
Cultivated Christmas trees ... farms	243	6	3	17	12	18
$1,000	(D)	1,798	(D)	1,703	1,930	517
Sales of $50,000 or more ... farms	27	3	1	5	11	7
$1,000	6,051	(D)	(D)	1,396	(D)	425
Short rotation woody crops ... farms	1	-	-	-	-	-
$1,000	(D)	-	-	-	-	-
Sales of $50,000 or more ... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other crops and hay ... farms	16,722	1,695	901	1,065	1,701	1,709
$1,000	981,348	701,992	76,160	50,096	56,658	42,097
Sales of $50,000 or more ... farms	2,437	1,083	363	289	368	334
$1,000	867,179	694,699	69,604	41,212	39,517	22,146
Maple syrup ... farms	364	2	6	3	10	17
$1,000	869	(D)	(D)	2	4	217
Sales of $50,000 or more ... farms	3	-	-	-	-	3
$1,000	191	-	-	-	-	191
Cattle and calves ... farms	14,649	1,911	1,410	1,664	2,061	1,786
$1,000	2,094,135	1,544,016	189,067	130,359	107,183	58,812
Sales of $50,000 or more ... farms	4,609	1,652	857	772	848	480
$1,000	1,933,030	1,538,217	174,310	109,427	80,095	30,981
Milk from cows ... farms	1,893	790	470	380	149	67
$1,000	2,504,638	2,157,961	224,369	100,064	18,017	3,885
Sales of $50,000 or more ... farms	1,826	790	469	377	143	47
$1,000	2,503,304	2,157,961	(D)	99,969	17,861	(D)
Hogs and pigs ... farms	3,352	1,658	283	196	184	100
$1,000	4,666,832	4,490,264	135,508	31,600	6,100	1,109
Sales of $50,000 or more ... farms	2,034	1,623	248	119	37	7
$1,000	4,660,288	4,489,857	135,050	30,534	4,317	530
Sheep, goats, wool, mohair, and milk ... farms	2,604	73	96	127	195	164
$1,000	33,457	3,617	7,574	5,599	4,821	3,669
Sales of $50,000 or more ... farms	120	14	24	20	26	36
$1,000	19,839	2,721	6,801	4,403	3,377	2,537
Horses, ponies, mules, burros, and donkeys ... farms	1,247	21	18	46	76	112
$1,000	18,147	112	(D)	2,619	4,012	2,958
Sales of $50,000 or more ... farms	76	-	1	10	32	33
$1,000	8,302	-	(D)	(D)	3,653	2,264
Poultry and eggs ... farms	4,445	367	105	142	208	260
$1,000	1,943,207	1,883,514	33,655	13,485	4,714	1,680
Sales of $50,000 or more ... farms	447	314	46	41	32	14
$1,000	1,935,336	1,883,420	33,545	13,191	4,228	952
Aquaculture ... farms	98	-	14	19	28	8
$1,000	19,763	-	9,043	5,571	4,405	520
Sales of $50,000 or more ... farms	62	-	13	15	27	7
$1,000	19,502	-	(D)	5,559	(D)	(D)
Other animals and other animal products ... farms	1,405	77	30	63	102	77
$1,000	58,149	27,177	6,366	11,004	8,047	1,534
Sales of $50,000 or more ... farms	154	33	11	35	57	18
$1,000	52,455	26,569	6,217	10,792	7,738	1,140
Value of-						
Government payments ... farms	31,583	4,925	2,937	3,064	3,590	2,639
$1,000	584,106	270,768	88,675	59,615	50,255	28,316
Landlord's share of total sales ... farms	1,294	407	224	207	175	108
$1,000	118,307	80,032	19,777	11,220	4,826	1,639
FOOD MARKETING PRACTICES						
Value of food sold directly to-						
Consumers ... farms	3,339	67	70	110	242	263
$1,000	44,673	6,185	3,901	6,011	8,656	5,526
Retail markets, institutions, and food hubs for local or regionally branded products ... farms	1,026	33	28	58	117	105
$1,000	108,704	84,229	7,238	4,251	5,816	2,775
FARM PRODUCTION EXPENSES						
Total farm production expenses [1] ... farms	65,531	7,266	4,529	5,477	6,899	5,488
$1,000	20,780,603	15,340,306	2,235,522	1,363,985	860,501	334,139
Average per farm ... dollars	317,111	2,111,245	493,602	249,039	124,728	60,885
Fertilizer, lime, and soil conditioners purchased ... farms	36,421	6,515	4,314	5,198	6,301	4,233
$1,000	2,325,700	1,471,062	390,962	248,494	141,644	43,405
Farms with expenses of-						
$1 to $4,999 ...	10,529	128	99	224	749	1,264
$5,000 to $24,999 ...	9,710	436	460	1,104	3,362	2,642
$25,000 to $49,999 ...	5,102	514	677	1,825	1,708	307
$50,000 or more ...	11,080	5,437	3,078	2,045	482	20
Chemicals purchased ... farms	37,339	6,554	4,338	5,208	6,309	4,317
$1,000	1,161,099	743,750	188,682	121,507	68,947	22,218

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.						
Total - Con.						
Total sales - Con.						
Cultivated Christmas trees and short rotation woody crops ..... farms	20	34	22	40	27	45
$1,000	467	299	105	(D)	(D)	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Cultivated Christmas trees ..... farms	20	34	22	39	27	45
$1,000	467	299	105	60	(D)	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Short rotation woody crops ..... farms	-	-	-	1	-	-
$1,000	-	-	-	(D)	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other crops and hay ..... farms	1,572	2,153	1,757	1,549	1,459	1,161
$1,000	22,857	17,520	7,465	3,988	1,922	593
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Maple syrup ..... farms	28	76	36	61	83	42
$1,000	191	214	134	38	53	13
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Cattle and calves ..... farms	1,588	1,943	1,201	676	365	44
$1,000	34,052	21,727	6,340	1,982	565	31
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Milk from cows ..... farms	16	14	3	1	1	2
$1,000	303	32	6	(D)	(D)	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Hogs and pigs ..... farms	116	230	244	172	130	39
$1,000	422	795	618	258	136	23
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sheep, goats, wool, mohair, and milk ..... farms	194	425	394	405	329	202
$1,000	2,549	2,863	1,386	864	422	92
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Horses, ponies, mules, burros, and donkeys ..... farms	141	331	224	138	116	24
$1,000	2,969	3,483	1,124	366	167	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Poultry and eggs ..... farms	321	642	587	697	880	236
$1,000	1,092	1,740	1,139	1,062	1,019	107
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Aquaculture ..... farms	6	10	8	2	1	2
$1,000	96	60	60	(D)	(D)	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other animals and other animal products ..... farms	105	309	205	171	180	86
$1,000	1,470	1,520	587	277	139	29
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Value of-						
Government payments ..... farms	2,168	3,051	2,839	2,758	3,063	549
$1,000	27,028	29,102	16,304	8,853	4,871	319
Landlord's share of total sales ..... farms	72	52	34	9	6	-
$1,000	514	219	67	9	4	-
FOOD MARKETING PRACTICES						
Value of food sold directly to-						
Consumers ..... farms	383	675	553	440	388	148
$1,000	5,657	4,802	2,616	864	392	61
Retail markets, institutions, and food hubs for local or regionally branded products ..... farms	130	211	109	108	100	27
$1,000	1,624	2,081	358	234	89	10
FARM PRODUCTION EXPENSES						
Total farm production expenses [1] ..... farms	4,813	7,125	6,141	5,681	6,033	6,079
$1,000	180,450	159,159	92,531	67,091	60,802	86,117
Average per farm ..... dollars	37,492	22,338	15,068	11,810	10,078	14,166
Fertilizer, lime, and soil conditioners purchased ..... farms	2,673	2,642	1,459	1,133	898	1,055
$1,000	14,786	7,598	2,989	1,939	1,087	1,734
Farms with expenses of-						
$1 to $4,999	1,531	2,232	1,355	1,075	865	1,007
$5,000 to $24,999	1,099	392	92	51	28	44
$25,000 to $49,999	37	15	8	4	5	2
$50,000 or more	6	3	4	3	-	2
Chemicals purchased ..... farms	2,882	2,940	1,737	1,265	925	864
$1,000	7,757	4,316	1,710	844	565	804

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Chemicals purchased - Con.						
Farms with expenses of-						
$1 to $4,999	15,060	268	196	421	1,563	2,643
$5,000 to $24,999	11,493	875	1,162	2,950	4,270	1,634
$25,000 to $49,999	4,407	999	1,545	1,394	399	31
$50,000 or more	6,379	4,412	1,435	443	77	9
Seeds, plants, vines, and trees purchased ..... farms	36,437	6,492	4,323	5,203	6,138	3,887
$1,000	1,772,341	1,151,313	273,518	171,652	108,238	37,427
Farms with expenses of-						
$1 to $999	5,343	15	12	19	109	293
$1,000 to $4,999	6,157	65	62	165	581	1,099
$5,000 to $24,999	10,290	394	565	1,650	4,224	2,294
$25,000 to $49,999	5,582	621	1,048	2,636	1,045	128
$50,000 or more	9,065	5,397	2,636	733	179	73
Cover crop seed purchased ..... farms	4,909	1,225	607	652	625	419
$1,000	20,527	11,242	3,771	2,304	1,664	701
Livestock and poultry purchased or leased ..... farms	13,933	2,770	1,047	1,095	1,324	1,048
$1,000	1,926,426	1,728,962	93,818	43,551	24,687	9,190
Farms with expenses of-						
$1 to $4,999	6,658	114	167	291	503	524
$5,000 to $24,999	3,161	168	256	343	513	435
$25,000 to $99,999	1,372	259	264	337	279	89
$100,000 to $249,999	912	488	281	114	29	-
$250,000 or more	1,830	1,741	79	10	-	-
Breeding livestock purchased or leased ..... farms	5,904	735	442	541	709	649
$1,000	171,016	124,684	14,286	9,068	6,697	4,460
Other livestock and poultry purchased or leased ..... farms	9,786	2,276	725	686	784	546
$1,000	1,755,410	1,604,279	79,531	34,483	17,990	4,730
Feed purchased ..... farms	26,145	3,631	1,766	2,040	2,474	2,076
$1,000	3,890,272	3,511,355	170,037	80,368	43,310	22,328
Farms with expenses of-						
$1 to $4,999	13,038	130	214	460	882	965
$5,000 to $24,999	6,844	177	457	772	1,070	857
$25,000 to $99,999	2,349	322	479	558	489	249
$100,000 to $249,999	1,155	477	419	221	27	5
$250,000 or more	2,759	2,525	197	29	6	-
Gasoline, fuels, and oils purchased ..... farms	61,621	7,248	4,520	5,442	6,763	5,321
$1,000	956,802	616,728	123,834	81,540	56,240	24,990
Farms with expenses of-						
$1 to $4,999	37,714	295	275	781	2,571	3,696
$5,000 to $24,999	14,760	1,202	2,019	3,891	3,936	1,556
$25,000 to $49,999	4,270	1,522	1,787	638	206	56
$50,000 or more	4,877	4,229	439	132	50	13
Utilities ..... farms	48,636	7,262	4,516	5,463	6,479	4,513
$1,000	400,978	256,265	42,120	30,720	24,223	12,967
Farms with expenses of-						
$1 to $999	9,923	68	111	322	722	772
$1,000 to $4,999	24,023	648	1,325	3,056	4,516	3,145
$5,000 to $24,999	12,077	4,287	2,877	1,992	1,207	580
$25,000 to $49,999	1,626	1,366	149	67	24	15
$50,000 or more	987	893	54	26	10	1
Repairs, supplies, and maintenance costs ..... farms	55,660	7,254	4,514	5,461	6,678	5,099
$1,000	1,322,234	786,690	185,674	126,721	92,154	41,501
Farms with expenses of-						
$1 to $4,999	25,809	225	180	537	1,731	2,148
$5,000 to $24,999	17,499	834	1,327	3,147	4,117	2,660
$25,000 to $49,999	5,425	1,294	1,737	1,296	625	259
$50,000 or more	6,927	4,901	1,270	481	205	32
Hired farm labor ..... farms	17,399	6,022	2,358	1,974	1,925	1,121
$1,000	1,320,974	1,101,028	84,484	47,300	36,992	14,966
Farms with expenses of-						
$1 to $4,999	5,944	416	546	676	883	616
$5,000 to $24,999	4,466	897	767	818	678	391
$25,000 to $99,999	3,749	1,844	897	389	301	96
$100,000 to $249,999	2,234	1,936	113	73	56	12
$250,000 or more	1,006	929	35	18	7	6
Contract labor ..... farms	4,311	1,300	410	426	464	338
$1,000	152,565	126,304	7,764	5,995	5,189	1,926
Farms with expenses of-						
$1 to $999	452	14	9	8	26	63
$1,000 to $4,999	1,452	130	88	146	184	149
$5,000 to $24,999	1,469	459	235	206	199	115
$25,000 to $49,999	315	152	46	46	35	9
$50,000 or more	623	545	32	20	20	2
Customwork and custom hauling ..... farms	19,181	4,315	2,185	2,564	3,058	2,003
$1,000	425,172	297,404	43,958	34,608	26,697	9,914
Farms with expenses of-						
$1 to $999	2,876	102	80	183	254	303
$1,000 to $4,999	6,088	396	430	640	1,041	1,001
$5,000 to $24,999	6,540	1,254	1,200	1,332	1,598	678

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Chemicals purchased - Con.						
Farms with expenses of-						
$1 to $4,999	2,491	2,800	1,689	1,241	910	838
$5,000 to $24,999	374	125	43	23	14	23
$25,000 to $49,999	17	15	3	1	1	2
$50,000 or more	-	-	2	-	-	1
Seeds, plants, vines, and trees purchased ... farms	2,605	2,704	1,665	1,333	1,153	934
$1,000	14,750	8,191	2,911	1,975	1,310	1,057
Farms with expenses of-						
$1 to $999	506	1,043	994	848	844	660
$1,000 to $4,999	1,312	1,357	575	416	270	255
$5,000 to $24,999	698	271	82	65	33	14
$25,000 to $49,999	54	25	12	4	6	3
$50,000 or more	35	8	2	-	-	2
Cover crop seed purchased ... farms	299	384	187	154	134	223
$1,000	303	233	92	65	43	108
Livestock and poultry purchased or leased ... farms	1,020	1,543	1,201	930	940	1,015
$1,000	6,966	8,049	3,866	2,045	1,703	3,587
Farms with expenses of-						
$1 to $4,999	559	1,053	985	832	850	780
$5,000 to $24,999	427	436	191	91	86	215
$25,000 to $99,999	34	54	25	7	4	20
$100,000 to $249,999	-	-	-	-	-	-
$250,000 or more	-	-	-	-	-	-
Breeding livestock purchased or leased ... farms	549	799	481	314	275	410
$1,000	3,207	4,096	1,663	716	711	1,428
Other livestock and poultry purchased or leased ... farms	628	995	911	730	764	741
$1,000	3,759	3,954	2,204	1,329	992	2,159
Feed purchased ... farms	1,988	2,963	2,208	1,770	1,856	3,373
$1,000	15,865	16,826	8,430	5,245	4,331	12,177
Farms with expenses of-						
$1 to $4,999	1,033	1,844	1,657	1,459	1,618	2,776
$5,000 to $24,999	838	1,041	529	307	236	560
$25,000 to $99,999	116	76	22	4	2	32
$100,000 to $249,999	1	2	-	-	-	3
$250,000 or more	-	-	-	-	-	2
Gasoline, fuels, and oils purchased ... farms	4,577	6,554	5,488	4,920	5,187	5,601
$1,000	14,151	13,047	7,975	5,930	5,699	6,668
Farms with expenses of-						
$1 to $4,999	3,767	5,997	5,211	4,734	5,019	5,368
$5,000 to $24,999	788	536	272	176	159	225
$25,000 to $49,999	16	17	4	9	7	8
$50,000 or more	6	4	1	1	2	-
Utilities ... farms	3,556	4,572	3,471	2,802	2,717	3,285
$1,000	8,390	8,316	5,443	3,852	3,667	5,014
Farms with expenses of-						
$1 to $999	834	1,565	1,453	1,312	1,270	1,494
$1,000 to $4,999	2,406	2,706	1,862	1,376	1,355	1,628
$5,000 to $24,999	313	301	156	113	91	160
$25,000 to $49,999	1	-	-	1	-	3
$50,000 or more	2	-	-	-	1	-
Repairs, supplies, and maintenance costs ... farms	4,257	5,787	4,604	3,910	3,851	4,245
$1,000	23,700	22,257	13,789	10,283	8,921	10,546
Farms with expenses of-						
$1 to $4,999	2,393	4,414	3,832	3,287	3,392	3,670
$5,000 to $24,999	1,771	1,307	732	609	442	553
$25,000 to $49,999	80	54	37	9	16	18
$50,000 or more	13	12	3	5	1	4
Hired farm labor ... farms	775	989	648	509	508	570
$1,000	11,164	9,322	4,093	3,939	2,376	5,309
Farms with expenses of-						
$1 to $4,999	442	674	504	406	421	360
$5,000 to $24,999	273	240	102	74	65	161
$25,000 to $99,999	43	57	37	21	22	42
$100,000 to $249,999	6	18	5	8	-	7
$250,000 or more	11	-	-	-	-	-
Contract labor ... farms	269	340	200	176	182	206
$1,000	1,702	1,448	587	502	428	719
Farms with expenses of-						
$1 to $999	36	64	51	46	66	69
$1,000 to $4,999	133	197	118	101	101	105
$5,000 to $24,999	89	66	31	29	13	27
$25,000 to $49,999	8	12	-	-	2	5
$50,000 or more	3	1	-	-	-	-
Customwork and custom hauling ... farms	1,426	1,335	755	561	510	469
$1,000	4,972	3,453	1,434	907	1,017	808
Farms with expenses of-						
$1 to $999	372	509	335	271	259	208
$1,000 to $4,999	801	681	365	263	222	248
$5,000 to $24,999	235	132	53	24	23	11

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Customwork and custom hauling - Con.						
Farms with expenses of- - Con.						
$25,000 to $49,999	2,030	1,247	296	308	133	14
$50,000 or more	1,647	1,316	179	101	32	7
Cash rent for land, buildings, and grazing fees ... farms	24,199	6,240	3,874	4,010	3,854	2,274
$1,000	2,302,712	1,697,435	323,169	166,027	77,262	21,362
Farms with expenses of-						
$1 to $4,999	5,289	87	150	330	772	946
$5,000 to $9,999	2,314	123	125	325	591	574
$10,000 to $24,999	4,009	309	468	966	1,373	613
$25,000 or more	12,587	5,721	3,131	2,389	1,118	141
Rent and lease expenses for machinery, equipment, and farm share of vehicles ... farms	6,598	1,983	859	894	818	466
$1,000	182,357	134,535	19,283	13,451	7,642	2,671
Farms with expenses of-						
$1 to $999	1,233	63	74	125	156	145
$1,000 to $4,999	1,683	236	177	222	236	154
$5,000 to $24,999	2,168	616	390	388	395	153
$25,000 to $49,999	538	287	109	98	19	5
$50,000 or more	976	781	109	61	12	9
Interest expense ... farms	27,274	6,081	3,277	3,460	3,447	2,291
$1,000	702,889	443,672	91,480	55,685	41,882	18,085
Farms with expenses of-						
$1 to $4,999	9,316	493	491	953	1,278	1,154
$5,000 to $24,999	11,255	1,498	1,552	1,843	1,790	1,002
$25,000 to $99,999	5,316	2,872	1,138	638	347	128
$100,000 or more	1,387	1,218	96	26	32	7
Secured by real estate ... farms	20,348	4,601	2,464	2,463	2,432	1,631
$1,000	467,669	281,695	63,334	39,695	28,638	13,020
Farms with expenses of-						
$1 to $999	1,511	81	76	145	150	158
$1,000 to $4,999	5,125	303	312	441	646	595
$5,000 to $24,999	9,127	1,397	1,229	1,426	1,404	793
$25,000 to $49,999	2,363	1,146	552	302	180	66
$50,000 or more	2,222	1,674	295	149	52	19
Not secured by real estate ... farms	16,953	4,245	2,232	2,265	2,230	1,376
$1,000	235,219	161,978	28,146	15,990	13,244	5,064
Farms with expenses of-						
$1 to $999	2,836	157	165	267	415	399
$1,000 to $4,999	6,264	544	485	862	992	721
$5,000 to $24,999	5,400	1,538	1,329	1,052	756	234
$25,000 to $49,999	1,506	1,164	200	70	43	13
$50,000 or more	947	842	53	14	24	9
Property taxes paid ... farms	61,644	6,861	4,242	4,985	6,211	4,982
$1,000	482,443	190,508	57,442	45,371	41,669	24,511
Farms with expenses of-						
$1 to $4,999	39,325	1,335	1,135	1,835	3,171	3,376
$5,000 to $9,999	11,291	1,122	1,039	1,593	1,994	1,205
$10,000 to $24,999	7,298	1,959	1,529	1,319	905	314
$25,000 or more	3,730	2,445	539	238	141	87
Medical supplies, veterinary, and custom services for livestock ... farms	19,351	3,471	1,627	1,782	1,993	1,618
$1,000	255,043	210,105	16,148	8,566	6,033	3,807
Farms with expenses of-						
$1 to $4,999	14,259	578	768	1,238	1,680	1,451
$5,000 to $24,999	3,318	1,332	728	514	294	151
$25,000 to $49,999	674	524	94	16	13	10
$50,000 to $99,999	623	568	32	13	4	6
$100,000 or more	477	469	5	1	2	-
All other production expenses ... farms	44,226	7,254	4,513	5,461	6,476	4,446
$1,000	1,200,596	873,188	123,149	82,430	57,692	22,872
Farms with expenses of-						
$1 to $4,999	22,214	454	582	1,268	2,554	3,096
$5,000 to $24,999	13,025	1,432	1,699	3,346	3,593	1,245
$25,000 to $49,999	3,867	1,143	1,664	648	238	85
$50,000 to $99,999	3,372	2,661	459	140	79	20
$100,000 or more	1,748	1,564	109	59	12	-
Production expenses paid by landlords [1] ... farms	2,062	737	329	289	185	130
$1,000	65,113	43,923	10,127	6,096	2,303	1,256
Depreciation expenses claimed ... farms	41,075	7,211	4,491	5,332	5,319	3,690
$1,000	2,240,389	1,440,001	297,950	205,945	124,000	55,318
NET CASH FARM INCOME						
Net cash farm income of operations ... farms	65,531	7,266	4,529	5,477	6,899	5,488
$1,000	9,296,848	6,938,589	1,105,247	713,591	360,010	141,691
Average per farm ... dollars	141,869	954,939	244,038	130,289	52,183	25,818
Farms with net gains [2] ... number	41,496	6,826	4,220	4,959	5,798	4,388
Average net gain ... dollars	242,705	1,053,130	277,412	155,309	75,332	42,843

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Customwork and custom hauling - Con.						
Farms with expenses of- - Con.						
$25,000 to $49,999	15	7	2	3	5	-
$50,000 or more	3	6	-	-	1	2
Cash rent for land, buildings, and grazing fees ... farms	1,439	1,184	543	295	225	261
$1,000	7,405	4,353	1,716	629	895	2,458
Farms with expenses of-						
$1 to $4,999	928	970	477	272	178	179
$5,000 to $9,999	325	137	34	12	29	39
$10,000 to $24,999	163	51	22	7	10	27
$25,000 or more	23	26	10	4	8	16
Rent and lease expenses for machinery, equipment, and farm share of vehicles ... farms	344	312	274	200	204	244
$1,000	1,353	1,191	624	552	426	631
Farms with expenses of-						
$1 to $999	125	153	122	76	82	112
$1,000 to $4,999	135	99	111	96	110	107
$5,000 to $24,999	79	51	41	25	8	22
$25,000 to $49,999	3	7	-	3	4	3
$50,000 or more	2	2	-	-	-	-
Interest expense ... farms	1,689	1,937	1,513	1,060	1,110	1,409
$1,000	12,182	11,387	8,452	5,590	5,359	9,115
Farms with expenses of-						
$1 to $4,999	907	1,089	900	625	708	718
$5,000 to $24,999	716	820	585	409	387	653
$25,000 to $99,999	62	27	27	26	14	37
$100,000 or more	4	1	1	-	1	1
Secured by real estate ... farms	1,245	1,500	1,147	843	852	1,170
$1,000	9,133	8,758	6,553	4,550	4,369	7,925
Farms with expenses of-						
$1 to $999	145	178	162	129	160	127
$1,000 to $4,999	470	696	522	355	338	447
$5,000 to $24,999	586	606	439	342	344	561
$25,000 to $49,999	31	17	17	13	6	33
$50,000 or more	13	3	7	4	4	2
Not secured by real estate ... farms	1,015	1,054	772	524	505	735
$1,000	3,049	2,629	1,898	1,040	990	1,191
Farms with expenses of-						
$1 to $999	281	315	242	151	171	273
$1,000 to $4,999	550	590	439	333	310	438
$5,000 to $24,999	182	144	88	34	19	24
$25,000 to $49,999	2	4	-	6	4	-
$50,000 or more	-	1	3	-	1	-
Property taxes paid ... farms	4,466	6,735	5,878	5,511	5,901	5,872
$1,000	20,050	26,441	21,131	18,010	18,441	18,867
Farms with expenses of-						
$1 to $4,999	3,247	5,434	4,976	4,780	5,087	4,949
$5,000 to $9,999	902	926	663	515	585	747
$10,000 to $24,999	251	325	192	171	188	145
$25,000 or more	66	50	47	45	41	31
Medical supplies, veterinary, and custom services for livestock ... farms	1,487	2,081	1,416	975	1,020	1,881
$1,000	2,300	2,751	1,386	840	871	2,236
Farms with expenses of-						
$1 to $4,999	1,403	1,990	1,378	945	997	1,831
$5,000 to $24,999	81	82	38	30	23	45
$25,000 to $49,999	3	9	-	-	-	5
$50,000 to $99,999	-	-	-	-	-	-
$100,000 or more	-	-	-	-	-	-
All other production expenses ... farms	3,304	3,840	2,622	2,091	2,066	2,153
$1,000	12,956	10,213	5,996	4,010	3,704	4,387
Farms with expenses of-						
$1 to $4,999	2,665	3,325	2,373	1,958	1,939	2,000
$5,000 to $24,999	585	493	237	127	124	144
$25,000 to $49,999	43	21	12	6	1	6
$50,000 to $99,999	8	1	-	-	2	2
$100,000 or more	3	-	-	-	-	1
Production expenses paid by landlords [1] ... farms	115	76	71	45	43	42
$1,000	755	216	202	64	91	80
Depreciation expenses claimed ... farms	2,886	3,487	2,569	2,151	2,110	1,829
$1,000	33,619	29,340	18,891	12,297	10,350	12,677
NET CASH FARM INCOME						
Net cash farm income of operations ... farms	4,813	7,125	6,141	5,681	6,033	6,079
$1,000	44,848	30,105	9,734	4,306	5,241	-56,515
Average per farm ... dollars	9,318	4,225	1,585	758	869	-9,297
Farms with net gains [2] ... number	3,338	4,367	2,917	2,191	1,822	670
Average net gain ... dollars	25,994	18,340	17,664	18,891	23,437	21,638

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
NET CASH FARM INCOME - Con.						
Net cash farm income of operations - Con.						
Farms with net gains [2] - Con.						
Gain of-						
Less than $1,000	1,541	6	3	10	20	20
$1,000 to $4,999	4,053	4	8	32	123	145
$5,000 to $9,999	3,053	10	7	40	133	270
$10,000 to $24,999	5,680	38	51	102	500	1,087
$25,000 to $49,999	5,396	51	101	278	1,195	1,628
$50,000 or more	21,773	6,717	4,050	4,497	3,827	1,238
Farms with net losses, number	24,035	440	309	518	1,101	1,100
Average net loss, dollars	32,221	568,363	211,755	109,242	69,726	42,094
Loss of-						
Less than $1,000	1,786	1	3	13	29	25
$1,000 to $4,999	6,380	14	7	26	82	162
$5,000 to $9,999	5,021	9	5	24	90	123
$10,000 to $24,999	5,999	15	34	101	250	271
$25,000 to $49,999	2,539	44	50	84	203	258
$50,000 or more	2,310	357	210	270	447	261
Net cash farm income of producers, farms	65,531	7,266	4,529	5,477	6,899	5,488
$1,000	8,390,544	6,084,853	1,065,765	702,238	358,011	141,268
Average per farm, dollars	128,039	837,442	235,320	128,216	51,893	25,741
Producers reporting net gains [2], farms	41,274	6,667	4,171	4,942	5,783	4,391
Average net gain, dollars	222,954	954,782	272,298	154,001	75,270	42,671
Gain of-						
Less than $1,000	1,557	7	2	9	20	24
$1,000 to $4,999	4,059	9	7	36	128	146
$5,000 to $9,999	3,084	29	16	41	131	274
$10,000 to $24,999	5,726	61	62	113	487	1,094
$25,000 to $49,999	5,475	107	109	295	1,195	1,621
$50,000 or more	21,373	6,454	3,975	4,448	3,822	1,232
Producers reporting net losses, farms	24,257	599	358	535	1,116	1,097
Average net loss, dollars	33,460	468,575	195,507	109,971	69,243	42,025
Loss of-						
Less than $1,000	1,780	-	3	9	29	27
$1,000 to $4,999	6,394	19	8	25	91	164
$5,000 to $9,999	5,032	17	12	24	95	122
$10,000 to $24,999	6,008	25	39	99	246	265
$25,000 to $49,999	2,576	64	68	87	210	255
$50,000 or more	2,467	474	228	291	445	264
COMMODITY CREDIT CORPORATION LOANS						
Total, farms	990	485	175	170	115	35
$1,000	197,241	167,502	16,580	9,247	3,447	415
INCOME FROM FARM-RELATED SOURCES						
Total income from farm-related sources, farms	38,287	5,083	3,645	4,339	5,275	3,838
$1,000	1,011,249	289,104	114,154	107,124	100,612	79,063
Customwork and other agricultural services, farms	4,779	1,273	740	750	638	367
$1,000	144,025	64,622	27,613	22,652	11,778	8,704
Gross cash rent or share payments, farms	15,680	901	622	717	1,341	1,478
$1,000	479,289	53,429	23,320	30,197	51,910	52,051
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products, farms	619	3	14	27	37	39
$1,000	5,384	(D)	(D)	436	585	231
Agri-tourism and recreational services, farms	509	15	19	41	57	66
$1,000	13,615	(D)	(D)	2,433	1,984	1,460
Patronage dividends and refunds from cooperatives, farms	23,672	4,347	3,295	3,823	4,280	2,585
$1,000	126,183	70,969	22,552	15,346	9,395	3,446
Crop and livestock insurance payments, farms	5,882	1,485	1,050	1,056	1,038	574
$1,000	171,530	76,106	34,148	26,932	16,994	7,963
Amount from State and local government agricultural program payments, farms	1,422	169	158	194	191	154
$1,000	7,129	1,988	1,176	1,165	826	379
Other farm-related income sources, farms	2,557	422	247	306	324	230
$1,000	64,095	20,179	5,032	7,961	7,140	4,828
LAND USE						
Total cropland, farms	58,762	6,715	4,409	5,297	6,708	5,299
acres	21,544,060	12,342,972	3,271,449	2,194,186	1,504,154	721,994
Harvested cropland, farms	47,549	6,620	4,381	5,259	6,668	5,098
acres	19,662,443	12,008,062	3,114,425	2,047,824	1,325,318	550,503
Farms by acres harvested:						
1 to 49 acres	16,934	146	66	130	332	737
50 to 99 acres	5,412	94	39	76	422	1,974
100 to 199 acres	6,580	141	152	286	3,071	1,938
200 to 499 acres	8,316	551	752	3,677	2,719	423
500 to 999 acres	4,858	1,021	2,648	1,036	120	26
1,000 to 1,999 acres	3,081	2,323	702	54	2	-
2,000 acres or more	2,368	2,344	22	-	2	-

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
NET CASH FARM INCOME - Con.						
Net cash farm income of operations - Con.						
Farms with net gains [2] - Con.						
Gain of-						
Less than $1,000	76	223	284	371	407	121
$1,000 to $4,999	315	918	1,172	854	347	135
$5,000 to $9,999	417	1,164	572	187	168	85
$10,000 to $24,999	1,299	1,406	372	297	362	166
$25,000 to $49,999	907	344	260	247	285	100
$50,000 or more	324	312	257	235	253	63
Farms with net losses, number	1,475	2,758	3,224	3,490	4,211	5,409
Average net loss, dollars	28,419	18,125	12,963	10,626	8,896	13,129
Loss of-						
Less than $1,000	63	209	274	407	485	277
$1,000 to $4,999	262	639	940	1,117	1,624	1,507
$5,000 to $9,999	246	520	720	834	973	1,477
$10,000 to $24,999	459	821	882	803	839	1,524
$25,000 to $49,999	249	390	307	256	225	473
$50,000 or more	196	179	101	73	65	151
Net cash farm income of producers, farms	4,813	7,125	6,141	5,681	6,033	6,079
$1,000	45,183	30,095	9,876	4,362	5,328	-56,434
Average per farm, dollars	9,388	4,224	1,608	768	883	-9,284
Producers reporting net gains [2], farms	3,343	4,366	2,920	2,197	1,824	670
Average net gain, dollars	26,000	18,340	17,657	18,847	23,414	21,653
Gain of-						
Less than $1,000	80	227	282	376	409	121
$1,000 to $4,999	307	913	1,176	856	347	134
$5,000 to $9,999	416	1,165	573	186	168	85
$10,000 to $24,999	1,306	1,405	372	297	362	167
$25,000 to $49,999	910	344	262	247	285	100
$50,000 or more	324	312	255	235	253	63
Producers reporting net losses, farms	1,470	2,759	3,221	3,484	4,209	5,409
Average net loss, dollars	28,391	18,114	12,941	10,633	8,881	13,116
Loss of-						
Less than $1,000	62	208	275	404	486	277
$1,000 to $4,999	254	644	943	1,117	1,622	1,507
$5,000 to $9,999	241	520	716	831	974	1,480
$10,000 to $24,999	472	816	879	803	837	1,527
$25,000 to $49,999	244	390	307	256	228	467
$50,000 or more	197	181	101	73	62	151
COMMODITY CREDIT CORPORATION LOANS						
Total, farms	8	1	-	1	-	-
$1,000	(D)	(D)	-	(D)	-	-
INCOME FROM FARM-RELATED SOURCES						
Total income from farm-related sources, farms	3,038	3,763	2,682	2,240	2,432	1,952
$1,000	52,986	74,526	58,386	50,972	56,046	28,275
Customwork and other agricultural services, farms	260	241	128	143	137	102
$1,000	2,811	2,200	883	710	1,234	819
Gross cash rent or share payments, farms	1,523	2,143	1,964	1,744	1,946	1,301
$1,000	39,272	54,493	53,096	48,190	52,619	20,711
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products, farms	65	101	60	69	89	115
$1,000	1,193	731	213	439	520	552
Agri-tourism and recreational services, farms	50	89	55	26	31	60
$1,000	723	3,276	817	77	121	1,080
Patronage dividends and refunds from cooperatives, farms	1,629	1,641	801	446	409	416
$1,000	1,519	1,389	439	418	362	347
Crop and livestock insurance payments, farms	292	202	75	56	24	30
$1,000	3,293	4,600	761	352	97	283
Amount from State and local government agricultural program payments, farms	127	143	102	63	67	54
$1,000	440	404	295	156	139	162
Other farm-related income sources, farms	199	295	107	91	122	214
$1,000	3,736	7,433	1,882	628	954	4,321
LAND USE						
Total cropland, farms	4,492	6,353	5,308	4,787	4,863	4,531
acres	443,705	429,231	239,855	152,340	107,245	136,929
Harvested cropland, farms	3,916	4,771	3,313	2,632	2,145	2,746
acres	251,989	177,435	80,410	45,826	28,595	32,056
Farms by acres harvested:						
1 to 49 acres	1,820	3,584	2,899	2,464	2,076	2,680
50 to 99 acres	1,378	843	330	147	56	53
100 to 199 acres	585	294	75	18	11	9
200 to 499 acres	126	50	9	3	2	4
500 to 999 acres	7	-	-	-	-	-
1,000 to 1,999 acres	-	-	-	-	-	-
2,000 acres or more	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
LAND USE - Con.						
Total cropland - Con.						
Cropland-						
Other pasture and grazing land that could have been used for crops without additional improvements ..... farms	3,908	229	240	318	524	445
acres	174,215	31,059	16,462	19,950	28,399	26,682
On which all crops failed or were abandoned ..... farms	2,413	242	201	231	307	264
acres	110,013	27,213	15,761	17,463	12,118	10,925
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed ..... farms	22,588	2,580	1,472	1,512	1,807	1,497
acres	1,546,009	268,281	120,774	103,198	133,291	129,313
In summer fallow ..... farms	2,242	141	124	184	212	203
acres	51,380	8,357	4,027	5,751	5,028	4,571
Total woodland ..... farms	23,960	1,022	899	1,294	1,978	1,974
acres	1,446,600	112,206	75,356	129,626	142,744	133,712
Woodland pastured ..... farms	7,908	249	281	442	770	865
acres	315,103	25,237	20,714	27,775	50,137	51,182
Woodland not pastured ..... farms	19,456	891	767	1,070	1,536	1,460
acres	1,131,497	86,969	54,642	101,851	92,607	82,530
Permanent pasture and rangeland, other than cropland and woodland pastured ..... farms	19,837	944	847	1,276	1,954	1,828
acres	1,031,215	131,354	104,073	114,193	164,842	144,325
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc. ..... farms	42,652	4,445	2,650	3,136	4,146	3,265
acres	1,420,750	361,985	145,926	148,157	138,750	92,823
Irrigated land ..... farms	3,625	763	369	347	490	351
acres	648,313	440,970	87,880	50,283	46,209	13,104
Harvested cropland ..... farms	3,551	762	368	347	488	346
acres	644,857	440,227	87,412	50,130	45,505	12,582
Pastureland and other land ..... farms	160	25	13	7	17	14
acres	3,456	743	468	153	704	522
CONSERVATION AND CROP INSURANCE						
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs ..... farms	19,069	2,327	1,168	1,084	1,324	1,140
acres	951,335	90,201	49,475	43,820	73,407	94,408
Land enrolled in crop insurance programs ..... farms	27,305	6,367	4,073	4,748	5,333	3,035
acres	18,167,226	11,658,028	2,978,040	1,904,185	1,067,945	333,947
ORGANIC AGRICULTURE						
Total organic product sales ..... farms	577	72	64	83	110	89
$1,000	121,783	57,751	26,635	20,995	9,818	4,267
VALUE OF LAND AND BUILDINGS						
Estimated market value of land and buildings ..... farms	65,531	7,266	4,529	5,477	6,899	5,488
$1,000	155,374,449	85,743,603	22,230,108	15,326,831	10,290,816	5,118,431
Average per farm ..... dollars	2,371,007	11,800,661	4,908,392	2,798,399	1,491,639	932,659
Average per acre ..... dollars	6,107	6,622	6,181	5,926	5,276	4,684
Farms by value group:						
$1 to $49,999	1,819	49	16	51	61	73
$50,000 to $99,999	2,318	43	21	19	30	51
$100,000 to $199,999	5,817	69	19	16	110	197
$200,000 to $499,999	17,490	174	73	156	567	1,186
$500,000 to $999,999	13,050	304	127	352	1,543	2,148
$1,000,000 to $1,999,999	8,615	387	379	1,193	3,027	1,432
$2,000,000 to $4,999,999	8,631	1,074	1,914	3,232	1,486	366
$5,000,000 to $9,999,999	3,992	1,638	1,752	434	69	33
$10,000,000 or more	3,799	3,528	228	24	6	2
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms	65,531	7,266	4,529	5,477	6,899	5,488
$1,000	17,904,134	9,001,608	2,675,624	1,994,852	1,472,256	788,720
Farms by value group:						
$1 to $4,999	3,305	-	2	1	12	83
$5,000 to $9,999	3,816	7	10	10	71	134
$10,000 to $19,999	6,447	23	7	48	204	300
$20,000 to $49,999	12,383	106	59	204	568	914
$50,000 to $99,999	10,506	240	122	386	1,145	1,386
$100,000 to $199,999	9,020	386	376	967	2,065	1,543
$200,000 to $499,999	9,719	1,066	1,459	2,484	2,262	909
$500,000 or more	10,335	5,438	2,494	1,377	572	219
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms	51,156	7,048	4,421	5,276	6,373	4,573
number	127,301	38,596	15,763	14,534	14,565	8,686
Tractors, all ..... farms	52,770	6,932	4,370	5,146	6,263	4,756
number	184,473	41,310	22,319	23,081	24,906	16,271
Less than 40 horsepower (PTO) ..... farms	22,815	2,021	1,541	1,886	2,462	1,959
number	36,863	4,040	2,598	3,310	4,259	3,184

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
LAND USE - Con.						
Total cropland - Con.						
Cropland-						
Other pasture and grazing land that could have been used for crops without additional improvements ..... farms	395	521	288	292	266	390
acres	14,113	15,289	7,126	4,295	5,636	5,204
On which all crops failed or were abandoned ..... farms	181	241	191	148	146	261
acres	6,826	5,262	4,071	2,342	1,915	6,117
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed ..... farms	1,498	2,495	2,556	2,489	2,920	1,762
acres	166,999	226,207	144,149	96,921	68,049	88,827
In summer fallow ..... farms	176	289	257	186	215	255
acres	3,778	5,038	4,099	2,956	3,050	4,725
Total woodland ..... farms	2,051	3,185	2,964	2,797	2,856	2,940
acres	141,116	191,254	157,821	126,594	117,864	118,307
Woodland pastured ..... farms	873	1,082	888	704	719	1,035
acres	35,372	32,010	22,669	14,025	14,406	21,576
Woodland not pastured ..... farms	1,580	2,584	2,480	2,401	2,414	2,273
acres	105,744	159,244	135,152	112,569	103,458	96,731
Permanent pasture and rangeland, other than cropland and woodland pastured ..... farms	1,786	2,785	2,069	1,659	1,674	3,015
acres	100,284	100,812	51,594	33,224	25,322	61,192
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc. ..... farms	3,104	4,837	4,301	4,071	4,177	4,520
acres	84,042	115,826	103,934	84,618	79,467	65,222
Irrigated land ..... farms	351	400	184	166	130	74
acres	4,728	2,439	769	679	467	785
Harvested cropland ..... farms	343	390	181	162	103	61
acres	4,503	2,171	760	595	391	581
Pastureland and other land ..... farms	13	14	5	6	29	17
acres	225	268	9	84	76	204
CONSERVATION AND CROP INSURANCE						
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs ..... farms	1,191	2,272	2,532	2,604	2,951	476
acres	142,401	187,596	132,771	81,131	49,047	7,078
Land enrolled in crop insurance programs ..... farms	1,566	1,065	457	265	213	183
acres	108,063	63,670	20,842	10,273	7,952	14,281
ORGANIC AGRICULTURE						
Total organic product sales ..... farms	73	40	17	16	9	4
$1,000	1,839	367	55	42	11	4
VALUE OF LAND AND BUILDINGS						
Estimated market value of land and buildings ..... farms	4,813	7,125	6,141	5,681	6,033	6,079
$1,000	3,402,072	3,893,355	2,702,472	2,175,693	2,063,403	2,427,664
Average per farm ..... dollars	706,851	546,436	440,070	382,977	342,019	399,353
Average per acre ..... dollars	4,423	4,651	4,885	5,483	6,255	6,361
Farms by value group:						
$1 to $49,999	87	185	242	267	483	305
$50,000 to $99,999	100	312	296	411	643	392
$100,000 to $199,999	396	761	990	1,045	1,186	1,028
$200,000 to $499,999	1,670	2,826	2,771	2,641	2,519	2,907
$500,000 to $999,999	1,636	2,281	1,452	1,053	995	1,159
$1,000,000 to $1,999,999	714	599	324	204	152	204
$2,000,000 to $4,999,999	178	147	56	53	49	76
$5,000,000 to $9,999,999	28	13	8	7	6	4
$10,000,000 or more	4	1	2	-	-	4
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms	4,813	7,125	6,141	5,681	6,033	6,079
$1,000	472,191	453,944	305,518	233,689	225,677	280,056
Farms by value group:						
$1 to $4,999	124	318	443	664	950	708
$5,000 to $9,999	212	453	606	688	932	693
$10,000 to $19,999	409	1,100	1,044	1,092	1,070	1,150
$20,000 to $49,999	1,153	2,259	1,993	1,751	1,645	1,731
$50,000 to $99,999	1,337	1,670	1,283	942	932	1,063
$100,000 to $199,999	1,003	888	550	396	355	491
$200,000 to $499,999	462	390	198	129	131	229
$500,000 or more	113	47	24	19	18	14
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms	3,739	5,071	3,963	3,328	3,361	4,003
number	6,419	8,000	5,764	4,698	4,630	5,646
Tractors, all ..... farms	3,983	5,443	4,401	3,699	3,635	4,142
number	12,139	13,350	9,732	7,422	6,588	7,355
Less than 40 horsepower (PTO) ..... farms	1,796	2,589	2,351	2,024	1,948	2,238
number	3,018	4,066	3,575	2,983	2,735	3,095

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
SELECTED MACHINERY AND EQUIPMENT - Con.						
Tractors, all - Con.						
40 to 99 horsepower (PTO) ... farms	35,619	4,177	2,963	3,471	4,502	3,370
number	60,537	8,010	5,593	6,199	8,261	6,238
100 horsepower (PTO) or more ... farms	31,912	6,604	4,220	4,821	5,435	3,484
number	87,073	29,260	14,128	13,572	12,386	6,849
Grain and bean combines, self-propelled ... farms	21,753	5,589	3,714	3,814	3,668	2,080
number	25,736	7,378	4,328	4,338	4,135	2,366
Cotton pickers and strippers, self-propelled ... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ... farms	2,195	563	234	259	291	206
number	2,384	593	242	288	314	229
Hay balers ... farms	19,296	1,777	1,531	1,865	2,568	2,145
number	24,300	2,184	1,935	2,344	3,374	2,809
FERTILIZERS AND CHEMICALS						
Commercial fertilizer, lime, and soil conditioners used ... farms	34,208	6,479	4,295	5,164	6,209	4,049
acres treated	14,076,782	8,504,804	2,403,611	1,593,683	970,191	346,026
Manure used ... farms	13,721	2,394	1,458	1,585	1,892	1,453
acres treated	1,453,615	846,342	205,789	148,625	110,152	57,115
Organic fertilizer used ... farms	1,053	91	85	105	122	125
acres treated	135,551	56,605	29,461	23,557	9,916	7,483
Acres treated to control-						
Insects ... farms	13,847	3,350	2,220	2,360	2,243	1,250
acres	5,229,304	3,272,452	925,206	585,891	293,154	90,063
Weeds, grass, or brush ... farms	34,397	6,466	4,271	5,117	6,183	4,128
acres	17,661,145	11,086,404	2,937,960	1,894,352	1,112,288	367,813
Nematodes ... farms	3,288	864	498	558	526	331
acres	977,113	585,492	179,094	114,119	63,486	22,796
Diseases in crops and orchards ... farms	5,080	1,602	870	768	709	395
acres	2,350,398	1,673,317	358,862	192,186	88,034	25,273
Chemicals used to control growth, thin fruit, ripen, or defoliate ... farms	1,762	498	245	214	280	157
acres on which used	318,341	198,786	46,526	34,069	24,240	7,989
LAND USE PRACTICES						
Land drained by tile ... farms	19,088	4,328	2,842	3,201	3,282	1,700
acres	8,247,260	5,306,635	1,353,048	891,561	449,027	129,343
Land artificially drained by ditches ... farms	9,435	1,864	1,189	1,197	1,242	844
acres	4,560,910	2,989,553	694,485	392,637	213,801	99,385
Land under conservation easement ... farms	4,909	441	340	323	438	340
acres	282,171	57,256	22,308	18,228	20,981	21,431
Cropland on which no-till practices were used ... farms	6,845	1,271	809	954	943	761
acres	1,194,987	580,274	245,002	184,499	101,829	43,397
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ... farms	15,574	3,775	2,175	2,423	2,618	1,624
acres	7,881,385	5,329,001	1,187,315	751,228	405,732	130,496
Cropland on which intensive or conventional tillage practices were used (see text) ... farms	22,330	3,827	2,596	3,087	3,989	2,687
acres	9,573,777	5,876,688	1,601,756	1,037,563	665,292	224,787
Cropland planted to a cover crop (excluding CRP) ... farms	6,050	1,300	728	763	785	497
acres	760,423	424,111	121,377	89,940	56,068	23,669
Use of precision agriculture practices (see text) ... farms	15,460	4,112	2,840	2,743	2,467	1,217
RENEWABLE ENERGY						
Renewable energy producing systems (see text) ... farms	4,247	821	422	418	381	280
Solar panels ... farms	2,063	285	157	180	171	132
Wind turbines ... farms	819	237	126	136	103	53
Methane digesters ... farms	15	14	-	1	-	-
Geothermal/geoexchange systems ... farms	1,695	369	179	137	141	105
Small hydro systems ... farms	24	3	1	5	-	2
Wind rights leased to others ... farms	1,189	248	141	183	188	82
TENURE						
Full owners ... farms	40,396	1,157	741	1,516	3,136	3,116
Part owners ... farms	20,564	5,529	3,365	3,296	2,865	1,764
Tenants ... farms	4,571	580	423	665	898	608
OWNED AND RENTED LAND						
Land owned ... farms	61,213	6,702	4,121	4,834	6,060	4,924
acres	15,768,785	4,992,213	1,811,227	1,628,477	1,605,975	1,108,948
Owned land in farms ... farms	60,960	6,686	4,106	4,812	6,001	4,880
acres	13,006,137	4,755,740	1,677,257	1,462,673	1,312,478	821,103
Land rented or leased from others ... farms	25,328	6,137	3,796	3,969	3,794	2,393
acres	12,515,140	8,221,456	1,930,647	1,127,533	648,661	278,646
Rented or leased land in farms ... farms	25,135	6,109	3,788	3,961	3,763	2,372
acres	12,436,488	8,192,777	1,919,547	1,123,489	638,012	271,751
Land rented or leased to others ... farms	15,946	899	608	721	1,343	1,448
acres	2,841,300	265,152	145,070	169,848	304,146	294,740

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
SELECTED MACHINERY AND EQUIPMENT - Con.						
Tractors, all - Con.						
40 to 99 horsepower (PTO) ... farms	2,908	3,925	2,991	2,438	2,300	2,574
number	5,296	6,303	4,569	3,514	3,075	3,479
100 horsepower (PTO) or more ... farms	2,262	2,051	1,166	693	582	594
number	3,825	2,981	1,588	925	778	781
Grain and bean combines, self-propelled ... farms	1,070	821	430	261	173	133
number	1,206	898	457	286	202	142
Cotton pickers and strippers, self-propelled ... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ... farms	161	166	98	74	63	80
number	179	190	104	86	70	89
Hay balers ... farms	1,828	2,220	1,561	1,208	1,078	1,515
number	2,399	2,815	1,988	1,477	1,246	1,729
FERTILIZERS AND CHEMICALS						
Commercial fertilizer, lime, and soil conditioners used ... farms	2,438	2,211	1,154	834	640	735
acres treated	123,874	73,038	24,809	13,856	8,365	14,525
Manure used ... farms	1,109	1,285	705	513	472	855
acres treated	28,926	24,228	10,857	6,584	4,493	10,504
Organic fertilizer used ... farms	136	141	63	70	58	57
acres treated	2,729	2,861	661	495	364	1,419
Acres treated to control-						
Insects ... farms	763	702	402	281	131	145
acres	28,042	16,625	6,452	4,807	1,533	5,079
Weeds, grass, or brush ... farms	2,598	2,386	1,276	840	611	521
acres	128,279	72,344	27,890	13,981	7,924	11,910
Nematodes ... farms	204	127	83	51	31	15
acres	7,381	3,054	918	500	180	93
Diseases in crops and orchards ... farms	240	196	141	82	46	31
acres	7,637	2,691	1,737	326	176	159
Chemicals used to control growth, thin fruit, ripen, or defoliate ... farms	137	92	45	60	23	11
acres on which used	3,919	1,492	687	388	176	69
LAND USE PRACTICES						
Land drained by tile ... farms	1,013	935	574	436	397	380
acres	46,686	28,774	14,526	9,638	6,539	11,483
Land artificially drained by ditches ... farms	576	722	545	382	438	436
acres	54,072	52,884	27,454	12,339	10,220	14,080
Land under conservation easement ... farms	336	649	540	577	590	335
acres	18,574	38,682	24,085	18,830	16,963	24,833
Cropland on which no-till practices were used ... farms	561	579	337	234	180	216
acres	19,471	10,150	4,117	2,469	1,255	2,524
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ... farms	955	828	477	324	187	188
acres	43,406	19,496	7,070	3,447	1,635	2,559
Cropland on which intensive or conventional tillage practices were used (see text) ... farms	1,801	1,769	1,035	643	485	411
acres	81,650	47,293	17,844	8,421	5,135	7,348
Cropland planted to a cover crop (excluding CRP) ... farms	412	479	296	233	253	304
acres	11,926	18,785	4,661	2,571	2,401	4,914
Use of precision agriculture practices (see text) ... farms	672	506	317	226	208	152
RENEWABLE ENERGY						
Renewable energy producing systems (see text) ... farms	264	401	330	285	319	326
Solar panels ... farms	154	238	207	174	177	188
Wind turbines ... farms	34	34	40	19	22	15
Methane digesters ... farms	-	-	-	-	-	-
Geothermal/geoexchange systems ... farms	99	149	123	102	135	156
Small hydro systems ... farms	6	3	-	1	3	-
Wind rights leased to others ... farms	63	86	62	53	46	37
TENURE						
Full owners ... farms	3,243	5,568	5,332	5,194	5,711	5,682
Part owners ... farms	1,176	1,168	562	354	220	265
Tenants ... farms	394	389	247	133	102	132
OWNED AND RENTED LAND						
Land owned ... farms	4,441	6,775	5,906	5,556	5,940	5,954
acres	912,732	1,082,028	852,192	667,177	609,071	498,745
Owned land in farms ... farms	4,419	6,736	5,894	5,548	5,931	5,947
acres	651,044	744,852	518,020	381,882	318,645	362,443
Land rented or leased from others ... farms	1,595	1,562	830	505	334	413
acres	124,471	94,346	36,759	17,923	14,451	20,247
Rented or leased land in farms ... farms	1,570	1,557	809	487	322	397
acres	118,103	92,271	35,184	14,894	11,253	19,207
Land rented or leased to others ... farms	1,473	2,165	2,058	1,822	2,028	1,381
acres	268,056	339,251	335,747	288,324	293,624	137,342

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS						
Total producers	118,256	15,155	7,937	9,261	11,626	9,434
Farms by number of producers:						
1 producer	28,348	2,606	2,149	2,746	3,414	2,579
2 producers	28,866	2,794	1,742	2,054	2,703	2,324
3 producers	4,480	1,042	396	442	486	314
4 producers	2,500	572	173	158	216	194
5 or more producers	1,337	252	69	77	80	77
Total male producers	81,062	11,695	6,035	7,011	8,532	6,562
Farms by number of male producers:						
1 producer	49,919	4,178	3,304	4,190	5,413	4,384
2 producers	8,600	1,954	905	916	1,016	679
3 producers	2,596	818	201	235	250	159
4 producers	766	178	51	43	54	37
5 or more producers	459	75	18	18	17	34
Total female producers	37,193	3,459	1,902	2,250	3,094	2,872
Farms by number of female producers:						
1 producer	29,936	2,376	1,548	1,893	2,543	2,348
2 producers	2,374	371	144	127	200	173
3 producers	466	65	14	19	35	33
4 producers	138	21	-	10	8	9
5 or more producers	90	10	4	1	2	4
PRODUCERS' CHARACTERISTICS [3]						
Sex of producers:						
Male	79,245	11,481	5,961	6,943	8,444	6,466
Female	35,623	3,135	1,828	2,177	3,018	2,787
Hired managers	6,902	3,757	1,082	705	504	298
Primary occupation:						
Farming	51,122	11,568	5,738	5,911	6,536	4,417
Other	63,746	3,048	2,051	3,209	4,926	4,836
Place of residence:						
On farm operated	79,195	10,041	6,002	6,672	8,091	6,299
Not on farm operated	35,673	4,575	1,787	2,448	3,371	2,954
Days of work off farm:						
None	46,862	8,779	4,146	4,195	4,682	3,535
Any	68,006	5,837	3,643	4,925	6,780	5,718
1 to 49 days	9,840	1,242	694	827	995	853
50 to 99 days	4,745	548	407	398	547	452
100 to 199 days	8,361	740	577	728	992	731
200 days or more	45,060	3,307	1,965	2,972	4,246	3,682
Years on present farm:						
2 years or less	4,867	268	133	251	390	351
3 or 4 years	7,650	694	280	479	646	614
5 to 9 years	18,524	1,790	924	1,234	1,591	1,403
10 years or more	83,827	11,864	6,452	7,156	8,835	6,885
Average years on present farm	24.2	26.8	28.5	27.9	27.2	25.9
Years operating any farm:						
5 years or less	13,846	1,095	487	800	1,116	1,030
6 to 10 years	15,740	1,244	775	1,056	1,365	1,100
11 years or more	85,282	12,277	6,527	7,264	8,981	7,123
Average years on any farm	26.1	29.2	30.5	29.9	29.4	28.1
Age group:						
Under 25 years	1,900	301	152	141	204	163
25 to 34 years	9,374	1,598	721	897	1,048	859
35 to 44 years	16,237	2,665	1,160	1,430	1,646	1,282
45 to 54 years	16,743	2,636	1,248	1,222	1,465	1,117
55 to 64 years	29,818	4,042	2,268	2,425	2,862	2,104
65 to 74 years	27,187	2,587	1,745	2,165	2,802	2,341
75 years and over	13,609	787	495	840	1,435	1,387
Average age	57.1	52.9	55.0	55.8	57.1	57.8
Young producers (see text)	11,274	1,899	873	1,038	1,252	1,022
Producers of Hispanic, Latino, or Spanish origin	754	122	37	38	47	40
Producers by race:						
American Indian or Alaska Native	244	7	11	10	24	8
Asian	306	12	3	24	22	39
Black or African American	61	1	5	1	4	4
Native Hawaiian or Other Pacific Islander	43	1	4	-	5	4
White	113,864	14,559	7,757	9,054	11,387	9,177
More than one race reported	350	36	9	31	20	21
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	105,603	14,090	7,466	8,617	10,592	8,404
Active duty now or in the past (see text)	9,265	526	323	503	870	849
Number of persons living in producers' households	228,210	34,775	16,704	19,195	23,043	18,210

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS						
Total producers	8,664	13,003	11,073	10,212	11,136	10,755
Farms by number of producers:						
1 producer	2,066	2,969	2,592	2,349	2,438	2,440
2 producers	2,136	3,379	2,880	2,744	2,978	3,132
3 producers	334	332	314	285	271	264
4 producers	185	279	217	186	188	132
5 or more producers	92	166	138	117	158	111
Total male producers	5,800	8,363	7,098	6,470	6,976	6,520
Farms by number of male producers:						
1 producer	3,773	5,677	4,806	4,491	4,810	4,893
2 producers	550	709	600	490	400	381
3 producers	185	191	155	150	149	103
4 producers	42	70	55	72	94	70
5 or more producers	30	62	60	34	65	46
Total female producers	2,864	4,640	3,975	3,742	4,160	4,235
Farms by number of female producers:						
1 producer	2,320	3,594	3,245	3,050	3,416	3,603
2 producers	187	323	234	218	198	199
3 producers	35	64	57	53	56	35
4 producers	3	22	14	13	23	15
5 or more producers	10	17	7	9	13	13
PRODUCERS' CHARACTERISTICS [3]						
Sex of producers:						
Male	5,685	8,103	6,877	6,273	6,622	6,390
Female	2,763	4,400	3,837	3,631	3,969	4,078
Hired managers	158	173	73	66	34	52
Primary occupation:						
Farming	3,370	4,059	2,893	2,206	2,043	2,381
Other	5,078	8,444	7,821	7,698	8,548	8,087
Place of residence:						
On farm operated	5,742	8,303	7,031	6,318	6,756	7,940
Not on farm operated	2,706	4,200	3,683	3,586	3,835	2,528
Days of work off farm:						
None	3,067	4,286	3,725	3,364	3,674	3,409
Any	5,381	8,217	6,989	6,540	6,917	7,059
1 to 49 days	716	1,080	977	849	851	756
50 to 99 days	395	506	387	351	350	404
100 to 199 days	752	1,001	851	636	698	655
200 days or more	3,518	5,630	4,774	4,704	5,018	5,244
Years on present farm:						
2 years or less	472	620	461	537	607	777
3 or 4 years	667	819	732	861	902	956
5 to 9 years	1,289	2,290	2,103	1,858	2,027	2,015
10 years or more	6,020	8,774	7,418	6,648	7,055	6,720
Average years on present farm	23.8	22.8	22.1	21.2	20.4	19.8
Years operating any farm:						
5 years or less	1,231	1,704	1,355	1,519	1,647	1,862
6 to 10 years	1,112	1,929	1,798	1,626	1,925	1,810
11 years or more	6,105	8,870	7,561	6,759	7,019	6,796
Average years on any farm	25.8	24.7	24.0	22.8	22.1	21.3
Age group:						
Under 25 years	126	225	170	140	130	148
25 to 34 years	708	875	626	607	719	716
35 to 44 years	1,121	1,583	1,294	1,274	1,382	1,400
45 to 54 years	1,208	1,656	1,656	1,412	1,498	1,625
55 to 64 years	2,083	3,277	2,650	2,610	2,666	2,831
65 to 74 years	2,043	3,118	2,697	2,401	2,686	2,602
75 years and over	1,159	1,769	1,621	1,460	1,510	1,146
Average age	57.7	58.5	59.0	58.8	58.7	57.5
Young producers (see text)	834	1,100	796	747	849	864
Producers of Hispanic, Latino, or Spanish origin	43	117	29	94	113	74
Producers by race:						
American Indian or Alaska Native	10	35	20	32	36	51
Asian	37	60	37	37	13	22
Black or African American	11	4	13	6	4	8
Native Hawaiian or Other Pacific Islander	2	1	9	2	9	6
White	8,358	12,368	10,594	9,794	10,478	10,338
More than one race reported	30	35	41	33	51	43
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	7,747	11,304	9,564	8,860	9,514	9,445
Active duty now or in the past (see text)	701	1,199	1,150	1,044	1,077	1,023
Number of persons living in producers' households	16,086	22,824	20,195	18,721	19,422	19,035

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
PRODUCERS' CHARACTERISTICS [3] - Con.						
On farm involvement in decisionmaking:						
Day-to-day decisions	98,292	12,988	6,940	8,066	10,000	7,909
Land use and/or crop decisions	83,860	11,262	6,281	7,227	9,169	7,090
Livestock decisions	49,585	6,522	3,051	3,601	4,598	3,902
Marketing decisions (see text)	68,020	10,820	6,076	7,056	8,636	6,346
Record keeping and/or financial management	84,043	11,629	6,417	7,418	9,309	7,048
Estate planning or succession planning	64,079	9,631	5,047	5,730	6,916	5,259
FARMS BY TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	62,111	6,435	4,245	5,236	6,564	5,270
Operation more than 50 percent owned by one producer's household and/or extended family — acres	22,990,670	11,252,688	3,365,057	2,431,077	1,847,537	1,045,007
Limited Liability Company — farms	4,803	916	319	367	448	347
Limited Liability Company — acres	2,179,815	1,425,916	223,501	156,149	119,159	58,009
LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	55,532	4,298	3,585	4,594	5,993	4,875
Family or individual — acres	17,410,756	7,072,758	2,830,970	2,111,398	1,656,472	948,285
Partnership — farms	5,022	1,486	430	484	556	309
Partnership — acres	4,452,974	3,400,070	351,025	223,765	182,692	75,654
Registered under State law — farms	4,156	1,343	369	409	451	218
Registered under State law — acres	3,904,476	3,059,858	298,664	182,652	139,495	50,577
Corporation — farms	3,803	1,445	466	347	229	225
Corporation — acres	3,244,861	2,417,088	387,275	182,336	63,400	48,696
Family held — farms	3,375	1,355	440	321	188	201
Family held — acres	3,085,380	2,332,208	369,236	175,877	50,635	44,990
More than 10 stockholders — farms	34	10	1	6	3	1
10 or less stockholders — farms	3,341	1,345	439	315	185	200
Other than family held — farms	428	90	26	26	41	24
Other than family held — acres	159,481	84,880	18,039	6,459	12,765	3,706
More than 10 stockholders — farms	67	22	-	7	-	4
10 or less stockholders — farms	361	68	26	19	41	20
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	1,174	37	48	52	121	79
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — acres	334,034	58,601	27,534	68,663	47,926	20,219
HIRED FARM LABOR						
Hired farm labor — farms	17,399	6,022	2,358	1,974	1,925	1,121
Hired farm labor — workers	72,097	41,802	7,364	6,282	5,489	2,812
Workers by days worked:						
150 days or more — farms	9,054	4,211	1,192	921	807	476
150 days or more — workers	30,983	21,707	2,612	1,992	1,613	754
Less than 150 days — farms	12,949	4,409	1,751	1,464	1,423	851
Less than 150 days — workers	41,114	20,095	4,752	4,290	3,876	2,058
Migrant farm labor on farms with hired labor — farms	573	446	45	33	28	7
Migrant farm labor on farms reporting only contract labor — farms	41	5	7	6	5	3
Unpaid workers — farms	17,519	1,306	1,233	1,509	1,830	1,577
Unpaid workers — workers	40,333	2,784	2,586	3,250	4,043	3,738
FARMS BY SIZE						
1 to 9 acres	4,401	260	63	110	104	119
10 to 49 acres	15,218	356	86	133	240	370
50 to 69 acres	3,598	61	16	19	67	261
70 to 99 acres	5,575	73	26	43	215	915
100 to 139 acres	4,857	72	26	42	484	987
140 to 179 acres	4,814	72	48	89	1,222	817
180 to 219 acres	2,981	65	65	118	880	506
220 to 259 acres	2,503	44	61	261	890	299
260 to 499 acres	8,699	400	533	2,853	2,102	841
500 to 999 acres	6,421	967	2,531	1,575	568	305
1,000 to 1,999 acres	3,752	2,326	984	210	110	62
2,000 acres or more	2,712	2,570	90	24	17	6
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	26,315	4,291	3,517	4,450	5,327	3,393
Vegetable and melon farming (1112)	1,072	69	20	47	95	105
Fruit and tree nut farming (1113)	972	5	6	22	54	85
Greenhouse, nursery, and floriculture production (1114)	971	65	41	66	85	90
Other crop farming (1119)	18,104	110	76	122	417	776
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	18,104	110	76	122	417	776
Beef cattle ranching and farming (112111)	6,753	127	81	125	434	695
Cattle feedlots (112112)	892	272	92	108	131	122
Dairy cattle and milk production (11212)	1,713	712	416	343	137	63
Hog and pig farming (1122)	1,855	1,280	193	86	33	10
Poultry and egg production (1123)	1,724	295	44	41	31	16
Sheep and goat farming (1124)	1,456	-	9	12	25	44
Aquaculture and other animal production (1125,1129)	3,704	40	34	55	130	89

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
PRODUCERS' CHARACTERISTICS [3] - Con.						
On farm involvement in decisionmaking:						
Day-to-day decisions	7,146	10,410	8,945	8,052	8,785	9,051
Land use and/or crop decisions	6,199	8,895	7,288	6,531	6,739	7,179
Livestock decisions	3,837	5,798	4,574	3,961	3,905	5,836
Marketing decisions (see text)	5,151	6,721	4,823	4,061	3,703	4,627
Record keeping and/or financial management	6,206	8,920	7,205	6,508	6,687	6,696
Estate planning or succession planning	4,546	6,405	5,345	4,955	4,950	5,295
FARMS BY TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	4,618	6,826	5,862	5,430	5,738	5,887
acres	714,994	785,010	513,747	372,921	306,413	356,219
Limited Liability Company — farms	345	537	415	331	364	414
acres	48,335	48,783	34,712	22,283	19,505	23,463
LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	4,309	6,293	5,454	5,117	5,402	5,612
acres	656,270	711,964	469,305	344,634	285,022	323,678
Partnership — farms	258	414	351	264	268	202
acres	57,223	57,610	40,496	22,168	19,215	23,056
Registered under State law — farms	204	324	281	207	200	150
acres	45,474	44,663	33,513	17,661	14,537	17,382
Corporation — farms	153	255	177	162	189	155
acres	35,043	36,458	21,734	18,393	13,743	20,695
Family held — farms	124	219	137	107	149	134
acres	30,846	27,421	17,286	10,744	9,478	16,659
More than 10 stockholders — farms	7	2	-	2	1	1
10 or less stockholders — farms	117	217	137	105	148	133
Other than family held — farms	29	36	40	55	40	21
acres	4,197	9,037	4,448	7,649	4,265	4,036
More than 10 stockholders — farms	-	3	1	13	14	3
10 or less stockholders — farms	29	33	39	42	26	18
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	93	163	159	138	174	110
acres	20,611	31,091	21,669	11,581	11,918	14,221
HIRED FARM LABOR						
Hired farm labor — farms	775	989	648	509	508	570
workers	1,978	2,214	1,184	987	881	1,104
Workers by days worked:						
150 days or more — farms	354	447	175	123	160	188
workers	583	661	267	211	236	347
Less than 150 days — farms	558	734	517	422	385	435
workers	1,395	1,553	917	776	645	757
Migrant farm labor on farms with hired labor — farms	2	10	1	-	1	-
Migrant farm labor on farms reporting only contract labor — farms	2	1	-	3	-	9
Unpaid workers — farms	1,382	2,110	1,764	1,514	1,505	1,789
workers	3,387	4,969	4,235	3,793	3,430	4,118
FARMS BY SIZE						
1 to 9 acres	223	455	533	596	976	962
10 to 49 acres	902	2,103	2,258	2,608	3,127	3,035
50 to 69 acres	461	674	613	562	451	413
70 to 99 acres	686	1,000	839	649	544	585
100 to 139 acres	620	767	651	499	375	334
140 to 179 acres	533	742	446	322	227	296
180 to 219 acres	316	386	251	130	122	142
220 to 259 acres	228	297	157	111	68	87
260 to 499 acres	619	556	340	174	109	172
500 to 999 acres	199	122	48	29	32	45
1,000 to 1,999 acres	23	21	5	1	2	8
2,000 acres or more	3	2	-	-	-	-
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	1,941	1,678	888	538	232	60
Vegetable and melon farming (1112)	158	229	148	101	73	27
Fruit and tree nut farming (1113)	91	219	172	85	69	164
Greenhouse, nursery, and floriculture production (1114)	127	176	85	70	53	113
Other crop farming (1119)	1,230	2,716	3,144	3,405	3,957	2,151
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	1,230	2,716	3,144	3,405	3,957	2,151
Beef cattle ranching and farming (112111)	890	1,367	966	593	379	1,096
Cattle feedlots (112112)	115	47	3	2	-	-
Dairy cattle and milk production (11212)	10	2	1	-	-	29
Hog and pig farming (1122)	4	36	60	65	75	13
Poultry and egg production (1123)	16	78	121	297	707	78
Sheep and goat farming (1124)	71	182	194	252	244	423
Aquaculture and other animal production (1125,1129)	160	395	359	273	244	1,925

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
FARM TYPOLOGY (SEE TEXT)						
Farms by typology group:						
Small family farms						
Gross cash farm income less than $150,000	41,924	133	82	68	2,508	5,060
Gross cash farm income $150,000 to $349,999	7,074	279	91	2,291	3,982	190
Midsize family farms						
Gross cash farm income $350,000 to $999,999	7,367	430	3,925	2,874	73	18
Large family farms						
Gross cash farm income $1,000,000 to $4,999,999	5,311	5,159	147	3	1	1
Gross cash farm income $5,000,000 or more	435	434	-	-	-	1
Non-family farms	3,420	831	284	241	335	218
OTHER FARM CHARACTERISTICS						
Farms reporting-						
Internet access	53,964	6,851	4,182	4,872	5,796	4,450
Dial-up	1,876	237	108	163	209	152
Broadband (DSL, cable, fiber optic) (see text)	33,399	4,358	2,625	2,941	3,505	2,688
Cellular data plan (see text)	32,121	4,572	2,763	3,072	3,495	2,681
Satellite	8,385	1,424	784	837	912	616
Don't know	2,877	238	182	252	335	285
Other	346	87	34	35	32	16
Farms by number of households sharing in net income of operation:						
1 household	52,287	4,747	3,423	4,244	5,500	4,387
2 households	9,039	1,545	828	942	1,065	835
3 households	2,321	624	203	211	232	136
4 households	1,024	200	38	51	67	53
5 or more households	860	150	37	29	35	77
LIVESTOCK						
Cattle and calves inventory ... farms	16,823	1,931	1,432	1,741	2,169	1,873
number	2,121,625	1,276,486	239,421	186,516	166,708	99,831
Farms with-						
1 to 9	3,446	32	50	98	127	172
10 to 49	6,556	173	222	443	797	852
50 to 99	2,582	103	208	434	654	606
100 to 199	1,927	177	466	559	451	223
200 to 499	1,348	556	441	185	133	20
500 or more	964	890	45	22	7	-
Cows and heifers that calved ... farms	13,439	1,372	1,060	1,313	1,731	1,660
number	824,165	458,623	89,568	69,208	74,322	52,656
Beef cows ... farms	11,691	685	656	995	1,598	1,590
number	364,629	75,406	44,912	45,509	68,669	51,326
Farms with-						
1 to 9	3,718	71	70	140	194	206
10 to 49	6,113	266	292	539	894	1,071
50 to 99	1,205	131	147	211	362	278
100 to 199	470	113	100	82	137	35
200 to 499	149	73	44	22	10	-
500 or more	36	31	3	1	1	-
Milk cows ... farms	2,185	789	471	387	162	102
number	459,536	383,217	44,656	23,699	5,653	1,330
Farms with-						
1 to 9	328	1	3	12	16	45
10 to 49	315	5	16	99	115	57
50 to 99	573	43	260	244	26	-
100 to 199	418	191	190	32	5	-
200 to 499	390	388	2	-	-	-
500 or more	161	161	-	-	-	-
Other cattle ... farms	14,574	1,848	1,372	1,651	2,051	1,716
number	1,297,460	817,863	149,853	117,308	92,386	47,175
Cattle and calves sold ... farms	14,649	1,911	1,410	1,664	2,061	1,786
number	1,599,910	1,115,782	149,038	113,776	97,207	56,865
$1,000	2,094,135	1,544,016	189,067	130,359	107,183	58,812
Calves weighing less than 500 pounds ... farms	4,938	730	485	574	630	638
number	345,069	251,894	25,085	19,482	20,083	11,976
Cattle weighing 500 pounds or more ... farms	13,933	1,890	1,396	1,634	2,020	1,718
number	1,254,841	863,888	123,953	94,294	77,124	44,889
Cattle on feed ... farms	2,685	811	515	484	460	231
number	636,782	521,492	55,567	32,902	17,806	5,837
Hogs and pigs inventory ... farms	2,928	1,474	241	179	141	79
number	8,873,776	8,385,211	346,932	104,112	23,670	4,203
Farms with-						
1 to 24	893	10	7	37	55	51
25 to 49	93	8	4	12	9	8
50 to 99	71	4	7	14	20	8
100 to 199	65	7	7	15	23	6
200 to 499	116	24	31	28	25	4
500 or more	1,690	1,421	185	73	9	2
Hogs and pigs sold ... farms	3,352	1,658	283	196	184	100
number	28,535,462	27,499,828	768,928	208,034	42,099	5,169
$1,000	4,666,832	4,490,264	135,508	31,600	6,100	1,109
Sheep and lambs inventory ... farms	2,137	69	81	98	133	133
number	109,592	11,452	20,107	16,049	11,086	11,199

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
FARM TYPOLOGY (SEE TEXT)						
Farms by typology group:						
Small family farms						
Gross cash farm income less than $150,000	4,553	6,736	5,812	5,394	5,706	5,872
Gross cash farm income $150,000 to $349,999	60	68	40	31	30	12
Midsize family farms						
Gross cash farm income $350,000 to $999,999	5	22	10	5	2	3
Large family farms						
Gross cash farm income $1,000,000 to $4,999,999	-	-	-	-	-	-
Gross cash farm income $5,000,000 or more	-	-	-	-	-	-
Non-family farms	195	299	279	251	295	192
OTHER FARM CHARACTERISTICS						
Farms reporting-						
Internet access	3,863	5,573	4,778	4,292	4,571	4,736
Dial-up	134	211	171	163	171	157
Broadband (DSL, cable, fiber optic) (see text)	2,322	3,447	3,022	2,675	2,896	2,920
Cellular data plan (see text)	2,314	3,128	2,634	2,296	2,495	2,671
Satellite	554	805	618	583	562	690
Don't know	235	293	278	265	254	260
Other	17	30	26	21	21	27
Farms by number of households sharing in net income of operation:						
1 household	3,921	5,880	5,125	4,651	5,064	5,345
2 households	636	867	653	629	560	479
3 households	134	177	183	165	152	104
4 households	75	108	84	120	151	77
5 or more households	47	93	96	116	106	74
LIVESTOCK						
Cattle and calves inventory ... farms	1,614	2,072	1,298	825	648	1,220
number	60,209	47,121	16,418	8,516	5,739	14,660
Farms with-						
1 to 9	172	476	606	489	437	787
10 to 49	1,031	1,414	679	326	208	411
50 to 99	377	171	13	10	1	5
100 to 199	28	11	-	-	2	10
200 to 499	6	-	-	-	-	7
500 or more	-	-	-	-	-	-
Cows and heifers that calved ... farms	1,416	1,752	1,035	678	500	922
number	31,090	25,849	9,078	4,595	3,196	5,980
Beef cows ... farms	1,386	1,725	1,013	665	486	892
number	30,748	25,597	8,971	4,548	3,149	5,794
Farms with-						
1 to 9	255	621	612	508	373	668
10 to 49	1,070	1,086	401	157	113	224
50 to 99	60	16	-	-	-	-
100 to 199	1	2	-	-	-	-
200 to 499	-	-	-	-	-	-
500 or more	-	-	-	-	-	-
Milk cows ... farms	59	80	42	22	30	41
number	342	252	107	47	47	186
Farms with-						
1 to 9	51	74	42	22	30	32
10 to 49	8	6	-	-	-	9
50 to 99	-	-	-	-	-	-
100 to 199	-	-	-	-	-	-
200 to 499	-	-	-	-	-	-
500 or more	-	-	-	-	-	-
Other cattle ... farms	1,435	1,721	972	590	429	789
number	29,119	21,272	7,340	3,921	2,543	8,680
Cattle and calves sold ... farms	1,588	1,943	1,201	676	365	44
number	33,969	22,753	7,149	2,446	854	71
$1,000	34,052	21,727	6,340	1,982	565	31
Calves weighing less than 500 pounds ... farms	532	650	393	191	99	16
number	7,848	5,536	2,128	735	264	38
Cattle weighing 500 pounds or more ... farms	1,506	1,807	1,042	587	305	28
number	26,121	17,217	5,021	1,711	590	33
Cattle on feed ... farms	131	48	3	2	-	-
number	2,423	716	(D)	(D)	-	-
Hogs and pigs inventory ... farms	98	179	175	141	125	96
number	1,155	3,326	2,255	905	775	1,232
Farms with-						
1 to 24	85	150	150	139	118	91
25 to 49	9	13	23	2	5	-
50 to 99	2	11	2	-	2	1
100 to 199	2	3	-	-	-	2
200 to 499	-	2	-	-	-	2
500 or more	-	-	-	-	-	-
Hogs and pigs sold ... farms	116	230	244	172	130	39
number	1,919	4,360	3,009	1,347	627	142
$1,000	422	795	618	258	136	23
Sheep and lambs inventory ... farms	150	308	282	233	246	404
number	7,126	12,674	8,010	4,437	3,106	4,346

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
LIVESTOCK - Con.						
Sheep and lambs sold ..... farms	1,500	61	71	84	102	109
number	92,512	15,372	21,240	13,003	8,874	8,604
Total horses and ponies inventory ..... farms	6,988	148	157	237	357	386
number	40,131	553	633	1,668	2,831	2,782
Total horses and ponies sold ..... farms	1,171	19	12	45	73	111
number	4,403	65	33	368	742	464
Goats, all inventory ..... farms	2,326	38	51	68	133	109
number	50,691	740	4,280	3,270	6,827	5,605
Goats, all sold ..... farms	1,215	12	38	38	91	70
number	38,339	188	14,535	3,144	4,657	3,559
POULTRY						
Layers inventory ..... farms	6,146	115	112	150	274	359
number	14,553,497	14,054,087	249,395	43,677	59,704	22,787
Farms with-						
1 to 399	6,045	77	93	142	256	346
400 to 3,199	36	-	1	2	15	13
3,200 to 9,999	8	-	-	5	3	-
10,000 to 19,999	24	5	18	1	-	-
20,000 to 49,999	4	4	-	-	-	-
50,000 to 99,999	5	5	-	-	-	-
100,000 or more	24	24	-	-	-	-
Pullets for laying flock replacement inventory ..... farms	723	16	8	19	26	31
number	4,185,443	3,788,035	179	115,253	64,386	200,997
Layers sold ..... farms	664	28	24	25	39	42
number	7,016,481	6,667,242	248,360	36,745	37,571	3,981
Pullets for laying flock replacement sold ..... farms	102	14	-	9	8	2
number	8,319,040	8,036,916	-	196,300	77,550	(D)
Broilers and other meat-type chickens sold ..... farms	1,028	128	21	40	42	61
number	41,793,592	41,400,984	156,266	56,471	89,107	12,912
Farms with-						
1 to 1,999	900	11	16	37	39	61
2,000 to 59,999	11	-	5	3	3	-
60,000 to 99,999	-	-	-	-	-	-
100,000 or more	117	117	-	-	-	-
Turkeys inventory ..... farms	623	148	15	24	10	19
number	14,927,734	14,696,953	128,157	89,455	9,612	240
Turkeys sold ..... farms	379	148	21	21	3	17
number	39,460,145	38,777,971	518,702	146,519	14,154	485
CROPS						
Barley for grain ..... farms	336	129	52	78	33	19
acres	55,330	34,511	7,319	10,180	2,466	415
bushels	4,011,381	2,588,008	536,533	707,522	138,526	27,945
Irrigated ..... farms	10	-	5	-	1	2
acres	116	-	92	-	(D)	(D)
Farms by acres harvested:						
1 to 24 acres	72	9	10	16	6	15
25 to 99 acres	96	27	14	20	22	4
100 to 249 acres	94	42	21	28	3	-
250 to 499 acres	53	31	6	14	2	-
500 acres or more	21	20	1	-	-	-
Corn for grain ..... farms	24,697	5,807	3,772	4,436	4,950	2,611
acres	7,732,455	5,051,223	1,225,299	811,537	458,149	126,425
bushels	1,478,451,268	993,942,280	229,449,166	148,842,881	78,249,970	20,071,747
Irrigated ..... farms	1,341	526	248	206	232	85
acres	302,897	210,735	47,598	23,152	15,899	4,639
Farms by acres harvested:						
1 to 24 acres	2,863	46	34	45	152	380
25 to 99 acres	6,867	246	236	474	2,886	2,125
100 to 249 acres	6,444	533	816	3,123	1,853	104
250 to 499 acres	4,136	1,073	2,236	766	59	2
500 acres or more	4,387	3,909	450	28	-	-
Corn for silage or greenchop ..... farms	2,768	951	442	434	397	242
acres	313,974	234,086	32,316	22,716	14,070	6,348
tons	6,334,518	4,927,813	621,147	411,844	229,271	94,153
Irrigated ..... farms	108	65	20	11	5	4
acres	13,135	11,184	947	676	153	78
Farms by acres harvested:						
1 to 24 acres	848	56	59	125	201	148
25 to 99 acres	1,133	272	296	259	173	91
100 to 249 acres	452	311	72	43	22	3
250 to 499 acres	218	198	12	7	1	-
500 acres or more	117	114	3	-	-	-
Dry edible beans, excluding chickpeas and limas ..... farms	573	343	73	56	53	21
acres	210,162	183,310	12,854	8,099	4,648	904
cwt	5,278,245	4,550,183	313,200	217,015	147,531	38,296
Irrigated ..... farms	95	70	5	13	5	1
acres	39,931	37,263	391	2,014	(D)	(D)
Farms by acres harvested:						
1 to 24 acres	34	-	-	1	4	8
25 to 99 acres	118	17	25	20	38	12
100 to 249 acres	146	70	35	29	11	1

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
LIVESTOCK - Con.						
Sheep and lambs sold ..... farms	112	260	217	239	153	92
number	6,767	9,521	4,731	2,924	1,189	287
Total horses and ponies inventory ..... farms	461	895	770	628	790	2,159
number	3,731	5,664	3,613	2,948	3,011	12,697
Total horses and ponies sold ..... farms	134	319	219	135	98	6
number	758	1,123	470	238	136	6
Goats, all inventory ..... farms	146	279	326	305	395	476
number	4,528	6,407	5,616	4,213	4,750	4,455
Goats, all sold ..... farms	89	185	193	205	196	98
number	2,804	3,244	2,503	1,930	1,469	306
POULTRY						
Layers inventory ..... farms	424	844	841	890	1,144	993
number	15,875	25,910	23,881	23,096	24,311	10,774
Farms with-						
1 to 399	419	844	841	890	1,144	993
400 to 3,199	5	-	-	-	-	-
3,200 to 9,999	-	-	-	-	-	-
10,000 to 19,999	-	-	-	-	-	-
20,000 to 49,999	-	-	-	-	-	-
50,000 to 99,999	-	-	-	-	-	-
100,000 or more	-	-	-	-	-	-
Pullets for laying flock replacement inventory ..... farms	63	113	107	132	141	67
number	3,301	4,295	2,706	2,368	2,106	1,817
Layers sold ..... farms	39	130	110	115	73	39
number	4,521	10,916	2,300	3,110	1,241	494
Pullets for laying flock replacement sold ..... farms	6	25	8	14	16	-
number	(D)	316	71	1,375	(D)	-
Broilers and other meat-type chickens sold ..... farms	78	186	163	158	97	54
number	12,258	40,740	9,971	7,494	4,343	3,046
Farms with-						
1 to 1,999	78	186	163	158	97	54
2,000 to 59,999	-	-	-	-	-	-
60,000 to 99,999	-	-	-	-	-	-
100,000 or more	-	-	-	-	-	-
Turkeys inventory ..... farms	21	70	97	81	73	65
number	585	699	665	666	438	264
Turkeys sold ..... farms	20	40	47	25	27	10
number	683	509	527	225	282	88
CROPS						
Barley for grain ..... farms	13	4	1	3	4	-
acres	298	39	(D)	40	(D)	-
bushels	10,062	(D)	(D)	360	566	-
Irrigated ..... farms	2	-	-	-	-	-
acres	(D)	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	6	3	-	3	4	-
25 to 99 acres	7	1	1	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Corn for grain ..... farms	1,360	946	429	221	105	60
acres	38,224	15,525	4,069	1,464	389	151
bushels	5,384,938	1,903,753	427,897	134,977	33,703	9,956
Irrigated ..... farms	20	19	3	1	1	-
acres	500	305	(D)	(D)	(D)	-
Farms by acres harvested:						
1 to 24 acres	635	777	414	215	105	60
25 to 99 acres	711	168	15	6	-	-
100 to 249 acres	14	1	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Corn for silage or greenchop ..... farms	156	78	30	18	10	10
acres	2,755	1,147	241	176	77	42
tons	34,352	12,985	1,764	748	309	132
Irrigated ..... farms	2	1	-	-	-	-
acres	(D)	(D)	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	128	63	30	18	10	10
25 to 99 acres	27	15	-	-	-	-
100 to 249 acres	1	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas ..... farms	4	8	5	7	2	1
acres	147	153	23	(D)	(D)	(D)
cwt	2,827	8,167	492	302	(D)	(D)
Irrigated ..... farms	-	-	-	-	-	1
acres	-	-	-	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	2	4	5	7	2	1
25 to 99 acres	2	4	-	-	-	-
100 to 249 acres	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
CROPS - Con.						
Dry edible beans, excluding chickpeas and limas - Con.						
Farms by acres harvested: - Con.						
250 to 499 acres	140	128	6	6	-	-
500 acres or more	135	128	7	-	-	-
Oats for grain ... farms	2,329	330	326	366	476	336
acres	126,011	33,697	20,698	17,367	24,716	15,645
bushels	9,470,546	3,132,189	1,712,906	1,417,501	1,569,581	998,227
Irrigated ... farms	66	25	15	12	10	2
acres	3,194	1,394	1,096	305	274	(D)
Farms by acres harvested:						
1 to 24 acres	906	48	82	142	186	140
25 to 99 acres	1,097	191	186	185	203	166
100 to 249 acres	286	73	51	39	75	27
250 to 499 acres	29	8	6	-	12	3
500 acres or more	11	10	1	-	-	-
Sorghum for grain ... farms	12	2	-	2	4	-
acres	364	(D)	-	(D)	39	-
bushels	24,260	(D)	-	(D)	1,470	-
Irrigated ... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	7	-	-	-	3	-
25 to 99 acres	4	1	-	2	1	-
100 to 249 acres	1	1	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Soybeans for beans ... farms	25,337	5,795	3,942	4,538	4,872	2,725
acres	7,597,171	4,563,322	1,360,169	867,395	519,056	186,713
bushels	373,669,175	232,476,503	64,387,210	41,160,439	23,814,866	8,059,963
Irrigated ... farms	892	311	164	142	149	67
acres	122,734	72,288	22,261	12,780	9,997	3,646
Farms by acres harvested:						
1 to 24 acres	2,307	56	34	34	112	262
25 to 99 acres	7,345	305	294	629	2,599	1,920
100 to 249 acres	6,879	658	835	2,862	1,949	519
250 to 499 acres	4,297	1,032	2,114	925	200	24
500 acres or more	4,509	3,744	665	88	12	-
Sugarbeets for sugar ... farms	1,106	741	163	102	63	22
acres	446,627	399,499	29,263	12,348	4,465	797
tons	11,642,041	10,491,419	699,081	306,111	117,875	21,310
Irrigated ... farms	31	31	-	-	-	-
acres	10,798	10,798	-	-	-	-
Sunflower seed, all ... farms	221	107	36	39	23	3
acres	66,924	49,690	9,979	4,533	2,245	(D)
pounds	151,726,117	119,112,520	19,420,775	8,297,366	4,337,014	(D)
Irrigated ... farms	2	-	1	-	-	-
acres	(D)	-	(D)	-	-	-
Farms by acres harvested:						
1 to 24 acres	8	-	-	-	1	1
25 to 99 acres	53	10	3	20	11	2
100 to 249 acres	62	15	19	17	11	-
250 to 499 acres	49	37	10	2	-	-
500 acres or more	49	45	4	-	-	-
Wheat for grain, all ... farms	3,669	1,185	679	650	547	253
acres	1,268,681	839,166	217,650	127,514	56,926	15,834
bushels	82,039,945	57,852,411	12,784,369	7,294,280	2,883,552	759,076
Irrigated ... farms	52	18	5	11	2	6
acres	6,251	3,105	355	2,177	(D)	133
Farms by acres harvested:						
1 to 24 acres	416	35	46	53	65	52
25 to 99 acres	1,023	158	129	164	239	153
100 to 249 acres	809	163	144	229	218	45
250 to 499 acres	544	186	169	161	25	3
500 acres or more	877	643	191	43	-	-
Forage-land used for all hay and haylage, grass silage, and greenchop ... farms	23,394	2,055	1,484	1,793	2,611	2,359
acres	1,392,072	317,511	136,575	130,391	207,895	189,754
tons, dry equivalent	3,565,994	1,263,798	432,682	377,800	505,407	401,913
Irrigated ... farms	675	155	84	75	113	59
acres	32,954	14,613	3,738	3,599	4,242	3,071
Farms by acres harvested:						
1 to 24 acres	11,106	449	373	588	917	714
25 to 99 acres	8,179	557	638	806	1,037	981
100 to 249 acres	3,115	647	371	325	470	516
250 to 499 acres	780	298	72	53	157	124
500 acres or more	214	104	30	21	30	24
Alfalfa hay ... farms	15,333	1,393	1,102	1,432	1,998	1,784
acres	744,117	151,205	77,388	83,063	122,775	108,966
tons, dry	1,971,568	568,561	253,551	247,313	317,545	252,089
Irrigated ... farms	421	94	55	55	90	47
acres	15,949	4,989	2,118	2,229	2,719	2,203
Other dry hay ... farms	8,556	562	441	532	869	858
acres	390,421	37,697	29,092	27,839	59,356	65,369
tons, dry	658,360	103,616	63,462	55,232	112,435	109,904

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
CROPS - Con.						
Dry edible beans, excluding chickpeas and limas - Con.						
Farms by acres harvested: - Con.						
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Oats for grain ... farms	194	160	79	46	12	4
acres	6,288	4,592	2,190	728	79	11
bushels	279,660	220,903	99,295	36,507	3,167	610
Irrigated ... farms	1	-	-	1	-	-
acres	(D)	-	-	(D)	-	-
Farms by acres harvested:						
1 to 24 acres	113	93	47	39	12	4
25 to 99 acres	66	61	32	7	-	-
100 to 249 acres	15	6	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Sorghum for grain ... farms	2	-	-	-	2	-
acres	(D)	-	-	-	(D)	-
bushels	(D)	-	-	-	(D)	-
Irrigated ... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	2	-	-	-	2	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Soybeans for beans ... farms	1,409	1,106	511	295	125	19
acres	60,047	29,130	7,905	2,557	718	159
bushels	2,379,415	1,055,414	243,823	71,200	15,527	4,815
Irrigated ... farms	26	20	2	8	3	-
acres	1,121	537	(D)	50	(D)	-
Farms by acres harvested:						
1 to 24 acres	378	569	438	282	125	17
25 to 99 acres	978	532	73	13	-	2
100 to 249 acres	51	5	-	-	-	-
250 to 499 acres	2	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Sugarbeets for sugar ... farms	5	10	-	-	-	-
acres	133	122	-	-	-	-
tons	3,318	2,927	-	-	-	-
Irrigated ... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Sunflower seed, all ... farms	6	6	1	-	-	-
acres	135	180	(D)	-	-	-
pounds	60,800	222,392	(D)	-	-	-
Irrigated ... farms	1	-	-	-	-	-
acres	(D)	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	2	3	1	-	-	-
25 to 99 acres	4	3	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Wheat for grain, all ... farms	142	99	65	35	10	4
acres	6,436	3,372	1,312	378	53	40
bushels	287,719	127,845	38,542	9,900	1,341	910
Irrigated ... farms	8	-	-	-	2	-
acres	446	-	-	-	(D)	-
Farms by acres harvested:						
1 to 24 acres	42	29	46	34	10	4
25 to 99 acres	92	68	19	1	-	-
100 to 249 acres	8	2	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Forage-land used for all hay and haylage, grass silage, and greenchop ... farms	2,115	2,863	2,205	1,848	1,699	2,362
acres	131,608	120,267	62,796	39,129	26,089	30,057
tons, dry equivalent	234,339	182,043	76,137	42,363	25,172	24,340
Irrigated ... farms	44	35	19	32	20	39
acres	1,431	806	457	370	228	399
Farms by acres harvested:						
1 to 24 acres	708	1,280	1,284	1,279	1,413	2,101
25 to 99 acres	963	1,282	844	548	275	248
100 to 249 acres	387	285	72	19	11	12
250 to 499 acres	52	16	5	2	-	1
500 acres or more	5	-	-	-	-	-
Alfalfa hay ... farms	1,506	1,860	1,277	955	824	1,202
acres	72,518	59,995	28,206	16,546	10,222	13,233
tons, dry	145,372	103,901	39,853	20,112	11,109	12,162
Irrigated ... farms	32	19	8	12	4	5
acres	1,111	296	121	111	(D)	(D)
Other dry hay ... farms	798	1,169	882	814	747	884
acres	49,660	50,556	27,678	18,511	12,398	12,265
tons, dry	75,138	66,727	31,281	19,039	11,463	10,063

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	All farms	$1,000,000 or more	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$50,000 to $99,999
CROPS - Con.						
Forage-land used for all hay and haylage, grass silage, and greenchop - Con.						
Other dry hay - Con.						
Irrigated ... farms	153	21	11	17	14	17
acres	3,658	735	148	762	230	721
Field and grass seed crops, all ... farms	155	58	32	31	9	14
acres	66,601	49,794	8,927	5,683	1,003	824
Irrigated ... farms	6	-	-	5	1	-
acres	505	-	-	(D)	(D)	-
Land in vegetables ... farms	2,620	565	215	198	249	193
acres	196,718	140,497	26,328	15,222	9,902	2,520
Irrigated ... farms	764	117	38	47	72	69
acres	54,640	43,982	5,278	2,925	1,505	394
Farms by acres harvested:						
0.1 to 4.9 acres	1,355	10	5	24	80	109
5.0 to 24.9 acres	225	16	3	39	55	52
25.0 to 99.9 acres	495	186	103	80	81	32
100.0 to 249.9 acres	364	205	81	45	33	-
250.0 acres or more	181	148	23	10	-	-
Beans, snap ... farms	390	31	3	23	35	54
acres	2,553	2,452	(D)	14	12	19
Harvested for processing ... farms	22	17	-	-	-	-
acres	2,278	2,265	-	-	-	-
Peas, green ... farms	599	283	114	71	31	28
acres	47,364	32,858	8,079	4,575	1,164	621
Harvested for processing ... farms	491	280	112	62	23	12
acres	47,345	32,857	8,076	4,573	1,163	617
Potatoes ... farms	509	70	19	32	59	49
acres	49,008	46,934	1,673	185	101	25
Harvested for processing ... farms	39	34	5	-	-	-
acres	35,127	34,342	785	-	-	-
Farms by acres harvested:						
0.1 to 4.9 acres	421	6	3	27	57	49
5.0 to 24.9 acres	5	2	-	2	-	-
25.0 to 99.9 acres	20	3	12	3	2	-
100.0 to 249.9 acres	8	6	2	-	-	-
250.0 acres or more	55	53	2	-	-	-
Sweet corn (see text) ... farms	1,243	384	159	141	158	87
acres	96,990	59,309	17,389	10,409	7,899	1,365
Harvested for processing ... farms	750	360	153	111	97	21
acres	94,536	57,822	17,264	10,293	7,685	1,175
Sweet potatoes ... farms	58	-	1	12	10	13
acres	23	-	(D)	9	4	5
Harvested for processing ... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Tomatoes in the open ... farms	592	15	5	32	53	57
acres	300	58	15	42	70	24
Harvested for processing ... farms	18	-	-	-	-	-
acres	2	-	-	-	-	-
Land in orchards ... farms	1,174	19	11	30	63	97
acres	5,049	530	282	638	848	563
Irrigated ... farms	204	9	2	5	12	27
acres	778	197	(D)	36	112	155
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	927	13	5	11	16	49
5.0 to 24.9 acres	212	1	2	8	34	47
25.0 to 99.9 acres	32	3	4	10	13	1
100.0 to 249.9 acres	3	2	-	1	-	-
250.0 acres or more	-	-	-	-	-	-
Apples ... farms	751	8	8	21	48	70
bearing and nonbearing acres	3,219	504	266	516	589	363
Grapes (including muscadine) (see text) ... farms	433	11	4	9	18	35
bearing and nonbearing acres	1,290	26	10	107	196	182
Peaches, all ... farms	17	-	-	1	-	2
bearing and nonbearing acres	(D)	-	-	(D)	-	(D)
Walnuts, English ... farms	29	-	-	1	1	-
bearing and nonbearing acres	142	-	-	(D)	(D)	-
Land in berries ... farms	578	11	6	22	45	55
acres	1,129	280	87	150	128	147

See footnote(s) at end of table.

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Table 73. **Summary by Combined Government Payments and Market Value of Agricultural Products Sold: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		$25,000 to $49,999	$10,000 to $24,999	$5,000 to $9,999	$2,500 to $4,999	$1,000 to $2,499	Less than $1,000
CROPS - Con.							
Forage-land used for all hay and haylage, grass silage, and greenchop - Con.							
Other dry hay - Con.							
Irrigated	farms	11	9	6	16	8	23
	acres	163	342	75	98	115	269
Field and grass seed crops, all	farms	4	2	-	5	-	-
	acres	145	(D)	-	(D)	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Land in vegetables	farms	262	402	222	151	111	52
	acres	1,118	661	267	103	81	19
Irrigated	farms	110	161	85	36	27	2
	acres	234	173	100	32	(D)	(D)
Farms by acres harvested:							
0.1 to 4.9 acres		217	382	216	151	109	52
5.0 to 24.9 acres		32	20	6	-	2	-
25.0 to 99.9 acres		13	-	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-	-
250.0 acres or more		-	-	-	-	-	-
Beans, snap	farms	61	104	47	11	15	6
	acres	12	18	7	(D)	14	1
Harvested for processing	farms	1	2	-	-	2	-
	acres	(D)	(D)	-	-	(D)	-
Peas, green	farms	27	19	23	-	3	-
	acres	43	22	2	-	(Z)	-
Harvested for processing	farms	1	1	-	-	-	-
	acres	(D)	(D)	-	-	-	-
Potatoes	farms	79	93	61	17	21	9
	acres	30	37	18	3	3	2
Harvested for processing	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
0.1 to 4.9 acres		79	92	61	17	21	9
5.0 to 24.9 acres		-	1	-	-	-	-
25.0 to 99.9 acres		-	-	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-	-
250.0 acres or more		-	-	-	-	-	-
Sweet corn (see text)	farms	93	109	54	31	18	9
	acres	455	88	43	15	16	3
Harvested for processing	farms	8	-	-	-	-	-
	acres	297	-	-	-	-	-
Sweet potatoes	farms	7	7	7	-	1	-
	acres	(D)	2	1	-	(D)	-
Harvested for processing	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Tomatoes in the open	farms	104	173	86	35	30	2
	acres	38	33	13	5	(D)	(D)
Harvested for processing	farms	1	5	3	6	3	-
	acres	(D)	(D)	(Z)	(D)	(Z)	-
Land in orchards	farms	133	279	208	105	85	144
	acres	431	679	480	163	164	270
Irrigated	farms	32	59	21	15	14	8
	acres	48	92	22	14	48	(D)
Farms by bearing and nonbearing acres:							
0.1 to 4.9 acres		105	246	178	98	80	126
5.0 to 24.9 acres		28	32	30	7	5	18
25.0 to 99.9 acres		-	1	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-	-
250.0 acres or more		-	-	-	-	-	-
Apples	farms	103	197	117	46	41	92
	bearing and nonbearing acres	246	382	155	42	48	108
Grapes (including muscadine) (see text)	farms	36	95	87	52	41	45
	bearing and nonbearing acres	92	192	200	81	96	109
Peaches, all	farms	3	10	1	-	-	-
	bearing and nonbearing acres	(Z)	3	(D)	-	-	-
Walnuts, English	farms	2	6	11	4	-	4
	bearing and nonbearing acres	(D)	4	72	27	-	15
Land in berries	farms	93	147	74	43	30	52
	acres	96	103	56	32	14	36

[1] Landlord production expenses are included with total farm production expenses.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.
[3] Data were collected for a maximum of four producers per farm.

Table 74. **Summary by Legal Status For Tax Purposes: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
FARMS AND LAND IN FARMS				
Farms ..... number	65,531	55,532	5,022	4,156
percent	100.0	84.7	7.7	6.3
Land in farms ..... acres	25,442,625	17,410,756	4,452,974	3,904,476
Average size of farm ..... acres	388	314	887	939
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS				
Total ..... farms	65,531	55,532	5,022	4,156
$1,000	29,066,202	16,792,779	5,891,182	5,416,247
Average per farm ..... dollars	443,549	302,398	1,173,075	1,303,236
Farms by economic class:				
Less than $1,000	6,079	5,612	202	150
$1,000 to $2,499	6,033	5,402	268	200
$2,500 to $4,999	5,681	5,117	264	207
$5,000 to $9,999	6,141	5,454	351	281
$10,000 to $24,999	7,125	6,293	414	324
$25,000 to $49,999	4,813	4,309	258	204
$50,000 to $99,999	5,488	4,875	309	218
$100,000 to $249,999	6,899	5,993	556	451
$250,000 to $499,999	5,477	4,594	484	409
$500,000 to $999,999	4,529	3,585	430	369
$1,000,000 or more	7,266	4,298	1,486	1,343
$1,000,000 to $2,499,999	4,148	2,761	684	605
$2,500,000 to $4,999,999	2,458	1,305	593	540
$5,000,000 or more	660	232	209	198
Total sales ..... farms	65,531	55,532	5,022	4,156
$1,000	28,482,097	16,392,603	5,795,056	5,329,538
Grains, oilseeds, dry beans, and dry peas ..... farms	32,075	26,394	3,050	2,532
$1,000	15,268,581	9,984,622	3,038,190	2,705,363
Sales of $50,000 or more ..... farms	23,618	18,769	2,612	2,222
$1,000	15,113,786	9,846,744	3,028,866	2,698,868
Corn ..... farms	25,230	20,639	2,497	2,107
$1,000	9,045,595	5,872,864	1,841,601	1,640,300
Sales of $50,000 or more ..... farms	18,777	14,801	2,148	1,845
$1,000	8,908,714	5,749,931	1,833,255	1,633,966
Wheat ..... farms	3,668	2,766	465	401
$1,000	735,504	442,165	165,371	151,275
Sales of $50,000 or more ..... farms	2,125	1,510	301	265
$1,000	707,000	419,402	161,822	148,148
Soybeans ..... farms	25,334	20,641	2,506	2,080
$1,000	5,087,514	3,437,333	940,202	830,629
Sales of $50,000 or more ..... farms	17,131	13,333	2,001	1,719
$1,000	4,898,487	3,270,596	926,463	820,415
Sorghum ..... farms	53	47	4	4
$1,000	437	231	(D)	(D)
Sales of $50,000 or more ..... farms	1	-	1	1
$1,000	(D)	-	(D)	(D)
Barley ..... farms	336	232	59	50
$1,000	27,673	19,305	(D)	(D)
Sales of $50,000 or more ..... farms	151	106	22	20
$1,000	24,984	17,274	3,877	(D)
Rice ..... farms	-	-	-	-
$1,000	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-
$1,000	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	3,613	2,768	482	404
$1,000	371,859	212,723	86,665	79,205
Sales of $50,000 or more ..... farms	1,013	648	178	157
$1,000	342,531	190,644	82,203	75,659
Tobacco ..... farms	-	-	-	-
$1,000	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-
$1,000	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-
$1,000	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-
$1,000	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	2,648	2,047	265	232
$1,000	446,099	179,600	93,503	91,185
Sales of $50,000 or more ..... farms	994	662	172	155
$1,000	424,789	161,875	92,279	90,215
Fruits, tree nuts, and berries ..... farms	1,212	963	101	93
$1,000	48,717	21,423	8,466	(D)
Sales of $50,000 or more ..... farms	178	99	27	25
$1,000	38,977	13,627	7,460	(D)
Fruits and tree nuts ..... farms	944	758	80	74
$1,000	30,052	12,250	6,846	(D)
Sales of $50,000 or more ..... farms	116	55	23	21
$1,000	22,967	6,630	6,095	(D)
Berries ..... farms	489	382	37	34
$1,000	18,665	9,173	1,620	1,604
Sales of $50,000 or more ..... farms	66	43	5	5
$1,000	15,470	6,621	(D)	(D)
Nursery, greenhouse, floriculture, and sod ..... farms	1,051	675	120	117
$1,000	391,444	43,838	(D)	63,161

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
FARMS AND LAND IN FARMS						
Farms ..... number	3,803	3,375	3,341	428	361	1,174
percent	5.8	5.2	5.1	0.7	0.6	1.8
Land in farms ..... acres	3,244,861	3,085,380	3,068,248	159,481	132,032	334,034
Average size of farm ..... acres	853	914	918	373	366	285
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS						
Total ..... farms	3,803	3,375	3,341	428	361	1,174
$1,000	6,193,994	5,451,033	5,394,992	742,961	278,872	188,248
Average per farm ..... dollars	1,628,713	1,615,121	1,614,784	1,735,890	772,500	160,348
Farms by economic class:						
Less than $1,000	155	134	133	21	18	110
$1,000 to $2,499	189	149	148	40	26	174
$2,500 to $4,999	162	107	105	55	42	138
$5,000 to $9,999	177	137	137	40	39	159
$10,000 to $24,999	255	219	217	36	33	163
$25,000 to $49,999	153	124	117	29	29	93
$50,000 to $99,999	225	201	200	24	20	79
$100,000 to $249,999	229	188	185	41	41	121
$250,000 to $499,999	347	321	315	26	19	52
$500,000 to $999,999	466	440	439	26	26	48
$1,000,000 or more	1,445	1,355	1,345	90	68	37
$1,000,000 to $2,499,999	677	638	632	39	34	26
$2,500,000 to $4,999,999	554	532	531	22	22	6
$5,000,000 or more	214	185	182	29	12	5
Total sales ..... farms	3,803	3,375	3,341	428	361	1,174
$1,000	6,113,383	5,373,389	5,317,608	739,994	276,032	181,055
Grains, oilseeds, dry beans, and dry peas ..... farms	2,255	2,135	2,125	120	115	376
$1,000	2,156,493	2,098,498	2,092,639	57,995	(D)	89,277
Sales of $50,000 or more ..... farms	2,014	1,935	1,925	79	76	223
$1,000	2,151,788	2,094,292	2,088,434	57,495	(D)	86,388
Corn ..... farms	1,830	1,755	1,750	75	71	264
$1,000	1,277,710	1,246,251	1,244,051	31,459	(D)	53,420
Sales of $50,000 or more ..... farms	1,662	1,608	1,603	54	51	166
$1,000	1,274,350	1,243,312	1,241,113	31,038	(D)	51,178
Wheat ..... farms	412	393	392	19	17	25
$1,000	126,753	124,406	(D)	2,348	(D)	1,214
Sales of $50,000 or more ..... farms	310	305	305	5	5	4
$1,000	124,759	122,567	122,567	2,191	2,191	1,017
Soybeans ..... farms	1,908	1,823	1,814	85	81	279
$1,000	681,641	658,585	657,846	23,057	(D)	28,337
Sales of $50,000 or more ..... farms	1,655	1,597	1,588	58	55	142
$1,000	675,737	652,921	652,182	22,816	(D)	25,691
Sorghum ..... farms	2	2	2	-	-	-
$1,000	(D)	(D)	(D)	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Barley ..... farms	42	40	40	2	2	3
$1,000	(D)	(D)	(D)	(D)	(D)	3
Sales of $50,000 or more ..... farms	23	23	23	-	-	-
$1,000	3,833	3,833	3,833	-	-	-
Rice ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	321	305	299	16	15	42
$1,000	66,168	(D)	(D)	(D)	(D)	6,303
Sales of $50,000 or more ..... farms	178	174	168	4	4	9
$1,000	63,761	62,748	(D)	1,013	1,013	5,923
Tobacco ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-
$1,000	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	277	239	237	38	35	59
$1,000	170,731	149,032	(D)	21,699	(D)	2,265
Sales of $50,000 or more ..... farms	146	129	128	17	14	14
$1,000	168,734	147,515	(D)	21,219	(D)	1,901
Fruits, tree nuts, and berries ..... farms	121	102	101	19	16	27
$1,000	17,214	15,437	(D)	1,778	(D)	1,614
Sales of $50,000 or more ..... farms	46	41	41	5	2	6
$1,000	16,563	14,888	14,888	1,675	(D)	1,327
Fruits and tree nuts ..... farms	86	73	73	13	10	20
$1,000	(D)	8,096	8,096	(D)	(D)	(D)
Sales of $50,000 or more ..... farms	34	30	30	4	1	4
$1,000	9,323	7,727	7,727	1,596	(D)	919
Berries ..... farms	56	47	46	9	9	14
$1,000	(D)	7,341	(D)	(D)	(D)	(D)
Sales of $50,000 or more ..... farms	16	15	15	1	1	2
$1,000	(D)	7,045	7,045	(D)	(D)	(D)
Nursery, greenhouse, floriculture, and sod ..... farms	235	175	171	60	58	21
$1,000	280,780	219,090	184,533	61,690	(D)	(D)

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Family or individual	Partnership	
				Total	Registered under State law
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.					
Total - Con.					
Total sales - Con.					
Nursery, greenhouse, floriculture, and sod - Con.					
Sales of $50,000 or more	farms	343	148	42	41
	$1,000	381,613	36,670	(D)	(D)
Cultivated Christmas trees and short rotation woody crops	farms	244	199	19	19
	$1,000	7,578	4,218	1,626	1,626
Sales of $50,000 or more	farms	27	12	8	8
	$1,000	6,051	2,995	1,551	1,551
Cultivated Christmas trees	farms	243	198	19	19
	$1,000	(D)	(D)	1,626	1,626
Sales of $50,000 or more	farms	27	12	8	8
	$1,000	6,051	2,995	1,551	1,551
Short rotation woody crops	farms	1	1	-	-
	$1,000	(D)	(D)	-	-
Sales of $50,000 or more	farms	-	-	-	-
	$1,000	-	-	-	-
Other crops and hay	farms	16,722	14,608	1,095	886
	$1,000	981,348	533,858	240,303	217,677
Sales of $50,000 or more	farms	2,437	1,647	405	351
	$1,000	867,179	432,587	233,370	212,454
Maple syrup	farms	364	322	14	12
	$1,000	869	(D)	74	(D)
Sales of $50,000 or more	farms	3	2	-	-
	$1,000	191	(D)	-	-
Cattle and calves	farms	14,649	12,669	1,191	980
	$1,000	2,094,135	1,184,684	416,198	378,540
Sales of $50,000 or more	farms	4,609	3,333	769	673
	$1,000	1,933,030	1,038,141	407,475	371,929
Milk from cows	farms	1,893	1,244	392	360
	$1,000	2,504,638	1,197,622	715,268	696,385
Sales of $50,000 or more	farms	1,826	1,183	386	354
	$1,000	2,503,304	1,196,455	715,101	696,218
Hogs and pigs	farms	3,352	2,548	391	357
	$1,000	4,666,832	2,547,614	1,092,752	1,045,089
Sales of $50,000 or more	farms	2,034	1,349	334	311
	$1,000	4,660,288	2,542,202	1,092,041	1,044,398
Sheep, goats, wool, mohair, and milk	farms	2,604	2,445	72	63
	$1,000	33,457	30,337	(D)	1,160
Sales of $50,000 or more	farms	120	110	1	1
	$1,000	19,839	17,773	(D)	(D)
Horses, ponies, mules, burros, and donkeys	farms	1,247	1,156	38	35
	$1,000	18,147	15,919	540	(D)
Sales of $50,000 or more	farms	76	64	-	-
	$1,000	8,302	7,109	-	-
Poultry and eggs	farms	4,445	3,974	150	128
	$1,000	1,943,207	615,250	120,360	(D)
Sales of $50,000 or more	farms	447	266	43	41
	$1,000	1,935,336	608,120	(D)	(D)
Aquaculture	farms	98	35	6	6
	$1,000	19,763	3,778	610	610
Sales of $50,000 or more	farms	62	10	6	6
	$1,000	19,502	3,691	610	610
Other animals and other animal products	farms	1,405	1,210	69	68
	$1,000	58,149	29,840	2,752	(D)
Sales of $50,000 or more	farms	154	115	11	11
	$1,000	52,455	24,743	2,537	2,537
Value of-					
Government payments	farms	31,583	25,562	3,130	2,641
	$1,000	584,106	400,175	96,126	86,709
Landlord's share of total sales	farms	1,294	1,078	96	81
	$1,000	118,307	80,157	19,044	16,412
FOOD MARKETING PRACTICES					
Value of food sold directly to-					
Consumers	farms	3,339	2,866	237	219
	$1,000	44,673	28,840	7,068	6,782
Retail markets, institutions, and food hubs for local or regionally branded products	farms	1,026	797	116	115
	$1,000	108,704	17,246	5,923	(D)
FARM PRODUCTION EXPENSES					
Total farm production expenses [1]	farms	65,531	55,532	5,022	4,156
	$1,000	20,780,603	11,908,343	4,232,820	3,931,146
Average per farm	dollars	317,111	214,441	842,855	945,896
Fertilizer, lime, and soil conditioners purchased	farms	36,421	30,079	3,342	2,805
	$1,000	2,325,700	1,515,581	463,155	413,699
Farms with expenses of-					
$1 to $4,999		10,529	9,476	484	375
$5,000 to $24,999		9,710	8,480	707	559

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
		Total	Family held		Other than family held		
			Total	10 or less stockholders	Total	10 or less stockholders	
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.							
Total - Con.							
Total sales - Con.							
Nursery, greenhouse, floriculture, and sod - Con.							
Sales of $50,000 or more	farms	146	114	110	32	30	7
	$1,000	279,056	217,797	183,239	61,259	(D)	(D)
Cultivated Christmas trees and short rotation woody crops	farms	24	19	18	5	5	2
	$1,000	(D)	(D)	(D)	635	635	(D)
Sales of $50,000 or more	farms	7	5	5	2	2	-
	$1,000	1,505	(D)	(D)	(D)	(D)	-
Cultivated Christmas trees	farms	24	19	18	5	5	2
	$1,000	(D)	(D)	(D)	635	635	(D)
Sales of $50,000 or more	farms	7	5	5	2	2	-
	$1,000	1,505	(D)	(D)	(D)	(D)	-
Short rotation woody crops	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Sales of $50,000 or more	farms	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-
Other crops and hay	farms	812	741	737	71	65	207
	$1,000	201,792	195,607	195,424	6,185	6,175	5,395
Sales of $50,000 or more	farms	369	356	354	13	13	16
	$1,000	197,147	191,457	(D)	5,690	5,690	4,075
Maple syrup	farms	20	15	15	5	5	8
	$1,000	(D)	(D)	(D)	10	10	(D)
Sales of $50,000 or more	farms	1	1	1	-	-	-
	$1,000	(D)	(D)	(D)	-	-	-
Cattle and calves	farms	679	642	642	37	32	110
	$1,000	457,746	452,162	452,162	5,584	3,226	35,506
Sales of $50,000 or more	farms	478	457	457	21	17	29
	$1,000	453,371	448,093	448,093	5,278	(D)	34,043
Milk from cows	farms	245	238	238	7	5	12
	$1,000	580,528	556,537	556,537	23,991	(D)	11,221
Sales of $50,000 or more	farms	245	238	238	7	5	12
	$1,000	580,528	556,537	556,537	23,991	(D)	11,221
Hogs and pigs	farms	385	342	336	43	36	28
	$1,000	1,006,207	918,814	905,614	87,393	78,786	20,259
Sales of $50,000 or more	farms	336	296	290	40	33	15
	$1,000	(D)	918,497	905,297	(D)	(D)	(D)
Sheep, goats, wool, mohair, and milk	farms	65	62	62	3	2	22
	$1,000	(D)	1,686	1,686	(D)	(D)	(D)
Sales of $50,000 or more	farms	8	7	7	1	-	1
	$1,000	(D)	1,431	1,431	(D)	-	(D)
Horses, ponies, mules, burros, and donkeys	farms	43	37	37	6	6	10
	$1,000	(D)	1,434	1,434	(D)	(D)	(D)
Sales of $50,000 or more	farms	10	10	10	-	-	2
	$1,000	(D)	(D)	(D)	-	-	(D)
Poultry and eggs	farms	286	241	241	45	31	35
	$1,000	1,207,277	754,669	754,669	452,607	31,466	321
Sales of $50,000 or more	farms	136	109	109	27	13	2
	$1,000	1,206,893	754,367	754,367	452,526	31,384	(D)
Aquaculture	farms	14	13	12	1	1	43
	$1,000	5,080	(D)	(D)	(D)	(D)	10,295
Sales of $50,000 or more	farms	11	11	10	-	-	35
	$1,000	5,063	5,063	(D)	-	-	10,137
Other animals and other animal products	farms	116	93	93	23	22	10
	$1,000	24,617	4,255	4,255	20,362	(D)	940
Sales of $50,000 or more	farms	24	16	16	8	7	4
	$1,000	24,251	3,932	3,932	20,319	(D)	924
Value of-							
Government payments	farms	2,195	1,992	1,978	203	168	696
	$1,000	80,611	77,643	77,384	2,968	2,840	7,193
Landlord's share of total sales	farms	106	100	100	6	6	14
	$1,000	18,588	18,345	18,345	243	243	518
FOOD MARKETING PRACTICES							
Value of food sold directly to-							
Consumers	farms	202	173	172	29	29	34
	$1,000	7,894	7,464	(D)	431	431	870
Retail markets, institutions, and food hubs for local or regionally branded products	farms	100	83	81	17	16	13
	$1,000	85,345	(D)	(D)	(D)	(D)	190
FARM PRODUCTION EXPENSES							
Total farm production expenses [1]	farms	3,803	3,375	3,341	428	361	1,174
	$1,000	4,478,704	3,966,042	3,907,003	512,662	182,553	160,736
Average per farm	dollars	1,177,677	1,175,123	1,169,411	1,197,809	505,687	136,913
Fertilizer, lime, and soil conditioners purchased	farms	2,605	2,426	2,409	179	163	395
	$1,000	333,870	321,528	318,460	12,342	9,474	13,094
Farms with expenses of-							
$1 to $4,999		409	334	329	75	69	160
$5,000 to $24,999		405	362	360	43	38	118

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
FARM PRODUCTION EXPENSES - Con.				
Total farm production expenses [1] - Con.				
Fertilizer, lime, and soil conditioners purchased - Con.				
Farms with expenses of- - Con.				
$25,000 to $49,999	5,102	4,303	485	402
$50,000 or more	11,080	7,820	1,666	1,469
Chemicals purchased ... farms	37,339	30,706	3,491	2,925
$1,000	1,161,099	749,208	223,657	200,130
Farms with expenses of-				
$1 to $4,999	15,060	13,348	845	659
$5,000 to $24,999	11,493	9,715	1,056	863
$25,000 to $49,999	4,407	3,516	434	371
$50,000 or more	6,379	4,127	1,156	1,032
Seeds, plants, vines, and trees purchased ... farms	36,437	29,863	3,432	2,884
$1,000	1,772,341	1,135,451	349,501	314,465
Farms with expenses of-				
$1 to $999	5,343	4,797	264	214
$1,000 to $4,999	6,157	5,452	322	236
$5,000 to $24,999	10,290	8,909	853	702
$25,000 to $49,999	5,582	4,598	528	437
$50,000 or more	9,065	6,107	1,465	1,295
Cover crop seed purchased ... farms	4,909	3,783	592	526
$1,000	20,527	14,520	3,437	3,072
Livestock and poultry purchased or leased ... farms	13,933	11,822	1,082	918
$1,000	1,926,426	1,042,554	369,621	352,619
Farms with expenses of-				
$1 to $4,999	6,658	6,130	276	211
$5,000 to $24,999	3,161	2,820	212	165
$25,000 to $99,999	1,372	1,111	135	117
$100,000 to $249,999	912	652	136	118
$250,000 or more	1,830	1,109	323	307
Breeding livestock purchased or leased ... farms	5,904	5,132	455	378
$1,000	171,016	90,437	37,749	35,098
Other livestock and poultry purchased or leased ... farms	9,786	8,232	754	647
$1,000	1,755,410	952,117	331,873	317,521
Feed purchased ... farms	26,145	22,713	1,757	1,487
$1,000	3,890,272	1,957,826	785,472	754,262
Farms with expenses of-				
$1 to $4,999	13,038	12,263	376	258
$5,000 to $24,999	6,844	6,170	368	306
$25,000 to $99,999	2,349	1,869	287	248
$100,000 to $249,999	1,155	779	224	204
$250,000 or more	2,759	1,632	502	471
Gasoline, fuels, and oils purchased ... farms	61,621	52,474	4,572	3,780
$1,000	956,802	575,315	191,084	174,235
Farms with expenses of-				
$1 to $4,999	37,714	33,966	1,812	1,408
$5,000 to $24,999	14,760	12,631	1,134	884
$25,000 to $49,999	4,270	3,179	491	446
$50,000 or more	4,877	2,698	1,135	1,042
Utilities ... farms	48,636	40,810	3,947	3,309
$1,000	400,978	226,145	72,380	67,335
Farms with expenses of-				
$1 to $999	9,923	9,038	452	333
$1,000 to $4,999	24,023	21,368	1,436	1,130
$5,000 to $24,999	12,077	9,159	1,392	1,219
$25,000 to $49,999	1,626	852	399	368
$50,000 or more	987	393	268	259
Repairs, supplies, and maintenance costs ... farms	55,660	47,074	4,343	3,606
$1,000	1,322,234	847,423	238,130	216,321
Farms with expenses of-				
$1 to $4,999	25,809	23,318	1,238	944
$5,000 to $24,999	17,499	15,120	1,244	1,015
$25,000 to $49,999	5,425	4,341	553	469
$50,000 or more	6,927	4,295	1,308	1,178
Hired farm labor ... farms	17,399	12,648	2,175	1,881
$1,000	1,320,974	533,118	305,815	291,236
Farms with expenses of-				
$1 to $4,999	5,944	5,169	408	327
$5,000 to $24,999	4,466	3,607	446	362
$25,000 to $99,999	3,749	2,407	584	504
$100,000 to $249,999	2,234	1,178	467	431
$250,000 or more	1,006	287	270	257
Contract labor ... farms	4,311	3,222	553	487
$1,000	152,565	67,355	29,235	27,426
Farms with expenses of-				
$1 to $999	452	404	19	14
$1,000 to $4,999	1,452	1,191	144	124
$5,000 to $24,999	1,469	1,105	182	157
$25,000 to $49,999	315	184	67	61
$50,000 or more	623	338	141	131

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Fertilizer, lime, and soil conditioners purchased - Con.						
Farms with expenses of- - Con.						
$25,000 to $49,999	265	258	257	7	5	49
$50,000 or more	1,526	1,472	1,463	54	51	68
Chemicals purchased ... farms	2,643	2,470	2,453	173	157	499
$1,000	181,497	174,959	173,264	6,538	4,801	6,737
Farms with expenses of-						
$1 to $4,999	570	496	491	74	67	297
$5,000 to $24,999	590	548	546	42	39	132
$25,000 to $49,999	422	400	393	22	20	35
$50,000 or more	1,061	1,026	1,023	35	31	35
Seeds, plants, vines, and trees purchased ... farms	2,699	2,493	2,473	206	190	443
$1,000	277,601	266,393	258,805	11,208	9,607	9,789
Farms with expenses of-						
$1 to $999	206	170	170	36	31	76
$1,000 to $4,999	269	209	203	60	55	114
$5,000 to $24,999	388	357	357	31	30	140
$25,000 to $49,999	411	384	376	27	25	45
$50,000 or more	1,425	1,373	1,367	52	49	68
Cover crop seed purchased ... farms	467	420	418	47	46	67
$1,000	2,390	2,210	(D)	181	(D)	180
Livestock and poultry purchased or leased ... farms	901	813	812	88	65	128
$1,000	485,576	423,420	(D)	62,156	23,690	28,673
Farms with expenses of-						
$1 to $4,999	179	161	161	18	17	73
$5,000 to $24,999	107	102	101	5	4	22
$25,000 to $99,999	113	92	92	21	18	13
$100,000 to $249,999	113	107	107	6	3	11
$250,000 or more	389	351	351	38	23	9
Breeding livestock purchased or leased ... farms	264	238	238	26	19	53
$1,000	40,452	35,313	35,313	5,139	2,838	2,378
Other livestock and poultry purchased or leased ... farms	715	643	642	72	54	85
$1,000	445,125	388,108	(D)	57,017	20,852	26,296
Feed purchased ... farms	1,416	1,275	1,268	141	117	259
$1,000	1,120,473	889,717	884,445	230,756	33,191	26,501
Farms with expenses of-						
$1 to $4,999	273	234	234	39	37	126
$5,000 to $24,999	240	206	206	34	31	66
$25,000 to $99,999	165	151	150	14	13	28
$100,000 to $249,999	139	133	133	6	6	13
$250,000 or more	599	551	545	48	30	26
Gasoline, fuels, and oils purchased ... farms	3,607	3,255	3,225	352	302	968
$1,000	183,390	157,865	155,857	25,525	4,950	7,013
Farms with expenses of-						
$1 to $4,999	1,215	1,016	1,009	199	173	721
$5,000 to $24,999	835	757	745	78	70	160
$25,000 to $49,999	541	510	503	31	30	59
$50,000 or more	1,016	972	968	44	29	28
Utilities ... farms	3,215	2,935	2,907	280	236	664
$1,000	98,626	84,928	77,929	13,698	4,131	3,827
Farms with expenses of-						
$1 to $999	275	231	227	44	40	158
$1,000 to $4,999	866	770	759	96	81	353
$5,000 to $24,999	1,397	1,323	1,320	74	68	129
$25,000 to $49,999	367	338	338	29	29	8
$50,000 or more	310	273	263	37	18	16
Repairs, supplies, and maintenance costs ... farms	3,425	3,103	3,073	322	279	818
$1,000	226,806	207,666	204,383	19,140	10,196	9,876
Farms with expenses of-						
$1 to $4,999	785	640	633	145	128	468
$5,000 to $24,999	876	802	789	74	70	259
$25,000 to $49,999	487	465	465	22	17	44
$50,000 or more	1,277	1,196	1,186	81	64	47
Hired farm labor ... farms	2,277	2,105	2,089	172	137	299
$1,000	461,534	402,532	385,452	59,002	35,816	20,506
Farms with expenses of-						
$1 to $4,999	247	217	216	30	22	120
$5,000 to $24,999	361	337	335	24	21	52
$25,000 to $99,999	688	661	659	27	26	70
$100,000 to $249,999	557	526	525	31	27	32
$250,000 or more	424	364	354	60	41	25
Contract labor ... farms	475	409	407	66	57	61
$1,000	54,903	45,273	(D)	9,630	5,892	1,073
Farms with expenses of-						
$1 to $999	19	16	16	3	3	10
$1,000 to $4,999	93	79	79	14	13	24
$5,000 to $24,999	167	145	145	22	21	15
$25,000 to $49,999	62	56	56	6	4	2
$50,000 or more	134	113	111	21	16	10

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
FARM PRODUCTION EXPENSES - Con.				
Total farm production expenses [1] - Con.				
Customwork and custom hauling ..... farms	19,181	15,561	1,875	1,647
$1,000	425,172	238,402	98,694	95,319
Farms with expenses of-				
$1 to $999	2,876	2,612	139	110
$1,000 to $4,999	6,088	5,293	413	343
$5,000 to $24,999	6,540	5,282	650	558
$25,000 to $49,999	2,030	1,441	292	270
$50,000 or more	1,647	933	381	366
Cash rent for land, buildings, and grazing fees ..... farms	24,199	19,296	2,648	2,262
$1,000	2,302,712	1,356,382	537,645	497,874
Farms with expenses of-				
$1 to $4,999	5,289	4,754	309	241
$5,000 to $9,999	2,314	2,039	163	128
$10,000 to $24,999	4,009	3,415	348	288
$25,000 or more	12,587	9,088	1,828	1,605
Rent and lease expenses for machinery, equipment, and farm share of vehicles ..... farms	6,598	5,075	779	713
$1,000	182,357	100,962	48,843	46,974
Farms with expenses of-				
$1 to $999	1,233	1,066	80	65
$1,000 to $4,999	1,683	1,382	137	119
$5,000 to $24,999	2,168	1,667	258	238
$25,000 to $49,999	538	382	91	88
$50,000 or more	976	578	213	203
Interest expense ..... farms	27,274	22,266	2,595	2,209
$1,000	702,889	458,361	131,741	119,603
Farms with expenses of-				
$1 to $4,999	9,316	8,073	620	491
$5,000 to $24,999	11,255	9,558	944	802
$25,000 to $99,999	5,316	3,854	691	604
$100,000 or more	1,387	781	340	312
Secured by real estate ..... farms	20,348	16,991	1,793	1,518
$1,000	467,669	318,361	83,195	74,777
Farms with expenses of-				
$1 to $999	1,511	1,327	98	78
$1,000 to $4,999	5,125	4,553	300	243
$5,000 to $24,999	9,127	7,877	709	592
$25,000 to $49,999	2,363	1,822	282	235
$50,000 or more	2,222	1,412	404	370
Not secured by real estate ..... farms	16,953	13,587	1,706	1,473
$1,000	235,219	140,000	48,546	44,826
Farms with expenses of-				
$1 to $999	2,836	2,505	163	135
$1,000 to $4,999	6,264	5,366	441	346
$5,000 to $24,999	5,400	4,265	588	526
$25,000 to $49,999	1,506	990	270	235
$50,000 or more	947	461	244	231
Property taxes paid ..... farms	61,644	52,543	4,561	3,758
$1,000	482,443	347,301	70,384	61,301
Farms with expenses of-				
$1 to $4,999	39,325	35,292	2,025	1,597
$5,000 to $9,999	11,291	9,510	876	717
$10,000 to $24,999	7,298	5,411	974	849
$25,000 or more	3,730	2,330	686	595
Medical supplies, veterinary, and custom services for livestock ..... farms	19,351	16,429	1,544	1,353
$1,000	255,043	118,045	64,745	62,573
Farms with expenses of-				
$1 to $4,999	14,259	13,040	647	528
$5,000 to $24,999	3,318	2,493	456	404
$25,000 to $49,999	674	409	140	129
$50,000 to $99,999	623	319	158	153
$100,000 or more	477	168	143	139
All other production expenses ..... farms	44,226	36,441	3,896	3,281
$1,000	1,200,596	638,914	252,717	235,772
Farms with expenses of-				
$1 to $4,999	22,214	19,662	1,303	1,023
$5,000 to $24,999	13,025	10,870	1,108	924
$25,000 to $49,999	3,867	2,912	449	395
$50,000 to $99,999	3,372	2,154	613	544
$100,000 or more	1,748	843	423	395
Production expenses paid by landlords [1] ..... farms	2,062	1,615	233	213
$1,000	65,113	37,725	17,322	16,678
Depreciation expenses claimed ..... farms	41,075	33,511	3,873	3,285
$1,000	2,240,389	1,408,629	433,894	394,887
NET CASH FARM INCOME				
Net cash farm income of operations ..... farms	65,531	55,532	5,022	4,156
$1,000	9,296,848	5,624,932	1,776,374	1,593,106
Average per farm ..... dollars	141,869	101,292	353,718	383,327

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
FARM PRODUCTION EXPENSES - Con.						
Total farm production expenses [1] - Con.						
Customwork and custom hauling ..... farms	1,516	1,421	1,406	95	85	229
$1,000	85,261	82,720	81,088	2,541	2,024	2,814
Farms with expenses of-						
$1 to $999	78	76	75	2	1	47
$1,000 to $4,999	286	255	251	31	31	96
$5,000 to $24,999	544	514	507	30	28	64
$25,000 to $49,999	286	265	265	21	17	11
$50,000 or more	322	311	308	11	8	11
Cash rent for land, buildings, and grazing fees ..... farms	2,091	1,968	1,962	123	116	164
$1,000	401,427	390,872	(D)	10,555	8,696	7,258
Farms with expenses of-						
$1 to $4,999	176	151	149	25	22	50
$5,000 to $9,999	92	71	70	21	21	20
$10,000 to $24,999	217	194	192	23	23	29
$25,000 or more	1,606	1,552	1,551	54	50	65
Rent and lease expenses for machinery, equipment, and farm share of vehicles ..... farms	674	632	625	42	38	70
$1,000	31,773	29,572	29,497	2,201	2,032	779
Farms with expenses of-						
$1 to $999	73	67	67	6	6	14
$1,000 to $4,999	131	121	121	10	9	33
$5,000 to $24,999	225	214	207	11	11	18
$25,000 to $49,999	63	54	54	9	7	2
$50,000 or more	182	176	176	6	5	3
Interest expense ..... farms	2,130	1,953	1,944	177	150	283
$1,000	108,272	99,866	99,733	8,406	4,673	4,515
Farms with expenses of-						
$1 to $4,999	491	442	437	49	46	132
$5,000 to $24,999	643	587	586	56	50	110
$25,000 to $99,999	736	680	677	56	47	35
$100,000 or more	260	244	244	16	7	6
Secured by real estate ..... farms	1,365	1,235	1,231	130	105	199
$1,000	62,297	56,079	(D)	6,217	3,772	3,817
Farms with expenses of-						
$1 to $999	67	52	52	15	13	19
$1,000 to $4,999	212	196	196	16	14	60
$5,000 to $24,999	458	413	411	45	40	83
$25,000 to $49,999	248	223	221	25	19	11
$50,000 or more	380	351	351	29	19	26
Not secured by real estate ..... farms	1,500	1,394	1,387	106	89	160
$1,000	45,975	43,787	(D)	2,189	901	698
Farms with expenses of-						
$1 to $999	131	119	114	12	11	37
$1,000 to $4,999	379	346	346	33	32	78
$5,000 to $24,999	505	464	462	41	36	42
$25,000 to $49,999	244	233	233	11	8	2
$50,000 or more	241	232	232	9	2	1
Property taxes paid ..... farms	3,438	3,048	3,014	390	326	1,102
$1,000	56,534	51,687	(D)	4,848	3,287	8,223
Farms with expenses of-						
$1 to $4,999	1,368	1,118	1,110	250	208	640
$5,000 to $9,999	651	591	585	60	58	254
$10,000 to $24,999	763	721	711	42	36	150
$25,000 or more	656	618	608	38	24	58
Medical supplies, veterinary, and custom services for livestock ..... farms	1,219	1,109	1,103	110	87	159
$1,000	70,458	60,048	59,148	10,410	3,579	1,794
Farms with expenses of-						
$1 to $4,999	452	402	402	50	46	120
$5,000 to $24,999	344	331	331	13	12	25
$25,000 to $49,999	123	112	112	11	9	2
$50,000 to $99,999	138	132	132	6	6	8
$100,000 or more	162	132	126	30	14	4
All other production expenses ..... farms	3,202	2,910	2,881	292	248	687
$1,000	300,703	276,995	272,587	23,708	16,515	8,263
Farms with expenses of-						
$1 to $4,999	824	683	674	141	121	425
$5,000 to $24,999	867	813	800	54	49	180
$25,000 to $49,999	458	427	425	31	31	48
$50,000 to $99,999	582	555	554	27	27	23
$100,000 or more	471	432	428	39	20	11
Production expenses paid by landlords [1] ..... farms	199	181	179	18	13	15
$1,000	9,723	9,583	(D)	141	139	343
Depreciation expenses claimed ..... farms	3,112	2,828	2,799	284	244	579
$1,000	379,681	351,518	344,786	28,163	16,982	18,184
NET CASH FARM INCOME						
Net cash farm income of operations ..... farms	3,803	3,375	3,341	428	361	1,174
$1,000	1,842,112	1,604,151	(D)	237,961	102,778	53,430
Average per farm ..... dollars	484,384	475,304	(D)	555,983	284,704	45,511

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
NET CASH FARM INCOME - Con.				
Net cash farm income of operations - Con.				
Farms with net gains [2] ... number	41,496	33,912	3,907	3,291
Average net gain ... dollars	242,705	180,771	485,014	517,948
Gain of-				
Less than $1,000	1,541	1,355	94	64
$1,000 to $4,999	4,053	3,612	231	175
$5,000 to $9,999	3,053	2,727	161	126
$10,000 to $24,999	5,680	4,967	385	299
$25,000 to $49,999	5,396	4,618	433	347
$50,000 or more	21,773	16,633	2,603	2,280
Farms with net losses ... number	24,035	21,620	1,115	865
Average net loss ... dollars	32,221	23,376	106,345	128,859
Loss of-				
Less than $1,000	1,786	1,610	107	84
$1,000 to $4,999	6,380	5,869	226	168
$5,000 to $9,999	5,021	4,669	166	130
$10,000 to $24,999	5,999	5,573	203	138
$25,000 to $49,999	2,539	2,225	137	105
$50,000 or more	2,310	1,674	276	240
Net cash farm income of producers ... farms	65,531	55,532	5,022	4,156
$1,000	8,390,544	5,004,602	1,663,586	1,493,393
Average per farm ... dollars	128,039	90,121	331,260	359,334
Producers reporting net gains [2] ... farms	41,274	33,753	3,877	3,260
Average net gain ... dollars	222,954	163,986	461,592	494,439
Gain of-				
Less than $1,000	1,557	1,375	90	62
$1,000 to $4,999	4,059	3,617	229	173
$5,000 to $9,999	3,084	2,750	170	133
$10,000 to $24,999	5,726	4,999	393	308
$25,000 to $49,999	5,475	4,698	431	345
$50,000 or more	21,373	16,314	2,564	2,239
Producers reporting net losses ... farms	24,257	21,779	1,145	896
Average net loss ... dollars	33,460	24,354	110,050	132,230
Loss of-				
Less than $1,000	1,780	1,604	107	84
$1,000 to $4,999	6,394	5,881	230	172
$5,000 to $9,999	5,032	4,683	165	129
$10,000 to $24,999	6,008	5,573	210	148
$25,000 to $49,999	2,576	2,251	139	106
$50,000 or more	2,467	1,787	294	257
COMMODITY CREDIT CORPORATION LOANS				
Total ... farms	990	713	172	159
$1,000	197,241	103,103	68,611	67,035
INCOME FROM FARM-RELATED SOURCES				
Total income from farm-related sources ... farms	38,287	32,004	3,086	2,606
$1,000	1,011,249	740,497	118,012	108,004
Customwork and other agricultural services ... farms	4,779	3,801	484	437
$1,000	144,025	101,527	19,242	18,659
Gross cash rent or share payments ... farms	15,680	13,299	1,016	832
$1,000	479,289	369,979	47,014	41,171
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products ... farms	619	544	36	30
$1,000	5,384	4,312	607	(D)
Agri-tourism and recreational services ... farms	509	363	66	64
$1,000	13,615	6,079	3,357	(D)
Patronage dividends and refunds from cooperatives ... farms	23,672	19,757	2,016	1,720
$1,000	126,183	84,356	19,212	17,871
Crop and livestock insurance payments ... farms	5,882	4,741	540	466
$1,000	171,530	127,006	20,244	18,729
Amount from State and local government agricultural program payments ... farms	1,422	1,102	183	162
$1,000	7,129	4,926	1,622	1,485
Other farm-related income sources ... farms	2,557	2,053	221	189
$1,000	64,095	42,314	6,714	6,490
LAND USE				
Total cropland ... farms	58,762	49,657	4,674	3,865
acres	21,544,060	14,409,653	4,018,562	3,556,859
Harvested cropland ... farms	47,549	40,299	3,744	3,111
acres	19,662,443	12,975,571	3,779,490	3,349,428
Farms by acres harvested:				
1 to 49 acres	16,934	15,418	650	524
50 to 99 acres	5,412	4,860	263	198
100 to 199 acres	6,580	5,889	426	317
200 to 499 acres	8,316	7,104	728	603
500 to 999 acres	4,858	3,734	563	482

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
NET CASH FARM INCOME - Con.						
Net cash farm income of operations - Con.						
Farms with net gains [2] ... number	2,893	2,585	2,561	308	260	784
Average net gain ... dollars	683,223	668,361	672,706	807,958	434,675	88,581
Gain of-						
Less than $1,000	67	51	49	16	8	25
$1,000 to $4,999	130	81	81	49	43	80
$5,000 to $9,999	90	65	65	25	22	75
$10,000 to $24,999	169	140	139	29	29	159
$25,000 to $49,999	197	161	159	36	36	148
$50,000 or more	2,240	2,087	2,068	153	122	297
Farms with net losses ... number	910	790	780	120	101	390
Average net loss ... dollars	147,749	156,406	(D)	90,756	101,361	41,070
Loss of-						
Less than $1,000	32	30	26	2	2	37
$1,000 to $4,999	172	131	131	41	29	113
$5,000 to $9,999	127	107	107	20	18	59
$10,000 to $24,999	151	138	137	13	12	72
$25,000 to $49,999	128	110	110	18	18	49
$50,000 or more	300	274	269	26	22	60
Net cash farm income of producers ... farms	3,803	3,375	3,341	428	361	1,174
$1,000	1,671,876	1,453,018	(D)	218,858	90,190	50,480
Average per farm ... dollars	439,620	430,524	(D)	511,351	249,835	42,999
Producers reporting net gains [2] ... farms	2,862	2,564	2,539	298	251	782
Average net gain ... dollars	633,016	616,264	620,317	777,155	405,960	84,250
Gain of-						
Less than $1,000	67	51	49	16	8	25
$1,000 to $4,999	132	83	83	49	43	81
$5,000 to $9,999	89	64	64	25	22	75
$10,000 to $24,999	175	150	149	25	24	159
$25,000 to $49,999	199	161	159	38	38	147
$50,000 or more	2,200	2,055	2,035	145	116	295
Producers reporting net losses ... farms	941	811	802	130	110	392
Average net loss ... dollars	148,583	156,699	(D)	97,955	106,413	39,294
Loss of-						
Less than $1,000	32	30	26	2	2	37
$1,000 to $4,999	170	129	129	41	29	113
$5,000 to $9,999	125	106	106	19	17	59
$10,000 to $24,999	153	141	140	12	11	72
$25,000 to $49,999	135	112	112	23	23	51
$50,000 or more	326	293	289	33	28	60
COMMODITY CREDIT CORPORATION LOANS						
Total ... farms	100	97	97	3	3	5
$1,000	25,160	24,882	24,882	278	278	367
INCOME FROM FARM-RELATED SOURCES						
Total income from farm-related sources ... farms	2,482	2,284	2,261	198	167	715
$1,000	126,822	119,160	117,616	7,662	6,459	25,918
Customwork and other agricultural services ... farms	463	449	448	14	9	31
$1,000	22,461	20,430	(D)	2,031	2,030	796
Gross cash rent or share payments ... farms	813	720	704	93	80	552
$1,000	41,053	37,332	36,096	3,721	2,557	21,243
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products ... farms	33	29	29	4	1	6
$1,000	344	(D)	(D)	(D)	(D)	121
Agri-tourism and recreational services ... farms	61	55	55	6	5	19
$1,000	2,855	2,699	2,699	155	(D)	1,324
Patronage dividends and refunds from cooperatives ... farms	1,684	1,599	1,590	85	82	215
$1,000	21,835	21,197	(D)	638	637	781
Crop and livestock insurance payments ... farms	558	540	540	18	18	43
$1,000	23,474	22,887	22,887	586	586	806
Amount from State and local government agricultural program payments ... farms	121	102	101	19	13	16
$1,000	511	(D)	399	(D)	(D)	69
Other farm-related income sources ... farms	260	242	241	18	18	23
$1,000	14,289	14,061	(D)	228	228	777
LAND USE						
Total cropland ... farms	3,369	3,028	3,002	341	293	1,062
acres	2,926,649	2,815,216	2,803,361	111,433	101,149	189,196
Harvested cropland ... farms	2,925	2,686	2,669	239	215	581
acres	2,769,606	2,676,362	2,667,831	93,244	83,382	137,776
Farms by acres harvested:						
1 to 49 acres	604	491	486	113	97	262
50 to 99 acres	196	165	164	31	31	93
100 to 199 acres	196	176	175	20	19	69
200 to 499 acres	398	370	363	28	27	86
500 to 999 acres	519	505	503	14	11	42

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Family or individual	Partnership	
				Total	Registered under State law
LAND USE - Con.					
Total cropland - Con.					
Harvested cropland - Con.					
Farms by acres harvested: - Con.					
1,000 to 1,999 acres		3,081	2,049	464	408
2,000 acres or more		2,368	1,245	650	579
Cropland-					
Other pasture and grazing land that could have been used for crops without additional improvements	farms	3,908	3,379	306	262
	acres	174,215	128,760	29,693	24,983
On which all crops failed or were abandoned	farms	2,413	2,044	191	156
	acres	110,013	85,998	12,223	11,624
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms	22,588	18,420	2,108	1,752
	acres	1,546,009	1,174,513	194,698	168,861
In summer fallow	farms	2,242	1,970	131	109
	acres	51,380	44,811	2,458	1,963
Total woodland	farms	23,960	20,959	1,556	1,239
	acres	1,446,600	1,138,077	137,384	111,984
Woodland pastured	farms	7,908	7,123	460	348
	acres	315,103	270,787	27,306	18,541
Woodland not pastured	farms	19,456	16,864	1,318	1,066
	acres	1,131,497	867,290	110,078	93,443
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	19,837	17,789	1,109	888
	acres	1,031,215	833,731	117,843	84,581
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	42,652	36,618	2,941	2,422
	acres	1,420,750	1,029,295	179,185	151,052
Irrigated land	farms	3,625	2,557	495	459
	acres	648,313	336,347	152,644	147,642
Harvested cropland	farms	3,551	2,500	485	449
	acres	644,857	333,786	(D)	(D)
Pastureland and other land	farms	160	108	27	26
	acres	3,456	2,561	(D)	(D)
CONSERVATION AND CROP INSURANCE					
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	19,069	15,394	1,815	1,507
	acres	951,335	738,125	113,256	97,694
Land enrolled in crop insurance programs	farms	27,305	21,983	2,841	2,399
	acres	18,167,226	11,867,171	3,549,209	3,162,631
ORGANIC AGRICULTURE					
Total organic product sales	farms	577	434	82	77
	$1,000	121,783	72,518	26,122	21,145
VALUE OF LAND AND BUILDINGS					
Estimated market value of land and buildings	farms	65,531	55,532	5,022	4,156
	$1,000	155,374,449	105,661,558	27,373,103	24,140,239
Average per farm	dollars	2,371,007	1,902,715	5,450,638	5,808,527
Average per acre	dollars	6,107	6,069	6,147	6,183
Farms by value group:					
$1 to $49,999		1,819	1,520	91	68
$50,000 to $99,999		2,318	2,071	121	86
$100,000 to $199,999		5,817	5,189	327	246
$200,000 to $499,999		17,490	15,905	736	602
$500,000 to $999,999		13,050	11,487	786	651
$1,000,000 to $1,999,999		8,615	7,335	677	513
$2,000,000 to $4,999,999		8,631	6,914	938	793
$5,000,000 to $9,999,999		3,992	2,956	486	433
$10,000,000 or more		3,799	2,155	860	764
VALUE OF MACHINERY AND EQUIPMENT					
Estimated market value of all machinery and equipment	farms	65,531	55,532	5,022	4,156
	$1,000	17,904,134	12,315,561	2,949,390	2,635,671
Farms by value group:					
$1 to $4,999		3,305	2,892	191	145
$5,000 to $9,999		3,816	3,309	214	175
$10,000 to $19,999		6,447	5,680	378	284
$20,000 to $49,999		12,383	11,089	652	524
$50,000 to $99,999		10,506	9,316	608	492
$100,000 to $199,999		9,020	8,003	533	421
$200,000 to $499,999		9,719	8,128	829	672
$500,000 or more		10,335	7,115	1,617	1,443

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
		Total	Family held		Other than family held		
			Total	10 or less stockholders	Total	10 or less stockholders	
LAND USE - Con.							
Total cropland - Con.							
Harvested cropland - Con.							
Farms by acres harvested: - Con.							
1,000 to 1,999 acres		546	525	525	21	19	22
2,000 acres or more		466	454	453	12	11	7
Cropland-							
Other pasture and grazing land that could have been used for crops without additional improvements	farms	159	149	144	10	10	64
	acres	13,867	13,097	(D)	770	770	1,895
On which all crops failed or were abandoned	farms	148	135	134	13	13	30
	acres	10,298	9,215	(D)	1,083	1,083	1,494
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms	1,422	1,249	1,236	173	147	638
	acres	129,511	113,325	110,939	16,186	15,764	47,287
In summer fallow	farms	100	91	91	9	9	41
	acres	3,367	3,217	3,217	150	150	744
Total woodland	farms	1,019	878	862	141	122	426
	acres	99,144	86,699	(D)	12,445	7,304	71,995
Woodland pastured	farms	236	209	206	27	27	89
	acres	13,353	12,774	(D)	579	579	3,657
Woodland not pastured	farms	890	767	752	123	104	384
	acres	85,791	73,925	69,413	11,866	6,725	68,338
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	705	635	634	70	65	234
	acres	65,180	54,766	(D)	10,414	10,350	14,461
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	2,341	2,053	2,033	288	238	752
	acres	153,888	128,699	128,178	25,189	13,229	58,382
Irrigated land	farms	505	430	421	75	67	68
	acres	129,477	119,609	114,470	9,868	(D)	29,845
Harvested cropland	farms	498	423	414	75	67	68
	acres	129,018	119,247	114,108	9,771	(D)	(D)
Pastureland and other land	farms	22	18	18	4	4	3
	acres	459	362	362	97	97	(D)
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	1,255	1,104	1,092	151	122	605
	acres	64,037	56,328	54,687	7,709	6,645	35,917
Land enrolled in crop insurance programs	farms	2,186	2,084	2,072	102	97	295
	acres	2,627,257	2,543,332	2,537,031	83,925	76,396	123,589
ORGANIC AGRICULTURE							
Total organic product sales	farms	45	41	41	4	4	16
	$1,000	(D)	16,380	16,380	(D)	(D)	(D)
VALUE OF LAND AND BUILDINGS							
Estimated market value of land and buildings	farms	3,803	3,375	3,341	428	361	1,174
	$1,000	20,605,995	19,703,707	19,611,024	902,288	774,241	1,733,793
Average per farm	dollars	5,418,353	5,838,135	5,869,807	2,108,149	2,144,713	1,476,825
Average per acre	dollars	6,350	6,386	6,392	5,658	5,864	5,190
Farms by value group:							
$1 to $49,999		135	94	94	41	29	73
$50,000 to $99,999		67	58	52	9	5	59
$100,000 to $199,999		194	140	140	54	41	107
$200,000 to $499,999		526	438	434	88	78	323
$500,000 to $999,999		507	415	411	92	89	270
$1,000,000 to $1,999,999		439	397	389	42	31	164
$2,000,000 to $4,999,999		672	611	606	61	54	107
$5,000,000 to $9,999,999		511	492	487	19	13	39
$10,000,000 or more		752	730	728	22	21	32
VALUE OF MACHINERY AND EQUIPMENT							
Estimated market value of all machinery and equipment	farms	3,803	3,375	3,341	428	361	1,174
	$1,000	2,485,096	2,340,892	2,328,101	144,203	85,829	154,087
Farms by value group:							
$1 to $4,999		124	92	90	32	31	98
$5,000 to $9,999		166	116	116	50	40	127
$10,000 to $19,999		199	168	164	31	28	190
$20,000 to $49,999		372	280	278	92	71	270
$50,000 to $99,999		411	325	322	86	78	171
$100,000 to $199,999		377	338	332	39	35	107
$200,000 to $499,999		641	595	584	46	38	121
$500,000 or more		1,513	1,461	1,455	52	40	90

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
SELECTED MACHINERY AND EQUIPMENT				
Trucks, including pickups ..... farms	51,156	43,598	3,777	3,127
number	127,301	97,823	14,952	12,781
Tractors, all ..... farms	52,770	44,820	4,024	3,341
number	184,473	148,877	18,843	15,990
Less than 40 horsepower (PTO) ..... farms	22,815	19,671	1,556	1,275
number	36,863	31,452	2,704	2,236
40 to 99 horsepower (PTO) ..... farms	35,619	30,452	2,674	2,198
number	60,537	51,242	4,916	4,071
100 horsepower (PTO) or more ..... farms	31,912	26,077	3,052	2,540
number	87,073	66,183	11,223	9,683
Grain and bean combines, self-propelled ..... farms	21,753	17,383	2,366	1,960
number	25,736	20,201	3,077	2,614
Cotton pickers and strippers, self-propelled ..... farms	-	-	-	-
number	-	-	-	-
Forage harvesters, self-propelled ..... farms	2,195	1,692	300	267
number	2,384	1,845	324	287
Hay balers ..... farms	19,296	16,965	1,335	1,077
number	24,300	21,381	1,694	1,354
FERTILIZERS AND CHEMICALS				
Commercial fertilizer, lime, and soil conditioners used ..... farms	34,208	28,149	3,210	2,689
acres treated	14,076,782	9,263,303	2,711,274	2,426,402
Manure used ..... farms	13,721	11,639	1,183	1,016
acres treated	1,453,615	922,709	307,959	287,826
Organic fertilizer used ..... farms	1,053	846	112	93
acres treated	135,551	95,288	26,681	25,473
Acres treated to control-				
Insects ..... farms	13,847	11,010	1,436	1,258
acres	5,229,304	3,432,634	1,014,854	918,440
Weeds, grass, or brush ..... farms	34,397	28,176	3,300	2,753
acres	17,661,145	11,545,648	3,430,975	3,053,119
Nematodes ..... farms	3,288	2,614	362	306
acres	977,113	638,883	207,778	187,468
Diseases in crops and orchards ..... farms	5,080	3,810	604	540
acres	2,350,398	1,430,309	488,766	439,590
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	1,762	1,324	187	172
acres on which used	318,341	185,083	57,602	54,328
LAND USE PRACTICES				
Land drained by tile ..... farms	19,088	15,409	1,881	1,623
acres	8,247,260	5,402,961	1,635,114	1,461,109
Land artificially drained by ditches ..... farms	9,435	7,587	910	791
acres	4,560,910	2,835,303	975,861	895,880
Land under conservation easement ..... farms	4,909	3,999	418	358
acres	282,171	198,219	42,663	39,871
Cropland on which no-till practices were used ..... farms	6,845	5,629	633	538
acres	1,194,987	869,478	192,185	174,816
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ..... farms	15,574	12,382	1,690	1,434
acres	7,881,385	4,998,375	1,621,120	1,460,732
Cropland on which intensive or conventional tillage practices were used (see text) ..... farms	22,330	18,653	1,937	1,616
acres	9,573,777	6,334,832	1,817,816	1,594,942
Cropland planted to a cover crop (excluding CRP) ..... farms	6,050	4,697	678	630
acres	760,423	496,401	151,815	145,496
Use of precision agriculture practices (see text) ..... farms	15,460	12,196	1,635	1,448
RENEWABLE ENERGY				
Renewable energy producing systems (see text) ..... farms	4,247	3,410	391	341
Solar panels ..... farms	2,063	1,641	211	194
Wind turbines ..... farms	819	630	87	69
Methane digesters ..... farms	15	13	-	-
Geothermal/geoexchange systems ..... farms	1,695	1,375	133	111
Small hydro systems ..... farms	24	21	1	1
Wind rights leased to others ..... farms	1,189	989	108	82
TENURE				
Full owners ..... farms	40,396	35,252	2,407	1,933
Part owners ..... farms	20,564	16,813	2,034	1,703
Tenants ..... farms	4,571	3,467	581	520
OWNED AND RENTED LAND				
Land owned ..... farms	61,213	52,283	4,453	3,648
acres	15,768,785	11,676,750	2,174,546	1,863,770
Owned land in farms ..... farms	60,960	52,065	4,441	3,636
acres	13,006,137	9,482,534	1,914,082	1,633,294
Land rented or leased from others ..... farms	25,328	20,427	2,644	2,248
acres	12,515,140	7,974,682	2,556,273	2,288,164
Rented or leased land in farms ..... farms	25,135	20,280	2,615	2,223
acres	12,436,488	7,928,222	2,538,892	2,271,182

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
		Total	Family held		Other than family held		
			Total	10 or less stockholders	Total	10 or less stockholders	
SELECTED MACHINERY AND EQUIPMENT							
Trucks, including pickups	farms	3,121	2,855	2,830	266	227	660
	number	12,938	12,049	11,971	889	670	1,588
Tractors, all	farms	3,179	2,898	2,877	281	240	747
	number	14,568	13,763	13,684	805	655	2,185
Less than 40 horsepower (PTO)	farms	1,226	1,092	1,081	134	111	362
	number	2,092	1,899	1,876	193	158	615
40 to 99 horsepower (PTO)	farms	1,982	1,799	1,786	183	153	511
	number	3,589	3,290	3,272	299	234	790
100 horsepower (PTO) or more	farms	2,413	2,295	2,280	118	99	370
	number	8,887	8,574	8,536	313	263	780
Grain and bean combines, self-propelled	farms	1,783	1,720	1,711	63	58	221
	number	2,194	2,110	2,096	84	74	264
Cotton pickers and strippers, self-propelled	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	181	172	172	9	9	22
	number	190	180	180	10	10	25
Hay balers	farms	782	736	729	46	39	214
	number	960	911	903	49	42	265
FERTILIZERS AND CHEMICALS							
Commercial fertilizer, lime, and soil conditioners used	farms	2,486	2,325	2,308	161	145	363
	acres treated	1,992,964	1,932,030	1,924,235	60,934	53,846	109,241
Manure used	farms	775	736	735	39	35	124
	acres treated	213,429	205,921	(D)	7,508	(D)	9,518
Organic fertilizer used	farms	75	54	54	21	21	20
	acres treated	12,725	12,594	12,594	131	131	857
Acres treated to control-							
Insects	farms	1,233	1,160	1,149	73	66	168
	acres	725,688	706,943	699,652	18,745	14,995	56,128
Weeds, grass, or brush	farms	2,467	2,314	2,303	153	137	454
	acres	2,559,339	2,472,872	2,466,790	86,467	76,919	125,183
Nematodes	farms	274	252	252	22	20	38
	acres	123,783	117,115	117,115	6,668	(D)	6,669
Diseases in crops and orchards	farms	627	595	595	32	30	39
	acres	423,135	412,863	412,863	10,272	(D)	8,188
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms	230	210	209	20	16	21
	acres on which used	73,880	67,990	(D)	5,890	(D)	1,776
LAND USE PRACTICES							
Land drained by tile	farms	1,498	1,415	1,410	83	77	300
	acres	1,151,632	1,114,587	1,113,487	37,045	(D)	57,553
Land artificially drained by ditches	farms	817	765	763	52	46	121
	acres	735,094	711,271	(D)	23,823	(D)	14,652
Land under conservation easement	farms	319	259	258	60	52	173
	acres	31,540	22,424	(D)	9,116	4,647	9,749
Cropland on which no-till practices were used	farms	497	442	440	55	52	86
	acres	127,403	118,042	(D)	9,361	8,983	5,921
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms	1,305	1,240	1,236	65	63	197
	acres	1,207,857	1,182,151	(D)	25,706	(D)	54,033
Cropland on which intensive or conventional tillage practices were used (see text)	farms	1,463	1,370	1,361	93	85	277
	acres	1,354,211	1,302,831	1,295,925	51,380	42,330	66,918
Cropland planted to a cover crop (excluding CRP)	farms	584	533	532	51	50	91
	acres	108,370	101,721	(D)	6,649	(D)	3,837
Use of precision agriculture practices (see text)	farms	1,432	1,376	1,364	56	53	197
RENEWABLE ENERGY							
Renewable energy producing systems (see text)	farms	362	336	333	26	26	84
Solar panels	farms	175	157	154	18	18	36
Wind turbines	farms	68	66	66	2	2	34
Methane digesters	farms	2	2	2	-	-	-
Geothermal/geoexchange systems	farms	158	148	148	10	10	29
Small hydro systems	farms	2	2	2	-	-	-
Wind rights leased to others	farms	60	56	56	4	3	32
TENURE							
Full owners	farms	1,732	1,425	1,396	307	251	1,005
Part owners	farms	1,598	1,518	1,514	80	72	119
Tenants	farms	473	432	431	41	38	50
OWNED AND RENTED LAND							
Land owned	farms	3,348	2,961	2,928	387	323	1,129
	acres	1,513,042	1,382,327	1,361,260	130,715	101,919	404,447
Owned land in farms	farms	3,330	2,943	2,910	387	323	1,124
	acres	1,320,202	1,208,324	1,192,806	111,878	88,291	289,319
Land rented or leased from others	farms	2,083	1,961	1,956	122	110	174
	acres	1,938,705	1,891,022	1,889,408	47,683	43,741	45,480
Rented or leased land in farms	farms	2,071	1,950	1,945	121	110	169
	acres	1,924,659	1,877,056	1,875,442	47,603	43,741	44,715

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
OWNED AND RENTED LAND - Con.				
Land rented or leased to others ..... farms	15,946	13,551	1,013	832
acres	2,841,300	2,240,676	277,845	247,458
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS				
Total producers	118,256	93,077	13,292	11,235
Farms by number of producers:				
1 producer	28,348	25,984	717	546
2 producers	28,866	24,730	2,300	1,886
3 producers	4,480	2,850	942	781
4 producers	2,500	1,408	669	586
5 or more producers	1,337	560	394	357
Total male producers	81,062	62,278	10,212	8,574
Farms by number of male producers:				
1 producer	49,919	45,658	1,519	1,229
2 producers	8,600	5,280	2,196	1,811
3 producers	2,596	1,357	741	640
4 producers	766	278	301	254
5 or more producers	459	137	149	132
Total female producers	37,193	30,799	3,080	2,661
Farms by number of female producers:				
1 producer	29,936	26,610	1,319	1,129
2 producers	2,374	1,490	554	492
3 producers	466	251	107	88
4 producers	138	65	46	34
5 or more producers	90	33	26	26
PRODUCERS' CHARACTERISTICS [3]				
Sex of producers:				
Male	79,245	61,694	9,782	8,181
Female	35,623	30,172	2,613	2,252
Hired managers	6,902	2,274	1,545	1,446
Primary occupation:				
Farming	51,122	39,312	6,305	5,415
Other	63,746	52,554	6,090	5,018
Place of residence:				
On farm operated	79,195	67,973	5,873	4,864
Not on farm operated	35,673	23,893	6,522	5,569
Days of work off farm:				
None	46,862	35,825	5,785	4,922
Any	68,006	56,041	6,610	5,511
1 to 49 days	9,840	7,913	1,005	848
50 to 99 days	4,745	3,938	425	380
100 to 199 days	8,361	7,031	731	600
200 days or more	45,060	37,159	4,449	3,683
Years on present farm:				
2 years or less	4,867	3,836	538	395
3 or 4 years	7,650	6,040	958	873
5 to 9 years	18,524	14,804	2,165	1,928
10 years or more	83,827	67,186	8,734	7,237
Average years on present farm	24.2	24.5	22.3	21.7
Years operating any farm:				
5 years or less	13,846	11,048	1,599	1,342
6 to 10 years	15,740	12,803	1,625	1,450
11 years or more	85,282	68,015	9,171	7,641
Average years on any farm	26.1	26.2	25.1	24.7
Age group:				
Under 25 years	1,900	1,560	154	132
25 to 34 years	9,374	7,421	1,104	969
35 to 44 years	16,237	12,666	2,015	1,813
45 to 54 years	16,743	13,418	1,878	1,621
55 to 64 years	29,818	23,814	3,169	2,590
65 to 74 years	27,187	21,692	2,906	2,391
75 years and over	13,609	11,295	1,169	917
Average age	57.1	57.2	56.0	55.4
Young producers (see text)	11,274	8,981	1,258	1,101
Producers of Hispanic, Latino, or Spanish origin	754	619	87	59
Producers by race:				
American Indian or Alaska Native	244	185	10	8
Asian	306	260	14	14
Black or African American	61	47	14	12
Native Hawaiian or Other Pacific Islander	43	39	1	1
White	113,864	91,036	12,345	10,387
More than one race reported	350	299	11	11

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
OWNED AND RENTED LAND - Con.						
Land rented or leased to others ..... farms	827	734	717	93	80	555
acres	206,886	187,969	182,420	18,917	13,628	115,893
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS						
Total producers	9,391	8,141	7,941	1,250	869	2,496
Farms by number of producers:						
1 producer	1,115	934	924	181	156	532
2 producers	1,423	1,320	1,317	103	97	413
3 producers	585	540	533	45	43	103
4 producers	364	327	325	37	28	59
5 or more producers	316	254	242	62	37	67
Total male producers	6,943	5,889	5,755	1,054	693	1,629
Farms by number of male producers:						
1 producer	1,986	1,761	1,749	225	201	756
2 producers	971	891	891	80	72	153
3 producers	442	411	400	31	27	56
4 producers	163	144	143	19	13	24
5 or more producers	141	87	78	54	31	32
Total female producers	2,447	2,251	2,185	196	176	867
Farms by number of female producers:						
1 producer	1,446	1,335	1,323	111	105	561
2 producers	262	239	239	23	19	68
3 producers	85	76	74	9	7	23
4 producers	19	16	16	3	3	8
5 or more producers	20	20	16	-	-	11
PRODUCERS' CHARACTERISTICS [3]						
Sex of producers:						
Male	6,370	5,613	5,537	757	593	1,399
Female	2,066	1,905	1,888	161	146	772
Hired managers	2,852	2,677	2,642	175	135	231
Primary occupation:						
Farming	4,793	4,489	4,445	304	269	712
Other	3,643	3,029	2,980	614	470	1,459
Place of residence:						
On farm operated	4,460	4,206	4,189	254	241	889
Not on farm operated	3,976	3,312	3,236	664	498	1,282
Days of work off farm:						
None	4,220	3,852	3,809	368	304	1,032
Any	4,216	3,666	3,616	550	435	1,139
1 to 49 days	741	704	687	37	36	181
50 to 99 days	311	297	292	14	14	71
100 to 199 days	506	446	444	60	59	93
200 days or more	2,658	2,219	2,193	439	326	794
Years on present farm:						
2 years or less	344	276	272	68	37	149
3 or 4 years	465	387	384	78	60	187
5 to 9 years	1,270	1,131	1,116	139	112	285
10 years or more	6,357	5,724	5,653	633	530	1,550
Average years on present farm	23.6	24.2	24.3	18.2	18.4	24.0
Years operating any farm:						
5 years or less	865	719	712	146	92	334
6 to 10 years	1,055	910	895	145	126	257
11 years or more	6,516	5,889	5,818	627	521	1,580
Average years on any farm	26.4	27.1	27.1	20.7	21.1	26.1
Age group:						
Under 25 years	147	144	144	3	3	39
25 to 34 years	719	632	631	87	67	130
35 to 44 years	1,380	1,236	1,207	144	129	176
45 to 54 years	1,238	1,107	1,092	131	105	209
55 to 64 years	2,287	1,978	1,964	309	247	548
65 to 74 years	1,985	1,801	1,781	184	141	604
75 years and over	680	620	606	60	47	465
Average age	55.6	55.6	55.6	55.9	55.4	62.0
Young producers (see text)	866	776	775	90	70	169
Producers of Hispanic, Latino, or Spanish origin	36	22	21	14	5	12
Producers by race:						
American Indian or Alaska Native	16	13	13	3	3	33
Asian	30	29	29	1	1	2
Black or African American	-	-	-	-	-	-
Native Hawaiian or Other Pacific Islander	3	-	-	3	3	-
White	8,359	7,450	7,357	909	730	2,124
More than one race reported	28	26	26	2	2	12

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
PRODUCERS' CHARACTERISTICS [3] - Con.				
Military service:				
Never served or only on active duty for training in the Reserves or National Guard (see text)	105,603	84,133	11,557	9,771
Active duty now or in the past (see text)	9,265	7,733	838	662
Number of persons living in producers' households	228,210	177,539	28,146	24,086
On farm involvement in decisionmaking:				
Day-to-day decisions	98,292	79,521	10,160	8,559
Land use and/or crop decisions	83,860	67,441	9,146	7,719
Livestock decisions	49,585	41,459	4,478	3,723
Marketing decisions (see text)	68,020	54,644	7,383	6,205
Record keeping and/or financial management	84,043	67,888	8,623	7,213
Estate planning or succession planning	64,079	51,473	6,453	5,471
FARMS BY TYPE OF ORGANIZATION				
Operation more than 50 percent owned by one producer's household and/or extended family — farms	62,111	55,532	3,213	2,756
Operation more than 50 percent owned by one producer's household and/or extended family — acres	22,990,670	17,410,756	2,985,794	2,665,267
Limited Liability Company — farms	4,803	2,747	2,012	1,950
Limited Liability Company — acres	2,179,815	876,257	1,290,512	1,227,263
LEGAL STATUS FOR TAX PURPOSES				
Family or individual — farms	55,532	55,532	-	-
Family or individual — acres	17,410,756	17,410,756	-	-
Partnership — farms	5,022	-	5,022	4,156
Partnership — acres	4,452,974	-	4,452,974	3,904,476
Registered under State law — farms	4,156	-	4,156	4,156
Registered under State law — acres	3,904,476	-	3,904,476	3,904,476
Corporation — farms	3,803	-	-	-
Corporation — acres	3,244,861	-	-	-
Family held — farms	3,375	-	-	-
Family held — acres	3,085,380	-	-	-
More than 10 stockholders — farms	34	-	-	-
10 or less stockholders — farms	3,341	-	-	-
Other than family held — farms	428	-	-	-
Other than family held — acres	159,481	-	-	-
More than 10 stockholders — farms	67	-	-	-
10 or less stockholders — farms	361	-	-	-
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	1,174	-	-	-
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — acres	334,034	-	-	-
HIRED FARM LABOR				
Hired farm labor — farms	17,399	12,648	2,175	1,881
Hired farm labor — workers	72,097	39,462	13,448	12,415
Workers by days worked:				
150 days or more — farms	9,054	5,676	1,449	1,297
150 days or more — workers	30,983	14,009	6,867	6,442
Less than 150 days — farms	12,949	9,598	1,565	1,345
Less than 150 days — workers	41,114	25,453	6,581	5,973
Migrant farm labor on farms with hired labor — farms	573	237	170	166
Migrant farm labor on farms reporting only contract labor — farms	41	34	5	5
Unpaid workers — farms	17,519	15,257	1,189	994
Unpaid workers — workers	40,333	34,126	3,448	2,937
FARMS BY SIZE				
1 to 9 acres	4,401	3,795	252	214
10 to 49 acres	15,218	13,808	610	494
50 to 69 acres	3,598	3,194	190	162
70 to 99 acres	5,575	4,933	303	231
100 to 139 acres	4,857	4,311	270	205
140 to 179 acres	4,814	4,196	349	262
180 to 219 acres	2,981	2,632	193	166
220 to 259 acres	2,503	2,188	167	129
260 to 499 acres	8,699	7,449	713	579
500 to 999 acres	6,421	5,030	704	595
1,000 to 1,999 acres	3,752	2,543	558	490
2,000 acres or more	2,712	1,453	713	629
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)				
Oilseed and grain farming (1111)	26,315	21,970	2,344	1,923
Vegetable and melon farming (1112)	1,072	890	75	61
Fruit and tree nut farming (1113)	972	754	97	91
Greenhouse, nursery, and floriculture production (1114)	971	630	112	110
Other crop farming (1119)	18,104	15,551	1,270	1,008
Tobacco farming (11191)	-	-	-	-
Cotton farming (11192)	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	18,104	15,551	1,270	1,008
Beef cattle ranching and farming (112111)	6,753	6,290	269	176
Cattle feedlots (112112)	892	734	73	69
Dairy cattle and milk production (11212)	1,713	1,136	340	311

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
PRODUCERS' CHARACTERISTICS [3] - Con.						
Military service:						
Never served or only on active duty for training in the Reserves or National Guard (see text)	7,957	7,096	7,010	861	694	1,956
Active duty now or in the past (see text)	479	422	415	57	45	215
Number of persons living in producers' households	18,460	16,297	16,043	2,163	1,812	4,065
On farm involvement in decisionmaking:						
Day-to-day decisions	7,046	6,282	6,215	764	621	1,565
Land use and/or crop decisions	5,988	5,376	5,331	612	514	1,285
Livestock decisions	3,101	2,836	2,791	265	232	547
Marketing decisions (see text)	5,260	4,813	4,769	447	379	733
Record keeping and/or financial management	6,141	5,494	5,441	647	517	1,391
Estate planning or succession planning	4,941	4,581	4,535	360	294	1,212
FARMS BY TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	2,684	2,523	2,508	161	152	682
acres	2,422,936	2,345,136	2,333,677	77,800	69,121	171,184
Limited Liability Company — farms	-	-	-	-	-	44
acres	-	-	-	-	-	13,046
LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Partnership — farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Registered under State law — farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Corporation — farms	3,803	3,375	3,341	428	361	-
acres	3,244,861	3,085,380	3,068,248	159,481	132,032	-
Family held — farms	3,375	3,375	3,341	-	-	-
acres	3,085,380	3,085,380	3,068,248	-	-	-
More than 10 stockholders — farms	34	34	-	-	-	-
10 or less stockholders — farms	3,341	3,341	3,341	-	-	-
Other than family held — farms	428	-	-	428	361	-
acres	159,481	-	-	159,481	132,032	-
More than 10 stockholders — farms	67	-	-	67	-	-
10 or less stockholders — farms	361	-	-	361	361	-
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	-	-	-	-	-	1,174
acres	-	-	-	-	-	334,034
HIRED FARM LABOR						
Hired farm labor — farms	2,277	2,105	2,089	172	137	299
workers	17,869	15,798	15,356	2,071	1,383	1,318
Workers by days worked:						
150 days or more — farms	1,745	1,608	1,596	137	104	184
workers	9,405	8,302	7,934	1,103	667	702
Less than 150 days — farms	1,586	1,466	1,459	120	97	200
workers	8,464	7,496	7,422	968	716	616
Migrant farm labor on farms with hired labor — farms	149	124	120	25	21	17
Migrant farm labor on farms reporting only contract labor — farms	2	2	2	-	-	-
Unpaid workers — farms	830	765	762	65	63	243
workers	2,112	1,950	1,935	162	(D)	647
FARMS BY SIZE						
1 to 9 acres	274	231	224	43	40	80
10 to 49 acres	526	408	408	118	90	274
50 to 69 acres	123	97	93	26	21	91
70 to 99 acres	218	181	181	37	31	121
100 to 139 acres	170	143	142	27	26	106
140 to 179 acres	159	140	140	19	17	110
180 to 219 acres	90	77	76	13	12	66
220 to 259 acres	94	84	84	10	8	54
260 to 499 acres	398	337	331	61	58	139
500 to 999 acres	610	583	570	27	22	77
1,000 to 1,999 acres	609	577	576	32	23	42
2,000 acres or more	532	517	516	15	13	14
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)	1,677	1,588	1,578	89	87	324
Vegetable and melon farming (1112)	76	55	55	21	18	31
Fruit and tree nut farming (1113)	108	93	92	15	12	13
Greenhouse, nursery, and floriculture production (1114)	221	172	168	49	47	8
Other crop farming (1119)	669	529	517	140	107	614
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	669	529	517	140	107	614
Beef cattle ranching and farming (112111)	140	125	125	15	11	54
Cattle feedlots (112112)	85	80	80	5	5	-
Dairy cattle and milk production (11212)	225	218	218	7	5	12

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS) - Con.				
Hog and pig farming (1122)	1,855	1,324	244	224
Poultry and egg production (1123)	1,724	1,482	69	62
Sheep and goat farming (1124)	1,456	1,404	25	25
Aquaculture and other animal production (1125,1129)	3,704	3,367	104	96
FARM TYPOLOGY (SEE TEXT)				
Farms by typology group:				
Small family farms				
Gross cash farm income less than $150,000	41,924	39,207	1,323	1,057
Gross cash farm income $150,000 to $349,999	7,074	6,329	410	357
Midsize family farms				
Gross cash farm income $350,000 to $999,999	7,367	6,315	444	384
Large family farms				
Gross cash farm income $1,000,000 to $4,999,999	5,311	3,501	918	846
Gross cash farm income $5,000,000 or more	435	180	118	112
Non-family farms	3,420	-	1,809	1,400
OTHER FARM CHARACTERISTICS				
Farms reporting-				
Internet access	53,964	45,486	4,194	3,536
Dial-up	1,876	1,615	134	121
Broadband (DSL, cable, fiber optic) (see text)	33,399	27,921	2,705	2,301
Cellular data plan (see text)	32,121	27,010	2,547	2,166
Satellite	8,385	6,987	702	602
Don't know	2,877	2,404	235	175
Other	346	265	42	36
Farms by number of households sharing in net income of operation:				
1 household	52,287	47,275	1,837	1,510
2 households	9,039	6,215	1,904	1,530
3 households	2,321	1,182	693	596
4 households	1,024	495	323	278
5 or more households	860	365	265	242
LIVESTOCK				
Cattle and calves inventory ... farms	16,823	14,739	1,224	992
number	2,121,625	1,303,726	454,801	416,984
Farms with-				
1 to 9	3,446	3,294	84	45
10 to 49	6,556	6,144	224	156
50 to 99	2,582	2,337	163	122
100 to 199	1,927	1,578	216	185
200 to 499	1,348	953	257	219
500 or more	964	433	280	265
Cows and heifers that calved ... farms	13,439	11,811	987	801
number	824,165	516,620	177,389	163,548
Beef cows ... farms	11,691	10,634	656	498
number	364,629	289,565	50,568	40,403
Farms with-				
1 to 9	3,718	3,546	86	53
10 to 49	6,113	5,625	311	236
50 to 99	1,205	1,014	127	104
100 to 199	470	342	74	57
200 to 499	149	91	42	34
500 or more	36	16	16	14
Milk cows ... farms	2,185	1,509	408	367
number	459,536	227,055	126,821	123,145
Farms with-				
1 to 9	328	297	20	11
10 to 49	315	272	35	31
50 to 99	573	466	69	60
100 to 199	418	263	96	81
200 to 499	390	171	118	114
500 or more	161	40	70	70
Other cattle ... farms	14,574	12,624	1,151	953
number	1,297,460	787,106	277,412	253,436
Cattle and calves sold ... farms	14,649	12,669	1,191	980
number	1,599,910	931,064	308,772	279,776
$1,000	2,094,135	1,184,684	416,198	378,540
Calves weighing less than 500 pounds ... farms	4,938	4,145	479	402
number	345,069	184,979	64,708	61,954
Cattle weighing 500 pounds or more ... farms	13,933	11,991	1,168	965
number	1,254,841	746,085	244,064	217,822
Cattle on feed ... farms	2,685	2,074	369	332
number	636,782	349,511	138,574	131,414
Hogs and pigs inventory ... farms	2,928	2,208	335	306
number	8,873,776	4,603,587	2,185,421	2,096,275
Farms with-				
1 to 24	893	832	27	21
25 to 49	93	87	-	-
50 to 99	71	66	-	-
100 to 199	65	55	7	7

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS) - Con.						
Hog and pig farming (1122)	278	246	240	32	29	9
Poultry and egg production (1123)	163	133	133	30	16	10
Sheep and goat farming (1124)	19	18	18	1	-	8
Aquaculture and other animal production (1125,1129)	142	118	117	24	24	91
FARM TYPOLOGY (SEE TEXT)						
Farms by typology group:						
Small family farms						
Gross cash farm income less than $150,000	880	789	784	91	91	514
Gross cash farm income $150,000 to $349,999	251	236	230	15	13	84
Midsize family farms						
Gross cash farm income $350,000 to $999,999	552	532	531	20	19	56
Large family farms						
Gross cash farm income $1,000,000 to $4,999,999	868	846	846	22	22	24
Gross cash farm income $5,000,000 or more	133	120	117	13	7	4
Non-family farms	1,119	852	833	267	209	492
OTHER FARM CHARACTERISTICS						
Farms reporting-						
Internet access	3,408	3,086	3,053	322	286	876
Dial-up	98	82	82	16	15	29
Broadband (DSL, cable, fiber optic) (see text)	2,229	2,022	2,002	207	185	544
Cellular data plan (see text)	2,068	1,902	1,880	166	146	496
Satellite	582	543	540	39	35	114
Don't know	168	147	146	21	19	70
Other	34	32	32	2	2	5
Farms by number of households sharing in net income of operation:						
1 household	2,268	1,979	1,963	289	248	907
2 households	769	735	727	34	32	151
3 households	406	359	353	47	46	40
4 households	172	148	148	24	18	34
5 or more households	188	154	150	34	17	42
LIVESTOCK						
Cattle and calves inventory ....farms	722	683	683	39	33	138
number	347,721	340,368	340,368	7,353	5,736	15,377
Farms with-						
1 to 9	36	32	32	4	4	32
10 to 49	132	115	115	17	14	56
50 to 99	66	57	57	9	7	16
100 to 199	117	112	112	5	5	16
200 to 499	132	132	132	-	-	6
500 or more	239	235	235	4	3	12
Cows and heifers that calved ....farms	538	509	509	29	27	103
number	125,565	120,768	120,768	4,797	(D)	4,591
Beef cows ....farms	307	285	285	22	22	94
number	21,974	21,350	21,350	624	624	2,522
Farms with-						
1 to 9	60	56	56	4	4	26
10 to 49	121	108	108	13	13	56
50 to 99	59	54	54	5	5	5
100 to 199	47	47	47	-	-	7
200 to 499	16	16	16	-	-	-
500 or more	4	4	4	-	-	-
Milk cows ....farms	252	245	245	7	5	16
number	103,591	99,418	99,418	4,173	(D)	2,069
Farms with-						
1 to 9	7	7	7	-	-	4
10 to 49	8	8	8	-	-	-
50 to 99	31	28	28	3	2	7
100 to 199	57	57	57	-	-	2
200 to 499	99	98	98	1	1	2
500 or more	50	47	47	3	2	1
Other cattle ....farms	676	645	645	31	26	123
number	222,156	219,600	219,600	2,556	(D)	10,786
Cattle and calves sold ....farms	679	642	642	37	32	110
number	309,660	303,673	303,673	5,987	3,118	50,414
$1,000	457,746	452,162	452,162	5,584	3,226	35,506
Calves weighing less than 500 pounds ....farms	272	254	254	18	13	42
number	48,817	45,732	45,732	3,085	1,239	46,565
Cattle weighing 500 pounds or more ....farms	670	633	633	37	32	104
number	260,843	257,941	257,941	2,902	1,879	3,849
Cattle on feed ....farms	229	222	222	7	7	13
number	147,236	146,666	146,666	570	570	1,461
Hogs and pigs inventory .... farms	361	320	314	41	34	24
number	2,040,014	1,857,165	1,842,165	182,849	125,847	44,754
Farms with-						
1 to 24	27	21	21	6	3	7
25 to 49	6	5	5	1	1	-
50 to 99	3	3	3	-	-	2
100 to 199	2	2	2	-	-	1

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Family or individual	Partnership	
				Total	Registered under State law
LIVESTOCK - Con.					
Hogs and pigs inventory - Con.					
Farms with- - Con.					
200 to 499		116	97	12	10
500 or more		1,690	1,071	289	268
Hogs and pigs sold	farms	3,352	2,548	391	357
	number	28,535,462	15,534,477	6,587,467	6,335,899
	$1,000	4,666,832	2,547,614	1,092,752	1,045,089
Sheep and lambs inventory	farms	2,137	1,998	54	45
	number	109,592	99,504	4,787	4,660
Sheep and lambs sold	farms	1,500	1,399	45	41
	number	92,512	83,842	4,214	4,122
Total horses and ponies inventory	farms	6,988	6,518	189	161
	number	40,131	35,941	1,235	1,069
Total horses and ponies sold	farms	1,171	1,080	38	35
	number	4,403	3,952	132	113
Goats, all inventory	farms	2,326	2,179	69	61
	number	50,691	47,326	2,159	2,087
Goats, all sold	farms	1,215	1,152	34	30
	number	38,339	36,312	1,567	1,537
POULTRY					
Layers inventory	farms	6,146	5,718	176	136
	number	14,553,497	3,863,417	(D)	(D)
Farms with-					
1 to 399		6,045	5,645	168	128
400 to 3,199		36	31	1	1
3,200 to 9,999		8	8	-	-
10,000 to 19,999		24	21	2	2
20,000 to 49,999		4	1	2	2
50,000 to 99,999		5	2	1	1
100,000 or more		24	10	2	2
Pullets for laying flock replacement inventory	farms	723	666	16	12
	number	4,185,443	(D)	(D)	(D)
Layers sold	farms	664	604	19	15
	number	7,016,481	1,951,247	(D)	307,415
Pullets for laying flock replacement sold	farms	102	87	3	2
	number	8,319,040	(D)	(D)	(D)
Broilers and other meat-type chickens sold	farms	1,028	946	37	29
	number	41,793,592	34,304,344	2,284,362	(D)
Farms with-					
1 to 1,999		900	842	29	22
2,000 to 59,999		11	4	2	2
60,000 to 99,999		-	-	-	-
100,000 or more		117	100	6	5
Turkeys inventory	farms	623	482	50	48
	number	14,927,734	3,450,829	1,015,606	(D)
Turkeys sold	farms	379	250	39	39
	number	39,460,145	8,914,554	2,334,888	2,334,888
CROPS					
Barley for grain	farms	336	232	59	50
	acres	55,330	37,857	9,804	8,786
	bushels	4,011,381	2,743,482	640,331	574,667
Irrigated	farms	10	6	2	2
	acres	116	107	(D)	(D)
Farms by acres harvested:					
1 to 24 acres		72	49	14	12
25 to 99 acres		96	66	21	16
100 to 249 acres		94	67	10	10
250 to 499 acres		53	35	9	7
500 acres or more		21	15	5	5
Corn for grain	farms	24,697	20,177	2,460	2,079
	acres	7,732,455	5,084,023	1,525,155	1,357,657
	bushels	1,478,451,268	964,114,900	297,659,666	264,867,843
Irrigated	farms	1,341	929	239	217
	acres	302,897	168,954	79,764	76,861
Farms by acres harvested:					
1 to 24 acres		2,863	2,663	96	68
25 to 99 acres		6,867	6,138	438	331
100 to 249 acres		6,444	5,515	565	484
250 to 499 acres		4,136	3,208	438	367
500 acres or more		4,387	2,653	923	829
Corn for silage or greenchop	farms	2,768	1,986	454	405
	acres	313,974	148,850	93,689	86,846
	tons	6,334,518	2,864,533	1,954,068	1,815,878
Irrigated	farms	108	43	34	33
	acres	13,135	4,403	(D)	(D)
Farms by acres harvested:					
1 to 24 acres		848	771	42	39
25 to 99 acres		1,133	847	179	157

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
		Total	Family held		Other than family held		
			Total	10 or less stockholders	Total	10 or less stockholders	
LIVESTOCK - Con.							
Hogs and pigs inventory - Con.							
Farms with- - Con.							
200 to 499		7	4	4	3	3	-
500 or more		316	285	279	31	27	14
Hogs and pigs sold	farms	385	342	336	43	36	28
	number	6,280,341	5,653,808	5,619,608	626,533	438,361	133,177
	$1,000	1,006,207	918,814	905,614	87,393	78,786	20,259
Sheep and lambs inventory	farms	59	57	57	2	2	26
	number	(D)	3,618	3,618	(D)	(D)	(D)
Sheep and lambs sold	farms	38	36	36	2	2	18
	number	(D)	3,413	3,413	(D)	(D)	(D)
Total horses and ponies inventory	farms	199	176	176	23	22	82
	number	2,433	2,222	2,222	211	(D)	522
Total horses and ponies sold	farms	43	37	37	6	6	10
	number	288	280	280	8	8	31
Goats, all inventory	farms	63	61	61	2	1	15
	number	(D)	931	931	(D)	(D)	(D)
Goats, all sold	farms	25	25	25	-	-	4
	number	375	375	375	-	-	85
POULTRY							
Layers inventory	farms	206	179	179	27	27	46
	number	(D)	9,864,714	9,864,714	(D)	(D)	1,483
Farms with-							
1 to 399		186	162	162	24	24	46
400 to 3,199		4	3	3	1	1	-
3,200 to 9,999		-	-	-	-	-	-
10,000 to 19,999		1	1	1	-	-	-
20,000 to 49,999		1	-	-	1	1	-
50,000 to 99,999		2	2	2	-	-	-
100,000 or more		12	11	11	1	1	-
Pullets for laying flock replacement inventory	farms	32	31	31	1	1	9
	number	(D)	2,898,875	2,898,875	(D)	(D)	335
Layers sold	farms	40	36	36	4	4	1
	number	4,757,741	4,757,593	4,757,593	148	148	(D)
Pullets for laying flock replacement sold	farms	12	12	12	-	-	-
	number	4,847,603	4,847,603	4,847,603	-	-	-
Broilers and other meat-type chickens sold	farms	37	31	31	6	6	8
	number	5,203,911	5,195,411	5,195,411	8,500	8,500	975
Farms with-							
1 to 1,999		21	16	16	5	5	8
2,000 to 59,999		5	4	4	1	1	-
60,000 to 99,999		-	-	-	-	-	-
100,000 or more		11	11	11	-	-	-
Turkeys inventory	farms	86	66	66	20	7	5
	number	10,460,869	5,076,678	5,076,678	5,384,191	85,893	430
Turkeys sold	farms	85	65	65	20	7	5
	number	28,210,143	14,174,764	14,174,764	14,035,379	364,585	560
CROPS							
Barley for grain	farms	42	40	40	2	2	3
	acres	(D)	7,649	7,649	(D)	(D)	(D)
	bushels	(D)	626,925	626,925	(D)	(D)	(D)
Irrigated	farms	-	-	-	-	-	2
	acres	-	-	-	-	-	(D)
Farms by acres harvested:							
1 to 24 acres		6	4	4	2	2	3
25 to 99 acres		9	9	9	-	-	-
100 to 249 acres		17	17	17	-	-	-
250 to 499 acres		9	9	9	-	-	-
500 acres or more		1	1	1	-	-	-
Corn for grain	farms	1,802	1,731	1,726	71	67	258
	acres	1,078,083	1,048,863	1,047,445	29,220	(D)	45,194
	bushels	208,421,914	202,959,111	202,657,308	5,462,803	(D)	8,254,788
Irrigated	farms	156	146	145	10	10	17
	acres	51,034	49,783	(D)	1,251	1,251	3,145
Farms by acres harvested:							
1 to 24 acres		63	54	54	9	8	41
25 to 99 acres		195	174	173	21	21	96
100 to 249 acres		305	290	288	15	13	59
250 to 499 acres		451	441	440	10	10	39
500 acres or more		788	772	771	16	15	23
Corn for silage or greenchop	farms	310	296	295	14	13	18
	acres	68,633	65,809	(D)	2,824	(D)	2,802
	tons	1,462,037	1,399,710	(D)	62,327	(D)	53,880
Irrigated	farms	29	25	24	4	3	2
	acres	4,485	(D)	(D)	(D)	(D)	(D)
Farms by acres harvested:							
1 to 24 acres		32	29	29	3	3	3
25 to 99 acres		98	92	92	6	5	9

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Family or individual	Partnership	
				Total	Registered under State law
CROPS - Con.					
Corn for silage or greenchop - Con.					
Farms by acres harvested: - Con.					
100 to 249 acres		452	245	116	101
250 to 499 acres		218	87	67	58
500 acres or more		117	36	50	50
Dry edible beans, excluding chickpeas and limas	farms	573	370	109	103
	acres	210,162	(D)	51,990	49,430
	cwt	5,278,245	3,116,158	1,169,520	1,068,723
Irrigated	farms	95	50	25	24
	acres	39,931	18,793	(D)	(D)
Farms by acres harvested:					
1 to 24 acres		34	27	4	4
25 to 99 acres		118	87	24	24
100 to 249 acres		146	103	25	23
250 to 499 acres		140	88	18	16
500 acres or more		135	65	38	36
Oats for grain	farms	2,329	1,874	280	220
	acres	126,011	91,955	21,483	17,387
	bushels	9,470,546	6,652,066	1,745,553	1,427,654
Irrigated	farms	66	51	2	2
	acres	3,194	2,283	(D)	(D)
Farms by acres harvested:					
1 to 24 acres		906	796	63	53
25 to 99 acres		1,097	849	156	121
100 to 249 acres		286	204	51	36
250 to 499 acres		29	20	6	6
500 acres or more		11	5	4	4
Sorghum for grain	farms	12	10	1	1
	acres	364	(D)	(D)	(D)
	bushels	24,260	(D)	(D)	(D)
Irrigated	farms	-	-	-	-
	acres	-	-	-	-
Farms by acres harvested:					
1 to 24 acres		7	7	-	-
25 to 99 acres		4	3	-	-
100 to 249 acres		1	-	1	1
250 to 499 acres		-	-	-	-
500 acres or more		-	-	-	-
Soybeans for beans	farms	25,337	20,644	2,506	2,080
	acres	7,597,171	5,174,663	1,373,595	1,205,519
	bushels	373,669,175	252,782,550	68,836,256	60,668,980
Irrigated	farms	892	666	118	109
	acres	122,734	79,905	18,427	17,461
Farms by acres harvested:					
1 to 24 acres		2,307	2,090	95	60
25 to 99 acres		7,345	6,534	479	354
100 to 249 acres		6,879	5,817	611	513
250 to 499 acres		4,297	3,374	428	373
500 acres or more		4,509	2,829	893	780
Sugarbeets for sugar	farms	1,106	645	210	185
	acres	446,627	200,621	133,594	120,479
	tons	11,642,041	5,168,550	3,510,034	3,171,995
Irrigated	farms	31	17	13	12
	acres	10,798	6,036	(D)	4,714
Sunflower seed, all	farms	221	158	22	19
	acres	66,924	40,982	11,827	9,835
	pounds	151,726,117	90,770,820	28,490,961	23,382,801
Irrigated	farms	2	2	-	-
	acres	(D)	(D)	-	-
Farms by acres harvested:					
1 to 24 acres		8	7	-	-
25 to 99 acres		53	45	3	3
100 to 249 acres		62	44	1	1
250 to 499 acres		49	34	8	6
500 acres or more		49	28	10	9
Wheat for grain, all	farms	3,669	2,767	465	401
	acres	1,268,681	779,628	270,961	245,008
	bushels	82,039,945	49,049,902	18,289,562	16,805,410
Irrigated	farms	52	36	7	6
	acres	6,251	4,385	850	(D)
Farms by acres harvested:					
1 to 24 acres		416	343	33	24
25 to 99 acres		1,023	825	119	101
100 to 249 acres		809	675	66	55
250 to 499 acres		544	410	65	52
500 acres or more		877	514	182	169
Forage-land used for all hay and haylage, grass silage, and greenchop	farms	23,394	20,683	1,565	1,289
	acres	1,392,072	1,068,754	200,619	165,609
	tons, dry equivalent	3,565,994	2,475,470	661,172	588,884
Irrigated	farms	675	497	119	108
	acres	32,954	18,816	9,218	8,566
Farms by acres harvested:					
1 to 24 acres		11,106	10,276	437	351
25 to 99 acres		8,179	7,335	481	395

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
CROPS - Con.						
Corn for silage or greenchop - Con.						
Farms by acres harvested: - Con.						
100 to 249 acres	86	84	84	2	2	5
250 to 499 acres	64	63	62	1	1	-
500 acres or more	30	28	28	2	2	1
Dry edible beans, excluding chickpeas and limas ..... farms	90	87	86	3	3	4
acres	38,527	37,762	(D)	765	765	(D)
cwt	946,189	922,837	(D)	23,352	23,352	46,378
Irrigated ..... farms	17	17	16	-	-	3
acres	8,700	8,700	(D)	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	2	2	2	-	-	1
25 to 99 acres	7	7	7	-	-	-
100 to 249 acres	18	18	18	-	-	-
250 to 499 acres	34	31	31	3	3	-
500 acres or more	29	29	28	-	-	3
Oats for grain ..... farms	146	138	138	8	8	29
acres	11,282	10,970	10,970	312	312	1,291
bushels	972,843	948,848	948,848	23,995	23,995	100,084
Irrigated ..... farms	9	9	9	-	-	4
acres	455	455	455	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	33	32	32	1	1	14
25 to 99 acres	86	79	79	7	7	6
100 to 249 acres	22	22	22	-	-	9
250 to 499 acres	3	3	3	-	-	-
500 acres or more	2	2	2	-	-	-
Sorghum for grain ..... farms	1	1	1	-	-	-
acres	(D)	(D)	(D)	-	-	-
bushels	(D)	(D)	(D)	-	-	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	1	1	1	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-
Soybeans for beans ..... farms	1,908	1,823	1,814	85	81	279
acres	1,003,929	967,706	965,674	36,223	33,931	44,984
bushels	49,917,979	48,230,926	48,170,530	1,687,053	(D)	2,132,390
Irrigated ..... farms	97	92	92	5	5	11
acres	(D)	20,923	20,923	(D)	(D)	(D)
Farms by acres harvested:						
1 to 24 acres	67	46	46	21	20	55
25 to 99 acres	228	220	219	8	8	104
100 to 249 acres	383	364	357	19	19	68
250 to 499 acres	464	450	449	14	12	31
500 acres or more	766	743	743	23	22	21
Sugarbeets for sugar ..... farms	248	245	245	3	3	3
acres	111,558	108,599	108,599	2,959	2,959	854
tons	2,939,308	2,859,493	2,859,493	79,815	79,815	24,149
Irrigated ..... farms	1	1	1	-	-	-
acres	(D)	(D)	(D)	-	-	-
Sunflower seed, all ..... farms	39	38	38	1	1	2
acres	(D)	13,615	13,615	(D)	(D)	(D)
pounds	(D)	(D)	(D)	(D)	(D)	(D)
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	1
25 to 99 acres	4	4	4	-	-	1
100 to 249 acres	17	17	17	-	-	-
250 to 499 acres	7	6	6	1	1	-
500 acres or more	11	11	11	-	-	-
Wheat for grain, all ..... farms	412	393	392	19	17	25
acres	216,015	212,370	(D)	3,645	(D)	2,077
bushels	14,565,510	14,284,241	(D)	281,269	(D)	134,971
Irrigated ..... farms	5	5	5	-	-	4
acres	989	989	989	-	-	27
Farms by acres harvested:						
1 to 24 acres	28	19	19	9	9	12
25 to 99 acres	70	65	64	5	3	9
100 to 249 acres	66	64	64	2	2	2
250 to 499 acres	68	68	68	-	-	1
500 acres or more	180	177	177	3	3	1
Forage-land used for all hay and haylage, grass silage, and greenchop ..... farms	874	801	797	73	61	272
acres	107,953	102,223	101,736	5,730	5,368	14,746
tons, dry equivalent	392,186	377,664	376,380	14,522	14,042	37,166
Irrigated ..... farms	49	45	44	4	3	10
acres	4,587	(D)	(D)	(D)	(D)	333
Farms by acres harvested:						
1 to 24 acres	254	224	224	30	21	139
25 to 99 acres	274	251	249	23	22	89

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Family or individual	Partnership	
				Total	Registered under State law
CROPS - Con.					
Forage-land used for all hay and haylage, grass silage, and greenchop - Con.					
Farms by acres harvested: - Con.					
100 to 249 acres		3,115	2,426	438	371
250 to 499 acres		780	547	130	112
500 acres or more		214	99	79	60
Alfalfa hay	farms	15,333	13,540	1,072	863
	acres	744,117	595,862	94,324	78,129
	tons, dry	1,971,568	1,500,176	302,292	263,171
Irrigated	farms	421	320	66	56
	acres	15,949	10,657	3,283	2,799
Other dry hay	farms	8,556	7,656	518	411
	acres	390,421	323,145	41,557	26,410
	tons, dry	658,360	510,013	82,753	61,335
Irrigated	farms	153	124	18	17
	acres	3,658	2,977	312	(D)
Field and grass seed crops, all	farms	155	97	19	16
	acres	66,601	31,116	15,036	14,527
Irrigated	farms	6	5	-	-
	acres	505	(D)	-	-
Land in vegetables	farms	2,620	2,024	265	232
	acres	196,718	101,692	38,729	36,663
Irrigated	farms	764	555	87	80
	acres	54,640	20,554	12,242	(D)
Farms by acres harvested:					
0.1 to 4.9 acres		1,355	1,136	80	69
5.0 to 24.9 acres		225	185	18	14
25.0 to 99.9 acres		495	378	64	53
100.0 to 249.9 acres		364	233	72	66
250.0 acres or more		181	92	31	30
Beans, snap	farms	390	279	40	39
	acres	2,553	1,112	1,331	(D)
Harvested for processing	farms	22	15	6	6
	acres	2,278	(D)	1,234	1,234
Peas, green	farms	599	428	90	81
	acres	47,364	28,003	11,174	10,425
Harvested for processing	farms	491	337	82	74
	acres	47,345	27,989	11,172	10,423
Potatoes	farms	509	386	45	35
	acres	49,008	10,907	9,617	9,262
Harvested for processing	farms	39	14	5	5
	acres	35,127	7,127	4,905	4,905
Farms by acres harvested:					
0.1 to 4.9 acres		421	349	24	18
5.0 to 24.9 acres		5	3	-	-
25.0 to 99.9 acres		20	10	8	4
100.0 to 249.9 acres		8	5	1	1
250.0 acres or more		55	19	12	12
Sweet corn (see text)	farms	1,243	950	147	131
	acres	96,990	62,596	17,555	16,583
Harvested for processing	farms	750	540	111	100
	acres	94,536	61,473	17,035	16,087
Sweet potatoes	farms	58	40	10	10
	acres	23	10	1	1
Harvested for processing	farms	-	-	-	-
	acres	-	-	-	-
Tomatoes in the open	farms	592	471	42	35
	acres	300	232	15	14
Harvested for processing	farms	18	17	-	-
	acres	2	(D)	-	-
Land in orchards	farms	1,174	927	99	91
	acres	5,049	2,688	878	809
Irrigated	farms	204	141	26	26
	acres	778	354	147	147
Farms by bearing and nonbearing acres:					
0.1 to 4.9 acres		927	783	54	50
5.0 to 24.9 acres		212	133	37	35
25.0 to 99.9 acres		32	11	7	5
100.0 to 249.9 acres		3	-	1	1
250.0 acres or more		-	-	-	-
Apples	farms	751	588	60	55
	bearing and nonbearing acres	3,219	1,611	621	555
Grapes (including muscadine) (see text)	farms	433	332	48	46
	bearing and nonbearing acres	1,290	722	(D)	(D)
Peaches, all	farms	17	17	-	-
	bearing and nonbearing acres	(D)	(D)	-	-
Walnuts, English	farms	29	18	3	-
	bearing and nonbearing acres	142	75	1	-

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
CROPS - Con.						
Forage-land used for all hay and haylage, grass silage, and greenchop - Con.						
Farms by acres harvested: - Con.						
100 to 249 acres	216	202	201	14	12	35
250 to 499 acres	97	92	91	5	5	6
500 acres or more	33	32	32	1	1	3
Alfalfa hay ... farms	555	507	505	48	47	166
acres	46,322	43,932	(D)	2,390	(D)	7,609
tons, dry	143,904	136,959	(D)	6,945	(D)	25,196
Irrigated ... farms	29	28	27	1	1	6
acres	1,828	(D)	(D)	(D)	(D)	181
Other dry hay ... farms	288	265	262	23	18	94
acres	20,339	18,353	18,152	1,986	1,926	5,380
tons, dry	57,460	53,666	53,305	3,794	3,665	8,134
Irrigated ... farms	6	6	5	-	-	5
acres	308	308	(D)	-	-	61
Field and grass seed crops, all ... farms	39	38	38	1	1	-
acres	20,449	(D)	(D)	(D)	(D)	-
Irrigated ... farms	1	1	1	-	-	-
acres	(D)	(D)	(D)	-	-	-
Land in vegetables ... farms	272	234	232	38	35	59
acres	54,906	48,148	(D)	6,759	3,053	1,390
Irrigated ... farms	96	79	78	17	15	26
acres	21,752	18,326	(D)	3,425	(D)	92
Farms by acres harvested:						
0.1 to 4.9 acres	100	83	82	17	17	39
5.0 to 24.9 acres	11	5	5	6	6	11
25.0 to 99.9 acres	50	47	47	3	3	3
100.0 to 249.9 acres	55	50	50	5	5	4
250.0 acres or more	56	49	48	7	4	2
Beans, snap ... farms	56	42	42	14	14	15
acres	104	98	98	7	7	6
Harvested for processing ... farms	1	-	-	1	1	-
acres	(D)	-	-	(D)	(D)	-
Peas, green ... farms	71	70	69	1	1	10
acres	7,841	(D)	(D)	(D)	(D)	346
Harvested for processing ... farms	66	66	65	-	-	6
acres	7,839	7,839	(D)	-	-	345
Potatoes ... farms	58	49	48	9	7	20
acres	28,469	(D)	24,854	(D)	(D)	15
Harvested for processing ... farms	20	18	17	2	-	-
acres	23,095	(D)	(D)	(D)	-	-
Farms by acres harvested:						
0.1 to 4.9 acres	29	23	23	6	6	19
5.0 to 24.9 acres	1	1	1	-	-	1
25.0 to 99.9 acres	2	1	1	1	1	-
100.0 to 249.9 acres	2	2	2	-	-	-
250.0 acres or more	24	22	21	2	-	-
Sweet corn (see text) ... farms	126	112	112	14	13	20
acres	15,937	13,783	13,783	2,154	(D)	902
Harvested for processing ... farms	93	85	85	8	7	6
acres	15,136	13,166	13,166	1,970	(D)	893
Sweet potatoes ... farms	3	2	2	1	1	5
acres	(D)	(D)	(D)	(D)	(D)	(D)
Harvested for processing ... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Tomatoes in the open ... farms	57	43	43	14	14	22
acres	46	39	39	7	7	7
Harvested for processing ... farms	-	-	-	-	-	1
acres	-	-	-	-	-	(D)
Land in orchards ... farms	124	107	106	17	14	24
acres	1,296	1,073	(D)	223	184	186
Irrigated ... farms	32	29	29	3	-	5
acres	263	233	233	30	-	15
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	71	61	60	10	10	19
5.0 to 24.9 acres	39	33	33	6	3	3
25.0 to 99.9 acres	12	12	12	-	-	2
100.0 to 249.9 acres	2	1	1	1	1	-
250.0 acres or more	-	-	-	-	-	-
Apples ... farms	82	69	69	13	13	21
bearing and nonbearing acres	892	735	735	158	158	95
Grapes (including muscadine) (see text) ... farms	50	43	43	7	4	3
bearing and nonbearing acres	281	222	222	59	20	(D)
Peaches, all ... farms	-	-	-	-	-	-
bearing and nonbearing acres	-	-	-	-	-	-
Walnuts, English ... farms	8	8	7	-	-	-
bearing and nonbearing acres	66	66	(D)	-	-	-

See footnote(s) at end of table.

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Table 74. **Summary by Legal Status For Tax Purposes: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Family or individual	Partnership	
			Total	Registered under State law
CROPS - Con.				
Land in berries ..... farms	578	449	40	37
acres	1,129	685	(D)	(D)

Item	Corporation					Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.
	Total	Family held		Other than family held		
		Total	10 or less stockholders	Total	10 or less stockholders	
CROPS - Con.						
Land in berries ..... farms	75	65	64	10	10	14
acres	273	264	(D)	9	9	(D)

[1] Landlord production expenses are included with total farm production expenses.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.
[3] Data were collected for a maximum of four producers per farm.

Table 75. **Summary by North American Industry Classification System: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
						Total	Tobacco farming (11191)
FARMS AND LAND IN FARMS							
Farms ..... number	65,531	26,315	1,072	972	971	18,104	-
percent	100.0	40.2	1.6	1.5	1.5	27.6	-
Land in farms ..... acres	25,442,625	18,449,252	174,341	89,074	73,678	2,830,168	-
Average size of farm ..... acres	388	701	163	92	76	156	-
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS							
Total ..... farms	65,531	26,315	1,072	972	971	18,104	-
$1,000	29,066,202	15,490,079	342,302	42,970	396,421	647,696	-
Average per farm ..... dollars	443,549	588,641	319,311	44,208	408,260	35,776	-
Farms by economic class:							
Less than $1,000	6,079	60	27	164	113	2,151	-
$1,000 to $2,499	6,033	232	73	69	53	3,957	-
$2,500 to $4,999	5,681	538	101	85	70	3,405	-
$5,000 to $9,999	6,141	888	148	172	85	3,144	-
$10,000 to $24,999	7,125	1,678	229	219	176	2,716	-
$25,000 to $49,999	4,813	1,941	158	91	127	1,230	-
$50,000 to $99,999	5,488	3,393	105	85	90	776	-
$100,000 to $249,999	6,899	5,327	95	54	85	417	-
$250,000 to $499,999	5,477	4,450	47	22	66	122	-
$500,000 to $999,999	4,529	3,517	20	6	41	76	-
$1,000,000 or more	7,266	4,291	69	5	65	110	-
$1,000,000 to $2,499,999	4,148	2,674	32	4	35	53	-
$2,500,000 to $4,999,999	2,458	1,439	19	1	17	50	-
$5,000,000 or more	660	178	18	-	13	7	-
Total sales ..... farms	65,531	26,315	1,072	972	971	18,104	-
$1,000	28,482,097	15,109,533	338,324	41,845	395,981	542,930	-
Grains, oilseeds, dry beans, and dry peas ..... farms	32,075	26,313	199	33	35	1,117	-
$1,000	15,268,581	13,686,342	39,283	343	1,812	160,530	-
Sales of $50,000 or more ..... farms	23,618	20,399	91	1	5	327	-
$1,000	15,113,786	13,568,708	38,126	(D)	(D)	151,050	-
Corn ..... farms	25,230	20,569	114	19	20	659	-
$1,000	9,045,595	7,991,772	21,895	132	842	61,114	-
Sales of $50,000 or more ..... farms	18,777	16,075	57	1	3	154	-
$1,000	8,908,714	7,887,178	21,150	(D)	(D)	53,921	-
Wheat ..... farms	3,668	3,253	19	2	2	183	-
$1,000	735,504	692,413	(D)	(D)	(D)	35,306	-
Sales of $50,000 or more ..... farms	2,125	1,984	8	-	1	107	-
$1,000	707,000	668,062	(D)	-	(D)	34,319	-
Soybeans ..... farms	25,334	22,128	129	13	20	486	-
$1,000	5,087,514	4,636,986	13,812	196	889	50,965	-
Sales of $50,000 or more ..... farms	17,131	15,254	69	-	3	175	-
$1,000	4,898,487	4,473,736	12,800	-	614	46,336	-
Sorghum ..... farms	53	37	-	1	-	5	-
$1,000	437	314	-	(D)	-	(D)	-
Sales of $50,000 or more ..... farms	1	1	-	-	-	-	-
$1,000	(D)	(D)	-	-	-	-	-
Barley ..... farms	336	228	1	1	-	37	-
$1,000	27,673	25,036	(D)	(D)	-	(D)	-
Sales of $50,000 or more ..... farms	151	139	-	-	-	10	-
$1,000	24,984	23,403	-	-	-	(D)	-
Rice ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	3,613	2,516	37	8	4	331	-
$1,000	371,859	339,821	1,849	(D)	(D)	(D)	-
Sales of $50,000 or more ..... farms	1,013	924	3	-	-	43	-
$1,000	342,531	319,232	1,528	-	-	9,337	-
Tobacco ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	2,648	776	1,072	141	177	209	-
$1,000	446,099	122,500	288,702	1,049	3,989	13,354	-
Sales of $50,000 or more ..... farms	994	549	306	3	13	36	-
$1,000	424,789	116,608	278,690	201	2,681	11,885	-
Fruits, tree nuts, and berries ..... farms	1,212	34	137	828	34	115	-
$1,000	48,717	1,388	3,118	39,216	217	4,495	-
Sales of $50,000 or more ..... farms	178	3	7	162	1	5	-
$1,000	38,977	(D)	2,539	31,714	(D)	(D)	-
Fruits and tree nuts ..... farms	944	30	79	685	20	84	-
$1,000	30,052	330	394	28,174	114	898	-
Sales of $50,000 or more ..... farms	116	-	2	111	1	2	-
$1,000	22,967	-	(D)	22,371	(D)	(D)	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
FARMS AND LAND IN FARMS									
Farms ..... number	-	18,104	6,753	892	1,713	1,855	1,724	1,456	3,704
percent	-	27.6	10.3	1.4	2.6	2.8	2.6	2.2	5.7
Land in farms ..... acres	-	2,830,168	1,197,691	352,949	1,021,298	682,599	166,005	59,864	345,706
Average size of farm ..... acres	-	156	177	396	596	368	96	41	93
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS									
Total ..... farms	-	18,104	6,753	892	1,713	1,855	1,724	1,456	3,704
$1,000	-	647,696	634,041	1,092,833	3,087,336	4,950,288	1,980,304	25,770	376,162
Average per farm ..... dollars	-	35,776	93,890	1,225,149	1,802,298	2,668,619	1,148,668	17,699	101,556
Farms by economic class:									
Less than $1,000	-	2,151	1,096	-	29	13	78	423	1,925
$1,000 to $2,499	-	3,957	379	-	-	75	707	244	244
$2,500 to $4,999	-	3,405	593	2	-	65	297	252	273
$5,000 to $9,999	-	3,144	966	3	1	60	121	194	359
$10,000 to $24,999	-	2,716	1,367	47	2	36	78	182	395
$25,000 to $49,999	-	1,230	890	115	10	4	16	71	160
$50,000 to $99,999	-	776	695	122	63	10	16	44	89
$100,000 to $249,999	-	417	434	131	137	33	31	25	130
$250,000 to $499,999	-	122	125	108	343	86	41	12	55
$500,000 to $999,999	-	76	81	92	416	193	44	9	34
$1,000,000 or more	-	110	127	272	712	1,280	295	-	40
$1,000,000 to $2,499,999	-	53	67	129	414	623	110	-	7
$2,500,000 to $4,999,999	-	50	51	99	209	461	97	-	15
$5,000,000 or more	-	7	9	44	89	196	88	-	18
Total sales ..... farms	-	18,104	6,753	892	1,713	1,855	1,724	1,456	3,704
$1,000	-	542,930	614,644	1,084,763	3,053,532	4,930,446	1,975,640	25,104	369,352
Grains, oilseeds, dry beans, and dry peas ..... farms	-	1,117	1,037	576	1,367	955	194	70	179
$1,000	-	160,530	110,381	224,133	303,385	591,043	61,904	1,205	88,220
Sales of $50,000 or more ..... farms	-	327	332	420	980	877	118	5	63
$1,000	-	151,050	101,064	221,077	294,302	589,631	60,701	583	86,945
Corn ..... farms	-	659	803	545	1,276	879	158	52	136
$1,000	-	61,114	77,139	173,426	214,738	397,059	41,542	772	65,163
Sales of $50,000 or more ..... farms	-	154	262	401	854	810	105	4	51
$1,000	-	53,921	69,609	170,554	204,923	395,489	40,620	412	64,112
Wheat ..... farms	-	183	50	20	96	19	6	3	15
$1,000	-	35,306	1,384	(D)	2,670	512	(D)	1	(D)
Sales of $50,000 or more ..... farms	-	107	9	-	11	2	2	-	1
$1,000	-	34,319	813	-	1,050	(D)	(D)	-	(D)
Soybeans ..... farms	-	486	414	343	732	829	133	23	84
$1,000	-	50,965	29,542	49,126	78,231	190,985	19,156	(D)	(D)
Sales of $50,000 or more ..... farms	-	175	147	225	431	722	68	1	36
$1,000	-	46,336	25,610	46,232	70,433	188,197	17,997	(D)	(D)
Sorghum ..... farms	-	5	5	2	1	1	-	-	1
$1,000	-	(D)	12	(D)	(D)	(D)	-	-	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Barley ..... farms	-	37	7	4	53	2	-	2	1
$1,000	-	(D)	17	77	(D)	(D)	-	(D)	(D)
Sales of $50,000 or more ..... farms	-	10	-	-	2	-	-	-	-
$1,000	-	(D)	-	-	(D)	-	-	-	-
Rice ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	-	331	220	79	307	36	17	24	34
$1,000	-	(D)	2,288	(D)	6,957	2,432	(D)	(D)	5,343
Sales of $50,000 or more ..... farms	-	43	5	3	17	14	1	-	3
$1,000	-	9,337	439	595	3,666	2,247	(D)	-	(D)
Tobacco ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	-	209	45	5	50	58	29	16	70
$1,000	-	13,354	882	374	5,024	9,035	274	245	673
Sales of $50,000 or more ..... farms	-	36	6	5	30	43	1	1	1
$1,000	-	11,885	624	374	4,535	8,761	(D)	(D)	(D)
Fruits, tree nuts, and berries ..... farms	-	115	14	2	1	6	16	4	21
$1,000	-	4,495	80	(D)	(D)	19	57	(D)	(D)
Sales of $50,000 or more ..... farms	-	5	-	-	-	-	-	-	-
$1,000	-	(D)	-	-	-	-	-	-	-
Fruits and tree nuts ..... farms	-	84	9	2	-	6	10	3	16
$1,000	-	898	28	(D)	-	(D)	34	3	56
Sales of $50,000 or more ..... farms	-	2	-	-	-	-	-	-	-
$1,000	-	(D)	-	-	-	-	-	-	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
							Total	Tobacco farming (11191)
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.								
Total - Con.								
Total sales - Con.								
Fruits, tree nuts, and berries - Con.								
Berries	farms	489	7	80	270	19	72	-
	$1,000	18,665	1,058	2,724	11,042	103	3,597	-
Sales of $50,000 or more	farms	66	3	4	55	-	4	-
	$1,000	15,470	(D)	(D)	8,901	-	(D)	-
Nursery, greenhouse, floriculture, and sod	farms	1,051	19	134	29	739	74	-
	$1,000	391,444	996	4,679	323	381,379	3,526	-
Sales of $50,000 or more	farms	343	4	11	1	314	10	-
	$1,000	381,613	(D)	3,311	(D)	374,345	2,803	-
Cultivated Christmas trees and short rotation woody crops	farms	244	9	2	15	178	27	-
	$1,000	7,578	5	(D)	(D)	7,478	(D)	-
Sales of $50,000 or more	farms	27	-	-	-	27	-	-
	$1,000	6,051	-	-	-	6,051	-	-
Cultivated Christmas trees	farms	243	9	2	15	177	27	-
	$1,000	(D)	5	(D)	(D)	(D)	(D)	-
Sales of $50,000 or more	farms	27	-	-	-	27	-	-
	$1,000	6,051	-	-	-	6,051	-	-
Short rotation woody crops	farms	1	-	-	-	1	-	-
	$1,000	(D)	-	-	-	(D)	-	-
Sales of $50,000 or more	farms	-	-	-	-	-	-	-
	$1,000	-	-	-	-	-	-	-
Other crops and hay	farms	16,722	5,509	171	97	93	7,554	-
	$1,000	981,348	613,454	1,197	243	292	300,717	-
Sales of $50,000 or more	farms	2,437	1,274	3	-	1	913	-
	$1,000	867,179	575,361	(D)	-	(D)	243,200	-
Maple syrup	farms	364	28	15	16	28	161	-
	$1,000	869	22	20	11	6	763	-
Sales of $50,000 or more	farms	3	-	-	-	-	3	-
	$1,000	191	-	-	-	-	191	-
Cattle and calves	farms	14,649	4,398	39	16	7	1,360	-
	$1,000	2,094,135	373,577	554	104	140	36,982	-
Sales of $50,000 or more	farms	4,609	1,533	2	-	1	138	-
	$1,000	1,933,030	319,098	(D)	-	(D)	21,490	-
Milk from cows	farms	1,893	114	-	-	1	30	-
	$1,000	2,504,638	41,239	-	-	(D)	(D)	-
Sales of $50,000 or more	farms	1,826	112	-	-	1	28	-
	$1,000	2,503,304	(D)	-	-	(D)	(D)	-
Hogs and pigs	farms	3,352	583	43	26	10	139	-
	$1,000	4,666,832	248,695	329	55	6	4,170	-
Sales of $50,000 or more	farms	2,034	330	2	-	-	6	-
	$1,000	4,660,288	245,977	(D)	-	-	(D)	-
Sheep, goats, wool, mohair, and milk	farms	2,604	365	26	25	17	221	-
	$1,000	33,457	6,599	67	19	95	612	-
Sales of $50,000 or more	farms	120	30	-	-	1	-	-
	$1,000	19,839	(D)	-	-	(D)	-	-
Horses, ponies, mules, burros, and donkeys	farms	1,247	109	2	7	8	55	-
	$1,000	18,147	1,041	(D)	(D)	(D)	203	-
Sales of $50,000 or more	farms	76	5	-	1	-	-	-
	$1,000	8,302	(D)	-	(D)	-	-	-
Poultry and eggs	farms	4,445	400	151	118	61	476	-
	$1,000	1,943,207	12,109	309	182	66	2,175	-
Sales of $50,000 or more	farms	447	7	-	-	-	3	-
	$1,000	1,935,336	(D)	-	-	-	(D)	-
Aquaculture	farms	98	6	-	-	3	3	-
	$1,000	19,763	3	-	-	(D)	(D)	-
Sales of $50,000 or more	farms	62	-	-	-	-	-	-
	$1,000	19,502	-	-	-	-	-	-
Other animals and other animal products	farms	1,405	89	71	62	21	155	-
	$1,000	58,149	1,587	80	(D)	(D)	333	-
Sales of $50,000 or more	farms	154	5	-	-	-	2	-
	$1,000	52,455	(D)	-	-	-	(D)	-
Value of-								
Government payments	farms	31,583	14,219	214	111	81	11,711	-
	$1,000	584,106	380,546	3,978	1,125	439	104,766	-
Landlord's share of total sales	farms	1,294	1,023	4	-	3	85	-
	$1,000	118,307	100,357	272	-	45	1,039	-
FOOD MARKETING PRACTICES								
Value of food sold directly to-								
Consumers	farms	3,339	306	478	352	142	366	-
	$1,000	44,673	2,649	9,658	12,503	1,865	2,501	-
Retail markets, institutions, and food hubs for local or regionally branded products	farms	1,026	87	152	168	66	101	-
	$1,000	108,704	10,403	9,415	3,581	39,682	641	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.									
Total - Con.									
Total sales - Con.									
Fruits, tree nuts, and berries - Con.									
Berries ..... farms	-	72	11	-	1	2	9	2	16
$1,000	-	3,597	52	-	(D)	(D)	23	(D)	(D)
Sales of $50,000 or more ..... farms	-	4	-	-	-	-	-	-	-
$1,000	-	(D)	-	-	-	-	-	-	-
Nursery, greenhouse, floriculture, and sod ..... farms	-	74	5	-	2	2	13	3	31
$1,000	-	3,526	37	-	(D)	(D)	189	4	290
Sales of $50,000 or more ..... farms	-	10	-	-	-	-	2	-	1
$1,000	-	2,803	-	-	-	-	(D)	-	(D)
Cultivated Christmas trees and short rotation woody crops ..... farms	-	27	4	-	2	-	6	1	-
$1,000	-	(D)	(D)	-	(D)	-	(D)	(D)	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Cultivated Christmas trees ..... farms	-	27	4	-	2	-	6	1	-
$1,000	-	(D)	(D)	-	(D)	-	(D)	(D)	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Short rotation woody crops ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-	-	-
$1,000	-	-	-	-	-	-	-	-	-
Other crops and hay ..... farms	-	7,554	1,485	154	269	192	317	287	594
$1,000	-	300,717	20,210	2,367	25,516	5,156	2,371	775	9,050
Sales of $50,000 or more ..... farms	-	913	70	14	122	24	9	2	5
$1,000	-	243,200	9,326	(D)	23,332	4,422	1,406	(D)	8,020
Maple syrup ..... farms	-	161	30	2	4	-	43	12	25
$1,000	-	763	8	(D)	(D)	-	11	10	15
Sales of $50,000 or more ..... farms	-	3	-	-	-	-	-	-	-
$1,000	-	191	-	-	-	-	-	-	-
Cattle and calves ..... farms	-	1,360	5,628	892	1,668	143	108	79	311
$1,000	-	36,982	465,762	842,125	276,872	20,436	4,953	545	72,084
Sales of $50,000 or more ..... farms	-	138	1,145	695	957	57	19	3	59
$1,000	-	21,490	402,378	836,520	259,553	19,331	3,887	230	70,337
Milk from cows ..... farms	-	30	32	-	1,684	2	8	-	22
$1,000	-	(D)	(D)	-	2,433,410	(D)	3,175	-	6,898
Sales of $50,000 or more ..... farms	-	28	12	-	1,655	2	7	-	9
$1,000	-	(D)	2,917	-	2,432,476	(D)	(D)	-	6,777
Hogs and pigs ..... farms	-	139	245	32	46	1,841	92	59	236
$1,000	-	4,170	10,711	15,232	6,991	4,292,520	6,151	55	81,918
Sales of $50,000 or more ..... farms	-	6	14	14	14	1,599	5	-	50
$1,000	-	(D)	9,986	15,094	6,806	4,291,258	6,049	-	81,184
Sheep, goats, wool, mohair, and milk ..... farms	-	221	258	32	39	54	135	1,162	270
$1,000	-	612	1,518	393	267	617	141	21,736	1,393
Sales of $50,000 or more ..... farms	-	-	3	2	-	1	-	82	1
$1,000	-	-	371	(D)	-	(D)	-	14,909	(D)
Horses, ponies, mules, burros, and donkeys ..... farms	-	55	112	2	17	18	23	37	857
$1,000	-	203	744	(D)	(D)	105	98	128	15,490
Sales of $50,000 or more ..... farms	-	-	2	-	-	-	-	-	68
$1,000	-	-	(D)	-	-	-	-	-	(D)
Poultry and eggs ..... farms	-	476	607	44	79	105	1,690	265	449
$1,000	-	2,175	763	63	1,055	8,535	1,894,418	331	23,199
Sales of $50,000 or more ..... farms	-	3	-	-	1	5	425	-	6
$1,000	-	(D)	-	-	(D)	(D)	1,890,707	-	22,395
Aquaculture ..... farms	-	3	-	-	-	-	2	-	84
$1,000	-	(D)	-	-	-	-	(D)	-	(D)
Sales of $50,000 or more ..... farms	-	-	-	-	-	-	-	-	62
$1,000	-	-	-	-	-	-	-	-	19,502
Other animals and other animal products ..... farms	-	155	86	2	12	49	91	73	694
$1,000	-	333	385	(D)	930	2,432	1,898	(D)	50,311
Sales of $50,000 or more ..... farms	-	2	3	1	3	17	3	-	120
$1,000	-	(D)	225	(D)	(D)	1,930	(D)	-	46,429
Value of-									
Government payments ..... farms	-	11,711	1,980	397	1,437	589	271	172	401
$1,000	-	104,766	19,397	8,070	33,804	19,842	4,663	666	6,810
Landlord's share of total sales ..... farms	-	85	63	25	26	39	8	6	12
$1,000	-	1,039	2,519	3,699	2,827	6,548	111	4	888
FOOD MARKETING PRACTICES									
Value of food sold directly to-									
Consumers ..... farms	-	366	574	63	46	90	360	207	355
$1,000	-	2,501	6,713	1,928	570	582	1,207	2,049	2,447
Retail markets, institutions, and food hubs for local or regionally branded products ..... farms	-	101	139	17	18	9	66	108	95
$1,000	-	641	2,011	658	1,424	251	37,075	1,287	2,277

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
						Total	Tobacco farming (11191)
FARM PRODUCTION EXPENSES							
Total farm production expenses [1] ..... farms	65,531	26,315	1,072	972	971	18,104	-
$1,000	20,780,603	10,585,960	258,866	35,438	258,542	540,194	-
Average per farm ..... dollars	317,111	402,279	241,480	36,459	266,264	29,838	-
Fertilizer, lime, and soil conditioners purchased ..... farms	36,421	24,252	768	474	550	3,621	-
$1,000	2,325,700	1,993,276	37,891	878	11,062	55,990	-
Farms with expenses of-							
$1 to $4,999	10,529	3,667	542	425	378	2,530	-
$5,000 to $24,999	9,710	7,009	77	47	104	735	-
$25,000 to $49,999	5,102	4,074	28	1	32	155	-
$50,000 or more	11,080	9,502	121	1	36	201	-
Chemicals purchased ..... farms	37,339	25,504	734	563	544	3,671	-
$1,000	1,161,099	986,262	32,796	1,392	5,352	31,455	-
Farms with expenses of-							
$1 to $4,999	15,060	7,061	528	508	439	3,079	-
$5,000 to $24,999	11,493	9,190	80	43	68	384	-
$25,000 to $49,999	4,407	3,720	37	6	15	69	-
$50,000 or more	6,379	5,533	89	6	22	139	-
Seeds, plants, vines, and trees purchased ..... farms	36,437	23,863	1,072	484	944	4,072	-
$1,000	1,772,341	1,481,270	31,761	1,248	32,977	43,888	-
Farms with expenses of-							
$1 to $999	5,343	809	481	282	299	1,961	-
$1,000 to $4,999	6,157	2,927	322	149	279	1,365	-
$5,000 to $24,999	10,290	7,960	124	47	194	494	-
$25,000 to $49,999	5,582	4,548	39	3	85	110	-
$50,000 or more	9,065	7,619	106	3	87	142	-
Cover crop seed purchased ..... farms	4,909	2,773	217	112	116	745	-
$1,000	20,527	16,482	404	40	148	823	-
Livestock and poultry purchased or leased ..... farms	13,933	2,959	155	145	67	1,125	-
$1,000	1,926,426	202,017	231	287	67	8,922	-
Farms with expenses of-							
$1 to $4,999	6,658	1,100	140	139	63	895	-
$5,000 to $24,999	3,161	907	15	2	4	187	-
$25,000 to $99,999	1,372	493	-	4	-	28	-
$100,000 to $249,999	912	243	-	-	-	8	-
$250,000 or more	1,830	216	-	-	-	7	-
Breeding livestock purchased or leased ..... farms	5,904	1,384	21	23	11	598	-
$1,000	171,016	18,083	41	117	17	3,162	-
Other livestock and poultry purchased or leased ..... farms	9,786	1,910	148	129	67	651	-
$1,000	1,755,410	183,933	190	170	50	5,760	-
Feed purchased ..... farms	26,145	5,796	251	275	134	2,478	-
$1,000	3,890,272	205,850	851	473	565	19,298	-
Farms with expenses of-							
$1 to $4,999	13,038	2,565	207	250	111	2,003	-
$5,000 to $24,999	6,844	2,048	40	25	21	394	-
$25,000 to $99,999	2,349	746	4	-	1	56	-
$100,000 to $249,999	1,155	226	-	-	1	15	-
$250,000 or more	2,759	211	-	-	-	10	-
Gasoline, fuels, and oils purchased ..... farms	61,621	25,703	1,020	923	895	15,432	-
$1,000	956,802	615,335	11,005	1,283	11,830	42,943	-
Farms with expenses of-							
$1 to $4,999	37,714	9,498	835	866	659	13,920	-
$5,000 to $24,999	14,760	9,685	107	53	153	1,268	-
$25,000 to $49,999	4,270	3,078	21	3	32	138	-
$50,000 or more	4,877	3,442	57	1	51	106	-
Utilities ..... farms	48,636	23,168	727	615	748	8,994	-
$1,000	400,978	165,850	7,964	1,658	13,606	19,455	-
Farms with expenses of-							
$1 to $999	9,923	2,582	282	261	194	3,174	-
$1,000 to $4,999	24,023	11,803	289	269	318	5,186	-
$5,000 to $24,999	12,077	7,767	94	80	184	572	-
$25,000 to $49,999	1,626	721	16	3	21	38	-
$50,000 or more	987	295	46	2	31	24	-
Repairs, supplies, and maintenance costs ..... farms	55,660	24,914	920	789	835	12,187	-
$1,000	1,322,234	796,464	24,169	3,073	17,357	64,187	-
Farms with expenses of-							
$1 to $4,999	25,809	6,332	619	641	462	9,161	-
$5,000 to $24,999	17,499	9,938	197	129	256	2,692	-
$25,000 to $49,999	5,425	3,927	36	16	53	176	-
$50,000 or more	6,927	4,717	68	3	64	158	-
Hired farm labor ..... farms	17,399	9,651	330	255	435	2,038	-
$1,000	1,320,974	484,591	44,628	11,642	106,705	38,641	-
Farms with expenses of-							
$1 to $4,999	5,944	2,821	139	84	67	1,401	-
$5,000 to $24,999	4,466	2,888	65	74	89	384	-
$25,000 to $99,999	3,749	2,104	51	65	147	158	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
FARM PRODUCTION EXPENSES									
Total farm production expenses [1] ..... farms	-	18,104	6,753	892	1,713	1,855	1,724	1,456	3,704
$1,000	-	540,194	561,856	804,590	2,205,867	3,772,178	1,392,398	35,023	329,692
Average per farm ..... dollars	-	29,838	83,201	902,006	1,287,722	2,033,519	807,655	24,054	89,010
Fertilizer, lime, and soil conditioners purchased ..... farms	-	3,621	2,262	614	1,510	977	286	264	843
$1,000	-	55,990	27,976	27,390	84,187	66,443	9,558	508	10,541
Farms with expenses of-									
$1 to $4,999	-	2,530	1,407	127	186	134	152	239	742
$5,000 to $24,999	-	735	630	198	536	231	61	24	58
$25,000 to $49,999	-	155	117	113	317	223	32	-	10
$50,000 or more	-	201	108	176	471	389	41	1	33
Chemicals purchased ..... farms	-	3,671	1,850	601	1,495	990	348	277	762
$1,000	-	31,455	10,050	13,373	37,289	33,958	4,010	228	4,934
Farms with expenses of-									
$1 to $4,999	-	3,079	1,492	216	381	161	237	272	686
$5,000 to $24,999	-	384	255	238	713	400	66	4	52
$25,000 to $49,999	-	69	59	69	214	191	22	-	5
$50,000 or more	-	139	44	78	187	238	23	1	19
Seeds, plants, vines, and trees purchased ..... farms	-	4,072	1,786	578	1,526	994	419	241	458
$1,000	-	43,888	17,401	25,613	68,547	55,356	6,179	322	7,779
Farms with expenses of-									
$1 to $999	-	1,961	639	25	34	66	253	185	309
$1,000 to $4,999	-	1,365	660	94	119	68	49	42	83
$5,000 to $24,999	-	494	336	210	594	233	57	14	27
$25,000 to $49,999	-	110	65	104	340	257	25	-	6
$50,000 or more	-	142	86	145	439	370	35	-	33
Cover crop seed purchased ..... farms	-	745	302	105	307	72	39	18	103
$1,000	-	823	394	218	1,403	343	80	8	185
Livestock and poultry purchased or leased ..... farms	-	1,125	3,359	704	535	1,690	1,131	779	1,284
$1,000	-	8,922	154,284	373,792	27,154	900,631	198,352	3,787	56,901
Farms with expenses of-									
$1 to $4,999	-	895	1,834	76	203	190	661	615	742
$5,000 to $24,999	-	187	1,059	167	187	61	100	123	349
$25,000 to $99,999	-	28	269	106	65	130	90	40	147
$100,000 to $249,999	-	8	90	92	56	286	125	-	12
$250,000 or more	-	7	107	263	24	1,023	155	1	34
Breeding livestock purchased or leased ..... farms	-	598	1,812	147	461	331	213	489	414
$1,000	-	3,162	35,423	7,820	20,538	54,129	18,407	1,873	11,405
Other livestock and poultry purchased or leased ..... farms	-	651	2,024	626	139	1,494	1,035	471	1,092
$1,000	-	5,760	118,862	365,972	6,615	846,502	179,946	1,915	45,496
Feed purchased ..... farms	-	2,478	6,566	887	1,713	1,834	1,662	1,360	3,189
$1,000	-	19,298	130,782	171,001	881,662	1,650,983	745,457	8,462	74,888
Farms with expenses of-									
$1 to $4,999	-	2,003	3,602	81	31	171	1,057	958	2,002
$5,000 to $24,999	-	394	2,267	291	192	81	211	328	946
$25,000 to $99,999	-	56	496	215	480	70	33	70	178
$100,000 to $249,999	-	15	101	97	423	229	33	4	26
$250,000 or more	-	10	100	203	587	1,283	328	-	37
Gasoline, fuels, and oils purchased ..... farms	-	15,432	6,618	884	1,712	1,829	1,644	1,409	3,552
$1,000	-	42,943	27,888	21,806	94,289	63,180	49,051	2,375	15,818
Farms with expenses of-									
$1 to $4,999	-	13,920	5,259	306	198	513	1,257	1,305	3,098
$5,000 to $24,999	-	1,268	1,200	353	597	680	208	96	360
$25,000 to $49,999	-	138	80	101	363	324	67	5	58
$50,000 or more	-	106	79	124	554	312	112	3	36
Utilities ..... farms	-	8,994	5,341	848	1,698	1,807	1,220	994	2,476
$1,000	-	19,455	13,738	7,505	65,958	53,123	39,787	1,950	10,383
Farms with expenses of-									
$1 to $999	-	3,174	1,455	66	27	116	413	486	867
$1,000 to $4,999	-	5,186	3,257	391	129	330	425	422	1,204
$5,000 to $24,999	-	572	612	351	948	830	211	82	346
$25,000 to $49,999	-	38	15	11	373	324	69	3	32
$50,000 or more	-	24	2	29	221	207	102	1	27
Repairs, supplies, and maintenance costs ..... farms	-	12,187	6,056	879	1,703	1,796	1,383	1,213	2,985
$1,000	-	64,187	41,346	30,529	163,970	91,788	62,088	3,949	23,313
Farms with expenses of-									
$1 to $4,999	-	9,161	3,855	195	115	349	871	976	2,233
$5,000 to $24,999	-	2,692	1,925	366	367	534	263	221	611
$25,000 to $49,999	-	176	166	149	349	385	76	15	77
$50,000 or more	-	158	110	169	872	528	173	1	64
Hired farm labor ..... farms	-	2,038	1,004	353	1,244	960	397	166	566
$1,000	-	38,641	23,324	26,486	269,040	166,278	107,495	2,590	39,553
Farms with expenses of-									
$1 to $4,999	-	1,401	619	66	109	163	124	129	222
$5,000 to $24,999	-	384	230	104	239	179	84	16	114
$25,000 to $99,999	-	158	123	131	380	360	61	17	152

See footnote(s) at end of table.

--continued

Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
						Total	Tobacco farming (11191)
FARM PRODUCTION EXPENSES - Con.							
Total farm production expenses [1] - Con.							
Hired farm labor - Con.							
Farms with expenses of- - Con.							
$100,000 to $249,999	2,234	1,525	26	24	53	58	-
$250,000 or more	1,006	313	49	8	79	37	-
Contract labor ... farms	4,311	1,961	103	114	144	675	-
$1,000	152,565	44,172	8,312	2,413	16,019	6,055	-
Farms with expenses of-							
$1 to $999	452	105	16	17	18	136	-
$1,000 to $4,999	1,452	615	12	49	43	387	-
$5,000 to $24,999	1,469	775	24	22	44	109	-
$25,000 to $49,999	315	125	20	14	18	18	-
$50,000 or more	623	341	31	12	21	25	-
Customwork and custom hauling ... farms	19,181	11,223	210	68	95	1,959	-
$1,000	425,172	192,450	5,123	150	1,950	8,739	-
Farms with expenses of-							
$1 to $999	2,876	1,100	39	34	38	634	-
$1,000 to $4,999	6,088	3,648	72	29	33	990	-
$5,000 to $24,999	6,540	4,624	68	4	19	266	-
$25,000 to $49,999	2,030	1,156	17	1	2	44	-
$50,000 or more	1,647	695	14	-	3	25	-
Cash rent for land, buildings, and grazing fees ... farms	24,199	16,662	271	71	158	1,713	-
$1,000	2,302,712	1,916,793	20,796	1,033	7,321	46,980	-
Farms with expenses of-							
$1 to $4,999	5,289	2,082	131	41	63	990	-
$5,000 to $9,999	2,314	1,373	25	5	19	246	-
$10,000 to $24,999	4,009	2,943	19	17	22	229	-
$25,000 or more	12,587	10,264	96	8	54	248	-
Rent and lease expenses for machinery, equipment, and farm share of vehicles ... farms	6,598	4,024	103	49	79	780	-
$1,000	182,357	144,222	2,527	234	3,457	4,624	-
Farms with expenses of-							
$1 to $999	1,233	471	36	20	21	288	-
$1,000 to $4,999	1,683	810	26	10	31	336	-
$5,000 to $24,999	2,168	1,551	25	18	11	112	-
$25,000 to $49,999	538	402	5	1	10	27	-
$50,000 or more	976	790	11	-	6	17	-
Interest expense ... farms	27,274	14,669	328	245	319	4,084	-
$1,000	702,889	461,574	6,354	2,204	3,818	32,516	-
Farms with expenses of-							
$1 to $4,999	9,316	3,970	156	125	159	2,266	-
$5,000 to $24,999	11,255	6,030	129	105	120	1,630	-
$25,000 to $99,999	5,316	3,730	30	14	38	163	-
$100,000 or more	1,387	939	13	1	2	25	-
Secured by real estate ... farms	20,348	10,603	226	184	210	3,141	-
$1,000	467,669	312,626	3,790	1,737	2,548	24,496	-
Farms with expenses of-							
$1 to $999	1,511	638	32	15	12	350	-
$1,000 to $4,999	5,125	2,042	73	71	85	1,219	-
$5,000 to $24,999	9,127	4,726	89	87	84	1,440	-
$25,000 to $49,999	2,363	1,595	9	4	15	85	-
$50,000 or more	2,222	1,602	23	7	14	47	-
Not secured by real estate ... farms	16,953	9,721	201	129	199	2,014	-
$1,000	235,219	148,949	2,564	467	1,271	8,021	-
Farms with expenses of-							
$1 to $999	2,836	1,222	48	58	58	497	-
$1,000 to $4,999	6,264	2,911	84	50	74	1,271	-
$5,000 to $24,999	5,400	3,889	52	17	60	199	-
$25,000 to $49,999	1,506	1,119	5	3	3	20	-
$50,000 or more	947	580	12	1	4	27	-
Property taxes paid ... farms	61,644	23,812	944	935	881	17,692	-
$1,000	482,443	286,988	6,001	3,178	4,888	79,590	-
Farms with expenses of-							
$1 to $4,999	39,325	10,806	717	779	624	13,691	-
$5,000 to $9,999	11,291	5,643	113	123	157	2,659	-
$10,000 to $24,999	7,298	4,611	71	27	77	1,027	-
$25,000 or more	3,730	2,752	43	6	23	315	-
Medical supplies, veterinary, and custom services for livestock ... farms	19,351	4,393	86	98	43	1,714	-
$1,000	255,043	20,574	68	53	58	3,406	-
Farms with expenses of-							
$1 to $4,999	14,259	3,428	85	98	42	1,642	-
$5,000 to $24,999	3,318	825	1	-	1	61	-
$25,000 to $49,999	674	91	-	-	-	4	-
$50,000 to $99,999	623	33	-	-	-	3	-
$100,000 or more	477	16	-	-	-	4	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
FARM PRODUCTION EXPENSES - Con.									
Total farm production expenses [1] - Con.									
Hired farm labor - Con.									
Farms with expenses of- - Con.									
$100,000 to $249,999	-	58	23	32	300	116	36	1	40
$250,000 or more	-	37	9	20	216	142	92	3	38
Contract labor ... farms	-	675	305	65	217	316	121	85	205
$1,000	-	6,055	2,004	1,790	9,868	19,800	38,783	306	3,041
Farms with expenses of-									
$1 to $999	-	136	59	-	3	4	13	26	55
$1,000 to $4,999	-	387	166	17	25	46	15	38	39
$5,000 to $24,999	-	109	63	29	110	162	37	20	74
$25,000 to $49,999	-	18	7	10	14	45	18	1	25
$50,000 or more	-	25	10	9	65	59	38	-	12
Customwork and custom hauling ... farms	-	1,959	1,553	456	1,281	1,374	305	220	437
$1,000	-	8,739	8,331	9,510	88,420	90,663	12,426	487	6,922
Farms with expenses of-									
$1 to $999	-	634	572	74	37	29	52	105	162
$1,000 to $4,999	-	990	635	89	187	95	26	94	190
$5,000 to $24,999	-	266	281	165	489	492	60	20	52
$25,000 to $49,999	-	44	44	85	210	387	72	1	11
$50,000 or more	-	25	21	43	358	371	95	-	22
Cash rent for land, buildings, and grazing fees ... farms	-	1,713	1,912	511	1,306	939	178	121	357
$1,000	-	46,980	27,661	33,439	95,662	125,100	11,226	305	16,397
Farms with expenses of-									
$1 to $4,999	-	990	1,222	135	187	84	47	104	203
$5,000 to $9,999	-	246	257	61	161	57	40	11	59
$10,000 to $24,999	-	229	244	72	276	124	23	5	35
$25,000 or more	-	248	189	243	682	674	68	1	60
Rent and lease expenses for machinery, equipment, and farm share of vehicles ... farms	-	780	416	109	434	260	104	83	157
$1,000	-	4,624	1,611	3,419	8,103	10,958	1,486	157	1,561
Farms with expenses of-									
$1 to $999	-	288	202	26	47	6	15	42	59
$1,000 to $4,999	-	336	146	21	119	46	46	31	61
$5,000 to $24,999	-	112	56	42	205	82	29	10	27
$25,000 to $49,999	-	27	6	5	35	41	3	-	3
$50,000 or more	-	17	6	15	28	85	11	-	7
Interest expense ... farms	-	4,084	2,421	550	1,298	1,277	609	381	1,093
$1,000	-	32,516	22,939	27,777	68,380	53,386	11,597	2,267	10,076
Farms with expenses of-									
$1 to $4,999	-	2,266	1,195	136	173	220	236	206	474
$5,000 to $24,999	-	1,630	1,034	224	489	491	260	169	574
$25,000 to $99,999	-	163	175	124	458	447	93	6	38
$100,000 or more	-	25	17	66	178	119	20	-	7
Secured by real estate ... farms	-	3,141	1,839	421	1,036	993	498	315	882
$1,000	-	24,496	16,064	13,686	45,986	29,186	8,284	1,690	7,578
Farms with expenses of-									
$1 to $999	-	350	193	28	34	51	30	50	78
$1,000 to $4,999	-	1,219	683	85	115	133	148	148	323
$5,000 to $24,999	-	1,440	849	183	436	425	247	115	446
$25,000 to $49,999	-	85	84	55	196	251	46	1	22
$50,000 or more	-	47	30	70	255	133	27	1	13
Not secured by real estate ... farms	-	2,014	1,464	363	877	792	286	239	668
$1,000	-	8,021	6,875	14,091	22,394	24,200	3,314	577	2,497
Farms with expenses of-									
$1 to $999	-	497	429	28	60	56	82	77	221
$1,000 to $4,999	-	1,271	748	127	216	197	112	132	342
$5,000 to $24,999	-	199	229	114	344	325	48	30	93
$25,000 to $49,999	-	20	37	36	142	104	33	-	4
$50,000 or more	-	27	21	58	115	110	11	-	8
Property taxes paid ... farms	-	17,692	6,403	857	1,656	1,775	1,674	1,384	3,631
$1,000	-	79,590	23,596	7,704	22,285	18,681	10,075	4,194	15,263
Farms with expenses of-									
$1 to $4,999	-	13,691	5,260	483	549	919	1,350	1,219	2,928
$5,000 to $9,999	-	2,659	831	183	415	332	170	128	537
$10,000 to $24,999	-	1,027	257	130	502	353	92	33	118
$25,000 or more	-	315	55	61	190	171	62	4	48
Medical supplies, veterinary, and custom services for livestock ... farms	-	1,714	4,486	818	1,683	1,707	924	1,113	2,286
$1,000	-	3,406	11,554	9,960	79,496	97,522	21,544	1,115	9,693
Farms with expenses of-									
$1 to $4,999	-	1,642	4,009	488	365	332	741	1,075	1,954
$5,000 to $24,999	-	61	403	217	676	732	97	38	267
$25,000 to $49,999	-	4	47	66	211	205	21	-	29
$50,000 to $99,999	-	3	25	33	274	213	18	-	24
$100,000 or more	-	4	2	14	157	225	47	-	12

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
						Total	Tobacco farming (11191)
FARM PRODUCTION EXPENSES - Con.							
Total farm production expenses [1] - Con.							
All other production expenses ..... farms	44,226	23,709	640	485	647	7,340	-
$1,000	1,200,596	588,272	18,391	4,239	21,509	33,504	-
Farms with expenses of-							
$1 to $4,999	22,214	8,376	427	360	385	6,231	-
$5,000 to $24,999	13,025	9,046	128	91	165	917	-
$25,000 to $49,999	3,867	2,804	22	15	38	64	-
$50,000 to $99,999	3,372	2,572	17	10	18	86	-
$100,000 or more	1,748	911	46	9	41	42	-
Production expenses paid by landlords [1] ..... farms	2,062	1,379	35	5	11	174	-
$1,000	65,113	51,898	(D)	10	(D)	2,152	-
Depreciation expenses claimed ..... farms	41,075	21,247	717	758	720	7,680	-
$1,000	2,240,389	1,496,842	23,669	6,430	25,865	102,145	-
NET CASH FARM INCOME							
Net cash farm income of operations ..... farms	65,531	26,315	1,072	972	971	18,104	-
$1,000	9,296,848	5,465,122	92,952	12,148	146,253	355,352	-
Average per farm ..... dollars	141,869	207,681	86,709	12,498	150,621	19,628	-
Farms with net gains [2] ..... number	41,496	21,574	717	493	503	10,397	-
Average net gain ..... dollars	242,705	265,594	143,713	41,070	350,873	42,740	-
Gain of-							
Less than $1,000	1,541	200	42	28	31	972	-
$1,000 to $4,999	4,053	840	114	129	52	2,167	-
$5,000 to $9,999	3,053	848	104	79	52	1,419	-
$10,000 to $24,999	5,680	2,183	161	81	99	2,222	-
$25,000 to $49,999	5,396	2,749	112	70	62	1,653	-
$50,000 or more	21,773	14,754	184	106	207	1,964	-
Farms with net losses ..... number	24,035	4,741	355	479	468	7,707	-
Average net loss ..... dollars	32,221	55,853	28,422	16,910	64,608	11,550	-
Loss of-							
Less than $1,000	1,786	245	27	42	26	1,008	-
$1,000 to $4,999	6,380	881	120	181	112	2,816	-
$5,000 to $9,999	5,021	672	70	105	67	1,748	-
$10,000 to $24,999	5,999	1,083	74	86	125	1,538	-
$25,000 to $49,999	2,539	766	16	30	55	367	-
$50,000 or more	2,310	1,094	48	35	83	230	-
Net cash farm income of producers ..... farms	65,531	26,315	1,072	972	971	18,104	-
$1,000	8,390,544	5,371,779	89,382	12,158	148,329	356,158	-
Average per farm ..... dollars	128,039	204,134	83,379	12,508	152,759	19,673	-
Producers reporting net gains [2] ..... farms	41,274	21,540	732	493	504	10,400	-
Average net gain ..... dollars	222,954	261,910	134,415	41,074	350,802	42,743	-
Gain of-							
Less than $1,000	1,557	202	45	28	31	982	-
$1,000 to $4,999	4,059	838	116	129	51	2,162	-
$5,000 to $9,999	3,084	851	99	79	53	1,417	-
$10,000 to $24,999	5,726	2,182	172	81	99	2,218	-
$25,000 to $49,999	5,475	2,749	107	70	62	1,654	-
$50,000 or more	21,373	14,718	193	106	208	1,967	-
Producers reporting net losses ..... farms	24,257	4,775	340	479	467	7,704	-
Average net loss ..... dollars	33,460	56,496	26,499	16,893	60,974	11,470	-
Loss of-							
Less than $1,000	1,780	249	27	42	25	1,005	-
$1,000 to $4,999	6,394	878	119	181	113	2,820	-
$5,000 to $9,999	5,032	680	65	105	70	1,751	-
$10,000 to $24,999	6,008	1,083	65	86	123	1,539	-
$25,000 to $49,999	2,576	771	16	30	54	359	-
$50,000 or more	2,467	1,114	48	35	82	230	-
COMMODITY CREDIT CORPORATION LOANS							
Total ..... farms	990	812	2	-	-	19	-
$1,000	197,241	176,662	(D)	-	-	(D)	-
INCOME FROM FARM-RELATED SOURCES							
Total income from farm-related sources ..... farms	38,287	19,673	398	340	369	8,795	-
$1,000	1,011,249	561,002	9,517	4,616	8,374	247,850	-
Customwork and other agricultural services ... farms	4,779	3,126	34	41	37	501	-
$1,000	144,025	102,554	449	378	2,783	6,484	-
Gross cash rent or share payments ..... farms	15,680	5,579	183	158	126	6,596	-
$1,000	479,289	195,758	6,543	1,285	1,630	220,152	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
FARM PRODUCTION EXPENSES - Con.									
Total farm production expenses [1] - Con.									
All other production expenses ..... farms	-	7,340	3,851	776	1,658	1,720	893	690	1,817
$1,000	-	33,504	17,371	13,495	141,557	274,327	63,283	2,021	22,628
Farms with expenses of-									
$1 to $4,999	-	6,231	3,001	296	232	350	555	632	1,369
$5,000 to $24,999	-	917	715	307	598	572	114	46	326
$25,000 to $49,999	-	64	109	141	276	192	114	6	86
$50,000 to $99,999	-	86	24	20	224	364	21	4	12
$100,000 or more	-	42	2	12	328	242	89	2	24
Production expenses paid by landlords [1] ..... farms	-	174	125	48	138	61	30	8	48
$1,000	-	2,152	1,277	1,236	3,953	1,514	246	59	323
Depreciation expenses claimed ..... farms	-	7,680	3,446	705	1,602	1,586	732	531	1,351
$1,000	-	102,145	54,308	45,106	202,394	155,851	86,781	4,820	36,180
NET CASH FARM INCOME									
Net cash farm income of operations ..... farms	-	18,104	6,753	892	1,713	1,855	1,724	1,456	3,704
$1,000	-	355,352	112,683	304,083	913,934	1,220,128	605,418	-4,637	73,414
Average per farm ..... dollars	-	19,628	16,686	340,900	533,528	657,751	351,171	-3,185	19,820
Farms with net gains [2] ..... number	-	10,397	2,515	684	1,551	1,492	535	291	744
Average net gain ..... dollars	-	42,740	75,095	465,317	616,258	888,288	1,223,917	33,429	194,088
Gain of-									
Less than $1,000	-	972	124	1	5	14	30	23	71
$1,000 to $4,999	-	2,167	435	22	9	7	54	81	143
$5,000 to $9,999	-	1,419	326	37	15	7	37	39	90
$10,000 to $24,999	-	2,222	586	56	47	15	24	60	146
$25,000 to $49,999	-	1,653	421	71	70	12	27	43	106
$50,000 or more	-	1,964	623	497	1,405	1,437	363	45	188
Farms with net losses ..... number	-	7,707	4,238	208	162	363	1,189	1,165	2,960
Average net loss ..... dollars	-	11,550	17,976	68,240	258,533	289,803	41,528	12,331	23,982
Loss of-									
Less than $1,000	-	1,008	177	4	4	14	81	50	108
$1,000 to $4,999	-	2,816	922	28	4	39	378	353	546
$5,000 to $9,999	-	1,748	886	40	18	54	273	346	742
$10,000 to $24,999	-	1,538	1,490	47	40	90	272	251	903
$25,000 to $49,999	-	367	516	29	17	52	117	145	429
$50,000 or more	-	230	247	60	79	114	68	20	232
Net cash farm income of producers ..... farms	-	18,104	6,753	892	1,713	1,855	1,724	1,456	3,704
$1,000	-	356,158	104,320	280,412	914,002	677,496	373,803	-4,620	67,324
Average per farm ..... dollars	-	19,673	15,448	314,363	533,568	365,227	216,823	-3,173	18,176
Producers reporting net gains [2] ..... farms	-	10,400	2,507	667	1,554	1,329	513	295	740
Average net gain ..... dollars	-	42,743	72,168	443,173	614,927	611,251	834,707	32,928	186,856
Gain of-									
Less than $1,000	-	982	121	1	6	14	30	26	71
$1,000 to $4,999	-	2,162	436	19	9	17	56	81	145
$5,000 to $9,999	-	1,417	328	39	16	33	40	39	90
$10,000 to $24,999	-	2,218	578	50	49	57	37	61	142
$25,000 to $49,999	-	1,654	422	77	68	67	50	43	106
$50,000 or more	-	1,967	622	481	1,406	1,141	300	45	186
Producers reporting net losses ..... farms	-	7,704	4,246	225	159	526	1,211	1,161	2,964
Average net loss ..... dollars	-	11,470	18,042	67,487	261,604	256,382	44,923	12,346	23,937
Loss of-									
Less than $1,000	-	1,005	177	4	1	13	81	47	109
$1,000 to $4,999	-	2,820	928	32	4	41	378	352	548
$5,000 to $9,999	-	1,751	876	40	18	61	278	346	742
$10,000 to $24,999	-	1,539	1,497	49	39	101	272	251	903
$25,000 to $49,999	-	359	518	37	18	72	125	146	430
$50,000 or more	-	230	250	63	79	238	77	19	232
COMMODITY CREDIT CORPORATION LOANS									
Total ..... farms	-	19	18	18	72	33	8	1	7
$1,000	-	(D)	(D)	2,077	6,972	4,700	661	(D)	1,410
INCOME FROM FARM-RELATED SOURCES									
Total income from farm-related sources ..... farms	-	8,795	3,285	609	1,230	1,229	598	497	1,264
$1,000	-	247,850	40,498	15,839	32,465	42,018	17,512	4,616	26,944
Customwork and other agricultural services ... farms	-	501	255	132	171	272	77	34	99
$1,000	-	6,484	3,094	4,502	5,288	15,176	1,785	256	1,278
Gross cash rent or share payments ..... farms	-	6,596	1,524	183	97	240	268	204	522
$1,000	-	220,152	22,756	6,177	3,021	8,638	4,364	3,092	5,874

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
							Total	Tobacco farming (11191)
INCOME FROM FARM-RELATED SOURCES - Con.								
Total income from farm-related sources - Con.								
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms	619	76	15	26	38	255	-
	$1,000	5,384	683	11	144	556	1,906	-
Agri-tourism and recreational services	farms	509	101	32	46	48	89	-
	$1,000	13,615	1,505	629	2,239	1,615	574	-
Patronage dividends and refunds from cooperatives	farms	23,672	15,491	168	78	125	2,393	-
	$1,000	126,183	93,759	229	49	177	4,474	-
Crop and livestock insurance payments	farms	5,882	4,446	31	16	15	328	-
	$1,000	171,530	135,562	1,124	272	184	7,776	-
Amount from State and local government agricultural program payments	farms	1,422	639	31	28	31	279	-
	$1,000	7,129	4,343	62	49	71	884	-
Other farm-related income sources	farms	2,557	1,141	46	30	60	318	-
	$1,000	64,095	26,839	471	200	1,357	5,601	-
LAND USE								
Total cropland	farms	58,762	26,315	1,072	972	971	17,122	-
	acres	21,544,060	17,148,359	143,783	13,968	39,182	1,660,526	-
Harvested cropland	farms	47,549	26,315	1,072	972	971	7,724	-
	acres	19,662,443	16,406,107	131,044	7,882	27,478	791,065	-
Farms by acres harvested:								
1 to 49 acres		16,934	3,986	872	945	870	4,857	-
50 to 99 acres		5,412	3,021	34	19	42	1,212	-
100 to 199 acres		6,580	4,484	37	7	27	915	-
200 to 499 acres		8,316	6,188	57	1	21	496	-
500 to 999 acres		4,858	3,884	31	-	9	129	-
1,000 to 1,999 acres		3,081	2,565	31	-	2	53	-
2,000 acres or more		2,368	2,187	10	-	-	62	-
Cropland-								
Other pasture and grazing land that could have been used for crops without additional improvements	farms	3,908	1,090	40	65	47	770	-
	acres	174,215	57,517	1,035	378	1,657	37,126	-
On which all crops failed or were abandoned	farms	2,413	1,114	79	53	63	647	-
	acres	110,013	68,590	814	399	1,129	20,747	-
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms	22,588	7,953	268	263	219	10,992	-
	acres	1,546,009	592,188	10,140	4,446	8,100	796,121	-
In summer fallow	farms	2,242	744	83	74	78	759	-
	acres	51,380	23,957	750	863	818	15,467	-
Total woodland	farms	23,960	6,035	392	524	432	8,581	-
	acres	1,446,600	387,189	13,719	48,425	20,753	596,862	-
Woodland pastured	farms	7,908	1,598	82	76	47	1,893	-
	acres	315,103	78,119	1,635	1,458	2,796	77,373	-
Woodland not pastured	farms	19,456	5,129	342	488	413	7,593	-
	acres	1,131,497	309,070	12,084	46,967	17,957	519,489	-
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	19,837	4,483	189	172	112	4,020	-
	acres	1,031,215	254,016	2,408	2,034	1,473	198,695	-
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	42,652	14,393	671	756	620	11,961	-
	acres	1,420,750	659,688	14,431	24,647	12,270	374,085	-
Irrigated land	farms	3,625	1,449	435	251	587	328	-
	acres	648,313	473,155	57,380	1,203	10,408	17,015	-
Harvested cropland	farms	3,551	1,443	435	249	587	315	-
	acres	644,857	472,352	57,289	1,190	9,942	16,183	-
Pastureland and other land	farms	160	27	10	5	13	23	-
	acres	3,456	803	91	13	466	832	-
CONSERVATION AND CROP INSURANCE								
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	19,069	6,706	101	89	57	10,557	-
	acres	951,335	275,505	3,749	2,194	1,365	616,507	-
Land enrolled in crop insurance programs	farms	27,305	21,558	229	70	76	1,619	-
	acres	18,167,226	15,791,416	105,121	1,939	9,099	492,777	-
ORGANIC AGRICULTURE								
Total organic product sales	farms	577	238	57	27	32	59	-
	$1,000	121,783	55,270	7,543	600	7,187	3,272	-
VALUE OF LAND AND BUILDINGS								
Estimated market value of land and buildings	farms	65,531	26,315	1,072	972	971	18,104	-
	$1,000	155,374,449	116,354,106	1,217,976	522,975	700,433	11,833,802	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
		Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
INCOME FROM FARM-RELATED SOURCES - Con.										
Total income from farm-related sources - Con.										
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms	-	255	92	5	12	-	25	7	68
	$1,000	-	1,906	819	3	722	-	265	46	229
Agri-tourism and recreational services	farms	-	89	26	-	7	5	27	23	105
	$1,000	-	574	1,284	-	40	6	3,150	108	2,466
Patronage dividends and refunds from cooperatives	farms	-	2,393	1,894	474	1,142	953	264	259	431
	$1,000	-	4,474	2,132	1,943	15,308	5,502	1,806	153	651
Crop and livestock insurance payments	farms	-	328	303	110	303	223	32	14	61
	$1,000	-	7,776	7,130	2,644	6,649	6,103	1,850	182	2,055
Amount from State and local government agricultural program payments	farms	-	279	189	16	112	18	11	31	37
	$1,000	-	884	547	36	565	257	64	145	105
Other farm-related income sources	farms	-	318	220	38	102	99	74	83	346
	$1,000	-	5,601	2,735	535	872	6,336	4,228	634	14,286
LAND USE										
Total cropland	farms	-	17,122	4,670	738	1,626	1,226	995	838	2,217
	acres	-	1,660,526	514,943	278,965	847,019	628,681	91,708	17,650	159,276
Harvested cropland	farms	-	7,724	4,114	715	1,606	1,106	631	575	1,748
	acres	-	791,065	405,425	263,314	798,509	611,116	76,977	11,232	132,294
Farms by acres harvested:										
1 to 49 acres		-	4,857	2,375	161	108	202	465	529	1,564
50 to 99 acres		-	1,212	644	88	108	65	48	32	99
100 to 199 acres		-	915	547	118	258	130	30	8	19
200 to 499 acres		-	496	407	172	613	281	53	5	22
500 to 999 acres		-	129	100	111	316	233	23	1	21
1,000 to 1,999 acres		-	53	36	53	165	156	9	-	11
2,000 acres or more		-	62	5	12	38	39	3	-	12
Cropland- Other pasture and grazing land that could have been used for crops without additional improvements	farms	-	770	829	68	258	54	117	192	378
	acres	-	37,126	40,034	4,111	16,096	2,787	1,169	2,757	9,548
On which all crops failed or were abandoned	farms	-	647	174	30	94	25	54	37	43
	acres	-	20,747	8,045	3,032	5,641	295	527	260	534
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms	-	10,992	1,021	164	390	342	379	195	402
	acres	-	796,121	56,242	8,151	25,444	14,182	11,959	2,970	16,066
In summer fallow	farms	-	759	230	21	51	21	87	40	54
	acres	-	15,467	5,197	357	1,329	301	1,076	431	834
Total woodland	farms	-	8,581	3,357	235	665	257	865	767	1,850
	acres	-	596,862	204,920	14,133	51,710	10,415	26,730	13,427	58,317
Woodland pastured	farms	-	1,893	2,143	95	318	79	324	378	875
	acres	-	77,373	102,987	5,705	16,015	2,865	5,748	4,288	16,114
Woodland not pastured	farms	-	7,593	2,107	175	514	209	642	504	1,340
	acres	-	519,489	101,933	8,428	35,695	7,550	20,982	9,139	42,203
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	-	4,020	5,062	398	838	253	752	1,012	2,546
	acres	-	198,695	372,576	40,240	59,258	8,376	12,178	18,637	61,324
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	-	11,961	5,121	644	1,304	1,493	1,450	1,170	3,069
	acres	-	374,085	105,252	19,611	63,311	35,127	35,389	10,150	66,789
Irrigated land	farms	-	328	112	54	167	69	63	23	87
	acres	-	17,015	5,106	11,729	39,501	11,900	6,870	167	13,879
Harvested cropland	farms	-	315	94	54	162	69	48	12	83
	acres	-	16,183	4,563	11,729	38,908	11,900	6,846	141	13,814
Pastureland and other land	farms	-	23	22	-	19	-	15	11	15
	acres	-	832	543	-	593	-	24	26	65
CONSERVATION AND CROP INSURANCE										
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	-	10,557	551	114	164	263	168	71	228
	acres	-	616,507	28,708	3,141	3,773	4,576	4,373	1,523	5,921
Land enrolled in crop insurance programs	farms	-	1,619	826	482	1,166	937	166	44	132
	acres	-	492,777	193,301	230,108	589,174	602,381	65,648	2,724	83,538
ORGANIC AGRICULTURE										
Total organic product sales	farms	-	59	23	5	84	6	18	19	9
	$1,000	-	3,272	1,035	120	39,313	3,061	3,331	431	620
VALUE OF LAND AND BUILDINGS										
Estimated market value of land and buildings	farms	-	18,104	6,753	892	1,713	1,855	1,724	1,456	3,704
	$1,000	-	11,833,802	5,216,412	2,376,562	6,274,764	6,787,401	1,304,050	527,594	2,258,373

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
						Total	Tobacco farming (11191)
VALUE OF LAND AND BUILDINGS - Con.							
Estimated market value of land and buildings - Con.							
Average per farm ..... dollars	2,371,007	4,421,589	1,136,172	538,040	721,352	653,657	-
Average per acre ..... dollars	6,107	6,307	6,986	5,871	9,507	4,181	-
Farms by value group:							
$1 to $49,999	1,819	213	129	55	87	581	-
$50,000 to $99,999	2,318	344	82	57	60	1,078	-
$100,000 to $199,999	5,817	901	134	129	104	2,555	-
$200,000 to $499,999	17,490	3,175	324	421	356	6,913	-
$500,000 to $999,999	13,050	4,130	173	243	206	4,575	-
$1,000,000 to $1,999,999	8,615	4,892	95	52	87	1,562	-
$2,000,000 to $4,999,999	8,631	6,228	77	13	56	644	-
$5,000,000 to $9,999,999	3,992	3,202	37	1	12	125	-
$10,000,000 or more	3,799	3,230	21	1	3	71	-
VALUE OF MACHINERY AND EQUIPMENT							
Estimated market value of all machinery and equipment ..... farms	65,531	26,315	1,072	972	971	18,104	-
$1,000	17,904,134	12,505,434	148,351	43,887	127,288	1,200,100	-
Farms by value group:							
$1 to $4,999	3,305	387	110	81	85	1,797	-
$5,000 to $9,999	3,816	513	110	105	104	2,137	-
$10,000 to $19,999	6,447	1,042	184	130	110	3,150	-
$20,000 to $49,999	12,383	2,508	284	351	249	5,181	-
$50,000 to $99,999	10,506	3,266	159	219	142	3,151	-
$100,000 to $199,999	9,020	4,357	89	63	111	1,567	-
$200,000 to $499,999	9,719	6,361	59	17	132	776	-
$500,000 or more	10,335	7,881	77	6	38	345	-
SELECTED MACHINERY AND EQUIPMENT							
Trucks, including pickups ..... farms	51,156	23,649	784	745	652	9,950	-
number	127,301	75,168	1,881	979	1,694	16,371	-
Tractors, all ..... farms	52,770	23,968	802	753	661	11,829	-
number	184,473	105,127	2,266	1,263	1,566	28,584	-
Less than 40 horsepower (PTO) ..... farms	22,815	8,932	528	566	472	5,803	-
number	36,863	15,556	853	783	774	8,900	-
40 to 99 horsepower (PTO) ..... farms	35,619	15,932	476	325	350	8,133	-
number	60,537	28,123	768	421	601	12,949	-
100 horsepower (PTO) or more ..... farms	31,912	20,947	225	44	84	3,800	-
number	87,073	61,448	645	59	191	6,735	-
Grain and bean combines, self-propelled ..... farms	21,753	17,739	117	10	14	1,222	-
number	25,736	21,189	136	11	21	1,436	-
Cotton pickers and strippers, self-propelled ..... farms	-	-	-	-	-	-	-
number	-	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	2,195	730	2	18	4	375	-
number	2,384	802	(D)	18	(D)	431	-
Hay balers ..... farms	19,296	7,077	120	49	54	4,638	-
number	24,300	8,868	126	55	74	5,912	-
FERTILIZERS AND CHEMICALS							
Commercial fertilizer, lime, and soil conditioners used ..... farms	34,208	24,004	649	330	400	2,845	-
acres treated	14,076,782	12,056,161	107,630	3,301	19,584	400,585	-
Manure used ..... farms	13,721	5,856	184	71	88	1,638	-
acres treated	1,453,615	743,795	3,888	597	274	55,249	-
Organic fertilizer used ..... farms	1,053	387	118	54	83	131	-
acres treated	135,551	99,033	1,858	278	147	5,462	-
Acres treated to control-							
Insects ..... farms	13,847	10,017	583	340	246	716	-
acres	5,229,304	4,525,155	81,130	2,973	8,716	154,207	-
Weeds, grass, or brush ..... farms	34,397	25,165	621	336	361	2,569	-
acres	17,661,145	15,416,183	114,923	3,010	18,760	392,688	-
Nematodes ..... farms	3,288	2,557	153	51	30	128	-
acres	977,113	842,933	46,768	448	501	12,037	-
Diseases in crops and orchards ..... farms	5,080	3,745	211	273	83	274	-
acres	2,350,398	2,033,776	56,980	2,018	2,481	111,963	-
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	1,762	1,101	164	140	40	131	-
acres on which used	318,341	227,642	50,621	2,266	607	22,110	-
LAND USE PRACTICES							
Land drained by tile ..... farms	19,088	14,031	186	66	78	1,655	-
acres	8,247,260	7,151,619	30,672	969	4,380	135,233	-
Land artificially drained by ditches ..... farms	9,435	5,600	85	55	83	1,845	-
acres	4,560,910	3,973,481	16,926	839	10,364	325,834	-
Land under conservation easement ..... farms	4,909	1,910	35	39	56	2,258	-
acres	282,171	127,640	3,078	1,287	3,739	110,406	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
VALUE OF LAND AND BUILDINGS - Con.									
Estimated market value of land and buildings - Con.									
Average per farm ..... dollars	-	653,657	772,458	2,664,308	3,663,027	3,658,976	756,410	362,359	609,712
Average per acre ..... dollars	-	4,181	4,355	6,733	6,144	9,943	7,855	8,813	6,533
Farms by value group:									
$1 to $49,999	-	581	245	32	15	79	59	79	245
$50,000 to $99,999	-	1,078	263	5	10	78	67	88	186
$100,000 to $199,999	-	2,555	748	50	50	88	274	291	493
$200,000 to $499,999	-	6,913	2,650	175	109	253	737	711	1,666
$500,000 to $999,999	-	4,575	1,647	170	179	313	360	242	812
$1,000,000 to $1,999,999	-	1,562	768	151	396	280	121	33	178
$2,000,000 to $4,999,999	-	644	340	190	593	330	68	11	81
$5,000,000 to $9,999,999	-	125	58	53	215	238	31	-	20
$10,000,000 or more	-	71	34	66	146	196	7	1	23
VALUE OF MACHINERY AND EQUIPMENT									
Estimated market value of all machinery and equipment ..... farms	-	18,104	6,753	892	1,713	1,855	1,724	1,456	3,704
$1,000	-	1,200,100	723,384	366,074	1,171,427	901,312	293,839	80,781	342,258
Farms by value group:									
$1 to $4,999	-	1,797	314	2	8	31	138	117	235
$5,000 to $9,999	-	2,137	377	8	7	28	104	118	205
$10,000 to $19,999	-	3,150	712	25	20	67	180	247	580
$20,000 to $49,999	-	5,181	1,577	95	78	202	436	457	965
$50,000 to $99,999	-	3,151	1,649	137	99	270	320	261	833
$100,000 to $199,999	-	1,567	1,181	180	211	285	294	174	508
$200,000 to $499,999	-	776	724	210	479	423	146	81	311
$500,000 or more	-	345	219	235	811	549	106	1	67
SELECTED MACHINERY AND EQUIPMENT									
Trucks, including pickups ..... farms	-	9,950	5,744	829	1,660	1,660	1,354	1,137	2,992
number	-	16,371	9,853	2,227	4,612	5,187	2,793	1,534	5,002
Tractors, all ..... farms	-	11,829	5,790	849	1,648	1,513	1,211	1,023	2,723
number	-	28,584	16,187	3,686	10,565	5,344	2,886	1,929	5,070
Less than 40 horsepower (PTO) ..... farms	-	5,803	2,388	265	589	483	763	570	1,456
number	-	8,900	3,699	461	1,238	715	1,126	785	1,973
40 to 99 horsepower (PTO) ..... farms	-	8,133	4,408	599	1,338	915	745	647	1,751
number	-	12,949	7,709	1,149	2,903	1,463	1,111	913	2,427
100 horsepower (PTO) or more ..... farms	-	3,800	2,537	713	1,548	1,104	337	166	407
number	-	6,735	4,779	2,076	6,424	3,166	649	231	670
Grain and bean combines, self-propelled ..... farms	-	1,222	613	357	769	661	122	26	103
number	-	1,436	704	372	863	711	150	26	117
Cotton pickers and strippers, self-propelled ..... farms	-	-	-	-	-	-	-	-	-
number	-	-	-	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	-	375	351	139	480	12	21	17	46
number	-	431	371	140	507	12	27	21	49
Hay balers ..... farms	-	4,638	3,517	550	1,194	305	292	470	1,030
number	-	5,912	4,425	728	1,582	353	336	587	1,254
FERTILIZERS AND CHEMICALS									
Commercial fertilizer, lime, and soil conditioners used ..... farms	-	2,845	1,911	593	1,463	944	224	208	637
acres treated	-	400,585	199,211	205,671	543,875	409,004	50,735	3,357	77,668
Manure used ..... farms	-	1,638	2,146	476	1,106	706	273	336	841
acres treated	-	55,249	94,087	77,673	276,400	150,101	16,803	3,651	31,097
Organic fertilizer used ..... farms	-	131	90	12	65	20	25	28	40
acres treated	-	5,462	5,562	1,388	16,371	2,337	399	911	1,805
Acres treated to control-									
Insects ..... farms	-	716	387	201	644	460	63	55	135
acres	-	154,207	44,666	54,288	148,844	173,488	6,228	647	28,962
Weeds, grass, or brush ..... farms	-	2,569	1,435	572	1,443	954	265	161	515
acres	-	392,688	171,920	229,000	551,201	596,663	66,314	2,957	97,526
Nematodes ..... farms	-	128	65	48	89	125	6	2	34
acres	-	12,037	3,606	10,964	16,555	34,372	(D)	(D)	7,984
Diseases in crops and orchards ..... farms	-	274	91	59	130	185	15	1	13
acres	-	111,963	12,113	15,296	36,299	67,401	(D)	(D)	9,960
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	-	131	54	24	41	48	-	4	15
acres on which used	-	22,110	1,007	1,593	5,779	6,283	-	(D)	(D)
LAND USE PRACTICES									
Land drained by tile ..... farms	-	1,655	661	334	701	818	126	138	294
acres	-	135,233	83,846	130,754	219,950	427,340	29,143	3,043	30,311
Land artificially drained by ditches ..... farms	-	1,845	666	114	307	172	132	100	276
acres	-	325,834	81,808	21,122	58,921	48,069	13,699	2,329	7,518
Land under conservation easement ..... farms	-	2,258	242	35	42	48	51	57	136
acres	-	110,406	18,189	1,659	3,084	1,985	2,383	2,036	6,685

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
							Total	Tobacco farming (11191)
LAND USE PRACTICES - Con.								
Cropland on which no-till practices were used	farms	6,845	4,587	235	88	119	638	-
	acres	1,194,987	1,017,652	8,690	639	1,983	36,479	-
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms	15,574	11,684	286	56	105	1,031	-
	acres	7,881,385	6,875,154	48,990	281	3,315	127,546	-
Cropland on which intensive or conventional tillage practices were used (see text)	farms	22,330	15,935	461	113	180	1,968	-
	acres	9,573,777	8,359,203	71,609	1,462	9,100	269,909	-
Cropland planted to a cover crop (excluding CRP)	farms	6,050	3,203	252	157	153	943	-
	acres	760,423	574,987	20,913	973	1,758	54,397	-
Use of precision agriculture practices (see text)	farms	15,460	12,137	93	26	41	947	-
RENEWABLE ENERGY								
Renewable energy producing systems (see text)	farms	4,247	1,804	103	101	104	832	-
Solar panels	farms	2,063	643	86	77	84	403	-
Wind turbines	farms	819	554	7	2	3	113	-
Methane digesters	farms	15	-	-	-	-	-	-
Geothermal/geoexchange systems	farms	1,695	770	18	38	26	363	-
Small hydro systems	farms	24	4	-	-	7	7	-
Wind rights leased to others	farms	1,189	752	2	4	-	226	-
TENURE								
Full owners	farms	40,396	9,553	751	891	789	15,942	-
Part owners	farms	20,564	13,603	173	43	91	1,816	-
Tenants	farms	4,571	3,159	148	38	91	346	-
OWNED AND RENTED LAND								
Land owned	farms	61,213	23,340	926	936	880	17,803	-
	acres	15,768,785	9,116,570	134,815	96,355	72,983	3,714,140	-
Owned land in farms	farms	60,960	23,156	924	934	880	17,758	-
	acres	13,006,137	8,058,830	101,706	87,667	61,384	2,386,406	-
Land rented or leased from others	farms	25,328	16,869	325	84	185	2,206	-
	acres	12,515,140	10,445,082	77,945	1,506	12,642	452,851	-
Rented or leased land in farms	farms	25,135	16,762	321	81	182	2,162	-
	acres	12,436,488	10,390,422	72,635	1,407	12,294	443,762	-
Land rented or leased to others	farms	15,946	5,631	184	176	152	6,648	-
	acres	2,841,300	1,112,400	38,419	8,787	11,947	1,336,823	-
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS								
Total producers		118,256	45,117	2,004	1,912	2,132	33,661	-
Farms by number of producers:								
1 producer		28,348	13,021	378	258	311	8,076	-
2 producers		28,866	9,959	568	596	447	7,657	-
3 producers		4,480	1,959	60	59	87	1,056	-
4 producers		2,500	984	45	48	70	723	-
5 or more producers		1,337	392	21	11	56	592	-
Total male producers		81,062	34,018	1,235	1,115	1,281	22,316	-
Farms by number of male producers:								
1 producer		49,919	19,808	823	775	662	13,663	-
2 producers		8,600	4,308	110	123	139	1,792	-
3 producers		2,596	1,211	50	21	66	672	-
4 producers		766	298	5	1	14	324	-
5 or more producers		459	124	4	2	14	240	-
Total female producers		37,193	11,098	769	797	851	11,345	-
Farms by number of female producers:								
1 producer		29,936	9,059	626	655	534	8,633	-
2 producers		2,374	758	39	46	81	748	-
3 producers		466	96	6	6	34	196	-
4 producers		138	37	4	3	5	73	-
5 or more producers		90	17	6	1	3	53	-
PRODUCERS' CHARACTERISTICS [3]								
Sex of producers:								
Male		79,245	33,645	1,210	1,088	1,217	21,232	-
Female		35,623	10,675	748	775	753	10,586	-
Hired managers		6,902	3,501	188	140	463	336	-
Primary occupation:								
Farming		51,122	26,324	882	645	885	7,918	-
Other		63,746	17,996	1,076	1,218	1,085	23,900	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
		Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
LAND USE PRACTICES - Con.										
Cropland on which no-till practices were used	farms	-	638	344	126	323	156	77	43	109
	acres	-	36,479	19,081	25,970	44,882	31,652	2,951	374	4,634
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms	-	1,031	580	280	781	468	103	61	139
	acres	-	127,546	72,558	95,947	280,971	288,683	35,471	1,131	51,338
Cropland on which intensive or conventional tillage practices were used (see text)	farms	-	1,968	1,164	376	942	601	220	103	267
	acres	-	269,909	97,541	116,959	284,786	285,892	30,725	2,263	44,328
Cropland planted to a cover crop (excluding CRP)	farms	-	943	401	137	436	76	83	49	160
	acres	-	54,397	17,950	14,451	50,117	13,852	3,730	850	6,445
Use of precision agriculture practices (see text)	farms	-	947	393	258	527	744	101	78	115
RENEWABLE ENERGY										
Renewable energy producing systems (see text)	farms	-	832	343	68	119	232	138	142	261
Solar panels	farms	-	403	188	26	62	114	109	102	169
Wind turbines	farms	-	113	34	19	19	47	3	5	13
Methane digesters	farms	-	-	1	-	5	6	-	-	3
Geothermal/geoexchange systems	farms	-	363	156	26	45	81	28	48	96
Small hydro systems	farms	-	7	2	-	1	-	1	-	2
Wind rights leased to others	farms	-	226	66	30	27	46	7	7	22
TENURE										
Full owners	farms	-	15,942	4,589	391	476	951	1,535	1,268	3,260
Part owners	farms	-	1,816	1,824	450	1,154	767	145	126	372
Tenants	farms	-	346	340	51	83	137	44	62	72
OWNED AND RENTED LAND										
Land owned	farms	-	17,803	6,426	843	1,630	1,720	1,682	1,394	3,633
	acres	-	3,714,140	1,000,153	219,245	594,553	303,200	153,391	71,992	291,388
Owned land in farms	farms	-	17,758	6,413	841	1,630	1,718	1,680	1,394	3,632
	acres	-	2,386,406	843,568	187,146	583,708	273,179	124,652	54,304	243,587
Land rented or leased from others	farms	-	2,206	2,184	501	1,241	908	192	189	444
	acres	-	452,851	359,031	165,824	440,704	410,010	41,792	5,612	102,141
Rented or leased land in farms	farms	-	2,162	2,164	501	1,237	904	189	188	444
	acres	-	443,762	354,123	165,803	437,590	409,420	41,353	5,560	102,119
Land rented or leased to others	farms	-	6,648	1,498	173	99	263	298	217	607
	acres	-	1,336,823	161,493	32,120	13,959	30,611	29,178	17,740	47,823
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS										
Total producers		-	33,661	11,690	1,590	3,873	3,611	3,248	2,694	6,724
Farms by number of producers:										
1 producer		-	8,076	2,719	410	455	684	432	430	1,174
2 producers		-	7,657	3,479	340	711	807	1,153	886	2,263
3 producers		-	1,056	316	90	298	241	65	86	163
4 producers		-	723	166	42	186	67	60	44	65
5 or more producers		-	592	73	10	63	56	14	10	39
Total male producers		-	22,316	7,478	1,140	2,732	2,682	1,852	1,466	3,747
Farms by number of male producers:										
1 producer		-	13,663	5,689	675	955	1,247	1,465	1,201	2,956
2 producers		-	1,792	637	136	480	397	120	106	252
3 producers		-	672	120	58	191	146	29	11	21
4 producers		-	324	32	2	48	20	15	-	7
5 or more producers		-	240	5	2	10	23	-	4	31
Total female producers		-	11,345	4,212	450	1,141	929	1,396	1,228	2,977
Farms by number of female producers:										
1 producer		-	8,633	3,651	374	823	766	1,232	989	2,594
2 producers		-	748	192	29	115	53	70	83	160
3 producers		-	196	48	4	18	19	8	15	16
4 producers		-	73	7	-	7	-	-	2	-
5 or more producers		-	53	1	1	1	-	-	4	3
PRODUCERS' CHARACTERISTICS [3]										
Sex of producers:										
Male		-	21,232	7,436	1,136	2,694	2,631	1,845	1,456	3,655
Female		-	10,586	4,145	432	1,073	882	1,384	1,220	2,950
Hired managers		-	336	181	169	1,008	504	203	25	184
Primary occupation:										
Farming		-	7,918	4,116	953	3,295	2,234	1,040	655	2,175
Other		-	23,900	7,465	615	472	1,279	2,189	2,021	4,430

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
						Total	Tobacco farming (11191)
PRODUCERS' CHARACTERISTICS [3] - Con.							
Place of residence:							
On farm operated	79,195	30,421	1,387	1,354	1,228	16,972	-
Not on farm operated	35,673	13,899	571	509	742	14,846	-
Days of work off farm:							
None	46,862	19,648	715	558	753	13,130	-
Any	68,006	24,672	1,243	1,305	1,217	18,688	-
1 to 49 days	9,840	4,240	155	186	184	2,860	-
50 to 99 days	4,745	2,184	121	116	91	1,030	-
100 to 199 days	8,361	3,297	224	167	151	1,907	-
200 days or more	45,060	14,951	743	836	791	12,891	-
Years on present farm:							
2 years or less	4,867	1,497	181	121	184	1,376	-
3 or 4 years	7,650	2,449	278	219	235	1,857	-
5 to 9 years	18,524	5,888	439	526	444	4,555	-
10 years or more	83,827	34,486	1,060	997	1,107	24,030	-
Average years on present farm	24.2	27.2	17.1	15.5	18.1	24.3	-
Years operating any farm:							
5 years or less	13,846	4,239	485	362	495	3,607	-
6 to 10 years	15,740	4,940	376	504	305	4,073	-
11 years or more	85,282	35,141	1,097	997	1,170	24,138	-
Average years on any farm	26.1	29.3	18.9	17.0	19.9	26.0	-
Age group:							
Under 25 years	1,900	648	43	29	38	282	-
25 to 34 years	9,374	3,959	214	141	204	1,375	-
35 to 44 years	16,237	6,483	370	265	409	2,794	-
45 to 54 years	16,743	6,174	332	291	290	3,961	-
55 to 64 years	29,818	11,559	459	517	450	8,349	-
65 to 74 years	27,187	10,418	386	443	428	9,119	-
75 years and over	13,609	5,079	154	177	151	5,938	-
Average age	57.1	56.8	53.3	56.5	53.9	61.9	-
Young producers (see text)	11,274	4,607	257	170	242	1,657	-
Producers of Hispanic, Latino, or Spanish origin	754	228	17	19	8	232	-
Producers by race:							
American Indian or Alaska Native	244	38	12	11	4	110	-
Asian	306	37	109	21	34	59	-
Black or African American	61	12	4	-	6	25	-
Native Hawaiian or Other Pacific Islander	43	11	1	-	1	21	-
White	113,864	44,145	1,819	1,826	1,909	31,459	-
More than one race reported	350	77	13	5	16	144	-
Military service:							
Never served or only on active duty for training in the Reserves or National Guard (see text)	105,603	41,360	1,832	1,658	1,840	28,183	-
Active duty now or in the past (see text)	9,265	2,960	126	205	130	3,635	-
Number of persons living in producers' households	228,210	92,890	3,874	3,197	3,940	58,510	-
On farm involvement in decisionmaking:							
Day-to-day decisions	98,292	38,503	1,690	1,654	1,691	25,252	-
Land use and/or crop decisions	83,860	35,528	1,563	1,486	1,494	20,511	-
Livestock decisions	49,585	13,071	636	597	383	9,180	-
Marketing decisions (see text)	68,020	32,488	1,295	1,203	1,285	10,590	-
Record keeping and/or financial management	84,043	35,292	1,425	1,324	1,400	20,251	-
Estate planning or succession planning	64,079	26,862	911	938	904	16,160	-
FARMS BY TYPE OF ORGANIZATION							
Operation more than 50 percent owned by one producer's household and/or extended family ... farms	62,111	24,935	1,025	922	908	16,937	-
acres	22,990,670	16,707,977	157,872	38,232	66,478	2,542,561	-
Limited Liability Company ... farms	4,803	1,514	175	245	260	1,013	-
acres	2,179,815	1,479,283	28,982	9,294	16,389	197,158	-
LEGAL STATUS FOR TAX PURPOSES							
Family or individual ... farms	55,532	21,970	890	754	630	15,551	-
acres	17,410,756	12,528,450	94,015	26,148	38,405	2,190,209	-
Partnership ... farms	5,022	2,344	75	97	112	1,270	-
acres	4,452,974	3,429,944	23,413	(D)	(D)	306,796	-
Registered under State law ... farms	4,156	1,923	61	91	110	1,008	-
acres	3,904,476	3,025,748	23,148	(D)	(D)	257,253	-
Corporation ... farms	3,803	1,677	76	108	221	669	-
acres	3,244,861	2,348,500	52,067	6,890	24,379	234,572	-
Family held ... farms	3,375	1,588	55	93	172	529	-
acres	3,085,380	2,284,321	45,179	5,627	19,604	197,819	-
More than 10 stockholders ... farms	34	10	-	1	4	12	-
10 or less stockholders ... farms	3,341	1,578	55	92	168	517	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
PRODUCERS' CHARACTERISTICS [3] - Con.									
Place of residence:									
On farm operated	-	16,972	9,972	1,238	3,117	2,237	2,914	2,459	5,896
Not on farm operated	-	14,846	1,609	330	650	1,276	315	217	709
Days of work off farm:									
None	-	13,130	3,301	674	2,921	1,577	935	580	2,070
Any	-	18,688	8,280	894	846	1,936	2,294	2,096	4,535
1 to 49 days	-	2,860	720	136	193	341	239	181	405
50 to 99 days	-	1,030	450	47	80	121	131	90	284
100 to 199 days	-	1,907	1,134	123	126	196	256	268	512
200 days or more	-	12,891	5,976	588	447	1,278	1,668	1,557	3,334
Years on present farm:									
2 years or less	-	1,376	499	21	117	98	261	166	346
3 or 4 years	-	1,857	805	91	191	217	414	337	557
5 to 9 years	-	4,555	2,060	187	404	811	959	814	1,437
10 years or more	-	24,030	8,217	1,269	3,055	2,387	1,595	1,359	4,265
Average years on present farm	-	24.3	22.6	25.9	26.6	21.2	15.4	15.4	19.3
Years operating any farm:									
5 years or less	-	3,607	1,543	135	280	431	693	563	1,013
6 to 10 years	-	4,073	1,656	149	325	530	926	715	1,241
11 years or more	-	24,138	8,382	1,284	3,162	2,552	1,610	1,398	4,351
Average years on any farm	-	26.0	24.4	28.1	29.1	24.4	17.1	17.3	21.4
Age group:									
Under 25 years	-	282	342	62	127	52	59	143	75
25 to 34 years	-	1,375	1,164	166	437	567	355	366	426
35 to 44 years	-	2,794	1,854	286	656	812	758	558	992
45 to 54 years	-	3,961	1,928	241	641	559	715	492	1,119
55 to 64 years	-	8,349	2,930	421	1,105	885	692	577	1,874
65 to 74 years	-	9,119	2,490	306	598	504	516	395	1,584
75 years and over	-	5,938	873	86	203	134	134	145	535
Average age	-	61.9	54.3	52.8	52.3	50.0	51.1	50.1	56.5
Young producers (see text)	-	1,657	1,506	228	564	619	414	509	501
Producers of Hispanic, Latino, or Spanish origin	-	232	44	6	29	48	64	33	26
Producers by race:									
American Indian or Alaska Native	-	110	18	2	-	1	21	7	20
Asian	-	59	14	-	3	6	9	6	8
Black or African American	-	25	3	-	-	-	2	3	6
Native Hawaiian or Other Pacific Islander	-	21	3	-	-	-	6	-	-
White	-	31,459	11,511	1,565	3,760	3,506	3,166	2,652	6,546
More than one race reported	-	144	32	1	4	-	25	8	25
Military service:									
Never served or only on active duty for training in the Reserves or National Guard (see text)	-	28,183	10,704	1,491	3,681	3,405	2,925	2,502	6,022
Active duty now or in the past (see text)	-	3,635	877	77	86	108	304	174	583
Number of persons living in producers' households	-	58,510	22,061	3,388	8,832	8,267	6,525	5,164	11,562
On farm involvement in decisionmaking:									
Day-to-day decisions	-	25,252	10,296	1,417	3,402	3,053	2,933	2,410	5,991
Land use and/or crop decisions	-	20,511	8,359	1,151	2,893	2,174	2,127	1,892	4,682
Livestock decisions	-	9,180	9,579	1,306	3,120	2,407	2,261	2,261	4,784
Marketing decisions (see text)	-	10,590	7,777	1,194	2,744	2,260	1,746	1,773	3,665
Record keeping and/or financial management	-	20,251	8,822	1,245	2,832	2,724	2,209	1,991	4,528
Estate planning or succession planning	-	16,160	6,466	1,033	2,286	2,144	1,619	1,357	3,399
FARMS BY TYPE OF ORGANIZATION									
Operation more than 50 percent owned by one producer's household and/or extended family ... farms	-	16,937	6,608	846	1,600	1,629	1,647	1,452	3,602
acres	-	2,542,561	1,149,211	318,539	921,126	610,802	136,876	59,296	281,700
Limited Liability Company ... farms	-	1,013	275	79	248	238	174	119	463
acres	-	197,158	73,318	46,378	204,059	71,308	17,494	3,320	32,832
LEGAL STATUS FOR TAX PURPOSES									
Family or individual ... farms	-	15,551	6,290	734	1,136	1,324	1,482	1,404	3,367
acres	-	2,190,209	1,016,707	226,409	499,668	423,401	98,348	54,412	214,584
Partnership ... farms	-	1,270	269	73	340	244	69	25	104
acres	-	306,796	109,232	70,038	287,647	119,569	13,249	3,433	73,926
Registered under State law ... farms	-	1,008	176	69	311	224	62	25	96
acres	-	257,253	59,672	65,867	264,425	104,964	12,258	3,433	72,617
Corporation ... farms	-	669	140	85	225	278	163	19	142
acres	-	234,572	62,892	56,502	230,241	136,121	53,332	1,246	38,119
Family held ... farms	-	529	125	80	218	246	133	18	118
acres	-	197,819	60,218	49,102	222,768	132,613	38,478	(D)	(D)
More than 10 stockholders ... farms	-	12	-	-	-	6	-	-	1
10 or less stockholders ... farms	-	517	125	80	218	240	133	18	117

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
							Total	Tobacco farming (11191)
LEGAL STATUS FOR TAX PURPOSES - Con.								
Corporation - Con.								
Other than family held	farms	428	89	21	15	49	140	-
	acres	159,481	64,179	6,888	1,263	4,775	36,753	-
More than 10 stockholders	farms	67	2	3	3	2	33	-
10 or less stockholders	farms	361	87	18	12	47	107	-
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	farms	1,174	324	31	13	8	614	-
	acres	334,034	142,358	4,846	(D)	(D)	98,591	-
HIRED FARM LABOR								
Hired farm labor	farms	17,399	9,651	330	255	435	2,038	-
	workers	72,097	31,138	2,804	1,896	5,925	5,352	-
Workers by days worked:								
150 days or more	farms	9,054	4,728	163	103	282	792	-
	workers	30,983	10,677	851	372	2,775	1,588	-
Less than 150 days	farms	12,949	7,456	265	230	352	1,541	-
	workers	41,114	20,461	1,953	1,524	3,150	3,764	-
Migrant farm labor on farms with hired labor	farms	573	232	53	20	30	24	-
Migrant farm labor on farms reporting only contract labor	farms	41	13	3	7	1	2	-
Unpaid workers	farms	17,519	6,395	350	427	334	4,101	-
	workers	40,333	13,348	1,021	1,274	862	9,358	-
FARMS BY SIZE								
1 to 9 acres		4,401	262	331	248	300	623	-
10 to 49 acres		15,218	2,239	402	509	358	5,447	-
50 to 69 acres		3,598	854	47	42	56	1,570	-
70 to 99 acres		5,575	1,631	60	74	69	2,522	-
100 to 139 acres		4,857	1,706	43	33	55	1,971	-
140 to 179 acres		4,814	2,129	22	21	26	1,691	-
180 to 219 acres		2,981	1,409	15	12	22	948	-
220 to 259 acres		2,503	1,287	11	9	10	712	-
260 to 499 acres		8,699	5,053	58	19	49	1,730	-
500 to 999 acres		6,421	4,447	33	3	19	635	-
1,000 to 1,999 acres		3,752	2,870	38	1	7	168	-
2,000 acres or more		2,712	2,428	12	1	-	87	-
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)								
Oilseed and grain farming (1111)		26,315	26,315	-	-	-	-	-
Vegetable and melon farming (1112)		1,072	-	1,072	-	-	-	-
Fruit and tree nut farming (1113)		972	-	-	972	-	-	-
Greenhouse, nursery, and floriculture production (1114)		971	-	-	-	971	-	-
Other crop farming (1119)		18,104	-	-	-	-	18,104	-
Tobacco farming (11191)		-	-	-	-	-	-	-
Cotton farming (11192)		-	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)		18,104	-	-	-	-	18,104	-
Beef cattle ranching and farming (112111)		6,753	-	-	-	-	-	-
Cattle feedlots (112112)		892	-	-	-	-	-	-
Dairy cattle and milk production (11212)		1,713	-	-	-	-	-	-
Hog and pig farming (1122)		1,855	-	-	-	-	-	-
Poultry and egg production (1123)		1,724	-	-	-	-	-	-
Sheep and goat farming (1124)		1,456	-	-	-	-	-	-
Aquaculture and other animal production (1125,1129)		3,704	-	-	-	-	-	-
FARM TYPOLOGY (SEE TEXT)								
Farms by typology group:								
Small family farms								
Gross cash farm income less than $150,000		41,924	10,065	845	865	704	16,217	-
Gross cash farm income $150,000 to $349,999		7,074	5,250	96	42	81	454	-
Midsize family farms								
Gross cash farm income $350,000 to $999,999		7,367	5,684	28	10	68	176	-
Large family farms								
Gross cash farm income $1,000,000 to $4,999,999		5,311	3,802	40	5	45	87	-
Gross cash farm income $5,000,000 or more		435	134	16	-	10	3	-
Non-family farms		3,420	1,380	47	50	63	1,167	-
OTHER FARM CHARACTERISTICS								
Farms reporting-								
Internet access		53,964	22,702	909	879	874	12,956	-
Dial-up		1,876	746	21	34	32	507	-
Broadband (DSL, cable, fiber optic) (see text)		33,399	13,960	575	616	625	8,086	-
Cellular data plan (see text)		32,121	14,124	563	522	486	7,021	-
Satellite		8,385	3,852	108	103	125	1,568	-
Don't know		2,877	1,303	39	21	20	834	-
Other		346	159	2	2	3	62	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
LEGAL STATUS FOR TAX PURPOSES - Con.									
Corporation - Con.									
Other than family held ..... farms	-	140	15	5	7	32	30	1	24
acres	-	36,753	2,674	7,400	7,473	3,508	14,854	(D)	(D)
More than 10 stockholders ..... farms	-	33	4	-	2	3	14	1	-
10 or less stockholders ..... farms	-	107	11	5	5	29	16	-	24
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. farms	-	614	54	-	12	9	10	8	91
acres	-	98,591	8,860	-	3,742	3,508	1,076	773	19,077
HIRED FARM LABOR									
Hired farm labor ..... farms	-	2,038	1,004	353	1,244	960	397	166	566
workers	-	5,352	2,262	1,385	9,222	6,080	3,061	409	2,563
Workers by days worked:									
150 days or more ..... farms	-	792	446	242	1,077	609	245	57	310
workers	-	1,588	844	742	6,198	3,730	1,812	126	1,268
Less than 150 days ..... farms	-	1,541	727	216	699	655	275	134	399
workers	-	3,764	1,418	643	3,024	2,350	1,249	283	1,295
Migrant farm labor on farms with hired labor ..... farms	-	24	3	4	122	38	8	3	36
Migrant farm labor on farms reporting only contract labor ..... farms	-	2	-	-	-	1	3	2	9
Unpaid workers ..... farms	-	4,101	2,270	220	438	468	585	560	1,371
workers	-	9,358	5,526	512	1,189	993	1,599	1,442	3,209
FARMS BY SIZE									
1 to 9 acres	-	623	676	66	37	389	346	425	698
10 to 49 acres	-	5,447	2,127	136	72	433	852	739	1,904
50 to 69 acres	-	1,570	445	45	35	48	90	86	280
70 to 99 acres	-	2,522	649	47	37	77	115	75	219
100 to 139 acres	-	1,971	557	62	52	60	77	63	178
140 to 179 acres	-	1,691	508	50	65	64	71	34	133
180 to 219 acres	-	948	266	33	118	52	25	7	74
220 to 259 acres	-	712	248	49	82	33	24	4	34
260 to 499 acres	-	1,730	725	178	479	235	57	16	100
500 to 999 acres	-	635	377	129	440	251	45	3	39
1,000 to 1,999 acres	-	168	135	82	251	162	14	3	21
2,000 acres or more	-	87	40	15	45	51	8	1	24
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)									
Oilseed and grain farming (1111)	-	-	-	-	-	-	-	-	-
Vegetable and melon farming (1112)	-	-	-	-	-	-	-	-	-
Fruit and tree nut farming (1113)	-	-	-	-	-	-	-	-	-
Greenhouse, nursery, and floriculture production (1114)	-	-	-	-	-	-	-	-	-
Other crop farming (1119)	-	18,104	-	-	-	-	-	-	-
Tobacco farming (11191)	-	-	-	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	-	18,104	-	-	-	-	-	-	-
Beef cattle ranching and farming (112111)	-	-	6,753	-	-	-	-	-	-
Cattle feedlots (112112)	-	-	-	892	-	-	-	-	-
Dairy cattle and milk production (11212)	-	-	-	-	1,713	-	-	-	-
Hog and pig farming (1122)	-	-	-	-	-	1,855	-	-	-
Poultry and egg production (1123)	-	-	-	-	-	-	1,724	-	-
Sheep and goat farming (1124)	-	-	-	-	-	-	-	1,456	-
Aquaculture and other animal production (1125,1129)	-	-	-	-	-	-	-	-	3,704
FARM TYPOLOGY (SEE TEXT)									
Farms by typology group:									
Small family farms									
Gross cash farm income less than $150,000	-	16,217	6,078	353	146	484	1,364	1,414	3,389
Gross cash farm income $150,000 to $349,999 ..	-	454	288	116	206	327	80	19	115
Midsize family farms									
Gross cash farm income $350,000 to $999,999 ..	-	176	135	163	606	328	80	19	70
Large family farms									
Gross cash farm income $1,000,000 to $4,999,999	-	87	100	178	570	392	74	-	18
Gross cash farm income $5,000,000 or more	-	3	7	36	72	98	49	-	10
Non-family farms	-	1,167	145	46	113	226	77	4	102
OTHER FARM CHARACTERISTICS									
Farms reporting-									
Internet access	-	12,956	5,637	768	1,502	1,727	1,562	1,295	3,153
Dial-up	-	507	202	23	71	59	52	30	99
Broadband (DSL, cable, fiber optic) (see text)	-	8,086	3,438	437	863	1,010	966	783	2,040
Cellular data plan (see text)	-	7,021	3,242	501	955	1,055	985	780	1,887
Satellite	-	1,568	799	135	295	360	242	263	535
Don't know	-	834	324	36	66	68	39	43	84
Other	-	62	24	5	16	31	22	4	16

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
						Total	Tobacco farming (11191)
OTHER FARM CHARACTERISTICS - Con.							
Farms by number of households sharing in net income of operation:							
1 household	52,287	20,246	920	821	798	14,347	-
2 households	9,039	4,404	103	126	99	2,125	-
3 households	2,321	1,069	29	13	29	717	-
4 households	1,024	337	12	9	37	463	-
5 or more households	860	259	8	3	8	452	-
LIVESTOCK							
Cattle and calves inventory ... farms	16,823	4,981	68	35	14	1,867	-
number	2,121,625	432,394	1,066	279	351	74,090	-
Farms with-							
1 to 9	3,446	576	43	26	7	502	-
10 to 49	6,556	2,141	21	8	5	971	-
50 to 99	2,582	1,036	2	1	1	225	-
100 to 199	1,927	723	2	-	1	121	-
200 to 499	1,348	366	-	-	-	35	-
500 or more	964	139	-	-	-	13	-
Cows and heifers that calved ... farms	13,439	3,675	54	23	11	1,664	-
number	824,165	138,249	666	97	227	38,281	-
Beef cows ... farms	11,691	3,561	46	23	10	1,621	-
number	364,629	129,075	(D)	(D)	(D)	35,109	-
Farms with-							
1 to 9	3,718	703	31	21	5	623	-
10 to 49	6,113	2,085	13	2	4	849	-
50 to 99	1,205	522	-	-	1	110	-
100 to 199	470	193	2	-	-	28	-
200 to 499	149	52	-	-	-	11	-
500 or more	36	6	-	-	-	-	-
Milk cows ... farms	2,185	156	17	1	1	84	-
number	459,536	9,174	(D)	(D)	(D)	3,172	-
Farms with-							
1 to 9	328	42	17	1	-	56	-
10 to 49	315	41	-	-	-	7	-
50 to 99	573	45	-	-	1	11	-
100 to 199	418	22	-	-	-	3	-
200 to 499	390	5	-	-	-	7	-
500 or more	161	1	-	-	-	-	-
Other cattle ... farms	14,574	4,520	43	24	9	1,529	-
number	1,297,460	294,145	400	182	124	35,809	-
Cattle and calves sold ... farms	14,649	4,398	39	16	7	1,360	-
number	1,599,910	273,496	616	91	125	34,119	-
$1,000	2,094,135	373,577	554	104	140	36,982	-
Calves weighing less than 500 pounds ... farms	4,938	1,044	12	-	2	485	-
number	345,069	28,416	(D)	-	(D)	6,846	-
Cattle weighing 500 pounds or more ... farms	13,933	4,229	34	16	7	1,242	-
number	1,254,841	245,080	(D)	91	(D)	27,273	-
Cattle on feed ... farms	2,685	1,165	2	1	-	99	-
number	636,782	117,839	(D)	(D)	-	5,708	-
Hogs and pigs inventory ... farms	2,928	486	39	22	1	128	-
number	8,873,776	519,012	848	(D)	(D)	8,123	-
Farms with-							
1 to 24	893	103	35	21	1	110	-
25 to 49	93	26	1	1	-	9	-
50 to 99	71	34	-	-	-	4	-
100 to 199	65	41	-	-	-	1	-
200 to 499	116	54	3	-	-	1	-
500 or more	1,690	228	-	-	-	3	-
Hogs and pigs sold ... farms	3,352	583	43	26	10	139	-
number	28,535,462	1,248,285	1,042	172	34	31,122	-
$1,000	4,666,832	248,695	329	55	6	4,170	-
Sheep and lambs inventory ... farms	2,137	298	25	26	20	233	-
number	109,592	27,079	487	193	493	5,578	-
Sheep and lambs sold ... farms	1,500	234	9	6	10	121	-
number	92,512	27,029	300	27	397	2,653	-
Total horses and ponies inventory ... farms	6,988	908	66	69	36	1,162	-
number	40,131	3,806	311	256	226	4,735	-
Total horses and ponies sold ... farms	1,171	95	2	7	8	45	-
number	4,403	436	(D)	31	(D)	97	-
Goats, all inventory ... farms	2,326	232	37	59	22	272	-
number	50,691	6,196	346	373	324	2,867	-
Goats, all sold ... farms	1,215	125	14	17	5	87	-
number	38,339	3,404	133	(D)	(D)	820	-
POULTRY							
Layers inventory ... farms	6,146	631	192	187	93	907	-
number	14,553,497	14,535	6,129	5,081	1,866	17,795	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
OTHER FARM CHARACTERISTICS - Con.									
Farms by number of households sharing in net income of operation:									
1 household	-	14,347	5,840	700	1,113	1,318	1,508	1,334	3,342
2 households	-	2,125	763	146	421	316	155	100	281
3 households	-	717	85	45	121	144	20	10	39
4 households	-	463	32	1	40	44	21	9	19
5 or more households	-	452	33	-	18	33	20	3	23
LIVESTOCK									
Cattle and calves inventory ... farms	-	1,867	6,234	859	1,712	201	312	141	399
number	-	74,090	404,094	352,123	784,632	17,551	7,877	1,565	45,603
Farms with-									
1 to 9	-	502	1,727	14	18	62	171	95	205
10 to 49	-	971	2,761	182	117	76	111	43	120
50 to 99	-	225	924	158	180	19	12	2	22
100 to 199	-	121	442	111	486	20	9	1	11
200 to 499	-	35	234	172	496	16	8	-	21
500 or more	-	13	146	222	415	8	1	-	20
Cows and heifers that calved ... farms	-	1,664	5,175	333	1,712	152	232	103	305
number	-	38,281	151,105	21,684	453,266	5,719	3,462	769	10,640
Beef cows ... farms	-	1,621	5,134	333	230	148	216	95	274
number	-	35,109	149,907	(D)	9,556	5,543	2,798	(D)	9,362
Farms with-									
1 to 9	-	623	1,785	36	65	68	134	74	173
10 to 49	-	849	2,631	191	117	53	73	20	75
50 to 99	-	110	477	53	18	10	7	1	6
100 to 199	-	28	168	37	19	11	1	-	11
200 to 499	-	11	52	10	11	6	1	-	6
500 or more	-	-	21	6	-	-	-	-	3
Milk cows ... farms	-	84	113	2	1,709	8	33	15	46
number	-	3,172	1,198	(D)	443,710	176	664	(D)	1,278
Farms with-									
1 to 9	-	56	95	2	31	6	26	15	37
10 to 49	-	7	11	-	255	-	1	-	-
50 to 99	-	11	2	-	504	2	5	-	3
100 to 199	-	3	5	-	386	-	-	-	2
200 to 499	-	7	-	-	373	-	1	-	4
500 or more	-	-	-	-	160	-	-	-	-
Other cattle ... farms	-	1,529	5,173	851	1,607	171	224	111	312
number	-	35,809	252,989	330,439	331,366	11,832	4,415	796	34,963
Cattle and calves sold ... farms	-	1,360	5,628	892	1,668	143	108	79	311
number	-	34,119	410,316	443,878	376,190	14,455	4,026	558	42,040
$1,000	-	36,982	465,762	842,125	276,872	20,436	4,953	545	72,084
Calves weighing less than 500 pounds ... farms	-	485	1,919	81	1,199	43	40	30	83
number	-	6,846	105,430	2,029	195,915	1,200	647	95	4,193
Cattle weighing 500 pounds or more ... farms	-	1,242	5,273	892	1,663	137	96	62	282
number	-	27,273	304,886	441,849	180,275	13,255	3,379	463	37,847
Cattle on feed ... farms	-	99	167	892	276	27	14	1	41
number	-	5,708	30,729	419,909	26,537	4,223	(D)	(D)	30,348
Hogs and pigs inventory ... farms	-	128	197	27	51	1,609	111	58	199
number	-	8,123	20,090	23,075	14,429	8,024,840	(D)	(D)	212,430
Farms with-									
1 to 24	-	110	166	9	26	128	102	58	134
25 to 49	-	9	9	2	3	26	4	-	12
50 to 99	-	4	9	-	8	14	-	-	2
100 to 199	-	1	4	2	-	9	-	-	8
200 to 499	-	1	-	-	5	46	-	-	7
500 or more	-	3	9	14	9	1,386	5	-	36
Hogs and pigs sold ... farms	-	139	245	32	46	1,841	92	59	236
number	-	31,122	50,197	62,945	34,501	26,577,943	89,510	218	439,493
$1,000	-	4,170	10,711	15,232	6,991	4,292,520	6,151	55	81,918
Sheep and lambs inventory ... farms	-	233	243	24	37	53	112	824	242
number	-	5,578	8,875	1,440	1,554	3,222	1,324	53,049	6,298
Sheep and lambs sold ... farms	-	121	156	19	23	43	41	679	159
number	-	2,653	5,667	1,257	1,462	3,273	303	45,211	4,933
Total horses and ponies inventory ... farms	-	1,162	1,241	50	111	110	361	276	2,598
number	-	4,735	5,317	204	635	408	1,686	1,040	21,507
Total horses and ponies sold ... farms	-	45	98	2	17	18	23	32	824
number	-	97	329	(D)	(D)	41	45	70	3,309
Goats, all inventory ... farms	-	272	304	27	36	44	262	723	308
number	-	2,867	3,865	1,154	593	456	2,824	27,803	3,890
Goats, all sold ... farms	-	87	112	15	16	17	94	571	142
number	-	820	1,086	355	196	159	572	29,793	1,494
POULTRY									
Layers inventory ... farms	-	907	1,232	62	118	135	1,290	480	819
number	-	17,795	21,498	1,500	20,643	2,523	14,347,374	8,968	105,585

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
						Total	Tobacco farming (11191)
POULTRY - Con.							
Layers inventory - Con.							
Farms with-							
1 to 399	6,045	628	192	184	93	906	-
400 to 3,199	36	3	-	3	-	1	-
3,200 to 9,999	8	-	-	-	-	-	-
10,000 to 19,999	24	-	-	-	-	-	-
20,000 to 49,999	4	-	-	-	-	-	-
50,000 to 99,999	5	-	-	-	-	-	-
100,000 or more	24	-	-	-	-	-	-
Pullets for laying flock replacement inventory ..... farms	723	33	13	27	6	72	-
number	4,185,443	200,909	458	203	121	1,390	-
Layers sold ..... farms	664	54	17	53	7	75	-
number	7,016,481	2,453	574	1,928	88	6,537	-
Pullets for laying flock replacement sold ..... farms	102	5	-	-	2	7	-
number	8,319,040	550	-	-	(D)	(D)	-
Broilers and other meat-type chickens sold ..... farms	1,028	103	36	35	6	129	-
number	41,793,592	52,615	6,406	1,407	199	16,430	-
Farms with-							
1 to 1,999	900	102	36	35	6	128	-
2,000 to 59,999	11	1	-	-	-	1	-
60,000 to 99,999	-	-	-	-	-	-	-
100,000 or more	117	-	-	-	-	-	-
Turkeys inventory ..... farms	623	37	9	13	5	54	-
number	14,927,734	(D)	144	43	36	(D)	-
Turkeys sold ..... farms	379	13	4	10	2	17	-
number	39,460,145	(D)	190	34	(D)	(D)	-
CROPS							
Barley for grain ..... farms	336	228	1	1	-	37	-
acres	55,330	(D)	(D)	(D)	-	4,470	-
bushels	4,011,381	3,575,916	(D)	(D)	-	(D)	-
Irrigated ..... farms	10	7	-	-	-	-	-
acres	116	92	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres	72	36	-	1	-	17	-
25 to 99 acres	96	43	1	-	-	5	-
100 to 249 acres	94	82	-	-	-	8	-
250 to 499 acres	53	49	-	-	-	4	-
500 acres or more	21	18	-	-	-	3	-
Corn for grain ..... farms	24,697	20,353	114	15	18	573	-
acres	7,732,455	6,786,463	21,867	176	759	57,987	-
bushels	1,478,451,268	1,299,702,508	3,912,786	21,258	136,340	10,233,276	-
Irrigated ..... farms	1,341	1,056	28	1	-	28	-
acres	302,897	250,763	(D)	(D)	-	2,681	-
Farms by acres harvested:							
1 to 24 acres	2,863	1,917	44	13	11	281	-
25 to 99 acres	6,867	5,679	26	2	6	176	-
100 to 249 acres	6,444	5,433	15	-	-	66	-
250 to 499 acres	4,136	3,485	17	-	1	16	-
500 acres or more	4,387	3,839	12	-	-	34	-
Corn for silage or greenchop ..... farms	2,768	1,109	2	4	2	174	-
acres	313,974	106,761	(D)	(D)	(D)	6,243	-
tons	6,334,518	2,078,204	(D)	66	(D)	(D)	-
Irrigated ..... farms	108	32	-	-	-	1	-
acres	13,135	(D)	-	-	-	(D)	-
Farms by acres harvested:							
1 to 24 acres	848	443	1	4	2	117	-
25 to 99 acres	1,133	437	-	-	-	40	-
100 to 249 acres	452	125	-	-	-	13	-
250 to 499 acres	218	60	1	-	-	4	-
500 acres or more	117	44	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas ..... farms	573	518	3	1	-	20	-
acres	210,162	190,458	(D)	(D)	-	8,252	-
cwt	5,278,245	4,862,304	(D)	(D)	-	136,911	-
Irrigated ..... farms	95	80	-	-	-	3	-
acres	39,931	(D)	-	-	-	(D)	-
Farms by acres harvested:							
1 to 24 acres	34	24	-	1	-	6	-
25 to 99 acres	118	108	-	-	-	1	-
100 to 249 acres	146	136	-	-	-	1	-
250 to 499 acres	140	129	3	-	-	5	-
500 acres or more	135	121	-	-	-	7	-
Oats for grain ..... farms	2,329	1,459	20	3	3	247	-
acres	126,011	88,766	1,367	15	76	9,914	-
bushels	9,470,546	6,831,650	122,389	(D)	(D)	608,425	-
Irrigated ..... farms	66	46	3	-	-	4	-
acres	3,194	2,724	109	-	-	40	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
POULTRY - Con.									
Layers inventory - Con.									
Farms with-									
1 to 399	-	906	1,232	62	117	135	1,201	480	815
400 to 3,199	-	1	-	-	-	-	26	-	3
3,200 to 9,999	-	-	-	-	-	-	8	-	-
10,000 to 19,999	-	-	-	-	1	-	23	-	-
20,000 to 49,999	-	-	-	-	-	-	4	-	-
50,000 to 99,999	-	-	-	-	-	-	4	-	1
100,000 or more	-	-	-	-	-	-	24	-	-
Pullets for laying flock replacement inventory ..... farms	-	72	115	6	13	20	255	55	108
number	-	1,390	1,715	124	189	274	3,975,378	884	3,798
Layers sold ..... farms	-	75	92	10	5	18	203	55	75
number	-	6,537	1,859	356	(D)	709	(D)	2,408	(D)
Pullets for laying flock replacement sold ..... farms	-	7	-	1	-	1	68	11	7
number	-	(D)	-	(D)	-	(D)	8,316,551	(D)	(D)
Broilers and other meat-type chickens sold ..... farms	-	129	124	11	9	47	333	74	121
number	-	16,430	(D)	1,230	280	1,069,481	40,360,819	3,795	(D)
Farms with-									
1 to 1,999	-	128	124	11	9	43	212	74	120
2,000 to 59,999	-	1	-	-	-	-	9	-	-
60,000 to 99,999	-	-	-	-	-	-	-	-	-
100,000 or more	-	-	-	-	-	4	112	-	1
Turkeys inventory ..... farms	-	54	63	9	3	14	287	42	87
number	-	(D)	288	28	412	(D)	14,543,591	307	(D)
Turkeys sold ..... farms	-	17	17	2	5	4	231	14	60
number	-	(D)	120	(D)	420	(D)	38,372,497	128	(D)
CROPS									
Barley for grain ..... farms	-	37	7	4	53	2	-	2	1
acres	-	4,470	183	152	2,783	(D)	-	(D)	(D)
bushels	-	(D)	6,119	10,684	170,973	(D)	-	(D)	(D)
Irrigated ..... farms	-	-	2	-	-	1	-	-	-
acres	-	-	(D)	-	-	(D)	-	-	-
Farms by acres harvested:									
1 to 24 acres	-	17	2	3	11	-	-	1	1
25 to 99 acres	-	5	5	1	38	2	-	1	-
100 to 249 acres	-	8	-	-	4	-	-	-	-
250 to 499 acres	-	4	-	-	-	-	-	-	-
500 acres or more	-	3	-	-	-	-	-	-	-
Corn for grain ..... farms	-	573	652	498	1,269	876	154	49	126
acres	-	57,987	70,731	135,938	244,441	326,820	35,895	828	50,550
bushels	-	10,233,276	11,799,888	25,240,539	44,690,782	66,133,142	6,766,106	121,744	9,692,899
Irrigated ..... farms	-	28	22	38	97	45	20	1	5
acres	-	2,681	(D)	8,455	10,928	7,612	3,873	(D)	6,425
Farms by acres harvested:									
1 to 24 acres	-	281	291	50	94	31	34	42	55
25 to 99 acres	-	176	191	123	438	152	44	6	24
100 to 249 acres	-	66	75	121	443	245	37	1	8
250 to 499 acres	-	16	53	113	183	228	26	-	14
500 acres or more	-	34	42	91	111	220	13	-	25
Corn for silage or greenchop ..... farms	-	174	300	170	919	21	23	6	38
acres	-	6,243	15,041	18,095	157,462	1,800	1,179	135	6,893
tons	-	(D)	245,040	373,262	3,312,154	37,782	22,570	2,686	150,080
Irrigated ..... farms	-	1	3	6	63	-	1	1	1
acres	-	(D)	149	504	10,144	-	(D)	(D)	(D)
Farms by acres harvested:									
1 to 24 acres	-	117	139	48	66	5	9	4	10
25 to 99 acres	-	40	124	74	422	7	13	2	14
100 to 249 acres	-	13	30	31	236	8	-	-	9
250 to 499 acres	-	4	4	12	134	1	1	-	1
500 acres or more	-	-	3	5	61	-	-	-	4
Dry edible beans, excluding chickpeas and limas ..... farms	-	20	6	1	9	11	1	-	3
acres	-	8,252	334	(D)	2,193	2,898	(D)	-	(D)
cwt	-	136,911	9,480	(D)	58,715	52,430	(D)	-	(D)
Irrigated ..... farms	-	3	-	1	3	6	-	-	2
acres	-	(D)	-	(D)	1,260	(D)	-	-	(D)
Farms by acres harvested:									
1 to 24 acres	-	6	2	-	-	-	-	-	1
25 to 99 acres	-	1	4	-	4	1	-	-	-
100 to 249 acres	-	1	-	-	1	8	-	-	-
250 to 499 acres	-	5	-	-	1	1	1	-	-
500 acres or more	-	7	-	1	3	1	-	-	2
Oats for grain ..... farms	-	247	192	62	256	22	11	24	30
acres	-	9,914	8,757	1,426	13,226	732	244	316	1,172
bushels	-	608,425	578,207	90,930	1,038,011	68,407	18,757	16,760	93,767
Irrigated ..... farms	-	4	4	2	6	1	-	-	-
acres	-	40	(D)	(D)	258	(D)	-	-	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
							Total	Tobacco farming (11191)
CROPS - Con.								
Oats for grain - Con.								
Farms by acres harvested:								
1 to 24 acres		906	525	13	3	2	125	-
25 to 99 acres		1,097	699	5	-	1	95	-
100 to 249 acres		286	201	-	-	-	24	-
250 to 499 acres		29	24	1	-	-	3	-
500 acres or more		11	10	1	-	-	-	-
Sorghum for grain	farms	12	9	-	-	-	1	-
	acres	364	(D)	-	-	-	(D)	-
	bushels	24,260	(D)	-	-	-	(D)	-
Irrigated	farms	-	-	-	-	-	-	-
	acres	-	-	-	-	-	-	-
Farms by acres harvested:								
1 to 24 acres		7	6	-	-	-	-	-
25 to 99 acres		4	2	-	-	-	1	-
100 to 249 acres		1	1	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-	-
500 acres or more		-	-	-	-	-	-	-
Soybeans for beans	farms	25,337	22,130	129	13	20	486	-
	acres	7,597,171	6,941,747	20,347	312	1,323	90,699	-
	bushels	373,669,175	340,481,431	1,010,992	14,803	61,104	3,883,246	-
Irrigated	farms	892	732	31	-	2	23	-
	acres	122,734	101,345	(D)	-	(D)	3,440	-
Farms by acres harvested:								
1 to 24 acres		2,307	1,800	29	7	10	149	-
25 to 99 acres		7,345	6,332	37	6	7	155	-
100 to 249 acres		6,879	6,001	39	-	1	76	-
250 to 499 acres		4,297	3,803	18	-	2	45	-
500 acres or more		4,509	4,194	6	-	-	61	-
Sugarbeets for sugar	farms	1,106	856	1	-	-	227	-
	acres	446,627	351,240	(D)	-	-	87,909	-
	tons	11,642,041	9,067,939	(D)	-	-	2,360,755	-
Irrigated	farms	31	21	-	-	-	2	-
	acres	10,798	6,800	-	-	-	(D)	-
Sunflower seed, all	farms	221	204	1	1	-	15	-
	acres	66,924	(D)	(D)	(D)	-	3,677	-
	pounds	151,726,117	142,433,867	(D)	(D)	-	(D)	-
Irrigated	farms	2	1	1	-	-	-	-
	acres	(D)	(D)	(D)	-	-	-	-
Farms by acres harvested:								
1 to 24 acres		8	6	1	1	-	-	-
25 to 99 acres		53	45	-	-	-	8	-
100 to 249 acres		62	62	-	-	-	-	-
250 to 499 acres		49	45	-	-	-	4	-
500 acres or more		49	46	-	-	-	3	-
Wheat for grain, all	farms	3,669	3,254	19	2	2	183	-
	acres	1,268,681	1,193,872	3,123	(D)	(D)	57,342	-
	bushels	82,039,945	77,081,841	184,892	(D)	(D)	4,086,573	-
Irrigated	farms	52	45	2	-	-	1	-
	acres	6,251	5,436	(D)	-	-	(D)	-
Farms by acres harvested:								
1 to 24 acres		416	325	8	2	1	39	-
25 to 99 acres		1,023	851	3	-	-	36	-
100 to 249 acres		809	729	1	-	1	50	-
250 to 499 acres		544	516	6	-	-	19	-
500 acres or more		877	833	1	-	-	39	-
Forage-land used for all hay and haylage, grass silage, and greenchop	farms	23,394	6,927	186	103	80	7,300	-
	acres	1,392,072	347,096	3,578	1,406	1,622	430,808	-
	tons, dry equivalent	3,565,994	966,370	6,851	2,168	2,926	936,959	-
Irrigated	farms	675	244	11	1	-	157	-
	acres	32,954	9,648	(D)	(D)	-	6,416	-
Farms by acres harvested:								
1 to 24 acres		11,106	3,336	158	91	65	3,283	-
25 to 99 acres		8,179	2,710	24	11	12	2,754	-
100 to 249 acres		3,115	699	2	1	2	988	-
250 to 499 acres		780	145	1	-	1	213	-
500 acres or more		214	37	1	-	-	62	-
Alfalfa hay	farms	15,333	5,265	91	37	43	4,460	-
	acres	744,117	230,628	1,986	470	833	227,103	-
	tons, dry	1,971,568	684,797	4,831	991	1,286	559,593	-
Irrigated	farms	421	186	4	1	-	88	-
	acres	15,949	6,064	(D)	(D)	-	3,686	-
Other dry hay	farms	8,556	2,091	72	44	29	2,907	-
	acres	390,421	73,854	1,273	709	690	154,842	-
	tons, dry	658,360	137,177	1,668	934	1,466	246,802	-
Irrigated	farms	153	45	4	-	-	43	-
	acres	3,658	1,176	21	-	-	1,270	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
	Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
CROPS - Con.									
Oats for grain - Con.									
Farms by acres harvested:									
1 to 24 acres	-	125	73	35	77	7	4	24	18
25 to 99 acres	-	95	89	26	152	14	7	-	9
100 to 249 acres	-	24	30	1	26	1	-	-	3
250 to 499 acres	-	3	-	-	1	-	-	-	-
500 acres or more	-	-	-	-	-	-	-	-	-
Sorghum for grain ... farms	-	1	-	-	1	-	-	-	1
acres	-	(D)	-	-	(D)	-	-	-	(D)
bushels	-	(D)	-	-	(D)	-	-	-	(D)
Irrigated ... farms	-	-	-	-	-	-	-	-	-
acres	-	-	-	-	-	-	-	-	-
Farms by acres harvested:									
1 to 24 acres	-	-	-	-	-	-	-	-	1
25 to 99 acres	-	1	-	-	1	-	-	-	-
100 to 249 acres	-	-	-	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-	-	-	-
500 acres or more	-	-	-	-	-	-	-	-	-
Soybeans for beans ... farms	-	486	414	343	732	830	133	23	84
acres	-	90,699	46,273	68,541	113,699	259,688	26,583	745	27,214
bushels	-	3,883,246	2,173,060	3,568,373	5,804,399	14,018,341	1,371,626	26,881	1,254,919
Irrigated ... farms	-	23	6	4	45	28	17	-	4
acres	-	3,440	412	834	2,634	2,334	2,493	-	1,134
Farms by acres harvested:									
1 to 24 acres	-	149	139	18	59	40	24	9	23
25 to 99 acres	-	155	145	136	317	128	42	14	26
100 to 249 acres	-	76	78	93	229	311	38	-	13
250 to 499 acres	-	45	39	65	85	211	20	-	9
500 acres or more	-	61	13	31	42	140	9	-	13
Sugarbeets for sugar ... farms	-	227	1	-	1	17	1	-	2
acres	-	87,909	(D)	-	(D)	2,547	(D)	-	(D)
tons	-	2,360,755	(D)	-	(D)	71,295	(D)	-	(D)
Irrigated ... farms	-	2	-	-	1	6	-	-	1
acres	-	(D)	-	-	(D)	780	-	-	(D)
Sunflower seed, all ... farms	-	15	-	-	-	-	-	-	-
acres	-	3,677	-	-	-	-	-	-	-
pounds	-	(D)	-	-	-	-	-	-	-
Irrigated ... farms	-	-	-	-	-	-	-	-	-
acres	-	-	-	-	-	-	-	-	-
Farms by acres harvested:									
1 to 24 acres	-	-	-	-	-	-	-	-	-
25 to 99 acres	-	8	-	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	-	-	-	-
250 to 499 acres	-	4	-	-	-	-	-	-	-
500 acres or more	-	3	-	-	-	-	-	-	-
Wheat for grain, all ... farms	-	183	50	20	96	19	6	3	15
acres	-	57,342	3,259	916	7,079	964	1,176	8	828
bushels	-	4,086,573	164,177	(D)	308,233	47,520	(D)	208	51,170
Irrigated ... farms	-	1	-	-	3	-	-	-	1
acres	-	(D)	-	-	(D)	-	-	-	(D)
Farms by acres harvested:									
1 to 24 acres	-	39	13	4	10	4	1	3	6
25 to 99 acres	-	36	27	13	69	13	3	-	8
100 to 249 acres	-	50	9	3	13	2	1	-	-
250 to 499 acres	-	19	1	-	1	-	-	-	1
500 acres or more	-	39	-	-	3	-	1	-	-
Forage-land used for all hay and haylage, grass silage, and greenchop ... farms	-	7,300	3,871	510	1,521	279	452	549	1,616
acres	-	430,808	257,846	36,328	249,402	7,275	10,541	8,954	37,216
tons, dry equivalent	-	936,959	476,712	111,257	944,559	17,977	20,169	15,150	64,896
Irrigated ... farms	-	157	64	20	123	8	10	4	33
acres	-	6,416	2,138	989	12,151	40	333	36	906
Farms by acres harvested:									
1 to 24 acres	-	3,283	1,651	171	88	174	340	459	1,290
25 to 99 acres	-	2,754	1,378	208	530	91	92	83	286
100 to 249 acres	-	988	634	99	629	13	18	4	26
250 to 499 acres	-	213	174	31	201	1	2	2	9
500 acres or more	-	62	34	1	73	-	-	1	5
Alfalfa hay ... farms	-	4,460	2,519	351	987	167	216	334	863
acres	-	227,103	133,354	23,028	97,325	3,790	4,567	4,167	16,866
tons, dry	-	559,593	268,578	66,868	319,778	11,485	11,250	8,468	33,643
Irrigated ... farms	-	88	45	15	58	8	3	1	12
acres	-	3,686	1,624	407	3,422	36	(D)	(D)	262
Other dry hay ... farms	-	2,907	1,607	155	410	112	195	235	699
acres	-	154,842	103,524	7,527	24,185	2,587	4,038	4,184	13,008
tons, dry	-	246,802	155,965	18,808	60,374	4,197	6,329	6,224	18,416
Irrigated ... farms	-	43	16	5	17	2	3	3	15
acres	-	1,270	345	122	508	(D)	64	(D)	142

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Oilseed and grain farming (1111)	Vegetable and melon farming (1112)	Fruit and tree nut farming (1113)	Greenhouse, nursery, and floriculture production (1114)	Other crop farming (1119)	
							Total	Tobacco farming (11191)
CROPS - Con.								
Field and grass seed crops, all	farms	155	117	2	-	-	33	-
	acres	66,601	(D)	(D)	-	-	13,205	-
Irrigated	farms	6	5	-	-	-	1	-
	acres	505	(D)	-	-	-	(D)	-
Land in vegetables	farms	2,620	776	1,070	141	153	207	-
	acres	196,718	94,192	78,106	278	1,173	8,975	-
Irrigated	farms	764	95	391	67	87	67	-
	acres	54,640	12,727	38,100	93	198	1,693	-
Farms by acres harvested:								
0.1 to 4.9 acres		1,355	66	714	131	132	155	-
5.0 to 24.9 acres		225	40	150	8	8	13	-
25.0 to 99.9 acres		495	343	67	2	12	15	-
100.0 to 249.9 acres		364	253	54	-	1	12	-
250.0 acres or more		181	74	85	-	-	12	-
Beans, snap	farms	390	13	246	20	35	36	-
	acres	2,553	1,093	1,319	3	12	35	-
Harvested for processing	farms	22	7	11	-	1	-	-
	acres	2,278	(D)	1,103	-	(D)	-	-
Peas, green	farms	599	350	139	3	9	25	-
	acres	47,364	33,117	(D)	(Z)	(D)	1,683	-
Harvested for processing	farms	491	348	56	-	1	20	-
	acres	47,345	33,117	(D)	-	(D)	1,682	-
Potatoes	farms	509	42	326	29	25	44	-
	acres	49,008	5,053	43,472	(D)	16	164	-
Harvested for processing	farms	39	3	34	-	-	1	-
	acres	35,127	(D)	33,655	-	-	(D)	-
Farms by acres harvested:								
0.1 to 4.9 acres		421	19	265	29	24	42	-
5.0 to 24.9 acres		5	-	3	-	1	1	-
25.0 to 99.9 acres		20	11	9	-	-	-	-
100.0 to 249.9 acres		8	3	4	-	-	1	-
250.0 acres or more		55	9	45	-	-	-	-
Sweet corn (see text)	farms	1,243	563	418	25	35	87	-
	acres	96,990	59,398	21,680	21	590	6,602	-
Harvested for processing	farms	750	514	117	-	6	31	-
	acres	94,536	59,179	19,813	-	522	6,357	-
Sweet potatoes	farms	58	1	40	5	7	3	-
	acres	23	(D)	12	1	1	(D)	-
Harvested for processing	farms	-	-	-	-	-	-	-
	acres	-	-	-	-	-	-	-
Tomatoes in the open	farms	592	12	376	47	66	48	-
	acres	300	3	231	10	27	24	-
Harvested for processing	farms	18	-	7	3	-	-	-
	acres	2	-	1	(D)	-	-	-
Land in orchards	farms	1,174	35	106	830	32	115	-
	acres	5,049	124	121	4,468	60	222	-
Irrigated	farms	204	1	21	148	7	10	-
	acres	778	(D)	15	717	(D)	13	-
Farms by bearing and nonbearing acres:								
0.1 to 4.9 acres		927	26	103	615	26	105	-
5.0 to 24.9 acres		212	9	3	182	6	8	-
25.0 to 99.9 acres		32	-	-	30	-	2	-
100.0 to 249.9 acres		3	-	-	3	-	-	-
250.0 acres or more		-	-	-	-	-	-	-
Apples	farms	751	15	81	534	24	66	-
bearing and nonbearing	acres	3,219	35	82	2,927	16	133	-
Grapes (including muscadine) (see text)	farms	433	18	28	329	7	33	-
bearing and nonbearing	acres	1,290	64	23	1,130	11	44	-
Peaches, all	farms	17	-	5	10	-	1	-
bearing and nonbearing	acres	(D)	-	1	(D)	-	(D)	-
Walnuts, English	farms	29	2	-	21	1	4	-
bearing and nonbearing	acres	142	(D)	-	118	(D)	(D)	-
Land in berries	farms	578	12	86	324	26	80	-
	acres	1,129	77	86	785	19	100	-

See footnote(s) at end of table.

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Table 75. **Summary by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Other crop farming - con. (1119)		Beef cattle ranching and farming (112111)	Cattle feedlots (112112)	Dairy cattle and milk production (11212)	Hog and pig farming (1122)	Poultry and egg production (1123)	Sheep and goat farming (1124)	Aquaculture and other animal production (1125,1129)
		Cotton farming (11192)	Sugarcane farming, hay farming, and all other crop farming (11193, 11194 11199)							
CROPS - Con.										
Field and grass seed crops, all	farms	-	33	2	-	-	-	1	-	-
	acres	-	13,205	(D)	-	-	-	(D)	-	-
Irrigated	farms	-	1	-	-	-	-	-	-	-
	acres	-	(D)	-	-	-	-	-	-	-
Land in vegetables	farms	-	207	45	5	50	58	29	16	70
	acres	-	8,975	901	477	4,632	7,380	(D)	(D)	380
Irrigated	farms	-	67	10	2	9	3	6	4	23
	acres	-	1,693	85	(D)	1,154	(D)	14	3	20
Farms by acres harvested:										
0.1 to 4.9 acres		-	155	35	-	7	8	27	15	65
5.0 to 24.9 acres		-	13	1	-	1	2	1	-	1
25.0 to 99.9 acres		-	15	5	2	27	18	1	-	3
100.0 to 249.9 acres		-	12	4	3	10	25	-	1	1
250.0 acres or more		-	12	-	-	5	5	-	-	-
Beans, snap	farms	-	36	7	-	3	1	-	7	22
	acres	-	35	1	-	84	(D)	-	1	(D)
Harvested for processing	farms	-	-	-	-	3	-	-	-	-
	acres	-	-	-	-	84	-	-	-	-
Peas, green	farms	-	25	6	5	33	21	-	1	7
	acres	-	1,683	(D)	(D)	2,460	(D)	-	(D)	(D)
Harvested for processing	farms	-	20	5	5	33	21	-	1	1
	acres	-	1,682	(D)	(D)	2,460	(D)	-	(D)	(D)
Potatoes	farms	-	44	5	-	3	2	8	9	16
	acres	-	164	1	-	4	(D)	4	3	5
Harvested for processing	farms	-	1	-	-	-	1	-	-	-
	acres	-	(D)	-	-	-	(D)	-	-	-
Farms by acres harvested:										
0.1 to 4.9 acres		-	42	5	-	3	1	8	9	16
5.0 to 24.9 acres		-	1	-	-	-	-	-	-	-
25.0 to 99.9 acres		-	-	-	-	-	-	-	-	-
100.0 to 249.9 acres		-	1	-	-	-	-	-	-	-
250.0 acres or more		-	-	-	-	-	1	-	-	-
Sweet corn (see text)	farms	-	87	16	-	32	41	8	3	15
	acres	-	6,602	478	-	2,317	5,517	(D)	(D)	268
Harvested for processing	farms	-	31	5	-	32	40	1	1	3
	acres	-	6,357	470	-	2,317	5,517	(D)	(D)	(D)
Sweet potatoes	farms	-	3	-	-	-	-	-	-	2
	acres	-	(D)	-	-	-	-	-	-	(D)
Harvested for processing	farms	-	-	-	-	-	-	-	-	-
	acres	-	-	-	-	-	-	-	-	-
Tomatoes in the open	farms	-	48	1	-	5	-	13	9	15
	acres	-	24	(D)	-	1	-	(D)	1	(D)
Harvested for processing	farms	-	-	-	-	-	-	6	-	2
	acres	-	-	-	-	-	-	(D)	-	(D)
Land in orchards	farms	-	115	12	2	1	6	10	3	22
	acres	-	222	17	(D)	(D)	4	6	(D)	21
Irrigated	farms	-	10	4	-	-	4	2	2	5
	acres	-	13	11	-	-	4	(D)	(D)	(D)
Farms by bearing and nonbearing acres:										
0.1 to 4.9 acres		-	105	10	2	1	6	10	3	20
5.0 to 24.9 acres		-	8	2	-	-	-	-	-	2
25.0 to 99.9 acres		-	2	-	-	-	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-	-	-	-	-
250.0 acres or more		-	-	-	-	-	-	-	-	-
Apples	farms	-	66	9	2	1	-	6	3	10
	bearing and nonbearing acres	-	133	14	(D)	(D)	-	(D)	2	6
Grapes (including muscadine) (see text)	farms	-	33	2	2	-	4	4	-	6
	bearing and nonbearing acres	-	44	(D)	(D)	-	4	(D)	-	12
Peaches, all	farms	-	1	-	-	-	-	-	-	1
	bearing and nonbearing acres	-	(D)	-	-	-	-	-	-	(D)
Walnuts, English	farms	-	4	-	-	-	-	-	-	1
	bearing and nonbearing acres	-	(D)	-	-	-	-	-	-	(D)
Land in berries	farms	-	80	14	-	1	2	11	2	20
	acres	-	100	19	-	(D)	(D)	7	(D)	7

[1] Landlord production expenses are included with total farm production expenses.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.
[3] Data were collected for a maximum of four producers per farm.

Table 76. **Summary by Tenure of Farm Operation: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
FARMS AND LAND IN FARMS				
Farms ..... number	65,531	40,396	20,564	4,571
percent	100.0	61.6	31.4	7.0
Land in farms ..... acres	25,442,625	5,657,674	17,880,717	1,904,234
Average size of farm ..... acres	388	140	870	417
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS				
Total ..... farms	65,531	40,396	20,564	4,571
$1,000	29,066,202	6,850,170	20,042,531	2,173,501
Average per farm ..... dollars	443,549	169,575	974,642	475,498
Farms by economic class:				
Less than $1,000	6,079	5,682	265	132
$1,000 to $2,499	6,033	5,711	220	102
$2,500 to $4,999	5,681	5,194	354	133
$5,000 to $9,999	6,141	5,332	562	247
$10,000 to $24,999	7,125	5,568	1,168	389
$25,000 to $49,999	4,813	3,243	1,176	394
$50,000 to $99,999	5,488	3,116	1,764	608
$100,000 to $249,999	6,899	3,136	2,865	898
$250,000 to $499,999	5,477	1,516	3,296	665
$500,000 to $999,999	4,529	741	3,365	423
$1,000,000 or more	7,266	1,157	5,529	580
$1,000,000 to $2,499,999	4,148	651	3,143	354
$2,500,000 to $4,999,999	2,458	318	1,951	189
$5,000,000 or more	660	188	435	37
Total sales ..... farms	65,531	40,396	20,564	4,571
$1,000	28,482,097	6,683,406	19,664,929	2,133,762
Grains, oilseeds, dry beans, and dry peas ..... farms	32,075	11,476	17,068	3,531
$1,000	15,268,581	1,559,314	12,270,439	1,438,829
Sales of $50,000 or more ..... farms	23,618	5,986	14,837	2,795
$1,000	15,113,786	1,468,816	12,222,584	1,422,386
Corn ..... farms	25,230	7,969	14,570	2,691
$1,000	9,045,595	912,187	7,270,388	863,019
Sales of $50,000 or more ..... farms	18,777	4,173	12,502	2,102
$1,000	8,908,714	839,366	7,221,363	847,985
Wheat ..... farms	3,668	756	2,522	390
$1,000	735,504	52,354	627,945	55,205
Sales of $50,000 or more ..... farms	2,125	254	1,622	249
$1,000	707,000	43,909	610,716	52,374
Soybeans ..... farms	25,334	7,765	14,679	2,890
$1,000	5,087,514	556,966	4,042,673	487,875
Sales of $50,000 or more ..... farms	17,131	3,295	11,890	1,946
$1,000	4,898,487	465,706	3,969,282	463,499
Sorghum ..... farms	53	23	22	8
$1,000	437	105	230	102
Sales of $50,000 or more ..... farms	1	-	-	1
$1,000	(D)	-	-	(D)
Barley ..... farms	336	57	243	36
$1,000	27,673	1,017	23,224	3,432
Sales of $50,000 or more ..... farms	151	7	120	24
$1,000	24,984	597	21,173	3,213
Rice ..... farms	-	-	-	-
$1,000	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-
$1,000	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	3,613	1,019	2,319	275
$1,000	371,859	36,685	305,978	29,196
Sales of $50,000 or more ..... farms	1,013	122	793	98
$1,000	342,531	29,956	286,075	26,500
Tobacco ..... farms	-	-	-	-
$1,000	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-
$1,000	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-
$1,000	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-
$1,000	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	2,648	1,408	981	259
$1,000	446,099	70,196	326,328	49,575
Sales of $50,000 or more ..... farms	994	217	685	92
$1,000	424,789	57,506	320,030	47,253
Fruits, tree nuts, and berries ..... farms	1,212	1,062	101	49
$1,000	48,717	35,872	10,559	2,287
Sales of $50,000 or more ..... farms	178	135	29	14
$1,000	38,977	27,529	9,681	1,767
Fruits and tree nuts ..... farms	944	848	72	24
$1,000	30,052	25,468	3,849	735
Sales of $50,000 or more ..... farms	116	93	18	5
$1,000	22,967	19,194	3,203	571
Berries ..... farms	489	411	45	33
$1,000	18,665	10,403	6,709	1,552
Sales of $50,000 or more ..... farms	66	45	12	9
$1,000	15,470	7,911	6,379	1,179
Nursery, greenhouse, floriculture, and sod ..... farms	1,051	807	130	114
$1,000	391,444	263,419	76,447	51,578
Sales of $50,000 or more ..... farms	343	228	75	40
$1,000	381,613	255,586	75,675	50,353
Cultivated Christmas trees and short rotation woody crops ..... farms	244	202	36	6
$1,000	7,578	3,449	3,907	222

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.				
Total - Con.				
Total sales - Con.				
Cultivated Christmas trees and short rotation woody crops - Con.				
Sales of $50,000 or more ..... farms	27	16	10	1
$1,000	6,051	(D)	3,494	(D)
Cultivated Christmas trees ..... farms	243	201	36	6
$1,000	(D)	(D)	3,907	222
Sales of $50,000 or more ..... farms	27	16	10	1
$1,000	6,051	(D)	3,494	(D)
Short rotation woody crops ..... farms	1	1	-	-
$1,000	(D)	(D)	-	-
Sales of $50,000 or more ..... farms	-	-	-	-
$1,000	-	-	-	-
Other crops and hay ..... farms	16,722	9,735	6,212	775
$1,000	981,348	128,909	780,858	71,580
Sales of $50,000 or more ..... farms	2,437	501	1,739	197
$1,000	867,179	71,398	730,114	65,667
Maple syrup ..... farms	364	300	56	8
$1,000	869	497	248	124
Sales of $50,000 or more ..... farms	3	1	1	1
$1,000	191	(D)	(D)	(D)
Cattle and calves ..... farms	14,649	6,632	7,192	825
$1,000	2,094,135	488,174	1,452,196	153,765
Sales of $50,000 or more ..... farms	4,609	1,160	3,139	310
$1,000	1,933,030	415,021	1,372,720	145,290
Milk from cows ..... farms	1,893	501	1,301	91
$1,000	2,504,638	616,267	1,796,051	92,320
Sales of $50,000 or more ..... farms	1,826	462	1,278	86
$1,000	2,503,304	615,711	1,795,490	92,103
Hogs and pigs ..... farms	3,352	1,650	1,484	218
$1,000	4,666,832	2,082,739	2,364,711	219,383
Sales of $50,000 or more ..... farms	2,034	796	1,101	137
$1,000	4,660,288	2,079,390	2,362,076	218,821
Sheep, goats, wool, mohair, and milk ..... farms	2,604	1,854	656	94
$1,000	33,457	18,538	13,555	1,364
Sales of $50,000 or more ..... farms	120	62	53	5
$1,000	19,839	10,859	8,213	767
Horses, ponies, mules, burros, and donkeys ..... farms	1,247	920	287	40
$1,000	18,147	14,043	3,619	485
Sales of $50,000 or more ..... farms	76	64	10	2
$1,000	8,302	7,007	(D)	(D)
Poultry and eggs ..... farms	4,445	3,463	847	135
$1,000	1,943,207	1,355,130	537,822	50,255
Sales of $50,000 or more ..... farms	447	305	121	21
$1,000	1,935,336	1,349,089	536,344	49,904
Aquaculture ..... farms	98	67	18	13
$1,000	19,763	13,674	4,314	1,775
Sales of $50,000 or more ..... farms	62	43	11	8
$1,000	19,502	13,479	4,280	1,743
Other animals and other animal products ..... farms	1,405	1,131	222	52
$1,000	58,149	33,681	24,122	346
Sales of $50,000 or more ..... farms	154	125	29	-
$1,000	52,455	29,396	23,059	-
Value of-				
Government payments ..... farms	31,583	17,771	12,211	1,601
$1,000	584,106	166,764	377,602	39,739
Landlord's share of total sales ..... farms	1,294	-	1,062	232
$1,000	118,307	-	105,415	12,892
FOOD MARKETING PRACTICES				
Value of food sold directly to-				
Consumers ..... farms	3,339	2,392	737	210
$1,000	44,673	27,137	15,020	2,516
Retail markets, institutions, and food hubs for local or regionally branded products ..... farms	1,026	710	228	88
$1,000	108,704	59,258	45,449	3,997
FARM PRODUCTION EXPENSES				
Total farm production expenses [1] ..... farms	65,531	40,396	20,564	4,571
$1,000	20,780,603	5,151,612	14,003,306	1,625,685
Average per farm ..... dollars	317,111	127,528	680,962	355,652
Fertilizer, lime, and soil conditioners purchased ..... farms	36,421	14,686	18,030	3,705
$1,000	2,325,700	258,948	1,846,135	220,617
Farms with expenses of-				
$1 to $4,999	10,529	7,586	2,137	806
$5,000 to $24,999	9,710	4,454	4,049	1,207
$25,000 to $49,999	5,102	1,479	3,034	589
$50,000 or more	11,080	1,167	8,810	1,103
Chemicals purchased ..... farms	37,339	15,789	17,750	3,800
$1,000	1,161,099	132,201	920,225	108,674
Farms with expenses of-				
$1 to $4,999	15,060	10,513	3,359	1,188
$5,000 to $24,999	11,493	4,071	5,838	1,584

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
FARM PRODUCTION EXPENSES - Con.				
Total farm production expenses [1] - Con.				
Chemicals purchased - Con.				
Farms with expenses of- - Con.				
$25,000 to $49,999	4,407	745	3,248	414
$50,000 or more	6,379	460	5,305	614
Seeds, plants, vines, and trees purchased ... farms	36,437	15,140	17,618	3,679
$1,000	1,772,341	219,165	1,389,074	164,102
Farms with expenses of-				
$1 to $999	5,343	4,418	670	255
$1,000 to $4,999	6,157	4,051	1,563	543
$5,000 to $24,999	10,290	4,456	4,412	1,422
$25,000 to $49,999	5,582	1,390	3,585	607
$50,000 or more	9,065	825	7,388	852
Cover crop seed purchased ... farms	4,909	1,776	2,729	404
$1,000	20,527	2,683	16,412	1,432
Livestock and poultry purchased or leased ... farms	13,933	7,656	5,506	771
$1,000	1,926,426	745,821	1,063,229	117,376
Farms with expenses of-				
$1 to $4,999	6,658	4,607	1,780	271
$5,000 to $24,999	3,161	1,575	1,370	216
$25,000 to $99,999	1,372	525	749	98
$100,000 to $249,999	912	325	538	49
$250,000 or more	1,830	624	1,069	137
Breeding livestock purchased or leased ... farms	5,904	2,938	2,623	343
$1,000	171,016	77,365	80,060	13,590
Other livestock and poultry purchased or leased ... farms	9,786	5,648	3,598	540
$1,000	1,755,410	668,455	983,169	103,786
Feed purchased ... farms	26,145	15,609	9,286	1,250
$1,000	3,890,272	1,699,946	2,017,079	173,247
Farms with expenses of-				
$1 to $4,999	13,038	9,656	2,900	482
$5,000 to $24,999	6,844	3,781	2,721	342
$25,000 to $99,999	2,349	867	1,324	158
$100,000 to $249,999	1,155	320	732	103
$250,000 or more	2,759	985	1,609	165
Gasoline, fuels, and oils purchased ... farms	61,621	36,802	20,434	4,385
$1,000	956,802	201,598	680,209	74,994
Farms with expenses of-				
$1 to $4,999	37,714	30,016	5,555	2,143
$5,000 to $24,999	14,760	5,544	7,747	1,469
$25,000 to $49,999	4,270	744	3,158	368
$50,000 or more	4,877	498	3,974	405
Utilities ... farms	48,636	25,863	19,315	3,458
$1,000	400,978	132,782	243,206	24,990
Farms with expenses of-				
$1 to $999	9,923	7,742	1,604	577
$1,000 to $4,999	24,023	14,202	8,083	1,738
$5,000 to $24,999	12,077	3,285	7,826	966
$25,000 to $49,999	1,626	361	1,154	111
$50,000 or more	987	273	648	66
Repairs, supplies, and maintenance costs ... farms	55,660	31,408	20,129	4,123
$1,000	1,322,234	314,841	907,029	100,364
Farms with expenses of-				
$1 to $4,999	25,809	20,541	3,754	1,514
$5,000 to $24,999	17,499	8,637	7,275	1,587
$25,000 to $49,999	5,425	1,256	3,675	494
$50,000 or more	6,927	974	5,425	528
Hired farm labor ... farms	17,399	6,427	9,395	1,577
$1,000	1,320,974	393,688	817,882	109,404
Farms with expenses of-				
$1 to $4,999	5,944	3,219	2,214	511
$5,000 to $24,999	4,466	1,677	2,360	429
$25,000 to $99,999	3,749	927	2,473	349
$100,000 to $249,999	2,234	325	1,724	185
$250,000 or more	1,006	279	624	103
Contract labor ... farms	4,311	2,047	1,941	323
$1,000	152,565	63,680	78,813	10,072
Farms with expenses of-				
$1 to $999	452	343	90	19
$1,000 to $4,999	1,452	891	454	107
$5,000 to $24,999	1,469	545	800	124
$25,000 to $49,999	315	121	172	22
$50,000 or more	623	147	425	51
Customwork and custom hauling ... farms	19,181	8,068	9,358	1,755
$1,000	425,172	116,127	272,429	36,616
Farms with expenses of-				
$1 to $999	2,876	1,883	797	196
$1,000 to $4,999	6,088	3,176	2,356	556
$5,000 to $24,999	6,540	2,227	3,662	651
$25,000 to $49,999	2,030	421	1,430	179
$50,000 or more	1,647	361	1,113	173
Cash rent for land, buildings, and grazing fees ... farms	24,199	1,605	18,648	3,946
$1,000	2,302,712	53,172	1,922,944	326,597

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
FARM PRODUCTION EXPENSES - Con.				
Total farm production expenses [1] - Con.				
Cash rent for land, buildings, and grazing fees - Con.				
Farms with expenses of-				
$1 to $4,999	5,289	683	3,879	727
$5,000 to $9,999	2,314	212	1,638	464
$10,000 to $24,999	4,009	287	2,961	761
$25,000 or more	12,587	423	10,170	1,994
Rent and lease expenses for machinery, equipment, and farm share of vehicles ..... farms	6,598	1,989	3,693	916
$1,000	182,357	21,849	135,731	24,778
Farms with expenses of-				
$1 to $999	1,233	652	452	129
$1,000 to $4,999	1,683	731	748	204
$5,000 to $24,999	2,168	475	1,326	367
$25,000 to $49,999	538	55	398	85
$50,000 or more	976	76	769	131
Interest expense ..... farms	27,274	11,883	13,629	1,762
$1,000	702,889	143,247	536,425	23,216
Farms with expenses of-				
$1 to $4,999	9,316	5,544	2,937	835
$5,000 to $24,999	11,255	5,137	5,436	682
$25,000 to $99,999	5,316	1,036	4,063	217
$100,000 or more	1,387	166	1,193	28
Secured by real estate ..... farms	20,348	9,457	10,891	-
$1,000	467,669	106,526	361,143	-
Farms with expenses of-				
$1 to $999	1,511	986	525	-
$1,000 to $4,999	5,125	3,266	1,859	-
$5,000 to $24,999	9,127	4,339	4,788	-
$25,000 to $49,999	2,363	537	1,826	-
$50,000 or more	2,222	329	1,893	-
Not secured by real estate ..... farms	16,953	6,248	8,943	1,762
$1,000	235,219	36,721	175,282	23,216
Farms with expenses of-				
$1 to $999	2,836	1,628	927	281
$1,000 to $4,999	6,264	3,145	2,565	554
$5,000 to $24,999	5,400	1,206	3,512	682
$25,000 to $49,999	1,506	175	1,191	140
$50,000 or more	947	94	748	105
Property taxes paid ..... farms	61,644	39,946	20,445	1,253
$1,000	482,443	209,599	263,918	8,926
Farms with expenses of-				
$1 to $4,999	39,325	29,390	9,160	775
$5,000 to $9,999	11,291	6,541	4,477	273
$10,000 to $24,999	7,298	3,012	4,153	133
$25,000 or more	3,730	1,003	2,655	72
Medical supplies, veterinary, and custom services for livestock ..... farms	19,351	10,410	7,972	969
$1,000	255,043	96,205	147,789	11,049
Farms with expenses of-				
$1 to $4,999	14,259	8,758	4,875	626
$5,000 to $24,999	3,318	1,107	1,952	259
$25,000 to $49,999	674	187	450	37
$50,000 to $99,999	623	164	432	27
$100,000 or more	477	194	263	20
All other production expenses ..... farms	44,226	21,831	18,608	3,787
$1,000	1,200,596	348,742	761,190	90,665
Farms with expenses of-				
$1 to $4,999	22,214	15,132	5,361	1,721
$5,000 to $24,999	13,025	5,194	6,560	1,271
$25,000 to $49,999	3,867	801	2,702	364
$50,000 to $99,999	3,372	412	2,683	277
$100,000 or more	1,748	292	1,302	154
Production expenses paid by landlords [1] ..... farms	2,062	274	1,530	258
$1,000	65,113	3,773	53,984	7,357
Depreciation expenses claimed ..... farms	41,075	20,008	17,740	3,327
$1,000	2,240,389	434,245	1,630,875	175,269
NET CASH FARM INCOME				
Net cash farm income of operations ..... farms	65,531	40,396	20,564	4,571
$1,000	9,296,848	2,211,864	6,472,914	612,071
Average per farm ..... dollars	141,869	54,755	314,769	133,903
Farms with net gains [2] ..... number	41,496	21,783	16,224	3,489
Average net gain ..... dollars	242,705	118,906	419,805	192,096
Gain of-				
Less than $1,000	1,541	1,344	116	81
$1,000 to $4,999	4,053	3,349	454	250
$5,000 to $9,999	3,053	2,377	462	214
$10,000 to $24,999	5,680	3,972	1,224	484
$25,000 to $49,999	5,396	3,408	1,458	530
$50,000 or more	21,773	7,333	12,510	1,930
Farms with net losses ..... number	24,035	18,613	4,340	1,082
Average net loss ..... dollars	32,221	20,323	77,882	53,746

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
NET CASH FARM INCOME - Con.				
Net cash farm income of operations - Con.				
Farms with net losses - Con.				
Loss of-				
Less than $1,000	1,786	1,526	185	75
$1,000 to $4,999	6,380	5,574	598	208
$5,000 to $9,999	5,021	4,224	608	189
$10,000 to $24,999	5,999	4,654	1,108	237
$25,000 to $49,999	2,539	1,670	714	155
$50,000 or more	2,310	965	1,127	218
Net cash farm income of producers, farms	65,531	40,396	20,564	4,571
$1,000	8,390,544	1,823,759	6,002,543	564,243
Average per farm, dollars	128,039	45,147	291,896	123,440
Producers reporting net gains [2], farms	41,274	21,682	16,124	3,468
Average net gain, dollars	222,954	102,347	394,292	180,369
Gain of-				
Less than $1,000	1,557	1,342	134	81
$1,000 to $4,999	4,059	3,358	442	259
$5,000 to $9,999	3,084	2,391	472	221
$10,000 to $24,999	5,726	4,021	1,215	490
$25,000 to $49,999	5,475	3,471	1,465	539
$50,000 or more	21,373	7,099	12,396	1,878
Producers reporting net losses, farms	24,257	18,714	4,440	1,103
Average net loss, dollars	33,460	21,125	79,960	55,556
Loss of-				
Less than $1,000	1,780	1,529	176	75
$1,000 to $4,999	6,394	5,566	625	203
$5,000 to $9,999	5,032	4,232	612	188
$10,000 to $24,999	6,008	4,671	1,098	239
$25,000 to $49,999	2,576	1,672	739	165
$50,000 or more	2,467	1,044	1,190	233
COMMODITY CREDIT CORPORATION LOANS				
Total, farms	990	152	769	69
$1,000	197,241	9,575	176,679	10,987
INCOME FROM FARM-RELATED SOURCES				
Total income from farm-related sources, farms	38,287	20,787	14,702	2,798
$1,000	1,011,249	513,306	433,689	64,254
Customwork and other agricultural services, farms	4,779	1,341	2,912	526
$1,000	144,025	28,250	99,250	16,525
Gross cash rent or share payments, farms	15,680	12,637	2,726	317
$1,000	479,289	388,294	78,566	12,429
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products, farms	619	489	124	6
$1,000	5,384	4,124	1,253	7
Agri-tourism and recreational services, farms	509	358	119	32
$1,000	13,615	8,079	3,662	1,873
Patronage dividends and refunds from cooperatives, farms	23,672	9,101	12,357	2,214
$1,000	126,183	24,508	91,517	10,158
Crop and livestock insurance payments, farms	5,882	1,372	3,759	751
$1,000	171,530	21,542	131,564	18,424
Amount from State and local government agricultural program payments, farms	1,422	643	684	95
$1,000	7,129	2,269	4,320	539
Other farm-related income sources, farms	2,557	1,326	1,061	170
$1,000	64,095	36,240	23,556	4,299
LAND USE				
Total cropland, farms	58,762	34,255	20,202	4,305
acres	21,544,060	3,522,835	16,198,177	1,823,048
Harvested cropland, farms	47,549	23,435	19,918	4,196
acres	19,662,443	2,453,729	15,440,721	1,767,993
Farms by acres harvested:				
1 to 49 acres	16,934	13,829	2,132	973
50 to 99 acres	5,412	3,283	1,545	584
100 to 199 acres	6,580	3,160	2,639	781
200 to 499 acres	8,316	2,338	5,058	920
500 to 999 acres	4,858	579	3,828	451
1,000 to 1,999 acres	3,081	169	2,630	282
2,000 acres or more	2,368	77	2,086	205
Cropland-				
Other pasture and grazing land that could have been used for crops without additional improvements, farms	3,908	2,317	1,445	146
acres	174,215	64,960	103,304	5,951
On which all crops failed or were abandoned, farms	2,413	1,221	1,039	153
acres	110,013	30,895	72,261	6,857
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed, farms	22,588	15,624	6,362	602
acres	1,546,009	948,396	557,179	40,434
In summer fallow, farms	2,242	1,400	726	116
acres	51,380	24,855	24,712	1,813
Total woodland, farms	23,960	17,753	5,911	296
acres	1,446,600	983,613	452,167	10,820

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Full owners	Part owners	Tenants
LAND USE - Con.					
Total woodland - Con.					
Woodland pastured	farms	7,908	5,203	2,563	142
	acres	315,103	151,166	159,331	4,606
Woodland not pastured	farms	19,456	14,755	4,511	190
	acres	1,131,497	832,447	292,836	6,214
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	19,837	13,126	6,148	563
	acres	1,031,215	434,011	557,050	40,154
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	42,652	28,631	13,188	833
	acres	1,420,750	717,215	673,323	30,212
Irrigated land	farms	3,625	1,826	1,447	352
	acres	648,313	108,117	464,516	75,680
Harvested cropland	farms	3,551	1,758	1,441	352
	acres	644,857	106,692	462,755	75,410
Pastureland and other land	farms	160	101	53	6
	acres	3,456	1,425	1,761	270
CONSERVATION AND CROP INSURANCE					
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	19,069	14,123	4,763	183
	acres	951,335	750,232	191,984	9,119
Land enrolled in crop insurance programs	farms	27,305	8,321	15,691	3,293
	acres	18,167,226	1,859,400	14,621,832	1,685,994
ORGANIC AGRICULTURE					
Total organic product sales	farms	577	233	270	74
	$1,000	121,783	23,716	83,415	14,652
VALUE OF LAND AND BUILDINGS					
Estimated market value of land and buildings	farms	65,531	40,396	20,564	4,571
	$1,000	155,374,449	29,984,383	112,693,878	12,696,187
Average per farm	dollars	2,371,007	742,261	5,480,154	2,777,551
Average per acre	dollars	6,107	5,300	6,303	6,667
Farms by value group:					
$1 to $49,999		1,819	1,449	35	335
$50,000 to $99,999		2,318	2,016	99	203
$100,000 to $199,999		5,817	5,205	297	315
$200,000 to $499,999		17,490	15,225	1,537	728
$500,000 to $999,999		13,050	9,552	2,736	762
$1,000,000 to $1,999,999		8,615	4,207	3,695	713
$2,000,000 to $4,999,999		8,631	2,186	5,602	843
$5,000,000 to $9,999,999		3,992	388	3,261	343
$10,000,000 or more		3,799	168	3,302	329
VALUE OF MACHINERY AND EQUIPMENT					
Estimated market value of all machinery and equipment	farms	65,531	40,396	20,564	4,571
	$1,000	17,904,134	4,084,485	12,199,536	1,620,113
Farms by value group:					
$1 to $4,999		3,305	3,018	149	138
$5,000 to $9,999		3,816	3,464	191	161
$10,000 to $19,999		6,447	5,647	497	303
$20,000 to $49,999		12,383	10,338	1,403	642
$50,000 to $99,999		10,506	7,660	2,179	667
$100,000 to $199,999		9,020	5,213	3,122	685
$200,000 to $499,999		9,719	3,552	5,176	991
$500,000 or more		10,335	1,504	7,847	984
SELECTED MACHINERY AND EQUIPMENT					
Trucks, including pickups	farms	51,156	27,770	19,546	3,840
	number	127,301	48,653	68,167	10,481
Tractors, all	farms	52,770	29,398	19,629	3,743
	number	184,473	76,067	94,312	14,094
Less than 40 horsepower (PTO)	farms	22,815	14,319	7,241	1,255
	number	36,863	21,933	12,942	1,988
40 to 99 horsepower (PTO)	farms	35,619	19,831	13,558	2,230
	number	60,537	31,153	25,564	3,820
100 horsepower (PTO) or more	farms	31,912	11,794	17,119	2,999
	number	87,073	22,981	55,806	8,286
Grain and bean combines, self-propelled	farms	21,753	6,058	13,358	2,337
	number	25,736	6,874	16,161	2,701
Cotton pickers and strippers, self-propelled	farms	-	-	-	-
	number	-	-	-	-
Forage harvesters, self-propelled	farms	2,195	823	1,250	122
	number	2,384	911	1,344	129
Hay balers	farms	19,296	9,884	8,406	1,006
	number	24,300	12,106	10,951	1,243

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
FERTILIZERS AND CHEMICALS				
Commercial fertilizer, lime, and soil conditioners used ..... farms	34,208	12,955	17,654	3,599
acres treated	14,076,782	1,621,844	11,094,799	1,360,139
Manure used ..... farms	13,721	5,817	6,987	917
acres treated	1,453,615	227,930	1,100,861	124,824
Organic fertilizer used ..... farms	1,053	576	350	127
acres treated	135,551	24,261	103,786	7,504
Acres treated to control-				
Insects ..... farms	13,847	4,299	7,662	1,886
acres	5,229,304	496,260	4,145,108	587,936
Weeds, grass, or brush ..... farms	34,397	13,455	17,294	3,648
acres	17,661,145	1,976,729	14,007,383	1,677,033
Nematodes ..... farms	3,288	1,004	1,824	460
acres	977,113	105,832	750,733	120,548
Diseases in crops and orchards ..... farms	5,080	1,411	2,887	782
acres	2,350,398	159,422	1,848,843	342,133
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	1,762	553	990	219
acres on which used	318,341	35,774	251,527	31,040
LAND USE PRACTICES				
Land drained by tile ..... farms	19,088	6,674	10,136	2,278
acres	8,247,260	879,653	6,501,501	866,106
Land artificially drained by ditches ..... farms	9,435	3,999	4,591	845
acres	4,560,910	445,502	3,703,925	411,483
Land under conservation easement ..... farms	4,909	3,630	1,196	83
acres	282,171	187,289	90,358	4,524
Cropland on which no-till practices were used ..... farms	6,845	2,829	3,413	603
acres	1,194,987	182,882	903,284	108,821
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ..... farms	15,574	5,362	8,720	1,492
acres	7,881,385	798,695	6,414,746	667,944
Cropland on which intensive or conventional tillage practices were used (see text) ..... farms	22,330	8,831	10,974	2,525
acres	9,573,777	1,107,281	7,510,065	956,431
Cropland planted to a cover crop (excluding CRP) ..... farms	6,050	2,387	3,113	550
acres	760,423	90,987	590,349	79,087
Use of precision agriculture practices (see text) ..... farms	15,460	4,016	9,156	2,288
RENEWABLE ENERGY				
Renewable energy producing systems (see text) ..... farms	4,247	2,316	1,671	260
Solar panels ..... farms	2,063	1,289	647	127
Wind turbines ..... farms	819	325	438	56
Methane digesters ..... farms	15	6	9	-
Geothermal/geoexchange systems ..... farms	1,695	884	724	87
Small hydro systems ..... farms	24	10	8	6
Wind rights leased to others ..... farms	1,189	583	545	61
TENURE				
Full owners ..... farms	40,396	40,396	-	-
Part owners ..... farms	20,564	-	20,564	-
Tenants ..... farms	4,571	-	-	4,571
OWNED AND RENTED LAND				
Land owned ..... farms	61,213	40,396	20,564	253
acres	15,768,785	7,939,313	7,774,795	54,677
Owned land in farms ..... farms	60,960	40,396	20,564	-
acres	13,006,137	5,657,674	7,348,463	-
Land rented or leased from others ..... farms	25,328	193	20,564	4,571
acres	12,515,140	36,556	10,558,870	1,919,714
Rented or leased land in farms ..... farms	25,135	-	20,564	4,571
acres	12,436,488	-	10,532,254	1,904,234
Land rented or leased to others ..... farms	15,946	12,942	2,687	317
acres	2,841,300	2,318,195	452,948	70,157
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS				
Total producers	118,256	73,133	36,812	8,311
Farms by number of producers:				
1 producer	28,348	16,803	9,302	2,243
2 producers	28,866	19,027	8,326	1,513
3 producers	4,480	2,291	1,732	457
4 producers	2,500	1,407	845	248
5 or more producers	1,337	868	359	110
Total male producers	81,062	47,406	27,242	6,414
Farms by number of male producers:				
1 producer	49,919	31,522	15,340	3,057
2 producers	8,600	4,098	3,528	974
3 producers	2,596	1,244	1,049	303
4 producers	766	450	251	65
5 or more producers	459	317	100	42
Total female producers	37,193	25,727	9,569	1,897
Farms by number of female producers:				
1 producer	29,936	20,856	7,777	1,303
2 producers	2,374	1,549	642	183
3 producers	466	317	98	51

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Full owners	Part owners	Tenants
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS - Con.					
Total producers - Con.					
Total female producers - Con.					
Farms by number of female producers: - Con.					
4 producers		138	102	30	6
5 or more producers		90	64	16	10
PRODUCERS' CHARACTERISTICS [3]					
Sex of producers:					
Male		79,245	46,104	26,840	6,301
Female		35,623	24,726	9,126	1,771
Hired managers		6,902	1,822	4,103	977
Primary occupation:					
Farming		51,122	24,473	22,707	3,942
Other		63,746	46,357	13,259	4,130
Place of residence:					
On farm operated		79,195	47,494	28,070	3,631
Not on farm operated		35,673	23,336	7,896	4,441
Days of work off farm:					
None		46,862	27,922	16,244	2,696
Any		68,006	42,908	19,722	5,376
1 to 49 days		9,840	5,867	3,212	761
50 to 99 days		4,745	2,654	1,696	395
100 to 199 days		8,361	4,857	2,842	662
200 days or more		45,060	29,530	11,972	3,558
Years on present farm:					
2 years or less		4,867	3,378	971	518
3 or 4 years		7,650	4,719	1,759	1,172
5 to 9 years		18,524	11,672	4,805	2,047
10 years or more		83,827	51,061	28,431	4,335
Average years on present farm		24.2	23.8	26.6	16.6
Years operating any farm:					
5 years or less		13,846	8,997	3,012	1,837
6 to 10 years		15,740	10,175	4,014	1,551
11 years or more		85,282	51,658	28,940	4,684
Average years on any farm		26.1	25.6	28.5	19.8
Age group:					
Under 25 years		1,900	909	756	235
25 to 34 years		9,374	4,216	3,599	1,559
35 to 44 years		16,237	8,311	5,965	1,961
45 to 54 years		16,743	9,615	5,857	1,271
55 to 64 years		29,818	18,496	9,838	1,484
65 to 74 years		27,187	18,524	7,542	1,121
75 years and over		13,609	10,759	2,409	441
Average age		57.1	59.5	54.3	48.7
Young producers (see text)		11,274	5,125	4,355	1,794
Producers of Hispanic, Latino, or Spanish origin		754	478	227	49
Producers by race:					
American Indian or Alaska Native		244	190	42	12
Asian		306	157	41	108
Black or African American		61	41	10	10
Native Hawaiian or Other Pacific Islander		43	33	9	1
White		113,864	70,186	35,763	7,915
More than one race reported		350	223	101	26
Military service:					
Never served or only on active duty for training in the Reserves or National Guard (see text)		105,603	63,905	34,039	7,659
Active duty now or in the past (see text)		9,265	6,925	1,927	413
Number of persons living in producers' households		228,210	131,726	77,362	19,122
On farm involvement in decisionmaking:					
Day-to-day decisions		98,292	59,304	32,051	6,937
Land use and/or crop decisions		83,860	48,486	28,959	6,415
Livestock decisions		49,585	30,158	16,884	2,543
Marketing decisions (see text)		68,020	34,697	27,391	5,932
Record keeping and/or financial management		84,043	48,735	29,020	6,288
Estate planning or succession planning		64,079	37,583	22,824	3,672
FARMS BY TYPE OF ORGANIZATION					
Operation more than 50 percent owned by one producer's household and/or extended family	farms	62,111	38,397	19,520	4,194
	acres	22,990,670	5,137,865	16,220,313	1,632,492
Limited Liability Company	farms	4,803	2,839	1,478	486
	acres	2,179,815	371,812	1,556,764	251,239
LEGAL STATUS FOR TAX PURPOSES					
Family or individual	farms	55,532	35,252	16,813	3,467
	acres	17,410,756	4,412,203	12,093,341	905,212

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
LEGAL STATUS FOR TAX PURPOSES - Con.				
Partnership ..... farms	5,022	2,407	2,034	581
acres	4,452,974	591,995	3,334,903	526,076
Registered under State law ..... farms	4,156	1,933	1,703	520
acres	3,904,476	495,224	2,921,376	487,876
Corporation ..... farms	3,803	1,732	1,598	473
acres	3,244,861	406,196	2,380,610	458,055
Family held ..... farms	3,375	1,425	1,518	432
acres	3,085,380	332,490	2,309,679	443,211
More than 10 stockholders ..... farms	34	29	4	1
10 or less stockholders ..... farms	3,341	1,396	1,514	431
Other than family held ..... farms	428	307	80	41
acres	159,481	73,706	70,931	14,844
More than 10 stockholders ..... farms	67	56	8	3
10 or less stockholders ..... farms	361	251	72	38
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. ..... farms	1,174	1,005	119	50
acres	334,034	247,280	71,863	14,891
HIRED FARM LABOR				
Hired farm labor ..... farms	17,399	6,427	9,395	1,577
workers	72,097	23,931	41,485	6,681
Workers by days worked:				
150 days or more ..... farms	9,054	3,026	5,221	807
workers	30,983	10,516	17,918	2,549
Less than 150 days ..... farms	12,949	4,670	7,100	1,179
workers	41,114	13,415	23,567	4,132
Migrant farm labor on farms with hired labor ..... farms	573	128	406	39
Migrant farm labor on farms reporting only contract labor ..... farms	41	21	19	1
Unpaid workers ..... farms	17,519	10,578	5,738	1,203
workers	40,333	24,650	12,922	2,761
FARMS BY SIZE				
1 to 9 acres	4,401	3,949	79	373
10 to 49 acres	15,218	13,313	1,175	730
50 to 69 acres	3,598	2,884	461	253
70 to 99 acres	5,575	4,471	731	373
100 to 139 acres	4,857	3,504	982	371
140 to 179 acres	4,814	3,453	995	366
180 to 219 acres	2,981	1,808	974	199
220 to 259 acres	2,503	1,489	821	193
260 to 499 acres	8,699	3,651	4,336	712
500 to 999 acres	6,421	1,418	4,528	475
1,000 to 1,999 acres	3,752	337	3,114	301
2,000 acres or more	2,712	119	2,368	225
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)				
Oilseed and grain farming (1111)	26,315	9,553	13,603	3,159
Vegetable and melon farming (1112)	1,072	751	173	148
Fruit and tree nut farming (1113)	972	891	43	38
Greenhouse, nursery, and floriculture production (1114)	971	789	91	91
Other crop farming (1119)	18,104	15,942	1,816	346
Tobacco farming (11191)	-	-	-	-
Cotton farming (11192)	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	18,104	15,942	1,816	346
Beef cattle ranching and farming (112111)	6,753	4,589	1,824	340
Cattle feedlots (112112)	892	391	450	51
Dairy cattle and milk production (11212)	1,713	476	1,154	83
Hog and pig farming (1122)	1,855	951	767	137
Poultry and egg production (1123)	1,724	1,535	145	44
Sheep and goat farming (1124)	1,456	1,268	126	62
Aquaculture and other animal production (1125,1129)	3,704	3,260	372	72
FARM TYPOLOGY (SEE TEXT)				
Farms by typology group:				
Small family farms				
Gross cash farm income less than $150,000	41,924	33,416	6,241	2,267
Gross cash farm income $150,000 to $349,999	7,074	2,938	3,345	791
Midsize family farms				
Gross cash farm income $350,000 to $999,999	7,367	1,434	5,231	702
Large family farms				
Gross cash farm income $1,000,000 to $4,999,999	5,311	492	4,408	411
Gross cash farm income $5,000,000 or more	435	117	295	23
Non-family farms	3,420	1,999	1,044	377
OTHER FARM CHARACTERISTICS				
Farms reporting-				
Internet access	53,964	31,524	18,369	4,071
Dial-up	1,876	1,202	623	51
Broadband (DSL, cable, fiber optic) (see text)	33,399	19,283	11,503	2,613
Cellular data plan (see text)	32,121	17,620	11,773	2,728
Satellite	8,385	4,534	3,156	695
Don't know	2,877	1,955	767	155
Other	346	188	149	9
Farms by number of households sharing in net income of operation:				
1 household	52,287	33,028	15,907	3,352

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
OTHER FARM CHARACTERISTICS - Con.				
Farms by number of households sharing in net income of operation: - Con.				
2 households	9,039	4,816	3,385	838
3 households	2,321	1,245	820	256
4 households	1,024	673	259	92
5 or more households	860	634	193	33
LIVESTOCK				
Cattle and calves inventory ... farms	16,823	8,232	7,681	910
number	2,121,625	505,131	1,500,513	115,981
Farms with-				
1 to 9	3,446	2,693	625	128
10 to 49	6,556	3,575	2,608	373
50 to 99	2,582	1,045	1,393	144
100 to 199	1,927	528	1,286	113
200 to 499	1,348	265	981	102
500 or more	964	126	788	50
Cows and heifers that calved ... farms	13,439	6,462	6,256	721
number	824,165	223,320	561,092	39,753
Beef cows ... farms	11,691	5,914	5,144	633
number	364,629	109,477	232,204	22,948
Farms with-				
1 to 9	3,718	2,595	957	166
10 to 49	6,113	2,935	2,835	343
50 to 99	1,205	296	836	73
100 to 199	470	66	364	40
200 to 499	149	19	122	8
500 or more	36	3	30	3
Milk cows ... farms	2,185	731	1,350	104
number	459,536	113,843	328,888	16,805
Farms with-				
1 to 9	328	251	70	7
10 to 49	315	157	134	24
50 to 99	573	161	386	26
100 to 199	418	86	307	25
200 to 499	390	49	325	16
500 or more	161	27	128	6
Other cattle ... farms	14,574	6,662	7,107	805
number	1,297,460	281,811	939,421	76,228
Cattle and calves sold ... farms	14,649	6,632	7,192	825
number	1,599,910	447,650	1,048,471	103,789
$1,000	2,094,135	488,174	1,452,196	153,765
Calves weighing less than 500 pounds ... farms	4,938	2,214	2,465	259
number	345,069	153,222	181,227	10,620
Cattle weighing 500 pounds or more ... farms	13,933	6,131	7,009	793
number	1,254,841	294,428	867,244	93,169
Cattle on feed ... farms	2,685	726	1,792	167
number	636,782	135,171	459,675	41,936
Hogs and pigs inventory ... farms	2,928	1,506	1,256	166
number	8,873,776	4,193,457	4,294,865	385,454
Farms with-				
1 to 24	893	638	218	37
25 to 49	93	41	49	3
50 to 99	71	41	22	8
100 to 199	65	26	29	10
200 to 499	116	50	56	10
500 or more	1,690	710	882	98
Hogs and pigs sold ... farms	3,352	1,650	1,484	218
number	28,535,462	15,213,396	12,068,291	1,253,775
$1,000	4,666,832	2,082,739	2,364,711	219,383
Sheep and lambs inventory ... farms	2,137	1,556	496	85
number	109,592	57,384	48,218	3,990
Sheep and lambs sold ... farms	1,500	1,037	404	59
number	92,512	42,124	47,799	2,589
Total horses and ponies inventory ... farms	6,988	5,328	1,498	162
number	40,131	30,730	8,312	1,089
Total horses and ponies sold ... farms	1,171	862	269	40
number	4,403	3,182	1,109	112
Goats, all inventory ... farms	2,326	1,794	455	77
number	50,691	32,432	15,977	2,282
Goats, all sold ... farms	1,215	903	265	47
number	38,339	26,798	8,956	2,585
POULTRY				
Layers inventory ... farms	6,146	4,883	1,103	160
number	14,553,497	11,195,784	3,351,744	5,969
Farms with-				
1 to 399	6,045	4,804	1,083	158
400 to 3,199	36	26	8	2
3,200 to 9,999	8	6	2	-
10,000 to 19,999	24	21	3	-
20,000 to 49,999	4	4	-	-
50,000 to 99,999	5	2	3	-
100,000 or more	24	20	4	-

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Full owners	Part owners	Tenants
POULTRY - Con.				
Pullets for laying flock replacement inventory ..... farms	723	601	104	18
number	4,185,443	2,673,993	(D)	(D)
Layers sold ..... farms	664	541	88	35
number	7,016,481	6,817,727	197,175	1,579
Pullets for laying flock replacement sold ..... farms	102	78	13	11
number	8,319,040	6,064,814	(D)	(D)
Broilers and other meat-type chickens sold ..... farms	1,028	751	247	30
number	41,793,592	23,116,781	(D)	(D)
Farms with-				
1 to 1,999	900	680	192	28
2,000 to 59,999	11	7	4	-
60,000 to 99,999	-	-	-	-
100,000 or more	117	64	51	2
Turkeys inventory ..... farms	623	471	120	32
number	14,927,734	10,846,399	3,714,003	367,332
Turkeys sold ..... farms	379	269	90	20
number	39,460,145	26,263,915	12,291,928	904,302
CROPS				
Barley for grain ..... farms	336	57	243	36
acres	55,330	2,888	45,761	6,681
bushels	4,011,381	158,104	3,355,286	497,991
Irrigated ..... farms	10	3	7	-
acres	116	6	110	-
Farms by acres harvested:				
1 to 24 acres	72	28	37	7
25 to 99 acres	96	22	72	2
100 to 249 acres	94	4	78	12
250 to 499 acres	53	3	36	14
500 acres or more	21	-	20	1
Corn for grain ..... farms	24,697	7,703	14,322	2,672
acres	7,732,455	826,084	6,160,013	746,358
bushels	1,478,451,268	150,680,769	1,183,822,996	143,947,503
Irrigated ..... farms	1,341	289	908	144
acres	302,897	37,802	227,593	37,502
Farms by acres harvested:				
1 to 24 acres	2,863	1,954	695	214
25 to 99 acres	6,867	3,363	2,608	896
100 to 249 acres	6,444	1,746	3,953	745
250 to 499 acres	4,136	412	3,290	434
500 acres or more	4,387	228	3,776	383
Corn for silage or greenchop ..... farms	2,768	693	1,898	177
acres	313,974	32,649	263,390	17,935
tons	6,334,518	601,263	5,379,114	354,141
Irrigated ..... farms	108	22	76	10
acres	13,135	1,459	10,659	1,017
Farms by acres harvested:				
1 to 24 acres	848	363	442	43
25 to 99 acres	1,133	261	792	80
100 to 249 acres	452	51	362	39
250 to 499 acres	218	15	192	11
500 acres or more	117	3	110	4
Dry edible beans, excluding chickpeas and limas ..... farms	573	79	437	57
acres	210,162	12,338	178,934	18,890
cwt	5,278,245	273,850	4,545,843	458,552
Irrigated ..... farms	95	16	66	13
acres	39,931	2,143	29,430	8,358
Farms by acres harvested:				
1 to 24 acres	34	22	12	-
25 to 99 acres	118	27	64	27
100 to 249 acres	146	19	118	9
250 to 499 acres	140	7	123	10
500 acres or more	135	4	120	11
Oats for grain ..... farms	2,329	762	1,402	165
acres	126,011	26,874	89,911	9,226
bushels	9,470,546	1,755,085	7,005,275	710,186
Irrigated ..... farms	66	18	43	5
acres	3,194	467	2,357	370
Farms by acres harvested:				
1 to 24 acres	906	390	465	51
25 to 99 acres	1,097	338	671	88
100 to 249 acres	286	30	231	25
250 to 499 acres	29	3	25	1
500 acres or more	11	1	10	-
Sorghum for grain ..... farms	12	9	2	1
acres	364	81	(D)	(D)
bushels	24,260	3,930	(D)	(D)
Irrigated ..... farms	-	-	-	-
acres	-	-	-	-
Farms by acres harvested:				
1 to 24 acres	7	7	-	-
25 to 99 acres	4	2	2	-
100 to 249 acres	1	-	-	1
250 to 499 acres	-	-	-	-
500 acres or more	-	-	-	-

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Full owners	Part owners	Tenants
CROPS - Con.					
Soybeans for beans	farms	25,337	7,767	14,680	2,890
	acres	7,597,171	869,989	6,000,540	726,642
	bushels	373,669,175	41,511,292	296,194,948	35,962,935
Irrigated	farms	892	202	589	101
	acres	122,734	15,899	93,031	13,804
Farms by acres harvested:					
1 to 24 acres		2,307	1,602	514	191
25 to 99 acres		7,345	3,573	2,803	969
100 to 249 acres		6,879	1,859	4,126	894
250 to 499 acres		4,297	523	3,345	429
500 acres or more		4,509	210	3,892	407
Sugarbeets for sugar	farms	1,106	104	871	131
	acres	446,627	21,024	388,463	37,140
	tons	11,642,041	557,189	10,144,449	940,403
Irrigated	farms	31	-	31	-
	acres	10,798	-	10,798	-
Sunflower seed, all	farms	221	24	168	29
	acres	66,924	5,547	52,549	8,828
	pounds	151,726,117	11,967,098	121,295,201	18,463,818
Irrigated	farms	2	1	1	-
	acres	(D)	(D)	(D)	-
Farms by acres harvested:					
1 to 24 acres		8	4	4	-
25 to 99 acres		53	9	40	4
100 to 249 acres		62	5	44	13
250 to 499 acres		49	-	42	7
500 acres or more		49	6	38	5
Wheat for grain, all	farms	3,669	757	2,522	390
	acres	1,268,681	104,462	1,064,250	99,969
	bushels	82,039,945	5,935,816	69,728,478	6,375,651
Irrigated	farms	52	9	40	3
	acres	6,251	458	5,748	45
Farms by acres harvested:					
1 to 24 acres		416	172	218	26
25 to 99 acres		1,023	301	613	109
100 to 249 acres		809	178	510	121
250 to 499 acres		544	67	409	68
500 acres or more		877	39	772	66
Forage-land used for all hay and haylage, grass silage, and greenchop	farms	23,394	13,409	9,010	975
	acres	1,392,072	469,195	865,292	57,585
	tons, dry equivalent	3,565,994	971,935	2,414,875	179,184
Irrigated	farms	675	259	383	33
	acres	32,954	7,789	23,386	1,779
Farms by acres harvested:					
1 to 24 acres		11,106	7,968	2,675	463
25 to 99 acres		8,179	4,332	3,497	350
100 to 249 acres		3,115	966	2,040	109
250 to 499 acres		780	122	609	49
500 acres or more		214	21	189	4
Alfalfa hay	farms	15,333	8,106	6,533	694
	acres	744,117	252,058	460,301	31,758
	tons, dry	1,971,568	572,862	1,308,363	90,343
Irrigated	farms	421	128	274	19
	acres	15,949	4,054	11,284	611
Other dry hay	farms	8,556	5,013	3,215	328
	acres	390,421	152,007	227,646	10,768
	tons, dry	658,360	234,123	401,071	23,166
Irrigated	farms	153	88	60	5
	acres	3,658	1,440	2,012	206
Field and grass seed crops, all	farms	155	32	107	16
	acres	66,601	3,601	56,883	6,117
Irrigated	farms	6	-	6	-
	acres	505	-	505	-
Land in vegetables	farms	2,620	1,383	978	259
	acres	196,718	26,244	150,594	19,879
Irrigated	farms	764	491	191	82
	acres	54,640	8,015	38,677	7,948
Farms by acres harvested:					
0.1 to 4.9 acres		1,355	1,072	135	148
5.0 to 24.9 acres		225	132	71	22
25.0 to 99.9 acres		495	115	350	30
100.0 to 249.9 acres		364	42	287	35
250.0 acres or more		181	22	135	24
Beans, snap	farms	390	256	81	53
	acres	2,553	313	2,152	88
Harvested for processing	farms	22	8	13	1
	acres	2,278	(D)	1,952	(D)
Peas, green	farms	599	132	407	60
	acres	47,364	4,585	36,410	6,369
Harvested for processing	farms	491	51	394	46
	acres	47,345	4,570	36,407	6,368
Potatoes	farms	509	338	112	59
	acres	49,008	4,737	37,946	6,326
Harvested for processing	farms	39	7	22	10
	acres	35,127	2,981	26,921	5,224
Farms by acres harvested:					
0.1 to 4.9 acres		421	322	54	45

See footnote(s) at end of table.

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Table 76. **Summary by Tenure of Farm Operation: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Full owners	Part owners	Tenants
CROPS - Con.					
Land in vegetables - Con.					
Potatoes - Con.					
Farms by acres harvested: - Con.					
5.0 to 24.9 acres		5	2	2	1
25.0 to 99.9 acres		20	5	15	-
100.0 to 249.9 acres		8	1	4	3
250.0 acres or more		55	8	37	10
Sweet corn (see text)	farms	1,243	489	648	106
	acres	96,990	13,886	74,663	8,441
Harvested for processing	farms	750	133	560	57
	acres	94,536	13,323	72,904	8,309
Sweet potatoes	farms	58	35	10	13
	acres	23	9	3	11
Harvested for processing	farms	-	-	-	-
	acres	-	-	-	-
Tomatoes in the open	farms	592	461	60	71
	acres	300	195	81	24
Harvested for processing	farms	18	15	-	3
	acres	2	2	-	1
Land in orchards	farms	1,174	1,062	78	34
	acres	5,049	4,203	667	179
Irrigated	farms	204	180	16	8
	acres	778	684	76	19
Farms by bearing and nonbearing acres:					
0.1 to 4.9 acres		927	860	48	19
5.0 to 24.9 acres		212	176	23	13
25.0 to 99.9 acres		32	23	7	2
100.0 to 249.9 acres		3	3	-	-
250.0 acres or more		-	-	-	-
Apples	farms	751	694	42	15
	bearing and nonbearing acres	3,219	2,762	408	49
Grapes (including muscadine) (see text)	farms	433	376	35	22
	bearing and nonbearing acres	1,290	982	188	121
Peaches, all	farms	17	14	1	2
	bearing and nonbearing acres	(D)	4	(D)	(D)
Walnuts, English	farms	29	27	2	-
	bearing and nonbearing acres	142	(D)	(D)	-
Land in berries	farms	578	490	54	34
	acres	1,129	849	226	53

[1] Landlord production expenses are included with total farm production expenses.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.
[3] Data were collected for a maximum of four producers per farm.

Table 77. **Summary by Operating Arrangements: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
FARMS AND LAND IN FARMS					
Farms ..... number	65,531	28,348	28,866	6,980	1,337
percent	100.0	43.3	44.0	10.7	2.0
Land in farms ..... acres	25,442,625	10,396,361	9,749,704	4,448,188	848,372
Average size of farm ..... acres	388	367	338	637	635
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS					
Total ..... farms	65,531	28,348	28,866	6,980	1,337
$1,000	29,066,202	10,761,828	10,457,114	6,573,688	1,273,572
Average per farm ..... dollars	443,549	379,633	362,264	941,789	952,559
Farms by economic class:					
Less than $1,000	6,079	2,440	3,132	396	111
$1,000 to $2,499	6,033	2,438	2,978	459	158
$2,500 to $4,999	5,681	2,349	2,744	471	117
$5,000 to $9,999	6,141	2,592	2,880	531	138
$10,000 to $24,999	7,125	2,969	3,379	611	166
$25,000 to $49,999	4,813	2,066	2,136	519	92
$50,000 to $99,999	5,488	2,579	2,324	508	77
$100,000 to $249,999	6,899	3,414	2,703	702	80
$250,000 to $499,999	5,477	2,746	2,054	600	77
$500,000 to $999,999	4,529	2,149	1,742	569	69
$1,000,000 or more	7,266	2,606	2,794	1,614	252
$1,000,000 to $2,499,999	4,148	1,553	1,664	832	99
$2,500,000 to $4,999,999	2,458	860	924	568	106
$5,000,000 or more	660	193	206	214	47
Total sales ..... farms	65,531	28,348	28,866	6,980	1,337
$1,000	28,482,097	10,516,266	10,234,288	6,476,992	1,254,551
Grains, oilseeds, dry beans, and dry peas ..... farms	32,075	15,142	12,455	3,937	541
$1,000	15,268,581	6,239,342	5,728,516	2,826,903	473,819
Sales of $50,000 or more ..... farms	23,618	11,171	8,922	3,118	407
$1,000	15,113,786	6,166,195	5,665,527	2,810,649	471,415
Corn ..... farms	25,230	11,855	9,902	3,063	410
$1,000	9,045,595	3,648,322	3,448,497	1,657,099	291,676
Sales of $50,000 or more ..... farms	18,777	8,888	7,077	2,476	336
$1,000	8,908,714	3,584,651	3,389,532	1,644,283	290,248
Wheat ..... farms	3,668	1,741	1,230	629	68
$1,000	735,504	304,780	240,883	171,523	18,318
Sales of $50,000 or more ..... farms	2,125	1,031	673	382	39
$1,000	707,000	291,580	230,117	167,475	17,827
Soybeans ..... farms	25,334	12,091	9,645	3,174	424
$1,000	5,087,514	2,132,437	1,904,408	915,806	134,862
Sales of $50,000 or more ..... farms	17,131	8,107	6,386	2,330	308
$1,000	4,898,487	2,040,107	1,829,979	896,075	132,327
Sorghum ..... farms	53	22	23	7	1
$1,000	437	226	141	(D)	(D)
Sales of $50,000 or more ..... farms	1	1	-	-	-
$1,000	(D)	(D)	-	-	-
Barley ..... farms	336	161	110	58	7
$1,000	27,673	14,467	8,703	(D)	(D)
Sales of $50,000 or more ..... farms	151	73	47	29	2
$1,000	24,984	12,998	8,021	(D)	(D)
Rice ..... farms	-	-	-	-	-
$1,000	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-
$1,000	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas ..... farms	3,613	1,586	1,391	562	74
$1,000	371,859	139,110	125,885	78,557	28,307
Sales of $50,000 or more ..... farms	1,013	431	365	191	26
$1,000	342,531	125,728	115,365	73,910	27,528
Tobacco ..... farms	-	-	-	-	-
$1,000	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-
$1,000	-	-	-	-	-
Cotton and cottonseed ..... farms	-	-	-	-	-
$1,000	-	-	-	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-
$1,000	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes ..... farms	2,648	933	1,318	353	44
$1,000	446,099	178,905	130,599	97,218	39,377
Sales of $50,000 or more ..... farms	994	397	406	168	23
$1,000	424,789	171,480	119,953	94,357	38,999
Fruits, tree nuts, and berries ..... farms	1,212	307	732	152	21
$1,000	48,717	12,312	24,395	8,290	3,720
Sales of $50,000 or more ..... farms	178	35	100	36	7
$1,000	38,977	9,831	18,257	7,304	3,585
Fruits and tree nuts ..... farms	944	244	580	105	15
$1,000	30,052	5,733	15,126	(D)	(D)
Sales of $50,000 or more ..... farms	116	24	60	29	3
$1,000	22,967	(D)	10,640	5,660	(D)
Berries ..... farms	489	104	302	75	8
$1,000	18,665	6,579	9,269	(D)	(D)
Sales of $50,000 or more ..... farms	66	12	41	8	5
$1,000	15,470	5,913	7,281	(D)	(D)
Nursery, greenhouse, floriculture, and sod ..... farms	1,051	303	503	196	49
$1,000	391,444	46,943	122,230	178,535	43,735
Sales of $50,000 or more ..... farms	343	107	116	94	26
$1,000	381,613	44,554	116,962	176,827	43,271
Cultivated Christmas trees and short rotation woody crops ..... farms	244	67	117	45	15
$1,000	7,578	1,053	2,327	2,117	2,082

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD AND GOVERNMENT PAYMENTS - Con.					
Total - Con.					
Total sales - Con.					
Cultivated Christmas trees and short rotation woody crops - Con.					
Sales of $50,000 or more ..... farms	27	4	11	8	4
$1,000	6,051	521	1,731	1,774	2,025
Cultivated Christmas trees ..... farms	243	67	116	45	15
$1,000	(D)	1,053	(D)	2,117	2,082
Sales of $50,000 or more ..... farms	27	4	11	8	4
$1,000	6,051	521	1,731	1,774	2,025
Short rotation woody crops ..... farms	1	-	1	-	-
$1,000	(D)	-	(D)	-	-
Sales of $50,000 or more ..... farms	-	-	-	-	-
$1,000	-	-	-	-	-
Other crops and hay ..... farms	16,722	7,219	7,606	1,649	248
$1,000	981,348	355,828	328,972	248,531	48,018
Sales of $50,000 or more ..... farms	2,437	1,019	917	436	65
$1,000	867,179	304,557	279,261	236,721	46,640
Maple syrup ..... farms	364	84	227	48	5
$1,000	869	149	491	221	8
Sales of $50,000 or more ..... farms	3	-	2	1	-
$1,000	191	-	(D)	(D)	-
Cattle and calves ..... farms	14,649	5,848	6,835	1,756	210
$1,000	2,094,135	763,285	646,512	574,676	109,662
Sales of $50,000 or more ..... farms	4,609	1,777	1,859	856	117
$1,000	1,933,030	696,466	569,796	558,470	108,298
Milk from cows ..... farms	1,893	498	793	533	69
$1,000	2,504,638	447,965	758,767	1,123,061	174,846
Sales of $50,000 or more ..... farms	1,826	487	750	520	69
$1,000	2,503,304	447,703	757,911	1,122,845	174,846
Hogs and pigs ..... farms	3,352	1,115	1,615	538	84
$1,000	4,666,832	1,494,500	1,883,853	941,085	347,394
Sales of $50,000 or more ..... farms	2,034	756	830	383	65
$1,000	4,660,288	1,492,370	1,880,457	940,158	347,302
Sheep, goats, wool, mohair, and milk ..... farms	2,604	714	1,602	269	19
$1,000	33,457	13,295	14,156	5,781	224
Sales of $50,000 or more ..... farms	120	48	48	24	-
$1,000	19,839	9,364	6,410	4,064	-
Horses, ponies, mules, burros, and donkeys ..... farms	1,247	332	788	122	5
$1,000	18,147	5,945	10,411	(D)	(D)
Sales of $50,000 or more ..... farms	76	28	41	6	1
$1,000	8,302	3,626	3,893	(D)	(D)
Poultry and eggs ..... farms	4,445	1,086	2,840	466	53
$1,000	1,943,207	916,592	557,563	459,356	9,696
Sales of $50,000 or more ..... farms	447	164	199	77	7
$1,000	1,935,336	914,585	552,885	458,283	9,584
Aquaculture ..... farms	98	65	25	6	2
$1,000	19,763	10,791	6,453	(D)	(D)
Sales of $50,000 or more ..... farms	62	38	18	5	1
$1,000	19,502	10,554	(D)	(D)	(D)
Other animals and other animal products ..... farms	1,405	443	784	148	30
$1,000	58,149	29,507	19,537	7,373	1,732
Sales of $50,000 or more ..... farms	154	48	72	24	10
$1,000	52,455	27,081	16,819	6,940	1,614
Value of-					
Government payments ..... farms	31,583	13,860	13,044	3,839	840
$1,000	584,106	245,562	222,826	96,696	19,021
Landlord's share of total sales ..... farms	1,294	637	459	180	18
$1,000	118,307	56,122	40,968	18,488	2,729
FOOD MARKETING PRACTICES					
Value of food sold directly to-					
Consumers ..... farms	3,339	822	2,087	378	52
$1,000	44,673	7,465	23,351	10,604	3,252
Retail markets, institutions, and food hubs for local or regionally branded products ..... farms	1,026	279	583	141	23
$1,000	108,704	6,623	39,750	40,545	21,786
FARM PRODUCTION EXPENSES					
Total farm production expenses [1] ..... farms	65,531	28,348	28,866	6,980	1,337
$1,000	20,780,603	7,623,829	7,477,902	4,729,265	949,608
Average per farm ..... dollars	317,111	268,937	259,056	677,545	710,253
Fertilizer, lime, and soil conditioners purchased ..... farms	36,421	16,389	15,028	4,346	658
$1,000	2,325,700	929,252	876,125	442,112	78,210
Farms with expenses of-					
$1 to $4,999	10,529	4,332	5,121	881	195
$5,000 to $24,999	9,710	4,653	3,884	1,056	117
$25,000 to $49,999	5,102	2,561	1,892	580	69
$50,000 or more	11,080	4,843	4,131	1,829	277
Chemicals purchased ..... farms	37,339	16,698	15,361	4,594	686
$1,000	1,161,099	467,203	425,759	227,528	40,610
Farms with expenses of-					
$1 to $4,999	15,060	6,330	6,951	1,512	267
$5,000 to $24,999	11,493	5,642	4,378	1,352	121

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
FARM PRODUCTION EXPENSES - Con.					
Total farm production expenses [1] - Con.					
Chemicals purchased - Con.					
Farms with expenses of- - Con.					
$25,000 to $49,999	4,407	2,181	1,592	539	95
$50,000 or more	6,379	2,545	2,440	1,191	203
Seeds, plants, vines, and trees purchased ... farms	36,437	16,389	14,907	4,469	672
$1,000	1,772,341	716,309	658,894	336,753	60,385
Farms with expenses of-					
$1 to $999	5,343	2,011	2,766	484	82
$1,000 to $4,999	6,157	2,756	2,702	588	111
$5,000 to $24,999	10,290	5,056	3,985	1,120	129
$25,000 to $49,999	5,582	2,809	2,007	678	88
$50,000 or more	9,065	3,757	3,447	1,599	262
Cover crop seed purchased ... farms	4,909	1,848	2,131	805	125
$1,000	20,527	7,258	9,485	3,271	513
Livestock and poultry purchased or leased ... farms	13,933	4,922	7,115	1,696	200
$1,000	1,926,426	704,206	675,692	451,671	94,857
Farms with expenses of-					
$1 to $4,999	6,658	2,129	3,835	633	61
$5,000 to $24,999	3,161	1,184	1,611	332	34
$25,000 to $99,999	1,372	560	598	190	24
$100,000 to $249,999	912	357	392	155	8
$250,000 or more	1,830	692	679	386	73
Breeding livestock purchased or leased ... farms	5,904	2,083	2,959	772	90
$1,000	171,016	50,855	71,856	39,961	8,344
Other livestock and poultry purchased or leased ... farms	9,786	3,368	5,118	1,164	136
$1,000	1,755,410	653,351	603,836	411,710	86,513
Feed purchased ... farms	26,145	9,554	13,386	2,852	353
$1,000	3,890,272	1,249,148	1,303,301	1,111,480	226,343
Farms with expenses of-					
$1 to $4,999	13,038	4,709	7,316	899	114
$5,000 to $24,999	6,844	2,648	3,466	673	57
$25,000 to $99,999	2,349	890	1,041	380	38
$100,000 to $249,999	1,155	416	475	239	25
$250,000 or more	2,759	891	1,088	661	119
Gasoline, fuels, and oils purchased ... farms	61,621	26,604	27,384	6,512	1,121
$1,000	956,802	367,968	344,797	202,969	41,068
Farms with expenses of-					
$1 to $4,999	37,714	16,061	17,873	3,129	651
$5,000 to $24,999	14,760	6,976	6,059	1,541	184
$25,000 to $49,999	4,270	1,874	1,631	664	101
$50,000 or more	4,877	1,693	1,821	1,178	185
Utilities ... farms	48,636	20,937	21,332	5,476	891
$1,000	400,978	145,731	144,382	90,291	20,574
Farms with expenses of-					
$1 to $999	9,923	4,104	4,827	831	161
$1,000 to $4,999	24,023	11,015	10,550	2,096	362
$5,000 to $24,999	12,077	5,030	4,991	1,815	241
$25,000 to $49,999	1,626	470	659	448	49
$50,000 or more	987	318	305	286	78
Repairs, supplies, and maintenance costs ... farms	55,660	24,014	24,604	6,045	997
$1,000	1,322,234	516,803	493,288	263,316	48,827
Farms with expenses of-					
$1 to $4,999	25,809	10,932	12,331	2,121	425
$5,000 to $24,999	17,499	8,086	7,383	1,741	289
$25,000 to $49,999	5,425	2,435	2,232	680	78
$50,000 or more	6,927	2,561	2,658	1,503	205
Hired farm labor ... farms	17,399	7,043	7,129	2,760	467
$1,000	1,320,974	417,748	437,197	374,337	91,692
Farms with expenses of-					
$1 to $4,999	5,944	2,647	2,630	577	90
$5,000 to $24,999	4,466	1,893	1,882	596	95
$25,000 to $99,999	3,749	1,415	1,486	717	131
$100,000 to $249,999	2,234	806	824	538	66
$250,000 or more	1,006	282	307	332	85
Contract labor ... farms	4,311	1,726	1,773	686	126
$1,000	152,565	54,381	43,568	46,962	7,655
Farms with expenses of-					
$1 to $999	452	168	223	60	1
$1,000 to $4,999	1,452	619	617	183	33
$5,000 to $24,999	1,469	581	604	229	55
$25,000 to $49,999	315	121	126	58	10
$50,000 or more	623	237	203	156	27
Customwork and custom hauling ... farms	19,181	8,481	7,957	2,443	300
$1,000	425,172	157,266	157,757	95,399	14,751
Farms with expenses of-					
$1 to $999	2,876	1,201	1,429	228	18
$1,000 to $4,999	6,088	2,782	2,572	641	93
$5,000 to $24,999	6,540	3,062	2,544	846	88
$25,000 to $49,999	2,030	872	785	332	41
$50,000 or more	1,647	564	627	396	60
Cash rent for land, buildings, and grazing fees ... farms	24,199	11,009	9,439	3,280	471
$1,000	2,302,712	874,584	827,361	508,093	92,674

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
FARM PRODUCTION EXPENSES - Con.					
Total farm production expenses [1] - Con.					
Cash rent for land, buildings, and grazing fees - Con.					
Farms with expenses of-					
$1 to $4,999	5,289	2,310	2,353	552	74
$5,000 to $9,999	2,314	1,064	945	264	41
$10,000 to $24,999	4,009	1,988	1,516	440	65
$25,000 or more	12,587	5,647	4,625	2,024	291
Rent and lease expenses for machinery, equipment, and farm share of vehicles ... farms	6,598	2,761	2,651	1,016	170
$1,000	182,357	63,775	67,333	38,564	12,685
Farms with expenses of-					
$1 to $999	1,233	501	545	161	26
$1,000 to $4,999	1,683	722	702	233	26
$5,000 to $24,999	2,168	958	809	344	57
$25,000 to $49,999	538	200	214	114	10
$50,000 or more	976	380	381	164	51
Interest expense ... farms	27,274	11,645	11,667	3,429	533
$1,000	702,889	265,979	271,398	136,967	28,544
Farms with expenses of-					
$1 to $4,999	9,316	4,122	4,108	940	146
$5,000 to $24,999	11,255	4,812	4,945	1,313	185
$25,000 to $99,999	5,316	2,226	2,115	849	126
$100,000 or more	1,387	485	499	327	76
Secured by real estate ... farms	20,348	8,658	8,873	2,433	384
$1,000	467,669	181,873	185,603	82,727	17,467
Farms with expenses of-					
$1 to $999	1,511	648	695	136	32
$1,000 to $4,999	5,125	2,255	2,322	462	86
$5,000 to $24,999	9,127	3,889	4,051	1,049	138
$25,000 to $49,999	2,363	1,008	951	346	58
$50,000 or more	2,222	858	854	440	70
Not secured by real estate ... farms	16,953	7,148	7,251	2,231	323
$1,000	235,219	84,107	85,795	54,240	11,077
Farms with expenses of-					
$1 to $999	2,836	1,176	1,345	283	32
$1,000 to $4,999	6,264	2,699	2,816	662	87
$5,000 to $24,999	5,400	2,334	2,205	747	114
$25,000 to $49,999	1,506	618	566	299	23
$50,000 or more	947	321	319	240	67
Property taxes paid ... farms	61,644	26,414	27,578	6,420	1,232
$1,000	482,443	195,541	198,363	74,534	14,005
Farms with expenses of-					
$1 to $4,999	39,325	16,862	18,376	3,376	711
$5,000 to $9,999	11,291	4,976	4,835	1,285	195
$10,000 to $24,999	7,298	3,132	2,889	1,100	177
$25,000 or more	3,730	1,444	1,478	659	149
Medical supplies, veterinary, and custom services for livestock ... farms	19,351	6,941	9,744	2,390	276
$1,000	255,043	74,806	92,367	68,684	19,185
Farms with expenses of-					
$1 to $4,999	14,259	5,257	7,591	1,290	121
$5,000 to $24,999	3,318	1,176	1,542	546	54
$25,000 to $49,999	674	201	249	193	31
$50,000 to $99,999	623	180	204	214	25
$100,000 or more	477	127	158	147	45
All other production expenses ... farms	44,226	19,192	18,819	5,351	864
$1,000	1,200,596	423,128	460,320	259,606	57,542
Farms with expenses of-					
$1 to $4,999	22,214	9,514	10,138	2,152	410
$5,000 to $24,999	13,025	6,061	5,291	1,462	211
$25,000 to $49,999	3,867	1,742	1,485	583	57
$50,000 to $99,999	3,372	1,340	1,291	669	72
$100,000 or more	1,748	535	614	485	114
Production expenses paid by landlords [1] ... farms	2,062	895	783	339	45
$1,000	65,113	22,901	23,678	16,007	2,527
Depreciation expenses claimed ... farms	41,075	17,715	17,494	5,058	808
$1,000	2,240,389	888,728	836,055	439,717	75,889
NET CASH FARM INCOME					
Net cash farm income of operations ... farms	65,531	28,348	28,866	6,980	1,337
$1,000	9,296,848	3,571,511	3,359,725	2,004,295	361,318
Average per farm ... dollars	141,869	125,988	116,390	287,148	270,245
Farms with net gains [2] ... number	41,496	18,795	16,839	4,962	900
Average net gain ... dollars	242,705	205,561	218,448	429,081	444,661
Gain of-					
Less than $1,000	1,541	680	652	148	61
$1,000 to $4,999	4,053	1,787	1,833	307	126
$5,000 to $9,999	3,053	1,368	1,341	272	72
$10,000 to $24,999	5,680	2,618	2,420	517	125
$25,000 to $49,999	5,396	2,484	2,249	578	85
$50,000 or more	21,773	9,858	8,344	3,140	431
Farms with net losses ... number	24,035	9,553	12,027	2,018	437
Average net loss ... dollars	32,221	30,568	26,501	61,845	88,964

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
NET CASH FARM INCOME - Con.					
Net cash farm income of operations - Con.					
Farms with net losses - Con.					
Loss of-					
Less than $1,000	1,786	789	784	160	53
$1,000 to $4,999	6,380	2,643	3,220	400	117
$5,000 to $9,999	5,021	1,931	2,625	408	57
$10,000 to $24,999	5,999	2,362	3,092	493	52
$25,000 to $49,999	2,539	953	1,292	233	61
$50,000 or more	2,310	875	1,014	324	97
Net cash farm income of producers ..... farms	65,531	28,348	28,866	6,980	1,337
$1,000	8,390,544	3,216,396	3,005,557	1,830,399	338,193
Average per farm ..... dollars	128,039	113,461	104,121	262,235	252,949
Producers reporting net gains [2] ..... farms	41,274	18,699	16,743	4,933	899
Average net gain ..... dollars	222,954	188,549	199,457	397,305	419,457
Gain of-					
Less than $1,000	1,557	695	652	148	62
$1,000 to $4,999	4,059	1,796	1,830	307	126
$5,000 to $9,999	3,084	1,374	1,361	278	71
$10,000 to $24,999	5,726	2,634	2,441	527	124
$25,000 to $49,999	5,475	2,512	2,297	582	84
$50,000 or more	21,373	9,688	8,162	3,091	432
Producers reporting net losses ..... farms	24,257	9,649	12,123	2,047	438
Average net loss ..... dollars	33,460	32,053	27,547	63,267	88,811
Loss of-					
Less than $1,000	1,780	785	782	160	53
$1,000 to $4,999	6,394	2,646	3,229	402	117
$5,000 to $9,999	5,032	1,933	2,625	417	57
$10,000 to $24,999	6,008	2,350	3,111	494	53
$25,000 to $49,999	2,576	988	1,294	233	61
$50,000 or more	2,467	947	1,082	341	97
COMMODITY CREDIT CORPORATION LOANS					
Total ..... farms	990	426	369	168	27
$1,000	197,241	60,017	78,808	51,915	6,501
INCOME FROM FARM-RELATED SOURCES					
Total income from farm-related sources ..... farms	38,287	16,952	16,114	4,453	768
$1,000	1,011,249	433,512	380,513	159,871	37,354
Customwork and other agricultural services ..... farms	4,779	2,017	1,905	743	114
$1,000	144,025	58,701	51,874	29,625	3,825
Gross cash rent or share payments ..... farms	15,680	6,944	6,644	1,668	424
$1,000	479,289	219,169	183,791	58,168	18,161
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products ..... farms	619	214	334	55	16
$1,000	5,384	1,743	2,410	910	320
Agri-tourism and recreational services ..... farms	509	149	278	56	26
$1,000	13,615	3,360	4,960	3,802	1,493
Patronage dividends and refunds from cooperatives ..... farms	23,672	10,643	9,856	2,810	363
$1,000	126,183	47,866	48,329	26,091	3,898
Crop and livestock insurance payments ..... farms	5,882	2,721	2,236	814	111
$1,000	171,530	78,014	59,624	30,253	3,639
Amount from State and local government agricultural program payments ..... farms	1,422	456	693	218	55
$1,000	7,129	2,065	3,656	1,226	181
Other farm-related income sources ..... farms	2,557	998	1,175	343	41
$1,000	64,095	22,593	25,869	9,797	5,836
LAND USE					
Total cropland ..... farms	58,762	25,859	25,303	6,391	1,209
acres	21,544,060	8,820,650	8,100,424	3,942,497	680,489
Harvested cropland ..... farms	47,549	21,102	20,449	5,244	754
acres	19,662,443	8,044,016	7,333,030	3,674,844	610,553
Farms by acres harvested:					
1 to 49 acres	16,934	6,896	8,503	1,302	233
50 to 99 acres	5,412	2,491	2,271	563	87
100 to 199 acres	6,580	3,231	2,650	624	75
200 to 499 acres	8,316	4,119	3,160	952	85
500 to 999 acres	4,858	2,293	1,812	659	94
1,000 to 1,999 acres	3,081	1,209	1,190	590	92
2,000 acres or more	2,368	863	863	554	88
Cropland-					
Other pasture and grazing land that could have been used for crops without additional improvements ..... farms	3,908	1,452	1,967	436	53
acres	174,215	70,648	75,637	24,253	3,677
On which all crops failed or were abandoned ..... farms	2,413	1,076	1,001	306	30
acres	110,013	50,284	41,088	15,072	3,569
Idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed ..... farms	22,588	9,733	9,645	2,564	646
acres	1,546,009	634,920	627,155	222,042	61,892
In summer fallow ..... farms	2,242	939	996	277	30
acres	51,380	20,782	23,514	6,286	798
Total woodland ..... farms	23,960	9,214	11,927	2,318	501
acres	1,446,600	568,718	618,665	171,781	87,436

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total producers	One producer	Two producers	Three or four producers	Five or more producers
LAND USE - Con.						
Total woodland - Con.						
Woodland pastured	farms	7,908	2,971	4,070	753	114
	acres	315,103	129,573	140,211	38,636	6,683
Woodland not pastured	farms	19,456	7,446	9,615	1,957	438
	acres	1,131,497	439,145	478,454	133,145	80,753
Permanent pasture and rangeland, other than cropland and woodland pastured	farms	19,837	7,391	10,363	1,837	246
	acres	1,031,215	407,862	462,374	141,097	19,882
Land in farmsteads, homes, buildings, livestock facilities, ponds, roads, wasteland, etc.	farms	42,652	17,335	20,175	4,349	793
	acres	1,420,750	599,131	568,241	192,813	60,565
Irrigated land	farms	3,625	1,249	1,647	605	124
	acres	648,313	235,371	220,064	148,442	44,436
Harvested cropland	farms	3,551	1,233	1,597	598	123
	acres	644,857	234,416	218,045	147,993	44,403
Pastureland and other land	farms	160	40	90	25	5
	acres	3,456	955	2,019	449	33
CONSERVATION AND CROP INSURANCE						
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms	19,069	8,280	7,936	2,240	613
	acres	951,335	389,414	396,326	123,089	42,506
Land enrolled in crop insurance programs	farms	27,305	12,740	10,523	3,557	485
	acres	18,167,226	7,428,225	6,731,507	3,476,792	530,702
ORGANIC AGRICULTURE						
Total organic product sales	farms	577	177	275	102	23
	$1,000	121,783	28,974	44,744	30,322	17,742
VALUE OF LAND AND BUILDINGS						
Estimated market value of land and buildings	farms	65,531	28,348	28,866	6,980	1,337
	$1,000	155,374,449	63,052,627	60,194,000	27,529,061	4,598,761
Average per farm	dollars	2,371,007	2,224,235	2,085,291	3,943,992	3,439,612
Average per acre	dollars	6,107	6,065	6,174	6,189	5,421
Farms by value group:						
$1 to $49,999		1,819	893	714	162	50
$50,000 to $99,999		2,318	1,095	974	207	42
$100,000 to $199,999		5,817	2,551	2,622	522	122
$200,000 to $499,999		17,490	7,121	8,632	1,395	342
$500,000 to $999,999		13,050	5,472	6,096	1,277	205
$1,000,000 to $1,999,999		8,615	3,893	3,630	918	174
$2,000,000 to $4,999,999		8,631	4,148	3,246	1,059	178
$5,000,000 to $9,999,999		3,992	1,823	1,506	579	84
$10,000,000 or more		3,799	1,352	1,446	861	140
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment	farms	65,531	28,348	28,866	6,980	1,337
	$1,000	17,904,134	7,135,135	6,983,336	3,213,748	571,915
Farms by value group:						
$1 to $4,999		3,305	1,447	1,455	285	118
$5,000 to $9,999		3,816	1,693	1,630	366	127
$10,000 to $19,999		6,447	2,814	2,925	549	159
$20,000 to $49,999		12,383	5,286	5,802	1,032	263
$50,000 to $99,999		10,506	4,416	5,064	880	146
$100,000 to $199,999		9,020	4,016	4,014	895	95
$200,000 to $499,999		9,719	4,474	3,996	1,121	128
$500,000 or more		10,335	4,202	3,980	1,852	301
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups	farms	51,156	21,845	23,058	5,486	767
	number	127,301	52,184	52,804	19,351	2,962
Tractors, all	farms	52,770	22,693	23,473	5,691	913
	number	184,473	79,320	76,731	24,811	3,611
Less than 40 horsepower (PTO)	farms	22,815	9,574	10,435	2,393	413
	number	36,863	15,555	16,325	4,348	635
40 to 99 horsepower (PTO)	farms	35,619	15,244	16,015	3,754	606
	number	60,537	26,031	26,630	6,872	1,004
100 horsepower (PTO) or more	farms	31,912	14,623	12,719	4,023	547
	number	87,073	37,734	33,776	13,591	1,972
Grain and bean combines, self-propelled	farms	21,753	10,210	8,228	2,906	409
	number	25,736	11,959	9,562	3,655	560
Cotton pickers and strippers, self-propelled	farms	-	-	-	-	-
	number	-	-	-	-	-
Forage harvesters, self-propelled	farms	2,195	847	912	375	61
	number	2,384	922	984	410	68
Hay balers	farms	19,296	8,067	8,850	2,090	289
	number	24,300	10,076	11,149	2,718	357

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
FERTILIZERS AND CHEMICALS					
Commercial fertilizer, lime, and soil conditioners used ..... farms	34,208	15,578	13,881	4,142	607
acres treated	14,076,782	5,674,084	5,302,695	2,652,963	447,040
Manure used ..... farms	13,721	5,150	6,559	1,809	203
acres treated	1,453,615	447,084	573,456	350,551	82,524
Organic fertilizer used ..... farms	1,053	383	499	136	35
acres treated	135,551	53,201	42,911	21,635	17,804
Acres treated to control-					
Insects ..... farms	13,847	5,972	5,688	1,919	268
acres	5,229,304	2,001,012	1,984,300	1,043,856	200,136
Weeds, grass, or brush ..... farms	34,397	15,710	13,799	4,271	617
acres	17,661,145	7,220,413	6,582,815	3,310,118	547,799
Nematodes ..... farms	3,288	1,506	1,215	490	77
acres	977,113	397,439	349,253	203,909	26,512
Diseases in crops and orchards ..... farms	5,080	2,117	2,051	796	116
acres	2,350,398	809,766	888,917	558,754	92,961
Chemicals used to control growth, thin fruit, ripen, or defoliate ..... farms	1,762	737	714	276	35
acres on which used	318,341	121,751	123,389	62,141	11,060
LAND USE PRACTICES					
Land drained by tile ..... farms	19,088	8,372	7,761	2,567	388
acres	8,247,260	3,076,246	3,234,058	1,627,468	309,488
Land artificially drained by ditches ..... farms	9,435	3,877	4,086	1,269	203
acres	4,560,910	1,657,119	1,706,182	1,033,175	164,434
Land under conservation easement ..... farms	4,909	1,912	2,196	614	187
acres	282,171	94,887	114,099	58,057	15,128
Cropland on which no-till practices were used ..... farms	6,845	2,809	3,005	898	133
acres	1,194,987	482,977	488,204	182,663	41,143
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text) ..... farms	15,574	6,932	6,311	2,066	265
acres	7,881,385	3,160,068	2,915,772	1,535,533	270,012
Cropland on which intensive or conventional tillage practices were used (see text) ..... farms	22,330	10,464	8,759	2,735	372
acres	9,573,777	4,014,086	3,504,377	1,787,043	268,271
Cropland planted to a cover crop (excluding CRP) ..... farms	6,050	2,271	2,678	957	144
acres	760,423	285,257	285,088	154,395	35,683
Use of precision agriculture practices (see text) ..... farms	15,460	6,824	6,075	2,201	360
RENEWABLE ENERGY					
Renewable energy producing systems (see text) ..... farms	4,247	1,444	2,170	552	81
Solar panels ..... farms	2,063	622	1,093	305	43
Wind turbines ..... farms	819	333	361	103	22
Methane digesters ..... farms	15	7	7	1	-
Geothermal/geoexchange systems ..... farms	1,695	570	901	201	23
Small hydro systems ..... farms	24	10	6	8	-
Wind rights leased to others ..... farms	1,189	506	501	137	45
TENURE					
Full owners ..... farms	40,396	16,803	19,027	3,698	868
Part owners ..... farms	20,564	9,302	8,326	2,577	359
Tenants ..... farms	4,571	2,243	1,513	705	110
OWNED AND RENTED LAND					
Land owned ..... farms	61,213	26,256	27,431	6,298	1,228
acres	15,768,785	6,579,434	6,321,754	2,334,643	532,954
Owned land in farms ..... farms	60,960	26,105	27,353	6,275	1,227
acres	13,006,137	5,327,453	5,245,987	2,003,434	429,263
Land rented or leased from others ..... farms	25,328	11,638	9,918	3,302	470
acres	12,515,140	5,105,907	4,530,059	2,457,135	422,039
Rented or leased land in farms ..... farms	25,135	11,545	9,839	3,282	469
acres	12,436,488	5,068,908	4,503,717	2,444,754	419,109
Land rented or leased to others ..... farms	15,946	7,015	6,813	1,689	429
acres	2,841,300	1,288,980	1,102,109	343,590	106,621
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS					
Total producers	118,256	28,348	57,732	23,440	8,736
Farms by number of producers:					
1 producer	28,348	28,348	-	-	-
2 producers	28,866	-	28,866	-	-
3 producers	4,480	-	-	4,480	-
4 producers	2,500	-	-	2,500	-
5 or more producers	1,337	-	-	-	1,337
Total male producers	81,062	25,523	33,451	16,236	5,852
Farms by number of male producers:					
1 producer	49,919	25,523	23,707	666	23
2 producers	8,600	-	4,872	3,612	116
3 producers	2,596	-	-	2,210	386
4 producers	766	-	-	429	337
5 or more producers	459	-	-	-	459
Total female producers	37,193	2,825	24,281	7,203	2,884
Farms by number of female producers:					
1 producer	29,936	2,825	23,707	3,167	237
2 producers	2,374	-	287	1,757	330
3 producers	466	-	-	158	308

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
TOTAL PRODUCERS AND FARMS BY NUMBER OF PRODUCERS - Con.					
Total producers - Con.					
Total female producers - Con.					
Farms by number of female producers: - Con.					
4 producers	138	-	-	12	126
5 or more producers	90	-	-	-	90
PRODUCERS' CHARACTERISTICS [3]					
Sex of producers:					
Male	79,245	25,523	33,451	16,237	4,034
Female	35,623	2,825	24,281	7,203	1,314
Hired managers	6,902	684	2,464	3,035	719
Primary occupation:					
Farming	51,122	14,940	23,972	10,530	1,680
Other	63,746	13,408	33,760	12,910	3,668
Place of residence:					
On farm operated	79,195	20,643	45,168	11,881	1,503
Not on farm operated	35,673	7,705	12,564	11,559	3,845
Days of work off farm:					
None	46,862	12,565	22,564	9,775	1,958
Any	68,006	15,783	35,168	13,665	3,390
1 to 49 days	9,840	2,817	4,657	1,911	455
50 to 99 days	4,745	1,184	2,419	989	153
100 to 199 days	8,361	2,152	4,532	1,377	300
200 days or more	45,060	9,630	23,560	9,388	2,482
Years on present farm:					
2 years or less	4,867	744	2,128	1,626	369
3 or 4 years	7,650	1,331	3,847	1,923	549
5 to 9 years	18,524	3,750	9,472	4,346	956
10 years or more	83,827	22,523	42,285	15,545	3,474
Average years on present farm	24.2	27.8	24.3	20.8	18.1
Years operating any farm:					
5 years or less	13,846	2,214	6,696	3,964	972
6 to 10 years	15,740	3,282	8,185	3,367	906
11 years or more	85,282	22,852	42,851	16,109	3,470
Average years on any farm	26.1	29.8	26.0	23.2	20.1
Age group:					
Under 25 years	1,900	153	363	1,155	229
25 to 34 years	9,374	1,746	4,310	2,819	499
35 to 44 years	16,237	3,281	8,424	3,627	905
45 to 54 years	16,743	3,906	8,597	3,355	885
55 to 64 years	29,818	7,251	15,665	5,679	1,223
65 to 74 years	27,187	7,426	14,053	4,564	1,144
75 years and over	13,609	4,585	6,320	2,241	463
Average age	57.1	60.0	57.4	53.4	53.8
Young producers (see text)	11,274	1,899	4,673	3,974	728
Producers of Hispanic, Latino, or Spanish origin	754	139	336	217	62
Producers by race:					
American Indian or Alaska Native	244	54	125	56	9
Asian	306	60	162	53	31
Black or African American	61	16	35	10	-
Native Hawaiian or Other Pacific Islander	43	1	29	13	-
White	113,864	28,133	57,216	23,228	5,287
More than one race reported	350	84	165	80	21
Military service:					
Never served or only on active duty for training in the Reserves or National Guard (see text)	105,603	25,204	53,382	22,046	4,971
Active duty now or in the past (see text)	9,265	3,144	4,350	1,394	377
Number of persons living in producers' households	228,210	66,456	100,647	48,776	12,331
On farm involvement in decisionmaking:					
Day-to-day decisions	98,292	26,800	50,090	17,622	3,780
Land use and/or crop decisions	83,860	23,672	41,292	15,681	3,215
Livestock decisions	49,585	12,885	26,605	8,761	1,334
Marketing decisions (see text)	68,020	19,736	33,623	12,452	2,209
Record keeping and/or financial management	84,043	24,024	42,619	14,527	2,873
Estate planning or succession planning	64,079	16,749	33,407	11,628	2,295
FARMS BY TYPE OF ORGANIZATION					
Operation more than 50 percent owned by one producer's household and/or extended family — farms	62,111	27,501	27,561	6,046	1,003
acres	22,990,670	9,947,794	8,765,607	3,704,363	572,906
Limited Liability Company — farms	4,803	1,182	2,255	1,109	257
acres	2,179,815	498,212	840,725	680,490	160,388
LEGAL STATUS FOR TAX PURPOSES					
Family or individual — farms	55,532	25,984	24,730	4,258	560
acres	17,410,756	8,743,094	6,529,194	1,901,673	236,795

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total producers	One producer	Two producers	Three or four producers	Five or more producers
LEGAL STATUS FOR TAX PURPOSES - Con.						
Partnership	farms	5,022	717	2,300	1,611	394
	acres	4,452,974	540,411	1,947,323	1,641,388	323,852
Registered under State law	farms	4,156	546	1,886	1,367	357
	acres	3,904,476	480,296	1,669,478	1,444,850	309,852
Corporation	farms	3,803	1,115	1,423	949	316
	acres	3,244,861	996,082	1,174,831	850,064	223,884
Family held	farms	3,375	934	1,320	867	254
	acres	3,085,380	924,005	1,133,405	818,513	209,457
More than 10 stockholders	farms	34	10	3	9	12
10 or less stockholders	farms	3,341	924	1,317	858	242
Other than family held	farms	428	181	103	82	62
	acres	159,481	72,077	41,426	31,551	14,427
More than 10 stockholders	farms	67	25	6	11	25
10 or less stockholders	farms	361	156	97	71	37
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc.	farms	1,174	532	413	162	67
	acres	334,034	116,774	98,356	55,063	63,841
HIRED FARM LABOR						
Hired farm labor	farms	17,399	7,043	7,129	2,760	467
	workers	72,097	24,723	26,704	16,550	4,120
Workers by days worked:						
150 days or more	farms	9,054	3,271	3,600	1,855	328
	workers	30,983	9,545	10,756	8,435	2,247
Less than 150 days	farms	12,949	5,279	5,357	1,984	329
	workers	41,114	15,178	15,948	8,115	1,873
Migrant farm labor on farms with hired labor	farms	573	196	198	136	43
Migrant farm labor on farms reporting only contract labor	farms	41	17	17	7	-
Unpaid workers	farms	17,519	5,610	9,226	2,279	404
	workers	40,333	10,354	21,337	6,792	1,850
FARMS BY SIZE						
1 to 9 acres		4,401	1,797	2,178	359	67
10 to 49 acres		15,218	6,071	7,757	1,138	252
50 to 69 acres		3,598	1,462	1,701	357	78
70 to 99 acres		5,575	2,383	2,520	554	118
100 to 139 acres		4,857	2,214	2,109	428	106
140 to 179 acres		4,814	2,203	2,009	517	85
180 to 219 acres		2,981	1,437	1,202	274	68
220 to 259 acres		2,503	1,152	1,069	224	58
260 to 499 acres		8,699	4,157	3,404	978	160
500 to 999 acres		6,421	2,985	2,463	853	120
1,000 to 1,999 acres		3,752	1,499	1,451	679	123
2,000 acres or more		2,712	988	1,003	619	102
FARMS BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS)						
Oilseed and grain farming (1111)		26,315	13,021	9,959	2,943	392
Vegetable and melon farming (1112)		1,072	378	568	105	21
Fruit and tree nut farming (1113)		972	258	596	107	11
Greenhouse, nursery, and floriculture production (1114)		971	311	447	157	56
Other crop farming (1119)		18,104	8,076	7,657	1,779	592
Tobacco farming (11191)		-	-	-	-	-
Cotton farming (11192)		-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)		18,104	8,076	7,657	1,779	592
Beef cattle ranching and farming (112111)		6,753	2,719	3,479	482	73
Cattle feedlots (112112)		892	410	340	132	10
Dairy cattle and milk production (11212)		1,713	455	711	484	63
Hog and pig farming (1122)		1,855	684	807	308	56
Poultry and egg production (1123)		1,724	432	1,153	125	14
Sheep and goat farming (1124)		1,456	430	886	130	10
Aquaculture and other animal production (1125,1129)		3,704	1,174	2,263	228	39
FARM TYPOLOGY (SEE TEXT)						
Farms by typology group:						
Small family farms						
Gross cash farm income less than $150,000		41,924	18,098	19,953	3,226	647
Gross cash farm income $150,000 to $349,999		7,074	3,611	2,658	713	92
Midsize family farms						
Gross cash farm income $350,000 to $999,999		7,367	3,632	2,818	824	93
Large family farms						
Gross cash farm income $1,000,000 to $4,999,999		5,311	2,023	2,001	1,149	138
Gross cash farm income $5,000,000 or more		435	137	131	134	33
Non-family farms		3,420	847	1,305	934	334
OTHER FARM CHARACTERISTICS						
Farms reporting-						
Internet access		53,964	22,214	24,732	5,996	1,022
Dial-up		1,876	825	824	197	30
Broadband (DSL, cable, fiber optic) (see text)		33,399	13,130	15,731	3,870	668
Cellular data plan (see text)		32,121	13,024	14,714	3,744	639
Satellite		8,385	3,304	3,904	1,047	130
Don't know		2,877	1,377	1,115	335	50
Other		346	133	136	74	3
Farms by number of households sharing in net income of operation:						
1 household		52,287	25,683	22,965	3,198	441

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
OTHER FARM CHARACTERISTICS - Con.					
Farms by number of households sharing in net income of operation: - Con.					
2 households	9,039	1,932	5,313	1,684	110
3 households	2,321	388	330	1,423	180
4 households	1,024	188	129	569	138
5 or more households	860	157	129	106	468
LIVESTOCK					
Cattle and calves inventory ... farms	16,823	6,736	7,939	1,918	230
number	2,121,625	699,246	731,429	589,966	100,984
Farms with-					
1 to 9	3,446	1,306	1,883	222	35
10 to 49	6,556	2,762	3,202	536	56
50 to 99	2,582	1,171	1,120	272	19
100 to 199	1,927	767	873	262	25
200 to 499	1,348	428	619	282	19
500 or more	964	302	242	344	76
Cows and heifers that calved ... farms	13,439	5,294	6,368	1,594	183
number	824,165	232,394	299,008	255,309	37,454
Beef cows ... farms	11,691	4,830	5,625	1,121	115
number	364,629	145,437	157,542	55,458	6,192
Farms with-					
1 to 9	3,718	1,388	2,021	290	19
10 to 49	6,113	2,671	2,786	591	65
50 to 99	1,205	545	522	132	6
100 to 199	470	164	225	62	19
200 to 499	149	49	64	30	6
500 or more	36	13	7	16	-
Milk cows ... farms	2,185	586	942	578	79
number	459,536	86,957	141,466	199,851	31,262
Farms with-					
1 to 9	328	93	179	46	10
10 to 49	315	111	143	58	3
50 to 99	573	181	263	116	13
100 to 199	418	106	179	129	4
200 to 499	390	67	136	155	32
500 or more	161	28	42	74	17
Other cattle ... farms	14,574	5,799	6,826	1,737	212
number	1,297,460	466,852	432,421	334,657	63,530
Cattle and calves sold ... farms	14,649	5,848	6,835	1,756	210
number	1,599,910	533,976	520,666	471,096	74,172
$1,000	2,094,135	763,285	646,512	574,676	109,662
Calves weighing less than 500 pounds ... farms	4,938	1,810	2,344	706	78
number	345,069	72,084	109,519	152,721	10,745
Cattle weighing 500 pounds or more ... farms	13,933	5,554	6,478	1,705	196
number	1,254,841	461,892	411,147	318,375	63,427
Cattle on feed ... farms	2,685	1,085	1,064	485	51
number	636,782	257,803	172,405	171,374	35,200
Hogs and pigs inventory ... farms	2,928	930	1,432	485	81
number	8,873,776	2,434,423	3,982,957	1,703,480	752,916
Farms with-					
1 to 24	893	218	558	103	14
25 to 49	93	29	52	12	-
50 to 99	71	34	30	5	2
100 to 199	65	25	27	13	-
200 to 499	116	62	44	10	-
500 or more	1,690	562	721	342	65
Hogs and pigs sold ... farms	3,352	1,115	1,615	538	84
number	28,535,462	8,520,485	12,760,866	5,350,120	1,903,991
$1,000	4,666,832	1,494,500	1,883,853	941,085	347,394
Sheep and lambs inventory ... farms	2,137	632	1,278	205	22
number	109,592	43,484	55,021	10,320	767
Sheep and lambs sold ... farms	1,500	440	920	128	12
number	92,512	38,274	42,122	11,436	680
Total horses and ponies inventory ... farms	6,988	2,130	4,231	575	52
number	40,131	12,513	23,517	3,780	321
Total horses and ponies sold ... farms	1,171	317	741	108	5
number	4,403	1,547	2,481	361	14
Goats, all inventory ... farms	2,326	639	1,421	249	17
number	50,691	12,460	29,719	8,269	243
Goats, all sold ... farms	1,215	303	756	149	7
number	38,339	17,700	16,295	4,263	81
POULTRY					
Layers inventory ... farms	6,146	1,555	3,956	574	61
number	14,553,497	3,760,404	3,439,332	7,351,613	2,148
Farms with-					
1 to 399	6,045	1,519	3,920	545	61
400 to 3,199	36	7	11	18	-
3,200 to 9,999	8	3	5	-	-
10,000 to 19,999	24	14	8	2	-
20,000 to 49,999	4	-	4	-	-
50,000 to 99,999	5	2	3	-	-
100,000 or more	24	10	5	9	-

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total producers	One producer	Two producers	Three or four producers	Five or more producers
POULTRY - Con.					
Pullets for laying flock replacement inventory ..... farms	723	191	439	91	2
number	4,185,443	(D)	1,392,615	1,790,184	(D)
Layers sold ..... farms	664	163	410	84	7
number	7,016,481	2,012,902	295,200	4,708,013	366
Pullets for laying flock replacement sold ..... farms	102	33	48	21	-
number	8,319,040	2,442,896	1,232,873	4,643,271	-
Broilers and other meat-type chickens sold ..... farms	1,028	192	691	136	9
number	41,793,592	10,564,800	23,635,552	7,592,745	495
Farms with-					
1 to 1,999	900	162	618	111	9
2,000 to 59,999	11	2	5	4	-
60,000 to 99,999	-	-	-	-	-
100,000 or more	117	28	68	21	-
Turkeys inventory ..... farms	623	188	352	72	11
number	14,927,734	9,312,448	2,987,665	(D)	(D)
Turkeys sold ..... farms	379	128	203	41	7
number	39,460,145	23,179,942	9,061,510	(D)	(D)
CROPS					
Barley for grain ..... farms	336	161	110	58	7
acres	55,330	26,840	17,718	9,341	1,431
bushels	4,011,381	2,032,265	1,304,582	567,249	107,285
Irrigated ..... farms	10	7	3	-	-
acres	116	81	35	-	-
Farms by acres harvested:					
1 to 24 acres	72	37	24	11	-
25 to 99 acres	96	45	33	17	1
100 to 249 acres	94	48	23	18	5
250 to 499 acres	53	22	24	7	-
500 acres or more	21	9	6	5	1
Corn for grain ..... farms	24,697	11,658	9,652	2,987	400
acres	7,732,455	3,133,966	2,945,932	1,405,915	246,642
bushels	1,478,451,268	595,159,815	565,630,006	269,657,377	48,004,070
Irrigated ..... farms	1,341	562	517	221	41
acres	302,897	106,554	116,313	64,243	15,787
Farms by acres harvested:					
1 to 24 acres	2,863	1,345	1,274	220	24
25 to 99 acres	6,867	3,414	2,719	653	81
100 to 249 acres	6,444	3,316	2,361	701	66
250 to 499 acres	4,136	1,941	1,589	526	80
500 acres or more	4,387	1,642	1,709	887	149
Corn for silage or greenchop ..... farms	2,768	935	1,150	604	79
acres	313,974	89,532	104,640	96,943	22,859
tons	6,334,518	1,720,099	2,103,171	2,029,939	481,309
Irrigated ..... farms	108	24	31	43	10
acres	13,135	1,854	3,387	5,609	2,285
Farms by acres harvested:					
1 to 24 acres	848	336	390	107	15
25 to 99 acres	1,133	372	512	229	20
100 to 249 acres	452	135	149	153	15
250 to 499 acres	218	63	66	73	16
500 acres or more	117	29	33	42	13
Dry edible beans, excluding chickpeas and limas ..... farms	573	237	213	102	21
acres	210,162	71,590	77,582	44,881	16,109
cwt	5,278,245	1,843,358	1,955,071	1,190,845	288,971
Irrigated ..... farms	95	35	37	18	5
acres	39,931	14,758	12,617	7,813	4,743
Farms by acres harvested:					
1 to 24 acres	34	21	11	1	1
25 to 99 acres	118	52	47	10	9
100 to 249 acres	146	62	57	27	-
250 to 499 acres	140	60	51	29	-
500 acres or more	135	42	47	35	11
Oats for grain ..... farms	2,329	1,018	935	338	38
acres	126,011	52,073	46,917	21,984	5,037
bushels	9,470,546	3,724,172	3,488,342	1,827,656	430,376
Irrigated ..... farms	66	30	22	8	6
acres	3,194	1,569	909	296	420
Farms by acres harvested:					
1 to 24 acres	906	378	423	101	4
25 to 99 acres	1,097	506	386	178	27
100 to 249 acres	286	119	113	51	3
250 to 499 acres	29	14	10	5	-
500 acres or more	11	1	3	3	4
Sorghum for grain ..... farms	12	2	10	-	-
acres	364	(D)	(D)	-	-
bushels	24,260	(D)	(D)	-	-
Irrigated ..... farms	-	-	-	-	-
acres	-	-	-	-	-
Farms by acres harvested:					
1 to 24 acres	7	-	7	-	-
25 to 99 acres	4	1	3	-	-
100 to 249 acres	1	1	-	-	-
250 to 499 acres	-	-	-	-	-
500 acres or more	-	-	-	-	-

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total producers	One producer	Two producers	Three or four producers	Five or more producers
CROPS - Con.						
Soybeans for beans	farms	25,337	12,093	9,645	3,175	424
	acres	7,597,171	3,240,240	2,812,296	1,346,513	198,122
	bushels	373,669,175	156,827,067	139,989,053	66,861,321	9,991,734
Irrigated	farms	892	410	330	133	19
	acres	122,734	55,474	42,345	22,024	2,891
Farms by acres harvested:						
1 to 24 acres		2,307	1,133	960	195	19
25 to 99 acres		7,345	3,578	2,816	828	123
100 to 249 acres		6,879	3,515	2,527	743	94
250 to 499 acres		4,297	2,090	1,648	501	58
500 acres or more		4,509	1,777	1,694	908	130
Sugarbeets for sugar	farms	1,106	501	349	226	30
	acres	446,627	155,420	143,130	123,987	24,090
	tons	11,642,041	4,064,976	3,640,480	3,304,520	632,065
Irrigated	farms	31	5	13	12	1
	acres	10,798	(D)	4,312	2,721	(D)
Sunflower seed, all	farms	221	119	63	38	1
	acres	66,924	31,734	22,012	(D)	(D)
	pounds	151,726,117	73,542,850	48,112,246	(D)	(D)
Irrigated	farms	2	1	-	1	-
	acres	(D)	(D)	-	(D)	-
Farms by acres harvested:						
1 to 24 acres		8	4	2	2	-
25 to 99 acres		53	43	8	1	1
100 to 249 acres		62	25	22	15	-
250 to 499 acres		49	21	18	10	-
500 acres or more		49	26	13	10	-
Wheat for grain, all	farms	3,669	1,741	1,231	629	68
	acres	1,268,681	531,403	428,431	274,511	34,336
	bushels	82,039,945	33,931,861	27,370,090	18,572,365	2,165,629
Irrigated	farms	52	20	13	11	8
	acres	6,251	3,265	785	763	1,438
Farms by acres harvested:						
1 to 24 acres		416	178	158	70	10
25 to 99 acres		1,023	502	349	156	16
100 to 249 acres		809	391	273	142	3
250 to 499 acres		544	325	135	64	20
500 acres or more		877	345	316	197	19
Forage-land used for all hay and haylage, grass silage, and greenchop	farms	23,394	9,600	11,003	2,460	331
	acres	1,392,072	538,780	584,112	228,197	40,983
	tons, dry equivalent	3,565,994	1,274,409	1,443,922	712,628	135,035
Irrigated	farms	675	238	283	128	26
	acres	32,954	9,952	11,647	8,822	2,533
Farms by acres harvested:						
1 to 24 acres		11,106	4,499	5,585	900	122
25 to 99 acres		8,179	3,569	3,694	815	101
100 to 249 acres		3,115	1,184	1,349	530	52
250 to 499 acres		780	284	307	154	35
500 acres or more		214	64	68	61	21
Alfalfa hay	farms	15,333	6,482	6,970	1,651	230
	acres	744,117	306,223	311,244	108,255	18,395
	tons, dry	1,971,568	806,120	804,813	306,310	54,325
Irrigated	farms	421	165	154	91	11
	acres	15,949	5,756	5,520	4,014	659
Other dry hay	farms	8,556	3,408	4,166	881	101
	acres	390,421	161,773	167,467	53,087	8,094
	tons, dry	658,360	256,569	276,241	110,239	15,311
Irrigated	farms	153	59	70	20	4
	acres	3,658	1,339	1,327	800	192
Field and grass seed crops, all	farms	155	78	51	25	1
	acres	66,601	25,787	22,016	(D)	(D)
Irrigated	farms	6	1	3	2	-
	acres	505	(D)	90	(D)	-
Land in vegetables	farms	2,620	924	1,304	348	44
	acres	196,718	80,446	71,219	35,441	9,611
Irrigated	farms	764	228	393	129	14
	acres	54,640	21,480	16,650	14,021	2,489
Farms by acres harvested:						
0.1 to 4.9 acres		1,355	399	797	144	15
5.0 to 24.9 acres		225	64	122	30	9
25.0 to 99.9 acres		495	240	169	82	4
100.0 to 249.9 acres		364	151	161	47	5
250.0 acres or more		181	70	55	45	11
Beans, snap	farms	390	96	233	48	13
	acres	2,553	574	1,226	21	732
Harvested for processing	farms	22	5	13	-	4
	acres	2,278	(D)	1,045	-	(D)
Peas, green	farms	599	244	249	94	12
	acres	47,364	19,633	17,864	8,339	1,528
Harvested for processing	farms	491	218	184	82	7
	acres	47,345	19,629	17,854	8,334	1,527
Potatoes	farms	509	138	282	71	18
	acres	49,008	21,884	12,895	9,974	4,256
Harvested for processing	farms	39	18	8	11	2
	acres	35,127	18,670	11,005	(D)	(D)
Farms by acres harvested:						
0.1 to 4.9 acres		421	106	259	46	10

See footnote(s) at end of table.

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Table 77. **Summary by Operating Arrangements: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total producers	One producer	Two producers	Three or four producers	Five or more producers
CROPS - Con.						
Land in vegetables - Con.						
Potatoes - Con.						
Farms by acres harvested: - Con.						
5.0 to 24.9 acres		5	-	4	1	-
25.0 to 99.9 acres		20	6	10	3	1
100.0 to 249.9 acres		8	4	1	3	-
250.0 acres or more		55	22	8	18	7
Sweet corn (see text)	farms	1,243	493	559	173	18
	acres	96,990	38,553	39,241	17,415	1,780
Harvested for processing	farms	750	327	299	114	10
	acres	94,536	37,901	38,168	16,740	1,727
Sweet potatoes	farms	58	12	37	6	3
	acres	23	(D)	7	10	(D)
Harvested for processing	farms	-	-	-	-	-
	acres	-	-	-	-	-
Tomatoes in the open	farms	592	168	350	64	10
	acres	300	70	171	41	19
Harvested for processing	farms	18	6	7	5	-
	acres	2	1	1	1	-
Land in orchards	farms	1,174	297	722	140	15
	acres	5,049	1,110	2,789	869	281
Irrigated	farms	204	48	127	27	2
	acres	778	(D)	414	164	(D)
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres		927	248	578	91	10
5.0 to 24.9 acres		212	42	129	39	2
25.0 to 99.9 acres		32	7	13	10	2
100.0 to 249.9 acres		3	-	2	-	1
250.0 acres or more		-	-	-	-	-
Apples	farms	751	176	493	74	8
	bearing and nonbearing acres	3,219	719	1,699	544	256
Grapes (including muscadine) (see text)	farms	433	114	246	66	7
	bearing and nonbearing acres	1,290	272	751	242	25
Peaches, all	farms	17	3	14	-	-
	bearing and nonbearing acres	(D)	(D)	(D)	-	-
Walnuts, English	farms	29	9	18	2	-
	bearing and nonbearing acres	142	(D)	122	(D)	-
Land in berries	farms	578	133	346	91	8
	acres	1,129	367	477	167	118

[1] Landlord production expenses are included with total farm production expenses.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.
[3] Data were collected for a maximum of four producers per farm.

Table 1. **County Summary Highlights: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Farms	number	65,531	449	355	952	608
Land in farms	acres	25,442,625	120,748	30,064	381,537	173,158
Average size of farm	acres	388	269	85	401	285
Median size of farm	acres	130	160	22	158	160
Estimated market value of land and buildings:						
Average per farm	dollars	2,371,007	767,525	807,463	1,367,916	872,261
Average per acre	dollars	6,107	2,854	9,535	3,413	3,063
Estimated market value of all machinery and equipment	$1,000	17,904,134	40,480	42,750	209,307	61,968
Average per farm	dollars	273,216	90,155	120,422	219,860	101,921
Farms by size:						
1 to 9 acres		4,401	9	53	28	14
10 to 49 acres		15,218	71	198	148	122
50 to 179 acres		18,844	168	70	356	196
180 to 499 acres		14,183	147	18	252	191
500 to 999 acres		6,421	43	12	95	52
1,000 acres or more		6,464	11	4	73	33
Total cropland	farms	58,762	413	311	814	523
	acres	21,544,060	54,562	21,934	279,390	87,778
Harvested cropland	farms	47,549	396	259	597	473
	acres	19,662,443	48,445	17,836	242,439	73,854
Irrigated land	farms	3,625	34	70	42	45
	acres	648,313	4,443	4,004	8,987	4,050
Market value of agricultural products sold	$1,000	28,482,097	22,332	72,811	305,922	38,203
Average per farm	dollars	434,635	49,737	205,100	321,346	62,834
Crops, including nursery and greenhouse crops	$1,000	17,143,767	13,454	71,779	190,394	26,620
Livestock, poultry, and their products	$1,000	11,338,329	8,878	1,032	115,528	11,584
Farms by value of sales:						
Less than $2,500		18,998	85	145	403	164
$2,500 to $4,999		3,533	72	34	66	53
$5,000 to $9,999		4,091	76	37	65	98
$10,000 to $24,999		5,562	79	50	80	96
$25,000 to $49,999		4,268	56	37	60	82
$50,000 to $99,999		5,328	45	10	68	49
$100,000 or more		23,751	36	42	210	66
Government payments	farms	31,583	82	26	516	180
	$1,000	584,106	827	270	8,045	2,214
Total income from farm-related sources	farms	38,287	136	131	473	319
	$1,000	1,011,249	628	4,714	11,145	1,977
Total farm production expenses	$1,000	20,780,603	16,805	47,729	224,714	34,895
Average per farm	dollars	317,111	37,428	134,447	236,044	57,393
Net cash farm income of the operations	farms	65,531	449	355	952	608
	$1,000	9,296,848	6,982	30,066	100,397	7,500
Average per farm	dollars	141,869	15,550	84,694	105,459	12,335
Livestock and poultry:						
Cattle and calves inventory	farms	16,823	180	43	295	222
	number	2,121,625	7,879	886	30,827	13,648
Beef cows	farms	11,691	161	29	233	206
	number	364,629	3,739	475	7,232	7,080
Milk cows	farms	2,185	5	-	43	6
	number	459,536	5	-	8,461	10
Cattle and calves sold	farms	14,649	149	32	269	194
	number	1,599,910	3,418	413	20,809	7,762
Hogs and pigs inventory	farms	2,928	18	12	11	16
	number	8,873,776	171	231	24,991	209
Hogs and pigs sold	farms	3,352	18	11	21	17
	number	28,535,462	219	85	(D)	245
Sheep and lambs inventory	farms	2,137	11	11	15	17
	number	109,592	125	176	243	370
Layers inventory	farms	6,146	77	56	53	64
	number	14,553,497	1,681	1,883	1,156	1,469
Broilers and other meat-type chickens sold	farms	1,028	11	5	2	9
	number	41,793,592	1,620	395	(D)	301
Selected crops harvested:						
Corn for grain	farms	24,697	25	32	164	32
	acres	7,732,455	905	3,750	72,931	1,975
	bushels	1,478,451,268	131,840	502,239	12,090,339	256,010
Corn for silage or greenchop	farms	2,768	18	6	51	15
	acres	313,974	648	119	8,207	1,173
	tons	6,334,518	7,309	852	145,196	17,496
Wheat for grain, all	farms	3,669	1	-	99	25
	acres	1,268,681	(D)	-	23,468	9,873
	bushels	82,039,945	(D)	-	1,521,552	505,116
Durum wheat for grain	farms	31	-	-	-	-
	acres	(D)	-	-	-	-
	bushels	54,556	-	-	-	-
Other spring wheat for grain	farms	3,557	1	-	99	25
	acres	1,261,299	(D)	-	23,468	9,873
	bushels	81,643,094	(D)	-	1,521,552	505,116
Winter wheat for grain	farms	102	-	-	-	-
	acres	(D)	-	-	-	-
	bushels	342,295	-	-	-	-
Oats for grain	farms	2,329	23	-	28	52
	acres	126,011	1,222	-	1,367	3,919
	bushels	9,470,546	91,150	-	66,886	219,833

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Farms	number	687	392	1,019	973	463
Land in farms	acres	134,358	263,888	478,133	302,331	125,420
Average size of farm	acres	196	673	469	311	271
Median size of farm	acres	75	269	150	170	120
Estimated market value of land and buildings:						
Average per farm	dollars	1,006,623	3,248,198	3,638,942	2,582,113	823,491
Average per acre	dollars	5,147	4,825	7,755	8,310	3,040
Estimated market value of all machinery and equipment	$1,000	135,496	162,740	409,468	259,726	42,696
Average per farm	dollars	197,229	415,153	401,833	266,933	92,216
Farms by size:						
1 to 9 acres		22	14	96	45	15
10 to 49 acres		240	61	222	190	109
50 to 179 acres		231	85	239	267	178
180 to 499 acres		142	98	203	281	137
500 to 999 acres		33	56	122	137	20
1,000 acres or more		19	78	137	53	4
Total cropland	farms	607	368	936	907	415
	acres	104,396	241,318	452,711	282,635	36,197
Harvested cropland	farms	541	290	768	756	377
	acres	95,943	213,843	437,712	260,346	30,672
Irrigated land	farms	64	11	25	35	23
	acres	19,429	2,092	3,269	3,293	233
Market value of agricultural products sold	$1,000	278,263	194,879	838,011	485,455	13,416
Average per farm	dollars	405,041	497,140	822,385	498,926	28,975
Crops, including nursery and greenhouse crops	$1,000	84,372	158,655	463,455	249,798	6,931
Livestock, poultry, and their products	$1,000	193,891	36,224	374,556	235,657	6,485
Farms by value of sales:						
Less than $2,500		164	96	249	188	148
$2,500 to $4,999		55	10	28	19	58
$5,000 to $9,999		63	12	34	43	86
$10,000 to $24,999		103	20	70	31	64
$25,000 to $49,999		52	28	45	58	43
$50,000 to $99,999		64	27	64	76	39
$100,000 or more		186	199	529	558	25
Government payments	farms	347	246	466	532	66
	$1,000	5,823	3,118	5,323	7,494	445
Total income from farm-related sources	farms	381	296	637	704	137
	$1,000	11,058	12,400	13,929	13,528	493
Total farm production expenses	$1,000	208,004	144,720	593,213	354,598	11,196
Average per farm	dollars	302,772	369,184	582,152	364,438	24,181
Net cash farm income of the operations	farms	687	392	1,019	973	463
	$1,000	87,140	65,677	264,049	151,878	3,158
Average per farm	dollars	126,841	167,543	259,126	156,093	6,820
Livestock and poultry:						
Cattle and calves inventory	farms	288	59	87	208	220
	number	44,073	4,375	5,372	33,601	7,167
Beef cows	farms	191	47	53	91	206
	number	3,799	1,562	(D)	4,057	(D)
Milk cows	farms	45	-	1	38	3
	number	17,161	-	(D)	4,697	(D)
Cattle and calves sold	farms	242	58	71	196	173
	number	20,763	3,656	4,370	32,017	4,283
Hogs and pigs inventory	farms	36	7	94	66	10
	number	34,685	45,114	669,744	244,365	60
Hogs and pigs sold	farms	27	9	114	75	12
	number	65,247	101,629	2,198,966	867,498	89
Sheep and lambs inventory	farms	27	1	27	16	22
	number	407	(D)	2,361	1,240	590
Layers inventory	farms	76	14	49	43	106
	number	31,573	273	(D)	2,231	3,822
Broilers and other meat-type chickens sold	farms	31	1	4	4	19
	number	7,126,050	(D)	790	455	1,399
Selected crops harvested:						
Corn for grain	farms	263	206	553	624	9
	acres	36,233	89,282	219,446	131,214	245
	bushels	6,414,145	15,223,986	46,453,017	26,682,697	29,238
Corn for silage or greenchop	farms	50	13	4	52	12
	acres	7,256	3,412	248	4,988	286
	tons	147,700	26,144	(D)	96,399	4,536
Wheat for grain, all	farms	12	41	6	27	3
	acres	206	2,492	102	930	(D)
	bushels	9,327	133,362	5,951	44,762	505
Durum wheat for grain	farms	-	-	-	-	-
	acres	-	-	-	-	-
	bushels	-	-	-	-	-
Other spring wheat for grain	farms	9	39	6	27	2
	acres	158	(D)	102	930	(D)
	bushels	7,319	(D)	5,951	44,762	(D)
Winter wheat for grain	farms	3	2	-	-	1
	acres	48	(D)	-	-	(D)
	bushels	2,008	(D)	-	-	(D)
Oats for grain	farms	28	3	17	27	13
	acres	473	86	627	806	860
	bushels	21,962	4,863	56,304	76,450	69,075

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Farms ..... number	606	488	563	740	655	404
Land in farms ..... acres	156,676	134,449	364,695	81,038	556,161	159,856
Average size of farm ..... acres	259	276	648	110	849	396
Median size of farm ..... acres	70	150	191	37	250	180
Estimated market value of land and buildings:						
Average per farm ..... dollars	2,104,397	840,132	5,015,059	768,510	4,022,707	1,139,890
Average per acre ..... dollars	8,140	3,049	7,742	7,018	4,738	2,881
Estimated market value of all machinery and equipment $1,000	158,429	47,814	274,154	77,167	254,196	61,416
Average per farm ..... dollars	261,434	97,980	486,951	104,280	388,085	152,019
Farms by size:						
1 to 9 acres	58	22	48	114	28	16
10 to 49 acres	193	83	130	347	120	80
50 to 179 acres	184	173	99	176	151	103
180 to 499 acres	99	152	107	77	119	113
500 to 999 acres	34	35	75	13	88	57
1,000 acres or more	38	23	104	13	149	35
Total cropland ..... farms	550	417	524	631	589	331
acres	137,542	56,299	332,842	58,198	508,962	77,211
Harvested cropland ..... farms	473	371	395	551	498	298
acres	129,717	46,589	316,194	53,977	476,475	62,929
Irrigated land ..... farms	19	28	15	76	30	22
acres	129	(D)	2,442	2,054	2,899	6,958
Market value of agricultural products sold $1,000	172,878	29,837	446,611	54,864	466,030	46,418
Average per farm ..... dollars	285,277	61,141	793,270	74,141	711,496	114,897
Crops, including nursery and greenhouse crops $1,000	118,943	9,647	334,319	44,472	400,878	35,732
Livestock, poultry, and their products $1,000	53,935	20,189	112,292	10,393	65,152	10,686
Farms by value of sales:						
Less than $2,500	178	144	166	216	142	112
$2,500 to $4,999	40	52	26	113	38	34
$5,000 to $9,999	56	61	7	98	26	29
$10,000 to $24,999	44	84	18	108	53	49
$25,000 to $49,999	32	47	35	71	51	59
$50,000 to $99,999	75	56	20	48	43	52
$100,000 or more	181	44	291	86	302	69
Government payments ..... farms	206	131	361	82	401	164
$1,000	1,739	1,271	4,826	1,094	10,985	2,651
Total income from farm-related sources ..... farms	360	182	410	279	394	199
$1,000	6,045	2,288	18,018	2,411	12,352	1,722
Total farm production expenses $1,000	116,714	24,955	310,905	46,958	311,838	31,971
Average per farm ..... dollars	192,598	51,136	552,229	63,457	476,088	79,136
Net cash farm income of the operations ..... farms	606	488	563	740	655	404
$1,000	63,948	8,441	158,550	11,411	177,528	18,820
Average per farm ..... dollars	105,524	17,297	281,615	15,420	271,036	46,585
Livestock and poultry:						
Cattle and calves inventory ..... farms	173	216	46	168	118	196
number	19,459	15,184	16,299	5,723	7,952	16,505
Beef cows ..... farms	100	199	24	120	94	178
number	2,250	8,782	536	1,648	3,379	9,563
Milk cows ..... farms	41	3	1	16	14	11
number	6,117	90	(D)	1,212	570	39
Cattle and calves sold ..... farms	160	194	42	142	106	174
number	10,832	8,179	15,913	2,340	3,987	10,267
Hogs and pigs inventory ..... farms	13	12	19	19	6	7
number	25,743	222	61,623	484	13,515	538
Hogs and pigs sold ..... farms	12	10	30	18	11	7
number	40,048	182	425,372	1,169	19,537	870
Sheep and lambs inventory ..... farms	33	9	20	52	18	29
number	2,127	152	1,928	1,126	492	1,108
Layers inventory ..... farms	88	111	19	175	52	38
number	1,809	2,539	360	4,324	830,278	851
Broilers and other meat-type chickens sold ..... farms	3	14	2	13	3	11
number	36	613	(D)	344	200	1,233
Selected crops harvested:						
Corn for grain ..... farms	243	25	320	159	234	17
acres	60,960	2,436	163,441	19,816	144,928	3,368
bushels	11,439,765	222,624	32,869,161	3,206,533	25,402,028	528,337
Corn for silage or greenchop ..... farms	39	14	13	15	19	11
acres	1,863	573	4,759	399	1,137	672
tons	28,692	10,826	103,841	5,723	21,217	9,656
Wheat for grain, all ..... farms	22	10	25	4	199	19
acres	537	705	1,164	141	65,878	3,402
bushels	18,676	23,855	47,916	(D)	4,108,121	187,283
Durum wheat for grain ..... farms	-	5	-	-	-	-
acres	-	(D)	-	-	-	-
bushels	-	(D)	-	-	-	-
Other spring wheat for grain ..... farms	21	4	25	2	197	19
acres	(D)	348	1,164	(D)	65,658	3,402
bushels	(D)	17,406	47,916	(D)	4,097,633	187,283
Winter wheat for grain ..... farms	1	1	-	2	4	-
acres	(D)	(D)	-	(D)	220	-
bushels	(D)	(D)	-	(D)	10,488	-
Oats for grain ..... farms	6	8	2	9	28	15
acres	108	384	(D)	215	2,213	1,357
bushels	8,602	17,773	(D)	20,647	117,970	120,420

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Farms ..... number	25	742	426	841	614	980
Land in farms ..... acres	1,940	392,494	92,791	208,517	280,440	268,096
Average size of farm ..... acres	78	529	218	248	457	274
Median size of farm ..... acres	60	201	115	50	78	88
Estimated market value of land and buildings:						
Average per farm ..... dollars	581,604	4,350,416	694,287	2,056,623	3,934,689	1,245,455
Average per acre ..... dollars	7,495	8,224	3,187	8,295	8,615	4,553
Estimated market value of all machinery and equipment $1,000	2,163	345,752	49,626	199,084	217,546	154,227
Average per farm ..... dollars	86,505	465,973	116,492	236,723	354,310	157,375
Farms by size:						
1 to 9 acres	-	64	30	131	81	48
10 to 49 acres	9	129	95	282	172	263
50 to 179 acres	16	160	166	190	146	331
180 to 499 acres	-	153	89	123	75	225
500 to 999 acres	-	101	21	68	58	55
1,000 acres or more	-	135	25	47	82	58
Total cropland ..... farms	22	681	357	704	527	883
acres	283	370,705	43,947	187,757	262,797	201,875
Harvested cropland ..... farms	21	548	327	657	436	660
acres	228	351,380	37,686	175,486	255,854	176,176
Irrigated land ..... farms	7	15	22	265	19	49
acres	17	2,909	3,482	60,105	(D)	6,918
Market value of agricultural products sold $1,000	506	601,642	26,272	364,822	413,313	168,616
Average per farm ..... dollars	20,225	810,838	61,671	433,796	673,148	172,057
Crops, including nursery and greenhouse crops $1,000	320	353,652	13,633	283,036	272,325	133,283
Livestock, poultry, and their products $1,000	185	247,990	12,639	81,786	140,988	35,333
Farms by value of sales:						
Less than $2,500	9	181	154	174	195	370
$2,500 to $4,999	5	10	48	66	23	68
$5,000 to $9,999	1	16	65	51	37	64
$10,000 to $24,999	3	25	56	95	40	89
$25,000 to $49,999	2	28	32	58	20	82
$50,000 to $99,999	5	45	33	98	34	74
$100,000 or more	-	437	38	299	265	233
Government payments ..... farms	2	402	90	249	190	554
$1,000	(D)	5,455	1,675	4,466	1,753	7,713
Total income from farm-related sources ..... farms	8	570	155	446	385	523
$1,000	(D)	19,787	1,329	10,083	10,675	7,490
Total farm production expenses $1,000	361	391,469	25,167	248,747	307,200	119,368
Average per farm ..... dollars	14,440	527,586	59,077	295,775	500,325	121,805
Net cash farm income of the operations ..... farms	25	742	426	841	614	980
$1,000	(D)	235,415	4,109	130,624	118,540	64,450
Average per farm ..... dollars	(D)	317,271	9,646	155,320	193,062	65,765
Livestock and poultry:						
Cattle and calves inventory ..... farms	4	121	163	189	179	238
number	49	18,565	6,631	33,205	23,457	14,600
Beef cows ..... farms	4	87	134	95	107	162
number	(D)	2,184	3,089	1,769	1,821	3,553
Milk cows ..... farms	1	10	5	26	28	22
number	(D)	799	734	5,143	6,544	2,969
Cattle and calves sold ..... farms	5	101	119	162	161	183
number	224	25,392	4,168	27,808	14,323	8,560
Hogs and pigs inventory ..... farms	1	50	3	19	37	15
number	(D)	341,754	25	4,808	243,721	1,179
Hogs and pigs sold ..... farms	1	61	4	24	49	13
number	(D)	1,438,910	48	16,751	391,126	2,202
Sheep and lambs inventory ..... farms	-	16	6	52	28	26
number	-	3,718	78	972	665	1,885
Layers inventory ..... farms	7	22	53	104	69	96
number	92	805	919	7,046	3,073	2,500
Broilers and other meat-type chickens sold ..... farms	1	14	23	10	16	16
number	(D)	492,832	348,661	1,923	1,760	2,375
Selected crops harvested:						
Corn for grain ..... farms	-	436	52	330	281	283
acres	-	181,404	7,339	87,720	140,265	73,291
bushels	-	37,787,711	876,782	16,360,503	29,571,963	12,507,296
Corn for silage or greenchop ..... farms	-	17	16	24	25	20
acres	-	2,971	1,151	3,897	2,374	1,287
tons	-	43,247	17,190	85,914	54,144	21,680
Wheat for grain, all ..... farms	-	14	3	18	2	73
acres	-	922	474	646	(D)	5,821
bushels	-	42,551	22,260	22,225	(D)	266,592
Durum wheat for grain ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
bushels	-	-	-	-	-	-
Other spring wheat for grain ..... farms	-	14	-	17	-	73
acres	-	922	-	(D)	-	5,821
bushels	-	42,551	-	(D)	-	266,592
Winter wheat for grain ..... farms	-	-	3	1	2	-
acres	-	-	474	(D)	(D)	-
bushels	-	-	22,260	(D)	(D)	-
Oats for grain ..... farms	-	8	26	27	15	59
acres	-	552	1,502	673	580	2,850
bushels	-	53,100	58,406	42,128	54,602	130,308

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Farms	number	773	1,458	908	1,406	529	511
Land in farms	acres	383,231	470,312	351,174	421,698	338,754	32,406
Average size of farm	acres	496	323	387	300	640	63
Median size of farm	acres	220	110	144	105	159	19
Estimated market value of land and buildings:							
Average per farm	dollars	4,050,200	1,909,448	2,977,299	2,490,231	3,120,701	1,093,093
Average per acre	dollars	8,169	5,919	7,698	8,303	4,873	17,237
Estimated market value of all machinery and equipment	$1,000	306,051	391,562	303,555	385,283	197,819	53,901
Average per farm	dollars	395,926	268,561	334,311	274,028	373,950	105,481
Farms by size:							
1 to 9 acres		61	82	62	112	25	150
10 to 49 acres		113	335	232	383	112	227
50 to 179 acres		180	507	215	406	155	94
180 to 499 acres		182	273	192	279	108	28
500 to 999 acres		132	150	115	142	42	11
1,000 acres or more		105	111	92	84	87	1
Total cropland	farms	715	1,287	850	1,218	489	425
	acres	366,048	377,220	332,702	357,142	316,178	21,319
Harvested cropland	farms	640	1,002	670	1,059	282	373
	acres	356,884	347,026	312,957	341,371	281,684	17,928
Irrigated land	farms	16	47	23	57	38	95
	acres	1,364	642	3,444	6,154	7,444	449
Market value of agricultural products sold	$1,000	587,680	519,865	475,632	595,613	313,725	56,766
Average per farm	dollars	760,259	356,560	523,823	423,622	593,053	111,089
Crops, including nursery and greenhouse crops	$1,000	379,350	336,081	319,725	339,139	253,439	51,495
Livestock, poultry, and their products	$1,000	208,331	183,784	155,906	256,474	60,286	5,272
Farms by value of sales:							
Less than $2,500		100	402	242	286	253	204
$2,500 to $4,999		23	68	24	44	4	45
$5,000 to $9,999		15	82	36	98	7	54
$10,000 to $24,999		40	134	57	138	27	72
$25,000 to $49,999		23	130	33	112	22	38
$50,000 to $99,999		64	124	65	144	41	43
$100,000 or more		508	518	451	584	175	55
Government payments	farms	300	612	459	488	421	69
	$1,000	3,052	4,980	4,730	3,835	7,378	324
Total income from farm-related sources	farms	507	873	596	946	358	200
	$1,000	12,186	19,042	16,790	19,471	13,784	5,467
Total farm production expenses	$1,000	417,856	386,109	355,304	438,614	230,900	50,012
Average per farm	dollars	540,565	264,821	391,304	311,959	436,485	97,870
Net cash farm income of the operations	farms	773	1,458	908	1,406	529	511
	$1,000	185,061	157,779	141,848	180,306	103,986	12,546
Average per farm	dollars	239,407	108,216	156,220	128,240	196,572	24,551
Livestock and poultry:							
Cattle and calves inventory	farms	91	546	150	475	47	66
	number	6,228	60,869	9,173	68,383	12,644	3,300
Beef cows	farms	58	422	104	263	28	46
	number	(D)	18,415	3,277	8,311	458	612
Milk cows	farms	3	67	4	95	4	6
	number	(D)	8,767	377	18,580	(D)	502
Cattle and calves sold	farms	89	480	135	463	44	50
	number	7,211	34,707	7,607	45,736	12,043	1,357
Hogs and pigs inventory	farms	65	84	60	62	1	7
	number	278,094	135,192	224,400	99,919	(D)	48
Hogs and pigs sold	farms	83	92	69	91	4	14
	number	982,656	317,527	638,353	364,058	(D)	84
Sheep and lambs inventory	farms	15	74	27	81	2	35
	number	506	2,932	583	3,045	(D)	472
Layers inventory	farms	36	128	47	151	18	106
	number	785	18,326	1,417	11,070	796	2,556
Broilers and other meat-type chickens sold	farms	6	17	8	27	3	14
	number	694	1,432	930	2,469	160	672
Selected crops harvested:							
Corn for grain	farms	484	644	477	703	197	58
	acres	177,166	182,006	162,436	182,876	133,860	4,368
	bushels	38,066,534	36,758,109	33,828,505	37,497,055	24,677,288	727,930
Corn for silage or greenchop	farms	5	88	10	97	8	4
	acres	(D)	8,120	650	7,437	1,380	262
	tons	(D)	169,889	12,160	178,562	26,728	6,000
Wheat for grain, all	farms	1	6	3	24	43	5
	acres	(D)	619	(D)	931	7,963	113
	bushels	(D)	27,912	(D)	38,626	471,155	4,500
Durum wheat for grain	farms	-	-	-	-	-	1
	acres	-	-	-	-	-	(D)
	bushels	-	-	-	-	-	(D)
Other spring wheat for grain	farms	1	6	3	21	41	4
	acres	(D)	(D)	(D)	791	(D)	(D)
	bushels	(D)	(D)	(D)	31,138	(D)	(D)
Winter wheat for grain	farms	-	1	-	3	2	-
	acres	-	(D)	-	140	(D)	-
	bushels	-	(D)	-	7,488	(D)	-
Oats for grain	farms	9	69	24	57	1	3
	acres	195	2,785	1,386	1,471	(D)	161
	bushels	16,487	265,569	105,989	82,172	(D)	7,130

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Farms	number	797	336	814	424	845	531
Land in farms	acres	223,021	98,144	101,666	96,375	384,337	99,182
Average size of farm	acres	280	292	125	227	455	187
Median size of farm	acres	158	127	44	110	196	80
Estimated market value of land and buildings:							
Average per farm	dollars	1,457,621	1,072,180	741,093	764,373	3,842,918	606,217
Average per acre	dollars	5,209	3,671	5,934	3,363	8,449	3,246
Estimated market value of all machinery and equipment	$1,000	165,816	46,646	94,946	42,532	299,422	54,356
Average per farm	dollars	208,050	138,828	116,641	100,310	354,345	102,366
Farms by size:							
1 to 9 acres		17	4	67	20	64	31
10 to 49 acres		151	79	362	99	139	164
50 to 179 acres		267	130	286	151	203	198
180 to 499 acres		228	82	64	101	213	83
500 to 999 acres		107	27	21	44	105	48
1,000 acres or more		27	14	14	9	121	7
Total cropland	farms	716	279	689	365	775	463
	acres	134,933	54,892	71,210	48,228	360,718	58,200
Harvested cropland	farms	525	231	584	330	653	432
	acres	117,902	47,705	64,610	42,596	349,235	53,672
Irrigated land	farms	21	42	55	35	9	30
	acres	483	26,682	2,657	(D)	1,530	150
Market value of agricultural products sold	$1,000	213,008	52,155	73,159	13,796	501,296	32,517
Average per farm	dollars	267,262	155,224	89,876	32,539	593,249	61,236
Crops, including nursery and greenhouse crops	$1,000	87,780	47,496	40,789	9,417	348,611	25,695
Livestock, poultry, and their products	$1,000	125,228	4,660	32,369	4,379	152,685	6,821
Farms by value of sales:							
Less than $2,500		269	129	324	125	150	157
$2,500 to $4,999		31	24	98	48	17	56
$5,000 to $9,999		30	47	98	42	21	70
$10,000 to $24,999		83	49	133	90	34	95
$25,000 to $49,999		50	30	37	54	28	51
$50,000 to $99,999		114	27	48	35	105	48
$100,000 or more		220	30	76	30	490	54
Government payments	farms	389	76	118	65	473	79
	$1,000	3,146	759	1,702	475	7,529	2,092
Total income from farm-related sources	farms	496	167	328	174	617	204
	$1,000	8,122	2,947	4,287	925	16,141	3,061
Total farm production expenses	$1,000	162,105	45,454	68,894	13,951	324,961	25,979
Average per farm	dollars	203,394	135,278	84,637	32,902	384,570	48,925
Net cash farm income of the operations	farms	797	336	814	424	845	531
	$1,000	62,170	10,408	10,253	1,247	200,004	11,690
Average per farm	dollars	78,005	30,977	12,596	2,940	236,691	22,015
Livestock and poultry:							
Cattle and calves inventory	farms	306	142	171	160	119	192
	number	46,700	5,981	7,620	5,421	15,036	6,258
Beef cows	farms	222	121	136	144	83	172
	number	7,524	(D)	1,735	2,731	(D)	(D)
Milk cows	farms	58	5	9	3	2	3
	number	13,685	(D)	1,954	5	(D)	(D)
Cattle and calves sold	farms	288	103	141	120	115	154
	number	37,367	3,312	2,831	2,625	19,896	3,081
Hogs and pigs inventory	farms	10	4	42	20	71	25
	number	18,419	16	20,543	123	229,617	(D)
Hogs and pigs sold	farms	19	5	50	21	73	26
	number	41,958	82	151,249	248	734,275	(D)
Sheep and lambs inventory	farms	23	6	43	25	23	44
	number	686	243	688	563	1,816	697
Layers inventory	farms	59	42	196	90	29	113
	number	1,471	756	4,592	2,312	(D)	29,040
Broilers and other meat-type chickens sold	farms	3	1	26	25	3	24
	number	142	(D)	2,162	1,648	145	4,322
Selected crops harvested:							
Corn for grain	farms	311	47	136	12	556	69
	acres	52,132	12,273	24,352	1,483	176,899	12,558
	bushels	10,310,358	2,093,412	3,476,006	174,888	36,322,400	1,881,809
Corn for silage or greenchop	farms	67	15	9	5	19	9
	acres	6,454	1,206	1,493	258	416	222
	tons	163,203	9,214	34,293	3,205	9,250	3,771
Wheat for grain, all	farms	7	6	7	1	7	15
	acres	309	314	680	(D)	250	2,243
	bushels	18,202	10,275	22,654	(D)	13,405	44,104
Durum wheat for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Other spring wheat for grain	farms	6	6	7	1	7	15
	acres	(D)	314	680	(D)	250	2,243
	bushels	(D)	10,275	22,654	(D)	13,405	44,104
Winter wheat for grain	farms	1	-	-	-	-	-
	acres	(D)	-	-	-	-	-
	bushels	(D)	-	-	-	-	-
Oats for grain	farms	30	28	13	18	7	25
	acres	923	1,558	523	932	215	1,561
	bushels	62,118	94,603	17,638	60,106	21,130	85,962

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Farms	number	1,252	613	190	735	34	186
Land in farms	acres	494,447	602,709	60,919	410,959	1,422	109,394
Average size of farm	acres	395	983	321	559	42	588
Median size of farm	acres	100	355	178	213	31	260
Estimated market value of land and buildings:							
Average per farm	dollars	2,935,043	3,304,679	832,044	3,557,035	333,095	1,539,800
Average per acre	dollars	7,432	3,361	2,595	6,362	7,964	2,618
Estimated market value of all machinery and equipment	$1,000	374,900	242,719	22,933	267,030	1,220	44,965
Average per farm	dollars	299,441	395,953	120,698	363,305	35,884	241,747
Farms by size:							
1 to 9 acres		62	3	1	25	7	1
10 to 49 acres		375	47	29	135	19	19
50 to 179 acres		381	128	66	167	8	52
180 to 499 acres		206	166	50	171	-	59
500 to 999 acres		101	87	36	95	-	32
1,000 acres or more		127	182	8	142	-	23
Total cropland	farms	1,098	589	165	695	21	166
	acres	436,466	514,102	29,974	373,794	227	72,744
Harvested cropland	farms	728	342	147	521	19	126
	acres	396,375	418,170	23,979	340,540	144	57,749
Irrigated land	farms	64	10	3	18	7	1
	acres	27,908	(D)	4	4,325	10	(D)
Market value of agricultural products sold	$1,000	715,674	301,443	10,444	394,270	468	32,786
Average per farm	dollars	571,625	491,751	54,967	536,421	13,767	176,267
Crops, including nursery and greenhouse crops	$1,000	376,326	295,748	8,207	289,072	(D)	31,158
Livestock, poultry, and their products	$1,000	339,348	5,696	2,236	105,198	(D)	1,628
Farms by value of sales:							
Less than $2,500		530	282	55	206	16	66
$2,500 to $4,999		73	11	18	24	6	10
$5,000 to $9,999		58	18	22	23	5	20
$10,000 to $24,999		70	27	33	21	3	20
$25,000 to $49,999		60	13	12	34	2	18
$50,000 to $99,999		56	35	20	36	1	20
$100,000 or more		405	227	30	391	1	32
Government payments	farms	784	542	45	476	-	66
	$1,000	14,886	24,526	425	5,324	-	891
Total income from farm-related sources	farms	662	366	80	574	1	99
	$1,000	27,669	14,270	733	18,288	(D)	2,677
Total farm production expenses	$1,000	510,125	217,936	8,367	270,478	630	26,309
Average per farm	dollars	407,448	355,524	44,036	367,997	18,536	141,447
Net cash farm income of the operations	farms	1,252	613	190	735	34	186
	$1,000	248,104	122,304	3,235	147,405	(D)	10,045
Average per farm	dollars	198,166	199,516	17,026	200,551	(D)	54,003
Livestock and poultry:							
Cattle and calves inventory	farms	256	56	58	83	9	37
	number	41,065	8,448	3,251	8,186	62	1,693
Beef cows	farms	174	54	57	75	7	37
	number	3,910	4,867	(D)	(D)	20	1,109
Milk cows	farms	30	3	2	1	-	-
	number	16,104	12	(D)	(D)	-	-
Cattle and calves sold	farms	219	46	50	81	4	32
	number	28,697	4,761	1,527	4,486	6	928
Hogs and pigs inventory	farms	32	1	4	50	2	3
	number	137,155	(D)	15	159,369	(D)	6
Hogs and pigs sold	farms	26	-	7	62	4	4
	number	182,144	-	36	591,377	74	20
Sheep and lambs inventory	farms	32	5	-	5	2	-
	number	939	43	-	270	(D)	-
Layers inventory	farms	90	9	36	17	17	19
	number	1,746	138	1,210	281	663	412
Broilers and other meat-type chickens sold	farms	8	1	6	1	4	2
	number	278	(D)	1,070	(D)	160	(D)
Selected crops harvested:							
Corn for grain	farms	421	38	7	424	-	3
	acres	194,117	13,946	440	165,302	-	1,125
	bushels	37,614,584	2,052,239	66,618	30,408,622	-	176,125
Corn for silage or greenchop	farms	43	10	2	6	-	-
	acres	9,182	427	(D)	430	-	-
	tons	204,359	9,123	(D)	8,840	-	-
Wheat for grain, all	farms	38	214	7	22	-	20
	acres	2,963	170,257	1,308	970	-	11,175
	bushels	140,190	11,514,162	79,500	45,939	-	725,625
Durum wheat for grain	farms	1	1	-	1	-	-
	acres	(D)	(D)	-	(D)	-	-
	bushels	(D)	(D)	-	(D)	-	-
Other spring wheat for grain	farms	37	213	7	19	-	20
	acres	(D)	(D)	1,308	(D)	-	11,175
	bushels	(D)	(D)	79,500	45,394	-	725,625
Winter wheat for grain	farms	-	1	-	2	-	-
	acres	-	(D)	-	(D)	-	-
	bushels	-	(D)	-	(D)	-	-
Oats for grain	farms	6	17	4	13	-	18
	acres	209	1,386	74	955	-	2,790
	bushels	10,388	129,942	2,534	58,536	-	290,213

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Farms	number	896	598	869	801	268	1,072
Land in farms	acres	205,774	212,420	424,591	246,163	217,882	912,128
Average size of farm	acres	230	355	489	307	813	851
Median size of farm	acres	73	160	270	73	310	364
Estimated market value of land and buildings:							
Average per farm	dollars	1,721,062	2,261,130	3,491,454	2,218,047	3,389,523	2,695,733
Average per acre	dollars	7,494	6,365	7,146	7,217	4,169	3,168
Estimated market value of all machinery and equipment	$1,000	160,835	163,147	330,494	232,663	88,361	376,367
Average per farm	dollars	179,503	272,822	380,315	290,466	329,705	351,089
Farms by size:							
1 to 9 acres		77	29	51	90	5	12
10 to 49 acres		288	106	110	241	23	55
50 to 179 acres		300	181	221	245	65	268
180 to 499 acres		133	157	208	105	79	288
500 to 999 acres		52	80	163	48	34	189
1,000 acres or more		46	45	116	72	62	260
Total cropland	farms	832	545	799	712	248	1,031
	acres	181,375	185,149	389,195	228,148	184,318	804,133
Harvested cropland	farms	523	351	639	570	197	717
	acres	159,857	153,500	360,873	218,209	171,244	646,007
Irrigated land	farms	23	7	11	22	1	12
	acres	2,624	184	1,482	117	(D)	4,046
Market value of agricultural products sold	$1,000	239,195	229,846	762,925	286,425	136,673	420,392
Average per farm	dollars	266,959	384,357	877,935	357,585	509,972	392,157
Crops, including nursery and greenhouse crops	$1,000	155,921	124,923	311,297	218,846	131,407	407,720
Livestock, poultry, and their products	$1,000	83,274	104,923	451,628	67,580	5,266	12,673
Farms by value of sales:							
Less than $2,500		390	226	205	263	65	374
$2,500 to $4,999		26	14	21	31	4	20
$5,000 to $9,999		32	18	23	68	11	47
$10,000 to $24,999		60	30	42	58	28	67
$25,000 to $49,999		57	17	36	52	21	45
$50,000 to $99,999		73	48	45	77	21	71
$100,000 or more		258	245	497	252	118	448
Government payments	farms	562	462	592	359	185	870
	$1,000	4,426	10,232	16,851	4,104	6,372	34,231
Total income from farm-related sources	farms	497	429	584	495	172	633
	$1,000	12,123	15,555	22,438	10,955	6,555	27,305
Total farm production expenses	$1,000	196,518	171,505	555,024	207,129	81,584	338,431
Average per farm	dollars	219,328	286,798	638,693	258,588	304,416	315,700
Net cash farm income of the operations	farms	896	598	869	801	268	1,072
	$1,000	59,227	84,127	247,190	94,356	68,016	143,497
Average per farm	dollars	66,101	140,680	284,454	117,797	253,792	133,859
Livestock and poultry:							
Cattle and calves inventory	farms	149	121	210	198	63	164
	number	11,800	17,734	57,000	17,922	5,169	10,835
Beef cows	farms	86	101	127	106	49	151
	number	2,114	5,105	5,621	1,343	(D)	5,290
Milk cows	farms	16	8	5	30	7	6
	number	1,545	2,848	411	4,566	(D)	570
Cattle and calves sold	farms	131	121	193	160	51	143
	number	6,788	16,073	56,835	51,962	2,334	5,985
Hogs and pigs inventory	farms	74	20	82	15	4	3
	number	109,236	131,627	444,988	7,779	57	9
Hogs and pigs sold	farms	87	21	92	22	4	5
	number	442,256	833,130	1,346,361	14,187	19	13
Sheep and lambs inventory	farms	22	13	38	38	3	6
	number	1,187	2,775	8,724	4,738	(D)	427
Layers inventory	farms	69	10	33	83	11	24
	number	1,489	166	(D)	3,374	386	497
Broilers and other meat-type chickens sold	farms	23	-	4	10	-	1
	number	5,347	-	780	2,537	-	(D)
Selected crops harvested:							
Corn for grain	farms	288	254	517	327	75	78
	acres	75,924	74,109	180,786	113,705	42,747	28,255
	bushels	15,528,082	13,230,886	32,297,253	22,618,847	8,327,208	4,162,308
Corn for silage or greenchop	farms	20	38	43	21	9	10
	acres	701	3,437	4,236	1,593	578	762
	tons	14,129	62,053	80,414	32,931	10,976	8,713
Wheat for grain, all	farms	20	32	22	26	93	404
	acres	1,017	1,977	1,363	984	32,220	217,709
	bushels	63,906	103,898	80,045	51,869	2,208,782	13,634,836
Durum wheat for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Other spring wheat for grain	farms	11	32	19	26	93	403
	acres	331	1,977	868	(D)	32,220	217,492
	bushels	13,306	103,898	44,334	(D)	2,208,782	(D)
Winter wheat for grain	farms	9	-	8	1	-	4
	acres	686	-	495	(D)	-	217
	bushels	50,600	-	35,711	(D)	-	(D)
Oats for grain	farms	28	10	23	21	32	74
	acres	975	1,367	1,297	389	3,107	9,096
	bushels	50,149	160,046	119,334	31,984	297,987	840,276

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Farms	number	823	991	603	1,571	999	789
Land in farms	acres	454,025	308,376	96,684	361,789	380,070	351,476
Average size of farm	acres	552	311	160	230	380	445
Median size of farm	acres	220	98	78	138	115	168
Estimated market value of land and buildings:							
Average per farm	dollars	4,947,147	1,851,915	630,813	895,624	3,134,992	3,822,492
Average per acre	dollars	8,968	5,951	3,934	3,889	8,240	8,581
Estimated market value of all machinery and equipment	$1,000	368,209	278,031	83,609	293,758	330,749	262,673
Average per farm	dollars	447,399	280,556	138,655	186,988	331,080	332,919
Farms by size:							
1 to 9 acres		70	89	29	52	110	62
10 to 49 acres		126	246	218	352	268	133
50 to 179 acres		177	336	196	559	207	204
180 to 499 acres		195	177	119	438	228	163
500 to 999 acres		109	68	33	116	72	131
1,000 acres or more		146	75	8	54	114	96
Total cropland	farms	745	888	533	1,406	894	740
	acres	433,735	267,627	62,663	211,270	351,321	314,260
Harvested cropland	farms	650	602	488	1,288	716	608
	acres	422,048	242,801	55,469	190,224	333,878	298,402
Irrigated land	farms	11	76	19	131	52	2
	acres	532	12,715	467	18,480	6,556	(D)
Market value of agricultural products sold	$1,000	943,050	497,668	65,669	538,309	529,254	451,948
Average per farm	dollars	1,145,868	502,188	108,905	342,654	529,783	572,811
Crops, including nursery and greenhouse crops	$1,000	461,489	198,492	27,365	121,192	348,518	253,460
Livestock, poultry, and their products	$1,000	481,561	299,176	38,304	417,117	180,736	198,487
Farms by value of sales:							
Less than $2,500		109	406	199	312	269	183
$2,500 to $4,999		13	62	63	133	28	18
$5,000 to $9,999		32	41	76	164	54	14
$10,000 to $24,999		28	53	86	203	69	32
$25,000 to $49,999		23	59	60	156	40	24
$50,000 to $99,999		67	65	30	175	61	99
$100,000 or more		551	305	89	428	478	419
Government payments	farms	371	649	155	817	412	461
	$1,000	6,575	11,594	2,009	13,828	3,948	4,913
Total income from farm-related sources	farms	514	573	267	880	642	543
	$1,000	22,446	15,003	1,929	10,922	21,334	20,186
Total farm production expenses	$1,000	707,717	394,331	48,613	338,009	393,494	314,594
Average per farm	dollars	859,923	397,912	80,619	215,155	393,888	398,725
Net cash farm income of the operations	farms	823	991	603	1,571	999	789
	$1,000	264,353	129,934	20,994	225,050	161,042	162,452
Average per farm	dollars	321,207	131,114	34,816	143,253	161,203	205,897
Livestock and poultry:							
Cattle and calves inventory	farms	115	227	210	668	223	165
	number	12,977	34,907	12,633	70,675	21,245	53,015
Beef cows	farms	74	144	180	509	115	110
	number	1,697	4,189	3,069	15,105	2,305	6,348
Milk cows	farms	11	39	16	132	24	12
	number	665	10,489	1,189	19,722	3,697	3,238
Cattle and calves sold	farms	109	188	146	594	192	160
	number	19,542	21,012	9,039	36,149	15,338	52,003
Hogs and pigs inventory	farms	157	20	21	48	82	60
	number	845,233	1,752	127	59,596	237,896	198,432
Hogs and pigs sold	farms	175	26	26	54	88	70
	number	2,742,812	(D)	361	148,794	774,484	584,268
Sheep and lambs inventory	farms	13	30	18	29	17	13
	number	1,819	771	644	1,099	434	3,361
Layers inventory	farms	36	75	119	195	87	23
	number	908	5,700,533	362,928	312,324	2,624	638
Broilers and other meat-type chickens sold	farms	6	14	16	91	6	5
	number	552	2,565	(D)	20,650,190	208	530
Selected crops harvested:							
Corn for grain	farms	512	359	117	613	500	488
	acres	223,294	114,219	14,937	74,544	174,442	144,562
	bushels	49,177,589	20,704,602	2,226,698	12,179,959	37,444,843	26,301,852
Corn for silage or greenchop	farms	5	31	25	148	24	39
	acres	553	6,435	2,147	13,093	2,582	4,055
	tons	12,742	130,352	41,871	248,318	56,666	59,225
Wheat for grain, all	farms	2	13	10	19	8	4
	acres	(D)	513	435	1,764	376	286
	bushels	(D)	24,196	10,650	42,079	18,044	15,317
Durum wheat for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Other spring wheat for grain	farms	2	13	10	19	6	3
	acres	(D)	513	435	1,764	(D)	(D)
	bushels	(D)	24,196	10,650	42,079	(D)	(D)
Winter wheat for grain	farms	-	-	-	-	2	1
	acres	-	-	-	-	(D)	(D)
	bushels	-	-	-	-	(D)	(D)
Oats for grain	farms	11	23	23	65	23	33
	acres	365	579	1,018	1,485	844	1,472
	bushels	33,912	47,185	41,616	69,070	71,022	113,737

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Farms	number	660	938	435	1,102	2,497	322
Land in farms	acres	278,870	366,330	491,694	308,004	770,922	258,956
Average size of farm	acres	423	391	1,130	279	309	804
Median size of farm	acres	172	175	455	76	134	293
Estimated market value of land and buildings:							
Average per farm	dollars	3,641,059	3,360,789	5,240,043	1,972,576	1,185,597	2,606,213
Average per acre	dollars	8,617	8,605	4,636	7,058	3,840	3,241
Estimated market value of all machinery and equipment	$1,000	287,567	371,336	229,143	258,228	446,155	101,201
Average per farm	dollars	435,707	395,880	526,764	234,326	178,676	314,288
Farms by size:							
1 to 9 acres		52	95	8	68	67	10
10 to 49 acres		143	168	49	381	436	36
50 to 179 acres		149	207	85	327	994	83
180 to 499 acres		176	236	82	179	606	72
500 to 999 acres		76	122	58	68	229	45
1,000 acres or more		64	110	153	79	165	76
Total cropland	farms	596	850	408	983	2,201	300
	acres	262,794	346,087	454,901	258,221	545,784	222,501
Harvested cropland	farms	510	716	344	782	1,598	213
	acres	253,410	334,873	428,145	238,968	472,434	187,360
Irrigated land	farms	16	4	9	40	246	1
	acres	246	599	559	949	70,140	(D)
Market value of agricultural products sold	$1,000	596,399	761,337	341,464	337,134	551,279	100,306
Average per farm	dollars	903,635	811,660	784,975	305,930	220,776	311,509
Crops, including nursery and greenhouse crops	$1,000	260,718	292,440	323,379	225,715	336,363	96,307
Livestock, poultry, and their products	$1,000	335,681	468,896	18,085	111,419	214,916	3,999
Farms by value of sales:							
Less than $2,500		121	164	100	341	952	117
$2,500 to $4,999		21	14	14	62	134	8
$5,000 to $9,999		17	37	13	76	154	14
$10,000 to $24,999		29	26	13	120	244	21
$25,000 to $49,999		28	27	13	70	209	17
$50,000 to $99,999		56	80	36	85	189	36
$100,000 or more		388	590	246	348	615	109
Government payments	farms	284	468	351	435	1,604	258
	$1,000	4,879	5,741	24,080	3,716	21,906	14,076
Total income from farm-related sources	farms	455	658	314	633	1,396	182
	$1,000	13,900	17,725	13,381	12,631	21,088	6,380
Total farm production expenses	$1,000	443,965	530,125	241,418	252,185	390,047	82,123
Average per farm	dollars	672,675	565,165	554,984	228,843	156,206	255,039
Net cash farm income of the operations	farms	660	938	435	1,102	2,497	322
	$1,000	171,212	254,678	137,508	101,297	204,225	38,639
Average per farm	dollars	259,413	271,512	316,110	91,921	81,788	119,997
Livestock and poultry:							
Cattle and calves inventory	farms	117	195	68	313	689	68
	number	22,187	74,944	3,536	45,167	70,204	7,058
Beef cows	farms	58	116	49	228	506	66
	number	1,105	6,864	1,652	8,815	16,973	3,706
Milk cows	farms	19	18	6	41	108	-
	number	12,116	7,670	88	11,263	12,283	-
Cattle and calves sold	farms	96	181	61	284	645	61
	number	19,612	91,598	2,024	24,718	45,931	4,427
Hogs and pigs inventory	farms	88	132	10	23	30	2
	number	405,026	504,733	(D)	37,041	599	(D)
Hogs and pigs sold	farms	102	145	10	31	43	1
	number	1,081,058	1,520,981	(D)	66,891	1,225	(D)
Sheep and lambs inventory	farms	22	26	8	24	84	4
	number	609	990	896	479	3,933	125
Layers inventory	farms	34	45	18	109	201	14
	number	1,978,554	1,585	387	1,977	4,145	238
Broilers and other meat-type chickens sold	farms	4	14	3	14	13	-
	number	386	1,090	(D)	456	300	-
Selected crops harvested:							
Corn for grain	farms	399	583	170	442	741	20
	acres	126,724	167,428	88,569	121,676	173,119	7,016
	bushels	25,977,990	30,637,107	14,837,436	25,031,695	28,762,851	1,027,438
Corn for silage or greenchop	farms	36	50	14	42	136	9
	acres	7,850	10,362	2,469	6,019	7,113	845
	tons	161,003	214,288	47,312	147,799	136,066	8,915
Wheat for grain, all	farms	22	5	203	4	176	100
	acres	629	515	101,089	84	20,131	57,079
	bushels	40,127	40,545	6,851,314	4,900	992,388	3,373,899
Durum wheat for grain	farms	-	-	3	-	11	-
	acres	-	-	(D)	-	(D)	-
	bushels	-	-	(D)	-	(D)	-
Other spring wheat for grain	farms	19	2	200	2	164	100
	acres	539	(D)	100,864	(D)	19,455	57,079
	bushels	33,377	(D)	6,842,971	(D)	974,124	3,373,899
Winter wheat for grain	farms	3	3	1	2	1	-
	acres	90	(D)	(D)	(D)	(D)	-
	bushels	6,750	(D)	(D)	(D)	(D)	-
Oats for grain	farms	11	14	16	41	134	26
	acres	723	654	947	1,978	8,081	4,426
	bushels	45,672	87,908	94,426	167,527	519,046	370,583

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Farms	number	728	529	1,223	821	47	274
Land in farms	acres	164,801	227,976	1,083,394	310,041	799	196,716
Average size of farm	acres	226	431	886	378	17	718
Median size of farm	acres	120	181	320	150	2	362
Estimated market value of land and buildings:							
Average per farm	dollars	740,022	3,210,283	3,827,718	2,000,879	798,533	2,118,613
Average per acre	dollars	3,269	7,449	4,321	5,298	46,973	2,951
Estimated market value of all machinery and equipment	$1,000	78,647	188,858	631,119	183,466	1,407	105,358
Average per farm	dollars	108,032	357,010	516,042	223,467	29,945	384,518
Farms by size:							
1 to 9 acres		39	37	29	34	40	2
10 to 49 acres		136	130	140	142	2	16
50 to 179 acres		292	96	297	274	5	68
180 to 499 acres		176	136	274	223	-	82
500 to 999 acres		61	77	146	75	-	47
1,000 acres or more		24	53	337	73	-	59
Total cropland	farms	662	463	1,143	712	44	260
	acres	87,197	189,619	986,385	254,036	503	176,822
Harvested cropland	farms	620	412	890	470	40	213
	acres	75,570	181,999	904,276	220,081	108	154,337
Irrigated land	farms	20	18	30	100	27	13
	acres	145	4,800	13,059	34,945	70	915
Market value of agricultural products sold	$1,000	58,065	397,208	697,381	244,815	3,449	109,527
Average per farm	dollars	79,760	750,866	570,222	298,191	73,387	399,734
Crops, including nursery and greenhouse crops	$1,000	30,766	139,438	683,717	176,399	(D)	91,408
Livestock, poultry, and their products	$1,000	27,300	257,770	13,665	68,416	(D)	18,119
Farms by value of sales:							
Less than $2,500		191	105	290	333	8	59
$2,500 to $4,999		95	29	47	23	2	6
$5,000 to $9,999		84	14	67	32	10	2
$10,000 to $24,999		109	30	62	60	4	15
$25,000 to $49,999		114	36	75	60	15	19
$50,000 to $99,999		47	30	86	59	2	43
$100,000 or more		88	285	596	254	6	130
Government payments	farms	75	261	902	564	5	204
	$1,000	863	5,955	50,998	12,499	(D)	8,410
Total income from farm-related sources	farms	273	332	815	459	8	184
	$1,000	1,694	13,840	38,275	24,849	925	5,757
Total farm production expenses	$1,000	40,723	284,775	537,941	180,411	3,231	82,605
Average per farm	dollars	55,938	538,327	439,854	219,746	68,751	301,477
Net cash farm income of the operations	farms	728	529	1,223	821	47	274
	$1,000	19,899	132,228	248,714	101,752	1,294	41,090
Average per farm	dollars	27,334	249,959	203,364	123,937	27,530	149,963
Livestock and poultry:							
Cattle and calves inventory	farms	308	197	151	194	-	67
	number	19,294	62,663	13,468	19,845	-	10,937
Beef cows	farms	260	133	128	166	-	60
	number	6,864	10,011	5,981	5,753	-	2,282
Milk cows	farms	24	14	15	15	-	3
	number	2,969	10,600	958	2,948	-	1,272
Cattle and calves sold	farms	256	183	145	159	-	56
	number	9,186	44,970	7,065	13,420	-	6,935
Hogs and pigs inventory	farms	23	34	28	15	-	2
	number	202	303,763	1,862	68,364	-	(D)
Hogs and pigs sold	farms	32	32	27	14	-	2
	number	352	1,355,511	575	199,280	-	(D)
Sheep and lambs inventory	farms	47	40	28	16	-	5
	number	1,219	4,162	809	903	-	161
Layers inventory	farms	156	27	53	50	-	5
	number	2,845	517	1,082	866	-	85
Broilers and other meat-type chickens sold	farms	14	5	9	8	-	-
	number	1,238	434	366	(D)	-	-
Selected crops harvested:							
Corn for grain	farms	107	277	183	271	-	45
	acres	12,696	85,909	90,389	102,075	-	13,891
	bushels	1,780,538	14,810,917	14,278,511	17,738,290	-	2,315,235
Corn for silage or greenchop	farms	38	39	12	34	-	9
	acres	3,333	7,390	927	2,984	-	1,607
	tons	55,814	120,243	19,342	52,908	-	27,782
Wheat for grain, all	farms	8	7	531	47	1	140
	acres	349	486	278,518	3,192	(D)	55,005
	bushels	13,565	19,920	20,189,206	140,742	(D)	3,470,736
Durum wheat for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Other spring wheat for grain	farms	6	7	530	47	1	140
	acres	(D)	486	278,188	3,192	(D)	55,005
	bushels	(D)	19,920	20,174,063	140,742	(D)	3,470,736
Winter wheat for grain	farms	2	-	3	-	-	-
	acres	(D)	-	330	-	-	-
	bushels	(D)	-	15,143	-	-	-
Oats for grain	farms	20	28	15	30	1	12
	acres	501	1,370	3,647	1,362	(D)	1,812
	bushels	27,265	124,983	284,041	81,918	(D)	204,850

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
Farms ..... number	1,323	931	1,111	573	751	821
Land in farms ..... acres	560,222	626,065	249,881	261,220	537,341	162,061
Average size of farm ..... acres	423	672	225	456	716	197
Median size of farm ..... acres	214	240	68	183	296	112
Estimated market value of land and buildings:						
Average per farm ..... dollars	3,560,316	5,472,284	1,873,628	4,026,064	1,825,381	775,243
Average per acre ..... dollars	8,408	8,138	8,330	8,831	2,551	3,927
Estimated market value of all machinery and equipment $1,000	490,671	471,272	235,260	234,510	225,261	68,608
Average per farm ..... dollars	370,878	506,200	211,755	409,268	299,948	83,566
Farms by size:						
1 to 9 acres	123	34	102	85	26	32
10 to 49 acres	216	177	367	95	69	242
50 to 179 acres	293	202	372	105	186	291
180 to 499 acres	318	182	161	142	206	189
500 to 999 acres	236	148	55	78	109	43
1,000 acres or more	137	188	54	68	155	24
Total cropland ..... farms	1,201	884	1,008	482	668	698
acres	535,304	598,705	216,032	241,588	418,239	80,998
Harvested cropland ..... farms	983	734	818	443	490	635
acres	509,922	571,420	197,825	235,233	339,987	70,850
Irrigated land ..... farms	21	14	55	9	-	72
acres	376	1,935	2,271	(D)	-	(D)
Market value of agricultural products sold $1,000	804,002	810,285	356,823	624,006	212,493	29,054
Average per farm ..... dollars	607,711	870,338	321,173	1,089,015	282,947	35,389
Crops, including nursery and greenhouse crops $1,000	462,562	581,026	225,622	226,806	178,824	16,083
Livestock, poultry, and their products $1,000	341,439	229,258	131,201	397,199	33,669	12,971
Farms by value of sales:						
Less than $2,500	273	182	335	83	280	280
$2,500 to $4,999	21	21	74	11	37	127
$5,000 to $9,999	33	19	78	15	37	117
$10,000 to $24,999	49	50	103	38	47	126
$25,000 to $49,999	71	39	88	22	45	68
$50,000 to $99,999	95	44	123	40	73	53
$100,000 or more	781	576	310	364	232	50
Government payments ..... farms	785	583	411	271	489	99
$1,000	15,663	12,261	2,916	3,108	15,069	1,078
Total income from farm-related sources ..... farms	958	696	627	370	479	204
$1,000	26,015	33,068	9,856	8,512	9,066	1,819
Total farm production expenses $1,000	600,313	589,067	258,143	427,209	174,553	23,456
Average per farm ..... dollars	453,752	632,725	232,352	745,565	232,428	28,570
Net cash farm income of the operations ..... farms	1,323	931	1,111	573	751	821
$1,000	245,366	266,546	111,452	208,417	62,075	8,495
Average per farm ..... dollars	185,462	286,301	100,317	363,729	82,656	10,347
Livestock and poultry:						
Cattle and calves inventory ..... farms	214	125	224	201	172	254
number	49,053	26,887	16,167	70,805	16,286	11,243
Beef cows ..... farms	125	63	124	102	161	225
number	7,583	2,677	2,218	5,168	9,135	4,971
Milk cows ..... farms	9	11	43	11	6	13
number	1,062	2,349	5,225	4,354	342	979
Cattle and calves sold ..... farms	208	111	179	191	140	190
number	58,478	35,071	7,377	81,116	9,593	5,763
Hogs and pigs inventory ..... farms	100	57	41	101	14	33
number	352,676	253,395	149,572	400,859	13,262	266
Hogs and pigs sold ..... farms	111	63	46	111	13	34
number	944,475	881,984	412,853	1,071,609	2,454	465
Sheep and lambs inventory ..... farms	31	43	38	15	23	39
number	2,056	6,685	1,841	665	1,016	401
Layers inventory ..... farms	47	37	139	29	48	216
number	852	930	5,350	523	1,076	6,331
Broilers and other meat-type chickens sold ..... farms	3	7	44	6	7	34
number	(D)	690	22,101	109	572	3,397
Selected crops harvested:						
Corn for grain ..... farms	833	564	419	337	41	-
acres	257,104	271,325	96,895	120,530	12,134	-
bushels	48,880,497	53,676,916	20,234,092	23,596,331	1,715,961	-
Corn for silage or greenchop ..... farms	40	23	34	46	15	11
acres	3,939	1,964	2,345	6,639	1,290	332
tons	58,901	45,026	48,820	166,296	22,476	5,352
Wheat for grain, all ..... farms	17	45	13	2	187	5
acres	506	3,050	368	(D)	89,637	64
bushels	24,819	175,764	20,706	(D)	5,754,165	1,683
Durum wheat for grain ..... farms	-	2	-	-	-	-
acres	-	(D)	-	-	-	-
bushels	-	(D)	-	-	-	-
Other spring wheat for grain ..... farms	17	42	9	2	181	5
acres	506	2,979	(D)	(D)	89,469	64
bushels	24,819	173,104	(D)	(D)	5,741,565	1,683
Winter wheat for grain ..... farms	-	1	5	-	6	-
acres	-	(D)	(D)	-	168	-
bushels	-	(D)	(D)	-	12,600	-
Oats for grain ..... farms	13	17	24	10	54	37
acres	390	560	360	690	6,502	2,298
bushels	29,722	37,042	34,153	80,024	535,248	147,772

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Farms	number	624	494	860	2,695	721	500
Land in farms	acres	99,629	85,044	373,628	643,463	245,834	330,936
Average size of farm	acres	160	172	434	239	341	662
Median size of farm	acres	31	40	140	118	68	168
Estimated market value of land and buildings:							
Average per farm	dollars	1,524,233	1,236,200	3,590,625	1,338,253	3,130,924	4,266,717
Average per acre	dollars	9,547	7,181	8,265	5,605	9,183	6,446
Estimated market value of all machinery and equipment	$1,000	105,424	82,965	300,378	593,687	217,310	180,393
Average per farm	dollars	168,948	167,945	349,277	220,292	301,401	360,785
Farms by size:							
1 to 9 acres		66	92	87	140	85	37
10 to 49 acres		304	179	175	695	208	95
50 to 179 acres		147	126	227	844	194	121
180 to 499 acres		58	54	171	732	122	89
500 to 999 acres		28	17	94	193	42	43
1,000 acres or more		21	26	106	91	70	115
Total cropland	farms	527	370	791	2,451	647	454
	acres	87,877	64,444	349,255	512,194	231,083	312,245
Harvested cropland	farms	442	325	670	2,118	442	326
	acres	81,167	57,043	333,743	458,204	215,514	283,965
Irrigated land	farms	27	96	13	325	18	55
	acres	154	37,673	1,062	58,778	2,337	22,814
Market value of agricultural products sold	$1,000	91,834	120,592	484,129	1,021,472	396,997	583,773
Average per farm	dollars	147,171	244,113	562,941	379,025	550,619	1,167,545
Crops, including nursery and greenhouse crops	$1,000	64,614	96,205	341,817	314,418	268,995	256,441
Livestock, poultry, and their products	$1,000	27,220	24,387	142,312	707,055	128,001	327,331
Farms by value of sales:							
Less than $2,500		232	217	208	622	287	165
$2,500 to $4,999		44	33	40	166	21	8
$5,000 to $9,999		48	55	36	149	38	7
$10,000 to $24,999		82	63	50	277	35	22
$25,000 to $49,999		50	18	46	215	30	15
$50,000 to $99,999		59	22	70	232	42	46
$100,000 or more		109	86	410	1,034	268	237
Government payments	farms	138	111	448	1,352	382	326
	$1,000	844	1,688	6,128	20,783	3,208	5,487
Total income from farm-related sources	farms	280	154	567	1,598	424	349
	$1,000	6,635	3,094	16,039	27,690	9,795	19,196
Total farm production expenses	$1,000	75,773	85,746	332,329	757,374	295,463	421,907
Average per farm	dollars	121,432	173,575	386,429	281,029	409,796	843,814
Net cash farm income of the operations	farms	624	494	860	2,695	721	500
	$1,000	23,541	39,628	173,967	312,571	114,537	186,548
Average per farm	dollars	37,725	80,219	202,287	115,982	158,859	373,097
Livestock and poultry:							
Cattle and calves inventory	farms	147	102	226	1,258	145	82
	number	10,819	11,468	28,226	187,176	6,622	53,804
Beef cows	farms	85	69	133	636	112	44
	number	1,188	1,063	3,250	16,101	1,531	(D)
Milk cows	farms	20	4	34	362	11	8
	number	2,416	144	7,972	57,890	1,507	(D)
Cattle and calves sold	farms	109	73	209	1,112	120	75
	number	8,139	9,353	20,460	109,820	3,156	39,461
Hogs and pigs inventory	farms	6	19	46	84	48	43
	number	(D)	(D)	79,804	65,897	116,411	210,165
Hogs and pigs sold	farms	13	26	49	95	64	47
	number	1,053	5,736	449,393	153,660	444,668	819,759
Sheep and lambs inventory	farms	36	36	17	72	16	12
	number	950	328	468	3,665	291	256
Layers inventory	farms	131	120	69	298	49	18
	number	3,977	(D)	(D)	897,819	588	280
Broilers and other meat-type chickens sold	farms	11	21	8	76	14	8
	number	1,935	(D)	350	11,989,349	1,520	446
Selected crops harvested:							
Corn for grain	farms	182	96	497	1,223	277	224
	acres	37,043	24,604	177,256	183,737	118,042	126,102
	bushels	6,481,477	4,212,532	35,479,978	32,564,050	24,945,640	22,496,743
Corn for silage or greenchop	farms	17	10	39	317	15	30
	acres	1,647	1,190	2,783	34,145	667	11,002
	tons	36,761	23,084	63,302	674,802	12,126	239,448
Wheat for grain, all	farms	5	3	25	55	14	41
	acres	131	(D)	1,312	2,568	1,017	7,848
	bushels	5,052	3,456	78,957	123,260	53,104	462,844
Durum wheat for grain	farms	-	-	-	2	-	-
	acres	-	-	-	(D)	-	-
	bushels	-	-	-	(D)	-	-
Other spring wheat for grain	farms	5	3	23	52	11	41
	acres	131	(D)	(D)	2,500	901	7,848
	bushels	5,052	(D)	(D)	120,828	51,189	462,844
Winter wheat for grain	farms	-	2	2	1	3	-
	acres	-	(D)	(D)	(D)	116	-
	bushels	-	(D)	(D)	(D)	1,915	-
Oats for grain	farms	18	8	16	293	5	1
	acres	539	431	309	11,452	314	(D)
	bushels	41,721	21,401	24,207	744,283	31,310	(D)

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Farms	number	708	1,529	358	743	442	622
Land in farms	acres	374,933	321,168	309,539	235,417	123,335	266,866
Average size of farm	acres	530	210	865	317	279	429
Median size of farm	acres	161	117	319	160	153	147
Estimated market value of land and buildings:							
Average per farm	dollars	3,377,922	767,599	4,731,445	2,102,705	901,351	3,786,478
Average per acre	dollars	6,379	3,654	5,472	6,636	3,230	8,825
Estimated market value of all machinery and equipment	$1,000	263,470	211,245	162,359	231,856	63,638	200,840
Average per farm	dollars	372,132	138,159	453,517	312,053	143,977	322,894
Farms by size:							
1 to 9 acres		33	26	7	39	14	83
10 to 49 acres		139	355	57	123	86	115
50 to 179 acres		191	607	86	226	154	143
180 to 499 acres		153	408	54	244	144	149
500 to 999 acres		79	87	49	59	19	57
1,000 acres or more		113	46	105	52	25	75
Total cropland	farms	645	1,375	345	693	385	566
	acres	339,539	200,294	291,513	180,270	79,942	251,700
Harvested cropland	farms	445	1,179	229	604	333	453
	acres	302,409	175,396	257,835	167,885	71,052	235,748
Irrigated land	farms	73	84	3	41	50	14
	acres	22,593	17,221	44	2,185	32,840	967
Market value of agricultural products sold	$1,000	453,273	346,248	259,570	329,119	105,639	393,883
Average per farm	dollars	640,217	226,454	725,056	442,960	239,002	633,253
Crops, including nursery and greenhouse crops	$1,000	278,222	108,415	199,004	133,265	59,702	262,973
Livestock, poultry, and their products	$1,000	175,051	237,832	60,566	195,854	45,937	130,911
Farms by value of sales:							
Less than $2,500		250	437	131	137	138	146
$2,500 to $4,999		8	99	3	33	49	29
$5,000 to $9,999		27	156	9	55	34	21
$10,000 to $24,999		34	191	6	65	50	31
$25,000 to $49,999		35	131	6	51	39	30
$50,000 to $99,999		44	185	22	51	62	38
$100,000 or more		310	330	181	351	70	327
Government payments	farms	469	649	306	279	175	296
	$1,000	5,356	6,186	8,127	3,221	2,002	3,374
Total income from farm-related sources	farms	467	740	263	501	195	428
	$1,000	16,723	6,792	15,632	9,427	1,618	11,417
Total farm production expenses	$1,000	316,031	276,843	197,283	240,549	78,202	284,379
Average per farm	dollars	446,372	181,061	551,071	323,754	176,929	457,201
Net cash farm income of the operations	farms	708	1,529	358	743	442	622
	$1,000	159,321	82,384	86,045	101,218	31,056	124,295
Average per farm	dollars	225,029	53,881	240,350	136,229	70,262	199,832
Livestock and poultry:							
Cattle and calves inventory	farms	110	600	19	317	180	101
	number	31,135	50,660	12,129	64,958	9,719	9,649
Beef cows	farms	90	413	11	190	148	58
	number	(D)	10,533	756	6,489	3,720	1,730
Milk cows	farms	5	141	1	103	17	3
	number	(D)	11,741	(D)	27,545	1,113	197
Cattle and calves sold	farms	93	484	18	298	151	81
	number	24,850	23,937	11,481	32,247	6,057	9,701
Hogs and pigs inventory	farms	14	54	6	36	13	51
	number	26,698	7,175	12,478	41,069	153	216,305
Hogs and pigs sold	farms	13	44	6	35	7	62
	number	76,620	(D)	49,373	180,203	194	597,022
Sheep and lambs inventory	farms	6	75	1	30	20	17
	number	110	2,228	(D)	1,099	2,098	746
Layers inventory	farms	17	236	2	56	56	49
	number	459	2,036,330	(D)	1,886	3,421	1,087
Broilers and other meat-type chickens sold	farms	5	38	-	5	8	2
	number	275	2,868	-	246	367	(D)
Selected crops harvested:							
Corn for grain	farms	357	502	185	424	92	331
	acres	157,921	57,958	115,605	76,700	19,535	120,236
	bushels	29,433,661	9,404,011	18,589,545	15,537,718	3,334,062	26,432,335
Corn for silage or greenchop	farms	40	112	22	73	29	11
	acres	9,735	9,516	6,967	11,700	2,294	321
	tons	223,033	174,415	144,063	268,431	35,946	4,824
Wheat for grain, all	farms	22	43	20	3	11	4
	acres	1,921	2,712	3,762	110	1,230	100
	bushels	93,639	111,215	189,957	7,608	72,238	6,040
Durum wheat for grain	farms	-	3	-	-	-	-
	acres	-	46	-	-	-	-
	bushels	-	1,098	-	-	-	-
Other spring wheat for grain	farms	22	35	20	3	10	4
	acres	1,921	2,410	3,762	110	(D)	100
	bushels	93,639	88,397	189,957	7,608	(D)	6,040
Winter wheat for grain	farms	-	7	-	-	1	-
	acres	-	256	-	-	(D)	-
	bushels	-	21,720	-	-	(D)	-
Oats for grain	farms	24	121	3	59	48	2
	acres	976	5,271	600	1,826	3,102	(D)
	bushels	82,301	355,300	60,000	168,701	188,693	(D)

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Farms	number	525	512	358	993	1,310	847
Land in farms	acres	50,806	263,479	401,044	295,658	224,831	383,404
Average size of farm	acres	97	515	1,120	298	172	453
Median size of farm	acres	23	160	326	146	50	160
Estimated market value of land and buildings:							
Average per farm	dollars	1,095,428	4,163,674	6,068,987	2,036,571	1,361,777	3,196,563
Average per acre	dollars	11,320	8,091	5,418	6,840	7,935	7,062
Estimated market value of all machinery and equipment	$1,000	59,204	213,589	185,963	257,758	226,809	268,428
Average per farm	dollars	112,770	417,167	519,451	259,575	173,136	316,916
Farms by size:							
1 to 9 acres		98	45	15	56	129	60
10 to 49 acres		256	112	69	158	511	186
50 to 179 acres		98	103	65	340	412	196
180 to 499 acres		52	87	44	281	158	167
500 to 999 acres		13	79	54	86	59	125
1,000 acres or more		8	86	111	72	41	113
Total cropland	farms	433	471	339	871	1,172	776
	acres	36,745	251,388	387,669	217,078	185,511	350,967
Harvested cropland	farms	392	390	260	742	995	588
	acres	33,731	241,723	358,050	198,115	171,228	316,017
Irrigated land	farms	78	35	9	31	119	5
	acres	2,840	8,318	515	46	7,775	807
Market value of agricultural products sold	$1,000	60,710	404,682	254,790	401,862	283,025	422,723
Average per farm	dollars	115,637	790,395	711,704	404,695	216,049	499,083
Crops, including nursery and greenhouse crops	$1,000	54,703	254,705	252,735	151,455	150,721	278,355
Livestock, poultry, and their products	$1,000	6,007	149,977	2,055	250,407	132,304	144,368
Farms by value of sales:							
Less than $2,500		138	98	102	271	475	250
$2,500 to $4,999		71	11	10	35	122	30
$5,000 to $9,999		66	40	9	39	97	35
$10,000 to $24,999		72	22	21	65	151	40
$25,000 to $49,999		38	16	8	73	109	27
$50,000 to $99,999		37	48	16	129	111	54
$100,000 or more		103	277	192	381	245	411
Government payments	farms	50	255	266	375	429	578
	$1,000	876	2,659	8,648	2,636	5,704	11,475
Total income from farm-related sources	farms	224	364	244	587	651	606
	$1,000	4,476	12,876	14,811	9,083	10,209	22,249
Total farm production expenses	$1,000	49,390	289,489	205,250	330,648	213,837	315,360
Average per farm	dollars	94,076	565,407	573,323	332,979	163,234	372,325
Net cash farm income of the operations	farms	525	512	358	993	1,310	847
	$1,000	16,671	130,728	73,000	82,933	85,101	141,088
Average per farm	dollars	31,755	255,329	203,911	83,518	64,962	166,574
Livestock and poultry:							
Cattle and calves inventory	farms	71	58	37	443	337	143
	number	2,133	5,979	3,241	85,123	27,929	19,424
Beef cows	farms	52	37	28	243	202	94
	number	655	587	1,800	7,763	2,518	3,842
Milk cows	farms	5	-	-	137	47	11
	number	361	-	-	33,382	7,760	2,667
Cattle and calves sold	farms	55	58	32	402	275	123
	number	1,231	6,691	1,716	40,872	23,909	18,823
Hogs and pigs inventory	farms	14	47	8	28	34	44
	number	338	248,970	22	55,794	4,681	214,088
Hogs and pigs sold	farms	13	67	1	29	49	51
	number	204	806,631	(D)	67,929	(D)	593,648
Sheep and lambs inventory	farms	39	18	4	33	59	35
	number	361	2,624	190	2,553	1,413	1,924
Layers inventory	farms	67	31	12	116	213	38
	number	1,544	1,426	341	12,886	(D)	664
Broilers and other meat-type chickens sold	farms	4	11	-	21	36	8
	number	125	4,224	-	11,919	2,365	1,900
Selected crops harvested:							
Corn for grain	farms	84	294	168	505	383	438
	acres	12,821	135,115	108,649	89,443	68,316	156,080
	bushels	2,197,670	28,429,538	16,711,248	17,257,708	12,038,709	28,714,015
Corn for silage or greenchop	farms	6	6	11	117	54	27
	acres	362	215	1,714	15,647	4,679	5,463
	tons	7,080	6,520	38,303	368,279	87,370	116,988
Wheat for grain, all	farms	8	16	139	4	32	29
	acres	237	571	53,565	210	1,653	2,038
	bushels	6,836	13,176	3,055,031	7,840	84,564	100,867
Durum wheat for grain	farms	-	-	1	-	-	-
	acres	-	-	(D)	-	-	-
	bushels	-	-	(D)	-	-	-
Other spring wheat for grain	farms	8	16	137	3	30	29
	acres	237	571	(D)	(D)	(D)	2,038
	bushels	6,836	13,176	(D)	(D)	(D)	100,867
Winter wheat for grain	farms	-	-	1	1	2	-
	acres	-	-	(D)	(D)	(D)	-
	bushels	-	-	(D)	(D)	(D)	-
Oats for grain	farms	16	12	5	42	37	14
	acres	997	534	153	1,138	2,094	945
	bushels	62,085	38,253	11,520	70,208	154,236	116,718

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Selected crops harvested: - Con.						
Barley for grain	farms	336	-	-	1	4
	acres	55,330	-	-	(D)	200
	bushels	4,011,381	-	-	(D)	12,522
Sorghum for grain	farms	12	-	2	1	-
	acres	364	-	(D)	(D)	-
	bushels	24,260	-	(D)	(D)	-
Sorghum for silage or greenchop	farms	54	-	-	3	-
	acres	1,394	-	-	92	-
	tons	11,883	-	-	460	-
Soybeans for beans	farms	25,337	29	27	182	90
	acres	7,597,171	3,967	4,195	82,288	16,300
	bushels	373,669,175	108,033	187,975	3,504,122	487,568
Dry edible beans, excluding chickpeas and limas	farms	573	-	-	14	-
	acres	210,162	-	-	7,575	-
	cwt	5,278,245	-	-	155,605	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	23,394	358	139	414	358
	acres	1,392,072	37,051	3,857	37,073	32,939
	tons, dry equivalent	3,565,994	54,042	10,153	81,264	55,330
Sunflower seed, all	farms	221	1	-	1	-
	acres	66,924	(D)	-	(D)	-
	pounds	151,726,117	(D)	-	(D)	-
Sugarbeets for sugar or seed	farms	1,106	-	-	14	-
	acres	446,627	-	-	5,503	-
	tons	11,642,041	-	-	164,645	-
Vegetables harvested for sale	farms	2,620	27	38	16	24
	acres	205,632	53	1,757	(D)	27
Potatoes	farms	509	11	6	3	4
	acres	49,008	4	(D)	(D)	2
Sweet potatoes	farms	58	2	1	-	-
	acres	23	(D)	(D)	-	-
Land in orchards	farms	1,174	13	11	21	10
	acres	5,049	31	28	37	9

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Selected crops harvested: - Con.						
Barley for grain	farms	2	-	1	3	-
	acres	(D)	-	(D)	31	-
	bushels	(D)	-	(D)	2,604	-
Sorghum for grain	farms	-	-	-	-	-
	acres	-	-	-	-	-
	bushels	-	-	-	-	-
Sorghum for silage or greenchop	farms	1	-	3	-	-
	acres	(D)	-	45	-	-
	tons	(D)	-	450	-	-
Soybeans for beans	farms	235	238	600	605	2
	acres	27,857	111,535	212,796	111,584	(D)
	bushels	1,231,840	4,631,099	12,522,067	6,101,554	(D)
Dry edible beans, excluding chickpeas and limas	farms	2	1	-	5	8
	acres	(D)	(D)	-	401	16
	cwt	(D)	(D)	-	20,501	300
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	354	78	132	201	350
	acres	16,115	5,970	2,898	6,860	28,711
	tons, dry equivalent	37,028	18,704	8,376	27,917	43,598
Sunflower seed, all	farms	-	-	-	-	1
	acres	-	-	-	-	(D)
	pounds	-	-	-	-	(D)
Sugarbeets for sugar or seed	farms	-	2	-	1	-
	acres	-	(D)	-	(D)	-
	tons	-	(D)	-	(D)	-
Vegetables harvested for sale	farms	20	4	39	31	25
	acres	4,158	15	1,355	3,248	45
Potatoes	farms	4	-	7	-	8
	acres	2,664	-	4	-	4
Sweet potatoes	farms	-	-	-	-	-
	acres	-	-	-	-	-
Land in orchards	farms	7	2	29	4	11
	acres	12	(D)	76	26	21

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Selected crops harvested: - Con.						
Barley for grain ..... farms	2	-	-	-	4	1
acres	(D)	-	-	-	829	(D)
bushels	(D)	-	-	-	60,664	(D)
Sorghum for grain ..... farms	-	-	-	2	-	-
acres	-	-	-	(D)	-	-
bushels	-	-	-	(D)	-	-
Sorghum for silage or greenchop ..... farms	-	-	-	1	-	1
acres	-	-	-	(D)	-	(D)
tons	-	-	-	(D)	-	(D)
Soybeans for beans ..... farms	229	17	305	173	313	47
acres	52,608	1,554	99,594	21,438	193,698	13,593
bushels	2,929,606	50,484	5,009,898	905,331	8,326,903	496,802
Dry edible beans, excluding chickpeas and limas ..... farms	2	-	32	1	3	3
acres	(D)	-	10,892	(D)	757	342
cwt	(D)	-	393,901	(D)	15,381	11,023
Forage - land used for all hay and haylage, grass silage, and greenchop ..... farms	294	322	76	297	194	253
acres	12,681	33,900	4,661	9,384	15,971	31,653
tons, dry equivalent	43,689	49,840	11,135	19,935	47,445	62,668
Sunflower seed, all ..... farms	-	-	-	-	22	1
acres	-	-	-	-	8,598	(D)
pounds	-	-	-	-	22,687,794	(D)
Sugarbeets for sugar or seed ..... farms	-	-	89	-	70	-
acres	-	-	29,626	-	39,558	-
tons	-	-	818,710	-	1,073,071	-
Vegetables harvested for sale ..... farms	26	14	17	37	26	21
acres	83	(D)	2,082	73	1,828	1,421
Potatoes ..... farms	4	5	3	5	10	12
acres	1	(D)	(Z)	1	1,778	1,054
Sweet potatoes ..... farms	-	-	2	-	2	-
acres	-	-	(D)	-	(D)	-
Land in orchards ..... farms	24	23	13	38	13	-
acres	173	22	46	186	15	-

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Selected crops harvested: - Con.						
Barley for grain ..... farms	-	1	-	4	-	-
acres	-	(D)	-	88	-	-
bushels	-	(D)	-	4,050	-	-
Sorghum for grain ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
bushels	-	-	-	-	-	-
Sorghum for silage or greenchop ..... farms	-	-	-	-	-	2
acres	-	-	-	-	-	(D)
tons	-	-	-	-	-	(D)
Soybeans for beans ..... farms	-	438	29	326	255	371
acres	-	161,145	5,821	54,577	102,376	74,900
bushels	-	8,673,177	134,182	2,819,858	6,145,192	3,154,860
Dry edible beans, excluding chickpeas and limas ..... farms	-	-	2	14	2	4
acres	-	-	(D)	1,068	(D)	178
cwt	-	-	(D)	31,834	(D)	6,520
Forage - land used for all hay and haylage, grass silage, and greenchop ..... farms	13	132	260	246	212	338
acres	204	3,357	17,548	8,477	6,261	13,046
tons, dry equivalent	120	11,507	28,458	24,927	24,726	32,220
Sunflower seed, all ..... farms	1	-	9	-	-	-
acres	(D)	-	1,632	-	-	-
pounds	(D)	-	2,358,000	-	-	-
Sugarbeets for sugar or seed ..... farms	-	1	-	-	-	6
acres	-	(D)	-	-	-	3,780
tons	-	(D)	-	-	-	98,280
Vegetables harvested for sale ..... farms	9	6	26	176	27	22
acres	8	462	58	18,755	4,619	116
Potatoes ..... farms	4	2	1	28	1	6
acres	1	(D)	(D)	(D)	(D)	1
Sweet potatoes ..... farms	-	-	-	11	-	4
acres	-	-	-	2	-	1
Land in orchards ..... farms	2	4	15	35	8	22
acres	(D)	4	26	198	9	98

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Selected crops harvested: - Con.							
Barley for grain	farms	-	5	3	3	1	-
	acres	-	301	124	(D)	(D)	-
	bushels	-	18,300	5,878	(D)	(D)	-
Sorghum for grain	farms	-	1	-	-	-	-
	acres	-	(D)	-	-	-	-
	bushels	-	(D)	-	-	-	-
Sorghum for silage or greenchop	farms	-	-	-	1	-	-
	acres	-	-	-	(D)	-	-
	tons	-	-	-	(D)	-	-
Soybeans for beans	farms	552	513	472	622	222	68
	acres	171,786	117,291	138,846	118,627	119,553	7,169
	bushels	10,642,575	6,869,263	7,992,460	7,114,715	5,270,661	347,164
Dry edible beans, excluding chickpeas and limas	farms	-	3	-	4	7	-
	acres	-	171	-	116	3,799	-
	cwt	-	10,420	-	7,584	143,163	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	78	591	226	546	67	193
	acres	2,015	33,931	4,732	25,556	2,540	4,944
	tons, dry equivalent	5,912	131,742	12,830	117,740	8,388	11,430
Sunflower seed, all	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	pounds	-	-	-	-	-	-
Sugarbeets for sugar or seed	farms	-	-	-	-	16	-
	acres	-	-	-	-	8,337	-
	tons	-	-	-	-	191,836	-
Vegetables harvested for sale	farms	45	52	35	60	3	79
	acres	4,571	965	5,675	3,560	(D)	391
Potatoes	farms	2	11	4	8	2	14
	acres	(D)	7	(D)	7	(D)	3
Sweet potatoes	farms	-	2	-	1	-	10
	acres	-	(D)	-	(D)	-	3
Land in orchards	farms	2	28	9	34	1	55
	acres	(D)	155	22	164	(D)	118

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Selected crops harvested: - Con.							
Barley for grain	farms	1	2	-	1	-	-
	acres	(D)	(D)	-	(D)	-	-
	bushels	(D)	(D)	-	(D)	-	-
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Sorghum for silage or greenchop	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	tons	-	-	-	-	-	-
Soybeans for beans	farms	236	11	160	23	545	81
	acres	27,414	2,225	22,282	4,743	167,355	15,789
	bushels	1,515,776	104,399	855,736	132,109	9,093,623	631,938
Dry edible beans, excluding chickpeas and limas	farms	-	6	1	-	1	-
	acres	-	8,926	(D)	-	(D)	-
	cwt	-	240,573	(D)	-	(D)	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	405	175	375	283	121	345
	acres	29,275	12,356	13,174	27,535	3,973	20,630
	tons, dry equivalent	103,956	16,135	24,434	40,777	10,761	32,686
Sunflower seed, all	farms	-	3	-	-	-	6
	acres	-	25	-	-	-	246
	pounds	-	29,800	-	-	-	486,000
Sugarbeets for sugar or seed	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	tons	-	-	-	-	-	-
Vegetables harvested for sale	farms	6	12	29	33	3	32
	acres	(D)	(D)	82	318	(D)	69
Potatoes	farms	1	7	4	15	-	16
	acres	(D)	(D)	3	264	-	5
Sweet potatoes	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Land in orchards	farms	8	10	23	8	2	11
	acres	121	41	72	7	(D)	56

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Selected crops harvested: - Con.							
Barley for grain	farms	1	14	1	2	-	10
	acres	(D)	3,452	(D)	(D)	-	2,807
	bushels	(D)	291,930	(D)	(D)	-	196,425
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Sorghum for silage or greenchop	farms	-	-	-	1	-	-
	acres	-	-	-	(D)	-	-
	tons	-	-	-	(D)	-	-
Soybeans for beans	farms	416	213	19	446	-	50
	acres	135,404	140,224	6,914	164,409	-	21,884
	bushels	6,723,133	6,275,192	212,020	7,715,294	-	794,930
Dry edible beans, excluding chickpeas and limas	farms	28	2	-	5	-	1
	acres	10,840	(D)	-	1,961	-	(D)
	cwt	288,549	(D)	-	93,742	-	(D)
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	335	93	121	115	11	70
	acres	16,369	13,484	13,342	5,056	126	7,218
	tons, dry equivalent	44,647	35,349	27,039	15,739	115	14,231
Sunflower seed, all	farms	-	24	-	1	-	4
	acres	-	9,401	-	(D)	-	2,037
	pounds	-	20,588,806	-	(D)	-	4,074,592
Sugarbeets for sugar or seed	farms	31	90	-	2	-	-
	acres	17,441	30,086	-	(D)	-	-
	tons	494,986	865,108	-	(D)	-	-
Vegetables harvested for sale	farms	49	4	1	2	8	2
	acres	9,583	1,308	(D)	(D)	10	(D)
Potatoes	farms	2	4	-	2	3	2
	acres	(D)	1,308	-	(D)	(Z)	(D)
Sweet potatoes	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Land in orchards	farms	19	-	-	3	5	2
	acres	44	-	-	23	7	(D)

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Selected crops harvested: - Con.							
Barley for grain	farms	-	-	-	-	13	49
	acres	-	-	-	-	2,787	13,099
	bushels	-	-	-	-	224,371	934,242
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Sorghum for silage or greenchop	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	tons	-	-	-	-	-	-
Soybeans for beans	farms	336	271	533	345	141	474
	acres	75,175	67,229	165,332	88,037	67,294	254,815
	bushels	4,331,080	2,918,612	7,769,052	4,910,620	3,008,680	9,638,917
Dry edible beans, excluding chickpeas and limas	farms	-	-	1	7	32	29
	acres	-	-	(D)	2,011	9,571	10,752
	cwt	-	-	(D)	68,277	242,599	258,531
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	240	135	198	281	92	239
	acres	4,654	5,326	7,154	8,110	7,261	22,450
	tons, dry equivalent	11,139	16,775	25,991	27,383	17,652	60,430
Sunflower seed, all	farms	-	-	-	-	2	39
	acres	-	-	-	-	(D)	13,662
	pounds	-	-	-	-	(D)	31,458,017
Sugarbeets for sugar or seed	farms	-	-	1	1	13	126
	acres	-	-	(D)	(D)	2,859	49,535
	tons	-	-	(D)	(D)	79,311	1,341,709
Vegetables harvested for sale	farms	15	6	1	43	4	9
	acres	1,296	2	(D)	2,866	(D)	367
Potatoes	farms	1	-	-	5	2	4
	acres	(D)	-	-	5	(D)	352
Sweet potatoes	farms	1	-	-	2	-	-
	acres	(D)	-	-	(D)	-	-
Land in orchards	farms	8	8	1	14	-	-
	acres	66	45	(D)	59	-	-

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Selected crops harvested: - Con.							
Barley for grain	farms	-	3	2	3	3	3
	acres	-	325	(D)	144	(D)	68
	bushels	-	24,528	(D)	8,900	(D)	3,600
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Sorghum for silage or greenchop	farms	-	-	-	4	-	-
	acres	-	-	-	40	-	-
	tons	-	-	-	513	-	-
Soybeans for beans	farms	533	340	126	361	480	491
	acres	191,866	100,336	17,351	34,256	136,298	137,597
	bushels	11,501,189	4,794,286	648,085	1,564,338	8,033,769	6,391,086
Dry edible beans, excluding chickpeas and limas	farms	1	2	-	6	-	1
	acres	(D)	(D)	-	2,563	-	(D)
	cwt	(D)	(D)	-	87,016	-	(D)
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	94	279	387	994	239	214
	acres	2,328	15,701	19,030	57,013	6,705	10,009
	tons, dry equivalent	4,819	44,283	37,147	132,991	21,271	30,468
Sunflower seed, all	farms	-	-	3	4	3	-
	acres	-	-	72	230	144	-
	pounds	-	-	17,900	460,000	270,000	-
Sugarbeets for sugar or seed	farms	-	2	-	-	-	-
	acres	-	(D)	-	-	-	-
	tons	-	(D)	-	-	-	-
Vegetables harvested for sale	farms	41	36	19	18	79	7
	acres	3,384	2,824	82	3,653	11,790	34
Potatoes	farms	-	8	6	11	3	4
	acres	-	1	3	2,664	(Z)	1
Sweet potatoes	farms	-	2	-	-	-	2
	acres	-	(D)	-	-	-	(D)
Land in orchards	farms	2	26	13	11	13	2
	acres	(D)	56	58	19	48	(D)

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Selected crops harvested: - Con.							
Barley for grain	farms	2	-	18	-	11	16
	acres	(D)	-	4,648	-	1,398	5,630
	bushels	(D)	-	405,295	-	100,821	415,080
Sorghum for grain	farms	-	-	-	1	2	-
	acres	-	-	-	(D)	(D)	-
	bushels	-	-	-	(D)	(D)	-
Sorghum for silage or greenchop	farms	-	-	-	3	7	-
	acres	-	-	-	34	113	-
	tons	-	-	-	214	1,272	-
Soybeans for beans	farms	403	586	262	407	693	124
	acres	111,495	148,252	172,160	79,016	159,496	87,787
	bushels	6,503,844	7,097,059	7,482,259	4,670,907	6,567,089	3,141,123
Dry edible beans, excluding chickpeas and limas	farms	-	-	12	3	46	4
	acres	-	-	4,773	333	15,001	1,793
	cwt	-	-	101,402	7,954	358,998	43,345
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	134	215	108	438	1,032	95
	acres	4,505	7,170	9,084	19,009	73,435	13,969
	tons, dry equivalent	10,159	23,059	23,527	71,139	177,089	37,558
Sunflower seed, all	farms	-	-	12	-	6	4
	acres	-	-	3,678	-	411	934
	pounds	-	-	8,564,000	-	806,550	1,680,000
Sugarbeets for sugar or seed	farms	1	-	86	-	3	1
	acres	(D)	-	39,058	-	978	(D)
	tons	(D)	-	1,003,105	-	23,116	(D)
Vegetables harvested for sale	farms	28	3	9	128	44	6
	acres	980	12	118	10,570	(D)	17
Potatoes	farms	5	1	5	19	13	3
	acres	1	(D)	(D)	16	(D)	(D)
Sweet potatoes	farms	-	-	-	-	2	-
	acres	-	-	-	-	(D)	-
Land in orchards	farms	6	3	2	41	38	11
	acres	3	(D)	(D)	141	91	23

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Selected crops harvested: - Con.							
Barley for grain	farms	4	2	22	1	1	7
	acres	126	(D)	5,457	(D)	(D)	1,425
	bushels	(D)	(D)	361,640	(D)	(D)	94,975
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Sorghum for silage or greenchop	farms	2	1	1	4	-	-
	acres	(D)	(D)	(D)	92	-	-
	tons	(D)	(D)	(D)	886	-	-
Soybeans for beans	farms	90	283	580	304	-	152
	acres	11,638	73,765	325,204	83,190	-	65,417
	bushels	433,252	3,267,256	12,771,360	3,572,368	-	2,502,348
Dry edible beans, excluding chickpeas and limas	farms	-	-	100	11	-	4
	acres	-	-	55,891	4,957	-	2,008
	cwt	-	-	1,071,414	109,418	-	35,158
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	528	228	220	229	-	77
	acres	45,525	11,017	19,520	17,386	-	6,937
	tons, dry equivalent	78,101	27,534	60,995	49,962	-	20,638
Sunflower seed, all	farms	-	1	25	-	-	5
	acres	-	(D)	7,106	-	-	1,288
	pounds	-	(D)	16,952,154	-	-	2,659,200
Sugarbeets for sugar or seed	farms	-	-	249	4	-	2
	acres	-	-	96,745	418	-	(D)
	tons	-	-	2,452,048	11,960	-	(D)
Vegetables harvested for sale	farms	20	4	27	18	29	-
	acres	52	(D)	5,237	4,399	49	-
Potatoes	farms	8	1	13	1	3	-
	acres	2	(D)	4,904	(D)	(Z)	-
Sweet potatoes	farms	-	1	-	-	-	-
	acres	-	(D)	-	-	-	-
Land in orchards	farms	31	-	5	6	-	-
	acres	59	-	9	5	-	-

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Selected crops harvested: - Con.							
Barley for grain	farms	2	4	1	-	18	11
	acres	(D)	12	(D)	-	6,436	218
	bushels	(D)	550	(D)	-	490,002	13,058
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Sorghum for silage or greenchop	farms	-	2	1	-	-	-
	acres	-	(D)	(D)	-	-	-
	tons	-	(D)	(D)	-	-	-
Soybeans for beans	farms	847	579	426	320	238	2
	acres	231,905	221,215	84,766	97,893	131,263	(D)
	bushels	11,457,738	11,855,304	4,981,172	5,299,981	4,945,922	(D)
Dry edible beans, excluding chickpeas and limas	farms	1	49	-	-	2	-
	acres	(D)	10,429	-	-	(D)	-
	cwt	(D)	304,399	-	-	(D)	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	173	133	383	197	262	510
	acres	4,263	4,039	11,080	8,005	30,953	59,337
	tons, dry equivalent	13,848	13,912	31,527	33,188	58,696	92,598
Sunflower seed, all	farms	-	-	-	1	20	-
	acres	-	-	-	(D)	8,098	-
	pounds	-	-	-	(D)	19,033,933	-
Sugarbeets for sugar or seed	farms	33	87	-	-	2	-
	acres	6,901	35,122	-	-	(D)	-
	tons	174,072	894,561	-	-	(D)	-
Vegetables harvested for sale	farms	20	152	44	11	3	76
	acres	2,910	25,545	683	17	8	114
Potatoes	farms	-	9	8	3	3	24
	acres	-	3	4	(Z)	(Z)	13
Sweet potatoes	farms	-	-	1	-	-	1
	acres	-	-	(D)	-	-	(D)
Land in orchards	farms	10	8	37	-	1	46
	acres	13	16	276	-	(D)	67

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Selected crops harvested: - Con.						
Barley for grain ..... farms	-	-	6	28	-	-
acres	-	-	239	954	-	-
bushels	-	-	14,443	48,972	-	-
Sorghum for grain ..... farms	-	-	2	-	-	-
acres	-	-	(D)	-	-	-
bushels	-	-	(D)	-	-	-
Sorghum for silage or greenchop ..... farms	-	-	1	10	1	-
acres	-	-	(D)	413	(D)	-
tons	-	-	(D)	4,984	(D)	-
Soybeans for beans ..... farms	158	73	467	876	280	212
acres	34,096	13,826	132,175	113,387	88,651	103,077
bushels	1,638,236	571,707	7,416,746	5,367,293	5,489,870	4,561,223
Dry edible beans, excluding chickpeas and limas ..... farms	-	3	-	9	1	31
acres	-	(D)	-	3,215	(D)	13,869
cwt	-	(D)	-	105,383	(D)	323,840
Forage - land used for all hay and haylage, grass silage, and greenchop ..... farms	277	156	261	1,490	183	103
acres	7,048	4,555	7,790	90,305	4,085	10,836
tons, dry equivalent	19,797	6,748	24,003	269,036	11,414	38,674
Sunflower seed, all ..... farms	-	-	-	-	-	2
acres	-	-	-	-	-	(D)
pounds	-	-	-	-	-	(D)
Sugarbeets for sugar or seed ..... farms	-	-	19	12	-	34
acres	-	-	6,049	10,294	-	10,884
tons	-	-	150,505	302,794	-	280,943
Vegetables harvested for sale ..... farms	29	51	53	75	21	9
acres	182	9,233	5,875	3,503	2,618	3
Potatoes ..... farms	5	33	-	17	3	-
acres	1	9,063	-	73	(D)	-
Sweet potatoes ..... farms	2	1	-	1	-	-
acres	(D)	(D)	-	(D)	-	-
Land in orchards ..... farms	34	28	1	35	4	2
acres	110	47	(D)	103	26	(D)

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Selected crops harvested: - Con.						
Barley for grain ..... farms	-	15	-	12	2	-
acres	-	758	-	718	(D)	-
bushels	-	41,875	-	42,924	(D)	-
Sorghum for grain ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
bushels	-	-	-	-	-	-
Sorghum for silage or greenchop ..... farms	-	1	-	1	-	-
acres	-	(D)	-	(D)	-	-
tons	-	(D)	-	(D)	-	-
Soybeans for beans ..... farms	332	401	196	291	57	326
acres	107,709	46,542	118,079	39,729	16,495	108,599
bushels	4,887,338	1,965,831	4,916,309	2,308,568	716,736	6,850,400
Dry edible beans, excluding chickpeas and limas ..... farms	29	3	3	2	9	1
acres	7,659	3,972	1,862	(D)	3,450	(D)
cwt	207,377	122,550	71,780	(D)	83,754	(D)
Forage - land used for all hay and haylage, grass silage, and greenchop ..... farms	115	865	57	386	293	105
acres	7,336	45,723	5,718	31,201	20,167	2,289
tons, dry equivalent	27,478	105,683	23,724	125,045	39,325	7,161
Sunflower seed, all ..... farms	-	-	3	-	7	-
acres	-	-	912	-	479	-
pounds	-	-	1,824,000	-	658,014	-
Sugarbeets for sugar or seed ..... farms	19	-	10	-	-	-
acres	8,256	-	4,248	-	-	-
tons	236,427	-	86,066	-	-	-
Vegetables harvested for sale ..... farms	8	42	1	72	8	51
acres	859	1,294	(D)	5,495	2,968	3,434
Potatoes ..... farms	-	13	-	3	5	5
acres	-	(D)	-	1	2,948	1
Sweet potatoes ..... farms	-	-	-	1	-	-
acres	-	-	-	(D)	-	-
Land in orchards ..... farms	1	24	2	22	3	7
acres	(D)	107	(D)	454	6	28

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Table 1. **County Summary Highlights: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Selected crops harvested: - Con.							
Barley for grain	farms	-	-	8	2	-	-
	acres	-	-	1,143	(D)	-	-
	bushels	-	-	82,662	(D)	-	-
Sorghum for grain	farms	-	-	-	-	1	-
	acres	-	-	-	-	(D)	-
	bushels	-	-	-	-	(D)	-
Sorghum for silage or greenchop	farms	1	-	-	1	-	-
	acres	(D)	-	-	(D)	-	-
	tons	(D)	-	-	(D)	-	-
Soybeans for beans	farms	83	298	197	376	369	458
	acres	11,080	101,160	148,655	45,868	73,396	140,040
	bushels	520,912	5,872,100	5,701,794	2,695,843	3,776,548	6,624,270
Dry edible beans, excluding chickpeas and limas	farms	2	-	7	1	3	7
	acres	(D)	-	1,581	(D)	208	756
	cwt	(D)	-	37,781	(D)	5,124	35,581
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	169	63	58	517	611	160
	acres	5,600	1,009	5,133	42,174	18,476	6,779
	tons, dry equivalent	9,607	2,426	10,051	179,296	43,500	22,154
Sunflower seed, all	farms	-	-	7	-	-	3
	acres	-	-	3,892	-	-	807
	pounds	-	-	9,927,600	-	-	1,251,640
Sugarbeets for sugar or seed	farms	-	-	71	-	-	8
	acres	-	-	33,147	-	-	2,469
	tons	-	-	685,888	-	-	62,592
Vegetables harvested for sale	farms	74	25	1	45	58	11
	acres	926	3,197	(D)	2,529	878	16
Potatoes	farms	18	-	-	8	7	8
	acres	12	-	-	3	7	3
Sweet potatoes	farms	5	-	-	1	-	-
	acres	2	-	-	(D)	-	-
Land in orchards	farms	47	3	-	35	56	2
	acres	394	2	-	501	282	(D)

Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD					
Total sales ... farms, 2022	65,531	449	355	952	608
2017	68,822	462	360	943	583
$1,000, 2022	28,482,097	22,332	72,811	305,922	38,203
2017	18,395,390	12,461	67,759	174,531	23,800
Average per farm ... dollars, 2022	434,635	49,737	205,100	321,346	62,834
2017	267,289	26,972	188,220	185,081	40,823
2022 value of sales:					
Less than $1,000 ... farms	15,502	47	100	359	132
$1,000	1,169	12	18	28	8
$1,000 to $2,499 ... farms	3,496	38	45	44	32
$1,000	5,706	63	66	71	51
$2,500 to $4,999 ... farms	3,533	72	34	66	53
$1,000	12,660	263	114	250	184
$5,000 to $9,999 ... farms	4,091	76	37	65	98
$1,000	29,240	550	241	469	693
$10,000 to $19,999 ... farms	4,177	64	44	68	65
$1,000	59,970	883	640	1,017	943
$20,000 to $24,999 ... farms	1,385	15	6	12	31
$1,000	30,596	332	121	267	696
$25,000 to $39,999 ... farms	2,858	38	20	41	56
$1,000	90,565	1,218	639	1,314	1,710
$40,000 to $49,999 ... farms	1,410	18	17	19	26
$1,000	62,843	813	775	863	1,146
$50,000 to $99,999 ... farms	5,328	45	10	68	49
$1,000	386,353	3,150	660	5,169	3,791
$100,000 to $249,999 ... farms	6,767	20	11	64	31
$1,000	1,101,110	2,773	2,001	10,842	4,692
$250,000 to $499,999 ... farms	5,372	5	11	44	15
$1,000	1,930,062	1,951	4,082	16,488	5,382
$500,000 or more ... farms	11,612	11	20	102	20
$1,000	24,771,823	10,325	63,454	269,144	18,908
2017 value of sales:					
Less than $1,000 ... farms	17,597	83	133	347	145
$1,000	2,048	(D)	37	37	33
$1,000 to $2,499 ... farms	3,510	49	36	51	42
$1,000	5,839	79	59	89	72
$2,500 to $4,999 ... farms	3,833	60	42	72	77
$1,000	13,846	230	150	271	287
$5,000 to $9,999 ... farms	4,385	83	33	75	79
$1,000	31,180	575	230	515	560
$10,000 to $19,999 ... farms	4,270	58	35	60	77
$1,000	61,573	804	485	853	1,124
$20,000 to $24,999 ... farms	1,552	24	6	30	17
$1,000	34,560	555	131	671	376
$25,000 to $39,999 ... farms	3,195	46	13	42	36
$1,000	102,282	1,450	405	1,258	1,206
$40,000 to $49,999 ... farms	1,542	14	7	21	17
$1,000	68,897	619	328	935	775
$50,000 to $99,999 ... farms	6,467	24	17	71	43
$1,000	469,267	1,656	1,271	4,967	3,193
$100,000 to $249,999 ... farms	7,597	14	15	52	31
$1,000	1,248,260	2,009	2,060	8,184	4,038
$250,000 to $499,999 ... farms	5,777	3	6	50	9
$1,000	2,070,536	(D)	2,171	17,520	2,971
$500,000 or more ... farms	9,097	4	17	72	10
$1,000	14,287,103	3,545	60,431	139,232	9,165
Value of sales by commodity or commodity group:					
Crops, including nursery and greenhouse crops ... farms, 2022	43,821	351	222	521	390
2017	46,722	342	227	541	359
$1,000, 2022	17,143,767	13,454	71,779	190,394	26,620
2017	10,191,518	7,045	35,168	103,639	13,287
Grains, oilseeds, dry beans, and dry peas ... farms, 2022	32,075	54	60	282	158
2017	35,101	55	84	308	114
$1,000, 2022	15,268,581	6,077	5,577	147,308	20,509
2017	8,843,440	3,534	7,755	74,253	9,733
Corn ... farms, 2022	25,230	36	34	184	47
2017	28,902	41	61	191	37
$1,000, 2022	9,045,595	1,226	3,045	78,597	2,427
2017	4,766,809	(D)	5,206	31,147	1,128
Wheat ... farms, 2022	3,668	1	-	99	25
2017	4,284	2	2	132	20
$1,000, 2022	735,504	(D)	-	13,738	4,144
2017	440,555	(D)	(D)	10,634	2,347
Soybeans ... farms, 2022	25,334	29	27	182	90
2017	27,864	18	38	191	80
$1,000, 2022	5,087,514	(D)	2,506	48,039	7,009
2017	3,447,327	1,493	2,330	28,477	4,055
Sorghum ... farms, 2022	53	-	2	2	-
2017	28	-	-	1	-
$1,000, 2022	437	-	(D)	(D)	-
2017	219	-	-	(D)	-
Barley ... farms, 2022	336	-	-	1	4
2017	536	-	-	3	5
$1,000, 2022	27,673	-	-	(D)	39
2017	23,008	-	-	(D)	51

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD						
Total sales	farms, 2022	687	392	1,019	973	463
	2017	816	438	983	1,040	529
	$1,000, 2022	278,263	194,879	838,011	485,455	13,416
	2017	207,177	138,754	483,499	381,510	10,985
Average per farm	dollars, 2022	405,041	497,140	822,385	498,926	28,975
	2017	253,893	316,790	491,860	366,837	20,766
2022 value of sales:						
Less than $1,000	farms	115	86	213	172	87
	$1,000	18	4	4	3	23
$1,000 to $2,499	farms	49	10	36	16	61
	$1,000	82	17	54	25	(D)
$2,500 to $4,999	farms	55	10	28	19	58
	$1,000	190	38	91	68	202
$5,000 to $9,999	farms	63	12	34	43	86
	$1,000	438	88	243	312	640
$10,000 to $19,999	farms	85	11	57	26	45
	$1,000	1,268	168	819	380	675
$20,000 to $24,999	farms	18	9	13	5	19
	$1,000	407	204	278	110	419
$25,000 to $39,999	farms	29	18	34	41	25
	$1,000	910	546	1,119	1,243	776
$40,000 to $49,999	farms	23	10	11	17	18
	$1,000	1,028	443	488	763	775
$50,000 to $99,999	farms	64	27	64	76	39
	$1,000	4,618	1,842	4,696	5,523	2,561
$100,000 to $249,999	farms	74	55	109	169	16
	$1,000	11,168	9,081	17,712	27,622	2,424
$250,000 to $499,999	farms	32	56	123	153	4
	$1,000	10,850	19,177	42,663	56,669	(D)
$500,000 or more	farms	80	88	297	236	5
	$1,000	247,286	163,271	769,844	392,738	3,604
2017 value of sales:						
Less than $1,000	farms	173	107	224	209	108
	$1,000	36	(D)	12	12	32
$1,000 to $2,499	farms	65	2	42	22	65
	$1,000	117	(D)	64	33	119
$2,500 to $4,999	farms	47	9	35	27	93
	$1,000	166	35	117	104	(D)
$5,000 to $9,999	farms	64	23	25	23	72
	$1,000	465	147	169	158	494
$10,000 to $19,999	farms	69	27	40	35	68
	$1,000	932	378	551	490	975
$20,000 to $24,999	farms	20	3	14	15	28
	$1,000	431	61	318	328	623
$25,000 to $39,999	farms	49	13	41	45	34
	$1,000	1,655	437	1,345	1,555	1,106
$40,000 to $49,999	farms	9	7	25	28	10
	$1,000	395	311	1,106	1,233	453
$50,000 to $99,999	farms	97	42	90	151	33
	$1,000	6,974	3,200	6,316	11,269	2,352
$100,000 to $249,999	farms	70	75	154	193	12
	$1,000	10,492	11,873	25,121	32,421	1,924
$250,000 to $499,999	farms	46	52	102	123	4
	$1,000	16,191	18,844	36,091	45,378	1,363
$500,000 or more	farms	107	78	191	169	2
	$1,000	169,322	103,449	412,290	288,530	(D)
Value of sales by commodity or commodity group:						
Crops, including nursery and greenhouse crops	farms, 2022	495	278	740	737	309
	2017	604	329	699	788	409
	$1,000, 2022	84,372	158,655	463,455	249,798	6,931
	2017	63,898	106,965	202,637	174,744	4,782
Grains, oilseeds, dry beans, and dry peas	farms, 2022	346	255	672	697	36
	2017	425	290	615	747	39
	$1,000, 2022	56,963	155,182	458,954	245,670	(D)
	2017	47,964	106,127	198,435	160,575	346
Corn	farms, 2022	268	206	553	625	20
	2017	357	238	542	680	21
	$1,000, 2022	37,887	91,338	286,180	161,859	462
	2017	27,187	52,713	111,683	93,778	290
Wheat	farms, 2022	12	41	6	27	3
	2017	7	85	8	35	1
	$1,000, 2022	78	(D)	56	391	(D)
	2017	(D)	3,778	(D)	294	(D)
Soybeans	farms, 2022	235	238	600	605	2
	2017	325	262	545	668	-
	$1,000, 2022	16,890	62,032	172,310	82,572	(D)
	2017	18,830	49,019	84,883	66,299	-
Sorghum	farms, 2022	-	-	3	-	-
	2017	-	-	-	2	-
	$1,000, 2022	-	-	(D)	-	-
	2017	-	-	-	(D)	-
Barley	farms, 2022	2	-	1	3	-
	2017	5	-	2	4	3
	$1,000, 2022	(D)	-	(D)	14	-
	2017	56	-	(D)	(D)	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	606	488	563	740	655	404
	2017	689	432	623	821	694	414
	$1,000, 2022	172,878	29,837	446,611	54,864	466,030	46,418
	2017	111,378	26,464	256,699	52,838	277,750	30,060
Average per farm	dollars, 2022	285,277	61,141	793,270	74,141	711,496	114,897
	2017	161,652	61,260	412,037	64,358	400,216	72,608
2022 value of sales:							
Less than $1,000	farms	130	89	150	142	109	60
	$1,000	17	12	(D)	31	2	9
$1,000 to $2,499	farms	48	55	16	74	33	52
	$1,000	80	97	(D)	126	58	82
$2,500 to $4,999	farms	40	52	26	113	38	34
	$1,000	149	175	97	400	126	118
$5,000 to $9,999	farms	56	61	7	98	26	29
	$1,000	393	445	64	686	196	193
$10,000 to $19,999	farms	34	71	7	86	35	37
	$1,000	466	985	102	1,269	470	538
$20,000 to $24,999	farms	10	13	11	22	18	12
	$1,000	233	292	239	469	390	275
$25,000 to $39,999	farms	27	28	25	54	29	35
	$1,000	854	882	823	1,681	993	1,139
$40,000 to $49,999	farms	5	19	10	17	22	24
	$1,000	223	837	435	738	993	1,085
$50,000 to $99,999	farms	75	56	20	48	43	52
	$1,000	5,384	3,820	1,542	3,343	2,856	3,611
$100,000 to $249,999	farms	50	31	68	47	49	37
	$1,000	8,566	4,442	11,245	7,806	8,241	5,752
$250,000 to $499,999	farms	52	10	52	15	62	19
	$1,000	17,152	3,498	19,147	4,686	22,127	6,709
$500,000 or more	farms	79	3	171	24	191	13
	$1,000	139,359	14,351	412,892	33,630	429,577	26,907
2017 value of sales:							
Less than $1,000	farms	170	88	140	207	165	90
	$1,000	28	17	5	59	19	16
$1,000 to $2,499	farms	51	49	25	92	15	23
	$1,000	84	85	39	143	26	37
$2,500 to $4,999	farms	45	57	12	82	34	46
	$1,000	159	210	45	292	132	169
$5,000 to $9,999	farms	28	58	15	107	32	42
	$1,000	196	392	104	806	242	324
$10,000 to $19,999	farms	45	47	32	84	37	60
	$1,000	650	642	438	1,181	535	845
$20,000 to $24,999	farms	18	17	10	38	10	8
	$1,000	405	390	231	854	212	181
$25,000 to $39,999	farms	37	24	23	40	25	21
	$1,000	1,114	766	775	1,220	792	653
$40,000 to $49,999	farms	17	17	14	17	22	12
	$1,000	759	759	636	767	975	547
$50,000 to $99,999	farms	89	29	62	50	48	55
	$1,000	6,287	2,187	4,623	3,325	3,425	3,832
$100,000 to $249,999	farms	77	29	95	54	76	32
	$1,000	12,069	4,003	16,825	8,600	12,334	4,728
$250,000 to $499,999	farms	53	9	73	22	66	16
	$1,000	18,653	2,863	25,987	7,422	25,179	5,333
$500,000 or more	farms	59	8	122	28	164	9
	$1,000	70,975	14,149	206,991	28,168	233,880	13,395
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	437	308	384	494	463	245
	2017	493	251	451	590	471	249
	$1,000, 2022	118,943	9,647	334,319	44,472	400,878	35,732
	2017	68,927	7,501	188,056	39,429	240,202	19,741
Grains, oilseeds, dry beans, and dry peas	farms, 2022	288	48	350	236	364	67
	2017	384	47	427	310	405	98
	$1,000, 2022	108,774	3,012	288,825	31,395	318,272	21,792
	2017	62,636	4,501	148,490	27,973	181,121	12,634
Corn	farms, 2022	245	32	323	163	235	24
	2017	361	42	383	229	264	42
	$1,000, 2022	67,925	1,955	205,155	19,054	157,701	3,931
	2017	39,953	(D)	94,306	16,773	80,227	2,546
Wheat	farms, 2022	22	10	25	4	199	19
	2017	23	-	43	10	236	28
	$1,000, 2022	154	228	378	(D)	36,264	(D)
	2017	143	-	(D)	(D)	25,703	(D)
Soybeans	farms, 2022	229	17	305	173	313	47
	2017	264	5	356	237	375	64
	$1,000, 2022	40,546	710	67,750	12,064	116,699	6,719
	2017	22,470	(D)	48,637	11,052	72,584	4,488
Sorghum	farms, 2022	-	-	-	3	-	1
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	(D)	-	(D)
	2017	-	-	-	-	-	-
Barley	farms, 2022	2	-	-	-	4	1
	2017	-	2	1	1	6	2
	$1,000, 2022	(D)	-	-	-	425	(D)
	2017	-	(D)	(D)	(D)	429	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD						
Total sales ... farms, 2022	25	742	426	841	614	980
2017	32	744	494	820	611	960
$1,000, 2022	506	601,642	26,272	364,822	413,313	168,616
2017	381	382,170	19,054	235,415	238,403	100,345
Average per farm ... dollars, 2022	20,225	810,838	61,671	433,796	673,148	172,057
2017	11,901	513,669	38,571	287,091	390,186	104,526
2022 value of sales:						
Less than $1,000 ... farms	7	166	114	126	146	301
$1,000	3	8	23	15	15	23
$1,000 to $2,499 ... farms	2	15	40	48	49	69
$1,000	(D)	26	64	78	74	112
$2,500 to $4,999 ... farms	5	10	48	66	23	68
$1,000	19	41	171	234	78	251
$5,000 to $9,999 ... farms	1	16	65	51	37	64
$1,000	(D)	130	469	353	258	456
$10,000 to $19,999 ... farms	3	20	40	60	27	64
$1,000	38	277	581	866	390	875
$20,000 to $24,999 ... farms	-	5	16	35	13	25
$1,000	-	113	363	757	279	558
$25,000 to $39,999 ... farms	2	15	19	40	11	56
$1,000	(D)	435	617	1,234	295	1,784
$40,000 to $49,999 ... farms	-	13	13	18	9	26
$1,000	-	575	594	817	392	1,154
$50,000 to $99,999 ... farms	5	45	33	98	34	74
$1,000	366	3,262	2,360	7,266	2,445	5,390
$100,000 to $249,999 ... farms	-	101	13	100	65	104
$1,000	-	16,177	2,136	15,173	10,803	16,845
$250,000 to $499,999 ... farms	-	87	8	69	34	51
$1,000	-	31,580	2,424	24,938	12,474	17,824
$500,000 or more ... farms	-	249	17	130	166	78
$1,000	-	549,017	16,469	313,091	385,810	123,344
2017 value of sales:						
Less than $1,000 ... farms	3	144	115	167	154	332
$1,000	1	4	28	41	21	38
$1,000 to $2,499 ... farms	8	22	63	52	38	33
$1,000	11	43	101	85	62	52
$2,500 to $4,999 ... farms	10	16	73	61	19	59
$1,000	(D)	59	265	219	71	217
$5,000 to $9,999 ... farms	6	12	70	51	36	65
$1,000	45	88	483	355	254	470
$10,000 to $19,999 ... farms	1	19	65	60	36	61
$1,000	(D)	262	943	831	528	912
$20,000 to $24,999 ... farms	3	7	17	18	6	16
$1,000	(D)	157	381	386	136	345
$25,000 to $39,999 ... farms	-	21	37	47	26	38
$1,000	-	698	1,158	1,510	851	1,176
$40,000 to $49,999 ... farms	-	27	5	23	10	27
$1,000	-	1,159	229	994	457	1,176
$50,000 to $99,999 ... farms	-	67	13	65	51	121
$1,000	-	4,798	987	4,784	3,382	8,932
$100,000 to $249,999 ... farms	1	117	17	109	62	99
$1,000	(D)	19,542	2,561	17,471	9,970	16,193
$250,000 to $499,999 ... farms	-	98	12	67	41	74
$1,000	-	35,979	5,097	23,306	13,917	26,773
$500,000 or more ... farms	-	194	7	100	132	35
$1,000	-	319,380	6,823	185,432	208,753	44,061
Value of sales by commodity or commodity group:						
Crops, including nursery and greenhouse crops ... farms, 2022	19	520	263	599	383	604
2017	24	556	309	606	405	615
$1,000, 2022	320	353,652	13,633	283,036	272,325	133,283
2017	365	193,984	9,256	179,531	138,341	74,108
Grains, oilseeds, dry beans, and dry peas ... farms, 2022	1	486	79	412	307	447
2017	-	526	83	398	337	484
$1,000, 2022	(D)	349,989	9,058	137,975	261,130	123,365
2017	-	190,736	6,467	98,346	130,985	70,431
Corn ... farms, 2022	-	439	61	332	285	286
2017	-	498	61	338	298	333
$1,000, 2022	-	230,891	5,138	98,200	176,821	76,711
2017	-	111,235	3,284	66,855	84,583	34,119
Wheat ... farms, 2022	-	14	3	18	2	73
2017	-	15	3	22	2	122
$1,000, 2022	-	422	194	207	(D)	2,434
2017	-	533	(D)	171	(D)	3,058
Soybeans ... farms, 2022	-	438	29	326	255	371
2017	-	474	30	315	261	405
$1,000, 2022	-	118,210	1,873	37,892	83,866	43,289
2017	-	78,934	2,225	31,032	46,247	32,278
Sorghum ... farms, 2022	-	-	-	-	-	2
2017	-	-	-	-	-	-
$1,000, 2022	-	-	-	-	-	(D)
2017	-	-	-	-	-	-
Barley ... farms, 2022	-	1	-	4	-	-
2017	-	3	-	3	4	2
$1,000, 2022	-	(D)	-	31	-	-
2017	-	10	-	59	(D)	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	773	1,458	908	1,406	529	511
	2017	822	1,401	1,076	1,461	524	467
	$1,000, 2022	587,680	519,865	475,632	595,613	313,725	56,766
	2017	337,734	291,747	363,999	348,588	190,286	58,570
Average per farm	dollars, 2022	760,259	356,560	523,823	423,622	593,053	111,089
	2017	410,869	208,242	338,289	238,596	363,142	125,418
2022 value of sales:							
Less than $1,000	farms	88	339	205	211	247	158
	$1,000	3	14	8	23	5	21
$1,000 to $2,499	farms	12	63	37	75	6	46
	$1,000	23	104	58	128	10	78
$2,500 to $4,999	farms	23	68	24	44	4	45
	$1,000	80	243	86	157	18	157
$5,000 to $9,999	farms	15	82	36	98	7	54
	$1,000	98	562	255	700	59	368
$10,000 to $19,999	farms	28	94	37	113	15	64
	$1,000	383	1,364	524	1,526	241	841
$20,000 to $24,999	farms	12	40	20	25	12	8
	$1,000	267	879	445	561	262	173
$25,000 to $39,999	farms	12	94	17	79	9	26
	$1,000	389	2,901	553	2,458	264	847
$40,000 to $49,999	farms	11	36	16	33	13	12
	$1,000	495	1,585	707	1,479	605	563
$50,000 to $99,999	farms	64	124	65	144	41	43
	$1,000	4,702	9,002	4,929	10,377	2,918	3,374
$100,000 to $249,999	farms	127	161	119	180	36	15
	$1,000	21,077	26,544	19,352	28,879	6,068	2,235
$250,000 to $499,999	farms	113	119	116	131	28	24
	$1,000	40,206	42,191	44,241	47,488	10,172	7,654
$500,000 or more	farms	268	238	216	273	111	16
	$1,000	519,959	434,477	404,474	501,836	293,103	40,456
2017 value of sales:							
Less than $1,000	farms	158	346	292	318	236	147
	$1,000	24	29	32	43	5	40
$1,000 to $2,499	farms	27	53	41	53	3	48
	$1,000	46	91	75	95	4	80
$2,500 to $4,999	farms	19	74	29	78	11	52
	$1,000	58	273	108	281	43	179
$5,000 to $9,999	farms	17	69	45	111	11	49
	$1,000	104	505	289	846	77	380
$10,000 to $19,999	farms	20	138	43	94	8	23
	$1,000	297	2,004	617	1,437	125	317
$20,000 to $24,999	farms	7	43	10	36	6	13
	$1,000	148	947	220	788	133	284
$25,000 to $39,999	farms	21	67	36	65	10	19
	$1,000	693	2,128	1,213	2,076	314	570
$40,000 to $49,999	farms	13	37	19	43	9	9
	$1,000	604	1,614	845	1,911	415	398
$50,000 to $99,999	farms	89	138	108	170	49	30
	$1,000	6,782	10,157	8,013	12,419	3,595	2,210
$100,000 to $249,999	farms	123	204	134	179	40	24
	$1,000	19,867	33,724	23,448	28,900	6,166	3,651
$250,000 to $499,999	farms	126	99	114	134	54	32
	$1,000	46,062	36,154	42,154	50,360	19,827	11,019
$500,000 or more	farms	202	133	205	180	87	21
	$1,000	263,049	204,122	286,983	249,434	159,583	39,442
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	621	901	632	992	267	313
	2017	620	881	731	983	280	343
	$1,000, 2022	379,350	336,081	319,725	339,139	253,439	51,495
	2017	231,175	141,313	220,813	174,108	143,813	51,923
Grains, oilseeds, dry beans, and dry peas	farms, 2022	596	727	548	812	244	96
	2017	598	738	647	819	254	120
	$1,000, 2022	372,587	321,201	308,537	324,676	231,150	8,844
	2017	222,443	128,145	207,292	160,525	131,068	13,000
Corn	farms, 2022	483	653	477	705	198	58
	2017	549	666	578	739	219	94
	$1,000, 2022	228,576	224,660	202,952	224,358	147,469	4,090
	2017	130,812	88,391	126,573	102,641	72,313	6,558
Wheat	farms, 2022	1	6	3	24	43	5
	2017	1	-	3	1	85	7
	$1,000, 2022	(D)	250	(D)	(D)	(D)	44
	2017	(D)	-	110	(D)	4,480	57
Soybeans	farms, 2022	552	513	472	622	222	68
	2017	526	463	560	615	245	91
	$1,000, 2022	143,870	94,802	104,716	99,129	73,681	4,668
	2017	90,634	39,328	80,455	57,383	52,468	6,346
Sorghum	farms, 2022	-	1	-	1	-	-
	2017	-	3	-	-	-	-
	$1,000, 2022	-	(D)	-	(D)	-	-
	2017	-	2	-	-	-	-
Barley	farms, 2022	-	5	3	3	1	-
	2017	3	6	4	6	1	3
	$1,000, 2022	-	(D)	(D)	(D)	(D)	-
	2017	(D)	95	20	(D)	(D)	(Z)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	797	336	814	424	845	531
	2017	891	384	805	337	799	624
	$1,000, 2022	213,008	52,155	73,159	13,796	501,296	32,517
	2017	116,174	44,244	48,673	8,004	314,510	29,832
Average per farm	dollars, 2022	267,262	155,224	89,876	32,539	593,249	61,236
	2017	130,386	115,220	60,464	23,750	393,629	47,807
2022 value of sales:							
Less than $1,000	farms	225	90	200	84	131	88
	$1,000	9	8	38	20	2	18
$1,000 to $2,499	farms	44	39	124	41	19	69
	$1,000	63	(D)	211	67	33	118
$2,500 to $4,999	farms	31	24	98	48	17	56
	$1,000	118	85	356	170	56	191
$5,000 to $9,999	farms	30	47	98	42	21	70
	$1,000	196	341	703	294	173	502
$10,000 to $19,999	farms	61	36	108	75	14	69
	$1,000	881	506	1,556	1,084	197	952
$20,000 to $24,999	farms	22	13	25	15	20	26
	$1,000	479	274	544	325	468	576
$25,000 to $39,999	farms	36	22	20	35	14	35
	$1,000	1,122	694	661	1,191	431	1,090
$40,000 to $49,999	farms	14	8	17	19	14	16
	$1,000	579	347	752	849	598	695
$50,000 to $99,999	farms	114	27	48	35	105	48
	$1,000	8,144	1,714	3,555	2,708	7,907	3,703
$100,000 to $249,999	farms	72	14	44	21	111	28
	$1,000	11,939	1,960	7,289	3,040	19,581	4,131
$250,000 to $499,999	farms	64	1	8	5	141	19
	$1,000	22,791	(D)	2,768	1,827	51,630	7,699
$500,000 or more	farms	84	15	24	4	238	7
	$1,000	166,687	45,739	54,726	2,221	420,220	12,841
2017 value of sales:							
Less than $1,000	farms	246	106	246	76	129	150
	$1,000	19	(D)	61	17	9	(D)
$1,000 to $2,499	farms	43	47	87	67	18	81
	$1,000	65	81	146	112	30	129
$2,500 to $4,999	farms	56	65	105	27	8	79
	$1,000	205	230	388	99	27	272
$5,000 to $9,999	farms	64	45	95	56	29	98
	$1,000	452	308	666	425	170	739
$10,000 to $19,999	farms	56	39	81	33	30	56
	$1,000	830	553	1,135	439	493	802
$20,000 to $24,999	farms	22	14	29	16	20	18
	$1,000	508	302	652	359	444	402
$25,000 to $39,999	farms	44	18	29	27	28	26
	$1,000	1,386	(D)	910	850	921	831
$40,000 to $49,999	farms	27	2	10	4	14	21
	$1,000	1,214	(D)	450	170	624	940
$50,000 to $99,999	farms	127	22	38	18	100	41
	$1,000	9,016	1,394	2,916	1,092	7,411	2,683
$100,000 to $249,999	farms	98	11	48	6	135	39
	$1,000	15,625	2,031	8,418	881	22,894	6,087
$250,000 to $499,999	farms	51	6	17	3	117	1
	$1,000	17,802	2,184	5,825	1,062	42,864	(D)
$500,000 or more	farms	57	9	20	4	171	14
	$1,000	69,052	36,501	27,108	2,498	238,623	16,615
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	483	190	491	299	635	355
	2017	549	215	508	240	619	429
	$1,000, 2022	87,780	47,496	40,789	9,417	348,611	25,695
	2017	44,905	39,203	36,097	5,176	182,899	17,958
Grains, oilseeds, dry beans, and dry peas	farms, 2022	368	62	226	42	612	121
	2017	428	53	260	33	582	143
	$1,000, 2022	78,958	23,238	33,281	3,530	347,593	20,808
	2017	37,643	15,721	30,766	1,343	182,299	15,782
Corn	farms, 2022	324	47	135	17	556	75
	2017	392	38	189	11	519	112
	$1,000, 2022	58,090	12,699	21,218	1,016	222,767	11,296
	2017	26,407	6,360	18,498	303	101,946	9,285
Wheat	farms, 2022	7	6	7	1	7	15
	2017	3	5	4	4	8	9
	$1,000, 2022	(D)	(D)	198	(D)	109	430
	2017	12	(D)	155	(D)	(D)	223
Soybeans	farms, 2022	236	11	158	23	545	81
	2017	264	14	192	15	534	101
	$1,000, 2022	20,505	1,458	11,570	1,779	124,424	8,460
	2017	10,994	(D)	11,663	650	80,225	6,209
Sorghum	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Barley	farms, 2022	1	2	-	1	-	-
	2017	3	-	-	3	2	3
	$1,000, 2022	(D)	(D)	-	(D)	-	-
	2017	5	-	-	1	(D)	3

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD						
Total sales ..... farms, 2022	1,252	613	190	735	34	186
2017	1,220	528	181	853	42	134
$1,000, 2022	715,674	301,443	10,444	394,270	468	32,786
2017	424,078	128,347	6,887	249,877	358	17,278
Average per farm ..... dollars, 2022	571,625	491,751	54,967	536,421	13,767	176,267
2017	347,605	243,081	38,050	292,939	8,525	128,941
2022 value of sales:						
Less than $1,000 ..... farms	461	271	32	193	5	51
$1,000	16	(D)	7	3	(D)	1
$1,000 to $2,499 ..... farms	69	11	23	13	11	15
$1,000	105	(D)	(D)	20	15	28
$2,500 to $4,999 ..... farms	73	11	18	24	6	10
$1,000	276	44	62	82	24	33
$5,000 to $9,999 ..... farms	58	18	22	23	5	20
$1,000	416	107	151	173	38	124
$10,000 to $19,999 ..... farms	58	17	21	16	2	17
$1,000	797	216	314	234	(D)	264
$20,000 to $24,999 ..... farms	12	10	12	5	1	3
$1,000	268	223	251	113	(D)	67
$25,000 to $39,999 ..... farms	47	8	12	20	2	13
$1,000	1,408	246	373	585	(D)	413
$40,000 to $49,999 ..... farms	13	5	-	14	-	5
$1,000	581	246	-	637	-	218
$50,000 to $99,999 ..... farms	56	35	20	36	1	20
$1,000	4,212	2,528	1,256	2,931	(D)	1,446
$100,000 to $249,999 ..... farms	112	37	20	100	1	6
$1,000	17,122	5,928	2,889	15,587	(D)	1,117
$250,000 to $499,999 ..... farms	84	36	8	87	-	13
$1,000	31,707	13,813	2,909	29,715	-	3,637
$500,000 or more ..... farms	209	154	2	204	-	13
$1,000	658,766	278,071	(D)	344,189	-	25,437
2017 value of sales:						
Less than $1,000 ..... farms	495	215	32	222	9	33
$1,000	35	(D)	6	4	(D)	2
$1,000 to $2,499 ..... farms	48	13	26	7	10	14
$1,000	85	(D)	43	14	19	24
$2,500 to $4,999 ..... farms	62	17	18	25	12	5
$1,000	221	57	(D)	83	47	21
$5,000 to $9,999 ..... farms	56	16	37	30	3	10
$1,000	415	113	257	213	23	74
$10,000 to $19,999 ..... farms	55	24	19	28	4	14
$1,000	807	346	255	428	63	197
$20,000 to $24,999 ..... farms	11	1	4	18	-	6
$1,000	241	(D)	91	391	-	139
$25,000 to $39,999 ..... farms	29	16	13	45	2	7
$1,000	848	536	(D)	1,450	(D)	203
$40,000 to $49,999 ..... farms	15	7	1	22	-	3
$1,000	661	305	(D)	1,005	-	132
$50,000 to $99,999 ..... farms	87	33	14	51	2	21
$1,000	6,437	2,394	1,012	3,935	(D)	1,675
$100,000 to $249,999 ..... farms	97	46	10	145	-	6
$1,000	15,277	7,587	1,633	24,075	-	1,075
$250,000 to $499,999 ..... farms	115	40	5	125	-	6
$1,000	39,211	14,690	1,601	46,679	-	2,482
$500,000 or more ..... farms	150	100	2	135	-	9
$1,000	359,840	102,270	(D)	171,602	-	11,253
Value of sales by commodity or commodity group:						
Crops, including nursery and greenhouse crops ..... farms, 2022	658	324	144	506	19	119
2017	663	290	126	596	29	96
$1,000, 2022	376,326	295,748	8,207	289,072	(D)	31,158
2017	199,391	122,742	4,447	170,765	297	16,570
Grains, oilseeds, dry beans, and dry peas ..... farms, 2022	523	278	31	475	-	63
2017	545	239	26	559	-	54
$1,000, 2022	337,603	230,107	3,982	286,489	-	24,826
2017	164,867	91,401	2,384	169,168	-	13,603
Corn ..... farms, 2022	429	42	8	424	-	3
2017	475	68	10	507	-	3
$1,000, 2022	233,710	12,377	443	180,786	-	1,127
2017	103,768	7,624	(D)	94,740	-	(D)
Wheat ..... farms, 2022	38	214	7	22	-	20
2017	39	158	7	66	-	31
$1,000, 2022	(D)	105,216	765	413	-	6,658
2017	(D)	35,477	244	1,052	-	2,438
Soybeans ..... farms, 2022	416	213	19	446	-	50
2017	440	214	13	513	-	48
$1,000, 2022	90,627	86,175	2,756	103,098	-	10,978
2017	54,051	40,455	1,058	72,912	-	8,515
Sorghum ..... farms, 2022	-	-	-	1	-	-
2017	-	-	-	-	-	-
$1,000, 2022	-	-	-	(D)	-	-
2017	-	-	-	-	-	-
Barley ..... farms, 2022	1	14	1	2	-	10
2017	3	15	1	7	-	3
$1,000, 2022	(D)	1,838	(D)	(D)	-	1,430
2017	(D)	1,243	(D)	12	-	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	896	598	869	801	268	1,072
	2017	937	672	893	880	311	1,086
	$1,000, 2022	239,195	229,846	762,925	286,425	136,673	420,392
	2017	181,357	186,041	412,331	185,617	70,097	261,455
Average per farm	dollars, 2022	266,959	384,357	877,935	357,585	509,972	392,157
	2017	193,551	276,847	461,737	210,929	225,393	240,750
2022 value of sales:							
Less than $1,000	farms	358	217	182	232	59	359
	$1,000	22	6	8	12	-	10
$1,000 to $2,499	farms	32	9	23	31	6	15
	$1,000	49	18	36	49	12	26
$2,500 to $4,999	farms	26	14	21	31	4	20
	$1,000	94	54	78	111	17	68
$5,000 to $9,999	farms	32	18	23	68	11	47
	$1,000	238	130	170	494	73	343
$10,000 to $19,999	farms	43	24	25	43	22	36
	$1,000	631	371	368	598	307	524
$20,000 to $24,999	farms	17	6	17	15	6	31
	$1,000	393	139	380	337	131	702
$25,000 to $39,999	farms	35	12	28	30	17	25
	$1,000	1,096	375	946	961	593	780
$40,000 to $49,999	farms	22	5	8	22	4	20
	$1,000	1,001	228	365	1,001	184	872
$50,000 to $99,999	farms	73	48	45	77	21	71
	$1,000	5,558	3,621	3,218	5,285	1,483	5,149
$100,000 to $249,999	farms	79	78	111	85	29	114
	$1,000	12,441	12,196	17,635	14,370	4,015	17,369
$250,000 to $499,999	farms	55	62	113	35	27	122
	$1,000	20,469	22,961	41,584	12,810	11,067	42,668
$500,000 or more	farms	124	105	273	132	62	212
	$1,000	197,204	189,746	698,138	250,397	118,790	351,883
2017 value of sales:							
Less than $1,000	farms	353	205	158	195	80	433
	$1,000	29	2	7	20	12	18
$1,000 to $2,499	farms	45	11	28	48	13	21
	$1,000	66	18	40	81	25	37
$2,500 to $4,999	farms	35	24	39	54	21	30
	$1,000	120	90	128	190	71	104
$5,000 to $9,999	farms	39	25	22	58	14	33
	$1,000	284	169	154	406	94	230
$10,000 to $19,999	farms	60	21	22	52	18	55
	$1,000	855	334	343	745	292	772
$20,000 to $24,999	farms	14	21	9	21	5	21
	$1,000	309	479	206	477	118	465
$25,000 to $39,999	farms	31	26	35	50	7	40
	$1,000	1,016	900	1,212	1,624	197	1,338
$40,000 to $49,999	farms	19	26	20	21	14	11
	$1,000	848	1,114	863	932	629	505
$50,000 to $99,999	farms	99	56	65	93	32	84
	$1,000	7,117	4,205	4,697	7,401	2,385	6,183
$100,000 to $249,999	farms	72	82	144	112	39	111
	$1,000	11,630	13,509	23,966	17,135	6,150	17,763
$250,000 to $499,999	farms	59	72	163	84	34	100
	$1,000	19,825	25,445	58,932	29,479	12,826	36,079
$500,000 or more	farms	111	103	188	92	34	147
	$1,000	139,259	139,777	321,783	127,129	47,299	197,962
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	480	340	628	525	190	681
	2017	562	421	676	621	224	599
	$1,000, 2022	155,921	124,923	311,297	218,846	131,407	407,720
	2017	116,103	112,540	182,478	128,557	66,192	246,171
Grains, oilseeds, dry beans, and dry peas	farms, 2022	374	301	585	395	158	555
	2017	438	391	630	496	171	498
	$1,000, 2022	152,420	123,035	309,334	212,209	125,724	317,029
	2017	111,447	111,084	180,068	118,787	61,305	195,181
Corn	farms, 2022	289	263	526	327	78	85
	2017	362	356	582	419	100	151
	$1,000, 2022	92,573	83,096	200,413	140,589	50,676	26,219
	2017	61,149	63,461	105,390	74,477	23,785	24,228
Wheat	farms, 2022	20	32	22	26	92	404
	2017	29	61	38	55	99	360
	$1,000, 2022	514	891	746	470	20,122	123,262
	2017	262	1,525	1,089	490	8,897	70,189
Soybeans	farms, 2022	336	271	533	345	141	474
	2017	386	352	562	443	148	447
	$1,000, 2022	59,016	38,316	107,540	68,664	41,364	130,225
	2017	49,979	45,540	73,363	42,298	25,434	86,466
Sorghum	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Barley	farms, 2022	-	-	-	-	13	49
	2017	2	1	2	3	2	60
	$1,000, 2022	-	-	-	-	1,505	6,497
	2017	(D)	(D)	(D)	8	(D)	6,055

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	823	991	603	1,571	999	789
	2017	911	1,028	707	1,760	1,068	864
	$1,000, 2022	943,050	497,668	65,669	538,309	529,254	451,948
	2017	635,524	265,151	43,931	394,721	413,225	337,829
Average per farm	dollars, 2022	1,145,868	502,188	108,905	342,654	529,783	572,811
	2017	697,611	257,929	62,138	224,273	386,915	391,005
2022 value of sales:							
Less than $1,000	farms	90	346	107	212	220	162
	$1,000	4	21	21	35	11	10
$1,000 to $2,499	farms	19	60	92	100	49	21
	$1,000	30	95	145	164	77	33
$2,500 to $4,999	farms	13	62	63	133	28	18
	$1,000	46	231	212	471	107	63
$5,000 to $9,999	farms	32	41	76	164	54	14
	$1,000	230	299	528	1,135	396	100
$10,000 to $19,999	farms	24	41	59	157	62	18
	$1,000	353	605	847	2,250	858	259
$20,000 to $24,999	farms	4	12	27	46	7	14
	$1,000	83	270	597	1,012	166	300
$25,000 to $39,999	farms	8	37	45	98	28	19
	$1,000	223	1,219	1,428	3,032	921	550
$40,000 to $49,999	farms	15	22	15	58	12	5
	$1,000	694	1,012	669	2,574	539	223
$50,000 to $99,999	farms	67	65	30	175	61	99
	$1,000	4,968	4,672	2,175	12,342	4,210	7,180
$100,000 to $249,999	farms	101	108	48	147	111	95
	$1,000	16,944	17,966	7,727	23,773	18,746	15,872
$250,000 to $499,999	farms	80	67	17	75	143	94
	$1,000	29,286	24,369	5,676	26,771	51,363	33,050
$500,000 or more	farms	370	130	24	206	224	230
	$1,000	890,188	446,910	45,645	464,749	451,860	394,307
2017 value of sales:							
Less than $1,000	farms	115	327	171	270	237	190
	$1,000	10	29	41	61	25	3
$1,000 to $2,499	farms	8	58	93	120	53	25
	$1,000	10	91	157	196	89	38
$2,500 to $4,999	farms	20	37	76	154	46	21
	$1,000	76	134	267	574	171	71
$5,000 to $9,999	farms	23	73	80	171	43	16
	$1,000	160	510	603	1,204	322	109
$10,000 to $19,999	farms	23	59	66	186	53	24
	$1,000	316	860	934	2,694	784	372
$20,000 to $24,999	farms	21	26	11	67	17	18
	$1,000	499	581	248	1,501	379	416
$25,000 to $39,999	farms	27	31	45	129	28	41
	$1,000	872	976	1,490	4,057	968	1,306
$40,000 to $49,999	farms	22	31	11	51	27	21
	$1,000	959	1,368	488	2,267	1,189	956
$50,000 to $99,999	farms	94	117	48	169	91	62
	$1,000	7,022	8,788	3,327	11,488	6,826	4,767
$100,000 to $249,999	farms	154	94	52	138	132	132
	$1,000	25,703	15,177	8,755	21,981	21,229	23,229
$250,000 to $499,999	farms	130	81	43	86	111	109
	$1,000	45,423	27,232	14,748	29,048	40,167	40,008
$500,000 or more	farms	274	94	11	219	230	205
	$1,000	554,475	209,405	12,875	319,649	341,077	266,553
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	639	557	433	1,173	659	582
	2017	720	615	490	1,321	762	629
	$1,000, 2022	461,489	198,492	27,365	121,192	348,518	253,460
	2017	265,667	118,463	23,249	68,103	242,698	184,081
Grains, oilseeds, dry beans, and dry peas	farms, 2022	596	425	177	735	577	548
	2017	690	507	220	861	641	581
	$1,000, 2022	457,205	190,733	22,956	97,626	335,694	251,649
	2017	261,863	111,034	20,155	55,748	225,550	182,523
Corn	farms, 2022	513	364	120	661	499	489
	2017	630	443	173	748	568	552
	$1,000, 2022	300,743	125,893	13,810	72,548	225,132	163,456
	2017	165,896	63,949	12,187	37,762	141,756	103,703
Wheat	farms, 2022	2	13	10	19	8	4
	2017	2	34	9	25	5	7
	$1,000, 2022	(D)	208	(D)	368	(D)	160
	2017	(D)	379	102	343	31	(D)
Soybeans	farms, 2022	533	340	126	361	480	491
	2017	603	415	155	448	568	553
	$1,000, 2022	156,229	64,086	8,861	20,556	109,322	87,383
	2017	95,808	46,080	7,772	13,902	83,474	78,401
Sorghum	farms, 2022	-	-	-	4	-	-
	2017	-	-	2	-	-	-
	$1,000, 2022	-	-	-	16	-	-
	2017	-	-	(D)	-	-	-
Barley	farms, 2022	-	3	2	3	3	3
	2017	2	5	1	13	6	1
	$1,000, 2022	-	61	(D)	49	(D)	10
	2017	(D)	77	(D)	31	109	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	660	938	435	1,102	2,497	322
	2017	689	885	505	1,139	2,544	409
	$1,000, 2022	596,399	761,337	341,464	337,134	551,279	100,306
	2017	339,306	518,965	218,262	214,415	349,919	66,456
Average per farm	dollars, 2022	903,635	811,660	784,975	305,930	220,776	311,509
	2017	492,461	586,401	432,202	188,249	137,547	162,483
2022 value of sales:							
Less than $1,000	farms	100	146	81	287	833	97
	$1,000	6	4	5	25	44	(D)
$1,000 to $2,499	farms	21	18	19	54	119	20
	$1,000	35	25	26	89	206	31
$2,500 to $4,999	farms	21	14	14	62	134	8
	$1,000	84	48	45	220	486	(D)
$5,000 to $9,999	farms	17	37	13	76	154	14
	$1,000	132	274	83	536	1,082	99
$10,000 to $19,999	farms	19	23	8	96	198	15
	$1,000	278	313	108	1,392	2,902	225
$20,000 to $24,999	farms	10	3	5	24	46	6
	$1,000	208	67	107	538	1,020	130
$25,000 to $39,999	farms	16	11	8	44	150	10
	$1,000	532	341	285	1,442	4,634	326
$40,000 to $49,999	farms	12	16	5	26	59	7
	$1,000	522	701	226	1,158	2,623	320
$50,000 to $99,999	farms	56	80	36	85	189	36
	$1,000	4,055	5,864	2,459	6,126	13,656	2,628
$100,000 to $249,999	farms	95	163	44	130	207	26
	$1,000	16,204	26,632	7,210	21,020	34,207	4,550
$250,000 to $499,999	farms	99	134	35	76	166	24
	$1,000	33,918	47,394	13,157	27,047	58,111	8,325
$500,000 or more	farms	194	293	167	142	242	59
	$1,000	540,424	679,676	317,753	277,544	432,305	83,644
2017 value of sales:							
Less than $1,000	farms	77	137	99	290	864	127
	$1,000	6	5	11	12	75	14
$1,000 to $2,499	farms	13	29	14	83	130	9
	$1,000	18	52	23	143	223	14
$2,500 to $4,999	farms	16	20	20	88	129	9
	$1,000	56	78	74	308	464	35
$5,000 to $9,999	farms	15	23	18	63	219	18
	$1,000	106	162	128	435	1,542	127
$10,000 to $19,999	farms	23	21	11	67	172	26
	$1,000	290	308	164	904	2,483	340
$20,000 to $24,999	farms	15	14	3	28	51	9
	$1,000	331	311	69	618	1,128	205
$25,000 to $39,999	farms	34	21	10	53	138	20
	$1,000	1,126	665	319	1,616	4,369	604
$40,000 to $49,999	farms	5	11	23	34	42	4
	$1,000	214	505	1,057	1,534	1,868	185
$50,000 to $99,999	farms	97	74	38	118	232	52
	$1,000	7,335	5,386	2,634	8,435	16,021	3,522
$100,000 to $249,999	farms	176	182	66	108	218	61
	$1,000	29,027	29,852	11,092	17,422	36,790	10,063
$250,000 to $499,999	farms	93	91	63	90	195	27
	$1,000	31,379	33,811	21,407	31,120	70,059	8,983
$500,000 or more	farms	125	262	140	117	154	47
	$1,000	269,419	447,830	181,284	151,868	214,897	42,364
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	502	692	334	712	1,453	199
	2017	583	676	381	701	1,525	278
	$1,000, 2022	260,718	292,440	323,379	225,715	336,363	96,307
	2017	137,808	205,610	205,738	121,634	200,860	60,863
Grains, oilseeds, dry beans, and dry peas	farms, 2022	448	653	287	512	1,020	148
	2017	527	644	338	547	1,076	215
	$1,000, 2022	258,325	290,405	262,270	205,881	288,880	90,336
	2017	135,339	203,343	157,690	105,970	178,869	56,932
Corn	farms, 2022	402	591	174	447	783	29
	2017	474	609	181	482	844	30
	$1,000, 2022	168,126	192,760	90,056	144,206	173,940	6,843
	2017	82,067	117,691	46,751	71,553	91,321	3,946
Wheat	farms, 2022	22	5	203	4	176	100
	2017	29	11	231	4	268	123
	$1,000, 2022	339	316	59,802	17	8,907	30,267
	2017	325	201	39,301	22	8,939	22,959
Soybeans	farms, 2022	403	586	262	407	693	124
	2017	469	585	323	417	676	197
	$1,000, 2022	89,522	96,786	102,371	60,527	88,041	42,967
	2017	52,802	85,260	66,890	33,970	68,048	24,949
Sorghum	farms, 2022	-	-	-	4	7	-
	2017	-	2	-	-	1	-
	$1,000, 2022	-	-	-	50	35	-
	2017	-	(D)	-	-	(D)	-
Barley	farms, 2022	2	-	18	-	11	16
	2017	2	-	21	8	16	23
	$1,000, 2022	(D)	-	2,879	-	699	3,519
	2017	(D)	-	1,814	19	(D)	2,677

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD						
Total sales ... farms, 2022	728	529	1,223	821	47	274
2017	823	595	1,258	837	55	263
$1,000, 2022	58,065	397,208	697,381	244,815	3,449	109,527
2017	38,978	326,053	429,771	199,295	2,951	65,599
Average per farm ... dollars, 2022	79,760	750,866	570,222	298,191	73,387	399,734
2017	47,361	547,988	341,630	238,106	53,655	249,426
2022 value of sales:						
Less than $1,000 ... farms	123	86	262	289	4	49
$1,000	18	8	4	4	-	(D)
$1,000 to $2,499 ... farms	68	19	28	44	4	10
$1,000	112	23	48	70	8	(D)
$2,500 to $4,999 ... farms	95	29	47	23	2	6
$1,000	331	98	173	86	(D)	28
$5,000 to $9,999 ... farms	84	14	67	32	10	2
$1,000	582	100	475	248	74	(D)
$10,000 to $19,999 ... farms	80	26	54	56	4	14
$1,000	1,089	370	792	831	51	213
$20,000 to $24,999 ... farms	29	4	8	4	-	1
$1,000	644	91	173	91	-	(D)
$25,000 to $39,999 ... farms	87	21	48	45	12	14
$1,000	2,664	664	1,632	1,446	366	425
$40,000 to $49,999 ... farms	27	15	27	15	3	5
$1,000	1,227	650	1,192	672	(D)	222
$50,000 to $99,999 ... farms	47	30	86	59	2	43
$1,000	3,439	2,115	6,235	4,105	(D)	2,993
$100,000 to $249,999 ... farms	49	90	121	84	2	41
$1,000	7,436	14,972	19,838	14,035	(D)	6,387
$250,000 to $499,999 ... farms	21	66	129	57	1	31
$1,000	7,346	25,315	45,525	20,785	(D)	9,942
$500,000 or more ... farms	18	129	346	113	3	58
$1,000	33,179	352,801	621,294	202,443	(D)	89,260
2017 value of sales:						
Less than $1,000 ... farms	207	108	366	318	6	71
$1,000	54	12	17	11	(D)	3
$1,000 to $2,499 ... farms	119	20	29	36	3	4
$1,000	186	33	45	63	(D)	8
$2,500 to $4,999 ... farms	80	20	45	31	10	11
$1,000	288	65	177	116	(D)	39
$5,000 to $9,999 ... farms	110	38	39	49	4	7
$1,000	784	238	292	343	30	56
$10,000 to $19,999 ... farms	100	30	48	22	5	14
$1,000	1,406	487	679	314	80	228
$20,000 to $24,999 ... farms	18	11	25	12	7	5
$1,000	406	244	533	271	149	110
$25,000 to $39,999 ... farms	54	14	70	23	9	5
$1,000	1,679	486	2,292	694	295	164
$40,000 to $49,999 ... farms	12	11	42	6	-	6
$1,000	531	504	1,894	283	-	285
$50,000 to $99,999 ... farms	57	45	101	89	3	41
$1,000	3,984	3,377	7,316	6,417	(D)	2,934
$100,000 to $249,999 ... farms	35	95	118	75	6	34
$1,000	5,252	16,436	19,417	11,620	(D)	5,804
$250,000 to $499,999 ... farms	20	57	102	64	-	25
$1,000	7,374	19,770	37,304	25,208	-	9,805
$500,000 or more ... farms	11	146	273	112	2	40
$1,000	17,034	284,400	359,805	153,955	(D)	46,163
Value of sales by commodity or commodity group:						
Crops, including nursery and greenhouse crops ... farms, 2022	497	363	853	449	41	195
2017	571	413	837	453	52	182
$1,000, 2022	30,766	139,438	683,717	176,399	(D)	91,408
2017	15,052	97,897	403,170	127,063	2,204	58,400
Grains, oilseeds, dry beans, and dry peas ... farms, 2022	163	322	705	361	2	179
2017	183	382	659	385	2	155
$1,000, 2022	16,489	137,584	497,022	162,771	(D)	84,832
2017	8,331	96,421	271,393	115,106	(D)	53,238
Corn ... farms, 2022	122	281	185	278	-	49
2017	134	356	203	333	1	52
$1,000, 2022	10,088	91,282	86,010	107,615	-	14,949
2017	4,568	55,774	40,643	69,055	(D)	9,112
Wheat ... farms, 2022	8	7	531	47	1	140
2017	5	24	486	63	1	118
$1,000, 2022	125	184	177,689	1,300	(D)	31,623
2017	47	702	103,493	(D)	(D)	19,887
Soybeans ... farms, 2022	90	283	580	304	-	152
2017	110	310	575	313	1	144
$1,000, 2022	6,102	44,764	170,637	48,869	-	34,251
2017	3,647	39,669	96,521	39,189	(D)	20,129
Sorghum ... farms, 2022	2	1	1	2	-	-
2017	-	-	-	2	-	-
$1,000, 2022	(D)	(D)	(D)	(D)	-	-
2017	-	-	-	(D)	-	-
Barley ... farms, 2022	4	2	22	1	1	7
2017	6	1	19	-	1	16
$1,000, 2022	(D)	(D)	(D)	(D)	(D)	666
2017	15	(D)	2,216	-	(D)	1,638

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	1,323	931	1,111	573	751	821
	2017	1,134	1,026	1,242	701	842	779
	$1,000, 2022	804,002	810,285	356,823	624,006	212,493	29,054
	2017	453,161	609,190	204,982	419,075	129,544	16,139
Average per farm	dollars, 2022	607,711	870,338	321,173	1,089,015	282,947	35,389
	2017	399,613	593,752	165,042	597,825	153,853	20,718
2022 value of sales:							
Less than $1,000	farms	253	162	264	60	240	174
	$1,000	11	4	15	2	12	47
$1,000 to $2,499	farms	20	20	71	23	40	106
	$1,000	38	31	116	35	63	167
$2,500 to $4,999	farms	21	21	74	11	37	127
	$1,000	74	84	266	35	126	457
$5,000 to $9,999	farms	33	19	78	15	37	117
	$1,000	231	141	577	121	262	867
$10,000 to $19,999	farms	33	34	83	29	37	94
	$1,000	480	483	1,208	400	568	1,400
$20,000 to $24,999	farms	16	16	20	9	10	32
	$1,000	348	349	440	188	222	696
$25,000 to $39,999	farms	47	30	62	12	37	49
	$1,000	1,432	998	2,051	370	1,152	1,570
$40,000 to $49,999	farms	24	9	26	10	8	19
	$1,000	1,079	422	1,164	428	358	832
$50,000 to $99,999	farms	95	44	123	40	73	53
	$1,000	7,052	3,163	8,625	3,045	5,289	3,866
$100,000 to $249,999	farms	190	117	120	63	89	29
	$1,000	33,451	19,139	18,939	10,548	14,847	4,258
$250,000 to $499,999	farms	219	110	63	76	35	14
	$1,000	78,711	40,625	22,058	28,171	12,989	5,016
$500,000 or more	farms	372	349	127	225	108	7
	$1,000	681,095	744,846	301,364	580,664	176,604	9,878
2017 value of sales:							
Less than $1,000	farms	201	216	376	73	344	220
	$1,000	10	8	41	10	12	61
$1,000 to $2,499	farms	26	18	68	19	28	90
	$1,000	45	33	108	29	40	145
$2,500 to $4,999	farms	19	19	56	9	40	103
	$1,000	67	70	200	30	134	370
$5,000 to $9,999	farms	40	30	94	23	58	156
	$1,000	279	224	643	168	430	1,124
$10,000 to $19,999	farms	18	34	90	31	42	72
	$1,000	264	500	1,313	396	625	1,059
$20,000 to $24,999	farms	21	9	35	11	17	25
	$1,000	484	193	773	236	373	565
$25,000 to $39,999	farms	46	30	78	25	34	35
	$1,000	1,452	972	2,555	767	1,115	1,074
$40,000 to $49,999	farms	20	21	37	19	8	11
	$1,000	909	964	1,667	896	377	490
$50,000 to $99,999	farms	99	93	126	95	78	40
	$1,000	7,566	6,847	9,191	6,923	5,605	2,667
$100,000 to $249,999	farms	209	140	142	102	71	16
	$1,000	34,634	23,305	23,948	17,528	11,080	2,581
$250,000 to $499,999	farms	188	133	54	77	40	8
	$1,000	68,347	45,987	18,399	29,009	13,607	2,424
$500,000 or more	farms	247	283	86	217	82	3
	$1,000	339,107	530,086	146,146	363,083	96,147	3,579
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	972	722	754	416	452	584
	2017	885	752	805	557	454	513
	$1,000, 2022	462,562	581,026	225,622	226,806	178,824	16,083
	2017	263,895	372,156	101,687	143,225	109,252	9,208
Grains, oilseeds, dry beans, and dry peas	farms, 2022	933	648	552	376	306	49
	2017	841	718	612	513	285	41
	$1,000, 2022	449,794	508,674	197,490	225,689	151,672	2,353
	2017	249,558	289,186	90,147	142,321	95,506	(D)
Corn	farms, 2022	833	575	419	345	53	11
	2017	777	649	506	483	44	3
	$1,000, 2022	294,485	331,868	126,255	154,080	10,364	280
	2017	144,965	174,206	55,157	83,764	5,011	(D)
Wheat	farms, 2022	17	45	13	2	187	5
	2017	32	41	15	-	162	1
	$1,000, 2022	(D)	1,521	181	(D)	50,686	(D)
	2017	309	745	122	-	28,052	(D)
Soybeans	farms, 2022	847	578	426	320	238	2
	2017	784	651	508	467	252	1
	$1,000, 2022	154,205	163,049	70,850	70,830	66,632	(D)
	2017	104,161	108,090	34,755	58,105	50,945	(D)
Sorghum	farms, 2022	-	2	1	-	-	-
	2017	-	2	-	-	-	-
	$1,000, 2022	-	(D)	(D)	-	-	-
	2017	-	(D)	-	-	-	-
Barley	farms, 2022	2	4	1	-	18	11
	2017	-	8	6	-	28	8
	$1,000, 2022	(D)	(D)	(D)	-	3,275	28
	2017	-	(D)	33	-	2,674	11

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	624	494	860	2,695	721	500
	2017	740	501	898	2,951	746	553
	$1,000, 2022	91,834	120,592	484,129	1,021,472	396,997	583,773
	2017	75,570	89,597	318,722	747,977	251,839	327,441
Average per farm	dollars, 2022	147,171	244,113	562,941	379,025	550,619	1,167,545
	2017	102,121	178,836	354,924	253,466	337,585	592,118
2022 value of sales:							
Less than $1,000	farms	159	152	169	470	265	147
	$1,000	20	43	21	58	9	7
$1,000 to $2,499	farms	73	65	39	152	22	18
	$1,000	116	107	60	249	41	25
$2,500 to $4,999	farms	44	33	40	166	21	8
	$1,000	152	133	149	605	76	31
$5,000 to $9,999	farms	48	55	36	149	38	7
	$1,000	344	397	256	1,101	290	50
$10,000 to $19,999	farms	66	50	46	182	28	12
	$1,000	979	709	610	2,680	391	149
$20,000 to $24,999	farms	16	13	4	95	7	10
	$1,000	356	279	94	2,094	155	235
$25,000 to $39,999	farms	33	15	36	150	18	9
	$1,000	1,083	510	1,201	4,803	550	270
$40,000 to $49,999	farms	17	3	10	65	12	6
	$1,000	729	141	449	2,822	530	273
$50,000 to $99,999	farms	59	22	70	232	42	46
	$1,000	4,057	1,464	5,457	16,793	2,982	3,702
$100,000 to $249,999	farms	30	26	111	345	76	37
	$1,000	4,944	4,196	18,080	53,704	12,570	6,229
$250,000 to $499,999	farms	37	19	96	273	51	40
	$1,000	12,661	6,853	35,256	100,478	17,380	14,659
$500,000 or more	farms	42	41	203	416	141	160
	$1,000	66,393	105,760	422,495	836,085	362,021	558,142
2017 value of sales:							
Less than $1,000	farms	230	178	185	579	257	175
	$1,000	36	37	18	84	13	11
$1,000 to $2,499	farms	46	56	36	132	20	14
	$1,000	85	91	54	223	35	23
$2,500 to $4,999	farms	50	45	30	160	31	9
	$1,000	174	165	111	577	112	32
$5,000 to $9,999	farms	59	50	30	180	27	24
	$1,000	413	356	223	1,344	200	197
$10,000 to $19,999	farms	55	36	55	197	30	11
	$1,000	808	494	777	2,917	443	149
$20,000 to $24,999	farms	15	10	20	61	11	9
	$1,000	330	228	442	1,365	246	192
$25,000 to $39,999	farms	58	26	38	168	21	13
	$1,000	1,861	897	1,229	5,457	650	390
$40,000 to $49,999	farms	24	3	14	78	23	6
	$1,000	1,094	131	647	3,429	1,001	275
$50,000 to $99,999	farms	70	11	109	305	63	43
	$1,000	5,003	710	8,054	21,323	4,755	3,137
$100,000 to $249,999	farms	63	27	133	364	69	35
	$1,000	10,685	4,605	21,169	59,684	11,267	5,574
$250,000 to $499,999	farms	32	8	86	364	50	81
	$1,000	11,413	2,758	30,910	127,836	17,245	29,164
$500,000 or more	farms	38	51	162	363	144	133
	$1,000	43,667	79,125	255,089	523,740	215,871	288,298
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	372	292	629	1,951	393	311
	2017	451	286	661	2,121	430	339
	$1,000, 2022	64,614	96,205	341,817	314,418	268,995	256,441
	2017	44,518	75,140	182,208	179,121	152,976	139,636
Grains, oilseeds, dry beans, and dry peas	farms, 2022	212	131	550	1,510	325	260
	2017	316	130	603	1,718	342	309
	$1,000, 2022	60,563	34,162	327,298	272,537	228,678	236,668
	2017	40,487	25,627	171,768	153,655	125,262	131,584
Corn	farms, 2022	181	96	499	1,284	278	228
	2017	248	103	549	1,518	315	293
	$1,000, 2022	38,925	25,625	219,456	191,336	153,488	152,149
	2017	22,771	16,755	106,159	98,573	80,522	72,811
Wheat	farms, 2022	5	3	25	55	14	41
	2017	16	5	34	89	8	78
	$1,000, 2022	35	(D)	769	1,114	482	6,811
	2017	96	217	414	1,594	(D)	(D)
Soybeans	farms, 2022	158	73	467	876	280	212
	2017	251	86	527	995	283	278
	$1,000, 2022	21,385	7,908	106,641	70,904	74,543	65,090
	2017	17,525	8,100	64,959	47,767	44,381	47,929
Sorghum	farms, 2022	-	-	3	5	-	-
	2017	2	-	-	3	-	-
	$1,000, 2022	-	-	7	34	-	-
	2017	(D)	-	-	92	-	-
Barley	farms, 2022	-	-	6	28	-	-
	2017	2	-	9	65	2	1
	$1,000, 2022	-	-	111	243	-	-
	2017	(D)	-	149	371	(D)	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD							
Total sales	farms, 2022	708	1,529	358	743	442	622
	2017	760	1,604	411	809	516	729
	$1,000, 2022	453,273	346,248	259,570	329,119	105,639	393,883
	2017	284,161	179,461	210,468	186,309	52,844	275,039
Average per farm	dollars, 2022	640,217	226,454	725,056	442,960	239,002	633,253
	2017	373,896	111,884	512,088	230,296	102,411	377,283
2022 value of sales:							
Less than $1,000	farms	239	321	128	108	118	127
	$1,000	4	28	(D)	3	15	3
$1,000 to $2,499	farms	11	116	3	29	20	19
	$1,000	18	179	(D)	54	33	34
$2,500 to $4,999	farms	8	99	3	33	49	29
	$1,000	24	356	12	115	170	100
$5,000 to $9,999	farms	27	156	9	55	34	21
	$1,000	201	1,152	77	378	244	160
$10,000 to $19,999	farms	24	121	4	50	38	19
	$1,000	324	1,798	(D)	746	581	237
$20,000 to $24,999	farms	10	70	2	15	12	12
	$1,000	215	1,579	(D)	324	253	263
$25,000 to $39,999	farms	15	86	5	30	24	22
	$1,000	465	2,703	163	983	735	695
$40,000 to $49,999	farms	20	45	1	21	15	8
	$1,000	931	2,005	(D)	885	674	358
$50,000 to $99,999	farms	44	185	22	51	62	38
	$1,000	3,333	13,455	1,649	3,724	4,488	2,693
$100,000 to $249,999	farms	81	148	23	109	32	104
	$1,000	14,328	24,502	4,196	17,389	4,635	18,485
$250,000 to $499,999	farms	68	81	38	94	11	72
	$1,000	23,573	28,712	14,668	33,942	4,092	26,326
$500,000 or more	farms	161	101	120	148	27	151
	$1,000	409,858	269,779	238,642	270,573	89,719	344,531
2017 value of sales:							
Less than $1,000	farms	231	381	111	165	120	184
	$1,000	13	72	(D)	23	25	11
$1,000 to $2,499	farms	16	60	8	35	31	18
	$1,000	25	106	13	60	58	31
$2,500 to $4,999	farms	24	115	3	23	53	21
	$1,000	84	416	(D)	83	192	75
$5,000 to $9,999	farms	28	143	14	33	66	34
	$1,000	200	992	97	251	448	248
$10,000 to $19,999	farms	37	175	10	29	67	27
	$1,000	535	2,576	(D)	460	984	375
$20,000 to $24,999	farms	14	70	1	25	18	3
	$1,000	309	1,550	(D)	555	400	61
$25,000 to $39,999	farms	27	140	12	59	50	23
	$1,000	877	4,459	341	1,836	1,586	756
$40,000 to $49,999	farms	18	56	9	12	4	16
	$1,000	800	2,523	395	547	187	724
$50,000 to $99,999	farms	83	177	38	124	37	68
	$1,000	6,062	13,008	2,475	9,329	2,548	5,084
$100,000 to $249,999	farms	92	147	41	124	28	96
	$1,000	15,921	23,914	6,240	21,001	4,318	15,747
$250,000 to $499,999	farms	54	81	51	94	21	94
	$1,000	20,143	28,860	19,305	33,871	8,232	32,314
$500,000 or more	farms	136	59	113	86	21	145
	$1,000	239,191	100,985	181,433	118,292	33,866	219,615
Value of sales by commodity or commodity group:							
Crops, including nursery and greenhouse crops	farms, 2022	440	1,041	224	560	275	444
	2017	505	1,129	291	605	322	502
	$1,000, 2022	278,222	108,415	199,004	133,265	59,702	262,973
	2017	150,481	56,695	164,813	80,167	29,866	132,628
Grains, oilseeds, dry beans, and dry peas	farms, 2022	410	684	211	443	132	380
	2017	473	804	278	526	153	450
	$1,000, 2022	263,616	89,035	190,295	117,118	36,535	257,513
	2017	142,908	45,867	158,634	64,975	15,429	127,815
Corn	farms, 2022	361	529	188	425	103	331
	2017	409	632	224	473	130	410
	$1,000, 2022	188,361	54,411	119,787	85,410	21,563	164,623
	2017	90,504	26,325	83,472	44,178	8,209	77,004
Wheat	farms, 2022	22	43	20	3	11	4
	2017	44	65	54	6	12	9
	$1,000, 2022	889	864	1,698	(D)	(D)	(D)
	2017	(D)	1,218	3,807	67	(D)	27
Soybeans	farms, 2022	332	401	196	291	57	326
	2017	361	449	260	332	72	388
	$1,000, 2022	65,997	26,303	65,158	30,194	9,879	92,177
	2017	47,557	16,778	70,384	20,278	5,658	50,335
Sorghum	farms, 2022	-	1	-	1	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	(D)	-	(D)	-	-
	2017	-	-	-	-	-	-
Barley	farms, 2022	-	15	-	12	2	-
	2017	1	29	-	18	1	-
	$1,000, 2022	-	(D)	-	310	(D)	-
	2017	(D)	170	-	109	(D)	-

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD						
Total sales ... farms, 2022	525	512	358	993	1,310	847
2017	612	497	391	1,034	1,338	852
$1,000, 2022	60,710	404,682	254,790	401,862	283,025	422,723
2017	59,779	269,528	185,597	228,165	196,508	256,427
Average per farm ... dollars, 2022	115,637	790,395	711,704	404,695	216,049	499,083
2017	97,677	542,309	474,674	220,662	146,867	300,970
2022 value of sales:						
Less than $1,000 ... farms	111	91	99	224	359	231
$1,000	14	(D)	3	24	61	8
$1,000 to $2,499 ... farms	27	7	3	47	116	19
$1,000	44	(D)	4	71	204	33
$2,500 to $4,999 ... farms	71	11	10	35	122	30
$1,000	266	40	34	122	438	116
$5,000 to $9,999 ... farms	66	40	9	39	97	35
$1,000	456	260	55	285	679	234
$10,000 to $19,999 ... farms	61	19	16	49	109	32
$1,000	865	299	215	750	1,512	433
$20,000 to $24,999 ... farms	11	3	5	16	42	8
$1,000	246	60	117	365	901	172
$25,000 to $39,999 ... farms	32	15	5	39	75	20
$1,000	970	469	175	1,268	2,394	702
$40,000 to $49,999 ... farms	6	1	3	34	34	7
$1,000	275	(D)	128	1,524	1,538	312
$50,000 to $99,999 ... farms	37	48	16	129	111	54
$1,000	2,670	3,343	1,139	9,266	8,067	4,229
$100,000 to $249,999 ... farms	53	48	34	127	96	103
$1,000	8,495	8,721	5,425	19,279	15,103	17,360
$250,000 to $499,999 ... farms	23	56	29	94	52	93
$1,000	6,748	20,525	10,083	32,686	18,328	34,226
$500,000 or more ... farms	27	173	129	160	97	215
$1,000	39,660	370,906	237,412	336,223	233,799	364,900
2017 value of sales:						
Less than $1,000 ... farms	181	125	98	207	365	231
$1,000	49	(D)	1	26	63	16
$1,000 to $2,499 ... farms	67	12	3	39	114	11
$1,000	105	(D)	7	72	192	18
$2,500 to $4,999 ... farms	50	9	9	67	103	31
$1,000	177	37	33	249	396	111
$5,000 to $9,999 ... farms	74	11	8	53	97	13
$1,000	473	79	58	370	658	92
$10,000 to $19,999 ... farms	51	16	16	90	97	25
$1,000	698	209	217	1,341	1,413	388
$20,000 to $24,999 ... farms	18	2	7	26	60	16
$1,000	401	(D)	156	593	1,322	353
$25,000 to $39,999 ... farms	25	8	6	64	86	22
$1,000	808	251	191	2,008	2,726	675
$40,000 to $49,999 ... farms	3	13	6	28	32	26
$1,000	140	573	256	1,265	1,422	1,185
$50,000 to $99,999 ... farms	53	46	27	150	137	82
$1,000	4,096	3,463	2,067	10,529	9,700	6,322
$100,000 to $249,999 ... farms	40	83	38	139	113	120
$1,000	5,928	14,513	6,013	23,583	19,895	21,123
$250,000 to $499,999 ... farms	25	38	62	76	60	130
$1,000	8,387	13,020	23,060	26,981	22,852	48,773
$500,000 or more ... farms	25	134	111	95	74	145
$1,000	38,516	237,308	153,538	161,148	135,870	177,371
Value of sales by commodity or commodity group:						
Crops, including nursery and greenhouse crops ... farms, 2022	348	379	244	680	891	559
2017	425	356	283	743	930	569
$1,000, 2022	54,703	254,705	252,735	151,455	150,721	278,355
2017	54,194	146,175	184,681	69,888	112,931	170,173
Grains, oilseeds, dry beans, and dry peas ... farms, 2022	125	352	216	544	521	510
2017	163	341	265	581	599	529
$1,000, 2022	20,842	251,134	214,415	136,871	124,074	273,145
2017	23,232	142,445	149,222	57,871	84,108	166,704
Corn ... farms, 2022	86	294	169	523	392	440
2017	129	313	204	545	495	481
$1,000, 2022	13,256	169,738	105,729	99,864	70,186	179,194
2017	14,338	86,527	65,103	40,872	46,081	95,519
Wheat ... farms, 2022	8	16	139	4	32	29
2017	-	10	173	7	29	80
$1,000, 2022	(D)	136	27,125	119	(D)	883
2017	-	68	20,775	(D)	470	1,470
Soybeans ... farms, 2022	83	298	197	376	369	458
2017	121	305	244	336	454	498
$1,000, 2022	7,163	81,074	76,961	36,263	51,993	90,473
2017	8,790	55,786	61,122	16,492	37,343	69,356
Sorghum ... farms, 2022	1	-	-	1	1	-
2017	3	-	-	1	4	-
$1,000, 2022	(D)	-	-	(D)	(D)	-
2017	2	-	-	(D)	(D)	-
Barley ... farms, 2022	-	-	8	2	-	-
2017	4	1	18	13	1	1
$1,000, 2022	-	-	573	(D)	-	-
2017	13	(D)	852	90	(D)	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.						
Total sales - Con.						
Value of sales by commodity or commodity group: - Con.						
Crops, including nursery and greenhouse crops - Con.						
Grains, oilseeds, dry beans, and dry peas - Con.						
Rice	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	3,613	28	10	51	82
	2017	3,577	25	23	58	46
	$1,000, 2022	371,859	3,323	(D)	6,869	6,890
	2017	165,523	1,396	(D)	3,958	2,153
Tobacco	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	2,648	27	40	16	24
	2017	2,860	24	25	23	23
	$1,000, 2022	446,099	(D)	9,293	(D)	176
	2017	383,264	172	2,176	(D)	112
Fruits, tree nuts, and berries	farms, 2022	1,212	11	15	25	12
	2017	1,118	16	16	18	19
	$1,000, 2022	48,717	1,217	820	(D)	(D)
	2017	25,839	313	(D)	261	(D)
Fruits and tree nuts	farms, 2022	944	8	11	19	10
	2017	833	11	8	15	11
	$1,000, 2022	30,052	(D)	(D)	198	91
	2017	21,398	81	91	253	20
Berries	farms, 2022	489	4	8	7	9
	2017	544	7	10	4	16
	$1,000, 2022	18,665	(D)	(D)	(D)	(D)
	2017	4,441	231	(D)	8	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	1,051	11	51	7	15
	2017	920	13	28	8	17
	$1,000, 2022	391,444	338	53,619	14,140	690
	2017	277,254	488	23,853	(D)	170
Cultivated Christmas trees and short rotation woody crops	farms, 2022	244	4	7	3	2
	2017	228	6	6	1	1
	$1,000, 2022	7,578	(D)	1,416	(D)	(D)
	2017	5,895	81	(D)	(D)	(D)
Cultivated Christmas trees	farms, 2022	243	4	7	3	2
	2017	208	6	6	1	1
	$1,000, 2022	(D)	(D)	1,416	(D)	(D)
	2017	5,800	81	(D)	(D)	(D)
Short rotation woody crops	farms, 2022	1	-	-	-	-
	2017	28	-	-	-	-
	$1,000, 2022	(D)	-	-	-	-
	2017	95	-	-	-	-
Other crops and hay	farms, 2022	16,722	310	109	294	265
	2017	18,158	289	137	329	275
	$1,000, 2022	981,348	5,105	1,054	16,926	5,067
	2017	655,825	2,458	740	7,594	3,175
Maple syrup	farms, 2022	364	12	14	12	6
	2017	289	10	6	4	2
	$1,000, 2022	869	(D)	5	15	6
	2017	758	44	1	8	(D)
Livestock, poultry, and their products	farms, 2022	22,770	207	113	322	250
	2017	26,062	227	135	334	313
	$1,000, 2022	11,338,329	8,878	1,032	115,528	11,584
	2017	8,203,872	5,415	32,592	70,892	10,513
Poultry and eggs	farms, 2022	4,445	53	40	32	42
	2017	4,175	60	42	44	78
	$1,000, 2022	1,943,207	4,566	75	28,814	64
	2017	1,285,951	(D)	26	29,593	49
Cattle and calves	farms, 2022	14,649	149	32	269	194
	2017	18,474	174	55	258	241
	$1,000, 2022	2,094,135	3,717	399	26,963	10,579
	2017	1,886,939	3,920	489	13,665	9,689
Milk from cows	farms, 2022	1,893	2	-	35	3
	2017	3,349	7	2	46	4
	$1,000, 2022	2,504,638	(D)	-	46,172	(D)
	2017	1,737,886	233	(D)	23,150	(D)
Hogs and pigs	farms, 2022	3,352	18	11	21	17
	2017	3,562	19	11	20	17
	$1,000, 2022	4,666,832	53	21	12,020	45
	2017	3,165,075	61	14	(D)	42
Sheep, goats, wool, mohair, and milk	farms, 2022	2,604	22	17	13	20
	2017	2,673	40	17	13	51
	$1,000, 2022	33,457	49	37	(D)	85
	2017	26,154	79	39	(D)	222

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.						
Total sales - Con.						
Value of sales by commodity or commodity group: - Con.						
Crops, including nursery and greenhouse crops - Con.						
Grains, oilseeds, dry beans, and dry peas - Con.						
Rice	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	32	4	18	35	20
	2017	45	12	17	33	21
	$1,000, 2022	(D)	(D)	361	834	177
	2017	(D)	617	(D)	173	53
Tobacco	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	20	4	39	31	25
	2017	17	3	18	127	25
	$1,000, 2022	20,330	82	1,874	2,863	472
	2017	13,191	40	1,631	13,042	669
Fruits, tree nuts, and berries	farms, 2022	9	2	27	4	20
	2017	3	14	29	8	16
	$1,000, 2022	(D)	(D)	(D)	(D)	548
	2017	66	18	(D)	55	217
Fruits and tree nuts	farms, 2022	7	2	19	4	11
	2017	2	14	29	6	5
	$1,000, 2022	86	(D)	195	57	92
	2017	(D)	18	238	36	16
Berries	farms, 2022	2	1	8	4	14
	2017	2	-	10	4	13
	$1,000, 2022	(D)	(D)	(D)	(D)	456
	2017	(D)	-	(D)	19	202
Nursery, greenhouse, floriculture, and sod	farms, 2022	6	3	14	1	12
	2017	12	-	8	3	11
	$1,000, 2022	2,258	(D)	1,410	(D)	(D)
	2017	318	-	1,936	(D)	142
Cultivated Christmas trees and short rotation woody crops	farms, 2022	2	-	1	-	5
	2017	7	-	2	1	5
	$1,000, 2022	(D)	-	(D)	-	(D)
	2017	89	-	(D)	(D)	9
Cultivated Christmas trees	farms, 2022	2	-	1	-	5
	2017	7	-	-	1	5
	$1,000, 2022	(D)	-	(D)	-	(D)
	2017	89	-	-	(D)	9
Short rotation woody crops	farms, 2022	-	-	-	-	-
	2017	-	-	2	-	-
	$1,000, 2022	-	-	-	-	-
	2017	-	-	(D)	-	-
Other crops and hay	farms, 2022	221	51	80	95	280
	2017	285	57	99	92	382
	$1,000, 2022	2,173	3,340	952	1,200	4,325
	2017	2,270	780	376	1,062	3,400
Maple syrup	farms, 2022	-	-	4	-	17
	2017	2	-	2	3	12
	$1,000, 2022	-	-	(D)	-	45
	2017	(D)	-	(D)	(Z)	65
Livestock, poultry, and their products	farms, 2022	328	81	239	300	241
	2017	411	106	293	346	300
	$1,000, 2022	193,891	36,224	374,556	235,657	6,485
	2017	143,279	31,789	280,861	206,767	6,203
Poultry and eggs	farms, 2022	70	10	31	43	70
	2017	92	17	54	33	83
	$1,000, 2022	67,640	(D)	(D)	10,668	208
	2017	87,002	(D)	13,119	9,804	124
Cattle and calves	farms, 2022	242	58	71	196	173
	2017	317	89	110	261	209
	$1,000, 2022	18,961	3,843	7,133	51,134	4,495
	2017	9,957	(D)	9,686	61,418	3,938
Milk from cows	farms, 2022	42	-	1	38	1
	2017	86	-	8	49	12
	$1,000, 2022	90,851	-	(D)	25,439	(D)
	2017	36,923	-	435	21,526	1,801
Hogs and pigs	farms, 2022	27	9	114	75	12
	2017	28	12	110	73	24
	$1,000, 2022	15,284	21,766	355,237	130,536	(D)
	2017	9,156	18,495	256,983	106,448	160
Sheep, goats, wool, mohair, and milk	farms, 2022	23	3	23	19	17
	2017	21	13	31	20	37
	$1,000, 2022	(D)	15	394	(D)	1,642
	2017	119	40	474	(D)	127

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	8	9	34	18	55	24
	2017	31	5	41	15	32	25
	$1,000, 2022	(D)	119	15,543	204	7,183	9,378
	2017	70	(D)	4,943	103	2,177	4,181
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	26	14	17	39	26	25
	2017	22	19	21	50	18	11
	$1,000, 2022	703	(D)	2,946	496	11,852	7,595
	2017	314	569	2,792	4,859	8,036	(D)
Fruits, tree nuts, and berries	farms, 2022	24	19	13	31	8	1
	2017	23	12	6	48	6	5
	$1,000, 2022	1,065	(D)	297	1,370	8	(D)
	2017	682	52	(D)	553	11	(D)
Fruits and tree nuts	farms, 2022	23	10	11	27	-	-
	2017	21	8	6	38	4	2
	$1,000, 2022	1,050	(D)	286	1,108	-	-
	2017	624	19	16	457	(D)	(D)
Berries	farms, 2022	3	9	4	13	8	1
	2017	6	8	4	20	5	5
	$1,000, 2022	15	81	11	262	8	(D)
	2017	58	33	(D)	96	(D)	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	15	8	-	51	6	10
	2017	14	6	3	33	10	5
	$1,000, 2022	6,006	153	-	9,588	1,815	(D)
	2017	3,508	156	(D)	4,871	(D)	277
Cultivated Christmas trees and short rotation woody crops	farms, 2022	-	5	-	12	-	-
	2017	-	3	-	12	1	-
	$1,000, 2022	-	2	-	70	-	-
	2017	-	4	-	85	(D)	-
Cultivated Christmas trees	farms, 2022	-	5	-	12	-	-
	2017	-	3	-	12	1	-
	$1,000, 2022	-	2	-	70	-	-
	2017	-	4	-	79	(D)	-
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	3	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	6	-	-
Other crops and hay	farms, 2022	187	257	141	235	200	184
	2017	202	219	147	277	236	188
	$1,000, 2022	2,397	3,662	42,251	1,553	68,930	5,971
	2017	1,787	2,219	36,686	1,087	50,002	3,609
Maple syrup	farms, 2022	7	5	-	29	-	2
	2017	2	4	-	26	-	1
	$1,000, 2022	10	(D)	-	42	-	(D)
	2017	(D)	21	-	46	-	(D)
Livestock, poultry, and their products	farms, 2022	238	264	87	339	179	226
	2017	280	245	132	371	183	221
	$1,000, 2022	53,935	20,189	112,292	10,393	65,152	10,686
	2017	42,451	18,963	68,643	13,409	37,549	10,319
Poultry and eggs	farms, 2022	38	71	16	116	51	26
	2017	27	43	25	98	42	28
	$1,000, 2022	533	(D)	(D)	230	53,293	(D)
	2017	(D)	(D)	(D)	(D)	20,126	(D)
Cattle and calves	farms, 2022	160	194	42	142	106	174
	2017	218	183	83	203	133	192
	$1,000, 2022	13,706	8,617	13,307	2,470	3,822	9,595
	2017	9,185	14,247	(D)	6,285	5,609	7,799
Milk from cows	farms, 2022	39	3	1	10	10	3
	2017	76	6	1	17	11	8
	$1,000, 2022	30,134	505	(D)	6,674	2,858	(D)
	2017	27,684	1,383	(D)	5,853	3,445	1,159
Hogs and pigs	farms, 2022	12	10	30	18	11	7
	2017	17	20	33	45	18	13
	$1,000, 2022	8,823	22	44,468	295	4,211	250
	2017	3,491	32	18,924	395	7,910	(D)
Sheep, goats, wool, mohair, and milk	farms, 2022	35	16	20	69	18	34
	2017	22	21	13	68	13	26
	$1,000, 2022	498	73	444	201	(D)	102
	2017	(D)	(D)	465	249	23	182

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	1	10	32	48	17	69
	2017	-	8	37	19	22	62
	$1,000, 2022	(D)	(D)	1,854	1,644	(D)	(D)
	2017	-	24	(D)	229	93	(D)
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	9	7	26	176	27	22
	2017	9	11	19	173	29	18
	$1,000, 2022	79	(D)	181	31,080	9,098	(D)
	2017	(D)	1,098	131	28,866	5,883	359
Fruits, tree nuts, and berries	farms, 2022	7	7	10	45	12	27
	2017	11	7	12	27	7	14
	$1,000, 2022	140	(D)	104	1,686	548	1,117
	2017	40	(D)	66	891	(D)	(D)
Fruits and tree nuts	farms, 2022	2	4	9	26	7	21
	2017	9	6	7	19	4	7
	$1,000, 2022	(D)	18	65	626	27	399
	2017	(D)	(D)	35	585	(D)	150
Berries	farms, 2022	6	3	4	25	9	12
	2017	3	5	8	10	4	11
	$1,000, 2022	(D)	(D)	39	1,061	521	719
	2017	(D)	64	31	306	50	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	2	3	13	68	8	7
	2017	6	6	17	45	2	11
	$1,000, 2022	(D)	(D)	1,745	110,780	(D)	849
	2017	28	(D)	1,215	50,206	(D)	465
Cultivated Christmas trees and short rotation woody crops	farms, 2022	-	-	6	-	3	1
	2017	-	-	4	5	2	1
	$1,000, 2022	-	-	8	-	3	(D)
	2017	-	-	6	33	(D)	(D)
Cultivated Christmas trees	farms, 2022	-	-	6	-	3	1
	2017	-	-	3	4	2	1
	$1,000, 2022	-	-	8	-	3	(D)
	2017	-	-	(D)	(D)	(D)	(D)
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	-	2	1	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	(D)	(D)	-	-
Other crops and hay	farms, 2022	12	76	191	140	100	233
	2017	10	87	251	168	125	256
	$1,000, 2022	92	1,189	2,538	1,515	(D)	7,536
	2017	(D)	(D)	1,371	1,189	751	2,644
Maple syrup	farms, 2022	3	-	6	6	-	7
	2017	3	-	7	1	2	6
	$1,000, 2022	(D)	-	15	4	-	25
	2017	(D)	-	3	(D)	(D)	2
Livestock, poultry, and their products	farms, 2022	10	197	186	280	248	287
	2017	18	218	241	273	256	322
	$1,000, 2022	185	247,990	12,639	81,786	140,988	35,333
	2017	16	188,186	9,798	55,884	100,062	26,237
Poultry and eggs	farms, 2022	4	32	48	72	40	62
	2017	10	26	44	62	46	44
	$1,000, 2022	(D)	12,500	4,215	2,115	(D)	(D)
	2017	(D)	8,494	3,788	(D)	13,900	(D)
Cattle and calves	farms, 2022	5	101	119	162	161	183
	2017	2	147	169	174	159	242
	$1,000, 2022	174	47,886	3,386	48,460	(D)	10,582
	2017	(D)	51,202	3,576	30,931	10,546	11,942
Milk from cows	farms, 2022	-	10	5	24	24	14
	2017	-	12	6	28	18	63
	$1,000, 2022	-	4,221	3,356	26,179	36,858	15,225
	2017	-	1,863	1,654	14,777	16,704	12,013
Hogs and pigs	farms, 2022	1	61	4	24	49	13
	2017	-	55	16	41	54	25
	$1,000, 2022	(D)	180,937	12	3,959	74,426	480
	2017	-	125,203	(D)	4,132	58,578	228
Sheep, goats, wool, mohair, and milk	farms, 2022	-	14	16	47	29	41
	2017	6	22	27	35	30	34
	$1,000, 2022	-	730	41	150	231	352
	2017	8	(D)	105	(D)	135	122

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	12	76	27	74	11	4
	2017	27	87	22	68	13	13
	$1,000, 2022	(D)	1,369	682	724	5,720	43
	2017	961	329	134	398	(D)	39
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	45	55	35	60	3	79
	2017	62	58	44	64	11	83
	$1,000, 2022	5,249	4,250	8,800	4,515	(D)	2,183
	2017	6,602	7,631	11,459	6,704	136	1,071
Fruits, tree nuts, and berries	farms, 2022	2	34	9	32	1	66
	2017	1	33	11	37	3	29
	$1,000, 2022	(D)	1,768	65	711	(D)	1,142
	2017	(D)	703	46	(D)	(D)	(D)
Fruits and tree nuts	farms, 2022	2	26	9	30	1	49
	2017	1	25	9	37	1	21
	$1,000, 2022	(D)	1,361	50	519	(D)	691
	2017	(D)	681	40	311	(D)	450
Berries	farms, 2022	-	15	5	6	-	24
	2017	-	17	8	2	2	13
	$1,000, 2022	-	406	16	192	-	451
	2017	-	22	6	(D)	(D)	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	5	27	11	12	-	39
	2017	5	16	4	17	1	56
	$1,000, 2022	1,027	(D)	1,054	985	-	37,960
	2017	1,682	251	1,069	3,571	(D)	36,355
Cultivated Christmas trees and short rotation woody crops	farms, 2022	-	1	-	3	-	4
	2017	-	3	-	2	-	2
	$1,000, 2022	-	(D)	-	75	-	2
	2017	-	20	-	(D)	-	(D)
Cultivated Christmas trees	farms, 2022	-	1	-	3	-	4
	2017	-	1	-	2	-	2
	$1,000, 2022	-	(D)	-	75	-	2
	2017	-	(D)	-	(D)	-	(D)
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	2	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	(D)	-	-	-	-
Other crops and hay	farms, 2022	42	327	147	328	64	128
	2017	66	330	128	329	70	147
	$1,000, 2022	(D)	8,055	1,268	8,177	22,146	1,364
	2017	(D)	4,563	948	2,978	12,589	852
Maple syrup	farms, 2022	-	5	-	9	-	12
	2017	-	4	-	9	-	7
	$1,000, 2022	-	1	-	4	-	36
	2017	-	4	-	11	-	21
Livestock, poultry, and their products	farms, 2022	186	664	241	655	60	165
	2017	181	739	356	722	69	142
	$1,000, 2022	208,331	183,784	155,906	256,474	60,286	5,272
	2017	106,559	150,434	143,186	174,481	46,473	6,647
Poultry and eggs	farms, 2022	20	86	29	99	7	81
	2017	12	94	48	113	14	28
	$1,000, 2022	37	17,842	14,682	(D)	35	113
	2017	11	20,052	9,914	21,844	10	(D)
Cattle and calves	farms, 2022	89	480	135	463	44	50
	2017	104	565	200	549	51	82
	$1,000, 2022	10,927	44,995	10,895	57,220	5,937	1,599
	2017	13,184	38,972	16,614	37,710	5,237	2,609
Milk from cows	farms, 2022	3	32	3	89	4	4
	2017	8	76	12	124	4	16
	$1,000, 2022	(D)	49,239	2,429	102,446	(D)	2,573
	2017	9,279	40,004	2,879	77,800	(D)	3,568
Hogs and pigs	farms, 2022	83	92	69	91	4	14
	2017	71	81	107	77	7	14
	$1,000, 2022	188,115	68,777	126,036	86,869	(D)	25
	2017	83,938	48,135	112,857	36,370	6,194	35
Sheep, goats, wool, mohair, and milk	farms, 2022	20	81	21	107	11	31
	2017	32	79	32	112	4	20
	$1,000, 2022	(D)	956	1,066	778	319	120
	2017	137	1,479	775	449	(D)	59

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	31	36	27	20	8	28
	2017	70	34	29	15	24	23
	$1,000, 2022	180	8,979	295	(D)	292	621
	2017	225	8,350	450	(D)	98	62
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	6	12	30	36	3	33
	2017	16	13	19	17	5	24
	$1,000, 2022	(D)	(D)	474	971	(D)	568
	2017	(D)	(D)	405	370	50	224
Fruits, tree nuts, and berries	farms, 2022	8	12	32	9	1	19
	2017	15	9	22	14	6	3
	$1,000, 2022	(D)	340	878	164	(D)	383
	2017	(D)	197	205	82	(D)	(D)
Fruits and tree nuts	farms, 2022	8	9	22	8	1	11
	2017	8	3	13	6	-	2
	$1,000, 2022	(D)	(D)	770	51	(D)	355
	2017	(D)	(D)	102	30	-	(D)
Berries	farms, 2022	-	4	21	6	-	8
	2017	8	7	14	11	6	1
	$1,000, 2022	-	(D)	108	113	-	28
	2017	76	(D)	103	51	(D)	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	6	4	21	27	1	17
	2017	17	11	19	17	2	10
	$1,000, 2022	1,234	(D)	2,550	660	(D)	783
	2017	1,301	(D)	2,162	1,757	(D)	471
Cultivated Christmas trees and short rotation woody crops	farms, 2022	-	-	19	5	-	5
	2017	1	-	9	5	-	5
	$1,000, 2022	-	-	1,695	182	-	16
	2017	(D)	-	1,556	66	-	(D)
Cultivated Christmas trees	farms, 2022	-	-	19	5	-	5
	2017	-	-	9	5	-	5
	$1,000, 2022	-	-	1,695	182	-	16
	2017	-	-	1,556	(D)	-	(D)
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	1	-	-	1	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	(D)	-	-	(D)	-	-
Other crops and hay	farms, 2022	255	138	274	252	68	246
	2017	309	167	286	205	83	337
	$1,000, 2022	5,629	(D)	1,911	3,910	660	3,138
	2017	3,590	922	1,004	1,558	450	1,388
Maple syrup	farms, 2022	2	4	6	18	-	7
	2017	2	4	8	7	-	8
	$1,000, 2022	(D)	1	4	51	-	8
	2017	(D)	1	10	(D)	-	4
Livestock, poultry, and their products	farms, 2022	361	149	321	206	229	263
	2017	441	206	309	177	212	326
	$1,000, 2022	125,228	4,660	32,369	4,379	152,685	6,821
	2017	71,269	5,042	12,576	2,828	131,611	11,874
Poultry and eggs	farms, 2022	43	28	130	67	25	82
	2017	41	52	81	48	14	72
	$1,000, 2022	(D)	(D)	(D)	102	(D)	1,224
	2017	(D)	19	(D)	34	(D)	274
Cattle and calves	farms, 2022	288	103	141	120	115	154
	2017	376	146	173	108	118	212
	$1,000, 2022	41,840	3,188	3,157	(D)	26,858	3,272
	2017	26,310	(D)	(D)	1,993	18,737	7,684
Milk from cows	farms, 2022	56	3	7	-	2	1
	2017	67	5	5	-	1	20
	$1,000, 2022	72,666	(D)	(D)	-	(D)	(D)
	2017	39,254	(D)	(D)	-	(D)	3,128
Hogs and pigs	farms, 2022	19	5	50	21	73	26
	2017	18	9	41	26	74	40
	$1,000, 2022	8,172	13	11,232	52	114,644	(D)
	2017	4,489	87	1,143	40	99,912	119
Sheep, goats, wool, mohair, and milk	farms, 2022	37	28	49	21	29	36
	2017	24	18	42	24	24	45
	$1,000, 2022	(D)	75	(D)	157	333	(D)
	2017	(D)	53	68	60	(D)	93

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	37	92	6	24	-	31
	2017	63	68	11	19	-	16
	$1,000, 2022	11,715	24,501	(D)	2,159	-	4,632
	2017	6,297	6,603	(D)	452	-	1,634
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	50	4	1	2	8	2
	2017	39	5	7	12	8	5
	$1,000, 2022	9,388	(D)	(D)	(D)	43	(D)
	2017	10,366	(D)	(D)	(D)	31	(D)
Fruits, tree nuts, and berries	farms, 2022	13	-	4	5	5	2
	2017	7	-	5	12	4	1
	$1,000, 2022	(D)	-	(D)	82	12	(D)
	2017	(D)	-	130	101	(D)	(D)
Fruits and tree nuts	farms, 2022	11	-	-	3	5	2
	2017	4	-	2	7	4	-
	$1,000, 2022	318	-	-	(D)	(D)	(D)
	2017	(D)	-	(D)	96	(D)	-
Berries	farms, 2022	2	-	4	2	2	2
	2017	3	-	3	5	-	1
	$1,000, 2022	(D)	-	(D)	(D)	(D)	(D)
	2017	(D)	-	(D)	6	-	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	5	2	2	1	5	-
	2017	1	2	-	2	6	1
	$1,000, 2022	679	(D)	(D)	(D)	(D)	-
	2017	(D)	(D)	-	(D)	164	(D)
Cultivated Christmas trees and short rotation woody crops	farms, 2022	2	-	1	-	-	2
	2017	1	-	1	-	2	-
	$1,000, 2022	(D)	-	(D)	-	-	(D)
	2017	(D)	-	(D)	-	(D)	-
Cultivated Christmas trees	farms, 2022	2	-	1	-	-	2
	2017	1	-	1	-	2	-
	$1,000, 2022	(D)	-	(D)	-	-	(D)
	2017	(D)	-	(D)	-	(D)	-
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other crops and hay	farms, 2022	242	158	123	73	11	74
	2017	234	145	105	107	18	57
	$1,000, 2022	28,310	57,828	4,090	(D)	28	(D)
	2017	23,439	24,882	1,895	1,400	77	(D)
Maple syrup	farms, 2022	1	-	-	-	1	1
	2017	2	-	-	-	4	-
	$1,000, 2022	(D)	-	-	-	(D)	(D)
	2017	(D)	-	-	-	12	-
Livestock, poultry, and their products	farms, 2022	357	62	77	140	20	46
	2017	390	68	72	189	21	38
	$1,000, 2022	339,348	5,696	2,236	105,198	(D)	1,628
	2017	224,687	5,605	2,440	79,112	61	708
Poultry and eggs	farms, 2022	76	6	27	9	19	9
	2017	57	4	14	10	16	10
	$1,000, 2022	179,641	5	50	(D)	28	16
	2017	104,028	(D)	15	(D)	14	(D)
Cattle and calves	farms, 2022	219	46	50	81	4	32
	2017	279	62	52	135	6	22
	$1,000, 2022	23,837	5,622	1,555	5,596	15	(D)
	2017	31,464	5,568	1,382	10,741	35	637
Milk from cows	farms, 2022	30	1	2	1	-	-
	2017	55	-	5	13	-	-
	$1,000, 2022	91,700	(D)	(D)	(D)	-	-
	2017	53,493	-	990	1,405	-	-
Hogs and pigs	farms, 2022	26	-	7	62	4	4
	2017	24	1	3	35	6	5
	$1,000, 2022	37,015	-	15	93,960	18	4
	2017	30,699	(D)	6	63,250	7	(D)
Sheep, goats, wool, mohair, and milk	farms, 2022	53	3	-	10	-	4
	2017	52	4	4	26	-	-
	$1,000, 2022	(D)	(D)	-	30	-	8
	2017	1,373	21	(D)	270	-	-

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	29	10	28	29	64	183
	2017	15	21	14	30	21	98
	$1,000, 2022	317	733	635	2,486	12,057	30,826
	2017	(D)	(D)	(D)	1,514	(D)	8,243
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	15	8	1	43	4	9
	2017	36	3	-	46	5	7
	$1,000, 2022	1,227	(D)	(D)	3,154	(D)	607
	2017	3,190	(D)	-	3,064	(D)	509
Fruits, tree nuts, and berries	farms, 2022	8	6	1	14	-	-
	2017	14	1	1	11	2	4
	$1,000, 2022	(D)	222	(D)	(D)	-	-
	2017	(D)	(D)	(D)	(D)	(D)	(D)
Fruits and tree nuts	farms, 2022	8	6	1	13	-	-
	2017	14	1	1	10	-	3
	$1,000, 2022	(D)	222	(D)	322	-	-
	2017	456	(D)	(D)	281	-	(D)
Berries	farms, 2022	-	-	-	10	-	-
	2017	3	-	-	3	2	3
	$1,000, 2022	-	-	-	(D)	-	-
	2017	(D)	-	-	(D)	(D)	9
Nursery, greenhouse, floriculture, and sod	farms, 2022	16	2	2	11	1	3
	2017	16	1	2	11	3	2
	$1,000, 2022	751	(D)	(D)	687	(D)	308
	2017	(D)	(D)	(D)	2,907	54	(D)
Cultivated Christmas trees and short rotation woody crops	farms, 2022	1	-	-	1	-	-
	2017	1	-	-	1	1	2
	$1,000, 2022	(D)	-	-	(D)	-	-
	2017	(D)	-	-	(D)	(D)	(D)
Cultivated Christmas trees	farms, 2022	1	-	-	1	-	-
	2017	1	-	-	1	-	-
	$1,000, 2022	(D)	-	-	(D)	-	-
	2017	(D)	-	-	(D)	-	-
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	1	2
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	(D)	(D)
Other crops and hay	farms, 2022	160	81	106	184	83	321
	2017	147	115	153	201	106	253
	$1,000, 2022	1,204	1,640	1,545	2,322	5,664	89,775
	2017	676	1,416	(D)	3,501	(D)	49,975
Maple syrup	farms, 2022	4	-	-	7	3	-
	2017	4	-	-	5	2	-
	$1,000, 2022	2	-	-	1	3	-
	2017	3	-	-	24	(D)	-
Livestock, poultry, and their products	farms, 2022	254	154	310	234	65	161
	2017	268	208	318	338	85	197
	$1,000, 2022	83,274	104,923	451,628	67,580	5,266	12,673
	2017	65,254	73,501	229,852	57,060	3,905	15,284
Poultry and eggs	farms, 2022	58	3	22	49	8	14
	2017	53	9	12	48	9	21
	$1,000, 2022	8,179	(D)	52,825	157	232	(D)
	2017	5,967	3	30,501	65	6	7,363
Cattle and calves	farms, 2022	131	121	193	160	51	143
	2017	140	178	234	265	68	164
	$1,000, 2022	10,425	21,574	104,979	36,404	(D)	6,133
	2017	12,890	21,316	90,729	28,849	(D)	5,380
Milk from cows	farms, 2022	16	6	4	28	5	6
	2017	23	14	11	69	6	6
	$1,000, 2022	7,935	16,060	1,836	26,070	(D)	(D)
	2017	10,764	7,794	7,167	26,207	1,269	938
Hogs and pigs	farms, 2022	87	21	92	22	4	5
	2017	85	15	86	20	-	7
	$1,000, 2022	53,975	65,905	289,712	2,431	3	3
	2017	34,564	43,532	100,539	1,627	-	(D)
Sheep, goats, wool, mohair, and milk	farms, 2022	30	14	41	30	2	7
	2017	36	16	41	38	13	11
	$1,000, 2022	(D)	354	2,131	2,125	(D)	63
	2017	171	(D)	(D)	187	60	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	12	35	28	87	32	37
	2017	13	34	27	133	23	36
	$1,000, 2022	(D)	485	189	4,088	946	640
	2017	94	548	85	3,709	179	274
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	41	38	19	18	79	7
	2017	44	40	20	26	93	6
	$1,000, 2022	3,183	2,846	678	13,057	11,578	(D)
	2017	3,080	3,201	220	5,172	15,029	29
Fruits, tree nuts, and berries	farms, 2022	3	19	10	10	12	2
	2017	4	17	16	10	16	5
	$1,000, 2022	(D)	(D)	536	33	142	(D)
	2017	(D)	45	211	83	(D)	(D)
Fruits and tree nuts	farms, 2022	2	19	10	10	9	2
	2017	4	14	13	8	16	5
	$1,000, 2022	(D)	241	(D)	(D)	118	(D)
	2017	(D)	38	141	75	194	13
Berries	farms, 2022	1	7	3	2	4	-
	2017	-	7	13	4	10	3
	$1,000, 2022	(D)	(D)	(D)	(D)	24	-
	2017	-	7	71	8	(D)	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	9	10	13	22	-	-
	2017	8	13	9	16	1	2
	$1,000, 2022	702	299	298	460	-	-
	2017	459	471	1,082	855	(D)	(D)
Cultivated Christmas trees and short rotation woody crops	farms, 2022	1	3	8	7	-	-
	2017	1	7	5	7	-	-
	$1,000, 2022	(D)	(D)	111	41	-	-
	2017	(D)	321	63	42	-	-
Cultivated Christmas trees	farms, 2022	1	3	8	6	-	-
	2017	1	7	5	7	-	-
	$1,000, 2022	(D)	(D)	111	(D)	-	-
	2017	(D)	321	63	(D)	-	-
Short rotation woody crops	farms, 2022	-	-	-	1	-	-
	2017	-	-	-	2	-	-
	$1,000, 2022	-	-	-	(D)	-	-
	2017	-	-	-	(D)	-	-
Other crops and hay	farms, 2022	67	188	312	677	123	120
	2017	72	175	340	779	189	111
	$1,000, 2022	(D)	4,123	2,786	9,976	1,103	1,557
	2017	192	3,391	1,517	6,202	1,921	1,115
Maple syrup	farms, 2022	2	1	8	10	-	-
	2017	-	1	9	6	1	1
	$1,000, 2022	(D)	(D)	17	9	-	-
	2017	-	(D)	6	4	(D)	(D)
Livestock, poultry, and their products	farms, 2022	293	274	263	833	352	233
	2017	322	333	355	1,027	391	279
	$1,000, 2022	481,561	299,176	38,304	417,117	180,736	198,487
	2017	369,856	146,689	20,683	326,618	170,527	153,747
Poultry and eggs	farms, 2022	26	61	72	216	64	10
	2017	25	59	80	220	53	15
	$1,000, 2022	(D)	209,100	21,294	238,135	(D)	(D)
	2017	1,812	86,027	1,685	167,579	9,843	(D)
Cattle and calves	farms, 2022	109	188	146	594	192	160
	2017	128	233	235	793	255	202
	$1,000, 2022	32,544	28,356	10,806	42,892	18,153	74,114
	2017	35,881	27,020	13,258	34,723	29,195	73,798
Milk from cows	farms, 2022	3	29	10	126	22	12
	2017	4	42	30	203	26	24
	$1,000, 2022	2,976	60,288	5,542	100,743	20,014	17,141
	2017	1,615	30,966	5,264	102,285	14,487	13,158
Hogs and pigs	farms, 2022	175	26	26	54	88	70
	2017	168	47	32	64	100	64
	$1,000, 2022	445,664	664	(D)	33,665	134,977	104,413
	2017	330,132	1,459	75	20,515	116,536	64,623
Sheep, goats, wool, mohair, and milk	farms, 2022	16	28	38	48	44	25
	2017	42	26	45	63	46	32
	$1,000, 2022	226	(D)	236	315	173	(D)
	2017	377	187	141	568	346	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	18	16	43	51	203	39
	2017	19	19	25	56	216	26
	$1,000, 2022	(D)	542	7,162	1,081	17,258	6,741
	2017	(D)	(D)	2,933	405	10,266	2,400
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	28	3	9	129	44	6
	2017	24	6	6	115	47	7
	$1,000, 2022	1,145	(D)	275	11,537	24,850	35
	2017	860	232	(D)	12,705	(D)	29
Fruits, tree nuts, and berries	farms, 2022	10	3	2	40	27	8
	2017	4	9	1	48	24	2
	$1,000, 2022	63	119	(D)	1,016	460	(D)
	2017	(D)	(D)	(D)	484	237	(D)
Fruits and tree nuts	farms, 2022	6	3	-	36	22	8
	2017	3	7	1	31	17	2
	$1,000, 2022	34	(D)	-	653	288	(D)
	2017	12	(D)	(D)	339	138	(D)
Berries	farms, 2022	7	1	2	20	8	-
	2017	3	2	1	30	10	2
	$1,000, 2022	29	(D)	(D)	364	172	-
	2017	(D)	(D)	(D)	144	99	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	11	2	1	17	31	1
	2017	7	2	5	13	27	4
	$1,000, 2022	431	(D)	(D)	2,046	4,536	(D)
	2017	416	(D)	(D)	557	2,922	(D)
Cultivated Christmas trees and short rotation woody crops	farms, 2022	-	-	-	10	16	-
	2017	2	-	-	10	4	-
	$1,000, 2022	-	-	-	32	517	-
	2017	(D)	-	-	10	(D)	-
Cultivated Christmas trees	farms, 2022	-	-	-	10	16	-
	2017	2	-	-	9	4	-
	$1,000, 2022	-	-	-	32	517	-
	2017	(D)	-	-	(D)	(D)	-
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	1	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	(D)	-	-
Other crops and hay	farms, 2022	88	134	163	265	744	84
	2017	104	129	154	244	838	116
	$1,000, 2022	754	1,779	60,816	5,202	17,120	5,755
	2017	1,163	1,619	47,288	1,908	10,704	3,884
Maple syrup	farms, 2022	4	1	-	8	9	-
	2017	1	-	-	2	19	-
	$1,000, 2022	7	(D)	-	1	43	-
	2017	(D)	-	-	(D)	17	-
Livestock, poultry, and their products	farms, 2022	226	335	84	407	813	82
	2017	240	345	96	521	949	122
	$1,000, 2022	335,681	468,896	18,085	111,419	214,916	3,999
	2017	201,498	313,354	12,524	92,781	149,059	5,593
Poultry and eggs	farms, 2022	18	36	15	56	127	8
	2017	21	32	14	52	105	11
	$1,000, 2022	47,749	(D)	(D)	(D)	92,085	(D)
	2017	27,527	12,634	(D)	(D)	51,715	5
Cattle and calves	farms, 2022	96	181	61	284	645	61
	2017	151	214	79	372	771	96
	$1,000, 2022	11,633	156,367	1,995	28,223	52,067	3,944
	2017	13,973	131,710	(D)	26,362	38,422	4,390
Milk from cows	farms, 2022	15	16	6	37	101	-
	2017	38	21	6	91	173	-
	$1,000, 2022	69,353	39,788	431	60,043	65,233	-
	2017	42,509	23,126	207	42,709	48,329	-
Hogs and pigs	farms, 2022	102	145	10	31	43	1
	2017	83	113	7	24	97	3
	$1,000, 2022	206,204	269,479	(D)	(D)	249	(D)
	2017	117,238	145,149	650	9,247	3,940	(D)
Sheep, goats, wool, mohair, and milk	farms, 2022	21	23	10	48	97	6
	2017	16	37	9	53	76	7
	$1,000, 2022	78	(D)	83	189	864	12
	2017	97	600	27	176	579	12

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	27	42	141	48	2	21
	2017	38	23	144	42	2	18
	$1,000, 2022	156	1,316	60,183	4,960	(D)	3,344
	2017	54	(D)	28,521	5,126	(D)	2,473
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	20	4	27	18	29	-
	2017	18	3	29	28	39	13
	$1,000, 2022	243	(D)	24,412	8,112	575	-
	2017	218	(D)	14,017	8,339	421	2,529
Fruits, tree nuts, and berries	farms, 2022	15	1	8	5	11	-
	2017	13	1	13	3	16	2
	$1,000, 2022	754	(D)	38	(D)	(D)	-
	2017	119	(D)	69	28	(D)	(D)
Fruits and tree nuts	farms, 2022	14	-	5	1	-	-
	2017	12	1	8	2	14	2
	$1,000, 2022	(D)	-	(D)	(D)	-	-
	2017	106	(D)	21	(D)	87	(D)
Berries	farms, 2022	6	1	3	5	11	-
	2017	5	-	8	3	7	-
	$1,000, 2022	(D)	(D)	(D)	(D)	(D)	-
	2017	13	-	48	(D)	(D)	-
Nursery, greenhouse, floriculture, and sod	farms, 2022	9	7	10	4	16	-
	2017	15	3	10	4	23	1
	$1,000, 2022	6,936	297	569	276	2,513	-
	2017	2,658	(D)	697	219	1,650	(D)
Cultivated Christmas trees and short rotation woody crops	farms, 2022	9	-	-	5	-	-
	2017	12	-	-	3	-	1
	$1,000, 2022	176	-	-	(D)	-	-
	2017	212	-	-	20	-	(D)
Cultivated Christmas trees	farms, 2022	9	-	-	5	-	-
	2017	12	-	-	3	-	1
	$1,000, 2022	176	-	-	(D)	-	-
	2017	(D)	-	-	20	-	(D)
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	1	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	(D)	-	-	-	-	-
Other crops and hay	farms, 2022	390	111	402	151	4	70
	2017	466	135	413	146	1	52
	$1,000, 2022	6,167	(D)	161,676	4,959	97	6,576
	2017	3,515	1,095	116,993	3,350	(D)	2,574
Maple syrup	farms, 2022	9	-	-	-	1	-
	2017	7	-	2	-	-	-
	$1,000, 2022	36	-	-	-	(D)	-
	2017	5	-	(D)	-	-	-
Livestock, poultry, and their products	farms, 2022	370	246	227	225	2	68
	2017	411	284	229	272	11	62
	$1,000, 2022	27,300	257,770	13,665	68,416	(D)	18,119
	2017	23,926	228,156	26,601	72,232	747	7,199
Poultry and eggs	farms, 2022	85	16	46	31	-	3
	2017	82	12	37	31	1	5
	$1,000, 2022	122	(D)	82	(D)	-	(D)
	2017	(D)	(D)	(D)	(D)	(D)	2
Cattle and calves	farms, 2022	256	183	145	159	-	56
	2017	303	221	174	211	1	61
	$1,000, 2022	9,936	67,805	7,003	18,590	-	9,786
	2017	(D)	70,440	9,947	18,897	(D)	3,787
Milk from cows	farms, 2022	19	14	11	15	-	3
	2017	43	17	29	32	1	2
	$1,000, 2022	16,186	58,159	3,062	16,530	-	7,696
	2017	12,303	32,039	4,797	13,651	(D)	(D)
Hogs and pigs	farms, 2022	32	32	27	14	-	2
	2017	27	52	23	33	1	1
	$1,000, 2022	(D)	125,456	116	28,615	-	(D)
	2017	53	121,537	9,526	37,980	(D)	(D)
Sheep, goats, wool, mohair, and milk	farms, 2022	52	50	38	22	-	13
	2017	40	33	19	22	1	4
	$1,000, 2022	220	(D)	308	185	-	42
	2017	79	(D)	106	259	(D)	7

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	19	64	33	10	110	41
	2017	23	67	32	20	84	37
	$1,000, 2022	746	12,220	(D)	(D)	20,715	1,895
	2017	123	6,060	81	453	8,823	(D)
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	20	152	44	11	3	76
	2017	69	168	31	2	17	67
	$1,000, 2022	2,647	24,601	1,485	62	16	683
	2017	7,564	30,198	1,200	(D)	(D)	419
Fruits, tree nuts, and berries	farms, 2022	12	8	34	-	-	54
	2017	9	4	27	-	2	41
	$1,000, 2022	(D)	(D)	2,230	-	-	585
	2017	(D)	(D)	1,388	-	(D)	265
Fruits and tree nuts	farms, 2022	10	8	29	-	-	40
	2017	5	3	26	-	-	25
	$1,000, 2022	103	(D)	1,939	-	-	333
	2017	(D)	(D)	1,255	-	-	134
Berries	farms, 2022	2	-	13	-	-	30
	2017	4	1	4	-	2	33
	$1,000, 2022	(D)	-	291	-	-	252
	2017	65	(D)	133	-	(D)	131
Nursery, greenhouse, floriculture, and sod	farms, 2022	7	1	30	3	1	59
	2017	-	1	20	2	2	49
	$1,000, 2022	220	(D)	21,765	12	(D)	3,377
	2017	-	(D)	7,978	(D)	(D)	3,430
Cultivated Christmas trees and short rotation woody crops	farms, 2022	1	-	5	-	6	15
	2017	1	-	2	-	4	6
	$1,000, 2022	(D)	-	73	-	(D)	160
	2017	(D)	-	(D)	-	3	(D)
Cultivated Christmas trees	farms, 2022	1	-	5	-	6	15
	2017	1	-	2	-	3	5
	$1,000, 2022	(D)	-	73	-	(D)	160
	2017	(D)	-	(D)	-	(D)	73
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	1	1
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	(D)	(D)
Other crops and hay	farms, 2022	124	164	254	118	247	469
	2017	144	177	284	157	253	419
	$1,000, 2022	9,743	47,268	2,579	1,043	27,054	8,925
	2017	6,634	52,639	(D)	859	12,579	3,787
Maple syrup	farms, 2022	-	-	7	-	-	34
	2017	-	1	10	1	-	11
	$1,000, 2022	-	-	22	-	-	60
	2017	-	(D)	9	(D)	-	50
Livestock, poultry, and their products	farms, 2022	364	222	345	296	203	394
	2017	359	251	409	367	212	384
	$1,000, 2022	341,439	229,258	131,201	397,199	33,669	12,971
	2017	189,266	237,034	103,295	275,850	20,292	6,931
Poultry and eggs	farms, 2022	38	28	97	12	39	177
	2017	45	31	77	16	25	122
	$1,000, 2022	30,424	38,621	32,167	(D)	16,516	310
	2017	27,778	50,288	13,637	10	8,544	(D)
Cattle and calves	farms, 2022	208	111	179	191	140	190
	2017	229	125	250	274	158	222
	$1,000, 2022	101,077	57,418	8,410	149,641	10,928	6,175
	2017	77,427	27,795	7,465	149,784	7,070	3,562
Milk from cows	farms, 2022	7	12	35	11	5	7
	2017	20	25	66	18	17	6
	$1,000, 2022	4,231	17,361	29,046	25,652	1,370	5,076
	2017	5,843	10,768	24,234	14,544	2,229	2,636
Hogs and pigs	farms, 2022	111	63	46	111	13	34
	2017	98	71	65	93	11	40
	$1,000, 2022	204,628	114,133	59,704	221,506	635	116
	2017	77,569	145,969	56,954	110,442	20	95
Sheep, goats, wool, mohair, and milk	farms, 2022	40	41	42	18	25	46
	2017	40	51	58	23	24	41
	$1,000, 2022	761	1,351	1,491	169	(D)	(D)
	2017	619	2,090	546	390	(D)	97

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	24	22	22	330	6	34
	2017	34	27	22	371	21	34
	$1,000, 2022	218	(D)	313	8,905	165	12,619
	2017	86	556	88	5,258	241	7,514
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	29	53	53	75	21	9
	2017	21	57	44	67	37	3
	$1,000, 2022	955	52,793	(D)	4,116	3,096	19
	2017	333	38,617	6,534	5,775	(D)	(D)
Fruits, tree nuts, and berries	farms, 2022	34	32	1	37	4	4
	2017	21	14	1	28	11	-
	$1,000, 2022	805	331	(D)	1,140	21	(D)
	2017	1,335	179	(D)	(D)	95	-
Fruits and tree nuts	farms, 2022	34	22	1	24	4	2
	2017	18	9	1	20	6	-
	$1,000, 2022	(D)	260	(D)	530	21	(D)
	2017	1,316	94	(D)	238	59	-
Berries	farms, 2022	4	19	-	18	-	2
	2017	8	7	1	12	6	-
	$1,000, 2022	(D)	72	-	610	-	(D)
	2017	18	85	(D)	(D)	36	-
Nursery, greenhouse, floriculture, and sod	farms, 2022	25	26	1	31	11	3
	2017	14	27	2	20	9	1
	$1,000, 2022	1,134	7,657	(D)	5,407	36,350	(D)
	2017	1,286	8,384	(D)	4,651	(D)	(D)
Cultivated Christmas trees and short rotation woody crops	farms, 2022	3	8	-	7	-	-
	2017	5	12	1	4	-	1
	$1,000, 2022	73	716	-	2	-	-
	2017	144	1,744	(D)	(D)	-	(D)
Cultivated Christmas trees	farms, 2022	3	8	-	7	-	-
	2017	5	12	-	3	-	1
	$1,000, 2022	73	716	-	2	-	-
	2017	144	1,744	-	(D)	-	(D)
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	-	1	1	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	(D)	(D)	-	-
Other crops and hay	farms, 2022	167	111	183	848	105	103
	2017	185	117	156	890	95	76
	$1,000, 2022	1,086	546	9,111	31,216	850	19,568
	2017	934	588	(D)	14,707	351	7,988
Maple syrup	farms, 2022	1	1	3	11	1	2
	2017	4	1	1	8	1	-
	$1,000, 2022	(D)	(D)	2	(D)	(D)	(D)
	2017	2	(D)	(D)	58	(D)	-
Livestock, poultry, and their products	farms, 2022	271	204	284	1,392	202	136
	2017	276	178	345	1,680	258	163
	$1,000, 2022	27,220	24,387	142,312	707,055	128,001	327,331
	2017	31,052	14,458	136,514	568,856	98,863	187,805
Poultry and eggs	farms, 2022	104	90	44	271	33	12
	2017	71	77	34	276	40	15
	$1,000, 2022	962	(D)	(D)	236,766	19,822	7
	2017	1,138	3,702	21,728	164,035	19,868	(D)
Cattle and calves	farms, 2022	109	73	209	1,112	120	75
	2017	176	93	267	1,372	159	106
	$1,000, 2022	10,423	15,838	(D)	136,194	3,476	(D)
	2017	12,636	7,550	34,126	112,985	(D)	(D)
Milk from cows	farms, 2022	17	4	28	349	9	8
	2017	33	12	44	629	40	9
	$1,000, 2022	14,085	694	45,450	303,340	7,076	(D)
	2017	12,185	1,946	26,263	254,768	13,178	(D)
Hogs and pigs	farms, 2022	13	26	49	95	64	47
	2017	24	28	55	98	78	55
	$1,000, 2022	(D)	1,436	48,308	24,644	96,951	122,341
	2017	(D)	1,034	53,168	32,114	61,133	54,098
Sheep, goats, wool, mohair, and milk	farms, 2022	57	38	33	92	17	12
	2017	42	30	28	88	22	17
	$1,000, 2022	263	110	219	1,045	192	15
	2017	105	126	(D)	654	139	51

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	53	155	11	66	61	4
	2017	20	145	5	75	56	15
	$1,000, 2022	8,369	7,310	3,652	1,132	4,435	(D)
	2017	3,351	1,377	971	344	1,411	448
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	8	42	1	72	8	51
	2017	11	44	4	96	14	48
	$1,000, 2022	(D)	8,601	(D)	5,710	19,080	3,605
	2017	497	5,197	(D)	8,440	(D)	3,850
Fruits, tree nuts, and berries	farms, 2022	1	25	2	21	3	8
	2017	4	22	2	18	13	3
	$1,000, 2022	(D)	(D)	(D)	3,169	(D)	252
	2017	5	191	(D)	2,454	64	(D)
Fruits and tree nuts	farms, 2022	1	20	2	19	3	6
	2017	-	15	2	14	7	1
	$1,000, 2022	(D)	(D)	(D)	3,142	60	(D)
	2017	-	163	(D)	2,448	39	(D)
Berries	farms, 2022	1	7	-	4	2	2
	2017	4	11	-	5	11	2
	$1,000, 2022	(D)	(D)	-	27	(D)	(D)
	2017	5	28	-	6	25	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	2	10	-	23	3	17
	2017	4	17	-	5	3	2
	$1,000, 2022	(D)	(D)	-	560	(D)	1,077
	2017	30	759	-	(D)	(D)	(D)
Cultivated Christmas trees and short rotation woody crops	farms, 2022	-	2	-	8	-	-
	2017	-	5	-	5	1	-
	$1,000, 2022	-	(D)	-	41	-	-
	2017	-	47	-	(D)	(D)	-
Cultivated Christmas trees	farms, 2022	-	2	-	8	-	-
	2017	-	3	-	5	1	-
	$1,000, 2022	-	(D)	-	41	-	-
	2017	-	(D)	-	(D)	(D)	-
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	2	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	(D)	-	-	-	-
Other crops and hay	farms, 2022	83	572	44	183	208	69
	2017	98	600	51	234	231	102
	$1,000, 2022	13,686	8,178	(D)	6,667	3,880	526
	2017	7,041	4,634	6,127	4,010	1,751	(D)
Maple syrup	farms, 2022	-	5	-	1	2	1
	2017	-	10	-	2	4	1
	$1,000, 2022	-	(D)	-	(D)	(D)	(D)
	2017	-	15	-	(D)	(D)	(D)
Livestock, poultry, and their products	farms, 2022	120	688	31	369	186	170
	2017	179	772	51	410	256	252
	$1,000, 2022	175,051	237,832	60,566	195,854	45,937	130,911
	2017	133,679	122,767	45,655	106,142	22,978	142,412
Poultry and eggs	farms, 2022	22	180	2	30	44	29
	2017	32	129	7	47	51	44
	$1,000, 2022	65,155	136,776	(D)	(D)	(D)	13,051
	2017	55,262	38,850	(D)	43	(D)	22,148
Cattle and calves	farms, 2022	93	484	18	298	151	81
	2017	133	650	26	340	198	135
	$1,000, 2022	21,545	26,725	(D)	29,358	5,822	15,237
	2017	25,177	22,946	(D)	20,144	5,598	16,856
Milk from cows	farms, 2022	5	96	1	105	13	3
	2017	21	216	1	133	30	21
	$1,000, 2022	(D)	64,862	(D)	147,991	(D)	657
	2017	46,721	52,897	(D)	81,834	8,964	4,266
Hogs and pigs	farms, 2022	13	44	6	35	7	62
	2017	8	48	12	31	19	76
	$1,000, 2022	(D)	4,977	(D)	17,905	30	101,100
	2017	6,430	4,348	9,089	3,564	37	98,675
Sheep, goats, wool, mohair, and milk	farms, 2022	4	106	1	41	21	31
	2017	12	85	9	43	31	38
	$1,000, 2022	11	2,145	(D)	169	366	806
	2017	78	955	10	220	108	438

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Crops, including nursery and greenhouse crops - Con.							
Grains, oilseeds, dry beans, and dry peas - Con.							
Rice	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Other grains, oilseeds, dry beans, and dry peas	farms, 2022	24	15	19	45	44	27
	2017	33	12	18	87	52	15
	$1,000, 2022	329	185	4,027	572	1,073	2,595
	2017	90	(D)	1,368	384	143	(D)
Tobacco	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Cotton and cottonseed	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Vegetables, melons, potatoes, and sweet potatoes	farms, 2022	77	25	1	45	58	11
	2017	103	19	3	32	56	9
	$1,000, 2022	8,545	3,142	(D)	3,554	4,827	(D)
	2017	3,862	3,524	(D)	2,496	(D)	(D)
Fruits, tree nuts, and berries	farms, 2022	40	3	-	33	56	2
	2017	55	1	2	28	45	1
	$1,000, 2022	6,734	11	-	2,664	3,626	(D)
	2017	3,944	(D)	(D)	2,180	2,076	(D)
Fruits and tree nuts	farms, 2022	33	3	-	26	52	2
	2017	45	1	1	26	43	1
	$1,000, 2022	5,066	10	-	2,553	(D)	(D)
	2017	3,279	(D)	(D)	2,039	1,794	(D)
Berries	farms, 2022	15	3	-	13	8	-
	2017	30	-	1	16	10	1
	$1,000, 2022	1,667	1	-	111	(D)	-
	2017	666	-	(D)	141	282	(D)
Nursery, greenhouse, floriculture, and sod	farms, 2022	40	6	7	16	35	-
	2017	48	2	-	16	31	2
	$1,000, 2022	17,066	198	(D)	1,031	14,895	-
	2017	21,793	(D)	-	1,410	(D)	(D)
Cultivated Christmas trees and short rotation woody crops	farms, 2022	17	-	-	6	12	-
	2017	14	-	-	14	8	-
	$1,000, 2022	665	-	-	5	92	-
	2017	275	-	-	73	(D)	-
Cultivated Christmas trees	farms, 2022	17	-	-	6	12	-
	2017	14	-	-	11	8	-
	$1,000, 2022	665	-	-	5	92	-
	2017	275	-	-	66	(D)	-
Short rotation woody crops	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	3	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	-	-	-	7	-	-
Other crops and hay	farms, 2022	136	37	99	247	402	110
	2017	180	38	129	337	423	109
	$1,000, 2022	852	220	(D)	7,331	3,206	5,103
	2017	1,088	(D)	(D)	5,858	1,644	3,382
Maple syrup	farms, 2022	16	-	1	4	11	-
	2017	3	-	-	-	17	6
	$1,000, 2022	22	-	(D)	2	5	-
	2017	1	-	-	-	14	1
Livestock, poultry, and their products	farms, 2022	190	133	46	502	485	202
	2017	231	134	36	555	546	212
	$1,000, 2022	6,007	149,977	2,055	250,407	132,304	144,368
	2017	5,584	123,353	916	158,277	83,577	86,254
Poultry and eggs	farms, 2022	56	24	13	68	149	29
	2017	64	16	11	49	144	19
	$1,000, 2022	367	(D)	(D)	(D)	(D)	(D)
	2017	282	(D)	(D)	(D)	34,302	(D)
Cattle and calves	farms, 2022	55	58	32	402	275	123
	2017	96	58	28	467	347	157
	$1,000, 2022	1,321	7,633	2,013	39,569	23,989	23,279
	2017	1,853	4,114	857	27,640	22,027	30,936
Milk from cows	farms, 2022	5	-	-	114	45	7
	2017	17	2	1	136	61	9
	$1,000, 2022	1,683	-	-	185,343	42,129	13,914
	2017	2,312	(D)	(D)	98,915	24,295	5,733
Hogs and pigs	farms, 2022	13	67	1	29	49	51
	2017	12	70	8	26	45	49
	$1,000, 2022	(D)	133,773	(D)	9,026	(D)	104,253
	2017	26	117,348	14	19,956	(D)	48,142
Sheep, goats, wool, mohair, and milk	farms, 2022	35	16	12	39	69	28
	2017	34	10	10	37	49	23
	$1,000, 2022	624	(D)	23	1,170	181	286
	2017	451	55	13	(D)	(D)	316

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.						
Total sales - Con.						
Value of sales by commodity or commodity group: - Con.						
Livestock, poultry, and their products - Con.						
Horses, ponies, mules, burros, and donkeys	farms, 2022	1,247	7	21	6	21
	2017	1,414	15	25	5	7
	$1,000, 2022	18,147	(D)	443	(D)	151
	2017	14,189	110	333	38	50
Aquaculture	farms, 2022	98	1	-	2	2
	2017	60	-	1	3	1
	$1,000, 2022	19,763	(D)	-	(D)	(D)
	2017	11,474	-	(D)	(D)	(D)
Other animals and other animal products	farms, 2022	1,405	18	26	10	15
	2017	1,209	11	20	24	27
	$1,000, 2022	58,149	310	57	679	(D)
	2017	76,204	(D)	31,534	1,439	(D)
FOOD MARKETING PRACTICES						
Value of food sold directly to consumers	farms, 2022	3,339	42	64	28	25
	2017	3,533	47	46	42	38
	$1,000, 2022	44,673	482	1,315	136	285
	2017	39,117	459	631	200	181
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	1,026	22	10	11	11
	2017	637	20	2	8	9
	$1,000, 2022	108,704	1,611	(D)	12	33
	2017	68,637	78	(D)	18	11
VALUE-ADDED PRODUCTS SOLD						
Value of processed or value-added agricultural products sold	farms, 2022	1,058	18	20	11	14
	2017	1,046	17	12	8	9
	$1,000, 2022	47,262	248	204	(D)	108
	2017	30,035	266	90	(D)	42

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.						
Total sales - Con.						
Value of sales by commodity or commodity group: - Con.						
Livestock, poultry, and their products - Con.						
Horses, ponies, mules, burros, and donkeys	farms, 2022	20	3	10	2	10
	2017	5	9	11	1	9
	$1,000, 2022	251	28	(D)	(D)	35
	2017	25	34	(D)	(D)	17
Aquaculture	farms, 2022	1	5	-	-	-
	2017	-	1	-	-	-
	$1,000, 2022	(D)	657	-	-	-
	2017	-	(D)	-	-	-
Other animals and other animal products	farms, 2022	20	4	21	15	13
	2017	8	1	11	8	13
	$1,000, 2022	689	(D)	71	17,546	18
	2017	96	(D)	(D)	7,193	36
FOOD MARKETING PRACTICES						
Value of food sold directly to consumers	farms, 2022	30	10	41	22	58
	2017	32	23	31	26	62
	$1,000, 2022	180	71	637	313	374
	2017	500	207	136	231	1,046
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	8	7	7	10	26
	2017	1	3	4	2	25
	$1,000, 2022	(D)	81	619	154	155
	2017	(D)	4	145	(D)	678
VALUE-ADDED PRODUCTS SOLD						
Value of processed or value-added agricultural products sold	farms, 2022	15	3	4	10	22
	2017	5	1	11	8	21
	$1,000, 2022	346	(D)	697	536	278
	2017	12	(D)	146	29	639

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	7	11	2	26	16	13
	2017	10	28	6	20	15	7
	$1,000, 2022	32	150	(D)	370	157	292
	2017	808	194	16	120	140	37
Aquaculture	farms, 2022	-	3	-	-	2	-
	2017	-	1	-	2	-	-
	$1,000, 2022	-	(D)	-	-	(D)	-
	2017	-	(D)	-	(D)	-	-
Other animals and other animal products	farms, 2022	16	23	4	37	12	7
	2017	16	16	9	37	17	4
	$1,000, 2022	209	70	5	154	696	333
	2017	851	29	16	219	296	(D)
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	43	47	11	109	34	31
	2017	45	44	14	123	28	22
	$1,000, 2022	460	145	737	1,208	268	551
	2017	366	141	58	497	136	113
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	21	18	6	19	11	19
	2017	7	2	5	23	-	1
	$1,000, 2022	438	148	121	72	455	(D)
	2017	13	(D)	27	(D)	-	(D)
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	10	19	8	37	14	10
	2017	2	18	9	30	6	7
	$1,000, 2022	74	18	648	822	287	68
	2017	(D)	14	30	380	105	5

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	1	4	20	22	12	11
	2017	-	5	29	22	8	15
	$1,000, 2022	(D)	1,059	148	169	54	(D)
	2017	-	16	137	187	(D)	(D)
Aquaculture	farms, 2022	-	2	4	-	-	12
	2017	-	1	1	-	-	7
	$1,000, 2022	-	(D)	418	-	-	4,694
	2017	-	(D)	(D)	-	-	1,270
Other animals and other animal products	farms, 2022	1	11	23	27	17	18
	2017	2	8	8	28	6	16
	$1,000, 2022	(D)	(D)	1,063	754	(D)	161
	2017	(D)	264	(D)	367	(D)	556
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	10	12	39	82	32	36
	2017	12	27	21	94	42	53
	$1,000, 2022	21	96	298	1,596	682	1,207
	2017	49	229	131	2,877	499	1,988
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	7	4	17	37	10	15
	2017	10	3	8	12	2	6
	$1,000, 2022	87	10	2,971	2,491	113	106
	2017	23	(D)	(D)	757	(D)	(D)
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	4	3	11	35	18	23
	2017	6	5	8	17	5	10
	$1,000, 2022	(D)	2	12	1,395	64	2,091
	2017	3	(D)	22	84	370	(D)

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	10	66	11	26	3	22
	2017	5	69	17	36	3	12
	$1,000, 2022	17	1,067	788	(D)	60	650
	2017	(D)	1,096	81	(D)	30	243
Aquaculture	farms, 2022	-	6	-	-	-	3
	2017	-	2	-	-	-	2
	$1,000, 2022	-	(D)	-	-	-	2
	2017	-	(D)	-	-	-	(D)
Other animals and other animal products	farms, 2022	1	37	7	28	4	51
	2017	6	33	16	31	7	17
	$1,000, 2022	(D)	(D)	11	1,178	452	191
	2017	(D)	(D)	65	(D)	(D)	84
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	8	76	24	112	15	110
	2017	11	79	42	95	15	88
	$1,000, 2022	38	1,559	487	1,322	145	1,404
	2017	58	2,391	314	760	85	653
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	2	23	14	26	3	36
	2017	2	17	5	23	9	18
	$1,000, 2022	(D)	1,967	160	404	450	3,300
	2017	(D)	4,591	(D)	150	(D)	376
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	5	50	10	30	9	24
	2017	3	35	10	36	5	21
	$1,000, 2022	454	381	187	2,271	47	192
	2017	10	528	73	842	33	(D)

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	20	23	40	11	10	42
	2017	15	17	33	10	11	36
	$1,000, 2022	245	(D)	570	100	80	302
	2017	189	172	199	31	428	299
Aquaculture	farms, 2022	1	1	-	2	-	-
	2017	1	1	-	2	-	-
	$1,000, 2022	(D)	(D)	-	(D)	-	-
	2017	(D)	(D)	-	(D)	-	-
Other animals and other animal products	farms, 2022	4	11	54	20	6	25
	2017	21	9	25	14	3	26
	$1,000, 2022	26	5	190	333	131	192
	2017	282	(D)	47	(D)	(D)	277
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	30	18	92	38	23	60
	2017	54	39	72	34	15	59
	$1,000, 2022	318	217	1,258	247	109	1,029
	2017	519	258	889	159	157	350
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	11	5	11	9	7	18
	2017	13	5	6	3	4	10
	$1,000, 2022	1,118	53	(D)	663	237	355
	2017	1,602	(D)	6	(D)	32	154
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	7	7	33	15	1	13
	2017	12	5	17	15	3	19
	$1,000, 2022	339	87	751	85	(D)	740
	2017	55	69	222	29	(D)	48

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	22	10	3	3	-	-
	2017	27	4	4	4	2	5
	$1,000, 2022	(D)	30	6	(D)	-	-
	2017	(D)	11	23	21	(D)	20
Aquaculture	farms, 2022	8	-	1	-	1	1
	2017	5	-	-	-	-	-
	$1,000, 2022	3,602	-	(D)	-	(D)	(D)
	2017	1,364	-	-	-	-	-
Other animals and other animal products	farms, 2022	27	1	3	2	3	3
	2017	16	1	5	1	4	2
	$1,000, 2022	2,209	(D)	5	(D)	1	(D)
	2017	(D)	(D)	(D)	(D)	(D)	(D)
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	36	1	16	6	10	3
	2017	38	3	15	33	13	12
	$1,000, 2022	311	(D)	86	71	46	(Z)
	2017	284	(D)	150	239	27	22
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	11	-	1	3	7	-
	2017	7	2	3	6	3	-
	$1,000, 2022	443	-	(D)	(D)	16	-
	2017	875	(D)	3	7	8	-
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	9	-	2	3	2	1
	2017	10	-	2	5	9	1
	$1,000, 2022	192	-	(D)	(D)	(D)	(D)
	2017	46	-	(D)	23	11	(D)

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	20	1	8	15	4	9
	2017	9	2	8	19	-	3
	$1,000, 2022	576	(D)	9	244	27	12
	2017	116	(D)	(D)	92	-	4
Aquaculture	farms, 2022	2	-	1	3	1	3
	2017	1	-	-	1	-	-
	$1,000, 2022	(D)	-	(D)	(D)	(D)	2
	2017	(D)	-	-	(D)	-	-
Other animals and other animal products	farms, 2022	15	10	3	22	2	1
	2017	13	5	-	9	3	12
	$1,000, 2022	602	1,026	(D)	(D)	(D)	(D)
	2017	(D)	(D)	-	(D)	(D)	409
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	62	9	6	56	5	5
	2017	62	8	3	47	10	16
	$1,000, 2022	591	77	21	1,565	35	26
	2017	791	34	6	687	185	43
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	6	6	3	16	7	2
	2017	9	-	-	10	3	-
	$1,000, 2022	57	185	(D)	281	84	(D)
	2017	154	-	-	(D)	21	-
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	22	5	2	11	7	-
	2017	15	1	2	10	4	4
	$1,000, 2022	1,936	45	(D)	487	71	-
	2017	502	(D)	(D)	(D)	182	41

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	2	20	17	27	38	1
	2017	8	31	28	29	21	8
	$1,000, 2022	(D)	(D)	157	(D)	(D)	(D)
	2017	(D)	534	136	430	(D)	26
Aquaculture	farms, 2022	-	-	1	1	-	-
	2017	-	1	-	1	-	-
	$1,000, 2022	-	-	(D)	(D)	-	-
	2017	-	(D)	-	(D)	-	-
Other animals and other animal products	farms, 2022	15	23	34	39	15	1
	2017	5	21	20	36	12	2
	$1,000, 2022	106	338	140	1,110	94	(D)
	2017	(D)	(D)	123	(D)	(D)	(D)
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	19	66	49	52	20	11
	2017	28	47	76	75	56	5
	$1,000, 2022	37	920	1,219	261	299	24
	2017	170	300	391	313	322	63
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	4	9	12	24	8	7
	2017	5	7	10	13	3	5
	$1,000, 2022	19	(D)	177	355	187	(D)
	2017	466	38	41	390	14	221
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	2	14	23	8	6	3
	2017	10	23	15	16	23	2
	$1,000, 2022	(D)	449	522	38	(D)	(D)
	2017	56	63	174	966	617	(D)

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	3	12	4	34	37	6
	2017	6	7	5	49	69	6
	$1,000, 2022	60	14	4	654	300	30
	2017	33	(D)	10	(D)	208	24
Aquaculture	farms, 2022	-	-	-	-	6	-
	2017	-	-	-	-	7	-
	$1,000, 2022	-	-	-	-	1,339	-
	2017	-	-	-	-	2,924	-
Other animals and other animal products	farms, 2022	9	8	5	45	32	5
	2017	6	2	3	50	30	9
	$1,000, 2022	604	(D)	(D)	482	2,780	(D)
	2017	120	(D)	(D)	7,227	2,942	(D)
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	27	14	12	67	128	3
	2017	11	19	13	73	99	10
	$1,000, 2022	325	76	(D)	1,212	798	(D)
	2017	248	255	187	529	1,157	24
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	2	8	3	19	40	-
	2017	-	3	1	15	16	-
	$1,000, 2022	(D)	(D)	24	157	754	-
	2017	-	229	(D)	198	212	-
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	6	1	1	16	39	2
	2017	16	1	4	15	35	4
	$1,000, 2022	12	(D)	(D)	324	244	(D)
	2017	403	(D)	77	112	460	4

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	26	2	24	12	-	8
	2017	34	5	24	19	-	2
	$1,000, 2022	267	(D)	170	(D)	-	80
	2017	77	57	115	83	-	(D)
Aquaculture	farms, 2022	1	-	-	4	2	-
	2017	1	-	1	1	3	-
	$1,000, 2022	(D)	-	-	1,100	(D)	-
	2017	(D)	-	(D)	(D)	(D)	-
Other animals and other animal products	farms, 2022	22	6	20	15	-	8
	2017	20	6	19	9	8	1
	$1,000, 2022	374	6	2,924	1,521	-	511
	2017	78	30	2,024	775	(D)	(D)
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	47	20	24	9	10	-
	2017	64	11	19	29	26	1
	$1,000, 2022	292	213	48	46	105	-
	2017	334	60	87	232	390	(D)
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	13	7	10	5	5	-
	2017	9	3	6	5	12	1
	$1,000, 2022	109	56	1,434	37	72	-
	2017	(D)	38	(D)	49	115	(D)
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	15	4	6	4	4	-
	2017	24	6	4	5	7	-
	$1,000, 2022	28	(D)	7	17	901	-
	2017	151	30	81	(D)	(D)	-

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	5	4	14	4	10	32
	2017	8	13	11	6	29	20
	$1,000, 2022	(D)	52	43	128	68	758
	2017	(D)	104	(D)	24	169	86
Aquaculture	farms, 2022	-	-	-	-	-	4
	2017	-	-	-	-	-	1
	$1,000, 2022	-	-	-	-	-	(D)
	2017	-	-	-	-	-	(D)
Other animals and other animal products	farms, 2022	22	8	32	2	5	43
	2017	7	5	25	8	6	52
	$1,000, 2022	(D)	322	340	(D)	(D)	107
	2017	(D)	20	(D)	657	(D)	367
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	26	23	78	14	8	170
	2017	16	13	79	6	20	142
	$1,000, 2022	85	201	1,117	36	12	1,273
	2017	103	157	1,005	28	33	545
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	3	2	38	-	-	34
	2017	1	-	15	-	-	14
	$1,000, 2022	(D)	(D)	1,034	-	-	268
	2017	(D)	-	854	-	-	86
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	11	9	18	5	2	79
	2017	6	10	35	2	6	51
	$1,000, 2022	23	73	1,075	2	(D)	579
	2017	34	1,007	892	(D)	9	272

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	30	17	6	31	5	9
	2017	28	7	22	71	10	11
	$1,000, 2022	582	(D)	187	(D)	16	183
	2017	1,139	20	190	361	23	152
Aquaculture	farms, 2022	1	-	-	1	-	-
	2017	3	-	-	-	-	-
	$1,000, 2022	(D)	-	-	(D)	-	-
	2017	1,016	-	-	-	-	-
Other animals and other animal products	farms, 2022	32	15	15	54	10	2
	2017	10	17	9	46	13	10
	$1,000, 2022	353	51	76	4,666	468	(D)
	2017	(D)	80	(D)	3,938	(D)	115
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	68	61	26	132	31	18
	2017	46	70	27	125	30	11
	$1,000, 2022	808	1,292	118	875	73	112
	2017	1,940	761	128	723	51	61
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	15	13	2	41	12	2
	2017	14	9	1	32	4	1
	$1,000, 2022	373	332	(D)	1,629	(D)	(D)
	2017	1,048	(D)	(D)	1,183	(D)	(D)
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	20	11	7	30	3	3
	2017	15	17	11	39	9	5
	$1,000, 2022	288	(D)	898	1,456	(D)	8
	2017	256	64	75	1,950	4	(D)

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	4	47	2	8	6	4
	2017	2	33	1	13	29	5
	$1,000, 2022	29	(D)	(D)	(D)	30	(D)
	2017	(D)	163	(D)	25	(D)	(D)
Aquaculture	farms, 2022	-	3	-	-	-	-
	2017	-	5	-	-	-	-
	$1,000, 2022	-	(D)	-	-	-	-
	2017	-	376	-	-	-	-
Other animals and other animal products	farms, 2022	-	38	4	16	3	6
	2017	3	32	3	18	3	2
	$1,000, 2022	-	2,052	291	78	6	(D)
	2017	(D)	2,233	(D)	312	(D)	(D)
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	10	65	-	17	11	29
	2017	15	94	6	33	23	22
	$1,000, 2022	16	726	-	120	41	148
	2017	50	1,085	24	416	53	97
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	2	37	-	14	5	9
	2017	-	19	-	15	9	-
	$1,000, 2022	(D)	315	-	1,107	127	307
	2017	-	371	-	1,719	374	-
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	-	16	-	10	3	2
	2017	4	30	1	10	11	9
	$1,000, 2022	-	180	-	35	17	(D)
	2017	39	550	(D)	(D)	92	24

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Table 2. **Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
MARKET VALUE OF AGRICULTURAL PRODUCTS SOLD - Con.							
Total sales - Con.							
Value of sales by commodity or commodity group: - Con.							
Livestock, poultry, and their products - Con.							
Horses, ponies, mules, burros, and donkeys	farms, 2022	42	1	-	18	36	15
	2017	42	3	4	28	49	15
	$1,000, 2022	1,584	(D)	-	(D)	760	(D)
	2017	529	37	16	(D)	1,457	(D)
Aquaculture	farms, 2022	2	-	-	4	-	-
	2017	-	-	-	3	-	-
	$1,000, 2022	(D)	-	-	553	-	-
	2017	-	-	-	142	-	-
Other animals and other animal products	farms, 2022	43	2	1	17	51	4
	2017	41	2	-	24	42	3
	$1,000, 2022	366	(D)	(D)	(D)	619	(D)
	2017	131	(D)	-	152	1,012	2
FOOD MARKETING PRACTICES							
Value of food sold directly to consumers	farms, 2022	109	15	12	62	129	20
	2017	122	4	4	77	135	16
	$1,000, 2022	6,141	81	93	765	1,408	1,157
	2017	3,534	(D)	34	874	2,513	58
Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products	farms, 2022	30	3	-	23	36	6
	2017	27	-	-	22	29	-
	$1,000, 2022	896	4	-	224	(D)	187
	2017	513	-	-	1,114	1,594	-
VALUE-ADDED PRODUCTS SOLD							
Value of processed or value-added agricultural products sold	farms, 2022	40	4	2	18	31	3
	2017	32	2	-	24	47	1
	$1,000, 2022	1,833	7	(D)	1,341	260	(Z)
	2017	2,692	(D)	-	508	535	(D)

Table 3. **Farm Production Expenses: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Total farm production expenses	farms, 2022	65,531	449	355	952	608
	2017	68,822	462	360	943	583
	$1,000, 2022	20,780,603	16,805	47,729	224,714	34,895
	2017	15,133,150	12,688	57,974	139,558	20,115
Average per farm	dollars, 2022	317,111	37,428	134,447	236,044	57,393
	2017	219,888	27,463	161,038	147,994	34,503
Fertilizer, lime, and soil conditioners purchased	farms, 2022	36,421	143	174	373	222
	2017	40,476	140	186	421	223
	$1,000, 2022	2,325,700	1,156	3,040	21,470	4,665
	2017	1,374,497	705	1,906	12,482	2,183
Chemicals purchased	farms, 2022	37,339	86	127	396	217
	2017	38,474	82	140	392	158
	$1,000, 2022	1,161,099	370	1,261	11,217	3,139
	2017	797,679	545	1,357	7,810	978
Seeds, plants, vines, and trees purchased	farms, 2022	36,437	153	172	355	197
	2017	36,673	108	125	358	185
	$1,000, 2022	1,772,341	832	3,709	22,467	2,525
	2017	1,516,361	862	6,626	15,451	1,363
Cover crop seed purchased	farms, 2022	4,909	24	25	55	24
	2017	4,084	23	13	63	33
	$1,000, 2022	20,527	7	16	153	214
	2017	12,103	11	4	129	44
Livestock and poultry purchased or leased	farms, 2022	13,933	125	65	176	150
	2017	16,345	132	106	191	175
	$1,000, 2022	1,926,426	1,065	196	13,438	2,420
	2017	1,649,648	516	317	6,831	2,007
Breeding livestock purchased or leased	farms, 2022	5,904	66	10	102	91
	2017	7,659	69	25	113	110
	$1,000, 2022	171,016	197	47	807	1,076
	2017	141,885	200	70	1,373	961
Other livestock and poultry purchased or leased	farms, 2022	9,786	82	58	92	86
	2017	11,036	80	92	101	116
	$1,000, 2022	1,755,410	867	149	12,632	1,343
	2017	1,507,763	316	247	5,458	1,046
Feed purchased	farms, 2022	26,145	234	178	363	313
	2017	29,902	259	191	396	369
	$1,000, 2022	3,890,272	2,758	1,114	28,215	3,049
	2017	2,668,319	1,412	7,002	23,793	2,203
Gasoline, fuels, and oils purchased	farms, 2022	61,621	436	340	865	586
	2017	63,964	437	348	859	572
	$1,000, 2022	956,802	1,374	3,487	14,781	2,916
	2017	630,623	1,259	2,514	7,816	1,485
Utilities	farms, 2022	48,636	313	216	655	424
	2017	51,248	329	228	597	411
	$1,000, 2022	400,978	768	1,455	4,981	1,441
	2017	305,957	612	985	3,531	889
Repairs, supplies, and maintenance costs	farms, 2022	55,660	379	282	750	517
	2017	58,445	400	299	736	474
	$1,000, 2022	1,322,234	2,243	3,872	18,983	3,852
	2017	889,519	1,790	2,912	9,887	2,305
Hired farm labor	farms, 2022	17,399	40	81	176	77
	2017	19,374	73	94	191	77
	$1,000, 2022	1,320,974	738	20,764	23,897	1,509
	2017	832,429	590	25,219	14,582	618
Contract labor	farms, 2022	4,311	21	18	39	32
	2017	4,724	28	16	29	19
	$1,000, 2022	152,565	132	329	1,425	191
	2017	82,304	188	320	221	148
Customwork and custom hauling	farms, 2022	19,181	59	35	161	114
	2017	21,712	63	51	159	95
	$1,000, 2022	425,172	188	294	5,812	590
	2017	310,122	235	151	2,267	415
Cash rent for land, buildings, and grazing fees	farms, 2022	24,199	88	58	263	143
	2017	24,769	85	75	236	119
	$1,000, 2022	2,302,712	1,038	1,606	24,120	1,969
	2017	1,851,799	748	1,626	12,605	1,214
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	6,598	41	17	69	52
	2017	7,187	31	12	64	43
	$1,000, 2022	182,357	270	33	4,195	588
	2017	130,176	78	541	2,300	66
Interest expense	farms, 2022	27,274	135	93	349	181
	2017	31,165	155	108	329	182
	$1,000, 2022	702,889	998	1,338	7,163	1,384
	2017	666,967	1,531	1,581	5,534	1,424
Secured by real estate	farms, 2022	20,348	92	74	265	140
	2017	24,135	135	82	265	155
	$1,000, 2022	467,669	687	908	5,424	873
	2017	452,333	1,330	1,155	4,019	937
Not secured by real estate	farms, 2022	16,953	89	58	204	105
	2017	19,739	83	48	211	114
	$1,000, 2022	235,219	311	430	1,740	511
	2017	214,634	200	426	1,515	487
Property taxes paid	farms, 2022	61,644	433	328	924	592
	2017	64,702	452	353	916	580
	$1,000, 2022	482,443	1,273	1,620	5,655	2,163
	2017	403,333	725	1,604	4,341	1,446

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Total farm production expenses	farms, 2022	687	392	1,019	973	463
	2017	816	438	983	1,040	529
	$1,000, 2022	208,004	144,720	593,213	354,598	11,196
	2017	155,212	112,827	382,030	301,433	11,496
Average per farm	dollars, 2022	302,772	369,184	582,152	364,438	24,181
	2017	190,211	257,595	388,637	289,839	21,732
Fertilizer, lime, and soil conditioners purchased	farms, 2022	378	246	692	697	188
	2017	488	286	628	754	210
	$1,000, 2022	13,378	21,368	54,404	33,240	638
	2017	8,842	13,760	24,618	24,513	555
Chemicals purchased	farms, 2022	369	266	717	732	84
	2017	446	298	640	762	71
	$1,000, 2022	7,441	11,431	28,262	17,131	55
	2017	4,618	8,704	13,688	14,168	66
Seeds, plants, vines, and trees purchased	farms, 2022	365	252	669	683	127
	2017	425	269	600	721	136
	$1,000, 2022	10,262	15,942	42,031	25,853	348
	2017	10,651	16,729	27,783	25,831	483
Cover crop seed purchased	farms, 2022	55	46	42	43	28
	2017	45	31	33	68	42
	$1,000, 2022	171	334	146	219	12
	2017	86	153	119	95	25
Livestock and poultry purchased or leased	farms, 2022	205	44	191	213	146
	2017	248	72	209	228	151
	$1,000, 2022	18,250	5,486	82,916	51,603	881
	2017	20,814	6,092	68,104	65,082	1,476
Breeding livestock purchased or leased	farms, 2022	100	23	49	76	81
	2017	105	22	59	61	89
	$1,000, 2022	1,962	1,249	4,057	3,222	291
	2017	1,242	532	2,561	1,385	348
Other livestock and poultry purchased or leased	farms, 2022	137	26	154	156	97
	2017	168	63	179	197	82
	$1,000, 2022	16,288	4,237	78,860	48,382	590
	2017	19,572	5,560	65,543	63,697	1,129
Feed purchased	farms, 2022	373	93	269	330	301
	2017	462	115	312	389	336
	$1,000, 2022	63,061	12,499	143,659	75,223	1,252
	2017	46,001	9,732	111,038	53,505	1,400
Gasoline, fuels, and oils purchased	farms, 2022	662	362	957	902	449
	2017	792	408	938	967	514
	$1,000, 2022	8,917	9,500	20,631	13,094	1,275
	2017	6,735	5,453	10,513	10,144	858
Utilities	farms, 2022	495	318	799	777	328
	2017	665	336	726	824	345
	$1,000, 2022	6,066	2,330	8,116	6,671	559
	2017	5,138	1,911	5,041	6,257	569
Repairs, supplies, and maintenance costs	farms, 2022	598	327	879	843	403
	2017	708	381	854	900	447
	$1,000, 2022	13,525	10,963	28,431	22,807	1,638
	2017	9,376	6,512	13,302	15,907	1,468
Hired farm labor	farms, 2022	134	128	319	293	57
	2017	223	122	309	364	89
	$1,000, 2022	27,969	8,427	25,870	17,761	879
	2017	10,427	3,964	11,364	11,613	854
Contract labor	farms, 2022	46	19	87	70	20
	2017	89	13	85	76	13
	$1,000, 2022	1,200	793	2,575	1,335	94
	2017	786	331	3,085	1,593	45
Customwork and custom hauling	farms, 2022	234	103	363	355	68
	2017	311	138	297	423	57
	$1,000, 2022	4,695	3,599	10,839	7,030	73
	2017	3,609	1,796	5,755	5,357	92
Cash rent for land, buildings, and grazing fees	farms, 2022	196	190	481	482	79
	2017	252	196	409	479	110
	$1,000, 2022	5,951	21,897	70,671	32,315	290
	2017	6,893	18,578	44,584	29,280	628
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	74	37	135	93	25
	2017	81	48	97	110	23
	$1,000, 2022	728	1,398	5,515	1,457	49
	2017	652	1,173	2,045	1,540	41
Interest expense	farms, 2022	252	207	456	493	132
	2017	349	220	502	554	175
	$1,000, 2022	6,969	5,522	15,245	10,957	753
	2017	6,460	6,199	13,101	11,500	940
Secured by real estate	farms, 2022	213	152	335	347	107
	2017	293	159	377	417	152
	$1,000, 2022	4,935	3,894	8,719	7,270	567
	2017	4,764	4,266	7,705	8,464	758
Not secured by real estate	farms, 2022	137	136	289	286	66
	2017	199	147	323	330	88
	$1,000, 2022	2,034	1,629	6,526	3,687	185
	2017	1,695	1,932	5,396	3,036	182
Property taxes paid	farms, 2022	666	357	934	895	453
	2017	802	400	917	951	512
	$1,000, 2022	3,717	3,083	9,651	6,892	1,382
	2017	4,665	2,692	8,093	6,839	1,219

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Total farm production expenses	farms, 2022	606	488	563	740	655	404
	2017	689	432	623	821	694	414
	$1,000, 2022	116,714	24,955	310,905	46,958	311,838	31,971
	2017	92,530	23,159	221,052	44,554	231,831	22,503
Average per farm	dollars, 2022	192,598	51,136	552,229	63,457	476,088	79,136
	2017	134,296	53,608	354,818	54,268	334,050	54,354
Fertilizer, lime, and soil conditioners purchased	farms, 2022	325	163	367	353	399	163
	2017	447	171	443	465	468	196
	$1,000, 2022	17,125	1,663	42,981	8,066	50,189	3,044
	2017	10,053	1,295	24,687	5,770	28,709	1,981
Chemicals purchased	farms, 2022	343	112	397	330	426	140
	2017	409	106	440	386	474	148
	$1,000, 2022	8,150	577	22,043	2,402	25,419	1,653
	2017	5,470	321	14,766	1,921	19,873	1,518
Seeds, plants, vines, and trees purchased	farms, 2022	325	154	373	342	398	149
	2017	380	123	419	360	436	117
	$1,000, 2022	10,122	847	32,454	4,953	38,303	2,147
	2017	10,900	938	28,564	4,561	33,152	1,488
Cover crop seed purchased	farms, 2022	35	36	43	39	58	22
	2017	25	21	64	51	49	24
	$1,000, 2022	75	13	258	45	391	48
	2017	22	10	182	41	233	17
Livestock and poultry purchased or leased	farms, 2022	140	175	57	204	104	110
	2017	160	149	92	235	119	143
	$1,000, 2022	5,609	2,233	16,685	1,004	13,512	1,293
	2017	2,634	2,885	11,176	2,574	6,934	1,184
Breeding livestock purchased or leased	farms, 2022	56	96	25	81	54	73
	2017	78	99	50	111	77	99
	$1,000, 2022	497	415	3,117	392	633	578
	2017	317	753	933	242	422	627
Other livestock and poultry purchased or leased	farms, 2022	103	102	41	155	66	55
	2017	100	76	67	169	63	54
	$1,000, 2022	5,111	1,818	13,567	612	12,879	715
	2017	2,318	2,132	10,244	2,332	6,512	557
Feed purchased	farms, 2022	285	324	98	415	187	248
	2017	327	287	124	445	207	257
	$1,000, 2022	12,609	5,850	44,755	3,560	17,623	2,769
	2017	9,944	4,623	32,553	4,039	12,855	2,028
Gasoline, fuels, and oils purchased	farms, 2022	579	482	530	722	624	400
	2017	651	424	561	788	641	382
	$1,000, 2022	7,201	1,804	14,851	2,614	16,190	2,462
	2017	5,721	1,215	9,224	2,195	12,608	1,560
Utilities	farms, 2022	476	359	418	492	505	312
	2017	521	331	465	568	549	325
	$1,000, 2022	3,318	910	4,169	1,531	5,771	1,159
	2017	2,372	750	2,678	1,326	4,415	945
Repairs, supplies, and maintenance costs	farms, 2022	548	407	480	630	570	362
	2017	596	388	504	706	593	353
	$1,000, 2022	9,512	2,432	19,536	5,371	22,400	3,466
	2017	8,124	2,011	12,577	4,112	15,804	1,941
Hired farm labor	farms, 2022	168	69	202	89	244	66
	2017	176	67	242	149	254	72
	$1,000, 2022	8,557	1,156	17,882	3,726	26,106	2,609
	2017	5,493	2,134	10,714	4,370	16,831	2,172
Contract labor	farms, 2022	41	20	38	40	42	24
	2017	25	22	46	33	42	10
	$1,000, 2022	607	377	1,170	363	2,241	1,084
	2017	206	153	703	244	754	105
Customwork and custom hauling	farms, 2022	155	61	160	163	178	81
	2017	228	59	184	204	182	88
	$1,000, 2022	1,892	370	7,869	1,098	2,986	715
	2017	1,430	268	4,824	1,167	2,952	349
Cash rent for land, buildings, and grazing fees	farms, 2022	182	117	262	146	336	126
	2017	217	93	311	226	348	120
	$1,000, 2022	14,043	1,607	48,308	2,398	47,981	2,755
	2017	14,635	2,215	39,726	3,356	42,428	2,111
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	44	11	81	40	98	37
	2017	53	17	104	41	122	37
	$1,000, 2022	381	10	5,169	185	3,591	181
	2017	523	228	2,418	157	4,825	113
Interest expense	farms, 2022	195	170	273	217	336	173
	2017	231	150	350	277	351	145
	$1,000, 2022	4,426	1,833	10,353	2,021	9,758	2,258
	2017	4,856	1,145	10,192	2,175	9,269	1,679
Secured by real estate	farms, 2022	145	118	225	163	234	118
	2017	169	128	258	217	273	120
	$1,000, 2022	2,966	1,327	7,046	1,631	6,069	1,859
	2017	3,304	779	5,991	1,624	6,201	1,359
Not secured by real estate	farms, 2022	119	105	160	145	245	115
	2017	152	74	248	143	209	94
	$1,000, 2022	1,460	506	3,307	390	3,688	399
	2017	1,553	365	4,202	551	3,068	320
Property taxes paid	farms, 2022	575	476	521	709	601	392
	2017	654	424	570	792	643	400
	$1,000, 2022	5,012	1,766	5,822	3,216	7,292	1,762
	2017	4,149	991	4,595	3,091	6,006	1,256

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Total farm production expenses	farms, 2022	25	742	426	841	614	980
	2017	32	744	494	820	611	960
	$1,000, 2022	361	391,469	25,167	248,747	307,200	119,368
	2017	212	302,683	16,626	189,288	205,184	84,615
Average per farm	dollars, 2022	14,440	527,586	59,077	295,775	500,325	121,805
	2017	6,624	406,832	33,656	230,839	335,817	88,140
Fertilizer, lime, and soil conditioners purchased	farms, 2022	10	491	175	515	358	446
	2017	9	535	206	544	363	525
	$1,000, 2022	14	44,837	2,656	30,785	39,072	17,534
	2017	2	25,223	1,721	21,589	21,095	11,743
Chemicals purchased	farms, 2022	3	534	123	561	347	513
	2017	2	554	136	478	348	559
	$1,000, 2022	2	20,966	722	14,651	22,122	10,800
	2017	(D)	12,953	490	10,431	12,267	5,642
Seeds, plants, vines, and trees purchased	farms, 2022	13	502	143	535	350	451
	2017	12	533	142	492	326	460
	$1,000, 2022	12	33,908	1,696	25,068	26,126	14,329
	2017	7	30,872	1,079	22,491	19,927	12,254
Cover crop seed purchased	farms, 2022	3	53	41	98	40	61
	2017	6	31	31	87	19	51
	$1,000, 2022	(D)	346	37	304	369	79
	2017	(Z)	115	20	149	36	161
Livestock and poultry purchased or leased	farms, 2022	3	149	113	196	166	166
	2017	12	141	150	171	158	178
	$1,000, 2022	(D)	60,822	1,249	14,900	27,961	3,605
	2017	3	52,515	1,034	14,271	22,185	4,304
Breeding livestock purchased or leased	farms, 2022	1	51	57	58	61	92
	2017	7	52	84	66	67	114
	$1,000, 2022	(D)	2,401	384	527	1,047	1,061
	2017	2	2,770	295	219	1,277	1,076
Other livestock and poultry purchased or leased	farms, 2022	3	115	71	156	131	112
	2017	5	105	86	136	121	100
	$1,000, 2022	(D)	58,421	865	14,373	26,913	2,545
	2017	1	49,746	740	14,052	20,908	3,228
Feed purchased	farms, 2022	13	227	237	352	295	337
	2017	17	230	298	320	291	357
	$1,000, 2022	(D)	76,712	4,037	20,328	49,725	10,256
	2017	27	65,377	2,585	13,347	37,669	5,103
Gasoline, fuels, and oils purchased	farms, 2022	24	663	411	776	587	898
	2017	31	655	478	756	578	854
	$1,000, 2022	35	14,194	1,676	11,211	15,423	7,124
	2017	22	10,055	903	7,408	8,228	5,305
Utilities	farms, 2022	14	591	312	632	470	640
	2017	24	595	348	613	423	608
	$1,000, 2022	13	6,245	817	5,716	4,018	2,518
	2017	20	4,546	807	4,964	3,065	2,232
Repairs, supplies, and maintenance costs	farms, 2022	20	644	355	719	531	762
	2017	30	654	418	686	507	754
	$1,000, 2022	51	18,626	2,536	16,577	17,583	9,359
	2017	26	13,911	1,753	10,836	9,490	7,455
Hired farm labor	farms, 2022	2	259	68	204	189	189
	2017	5	310	90	244	214	220
	$1,000, 2022	(D)	17,180	3,419	41,692	16,049	6,809
	2017	10	8,612	1,757	26,099	9,248	3,940
Contract labor	farms, 2022	1	55	30	84	38	42
	2017	-	70	13	85	61	31
	$1,000, 2022	(D)	1,536	402	8,948	1,104	426
	2017	-	874	23	2,574	1,053	370
Customwork and custom hauling	farms, 2022	-	275	74	282	231	192
	2017	3	271	60	302	251	253
	$1,000, 2022	-	6,473	280	5,464	6,758	3,245
	2017	3	4,781	225	4,449	4,192	1,340
Cash rent for land, buildings, and grazing fees	farms, 2022	3	363	86	312	239	313
	2017	2	394	85	322	232	311
	$1,000, 2022	(D)	43,583	969	21,552	43,715	16,331
	2017	(D)	38,492	531	19,892	29,755	8,813
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	-	91	27	87	73	74
	2017	3	89	32	88	51	89
	$1,000, 2022	-	1,879	46	2,523	3,281	1,937
	2017	(D)	1,198	25	1,600	1,487	524
Interest expense	farms, 2022	5	347	124	329	278	327
	2017	8	451	170	337	265	401
	$1,000, 2022	8	10,788	1,411	8,519	8,005	4,533
	2017	20	10,760	1,450	6,927	8,140	5,468
Secured by real estate	farms, 2022	3	238	96	229	192	263
	2017	7	333	151	232	196	326
	$1,000, 2022	(D)	7,355	1,025	5,449	4,059	3,277
	2017	17	7,244	1,233	5,134	4,927	3,670
Not secured by real estate	farms, 2022	4	229	80	210	188	166
	2017	3	308	91	216	198	238
	$1,000, 2022	(D)	3,434	386	3,070	3,946	1,257
	2017	3	3,516	217	1,793	3,213	1,798
Property taxes paid	farms, 2022	22	671	411	750	563	940
	2017	32	675	484	694	563	892
	$1,000, 2022	158	7,829	1,055	6,458	6,621	5,169
	2017	44	5,476	1,039	6,082	5,235	4,291

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Total farm production expenses	farms, 2022	773	1,458	908	1,406	529	511
	2017	822	1,401	1,076	1,461	524	467
	$1,000, 2022	417,856	386,109	355,304	438,614	230,900	50,012
	2017	277,104	254,852	308,625	291,241	168,260	53,985
Average per farm	dollars, 2022	540,565	264,821	391,304	311,959	436,485	97,870
	2017	337,110	181,907	286,826	199,344	321,107	115,600
Fertilizer, lime, and soil conditioners purchased	farms, 2022	580	829	592	903	260	204
	2017	613	889	690	957	277	205
	$1,000, 2022	50,144	57,078	41,580	50,229	36,079	2,051
	2017	31,235	25,082	30,162	27,089	20,163	3,669
Chemicals purchased	farms, 2022	628	861	608	925	280	220
	2017	603	789	671	921	288	193
	$1,000, 2022	22,000	23,201	21,214	21,814	15,750	1,033
	2017	16,283	11,113	18,651	13,595	11,707	1,462
Seeds, plants, vines, and trees purchased	farms, 2022	591	812	583	899	263	248
	2017	581	751	656	857	272	218
	$1,000, 2022	38,571	30,678	34,251	34,103	28,861	4,521
	2017	34,299	22,841	32,659	25,967	22,046	6,193
Cover crop seed purchased	farms, 2022	46	146	64	157	44	35
	2017	33	117	65	135	36	22
	$1,000, 2022	397	487	619	1,389	205	18
	2017	159	197	348	186	119	55
Livestock and poultry purchased or leased	farms, 2022	137	400	166	381	34	113
	2017	140	442	227	530	36	84
	$1,000, 2022	50,068	30,949	27,205	36,334	1,732	580
	2017	27,275	33,383	34,554	23,571	2,524	724
Breeding livestock purchased or leased	farms, 2022	28	200	46	162	14	24
	2017	49	250	64	261	22	26
	$1,000, 2022	1,365	2,034	3,259	6,603	(D)	96
	2017	885	9,797	3,644	3,123	(D)	259
Other livestock and poultry purchased or leased	farms, 2022	118	271	136	281	25	96
	2017	112	271	191	377	15	67
	$1,000, 2022	48,704	28,915	23,946	29,732	(D)	484
	2017	26,390	23,587	30,910	20,448	(D)	465
Feed purchased	farms, 2022	203	720	266	747	77	241
	2017	211	801	420	858	82	212
	$1,000, 2022	70,051	60,711	55,412	83,045	26,933	2,749
	2017	32,656	40,689	51,199	51,397	23,449	2,000
Gasoline, fuels, and oils purchased	farms, 2022	740	1,372	844	1,351	456	485
	2017	778	1,299	988	1,390	451	423
	$1,000, 2022	15,566	18,989	14,964	23,594	11,731	2,589
	2017	10,886	11,189	11,209	10,720	7,874	2,486
Utilities	farms, 2022	633	1,091	706	1,083	364	325
	2017	648	1,041	788	1,151	340	293
	$1,000, 2022	5,837	7,097	4,846	7,260	4,183	2,370
	2017	3,899	5,367	4,057	6,040	3,540	2,452
Repairs, supplies, and maintenance costs	farms, 2022	697	1,225	772	1,241	409	408
	2017	710	1,194	888	1,281	400	374
	$1,000, 2022	23,055	26,604	20,203	25,390	14,351	3,962
	2017	13,941	16,079	14,136	19,046	9,183	3,659
Hired farm labor	farms, 2022	263	365	269	368	160	127
	2017	298	356	378	442	156	137
	$1,000, 2022	16,661	20,887	14,608	24,567	16,285	18,695
	2017	7,515	14,817	9,715	22,216	11,941	16,594
Contract labor	farms, 2022	63	111	61	75	42	50
	2017	95	94	92	97	30	33
	$1,000, 2022	2,614	1,246	1,422	2,100	1,113	753
	2017	2,161	1,770	1,694	1,614	497	516
Customwork and custom hauling	farms, 2022	347	481	347	633	112	91
	2017	342	502	380	685	134	87
	$1,000, 2022	12,749	9,281	6,930	13,117	4,287	340
	2017	6,144	4,999	7,240	9,818	3,122	397
Cash rent for land, buildings, and grazing fees	farms, 2022	463	514	412	573	194	98
	2017	453	448	478	487	201	155
	$1,000, 2022	54,155	43,546	50,808	52,711	38,109	1,988
	2017	51,479	28,684	51,442	32,463	26,456	3,741
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	114	108	90	105	74	34
	2017	124	111	103	150	84	38
	$1,000, 2022	3,635	3,722	3,007	3,220	6,311	242
	2017	3,541	889	1,842	3,464	2,555	196
Interest expense	farms, 2022	410	664	448	611	215	129
	2017	491	713	547	736	255	136
	$1,000, 2022	14,078	16,313	11,850	16,771	7,483	1,478
	2017	14,049	14,590	14,412	15,092	7,091	2,489
Secured by real estate	farms, 2022	307	490	341	460	165	103
	2017	367	567	421	606	204	97
	$1,000, 2022	8,530	11,248	7,500	10,158	5,190	1,138
	2017	8,129	10,614	8,899	10,092	4,653	1,548
Not secured by real estate	farms, 2022	279	424	277	414	120	74
	2017	367	409	360	461	184	93
	$1,000, 2022	5,548	5,065	4,349	6,613	2,293	340
	2017	5,921	3,976	5,514	5,000	2,438	941
Property taxes paid	farms, 2022	690	1,377	846	1,313	506	477
	2017	730	1,327	986	1,396	498	376
	$1,000, 2022	8,027	9,442	8,439	11,026	5,350	3,423
	2017	6,057	6,858	7,902	9,239	4,150	2,773

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Total farm production expenses	farms, 2022	797	336	814	424	845	531
	2017	891	384	805	337	799	624
	$1,000, 2022	162,105	45,454	68,894	13,951	324,961	25,979
	2017	100,405	35,175	50,333	8,802	251,469	25,521
Average per farm	dollars, 2022	203,394	135,278	84,637	32,902	384,570	48,925
	2017	112,688	91,601	62,525	26,118	314,730	40,899
Fertilizer, lime, and soil conditioners purchased	farms, 2022	416	119	346	130	600	191
	2017	491	153	424	100	568	218
	$1,000, 2022	15,985	6,007	7,617	1,045	40,506	3,962
	2017	7,012	3,362	8,078	509	24,731	2,806
Chemicals purchased	farms, 2022	452	99	298	94	638	146
	2017	447	85	313	72	594	143
	$1,000, 2022	5,636	5,876	2,636	247	19,847	1,487
	2017	3,581	2,395	2,143	93	13,694	2,004
Seeds, plants, vines, and trees purchased	farms, 2022	396	125	334	154	606	198
	2017	438	118	304	95	559	181
	$1,000, 2022	9,846	4,811	4,234	896	32,788	2,418
	2017	7,463	7,973	5,911	305	26,533	2,579
Cover crop seed purchased	farms, 2022	86	20	37	42	58	26
	2017	74	24	37	17	48	22
	$1,000, 2022	228	7	50	62	348	29
	2017	216	99	66	13	169	6
Livestock and poultry purchased or leased	farms, 2022	198	98	185	122	174	174
	2017	233	106	206	114	150	185
	$1,000, 2022	14,060	634	9,819	1,027	42,079	1,246
	2017	11,214	670	2,408	674	34,746	736
Breeding livestock purchased or leased	farms, 2022	116	45	97	59	64	99
	2017	118	68	71	72	58	106
	$1,000, 2022	6,383	269	909	188	1,418	765
	2017	527	296	310	294	717	333
Other livestock and poultry purchased or leased	farms, 2022	97	63	134	80	130	114
	2017	146	60	148	76	113	110
	$1,000, 2022	7,677	365	8,910	839	40,661	481
	2017	10,687	374	2,098	380	34,029	403
Feed purchased	farms, 2022	396	198	408	246	248	305
	2017	505	244	417	209	241	381
	$1,000, 2022	35,206	1,833	10,526	1,619	45,641	1,777
	2017	18,667	1,282	4,124	835	42,967	2,996
Gasoline, fuels, and oils purchased	farms, 2022	741	328	778	417	779	511
	2017	831	371	775	325	721	601
	$1,000, 2022	7,717	2,393	3,217	1,526	13,190	1,945
	2017	4,211	1,759	2,679	655	8,047	1,958
Utilities	farms, 2022	599	243	518	305	700	382
	2017	647	263	554	260	640	458
	$1,000, 2022	3,146	1,390	1,670	643	5,485	986
	2017	2,457	1,023	1,216	535	3,900	899
Repairs, supplies, and maintenance costs	farms, 2022	680	296	682	382	739	488
	2017	734	309	674	284	685	555
	$1,000, 2022	11,770	3,989	5,535	1,879	20,071	3,092
	2017	7,940	2,304	4,281	1,286	12,408	2,446
Hired farm labor	farms, 2022	155	50	103	78	269	92
	2017	199	50	131	47	253	86
	$1,000, 2022	12,745	4,121	5,432	1,316	14,446	1,344
	2017	7,559	4,216	3,507	1,538	7,662	907
Contract labor	farms, 2022	41	20	29	22	48	26
	2017	37	23	33	10	83	18
	$1,000, 2022	739	386	211	87	3,548	152
	2017	168	175	287	21	1,237	54
Customwork and custom hauling	farms, 2022	236	49	128	48	292	92
	2017	336	50	170	36	289	118
	$1,000, 2022	4,914	1,039	1,037	176	7,798	294
	2017	3,539	599	1,415	51	4,334	440
Cash rent for land, buildings, and grazing fees	farms, 2022	225	74	180	84	452	131
	2017	237	75	199	66	411	127
	$1,000, 2022	13,086	7,762	3,466	506	40,885	1,668
	2017	8,915	3,726	2,849	143	34,507	1,428
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	65	28	30	31	60	43
	2017	65	27	53	18	108	32
	$1,000, 2022	587	571	180	271	1,574	285
	2017	865	166	330	38	1,410	87
Interest expense	farms, 2022	312	113	244	113	418	192
	2017	327	99	214	113	415	213
	$1,000, 2022	5,695	1,087	2,988	747	10,226	1,650
	2017	3,551	847	3,364	703	9,287	2,337
Secured by real estate	farms, 2022	245	71	196	74	247	147
	2017	251	87	170	93	285	179
	$1,000, 2022	3,780	695	1,987	601	6,228	1,034
	2017	2,846	715	2,705	514	6,022	1,852
Not secured by real estate	farms, 2022	181	68	132	78	297	119
	2017	183	46	121	75	295	117
	$1,000, 2022	1,915	391	1,001	145	3,998	617
	2017	706	131	659	189	3,264	485
Property taxes paid	farms, 2022	773	320	791	414	779	517
	2017	850	377	791	326	727	615
	$1,000, 2022	5,152	1,077	3,207	1,107	8,048	1,831
	2017	5,680	981	2,794	681	5,863	1,938

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Total farm production expenses	farms, 2022	1,252	613	190	735	34	186
	2017	1,220	528	181	853	42	134
	$1,000, 2022	510,125	217,936	8,367	270,478	630	26,309
	2017	364,108	106,110	6,257	206,294	588	13,215
Average per farm	dollars, 2022	407,448	355,524	44,036	367,997	18,536	141,447
	2017	298,449	200,965	34,571	241,846	13,989	98,622
Fertilizer, lime, and soil conditioners purchased	farms, 2022	567	303	38	485	15	75
	2017	582	269	56	565	25	59
	$1,000, 2022	52,845	45,902	1,062	37,121	10	4,637
	2017	27,980	14,597	592	23,962	32	2,627
Chemicals purchased	farms, 2022	655	335	35	510	5	88
	2017	615	266	30	591	9	63
	$1,000, 2022	29,203	27,040	280	16,441	4	2,591
	2017	17,373	11,575	183	12,525	(D)	1,574
Seeds, plants, vines, and trees purchased	farms, 2022	575	314	68	478	17	95
	2017	531	265	52	562	19	59
	$1,000, 2022	42,070	28,440	594	28,831	16	3,545
	2017	29,523	17,019	474	27,468	44	2,408
Cover crop seed purchased	farms, 2022	87	48	13	44	1	9
	2017	39	18	13	50	4	3
	$1,000, 2022	439	120	3	240	(D)	3
	2017	106	84	6	410	(Z)	2
Livestock and poultry purchased or leased	farms, 2022	222	41	36	96	14	26
	2017	235	39	32	122	19	11
	$1,000, 2022	24,424	1,388	320	27,830	11	192
	2017	28,921	391	239	22,045	34	34
Breeding livestock purchased or leased	farms, 2022	100	24	20	40	1	7
	2017	102	36	19	64	5	7
	$1,000, 2022	5,661	209	289	471	(D)	115
	2017	8,676	360	149	838	24	28
Other livestock and poultry purchased or leased	farms, 2022	138	24	21	67	13	20
	2017	168	8	21	89	16	6
	$1,000, 2022	18,764	1,180	31	27,359	(D)	77
	2017	20,245	31	90	21,207	10	6
Feed purchased	farms, 2022	412	69	92	161	23	52
	2017	428	79	87	201	22	41
	$1,000, 2022	134,940	1,057	499	37,101	73	421
	2017	92,720	790	484	28,003	51	139
Gasoline, fuels, and oils purchased	farms, 2022	1,140	555	187	666	34	180
	2017	1,049	459	177	755	42	128
	$1,000, 2022	27,858	14,761	740	11,484	40	2,069
	2017	16,320	6,990	543	8,490	56	994
Utilities	farms, 2022	840	438	138	541	24	130
	2017	826	360	111	668	30	93
	$1,000, 2022	11,523	3,903	346	4,358	38	749
	2017	8,291	2,322	298	3,444	39	426
Repairs, supplies, and maintenance costs	farms, 2022	972	489	152	592	32	163
	2017	988	413	149	723	37	117
	$1,000, 2022	25,808	15,862	1,319	18,924	73	2,346
	2017	18,539	7,550	680	12,867	111	1,023
Hired farm labor	farms, 2022	344	223	22	242	8	45
	2017	316	160	27	313	8	33
	$1,000, 2022	36,174	13,099	379	9,810	(D)	1,929
	2017	23,454	6,271	322	5,897	34	866
Contract labor	farms, 2022	72	59	9	41	1	15
	2017	80	42	9	71	3	2
	$1,000, 2022	4,424	925	297	1,382	(D)	200
	2017	1,864	671	40	1,074	(D)	(D)
Customwork and custom hauling	farms, 2022	299	150	23	246	1	49
	2017	350	175	20	253	3	28
	$1,000, 2022	5,383	2,441	193	5,531	(D)	1,244
	2017	6,265	2,916	570	3,238	(D)	183
Cash rent for land, buildings, and grazing fees	farms, 2022	382	226	40	345	2	60
	2017	332	216	42	391	6	43
	$1,000, 2022	53,039	33,140	538	39,256	(D)	2,306
	2017	43,773	17,327	483	28,320	(D)	1,245
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	97	94	3	84	-	34
	2017	101	67	5	125	3	8
	$1,000, 2022	2,365	3,073	13	1,523	-	914
	2017	1,510	1,247	18	1,651	12	(D)
Interest expense	farms, 2022	468	260	61	393	3	80
	2017	543	247	56	451	5	52
	$1,000, 2022	17,679	9,194	579	9,046	14	866
	2017	14,163	5,871	360	10,928	9	455
Secured by real estate	farms, 2022	384	184	39	291	3	51
	2017	442	181	40	355	4	40
	$1,000, 2022	12,692	5,907	280	5,944	(D)	607
	2017	9,787	4,077	222	8,154	5	354
Not secured by real estate	farms, 2022	245	195	39	266	2	54
	2017	333	143	35	292	3	31
	$1,000, 2022	4,987	3,287	299	3,102	(D)	259
	2017	4,376	1,794	138	2,773	4	101
Property taxes paid	farms, 2022	1,197	590	186	679	34	178
	2017	1,170	493	178	779	39	133
	$1,000, 2022	11,204	4,874	453	6,671	78	1,055
	2017	8,646	2,623	333	4,800	97	464

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Total farm production expenses	farms, 2022	896	598	869	801	268	1,072
	2017	937	672	893	880	311	1,086
	$1,000, 2022	196,518	171,505	555,024	207,129	81,584	338,431
	2017	153,150	161,616	315,770	170,418	58,801	229,432
Average per farm	dollars, 2022	219,328	286,798	638,693	258,588	304,416	315,700
	2017	163,447	240,500	353,606	193,656	189,071	211,264
Fertilizer, lime, and soil conditioners purchased	farms, 2022	396	330	572	439	157	590
	2017	460	392	633	517	184	544
	$1,000, 2022	20,830	16,644	37,310	30,222	14,515	67,205
	2017	14,989	14,508	23,129	19,324	8,565	35,140
Chemicals purchased	farms, 2022	463	364	623	477	166	608
	2017	493	409	651	528	194	539
	$1,000, 2022	9,804	8,240	18,571	13,505	8,661	36,056
	2017	9,253	9,045	13,183	9,007	6,302	22,443
Seeds, plants, vines, and trees purchased	farms, 2022	422	328	601	444	164	627
	2017	450	370	634	485	176	521
	$1,000, 2022	17,209	13,513	33,033	21,931	10,783	46,130
	2017	17,167	19,464	29,138	19,299	8,577	35,743
Cover crop seed purchased	farms, 2022	51	24	70	35	29	119
	2017	31	29	33	45	32	29
	$1,000, 2022	122	89	324	271	61	692
	2017	89	125	317	126	95	350
Livestock and poultry purchased or leased	farms, 2022	163	91	246	157	36	93
	2017	188	114	251	199	37	91
	$1,000, 2022	19,898	20,332	121,206	26,144	448	1,312
	2017	14,029	20,646	63,164	14,786	803	1,754
Breeding livestock purchased or leased	farms, 2022	52	51	75	68	26	56
	2017	74	67	101	65	22	63
	$1,000, 2022	2,134	3,631	3,953	1,535	202	498
	2017	1,919	2,335	4,165	346	208	369
Other livestock and poultry purchased or leased	farms, 2022	129	60	208	97	15	48
	2017	151	61	197	153	24	41
	$1,000, 2022	17,764	16,701	117,253	24,609	246	813
	2017	12,110	18,311	58,999	14,440	595	1,385
Feed purchased	farms, 2022	293	159	330	324	77	176
	2017	330	224	343	405	93	206
	$1,000, 2022	31,194	34,244	170,186	13,635	1,297	3,510
	2017	19,756	20,068	68,093	13,170	633	5,647
Gasoline, fuels, and oils purchased	farms, 2022	808	533	807	767	255	982
	2017	875	601	849	831	297	964
	$1,000, 2022	8,991	6,189	14,759	10,107	6,101	22,199
	2017	7,241	6,385	10,695	8,368	3,368	13,657
Utilities	farms, 2022	594	451	709	584	221	790
	2017	615	530	736	688	235	777
	$1,000, 2022	3,468	3,270	8,063	3,748	1,591	6,509
	2017	2,801	3,215	4,686	3,813	1,170	4,468
Repairs, supplies, and maintenance costs	farms, 2022	702	477	747	684	228	915
	2017	721	583	814	763	265	858
	$1,000, 2022	14,148	11,976	21,441	16,621	7,312	25,917
	2017	9,413	9,643	14,766	11,577	4,169	16,879
Hired farm labor	farms, 2022	204	140	304	218	82	331
	2017	216	216	319	221	84	298
	$1,000, 2022	8,243	11,374	15,982	10,158	3,825	19,315
	2017	7,294	6,089	9,690	8,702	2,194	10,680
Contract labor	farms, 2022	46	40	75	51	28	85
	2017	48	32	86	36	27	85
	$1,000, 2022	451	796	3,878	749	326	2,885
	2017	376	408	880	327	337	675
Customwork and custom hauling	farms, 2022	212	153	234	206	74	285
	2017	245	184	291	284	87	316
	$1,000, 2022	3,296	3,168	5,853	3,173	1,724	7,030
	2017	2,010	3,146	4,088	2,514	1,367	6,778
Cash rent for land, buildings, and grazing fees	farms, 2022	268	219	475	265	126	460
	2017	291	264	481	357	123	379
	$1,000, 2022	27,358	18,077	54,302	29,861	13,790	51,845
	2017	24,034	23,939	38,493	32,343	9,599	35,154
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	70	62	112	74	28	109
	2017	77	77	101	79	33	122
	$1,000, 2022	1,493	1,822	2,648	1,089	910	5,230
	2017	1,598	2,027	1,361	890	971	3,168
Interest expense	farms, 2022	302	269	429	308	141	508
	2017	392	336	458	449	150	464
	$1,000, 2022	6,261	5,855	12,349	9,279	3,138	15,099
	2017	6,402	7,787	11,786	8,914	4,412	10,602
Secured by real estate	farms, 2022	226	208	320	233	106	355
	2017	286	282	343	358	126	350
	$1,000, 2022	4,164	3,831	8,005	6,043	2,406	11,059
	2017	3,716	5,610	8,379	5,854	3,537	7,083
Not secured by real estate	farms, 2022	153	164	278	186	92	356
	2017	225	200	305	280	103	325
	$1,000, 2022	2,097	2,023	4,345	3,236	731	4,040
	2017	2,686	2,177	3,408	3,060	876	3,519
Property taxes paid	farms, 2022	829	558	774	760	250	1,011
	2017	890	617	802	836	295	1,036
	$1,000, 2022	6,454	4,117	7,511	6,034	2,390	8,523
	2017	7,234	4,889	6,211	5,422	1,981	6,083

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Total farm production expenses	farms, 2022	823	991	603	1,571	999	789
	2017	911	1,028	707	1,760	1,068	864
	$1,000, 2022	707,717	394,331	48,613	338,009	393,494	314,594
	2017	507,202	214,893	42,162	294,529	349,399	266,969
Average per farm	dollars, 2022	859,923	397,912	80,619	215,155	393,888	398,725
	2017	556,753	209,040	59,634	167,346	327,153	308,992
Fertilizer, lime, and soil conditioners purchased	farms, 2022	596	517	254	852	614	538
	2017	693	541	285	1,048	691	599
	$1,000, 2022	53,754	28,620	6,088	22,068	49,368	32,761
	2017	32,040	17,422	4,365	11,269	32,444	25,001
Chemicals purchased	farms, 2022	619	525	215	800	618	579
	2017	702	560	242	883	674	610
	$1,000, 2022	24,037	14,094	1,886	8,355	25,696	14,976
	2017	16,617	11,991	2,112	5,900	18,857	14,453
Seeds, plants, vines, and trees purchased	farms, 2022	599	506	231	777	590	517
	2017	672	504	242	840	660	568
	$1,000, 2022	47,522	22,969	3,348	12,941	34,227	26,510
	2017	39,281	19,194	4,114	11,003	35,775	29,042
Cover crop seed purchased	farms, 2022	29	53	34	93	73	52
	2017	26	37	27	78	59	38
	$1,000, 2022	103	201	172	91	367	327
	2017	68	121	111	99	187	108
Livestock and poultry purchased or leased	farms, 2022	233	162	151	497	213	148
	2017	261	206	242	568	283	196
	$1,000, 2022	108,022	24,343	4,733	41,083	33,059	54,015
	2017	103,363	13,528	5,098	34,821	46,294	45,788
Breeding livestock purchased or leased	farms, 2022	58	68	74	233	77	51
	2017	67	92	142	300	95	78
	$1,000, 2022	5,822	1,441	3,354	8,119	2,684	3,923
	2017	3,316	926	2,816	3,750	1,137	3,323
Other livestock and poultry purchased or leased	farms, 2022	193	110	96	303	155	111
	2017	223	138	134	358	224	138
	$1,000, 2022	102,201	22,901	1,379	32,964	30,375	50,092
	2017	100,046	12,602	2,283	31,071	45,157	42,466
Feed purchased	farms, 2022	308	316	325	913	385	255
	2017	352	399	432	1,083	451	310
	$1,000, 2022	194,158	131,702	11,453	115,854	61,522	62,937
	2017	124,756	55,750	5,530	118,593	54,833	44,783
Gasoline, fuels, and oils purchased	farms, 2022	770	899	578	1,537	928	730
	2017	873	939	686	1,709	1,001	761
	$1,000, 2022	18,751	19,699	3,181	15,520	17,433	11,321
	2017	12,719	11,188	1,998	10,448	13,647	9,671
Utilities	farms, 2022	696	635	397	1,218	802	609
	2017	752	699	512	1,471	858	616
	$1,000, 2022	8,738	12,560	1,244	11,321	6,682	5,444
	2017	7,002	4,498	1,211	8,231	5,058	4,019
Repairs, supplies, and maintenance costs	farms, 2022	742	781	498	1,383	888	685
	2017	827	810	582	1,590	929	721
	$1,000, 2022	28,129	19,327	4,506	25,122	24,005	16,674
	2017	22,027	11,052	4,427	18,689	17,034	13,773
Hired farm labor	farms, 2022	337	218	89	335	304	281
	2017	363	241	120	463	389	295
	$1,000, 2022	27,467	27,751	1,861	18,928	19,645	13,861
	2017	15,145	13,858	1,516	16,842	11,593	7,147
Contract labor	farms, 2022	79	54	19	75	100	54
	2017	142	36	36	202	114	61
	$1,000, 2022	3,021	1,210	118	4,279	1,989	1,024
	2017	3,676	1,081	62	1,697	2,875	711
Customwork and custom hauling	farms, 2022	392	229	136	506	411	264
	2017	441	275	153	631	430	324
	$1,000, 2022	14,650	7,194	822	9,561	11,028	5,963
	2017	10,562	3,209	1,075	9,552	7,119	4,113
Cash rent for land, buildings, and grazing fees	farms, 2022	465	292	170	457	422	391
	2017	508	313	204	472	455	430
	$1,000, 2022	82,098	28,988	2,212	7,956	54,413	32,317
	2017	63,152	21,465	3,140	5,745	58,663	34,877
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	110	103	38	144	130	111
	2017	148	95	33	191	154	110
	$1,000, 2022	7,278	2,638	331	1,050	4,051	2,134
	2017	4,389	672	299	1,789	4,901	1,182
Interest expense	farms, 2022	452	382	203	584	477	392
	2017	514	432	233	778	574	497
	$1,000, 2022	16,374	8,842	1,850	9,882	13,667	11,580
	2017	16,722	8,622	2,512	12,898	14,811	13,270
Secured by real estate	farms, 2022	329	314	157	448	352	291
	2017	360	350	186	646	444	379
	$1,000, 2022	10,383	5,044	1,185	6,990	8,662	7,962
	2017	10,696	5,991	1,635	8,893	9,300	8,480
Not secured by real estate	farms, 2022	285	212	125	309	274	252
	2017	355	260	151	440	387	327
	$1,000, 2022	5,991	3,798	664	2,892	5,005	3,618
	2017	6,026	2,630	878	4,005	5,511	4,789
Property taxes paid	farms, 2022	745	928	592	1,520	897	733
	2017	785	976	700	1,718	1,002	790
	$1,000, 2022	8,818	8,281	2,298	7,069	9,061	5,753
	2017	6,828	5,892	2,190	5,813	8,544	4,239

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Total farm production expenses	farms, 2022	660	938	435	1,102	2,497	322
	2017	689	885	505	1,139	2,544	409
	$1,000, 2022	443,965	530,125	241,418	252,185	390,047	82,123
	2017	264,658	418,906	199,395	187,497	281,284	59,967
Average per farm	dollars, 2022	672,675	565,165	554,984	228,843	156,206	255,039
	2017	384,119	473,340	394,841	164,616	110,568	146,619
Fertilizer, lime, and soil conditioners purchased	farms, 2022	456	650	304	600	1,190	164
	2017	536	646	367	622	1,291	248
	$1,000, 2022	30,097	35,410	42,129	38,234	51,583	16,155
	2017	17,703	24,409	25,671	20,201	31,225	11,036
Chemicals purchased	farms, 2022	468	686	310	641	1,318	174
	2017	536	672	360	600	1,277	241
	$1,000, 2022	15,508	19,736	23,527	15,752	25,522	11,239
	2017	10,914	15,037	20,232	10,987	15,606	6,104
Seeds, plants, vines, and trees purchased	farms, 2022	463	657	310	612	1,207	163
	2017	532	614	347	548	1,154	221
	$1,000, 2022	25,642	31,242	36,193	23,355	33,993	8,853
	2017	22,162	32,318	31,026	18,919	30,947	8,980
Cover crop seed purchased	farms, 2022	30	42	69	123	187	13
	2017	21	46	35	87	152	21
	$1,000, 2022	140	275	241	362	411	47
	2017	38	501	139	290	330	52
Livestock and poultry purchased or leased	farms, 2022	159	251	45	220	434	42
	2017	162	271	57	297	520	80
	$1,000, 2022	41,142	106,569	2,800	11,764	18,885	577
	2017	36,404	81,960	1,650	10,278	14,596	1,026
Breeding livestock purchased or leased	farms, 2022	22	94	25	103	244	21
	2017	49	113	36	142	314	59
	$1,000, 2022	5,797	7,396	(D)	1,049	2,955	101
	2017	4,663	7,184	192	686	3,729	561
Other livestock and poultry purchased or leased	farms, 2022	145	190	26	147	244	24
	2017	127	206	31	181	269	33
	$1,000, 2022	35,345	99,173	(D)	10,715	15,929	476
	2017	31,741	74,776	1,458	9,592	10,867	465
Feed purchased	farms, 2022	244	362	91	480	883	83
	2017	267	369	115	635	1,037	147
	$1,000, 2022	138,895	143,299	6,780	30,844	71,084	1,170
	2017	64,981	103,232	6,235	24,785	44,928	738
Gasoline, fuels, and oils purchased	farms, 2022	630	876	418	1,064	2,345	286
	2017	666	822	490	1,051	2,281	394
	$1,000, 2022	14,704	18,364	13,891	13,213	20,915	5,360
	2017	8,604	13,176	10,523	8,301	13,863	4,252
Utilities	farms, 2022	571	786	362	801	1,675	232
	2017	587	751	429	805	1,707	344
	$1,000, 2022	7,287	7,584	3,804	8,024	9,527	1,394
	2017	4,651	7,052	3,129	4,019	8,190	1,498
Repairs, supplies, and maintenance costs	farms, 2022	613	829	385	915	1,994	254
	2017	634	804	455	965	2,077	366
	$1,000, 2022	19,409	23,144	16,651	17,432	29,933	6,875
	2017	11,729	18,061	14,795	15,528	22,398	5,101
Hired farm labor	farms, 2022	229	342	190	279	438	90
	2017	233	318	225	299	494	104
	$1,000, 2022	23,851	25,357	12,584	20,006	29,344	4,634
	2017	10,173	11,595	10,592	13,117	20,455	2,119
Contract labor	farms, 2022	74	64	32	72	121	35
	2017	74	105	33	61	95	23
	$1,000, 2022	11,441	2,445	1,832	1,293	3,943	554
	2017	1,491	1,985	552	2,488	941	225
Customwork and custom hauling	farms, 2022	286	389	110	369	537	86
	2017	258	366	148	400	603	111
	$1,000, 2022	7,878	7,991	1,676	3,959	8,388	1,766
	2017	4,886	7,061	2,833	3,972	6,022	1,121
Cash rent for land, buildings, and grazing fees	farms, 2022	320	491	250	355	727	128
	2017	368	474	266	340	727	136
	$1,000, 2022	39,543	46,137	43,367	30,380	34,570	13,444
	2017	32,878	43,139	38,435	24,458	26,939	7,030
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	90	108	97	96	181	22
	2017	97	139	128	65	227	30
	$1,000, 2022	3,151	3,397	4,198	1,937	3,052	820
	2017	1,439	2,681	4,111	1,084	2,828	830
Interest expense	farms, 2022	360	496	257	422	791	131
	2017	398	550	281	450	997	197
	$1,000, 2022	10,412	13,953	11,673	10,397	14,022	2,712
	2017	9,560	14,733	9,984	8,268	15,186	2,587
Secured by real estate	farms, 2022	248	343	190	325	599	108
	2017	312	422	200	352	777	145
	$1,000, 2022	4,897	8,875	8,327	7,026	8,867	1,898
	2017	5,871	9,315	6,602	5,734	10,250	1,727
Not secured by real estate	farms, 2022	232	311	165	258	475	88
	2017	263	384	205	290	631	122
	$1,000, 2022	5,515	5,078	3,346	3,371	5,155	814
	2017	3,689	5,419	3,382	2,534	4,936	860
Property taxes paid	farms, 2022	602	850	392	1,048	2,387	318
	2017	621	815	461	1,054	2,457	390
	$1,000, 2022	6,170	8,190	5,681	8,381	11,157	2,540
	2017	7,411	6,115	4,012	8,459	8,802	2,453

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Total farm production expenses	farms, 2022	728	529	1,223	821	47	274
	2017	823	595	1,258	837	55	263
	$1,000, 2022	40,723	284,775	537,941	180,411	3,231	82,605
	2017	32,873	247,189	378,359	169,412	3,207	51,104
Average per farm	dollars, 2022	55,938	538,327	439,854	219,746	68,751	301,477
	2017	39,942	415,444	300,762	202,404	58,308	194,310
Fertilizer, lime, and soil conditioners purchased	farms, 2022	310	335	782	409	21	184
	2017	351	400	745	457	36	176
	$1,000, 2022	4,440	18,786	90,958	23,917	132	13,726
	2017	2,207	12,549	49,291	19,486	48	10,066
Chemicals purchased	farms, 2022	230	349	816	435	19	188
	2017	271	414	740	456	24	170
	$1,000, 2022	1,329	8,254	57,695	11,172	9	7,926
	2017	659	7,847	38,002	9,656	27	5,064
Seeds, plants, vines, and trees purchased	farms, 2022	281	326	795	424	40	181
	2017	256	353	716	418	43	157
	$1,000, 2022	2,598	15,349	73,466	19,212	405	11,034
	2017	1,818	15,224	55,313	18,152	177	7,278
Cover crop seed purchased	farms, 2022	55	34	148	41	7	14
	2017	23	51	130	51	4	10
	$1,000, 2022	62	161	822	112	1	46
	2017	47	126	503	71	1	19
Livestock and poultry purchased or leased	farms, 2022	154	139	147	150	1	41
	2017	258	197	130	162	5	41
	$1,000, 2022	873	42,602	2,671	11,655	(D)	1,816
	2017	1,817	48,342	6,142	13,560	16	464
Breeding livestock purchased or leased	farms, 2022	90	73	92	69	-	30
	2017	151	103	82	80	1	36
	$1,000, 2022	463	5,731	1,014	1,429	-	364
	2017	713	5,161	651	1,069	(D)	(D)
Other livestock and poultry purchased or leased	farms, 2022	88	87	84	97	1	25
	2017	150	130	69	112	5	8
	$1,000, 2022	410	36,871	1,658	10,225	(D)	1,453
	2017	1,104	43,180	5,491	12,492	(D)	(D)
Feed purchased	farms, 2022	414	282	265	266	2	76
	2017	476	330	262	303	7	76
	$1,000, 2022	6,545	80,379	2,978	17,529	(D)	3,816
	2017	6,929	65,031	4,534	21,063	89	1,366
Gasoline, fuels, and oils purchased	farms, 2022	713	515	1,144	754	36	259
	2017	781	557	1,158	731	46	253
	$1,000, 2022	3,455	11,613	32,441	9,828	312	6,012
	2017	2,147	7,582	20,042	10,809	149	2,956
Utilities	farms, 2022	534	436	952	544	26	219
	2017	582	501	945	581	42	196
	$1,000, 2022	1,647	5,531	8,531	3,688	142	1,803
	2017	1,375	5,201	6,902	4,158	188	1,144
Repairs, supplies, and maintenance costs	farms, 2022	624	486	1,046	641	33	252
	2017	685	524	1,047	672	41	227
	$1,000, 2022	4,972	13,258	44,112	15,980	127	7,268
	2017	3,141	10,224	29,061	11,461	116	3,787
Hired farm labor	farms, 2022	127	172	477	189	28	98
	2017	147	210	464	257	29	95
	$1,000, 2022	4,174	18,426	46,368	12,596	1,406	7,193
	2017	3,145	12,585	31,277	10,857	1,760	2,891
Contract labor	farms, 2022	19	48	105	49	4	15
	2017	23	48	87	49	3	25
	$1,000, 2022	132	1,974	2,525	747	(D)	318
	2017	75	1,449	1,184	1,123	75	363
Customwork and custom hauling	farms, 2022	119	174	353	233	2	89
	2017	150	217	352	267	4	77
	$1,000, 2022	876	5,574	11,512	3,867	(D)	1,848
	2017	816	3,976	8,915	4,258	(D)	778
Cash rent for land, buildings, and grazing fees	farms, 2022	194	240	670	254	12	140
	2017	183	266	578	253	16	117
	$1,000, 2022	1,748	20,889	87,539	22,527	26	8,040
	2017	916	22,789	65,211	17,460	31	7,349
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	47	59	196	92	3	35
	2017	41	74	191	95	1	38
	$1,000, 2022	172	2,398	7,977	1,026	3	1,213
	2017	127	1,743	5,044	1,987	(D)	484
Interest expense	farms, 2022	223	284	609	348	5	130
	2017	310	329	614	377	17	130
	$1,000, 2022	2,115	7,650	20,156	7,207	5	2,941
	2017	2,274	8,320	17,284	7,791	124	2,266
Secured by real estate	farms, 2022	181	222	449	253	-	86
	2017	235	264	443	295	12	98
	$1,000, 2022	1,374	5,143	13,846	5,030	-	1,665
	2017	1,600	4,909	11,549	5,315	42	1,305
Not secured by real estate	farms, 2022	131	167	403	203	5	96
	2017	160	221	421	254	12	95
	$1,000, 2022	742	2,507	6,310	2,177	5	1,276
	2017	675	3,412	5,736	2,477	82	961
Property taxes paid	farms, 2022	715	511	1,105	765	35	255
	2017	806	559	1,148	813	37	241
	$1,000, 2022	2,429	5,643	12,405	5,795	140	1,784
	2017	2,068	3,473	10,805	4,720	145	1,545

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Total farm production expenses	farms, 2022	1,323	931	1,111	573	751	821
	2017	1,134	1,026	1,242	701	842	779
	$1,000, 2022	600,313	589,067	258,143	427,209	174,553	23,456
	2017	355,740	485,649	171,393	329,188	111,744	15,752
Average per farm	dollars, 2022	453,752	632,725	232,352	745,565	232,428	28,570
	2017	313,704	473,342	137,998	469,598	132,713	20,221
Fertilizer, lime, and soil conditioners purchased	farms, 2022	915	680	559	402	361	247
	2017	834	729	681	551	375	217
	$1,000, 2022	61,000	75,866	28,696	25,243	33,402	644
	2017	34,423	45,651	13,884	16,847	18,012	499
Chemicals purchased	farms, 2022	972	703	626	414	384	118
	2017	838	737	660	564	350	82
	$1,000, 2022	29,008	41,560	12,986	12,714	16,311	331
	2017	20,706	27,558	7,484	9,678	12,320	151
Seeds, plants, vines, and trees purchased	farms, 2022	945	680	605	379	365	289
	2017	808	709	618	504	349	215
	$1,000, 2022	53,262	59,485	18,060	22,539	18,444	925
	2017	40,672	50,080	14,646	21,894	14,786	1,052
Cover crop seed purchased	farms, 2022	56	84	95	43	40	55
	2017	57	101	89	46	39	64
	$1,000, 2022	296	382	381	135	188	10
	2017	304	448	159	76	68	27
Livestock and poultry purchased or leased	farms, 2022	261	149	225	222	107	232
	2017	257	182	288	298	112	243
	$1,000, 2022	103,366	49,088	21,498	99,573	7,218	602
	2017	59,485	49,811	18,805	93,622	3,542	804
Breeding livestock purchased or leased	farms, 2022	58	65	71	60	57	88
	2017	66	82	116	105	74	100
	$1,000, 2022	4,870	4,097	400	3,563	972	296
	2017	837	4,110	1,430	2,622	963	382
Other livestock and poultry purchased or leased	farms, 2022	232	96	176	175	56	166
	2017	212	122	221	217	41	173
	$1,000, 2022	98,496	44,991	21,098	96,010	6,245	306
	2017	58,648	45,700	17,375	91,000	2,580	422
Feed purchased	farms, 2022	379	240	411	314	246	459
	2017	369	273	529	410	260	472
	$1,000, 2022	127,652	69,324	47,348	132,188	11,594	3,927
	2017	56,211	84,427	31,758	80,285	6,289	2,444
Gasoline, fuels, and oils purchased	farms, 2022	1,224	860	1,046	552	702	786
	2017	1,020	939	1,130	673	780	735
	$1,000, 2022	20,448	26,102	12,527	12,228	10,600	2,464
	2017	12,934	16,578	6,582	8,395	6,975	1,282
Utilities	farms, 2022	1,038	752	766	489	573	537
	2017	938	839	826	621	601	492
	$1,000, 2022	7,731	9,140	5,434	5,432	4,181	1,410
	2017	5,088	6,650	3,943	4,548	2,832	904
Repairs, supplies, and maintenance costs	farms, 2022	1,163	812	939	513	658	698
	2017	1,000	905	1,009	652	721	646
	$1,000, 2022	29,914	31,406	17,794	16,353	14,182	2,868
	2017	18,223	22,165	12,350	11,722	8,077	1,862
Hired farm labor	farms, 2022	463	364	232	221	205	123
	2017	410	425	266	290	198	101
	$1,000, 2022	19,386	35,003	17,481	15,532	11,267	2,357
	2017	9,298	24,289	9,926	7,148	6,087	1,450
Contract labor	farms, 2022	96	88	53	42	55	37
	2017	103	99	65	95	40	21
	$1,000, 2022	6,041	4,039	3,587	1,227	1,219	139
	2017	1,105	4,518	970	1,451	496	70
Customwork and custom hauling	farms, 2022	400	426	314	294	187	85
	2017	394	419	348	344	168	70
	$1,000, 2022	9,450	16,126	7,503	8,445	4,311	255
	2017	5,982	10,840	4,136	6,522	3,063	171
Cash rent for land, buildings, and grazing fees	farms, 2022	719	516	328	301	266	102
	2017	590	551	381	373	226	106
	$1,000, 2022	74,014	92,642	26,401	30,128	17,621	1,241
	2017	50,900	78,432	21,176	33,285	9,726	588
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	156	120	118	79	83	29
	2017	131	143	93	95	75	37
	$1,000, 2022	2,639	6,155	2,259	3,373	3,163	95
	2017	1,011	3,361	743	2,032	1,802	97
Interest expense	farms, 2022	672	511	420	313	310	206
	2017	646	600	445	437	393	204
	$1,000, 2022	14,969	22,432	11,408	17,636	5,836	1,825
	2017	13,900	19,716	7,379	12,695	5,718	1,129
Secured by real estate	farms, 2022	459	361	304	232	242	152
	2017	492	453	341	343	302	150
	$1,000, 2022	9,255	14,323	7,376	9,550	3,734	1,217
	2017	9,567	13,290	5,190	8,070	4,059	947
Not secured by real estate	farms, 2022	461	354	249	199	192	135
	2017	439	393	251	271	209	110
	$1,000, 2022	5,714	8,109	4,033	8,086	2,101	608
	2017	4,332	6,426	2,188	4,625	1,659	181
Property taxes paid	farms, 2022	1,170	863	1,042	541	727	804
	2017	1,035	954	1,169	638	824	767
	$1,000, 2022	9,946	12,479	7,571	5,507	4,665	2,288
	2017	7,698	8,507	6,065	3,603	4,237	1,738

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Total farm production expenses	farms, 2022	624	494	860	2,695	721	500
	2017	740	501	898	2,951	746	553
	$1,000, 2022	75,773	85,746	332,329	757,374	295,463	421,907
	2017	66,317	70,062	264,159	591,709	199,383	272,985
Average per farm	dollars, 2022	121,432	173,575	386,429	281,029	409,796	843,814
	2017	89,618	139,844	294,164	200,511	267,269	493,643
Fertilizer, lime, and soil conditioners purchased	farms, 2022	298	187	561	1,632	352	294
	2017	386	235	602	1,925	390	325
	$1,000, 2022	8,484	11,952	44,746	51,552	30,833	34,315
	2017	5,107	9,541	23,166	27,345	18,223	17,785
Chemicals purchased	farms, 2022	286	209	579	1,701	370	305
	2017	369	192	606	1,816	378	339
	$1,000, 2022	4,457	9,162	23,899	23,016	17,791	15,799
	2017	3,013	5,351	13,092	16,091	10,204	11,904
Seeds, plants, vines, and trees purchased	farms, 2022	307	216	547	1,557	366	286
	2017	317	205	589	1,660	371	309
	$1,000, 2022	7,913	8,552	33,053	40,353	26,255	26,694
	2017	5,931	7,957	28,039	29,915	20,303	22,464
Cover crop seed purchased	farms, 2022	39	40	63	180	66	55
	2017	27	59	51	172	25	33
	$1,000, 2022	37	119	298	540	607	248
	2017	11	159	1,076	292	111	80
Livestock and poultry purchased or leased	farms, 2022	158	119	171	774	152	80
	2017	188	113	207	985	175	130
	$1,000, 2022	3,729	7,878	23,163	63,912	29,754	39,137
	2017	7,671	4,025	32,895	64,181	21,239	25,452
Breeding livestock purchased or leased	farms, 2022	57	30	54	318	46	28
	2017	83	38	64	424	84	60
	$1,000, 2022	344	54	2,418	8,985	319	398
	2017	592	213	2,069	16,311	797	1,246
Other livestock and poultry purchased or leased	farms, 2022	124	112	138	565	131	68
	2017	131	96	161	672	122	103
	$1,000, 2022	3,385	7,824	20,745	54,927	29,435	38,739
	2017	7,080	3,812	30,826	47,870	20,442	24,207
Feed purchased	farms, 2022	338	264	312	1,502	255	142
	2017	370	243	390	1,860	306	186
	$1,000, 2022	6,609	5,495	38,102	226,778	50,221	154,920
	2017	6,931	3,602	44,072	184,329	36,946	76,400
Gasoline, fuels, and oils purchased	farms, 2022	596	456	809	2,594	667	453
	2017	708	471	854	2,797	670	483
	$1,000, 2022	4,849	3,761	16,583	36,765	11,008	14,807
	2017	3,872	3,594	10,173	25,147	7,858	8,414
Utilities	farms, 2022	420	318	680	2,119	518	357
	2017	531	335	721	2,365	534	390
	$1,000, 2022	1,877	3,015	5,607	21,337	9,179	4,728
	2017	1,626	2,895	4,178	18,336	5,344	5,543
Repairs, supplies, and maintenance costs	farms, 2022	521	387	748	2,355	595	397
	2017	652	400	771	2,574	610	437
	$1,000, 2022	6,040	7,753	22,248	55,448	17,397	17,111
	2017	5,498	5,737	13,341	41,307	10,090	13,296
Hired farm labor	farms, 2022	136	101	244	725	199	201
	2017	189	101	267	868	204	201
	$1,000, 2022	6,078	10,487	20,390	64,650	23,315	25,365
	2017	5,071	8,403	11,524	41,665	9,781	15,429
Contract labor	farms, 2022	50	20	52	221	42	37
	2017	35	29	54	277	90	31
	$1,000, 2022	420	748	1,956	11,998	6,370	430
	2017	324	936	2,116	3,460	1,813	1,444
Customwork and custom hauling	farms, 2022	123	94	300	1,064	224	145
	2017	204	79	348	1,357	272	174
	$1,000, 2022	1,295	771	5,474	24,259	4,461	7,577
	2017	1,280	1,581	3,396	19,495	3,852	4,280
Cash rent for land, buildings, and grazing fees	farms, 2022	174	105	355	895	236	225
	2017	207	120	385	867	255	235
	$1,000, 2022	11,895	5,787	44,013	41,366	28,144	38,218
	2017	7,131	3,518	42,347	24,732	25,720	29,680
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	55	35	92	289	78	75
	2017	49	52	86	371	82	90
	$1,000, 2022	681	387	3,164	4,082	2,284	4,538
	2017	234	587	1,865	3,775	1,542	3,836
Interest expense	farms, 2022	191	121	402	1,102	292	256
	2017	233	135	454	1,337	345	280
	$1,000, 2022	3,460	2,255	13,925	22,358	15,305	9,221
	2017	4,538	3,450	11,178	24,675	10,923	8,767
Secured by real estate	farms, 2022	144	95	304	849	232	162
	2017	180	105	366	1,044	279	181
	$1,000, 2022	2,488	1,515	10,353	14,974	12,210	6,406
	2017	3,724	1,815	7,961	16,954	8,595	5,486
Not secured by real estate	farms, 2022	122	79	236	680	183	162
	2017	146	65	269	794	225	200
	$1,000, 2022	972	741	3,573	7,384	3,095	2,814
	2017	814	1,636	3,217	7,721	2,328	3,281
Property taxes paid	farms, 2022	591	470	815	2,572	685	463
	2017	702	469	840	2,846	712	498
	$1,000, 2022	3,824	2,444	10,042	16,998	7,842	5,199
	2017	4,241	2,415	7,809	15,210	6,255	4,473

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Total farm production expenses	farms, 2022	708	1,529	358	743	442	622
	2017	760	1,604	411	809	516	729
	$1,000, 2022	316,031	276,843	197,283	240,549	78,202	284,379
	2017	233,901	140,128	175,500	150,918	40,728	222,787
Average per farm	dollars, 2022	446,372	181,061	551,071	323,754	176,929	457,201
	2017	307,764	87,361	427,006	186,549	78,930	305,606
Fertilizer, lime, and soil conditioners purchased	farms, 2022	396	800	206	508	204	408
	2017	475	942	274	579	269	477
	$1,000, 2022	39,001	18,735	26,482	22,026	8,696	34,108
	2017	22,530	8,906	19,401	13,822	4,324	15,562
Chemicals purchased	farms, 2022	435	796	217	517	183	427
	2017	476	861	283	527	189	487
	$1,000, 2022	16,748	8,145	12,620	9,741	6,526	16,788
	2017	10,929	4,703	12,429	6,409	2,095	11,335
Seeds, plants, vines, and trees purchased	farms, 2022	433	763	223	512	186	415
	2017	461	775	270	490	179	460
	$1,000, 2022	29,935	11,374	23,486	15,749	7,198	27,040
	2017	23,277	8,225	23,810	12,771	3,584	20,642
Cover crop seed purchased	farms, 2022	62	100	59	110	37	56
	2017	34	94	12	88	47	21
	$1,000, 2022	335	159	359	257	59	148
	2017	97	157	156	139	132	116
Livestock and poultry purchased or leased	farms, 2022	90	333	23	168	101	123
	2017	116	445	36	232	143	203
	$1,000, 2022	23,779	15,120	5,507	11,235	5,509	31,879
	2017	21,941	10,235	6,828	4,293	1,616	37,613
Breeding livestock purchased or leased	farms, 2022	50	183	7	91	68	29
	2017	47	257	15	134	83	61
	$1,000, 2022	2,826	2,140	70	1,480	(D)	3,403
	2017	480	1,343	358	1,605	374	1,445
Other livestock and poultry purchased or leased	farms, 2022	47	210	16	106	51	103
	2017	73	260	25	128	82	164
	$1,000, 2022	20,953	12,979	5,437	9,755	(D)	28,476
	2017	21,461	8,891	6,470	2,688	1,242	36,168
Feed purchased	farms, 2022	149	784	38	411	229	194
	2017	194	902	50	448	279	270
	$1,000, 2022	65,268	87,105	24,731	59,330	15,566	49,830
	2017	54,798	38,501	19,582	26,284	8,046	47,929
Gasoline, fuels, and oils purchased	farms, 2022	617	1,460	331	712	431	585
	2017	639	1,514	387	790	491	657
	$1,000, 2022	17,766	12,095	9,437	13,104	4,206	11,750
	2017	10,796	7,306	7,675	7,278	2,839	8,143
Utilities	farms, 2022	496	1,041	269	601	315	494
	2017	547	1,173	348	644	353	563
	$1,000, 2022	4,799	7,737	2,977	5,651	2,424	3,995
	2017	3,917	5,060	2,846	4,220	1,927	3,899
Repairs, supplies, and maintenance costs	farms, 2022	575	1,325	299	657	375	549
	2017	588	1,422	356	722	437	626
	$1,000, 2022	18,398	40,084	12,031	21,505	5,155	15,212
	2017	11,988	12,652	9,136	12,381	3,420	10,803
Hired farm labor	farms, 2022	213	290	134	226	98	208
	2017	225	398	153	234	96	284
	$1,000, 2022	20,736	23,985	12,642	21,036	7,221	14,255
	2017	13,457	9,471	10,061	14,628	2,787	7,435
Contract labor	farms, 2022	37	56	19	53	40	54
	2017	43	72	17	55	19	72
	$1,000, 2022	1,581	3,568	293	1,226	878	730
	2017	818	852	178	810	28	1,653
Customwork and custom hauling	farms, 2022	222	424	100	350	99	259
	2017	256	498	129	389	121	316
	$1,000, 2022	6,019	6,009	4,373	8,991	1,717	4,511
	2017	4,959	4,851	3,902	4,940	1,252	3,599
Cash rent for land, buildings, and grazing fees	farms, 2022	271	432	168	298	114	240
	2017	284	428	215	290	126	309
	$1,000, 2022	31,126	9,740	34,022	17,797	4,015	37,142
	2017	23,930	5,794	27,378	15,253	1,331	24,692
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	95	134	62	54	33	81
	2017	99	169	78	83	43	88
	$1,000, 2022	1,497	1,299	3,837	1,003	1,182	2,506
	2017	1,803	664	5,429	1,380	931	1,009
Interest expense	farms, 2022	345	560	186	359	147	286
	2017	402	651	231	386	193	401
	$1,000, 2022	17,175	6,542	6,845	9,036	1,406	10,096
	2017	9,711	6,795	9,961	7,531	1,788	10,268
Secured by real estate	farms, 2022	267	483	143	271	118	215
	2017	307	532	168	295	143	309
	$1,000, 2022	12,695	4,742	5,004	6,747	766	6,331
	2017	6,429	4,706	7,746	5,030	1,023	6,995
Not secured by real estate	farms, 2022	208	286	98	205	97	189
	2017	296	368	161	244	113	276
	$1,000, 2022	4,480	1,800	1,840	2,289	639	3,765
	2017	3,282	2,089	2,215	2,501	765	3,273
Property taxes paid	farms, 2022	660	1,475	331	711	434	579
	2017	690	1,573	352	752	499	675
	$1,000, 2022	7,794	5,870	4,334	6,107	1,955	7,602
	2017	5,753	5,144	4,227	5,527	1,652	7,046

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Total farm production expenses	farms, 2022	525	512	358	993	1,310	847
	2017	612	497	391	1,034	1,338	852
	$1,000, 2022	49,390	289,489	205,250	330,648	213,837	315,360
	2017	52,724	218,379	163,696	194,638	173,024	224,539
Average per farm	dollars, 2022	94,076	565,407	573,323	332,979	163,234	372,325
	2017	86,151	439,395	418,661	188,238	129,316	263,543
Fertilizer, lime, and soil conditioners purchased	farms, 2022	251	327	231	625	660	526
	2017	341	335	271	655	743	554
	$1,000, 2022	5,150	31,410	35,556	25,882	21,897	39,892
	2017	4,809	20,091	24,323	13,167	13,742	24,130
Chemicals purchased	farms, 2022	266	353	247	607	675	558
	2017	294	340	271	588	689	570
	$1,000, 2022	2,268	11,688	20,323	12,799	10,424	18,331
	2017	2,170	8,862	16,302	6,324	6,353	15,373
Seeds, plants, vines, and trees purchased	farms, 2022	273	342	242	600	655	522
	2017	301	342	260	577	643	535
	$1,000, 2022	4,349	23,852	30,748	22,120	17,646	28,446
	2017	5,139	21,780	27,561	12,747	17,361	27,900
Cover crop seed purchased	farms, 2022	29	26	51	157	99	48
	2017	79	18	37	128	57	44
	$1,000, 2022	34	140	393	1,558	253	206
	2017	39	56	124	164	115	194
Livestock and poultry purchased or leased	farms, 2022	134	107	17	253	317	129
	2017	142	109	28	290	327	149
	$1,000, 2022	861	36,335	173	12,191	12,905	31,025
	2017	704	37,757	168	14,341	8,399	26,809
Breeding livestock purchased or leased	farms, 2022	38	34	9	122	90	50
	2017	59	31	18	182	120	69
	$1,000, 2022	167	5,847	22	4,760	2,752	1,123
	2017	185	242	150	2,580	761	2,002
Other livestock and poultry purchased or leased	farms, 2022	106	83	9	163	254	90
	2017	106	93	11	159	249	98
	$1,000, 2022	693	30,488	151	7,431	10,153	29,903
	2017	519	37,515	18	11,761	7,638	24,807
Feed purchased	farms, 2022	245	141	54	552	627	214
	2017	314	155	43	598	667	234
	$1,000, 2022	2,424	62,203	577	77,232	37,863	50,292
	2017	2,292	42,155	209	46,348	24,868	27,413
Gasoline, fuels, and oils purchased	farms, 2022	483	486	324	965	1,231	798
	2017	595	469	352	977	1,242	778
	$1,000, 2022	2,364	10,161	11,319	17,835	10,904	14,229
	2017	2,324	6,668	9,891	8,741	8,234	8,849
Utilities	farms, 2022	339	414	278	754	949	669
	2017	410	385	308	811	904	648
	$1,000, 2022	1,586	4,380	2,809	7,922	6,701	4,922
	2017	1,616	3,466	2,152	4,990	4,990	4,046
Repairs, supplies, and maintenance costs	farms, 2022	440	443	299	893	1,079	713
	2017	534	461	332	909	1,122	696
	$1,000, 2022	4,965	14,553	17,042	27,862	16,973	17,605
	2017	4,266	9,542	12,767	15,713	11,781	13,576
Hired farm labor	farms, 2022	151	173	144	249	301	259
	2017	206	175	153	306	278	271
	$1,000, 2022	9,617	13,420	12,482	33,096	17,704	13,423
	2017	10,271	4,626	8,882	16,887	21,209	5,689
Contract labor	farms, 2022	59	31	34	52	82	65
	2017	45	63	44	59	73	34
	$1,000, 2022	1,494	1,294	981	1,979	2,668	1,665
	2017	813	1,621	529	809	2,054	727
Customwork and custom hauling	farms, 2022	100	157	93	386	282	236
	2017	129	206	109	443	432	256
	$1,000, 2022	422	2,422	3,266	8,774	5,383	7,513
	2017	504	5,044	2,033	5,686	4,247	3,397
Cash rent for land, buildings, and grazing fees	farms, 2022	152	281	181	382	372	375
	2017	182	261	215	378	418	377
	$1,000, 2022	3,406	37,986	38,256	24,036	19,768	42,411
	2017	4,488	28,255	30,742	15,276	19,169	35,912
Rent and lease expenses for machinery, equipment, and farm share of vehicles	farms, 2022	49	84	61	93	122	104
	2017	49	85	85	86	114	101
	$1,000, 2022	519	3,056	5,188	1,335	1,094	2,096
	2017	391	1,266	5,714	987	1,137	1,564
Interest expense	farms, 2022	128	272	176	430	429	451
	2017	201	296	226	466	502	451
	$1,000, 2022	1,597	9,797	8,796	14,193	6,131	11,240
	2017	2,547	9,442	8,521	8,947	9,404	10,918
Secured by real estate	farms, 2022	84	200	125	355	335	326
	2017	145	233	165	351	427	325
	$1,000, 2022	1,113	7,008	6,205	10,380	4,529	7,198
	2017	1,929	6,566	5,641	6,804	7,378	6,964
Not secured by real estate	farms, 2022	80	176	119	274	244	305
	2017	128	206	157	301	305	331
	$1,000, 2022	484	2,789	2,591	3,813	1,603	4,042
	2017	618	2,876	2,880	2,143	2,025	3,954
Property taxes paid	farms, 2022	461	468	335	937	1,266	784
	2017	539	456	356	949	1,279	782
	$1,000, 2022	2,929	5,158	5,169	7,282	6,826	7,928
	2017	2,959	5,685	4,143	6,258	5,788	5,809

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Total farm production expenses - Con.						
Medical supplies, veterinary, and custom services for livestock	farms, 2022	19,351	153	97	243	241
	2017	24,677	226	144	315	287
	$1,000, 2022	255,043	184	136	2,351	445
	2017	189,609	198	737	1,581	424
All other production expenses	farms, 2022	44,226	255	198	515	321
	2017	38,536	195	155	405	202
	$1,000, 2022	1,200,596	1,419	3,474	14,545	2,050
	2017	833,806	696	2,576	8,526	950
Production expenses paid by landlords [1]	farms, 2022	2,062	4	1	16	20
	2017	1,960	5	8	23	8
	$1,000, 2022	65,113	(D)	(D)	918	328
	2017	40,456	(D)	18	163	43
Depreciation expenses claimed	farms, 2022	41,075	255	181	486	300
	2017	37,853	213	140	401	207
	$1,000, 2022	2,240,389	3,438	6,960	26,668	4,398
	2017	1,467,973	2,233	4,604	13,830	3,215

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Total farm production expenses - Con.						
Medical supplies, veterinary, and custom services for livestock	farms, 2022	283	64	215	260	216
	2017	385	96	255	340	263
	$1,000, 2022	5,457	757	7,318	5,556	246
	2017	2,361	1,301	5,125	3,282	267
All other production expenses	farms, 2022	461	322	757	766	208
	2017	434	287	645	711	190
	$1,000, 2022	10,418	9,724	37,080	25,672	784
	2017	7,185	7,900	14,793	15,022	534
Production expenses paid by landlords [1]	farms, 2022	10	20	40	26	-
	2017	13	21	24	25	6
	$1,000, 2022	59	377	1,310	380	-
	2017	89	227	1,319	267	4
Depreciation expenses claimed	farms, 2022	414	264	740	696	254
	2017	443	273	631	649	229
	$1,000, 2022	18,531	19,654	43,664	29,995	3,125
	2017	14,951	13,410	25,876	24,299	2,384

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	213	201	68	228	135	194
	2017	272	234	116	302	173	219
	$1,000, 2022	2,048	344	2,238	431	1,837	422
	2017	1,834	475	1,025	660	846	423
All other production expenses	farms, 2022	399	252	429	369	507	249
	2017	361	192	399	293	448	204
	$1,000, 2022	6,104	1,177	14,621	4,021	20,639	2,193
	2017	4,184	1,514	10,631	2,836	13,572	1,649
Production expenses paid by landlords [1]	farms, 2022	6	12	27	10	25	3
	2017	3	9	19	12	29	5
	$1,000, 2022	5	30	1,188	175	1,298	19
	2017	(D)	47	302	85	768	10
Depreciation expenses claimed	farms, 2022	331	256	385	338	438	212
	2017	353	191	392	344	409	182
	$1,000, 2022	15,774	3,322	38,116	5,345	36,481	6,122
	2017	11,330	2,459	18,952	4,830	22,323	3,223

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	4	166	146	241	237	227
	2017	10	192	240	254	224	287
	$1,000, 2022	(D)	4,844	318	1,514	3,872	626
	2017	(D)	3,439	280	1,115	1,908	793
All other production expenses	farms, 2022	11	622	237	563	442	582
	2017	14	538	204	479	366	461
	$1,000, 2022	11	21,045	1,879	12,839	15,766	4,768
	2017	18	13,598	923	15,211	10,240	5,038
Production expenses paid by landlords [1]	farms, 2022	-	25	3	20	30	18
	2017	-	45	2	20	16	15
	$1,000, 2022	-	905	4	514	996	116
	2017	-	1,036	(D)	339	485	35
Depreciation expenses claimed	farms, 2022	14	554	204	576	434	540
	2017	12	498	184	443	366	436
	$1,000, 2022	60	49,323	3,669	23,221	31,504	17,896
	2017	24	27,185	2,227	19,382	23,944	11,178

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	163	543	218	600	43	140
	2017	181	722	330	731	53	166
	$1,000, 2022	3,984	4,170	4,174	5,851	1,894	431
	2017	1,788	4,037	2,712	6,426	1,411	362
All other production expenses	farms, 2022	634	982	700	1,009	355	257
	2017	570	782	624	908	323	223
	$1,000, 2022	26,660	22,197	34,389	27,481	10,448	2,807
	2017	13,895	12,464	15,041	13,483	10,552	4,273
Production expenses paid by landlords [1]	farms, 2022	24	33	34	48	15	17
	2017	32	40	25	25	12	7
	$1,000, 2022	909	196	1,022	3,732	343	97
	2017	823	2,608	598	479	154	94
Depreciation expenses claimed	farms, 2022	591	952	664	897	297	276
	2017	539	747	645	829	314	202
	$1,000, 2022	37,724	45,127	36,617	45,659	27,035	6,596
	2017	25,943	21,536	24,436	28,069	19,410	7,087

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	352	122	290	150	207	222
	2017	442	166	266	163	190	301
	$1,000, 2022	3,804	153	2,761	207	3,737	368
	2017	2,409	284	1,139	164	2,180	451
All other production expenses	farms, 2022	506	182	384	217	719	298
	2017	439	146	293	137	570	234
	$1,000, 2022	12,015	2,323	4,358	652	15,091	1,474
	2017	5,174	3,414	3,808	569	17,963	1,456
Production expenses paid by landlords [1]	farms, 2022	28	4	12	3	46	2
	2017	10	3	5	7	56	7
	$1,000, 2022	263	(D)	183	(D)	1,687	(D)
	2017	13	(D)	144	22	1,080	46
Depreciation expenses claimed	farms, 2022	461	177	397	263	621	259
	2017	491	162	347	128	530	251
	$1,000, 2022	16,941	3,455	7,917	4,273	37,976	4,073
	2017	10,106	3,380	6,426	1,145	21,539	4,210

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	319	52	52	124	7	27
	2017	354	76	68	187	15	23
	$1,000, 2022	6,893	145	118	1,448	7	42
	2017	5,128	174	104	1,668	9	32
All other production expenses	farms, 2022	792	408	94	587	22	105
	2017	616	309	64	580	11	74
	$1,000, 2022	24,291	12,692	638	13,721	20	1,204
	2017	19,638	7,776	536	9,914	22	717
Production expenses paid by landlords [1]	farms, 2022	24	37	3	44	-	9
	2017	28	23	1	65	-	4
	$1,000, 2022	628	2,698	41	1,957	-	33
	2017	704	361	(D)	1,661	-	(D)
Depreciation expenses claimed	farms, 2022	716	424	94	535	16	106
	2017	670	310	69	536	8	68
	$1,000, 2022	64,230	29,822	1,789	31,779	68	5,368
	2017	30,476	15,499	1,216	20,767	38	2,233

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	222	134	279	240	56	138
	2017	248	199	312	330	76	189
	$1,000, 2022	2,345	2,824	8,232	2,349	296	464
	2017	1,617	2,281	3,305	3,132	152	436
All other production expenses	farms, 2022	532	405	677	530	208	761
	2017	470	425	620	512	169	604
	$1,000, 2022	15,074	9,064	19,701	8,523	4,478	19,203
	2017	7,937	8,076	13,100	8,830	4,200	20,123
Production expenses paid by landlords [1]	farms, 2022	19	20	41	14	6	45
	2017	24	13	52	21	5	37
	$1,000, 2022	417	613	1,042	228	464	1,636
	2017	555	439	527	66	178	1,483
Depreciation expenses claimed	farms, 2022	503	401	646	447	187	718
	2017	468	415	633	493	178	593
	$1,000, 2022	19,954	17,184	37,773	31,392	13,333	44,132
	2017	15,662	16,506	29,746	16,136	9,435	26,084

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	268	227	212	665	276	223
	2017	282	288	309	939	411	286
	$1,000, 2022	10,300	3,863	596	7,966	6,212	4,336
	2017	5,459	2,454	675	7,212	3,696	2,804
All other production expenses	farms, 2022	692	622	312	1,012	756	634
	2017	660	546	288	889	694	594
	$1,000, 2022	54,599	32,251	2,087	19,052	21,435	12,987
	2017	23,464	13,017	1,837	14,026	13,254	12,095
Production expenses paid by landlords [1]	farms, 2022	46	18	15	39	32	52
	2017	37	22	11	34	36	65
	$1,000, 2022	1,134	1,185	233	421	604	1,296
	2017	1,018	287	25	177	1,517	3,334
Depreciation expenses claimed	farms, 2022	655	533	300	910	695	548
	2017	630	515	285	934	639	531
	$1,000, 2022	50,420	40,322	12,552	35,538	40,433	36,390
	2017	38,267	22,931	4,657	33,042	26,859	34,393

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	201	301	69	346	649	63
	2017	239	322	88	513	842	114
	$1,000, 2022	7,246	9,982	170	3,121	5,087	164
	2017	3,694	6,977	149	3,075	3,644	264
All other production expenses	farms, 2022	543	789	339	710	1,400	214
	2017	507	678	357	586	1,183	218
	$1,000, 2022	41,589	27,324	14,462	14,091	19,042	3,864
	2017	15,977	29,373	15,466	9,560	14,715	4,603
Production expenses paid by landlords [1]	farms, 2022	27	60	27	47	48	13
	2017	20	70	22	22	57	20
	$1,000, 2022	476	2,819	912	1,175	800	349
	2017	325	1,914	502	359	402	365
Depreciation expenses claimed	farms, 2022	515	680	327	660	1,331	208
	2017	454	602	362	581	1,223	223
	$1,000, 2022	37,628	49,412	28,694	29,343	48,054	11,010
	2017	29,353	37,515	17,580	16,162	29,934	7,640

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	329	238	179	189	2	62
	2017	384	299	233	260	3	68
	$1,000, 2022	871	7,088	771	2,917	(D)	475
	2017	557	6,332	703	2,266	(D)	260
All other production expenses	farms, 2022	393	431	884	537	30	219
	2017	342	380	802	427	42	157
	$1,000, 2022	2,346	19,361	35,835	10,749	345	5,393
	2017	2,802	14,521	28,650	10,604	193	3,043
Production expenses paid by landlords [1]	farms, 2022	18	18	65	30	-	19
	2017	24	23	56	31	3	19
	$1,000, 2022	145	865	2,711	1,027	-	616
	2017	62	506	1,885	858	1	239
Depreciation expenses claimed	farms, 2022	319	382	881	494	33	185
	2017	347	394	793	452	30	164
	$1,000, 2022	6,536	24,454	76,600	22,813	379	16,848
	2017	4,626	27,114	43,394	18,700	194	6,220

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	309	195	316	275	170	267
	2017	336	243	424	375	222	292
	$1,000, 2022	5,042	5,094	4,462	5,947	987	428
	2017	3,016	5,570	3,237	4,285	525	288
All other production expenses	farms, 2022	1,107	757	697	490	510	393
	2017	836	770	596	534	408	246
	$1,000, 2022	26,444	33,125	13,129	13,146	9,551	1,656
	2017	15,090	27,498	8,311	11,177	7,256	1,225
Production expenses paid by landlords [1]	farms, 2022	69	31	22	26	32	16
	2017	70	33	18	41	36	5
	$1,000, 2022	1,879	1,494	3,693	784	711	83
	2017	1,355	1,014	262	972	415	27
Depreciation expenses claimed	farms, 2022	997	699	640	410	467	423
	2017	798	745	563	459	435	289
	$1,000, 2022	51,224	64,175	28,553	31,098	26,000	4,439
	2017	30,407	41,890	13,188	23,974	14,246	2,438

See footnote(s) at end of table.

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Table 3. **Farm Production Expenses: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	216	170	250	1,140	179	110
	2017	302	179	333	1,617	237	152
	$1,000, 2022	944	518	3,805	16,469	2,005	4,633
	2017	1,107	517	2,990	16,487	1,404	4,093
All other production expenses	farms, 2022	384	209	648	1,866	481	377
	2017	368	186	550	1,711	446	385
	$1,000, 2022	3,217	4,780	22,159	36,034	13,298	19,216
	2017	2,741	5,951	11,979	35,559	7,884	19,724
Production expenses paid by landlords [1]	farms, 2022	7	15	25	103	22	29
	2017	13	7	27	72	15	24
	$1,000, 2022	71	83	426	2,430	2,961	1,206
	2017	38	130	557	405	455	356
Depreciation expenses claimed	farms, 2022	350	229	592	1,708	466	347
	2017	385	225	530	1,732	418	360
	$1,000, 2022	10,595	10,987	40,190	81,063	36,863	28,615
	2017	6,646	8,134	25,004	65,690	18,237	23,845

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	110	581	35	339	143	148
	2017	165	737	42	403	217	227
	$1,000, 2022	1,865	4,259	1,314	5,170	446	2,273
	2017	1,374	3,510	1,299	3,953	376	2,900
All other production expenses	farms, 2022	505	873	279	537	228	480
	2017	467	703	292	479	228	486
	$1,000, 2022	12,546	15,176	12,353	11,842	4,102	14,664
	2017	11,920	7,459	11,358	9,437	2,733	8,257
Production expenses paid by landlords [1]	farms, 2022	21	26	12	35	13	30
	2017	23	14	20	17	1	24
	$1,000, 2022	672	166	363	773	272	713
	2017	386	103	320	108	(D)	564
Depreciation expenses claimed	farms, 2022	479	816	257	499	204	444
	2017	443	766	263	460	231	470
	$1,000, 2022	32,488	26,663	19,882	27,809	5,533	26,431
	2017	21,143	16,370	16,322	16,642	3,795	16,255

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Total farm production expenses - Con.							
Medical supplies, veterinary, and custom services for livestock	farms, 2022	164	118	34	455	407	189
	2017	245	128	36	528	518	217
	$1,000, 2022	416	3,479	108	10,366	2,891	3,309
	2017	574	1,546	65	5,775	3,102	1,885
All other production expenses	farms, 2022	296	394	277	704	723	665
	2017	275	328	268	592	609	537
	$1,000, 2022	5,024	18,295	12,457	25,744	16,058	21,032
	2017	6,856	10,573	9,692	11,643	11,185	10,541
Production expenses paid by landlords [1]	farms, 2022	11	20	7	30	17	25
	2017	7	8	17	24	32	30
	$1,000, 2022	63	463	282	1,058	144	512
	2017	(D)	194	814	260	146	286
Depreciation expenses claimed	farms, 2022	297	371	260	648	693	603
	2017	249	312	256	554	608	521
	$1,000, 2022	6,326	27,825	24,712	36,590	30,736	36,681
	2017	3,888	16,022	15,391	17,230	18,960	24,730

[1] Landlord production expenses are included within total farm production expenses.

Table 4. **Net Cash Farm Income of the Operations and Producers: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Net cash farm income of the operations	$1,000, 2022	9,296,848	6,982	30,066	100,397	7,500
	2017	4,525,276	969	13,024	51,298	5,768
Average per farm	dollars, 2022	141,869	15,550	84,694	105,459	12,335
	2017	65,753	2,097	36,178	54,399	9,893
Farms with net gains [1]	farms, 2022	41,496	237	100	573	266
	2017	42,786	213	91	562	272
Average per farm	dollars, 2022	242,705	39,737	347,281	191,496	49,985
	2017	119,206	17,579	192,840	101,689	33,039
Farms with net losses	farms, 2022	24,035	212	255	379	342
	2017	26,036	249	269	381	311
Average per farm	dollars, 2022	32,221	11,490	18,281	24,617	16,948
	2017	22,087	11,147	16,819	15,358	10,351
Net cash farm income of producers	$1,000, 2022	8,390,544	6,736	30,110	98,937	7,795
	2017	3,899,993	957	13,033	50,656	5,786
Average per farm	dollars, 2022	128,039	15,003	84,818	103,926	12,820
	2017	56,668	2,072	36,202	53,718	9,924
Producers reporting net gains [1]	farms, 2022	41,274	237	97	572	266
	2017	42,429	213	91	560	272
Average per farm	dollars, 2022	222,954	38,732	358,555	189,809	50,381
	2017	106,395	17,864	192,738	101,170	33,052
Producers reporting net losses	farms, 2022	24,257	212	258	380	342
	2017	26,393	249	269	383	311
Average per farm	dollars, 2022	33,460	11,525	18,099	25,351	16,394
	2017	23,274	11,437	16,753	15,663	10,303

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Net cash farm income of the operations	$1,000, 2022	87,140	65,677	264,049	151,878	3,158
	2017	58,346	36,948	130,006	100,335	669
Average per farm	dollars, 2022	126,841	167,543	259,126	156,093	6,820
	2017	71,503	84,356	132,254	96,476	1,265
Farms with net gains [1]	farms, 2022	347	291	773	723	168
	2017	412	336	699	772	172
Average per farm	dollars, 2022	267,901	237,728	364,246	233,449	38,460
	2017	156,221	117,297	196,609	137,764	25,368
Farms with net losses	farms, 2022	340	101	246	250	295
	2017	404	102	284	268	357
Average per farm	dollars, 2022	17,123	34,673	71,191	67,623	11,198
	2017	14,893	24,155	26,141	22,458	10,348
Net cash farm income of producers	$1,000, 2022	69,402	62,534	206,071	135,798	3,148
	2017	39,386	33,987	91,370	76,567	647
Average per farm	dollars, 2022	101,021	159,526	202,229	139,566	6,800
	2017	48,267	77,596	92,951	73,623	1,223
Producers reporting net gains [1]	farms, 2022	345	291	762	713	168
	2017	406	337	693	766	172
Average per farm	dollars, 2022	218,450	226,991	297,746	217,731	38,460
	2017	113,055	108,037	143,114	109,262	25,373
Producers reporting net losses	farms, 2022	342	101	257	260	295
	2017	410	101	290	274	357
Average per farm	dollars, 2022	17,438	34,853	80,976	74,787	11,231
	2017	15,889	23,973	26,922	26,011	10,413

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Net cash farm income of the operations	$1,000, 2022	63,948	8,441	158,550	11,411	177,528	18,820
	2017	27,008	4,947	61,616	12,301	65,839	9,127
Average per farm	dollars, 2022	105,524	17,297	281,615	15,420	271,036	46,585
	2017	39,198	11,451	98,903	14,983	94,869	22,046
Farms with net gains [1]	farms, 2022	379	209	424	264	462	198
	2017	411	180	475	298	481	206
Average per farm	dollars, 2022	178,084	59,870	384,239	71,767	413,224	115,403
	2017	76,309	45,199	142,940	62,776	156,999	59,081
Farms with net losses	farms, 2022	227	279	139	476	193	206
	2017	278	252	148	523	213	208
Average per farm	dollars, 2022	15,621	14,594	31,422	15,831	69,332	19,561
	2017	15,667	12,655	42,433	12,248	45,434	14,632
Net cash farm income of producers	$1,000, 2022	63,948	3,097	148,037	11,555	177,438	18,722
	2017	27,059	4,187	57,171	12,386	65,197	8,882
Average per farm	dollars, 2022	105,525	6,347	262,944	15,614	270,898	46,342
	2017	39,273	9,693	91,767	15,087	93,944	21,455
Producers reporting net gains [1]	farms, 2022	379	203	425	266	461	199
	2017	411	180	468	298	478	206
Average per farm	dollars, 2022	178,085	36,462	360,098	71,536	414,033	114,260
	2017	76,434	40,904	139,840	62,852	156,726	58,963
Producers reporting net losses	farms, 2022	227	285	138	474	194	205
	2017	278	252	155	523	216	208
Average per farm	dollars, 2022	15,620	15,104	36,263	15,768	69,233	19,588
	2017	15,667	12,600	53,382	12,130	44,991	15,692

See footnote(s) at end of table.

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Table 4. **Net Cash Farm Income of the Operations and Producers: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Net cash farm income of the operations	$1,000, 2022	(D)	235,415	4,109	130,624	118,540	64,450
	2017	196	100,264	3,258	58,183	49,354	25,918
Average per farm	dollars, 2022	(D)	317,271	9,646	155,320	193,062	65,765
	2017	6,128	134,764	6,595	70,955	80,776	26,997
Farms with net gains [1]	farms, 2022	8	620	155	453	388	567
	2017	11	591	192	465	407	584
Average per farm	dollars, 2022	(D)	385,544	61,433	334,901	317,351	128,661
	2017	22,434	175,054	35,944	144,405	134,774	53,221
Farms with net losses	farms, 2022	17	122	271	388	226	413
	2017	21	153	302	355	204	376
Average per farm	dollars, 2022	11,445	29,689	19,973	54,346	20,318	20,583
	2017	2,414	20,867	12,065	25,256	26,957	13,734
Net cash farm income of producers	$1,000, 2022	(D)	212,592	3,540	122,715	100,991	62,179
	2017	196	86,795	2,334	50,573	37,978	25,453
Average per farm	dollars, 2022	(D)	286,512	8,311	145,915	164,480	63,448
	2017	6,128	116,660	4,724	61,674	62,157	26,514
Producers reporting net gains [1]	farms, 2022	8	615	155	448	375	566
	2017	11	583	192	456	402	581
Average per farm	dollars, 2022	(D)	351,937	57,739	320,445	285,119	125,094
	2017	22,434	154,804	31,131	132,057	109,124	53,010
Producers reporting net losses	farms, 2022	17	127	271	393	239	414
	2017	21	161	302	364	209	379
Average per farm	dollars, 2022	11,445	30,313	19,960	53,040	24,805	20,832
	2017	2,414	21,463	12,065	26,499	28,180	14,104

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Net cash farm income of the operations	$1,000, 2022	185,061	157,779	141,848	180,306	103,986	12,546
	2017	81,580	59,384	85,964	87,341	42,504	10,033
Average per farm	dollars, 2022	239,407	108,216	156,220	128,240	196,572	24,551
	2017	99,245	42,387	79,892	59,782	81,115	21,483
Farms with net gains [1]	farms, 2022	627	949	664	893	402	181
	2017	618	852	747	862	420	186
Average per farm	dollars, 2022	320,449	186,671	240,973	216,598	275,693	108,790
	2017	145,658	87,704	128,546	117,798	114,581	111,031
Farms with net losses	farms, 2022	146	509	244	513	127	330
	2017	204	549	329	599	104	281
Average per farm	dollars, 2022	108,631	38,058	74,419	25,568	53,873	21,653
	2017	41,357	27,942	30,578	23,707	54,036	37,790
Net cash farm income of producers	$1,000, 2022	153,748	144,779	125,524	167,182	102,575	12,582
	2017	63,306	54,774	71,699	78,905	42,082	10,101
Average per farm	dollars, 2022	198,898	99,300	138,242	118,906	193,903	24,622
	2017	77,015	39,096	66,635	54,008	80,309	21,630
Producers reporting net gains [1]	farms, 2022	627	943	657	891	402	181
	2017	608	848	741	859	419	186
Average per farm	dollars, 2022	274,798	175,147	219,289	202,571	272,291	108,958
	2017	120,037	82,929	110,970	109,075	113,860	111,399
Producers reporting net losses	farms, 2022	146	515	251	515	127	330
	2017	214	553	335	602	105	281
Average per farm	dollars, 2022	127,057	39,583	73,902	25,842	54,221	21,634
	2017	45,216	28,119	31,431	24,569	53,577	37,790

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Net cash farm income of the operations	$1,000, 2022	62,170	10,408	10,253	1,247	200,004	11,690
	2017	24,958	12,793	1,699	-238	86,427	5,757
Average per farm	dollars, 2022	78,005	30,977	12,596	2,940	236,691	22,015
	2017	28,011	33,314	2,111	-706	108,169	9,226
Farms with net gains [1]	farms, 2022	498	101	219	200	664	219
	2017	544	146	247	118	645	230
Average per farm	dollars, 2022	136,197	156,181	89,133	23,765	305,736	76,798
	2017	56,583	105,837	37,832	28,582	138,298	41,791
Farms with net losses	farms, 2022	299	235	595	224	181	312
	2017	347	238	558	219	154	394
Average per farm	dollars, 2022	18,918	22,835	15,574	15,654	16,602	16,439
	2017	16,783	11,175	13,701	16,487	18,021	9,784
Net cash farm income of producers	$1,000, 2022	59,686	10,302	9,470	1,187	183,579	11,692
	2017	23,497	12,784	1,625	-233	71,765	6,014
Average per farm	dollars, 2022	74,888	30,662	11,634	2,799	217,253	22,019
	2017	26,371	33,291	2,018	-691	89,819	9,637
Producers reporting net gains [1]	farms, 2022	499	101	219	198	653	218
	2017	541	146	247	120	639	231
Average per farm	dollars, 2022	130,940	155,109	85,585	23,909	287,811	77,206
	2017	54,581	105,778	37,536	28,132	117,333	42,073
Producers reporting net losses	farms, 2022	298	235	595	226	192	313
	2017	350	238	558	217	160	393
Average per farm	dollars, 2022	18,970	22,824	15,585	15,696	22,719	16,418
	2017	17,233	11,176	13,704	16,631	20,068	9,428

See footnote(s) at end of table.

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Table 4. **Net Cash Farm Income of the Operations and Producers: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Net cash farm income of the operations	$1,000, 2022	248,104	122,304	3,235	147,405	(D)	10,045
	2017	97,407	45,408	1,418	65,839	-128	5,283
Average per farm	dollars, 2022	198,166	199,516	17,026	200,551	(D)	54,003
	2017	79,842	86,000	7,833	77,185	-3,048	39,428
Farms with net gains [1]	farms, 2022	815	461	96	584	5	86
	2017	837	410	93	699	12	60
Average per farm	dollars, 2022	318,292	277,498	43,346	262,692	(D)	149,417
	2017	132,772	118,760	23,672	102,310	10,525	103,351
Farms with net losses	farms, 2022	437	152	94	151	29	100
	2017	383	118	88	154	30	74
Average per farm	dollars, 2022	25,866	36,994	9,854	39,783	12,127	28,053
	2017	35,831	27,827	8,906	36,857	8,478	12,402
Net cash farm income of producers	$1,000, 2022	232,453	123,044	3,217	122,927	(D)	10,076
	2017	84,133	45,509	1,412	51,525	-129	5,278
Average per farm	dollars, 2022	185,665	200,725	16,930	167,247	(D)	54,169
	2017	68,962	86,192	7,803	60,404	-3,063	39,388
Producers reporting net gains [1]	farms, 2022	811	460	95	577	5	86
	2017	831	409	93	684	12	60
Average per farm	dollars, 2022	302,858	279,570	43,347	225,027	(D)	149,688
	2017	119,142	119,213	23,622	86,016	10,525	103,263
Producers reporting net losses	farms, 2022	441	153	95	158	29	100
	2017	389	119	88	169	30	74
Average per farm	dollars, 2022	29,852	36,325	9,487	43,758	12,127	27,976
	2017	38,235	27,299	8,914	43,254	8,499	12,402

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Net cash farm income of the operations	$1,000, 2022	59,227	84,127	247,190	94,356	68,016	143,497
	2017	45,747	46,682	119,627	33,872	19,106	69,532
Average per farm	dollars, 2022	66,101	140,680	284,454	117,797	253,792	133,859
	2017	48,823	69,468	133,961	38,491	61,433	64,026
Farms with net gains [1]	farms, 2022	616	472	694	501	187	789
	2017	598	546	682	530	221	814
Average per farm	dollars, 2022	119,500	183,818	360,842	203,316	369,969	200,629
	2017	88,687	93,611	183,888	78,273	95,876	95,253
Farms with net losses	farms, 2022	280	126	175	300	81	283
	2017	339	126	211	350	90	272
Average per farm	dollars, 2022	51,375	20,917	18,480	25,019	14,419	52,293
	2017	21,499	35,154	27,418	21,751	23,146	29,426
Net cash farm income of producers	$1,000, 2022	47,634	79,768	217,476	94,278	67,897	142,673
	2017	42,571	43,973	104,374	32,873	18,789	70,429
Average per farm	dollars, 2022	53,162	133,391	250,260	117,700	253,348	133,090
	2017	45,433	65,437	116,881	37,355	60,416	64,852
Producers reporting net gains [1]	farms, 2022	602	473	683	501	188	784
	2017	594	546	669	524	221	813
Average per farm	dollars, 2022	104,843	174,293	324,024	203,102	367,235	201,174
	2017	84,138	88,642	165,750	78,135	94,446	96,564
Producers reporting net losses	farms, 2022	294	125	186	300	80	288
	2017	343	126	224	356	90	273
Average per farm	dollars, 2022	52,660	21,383	20,604	24,922	14,287	52,248
	2017	21,595	35,119	29,074	22,669	23,146	29,587

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Net cash farm income of the operations	$1,000, 2022	264,353	129,934	20,994	225,050	161,042	162,452
	2017	155,680	67,680	4,688	111,495	92,780	90,756
Average per farm	dollars, 2022	321,207	131,114	34,816	143,253	161,203	205,897
	2017	170,889	65,836	6,630	63,349	86,873	105,041
Farms with net gains [1]	farms, 2022	685	644	231	901	685	604
	2017	693	615	257	989	717	663
Average per farm	dollars, 2022	411,219	219,619	118,215	263,682	258,857	276,724
	2017	241,478	122,617	44,426	122,225	146,328	145,417
Farms with net losses	farms, 2022	138	347	372	670	314	185
	2017	218	413	450	771	351	201
Average per farm	dollars, 2022	125,596	33,142	16,972	18,697	51,831	25,346
	2017	53,507	18,716	14,955	12,174	34,578	28,137
Net cash farm income of producers	$1,000, 2022	199,493	129,523	20,626	145,035	140,741	140,676
	2017	107,899	64,755	4,083	68,765	68,572	79,993
Average per farm	dollars, 2022	242,398	130,699	34,206	92,320	140,882	178,297
	2017	118,440	62,992	5,775	39,071	64,206	92,584
Producers reporting net gains [1]	farms, 2022	677	642	231	881	683	597
	2017	670	614	255	964	702	657
Average per farm	dollars, 2022	321,535	219,971	116,376	180,587	231,458	246,087
	2017	183,562	119,492	42,129	83,650	117,219	131,885
Producers reporting net losses	farms, 2022	146	349	372	690	316	192
	2017	241	414	452	796	366	207
Average per farm	dollars, 2022	124,563	33,521	16,819	20,379	54,889	32,487
	2017	62,606	20,804	14,735	14,916	37,476	32,155

See footnote(s) at end of table.

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Table 4. **Net Cash Farm Income of the Operations and Producers: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Net cash farm income of the operations	$1,000, 2022	171,212	254,678	137,508	101,297	204,225	38,639
	2017	88,609	124,159	40,302	49,373	94,351	19,518
Average per farm	dollars, 2022	259,413	271,512	316,110	91,921	81,788	119,997
	2017	128,605	140,293	79,805	43,347	37,088	47,720
Farms with net gains [1]	farms, 2022	488	754	343	652	1,516	223
	2017	462	665	368	675	1,556	263
Average per farm	dollars, 2022	377,502	348,151	414,870	168,304	145,910	186,342
	2017	209,204	195,445	132,958	87,183	71,293	85,468
Farms with net losses	farms, 2022	172	184	92	450	981	99
	2017	227	220	137	464	988	146
Average per farm	dollars, 2022	75,632	42,542	52,097	18,748	17,303	29,446
	2017	35,434	26,418	62,970	20,422	16,782	20,277
Net cash farm income of producers	$1,000, 2022	146,237	211,271	135,372	101,029	199,721	38,737
	2017	63,460	103,239	38,351	44,443	93,332	19,366
Average per farm	dollars, 2022	221,571	225,236	311,200	91,678	79,984	120,300
	2017	92,104	116,654	75,943	39,019	36,687	47,349
Producers reporting net gains [1]	farms, 2022	479	737	342	657	1,515	222
	2017	448	653	367	673	1,555	263
Average per farm	dollars, 2022	335,219	299,173	410,684	166,992	143,215	187,579
	2017	166,197	168,784	128,497	80,447	70,842	85,296
Producers reporting net losses	farms, 2022	181	201	93	445	982	100
	2017	241	232	138	466	989	146
Average per farm	dollars, 2022	79,187	45,869	54,643	19,515	17,567	29,059
	2017	45,628	30,074	63,821	20,810	17,015	21,008

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Net cash farm income of the operations	$1,000, 2022	19,899	132,228	248,714	101,752	1,294	41,090
	2017	7,801	88,180	95,146	46,198	-216	20,266
Average per farm	dollars, 2022	27,334	249,959	203,364	123,937	27,530	149,963
	2017	9,479	148,202	75,632	55,194	-3,933	77,059
Farms with net gains [1]	farms, 2022	309	386	907	525	26	199
	2017	291	418	909	553	30	205
Average per farm	dollars, 2022	83,352	352,554	298,591	203,853	102,199	247,139
	2017	42,739	221,919	124,332	98,227	34,853	116,511
Farms with net losses	farms, 2022	419	143	316	296	21	75
	2017	532	177	349	284	25	58
Average per farm	dollars, 2022	13,978	26,976	69,962	17,806	64,918	107,880
	2017	8,714	25,889	51,211	28,599	50,477	62,384
Net cash farm income of producers	$1,000, 2022	19,998	122,529	245,282	99,174	1,294	41,482
	2017	7,837	79,412	94,443	42,004	-215	20,451
Average per farm	dollars, 2022	27,470	231,624	200,557	120,797	27,530	151,394
	2017	9,522	133,466	75,074	50,184	-3,918	77,760
Producers reporting net gains [1]	farms, 2022	311	384	903	523	26	199
	2017	291	408	908	547	30	205
Average per farm	dollars, 2022	83,117	329,623	297,976	200,558	102,199	246,555
	2017	42,889	207,193	123,988	92,742	34,881	117,556
Producers reporting net losses	farms, 2022	417	145	320	298	21	75
	2017	532	187	350	290	25	58
Average per farm	dollars, 2022	14,032	27,902	74,346	19,186	64,918	101,098
	2017	8,729	27,392	51,821	30,089	50,477	62,902

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Net cash farm income of the operations	$1,000, 2022	245,366	266,546	111,452	208,417	62,075	8,495
	2017	126,454	156,475	49,529	103,011	35,306	2,078
Average per farm	dollars, 2022	185,462	286,301	100,317	363,729	82,656	10,347
	2017	111,512	152,510	39,879	146,949	41,931	2,667
Farms with net gains [1]	farms, 2022	1,052	750	672	453	446	322
	2017	906	778	730	508	507	267
Average per farm	dollars, 2022	246,513	376,125	184,098	467,963	165,324	46,743
	2017	146,172	211,697	79,166	211,089	85,999	25,198
Farms with net losses	farms, 2022	271	181	439	120	305	499
	2017	228	248	512	193	335	512
Average per farm	dollars, 2022	51,533	85,898	27,932	29,752	38,228	13,139
	2017	26,217	33,165	16,137	21,874	24,762	9,082
Net cash farm income of producers	$1,000, 2022	212,428	239,084	101,589	174,938	61,843	8,440
	2017	108,038	121,007	44,491	75,279	35,491	2,053
Average per farm	dollars, 2022	160,565	256,804	91,439	305,302	82,347	10,280
	2017	95,271	117,941	35,822	107,387	42,151	2,636
Producers reporting net gains [1]	farms, 2022	1,046	751	672	440	448	320
	2017	880	760	730	491	508	266
Average per farm	dollars, 2022	218,896	339,544	169,918	408,441	163,882	46,852
	2017	132,074	172,078	71,911	163,043	86,275	25,305
Producers reporting net losses	farms, 2022	277	180	439	133	303	501
	2017	254	266	512	210	334	513
Average per farm	dollars, 2022	59,700	88,409	28,693	35,912	38,205	13,079
	2017	32,233	36,737	15,634	22,741	24,962	9,119

See footnote(s) at end of table.

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Table 4. **Net Cash Farm Income of the Operations and Producers: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Net cash farm income of the operations	$1,000, 2022	23,541	39,628	173,967	312,571	114,537	186,548
	2017	15,942	22,655	75,977	180,637	66,372	69,784
Average per farm	dollars, 2022	37,725	80,219	202,287	115,982	158,859	373,097
	2017	21,543	45,219	84,607	61,212	88,970	126,192
Farms with net gains [1]	farms, 2022	265	173	632	1,685	490	393
	2017	363	180	605	1,855	489	398
Average per farm	dollars, 2022	120,445	254,126	290,042	215,455	244,567	496,840
	2017	62,723	151,002	135,078	108,478	145,323	189,673
Farms with net losses	farms, 2022	359	321	228	1,010	231	107
	2017	377	321	293	1,096	257	155
Average per farm	dollars, 2022	23,335	13,507	40,961	49,971	22,947	81,402
	2017	18,107	14,098	19,610	18,787	18,253	36,809
Net cash farm income of producers	$1,000, 2022	23,612	36,568	154,744	254,082	93,850	180,579
	2017	15,969	22,062	66,798	154,267	48,446	67,252
Average per farm	dollars, 2022	37,840	74,024	179,935	94,279	130,166	361,159
	2017	21,580	44,036	74,385	52,276	64,941	121,613
Producers reporting net gains [1]	farms, 2022	265	173	631	1,687	481	392
	2017	365	181	603	1,841	477	398
Average per farm	dollars, 2022	120,679	236,427	260,059	181,136	207,322	483,124
	2017	62,487	146,196	120,354	96,920	113,089	183,478
Producers reporting net losses	farms, 2022	359	321	229	1,008	240	108
	2017	375	320	295	1,110	269	155
Average per farm	dollars, 2022	23,308	13,501	40,841	51,086	24,467	81,531
	2017	18,235	13,748	19,579	21,769	20,436	37,238

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Net cash farm income of the operations	$1,000, 2022	159,321	82,384	86,045	101,218	31,056	124,295
	2017	70,534	46,629	51,208	49,301	14,716	69,392
Average per farm	dollars, 2022	225,029	53,881	240,350	136,229	70,262	199,832
	2017	92,807	29,071	124,594	60,941	28,519	95,187
Farms with net gains [1]	farms, 2022	559	777	299	521	201	461
	2017	540	871	316	551	261	524
Average per farm	dollars, 2022	301,353	117,335	307,266	209,372	171,679	291,215
	2017	146,317	62,620	192,945	101,131	66,733	142,208
Farms with net losses	farms, 2022	149	752	59	222	241	161
	2017	220	733	95	258	255	205
Average per farm	dollars, 2022	61,313	11,683	98,768	35,427	14,321	61,832
	2017	38,534	10,795	102,762	24,891	10,594	25,002
Net cash farm income of producers	$1,000, 2022	149,563	81,338	83,822	99,663	30,878	102,962
	2017	63,539	43,824	49,695	47,001	14,640	51,980
Average per farm	dollars, 2022	211,248	53,197	234,141	134,136	69,859	165,533
	2017	83,604	27,322	120,914	58,098	28,371	71,304
Producers reporting net gains [1]	farms, 2022	556	775	298	522	200	463
	2017	540	868	317	548	261	517
Average per farm	dollars, 2022	286,069	116,318	301,917	206,264	171,755	242,871
	2017	133,348	59,634	189,486	97,986	66,440	110,432
Producers reporting net losses	farms, 2022	152	754	60	221	242	159
	2017	220	736	94	261	255	212
Average per farm	dollars, 2022	62,441	11,682	102,483	36,229	14,353	59,671
	2017	38,495	10,785	110,336	25,654	10,593	24,117

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Net cash farm income of the operations	$1,000, 2022	16,671	130,728	73,000	82,933	85,101	141,088
	2017	15,342	69,215	38,839	47,412	34,636	53,703
Average per farm	dollars, 2022	31,755	255,329	203,911	83,518	64,962	166,574
	2017	25,069	139,266	99,332	45,853	25,886	63,032
Farms with net gains [1]	farms, 2022	225	401	270	596	604	643
	2017	252	400	300	627	672	610
Average per farm	dollars, 2022	106,195	345,411	288,644	181,441	173,557	238,897
	2017	93,345	188,776	156,416	88,695	66,365	103,408
Farms with net losses	farms, 2022	300	111	88	397	706	204
	2017	360	97	91	407	666	242
Average per farm	dollars, 2022	24,075	70,101	56,068	63,490	27,943	61,386
	2017	22,724	64,898	88,854	20,147	14,957	38,745
Net cash farm income of producers	$1,000, 2022	16,692	112,184	72,075	83,300	85,165	123,814
	2017	15,424	56,720	37,799	47,324	34,047	49,000
Average per farm	dollars, 2022	31,795	219,109	201,328	83,887	65,011	146,179
	2017	25,203	114,124	96,672	45,768	25,446	57,511
Producers reporting net gains [1]	farms, 2022	225	401	270	595	606	643
	2017	251	400	296	626	672	606
Average per farm	dollars, 2022	106,238	301,720	285,223	182,446	173,068	212,744
	2017	94,039	157,985	156,426	88,742	65,540	97,266
Producers reporting net losses	farms, 2022	300	111	88	398	704	204
	2017	361	97	95	408	666	246
Average per farm	dollars, 2022	24,038	79,333	56,075	63,456	28,004	63,629
	2017	22,657	66,748	89,512	20,169	15,009	40,421

[1] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.

Table 5. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
GOVERNMENT PAYMENTS						
Total received	farms, 2022	31,583	82	26	516	180
	2017	41,230	76	33	551	123
	$1,000, 2022	584,106	827	270	8,045	2,214
	2017	394,491	282	239	5,253	775
Average per farm	dollars, 2022	18,494	10,084	10,401	15,591	12,302
	2017	9,568	3,709	7,245	9,534	6,303
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	19,069	5	3	349	20
	2017	19,972	13	8	359	29
	$1,000, 2022	126,510	5	5	2,200	64
	2017	107,308	19	12	1,720	86
Average per farm	dollars, 2022	6,634	1,029	1,693	6,303	3,220
	2017	5,373	1,491	1,561	4,790	2,967
Amount from other Federal farm programs	farms, 2022	16,968	77	23	238	163
	2017	33,153	69	29	363	107
	$1,000, 2022	457,596	822	265	5,845	2,150
	2017	287,183	263	227	3,533	689
Average per farm	dollars, 2022	26,968	10,672	11,536	24,559	13,190
	2017	8,662	3,805	7,814	9,734	6,441
COMMODITY CREDIT CORPORATION LOANS						
Total	farms, 2022	990	-	-	1	2
	2017	2,777	1	5	17	4
	$1,000, 2022	197,241	-	-	(D)	(D)
	2017	414,580	(D)	1,594	4,124	(D)
Amount spent to repay CCC loans	farms, 2022	1,256	-	2	-	1
	2017	2,618	-	7	13	4
	$1,000, 2022	195,908	-	(D)	-	(D)
	2017	357,144	-	1,260	1,699	73

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
GOVERNMENT PAYMENTS						
Total received	farms, 2022	347	246	466	532	66
	2017	355	329	751	855	23
	$1,000, 2022	5,823	3,118	5,323	7,494	445
	2017	1,702	3,315	12,899	6,242	196
Average per farm	dollars, 2022	16,780	12,676	11,422	14,086	6,746
	2017	4,794	10,077	17,176	7,300	8,542
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	102	189	332	336	9
	2017	111	184	325	342	6
	$1,000, 2022	186	830	1,459	2,685	45
	2017	233	1,014	1,057	2,086	14
Average per farm	dollars, 2022	1,820	4,389	4,395	7,992	4,969
	2017	2,102	5,511	3,254	6,101	2,277
Amount from other Federal farm programs	farms, 2022	274	115	180	290	58
	2017	295	274	609	750	19
	$1,000, 2022	5,637	2,289	3,864	4,808	401
	2017	1,469	2,301	11,842	4,155	183
Average per farm	dollars, 2022	20,574	19,901	21,464	16,580	6,906
	2017	4,979	8,399	19,444	5,540	9,621
COMMODITY CREDIT CORPORATION LOANS						
Total	farms, 2022	13	7	13	4	-
	2017	34	19	64	64	-
	$1,000, 2022	1,923	1,741	1,046	477	-
	2017	7,416	3,053	7,896	4,804	-
Amount spent to repay CCC loans	farms, 2022	4	20	17	14	-
	2017	29	22	54	44	-
	$1,000, 2022	1,790	1,841	1,512	3,427	-
	2017	5,236	3,441	5,717	3,796	-

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Table 5. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
GOVERNMENT PAYMENTS						
Total received ..... farms, 2022	206	131	361	82	401	164
2017	325	61	527	259	510	112
$1,000, 2022	1,739	1,271	4,826	1,094	10,985	2,651
2017	963	325	7,059	1,379	5,759	417
Average per farm ..... dollars, 2022	8,440	9,699	13,367	13,342	27,394	16,164
2017	2,962	5,325	13,394	5,323	11,292	3,722
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs ..... farms, 2022	141	7	276	26	186	18
2017	152	12	290	35	210	41
$1,000, 2022	786	14	1,462	56	1,144	112
2017	563	38	1,297	48	1,405	103
Average per farm ..... dollars, 2022	5,573	2,042	5,297	2,139	6,153	6,214
2017	3,706	3,196	4,474	1,368	6,691	2,511
Amount from other Federal farm programs ..... farms, 2022	87	129	157	59	282	155
2017	232	54	444	247	429	92
$1,000, 2022	953	1,256	3,364	1,038	9,841	2,539
2017	399	286	5,761	1,331	4,354	314
Average per farm ..... dollars, 2022	10,951	9,739	21,425	17,601	34,896	16,381
2017	1,721	5,305	12,976	5,388	10,149	3,412
COMMODITY CREDIT CORPORATION LOANS						
Total ..... farms, 2022	22	-	19	4	4	6
2017	19	-	39	10	33	2
$1,000, 2022	3,320	-	8,006	(D)	1,361	246
2017	3,362	-	8,253	390	4,757	(D)
Amount spent to repay CCC loans ..... farms, 2022	19	-	24	3	11	1
2017	18	-	36	6	22	-
$1,000, 2022	2,170	-	8,193	(D)	2,929	(D)
2017	2,728	-	6,300	490	3,874	-

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
GOVERNMENT PAYMENTS						
Total received ..... farms, 2022	2	402	90	249	190	554
2017	1	636	104	356	395	639
$1,000, 2022	(D)	5,455	1,675	4,466	1,753	7,713
2017	(D)	5,155	159	2,990	6,605	3,133
Average per farm ..... dollars, 2022	(D)	13,570	18,616	17,935	9,224	13,922
2017	(D)	8,105	1,528	8,399	16,722	4,903
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs ..... farms, 2022	-	278	3	96	152	356
2017	1	301	3	110	166	362
$1,000, 2022	-	1,590	4	442	1,070	1,642
2017	(D)	1,499	(D)	395	519	1,296
Average per farm ..... dollars, 2022	-	5,719	1,366	4,602	7,040	4,612
2017	(D)	4,979	(D)	3,588	3,128	3,580
Amount from other Federal farm programs ..... farms, 2022	2	179	88	177	52	262
2017	-	553	103	323	347	444
$1,000, 2022	(D)	3,865	1,671	4,024	683	6,071
2017	-	3,656	(D)	2,595	6,086	1,837
Average per farm ..... dollars, 2022	(D)	21,595	18,993	22,734	13,126	23,171
2017	-	6,611	(D)	8,035	17,539	4,138
COMMODITY CREDIT CORPORATION LOANS						
Total ..... farms, 2022	-	21	1	25	17	3
2017	-	61	3	53	54	26
$1,000, 2022	-	1,050	(D)	2,424	4,265	(D)
2017	-	7,327	(D)	9,243	15,127	1,844
Amount spent to repay CCC loans ..... farms, 2022	-	29	1	18	22	3
2017	-	60	-	41	46	23
$1,000, 2022	-	1,370	(D)	2,126	5,783	78
2017	-	5,959	-	7,259	15,373	1,423

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Table 5. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
GOVERNMENT PAYMENTS							
Total received	farms, 2022	300	612	459	488	421	69
	2017	672	940	806	867	475	126
	$1,000, 2022	3,052	4,980	4,730	3,835	7,378	324
	2017	5,464	8,723	11,605	11,779	7,264	193
Average per farm	dollars, 2022	10,173	8,138	10,306	7,859	17,524	4,693
	2017	8,132	9,280	14,398	13,586	15,293	1,533
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	199	509	379	299	362	46
	2017	253	437	403	284	353	33
	$1,000, 2022	783	3,913	2,658	1,105	3,201	182
	2017	641	2,481	1,718	954	2,659	95
Average per farm	dollars, 2022	3,933	7,687	7,013	3,695	8,844	3,950
	2017	2,534	5,676	4,264	3,358	7,532	2,883
Amount from other Federal farm programs	farms, 2022	149	146	152	238	142	26
	2017	605	781	640	752	313	109
	$1,000, 2022	2,269	1,068	2,073	2,731	4,176	142
	2017	4,823	6,242	9,886	10,826	4,606	98
Average per farm	dollars, 2022	15,230	7,314	13,635	11,474	29,409	5,466
	2017	7,972	7,993	15,447	14,396	14,715	899
COMMODITY CREDIT CORPORATION LOANS							
Total	farms, 2022	20	18	19	45	9	1
	2017	70	40	75	87	24	9
	$1,000, 2022	3,668	4,683	4,196	25,836	935	(D)
	2017	12,837	4,661	9,049	18,125	3,680	529
Amount spent to repay CCC loans	farms, 2022	30	31	23	38	9	2
	2017	67	35	71	77	34	5
	$1,000, 2022	4,820	5,044	5,676	8,156	1,053	(D)
	2017	11,850	3,485	9,090	17,436	2,725	364

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
GOVERNMENT PAYMENTS							
Total received	farms, 2022	389	76	118	65	473	79
	2017	610	71	101	20	625	123
	$1,000, 2022	3,146	759	1,702	475	7,529	2,092
	2017	3,372	495	635	(D)	9,173	109
Average per farm	dollars, 2022	8,086	9,990	14,425	7,315	15,918	26,476
	2017	5,527	6,977	6,289	(D)	14,677	885
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	296	7	31	12	301	4
	2017	323	13	39	10	274	9
	$1,000, 2022	1,733	18	45	24	1,755	(D)
	2017	1,430	12	103	(D)	1,037	6
Average per farm	dollars, 2022	5,856	2,522	1,457	2,023	5,830	(D)
	2017	4,426	901	2,650	(D)	3,786	700
Amount from other Federal farm programs	farms, 2022	132	72	94	59	257	75
	2017	461	63	74	16	574	118
	$1,000, 2022	1,412	742	1,657	451	5,774	(D)
	2017	1,942	484	532	29	8,136	103
Average per farm	dollars, 2022	10,700	10,299	17,628	7,648	22,468	(D)
	2017	4,213	7,677	7,187	1,844	14,174	869
COMMODITY CREDIT CORPORATION LOANS							
Total	farms, 2022	2	1	3	-	21	8
	2017	11	-	6	-	32	14
	$1,000, 2022	(D)	(D)	48	-	1,523	1,908
	2017	787	-	1,311	-	3,236	460
Amount spent to repay CCC loans	farms, 2022	3	1	-	-	22	9
	2017	6	2	13	-	21	10
	$1,000, 2022	(D)	(D)	-	-	1,578	(D)
	2017	918	(D)	2,280	-	2,051	401

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Table 5. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item			Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
GOVERNMENT PAYMENTS								
Total received	farms,	2022	784	542	45	476	-	66
		2017	991	483	26	752	3	62
	$1,000,	2022	14,886	24,526	425	5,324	-	891
		2017	10,884	12,450	320	6,064	41	772
Average per farm	dollars,	2022	18,988	45,252	9,447	11,185	-	13,502
		2017	10,983	25,777	12,290	8,064	13,710	12,452
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms,	2022	604	428	5	360	-	28
		2017	680	388	5	485	-	18
	$1,000,	2022	4,361	5,187	10	2,467	-	109
		2017	3,991	4,200	6	3,042	-	35
Average per farm	dollars,	2022	7,219	12,119	2,076	6,853	-	3,885
		2017	5,869	10,825	1,140	6,273	-	1,919
Amount from other Federal farm programs	farms,	2022	314	264	40	199	-	40
		2017	676	364	22	595	3	55
	$1,000,	2022	10,526	19,339	415	2,857	-	782
		2017	6,893	8,250	314	3,022	41	738
Average per farm	dollars,	2022	33,522	73,255	10,369	14,358	-	19,559
		2017	10,196	22,665	14,266	5,079	13,710	13,409
COMMODITY CREDIT CORPORATION LOANS								
Total	farms,	2022	8	17	-	10	-	-
		2017	57	9	-	69	-	-
	$1,000,	2022	1,748	876	-	767	-	-
		2017	7,246	421	-	7,782	-	-
Amount spent to repay CCC loans	farms,	2022	16	10	-	15	-	3
		2017	48	9	-	56	-	-
	$1,000,	2022	2,030	438	-	897	-	4
		2017	7,215	504	-	6,508	-	-

Item			Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
GOVERNMENT PAYMENTS								
Total received	farms,	2022	562	462	592	359	185	870
		2017	682	540	563	584	217	931
	$1,000,	2022	4,426	10,232	16,851	4,104	6,372	34,231
		2017	4,652	7,124	5,565	4,093	2,742	18,205
Average per farm	dollars,	2022	7,876	22,147	28,465	11,431	34,445	39,346
		2017	6,821	13,193	9,884	7,008	12,636	19,554
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms,	2022	509	370	318	263	80	522
		2017	487	400	299	231	87	616
	$1,000,	2022	3,711	4,751	3,535	1,480	487	6,008
		2017	3,127	3,979	1,816	952	349	7,430
Average per farm	dollars,	2022	7,291	12,841	11,116	5,626	6,081	11,510
		2017	6,421	9,948	6,073	4,120	4,008	12,062
Amount from other Federal farm programs	farms,	2022	123	189	387	139	136	512
		2017	460	410	440	495	185	661
	$1,000,	2022	715	5,481	13,316	2,624	5,886	28,223
		2017	1,525	3,145	3,749	3,141	2,393	10,775
Average per farm	dollars,	2022	5,813	28,999	34,409	18,879	43,279	55,123
		2017	3,314	7,671	8,520	6,345	12,937	16,301
COMMODITY CREDIT CORPORATION LOANS								
Total	farms,	2022	27	7	9	19	3	10
		2017	41	39	45	54	15	30
	$1,000,	2022	8,871	393	139	10,398	194	300
		2017	7,450	4,379	6,393	7,082	2,239	3,715
Amount spent to repay CCC loans	farms,	2022	34	19	13	23	4	21
		2017	49	37	47	53	12	35
	$1,000,	2022	8,725	462	439	11,642	50	1,238
		2017	8,473	4,499	4,771	7,266	1,406	3,843

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Table 5. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
GOVERNMENT PAYMENTS						
Total received ..... farms, 2022	371	649	155	817	412	461
2017	726	749	170	701	794	566
$1,000, 2022	6,575	11,594	2,009	13,828	3,948	4,913
2017	8,613	5,200	190	2,301	10,064	5,522
Average per farm ..... dollars, 2022	17,722	17,865	12,959	16,925	9,582	10,657
2017	11,864	6,942	1,119	3,282	12,675	9,756
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs ..... farms, 2022	196	458	39	165	323	319
2017	193	423	30	200	370	368
$1,000, 2022	1,136	2,873	82	322	2,208	1,706
2017	744	2,012	30	306	1,652	1,911
Average per farm ..... dollars, 2022	5,795	6,273	2,094	1,950	6,836	5,349
2017	3,857	4,756	992	1,531	4,466	5,193
Amount from other Federal farm programs ..... farms, 2022	221	292	124	716	137	222
2017	666	524	150	627	688	409
$1,000, 2022	5,439	8,721	1,927	13,506	1,740	3,206
2017	7,869	3,188	160	1,995	8,411	3,611
Average per farm ..... dollars, 2022	24,610	29,868	15,540	18,863	12,699	14,443
2017	11,815	6,083	1,070	3,181	12,226	8,829
COMMODITY CREDIT CORPORATION LOANS						
Total ..... farms, 2022	32	14	1	9	20	14
2017	62	47	13	25	90	50
$1,000, 2022	7,282	8,054	(D)	103	1,651	372
2017	8,025	7,400	718	2,222	14,776	6,268
Amount spent to repay CCC loans ..... farms, 2022	18	15	7	16	30	30
2017	65	47	11	26	87	57
$1,000, 2022	1,925	7,895	156	501	3,053	16,680
2017	8,847	7,647	439	878	11,927	6,945

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
GOVERNMENT PAYMENTS						
Total received ..... farms, 2022	284	468	351	435	1,604	258
2017	329	721	396	696	1,633	308
$1,000, 2022	4,879	5,741	24,080	3,716	21,906	14,076
2017	2,277	8,236	5,243	9,079	8,675	5,293
Average per farm ..... dollars, 2022	17,179	12,266	68,604	8,543	13,657	54,559
2017	6,921	11,423	13,239	13,044	5,312	17,184
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs ..... farms, 2022	175	314	150	352	970	134
2017	149	293	175	252	957	150
$1,000, 2022	1,083	1,309	1,165	2,446	3,797	1,640
2017	564	966	1,105	1,161	3,065	1,331
Average per farm ..... dollars, 2022	6,189	4,170	7,766	6,948	3,914	12,236
2017	3,782	3,298	6,314	4,607	3,203	8,872
Amount from other Federal farm programs ..... farms, 2022	150	231	277	121	833	177
2017	266	628	342	605	1,198	248
$1,000, 2022	3,796	4,431	22,915	1,271	18,109	12,437
2017	1,713	7,270	4,138	7,918	5,610	3,962
Average per farm ..... dollars, 2022	25,305	19,183	82,726	10,501	21,739	70,264
2017	6,442	11,576	12,099	13,088	4,683	15,975
COMMODITY CREDIT CORPORATION LOANS						
Total ..... farms, 2022	12	17	15	18	19	5
2017	32	43	60	42	46	14
$1,000, 2022	2,622	2,883	3,411	6,615	2,572	(D)
2017	7,297	6,123	11,160	8,574	9,740	1,759
Amount spent to repay CCC loans ..... farms, 2022	15	32	18	25	20	6
2017	33	40	56	47	47	13
$1,000, 2022	2,778	6,202	1,894	4,527	2,700	301
2017	6,996	3,721	8,599	8,593	8,822	1,231

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Table 5. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
GOVERNMENT PAYMENTS							
Total received	farms, 2022	75	261	902	564	5	204
	2017	149	293	979	626	1	213
	$1,000, 2022	863	5,955	50,998	12,499	(D)	8,410
	2017	174	1,582	17,113	4,173	(D)	2,688
Average per farm	dollars, 2022	11,509	22,818	56,539	22,161	(D)	41,228
	2017	1,170	5,400	17,480	6,666	(D)	12,618
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	9	132	429	350	4	69
	2017	5	136	495	415	1	90
	$1,000, 2022	28	597	4,299	1,909	13	558
	2017	5	507	4,918	2,035	(D)	761
Average per farm	dollars, 2022	3,105	4,521	10,021	5,455	3,339	8,085
	2017	953	3,726	9,936	4,904	(D)	8,457
Amount from other Federal farm programs	farms, 2022	69	186	631	306	1	166
	2017	146	231	786	426	1	185
	$1,000, 2022	835	5,359	46,699	10,590	(D)	7,853
	2017	169	1,076	12,195	2,138	(D)	1,927
Average per farm	dollars, 2022	12,105	28,810	74,008	34,608	(D)	47,305
	2017	1,161	4,656	15,515	5,019	(D)	10,414
COMMODITY CREDIT CORPORATION LOANS							
Total	farms, 2022	5	6	23	8	-	3
	2017	4	32	38	35	-	11
	$1,000, 2022	303	288	1,242	954	-	(D)
	2017	2	2,942	7,118	3,191	-	1,703
Amount spent to repay CCC loans	farms, 2022	1	7	33	10	-	6
	2017	1	36	42	28	-	13
	$1,000, 2022	(D)	267	673	712	-	290
	2017	(D)	2,123	8,386	2,625	-	1,136

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
GOVERNMENT PAYMENTS							
Total received	farms, 2022	785	583	411	271	489	99
	2017	755	868	770	518	605	26
	$1,000, 2022	15,663	12,261	2,916	3,108	15,069	1,078
	2017	6,220	5,570	6,228	2,105	10,057	48
Average per farm	dollars, 2022	19,953	21,031	7,095	11,469	30,815	10,889
	2017	8,239	6,418	8,089	4,063	16,624	1,853
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	468	315	322	125	270	3
	2017	433	343	363	124	422	4
	$1,000, 2022	2,811	2,789	1,643	675	1,843	(D)
	2017	2,479	1,616	1,383	378	4,008	3
Average per farm	dollars, 2022	6,007	8,853	5,102	5,397	6,827	(D)
	2017	5,725	4,712	3,810	3,048	9,497	729
Amount from other Federal farm programs	farms, 2022	470	366	126	199	295	96
	2017	590	758	591	494	396	24
	$1,000, 2022	12,852	9,473	1,273	2,434	13,225	(D)
	2017	3,741	3,954	4,845	1,727	6,050	45
Average per farm	dollars, 2022	27,344	25,881	10,104	12,229	44,831	(D)
	2017	6,341	5,216	8,199	3,495	15,277	1,886
COMMODITY CREDIT CORPORATION LOANS							
Total	farms, 2022	20	24	15	18	4	-
	2017	63	70	40	41	36	-
	$1,000, 2022	3,043	6,223	4,842	651	72	-
	2017	6,907	15,511	5,327	3,397	6,822	-
Amount spent to repay CCC loans	farms, 2022	27	17	20	26	17	-
	2017	74	62	37	31	39	-
	$1,000, 2022	4,509	3,789	4,334	933	219	-
	2017	6,190	11,940	5,436	2,994	5,657	-

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Table 5. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
GOVERNMENT PAYMENTS							
Total received	farms, 2022	138	111	448	1,352	382	326
	2017	288	125	557	1,663	530	420
	$1,000, 2022	844	1,688	6,128	20,783	3,208	5,487
	2017	900	1,068	4,299	5,926	5,216	3,945
Average per farm	dollars, 2022	6,118	15,207	13,679	15,372	8,398	16,831
	2017	3,124	8,541	7,718	3,563	9,841	9,394
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	104	28	307	522	347	264
	2017	106	42	265	602	318	293
	$1,000, 2022	353	63	2,668	2,268	2,311	1,357
	2017	371	53	1,407	2,171	1,476	1,625
Average per farm	dollars, 2022	3,392	2,248	8,691	4,345	6,660	5,142
	2017	3,501	1,264	5,310	3,607	4,642	5,545
Amount from other Federal farm programs	farms, 2022	50	95	183	961	73	138
	2017	236	105	454	1,334	387	322
	$1,000, 2022	492	1,625	3,460	18,515	897	4,130
	2017	529	1,015	2,892	3,754	3,740	2,321
Average per farm	dollars, 2022	9,831	17,105	18,907	19,266	12,285	29,924
	2017	2,240	9,662	6,369	2,814	9,663	7,208
COMMODITY CREDIT CORPORATION LOANS							
Total	farms, 2022	20	10	23	37	12	2
	2017	17	7	49	67	53	20
	$1,000, 2022	4,370	2,161	6,110	7,336	1,403	(D)
	2017	2,982	2,209	8,182	3,704	7,178	2,805
Amount spent to repay CCC loans	farms, 2022	17	8	25	57	16	10
	2017	14	6	41	85	37	22
	$1,000, 2022	1,530	1,393	5,908	3,266	1,644	410
	2017	2,123	2,083	4,961	2,548	4,048	2,780

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
GOVERNMENT PAYMENTS							
Total received	farms, 2022	469	649	306	279	175	296
	2017	641	721	343	567	213	590
	$1,000, 2022	5,356	6,186	8,127	3,221	2,002	3,374
	2017	4,405	1,987	4,735	6,359	865	5,793
Average per farm	dollars, 2022	11,421	9,532	26,557	11,545	11,437	11,398
	2017	6,871	2,756	13,804	11,215	4,059	9,818
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	368	272	260	174	41	268
	2017	397	251	254	190	76	314
	$1,000, 2022	2,950	939	2,990	1,213	49	1,885
	2017	2,577	762	1,820	1,058	122	1,046
Average per farm	dollars, 2022	8,015	3,452	11,501	6,970	1,183	7,033
	2017	6,492	3,036	7,165	5,568	1,610	3,332
Amount from other Federal farm programs	farms, 2022	172	428	134	136	147	63
	2017	501	594	253	486	179	503
	$1,000, 2022	2,407	5,247	5,136	2,008	1,953	1,489
	2017	1,827	1,225	2,915	5,301	742	4,746
Average per farm	dollars, 2022	13,992	12,260	38,330	14,766	13,286	23,636
	2017	3,647	2,062	11,520	10,908	4,146	9,436
COMMODITY CREDIT CORPORATION LOANS							
Total	farms, 2022	9	15	1	34	2	24
	2017	59	16	40	44	2	67
	$1,000, 2022	3,401	1,669	(D)	7,565	(D)	5,963
	2017	8,984	869	12,955	4,743	(D)	12,640
Amount spent to repay CCC loans	farms, 2022	17	20	2	37	1	27
	2017	44	19	35	48	1	60
	$1,000, 2022	3,784	2,564	(D)	7,428	(D)	5,864
	2017	7,926	650	8,738	3,610	(D)	9,576

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Table 5. **Federal Government Payments and Commodity Credit Corporation Loans: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
GOVERNMENT PAYMENTS							
Total received	farms, 2022	50	255	266	375	429	578
	2017	153	434	336	624	510	632
	$1,000, 2022	876	2,659	8,648	2,636	5,704	11,475
	2017	1,036	9,171	4,555	3,952	1,301	5,699
Average per farm	dollars, 2022	17,517	10,427	32,511	7,030	13,296	19,854
	2017	6,772	21,132	13,557	6,334	2,551	9,017
Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs	farms, 2022	16	194	164	241	199	393
	2017	11	213	188	242	224	408
	$1,000, 2022	35	916	1,003	1,386	770	3,069
	2017	11	947	1,001	1,012	665	2,730
Average per farm	dollars, 2022	2,165	4,722	6,117	5,749	3,870	7,809
	2017	1,042	4,446	5,325	4,183	2,969	6,690
Amount from other Federal farm programs	farms, 2022	34	95	175	167	264	309
	2017	149	370	280	520	379	467
	$1,000, 2022	841	1,743	7,645	1,251	4,934	8,407
	2017	1,025	8,224	3,554	2,940	636	2,969
Average per farm	dollars, 2022	24,742	18,346	43,684	7,488	18,688	27,206
	2017	6,877	22,228	12,693	5,654	1,678	6,358
COMMODITY CREDIT CORPORATION LOANS							
Total	farms, 2022	9	23	1	16	20	11
	2017	20	60	16	29	37	45
	$1,000, 2022	878	3,863	(D)	806	1,112	1,678
	2017	2,022	11,957	2,920	2,608	5,505	4,373
Amount spent to repay CCC loans	farms, 2022	15	27	15	14	21	16
	2017	15	61	25	35	33	33
	$1,000, 2022	617	5,000	1,168	930	1,336	1,176
	2017	2,115	12,405	2,700	3,040	3,575	3,359

Table 6. **Income From Farm-Related Sources: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Total income from farm-related sources	farms, 2022	38,287	136	131	473	319
	2017	42,569	161	118	502	282
	$1,000, 2022	1,011,249	628	4,714	11,145	1,977
	2017	868,545	914	3,000	11,072	1,308
Average per farm	dollars, 2022	26,412	4,619	35,986	23,562	6,197
	2017	20,403	5,674	25,421	22,056	4,637
Customwork and other agricultural services	farms, 2022	4,779	22	18	44	17
	2017	5,718	16	16	49	22
	$1,000, 2022	144,025	118	1,598	367	78
	2017	119,832	72	126	445	257
Gross cash rent or share payments	farms, 2022	15,680	33	51	242	129
	2017	16,598	55	33	231	78
	$1,000, 2022	479,289	217	217	7,138	618
	2017	420,859	213	314	7,969	400
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	619	20	3	18	26
	2017	670	25	3	11	43
	$1,000, 2022	5,384	42	(D)	172	124
	2017	4,701	169	(D)	202	350
Agri-tourism and recreational services	farms, 2022	509	7	8	2	14
	2017	473	3	9	5	5
	$1,000, 2022	13,615	19	1,359	(D)	401
	2017	13,217	(D)	693	(D)	14
Patronage dividends and refunds from cooperatives	farms, 2022	23,672	48	37	232	194
	2017	27,504	66	35	315	189
	$1,000, 2022	126,183	144	132	1,978	167
	2017	115,527	99	83	1,185	89
Crop and livestock insurance payments	farms, 2022	5,882	8	17	46	30
	2017	5,640	5	10	47	12
	$1,000, 2022	171,530	8	256	1,196	480
	2017	125,828	272	390	762	60
Amount from State and local government agricultural program payments	farms, 2022	1,422	20	7	41	13
	2017	1,190	3	6	27	10
	$1,000, 2022	7,129	59	(D)	(D)	47
	2017	5,819	(D)	(D)	(D)	22
Average per farm	dollars, 2022	5,013	2,967	(D)	(D)	3,587
	2017	4,890	(D)	(D)	(D)	2,178
Other farm-related income sources	farms, 2022	2,557	10	30	21	19
	2017	3,475	19	32	40	14
	$1,000, 2022	64,095	22	1,058	169	63
	2017	62,761	52	1,265	373	117

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Total income from farm-related sources	farms, 2022	381	296	637	704	137
	2017	484	333	663	790	138
	$1,000, 2022	11,058	12,400	13,929	13,528	493
	2017	4,680	7,705	15,638	14,016	984
Average per farm	dollars, 2022	29,023	41,890	21,867	19,216	3,597
	2017	9,669	23,139	23,586	17,742	7,130
Customwork and other agricultural services	farms, 2022	51	22	69	65	23
	2017	46	93	84	73	6
	$1,000, 2022	1,912	722	1,193	2,054	60
	2017	834	1,393	1,003	2,154	(D)
Gross cash rent or share payments	farms, 2022	152	131	242	203	32
	2017	177	138	268	236	32
	$1,000, 2022	2,253	5,278	8,718	7,496	55
	2017	1,119	3,844	9,339	7,682	278
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	-	-	4	2	23
	2017	4	-	10	1	25
	$1,000, 2022	-	-	(D)	(D)	126
	2017	6	-	(D)	(D)	186
Agri-tourism and recreational services	farms, 2022	3	-	8	2	10
	2017	3	-	2	8	3
	$1,000, 2022	(D)	-	937	(D)	(D)
	2017	18	-	(D)	29	(D)
Patronage dividends and refunds from cooperatives	farms, 2022	220	196	423	542	62
	2017	297	224	430	626	65
	$1,000, 2022	1,463	1,630	1,912	2,153	59
	2017	1,042	1,172	1,226	1,885	24
Crop and livestock insurance payments	farms, 2022	60	105	51	98	1
	2017	94	66	103	120	2
	$1,000, 2022	2,625	4,154	629	1,160	(D)
	2017	1,192	1,144	2,246	1,341	(D)
Amount from State and local government agricultural program payments	farms, 2022	25	14	15	12	5
	2017	13	10	13	11	8
	$1,000, 2022	(D)	234	(D)	45	25
	2017	9	(D)	143	(D)	6
Average per farm	dollars, 2022	(D)	16,725	(D)	3,791	4,972
	2017	693	(D)	10,994	(D)	706
Other farm-related income sources	farms, 2022	43	12	23	29	20
	2017	36	3	59	52	26
	$1,000, 2022	2,585	381	491	607	165
	2017	461	(D)	1,670	901	405

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Total income from farm-related sources	farms, 2022	360	182	410	279	394	199
	2017	470	160	471	320	477	206
	$1,000, 2022	6,045	2,288	18,018	2,411	12,352	1,722
	2017	7,197	1,317	18,910	2,639	14,161	1,153
Average per farm	dollars, 2022	16,793	12,574	43,946	8,641	31,349	8,653
	2017	15,312	8,229	40,150	8,246	29,687	5,598
Customwork and other agricultural services	farms, 2022	30	23	69	28	47	16
	2017	53	21	84	40	83	16
	$1,000, 2022	766	129	1,454	748	1,101	152
	2017	616	151	1,987	435	1,185	224
Gross cash rent or share payments	farms, 2022	166	73	158	118	167	77
	2017	189	48	165	148	218	84
	$1,000, 2022	2,668	641	8,336	465	4,517	971
	2017	2,863	494	8,273	617	6,840	500
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	4	11	2	17	-	2
	2017	2	18	2	12	1	20
	$1,000, 2022	3	68	(D)	12	-	(D)
	2017	(D)	221	(D)	(D)	(D)	168
Agri-tourism and recreational services	farms, 2022	13	8	4	15	6	5
	2017	4	6	2	7	6	1
	$1,000, 2022	914	557	55	40	59	(D)
	2017	(D)	(D)	(D)	179	45	(D)
Patronage dividends and refunds from cooperatives	farms, 2022	197	90	272	95	236	120
	2017	297	93	333	145	309	123
	$1,000, 2022	859	68	1,677	275	2,412	173
	2017	1,725	56	3,994	258	1,663	80
Crop and livestock insurance payments	farms, 2022	21	15	77	26	79	11
	2017	67	4	134	29	67	10
	$1,000, 2022	238	376	3,783	370	2,696	235
	2017	1,370	38	4,022	300	2,255	61
Amount from State and local government agricultural program payments	farms, 2022	5	8	5	10	17	22
	2017	2	9	7	6	11	11
	$1,000, 2022	9	36	(D)	19	47	125
	2017	(D)	(D)	42	(D)	(D)	(D)
Average per farm	dollars, 2022	1,801	4,482	(D)	1,943	2,781	5,686
	2017	(D)	(D)	5,945	(D)	(D)	(D)
Other farm-related income sources	farms, 2022	33	28	37	30	29	6
	2017	31	15	36	29	78	12
	$1,000, 2022	589	413	2,692	481	1,519	29
	2017	596	77	582	749	2,148	102

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Total income from farm-related sources	farms, 2022	8	570	155	446	385	523
	2017	6	573	190	427	392	533
	$1,000, 2022	(D)	19,787	1,329	10,083	10,675	7,490
	2017	(D)	15,623	671	9,066	9,530	7,054
Average per farm	dollars, 2022	(D)	34,715	8,572	22,607	27,726	14,321
	2017	(D)	27,265	3,533	21,232	24,310	13,235
Customwork and other agricultural services	farms, 2022	-	61	17	91	42	55
	2017	3	115	22	43	60	64
	$1,000, 2022	-	2,323	108	2,317	2,102	389
	2017	2	2,668	100	1,457	1,124	1,523
Gross cash rent or share payments	farms, 2022	2	222	48	132	148	255
	2017	-	215	65	152	168	218
	$1,000, 2022	(D)	10,969	221	3,720	5,426	4,248
	2017	-	9,172	156	4,497	6,453	3,408
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	3	-	13	2	6	15
	2017	2	1	26	7	2	4
	$1,000, 2022	(D)	-	40	(D)	3	50
	2017	(D)	(D)	71	(D)	(D)	35
Agri-tourism and recreational services	farms, 2022	-	5	5	5	5	10
	2017	1	3	4	9	1	7
	$1,000, 2022	-	7	2	132	10	(D)
	2017	(D)	(D)	38	(D)	(D)	820
Patronage dividends and refunds from cooperatives	farms, 2022	3	420	71	283	274	299
	2017	-	442	96	285	247	346
	$1,000, 2022	1	1,631	83	1,110	2,689	930
	2017	-	1,498	102	1,081	926	673
Crop and livestock insurance payments	farms, 2022	-	96	18	89	26	78
	2017	-	94	9	35	34	39
	$1,000, 2022	-	4,324	115	1,924	171	1,548
	2017	-	974	83	338	331	516
Amount from State and local government agricultural program payments	farms, 2022	-	11	17	23	18	23
	2017	-	22	3	9	3	10
	$1,000, 2022	-	107	91	(D)	90	68
	2017	-	122	5	63	(D)	16
Average per farm	dollars, 2022	-	9,730	5,362	(D)	4,995	2,951
	2017	-	5,557	1,547	7,034	(D)	1,566
Other farm-related income sources	farms, 2022	-	34	18	23	23	11
	2017	1	46	33	43	31	21
	$1,000, 2022	-	426	668	812	185	(D)
	2017	(D)	1,174	117	1,193	650	64

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Total income from farm-related sources	farms, 2022	507	873	596	946	358	200
	2017	517	864	713	1,074	403	186
	$1,000, 2022	12,186	19,042	16,790	19,471	13,784	5,467
	2017	15,485	13,765	18,985	18,215	13,214	5,255
Average per farm	dollars, 2022	24,035	21,813	28,171	20,583	38,504	27,336
	2017	29,952	15,932	26,628	16,960	32,788	28,252
Customwork and other agricultural services	farms, 2022	107	143	82	156	37	22
	2017	110	114	99	176	47	25
	$1,000, 2022	1,895	2,461	2,266	4,528	1,395	209
	2017	3,133	2,522	1,665	3,640	892	121
Gross cash rent or share payments	farms, 2022	181	400	249	313	202	82
	2017	200	391	309	391	225	76
	$1,000, 2022	7,976	11,755	11,457	7,360	8,593	1,622
	2017	9,226	8,139	11,926	6,878	8,989	1,238
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	-	30	6	9	-	10
	2017	-	6	2	8	2	7
	$1,000, 2022	-	320	(D)	(D)	-	(D)
	2017	-	53	(D)	21	(D)	(D)
Agri-tourism and recreational services	farms, 2022	-	11	1	3	4	22
	2017	-	14	3	13	3	20
	$1,000, 2022	-	366	(D)	(D)	11	(D)
	2017	-	28	(D)	286	(D)	1,688
Patronage dividends and refunds from cooperatives	farms, 2022	367	478	390	702	189	67
	2017	318	471	418	765	242	86
	$1,000, 2022	1,286	2,430	1,266	4,076	1,532	136
	2017	715	1,505	1,358	3,610	1,655	113
Crop and livestock insurance payments	farms, 2022	66	67	78	91	60	9
	2017	75	68	108	99	52	19
	$1,000, 2022	866	621	1,328	1,589	2,199	(D)
	2017	1,744	540	1,468	1,029	1,293	36
Amount from State and local government agricultural program payments	farms, 2022	10	20	14	20	8	1
	2017	7	39	22	36	9	2
	$1,000, 2022	35	129	63	89	29	(D)
	2017	36	106	113	120	34	(D)
Average per farm	dollars, 2022	3,526	6,448	4,473	4,456	3,581	(D)
	2017	5,191	2,715	5,116	3,326	3,818	(D)
Other farm-related income sources	farms, 2022	19	68	21	69	7	40
	2017	54	97	57	85	13	24
	$1,000, 2022	127	962	356	1,333	25	2,720
	2017	630	871	2,303	2,632	327	2,042

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Total income from farm-related sources	farms, 2022	496	167	328	174	617	204
	2017	504	164	323	146	583	279
	$1,000, 2022	8,122	2,947	4,287	925	16,141	3,061
	2017	5,816	3,228	2,724	521	14,213	1,337
Average per farm	dollars, 2022	16,374	17,647	13,070	5,317	26,160	15,005
	2017	11,541	19,681	8,432	3,570	24,380	4,792
Customwork and other agricultural services	farms, 2022	54	20	37	17	86	26
	2017	64	3	39	16	113	26
	$1,000, 2022	692	38	1,861	50	2,886	1,919
	2017	865	(D)	599	110	4,743	565
Gross cash rent or share payments	farms, 2022	238	69	154	37	223	100
	2017	264	66	138	31	205	139
	$1,000, 2022	4,588	1,803	463	225	9,469	280
	2017	3,239	1,856	400	88	6,555	480
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	33	20	14	34	-	12
	2017	36	13	15	11	3	17
	$1,000, 2022	639	192	251	305	-	83
	2017	607	122	83	76	(D)	87
Agri-tourism and recreational services	farms, 2022	10	3	12	-	2	5
	2017	14	5	2	2	2	3
	$1,000, 2022	26	(D)	32	-	(D)	(D)
	2017	95	(D)	(D)	(D)	(D)	(D)
Patronage dividends and refunds from cooperatives	farms, 2022	256	85	127	93	460	79
	2017	197	90	152	78	397	126
	$1,000, 2022	1,008	257	188	49	1,618	200
	2017	295	152	507	38	1,380	66
Crop and livestock insurance payments	farms, 2022	54	24	22	5	92	22
	2017	38	14	18	9	98	5
	$1,000, 2022	794	547	640	122	1,228	454
	2017	352	829	259	74	610	26
Amount from State and local government agricultural program payments	farms, 2022	20	7	12	6	8	12
	2017	36	11	7	3	23	2
	$1,000, 2022	86	(D)	22	23	(D)	(D)
	2017	139	42	(D)	(D)	166	(D)
Average per farm	dollars, 2022	4,313	(D)	1,797	3,761	(D)	(D)
	2017	3,864	3,810	(D)	(D)	7,199	(D)
Other farm-related income sources	farms, 2022	38	10	44	7	46	17
	2017	27	13	49	31	59	35
	$1,000, 2022	288	86	830	152	761	104
	2017	224	101	848	114	755	97

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Total income from farm-related sources	farms, 2022	662	366	80	574	1	99
	2017	768	327	68	696	9	70
	$1,000, 2022	27,669	14,270	733	18,288	(D)	2,677
	2017	26,552	10,721	469	16,192	(D)	448
Average per farm	dollars, 2022	41,796	38,989	9,164	31,861	(D)	27,040
	2017	34,573	32,785	6,892	23,264	(D)	6,406
Customwork and other agricultural services	farms, 2022	74	44	10	59	-	7
	2017	82	44	4	68	1	1
	$1,000, 2022	3,025	1,833	24	1,895	-	109
	2017	2,324	1,281	5	1,404	(D)	(D)
Gross cash rent or share payments	farms, 2022	295	221	16	260	-	41
	2017	330	187	13	304	1	27
	$1,000, 2022	12,540	8,243	96	10,606	-	1,245
	2017	13,205	3,943	(D)	10,276	(D)	257
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	1	5	3	-	1	9
	2017	6	-	6	-	1	9
	$1,000, 2022	(D)	42	16	-	(D)	143
	2017	2	-	72	-	(D)	81
Agri-tourism and recreational services	farms, 2022	6	3	2	2	-	-
	2017	6	-	-	3	-	4
	$1,000, 2022	50	1	(D)	(D)	-	-
	2017	11	-	-	5	-	(D)
Patronage dividends and refunds from cooperatives	farms, 2022	432	203	55	406	-	50
	2017	496	162	41	482	-	48
	$1,000, 2022	3,521	1,549	44	2,541	-	112
	2017	4,406	1,096	66	2,763	-	42
Crop and livestock insurance payments	farms, 2022	106	35	7	139	-	17
	2017	125	64	2	128	-	4
	$1,000, 2022	6,093	2,029	359	3,057	-	1,031
	2017	5,747	4,066	(D)	1,251	-	39
Amount from State and local government agricultural program payments	farms, 2022	16	22	4	6	-	3
	2017	24	8	6	19	4	3
	$1,000, 2022	(D)	145	17	(D)	-	13
	2017	172	64	15	41	2	5
Average per farm	dollars, 2022	(D)	6,613	4,275	(D)	-	4,284
	2017	7,148	8,042	2,530	2,165	556	1,500
Other farm-related income sources	farms, 2022	45	7	4	18	-	5
	2017	57	28	8	27	4	4
	$1,000, 2022	2,410	428	(D)	162	-	24
	2017	687	271	(D)	453	(D)	4

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Total income from farm-related sources	farms, 2022	497	429	584	495	172	633
	2017	559	496	659	567	216	695
	$1,000, 2022	12,123	15,555	22,438	10,955	6,555	27,305
	2017	12,888	15,133	17,501	14,579	5,067	19,304
Average per farm	dollars, 2022	24,393	36,258	38,422	22,132	38,110	43,135
	2017	23,055	30,510	26,557	25,713	23,460	27,776
Customwork and other agricultural services	farms, 2022	68	42	84	54	31	79
	2017	101	61	114	65	41	64
	$1,000, 2022	2,754	1,828	2,611	2,130	1,692	1,558
	2017	(D)	755	3,852	2,401	406	1,197
Gross cash rent or share payments	farms, 2022	242	226	200	193	75	293
	2017	244	214	214	200	102	323
	$1,000, 2022	7,337	10,873	8,928	4,859	2,398	8,513
	2017	6,614	8,499	7,391	4,533	2,764	7,759
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	2	-	-	12	1	2
	2017	2	-	-	2	1	2
	$1,000, 2022	(D)	-	-	(D)	(D)	(D)
	2017	(D)	-	-	(D)	(D)	(D)
Agri-tourism and recreational services	farms, 2022	11	-	1	1	2	1
	2017	7	-	3	6	1	3
	$1,000, 2022	250	-	(D)	(D)	(D)	(D)
	2017	(D)	-	30	(D)	(D)	(D)
Patronage dividends and refunds from cooperatives	farms, 2022	274	244	402	338	120	378
	2017	341	321	487	411	134	429
	$1,000, 2022	1,193	717	1,520	3,292	714	3,166
	2017	978	842	1,417	2,116	547	2,775
Crop and livestock insurance payments	farms, 2022	28	65	197	49	27	212
	2017	54	85	152	150	29	153
	$1,000, 2022	312	1,486	8,472	351	973	13,402
	2017	(D)	4,250	4,681	4,649	1,137	6,065
Amount from State and local government agricultural program payments	farms, 2022	7	12	14	22	11	21
	2017	21	19	21	5	12	30
	$1,000, 2022	(D)	68	(D)	48	47	(D)
	2017	57	210	21	112	104	550
Average per farm	dollars, 2022	(D)	5,675	(D)	2,184	4,272	(D)
	2017	2,692	11,027	991	22,492	8,645	18,333
Other farm-related income sources	farms, 2022	35	34	32	25	8	25
	2017	62	52	25	29	9	66
	$1,000, 2022	214	583	762	264	128	585
	2017	(D)	578	109	(D)	(D)	917

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Total income from farm-related sources	farms, 2022	514	573	267	880	642	543
	2017	628	638	349	1,053	674	614
	$1,000, 2022	22,446	15,003	1,929	10,922	21,334	20,186
	2017	18,745	12,222	2,728	9,002	18,891	14,374
Average per farm	dollars, 2022	43,669	26,183	7,224	12,411	33,231	37,175
	2017	29,849	19,156	7,815	8,549	28,028	23,410
Customwork and other agricultural services	farms, 2022	96	41	33	80	98	93
	2017	126	85	54	110	136	95
	$1,000, 2022	3,790	1,186	281	853	1,466	3,540
	2017	2,423	683	763	1,875	3,115	1,989
Gross cash rent or share payments	farms, 2022	166	241	107	385	246	218
	2017	153	215	122	407	277	230
	$1,000, 2022	11,076	6,002	499	3,540	15,886	11,677
	2017	6,924	4,960	591	2,440	11,410	9,147
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	-	5	13	15	3	-
	2017	2	10	9	28	-	-
	$1,000, 2022	-	(D)	38	167	(D)	-
	2017	(D)	3	26	146	-	-
Agri-tourism and recreational services	farms, 2022	-	6	5	8	2	4
	2017	7	8	3	2	5	1
	$1,000, 2022	-	(D)	27	176	(D)	24
	2017	(D)	257	12	(D)	(D)	(D)
Patronage dividends and refunds from cooperatives	farms, 2022	346	383	147	506	446	366
	2017	437	464	215	663	438	419
	$1,000, 2022	1,199	3,030	375	1,583	1,720	1,323
	2017	1,858	2,043	486	2,825	1,364	1,387
Crop and livestock insurance payments	farms, 2022	81	115	23	126	102	163
	2017	111	126	31	126	63	70
	$1,000, 2022	1,469	3,216	276	3,230	1,376	3,142
	2017	4,125	4,026	637	1,386	1,079	1,317
Amount from State and local government agricultural program payments	farms, 2022	2	17	12	53	9	14
	2017	12	19	8	37	15	29
	$1,000, 2022	(D)	123	79	252	49	70
	2017	63	80	61	(D)	(D)	(D)
Average per farm	dollars, 2022	(D)	7,237	6,575	4,756	5,484	4,974
	2017	5,261	4,233	7,651	(D)	(D)	(D)
Other farm-related income sources	farms, 2022	29	35	17	60	60	19
	2017	68	42	33	89	73	33
	$1,000, 2022	(D)	1,131	354	1,120	832	410
	2017	3,342	170	151	236	1,814	375

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Total income from farm-related sources	farms, 2022	455	658	314	633	1,396	182
	2017	517	672	377	713	1,444	296
	$1,000, 2022	13,900	17,725	13,381	12,631	21,088	6,380
	2017	11,684	15,864	16,192	13,376	17,041	7,737
Average per farm	dollars, 2022	30,549	26,938	42,616	19,954	15,106	35,054
	2017	22,599	23,607	42,949	18,760	11,801	26,137
Customwork and other agricultural services	farms, 2022	65	82	37	77	118	14
	2017	93	126	48	106	114	30
	$1,000, 2022	2,377	2,394	644	1,263	4,268	756
	2017	1,923	4,172	1,092	3,297	1,637	563
Gross cash rent or share payments	farms, 2022	134	210	130	265	668	89
	2017	120	218	150	268	658	129
	$1,000, 2022	7,140	10,210	6,662	7,521	8,663	1,673
	2017	5,269	6,834	6,052	5,880	8,422	2,898
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	-	2	1	10	30	1
	2017	2	2	3	9	31	4
	$1,000, 2022	-	(D)	(D)	13	276	(D)
	2017	(D)	(D)	18	30	88	(D)
Agri-tourism and recreational services	farms, 2022	-	2	-	15	25	1
	2017	4	2	-	12	24	1
	$1,000, 2022	-	(D)	-	132	191	(D)
	2017	(D)	(D)	-	59	581	(D)
Patronage dividends and refunds from cooperatives	farms, 2022	356	478	217	365	756	104
	2017	444	507	281	457	878	198
	$1,000, 2022	3,493	1,694	2,769	1,777	3,135	604
	2017	1,622	1,764	3,499	1,857	2,796	1,210
Crop and livestock insurance payments	farms, 2022	30	132	87	30	198	54
	2017	74	135	98	57	127	47
	$1,000, 2022	418	1,848	2,783	672	3,460	2,954
	2017	1,759	1,502	4,986	534	2,128	2,566
Amount from State and local government agricultural program payments	farms, 2022	8	23	10	15	71	12
	2017	5	23	14	18	38	19
	$1,000, 2022	136	17	(D)	167	243	208
	2017	13	258	138	65	56	(D)
Average per farm	dollars, 2022	17,036	733	(D)	11,108	3,419	17,366
	2017	2,645	11,206	9,873	3,591	1,468	(D)
Other farm-related income sources	farms, 2022	32	40	40	46	90	6
	2017	47	38	30	63	120	14
	$1,000, 2022	336	1,558	474	1,086	852	(D)
	2017	1,091	1,329	406	1,655	1,333	151

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Total income from farm-related sources	farms, 2022	273	332	815	459	8	184
	2017	292	392	868	512	18	182
	$1,000, 2022	1,694	13,840	38,275	24,849	925	5,757
	2017	1,522	7,734	26,620	12,142	21	3,083
Average per farm	dollars, 2022	6,204	41,687	46,964	54,138	115,641	31,289
	2017	5,211	19,730	30,668	23,716	1,164	16,942
Customwork and other agricultural services	farms, 2022	40	48	108	53	-	19
	2017	31	59	87	81	-	12
	$1,000, 2022	222	3,213	5,486	3,587	-	2,106
	2017	141	1,434	1,863	2,881	-	108
Gross cash rent or share payments	farms, 2022	107	133	342	244	2	58
	2017	102	168	379	242	-	70
	$1,000, 2022	424	5,579	11,192	15,010	(D)	1,597
	2017	527	3,574	9,745	6,964	-	1,812
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	11	-	10	1	-	2
	2017	14	-	6	3	-	-
	$1,000, 2022	20	-	555	(D)	-	(D)
	2017	23	-	19	4	-	-
Agri-tourism and recreational services	farms, 2022	13	1	3	2	3	2
	2017	3	-	11	8	-	-
	$1,000, 2022	47	(D)	187	(D)	(D)	(D)
	2017	(D)	-	23	49	-	-
Patronage dividends and refunds from cooperatives	farms, 2022	125	194	516	257	-	139
	2017	155	243	574	302	5	134
	$1,000, 2022	167	853	5,812	1,764	-	752
	2017	346	537	7,323	1,237	(Z)	601
Crop and livestock insurance payments	farms, 2022	22	92	210	98	-	26
	2017	21	43	167	45	-	21
	$1,000, 2022	516	2,778	13,243	2,554	-	1,126
	2017	83	1,288	5,870	737	-	297
Amount from State and local government agricultural program payments	farms, 2022	16	19	32	32	-	10
	2017	2	2	19	12	-	6
	$1,000, 2022	39	(D)	181	263	-	(D)
	2017	(D)	(D)	119	51	-	25
Average per farm	dollars, 2022	2,445	(D)	5,663	8,215	-	(D)
	2017	(D)	(D)	6,255	4,247	-	4,134
Other farm-related income sources	farms, 2022	16	25	51	33	3	5
	2017	36	25	44	30	13	11
	$1,000, 2022	259	1,298	1,619	1,661	900	104
	2017	394	(D)	1,658	221	21	241

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Total income from farm-related sources	farms, 2022	958	696	627	370	479	204
	2017	867	810	731	512	513	183
	$1,000, 2022	26,015	33,068	9,856	8,512	9,066	1,819
	2017	22,813	27,364	9,712	11,020	7,449	1,643
Average per farm	dollars, 2022	27,156	47,511	15,719	23,004	18,928	8,916
	2017	26,313	33,783	13,286	21,523	14,521	8,979
Customwork and other agricultural services	farms, 2022	128	128	67	49	38	30
	2017	99	121	86	149	57	16
	$1,000, 2022	2,688	7,250	1,603	1,894	1,576	475
	2017	2,375	3,036	1,796	4,509	912	102
Gross cash rent or share payments	farms, 2022	323	225	273	126	188	47
	2017	282	290	302	140	236	44
	$1,000, 2022	13,909	11,590	4,907	3,811	3,048	413
	2017	11,554	13,633	4,739	3,428	3,506	130
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	-	-	8	-	14	23
	2017	1	2	10	-	8	29
	$1,000, 2022	-	-	(D)	-	38	140
	2017	(D)	(D)	26	-	209	200
Agri-tourism and recreational services	farms, 2022	7	8	12	3	14	16
	2017	1	1	10	-	3	22
	$1,000, 2022	65	15	(D)	19	436	188
	2017	(D)	(D)	64	-	(D)	97
Patronage dividends and refunds from cooperatives	farms, 2022	662	516	377	299	313	40
	2017	646	579	463	395	330	45
	$1,000, 2022	3,035	5,966	1,807	891	1,023	41
	2017	2,570	4,110	776	1,220	1,359	30
Crop and livestock insurance payments	farms, 2022	258	219	55	77	89	12
	2017	151	206	84	71	47	7
	$1,000, 2022	5,272	5,890	1,025	1,460	2,811	51
	2017	4,854	6,001	542	896	1,243	20
Amount from State and local government agricultural program payments	farms, 2022	23	22	24	11	26	27
	2017	29	15	12	6	18	6
	$1,000, 2022	80	230	50	115	77	54
	2017	(D)	25	35	60	(D)	9
Average per farm	dollars, 2022	3,485	10,463	2,102	10,411	2,975	2,005
	2017	(D)	1,657	2,898	10,010	(D)	1,544
Other farm-related income sources	farms, 2022	50	76	42	10	18	43
	2017	46	41	64	27	24	57
	$1,000, 2022	966	2,126	376	322	55	456
	2017	1,194	555	1,733	907	147	1,054

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Total income from farm-related sources	farms, 2022	280	154	567	1,598	424	349
	2017	397	207	653	1,861	467	412
	$1,000, 2022	6,635	3,094	16,039	27,690	9,795	19,196
	2017	5,790	2,052	17,115	18,444	8,700	11,382
Average per farm	dollars, 2022	23,697	20,090	28,288	17,328	23,102	55,002
	2017	14,584	9,914	26,210	9,911	18,630	27,627
Customwork and other agricultural services	farms, 2022	51	10	60	192	50	59
	2017	32	44	94	236	42	73
	$1,000, 2022	376	366	2,137	3,275	1,325	2,506
	2017	335	660	2,538	3,204	942	2,250
Gross cash rent or share payments	farms, 2022	94	70	234	578	235	162
	2017	149	72	220	609	218	179
	$1,000, 2022	1,350	1,072	8,610	7,418	6,900	9,921
	2017	2,291	650	8,364	6,972	6,264	6,416
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	1	5	4	12	3	-
	2017	4	10	5	15	1	-
	$1,000, 2022	(D)	(D)	5	35	14	-
	2017	(D)	7	4	87	(D)	-
Agri-tourism and recreational services	farms, 2022	22	4	-	8	-	-
	2017	14	15	-	20	3	1
	$1,000, 2022	1,626	(D)	-	718	-	-
	2017	1,070	159	-	43	(D)	(D)
Patronage dividends and refunds from cooperatives	farms, 2022	125	56	405	1,054	237	225
	2017	214	97	488	1,317	279	274
	$1,000, 2022	453	188	3,956	5,219	1,001	1,600
	2017	428	215	3,552	4,775	606	1,588
Crop and livestock insurance payments	farms, 2022	36	34	49	253	24	74
	2017	26	9	89	170	43	67
	$1,000, 2022	1,171	889	728	7,191	246	3,493
	2017	394	78	2,243	1,368	451	640
Amount from State and local government agricultural program payments	farms, 2022	12	10	8	87	12	16
	2017	18	13	17	36	13	6
	$1,000, 2022	(D)	64	34	393	23	454
	2017	(D)	15	47	237	70	(D)
Average per farm	dollars, 2022	(D)	6,370	4,244	4,520	1,928	28,367
	2017	(D)	1,148	2,781	6,580	5,370	(D)
Other farm-related income sources	farms, 2022	43	18	23	107	27	30
	2017	56	15	47	150	49	23
	$1,000, 2022	1,567	305	569	3,440	286	1,223
	2017	1,242	269	367	1,758	348	477

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Total income from farm-related sources	farms, 2022	467	740	263	501	195	428
	2017	507	948	323	554	273	521
	$1,000, 2022	16,723	6,792	15,632	9,427	1,618	11,417
	2017	15,869	5,309	11,505	7,551	1,735	11,347
Average per farm	dollars, 2022	35,809	9,179	59,437	18,816	8,297	26,675
	2017	31,300	5,600	35,619	13,630	6,357	21,779
Customwork and other agricultural services	farms, 2022	54	76	25	55	21	70
	2017	54	100	38	79	26	88
	$1,000, 2022	1,613	1,366	1,043	1,734	52	3,396
	2017	1,526	1,542	794	1,125	260	2,773
Gross cash rent or share payments	farms, 2022	227	315	155	197	96	175
	2017	240	344	159	198	131	180
	$1,000, 2022	9,098	1,963	8,066	4,742	644	6,449
	2017	10,430	1,739	7,928	3,912	1,096	5,860
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	-	14	-	5	6	1
	2017	-	15	-	13	17	-
	$1,000, 2022	-	(D)	-	67	116	(D)
	2017	-	17	-	96	67	-
Agri-tourism and recreational services	farms, 2022	-	3	1	4	4	2
	2017	1	5	-	12	5	7
	$1,000, 2022	-	(D)	(D)	27	1	(D)
	2017	(D)	4	-	15	1	4
Patronage dividends and refunds from cooperatives	farms, 2022	297	441	123	333	102	285
	2017	277	651	198	390	166	342
	$1,000, 2022	2,470	1,135	917	2,087	97	858
	2017	1,462	1,386	1,180	1,125	241	802
Crop and livestock insurance payments	farms, 2022	91	89	67	37	32	25
	2017	110	91	44	70	8	42
	$1,000, 2022	2,906	2,010	5,488	441	636	346
	2017	1,992	411	1,467	828	4	1,067
Amount from State and local government agricultural program payments	farms, 2022	23	41	7	9	14	9
	2017	14	14	8	18	6	20
	$1,000, 2022	185	99	57	17	44	13
	2017	(D)	68	51	103	11	236
Average per farm	dollars, 2022	8,045	2,409	8,141	1,923	3,160	1,396
	2017	(D)	4,846	6,346	5,700	1,906	11,776
Other farm-related income sources	farms, 2022	19	36	3	39	20	27
	2017	27	61	13	45	20	41
	$1,000, 2022	451	179	(D)	313	28	328
	2017	426	142	84	347	54	605

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Table 6. **Income From Farm-Related Sources: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Total income from farm-related sources	farms, 2022	224	364	244	587	651	606
	2017	245	373	283	646	807	655
	$1,000, 2022	4,476	12,876	14,811	9,083	10,209	22,249
	2017	7,252	8,896	12,383	9,933	9,852	16,116
Average per farm	dollars, 2022	19,980	35,374	60,702	15,473	15,682	36,714
	2017	29,599	23,849	43,755	15,376	12,208	24,605
Customwork and other agricultural services	farms, 2022	32	58	40	92	79	64
	2017	30	55	35	119	90	75
	$1,000, 2022	579	3,572	1,778	2,661	1,642	2,337
	2017	97	1,006	1,289	2,775	932	1,855
Gross cash rent or share payments	farms, 2022	86	133	123	220	276	286
	2017	82	128	126	237	349	263
	$1,000, 2022	915	7,709	6,528	3,085	3,647	13,712
	2017	409	5,847	6,722	3,888	2,886	9,977
Sales of forest products, excluding Christmas trees, short rotation woody crops, and maple products	farms, 2022	5	-	-	31	8	-
	2017	4	-	-	32	11	2
	$1,000, 2022	28	-	-	473	8	-
	2017	5	-	-	336	17	(D)
Agri-tourism and recreational services	farms, 2022	22	-	-	18	28	4
	2017	20	-	3	12	24	-
	$1,000, 2022	1,046	-	-	123	651	11
	2017	959	-	16	186	598	-
Patronage dividends and refunds from cooperatives	farms, 2022	79	251	143	359	329	411
	2017	116	288	178	396	464	442
	$1,000, 2022	213	901	1,423	1,860	949	2,078
	2017	238	1,002	1,755	1,111	2,319	1,619
Crop and livestock insurance payments	farms, 2022	6	38	71	44	56	133
	2017	23	48	74	85	86	97
	$1,000, 2022	102	396	4,867	599	1,051	3,076
	2017	1,799	660	2,244	1,079	1,510	1,113
Amount from State and local government agricultural program payments	farms, 2022	12	4	21	29	21	12
	2017	13	5	6	27	6	23
	$1,000, 2022	14	42	93	24	56	89
	2017	18	(D)	31	87	11	(D)
Average per farm	dollars, 2022	1,154	10,500	4,420	829	2,672	7,455
	2017	1,420	(D)	5,088	3,225	1,871	(D)
Other farm-related income sources	farms, 2022	43	12	10	74	66	11
	2017	63	16	23	58	77	51
	$1,000, 2022	1,580	255	123	259	2,206	945
	2017	3,727	(D)	327	470	1,579	1,359

Table 7. **Hired Farm Labor - Workers and Payroll: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
Hired farm labor ..... farms	17,399	40	81	176	77
workers	72,097	149	1,238	1,034	165
$1,000 payroll	1,320,974	738	20,764	23,897	1,509
Farms with-					
1 to 4 workers (see text) ..... farms	13,359	35	40	137	72
workers	26,869	62	75	309	125
5 to 9 workers ..... farms	2,603	3	19	16	3
workers	16,125	(D)	129	93	(D)
10 workers or more ..... farms	1,437	2	22	23	2
workers	29,103	(D)	1,034	632	(D)
Workers by days worked:					
150 days or more ..... farms	9,054	23	47	97	35
workers	30,983	64	523	594	60
Farms with-					
1 to 4 workers (see text) ..... farms	7,696	21	28	79	33
workers	14,920	(D)	54	168	(D)
5 to 9 workers ..... farms	768	1	5	5	2
workers	4,829	(D)	37	31	(D)
10 workers or more ..... farms	590	1	14	13	-
workers	11,234	(D)	432	395	-
Less than 150 days ..... farms	12,949	27	67	119	58
workers	41,114	85	715	440	105
Farms with-					
1 to 4 workers (see text) ..... farms	10,967	26	36	93	56
workers	21,670	(D)	69	198	(D)
5 to 9 workers ..... farms	1,386	-	13	17	1
workers	8,642	-	71	113	(D)
10 workers or more ..... farms	596	1	18	9	1
workers	10,802	(D)	575	129	(D)
Reported only workers working 150 days or more ..... farms	4,450	13	14	57	19
workers	13,337	48	60	191	32
$1,000 payroll	397,811	254	3,006	5,139	546
Reported only workers working less than 150 days ..... farms	8,345	17	34	79	42
workers	21,220	72	243	212	79
$1,000 payroll	180,497	209	715	2,327	285
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	4,604	10	33	40	16
150 days or more, workers	17,646	16	463	403	28
less than 150 days, workers	19,894	13	472	228	26
$1,000 payroll	742,666	275	17,044	16,431	677
Total migrant workers ..... farms	614	1	10	3	1
workers	4,641	(D)	129	62	(D)
Migrant farm labor on farms with hired labor ..... farms	573	1	8	3	1
workers	4,518	(D)	(D)	62	(D)
Migrant farm labor on farms reporting only contract labor ..... farms	41	-	2	-	-
workers	123	-	(D)	-	-
Unpaid workers ..... farms	17,519	149	119	254	204
workers	40,333	436	280	687	512

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
Hired farm labor ..... farms	134	128	319	293	57
workers	956	398	1,334	973	188
$1,000 payroll	27,969	8,427	25,870	17,761	879
Farms with-					
1 to 4 workers (see text) ..... farms	98	114	240	229	41
workers	196	238	534	446	73
5 to 9 workers ..... farms	18	8	50	54	13
workers	113	51	319	323	77
10 workers or more ..... farms	18	6	29	10	3
workers	647	109	481	204	38
Workers by days worked:					
150 days or more ..... farms	79	69	161	149	19
workers	466	180	538	430	38
Farms with-					
1 to 4 workers (see text) ..... farms	53	63	145	129	18
workers	93	106	317	251	(D)
5 to 9 workers ..... farms	15	2	7	14	1
workers	90	(D)	52	78	(D)
10 workers or more ..... farms	11	4	9	6	-
workers	283	(D)	169	101	-
Less than 150 days ..... farms	90	89	254	216	50
workers	490	218	796	543	150
Farms with-					
1 to 4 workers (see text) ..... farms	73	81	222	198	43
workers	138	151	470	394	97
5 to 9 workers ..... farms	10	6	22	14	5
workers	68	(D)	159	87	(D)
10 workers or more ..... farms	7	2	10	4	2
workers	284	(D)	167	62	(D)
Reported only workers working 150 days or more ..... farms	44	39	65	77	7
workers	207	103	228	229	11
$1,000 payroll	7,799	2,386	9,377	9,442	21
Reported only workers working less than 150 days ..... farms	55	59	158	144	38
workers	160	129	388	299	96
$1,000 payroll	1,473	1,967	4,676	2,218	348
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	35	30	96	72	12
150 days or more, workers	259	77	310	201	27
less than 150 days, workers	330	89	408	244	54
$1,000 payroll	18,697	4,074	11,817	6,100	511
Total migrant workers ..... farms	8	9	3	12	-
workers	148	26	11	42	-
Migrant farm labor on farms with hired labor ..... farms	8	9	2	10	-
workers	148	26	(D)	(D)	-
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	1	2	-
workers	-	-	(D)	(D)	-
Unpaid workers ..... farms	165	84	267	223	191
workers	352	242	565	470	496

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Hired farm labor ..... farms	168	69	202	89	244	66
workers	593	184	903	323	1,183	249
$1,000 payroll	8,557	1,156	17,882	3,726	26,106	2,609
Farms with-						
1 to 4 workers (see text) ..... farms	127	63	137	71	175	54
workers	238	104	316	128	413	84
5 to 9 workers ..... farms	29	4	45	13	41	7
workers	182	(D)	289	86	264	49
10 workers or more ..... farms	12	2	20	5	28	5
workers	173	(D)	298	109	506	116
Workers by days worked:						
150 days or more ..... farms	86	28	108	45	142	35
workers	251	74	287	101	466	84
Farms with-						
1 to 4 workers (see text) ..... farms	67	24	99	39	127	31
workers	120	34	199	67	267	50
5 to 9 workers ..... farms	15	3	6	6	3	2
workers	89	(D)	39	34	17	(D)
10 workers or more ..... farms	4	1	3	-	12	2
workers	42	(D)	49	-	182	(D)
Less than 150 days ..... farms	124	47	163	67	169	46
workers	342	110	616	222	717	165
Farms with-						
1 to 4 workers (see text) ..... farms	107	45	128	55	121	36
workers	202	(D)	315	99	269	52
5 to 9 workers ..... farms	13	1	23	10	34	5
workers	75	(D)	146	(D)	229	35
10 workers or more ..... farms	4	1	12	2	14	5
workers	65	(D)	155	(D)	219	78
Reported only workers working 150 days or more ..... farms	44	22	39	22	75	20
workers	126	50	84	44	220	27
$1,000 payroll	3,320	368	2,219	877	11,394	122
Reported only workers working less than 150 days ..... farms	82	41	94	44	102	31
workers	187	77	290	77	383	71
$1,000 payroll	1,353	(D)	4,740	399	4,147	297
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	42	6	69	23	67	15
150 days or more, workers	125	24	203	57	246	57
less than 150 days, workers	155	33	326	145	334	94
$1,000 payroll	3,884	(D)	10,924	2,450	10,566	2,190
Total migrant workers ..... farms	5	1	17	1	13	1
workers	14	(D)	87	(D)	74	(D)
Migrant farm labor on farms with hired labor ..... farms	4	1	17	1	13	1
workers	(D)	(D)	87	(D)	74	(D)
Migrant farm labor on farms reporting only contract labor ..... farms	1	-	-	-	-	-
workers	(D)	-	-	-	-	-
Unpaid workers ..... farms	195	172	93	242	179	120
workers	453	404	163	521	361	323

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Hired farm labor ..... farms	2	259	68	204	189	189
workers	(D)	1,009	229	1,756	837	547
$1,000 payroll	(D)	17,180	3,419	41,692	16,049	6,809
Farms with-						
1 to 4 workers (see text) ..... farms	2	206	55	121	140	159
workers	(D)	467	97	254	276	303
5 to 9 workers ..... farms	-	40	9	21	29	20
workers	-	218	66	127	202	120
10 workers or more ..... farms	-	13	4	62	20	10
workers	-	324	66	1,375	359	124
Workers by days worked:						
150 days or more ..... farms	-	139	34	139	102	76
workers	-	453	109	934	400	192
Farms with-						
1 to 4 workers (see text) ..... farms	-	130	25	92	78	68
workers	-	240	(D)	201	155	127
5 to 9 workers ..... farms	-	3	8	22	15	4
workers	-	18	58	145	84	24
10 workers or more ..... farms	-	6	1	25	9	4
workers	-	195	(D)	588	161	41
Less than 150 days ..... farms	2	191	47	145	150	147
workers	(D)	556	120	822	437	355
Farms with-						
1 to 4 workers (see text) ..... farms	2	174	45	98	126	134
workers	(D)	397	(D)	179	242	250
5 to 9 workers ..... farms	-	10	1	26	18	10
workers	-	58	(D)	166	114	62
10 workers or more ..... farms	-	7	1	21	6	3
workers	-	101	(D)	477	81	43
Reported only workers working 150 days or more ..... farms	-	68	21	59	39	42
workers	-	275	57	282	130	91
$1,000 payroll	-	8,459	1,777	14,070	4,369	1,486
Reported only workers working less than 150 days ..... farms	2	120	34	65	87	113
workers	(D)	350	66	287	195	261
$1,000 payroll	(D)	2,902	173	4,764	907	1,186
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	-	71	13	80	63	34
150 days or more, workers	-	178	52	652	270	101
less than 150 days, workers	-	206	54	535	242	94
$1,000 payroll	-	5,819	1,468	22,859	10,774	4,137
Total migrant workers ..... farms	-	8	-	11	1	6
workers	-	58	-	392	(D)	11
Migrant farm labor on farms with hired labor ..... farms	-	6	-	7	1	6
workers	-	(D)	-	(D)	(D)	11
Migrant farm labor on farms reporting only contract labor ..... farms	-	2	-	4	-	-
workers	-	(D)	-	(D)	-	-
Unpaid workers ..... farms	7	190	130	252	174	262
workers	19	400	335	614	415	526

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Hired farm labor ..... farms	263	365	269	368	160	127
workers	1,005	1,241	871	1,324	633	932
$1,000 payroll	16,661	20,887	14,608	24,567	16,285	18,695
Farms with-						
1 to 4 workers (see text) ..... farms	194	295	229	279	119	90
workers	390	618	446	508	237	176
5 to 9 workers ..... farms	54	50	27	62	31	13
workers	318	300	154	379	178	84
10 workers or more ..... farms	15	20	13	27	10	24
workers	297	323	271	437	218	672
Workers by days worked:						
150 days or more ..... farms	128	204	95	186	99	74
workers	390	583	298	632	329	498
Farms with-						
1 to 4 workers (see text) ..... farms	115	178	85	151	89	52
workers	222	353	157	292	176	102
5 to 9 workers ..... farms	6	21	4	24	2	11
workers	37	128	23	150	(D)	75
10 workers or more ..... farms	7	5	6	11	8	11
workers	131	102	118	190	(D)	321
Less than 150 days ..... farms	209	269	228	269	116	98
workers	615	658	573	692	304	434
Farms with-						
1 to 4 workers (see text) ..... farms	185	241	207	231	108	70
workers	407	451	389	432	223	120
5 to 9 workers ..... farms	16	21	16	34	6	19
workers	110	121	100	194	(D)	106
10 workers or more ..... farms	8	7	5	4	2	9
workers	98	86	84	66	(D)	208
Reported only workers working 150 days or more ..... farms	54	96	41	99	44	29
workers	115	252	123	313	177	168
$1,000 payroll	2,494	5,136	3,603	10,349	7,528	4,621
Reported only workers working less than 150 days ..... farms	135	161	174	182	61	53
workers	359	346	381	385	120	109
$1,000 payroll	3,661	3,580	2,471	3,200	1,158	605
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	74	108	54	87	55	45
150 days or more, workers	275	331	175	319	152	330
less than 150 days, workers	256	312	192	307	184	325
$1,000 payroll	10,506	12,171	8,534	11,018	7,598	13,469
Total migrant workers ..... farms	8	12	5	8	12	12
workers	56	77	48	49	52	86
Migrant farm labor on farms with hired labor ..... farms	8	12	5	8	12	12
workers	56	77	48	49	52	86
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	-	-	-	-
workers	-	-	-	-	-	-
Unpaid workers ..... farms	174	417	221	445	115	193
workers	317	910	430	987	253	553

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Hired farm labor ..... farms	155	50	103	78	269	92
workers	562	221	315	183	868	202
$1,000 payroll	12,745	4,121	5,432	1,316	14,446	1,344
Farms with-						
1 to 4 workers (see text) ..... farms	118	43	93	68	232	83
workers	233	69	173	119	490	144
5 to 9 workers ..... farms	24	1	5	9	29	9
workers	145	(D)	29	(D)	169	58
10 workers or more ..... farms	13	6	5	1	8	-
workers	184	(D)	113	(D)	209	-
Workers by days worked:						
150 days or more ..... farms	94	24	44	20	113	48
workers	321	86	127	44	371	90
Farms with-						
1 to 4 workers (see text) ..... farms	71	19	42	18	101	47
workers	120	(D)	(D)	(D)	208	(D)
5 to 9 workers ..... farms	17	2	-	2	6	1
workers	109	(D)	-	(D)	33	(D)
10 workers or more ..... farms	6	3	2	-	6	-
workers	92	40	(D)	-	130	-
Less than 150 days ..... farms	102	33	73	62	199	62
workers	241	135	188	139	497	112
Farms with-						
1 to 4 workers (see text) ..... farms	90	27	67	54	178	56
workers	169	39	130	92	339	75
5 to 9 workers ..... farms	12	3	3	7	17	6
workers	72	23	21	(D)	100	37
10 workers or more ..... farms	-	3	3	1	4	-
workers	-	73	37	(D)	58	-
Reported only workers working 150 days or more ..... farms	53	17	30	16	70	30
workers	205	32	50	40	184	67
$1,000 payroll	6,989	477	517	885	4,863	673
Reported only workers working less than 150 days ..... farms	61	26	59	58	156	44
workers	123	52	125	123	363	74
$1,000 payroll	643	434	472	311	2,947	218
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	41	7	14	4	43	18
150 days or more, workers	116	54	77	4	187	23
less than 150 days, workers	118	83	63	16	134	38
$1,000 payroll	5,113	3,209	4,443	120	6,637	453
Total migrant workers ..... farms	9	1	2	-	1	1
workers	70	(D)	(D)	-	(D)	(D)
Migrant farm labor on farms with hired labor ..... farms	9	1	2	-	1	1
workers	70	(D)	(D)	-	(D)	(D)
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	-	-	-	-
workers	-	-	-	-	-	-
Unpaid workers ..... farms	262	101	299	148	158	166
workers	697	294	695	329	313	354

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Hired farm labor ..... farms	344	223	22	242	8	45
workers	1,461	882	(D)	683	31	111
$1,000 payroll	36,174	13,099	379	9,810	(D)	1,929
Farms with-						
1 to 4 workers (see text) ..... farms	256	168	21	210	6	40
workers	504	359	(D)	401	(D)	70
5 to 9 workers ..... farms	50	36	-	28	1	3
workers	310	241	-	165	(D)	(D)
10 workers or more ..... farms	38	19	1	4	1	2
workers	647	282	(D)	117	(D)	(D)
Workers by days worked:						
150 days or more ..... farms	156	129	8	92	5	23
workers	621	288	31	224	13	50
Farms with-						
1 to 4 workers (see text) ..... farms	119	121	7	88	4	21
workers	218	247	(D)	146	(D)	(D)
5 to 9 workers ..... farms	24	8	-	-	1	2
workers	148	41	-	-	(D)	(D)
10 workers or more ..... farms	13	-	1	4	-	-
workers	255	-	(D)	78	-	-
Less than 150 days ..... farms	269	168	15	195	7	35
workers	840	594	(D)	459	18	61
Farms with-						
1 to 4 workers (see text) ..... farms	216	134	15	179	5	34
workers	432	281	(D)	350	(D)	(D)
5 to 9 workers ..... farms	39	22	-	15	2	1
workers	225	149	-	(D)	(D)	(D)
10 workers or more ..... farms	14	12	-	1	-	-
workers	183	164	-	(D)	-	-
Reported only workers working 150 days or more ..... farms	75	55	7	47	1	10
workers	274	119	(D)	77	(D)	18
$1,000 payroll	12,347	2,875	(D)	1,628	(D)	385
Reported only workers working less than 150 days ..... farms	188	94	14	150	3	22
workers	502	206	(D)	328	(D)	35
$1,000 payroll	4,271	2,889	(D)	3,378	4	194
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	81	74	1	45	4	13
150 days or more, workers	347	169	(D)	147	(D)	32
less than 150 days, workers	338	388	(D)	131	(D)	26
$1,000 payroll	19,555	7,335	(D)	4,804	183	1,350
Total migrant workers ..... farms	23	12	1	10	-	2
workers	99	37	(D)	49	-	(D)
Migrant farm labor on farms with hired labor ..... farms	23	12	1	8	-	2
workers	99	37	(D)	(D)	-	(D)
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	-	2	-	-
workers	-	-	-	(D)	-	-
Unpaid workers ..... farms	310	146	45	157	8	65
workers	688	400	84	311	25	155

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Hired farm labor	farms	204	140	304	218	82	331
	workers	642	513	968	722	252	1,257
	$1,000 payroll	8,243	11,374	15,982	10,158	3,825	19,315
Farms with-							
1 to 4 workers (see text)	farms	171	112	272	177	63	258
	workers	355	217	570	348	124	567
5 to 9 workers	farms	22	14	15	30	17	54
	workers	127	82	85	191	(D)	335
10 workers or more	farms	11	14	17	11	2	19
	workers	160	214	313	183	(D)	355
Workers by days worked:							
150 days or more	farms	98	73	136	110	44	183
	workers	312	212	390	298	70	435
Farms with-							
1 to 4 workers (see text)	farms	80	63	126	101	43	174
	workers	145	110	232	209	(D)	364
5 to 9 workers	farms	11	6	-	6	1	7
	workers	59	35	-	38	(D)	(D)
10 workers or more	farms	7	4	10	3	-	2
	workers	108	67	158	51	-	(D)
Less than 150 days	farms	135	103	240	165	63	241
	workers	330	301	578	424	182	822
Farms with-							
1 to 4 workers (see text)	farms	126	87	218	144	52	203
	workers	255	158	392	277	112	429
5 to 9 workers	farms	6	10	14	19	10	23
	workers	35	66	86	(D)	(D)	148
10 workers or more	farms	3	6	8	2	1	15
	workers	40	77	100	(D)	(D)	245
Reported only workers working 150 days or more	farms	69	37	64	53	19	90
	workers	264	76	156	108	23	178
	$1,000 payroll	4,834	1,504	4,869	1,755	687	4,245
Reported only workers working less than 150 days	farms	106	67	168	108	38	148
	workers	266	175	387	228	102	453
	$1,000 payroll	1,605	751	3,051	1,200	906	4,818
Reported both - workers working 150 days or more and workers working less than 150 days	farms	29	36	72	57	25	93
	150 days or more, workers	48	136	234	190	47	257
	less than 150 days, workers	64	126	191	196	80	369
	$1,000 payroll	1,804	9,119	8,061	7,203	2,232	10,251
Total migrant workers	farms	6	3	6	4	3	9
	workers	39	22	43	39	11	62
Migrant farm labor on farms with hired labor	farms	6	3	5	4	3	9
	workers	39	22	(D)	39	11	62
Migrant farm labor on farms reporting only contract labor	farms	-	-	1	-	-	-
	workers	-	-	(D)	-	-	-
Unpaid workers	farms	206	114	213	220	51	242
	workers	450	253	455	466	101	559

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Hired farm labor ..... farms	337	218	89	335	304	281
workers	1,485	1,115	196	1,372	1,189	1,069
$1,000 payroll	27,467	27,751	1,861	18,928	19,645	13,861
Farms with-						
1 to 4 workers (see text) ..... farms	257	163	82	257	230	220
workers	572	332	147	495	452	416
5 to 9 workers ..... farms	48	19	6	41	56	46
workers	282	121	(D)	259	372	269
10 workers or more ..... farms	32	36	1	37	18	15
workers	631	662	(D)	618	365	384
Workers by days worked:						
150 days or more ..... farms	155	119	36	152	157	149
workers	748	595	74	540	550	399
Farms with-						
1 to 4 workers (see text) ..... farms	122	92	35	124	128	136
workers	244	179	(D)	226	243	273
5 to 9 workers ..... farms	4	13	-	19	19	7
workers	26	101	-	122	136	44
10 workers or more ..... farms	29	14	1	9	10	6
workers	478	315	(D)	192	171	82
Less than 150 days ..... farms	264	167	60	232	221	195
workers	737	520	122	832	639	670
Farms with-						
1 to 4 workers (see text) ..... farms	235	143	55	181	193	170
workers	513	283	89	337	387	313
5 to 9 workers ..... farms	22	14	5	29	21	19
workers	142	82	33	172	148	111
10 workers or more ..... farms	7	10	-	22	7	6
workers	82	155	-	323	104	246
Reported only workers working 150 days or more ..... farms	73	51	29	103	83	86
workers	354	337	63	337	273	245
$1,000 payroll	5,591	12,882	1,320	9,680	7,767	7,256
Reported only workers working less than 150 days ..... farms	182	99	53	183	147	132
workers	467	301	111	632	321	477
$1,000 payroll	5,136	1,139	390	3,938	3,035	2,516
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	82	68	7	49	74	63
150 days or more, workers	394	258	11	203	277	154
less than 150 days, workers	270	219	11	200	318	193
$1,000 payroll	16,739	13,730	151	5,310	8,842	4,089
Total migrant workers ..... farms	4	8	1	14	8	5
workers	29	79	(D)	101	41	13
Migrant farm labor on farms with hired labor ..... farms	4	8	1	13	8	5
workers	29	79	(D)	(D)	41	13
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	-	1	-	-
workers	-	-	-	(D)	-	-
Unpaid workers ..... farms	189	258	210	424	293	156
workers	411	597	502	976	669	333

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Hired farm labor ..... farms	229	342	190	279	438	90
workers	1,039	1,277	770	1,179	1,586	236
$1,000 payroll	23,851	25,357	12,584	20,006	29,344	4,634
Farms with-						
1 to 4 workers (see text) ..... farms	153	280	131	209	336	83
workers	281	580	276	403	644	191
5 to 9 workers ..... farms	54	42	48	36	75	6
workers	323	253	293	228	451	(D)
10 workers or more ..... farms	22	20	11	34	27	1
workers	435	444	201	548	491	(D)
Workers by days worked:						
150 days or more ..... farms	132	181	116	144	219	38
workers	533	575	268	471	676	76
Farms with-						
1 to 4 workers (see text) ..... farms	106	163	112	114	184	38
workers	222	306	221	206	348	76
5 to 9 workers ..... farms	13	4	2	21	23	-
workers	80	22	(D)	136	149	-
10 workers or more ..... farms	13	14	2	9	12	-
workers	231	247	(D)	129	179	-
Less than 150 days ..... farms	177	249	144	207	346	69
workers	506	702	502	708	910	160
Farms with-						
1 to 4 workers (see text) ..... farms	155	225	115	166	311	67
workers	312	456	255	325	597	(D)
5 to 9 workers ..... farms	17	17	19	31	25	2
workers	122	116	109	204	146	(D)
10 workers or more ..... farms	5	7	10	10	10	-
workers	72	130	138	179	167	-
Reported only workers working 150 days or more ..... farms	52	93	46	72	92	21
workers	190	253	82	156	242	46
$1,000 payroll	3,724	5,785	1,839	3,626	7,007	2,025
Reported only workers working less than 150 days ..... farms	97	161	74	135	219	52
workers	210	452	208	425	479	127
$1,000 payroll	2,966	4,957	2,910	3,443	4,275	1,274
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	80	88	70	72	127	17
150 days or more, workers	343	322	186	315	434	30
less than 150 days, workers	296	250	294	283	431	33
$1,000 payroll	17,161	14,615	7,834	12,937	18,063	1,335
Total migrant workers ..... farms	6	8	8	3	8	1
workers	45	81	14	21	82	(D)
Migrant farm labor on farms with hired labor ..... farms	6	8	8	3	6	1
workers	45	81	14	21	(D)	(D)
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	-	-	2	-
workers	-	-	-	-	(D)	-
Unpaid workers ..... farms	161	211	87	334	656	75
workers	357	459	201	757	1,475	147

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Hired farm labor ..... farms	127	172	477	189	28	98
workers	388	749	2,738	812	166	350
$1,000 payroll	4,174	18,426	46,368	12,596	1,406	7,193
Farms with-						
1 to 4 workers (see text) ..... farms	109	135	277	139	18	70
workers	196	283	586	280	34	157
5 to 9 workers ..... farms	9	19	119	33	5	24
workers	49	108	794	214	38	145
10 workers or more ..... farms	9	18	81	17	5	4
workers	143	358	1,358	318	94	48
Workers by days worked:						
150 days or more ..... farms	52	93	283	96	19	52
workers	145	386	829	341	79	141
Farms with-						
1 to 4 workers (see text) ..... farms	45	73	256	78	15	43
workers	75	133	568	153	34	74
5 to 9 workers ..... farms	4	9	18	11	3	6
workers	24	53	107	67	(D)	36
10 workers or more ..... farms	3	11	9	7	1	3
workers	46	200	154	121	(D)	31
Less than 150 days ..... farms	91	121	394	141	19	78
workers	243	363	1,909	471	87	209
Farms with-						
1 to 4 workers (see text) ..... farms	81	106	255	117	13	66
workers	159	206	549	245	32	140
5 to 9 workers ..... farms	7	11	82	17	3	11
workers	36	62	542	121	16	(D)
10 workers or more ..... farms	3	4	57	7	3	1
workers	48	95	818	105	39	(D)
Reported only workers working 150 days or more ..... farms	36	51	83	48	9	20
workers	65	226	173	181	33	76
$1,000 payroll	1,226	8,848	5,249	2,703	497	2,851
Reported only workers working less than 150 days ..... farms	75	79	194	93	9	46
workers	168	218	625	216	18	131
$1,000 payroll	624	2,511	5,556	1,463	108	1,372
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	16	42	200	48	10	32
150 days or more, workers	80	160	656	160	46	65
less than 150 days, workers	75	145	1,284	255	69	78
$1,000 payroll	2,324	7,068	35,563	8,431	800	2,970
Total migrant workers ..... farms	1	5	28	7	-	4
workers	(D)	93	124	40	-	10
Migrant farm labor on farms with hired labor ..... farms	1	5	26	7	-	4
workers	(D)	93	(D)	40	-	10
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	2	-	-	-
workers	-	-	(D)	-	-	-
Unpaid workers ..... farms	256	114	283	171	13	46
workers	599	258	592	484	27	90

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
Hired farm labor ..... farms	463	364	232	221	205	123
workers	1,349	1,707	1,321	940	612	417
$1,000 payroll	19,386	35,003	17,481	15,532	11,267	2,357
Farms with-						
1 to 4 workers (see text) ..... farms	375	268	172	157	174	101
workers	725	568	355	321	326	190
5 to 9 workers ..... farms	78	58	36	44	20	11
workers	454	345	220	254	112	68
10 workers or more ..... farms	10	38	24	20	11	11
workers	170	794	746	365	174	159
Workers by days worked:						
150 days or more ..... farms	219	199	126	125	105	53
workers	494	590	495	448	267	138
Farms with-						
1 to 4 workers (see text) ..... farms	206	175	100	106	94	46
workers	381	344	177	235	181	100
5 to 9 workers ..... farms	9	10	16	6	8	7
workers	48	61	95	35	45	38
10 workers or more ..... farms	4	14	10	13	3	-
workers	65	185	223	178	41	-
Less than 150 days ..... farms	359	281	175	164	155	96
workers	855	1,117	826	492	345	279
Farms with-						
1 to 4 workers (see text) ..... farms	331	228	137	143	144	80
workers	649	486	285	295	247	135
5 to 9 workers ..... farms	24	35	25	15	4	12
workers	148	227	155	107	28	68
10 workers or more ..... farms	4	18	13	6	7	4
workers	58	404	386	90	70	76
Reported only workers working 150 days or more ..... farms	104	83	57	57	50	27
workers	227	190	126	171	105	58
$1,000 payroll	6,220	6,986	4,459	4,958	2,967	428
Reported only workers working less than 150 days ..... farms	244	165	106	96	100	70
workers	531	519	280	230	177	155
$1,000 payroll	4,965	6,306	1,476	2,325	2,253	466
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	115	116	69	68	55	26
150 days or more, workers	267	400	369	277	162	80
less than 150 days, workers	324	598	546	262	168	124
$1,000 payroll	8,201	21,711	11,547	8,250	6,047	1,462
Total migrant workers ..... farms	8	22	15	3	3	1
workers	48	207	100	11	10	(D)
Migrant farm labor on farms with hired labor ..... farms	8	22	15	3	3	1
workers	48	207	100	11	10	(D)
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	-	-	-	-
workers	-	-	-	-	-	-
Unpaid workers ..... farms	312	173	366	104	223	352
workers	637	388	870	212	527	934

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Hired farm labor ..... farms	136	101	244	725	199	201
workers	511	795	878	3,414	780	1,029
$1,000 payroll	6,078	10,487	20,390	64,650	23,315	25,365
Farms with-						
1 to 4 workers (see text) ..... farms	98	66	199	518	154	125
workers	173	126	434	1,082	293	274
5 to 9 workers ..... farms	26	12	28	134	38	64
workers	174	83	188	828	239	424
10 workers or more ..... farms	12	23	17	73	7	12
workers	164	586	256	1,504	248	331
Workers by days worked:						
150 days or more ..... farms	63	44	132	415	96	114
workers	185	243	407	1,704	371	444
Farms with-						
1 to 4 workers (see text) ..... farms	53	25	109	318	89	96
workers	117	61	216	632	(D)	222
5 to 9 workers ..... farms	8	12	18	65	1	8
workers	(D)	86	111	417	(D)	42
10 workers or more ..... farms	2	7	5	32	6	10
workers	(D)	96	80	655	198	180
Less than 150 days ..... farms	114	88	169	497	164	159
workers	326	552	471	1,710	409	585
Farms with-						
1 to 4 workers (see text) ..... farms	98	62	144	389	150	127
workers	174	97	307	759	302	293
5 to 9 workers ..... farms	12	9	23	82	12	29
workers	82	54	(D)	496	(D)	181
10 workers or more ..... farms	4	17	2	26	2	3
workers	70	401	(D)	455	(D)	111
Reported only workers working 150 days or more ..... farms	22	13	75	228	35	42
workers	38	107	209	797	153	178
$1,000 payroll	1,379	2,815	7,787	21,414	6,105	6,960
Reported only workers working less than 150 days ..... farms	73	57	112	310	103	87
workers	212	142	261	861	228	209
$1,000 payroll	654	1,245	4,233	5,461	2,481	2,518
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	41	31	57	187	61	72
150 days or more, workers	147	136	198	907	218	266
less than 150 days, workers	114	410	210	849	181	376
$1,000 payroll	4,044	6,427	8,371	37,775	14,728	15,886
Total migrant workers ..... farms	3	11	5	26	1	7
workers	6	220	17	166	(D)	48
Migrant farm labor on farms with hired labor ..... farms	3	11	3	26	1	7
workers	6	220	(D)	166	(D)	48
Migrant farm labor on farms reporting only contract labor ..... farms	-	-	2	-	-	-
workers	-	-	(D)	-	-	-
Unpaid workers ..... farms	190	144	221	717	191	99
workers	466	341	475	1,754	424	183

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Hired farm labor ..... farms	213	290	134	226	98	208
workers	961	1,190	461	976	346	721
$1,000 payroll	20,736	23,985	12,642	21,036	7,221	14,255
Farms with-						
1 to 4 workers (see text) ..... farms	156	234	108	177	86	166
workers	336	428	241	348	171	342
5 to 9 workers ..... farms	41	35	19	28	7	34
workers	248	220	115	174	54	202
10 workers or more ..... farms	16	21	7	21	5	8
workers	377	542	105	454	121	177
Workers by days worked:						
150 days or more ..... farms	113	165	81	150	49	101
workers	415	537	222	536	168	298
Farms with-						
1 to 4 workers (see text) ..... farms	99	145	75	120	41	91
workers	197	268	161	217	84	181
5 to 9 workers ..... farms	3	10	4	20	6	6
workers	22	63	(D)	122	(D)	30
10 workers or more ..... farms	11	10	2	10	2	4
workers	196	206	(D)	197	(D)	87
Less than 150 days ..... farms	169	197	89	129	67	155
workers	546	653	239	440	178	423
Farms with-						
1 to 4 workers (see text) ..... farms	143	167	80	107	59	138
workers	315	298	172	193	90	276
5 to 9 workers ..... farms	20	17	7	11	5	13
workers	122	106	(D)	62	29	87
10 workers or more ..... farms	6	13	2	11	3	4
workers	109	249	(D)	185	59	60
Reported only workers working 150 days or more ..... farms	44	93	45	97	31	53
workers	132	192	131	306	101	151
$1,000 payroll	4,216	3,076	6,151	11,761	3,537	3,985
Reported only workers working less than 150 days ..... farms	100	125	53	76	49	107
workers	295	278	120	186	84	269
$1,000 payroll	2,329	1,669	2,007	974	239	2,938
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	69	72	36	53	18	48
150 days or more, workers	283	345	91	230	67	147
less than 150 days, workers	251	375	119	254	94	154
$1,000 payroll	14,191	19,240	4,484	8,301	3,446	7,332
Total migrant workers ..... farms	9	6	8	16	2	1
workers	70	38	22	218	(D)	(D)
Migrant farm labor on farms with hired labor ..... farms	9	5	8	15	2	1
workers	70	(D)	22	(D)	(D)	(D)
Migrant farm labor on farms reporting only contract labor ..... farms	-	1	-	1	-	-
workers	-	(D)	-	(D)	-	-
Unpaid workers ..... farms	130	447	47	244	122	150
workers	282	1,202	92	519	268	332

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Table 7. **Hired Farm Labor - Workers and Payroll: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Hired farm labor ..... farms	151	173	144	249	301	259
workers	798	771	679	1,398	1,293	847
$1,000 payroll	9,617	13,420	12,482	33,096	17,704	13,423
Farms with-						
1 to 4 workers (see text) ..... farms	114	144	98	155	248	204
workers	239	310	190	307	464	395
5 to 9 workers ..... farms	19	13	28	41	29	48
workers	136	80	172	267	190	296
10 workers or more ..... farms	18	16	18	53	24	7
workers	423	381	317	824	639	156
Workers by days worked:						
150 days or more ..... farms	89	84	94	167	153	125
workers	305	343	262	874	501	353
Farms with-						
1 to 4 workers (see text) ..... farms	79	70	86	104	128	113
workers	165	(D)	164	205	204	205
5 to 9 workers ..... farms	6	2	4	37	19	6
workers	46	(D)	22	251	128	38
10 workers or more ..... farms	4	12	4	26	6	6
workers	94	181	76	418	169	110
Less than 150 days ..... farms	105	137	104	169	215	193
workers	493	428	417	524	792	494
Farms with-						
1 to 4 workers (see text) ..... farms	80	122	84	126	181	167
workers	155	235	195	238	345	320
5 to 9 workers ..... farms	16	7	11	40	21	24
workers	106	46	83	225	117	(D)
10 workers or more ..... farms	9	8	9	3	13	2
workers	232	147	139	61	330	(D)
Reported only workers working 150 days or more ..... farms	46	36	40	80	86	66
workers	132	140	74	388	170	182
$1,000 payroll	2,701	5,341	3,080	12,033	3,041	6,724
Reported only workers working less than 150 days ..... farms	62	89	50	82	148	134
workers	176	179	136	184	405	322
$1,000 payroll	855	976	1,666	1,143	3,493	1,955
Reported both - workers working 150 days or more and workers working less than 150 days ..... farms	43	48	54	87	67	59
150 days or more, workers	173	203	188	486	331	171
less than 150 days, workers	317	249	281	340	387	172
$1,000 payroll	6,061	7,104	7,736	19,920	11,169	4,744
Total migrant workers ..... farms	11	8	7	38	16	7
workers	81	64	16	258	108	42
Migrant farm labor on farms with hired labor ..... farms	6	7	7	38	6	6
workers	71	(D)	16	258	83	(D)
Migrant farm labor on farms reporting only contract labor ..... farms	5	1	-	-	10	1
workers	10	(D)	-	-	25	(D)
Unpaid workers ..... farms	167	111	72	259	418	175
workers	457	239	150	657	988	349

Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
FARMS AND LAND IN FARMS					
Farms ..... number, 2022	65,531	449	355	952	608
2017	68,822	462	360	943	583
Land in farms ..... acres, 2022	25,442,625	120,748	30,064	381,537	173,158
2017	25,516,982	105,730	39,047	367,799	168,667
Average size of farm ..... acres, 2022	388	269	85	401	285
2017	371	229	108	390	289
Estimated market value of land and buildings ..... farms, 2022	65,531	449	355	952	608
2017	68,822	462	360	943	583
$1,000, 2022	155,374,449	344,619	286,649	1,302,256	530,335
2017	123,824,645	223,008	296,378	1,068,703	331,547
Average per farm ..... dollars, 2022	2,371,007	767,525	807,463	1,367,916	872,261
2017	1,799,201	482,701	823,272	1,133,301	568,690
Average per acre ..... dollars, 2022	6,107	2,854	9,535	3,413	3,063
2017	4,853	2,109	7,590	2,906	1,966
2022 farms by value group:					
$1 to $49,999	1,819	16	3	27	12
$50,000 to $99,999	2,318	5	11	37	25
$100,000 to $199,999	5,817	56	35	140	101
$200,000 to $499,999	17,490	197	126	284	212
$500,000 to $999,999	13,050	113	124	232	108
$1,000,000 to $1,999,999	8,615	42	28	111	90
$2,000,000 to $4,999,999	8,631	16	23	78	42
$5,000,000 to $9,999,999	3,992	1	3	11	16
$10,000,000 or more	3,799	3	2	32	2
Approximate land area ..... acres, 2022	50,960,343	1,165,910	270,701	841,682	1,603,002
Proportion in farms ..... percent, 2022	49.9	10.4	11.1	45.3	10.8
2022 size of farm:					
1 to 9 acres ..... farms	4,401	9	53	28	14
acres	22,106	30	(D)	104	47
10 to 49 acres ..... farms	15,218	71	198	148	122
acres	398,319	2,126	4,426	4,016	3,640
50 to 69 acres ..... farms	3,598	26	29	60	29
acres	211,291	1,603	1,724	3,522	1,826
70 to 99 acres ..... farms	5,575	46	23	101	57
acres	455,348	3,696	1,885	8,338	4,676
100 to 139 acres ..... farms	4,857	46	16	103	41
acres	567,895	5,461	1,897	12,195	4,822
140 to 179 acres ..... farms	4,814	50	2	92	69
acres	757,338	7,810	(D)	14,563	10,823
180 to 219 acres ..... farms	2,981	26	5	74	50
acres	588,138	5,081	1,045	14,669	9,739
220 to 259 acres ..... farms	2,503	35	2	46	35
acres	594,776	8,311	(D)	10,875	8,207
260 to 499 acres ..... farms	8,699	86	11	132	106
acres	3,130,858	30,592	3,790	46,919	37,209
500 to 999 acres ..... farms	6,421	43	12	95	52
acres	4,468,495	27,722	7,188	65,145	33,773
1,000 to 1,999 acres ..... farms	3,752	5	3	30	27
acres	5,173,695	6,066	4,810	40,568	33,196
2,000 acres or more ..... farms	2,712	6	1	43	6
acres	9,074,366	22,250	(D)	160,623	25,200
2017 size of farm:					
1 to 9 acres ..... farms	5,234	11	79	49	30
acres	26,402	(D)	(D)	266	157
10 to 49 acres ..... farms	14,618	78	137	144	119
acres	396,828	2,358	3,273	4,317	4,050
50 to 69 acres ..... farms	3,712	35	34	51	21
acres	217,056	(D)	1,917	2,957	1,254
70 to 99 acres ..... farms	5,741	63	35	94	55
acres	467,485	5,102	2,842	7,722	4,419
100 to 139 acres ..... farms	5,087	48	24	116	56
acres	594,116	5,601	2,869	13,661	6,491
140 to 179 acres ..... farms	4,916	54	9	94	70
acres	773,134	8,491	1,448	14,830	11,241
180 to 219 acres ..... farms	3,253	20	10	56	36
acres	643,027	3,897	(D)	10,961	6,986
220 to 259 acres ..... farms	2,916	29	2	53	19
acres	691,707	6,868	(D)	12,587	4,580
260 to 499 acres ..... farms	9,754	82	14	137	83
acres	3,494,375	29,735	5,067	47,527	29,709
500 to 999 acres ..... farms	7,164	31	10	76	69
acres	5,002,107	19,594	(D)	52,149	44,199
1,000 to 1,999 acres ..... farms	4,182	9	2	37	17
acres	5,720,340	13,536	(D)	49,433	23,113
2,000 acres or more ..... farms	2,245	2	4	36	8
acres	7,490,405	(D)	8,800	151,389	32,468
LAND IN FARMS ACCORDING TO USE					
Total cropland ..... farms, 2022	58,762	413	311	814	523
2017	61,686	414	274	813	460
acres, 2022	21,544,060	54,562	21,934	279,390	87,778
2017	21,786,756	54,095	29,420	255,999	79,842
Harvested cropland ..... farms, 2022	47,549	396	259	597	473
2017	50,272	389	250	614	413
acres, 2022	19,662,443	48,445	17,836	242,439	73,854
2017	20,054,132	45,661	26,945	226,915	68,263

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
FARMS AND LAND IN FARMS					
Farms ..... number, 2022	687	392	1,019	973	463
2017	816	438	983	1,040	529
Land in farms ..... acres, 2022	134,358	263,888	478,133	302,331	125,420
2017	194,832	268,769	382,730	355,766	93,397
Average size of farm ..... acres, 2022	196	673	469	311	271
2017	239	614	389	342	177
Estimated market value of land and buildings ..... farms, 2022	687	392	1,019	973	463
2017	816	438	983	1,040	529
$1,000, 2022	691,550	1,273,294	3,708,082	2,512,396	381,276
2017	855,276	1,168,473	2,756,591	2,338,846	201,288
Average per farm ..... dollars, 2022	1,006,623	3,248,198	3,638,942	2,582,113	823,491
2017	1,048,133	2,667,748	2,804,263	2,248,890	380,506
Average per acre ..... dollars, 2022	5,147	4,825	7,755	8,310	3,040
2017	4,390	4,348	7,202	6,574	2,155
2022 farms by value group:					
$1 to $49,999	10	20	33	24	6
$50,000 to $99,999	28	12	41	19	6
$100,000 to $199,999	70	31	68	89	43
$200,000 to $499,999	247	81	181	179	217
$500,000 to $999,999	193	50	157	123	119
$1,000,000 to $1,999,999	91	54	143	156	47
$2,000,000 to $4,999,999	30	74	175	243	22
$5,000,000 to $9,999,999	7	39	130	106	2
$10,000,000 or more	11	31	91	34	1
Approximate land area ..... acres, 2022	261,310	319,378	478,602	391,084	551,248
Proportion in farms ..... percent, 2022	51.4	82.6	99.9	77.3	22.8
2022 size of farm:					
1 to 9 acres ..... farms	22	14	96	45	15
acres	105	47	471	269	65
10 to 49 acres ..... farms	240	61	222	190	109
acres	7,074	1,872	5,670	4,699	(D)
50 to 69 acres ..... farms	62	15	44	57	16
acres	3,673	879	2,506	3,395	965
70 to 99 acres ..... farms	71	26	73	63	69
acres	5,729	2,114	5,955	5,116	5,500
100 to 139 acres ..... farms	65	21	57	71	40
acres	7,695	2,488	6,781	8,245	4,620
140 to 179 acres ..... farms	33	23	65	76	53
acres	5,112	3,664	10,262	12,281	8,332
180 to 219 acres ..... farms	41	14	34	42	30
acres	7,990	2,805	6,719	8,346	5,854
220 to 259 acres ..... farms	18	18	31	35	24
acres	4,326	4,236	7,275	8,274	5,685
260 to 499 acres ..... farms	83	66	138	204	83
acres	28,952	24,337	49,207	74,500	28,936
500 to 999 acres ..... farms	33	56	122	137	20
acres	22,307	39,594	84,214	93,398	12,470
1,000 to 1,999 acres ..... farms	9	47	62	40	3
acres	10,869	69,679	79,596	50,917	(D)
2,000 acres or more ..... farms	10	31	75	13	1
acres	30,526	112,173	219,477	32,891	(D)
2017 size of farm:					
1 to 9 acres ..... farms	29	16	95	83	6
acres	160	62	476	419	22
10 to 49 acres ..... farms	234	62	209	178	130
acres	7,265	1,652	5,199	4,565	4,183
50 to 69 acres ..... farms	69	24	45	46	31
acres	4,002	1,407	2,600	2,777	1,829
70 to 99 acres ..... farms	86	29	74	62	74
acres	6,956	2,372	6,033	5,079	5,913
100 to 139 acres ..... farms	68	20	69	58	45
acres	7,823	2,247	8,120	6,748	5,098
140 to 179 acres ..... farms	41	30	61	59	49
acres	6,482	4,625	9,702	9,303	7,651
180 to 219 acres ..... farms	41	12	35	70	43
acres	8,088	2,441	6,844	13,810	8,356
220 to 259 acres ..... farms	44	24	31	54	28
acres	10,389	5,635	7,395	12,678	6,784
260 to 499 acres ..... farms	118	74	134	218	89
acres	41,165	27,423	49,082	80,219	29,676
500 to 999 acres ..... farms	53	62	123	151	29
acres	37,332	44,233	83,729	106,115	17,610
1,000 to 1,999 acres ..... farms	21	60	73	41	5
acres	29,895	86,658	98,535	55,694	6,275
2,000 acres or more ..... farms	12	25	34	20	-
acres	35,275	90,014	105,015	58,359	-
LAND IN FARMS ACCORDING TO USE					
Total cropland ..... farms, 2022	607	368	936	907	415
2017	739	424	894	959	471
acres, 2022	104,396	241,318	452,711	282,635	36,197
2017	155,769	246,358	355,453	330,839	41,339
Harvested cropland ..... farms, 2022	541	290	768	756	377
2017	665	341	718	815	452
acres, 2022	95,943	213,843	437,712	260,346	30,672
2017	146,183	231,596	342,744	309,845	37,057

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	606	488	563	740	655	404
2017	689	432	623	821	694	414
Land in farms ..... acres, 2022	156,676	134,449	364,695	81,038	556,161	159,856
2017	158,644	133,541	341,030	115,500	576,646	155,673
Average size of farm ..... acres, 2022	259	276	648	110	849	396
2017	230	309	547	141	831	376
Estimated market value of land and buildings ..... farms, 2022	606	488	563	740	655	404
2017	689	432	623	821	694	414
$1,000, 2022	1,275,264	409,984	2,823,478	568,698	2,634,873	460,516
2017	1,069,585	334,298	2,009,941	528,357	2,276,472	315,435
Average per farm ..... dollars, 2022	2,104,397	840,132	5,015,059	768,510	4,022,707	1,139,890
2017	1,552,374	773,837	3,226,230	643,553	3,280,220	761,920
Average per acre ..... dollars, 2022	8,140	3,049	7,742	7,018	4,738	2,881
2017	6,742	2,503	5,894	4,575	3,948	2,026
2022 farms by value group:						
$1 to $49,999	14	12	20	17	27	6
$50,000 to $99,999	15	17	31	13	23	19
$100,000 to $199,999	42	65	56	90	43	75
$200,000 to $499,999	177	163	86	310	144	123
$500,000 to $999,999	131	138	71	189	103	87
$1,000,000 to $1,999,999	97	54	70	79	73	41
$2,000,000 to $4,999,999	69	33	80	32	91	41
$5,000,000 to $9,999,999	37	4	63	7	70	5
$10,000,000 or more	24	2	86	3	81	7
Approximate land area ..... acres, 2022	226,682	1,293,740	371,910	265,544	668,924	639,363
Proportion in farms ..... percent, 2022	69.1	10.4	98.1	30.5	83.1	25.0
2022 size of farm:						
1 to 9 acres ..... farms	58	22	48	114	28	16
acres	290	81	267	532	121	87
10 to 49 acres ..... farms	193	83	130	347	120	80
acres	4,834	2,340	3,243	9,217	3,216	2,317
50 to 69 acres ..... farms	49	32	11	33	29	7
acres	2,941	1,920	639	1,881	1,682	371
70 to 99 acres ..... farms	61	45	29	62	45	30
acres	4,888	3,605	2,322	5,076	3,653	2,495
100 to 139 acres ..... farms	43	51	28	44	27	39
acres	5,073	5,950	3,225	5,121	3,120	4,631
140 to 179 acres ..... farms	31	45	31	37	50	27
acres	4,994	7,028	4,894	5,742	7,747	4,304
180 to 219 acres ..... farms	16	33	22	23	16	26
acres	3,099	6,391	4,368	4,485	3,107	5,088
220 to 259 acres ..... farms	27	39	14	16	15	18
acres	6,404	9,202	3,339	3,867	3,558	4,394
260 to 499 acres ..... farms	56	80	71	38	88	69
acres	19,711	28,471	25,019	13,523	32,381	25,534
500 to 999 acres ..... farms	34	35	75	13	88	57
acres	23,351	24,021	54,327	9,553	64,090	38,106
1,000 to 1,999 acres ..... farms	22	15	38	10	63	21
acres	29,650	20,106	55,564	12,917	88,444	28,005
2,000 acres or more ..... farms	16	8	66	3	86	14
acres	51,441	25,334	207,488	9,124	345,042	44,524
2017 size of farm:						
1 to 9 acres ..... farms	55	24	43	92	27	21
acres	239	153	222	437	114	103
10 to 49 acres ..... farms	209	66	123	336	113	78
acres	5,267	1,734	3,587	8,906	3,142	2,541
50 to 69 acres ..... farms	37	29	24	42	42	11
acres	2,109	1,728	1,378	2,368	2,530	662
70 to 99 acres ..... farms	76	53	42	90	31	40
acres	6,348	4,218	3,409	7,520	2,473	3,214
100 to 139 acres ..... farms	50	30	34	58	26	41
acres	5,727	3,625	3,988	6,806	3,154	4,960
140 to 179 acres ..... farms	48	41	38	30	38	37
acres	7,588	6,483	5,977	4,664	6,109	5,793
180 to 219 acres ..... farms	32	33	21	38	23	17
acres	6,227	6,488	4,193	7,418	4,474	3,343
220 to 259 acres ..... farms	37	21	29	21	28	17
acres	8,933	5,074	6,860	4,982	6,513	4,049
260 to 499 acres ..... farms	79	78	78	66	97	71
acres	26,954	27,617	29,168	23,416	36,443	26,576
500 to 999 acres ..... farms	30	38	95	34	103	45
acres	18,806	26,172	69,422	22,006	73,543	30,732
1,000 to 1,999 acres ..... farms	22	8	48	8	76	26
acres	31,890	11,752	63,848	10,033	110,912	34,740
2,000 acres or more ..... farms	14	11	48	6	90	10
acres	38,556	38,497	148,978	16,944	327,239	38,960
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	550	417	524	631	589	331
2017	651	346	589	712	619	343
acres, 2022	137,542	56,299	332,842	58,198	508,962	77,211
2017	136,071	57,910	320,528	82,706	538,136	76,106
Harvested cropland ..... farms, 2022	473	371	395	551	498	298
2017	542	311	464	620	502	303
acres, 2022	129,717	46,589	316,194	53,977	476,475	62,929
2017	129,117	52,040	302,453	74,829	507,417	65,646

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	25	742	426	841	614	980
2017	32	744	494	820	611	960
Land in farms ..... acres, 2022	1,940	392,494	92,791	208,517	280,440	268,096
2017	1,393	370,389	89,196	227,081	248,036	263,265
Average size of farm ..... acres, 2022	78	529	218	248	457	274
2017	44	498	181	277	406	274
Estimated market value of land and buildings ..... farms, 2022	25	742	426	841	614	980
2017	32	744	494	820	611	960
$1,000, 2022	14,540	3,228,009	295,766	1,729,620	2,415,899	1,220,546
2017	8,257	2,341,221	239,789	1,567,378	1,709,560	1,038,869
Average per farm ..... dollars, 2022	581,604	4,350,416	694,287	2,056,623	3,934,689	1,245,455
2017	258,025	3,146,803	485,403	1,911,437	2,797,971	1,082,155
Average per acre ..... dollars, 2022	7,495	8,224	3,187	8,295	8,615	4,553
2017	5,927	6,321	2,688	6,902	6,892	3,946
2022 farms by value group:						
$1 to $49,999	-	21	17	39	12	39
$50,000 to $99,999	-	42	11	27	23	40
$100,000 to $199,999	6	66	37	43	55	95
$200,000 to $499,999	12	125	196	205	160	359
$500,000 to $999,999	1	83	97	241	108	201
$1,000,000 to $1,999,999	4	95	33	99	71	123
$2,000,000 to $4,999,999	2	119	32	117	70	80
$5,000,000 to $9,999,999	-	79	-	33	45	20
$10,000,000 or more	-	112	3	37	70	23
Approximate land area ..... acres, 2022	929,517	409,564	638,961	359,962	281,138	407,526
Proportion in farms ..... percent, 2022	0.2	95.8	14.5	57.9	99.8	65.8
2022 size of farm:						
1 to 9 acres ..... farms	-	64	30	131	81	48
acres	-	400	114	575	464	250
10 to 49 acres ..... farms	9	129	95	282	172	263
acres	174	3,280	2,500	6,246	3,862	7,568
50 to 69 acres ..... farms	4	30	33	48	44	89
acres	235	1,807	1,971	2,782	2,604	5,200
70 to 99 acres ..... farms	3	47	38	72	39	111
acres	235	3,787	3,095	5,948	3,279	8,923
100 to 139 acres ..... farms	3	36	44	30	23	55
acres	336	4,172	5,127	3,591	2,684	6,406
140 to 179 acres ..... farms	6	47	51	40	40	76
acres	960	7,323	7,724	6,251	6,330	12,182
180 to 219 acres ..... farms	-	26	29	32	21	45
acres	-	5,089	5,741	6,332	4,184	8,982
220 to 259 acres ..... farms	-	28	17	22	16	38
acres	-	6,613	4,035	5,240	3,863	9,088
260 to 499 acres ..... farms	-	99	43	69	38	142
acres	-	35,734	15,097	26,139	13,177	49,607
500 to 999 acres ..... farms	-	101	21	68	58	55
acres	-	73,698	12,469	46,531	41,935	39,099
1,000 to 1,999 acres ..... farms	-	89	21	32	46	32
acres	-	123,481	26,139	43,520	64,511	40,138
2,000 acres or more ..... farms	-	46	4	15	36	26
acres	-	127,110	8,779	55,362	133,547	80,653
2017 size of farm:						
1 to 9 acres ..... farms	12	53	33	156	88	31
acres	60	280	125	617	432	174
10 to 49 acres ..... farms	13	114	114	242	162	236
acres	311	2,750	3,637	5,864	3,968	7,398
50 to 69 acres ..... farms	2	28	38	47	27	72
acres	(D)	1,665	2,186	2,716	1,592	4,223
70 to 99 acres ..... farms	-	48	70	48	42	82
acres	-	3,850	5,661	3,919	3,526	6,510
100 to 139 acres ..... farms	2	34	55	29	30	73
acres	(D)	3,849	6,337	3,390	3,488	8,691
140 to 179 acres ..... farms	2	38	49	38	42	80
acres	(D)	5,885	7,482	6,002	6,484	12,748
180 to 219 acres ..... farms	-	25	33	28	26	70
acres	-	5,100	6,531	5,508	5,260	13,987
220 to 259 acres ..... farms	-	27	11	22	21	45
acres	-	6,364	2,538	5,256	5,022	10,700
260 to 499 acres ..... farms	1	108	48	81	46	145
acres	(D)	39,670	16,539	29,416	16,152	50,310
500 to 999 acres ..... farms	-	137	30	79	46	71
acres	-	96,230	20,145	54,738	33,681	51,408
1,000 to 1,999 acres ..... farms	-	110	13	27	56	40
acres	-	147,613	18,015	39,415	73,582	49,861
2,000 acres or more ..... farms	-	22	-	23	25	15
acres	-	57,133	-	70,240	94,849	47,255
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	22	681	357	704	527	883
2017	23	690	406	692	525	894
acres, 2022	283	370,705	43,947	187,757	262,797	201,875
2017	181	345,460	41,839	205,444	231,948	205,324
Harvested cropland ..... farms, 2022	21	548	327	657	436	660
2017	23	571	357	642	431	654
acres, 2022	228	351,380	37,686	175,486	255,854	176,176
2017	137	329,040	37,367	196,549	227,125	180,126

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	773	1,458	908	1,406	529	511
2017	822	1,401	1,076	1,461	524	467
Land in farms ..... acres, 2022	383,231	470,312	351,174	421,698	338,754	32,406
2017	407,766	375,533	394,024	384,651	324,188	45,885
Average size of farm ..... acres, 2022	496	323	387	300	640	63
2017	496	268	366	263	619	98
Estimated market value of land and buildings ..... farms, 2022	773	1,458	908	1,406	529	511
2017	822	1,401	1,076	1,461	524	467
$1,000, 2022	3,130,804	2,783,975	2,703,388	3,501,264	1,650,851	558,570
2017	2,772,547	2,085,670	2,376,055	2,386,396	1,427,392	617,798
Average per farm ..... dollars, 2022	4,050,200	1,909,448	2,977,299	2,490,231	3,120,701	1,093,093
2017	3,372,928	1,488,701	2,208,230	1,633,399	2,724,030	1,322,909
Average per acre ..... dollars, 2022	8,169	5,919	7,698	8,303	4,873	17,237
2017	6,799	5,554	6,030	6,204	4,403	13,464
2022 farms by value group:						
$1 to $49,999	27	39	34	24	21	20
$50,000 to $99,999	23	28	29	24	19	10
$100,000 to $199,999	41	106	96	52	82	36
$200,000 to $499,999	95	422	176	359	117	108
$500,000 to $999,999	97	318	118	347	89	159
$1,000,000 to $1,999,999	129	189	133	224	53	98
$2,000,000 to $4,999,999	165	219	178	205	60	65
$5,000,000 to $9,999,999	104	73	84	98	35	15
$10,000,000 or more	92	64	60	73	53	-
Approximate land area ..... acres, 2022	455,984	551,229	452,537	484,384	350,590	354,309
Proportion in farms ..... percent, 2022	84.0	85.3	77.6	87.1	96.6	9.1
2022 size of farm:						
1 to 9 acres ..... farms	61	82	62	112	25	150
acres	341	409	357	647	127	(D)
10 to 49 acres ..... farms	113	335	232	383	112	227
acres	3,325	9,079	6,072	9,948	3,430	4,823
50 to 69 acres ..... farms	40	137	41	89	21	24
acres	2,395	7,952	2,401	5,159	1,267	1,405
70 to 99 acres ..... farms	56	135	70	90	45	23
acres	4,784	11,128	5,614	7,289	3,638	1,865
100 to 139 acres ..... farms	26	141	42	111	40	31
acres	2,991	16,535	5,043	12,752	4,569	3,747
140 to 179 acres ..... farms	58	94	62	116	49	16
acres	9,081	14,588	9,649	18,381	7,776	2,465
180 to 219 acres ..... farms	28	44	38	54	27	5
acres	5,534	8,592	7,527	10,779	5,322	960
220 to 259 acres ..... farms	28	52	29	52	21	4
acres	6,564	12,452	6,952	12,384	4,950	(D)
260 to 499 acres ..... farms	126	177	125	173	60	19
acres	46,980	63,125	47,074	62,457	22,414	7,619
500 to 999 acres ..... farms	132	150	115	142	42	11
acres	93,831	103,635	79,385	96,133	30,365	6,890
1,000 to 1,999 acres ..... farms	73	63	59	51	32	1
acres	100,928	84,433	77,289	67,650	46,486	(D)
2,000 acres or more ..... farms	32	48	33	33	55	-
acres	106,477	138,384	103,811	118,119	208,410	-
2017 size of farm:						
1 to 9 acres ..... farms	124	114	128	160	12	123
acres	557	638	748	856	79	430
10 to 49 acres ..... farms	111	330	253	374	96	198
acres	2,678	8,761	5,960	9,927	2,627	4,675
50 to 69 acres ..... farms	17	87	44	73	28	17
acres	960	5,147	2,578	4,130	1,698	974
70 to 99 acres ..... farms	26	129	78	105	56	30
acres	2,141	10,724	6,304	8,662	4,576	2,403
100 to 139 acres ..... farms	35	122	59	106	38	18
acres	4,144	14,103	7,048	12,530	4,403	2,042
140 to 179 acres ..... farms	61	86	46	109	34	12
acres	9,583	13,385	7,141	16,856	5,277	1,844
180 to 219 acres ..... farms	31	67	53	89	37	9
acres	6,015	13,550	10,382	17,538	7,151	1,779
220 to 259 acres ..... farms	26	60	31	57	15	15
acres	6,137	14,334	7,295	13,660	3,574	3,493
260 to 499 acres ..... farms	101	202	120	196	56	23
acres	38,316	71,614	44,688	71,908	19,427	8,346
500 to 999 acres ..... farms	172	132	137	128	65	14
acres	123,921	90,889	98,496	88,506	45,411	8,780
1,000 to 1,999 acres ..... farms	89	47	103	41	44	8
acres	120,963	61,628	131,219	52,810	65,807	11,119
2,000 acres or more ..... farms	29	25	24	23	43	-
acres	92,351	70,760	72,165	87,268	164,158	-
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	715	1,287	850	1,218	489	425
2017	747	1,211	972	1,231	509	407
acres, 2022	366,048	377,220	332,702	357,142	316,178	21,319
2017	388,946	287,633	374,911	325,761	302,999	36,623
Harvested cropland ..... farms, 2022	640	1,002	670	1,059	282	373
2017	634	970	769	1,079	290	376
acres, 2022	356,884	347,026	312,957	341,371	281,684	17,928
2017	379,969	262,059	360,587	309,916	280,145	34,395

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	797	336	814	424	845	531
2017	891	384	805	337	799	624
Land in farms ..... acres, 2022	223,021	98,144	101,666	96,375	384,337	99,182
2017	217,048	94,581	132,421	71,710	356,306	118,788
Average size of farm ..... acres, 2022	280	292	125	227	455	187
2017	244	246	164	213	446	190
Estimated market value of land and buildings ..... farms, 2022	797	336	814	424	845	531
2017	891	384	805	337	799	624
$1,000, 2022	1,161,724	360,253	603,250	324,094	3,247,266	321,901
2017	931,062	250,308	514,772	203,771	2,293,725	315,070
Average per farm ..... dollars, 2022	1,457,621	1,072,180	741,093	764,373	3,842,918	606,217
2017	1,044,963	651,843	639,469	604,662	2,870,744	504,920
Average per acre ..... dollars, 2022	5,209	3,671	5,934	3,363	8,449	3,246
2017	4,290	2,646	3,887	2,842	6,438	2,652
2022 farms by value group:						
$1 to $49,999	5	3	23	19	12	20
$50,000 to $99,999	13	19	38	17	24	31
$100,000 to $199,999	62	31	59	44	68	72
$200,000 to $499,999	214	135	364	178	127	245
$500,000 to $999,999	199	89	219	89	124	97
$1,000,000 to $1,999,999	157	38	69	44	138	38
$2,000,000 to $4,999,999	101	9	31	27	168	24
$5,000,000 to $9,999,999	29	1	5	5	88	1
$10,000,000 or more	17	11	6	1	96	3
Approximate land area ..... acres, 2022	353,308	592,577	278,876	1,706,948	449,902	333,818
Proportion in farms ..... percent, 2022	63.1	16.6	36.5	5.6	85.4	29.7
2022 size of farm:						
1 to 9 acres ..... farms	17	4	67	20	64	31
acres	92	26	305	89	367	150
10 to 49 acres ..... farms	151	79	362	99	139	164
acres	4,666	2,157	9,190	(D)	3,487	4,823
50 to 69 acres ..... farms	46	27	68	15	31	32
acres	2,596	1,609	3,996	867	1,877	1,898
70 to 99 acres ..... farms	86	32	82	69	69	76
acres	7,081	2,559	6,837	5,536	5,545	6,289
100 to 139 acres ..... farms	65	37	79	34	44	55
acres	7,558	4,370	9,177	4,009	5,121	6,260
140 to 179 acres ..... farms	70	34	57	33	59	35
acres	11,040	5,439	8,857	5,137	9,225	5,482
180 to 219 acres ..... farms	66	15	13	26	38	31
acres	13,029	2,896	2,532	5,142	7,546	6,203
220 to 259 acres ..... farms	52	15	9	19	37	15
acres	12,234	3,513	2,094	4,506	8,801	3,578
260 to 499 acres ..... farms	110	52	42	56	138	37
acres	38,690	19,252	14,020	19,355	52,706	12,844
500 to 999 acres ..... farms	107	27	21	44	105	48
acres	70,916	17,361	14,679	32,017	72,164	33,461
1,000 to 1,999 acres ..... farms	17	8	8	7	89	3
acres	24,650	10,992	10,337	8,061	120,477	3,609
2,000 acres or more ..... farms	10	6	6	2	32	4
acres	30,469	27,970	19,642	(D)	97,021	14,585
2017 size of farm:						
1 to 9 acres ..... farms	51	10	64	12	80	26
acres	279	(D)	462	83	352	127
10 to 49 acres ..... farms	140	74	306	79	123	181
acres	4,146	2,217	8,573	2,579	3,064	5,958
50 to 69 acres ..... farms	43	24	76	13	31	39
acres	2,489	1,329	4,317	781	1,807	2,259
70 to 99 acres ..... farms	91	56	89	50	35	94
acres	7,595	4,583	7,058	3,987	2,844	7,539
100 to 139 acres ..... farms	82	39	81	31	47	50
acres	9,489	4,755	9,580	3,479	5,429	5,756
140 to 179 acres ..... farms	71	53	42	39	60	54
acres	11,195	8,136	6,497	6,125	9,482	8,588
180 to 219 acres ..... farms	56	18	21	18	29	31
acres	11,007	3,645	4,202	3,638	5,712	6,120
220 to 259 acres ..... farms	84	16	11	13	34	25
acres	19,798	3,738	2,636	3,020	8,245	5,832
260 to 499 acres ..... farms	160	60	49	57	121	81
acres	58,047	20,335	16,405	19,680	44,220	30,947
500 to 999 acres ..... farms	93	26	39	17	135	33
acres	59,729	16,554	27,210	12,094	97,410	23,000
1,000 to 1,999 acres ..... farms	17	2	23	5	82	3
acres	23,834	(D)	34,091	5,434	113,593	3,660
2,000 acres or more ..... farms	3	6	4	3	22	7
acres	9,440	25,586	11,390	10,810	64,148	19,002
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	716	279	689	365	775	463
2017	768	313	659	294	736	540
acres, 2022	134,933	54,892	71,210	48,228	360,718	58,200
2017	125,785	53,391	96,253	36,637	335,524	66,162
Harvested cropland ..... farms, 2022	525	231	584	330	653	432
2017	600	261	580	274	631	510
acres, 2022	117,902	47,705	64,610	42,596	349,235	53,672
2017	107,172	46,107	87,663	32,546	323,756	61,657

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	1,252	613	190	735	34	186
2017	1,220	528	181	853	42	134
Land in farms ..... acres, 2022	494,447	602,709	60,919	410,959	1,422	109,394
2017	455,854	479,322	55,816	419,884	3,565	91,288
Average size of farm ..... acres, 2022	395	983	321	559	42	588
2017	374	908	308	492	85	681
Estimated market value of land and buildings ..... farms, 2022	1,252	613	190	735	34	186
2017	1,220	528	181	853	42	134
$1,000, 2022	3,674,673	2,025,768	158,088	2,614,421	11,325	286,403
2017	2,378,543	1,077,844	80,530	1,880,154	12,938	154,937
Average per farm ..... dollars, 2022	2,935,043	3,304,679	832,044	3,557,035	333,095	1,539,800
2017	1,949,625	2,041,371	444,918	2,204,166	308,042	1,156,249
Average per acre ..... dollars, 2022	7,432	3,361	2,595	6,362	7,964	2,618
2017	5,218	2,249	1,443	4,478	3,629	1,697
2022 farms by value group:						
$1 to $49,999	36	18	1	29	1	4
$50,000 to $99,999	53	18	9	26	2	9
$100,000 to $199,999	115	46	36	57	7	27
$200,000 to $499,999	374	141	57	145	19	44
$500,000 to $999,999	250	104	38	104	4	39
$1,000,000 to $1,999,999	130	64	33	85	1	34
$2,000,000 to $4,999,999	136	90	13	119	-	14
$5,000,000 to $9,999,999	57	73	2	102	-	8
$10,000,000 or more	101	59	1	68	-	7
Approximate land area ..... acres, 2022	510,268	703,236	1,986,683	489,613	1,349,939	830,636
Proportion in farms ..... percent, 2022	96.9	85.7	3.1	83.9	0.1	13.2
2022 size of farm:						
1 to 9 acres ..... farms	62	3	1	25	7	1
acres	319	11	(D)	171	(D)	(D)
10 to 49 acres ..... farms	375	47	29	135	19	19
acres	9,563	1,385	(D)	3,555	547	(D)
50 to 69 acres ..... farms	67	8	7	29	-	4
acres	3,938	478	380	1,619	-	250
70 to 99 acres ..... farms	111	43	25	45	3	17
acres	8,962	3,547	2,008	3,693	250	1,380
100 to 139 acres ..... farms	108	23	19	33	4	19
acres	12,720	2,795	2,359	3,809	460	2,060
140 to 179 acres ..... farms	95	54	15	60	1	12
acres	14,754	8,541	2,322	9,299	(D)	1,988
180 to 219 acres ..... farms	48	33	9	44	-	13
acres	9,347	6,468	1,825	8,517	-	2,568
220 to 259 acres ..... farms	51	25	10	15	-	8
acres	12,092	5,972	2,408	3,513	-	1,969
260 to 499 acres ..... farms	107	108	31	112	-	38
acres	37,858	37,175	11,060	40,319	-	13,166
500 to 999 acres ..... farms	101	87	36	95	-	32
acres	68,524	62,193	25,053	67,106	-	20,721
1,000 to 1,999 acres ..... farms	64	79	6	96	-	10
acres	89,564	109,096	8,625	136,579	-	13,103
2,000 acres or more ..... farms	63	103	2	46	-	13
acres	226,806	365,048	(D)	132,779	-	51,585
2017 size of farm:						
1 to 9 acres ..... farms	113	15	4	49	5	1
acres	589	68	14	286	5	(D)
10 to 49 acres ..... farms	281	29	14	123	18	18
acres	7,195	919	550	3,384	576	645
50 to 69 acres ..... farms	82	14	14	53	1	-
acres	4,886	788	837	3,061	(D)	-
70 to 99 acres ..... farms	105	35	20	50	5	4
acres	8,644	2,857	1,577	4,021	397	337
100 to 139 acres ..... farms	112	17	28	39	7	9
acres	13,321	2,008	3,508	4,462	(D)	1,076
140 to 179 acres ..... farms	80	40	18	43	3	8
acres	12,695	6,453	2,766	6,705	455	1,273
180 to 219 acres ..... farms	61	31	12	41	-	8
acres	12,004	6,157	2,343	8,216	-	(D)
220 to 259 acres ..... farms	35	21	9	38	-	9
acres	8,262	4,969	2,129	8,756	-	2,168
260 to 499 acres ..... farms	133	99	30	130	2	28
acres	48,651	34,763	10,995	47,876	(D)	10,209
500 to 999 acres ..... farms	105	76	21	161	1	30
acres	74,999	54,075	15,451	116,880	(D)	20,303
1,000 to 1,999 acres ..... farms	69	75	11	95	-	10
acres	91,733	113,411	15,646	126,708	-	16,325
2,000 acres or more ..... farms	44	76	-	31	-	9
acres	172,875	252,854	-	89,529	-	37,355
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	1,098	589	165	695	21	166
2017	1,110	513	161	814	33	122
acres, 2022	436,466	514,102	29,974	373,794	227	72,744
2017	402,756	408,591	28,160	375,245	1,407	67,779
Harvested cropland ..... farms, 2022	728	342	147	521	19	126
2017	702	302	145	615	33	101
acres, 2022	396,375	418,170	23,979	340,540	144	57,749
2017	361,522	329,127	23,961	343,238	1,010	56,367

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	896	598	869	801	268	1,072
2017	937	672	893	880	311	1,086
Land in farms ..... acres, 2022	205,774	212,420	424,591	246,163	217,882	912,128
2017	249,463	297,836	395,132	268,636	221,252	902,436
Average size of farm ..... acres, 2022	230	355	489	307	813	851
2017	266	443	442	305	711	831
Estimated market value of land and buildings ..... farms, 2022	896	598	869	801	268	1,072
2017	937	672	893	880	311	1,086
$1,000, 2022	1,542,072	1,352,155	3,034,074	1,776,655	908,392	2,889,826
2017	1,540,320	1,440,450	2,312,449	1,537,784	653,865	2,233,014
Average per farm ..... dollars, 2022	1,721,062	2,261,130	3,491,454	2,218,047	3,389,523	2,695,733
2017	1,643,885	2,143,527	2,589,529	1,747,482	2,102,461	2,056,182
Average per acre ..... dollars, 2022	7,494	6,365	7,146	7,217	4,169	3,168
2017	6,175	4,836	5,852	5,724	2,955	2,474
2022 farms by value group:						
$1 to $49,999	20	11	34	28	6	14
$50,000 to $99,999	54	25	30	37	7	33
$100,000 to $199,999	96	55	61	62	21	98
$200,000 to $499,999	213	117	127	261	71	228
$500,000 to $999,999	227	109	114	167	41	191
$1,000,000 to $1,999,999	144	95	99	76	37	150
$2,000,000 to $4,999,999	75	125	234	77	44	216
$5,000,000 to $9,999,999	35	33	89	33	10	78
$10,000,000 or more	32	28	81	60	31	64
Approximate land area ..... acres, 2022	287,150	343,521	457,223	314,550	357,039	1,136,038
Proportion in farms ..... percent, 2022	71.7	61.8	92.9	78.3	61.0	80.3
2022 size of farm:						
1 to 9 acres ..... farms	77	29	51	90	5	12
acres	413	180	282	474	20	45
10 to 49 acres ..... farms	288	106	110	241	23	55
acres	7,674	2,636	2,611	5,966	764	1,696
50 to 69 acres ..... farms	61	26	23	59	13	26
acres	3,612	1,518	1,332	3,431	751	1,573
70 to 99 acres ..... farms	102	37	76	71	16	78
acres	8,350	3,102	6,412	5,836	1,370	6,259
100 to 139 acres ..... farms	80	39	48	65	9	70
acres	9,481	4,457	5,587	7,746	1,088	8,262
140 to 179 acres ..... farms	57	79	74	50	27	94
acres	8,914	12,368	11,485	7,737	4,317	14,706
180 to 219 acres ..... farms	35	35	20	27	13	45
acres	6,825	6,883	3,982	5,191	2,597	8,838
220 to 259 acres ..... farms	27	27	27	17	13	37
acres	6,401	6,427	6,330	3,922	3,021	8,814
260 to 499 acres ..... farms	71	95	161	61	53	206
acres	25,433	36,494	59,252	21,137	18,776	74,008
500 to 999 acres ..... farms	52	80	163	48	34	189
acres	33,826	55,882	115,158	33,964	25,039	131,390
1,000 to 1,999 acres ..... farms	30	35	80	31	29	141
acres	41,599	47,971	105,351	40,875	38,303	209,921
2,000 acres or more ..... farms	16	10	36	41	33	119
acres	53,246	34,502	106,809	109,884	121,836	446,616
2017 size of farm:						
1 to 9 acres ..... farms	89	47	61	95	22	19
acres	515	265	309	539	94	120
10 to 49 acres ..... farms	283	91	117	243	37	59
acres	7,480	2,318	2,823	6,032	1,044	1,575
50 to 69 acres ..... farms	69	35	39	52	13	30
acres	4,135	2,015	2,297	3,102	730	1,766
70 to 99 acres ..... farms	90	49	71	63	11	84
acres	7,408	3,994	5,897	5,233	940	6,786
100 to 139 acres ..... farms	75	39	34	43	30	77
acres	8,894	4,469	3,874	4,926	3,639	8,843
140 to 179 acres ..... farms	44	61	49	64	19	97
acres	6,989	9,734	7,627	10,180	2,948	15,178
180 to 219 acres ..... farms	54	38	15	38	9	56
acres	10,576	7,632	2,957	7,346	1,774	11,086
220 to 259 acres ..... farms	26	24	54	36	26	57
acres	6,111	5,566	12,752	8,569	6,296	13,724
260 to 499 acres ..... farms	90	99	155	92	38	213
acres	31,618	34,662	55,128	30,562	13,577	76,220
500 to 999 acres ..... farms	54	100	190	85	44	151
acres	37,758	68,805	126,275	59,876	29,765	104,503
1,000 to 1,999 acres ..... farms	48	72	93	45	31	111
acres	67,185	99,925	120,561	63,022	42,033	164,145
2,000 acres or more ..... farms	15	17	15	24	31	132
acres	60,794	58,451	54,632	69,249	118,412	498,490
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	832	545	799	712	248	1,031
2017	876	633	828	774	285	1,026
acres, 2022	181,375	185,149	389,195	228,148	184,318	804,133
2017	224,188	269,765	366,313	248,863	186,284	824,103
Harvested cropland ..... farms, 2022	523	351	639	570	197	717
2017	602	443	694	644	240	632
acres, 2022	159,857	153,500	360,873	218,209	171,244	646,007
2017	203,903	238,313	347,042	237,904	173,972	680,360

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	823	991	603	1,571	999	789
2017	911	1,028	707	1,760	1,068	864
Land in farms ..... acres, 2022	454,025	308,376	96,684	361,789	380,070	351,476
2017	449,064	301,439	125,905	382,376	447,193	395,079
Average size of farm ..... acres, 2022	552	311	160	230	380	445
2017	493	293	178	217	419	457
Estimated market value of land and buildings ..... farms, 2022	823	991	603	1,571	999	789
2017	911	1,028	707	1,760	1,068	864
$1,000, 2022	4,071,502	1,835,248	380,380	1,407,025	3,131,857	3,015,946
2017	3,014,024	1,564,560	390,597	1,265,550	3,046,826	2,436,254
Average per farm ..... dollars, 2022	4,947,147	1,851,915	630,813	895,624	3,134,992	3,822,492
2017	3,308,478	1,521,946	552,471	719,062	2,852,833	2,819,738
Average per acre ..... dollars, 2022	8,968	5,951	3,934	3,889	8,240	8,581
2017	6,712	5,190	3,102	3,310	6,813	6,166
2022 farms by value group:						
$1 to $49,999	22	34	14	14	28	24
$50,000 to $99,999	17	55	14	53	54	19
$100,000 to $199,999	48	112	59	155	71	81
$200,000 to $499,999	97	282	293	543	244	133
$500,000 to $999,999	101	206	128	423	129	118
$1,000,000 to $1,999,999	134	111	66	236	123	77
$2,000,000 to $4,999,999	185	112	25	124	184	141
$5,000,000 to $9,999,999	96	33	4	13	72	133
$10,000,000 or more	123	46	-	10	94	63
Approximate land area ..... acres, 2022	455,896	389,218	366,296	720,058	455,250	451,008
Proportion in farms ..... percent, 2022	99.6	79.2	26.4	50.2	83.5	77.9
2022 size of farm:						
1 to 9 acres ..... farms	70	89	29	52	110	62
acres	303	478	139	286	624	306
10 to 49 acres ..... farms	126	246	218	352	268	133
acres	2,824	6,681	6,159	9,947	6,313	3,111
50 to 69 acres ..... farms	22	69	44	84	30	37
acres	1,229	4,109	2,564	4,865	1,717	2,222
70 to 99 acres ..... farms	65	96	55	166	60	75
acres	5,393	7,807	4,492	13,696	4,877	5,991
100 to 139 acres ..... farms	46	85	59	137	71	49
acres	5,215	9,871	6,786	16,104	8,250	5,818
140 to 179 acres ..... farms	44	86	38	172	46	43
acres	6,881	13,524	5,907	27,153	7,208	6,816
180 to 219 acres ..... farms	34	41	37	101	25	22
acres	6,692	8,124	7,432	20,134	5,022	4,376
220 to 259 acres ..... farms	34	40	22	83	41	31
acres	8,006	9,633	5,244	19,785	9,587	7,402
260 to 499 acres ..... farms	127	96	60	254	162	110
acres	46,477	34,265	21,242	88,925	57,686	40,688
500 to 999 acres ..... farms	109	68	33	116	72	131
acres	75,528	46,522	22,522	78,352	48,850	94,082
1,000 to 1,999 acres ..... farms	83	45	5	44	64	74
acres	113,274	61,813	6,810	52,729	84,662	99,826
2,000 acres or more ..... farms	63	30	3	10	50	22
acres	182,203	105,549	7,387	29,813	145,274	80,838
2017 size of farm:						
1 to 9 acres ..... farms	99	108	51	86	129	49
acres	511	578	(D)	475	739	233
10 to 49 acres ..... farms	116	253	232	354	244	159
acres	2,836	7,111	7,161	10,351	5,833	3,811
50 to 69 acres ..... farms	24	63	40	85	43	33
acres	1,379	3,667	2,337	5,027	2,499	2,003
70 to 99 acres ..... farms	54	112	74	228	59	59
acres	4,421	9,265	5,854	18,755	4,791	4,855
100 to 139 acres ..... farms	61	81	71	167	53	29
acres	6,981	9,456	8,434	19,198	6,310	3,350
140 to 179 acres ..... farms	54	51	55	167	56	68
acres	8,454	8,056	8,490	26,455	8,635	10,559
180 to 219 acres ..... farms	35	40	34	115	40	11
acres	6,890	7,936	6,844	22,894	8,005	2,177
220 to 259 acres ..... farms	50	50	16	70	61	37
acres	12,056	11,616	3,718	16,513	14,561	8,753
260 to 499 acres ..... farms	122	116	67	330	131	149
acres	44,724	41,684	21,775	116,722	47,688	54,920
500 to 999 acres ..... farms	147	78	48	115	118	149
acres	105,202	53,446	33,862	76,434	85,166	106,045
1,000 to 1,999 acres ..... farms	121	54	17	34	91	96
acres	167,495	73,606	22,294	44,765	123,678	128,407
2,000 acres or more ..... farms	28	22	2	9	43	25
acres	88,115	75,018	(D)	24,787	139,288	69,966
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	745	888	533	1,406	894	740
2017	819	925	626	1,571	978	808
acres, 2022	433,735	267,627	62,663	211,270	351,321	314,260
2017	434,319	262,081	86,918	232,790	420,938	362,578
Harvested cropland ..... farms, 2022	650	602	488	1,288	716	608
2017	725	665	569	1,473	804	651
acres, 2022	422,048	242,801	55,469	190,224	333,878	298,402
2017	427,112	241,359	81,641	210,362	406,191	346,082

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	660	938	435	1,102	2,497	322
2017	689	885	505	1,139	2,544	409
Land in farms ..... acres, 2022	278,870	366,330	491,694	308,004	770,922	258,956
2017	264,832	414,405	525,866	285,944	794,496	285,852
Average size of farm ..... acres, 2022	423	391	1,130	279	309	804
2017	384	468	1,041	251	312	699
Estimated market value of land and buildings ..... farms, 2022	660	938	435	1,102	2,497	322
2017	689	885	505	1,139	2,544	409
$1,000, 2022	2,403,099	3,152,420	2,279,419	2,173,779	2,960,436	839,201
2017	1,854,459	2,863,932	1,736,052	1,903,527	2,358,726	551,116
Average per farm ..... dollars, 2022	3,641,059	3,360,789	5,240,043	1,972,576	1,185,597	2,606,213
2017	2,691,522	3,236,081	3,437,726	1,671,227	927,172	1,347,472
Average per acre ..... dollars, 2022	8,617	8,605	4,636	7,058	3,840	3,241
2017	7,002	6,911	3,301	6,657	2,969	1,928
2022 farms by value group:						
$1 to $49,999	24	46	5	19	70	6
$50,000 to $99,999	6	15	16	29	90	8
$100,000 to $199,999	35	64	44	50	306	22
$200,000 to $499,999	113	188	58	269	851	106
$500,000 to $999,999	115	81	68	312	578	46
$1,000,000 to $1,999,999	118	155	40	154	287	38
$2,000,000 to $4,999,999	136	187	71	157	198	53
$5,000,000 to $9,999,999	51	110	61	67	70	23
$10,000,000 or more	62	92	72	45	47	20
Approximate land area ..... acres, 2022	287,117	457,658	558,585	418,246	1,262,075	394,610
Proportion in farms ..... percent, 2022	97.1	80.0	88.0	73.6	61.1	65.6
2022 size of farm:						
1 to 9 acres ..... farms	52	95	8	68	67	10
acres	251	592	60	327	256	45
10 to 49 acres ..... farms	143	168	49	381	436	36
acres	3,689	3,209	1,255	10,385	12,972	941
50 to 69 acres ..... farms	32	31	17	78	168	16
acres	1,842	1,748	995	4,435	9,934	952
70 to 99 acres ..... farms	45	59	28	93	313	21
acres	3,837	4,868	2,229	7,646	25,311	1,722
100 to 139 acres ..... farms	31	43	15	79	285	11
acres	3,575	4,935	1,727	9,108	33,569	1,306
140 to 179 acres ..... farms	41	74	25	77	228	35
acres	6,657	11,755	3,995	12,219	36,022	5,522
180 to 219 acres ..... farms	38	31	19	41	132	17
acres	7,578	6,023	3,909	8,001	25,875	3,204
220 to 259 acres ..... farms	34	50	10	26	110	9
acres	8,144	11,995	2,411	6,209	26,110	2,191
260 to 499 acres ..... farms	104	155	53	112	364	46
acres	37,076	56,462	19,092	39,818	129,344	16,899
500 to 999 acres ..... farms	76	122	58	68	229	45
acres	53,900	83,111	42,659	45,636	157,850	34,712
1,000 to 1,999 acres ..... farms	18	81	67	45	118	35
acres	24,123	106,235	96,300	58,823	155,561	51,767
2,000 acres or more ..... farms	46	29	86	34	47	41
acres	128,198	75,397	317,062	105,397	158,118	139,695
2017 size of farm:						
1 to 9 acres ..... farms	41	66	8	127	122	20
acres	184	379	(D)	555	512	104
10 to 49 acres ..... farms	114	173	60	365	371	43
acres	2,755	3,952	1,508	9,725	11,503	1,252
50 to 69 acres ..... farms	23	21	22	84	199	16
acres	1,315	1,156	1,394	5,003	11,602	959
70 to 99 acres ..... farms	32	37	31	78	341	24
acres	2,673	3,000	2,571	6,286	27,691	1,948
100 to 139 acres ..... farms	36	19	22	70	254	33
acres	4,352	2,246	2,656	8,199	29,864	3,943
140 to 179 acres ..... farms	60	62	36	54	215	36
acres	9,437	9,680	5,668	8,588	34,051	5,630
180 to 219 acres ..... farms	55	20	14	48	165	18
acres	10,833	3,840	2,801	9,601	32,343	3,629
220 to 259 acres ..... farms	25	30	5	35	115	10
acres	5,982	7,175	(D)	8,302	27,315	2,352
260 to 499 acres ..... farms	154	188	57	126	355	65
acres	56,605	69,821	20,615	43,385	127,216	24,897
500 to 999 acres ..... farms	96	136	69	81	223	59
acres	66,741	97,948	50,617	57,293	158,776	42,408
1,000 to 1,999 acres ..... farms	28	107	89	48	140	42
acres	37,857	148,576	121,800	58,443	187,799	57,144
2,000 acres or more ..... farms	25	26	92	23	44	43
acres	66,098	66,632	314,981	70,564	145,824	141,586
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	596	850	408	983	2,201	300
2017	653	812	473	929	2,245	377
acres, 2022	262,794	346,087	454,901	258,221	545,784	222,501
2017	249,513	392,313	498,943	239,087	576,163	249,201
Harvested cropland ..... farms, 2022	510	716	344	782	1,598	213
2017	600	690	395	773	1,665	286
acres, 2022	253,410	334,873	428,145	238,968	472,434	187,360
2017	238,885	380,893	474,773	216,630	502,572	218,152

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	728	529	1,223	821	47	274
2017	823	595	1,258	837	55	263
Land in farms ..... acres, 2022	164,801	227,976	1,083,394	310,041	799	196,716
2017	160,316	239,991	1,023,140	333,009	645	208,748
Average size of farm ..... acres, 2022	226	431	886	378	17	718
2017	195	403	813	398	12	794
Estimated market value of land and buildings ..... farms, 2022	728	529	1,223	821	47	274
2017	823	595	1,258	837	55	263
$1,000, 2022	538,736	1,698,240	4,681,299	1,642,722	37,531	580,500
2017	379,016	1,399,942	3,355,899	1,379,830	17,187	494,769
Average per farm ..... dollars, 2022	740,022	3,210,283	3,827,718	2,000,879	798,533	2,118,613
2017	460,529	2,352,844	2,667,646	1,648,542	312,488	1,881,249
Average per acre ..... dollars, 2022	3,269	7,449	4,321	5,298	46,973	2,951
2017	2,364	5,833	3,280	4,144	26,646	2,370
2022 farms by value group:						
$1 to $49,999	14	9	46	16	10	9
$50,000 to $99,999	42	21	52	26	4	9
$100,000 to $199,999	95	39	86	87	6	19
$200,000 to $499,999	279	113	240	273	9	55
$500,000 to $999,999	170	59	196	150	7	60
$1,000,000 to $1,999,999	96	85	135	117	6	48
$2,000,000 to $4,999,999	22	96	178	71	5	43
$5,000,000 to $9,999,999	3	70	137	36	-	23
$10,000,000 or more	7	37	153	45	-	8
Approximate land area ..... acres, 2022	903,225	297,635	1,261,490	428,514	97,381	276,740
Proportion in farms ..... percent, 2022	18.2	76.6	85.9	72.4	0.8	71.1
2022 size of farm:						
1 to 9 acres ..... farms	39	37	29	34	40	2
acres	179	198	139	139	108	(D)
10 to 49 acres ..... farms	136	130	140	142	2	16
acres	4,152	2,884	3,548	4,038	(D)	(D)
50 to 69 acres ..... farms	37	27	35	58	-	8
acres	2,252	1,555	2,075	3,488	-	456
70 to 99 acres ..... farms	91	22	78	80	-	20
acres	7,428	1,827	6,234	6,518	-	1,534
100 to 139 acres ..... farms	92	19	88	68	3	23
acres	10,579	2,177	10,189	8,025	335	2,794
140 to 179 acres ..... farms	72	28	96	68	2	17
acres	11,340	4,492	15,086	10,623	(D)	2,699
180 to 219 acres ..... farms	48	21	46	52	-	6
acres	9,509	4,187	8,989	10,322	-	1,241
220 to 259 acres ..... farms	34	24	38	45	-	13
acres	8,178	5,633	9,002	10,765	-	3,000
260 to 499 acres ..... farms	94	91	190	126	-	63
acres	34,759	32,575	69,383	46,013	-	23,232
500 to 999 acres ..... farms	61	77	146	75	-	47
acres	39,617	55,429	104,764	52,112	-	31,446
1,000 to 1,999 acres ..... farms	20	28	167	37	-	42
acres	27,098	39,686	248,815	55,046	-	65,825
2,000 acres or more ..... farms	4	25	170	36	-	17
acres	9,710	77,333	605,170	102,952	-	64,125
2017 size of farm:						
1 to 9 acres ..... farms	47	78	22	27	42	8
acres	266	447	114	130	(D)	40
10 to 49 acres ..... farms	172	118	157	190	11	21
acres	5,414	2,830	4,536	5,301	195	529
50 to 69 acres ..... farms	38	17	48	47	-	11
acres	2,213	993	2,837	2,776	-	615
70 to 99 acres ..... farms	115	37	87	74	-	12
acres	9,145	3,003	7,072	5,940	-	982
100 to 139 acres ..... farms	110	22	85	58	-	18
acres	12,537	2,730	10,054	6,660	-	2,159
140 to 179 acres ..... farms	80	55	99	49	1	22
acres	12,660	8,662	15,543	7,593	(D)	3,472
180 to 219 acres ..... farms	43	16	43	50	1	7
acres	8,462	3,143	8,620	9,997	(D)	1,403
220 to 259 acres ..... farms	40	10	45	31	-	7
acres	9,486	2,363	10,744	7,379	-	1,614
260 to 499 acres ..... farms	107	98	207	127	-	50
acres	37,480	36,795	73,688	44,211	-	18,534
500 to 999 acres ..... farms	56	91	146	83	-	55
acres	36,570	65,363	106,780	56,773	-	40,410
1,000 to 1,999 acres ..... farms	12	30	159	63	-	25
acres	17,272	39,779	227,268	81,539	-	36,471
2,000 acres or more ..... farms	3	23	160	38	-	27
acres	8,811	73,883	555,884	104,710	-	102,519
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	662	463	1,143	712	44	260
2017	726	516	1,184	746	52	246
acres, 2022	87,197	189,619	986,385	254,036	503	176,822
2017	81,694	210,561	938,528	280,326	434	189,347
Harvested cropland ..... farms, 2022	620	412	890	470	40	213
2017	675	451	864	488	52	195
acres, 2022	75,570	181,999	904,276	220,081	108	154,337
2017	69,230	198,596	840,247	246,281	373	167,953

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	1,323	931	1,111	573	751	821
2017	1,134	1,026	1,242	701	842	779
Land in farms ..... acres, 2022	560,222	626,065	249,881	261,220	537,341	162,061
2017	523,912	624,114	226,255	287,871	558,152	138,753
Average size of farm ..... acres, 2022	423	672	225	456	716	197
2017	462	608	182	411	663	178
Estimated market value of land and buildings ..... farms, 2022	1,323	931	1,111	573	751	821
2017	1,134	1,026	1,242	701	842	779
$1,000, 2022	4,710,298	5,094,697	2,081,601	2,306,935	1,370,861	636,474
2017	3,268,626	4,094,421	1,551,325	2,196,765	972,784	276,330
Average per farm ..... dollars, 2022	3,560,316	5,472,284	1,873,628	4,026,064	1,825,381	775,243
2017	2,882,387	3,990,664	1,249,054	3,133,759	1,155,325	354,725
Average per acre ..... dollars, 2022	8,408	8,138	8,330	8,831	2,551	3,927
2017	6,239	6,560	6,857	7,631	1,743	1,992
2022 farms by value group:						
$1 to $49,999	44	25	47	14	18	9
$50,000 to $99,999	79	33	40	11	25	18
$100,000 to $199,999	94	53	70	36	76	134
$200,000 to $499,999	238	172	298	98	193	355
$500,000 to $999,999	122	102	312	82	148	138
$1,000,000 to $1,999,999	148	81	137	80	143	94
$2,000,000 to $4,999,999	331	168	134	135	86	55
$5,000,000 to $9,999,999	140	135	33	51	31	18
$10,000,000 or more	127	162	40	66	31	-
Approximate land area ..... acres, 2022	562,289	629,068	317,339	308,773	1,069,836	3,998,435
Proportion in farms ..... percent, 2022	99.6	99.5	78.7	84.6	50.2	4.1
2022 size of farm:						
1 to 9 acres ..... farms	123	34	102	85	26	32
acres	693	211	473	476	144	91
10 to 49 acres ..... farms	216	177	367	95	69	242
acres	5,200	4,367	10,468	2,113	1,901	6,937
50 to 69 acres ..... farms	44	34	90	20	13	31
acres	2,650	2,024	5,379	1,174	779	1,816
70 to 99 acres ..... farms	90	67	123	31	49	75
acres	7,570	5,428	10,093	2,430	4,051	6,129
100 to 139 acres ..... farms	77	40	98	27	60	107
acres	9,183	4,725	11,819	3,256	7,047	12,509
140 to 179 acres ..... farms	82	61	61	27	64	78
acres	12,726	9,620	9,502	4,446	10,111	12,451
180 to 219 acres ..... farms	32	35	39	25	34	59
acres	6,272	6,951	7,668	5,081	6,762	11,626
220 to 259 acres ..... farms	52	36	28	21	37	42
acres	12,036	8,578	6,693	5,043	8,832	9,985
260 to 499 acres ..... farms	234	111	94	96	135	88
acres	85,141	39,909	33,913	36,166	50,376	32,883
500 to 999 acres ..... farms	236	148	55	78	109	43
acres	171,766	107,516	34,735	56,579	72,607	25,167
1,000 to 1,999 acres ..... farms	91	111	26	42	91	21
acres	123,688	155,118	37,558	60,543	120,737	29,812
2,000 acres or more ..... farms	46	77	28	26	64	3
acres	123,297	281,618	81,580	83,913	253,994	12,655
2017 size of farm:						
1 to 9 acres ..... farms	101	72	127	80	20	37
acres	539	314	639	467	128	116
10 to 49 acres ..... farms	162	176	396	106	101	176
acres	4,021	4,505	11,232	2,289	3,317	5,047
50 to 69 acres ..... farms	36	30	105	22	24	62
acres	2,085	1,770	6,214	1,231	1,442	3,687
70 to 99 acres ..... farms	63	65	109	34	57	97
acres	5,160	5,337	8,943	2,607	4,620	7,731
100 to 139 acres ..... farms	36	52	97	23	60	118
acres	4,223	6,100	11,142	2,698	7,147	13,879
140 to 179 acres ..... farms	66	47	100	48	95	61
acres	10,441	7,369	15,595	7,615	14,905	9,558
180 to 219 acres ..... farms	28	51	40	22	36	51
acres	5,573	10,269	8,000	4,399	7,220	10,163
220 to 259 acres ..... farms	44	40	33	42	38	46
acres	10,450	9,383	7,949	9,863	8,982	10,935
260 to 499 acres ..... farms	214	143	125	141	141	85
acres	78,591	52,179	44,308	50,954	52,475	28,985
500 to 999 acres ..... farms	248	152	73	118	134	32
acres	178,404	107,344	46,713	80,516	88,926	19,954
1,000 to 1,999 acres ..... farms	98	129	29	41	65	11
acres	124,128	175,839	37,670	56,023	91,868	16,149
2,000 acres or more ..... farms	38	69	8	24	71	3
acres	100,297	243,705	27,850	69,209	277,122	12,549
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	1,201	884	1,008	482	668	698
2017	1,065	958	1,093	621	775	668
acres, 2022	535,304	598,705	216,032	241,588	418,239	80,998
2017	494,893	598,247	192,613	266,434	463,108	67,103
Harvested cropland ..... farms, 2022	983	734	818	443	490	635
2017	890	773	858	584	490	603
acres, 2022	509,922	571,420	197,825	235,233	339,987	70,850
2017	474,337	579,341	177,101	259,762	361,883	55,785

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	624	494	860	2,695	721	500
2017	740	501	898	2,951	746	553
Land in farms ..... acres, 2022	99,629	85,044	373,628	643,463	245,834	330,936
2017	115,504	102,544	350,036	650,821	251,221	330,334
Average size of farm ..... acres, 2022	160	172	434	239	341	662
2017	156	205	390	221	337	597
Estimated market value of land and buildings ..... farms, 2022	624	494	860	2,695	721	500
2017	740	501	898	2,951	746	553
$1,000, 2022	951,121	610,683	3,087,938	3,606,592	2,257,396	2,133,358
2017	876,656	528,595	2,361,502	3,351,187	1,557,711	1,677,117
Average per farm ..... dollars, 2022	1,524,233	1,236,200	3,590,625	1,338,253	3,130,924	4,266,717
2017	1,184,671	1,055,081	2,629,735	1,135,611	2,088,084	3,032,762
Average per acre ..... dollars, 2022	9,547	7,181	8,265	5,605	9,183	6,446
2017	7,590	5,155	6,746	5,149	6,201	5,077
2022 farms by value group:						
$1 to $49,999	23	17	31	41	41	12
$50,000 to $99,999	14	11	27	77	47	17
$100,000 to $199,999	51	37	95	184	74	53
$200,000 to $499,999	153	196	136	706	168	98
$500,000 to $999,999	210	132	146	695	131	58
$1,000,000 to $1,999,999	75	47	124	495	81	63
$2,000,000 to $4,999,999	56	23	138	359	76	67
$5,000,000 to $9,999,999	21	18	79	112	40	67
$10,000,000 or more	21	13	84	26	63	65
Approximate land area ..... acres, 2022	228,003	277,062	376,821	859,403	274,973	360,712
Proportion in farms ..... percent, 2022	43.7	30.7	99.2	74.9	89.4	91.7
2022 size of farm:						
1 to 9 acres ..... farms	66	92	87	140	85	37
acres	317	(D)	419	713	423	167
10 to 49 acres ..... farms	304	179	175	695	208	95
acres	5,972	4,377	4,801	19,772	4,854	2,549
50 to 69 acres ..... farms	39	38	44	161	72	25
acres	2,213	2,174	2,582	9,477	4,297	1,502
70 to 99 acres ..... farms	40	43	56	215	41	33
acres	3,137	3,472	4,722	17,836	3,270	2,624
100 to 139 acres ..... farms	38	31	68	247	52	30
acres	4,237	3,576	7,928	28,672	6,049	3,500
140 to 179 acres ..... farms	30	14	59	221	29	33
acres	4,712	2,222	9,379	34,686	4,671	5,085
180 to 219 acres ..... farms	17	13	32	196	35	19
acres	3,396	2,583	6,253	38,868	7,003	3,782
220 to 259 acres ..... farms	12	11	29	124	21	25
acres	2,909	2,577	6,884	29,575	5,038	6,034
260 to 499 acres ..... farms	29	30	110	412	66	45
acres	10,661	10,609	38,955	145,123	23,835	17,263
500 to 999 acres ..... farms	28	17	94	193	42	43
acres	19,665	12,361	64,190	131,773	30,904	31,262
1,000 to 1,999 acres ..... farms	11	24	50	65	34	68
acres	16,342	33,875	67,495	87,366	45,743	93,577
2,000 acres or more ..... farms	10	2	56	26	36	47
acres	26,068	(D)	160,020	99,602	109,747	163,591
2017 size of farm:						
1 to 9 acres ..... farms	37	66	112	104	80	45
acres	155	329	647	513	419	201
10 to 49 acres ..... farms	333	173	164	615	218	106
acres	6,989	4,333	4,494	17,257	5,587	2,890
50 to 69 acres ..... farms	54	43	35	208	46	26
acres	3,104	2,590	2,013	12,224	2,688	1,423
70 to 99 acres ..... farms	54	45	51	278	51	23
acres	4,477	3,687	4,211	22,736	4,115	1,845
100 to 139 acres ..... farms	59	49	70	279	55	22
acres	6,790	5,663	8,388	32,265	6,450	2,637
140 to 179 acres ..... farms	47	17	76	257	34	35
acres	7,419	2,629	12,007	40,356	5,270	5,542
180 to 219 acres ..... farms	34	22	23	198	37	8
acres	6,636	4,343	4,500	39,122	7,188	1,551
220 to 259 acres ..... farms	20	10	46	217	23	23
acres	4,707	2,431	10,815	51,764	5,578	5,374
260 to 499 acres ..... farms	58	24	141	551	66	81
acres	20,303	8,815	52,440	194,048	22,937	28,412
500 to 999 acres ..... farms	24	23	82	176	62	75
acres	17,488	15,634	57,119	114,418	45,769	57,309
1,000 to 1,999 acres ..... farms	11	24	62	44	42	80
acres	15,352	34,665	88,294	55,757	53,795	115,670
2,000 acres or more ..... farms	9	5	36	24	32	29
acres	22,084	17,425	105,108	70,361	91,425	107,480
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	527	370	791	2,451	647	454
2017	638	390	830	2,677	670	505
acres, 2022	87,877	64,444	349,255	512,194	231,083	312,245
2017	97,972	78,462	326,640	515,928	233,482	308,002
Harvested cropland ..... farms, 2022	442	325	670	2,118	442	326
2017	534	321	708	2,307	469	358
acres, 2022	81,167	57,043	333,743	458,204	215,514	283,965
2017	91,052	71,515	315,230	462,585	221,014	289,168

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	708	1,529	358	743	442	622
2017	760	1,604	411	809	516	729
Land in farms ..... acres, 2022	374,933	321,168	309,539	235,417	123,335	266,866
2017	344,976	333,408	364,504	230,800	128,243	247,045
Average size of farm ..... acres, 2022	530	210	865	317	279	429
2017	454	208	887	285	249	339
Estimated market value of land and buildings ..... farms, 2022	708	1,529	358	743	442	622
2017	760	1,604	411	809	516	729
$1,000, 2022	2,391,568	1,173,659	1,693,857	1,562,310	398,397	2,355,190
2017	1,739,658	915,210	1,814,806	1,273,722	282,161	1,635,680
Average per farm ..... dollars, 2022	3,377,922	767,599	4,731,445	2,102,705	901,351	3,786,478
2017	2,289,023	570,580	4,415,585	1,574,440	546,823	2,243,731
Average per acre ..... dollars, 2022	6,379	3,654	5,472	6,636	3,230	8,825
2017	5,043	2,745	4,979	5,519	2,200	6,621
2022 farms by value group:						
$1 to $49,999	14	25	14	4	2	31
$50,000 to $99,999	41	61	14	15	25	27
$100,000 to $199,999	59	181	29	35	52	48
$200,000 to $499,999	167	629	56	157	204	118
$500,000 to $999,999	92	385	52	133	93	89
$1,000,000 to $1,999,999	107	153	31	165	37	76
$2,000,000 to $4,999,999	101	74	67	174	16	121
$5,000,000 to $9,999,999	54	13	30	37	3	44
$10,000,000 or more	73	8	65	23	10	68
Approximate land area ..... acres, 2022	474,905	604,778	367,278	334,669	343,210	270,952
Proportion in farms ..... percent, 2022	78.9	53.1	84.3	70.3	35.9	98.5
2022 size of farm:						
1 to 9 acres ..... farms	33	26	7	39	14	83
acres	205	142	43	190	75	445
10 to 49 acres ..... farms	139	355	57	123	86	115
acres	3,933	10,311	1,493	3,101	2,426	3,101
50 to 69 acres ..... farms	27	99	24	33	26	32
acres	1,640	5,829	1,418	1,992	1,487	1,882
70 to 99 acres ..... farms	49	208	22	60	45	40
acres	4,038	16,844	1,847	4,856	3,792	3,306
100 to 139 acres ..... farms	48	171	15	64	43	38
acres	5,673	19,878	1,712	7,479	4,959	4,547
140 to 179 acres ..... farms	67	129	25	69	40	33
acres	10,372	20,283	3,955	10,790	6,323	5,244
180 to 219 acres ..... farms	32	108	9	36	39	25
acres	6,439	21,185	1,834	7,012	7,720	4,921
220 to 259 acres ..... farms	22	73	9	42	15	22
acres	5,276	17,284	2,125	9,922	3,542	5,205
260 to 499 acres ..... farms	99	227	36	166	90	102
acres	35,270	78,718	13,489	62,156	31,686	35,205
500 to 999 acres ..... farms	79	87	49	59	19	57
acres	58,485	56,813	33,746	43,214	11,764	40,939
1,000 to 1,999 acres ..... farms	73	37	49	38	14	40
acres	104,724	47,838	69,955	51,396	19,522	55,843
2,000 acres or more ..... farms	40	9	56	14	11	35
acres	138,878	26,043	177,922	33,309	30,039	106,228
2017 size of farm:						
1 to 9 acres ..... farms	45	49	10	43	14	84
acres	242	237	71	232	62	459
10 to 49 acres ..... farms	145	306	82	142	88	158
acres	3,988	9,108	2,221	3,830	2,567	4,375
50 to 69 acres ..... farms	34	110	17	48	26	29
acres	2,057	6,435	1,008	2,933	1,485	1,754
70 to 99 acres ..... farms	52	176	15	55	59	49
acres	4,171	14,258	1,297	4,495	4,941	3,747
100 to 139 acres ..... farms	58	213	17	55	69	43
acres	6,820	24,879	1,956	6,337	8,039	4,937
140 to 179 acres ..... farms	62	156	27	67	45	53
acres	9,769	24,810	4,216	10,276	7,149	8,395
180 to 219 acres ..... farms	35	112	12	51	31	24
acres	7,060	21,805	2,407	10,046	6,140	4,750
220 to 259 acres ..... farms	35	93	12	50	34	21
acres	8,209	21,863	2,868	11,994	8,115	4,888
260 to 499 acres ..... farms	107	261	51	162	98	109
acres	39,634	91,527	17,516	57,297	33,713	38,452
500 to 999 acres ..... farms	82	94	41	97	31	93
acres	56,471	64,670	30,395	63,852	20,635	65,135
1,000 to 1,999 acres ..... farms	73	30	64	32	17	51
acres	102,398	41,394	94,882	42,729	24,220	68,600
2,000 acres or more ..... farms	32	4	63	7	4	15
acres	104,157	12,422	205,667	16,779	11,177	41,553
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	645	1,375	345	693	385	566
2017	709	1,435	402	743	427	662
acres, 2022	339,539	200,294	291,513	180,270	79,942	251,700
2017	316,378	210,494	350,906	175,836	75,336	231,047
Harvested cropland ..... farms, 2022	445	1,179	229	604	333	453
2017	515	1,245	296	640	388	518
acres, 2022	302,409	175,396	257,835	167,885	71,052	235,748
2017	286,488	178,434	332,332	158,783	65,340	220,201

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
FARMS AND LAND IN FARMS						
Farms ..... number, 2022	525	512	358	993	1,310	847
2017	612	497	391	1,034	1,338	852
Land in farms ..... acres, 2022	50,806	263,479	401,044	295,658	224,831	383,404
2017	76,148	252,417	428,148	268,663	240,651	383,646
Average size of farm ..... acres, 2022	97	515	1,120	298	172	453
2017	124	508	1,095	260	180	450
Estimated market value of land and buildings ..... farms, 2022	525	512	358	993	1,310	847
2017	612	497	391	1,034	1,338	852
$1,000, 2022	575,100	2,131,801	2,172,697	2,022,315	1,783,928	2,707,489
2017	662,074	1,791,446	1,657,620	1,545,543	1,549,943	2,074,828
Average per farm ..... dollars, 2022	1,095,428	4,163,674	6,068,987	2,036,571	1,361,777	3,196,563
2017	1,081,821	3,604,518	4,239,436	1,494,722	1,158,403	2,435,244
Average per acre ..... dollars, 2022	11,320	8,091	5,418	6,840	7,935	7,062
2017	8,695	7,097	3,872	5,753	6,441	5,408
2022 farms by value group:						
$1 to $49,999	38	22	26	17	29	41
$50,000 to $99,999	17	37	19	21	42	47
$100,000 to $199,999	36	59	27	38	103	78
$200,000 to $499,999	133	77	55	254	380	182
$500,000 to $999,999	177	55	39	217	390	103
$1,000,000 to $1,999,999	61	54	26	180	172	100
$2,000,000 to $4,999,999	40	84	47	172	128	127
$5,000,000 to $9,999,999	18	63	56	52	33	106
$10,000,000 or more	5	61	63	42	33	63
Approximate land area ..... acres, 2022	246,008	278,371	480,640	400,696	423,192	485,825
Proportion in farms ..... percent, 2022	20.7	94.7	83.4	73.8	53.1	78.9
2022 size of farm:						
1 to 9 acres ..... farms	98	45	15	56	129	60
acres	(D)	178	92	231	630	275
10 to 49 acres ..... farms	256	112	69	158	511	186
acres	5,446	2,585	1,534	4,007	12,580	4,205
50 to 69 acres ..... farms	35	22	14	65	130	46
acres	2,098	1,309	771	3,871	7,399	2,660
70 to 99 acres ..... farms	24	38	15	93	138	45
acres	1,964	3,037	1,174	7,582	11,444	3,643
100 to 139 acres ..... farms	23	22	18	108	79	44
acres	2,725	2,731	2,050	12,453	9,176	5,052
140 to 179 acres ..... farms	16	21	18	74	65	61
acres	2,650	3,306	2,835	11,629	10,269	9,495
180 to 219 acres ..... farms	11	13	6	64	53	26
acres	2,179	2,520	1,192	12,631	10,336	5,089
220 to 259 acres ..... farms	14	9	7	56	29	39
acres	3,321	2,126	1,635	13,369	7,094	9,307
260 to 499 acres ..... farms	27	65	31	161	76	102
acres	9,115	23,121	10,438	57,766	27,605	37,470
500 to 999 acres ..... farms	13	79	54	86	59	125
acres	9,502	55,277	41,909	58,597	40,067	89,881
1,000 to 1,999 acres ..... farms	7	51	39	66	22	82
acres	8,848	75,563	55,861	91,407	30,084	113,985
2,000 acres or more ..... farms	1	35	72	6	19	31
acres	(D)	91,726	281,553	22,115	58,147	102,342
2017 size of farm:						
1 to 9 acres ..... farms	139	49	16	105	152	60
acres	520	198	73	568	823	306
10 to 49 acres ..... farms	255	89	50	154	452	143
acres	6,340	2,412	1,196	4,208	12,917	3,429
50 to 69 acres ..... farms	38	15	23	65	108	45
acres	(D)	890	1,324	3,853	6,063	2,584
70 to 99 acres ..... farms	35	24	12	78	142	43
acres	2,773	1,990	967	6,401	11,520	3,611
100 to 139 acres ..... farms	29	41	16	119	105	29
acres	3,524	4,519	1,785	13,524	12,354	3,438
140 to 179 acres ..... farms	11	24	14	67	83	63
acres	1,740	3,710	2,157	10,723	13,240	10,020
180 to 219 acres ..... farms	19	14	12	61	50	36
acres	3,718	2,759	2,261	12,055	9,945	7,148
220 to 259 acres ..... farms	15	11	15	65	41	20
acres	3,622	2,583	3,538	15,443	9,743	4,733
260 to 499 acres ..... farms	36	80	38	178	92	141
acres	12,190	28,124	13,593	63,532	31,980	50,526
500 to 999 acres ..... farms	14	75	47	95	69	156
acres	9,643	54,447	34,771	61,890	46,913	114,471
1,000 to 1,999 acres ..... farms	19	42	71	39	30	99
acres	25,191	60,130	92,907	50,631	40,881	130,084
2,000 acres or more ..... farms	2	33	77	8	14	17
acres	(D)	90,655	273,576	25,835	44,272	53,296
LAND IN FARMS ACCORDING TO USE						
Total cropland ..... farms, 2022	433	471	339	871	1,172	776
2017	505	467	381	904	1,193	782
acres, 2022	36,745	251,388	387,669	217,078	185,511	350,967
2017	57,763	241,120	414,596	180,797	203,685	355,334
Harvested cropland ..... farms, 2022	392	390	260	742	995	588
2017	478	367	298	802	1,004	601
acres, 2022	33,731	241,723	358,050	198,115	171,228	316,017
2017	54,175	231,991	394,883	165,353	190,596	329,705

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
LAND IN FARMS ACCORDING TO USE - Con.						
Total cropland - Con.						
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	3,908	34	34	68	35
	2017	3,907	39	22	66	47
	acres, 2022	174,215	1,537	334	6,569	4,212
	2017	161,930	2,489	278	4,329	3,934
Other cropland	farms, 2022	25,702	106	91	409	163
	2017	25,085	107	99	391	159
	acres, 2022	1,707,402	4,580	3,764	30,382	9,712
	2017	1,570,694	5,945	2,197	24,755	7,645
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	22,588	57	68	353	87
	2017	21,950	65	63	355	118
	acres, 2022	1,546,009	2,424	3,181	28,661	6,675
	2017	1,458,432	3,572	1,558	23,298	5,886
Cropland on which all crops failed	farms, 2022	2,413	35	20	49	38
	2017	2,288	29	27	34	40
	acres, 2022	110,013	1,697	383	1,183	1,489
	2017	56,872	1,641	314	999	693
Cropland in summer fallow	farms, 2022	2,242	29	23	33	56
	2017	2,185	31	25	26	28
	acres, 2022	51,380	459	200	538	1,548
	2017	55,390	732	325	458	1,066
Total woodland	farms, 2022	23,960	322	154	558	404
	2017	24,988	318	151	557	397
	acres, 2022	1,446,600	29,838	2,648	48,983	32,617
	2017	1,392,385	25,483	3,500	53,025	35,994
Woodland pastured	farms, 2022	7,908	141	52	199	167
	2017	8,836	140	56	210	220
	acres, 2022	315,103	6,208	710	13,328	10,527
	2017	345,599	5,750	436	12,582	14,439
Woodland not pastured	farms, 2022	19,456	261	116	448	314
	2017	19,859	251	112	439	287
	acres, 2022	1,131,497	23,630	1,938	35,655	22,090
	2017	1,046,786	19,733	3,064	40,443	21,555
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	19,837	237	145	364	331
	2017	22,224	255	170	370	340
	acres, 2022	1,031,215	13,844	2,195	22,822	39,384
	2017	1,073,788	16,669	2,182	24,267	37,476
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	42,652	333	261	653	426
	2017	45,547	330	271	625	420
	acres, 2022	1,420,750	22,504	3,287	30,342	13,379
	2017	1,264,053	9,483	3,945	34,508	15,355
Pastureland, all types	farms, 2022	23,581	280	168	440	365
	2017	26,467	284	183	432	410
	acres, 2022	1,520,533	21,589	3,239	42,719	54,123
	2017	1,581,317	24,908	2,896	41,178	55,849
CONSERVATION AND CROP INSURANCE						
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	19,069	5	3	349	20
	2017	19,972	13	8	359	29
	acres, 2022	951,335	36	52	23,300	1,030
	2017	1,073,549	496	171	23,695	1,765
Land enrolled in crop insurance programs	farms, 2022	27,305	19	22	199	92
	2017	29,578	33	40	196	72
	acres, 2022	18,167,226	8,487	9,162	199,310	41,864
	2017	17,684,964	11,922	16,806	177,276	35,638

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
LAND IN FARMS ACCORDING TO USE - Con.						
Total cropland - Con.						
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	48	8	27	23	54
	2017	66	16	22	19	40
	acres, 2022	2,274	292	932	698	2,080
	2017	2,192	429	759	288	1,691
Other cropland	farms, 2022	174	220	394	397	112
	2017	241	197	337	332	103
	acres, 2022	6,179	27,183	14,067	21,591	3,445
	2017	7,394	14,333	11,950	20,706	2,591
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	130	193	367	377	76
	2017	154	177	318	307	70
	acres, 2022	4,543	24,702	13,438	20,961	1,877
	2017	4,934	13,350	11,628	19,959	1,636
Cropland on which all crops failed	farms, 2022	26	33	25	12	27
	2017	46	15	15	17	26
	acres, 2022	859	1,593	299	295	1,075
	2017	778	296	142	400	625
Cropland in summer fallow	farms, 2022	31	16	18	11	25
	2017	62	17	13	11	19
	acres, 2022	777	888	330	335	493
	2017	1,682	687	180	347	330
Total woodland	farms, 2022	329	54	305	165	361
	2017	397	57	255	194	396
	acres, 2022	10,801	1,184	10,565	5,305	55,892
	2017	13,263	1,505	9,511	7,587	25,700
Woodland pastured	farms, 2022	106	11	41	44	169
	2017	166	8	40	39	192
	acres, 2022	2,182	323	654	1,071	7,302
	2017	4,283	109	1,221	1,294	8,044
Woodland not pastured	farms, 2022	248	47	277	128	295
	2017	284	52	236	162	321
	acres, 2022	8,619	861	9,911	4,234	48,590
	2017	8,980	1,396	8,290	6,293	17,656
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	299	80	117	109	291
	2017	350	95	117	148	346
	acres, 2022	8,278	7,128	2,184	4,416	12,237
	2017	12,685	7,178	1,647	4,685	17,295
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	497	240	552	500	353
	2017	612	268	572	620	390
	acres, 2022	10,883	14,258	12,673	9,975	21,094
	2017	13,115	13,728	16,119	12,655	9,063
Pastureland, all types	farms, 2022	343	89	161	143	334
	2017	442	113	149	184	377
	acres, 2022	12,734	7,743	3,770	6,185	21,619
	2017	19,160	7,716	3,627	6,267	27,030
CONSERVATION AND CROP INSURANCE						
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	102	189	332	336	9
	2017	111	184	325	342	6
	acres, 2022	2,455	7,573	7,825	14,048	238
	2017	2,784	10,966	7,630	14,456	87
Land enrolled in crop insurance programs	farms, 2022	264	249	598	679	4
	2017	355	265	564	690	7
	acres, 2022	75,210	215,402	431,503	257,137	128
	2017	115,369	221,343	323,157	287,297	2,443

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	57	51	6	82	45	54
	2017	42	39	7	78	33	36
	acres, 2022	1,004	3,204	169	1,056	3,264	4,954
	2017	723	2,046	351	2,694	1,212	2,279
Other cropland	farms, 2022	199	111	308	161	278	116
	2017	254	97	335	196	269	103
	acres, 2022	6,821	6,506	16,479	3,165	29,223	9,328
	2017	6,231	3,824	17,724	5,183	29,507	8,181
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	167	81	296	120	243	86
	2017	218	63	307	127	246	73
	acres, 2022	6,416	4,957	15,519	2,155	26,022	7,612
	2017	5,500	2,849	16,085	3,842	28,110	6,219
Cropland on which all crops failed	farms, 2022	25	27	16	38	21	9
	2017	35	31	35	49	26	9
	acres, 2022	163	1,056	654	788	2,448	349
	2017	552	636	1,365	537	321	185
Cropland in summer fallow	farms, 2022	31	22	17	27	38	32
	2017	12	20	23	46	30	30
	acres, 2022	242	493	306	222	753	1,367
	2017	179	339	274	804	1,076	1,777
Total woodland	farms, 2022	244	336	84	368	140	247
	2017	253	301	80	437	148	269
	acres, 2022	5,749	28,510	3,521	10,244	7,267	29,057
	2017	8,276	26,718	2,360	14,663	9,369	29,209
Woodland pastured	farms, 2022	73	188	14	116	40	135
	2017	93	169	7	200	61	138
	acres, 2022	1,176	14,085	80	2,251	1,974	13,287
	2017	1,419	13,286	96	4,061	3,853	11,855
Woodland not pastured	farms, 2022	190	228	73	295	121	162
	2017	178	205	78	321	108	202
	acres, 2022	4,573	14,425	3,441	7,993	5,293	15,770
	2017	6,857	13,432	2,264	10,602	5,516	17,354
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	188	284	80	332	147	254
	2017	221	254	107	371	159	235
	acres, 2022	2,743	40,456	2,929	5,087	10,937	43,127
	2017	3,911	41,094	6,747	7,061	13,977	39,006
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	436	349	328	541	400	284
	2017	517	314	365	609	409	264
	acres, 2022	10,642	9,184	25,403	7,509	28,995	10,461
	2017	10,386	7,819	11,395	11,070	15,164	11,352
Pastureland, all types	farms, 2022	253	329	86	374	180	276
	2017	288	307	114	454	189	266
	acres, 2022	4,923	57,745	3,178	8,394	16,175	61,368
	2017	6,053	56,426	7,194	13,816	19,042	53,140
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	141	7	276	26	186	18
	2017	152	12	290	35	210	41
	acres, 2022	5,161	331	8,513	629	13,262	1,250
	2017	3,284	962	8,736	591	22,271	2,068
Land enrolled in crop insurance programs	farms, 2022	226	24	350	128	335	55
	2017	263	29	397	186	368	46
	acres, 2022	114,897	12,499	316,868	40,944	473,608	43,847
	2017	106,312	15,945	285,391	52,465	435,444	33,375

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	-	30	52	43	28	102
	2017	6	19	54	55	21	81
	acres, 2022	-	2,128	2,965	1,370	419	2,848
	2017	18	1,112	1,469	1,819	266	3,130
Other cropland	farms, 2022	6	297	92	222	200	416
	2017	11	273	93	175	179	442
	acres, 2022	55	17,197	3,296	10,901	6,524	22,851
	2017	26	15,308	3,003	7,076	4,557	22,068
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	2	290	48	190	182	373
	2017	8	253	54	141	167	401
	acres, 2022	(D)	16,874	2,040	9,410	6,360	20,875
	2017	18	15,118	2,141	6,314	4,307	20,809
Cropland on which all crops failed	farms, 2022	2	6	32	27	10	35
	2017	1	21	31	26	2	45
	acres, 2022	(D)	(D)	690	1,275	76	1,403
	2017	(D)	103	581	594	(D)	774
Cropland in summer fallow	farms, 2022	4	2	38	18	14	32
	2017	3	3	13	18	12	31
	acres, 2022	(D)	(D)	566	216	88	573
	2017	(D)	87	281	168	(D)	485
Total woodland	farms, 2022	23	73	290	222	169	441
	2017	25	86	335	219	195	427
	acres, 2022	1,081	2,376	23,717	4,819	5,082	20,791
	2017	1,041	2,916	23,444	5,610	4,926	18,304
Woodland pastured	farms, 2022	5	21	139	72	51	109
	2017	3	25	187	62	51	128
	acres, 2022	151	526	5,846	863	1,159	3,309
	2017	21	662	8,684	782	910	3,195
Woodland not pastured	farms, 2022	23	63	215	181	139	377
	2017	25	74	232	179	165	374
	acres, 2022	930	1,850	17,871	3,956	3,923	17,482
	2017	1,020	2,254	14,760	4,828	4,016	15,109
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	9	140	218	250	195	300
	2017	6	164	262	247	177	301
	acres, 2022	132	5,611	14,618	4,503	3,387	9,407
	2017	116	7,755	14,541	4,449	3,548	11,001
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	21	422	318	521	422	678
	2017	19	455	360	516	408	663
	acres, 2022	444	13,802	10,509	11,438	9,174	36,023
	2017	55	14,258	9,372	11,578	7,614	28,636
Pastureland, all types	farms, 2022	10	170	258	292	234	373
	2017	13	188	345	294	210	395
	acres, 2022	283	8,265	23,429	6,736	4,965	15,564
	2017	155	9,529	24,694	7,050	4,724	17,326
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	-	278	3	96	152	356
	2017	1	301	3	110	166	362
	acres, 2022	-	12,800	38	2,248	4,454	17,188
	2017	(D)	13,078	(D)	2,536	2,884	16,935
Land enrolled in crop insurance programs	farms, 2022	-	470	39	355	270	311
	2017	-	505	39	355	289	356
	acres, 2022	-	349,598	17,934	149,942	217,561	155,650
	2017	-	318,657	11,943	175,789	209,615	143,822

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	14	128	20	115	11	39
	2017	6	145	45	152	12	39
	acres, 2022	132	4,857	488	5,535	729	798
	2017	123	5,004	916	3,978	726	661
Other cropland	farms, 2022	243	564	421	398	365	113
	2017	248	523	412	341	342	80
	acres, 2022	9,032	25,337	19,257	10,236	33,765	2,593
	2017	8,854	20,570	13,408	11,867	22,128	1,567
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	234	537	404	344	349	89
	2017	228	500	398	304	310	62
	acres, 2022	8,773	23,750	18,856	9,275	32,497	2,052
	2017	8,528	20,036	12,698	10,768	20,544	1,355
Cropland on which all crops failed	farms, 2022	17	22	13	45	24	19
	2017	6	12	15	30	24	14
	acres, 2022	259	1,090	106	728	942	430
	2017	48	196	481	844	520	124
Cropland in summer fallow	farms, 2022	-	34	17	16	17	19
	2017	16	23	8	23	17	14
	acres, 2022	-	497	295	233	326	111
	2017	278	338	229	255	1,064	88
Total woodland	farms, 2022	116	776	183	557	119	176
	2017	107	730	228	594	74	140
	acres, 2022	3,141	43,133	4,332	24,600	4,151	4,823
	2017	4,683	41,818	4,979	22,640	2,146	2,929
Woodland pastured	farms, 2022	27	294	45	153	31	45
	2017	36	293	81	173	9	54
	acres, 2022	587	13,958	842	4,110	1,059	363
	2017	578	13,977	1,019	3,926	275	784
Woodland not pastured	farms, 2022	101	589	145	474	100	147
	2017	72	563	156	501	70	99
	acres, 2022	2,554	29,175	3,490	20,490	3,092	4,460
	2017	4,105	27,841	3,960	18,714	1,871	2,145
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	83	621	147	606	91	197
	2017	105	641	196	693	67	172
	acres, 2022	1,402	33,294	2,754	20,439	4,820	2,454
	2017	1,490	30,280	2,789	19,350	3,030	2,982
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	396	967	557	1,004	303	365
	2017	443	944	662	1,031	310	289
	acres, 2022	12,640	16,665	11,386	19,517	13,605	3,810
	2017	12,647	15,802	11,345	16,900	16,013	3,351
Pastureland, all types	farms, 2022	100	727	176	676	105	209
	2017	122	781	243	784	76	209
	acres, 2022	2,121	52,109	4,084	30,084	6,608	3,615
	2017	2,191	49,261	4,724	27,254	4,031	4,427
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	199	509	379	299	362	46
	2017	253	437	403	284	353	33
	acres, 2022	3,418	18,205	11,738	5,790	21,959	1,253
	2017	3,993	14,294	9,606	6,824	21,063	891
Land enrolled in crop insurance programs	farms, 2022	565	602	545	663	232	60
	2017	547	575	603	671	247	80
	acres, 2022	350,400	320,497	305,428	308,486	287,797	8,884
	2017	364,611	231,159	347,296	269,999	276,738	26,458

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	83	32	47	36	19	42
	2017	76	20	60	23	18	32
	acres, 2022	1,776	735	457	2,096	349	1,857
	2017	2,947	1,954	1,853	730	230	1,116
Other cropland	farms, 2022	350	92	238	100	328	107
	2017	351	96	219	83	270	143
	acres, 2022	15,255	6,452	6,143	3,536	11,134	2,671
	2017	15,666	5,330	6,737	3,361	11,538	3,389
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	333	59	158	71	310	67
	2017	330	67	151	44	248	66
	acres, 2022	14,698	5,504	4,570	2,330	10,776	1,651
	2017	14,568	4,213	5,415	1,877	10,764	2,078
Cropland on which all crops failed	farms, 2022	19	26	56	15	15	33
	2017	17	16	44	20	19	43
	acres, 2022	327	676	846	782	125	772
	2017	300	504	553	588	592	723
Cropland in summer fallow	farms, 2022	19	20	48	26	9	20
	2017	37	32	39	37	8	58
	acres, 2022	230	272	727	424	233	248
	2017	798	613	769	896	182	588
Total woodland	farms, 2022	560	224	427	307	79	339
	2017	626	270	426	249	70	388
	acres, 2022	56,829	22,302	10,850	26,410	2,825	17,003
	2017	58,775	22,326	15,341	19,275	2,545	22,883
Woodland pastured	farms, 2022	190	111	149	148	24	151
	2017	221	122	123	127	23	186
	acres, 2022	12,775	7,653	1,602	5,962	546	6,267
	2017	15,337	7,638	1,896	3,765	410	7,870
Woodland not pastured	farms, 2022	474	170	334	235	63	237
	2017	526	207	356	181	51	283
	acres, 2022	44,054	14,649	9,248	20,448	2,279	10,736
	2017	43,438	14,688	13,445	15,510	2,135	15,013
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	373	155	368	242	136	281
	2017	444	209	429	202	153	371
	acres, 2022	18,368	14,336	6,388	14,157	5,138	14,044
	2017	21,432	14,317	7,373	10,813	6,742	21,308
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	572	252	636	307	463	401
	2017	606	284	625	239	463	456
	acres, 2022	12,891	6,614	13,218	7,580	15,656	9,935
	2017	11,056	4,547	13,454	4,985	11,495	8,435
Pastureland, all types	farms, 2022	427	205	422	269	159	333
	2017	491	241	477	244	164	436
	acres, 2022	32,919	22,724	8,447	22,215	6,033	22,168
	2017	39,716	23,909	11,122	15,308	7,382	30,294
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	296	7	31	12	301	4
	2017	323	13	39	10	274	9
	acres, 2022	10,883	109	538	495	9,595	94
	2017	10,296	216	1,045	234	7,700	130
Land enrolled in crop insurance programs	farms, 2022	257	38	115	17	591	74
	2017	279	28	153	6	549	93
	acres, 2022	82,349	35,695	44,805	11,676	341,905	32,509
	2017	62,302	27,357	71,732	(D)	317,818	29,707

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	56	35	17	18	3	8
	2017	56	26	27	19	5	7
	acres, 2022	1,883	7,423	1,342	1,105	(D)	2,367
	2017	1,369	4,369	1,709	1,017	(D)	688
Other cropland	farms, 2022	661	440	76	417	3	97
	2017	658	365	53	478	4	68
	acres, 2022	38,208	88,509	4,653	32,149	(D)	12,628
	2017	39,865	75,095	2,490	30,990	(D)	10,724
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	627	410	35	369	3	64
	2017	633	341	21	406	1	50
	acres, 2022	35,904	84,538	2,787	29,297	(D)	8,413
	2017	37,867	72,805	1,132	27,971	(D)	8,966
Cropland on which all crops failed	farms, 2022	33	21	28	40	-	21
	2017	31	19	16	51	3	6
	acres, 2022	1,674	2,825	956	1,745	-	3,659
	2017	1,495	1,351	433	1,186	(D)	163
Cropland in summer fallow	farms, 2022	25	33	39	37	-	23
	2017	16	21	19	36	1	26
	acres, 2022	630	1,146	910	1,107	-	556
	2017	503	939	925	1,833	(D)	1,595
Total woodland	farms, 2022	365	249	138	96	20	130
	2017	319	204	140	102	26	96
	acres, 2022	10,762	48,981	16,020	2,816	586	23,545
	2017	11,955	33,718	15,576	3,225	1,043	14,968
Woodland pastured	farms, 2022	122	60	49	15	11	32
	2017	108	51	60	32	13	26
	acres, 2022	2,209	11,415	2,737	219	134	1,835
	2017	2,506	10,867	3,644	1,172	(D)	1,331
Woodland not pastured	farms, 2022	283	218	114	82	19	113
	2017	245	180	104	73	20	87
	acres, 2022	8,553	37,566	13,283	2,597	452	21,710
	2017	9,449	22,851	11,932	2,053	(D)	13,637
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	323	92	94	128	11	58
	2017	303	90	84	159	21	36
	acres, 2022	10,509	22,597	9,198	15,888	(D)	6,486
	2017	9,908	22,801	8,673	18,701	488	3,700
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	821	329	141	429	22	127
	2017	775	269	126	482	35	98
	acres, 2022	36,710	17,029	5,727	18,461	(D)	6,619
	2017	31,235	14,212	3,407	22,713	627	4,841
Pastureland, all types	farms, 2022	386	130	101	150	18	69
	2017	365	119	113	181	28	49
	acres, 2022	14,601	41,435	13,277	17,212	305	10,688
	2017	13,783	38,037	14,026	20,890	608	5,719
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	604	428	5	360	-	28
	2017	680	388	5	485	-	18
	acres, 2022	28,557	74,455	110	21,177	-	1,951
	2017	31,325	67,560	140	27,088	-	924
Land enrolled in crop insurance programs	farms, 2022	440	268	20	462	-	63
	2017	469	246	11	541	-	52
	acres, 2022	378,973	426,924	11,644	343,306	-	54,784
	2017	319,105	292,841	5,819	341,887	-	38,174

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	36	9	21	31	13	27
	2017	21	17	6	35	11	38
	acres, 2022	709	760	1,758	476	476	2,043
	2017	486	1,947	554	616	664	2,958
Other cropland	farms, 2022	510	360	366	309	118	727
	2017	489	366	329	333	99	654
	acres, 2022	20,809	30,889	26,564	9,463	12,598	156,083
	2017	19,799	29,505	18,717	10,343	11,648	140,785
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	485	350	357	278	102	644
	2017	460	348	320	287	90	626
	acres, 2022	20,197	30,233	25,843	8,590	10,627	143,642
	2017	19,209	28,575	18,133	9,340	11,317	139,137
Cropland on which all crops failed	farms, 2022	30	19	11	16	8	55
	2017	20	28	13	33	8	18
	acres, 2022	403	613	641	452	410	9,525
	2017	197	660	529	430	(D)	860
Cropland in summer fallow	farms, 2022	14	4	3	21	14	77
	2017	15	8	7	32	2	33
	acres, 2022	209	43	80	421	1,561	2,916
	2017	393	270	55	573	(D)	788
Total woodland	farms, 2022	335	67	74	252	104	425
	2017	358	41	60	235	138	454
	acres, 2022	8,817	1,993	2,158	4,647	14,520	40,261
	2017	8,252	1,337	1,844	4,397	13,728	39,899
Woodland pastured	farms, 2022	65	12	22	78	32	98
	2017	82	18	19	78	40	118
	acres, 2022	975	158	612	1,379	4,023	5,740
	2017	845	496	355	998	3,097	7,478
Woodland not pastured	farms, 2022	297	58	62	203	89	371
	2017	322	27	51	190	118	392
	acres, 2022	7,842	1,835	1,546	3,268	10,497	34,521
	2017	7,407	841	1,489	3,399	10,631	32,421
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	186	158	204	186	70	163
	2017	206	214	210	246	92	190
	acres, 2022	2,972	11,463	19,351	2,484	10,190	19,171
	2017	3,132	12,657	11,869	2,924	11,765	17,603
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	591	369	452	505	160	570
	2017	663	432	524	596	202	577
	acres, 2022	12,610	13,815	13,887	10,884	8,854	48,563
	2017	13,891	14,077	15,106	12,452	9,475	20,831
Pastureland, all types	farms, 2022	233	167	221	246	74	211
	2017	258	225	222	313	108	248
	acres, 2022	4,656	12,381	21,721	4,339	14,689	26,954
	2017	4,463	15,100	12,778	4,538	15,526	28,039
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	509	370	318	263	80	522
	2017	487	400	299	231	87	616
	acres, 2022	15,819	27,241	17,506	6,554	4,716	84,088
	2017	16,639	26,486	12,714	6,981	4,122	112,703
Land enrolled in crop insurance programs	farms, 2022	319	284	555	343	149	548
	2017	352	370	591	424	149	474
	acres, 2022	154,062	147,037	346,327	199,398	170,210	678,314
	2017	183,668	227,760	332,162	210,291	158,229	630,070

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	18	54	60	144	56	29
	2017	18	51	55	107	55	40
	acres, 2022	353	1,169	2,430	5,078	1,858	357
	2017	210	1,183	1,223	4,881	1,617	1,377
Other cropland	farms, 2022	263	476	176	415	363	334
	2017	210	447	178	433	352	328
	acres, 2022	11,334	23,657	4,764	15,968	15,585	15,501
	2017	6,997	19,539	4,054	17,547	13,130	15,119
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	249	456	109	290	342	326
	2017	183	421	87	269	339	313
	acres, 2022	11,242	22,803	2,932	11,380	15,035	15,348
	2017	6,582	18,829	2,086	12,001	12,149	14,816
Cropland on which all crops failed	farms, 2022	14	32	38	77	15	3
	2017	23	22	44	104	17	10
	acres, 2022	(D)	682	1,065	2,941	152	31
	2017	258	423	1,038	2,660	761	146
Cropland in summer fallow	farms, 2022	2	10	52	83	18	6
	2017	9	18	50	102	11	11
	acres, 2022	(D)	172	767	1,647	398	122
	2017	157	287	930	2,886	220	157
Total woodland	farms, 2022	108	367	335	914	210	61
	2017	81	384	351	939	239	72
	acres, 2022	2,325	10,079	15,239	67,773	6,867	4,915
	2017	1,993	11,023	15,550	63,659	6,835	1,653
Woodland pastured	farms, 2022	30	86	134	392	67	5
	2017	22	97	138	439	75	16
	acres, 2022	358	1,125	3,543	16,217	1,260	53
	2017	203	2,514	3,808	19,242	1,495	146
Woodland not pastured	farms, 2022	91	314	263	720	151	56
	2017	64	317	261	662	185	56
	acres, 2022	1,967	8,954	11,696	51,556	5,607	4,862
	2017	1,790	8,509	11,742	44,417	5,340	1,507
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	84	229	291	724	218	152
	2017	92	268	408	829	246	168
	acres, 2022	2,465	7,178	9,637	38,463	3,354	18,629
	2017	2,465	5,913	12,778	42,635	4,418	18,460
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	452	664	468	1,201	600	461
	2017	554	707	547	1,318	700	496
	acres, 2022	15,500	23,492	9,145	44,283	18,528	13,672
	2017	10,287	22,422	10,659	43,292	15,002	12,388
Pastureland, all types	farms, 2022	101	276	360	867	282	171
	2017	112	323	443	1,014	313	199
	acres, 2022	3,176	9,472	15,610	59,758	6,472	19,039
	2017	2,878	9,610	17,809	66,758	7,530	19,983
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	196	458	39	165	323	319
	2017	193	423	30	200	370	368
	acres, 2022	7,182	18,707	1,033	5,506	8,557	10,990
	2017	5,499	15,965	523	5,538	8,768	14,214
Land enrolled in crop insurance programs	farms, 2022	564	355	114	524	541	507
	2017	653	423	169	634	593	589
	acres, 2022	415,124	198,546	33,095	128,805	311,051	292,750
	2017	405,355	223,568	59,861	134,757	370,897	334,661

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	18	18	19	65	170	10
	2017	23	20	16	116	218	10
	acres, 2022	279	348	1,342	2,502	8,258	598
	2017	471	544	667	7,567	10,444	702
Other cropland	farms, 2022	221	356	205	438	1,177	170
	2017	188	266	204	339	1,079	194
	acres, 2022	9,105	10,866	25,414	16,751	65,092	34,543
	2017	10,157	10,876	23,503	14,890	63,147	30,347
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	203	340	173	401	1,052	149
	2017	163	258	186	298	973	172
	acres, 2022	7,997	10,442	22,667	15,022	60,037	31,684
	2017	9,774	10,645	22,303	13,757	57,873	28,232
Cropland on which all crops failed	farms, 2022	14	13	21	31	107	15
	2017	20	1	8	16	111	8
	acres, 2022	1,076	241	2,168	1,078	3,018	2,164
	2017	296	(D)	110	475	2,903	1,134
Cropland in summer fallow	farms, 2022	8	10	24	33	97	15
	2017	8	8	25	33	89	20
	acres, 2022	32	183	579	651	2,037	695
	2017	87	(D)	1,090	658	2,371	981
Total woodland	farms, 2022	152	40	147	465	1,415	150
	2017	128	39	155	476	1,431	178
	acres, 2022	4,937	483	10,330	17,829	95,876	11,023
	2017	6,643	873	9,343	15,479	91,198	16,640
Woodland pastured	farms, 2022	35	10	42	139	429	51
	2017	33	11	48	159	458	46
	acres, 2022	458	46	1,360	3,026	21,061	1,745
	2017	726	164	1,733	3,582	21,713	1,388
Woodland not pastured	farms, 2022	132	33	127	383	1,205	127
	2017	104	29	129	368	1,187	160
	acres, 2022	4,479	437	8,970	14,803	74,815	9,278
	2017	5,917	709	7,610	11,897	69,485	15,252
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	83	181	66	397	862	85
	2017	68	181	94	555	906	102
	acres, 2022	2,003	6,730	5,936	12,289	56,121	10,534
	2017	690	7,323	4,558	17,300	49,313	10,544
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	404	537	225	786	1,826	192
	2017	400	533	294	827	1,817	256
	acres, 2022	9,136	13,030	20,527	19,665	73,141	14,898
	2017	7,986	13,896	13,022	14,078	77,822	9,467
Pastureland, all types	farms, 2022	105	205	87	464	1,031	103
	2017	100	197	122	632	1,125	123
	acres, 2022	2,740	7,124	8,638	17,817	85,440	12,877
	2017	1,887	8,031	6,958	28,449	81,470	12,634
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	175	314	150	352	970	134
	2017	149	293	175	252	957	150
	acres, 2022	4,680	7,263	10,394	11,381	45,653	19,218
	2017	3,736	7,394	14,829	6,570	45,409	21,643
Land enrolled in crop insurance programs	farms, 2022	424	652	282	419	763	151
	2017	510	625	324	450	808	186
	acres, 2022	249,107	323,665	434,817	200,635	403,561	189,188
	2017	230,995	367,878	432,572	196,452	407,539	200,377

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	104	16	63	54	1	27
	2017	76	19	83	55	7	21
	acres, 2022	5,193	651	3,752	2,914	(D)	3,769
	2017	3,073	2,474	6,471	2,694	(D)	2,887
Other cropland	farms, 2022	171	150	595	417	13	105
	2017	183	160	599	415	5	102
	acres, 2022	6,434	6,969	78,357	31,041	(D)	18,716
	2017	9,391	9,491	91,810	31,351	(D)	18,507
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	96	144	499	387	12	83
	2017	97	151	565	392	4	94
	acres, 2022	4,596	6,813	71,307	29,846	(D)	15,191
	2017	6,447	9,128	89,272	30,549	(D)	18,243
Cropland on which all crops failed	farms, 2022	40	7	54	33	1	16
	2017	45	5	18	14	2	1
	acres, 2022	635	156	5,140	952	(D)	3,025
	2017	1,305	39	1,140	428	(D)	(D)
Cropland in summer fallow	farms, 2022	59	-	64	17	-	21
	2017	58	7	40	20	1	12
	acres, 2022	1,203	-	1,910	243	-	500
	2017	1,639	324	1,398	374	(D)	(D)
Total woodland	farms, 2022	465	34	344	230	4	105
	2017	509	48	399	262	7	109
	acres, 2022	39,219	384	32,519	9,602	199	8,096
	2017	36,925	866	31,429	10,000	120	8,266
Woodland pastured	farms, 2022	199	5	93	53	2	34
	2017	233	22	112	56	-	32
	acres, 2022	10,045	45	4,808	1,507	(D)	1,414
	2017	11,407	408	5,932	1,614	-	2,081
Woodland not pastured	farms, 2022	364	29	284	203	2	82
	2017	398	33	328	218	7	94
	acres, 2022	29,174	339	27,711	8,095	(D)	6,682
	2017	25,518	458	25,497	8,386	120	6,185
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	424	230	202	244	1	61
	2017	442	268	237	258	1	51
	acres, 2022	23,481	20,876	25,046	20,229	(D)	5,176
	2017	23,785	18,421	21,126	19,926	(D)	4,591
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	553	357	601	527	17	155
	2017	619	402	721	594	21	161
	acres, 2022	14,904	17,097	39,444	26,174	(D)	6,622
	2017	17,912	10,143	32,057	22,757	(D)	6,544
Pastureland, all types	farms, 2022	469	236	272	274	3	79
	2017	511	293	297	294	7	71
	acres, 2022	38,719	21,572	33,606	24,650	257	10,359
	2017	38,265	21,303	33,529	24,234	64	9,559
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	9	132	429	350	4	69
	2017	5	136	495	415	1	90
	acres, 2022	224	4,126	43,793	19,133	156	7,083
	2017	119	4,252	64,555	25,075	(D)	12,923
Land enrolled in crop insurance programs	farms, 2022	92	302	692	298	-	167
	2017	91	345	648	337	4	142
	acres, 2022	24,999	174,404	896,686	197,887	-	155,975
	2017	21,516	180,239	793,109	226,640	13	149,759

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	32	24	70	11	58	64
	2017	15	25	62	21	38	86
	acres, 2022	947	895	1,000	330	5,716	3,756
	2017	492	1,252	935	409	2,413	3,397
Other cropland	farms, 2022	512	372	419	172	431	183
	2017	436	386	457	142	512	217
	acres, 2022	24,435	26,390	17,207	6,025	72,536	6,392
	2017	20,064	17,654	14,577	6,263	98,812	7,921
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	493	351	376	164	347	97
	2017	414	359	409	131	454	126
	acres, 2022	23,581	25,534	16,007	5,822	62,755	3,923
	2017	19,468	16,530	13,671	5,978	95,035	3,905
Cropland on which all crops failed	farms, 2022	23	26	48	7	50	42
	2017	24	27	31	8	16	72
	acres, 2022	682	(D)	893	160	4,590	1,256
	2017	286	960	368	107	712	2,499
Cropland in summer fallow	farms, 2022	12	2	18	5	77	86
	2017	8	6	31	4	83	72
	acres, 2022	172	(D)	307	43	5,191	1,213
	2017	310	164	538	178	3,065	1,517
Total woodland	farms, 2022	115	130	463	42	417	609
	2017	102	132	520	42	430	591
	acres, 2022	4,143	5,409	12,582	687	53,451	47,340
	2017	4,289	6,506	13,356	394	44,435	44,303
Woodland pastured	farms, 2022	36	36	85	14	131	220
	2017	23	27	120	16	136	267
	acres, 2022	789	486	1,407	182	10,167	8,032
	2017	585	540	2,357	81	8,824	10,308
Woodland not pastured	farms, 2022	95	107	402	34	352	513
	2017	88	112	443	33	351	478
	acres, 2022	3,354	4,923	11,175	505	43,284	39,308
	2017	3,704	5,966	10,999	313	35,611	33,995
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	139	97	291	186	204	424
	2017	136	111	399	228	238	377
	acres, 2022	3,803	5,706	4,548	10,099	27,922	19,311
	2017	5,877	2,844	6,308	10,786	29,414	16,669
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	679	497	751	395	504	611
	2017	638	568	864	466	515	552
	acres, 2022	16,972	16,245	16,719	8,846	37,729	14,412
	2017	18,853	16,517	13,978	10,257	21,195	10,678
Pastureland, all types	farms, 2022	169	126	386	201	265	484
	2017	152	144	471	247	291	475
	acres, 2022	5,539	7,087	6,955	10,611	43,805	31,099
	2017	6,954	4,636	9,600	11,276	40,651	30,374
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	468	315	322	125	270	3
	2017	433	343	363	124	422	4
	acres, 2022	15,012	12,357	8,554	3,669	34,618	113
	2017	16,382	11,391	10,804	2,664	85,350	38
Land enrolled in crop insurance programs	farms, 2022	904	617	401	362	293	9
	2017	780	699	424	476	268	3
	acres, 2022	494,228	532,416	176,035	217,114	338,234	9,795
	2017	457,349	543,842	145,488	250,334	315,549	(D)

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	57	24	42	242	25	17
	2017	69	14	24	200	31	24
	acres, 2022	582	554	1,374	9,470	514	284
	2017	1,281	270	914	8,198	603	803
Other cropland	farms, 2022	174	141	313	883	363	291
	2017	199	173	311	1,029	356	278
	acres, 2022	6,128	6,847	14,138	44,520	15,055	27,996
	2017	5,639	6,677	10,496	45,145	11,865	18,031
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	156	84	292	730	345	265
	2017	180	129	271	882	342	263
	acres, 2022	5,666	4,353	13,442	36,884	13,985	25,088
	2017	4,947	5,313	9,504	39,229	11,502	17,325
Cropland on which all crops failed	farms, 2022	18	38	14	94	15	27
	2017	12	33	31	105	22	17
	acres, 2022	282	1,408	532	5,910	743	2,505
	2017	164	456	624	2,750	(D)	567
Cropland in summer fallow	farms, 2022	14	33	8	113	9	13
	2017	20	29	17	93	2	4
	acres, 2022	180	1,086	164	1,726	327	403
	2017	528	908	368	3,166	(D)	139
Total woodland	farms, 2022	230	235	187	1,035	168	78
	2017	288	275	194	1,219	173	63
	acres, 2022	4,001	8,422	8,745	43,154	3,247	1,470
	2017	6,353	11,027	6,246	42,204	3,062	1,747
Woodland pastured	farms, 2022	73	98	48	385	31	19
	2017	82	110	63	443	43	16
	acres, 2022	767	3,439	1,310	10,814	308	296
	2017	1,000	3,648	1,227	11,012	482	388
Woodland not pastured	farms, 2022	179	173	156	786	148	65
	2017	231	185	154	935	143	54
	acres, 2022	3,234	4,983	7,435	32,340	2,939	1,174
	2017	5,353	7,379	5,019	31,192	2,580	1,359
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	253	169	183	976	130	83
	2017	264	179	184	1,171	152	118
	acres, 2022	3,787	4,732	3,296	30,938	3,126	5,002
	2017	4,093	5,336	4,038	38,100	3,498	6,185
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	401	368	543	2,003	487	290
	2017	520	336	617	2,192	496	341
	acres, 2022	3,964	7,446	12,332	57,177	8,378	12,219
	2017	7,086	7,719	13,112	54,589	11,179	14,400
Pastureland, all types	farms, 2022	300	213	232	1,224	168	99
	2017	329	239	236	1,408	194	130
	acres, 2022	5,136	8,725	5,980	51,222	3,948	5,582
	2017	6,374	9,254	6,179	57,310	4,583	7,376
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	104	28	307	522	347	264
	2017	106	42	265	602	318	293
	acres, 2022	1,756	957	9,152	20,038	11,373	10,245
	2017	2,519	1,127	7,710	22,311	8,262	15,679
Land enrolled in crop insurance programs	farms, 2022	153	75	490	1,059	291	272
	2017	195	86	509	1,333	341	286
	acres, 2022	69,840	37,290	322,017	342,246	207,713	289,148
	2017	68,646	46,847	286,784	338,311	201,590	275,627

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	18	153	5	58	44	15
	2017	22	173	2	77	39	33
	acres, 2022	451	5,013	106	1,860	2,637	937
	2017	949	6,511	(D)	3,950	1,462	281
Other cropland	farms, 2022	416	518	261	259	131	296
	2017	393	517	243	282	162	288
	acres, 2022	36,679	19,885	33,572	10,525	6,253	15,015
	2017	28,941	25,549	(D)	13,103	8,534	10,565
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	397	395	251	231	102	283
	2017	360	382	234	258	118	271
	acres, 2022	35,167	15,678	27,401	9,411	4,105	14,674
	2017	28,093	21,823	17,589	12,248	7,037	9,984
Cropland on which all crops failed	farms, 2022	26	99	24	23	31	17
	2017	27	91	11	16	39	16
	acres, 2022	1,199	3,141	5,998	857	1,657	281
	2017	460	2,056	846	646	995	369
Cropland in summer fallow	farms, 2022	19	51	6	22	31	6
	2017	23	98	4	19	27	10
	acres, 2022	313	1,066	173	257	491	60
	2017	388	1,670	(D)	209	502	212
Total woodland	farms, 2022	125	837	31	366	254	133
	2017	96	893	40	449	322	168
	acres, 2022	3,709	46,699	3,975	30,557	19,183	2,985
	2017	2,391	46,766	4,018	31,276	22,452	4,282
Woodland pastured	farms, 2022	15	325	5	112	128	34
	2017	25	338	14	155	140	41
	acres, 2022	168	11,387	89	4,942	5,976	286
	2017	366	11,114	(D)	6,524	5,565	551
Woodland not pastured	farms, 2022	115	657	26	315	186	107
	2017	80	689	31	362	257	144
	acres, 2022	3,541	35,312	3,886	25,615	13,207	2,699
	2017	2,025	35,652	(D)	24,752	16,887	3,731
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	114	729	29	300	210	78
	2017	137	805	38	360	267	114
	acres, 2022	10,230	34,611	2,109	12,804	12,767	899
	2017	8,301	39,476	(D)	14,028	16,604	1,714
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	390	1,137	170	533	297	385
	2017	442	1,215	197	561	384	461
	acres, 2022	21,455	39,564	11,942	11,786	11,443	11,282
	2017	17,906	36,672	(D)	9,660	13,851	10,002
Pastureland, all types	farms, 2022	132	840	36	348	245	107
	2017	160	953	47	429	308	154
	acres, 2022	10,849	51,011	2,304	19,606	21,380	2,122
	2017	9,616	57,101	2,025	24,502	23,631	2,546
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	368	272	260	174	41	268
	2017	397	251	254	190	76	314
	acres, 2022	21,112	12,553	16,784	5,942	794	8,318
	2017	22,595	10,318	13,584	8,539	2,002	6,020
Land enrolled in crop insurance programs	farms, 2022	377	397	215	365	86	351
	2017	425	419	269	415	84	396
	acres, 2022	303,065	116,558	270,870	126,562	51,623	222,738
	2017	276,060	108,646	306,495	123,327	30,868	203,056

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Table 8. **Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
LAND IN FARMS ACCORDING TO USE - Con.							
Total cropland - Con.							
Other pasture and grazing land that could have been used for crops without additional improvements	farms, 2022	37	9	7	88	115	26
	2017	41	22	3	88	77	27
	acres, 2022	406	(D)	1,798	3,318	2,830	4,983
	2017	1,009	584	251	3,849	1,624	1,684
Other cropland	farms, 2022	102	201	205	335	369	435
	2017	145	190	198	313	399	380
	acres, 2022	2,608	(D)	27,821	15,645	11,453	29,967
	2017	2,579	8,545	19,462	11,595	11,465	23,945
Cropland idle or used for cover crops or soil improvement, but not harvested and not pastured or grazed	farms, 2022	70	189	172	308	293	421
	2017	107	180	175	275	321	368
	acres, 2022	2,373	8,401	25,387	14,558	8,526	29,047
	2017	2,115	8,250	17,797	10,693	10,090	23,170
Cropland on which all crops failed	farms, 2022	22	17	14	33	62	13
	2017	24	8	24	21	67	11
	acres, 2022	139	176	1,277	468	1,621	728
	2017	275	(D)	1,375	281	1,032	410
Cropland in summer fallow	farms, 2022	18	2	27	31	57	11
	2017	23	4	7	35	33	10
	acres, 2022	96	(D)	1,157	619	1,306	192
	2017	189	(D)	290	621	343	365
Total woodland	farms, 2022	194	80	53	583	540	102
	2017	226	71	30	602	579	104
	acres, 2022	4,280	2,708	1,578	48,148	12,992	3,888
	2017	4,982	2,373	866	51,254	12,784	3,838
Woodland pastured	farms, 2022	44	3	8	184	176	35
	2017	69	7	3	212	166	35
	acres, 2022	908	(D)	37	7,312	2,637	784
	2017	1,137	251	11	10,217	2,816	834
Woodland not pastured	farms, 2022	170	78	45	496	429	77
	2017	189	68	27	500	465	81
	acres, 2022	3,372	(D)	1,541	40,836	10,355	3,104
	2017	3,845	2,122	855	41,037	9,968	3,004
Permanent pasture and rangeland, other than cropland and woodland pastured	farms, 2022	197	55	48	448	453	164
	2017	295	54	23	474	543	155
	acres, 2022	4,894	1,120	2,212	17,865	7,289	10,523
	2017	7,781	1,222	1,821	22,889	9,389	8,103
Land in farmsteads, homes, buildings, livestock facilities, roads, wasteland, etc.	farms, 2022	367	290	167	645	958	484
	2017	421	323	175	703	962	493
	acres, 2022	4,887	8,263	9,585	12,567	19,039	18,026
	2017	5,622	7,702	10,865	13,723	14,793	16,371
Pastureland, all types	farms, 2022	229	65	53	530	577	195
	2017	319	78	24	571	616	182
	acres, 2022	6,208	2,319	4,047	28,495	12,756	16,290
	2017	9,927	2,057	2,083	36,955	13,829	10,621
CONSERVATION AND CROP INSURANCE							
Land enrolled in Conservation Reserve, Wetlands Reserve, Farmable Wetlands, or Conservation Reserve Enhancement Programs	farms, 2022	16	194	164	241	199	393
	2017	11	213	188	242	224	408
	acres, 2022	190	5,001	9,021	7,878	4,604	17,533
	2017	182	5,991	11,706	7,133	5,965	19,625
Land enrolled in crop insurance programs	farms, 2022	92	312	215	398	339	486
	2017	140	316	256	400	435	527
	acres, 2022	26,538	237,928	360,121	151,643	140,285	319,963
	2017	43,246	212,409	372,201	110,076	165,331	312,089

Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
Farms ..... number, 2022	47,549	396	259	597	473
2017	50,272	389	250	614	413
acres harvested, 2022	19,662,443	48,445	17,836	242,439	73,854
2017	20,054,132	45,661	26,945	226,915	68,263
HARVESTED CROPLAND BY SIZE OF FARM					
2022 size of farm:					
1 to 9 acres ..... farms	1,928	5	28	18	10
acres harvested	5,447	6	(D)	25	29
10 to 49 acres ..... farms	8,326	56	147	63	72
acres harvested	116,138	657	1,630	845	1,051
50 to 69 acres ..... farms	2,150	19	19	28	19
acres harvested	67,610	721	(D)	625	610
70 to 99 acres ..... farms	3,531	39	17	54	46
acres harvested	163,112	1,216	772	1,508	1,379
100 to 139 acres ..... farms	3,351	39	15	54	31
acres harvested	230,286	1,930	934	2,981	1,328
140 to 179 acres ..... farms	3,598	39	2	56	57
acres harvested	356,651	2,574	(D)	3,360	3,355
180 to 219 acres ..... farms	2,357	26	4	39	28
acres harvested	292,947	1,385	219	3,176	2,158
220 to 259 acres ..... farms	2,054	34	2	29	32
acres harvested	322,004	3,296	(D)	2,879	3,923
260 to 499 acres ..... farms	7,726	85	9	98	99
acres harvested	2,022,637	11,544	2,077	18,417	12,889
500 to 999 acres ..... farms	6,142	43	12	88	48
acres harvested	3,462,397	12,798	5,411	37,582	15,283
1,000 to 1,999 acres ..... farms	3,693	5	3	27	25
acres harvested	4,417,695	2,407	4,377	29,498	17,891
2,000 acres or more ..... farms	2,693	6	1	43	6
acres harvested	8,205,519	9,911	(D)	141,543	13,958
2017 size of farm:					
1 to 9 acres ..... farms	2,155	7	20	32	17
acres harvested	6,902	11	(D)	119	29
10 to 49 acres ..... farms	7,685	49	109	59	49
acres harvested	110,999	801	1,361	831	703
50 to 69 acres ..... farms	2,178	28	20	32	12
acres harvested	70,295	(D)	649	609	262
70 to 99 acres ..... farms	3,663	53	30	52	37
acres harvested	168,375	1,872	1,225	1,719	1,240
100 to 139 acres ..... farms	3,485	34	23	66	41
acres harvested	237,404	1,782	1,314	4,042	1,679
140 to 179 acres ..... farms	3,719	50	7	58	54
acres harvested	371,727	2,216	312	4,102	2,401
180 to 219 acres ..... farms	2,690	17	9	39	28
acres harvested	352,517	1,191	1,312	3,244	2,195
220 to 259 acres ..... farms	2,553	29	2	34	15
acres harvested	415,194	2,296	(D)	3,578	1,014
260 to 499 acres ..... farms	8,864	81	14	98	71
acres harvested	2,348,311	11,652	3,949	13,746	10,589
500 to 999 acres ..... farms	6,909	30	10	74	64
acres harvested	4,029,020	10,424	5,393	33,828	21,001
1,000 to 1,999 acres ..... farms	4,142	9	2	35	17
acres harvested	5,107,505	7,432	(D)	36,435	11,007
2,000 acres or more ..... farms	2,229	2	4	35	8
acres harvested	6,835,883	(D)	8,413	124,662	16,143
HARVESTED CROPLAND BY ACRES HARVESTED					
2022 acres harvested:					
1 to 9 acres ..... farms	6,328	36	109	68	41
acres	25,348	114	402	227	154
10 to 19 acres ..... farms	4,271	49	56	60	60
acres	55,737	638	665	763	796
20 to 29 acres ..... farms	2,676	45	19	39	46
acres	61,683	1,004	425	917	1,042
30 to 49 acres ..... farms	3,659	51	24	78	70
acres	136,392	1,925	844	2,840	2,571
50 to 99 acres ..... farms	5,412	84	20	80	80
acres	384,679	5,574	1,234	5,636	5,606
100 to 199 acres ..... farms	6,580	67	8	87	90
acres	926,151	8,582	1,136	12,084	12,233
200 to 499 acres ..... farms	8,316	45	13	86	57
acres	2,672,271	12,265	4,131	27,070	18,737
500 to 999 acres ..... farms	4,858	14	6	39	19
acres	3,407,244	8,620	3,414	26,508	12,357
1,000 acres or more ..... farms	5,449	5	4	60	10
acres	11,992,938	9,723	5,585	166,394	20,358
2017 acres harvested:					
1 to 9 acres ..... farms	6,092	32	74	75	44
acres	25,568	117	296	297	129
10 to 19 acres ..... farms	3,923	45	52	73	51
acres	51,730	634	693	974	736
20 to 29 acres ..... farms	2,718	52	22	53	28
acres	61,964	1,154	527	1,186	650
30 to 49 acres ..... farms	3,738	71	29	47	55
acres	139,767	2,734	1,072	1,655	2,044
50 to 99 acres ..... farms	5,609	75	32	96	82
acres	395,072	4,789	2,055	6,526	5,564
100 to 199 acres ..... farms	7,345	55	8	98	60
acres	1,046,405	6,964	1,178	12,866	8,164
200 to 499 acres ..... farms	9,769	44	19	75	67
acres	3,081,911	13,321	5,717	22,362	20,551
500 to 999 acres ..... farms	5,555	10	8	46	16
acres	3,933,654	6,264	4,494	31,959	10,132
1,000 acres or more ..... farms	5,523	5	6	51	10
acres	11,318,061	9,684	10,913	149,090	20,293

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
Farms ..... number, 2022	541	290	768	756	377
2017	665	341	718	815	452
acres harvested, 2022	95,943	213,843	437,712	260,346	30,672
2017	146,183	231,596	342,744	309,845	37,057
HARVESTED CROPLAND BY SIZE OF FARM					
2022 size of farm:					
1 to 9 acres ..... farms	9	6	44	13	8
acres harvested	37	12	132	52	(D)
10 to 49 acres ..... farms	156	25	115	99	64
acres harvested	2,746	455	1,768	1,838	824
50 to 69 acres ..... farms	48	3	19	33	16
acres harvested	1,254	90	684	1,704	(D)
70 to 99 acres ..... farms	53	19	46	40	62
acres harvested	2,423	970	2,877	2,449	1,686
100 to 139 acres ..... farms	60	15	37	54	31
acres harvested	3,904	1,088	3,353	5,404	1,555
140 to 179 acres ..... farms	31	14	51	66	43
acres harvested	2,886	1,523	6,270	8,653	2,797
180 to 219 acres ..... farms	38	8	31	38	26
acres harvested	4,806	1,121	4,798	6,449	1,757
220 to 259 acres ..... farms	15	11	30	31	24
acres harvested	2,564	2,152	5,677	6,531	2,362
260 to 499 acres ..... farms	82	61	136	197	79
acres harvested	21,084	16,444	43,745	65,842	11,690
500 to 999 acres ..... farms	30	54	122	135	20
acres harvested	17,260	29,944	79,989	85,738	4,627
1,000 to 1,999 acres ..... farms	9	47	62	37	3
acres harvested	8,961	62,643	76,752	44,073	2,760
2,000 acres or more ..... farms	10	27	75	13	1
acres harvested	28,018	97,401	211,667	31,613	(D)
2017 size of farm:					
1 to 9 acres ..... farms	10	12	38	30	5
acres harvested	32	36	83	102	5
10 to 49 acres ..... farms	162	31	82	88	86
acres harvested	2,548	428	1,276	1,506	1,251
50 to 69 acres ..... farms	51	17	23	27	31
acres harvested	1,433	272	996	1,142	870
70 to 99 acres ..... farms	67	19	45	38	61
acres harvested	2,825	702	2,624	2,760	1,651
100 to 139 acres ..... farms	56	6	56	46	37
acres harvested	3,888	405	5,031	4,716	1,809
140 to 179 acres ..... farms	37	23	52	53	45
acres harvested	3,524	2,664	5,665	7,103	2,491
180 to 219 acres ..... farms	38	5	31	59	40
acres harvested	5,339	790	5,741	10,210	3,234
220 to 259 acres ..... farms	42	14	31	54	27
acres harvested	6,530	2,755	6,443	10,837	2,768
260 to 499 acres ..... farms	117	71	131	209	86
acres harvested	31,248	20,976	44,114	69,083	13,188
500 to 999 acres ..... farms	52	58	122	150	29
acres harvested	30,601	34,842	77,697	97,063	6,445
1,000 to 1,999 acres ..... farms	21	60	73	41	5
acres harvested	25,865	80,146	95,420	50,427	3,345
2,000 acres or more ..... farms	12	25	34	20	-
acres harvested	32,350	87,580	97,654	54,896	-
HARVESTED CROPLAND BY ACRES HARVESTED					
2022 acres harvested:					
1 to 9 acres ..... farms	58	23	93	53	43
acres	255	89	361	256	154
10 to 19 acres ..... farms	76	10	53	26	41
acres	971	161	703	367	544
20 to 29 acres ..... farms	54	10	19	17	57
acres	1,240	245	513	405	1,318
30 to 49 acres ..... farms	78	14	33	46	55
acres	2,805	526	1,178	1,753	2,055
50 to 99 acres ..... farms	79	27	73	77	78
acres	5,668	2,132	5,456	5,337	5,230
100 to 199 acres ..... farms	78	28	85	133	70
acres	10,995	4,100	12,585	19,081	9,570
200 to 499 acres ..... farms	83	72	165	239	30
acres	25,481	24,687	53,400	80,391	9,041
500 to 999 acres ..... farms	22	39	121	125	3
acres	16,182	27,827	85,325	86,350	2,760
1,000 acres or more ..... farms	13	67	126	40	-
acres	32,346	154,076	278,191	66,406	-
2017 acres harvested:					
1 to 9 acres ..... farms	62	33	73	81	46
acres	287	129	244	368	229
10 to 19 acres ..... farms	89	16	35	11	54
acres	1,184	226	471	160	755
20 to 29 acres ..... farms	64	16	26	16	68
acres	1,416	343	610	368	1,503
30 to 49 acres ..... farms	70	12	28	33	66
acres	2,537	487	1,056	1,317	2,440
50 to 99 acres ..... farms	75	18	76	69	89
acres	5,276	1,243	5,449	5,037	6,091
100 to 199 acres ..... farms	104	40	98	153	80
acres	14,408	5,911	13,991	22,716	11,146
200 to 499 acres ..... farms	139	77	167	271	43
acres	42,504	24,859	55,532	91,325	10,713
500 to 999 acres ..... farms	34	47	114	125	6
acres	24,459	33,222	78,124	87,007	4,180
1,000 acres or more ..... farms	28	82	101	56	-
acres	54,112	165,176	187,267	101,547	-

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Farms ..... number, 2022	473	371	395	551	498	298
2017	542	311	464	620	502	303
acres harvested, 2022	129,717	46,589	316,194	53,977	476,475	62,929
2017	129,117	52,040	302,453	74,829	507,417	65,646
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	37	16	8	63	5	2
acres harvested	124	52	(D)	184	11	(D)
10 to 49 acres ..... farms	122	51	60	240	75	44
acres harvested	1,570	590	948	3,327	1,049	687
50 to 69 acres ..... farms	35	19	2	20	14	4
acres harvested	1,284	381	(D)	524	555	(D)
70 to 99 acres ..... farms	49	31	18	56	30	19
acres harvested	2,133	1,171	798	2,417	1,200	577
100 to 139 acres ..... farms	36	37	18	42	14	28
acres harvested	2,879	1,711	1,633	2,355	1,042	1,012
140 to 179 acres ..... farms	29	39	20	27	25	18
acres harvested	3,396	2,018	2,681	2,610	2,410	1,274
180 to 219 acres ..... farms	16	28	18	23	8	18
acres harvested	2,151	1,607	2,789	2,367	1,216	1,226
220 to 259 acres ..... farms	25	28	8	16	13	17
acres harvested	4,885	2,632	1,160	2,134	972	1,296
260 to 499 acres ..... farms	53	72	66	38	80	60
acres harvested	15,025	8,961	20,957	9,851	22,529	8,285
500 to 999 acres ..... farms	33	32	73	13	85	55
acres harvested	20,370	10,627	48,161	7,820	50,130	14,693
1,000 to 1,999 acres ..... farms	22	10	38	10	63	21
acres harvested	27,042	4,432	52,452	12,003	79,542	11,934
2,000 acres or more ..... farms	16	8	66	3	86	12
acres harvested	48,858	12,407	184,560	8,385	315,819	21,903
2017 size of farm:						
1 to 9 acres ..... farms	32	8	13	47	6	8
acres harvested	106	30	26	156	11	22
10 to 49 acres ..... farms	136	31	47	226	50	45
acres harvested	1,722	439	1,074	2,996	868	732
50 to 69 acres ..... farms	20	16	9	33	16	6
acres harvested	593	596	354	758	667	119
70 to 99 acres ..... farms	57	33	27	69	12	24
acres harvested	2,954	1,161	1,394	2,516	602	839
100 to 139 acres ..... farms	42	22	26	52	12	25
acres harvested	3,752	1,132	2,146	3,551	825	781
140 to 179 acres ..... farms	47	34	30	25	16	24
acres harvested	5,389	1,960	4,031	1,828	1,236	1,560
180 to 219 acres ..... farms	30	31	19	35	18	12
acres harvested	4,637	2,089	2,678	4,721	2,255	634
220 to 259 acres ..... farms	35	14	28	20	25	15
acres harvested	6,843	1,330	5,189	1,986	2,906	1,239
260 to 499 acres ..... farms	77	69	75	65	85	65
acres harvested	22,298	9,722	24,464	14,195	25,193	9,649
500 to 999 acres ..... farms	30	34	94	34	96	45
acres harvested	16,507	10,196	60,880	18,818	59,831	13,586
1,000 to 1,999 acres ..... farms	22	8	48	8	76	24
acres harvested	28,683	5,005	61,074	9,298	104,792	16,044
2,000 acres or more ..... farms	14	11	48	6	90	10
acres harvested	35,633	18,380	139,143	14,006	308,231	20,441
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	121	61	41	173	47	24
acres	534	175	167	708	193	87
10 to 19 acres ..... farms	38	27	16	91	26	29
acres	513	388	204	1,155	366	350
20 to 29 acres ..... farms	29	40	7	66	25	21
acres	680	876	180	1,521	602	493
30 to 49 acres ..... farms	34	47	26	57	29	40
acres	1,303	1,806	930	2,191	1,100	1,374
50 to 99 acres ..... farms	62	79	14	62	44	41
acres	4,093	5,665	1,043	4,393	2,997	3,049
100 to 199 acres ..... farms	58	60	50	39	42	61
acres	8,077	7,603	7,369	5,154	5,788	7,797
200 to 499 acres ..... farms	65	40	72	40	85	58
acres	19,692	11,528	24,111	11,805	30,828	16,641
500 to 999 acres ..... farms	29	14	67	11	67	14
acres	18,947	9,341	47,088	7,562	51,003	10,597
1,000 acres or more ..... farms	37	3	102	12	133	10
acres	75,878	9,207	235,102	19,488	383,598	22,541
2017 acres harvested:						
1 to 9 acres ..... farms	105	33	32	161	23	22
acres	480	153	100	667	102	75
10 to 19 acres ..... farms	51	20	17	87	14	49
acres	699	258	258	1,152	199	612
20 to 29 acres ..... farms	26	30	8	78	32	18
acres	587	693	190	1,798	696	392
30 to 49 acres ..... farms	33	42	32	62	33	25
acres	1,254	1,588	1,169	2,279	1,257	881
50 to 99 acres ..... farms	68	77	28	65	26	47
acres	4,630	5,162	1,938	4,500	1,915	3,141
100 to 199 acres ..... farms	109	51	66	75	45	69
acres	15,786	6,929	9,083	10,370	6,305	9,417
200 to 499 acres ..... farms	96	40	112	59	95	44
acres	29,062	11,718	36,870	18,812	33,031	13,851
500 to 999 acres ..... farms	22	12	80	20	74	16
acres	14,077	7,979	58,608	12,897	54,106	10,941
1,000 acres or more ..... farms	32	6	89	13	160	13
acres	62,542	17,560	194,237	22,354	409,806	26,336

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Farms ..... number, 2022	21	548	327	657	436	660
2017	23	571	357	642	431	654
acres harvested, 2022	228	351,380	37,686	175,486	255,854	176,176
2017	137	329,040	37,367	196,549	227,125	180,126
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	-	20	23	64	35	25
acres harvested	-	67	46	147	84	89
10 to 49 acres ..... farms	9	56	45	200	90	154
acres harvested	(D)	838	696	2,504	1,051	2,031
50 to 69 acres ..... farms	4	11	24	37	29	59
acres harvested	(D)	568	571	1,315	844	2,284
70 to 99 acres ..... farms	-	27	29	60	28	57
acres harvested	-	1,488	735	4,179	1,409	1,674
100 to 139 acres ..... farms	3	21	39	26	14	35
acres harvested	33	1,672	1,673	2,562	1,021	1,835
140 to 179 acres ..... farms	5	40	42	38	31	47
acres harvested	142	5,564	2,108	5,333	4,247	4,192
180 to 219 acres ..... farms	-	23	27	28	20	36
acres harvested	-	3,915	1,781	4,311	3,487	4,570
220 to 259 acres ..... farms	-	26	16	22	14	23
acres harvested	-	5,157	1,358	4,351	3,007	3,146
260 to 499 acres ..... farms	-	94	36	67	36	117
acres harvested	-	30,107	4,368	21,651	11,243	26,519
500 to 999 acres ..... farms	-	96	21	68	57	54
acres harvested	-	65,367	4,714	40,054	37,372	31,087
1,000 to 1,999 acres ..... farms	-	88	21	32	46	29
acres harvested	-	117,923	13,935	41,049	61,712	29,185
2,000 acres or more ..... farms	-	46	4	15	36	24
acres harvested	-	118,714	5,701	48,030	130,377	69,564
2017 size of farm:						
1 to 9 acres ..... farms	6	15	12	97	26	16
acres harvested	6	68	44	254	108	48
10 to 49 acres ..... farms	12	51	69	161	85	110
acres harvested	62	618	899	2,483	933	1,436
50 to 69 acres ..... farms	2	14	28	34	15	46
acres harvested	(D)	697	926	1,394	318	1,253
70 to 99 acres ..... farms	-	32	40	40	26	46
acres harvested	-	2,336	1,258	2,077	1,285	1,933
100 to 139 acres ..... farms	1	22	42	22	24	32
acres harvested	(D)	2,031	2,123	1,901	2,107	1,863
140 to 179 acres ..... farms	2	26	38	34	38	53
acres harvested	(D)	3,436	2,370	4,516	4,501	5,013
180 to 219 acres ..... farms	-	20	31	26	26	59
acres harvested	-	3,533	2,312	4,454	4,217	7,460
220 to 259 acres ..... farms	-	26	11	22	20	37
acres harvested	-	5,694	1,288	4,471	4,036	5,002
260 to 499 acres ..... farms	-	101	43	79	44	133
acres harvested	-	32,260	6,666	25,191	14,473	31,620
500 to 999 acres ..... farms	-	133	30	77	46	70
acres harvested	-	85,865	11,394	48,412	31,395	41,453
1,000 to 1,999 acres ..... farms	-	109	13	27	56	39
acres harvested	-	137,612	8,087	37,875	70,839	43,212
2,000 acres or more ..... farms	-	22	-	23	25	13
acres harvested	-	54,890	-	63,521	92,913	39,833
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	13	45	48	160	92	108
acres	33	178	151	611	368	482
10 to 19 acres ..... farms	4	28	62	81	33	88
acres	(D)	354	811	1,054	464	1,216
20 to 29 acres ..... farms	1	7	37	26	24	53
acres	(D)	164	840	584	599	1,226
30 to 49 acres ..... farms	3	15	56	37	17	63
acres	110	546	2,006	1,381	654	2,390
50 to 99 acres ..... farms	-	40	48	76	35	82
acres	-	2,906	3,360	5,580	2,643	5,774
100 to 199 acres ..... farms	-	70	35	90	46	71
acres	-	10,111	4,524	13,287	7,151	9,828
200 to 499 acres ..... farms	-	127	26	92	57	112
acres	-	40,882	7,240	30,984	17,690	33,347
500 to 999 acres ..... farms	-	90	3	54	53	37
acres	-	66,298	1,990	38,015	36,866	27,422
1,000 acres or more ..... farms	-	126	12	41	79	46
acres	-	229,941	16,764	83,990	189,419	94,491
2017 acres harvested:						
1 to 9 acres ..... farms	18	49	49	162	83	83
acres	(D)	228	(D)	623	396	368
10 to 19 acres ..... farms	3	10	54	65	22	63
acres	36	(D)	717	834	258	765
20 to 29 acres ..... farms	-	2	44	20	16	54
acres	-	(D)	1,051	446	363	1,239
30 to 49 acres ..... farms	2	16	44	59	19	50
acres	(D)	586	1,713	2,226	651	1,870
50 to 99 acres ..... farms	-	59	75	47	41	61
acres	-	4,271	5,315	3,267	3,124	4,267
100 to 199 acres ..... farms	-	51	43	62	59	112
acres	-	7,176	5,590	8,887	8,428	16,285
200 to 499 acres ..... farms	-	145	32	121	72	132
acres	-	47,676	8,824	38,724	22,598	39,621
500 to 999 acres ..... farms	-	126	12	61	45	67
acres	-	92,572	8,997	44,844	33,953	50,346
1,000 acres or more ..... farms	-	113	4	45	74	32
acres	-	176,381	(D)	96,698	157,354	65,365

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Farms ..... number, 2022	640	1,002	670	1,059	282	373
2017	634	970	769	1,079	290	376
acres harvested, 2022	356,884	347,026	312,957	341,371	281,684	17,928
2017	379,969	262,059	360,587	309,916	280,145	34,395
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	23	44	23	54	12	97
acres harvested	123	114	97	191	35	(D)
10 to 49 acres ..... farms	51	175	111	202	18	162
acres harvested	1,217	2,300	1,623	3,041	218	1,815
50 to 69 acres ..... farms	35	51	14	59	7	19
acres harvested	1,442	1,283	367	1,817	272	355
70 to 99 acres ..... farms	46	72	53	77	7	20
acres harvested	3,168	3,468	3,145	3,850	447	772
100 to 139 acres ..... farms	21	103	32	88	16	25
acres harvested	2,257	6,442	2,674	6,381	975	2,093
140 to 179 acres ..... farms	50	63	56	90	24	13
acres harvested	7,302	5,443	6,849	10,110	2,256	1,641
180 to 219 acres ..... farms	25	29	35	49	13	5
acres harvested	4,370	2,916	5,815	7,090	1,453	842
220 to 259 acres ..... farms	26	41	28	49	13	4
acres harvested	5,929	5,754	5,792	8,734	1,583	(D)
260 to 499 acres ..... farms	126	164	114	165	46	18
acres harvested	43,004	40,291	38,657	47,958	11,478	3,812
500 to 999 acres ..... farms	132	149	113	142	39	9
acres harvested	88,735	82,338	71,794	82,801	24,102	4,798
1,000 to 1,999 acres ..... farms	73	63	58	51	32	1
acres harvested	97,949	64,591	74,138	59,496	41,436	(D)
2,000 acres or more ..... farms	32	48	33	55	-	-
acres harvested	101,388	132,086	102,006	109,902	197,429	-
2017 size of farm:						
1 to 9 acres ..... farms	36	44	45	64	2	94
acres harvested	(D)	141	139	244	(D)	176
10 to 49 acres ..... farms	42	152	116	207	14	150
acres harvested	789	1,706	1,347	2,946	142	1,758
50 to 69 acres ..... farms	8	43	19	47	5	12
acres harvested	(D)	1,222	602	1,657	(D)	350
70 to 99 acres ..... farms	20	82	43	72	11	23
acres harvested	1,386	3,266	2,688	3,386	491	894
100 to 139 acres ..... farms	25	87	48	71	12	18
acres harvested	2,639	4,832	4,948	5,388	495	1,244
140 to 179 acres ..... farms	55	58	43	103	16	11
acres harvested	7,511	5,359	5,570	11,257	1,769	1,174
180 to 219 acres ..... farms	31	60	49	83	27	9
acres harvested	5,268	6,255	8,394	13,087	3,258	1,371
220 to 259 acres ..... farms	26	51	27	52	9	15
acres harvested	5,652	7,295	4,989	9,904	1,667	2,953
260 to 499 acres ..... farms	101	189	115	190	43	22
acres harvested	36,410	48,730	40,263	52,746	11,505	5,857
500 to 999 acres ..... farms	172	132	137	126	64	14
acres harvested	119,164	69,794	92,756	77,654	38,432	7,719
1,000 to 1,999 acres ..... farms	89	47	103	41	44	8
acres harvested	114,670	46,578	128,569	48,855	62,374	10,899
2,000 acres or more ..... farms	29	25	24	23	43	-
acres harvested	86,107	66,881	70,322	82,792	159,868	-
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	39	166	89	151	24	200
acres	202	710	461	734	100	663
10 to 19 acres ..... farms	21	63	39	91	9	56
acres	289	836	555	1,170	114	736
20 to 29 acres ..... farms	11	65	22	65	7	15
acres	251	1,542	531	1,548	161	(D)
30 to 49 acres ..... farms	32	89	31	81	20	30
acres	1,215	3,300	1,157	2,916	711	1,161
50 to 99 acres ..... farms	63	127	57	123	25	17
acres	4,559	9,123	4,214	9,218	1,844	1,183
100 to 199 acres ..... farms	84	124	92	169	37	34
acres	12,418	17,662	13,615	24,221	5,093	4,623
200 to 499 acres ..... farms	163	166	150	205	46	15
acres	53,564	55,251	50,421	67,558	15,107	4,959
500 to 999 acres ..... farms	123	123	102	100	33	5
acres	85,999	86,307	68,396	70,921	24,355	3,238
1,000 acres or more ..... farms	104	79	88	74	81	1
acres	198,387	172,295	173,607	163,085	234,199	(D)
2017 acres harvested:						
1 to 9 acres ..... farms	51	173	120	169	21	175
acres	178	768	527	712	(D)	645
10 to 19 acres ..... farms	13	71	26	84	9	45
acres	190	931	343	1,087	(D)	537
20 to 29 acres ..... farms	9	38	25	47	4	37
acres	194	910	591	1,080	94	827
30 to 49 acres ..... farms	19	82	28	77	7	23
acres	762	3,080	1,062	2,898	263	874
50 to 99 acres ..... farms	32	114	50	119	23	20
acres	2,422	8,175	3,635	8,754	1,558	1,373
100 to 199 acres ..... farms	93	140	122	217	35	24
acres	13,782	19,907	18,009	32,390	5,385	3,461
200 to 499 acres ..... farms	139	212	148	215	58	37
acres	47,272	67,412	51,240	69,460	17,541	10,747
500 to 999 acres ..... farms	164	95	133	100	52	8
acres	117,276	67,562	96,089	73,008	38,341	5,832
1,000 acres or more ..... farms	114	45	117	51	81	7
acres	197,893	93,314	189,091	120,527	216,780	10,099

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Farms ..... number, 2022	525	231	584	330	653	432
2017	600	261	580	274	631	510
acres harvested, 2022	117,902	47,705	64,610	42,596	349,235	53,672
2017	107,172	46,107	87,663	32,546	323,756	61,657
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	5	4	21	14	16	9
acres harvested	19	26	54	23	57	16
10 to 49 acres ..... farms	60	38	246	58	56	123
acres harvested	713	512	2,867	660	1,056	1,627
50 to 69 acres ..... farms	35	11	49	12	18	27
acres harvested	924	280	1,138	(D)	916	933
70 to 99 acres ..... farms	36	19	68	41	50	59
acres harvested	1,316	755	2,601	1,358	3,337	1,752
100 to 139 acres ..... farms	43	27	61	28	33	48
acres harvested	2,649	1,339	3,488	902	2,981	1,938
140 to 179 acres ..... farms	49	27	43	29	50	35
acres harvested	3,278	1,539	3,488	1,669	7,128	1,904
180 to 219 acres ..... farms	49	8	13	25	34	31
acres harvested	4,762	482	1,414	1,790	5,611	2,354
220 to 259 acres ..... farms	42	14	9	16	34	13
acres harvested	4,053	706	743	1,881	7,481	1,382
260 to 499 acres ..... farms	77	43	39	54	136	34
acres harvested	13,891	5,836	9,731	7,278	47,377	5,292
500 to 999 acres ..... farms	102	26	21	44	105	46
acres harvested	44,586	6,827	12,444	14,861	64,819	22,841
1,000 to 1,999 acres ..... farms	17	8	8	7	89	3
acres harvested	18,726	3,658	8,539	5,385	116,937	2,043
2,000 acres or more ..... farms	10	6	6	2	32	4
acres harvested	22,985	25,745	18,103	(D)	91,535	11,590
2017 size of farm:						
1 to 9 acres ..... farms	24	10	19	2	27	9
acres harvested	114	(D)	93	(D)	73	20
10 to 49 acres ..... farms	57	31	199	48	47	132
acres harvested	615	402	2,659	677	1,000	1,958
50 to 69 acres ..... farms	23	9	47	12	24	32
acres harvested	382	323	1,191	(D)	1,168	833
70 to 99 acres ..... farms	51	34	73	40	29	77
acres harvested	2,073	1,100	2,520	1,154	1,966	2,737
100 to 139 acres ..... farms	32	26	66	28	33	36
acres harvested	1,655	895	3,309	1,158	2,837	1,932
140 to 179 acres ..... farms	47	39	32	34	58	49
acres harvested	2,789	1,885	1,759	2,118	8,301	3,073
180 to 219 acres ..... farms	39	16	20	18	22	31
acres harvested	4,559	850	2,182	1,554	3,925	2,708
220 to 259 acres ..... farms	73	12	11	13	32	24
acres harvested	7,347	688	1,309	1,336	7,126	2,315
260 to 499 acres ..... farms	145	53	47	54	120	78
acres harvested	26,959	7,265	9,299	8,470	39,467	15,076
500 to 999 acres ..... farms	89	23	39	17	135	32
acres harvested	34,332	7,564	22,349	(D)	90,719	13,886
1,000 to 1,999 acres ..... farms	17	2	23	5	82	3
acres harvested	18,347	(D)	29,867	3,424	107,323	1,616
2,000 acres or more ..... farms	3	6	4	3	22	7
acres harvested	8,000	23,066	11,126	(D)	59,851	15,503
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	61	23	144	57	39	59
acres	290	102	614	208	159	244
10 to 19 acres ..... farms	37	40	133	39	15	100
acres	524	510	1,659	522	197	1,316
20 to 29 acres ..... farms	31	20	75	33	9	55
acres	744	467	1,693	742	225	1,294
30 to 49 acres ..... farms	57	31	58	47	23	55
acres	2,211	1,166	2,143	1,744	857	2,004
50 to 99 acres ..... farms	90	39	65	54	75	59
acres	6,414	2,814	4,557	3,421	5,441	3,999
100 to 199 acres ..... farms	97	37	44	46	105	44
acres	13,324	4,700	6,192	6,209	15,101	5,964
200 to 499 acres ..... farms	97	25	35	36	182	28
acres	31,381	6,452	10,385	10,161	61,325	8,519
500 to 999 acres ..... farms	38	10	21	13	99	29
acres	28,797	5,749	14,895	9,290	71,757	19,525
1,000 acres or more ..... farms	17	6	9	5	106	3
acres	34,217	25,745	22,472	10,299	194,173	10,807
2017 acres harvested:						
1 to 9 acres ..... farms	93	32	110	32	45	63
acres	419	135	473	142	169	286
10 to 19 acres ..... farms	37	29	116	34	12	72
acres	514	370	1,533	426	160	949
20 to 29 acres ..... farms	33	35	78	28	6	67
acres	769	792	1,790	628	129	1,491
30 to 49 acres ..... farms	49	49	74	49	30	97
acres	1,795	1,721	2,739	1,827	1,135	3,681
50 to 99 acres ..... farms	95	54	76	48	56	77
acres	7,062	3,807	5,353	3,121	3,937	5,205
100 to 199 acres ..... farms	132	25	32	41	93	64
acres	19,254	3,542	4,459	5,479	13,610	8,845
200 to 499 acres ..... farms	119	22	34	36	165	49
acres	37,670	6,321	9,845	9,599	52,850	15,219
500 to 999 acres ..... farms	28	9	36	3	127	15
acres	17,851	6,229	23,178	2,090	91,322	10,881
1,000 acres or more ..... farms	14	6	24	3	97	6
acres	21,838	23,190	38,293	9,234	160,444	15,100

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Farms ..... number, 2022	728	342	147	521	19	126
2017	702	302	145	615	33	101
acres harvested, 2022	396,375	418,170	23,979	340,540	144	57,749
2017	361,522	329,127	23,961	343,238	1,010	56,367
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	12	-	-	13	6	-
acres harvested	32	-	-	43	(D)	-
10 to 49 acres ..... farms	145	17	15	47	10	9
acres harvested	1,945	302	224	741	94	95
50 to 69 acres ..... farms	39	-	7	12	-	3
acres harvested	968	-	(D)	556	-	160
70 to 99 acres ..... farms	45	13	13	20	1	10
acres harvested	1,656	661	408	1,072	(D)	205
100 to 139 acres ..... farms	57	10	18	14	1	15
acres harvested	4,070	678	902	1,145	(D)	744
140 to 179 acres ..... farms	65	14	13	37	1	6
acres harvested	6,530	1,380	562	4,808	(D)	448
180 to 219 acres ..... farms	27	7	7	28	-	9
acres harvested	3,189	746	660	3,899	-	1,053
220 to 259 acres ..... farms	32	8	9	12	-	4
acres harvested	4,940	1,116	946	2,470	-	444
260 to 499 acres ..... farms	82	43	29	106	-	27
acres harvested	22,807	5,455	3,887	30,790	-	3,129
500 to 999 acres ..... farms	100	57	28	92	-	20
acres harvested	54,923	21,861	9,839	54,678	-	6,373
1,000 to 1,999 acres ..... farms	63	73	6	94	-	10
acres harvested	84,449	76,478	(D)	122,296	-	5,095
2,000 acres or more ..... farms	61	100	2	46	-	13
acres harvested	210,866	309,493	(D)	118,042	-	40,003
2017 size of farm:						
1 to 9 acres ..... farms	34	1	2	21	5	-
acres harvested	145	(D)	(D)	80	5	-
10 to 49 acres ..... farms	100	13	5	41	16	9
acres harvested	1,237	223	145	687	156	147
50 to 69 acres ..... farms	39	3	11	30	1	-
acres harvested	1,396	(D)	235	1,159	(D)	-
70 to 99 acres ..... farms	37	11	17	23	4	2
acres harvested	1,381	712	556	1,590	(D)	(D)
100 to 139 acres ..... farms	65	7	23	16	2	3
acres harvested	5,250	463	1,163	1,056	(D)	(D)
140 to 179 acres ..... farms	36	9	18	24	3	6
acres harvested	3,666	1,133	862	3,180	216	511
180 to 219 acres ..... farms	39	14	10	35	-	8
acres harvested	5,727	1,464	772	4,638	-	(D)
220 to 259 acres ..... farms	27	6	5	25	-	6
acres harvested	5,334	948	(D)	4,422	-	(D)
260 to 499 acres ..... farms	112	41	25	121	1	22
acres harvested	31,916	7,550	4,070	38,117	(D)	(D)
500 to 999 acres ..... farms	103	53	18	154	1	26
acres harvested	63,208	24,940	6,776	97,207	(D)	9,526
1,000 to 1,999 acres ..... farms	68	69	11	94	-	10
acres harvested	84,221	82,189	8,976	116,831	-	11,257
2,000 acres or more ..... farms	42	75	-	31	-	9
acres harvested	158,041	209,382	-	74,271	-	30,030
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	101	8	6	42	16	6
acres	441	42	15	200	73	35
10 to 19 acres ..... farms	88	23	19	15	1	13
acres	1,143	319	220	202	(D)	180
20 to 29 acres ..... farms	49	15	12	13	1	11
acres	1,153	345	(D)	304	(D)	240
30 to 49 acres ..... farms	45	18	22	13	1	9
acres	1,720	628	736	522	(D)	323
50 to 99 acres ..... farms	48	27	26	42	-	22
acres	3,503	1,883	1,644	2,819	-	1,618
100 to 199 acres ..... farms	100	32	29	68	-	20
acres	13,927	4,720	3,895	10,254	-	2,689
200 to 499 acres ..... farms	107	33	22	123	-	21
acres	35,893	9,612	7,140	40,792	-	5,935
500 to 999 acres ..... farms	72	36	8	82	-	12
acres	48,416	24,159	5,248	59,369	-	6,843
1,000 acres or more ..... farms	118	150	3	123	-	12
acres	290,179	376,462	(D)	226,078	-	39,886
2017 acres harvested:						
1 to 9 acres ..... farms	97	4	11	49	16	5
acres	465	22	25	212	(D)	17
10 to 19 acres ..... farms	55	9	11	17	5	5
acres	769	132	(D)	184	70	75
20 to 29 acres ..... farms	34	9	9	9	3	4
acres	801	200	196	227	67	96
30 to 49 acres ..... farms	37	13	18	20	4	9
acres	1,347	511	635	730	(D)	328
50 to 99 acres ..... farms	58	38	39	54	-	12
acres	4,042	2,714	2,508	3,858	-	883
100 to 199 acres ..... farms	102	26	21	51	4	20
acres	14,405	3,795	2,566	7,447	(D)	2,808
200 to 499 acres ..... farms	127	39	23	174	1	22
acres	41,230	12,082	(D)	56,531	(D)	7,799
500 to 999 acres ..... farms	93	46	11	133	-	9
acres	64,553	31,211	7,618	97,458	-	5,827
1,000 acres or more ..... farms	99	118	2	108	-	15
acres	233,910	278,460	(D)	176,591	-	38,534

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Farms ..... number, 2022	523	351	639	570	197	717
2017	602	443	694	644	240	632
acres harvested, 2022	159,857	153,500	360,873	218,209	171,244	646,007
2017	203,903	238,313	347,042	237,904	173,972	680,360
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	47	8	15	40	2	6
acres harvested	146	(D)	61	113	(D)	6
10 to 49 acres ..... farms	105	40	38	133	8	21
acres harvested	1,386	472	476	2,020	233	485
50 to 69 acres ..... farms	33	2	13	42	7	11
acres harvested	999	(D)	702	1,465	(D)	342
70 to 99 acres ..... farms	45	12	44	52	12	22
acres harvested	2,305	870	2,612	3,146	646	674
100 to 139 acres ..... farms	53	13	25	47	4	28
acres harvested	4,549	968	2,061	3,820	353	1,357
140 to 179 acres ..... farms	36	37	45	43	13	52
acres harvested	3,773	4,555	5,945	5,120	1,049	3,848
180 to 219 acres ..... farms	25	22	19	18	8	21
acres harvested	3,375	2,804	2,971	2,864	661	2,225
220 to 259 acres ..... farms	17	15	22	16	9	18
acres harvested	2,650	2,762	4,347	3,000	1,180	2,324
260 to 499 acres ..... farms	68	83	145	60	42	129
acres harvested	20,672	23,390	44,759	18,322	9,516	29,063
500 to 999 acres ..... farms	48	74	160	47	30	153
acres harvested	28,429	42,135	105,303	31,056	16,412	68,386
1,000 to 1,999 acres ..... farms	30	35	77	31	29	138
acres harvested	39,468	42,493	93,403	39,317	33,507	156,661
2,000 acres or more ..... farms	16	10	36	41	33	118
acres harvested	52,105	32,984	98,233	107,966	107,477	380,636
2017 size of farm:						
1 to 9 acres ..... farms	49	11	27	28	11	6
acres harvested	175	44	103	91	25	30
10 to 49 acres ..... farms	128	30	44	142	21	21
acres harvested	1,713	421	563	2,019	407	355
50 to 69 acres ..... farms	34	10	20	35	9	3
acres harvested	804	345	882	1,410	201	80
70 to 99 acres ..... farms	52	27	43	40	6	36
acres harvested	2,301	1,436	3,129	2,458	250	1,750
100 to 139 acres ..... farms	42	23	14	33	14	26
acres harvested	3,049	1,830	1,078	2,516	428	1,734
140 to 179 acres ..... farms	31	36	37	59	12	29
acres harvested	3,410	3,466	4,239	7,547	634	2,566
180 to 219 acres ..... farms	40	15	14	36	7	17
acres harvested	6,136	2,155	2,336	5,826	1,085	1,878
220 to 259 acres ..... farms	23	18	49	30	22	27
acres harvested	3,951	2,962	9,520	6,296	3,098	4,725
260 to 499 acres ..... farms	87	90	151	88	35	109
acres harvested	25,980	23,479	47,444	25,608	7,423	25,759
500 to 999 acres ..... farms	53	94	188	84	41	123
acres harvested	34,484	54,610	116,772	55,034	20,091	60,628
1,000 to 1,999 acres ..... farms	48	72	92	45	31	106
acres harvested	62,973	92,651	110,707	61,698	31,939	136,873
2,000 acres or more ..... farms	15	17	15	24	31	129
acres harvested	58,927	54,914	50,269	67,401	108,391	443,982
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	111	29	38	98	10	24
acres	449	92	167	420	62	90
10 to 19 acres ..... farms	50	17	21	53	2	18
acres	627	209	282	710	(D)	222
20 to 29 acres ..... farms	19	12	14	38	7	25
acres	422	292	320	870	(D)	565
30 to 49 acres ..... farms	36	11	20	41	20	54
acres	1,341	413	819	1,544	744	2,073
50 to 99 acres ..... farms	59	27	49	75	23	77
acres	4,175	1,992	3,601	5,263	1,736	5,412
100 to 199 acres ..... farms	84	70	85	75	13	67
acres	10,903	10,506	12,455	9,968	1,709	9,663
200 to 499 acres ..... farms	78	84	151	76	42	132
acres	24,721	27,764	49,314	23,261	12,169	42,666
500 to 999 acres ..... farms	43	62	164	45	33	125
acres	28,486	41,626	116,147	31,605	25,555	85,017
1,000 acres or more ..... farms	43	39	97	69	47	195
acres	88,733	70,606	177,768	144,568	129,089	500,299
2017 acres harvested:						
1 to 9 acres ..... farms	131	28	55	89	34	17
acres	581	126	237	393	161	95
10 to 19 acres ..... farms	52	28	16	58	10	29
acres	729	374	205	770	136	388
20 to 29 acres ..... farms	34	9	6	31	10	18
acres	773	208	147	714	231	428
30 to 49 acres ..... farms	44	14	22	36	15	34
acres	1,658	520	832	1,407	535	1,266
50 to 99 acres ..... farms	48	46	60	66	19	52
acres	3,502	3,321	4,488	4,732	1,279	3,783
100 to 199 acres ..... farms	89	59	62	107	21	56
acres	13,035	8,455	8,668	16,001	2,950	7,897
200 to 499 acres ..... farms	97	98	206	117	53	133
acres	30,746	30,998	66,051	35,244	15,787	41,354
500 to 999 acres ..... farms	52	81	175	72	28	80
acres	37,999	55,111	116,981	50,526	20,580	57,877
1,000 acres or more ..... farms	55	80	92	68	50	213
acres	114,880	139,200	149,433	128,117	132,313	567,272

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Farms ..... number, 2022	650	602	488	1,288	716	608
2017	725	665	569	1,473	804	651
acres harvested, 2022	422,048	242,801	55,469	190,224	333,878	298,402
2017	427,112	241,359	81,641	210,362	406,191	346,082
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	19	42	9	29	47	25
acres harvested	59	111	22	71	188	74
10 to 49 acres ..... farms	61	90	154	238	126	56
acres harvested	822	1,368	2,305	3,842	1,834	591
50 to 69 acres ..... farms	7	33	36	60	18	21
acres harvested	270	834	834	1,427	526	966
70 to 99 acres ..... farms	50	54	52	135	32	52
acres harvested	3,815	2,132	1,682	4,988	1,864	3,635
100 to 139 acres ..... farms	36	41	46	124	56	39
acres harvested	3,573	3,322	2,230	6,538	5,393	3,717
140 to 179 acres ..... farms	41	57	35	147	38	38
acres harvested	5,408	6,169	2,633	11,500	5,158	4,774
180 to 219 acres ..... farms	32	31	35	89	21	20
acres harvested	5,985	4,387	4,395	9,110	3,623	3,242
220 to 259 acres ..... farms	34	29	22	73	40	28
acres harvested	7,691	4,965	2,862	8,723	8,370	5,339
260 to 499 acres ..... farms	115	83	58	232	153	102
acres harvested	38,674	23,462	10,744	43,306	49,262	33,212
500 to 999 acres ..... farms	109	68	33	110	72	131
acres harvested	70,322	41,799	15,390	43,353	42,853	83,760
1,000 to 1,999 acres ..... farms	83	44	5	41	63	74
acres harvested	107,713	54,794	5,787	32,980	78,911	91,374
2,000 acres or more ..... farms	63	30	3	10	50	22
acres harvested	177,716	99,458	6,585	24,386	135,896	67,718
2017 size of farm:						
1 to 9 acres ..... farms	26	42	17	39	60	16
acres harvested	71	148	(D)	172	249	46
10 to 49 acres ..... farms	45	118	163	260	120	62
acres harvested	915	1,571	2,395	4,165	1,670	1,008
50 to 69 acres ..... farms	9	31	29	65	21	11
acres harvested	339	945	813	2,088	806	470
70 to 99 acres ..... farms	45	57	65	179	36	37
acres harvested	3,361	2,964	2,188	7,557	2,249	2,560
100 to 139 acres ..... farms	56	44	63	136	38	19
acres harvested	5,383	2,971	3,037	7,349	3,677	1,673
140 to 179 acres ..... farms	45	36	52	140	50	49
acres harvested	6,502	4,211	3,747	9,689	6,185	6,152
180 to 219 acres ..... farms	35	33	32	106	38	10
acres harvested	6,448	4,893	3,538	9,818	6,043	1,226
220 to 259 acres ..... farms	50	42	16	69	60	34
acres harvested	11,413	7,467	2,088	8,038	12,707	6,343
260 to 499 acres ..... farms	119	110	66	326	129	144
acres harvested	41,955	31,152	13,455	63,154	40,016	46,487
500 to 999 acres ..... farms	146	77	47	112	118	148
acres harvested	100,304	47,694	25,344	46,996	78,840	97,389
1,000 to 1,999 acres ..... farms	121	53	17	32	91	96
acres harvested	163,502	67,164	20,533	30,766	118,015	121,488
2,000 acres or more ..... farms	28	22	2	9	43	25
acres harvested	86,919	70,179	(D)	20,570	135,734	61,240
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	42	85	77	132	103	59
acres	164	302	400	605	413	200
10 to 19 acres ..... farms	24	70	90	167	46	21
acres	285	884	1,208	2,198	572	280
20 to 29 acres ..... farms	14	33	65	125	28	8
acres	316	750	1,473	2,846	653	183
30 to 49 acres ..... farms	9	26	58	164	30	17
acres	335	994	2,173	6,136	1,096	629
50 to 99 acres ..... farms	66	62	56	212	45	76
acres	4,941	4,393	3,683	15,424	3,434	5,617
100 to 199 acres ..... farms	88	96	72	230	103	84
acres	12,662	13,367	10,155	31,504	13,892	11,627
200 to 499 acres ..... farms	173	104	51	184	191	138
acres	56,426	31,766	15,387	55,664	60,858	46,073
500 to 999 acres ..... farms	92	59	12	48	69	123
acres	63,972	40,814	8,868	31,923	47,766	85,714
1,000 acres or more ..... farms	142	67	7	26	101	82
acres	282,947	149,531	12,122	43,924	205,194	148,079
2017 acres harvested:						
1 to 9 acres ..... farms	38	104	77	137	116	50
acres	133	434	355	686	526	214
10 to 19 acres ..... farms	19	52	91	167	45	25
acres	261	681	1,242	2,104	578	338
20 to 29 acres ..... farms	12	43	77	150	21	5
acres	288	931	1,701	3,377	493	126
30 to 49 acres ..... farms	19	37	71	202	31	20
acres	746	1,353	2,544	7,539	1,081	805
50 to 99 acres ..... farms	59	68	77	245	63	54
acres	4,648	4,933	5,205	17,359	4,713	4,086
100 to 199 acres ..... farms	104	93	74	268	108	77
acres	14,595	14,004	10,325	36,394	15,526	11,117
200 to 499 acres ..... farms	198	132	54	230	176	164
acres	64,289	40,514	17,086	68,483	53,517	54,112
500 to 999 acres ..... farms	130	74	33	50	119	146
acres	93,793	52,996	21,844	33,461	84,662	102,052
1,000 acres or more ..... farms	146	62	15	24	125	110
acres	248,359	125,513	21,339	40,959	245,095	173,232

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Farms ..... number, 2022	510	716	344	782	1,598	213
2017	600	690	395	773	1,665	286
acres harvested, 2022	253,410	334,873	428,145	238,968	472,434	187,360
2017	238,885	380,893	474,773	216,630	502,572	218,152
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	19	31	3	23	26	6
acres harvested	58	107	3	66	63	12
10 to 49 acres ..... farms	70	46	25	224	222	17
acres harvested	1,086	580	353	2,682	3,108	211
50 to 69 acres ..... farms	21	19	12	48	79	1
acres harvested	901	841	243	1,494	1,877	(D)
70 to 99 acres ..... farms	31	52	15	56	143	8
acres harvested	2,203	3,874	534	2,534	4,607	458
100 to 139 acres ..... farms	26	33	4	52	154	4
acres harvested	2,437	3,228	353	2,900	9,259	(D)
140 to 179 acres ..... farms	38	71	16	64	151	15
acres harvested	5,027	10,084	1,586	6,432	10,236	1,382
180 to 219 acres ..... farms	36	30	17	37	78	12
acres harvested	6,520	5,383	3,185	5,002	7,643	1,058
220 to 259 acres ..... farms	32	48	3	25	59	6
acres harvested	5,674	9,780	421	4,344	6,694	835
260 to 499 acres ..... farms	99	154	39	109	307	33
acres harvested	31,738	51,717	9,506	30,072	61,365	6,821
500 to 999 acres ..... farms	74	122	57	65	218	38
acres harvested	49,357	77,064	34,605	37,832	107,898	18,603
1,000 to 1,999 acres ..... farms	18	81	67	45	114	32
acres harvested	22,868	100,046	85,789	50,577	117,223	34,447
2,000 acres or more ..... farms	46	29	86	34	47	41
acres harvested	125,541	72,169	291,567	95,033	142,461	123,434
2017 size of farm:						
1 to 9 acres ..... farms	21	15	2	31	38	9
acres harvested	67	71	(D)	79	91	23
10 to 49 acres ..... farms	74	63	25	189	171	24
acres harvested	1,213	1,155	319	2,276	2,617	480
50 to 69 acres ..... farms	17	10	13	52	123	5
acres harvested	756	468	(D)	2,034	3,099	152
70 to 99 acres ..... farms	25	28	14	50	179	9
acres harvested	1,647	1,893	782	2,445	6,507	510
100 to 139 acres ..... farms	31	17	16	52	138	18
acres harvested	3,544	1,609	1,041	3,121	6,727	1,428
140 to 179 acres ..... farms	56	57	25	46	133	21
acres harvested	7,839	7,988	3,259	4,680	9,182	1,953
180 to 219 acres ..... farms	51	14	9	46	101	9
acres harvested	9,001	2,535	1,624	5,977	11,864	1,261
220 to 259 acres ..... farms	24	29	-	34	88	6
acres harvested	4,860	6,404	-	5,989	9,973	889
260 to 499 acres ..... farms	153	188	46	122	301	48
acres harvested	51,795	63,464	13,171	33,188	64,670	11,826
500 to 999 acres ..... farms	96	136	64	80	212	53
acres harvested	62,223	90,306	40,186	47,269	113,733	29,318
1,000 to 1,999 acres ..... farms	27	107	89	48	139	42
acres harvested	31,152	141,732	112,449	52,386	154,210	45,856
2,000 acres or more ..... farms	25	26	92	23	42	42
acres harvested	64,788	63,268	301,758	57,186	119,899	124,456
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	53	55	22	144	176	15
acres	177	238	123	564	714	36
10 to 19 acres ..... farms	19	26	11	104	150	7
acres	226	392	135	1,413	2,040	80
20 to 29 acres ..... farms	19	4	14	51	127	7
acres	406	80	319	1,184	2,936	172
30 to 49 acres ..... farms	21	12	10	73	198	10
acres	793	483	376	2,660	7,459	386
50 to 99 acres ..... farms	59	78	14	58	186	26
acres	4,212	5,985	814	4,231	12,855	1,911
100 to 199 acres ..... farms	78	121	35	102	233	30
acres	11,947	18,291	5,478	14,849	31,604	4,552
200 to 499 acres ..... farms	135	207	41	122	269	34
acres	43,085	68,285	11,688	36,988	88,368	11,469
500 to 999 acres ..... farms	63	117	53	64	153	28
acres	44,635	81,729	38,093	44,968	103,146	20,759
1,000 acres or more ..... farms	63	96	144	64	106	56
acres	147,929	159,390	371,119	132,111	223,312	147,995
2017 acres harvested:						
1 to 9 acres ..... farms	62	28	23	119	174	15
acres	215	134	134	474	771	35
10 to 19 acres ..... farms	12	26	10	91	176	12
acres	171	311	117	1,248	2,446	149
20 to 29 acres ..... farms	11	12	11	48	109	5
acres	265	267	251	1,133	2,489	106
30 to 49 acres ..... farms	27	31	12	60	161	20
acres	1,008	1,188	442	2,222	6,046	759
50 to 99 acres ..... farms	43	36	16	83	241	32
acres	3,093	2,525	1,089	5,890	16,555	2,436
100 to 199 acres ..... farms	116	82	42	100	241	35
acres	17,219	12,201	6,248	14,207	34,320	4,741
200 to 499 acres ..... farms	194	224	51	150	271	49
acres	63,261	76,227	15,681	45,668	86,682	16,873
500 to 999 acres ..... farms	91	126	59	65	159	57
acres	62,615	90,255	42,657	47,974	111,983	41,755
1,000 acres or more ..... farms	44	125	171	57	133	61
acres	91,038	197,785	408,154	97,814	241,280	151,298

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Farms ..... number, 2022	620	412	890	470	40	213
2017	675	451	864	488	52	195
acres harvested, 2022	75,570	181,999	904,276	220,081	108	154,337
2017	69,230	198,596	840,247	246,281	373	167,953
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	22	11	12	8	35	-
acres harvested	36	24	57	25	57	-
10 to 49 acres ..... farms	96	63	65	51	1	11
acres harvested	1,382	930	1,078	880	(D)	(D)
50 to 69 acres ..... farms	32	21	11	26	-	2
acres harvested	862	574	475	941	-	(D)
70 to 99 acres ..... farms	81	18	40	27	-	15
acres harvested	2,679	931	2,355	1,027	-	687
100 to 139 acres ..... farms	75	14	57	27	2	14
acres harvested	3,334	1,028	4,459	1,553	(D)	1,546
140 to 179 acres ..... farms	64	25	49	37	2	8
acres harvested	3,909	3,309	4,749	2,877	(D)	494
180 to 219 acres ..... farms	47	17	28	31	-	6
acres harvested	2,771	2,541	3,301	2,785	-	229
220 to 259 acres ..... farms	33	24	28	30	-	6
acres harvested	2,858	4,605	3,828	4,992	-	844
260 to 499 acres ..... farms	87	90	133	92	-	47
acres harvested	14,539	26,277	33,933	23,599	-	12,471
500 to 999 acres ..... farms	59	76	130	69	-	45
acres harvested	19,353	44,695	78,958	41,208	-	20,696
1,000 to 1,999 acres ..... farms	20	28	167	36	-	42
acres harvested	14,806	30,076	218,260	45,210	-	57,665
2,000 acres or more ..... farms	4	25	170	36	-	17
acres harvested	9,041	67,009	552,823	94,984	-	59,496
2017 size of farm:						
1 to 9 acres ..... farms	25	32	10	5	39	5
acres harvested	(D)	96	42	31	(D)	21
10 to 49 acres ..... farms	119	54	65	75	11	11
acres harvested	1,924	858	1,195	942	66	68
50 to 69 acres ..... farms	19	11	21	16	-	8
acres harvested	622	373	852	439	-	229
70 to 99 acres ..... farms	99	28	36	20	-	6
acres harvested	3,388	1,411	1,915	832	-	195
100 to 139 acres ..... farms	96	18	40	22	-	9
acres harvested	3,807	1,758	2,974	1,444	-	874
140 to 179 acres ..... farms	71	47	49	18	1	9
acres harvested	4,565	6,012	4,549	1,680	(D)	763
180 to 219 acres ..... farms	42	14	29	27	1	4
acres harvested	2,965	2,484	4,233	3,558	(D)	653
220 to 259 acres ..... farms	39	10	33	25	-	5
acres harvested	3,465	2,038	5,678	3,293	-	770
260 to 499 acres ..... farms	97	95	139	105	-	34
acres harvested	15,595	29,798	30,541	24,792	-	7,698
500 to 999 acres ..... farms	53	89	126	75	-	52
acres harvested	17,182	54,596	72,663	40,954	-	26,930
1,000 to 1,999 acres ..... farms	12	30	156	62	-	25
acres harvested	10,147	33,370	202,564	70,420	-	31,884
2,000 acres or more ..... farms	3	23	160	38	-	27
acres harvested	(D)	65,802	513,041	97,896	-	97,868
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	77	44	31	38	38	6
acres	248	220	132	183	60	36
10 to 19 acres ..... farms	99	32	44	37	1	13
acres	1,257	433	597	492	(D)	207
20 to 29 acres ..... farms	48	21	22	29	-	10
acres	1,065	468	548	666	-	219
30 to 49 acres ..... farms	95	11	56	34	1	6
acres	3,510	415	1,953	1,263	(D)	227
50 to 99 acres ..... farms	121	33	77	58	-	12
acres	8,288	2,307	5,718	4,093	-	862
100 to 199 acres ..... farms	80	49	110	54	-	35
acres	10,721	7,380	14,860	7,614	-	4,949
200 to 499 acres ..... farms	72	109	124	105	-	48
acres	23,041	33,751	41,937	34,235	-	14,923
500 to 999 acres ..... farms	20	68	120	53	-	24
acres	12,511	45,591	85,181	37,320	-	15,753
1,000 acres or more ..... farms	8	45	306	62	-	59
acres	14,929	91,434	753,350	134,215	-	117,161
2017 acres harvested:						
1 to 9 acres ..... farms	71	49	43	50	49	15
acres	334	181	205	235	117	67
10 to 19 acres ..... farms	81	27	31	35	1	4
acres	1,090	379	397	490	(D)	46
20 to 29 acres ..... farms	96	19	34	26	-	7
acres	2,123	443	796	621	-	159
30 to 49 acres ..... farms	127	12	46	25	-	11
acres	4,818	449	1,782	1,003	-	434
50 to 99 acres ..... farms	128	34	69	34	-	16
acres	8,633	2,241	4,868	2,314	-	1,129
100 to 199 acres ..... farms	76	77	108	78	2	24
acres	10,556	11,423	15,384	12,044	(D)	3,412
200 to 499 acres ..... farms	80	108	138	98	-	36
acres	23,974	36,165	42,292	30,410	-	11,336
500 to 999 acres ..... farms	10	76	104	57	-	35
acres	6,701	50,247	76,004	41,036	-	25,318
1,000 acres or more ..... farms	6	49	291	85	-	47
acres	11,001	97,068	698,519	158,128	-	126,052

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
Farms ..... number, 2022	983	734	818	443	490	635
2017	890	773	858	584	490	603
acres harvested, 2022	509,922	571,420	197,825	235,233	339,987	70,850
2017	474,337	579,341	177,101	259,762	361,883	55,785
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	34	8	49	21	9	19
acres harvested	86	30	164	59	52	31
10 to 49 acres ..... farms	91	92	250	57	25	147
acres harvested	1,847	1,358	3,495	973	465	1,494
50 to 69 acres ..... farms	20	23	59	16	7	22
acres harvested	851	964	2,060	716	181	(D)
70 to 99 acres ..... farms	46	32	75	26	20	55
acres harvested	3,484	2,116	4,025	1,379	889	1,616
100 to 139 acres ..... farms	54	33	72	24	33	77
acres harvested	5,873	3,469	6,362	2,581	2,016	3,899
140 to 179 acres ..... farms	66	44	56	24	32	66
acres harvested	9,244	5,935	6,506	2,831	2,236	3,802
180 to 219 acres ..... farms	29	29	37	22	20	55
acres harvested	5,114	5,055	5,684	3,580	1,686	3,710
220 to 259 acres ..... farms	51	30	25	20	16	42
acres harvested	10,549	6,011	4,200	4,127	1,514	4,189
260 to 499 acres ..... farms	222	107	89	91	90	85
acres harvested	75,067	34,960	26,441	30,755	15,335	14,890
500 to 999 acres ..... farms	234	148	52	74	89	43
acres harvested	160,145	99,753	27,046	49,526	30,880	11,194
1,000 to 1,999 acres ..... farms	90	111	26	42	85	21
acres harvested	118,416	143,372	33,542	56,812	76,785	17,432
2,000 acres or more ..... farms	46	77	28	26	64	3
acres harvested	119,246	268,397	78,300	81,894	207,948	(D)
2017 size of farm:						
1 to 9 acres ..... farms	27	8	50	36	15	27
acres harvested	79	15	148	123	59	62
10 to 49 acres ..... farms	75	76	237	58	42	95
acres harvested	1,497	1,426	3,618	975	573	1,009
50 to 69 acres ..... farms	19	17	59	11	10	38
acres harvested	905	567	1,951	495	253	(D)
70 to 99 acres ..... farms	37	31	62	26	19	77
acres harvested	2,291	1,904	3,435	1,724	687	2,780
100 to 139 acres ..... farms	25	40	72	22	30	94
acres harvested	2,599	4,077	5,891	2,203	2,287	3,703
140 to 179 acres ..... farms	55	33	89	44	32	53
acres harvested	7,969	4,536	10,560	5,823	3,243	2,200
180 to 219 acres ..... farms	23	42	36	22	14	50
acres harvested	4,066	6,525	5,922	3,595	1,199	4,386
220 to 259 acres ..... farms	41	38	30	42	21	44
acres harvested	8,342	7,872	6,625	8,289	2,013	4,438
260 to 499 acres ..... farms	208	138	115	140	76	79
acres harvested	69,072	47,638	34,407	45,431	14,472	11,483
500 to 999 acres ..... farms	246	152	71	118	100	32
acres harvested	165,515	100,351	42,304	74,717	35,787	7,129
1,000 to 1,999 acres ..... farms	96	129	29	41	61	11
acres harvested	116,345	170,010	34,843	50,555	64,312	9,157
2,000 acres or more ..... farms	38	69	8	24	70	3
acres harvested	95,657	234,420	27,397	65,832	236,998	(D)
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	61	54	181	43	22	128
acres	222	246	752	151	122	329
10 to 19 acres ..... farms	27	23	82	23	25	77
acres	385	308	1,080	280	314	1,046
20 to 29 acres ..... farms	19	22	54	6	21	53
acres	446	497	1,230	137	478	1,163
30 to 49 acres ..... farms	38	25	71	30	35	97
acres	1,462	908	2,725	1,135	1,320	3,638
50 to 99 acres ..... farms	74	57	112	35	73	107
acres	5,593	3,938	7,822	2,506	4,812	7,537
100 to 199 acres ..... farms	135	95	116	59	53	83
acres	19,406	13,797	16,063	8,404	7,412	10,655
200 to 499 acres ..... farms	285	140	120	115	118	68
acres	95,188	45,476	37,906	38,701	37,368	20,041
500 to 999 acres ..... farms	211	149	30	68	39	11
acres	152,416	109,298	19,005	48,415	26,465	7,230
1,000 acres or more ..... farms	133	169	52	64	104	11
acres	234,804	396,952	111,242	135,504	261,696	19,211
2017 acres harvested:						
1 to 9 acres ..... farms	57	30	144	56	43	110
acres	236	129	623	222	207	338
10 to 19 acres ..... farms	25	24	96	25	18	66
acres	339	306	1,257	319	215	804
20 to 29 acres ..... farms	7	32	52	8	23	59
acres	179	791	1,212	179	517	1,301
30 to 49 acres ..... farms	29	26	82	23	30	96
acres	1,127	956	2,937	886	1,145	3,526
50 to 99 acres ..... farms	51	39	95	39	62	127
acres	3,558	2,820	6,784	2,860	4,215	8,536
100 to 199 acres ..... farms	106	108	146	84	76	87
acres	15,442	15,601	20,007	11,991	10,545	11,054
200 to 499 acres ..... farms	259	177	154	180	88	46
acres	85,421	58,316	48,204	58,328	28,887	12,676
500 to 999 acres ..... farms	237	157	59	110	53	6
acres	170,179	113,021	39,144	73,256	39,206	4,476
1,000 acres or more ..... farms	119	180	30	59	97	6
acres	197,856	387,401	56,933	111,721	276,946	13,074

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Farms ..... number, 2022	442	325	670	2,118	442	326
2017	534	321	708	2,307	469	358
acres harvested, 2022	81,167	57,043	333,743	458,204	215,514	283,965
2017	91,052	71,515	315,230	462,585	221,014	289,168
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	35	27	44	65	26	11
acres harvested	95	79	113	218	74	15
10 to 49 acres ..... farms	183	111	100	445	92	29
acres harvested	2,080	1,336	1,754	7,024	1,003	610
50 to 69 acres ..... farms	28	35	23	119	34	7
acres harvested	910	876	562	3,779	1,475	186
70 to 99 acres ..... farms	38	36	43	153	26	18
acres harvested	1,934	1,175	2,136	7,469	1,379	878
100 to 139 acres ..... farms	32	21	54	196	27	17
acres harvested	2,443	808	4,206	13,914	2,354	1,503
140 to 179 acres ..... farms	24	7	51	191	25	18
acres harvested	2,363	(D)	6,368	19,222	3,266	1,594
180 to 219 acres ..... farms	17	9	26	169	27	10
acres harvested	2,588	1,140	3,541	22,534	4,664	1,019
220 to 259 acres ..... farms	11	9	27	117	20	16
acres harvested	1,888	1,280	5,591	18,639	4,298	2,475
260 to 499 acres ..... farms	29	27	103	384	53	42
acres harvested	8,991	5,191	32,149	105,029	15,985	13,046
500 to 999 acres ..... farms	24	17	93	191	42	43
acres harvested	16,267	10,442	57,954	102,549	28,939	25,713
1,000 to 1,999 acres ..... farms	11	24	50	64	34	68
acres harvested	16,106	27,993	65,212	73,137	44,735	84,623
2,000 acres or more ..... farms	10	2	56	24	36	47
acres harvested	25,502	(D)	154,157	84,690	107,342	152,303
2017 size of farm:						
1 to 9 acres ..... farms	15	31	59	32	27	10
acres harvested	63	119	197	152	93	28
10 to 49 acres ..... farms	198	86	83	350	82	40
acres harvested	2,220	1,168	1,344	4,887	949	541
50 to 69 acres ..... farms	37	28	17	145	24	5
acres harvested	1,312	650	605	4,730	778	110
70 to 99 acres ..... farms	46	32	37	199	23	9
acres harvested	2,966	1,170	2,184	9,134	1,320	543
100 to 139 acres ..... farms	46	30	55	199	33	11
acres harvested	4,019	1,426	4,732	14,210	3,080	989
140 to 179 acres ..... farms	44	11	69	212	30	15
acres harvested	5,394	1,158	8,910	21,301	4,008	1,779
180 to 219 acres ..... farms	34	19	22	186	30	6
acres harvested	5,216	2,085	3,504	25,720	4,975	972
220 to 259 acres ..... farms	18	9	46	210	21	20
acres harvested	2,676	1,314	9,324	37,756	4,615	4,120
260 to 499 acres ..... farms	55	23	140	537	63	59
acres harvested	15,771	4,513	45,144	145,446	19,289	18,409
500 to 999 acres ..... farms	21	23	82	170	62	75
acres harvested	14,629	12,311	53,705	92,436	44,217	49,871
1,000 to 1,999 acres ..... farms	11	24	62	44	42	79
acres harvested	15,021	29,608	85,468	46,977	52,275	109,363
2,000 acres or more ..... farms	9	5	36	23	32	29
acres harvested	21,765	15,993	100,113	59,836	85,415	102,443
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	145	95	97	232	80	25
acres	644	322	345	974	354	70
10 to 19 acres ..... farms	65	59	55	232	33	23
acres	817	815	747	2,989	402	266
20 to 29 acres ..... farms	25	28	17	136	11	4
acres	564	638	416	3,178	237	96
30 to 49 acres ..... farms	36	36	39	182	26	22
acres	1,350	1,305	1,451	6,819	982	897
50 to 99 acres ..... farms	47	26	45	308	54	19
acres	3,474	1,820	3,376	22,173	3,802	1,435
100 to 199 acres ..... farms	45	27	105	407	57	37
acres	5,872	3,952	14,308	58,164	8,285	5,245
200 to 499 acres ..... farms	39	18	129	419	73	48
acres	12,399	6,044	42,198	130,777	22,362	16,078
500 to 999 acres ..... farms	19	17	83	133	41	47
acres	14,439	13,529	57,121	90,364	29,818	33,319
1,000 acres or more ..... farms	21	19	100	69	67	101
acres	41,608	28,618	213,781	142,766	149,272	226,559
2017 acres harvested:						
1 to 9 acres ..... farms	134	80	108	182	80	29
acres	673	387	434	870	381	127
10 to 19 acres ..... farms	67	52	21	234	35	18
acres	889	683	246	3,029	479	205
20 to 29 acres ..... farms	25	31	20	110	6	8
acres	590	712	470	2,528	144	175
30 to 49 acres ..... farms	33	30	32	178	20	5
acres	1,237	1,073	1,232	6,720	837	176
50 to 99 acres ..... farms	89	38	68	340	34	16
acres	6,594	2,880	5,178	23,805	2,401	1,128
100 to 199 acres ..... farms	80	25	115	457	74	27
acres	11,047	3,579	16,938	65,792	10,589	4,089
200 to 499 acres ..... farms	65	24	173	636	95	81
acres	18,607	8,117	55,248	186,563	29,446	24,765
500 to 999 acres ..... farms	23	18	75	122	57	68
acres	16,607	12,942	51,838	80,697	44,718	48,660
1,000 acres or more ..... farms	18	23	96	48	68	106
acres	34,808	41,142	183,646	92,581	132,019	209,843

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Farms ..... number, 2022	445	1,179	229	604	333	453
2017	515	1,245	296	640	388	518
acres harvested, 2022	302,409	175,396	257,835	167,885	71,052	235,748
2017	286,488	178,434	332,332	158,783	65,340	220,201
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	6	6	2	25	14	31
acres harvested	27	13	(D)	57	74	94
10 to 49 acres ..... farms	51	229	13	84	45	50
acres harvested	918	3,136	228	1,111	743	785
50 to 69 acres ..... farms	6	80	4	22	20	21
acres harvested	232	2,497	(D)	552	384	645
70 to 99 acres ..... farms	17	143	5	34	29	20
acres harvested	841	5,105	(D)	1,390	1,077	1,101
100 to 139 acres ..... farms	23	130	3	47	26	29
acres harvested	1,922	6,871	244	2,356	999	2,989
140 to 179 acres ..... farms	41	92	12	59	36	33
acres harvested	5,014	6,268	1,689	6,196	2,616	4,768
180 to 219 acres ..... farms	23	94	5	25	33	22
acres harvested	3,647	9,607	778	2,570	2,597	3,419
220 to 259 acres ..... farms	12	64	7	40	11	17
acres harvested	2,349	7,332	1,289	5,843	1,174	3,508
260 to 499 acres ..... farms	81	210	29	160	79	100
acres harvested	22,669	38,755	9,074	45,304	14,061	29,258
500 to 999 acres ..... farms	76	85	45	57	15	55
acres harvested	44,708	37,462	27,462	33,963	5,263	36,501
1,000 to 1,999 acres ..... farms	69	37	49	38	14	40
acres harvested	91,560	33,253	60,484	41,732	15,403	52,519
2,000 acres or more ..... farms	40	9	55	13	11	35
acres harvested	128,522	25,097	156,083	26,811	26,661	100,161
2017 size of farm:						
1 to 9 acres ..... farms	16	18	2	6	6	22
acres harvested	33	57	(D)	18	18	76
10 to 49 acres ..... farms	62	178	27	91	47	64
acres harvested	1,168	2,701	457	1,419	785	1,161
50 to 69 acres ..... farms	9	79	4	33	15	13
acres harvested	458	2,726	(D)	1,261	398	367
70 to 99 acres ..... farms	25	134	7	38	38	24
acres harvested	1,279	4,866	542	2,117	814	1,235
100 to 139 acres ..... farms	26	165	8	44	50	36
acres harvested	2,157	9,638	641	2,698	2,627	3,353
140 to 179 acres ..... farms	50	118	18	55	32	52
acres harvested	6,383	7,319	2,456	5,863	2,080	7,202
180 to 219 acres ..... farms	22	102	8	39	28	22
acres harvested	2,810	9,772	997	4,217	2,185	3,577
220 to 259 acres ..... farms	26	90	11	47	30	18
acres harvested	4,824	11,680	2,355	7,137	2,343	3,623
260 to 499 acres ..... farms	94	240	45	153	92	109
acres harvested	27,264	48,628	13,531	35,443	16,557	34,539
500 to 999 acres ..... farms	82	88	40	95	30	92
acres harvested	48,250	38,411	28,030	47,895	10,642	60,707
1,000 to 1,999 acres ..... farms	71	29	64	32	16	51
acres harvested	94,585	32,745	89,656	36,660	18,758	63,529
2,000 acres or more ..... farms	32	4	62	7	4	15
acres harvested	97,277	9,891	193,501	14,055	8,133	40,832
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	25	127	5	82	36	66
acres	109	555	18	315	195	253
10 to 19 acres ..... farms	21	161	11	55	41	8
acres	257	2,028	128	762	529	111
20 to 29 acres ..... farms	9	108	3	32	31	11
acres	201	2,492	70	731	679	262
30 to 49 acres ..... farms	23	162	4	26	41	21
acres	868	6,076	152	1,002	1,545	754
50 to 99 acres ..... farms	34	217	7	65	57	32
acres	2,375	15,221	503	4,598	3,922	2,270
100 to 199 acres ..... farms	80	176	23	103	60	86
acres	11,485	24,272	3,557	14,868	8,354	12,473
200 to 499 acres ..... farms	84	151	39	154	39	106
acres	27,171	45,265	14,440	49,891	10,950	33,537
500 to 999 acres ..... farms	68	54	44	52	8	55
acres	46,368	36,178	31,476	38,837	5,791	39,075
1,000 acres or more ..... farms	101	23	93	35	20	68
acres	213,575	43,309	207,491	56,881	39,087	147,013
2017 acres harvested:						
1 to 9 acres ..... farms	28	119	10	52	31	46
acres	104	515	(D)	245	109	172
10 to 19 acres ..... farms	37	128	15	39	53	22
acres	471	1,636	196	501	687	288
20 to 29 acres ..... farms	12	99	1	30	36	17
acres	241	2,253	(D)	670	824	400
30 to 49 acres ..... farms	28	163	8	48	47	28
acres	1,008	6,213	278	1,729	1,766	986
50 to 99 acres ..... farms	46	256	17	83	64	36
acres	3,128	18,411	1,362	5,547	4,373	2,709
100 to 199 acres ..... farms	91	239	27	147	75	93
acres	13,026	33,738	3,790	20,931	10,260	13,504
200 to 499 acres ..... farms	106	176	55	158	55	122
acres	33,915	52,271	16,926	47,935	15,571	38,847
500 to 999 acres ..... farms	74	43	39	55	10	99
acres	51,267	27,416	28,392	38,157	6,263	67,960
1,000 acres or more ..... farms	93	22	124	28	17	55
acres	183,328	35,981	281,335	43,068	25,487	95,335

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Table 9. **Harvested Cropland by Size of Farm and Acres Harvested: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Farms ..... number, 2022	392	390	260	742	995	588
2017	478	367	298	802	1,004	601
acres harvested, 2022	33,731	241,723	358,050	198,115	171,228	316,017
2017	54,175	231,991	394,883	165,353	190,596	329,705
HARVESTED CROPLAND BY SIZE OF FARM						
2022 size of farm:						
1 to 9 acres ..... farms	60	22	6	27	80	24
acres harvested	140	45	6	76	207	57
10 to 49 acres ..... farms	185	59	28	81	356	76
acres harvested	1,896	818	308	1,068	4,212	1,040
50 to 69 acres ..... farms	27	9	6	37	90	20
acres harvested	913	479	138	1,145	2,972	650
70 to 99 acres ..... farms	16	23	8	63	106	21
acres harvested	728	1,369	609	2,736	4,588	1,378
100 to 139 acres ..... farms	18	12	9	63	59	29
acres harvested	1,480	1,251	402	4,319	4,055	2,339
140 to 179 acres ..... farms	15	19	11	67	55	47
acres harvested	1,220	2,314	1,477	5,518	5,499	6,162
180 to 219 acres ..... farms	11	10	4	57	48	18
acres harvested	1,628	1,651	682	7,090	6,318	2,850
220 to 259 acres ..... farms	13	8	4	48	26	33
acres harvested	2,306	1,715	520	6,365	4,536	6,728
260 to 499 acres ..... farms	27	63	20	143	75	89
acres harvested	7,389	20,778	6,186	32,035	21,184	27,784
500 to 999 acres ..... farms	13	79	53	84	59	119
acres harvested	7,920	51,962	36,255	43,673	33,823	75,883
1,000 to 1,999 acres ..... farms	7	51	39	66	22	81
acres harvested	8,111	71,130	47,678	75,447	27,283	95,126
2,000 acres or more ..... farms	-	35	72	6	19	31
acres harvested	-	88,211	263,789	18,643	56,551	96,020
2017 size of farm:						
1 to 9 acres ..... farms	92	24	5	58	93	16
acres harvested	(D)	75	15	204	331	52
10 to 49 acres ..... farms	181	33	17	89	281	41
acres harvested	2,269	527	254	1,255	4,304	616
50 to 69 acres ..... farms	33	7	13	39	78	28
acres harvested	800	317	480	1,866	2,594	978
70 to 99 acres ..... farms	32	10	6	54	105	18
acres harvested	1,033	715	464	2,129	5,041	1,232
100 to 139 acres ..... farms	28	26	8	90	84	13
acres harvested	2,282	2,344	525	5,405	6,017	996
140 to 179 acres ..... farms	8	21	7	59	70	46
acres harvested	981	2,678	956	5,798	7,617	6,094
180 to 219 acres ..... farms	19	12	10	51	49	30
acres harvested	2,847	2,136	1,183	6,276	6,864	4,918
220 to 259 acres ..... farms	15	7	10	57	40	14
acres harvested	2,966	1,577	1,819	7,962	5,798	2,755
260 to 499 acres ..... farms	36	77	29	165	91	125
acres harvested	9,030	24,017	9,327	33,690	26,575	38,637
500 to 999 acres ..... farms	14	75	45	93	69	154
acres harvested	7,239	52,166	27,611	40,653	43,033	102,004
1,000 to 1,999 acres ..... farms	19	42	71	39	30	99
acres harvested	22,533	58,015	88,196	40,750	38,851	121,713
2,000 acres or more ..... farms	1	33	77	8	14	17
acres harvested	(D)	87,424	264,053	19,365	43,571	49,710
HARVESTED CROPLAND BY ACRES HARVESTED						
2022 acres harvested:						
1 to 9 acres ..... farms	148	48	24	82	263	64
acres	517	150	84	311	968	255
10 to 19 acres ..... farms	92	13	8	62	171	26
acres	1,113	167	100	754	2,183	323
20 to 29 acres ..... farms	20	25	8	42	80	20
acres	437	559	169	954	1,856	475
30 to 49 acres ..... farms	18	6	9	52	89	23
acres	628	221	356	1,944	3,285	880
50 to 99 acres ..... farms	36	31	12	119	116	40
acres	2,510	2,239	924	8,416	7,916	2,920
100 to 199 acres ..... farms	28	34	14	139	105	89
acres	3,573	4,943	1,952	19,523	14,736	12,534
200 to 499 acres ..... farms	34	86	30	125	92	116
acres	9,865	29,617	9,364	40,306	30,389	38,693
500 to 999 acres ..... farms	10	66	53	73	41	115
acres	7,440	47,756	39,563	48,612	28,776	81,038
1,000 acres or more ..... farms	6	81	102	48	38	95
acres	7,648	156,071	305,538	77,295	81,119	178,899
2017 acres harvested:						
1 to 9 acres ..... farms	177	40	13	117	191	35
acres	584	156	49	429	771	140
10 to 19 acres ..... farms	89	8	15	36	150	21
acres	1,172	84	212	496	2,044	269
20 to 29 acres ..... farms	42	8	3	66	69	12
acres	949	199	65	1,491	1,592	256
30 to 49 acres ..... farms	27	10	10	60	110	25
acres	941	369	388	2,324	4,118	938
50 to 99 acres ..... farms	30	23	13	106	139	38
acres	2,112	1,751	960	7,270	9,412	2,489
100 to 199 acres ..... farms	39	46	23	179	139	83
acres	5,624	6,470	3,598	24,355	19,372	12,869
200 to 499 acres ..... farms	45	91	41	161	116	138
acres	12,070	29,488	13,241	48,107	37,612	46,637
500 to 999 acres ..... farms	16	67	40	42	54	149
acres	11,953	48,660	31,090	28,553	40,713	108,572
1,000 acres or more ..... farms	13	74	140	35	36	100
acres	18,770	144,814	345,280	52,328	74,962	157,535

Table 10. **Irrigation: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
Irrigated farms (see text) ..... number, 2022	3,625	34	70	42	45
2017	3,220	15	43	34	37
Land in irrigated farms ..... acres, 2022	2,331,272	11,757	10,475	29,510	17,695
2017	2,142,296	9,678	12,230	25,129	17,685
Harvested cropland ..... farms, 2022	3,575	34	64	42	45
2017	3,180	15	43	34	31
acres, 2022	1,948,596	7,063	6,612	22,060	9,899
2017	1,859,878	4,189	10,614	19,446	5,945
Other cropland, excluding cropland pastured ..... farms, 2022	1,257	7	27	13	15
2017	1,134	5	17	13	24
acres, 2022	79,812	407	2,297	1,163	445
2017	67,180	(D)	609	977	1,178
Pastureland, excluding woodland pastured ..... farms, 2022	992	11	11	18	17
2017	979	12	4	10	21
acres, 2022	75,308	251	112	482	3,323
2017	63,468	236	66	392	1,276
Irrigated land ..... acres, 2022	648,313	4,443	4,004	8,987	4,050
2017	611,621	2,969	3,000	13,434	3,493
Harvested cropland ..... farms, 2022	3,551	34	64	39	45
2017	3,131	15	43	33	31
acres, 2022	644,857	4,443	3,990	8,911	4,050
2017	609,225	2,969	3,000	(D)	3,481
Pastureland and other land ..... farms, 2022	160	-	7	4	-
2017	132	-	-	1	6
acres, 2022	3,456	-	14	76	-
2017	2,396	-	-	(D)	12
2022 irrigated acres by size of farm:					
1 to 9 acres ..... farms	559	5	23	8	7
acres irrigated	799	6	39	(D)	9
10 to 49 acres ..... farms	723	9	24	4	7
acres irrigated	3,844	82	140	38	12
50 to 69 acres ..... farms	104	1	2	-	-
acres irrigated	1,403	(D)	(D)	-	-
70 to 99 acres ..... farms	176	10	3	4	4
acres irrigated	4,129	185	(D)	78	4
100 to 139 acres ..... farms	158	-	4	4	2
acres irrigated	6,061	-	305	39	(D)
140 to 179 acres ..... farms	121	2	-	-	3
acres irrigated	6,927	(D)	-	-	4
180 to 219 acres ..... farms	111	1	3	1	-
acres irrigated	7,815	(D)	27	(D)	-
220 to 259 acres ..... farms	98	1	1	-	2
acres irrigated	7,323	(D)	(D)	-	(D)
260 to 499 acres ..... farms	423	-	1	7	10
acres irrigated	53,545	-	(D)	322	896
500 to 999 acres ..... farms	478	3	7	4	8
acres irrigated	105,801	1,350	2,174	197	2,130
1,000 to 1,999 acres ..... farms	368	1	1	6	-
acres irrigated	150,689	(D)	(D)	1,890	-
2,000 acres or more ..... farms	306	1	1	4	2
acres irrigated	299,977	(D)	(D)	6,338	(D)
2017 irrigated acres by size of farm:					
1 to 9 acres ..... farms	394	-	13	6	7
acres irrigated	627	-	15	6	7
10 to 49 acres ..... farms	528	3	11	2	10
acres irrigated	2,415	5	56	(D)	16
50 to 69 acres ..... farms	118	5	3	4	2
acres irrigated	1,328	5	45	6	(D)
70 to 99 acres ..... farms	134	1	1	3	2
acres irrigated	2,455	(D)	(D)	6	(D)
100 to 139 acres ..... farms	113	1	2	2	-
acres irrigated	3,976	(D)	(D)	(D)	-
140 to 179 acres ..... farms	112	1	3	-	2
acres irrigated	6,626	(D)	(D)	-	(D)
180 to 219 acres ..... farms	112	1	2	-	3
acres irrigated	9,359	(D)	(D)	-	12
220 to 259 acres ..... farms	140	-	2	-	-
acres irrigated	13,809	-	(D)	-	-
260 to 499 acres ..... farms	443	-	1	5	-
acres irrigated	53,865	-	(D)	161	-
500 to 999 acres ..... farms	469	1	1	4	5
acres irrigated	113,182	(D)	(D)	1,440	1,462
1,000 to 1,999 acres ..... farms	398	1	-	4	4
acres irrigated	159,593	(D)	-	2,374	(D)
2,000 acres or more ..... farms	259	1	4	4	2
acres irrigated	244,386	(D)	1,607	(D)	(D)
Land with irrigation systems or equipment present (see text) ..... farms, 2022	3,968	35	80	46	48
acres, 2022	709,449	4,444	6,203	10,168	6,122

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
Irrigated farms (see text) ..... number, 2022	64	11	25	35	23
2017	59	10	23	34	23
Land in irrigated farms ..... acres, 2022	39,322	17,800	22,966	18,809	(D)
2017	38,020	22,701	21,681	20,395	2,260
Harvested cropland ..... farms, 2022	62	11	25	35	23
2017	59	10	21	34	23
acres, 2022	34,929	16,121	22,233	16,201	448
2017	32,733	21,590	21,010	17,937	1,041
Other cropland, excluding cropland pastured ..... farms, 2022	16	6	4	21	14
2017	9	3	11	15	11
acres, 2022	877	385	(D)	2,013	356
2017	608	101	249	1,216	99
Pastureland, excluding woodland pastured ..... farms, 2022	25	3	3	2	3
2017	16	3	4	6	4
acres, 2022	698	877	65	(D)	260
2017	1,216	901	(D)	91	120
Irrigated land ..... acres, 2022	19,429	2,092	3,269	3,293	233
2017	16,699	4,099	4,282	4,085	(D)
Harvested cropland ..... farms, 2022	62	11	25	35	23
2017	55	10	21	34	23
acres, 2022	19,401	2,092	3,269	3,293	(D)
2017	16,646	(D)	(D)	4,085	(D)
Pastureland and other land ..... farms, 2022	3	-	-	-	1
2017	5	1	2	-	-
acres, 2022	28	-	-	-	(D)
2017	53	(D)	(D)	-	-
2022 irrigated acres by size of farm:					
1 to 9 acres ..... farms	1	-	7	-	6
acres irrigated	(D)	-	7	-	8
10 to 49 acres ..... farms	15	-	3	2	10
acres irrigated	72	-	7	(D)	19
50 to 69 acres ..... farms	3	-	-	-	-
acres irrigated	39	-	-	-	-
70 to 99 acres ..... farms	4	3	-	-	2
acres irrigated	220	(D)	-	-	(D)
100 to 139 acres ..... farms	6	-	-	6	-
acres irrigated	260	-	-	240	-
140 to 179 acres ..... farms	2	-	-	2	1
acres irrigated	(D)	-	-	(D)	(D)
180 to 219 acres ..... farms	4	-	1	-	1
acres irrigated	215	-	(D)	-	(D)
220 to 259 acres ..... farms	2	-	1	1	1
acres irrigated	(D)	-	(D)	(D)	(D)
260 to 499 acres ..... farms	6	-	2	11	1
acres irrigated	992	-	(D)	1,121	(D)
500 to 999 acres ..... farms	9	3	6	7	-
acres irrigated	1,873	359	510	827	-
1,000 to 1,999 acres ..... farms	4	4	1	6	-
acres irrigated	3,225	736	(D)	998	-
2,000 acres or more ..... farms	8	1	4	-	1
acres irrigated	12,428	(D)	2,440	-	(D)
2017 irrigated acres by size of farm:					
1 to 9 acres ..... farms	4	-	6	2	3
acres irrigated	4	-	10	(D)	3
10 to 49 acres ..... farms	4	-	5	1	14
acres irrigated	42	-	9	(D)	35
50 to 69 acres ..... farms	2	1	-	-	2
acres irrigated	(D)	(D)	-	-	(D)
70 to 99 acres ..... farms	4	-	-	-	1
acres irrigated	42	-	-	-	(D)
100 to 139 acres ..... farms	7	-	1	-	1
acres irrigated	304	-	(D)	-	(D)
140 to 179 acres ..... farms	-	-	-	3	-
acres irrigated	-	-	-	170	-
180 to 219 acres ..... farms	2	-	-	-	-
acres irrigated	(D)	-	-	-	-
220 to 259 acres ..... farms	8	-	1	-	-
acres irrigated	576	-	(D)	-	-
260 to 499 acres ..... farms	5	1	2	13	1
acres irrigated	1,200	(D)	(D)	1,446	(D)
500 to 999 acres ..... farms	12	2	3	13	-
acres irrigated	2,721	(D)	134	2,027	-
1,000 to 1,999 acres ..... farms	6	3	1	1	1
acres irrigated	714	710	(D)	(D)	(D)
2,000 acres or more ..... farms	5	3	4	1	-
acres irrigated	10,770	(D)	3,412	(D)	-
Land with irrigation systems or equipment present (see text) ..... farms, 2022	67	13	27	36	25
acres, 2022	20,832	2,276	3,308	3,616	321

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Irrigated farms (see text) ..... number, 2022	19	28	15	76	30	22
2017	19	19	15	56	18	8
Land in irrigated farms ..... acres, 2022	1,327	12,371	21,162	8,666	44,371	17,367
2017	8,146	12,996	30,239	11,891	22,907	15,915
Harvested cropland ..... farms, 2022	19	28	15	70	30	22
2017	19	18	15	56	18	8
acres, 2022	586	8,366	20,587	6,704	34,640	12,367
2017	5,826	10,054	27,222	8,467	19,726	8,268
Other cropland, excluding cropland pastured ..... farms, 2022	11	8	6	20	8	12
2017	10	3	6	22	10	4
acres, 2022	213	107	143	399	(D)	1,648
2017	198	12	955	1,469	2,178	1,420
Pastureland, excluding woodland pastured ..... farms, 2022	3	14	-	30	4	10
2017	8	9	-	20	4	5
acres, 2022	(D)	2,267	-	353	358	1,920
2017	(D)	1,647	-	255	256	(D)
Irrigated land ..... acres, 2022	129	(D)	2,442	2,054	2,899	6,958
2017	552	8,439	4,509	3,966	2,940	4,921
Harvested cropland ..... farms, 2022	18	28	15	70	30	22
2017	19	18	15	51	18	8
acres, 2022	(D)	(D)	2,442	2,042	2,899	6,958
2017	552	(D)	4,509	3,869	2,940	(D)
Pastureland and other land ..... farms, 2022	1	1	-	6	-	-
2017	-	1	-	5	-	1
acres, 2022	(D)	(D)	-	12	-	-
2017	-	(D)	-	97	-	(D)
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	2	5	2	28	2	-
acres irrigated	(D)	5	(D)	49	(D)	-
10 to 49 acres ..... farms	10	5	3	34	11	7
acres irrigated	27	6	3	134	(D)	13
50 to 69 acres ..... farms	1	5	-	1	-	2
acres irrigated	(D)	6	-	(D)	-	(D)
70 to 99 acres ..... farms	1	2	-	7	-	2
acres irrigated	(D)	(D)	-	(D)	-	(D)
100 to 139 acres ..... farms	2	5	-	-	-	3
acres irrigated	(D)	15	-	-	-	4
140 to 179 acres ..... farms	-	-	-	-	-	-
acres irrigated	-	-	-	-	-	-
180 to 219 acres ..... farms	1	1	-	-	-	-
acres irrigated	(D)	(D)	-	-	-	-
220 to 259 acres ..... farms	1	-	-	1	-	2
acres irrigated	(D)	-	-	(D)	-	(D)
260 to 499 acres ..... farms	1	2	1	1	8	-
acres irrigated	(D)	(D)	(D)	(D)	378	-
500 to 999 acres ..... farms	-	1	-	-	4	2
acres irrigated	-	(D)	-	-	1,275	(D)
1,000 to 1,999 acres ..... farms	-	-	3	3	2	-
acres irrigated	-	-	(D)	1,430	(D)	-
2,000 acres or more ..... farms	-	2	6	1	3	4
acres irrigated	-	(D)	660	(D)	964	6,463
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	3	-	-	16	1	-
acres irrigated	3	-	-	(D)	(D)	-
10 to 49 acres ..... farms	8	4	4	16	4	-
acres irrigated	42	7	7	104	24	-
50 to 69 acres ..... farms	2	2	-	7	-	-
acres irrigated	(D)	(D)	-	59	-	-
70 to 99 acres ..... farms	-	4	-	8	-	3
acres irrigated	-	5	-	91	-	(D)
100 to 139 acres ..... farms	-	1	-	1	1	-
acres irrigated	-	(D)	-	(D)	(D)	-
140 to 179 acres ..... farms	1	1	-	1	-	-
acres irrigated	(D)	(D)	-	(D)	-	-
180 to 219 acres ..... farms	-	-	-	-	1	-
acres irrigated	-	-	-	-	(D)	-
220 to 259 acres ..... farms	1	-	2	-	1	-
acres irrigated	(D)	-	(D)	-	(D)	-
260 to 499 acres ..... farms	-	3	-	3	1	1
acres irrigated	-	(D)	-	45	(D)	(D)
500 to 999 acres ..... farms	1	1	2	-	2	-
acres irrigated	(D)	(D)	(D)	-	(D)	-
1,000 to 1,999 acres ..... farms	1	1	3	1	4	1
acres irrigated	(D)	(D)	881	(D)	940	(D)
2,000 acres or more ..... farms	2	2	4	3	3	3
acres irrigated	(D)	(D)	3,021	3,528	1,520	(D)
Land with irrigation systems or equipment present (see text) ..... farms, 2022	20	29	21	88	33	26
acres, 2022	258	(D)	2,988	2,137	3,043	7,004

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Irrigated farms (see text) ..... number, 2022	7	15	22	265	19	49
2017	10	13	24	221	10	47
Land in irrigated farms ..... acres, 2022	244	21,665	7,092	123,256	(D)	34,173
2017	214	11,534	8,622	131,077	35,278	33,001
Harvested cropland ..... farms, 2022	7	15	22	262	19	49
2017	10	13	24	217	10	47
acres, 2022	18	17,855	5,625	107,929	(D)	30,142
2017	20	10,255	7,081	123,954	34,221	29,146
Other cropland, excluding cropland pastured ..... farms, 2022	3	9	8	95	4	26
2017	4	6	10	66	2	21
acres, 2022	7	2,586	55	5,637	84	1,513
2017	8	(D)	163	2,332	(D)	738
Pastureland, excluding woodland pastured ..... farms, 2022	4	1	4	44	3	11
2017	1	1	5	36	-	14
acres, 2022	14	(D)	(D)	1,169	20	520
2017	(D)	(D)	93	832	-	1,341
Irrigated land ..... acres, 2022	17	2,909	3,482	60,105	(D)	6,918
2017	14	2,090	4,514	62,812	4,935	3,257
Harvested cropland ..... farms, 2022	7	15	22	262	19	46
2017	10	13	24	217	10	47
acres, 2022	17	2,909	(D)	59,839	(D)	6,903
2017	14	2,090	(D)	62,802	4,935	(D)
Pastureland and other land ..... farms, 2022	-	-	2	8	-	3
2017	-	-	2	7	-	1
acres, 2022	-	-	(D)	266	-	15
2017	-	-	(D)	10	-	(D)
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	-	1	8	36	8	7
acres irrigated	-	(D)	16	47	8	12
10 to 49 acres ..... farms	6	1	7	58	6	3
acres irrigated	(D)	(D)	15	340	89	14
50 to 69 acres ..... farms	-	-	-	12	-	1
acres irrigated	-	-	-	151	-	(D)
70 to 99 acres ..... farms	-	-	1	14	1	4
acres irrigated	-	-	(D)	869	(D)	88
100 to 139 acres ..... farms	1	-	2	10	-	-
acres irrigated	(D)	-	(D)	603	-	-
140 to 179 acres ..... farms	-	-	-	9	-	4
acres irrigated	-	-	-	1,114	-	17
180 to 219 acres ..... farms	-	-	1	8	2	1
acres irrigated	-	-	(D)	1,026	(D)	(D)
220 to 259 acres ..... farms	-	-	-	3	-	-
acres irrigated	-	-	-	497	-	-
260 to 499 acres ..... farms	-	1	-	32	-	14
acres irrigated	-	(D)	-	7,409	-	967
500 to 999 acres ..... farms	-	6	-	47	-	2
acres irrigated	-	(D)	-	14,500	-	(D)
1,000 to 1,999 acres ..... farms	-	-	-	29	-	5
acres irrigated	-	-	-	25,180	-	501
2,000 acres or more ..... farms	-	6	3	7	2	8
acres irrigated	-	1,800	3,420	8,369	(D)	4,963
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	-	2	2	20	1	5
acres irrigated	-	(D)	(D)	30	(D)	7
10 to 49 acres ..... farms	10	3	7	34	-	3
acres irrigated	14	10	16	299	-	10
50 to 69 acres ..... farms	-	-	-	9	-	1
acres irrigated	-	-	-	322	-	(D)
70 to 99 acres ..... farms	-	-	4	3	-	5
acres irrigated	-	-	6	205	-	(D)
100 to 139 acres ..... farms	-	1	2	3	-	-
acres irrigated	-	(D)	(D)	211	-	-
140 to 179 acres ..... farms	-	-	1	15	1	2
acres irrigated	-	-	(D)	1,931	(D)	(D)
180 to 219 acres ..... farms	-	-	-	7	-	6
acres irrigated	-	-	-	1,079	-	660
220 to 259 acres ..... farms	-	-	-	10	-	3
acres irrigated	-	-	-	1,824	-	216
260 to 499 acres ..... farms	-	-	-	32	-	4
acres irrigated	-	-	-	6,143	-	362
500 to 999 acres ..... farms	-	2	7	48	1	9
acres irrigated	-	(D)	(D)	16,977	(D)	1,210
1,000 to 1,999 acres ..... farms	-	2	1	26	6	4
acres irrigated	-	(D)	(D)	20,361	(D)	280
2,000 acres or more ..... farms	-	3	-	14	1	5
acres irrigated	-	960	-	13,430	(D)	438
Land with irrigation systems or equipment present (see text) ..... farms, 2022	7	15	23	278	19	56
acres, 2022	26	2,910	3,611	66,319	(D)	7,101

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Irrigated farms (see text) ..... number, 2022	16	47	23	57	38	95
2017	5	26	28	57	37	52
Land in irrigated farms ..... acres, 2022	6,342	3,280	20,280	22,548	79,143	3,544
2017	(D)	3,152	14,485	21,607	63,122	1,828
Harvested cropland ..... farms, 2022	16	46	23	51	38	95
2017	5	24	26	57	37	52
acres, 2022	5,572	1,824	19,546	20,956	75,963	1,559
2017	(D)	1,943	13,968	19,446	60,561	591
Other cropland, excluding cropland pastured ..... farms, 2022	5	14	12	10	23	21
2017	-	10	10	9	17	16
acres, 2022	76	186	242	194	1,873	108
2017	-	187	99	779	1,171	168
Pastureland, excluding woodland pastured ..... farms, 2022	4	19	4	17	2	16
2017	-	21	3	26	13	11
acres, 2022	280	328	32	426	(D)	254
2017	-	535	(D)	678	582	76
Irrigated land ..... acres, 2022	1,364	642	3,444	6,154	7,444	449
2017	(D)	661	1,694	5,959	5,853	279
Harvested cropland ..... farms, 2022	14	46	23	51	38	95
2017	5	24	24	53	37	52
acres, 2022	(D)	(D)	3,444	6,101	7,390	449
2017	(D)	(D)	1,662	5,896	5,853	279
Pastureland and other land ..... farms, 2022	2	1	-	8	6	-
2017	-	2	4	7	-	-
acres, 2022	(D)	(D)	-	53	54	-
2017	-	(D)	32	63	-	-
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	3	11	-	9	5	53
acres irrigated	(D)	11	-	19	13	70
10 to 49 acres ..... farms	-	25	3	14	-	28
acres irrigated	-	100	11	103	-	74
50 to 69 acres ..... farms	2	1	2	2	-	5
acres irrigated	(D)	(D)	(D)	(D)	-	25
70 to 99 acres ..... farms	-	3	1	1	-	3
acres irrigated	-	(D)	(D)	(D)	-	10
100 to 139 acres ..... farms	-	3	-	4	-	1
acres irrigated	-	30	-	204	-	(D)
140 to 179 acres ..... farms	-	1	-	6	-	-
acres irrigated	-	(D)	-	269	-	-
180 to 219 acres ..... farms	3	-	-	-	-	1
acres irrigated	48	-	-	-	-	(D)
220 to 259 acres ..... farms	-	-	-	1	-	-
acres irrigated	-	-	-	(D)	-	-
260 to 499 acres ..... farms	3	2	3	3	8	3
acres irrigated	996	(D)	(D)	356	630	(D)
500 to 999 acres ..... farms	5	-	7	13	3	1
acres irrigated	313	-	1,138	3,404	200	(D)
1,000 to 1,999 acres ..... farms	-	1	6	3	6	-
acres irrigated	-	(D)	1,924	(D)	1,620	-
2,000 acres or more ..... farms	-	-	1	1	16	-
acres irrigated	-	-	(D)	(D)	4,981	-
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	4	-	8	17	-	28
acres irrigated	4	-	8	24	-	45
10 to 49 acres ..... farms	-	14	3	10	-	17
acres irrigated	-	101	4	28	-	95
50 to 69 acres ..... farms	-	-	-	1	1	1
acres irrigated	-	-	-	(D)	(D)	(D)
70 to 99 acres ..... farms	-	3	1	2	2	1
acres irrigated	-	26	(D)	(D)	(D)	(D)
100 to 139 acres ..... farms	-	2	1	1	1	1
acres irrigated	-	(D)	(D)	(D)	(D)	(D)
140 to 179 acres ..... farms	-	1	2	-	-	1
acres irrigated	-	(D)	(D)	-	-	(D)
180 to 219 acres ..... farms	-	2	-	4	1	1
acres irrigated	-	(D)	-	323	(D)	(D)
220 to 259 acres ..... farms	-	3	-	-	-	-
acres irrigated	-	291	-	-	-	-
260 to 499 acres ..... farms	-	-	2	8	4	2
acres irrigated	-	-	(D)	1,576	233	(D)
500 to 999 acres ..... farms	-	-	4	8	14	-
acres irrigated	-	-	416	1,550	1,182	-
1,000 to 1,999 acres ..... farms	1	1	5	3	3	-
acres irrigated	(D)	(D)	772	555	714	-
2,000 acres or more ..... farms	-	-	2	3	11	-
acres irrigated	-	-	(D)	1,680	3,560	-
Land with irrigation systems or equipment present (see text) ..... farms, 2022	16	51	24	71	38	105
acres, 2022	1,392	984	3,732	6,248	8,010	468

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Irrigated farms (see text) ..... number, 2022	21	42	55	35	9	30
2017	22	37	53	22	2	29
Land in irrigated farms ..... acres, 2022	5,277	44,640	16,639	9,691	11,330	1,743
2017	6,394	34,739	34,068	8,146	(D)	11,384
Harvested cropland ..... farms, 2022	20	42	55	35	9	30
2017	22	36	53	22	2	29
acres, 2022	3,639	33,548	12,820	(D)	11,240	318
2017	(D)	28,535	29,343	(D)	(D)	9,938
Other cropland, excluding cropland pastured ..... farms, 2022	7	18	21	5	1	13
2017	5	15	22	7	-	11
acres, 2022	129	3,977	1,135	331	(D)	233
2017	548	988	649	30	-	57
Pastureland, excluding woodland pastured ..... farms, 2022	9	13	5	13	-	9
2017	2	14	16	12	-	10
acres, 2022	487	2,524	141	842	-	257
2017	(D)	2,160	317	266	-	137
Irrigated land ..... acres, 2022	483	26,682	2,657	(D)	1,530	150
2017	186	24,522	3,954	(D)	(D)	2,160
Harvested cropland ..... farms, 2022	20	42	55	35	9	30
2017	22	35	51	22	2	28
acres, 2022	(D)	(D)	2,657	(D)	1,530	150
2017	186	(D)	(D)	(D)	(D)	(D)
Pastureland and other land ..... farms, 2022	1	1	-	-	-	-
2017	-	3	2	-	-	1
acres, 2022	(D)	(D)	-	-	-	-
2017	-	(D)	(D)	-	-	(D)
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	1	2	2	10	1	1
acres irrigated	(D)	(D)	(D)	11	(D)	(D)
10 to 49 acres ..... farms	3	7	22	13	1	18
acres irrigated	5	9	112	26	(D)	41
50 to 69 acres ..... farms	-	-	1	-	-	-
acres irrigated	-	-	(D)	-	-	-
70 to 99 acres ..... farms	3	6	5	2	-	7
acres irrigated	15	244	144	(D)	-	55
100 to 139 acres ..... farms	2	1	7	3	-	2
acres irrigated	(D)	(D)	(D)	5	-	(D)
140 to 179 acres ..... farms	2	4	5	2	-	2
acres irrigated	(D)	398	510	(D)	-	(D)
180 to 219 acres ..... farms	3	-	2	1	-	-
acres irrigated	133	-	(D)	(D)	-	-
220 to 259 acres ..... farms	5	-	-	-	-	-
acres irrigated	102	-	-	-	-	-
260 to 499 acres ..... farms	1	4	4	1	1	-
acres irrigated	(D)	356	236	(D)	(D)	-
500 to 999 acres ..... farms	-	4	-	1	-	-
acres irrigated	-	2,163	-	(D)	-	-
1,000 to 1,999 acres ..... farms	-	8	4	1	6	-
acres irrigated	-	2,650	449	(D)	1,500	-
2,000 acres or more ..... farms	1	6	3	1	-	-
acres irrigated	(D)	20,764	876	(D)	-	-
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	6	4	6	2	1	-
acres irrigated	30	14	9	(D)	(D)	-
10 to 49 acres ..... farms	2	6	13	11	1	16
acres irrigated	(D)	9	25	27	(D)	60
50 to 69 acres ..... farms	3	3	2	-	-	-
acres irrigated	3	9	(D)	-	-	-
70 to 99 acres ..... farms	2	3	6	-	-	-
acres irrigated	(D)	41	104	-	-	-
100 to 139 acres ..... farms	1	3	2	5	-	-
acres irrigated	(D)	(D)	(D)	6	-	-
140 to 179 acres ..... farms	-	1	-	1	-	2
acres irrigated	-	(D)	-	(D)	-	(D)
180 to 219 acres ..... farms	-	3	-	-	-	2
acres irrigated	-	(D)	-	-	-	(D)
220 to 259 acres ..... farms	6	-	-	-	-	-
acres irrigated	12	-	-	-	-	-
260 to 499 acres ..... farms	-	2	2	1	-	1
acres irrigated	-	(D)	(D)	(D)	-	(D)
500 to 999 acres ..... farms	1	4	5	1	-	6
acres irrigated	(D)	1,842	213	(D)	-	1,800
1,000 to 1,999 acres ..... farms	-	2	15	-	-	-
acres irrigated	-	(D)	3,075	-	-	-
2,000 acres or more ..... farms	1	6	2	1	-	2
acres irrigated	(D)	21,371	(D)	(D)	-	(D)
Land with irrigation systems or equipment present (see text) ..... farms, 2022	23	47	64	37	12	32
acres, 2022	485	29,946	3,062	(D)	1,681	702

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Irrigated farms (see text) ..... number, 2022	64	10	3	18	7	1
2017	50	7	3	34	10	5
Land in irrigated farms ..... acres, 2022	88,026	6,151	448	17,799	341	(D)
2017	92,959	9,541	(D)	22,183	310	5,653
Harvested cropland ..... farms, 2022	62	10	3	18	7	1
2017	50	7	3	34	10	4
acres, 2022	79,148	4,638	(D)	15,672	31	(D)
2017	87,963	8,005	8	19,321	20	3,967
Other cropland, excluding cropland pastured ..... farms, 2022	37	5	1	11	2	1
2017	24	4	-	15	-	3
acres, 2022	4,294	734	(D)	1,084	(D)	(D)
2017	2,075	1,048	-	713	-	1,350
Pastureland, excluding woodland pastured ..... farms, 2022	25	-	1	2	2	-
2017	18	-	-	14	2	1
acres, 2022	2,218	-	(D)	(D)	(D)	-
2017	1,232	-	-	368	(D)	(D)
Irrigated land ..... acres, 2022	27,908	(D)	4	4,325	10	(D)
2017	26,580	2,395	(D)	5,072	12	1,188
Harvested cropland ..... farms, 2022	62	10	3	18	7	1
2017	50	7	3	34	10	4
acres, 2022	27,812	(D)	4	4,325	10	(D)
2017	26,580	2,395	(D)	5,072	12	(D)
Pastureland and other land ..... farms, 2022	5	1	-	-	-	-
2017	-	-	-	-	-	1
acres, 2022	96	(D)	-	-	-	-
2017	-	-	-	-	-	(D)
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	2	-	-	-	3	-
acres irrigated	(D)	-	-	-	5	-
10 to 49 acres ..... farms	3	3	1	4	2	-
acres irrigated	7	28	(D)	19	(D)	-
50 to 69 acres ..... farms	-	-	-	-	-	-
acres irrigated	-	-	-	-	-	-
70 to 99 acres ..... farms	-	-	-	-	-	-
acres irrigated	-	-	-	-	-	-
100 to 139 acres ..... farms	2	1	1	-	1	-
acres irrigated	(D)	(D)	(D)	-	(D)	-
140 to 179 acres ..... farms	3	-	-	1	1	-
acres irrigated	41	-	-	(D)	(D)	-
180 to 219 acres ..... farms	1	-	-	-	-	-
acres irrigated	(D)	-	-	-	-	-
220 to 259 acres ..... farms	8	-	-	-	-	-
acres irrigated	574	-	-	-	-	-
260 to 499 acres ..... farms	13	3	1	5	-	-
acres irrigated	2,004	(D)	(D)	1,000	-	-
500 to 999 acres ..... farms	14	1	-	2	-	-
acres irrigated	2,075	(D)	-	(D)	-	-
1,000 to 1,999 acres ..... farms	10	1	-	3	-	-
acres irrigated	2,154	(D)	-	1,909	-	-
2,000 acres or more ..... farms	8	1	-	3	-	1
acres irrigated	20,958	(D)	-	1,172	-	(D)
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	-	1	2	1	5	1
acres irrigated	-	(D)	(D)	(D)	5	(D)
10 to 49 acres ..... farms	2	-	-	5	4	-
acres irrigated	(D)	-	-	9	(D)	-
50 to 69 acres ..... farms	2	-	-	6	-	-
acres irrigated	(D)	-	-	(D)	-	-
70 to 99 acres ..... farms	-	-	-	-	-	-
acres irrigated	-	-	-	-	-	-
100 to 139 acres ..... farms	1	-	-	-	-	-
acres irrigated	(D)	-	-	-	-	-
140 to 179 acres ..... farms	1	-	-	-	1	-
acres irrigated	(D)	-	-	-	(D)	-
180 to 219 acres ..... farms	1	-	-	5	-	1
acres irrigated	(D)	-	-	550	-	(D)
220 to 259 acres ..... farms	3	-	-	-	-	-
acres irrigated	340	-	-	-	-	-
260 to 499 acres ..... farms	6	-	1	4	-	-
acres irrigated	655	-	(D)	(D)	-	-
500 to 999 acres ..... farms	12	-	-	5	-	-
acres irrigated	1,919	-	-	596	-	-
1,000 to 1,999 acres ..... farms	13	4	-	5	-	3
acres irrigated	4,966	(D)	-	2,208	-	(D)
2,000 acres or more ..... farms	9	2	-	3	-	-
acres irrigated	18,466	(D)	-	1,260	-	-
Land with irrigation systems or equipment present (see text) ..... farms, 2022	66	10	3	19	7	1
acres, 2022	32,732	(D)	4	4,513	13	(D)

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Irrigated farms (see text) ..... number, 2022	23	7	11	22	1	12
2017	19	2	8	20	1	8
Land in irrigated farms ..... acres, 2022	10,871	(D)	24,250	2,878	(D)	6,394
2017	9,340	(D)	(D)	2,444	(D)	(D)
Harvested cropland ..... farms, 2022	22	7	11	22	1	12
2017	19	2	8	20	1	8
acres, 2022	9,336	(D)	21,501	2,161	(D)	4,247
2017	8,055	(D)	(D)	1,827	(D)	(D)
Other cropland, excluding cropland pastured ..... farms, 2022	11	2	8	9	-	6
2017	10	1	5	7	1	5
acres, 2022	340	(D)	1,520	121	-	728
2017	203	(D)	128	208	(D)	202
Pastureland, excluding woodland pastured ..... farms, 2022	2	1	2	7	1	6
2017	4	-	2	4	-	2
acres, 2022	(D)	(D)	(D)	94	(D)	652
2017	94	-	(D)	109	-	(D)
Irrigated land ..... acres, 2022	2,624	184	1,482	117	(D)	4,046
2017	1,794	(D)	367	132	(D)	(D)
Harvested cropland ..... farms, 2022	22	7	11	22	1	12
2017	19	2	6	19	1	8
acres, 2022	(D)	184	1,482	(D)	(D)	(D)
2017	1,794	(D)	(D)	(D)	(D)	(D)
Pastureland and other land ..... farms, 2022	1	-	-	1	-	2
2017	-	-	2	1	-	-
acres, 2022	(D)	-	-	(D)	-	(D)
2017	-	-	(D)	(D)	-	-
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	6	2	-	5	-	-
acres irrigated	6	(D)	-	14	-	-
10 to 49 acres ..... farms	4	3	4	9	-	-
acres irrigated	30	30	22	21	-	-
50 to 69 acres ..... farms	1	-	-	1	-	-
acres irrigated	(D)	-	-	(D)	-	-
70 to 99 acres ..... farms	-	-	-	2	-	1
acres irrigated	-	-	-	(D)	-	(D)
100 to 139 acres ..... farms	-	-	-	-	-	3
acres irrigated	-	-	-	-	-	4
140 to 179 acres ..... farms	2	-	-	-	-	2
acres irrigated	(D)	-	-	-	-	(D)
180 to 219 acres ..... farms	-	-	-	1	-	-
acres irrigated	-	-	-	(D)	-	-
220 to 259 acres ..... farms	-	-	-	-	-	-
acres irrigated	-	-	-	-	-	-
260 to 499 acres ..... farms	2	1	-	3	1	1
acres irrigated	(D)	(D)	-	32	(D)	(D)
500 to 999 acres ..... farms	6	-	-	-	-	3
acres irrigated	1,781	-	-	-	-	960
1,000 to 1,999 acres ..... farms	1	-	-	1	-	2
acres irrigated	(D)	-	-	(D)	-	(D)
2,000 acres or more ..... farms	1	1	7	-	-	-
acres irrigated	(D)	(D)	1,460	-	-	-
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	4	1	1	7	-	-
acres irrigated	4	(D)	(D)	7	-	-
10 to 49 acres ..... farms	5	-	2	5	-	1
acres irrigated	(D)	-	(D)	(D)	-	(D)
50 to 69 acres ..... farms	-	-	-	1	-	2
acres irrigated	-	-	-	(D)	-	(D)
70 to 99 acres ..... farms	3	-	-	1	1	1
acres irrigated	100	-	-	(D)	(D)	(D)
100 to 139 acres ..... farms	-	-	2	2	-	1
acres irrigated	-	-	(D)	(D)	-	(D)
140 to 179 acres ..... farms	1	-	-	1	-	1
acres irrigated	(D)	-	-	(D)	-	(D)
180 to 219 acres ..... farms	-	-	-	1	-	-
acres irrigated	-	-	-	(D)	-	-
220 to 259 acres ..... farms	1	-	-	-	-	1
acres irrigated	(D)	-	-	-	-	(D)
260 to 499 acres ..... farms	-	-	2	-	-	-
acres irrigated	-	-	(D)	-	-	-
500 to 999 acres ..... farms	1	-	-	2	-	-
acres irrigated	(D)	-	-	(D)	-	-
1,000 to 1,999 acres ..... farms	3	-	-	-	-	-
acres irrigated	1,024	-	-	-	-	-
2,000 acres or more ..... farms	1	1	1	-	-	1
acres irrigated	(D)	(D)	(D)	-	-	(D)
Land with irrigation systems or equipment present (see text) ..... farms, 2022	24	8	11	22	1	13
acres, 2022	2,694	314	1,482	128	(D)	4,331

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Irrigated farms (see text) ..... number, 2022	11	76	19	131	52	2
2017	11	60	20	140	39	2
Land in irrigated farms ..... acres, 2022	5,146	52,711	4,886	76,197	43,885	(D)
2017	4,650	41,291	3,953	76,104	26,606	(D)
Harvested cropland ..... farms, 2022	11	74	19	131	52	2
2017	11	58	20	140	35	2
acres, 2022	4,609	49,636	3,523	59,356	38,754	(D)
2017	4,404	36,588	3,072	62,708	25,216	(D)
Other cropland, excluding cropland pastured ..... farms, 2022	1	21	8	33	18	-
2017	3	18	9	34	9	-
acres, 2022	(D)	967	(D)	1,344	672	-
2017	44	1,287	128	1,040	523	-
Pastureland, excluding woodland pastured ..... farms, 2022	3	9	6	60	5	-
2017	1	12	11	61	11	2
acres, 2022	3	415	52	3,022	64	-
2017	(D)	543	202	3,927	104	(D)
Irrigated land ..... acres, 2022	532	12,715	467	18,480	6,556	(D)
2017	484	8,832	454	30,281	5,040	(D)
Harvested cropland ..... farms, 2022	11	74	19	130	51	2
2017	11	56	20	135	35	2
acres, 2022	532	12,676	467	18,283	(D)	(D)
2017	484	8,774	(D)	30,220	5,012	(D)
Pastureland and other land ..... farms, 2022	-	4	-	5	1	-
2017	-	4	1	7	4	-
acres, 2022	-	39	-	197	(D)	-
2017	-	58	(D)	61	28	-
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	5	18	-	12	7	2
acres irrigated	(D)	(D)	-	(D)	7	(D)
10 to 49 acres ..... farms	-	9	13	10	5	-
acres irrigated	-	103	(D)	98	69	-
50 to 69 acres ..... farms	-	1	1	5	1	-
acres irrigated	-	(D)	(D)	172	(D)	-
70 to 99 acres ..... farms	-	-	-	3	-	-
acres irrigated	-	-	-	(D)	-	-
100 to 139 acres ..... farms	-	1	-	-	1	-
acres irrigated	-	(D)	-	-	(D)	-
140 to 179 acres ..... farms	-	3	-	6	2	-
acres irrigated	-	216	-	365	(D)	-
180 to 219 acres ..... farms	-	-	-	5	-	-
acres irrigated	-	-	-	206	-	-
220 to 259 acres ..... farms	-	3	-	6	6	-
acres irrigated	-	275	-	588	285	-
260 to 499 acres ..... farms	-	9	4	37	1	-
acres irrigated	-	1,339	300	4,840	(D)	-
500 to 999 acres ..... farms	4	11	-	25	8	-
acres irrigated	312	1,834	-	4,495	1,494	-
1,000 to 1,999 acres ..... farms	2	14	-	14	16	-
acres irrigated	(D)	3,856	-	3,043	3,373	-
2,000 acres or more ..... farms	-	7	1	8	5	-
acres irrigated	-	5,055	(D)	4,634	1,022	-
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	4	6	5	5	4	2
acres irrigated	4	9	5	(D)	28	(D)
10 to 49 acres ..... farms	3	6	5	14	9	-
acres irrigated	10	55	19	91	13	-
50 to 69 acres ..... farms	-	2	3	2	-	-
acres irrigated	-	(D)	18	(D)	-	-
70 to 99 acres ..... farms	1	-	2	6	-	-
acres irrigated	(D)	-	(D)	107	-	-
100 to 139 acres ..... farms	-	2	-	5	2	-
acres irrigated	-	(D)	-	279	(D)	-
140 to 179 acres ..... farms	-	2	-	10	-	-
acres irrigated	-	(D)	-	448	-	-
180 to 219 acres ..... farms	-	-	-	6	1	-
acres irrigated	-	-	-	335	(D)	-
220 to 259 acres ..... farms	-	3	-	9	3	-
acres irrigated	-	450	-	1,155	600	-
260 to 499 acres ..... farms	-	12	2	36	1	-
acres irrigated	-	851	(D)	4,334	(D)	-
500 to 999 acres ..... farms	1	10	1	25	10	-
acres irrigated	(D)	2,033	(D)	6,258	2,659	-
1,000 to 1,999 acres ..... farms	2	13	2	16	6	-
acres irrigated	(D)	3,156	(D)	9,775	1,103	-
2,000 acres or more ..... farms	-	4	-	6	3	-
acres irrigated	-	2,038	-	7,488	388	-
Land with irrigation systems or equipment present (see text) ..... farms, 2022	14	85	27	142	53	2
acres, 2022	1,021	13,230	502	21,508	7,185	(D)

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Irrigated farms (see text) ..... number, 2022	16	4	9	40	246	1
2017	8	6	10	14	227	2
Land in irrigated farms ..... acres, 2022	2,077	928	14,718	2,704	211,580	(D)
2017	195	972	26,237	2,536	188,167	(D)
Harvested cropland ..... farms, 2022	16	4	9	40	244	1
2017	8	4	10	13	226	2
acres, 2022	1,604	926	13,751	1,719	170,246	(D)
2017	15	924	25,168	1,869	154,397	(D)
Other cropland, excluding cropland pastured ..... farms, 2022	6	-	6	16	97	1
2017	-	-	8	6	89	-
acres, 2022	129	-	(D)	195	5,857	(D)
2017	-	-	445	202	6,555	-
Pastureland, excluding woodland pastured ..... farms, 2022	4	-	4	20	99	1
2017	-	2	2	8	88	2
acres, 2022	80	-	66	321	12,152	(D)
2017	-	(D)	(D)	180	7,319	(D)
Irrigated land ..... acres, 2022	246	599	559	949	70,140	(D)
2017	10	88	1,432	133	75,537	(D)
Harvested cropland ..... farms, 2022	16	4	9	40	242	1
2017	8	4	10	10	226	2
acres, 2022	246	599	559	(D)	70,051	(D)
2017	10	(D)	1,432	18	75,486	(D)
Pastureland and other land ..... farms, 2022	-	-	-	2	6	-
2017	-	2	-	7	4	-
acres, 2022	-	-	-	(D)	89	-
2017	-	(D)	-	115	51	-
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	8	-	1	5	11	-
acres irrigated	10	-	(D)	5	(D)	-
10 to 49 acres ..... farms	3	-	2	17	12	-
acres irrigated	(D)	-	(D)	89	25	-
50 to 69 acres ..... farms	-	-	-	4	2	-
acres irrigated	-	-	-	74	(D)	-
70 to 99 acres ..... farms	-	-	2	7	10	-
acres irrigated	-	-	(D)	252	360	-
100 to 139 acres ..... farms	-	1	-	1	12	-
acres irrigated	-	(D)	-	(D)	805	-
140 to 179 acres ..... farms	1	-	-	3	10	-
acres irrigated	(D)	-	-	360	824	-
180 to 219 acres ..... farms	-	-	-	1	5	-
acres irrigated	-	-	-	(D)	334	-
220 to 259 acres ..... farms	1	-	-	1	5	-
acres irrigated	(D)	-	-	(D)	99	-
260 to 499 acres ..... farms	-	3	-	1	28	-
acres irrigated	-	(D)	-	(D)	3,110	-
500 to 999 acres ..... farms	3	-	1	-	86	-
acres irrigated	90	-	(D)	-	18,192	-
1,000 to 1,999 acres ..... farms	-	-	-	-	39	1
acres irrigated	-	-	-	-	15,848	(D)
2,000 acres or more ..... farms	-	-	3	-	26	-
acres irrigated	-	-	(D)	-	30,474	-
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	2	-	2	1	13	2
acres irrigated	(D)	-	(D)	(D)	(D)	(D)
10 to 49 acres ..... farms	6	2	-	7	10	-
acres irrigated	(D)	(D)	-	34	22	-
50 to 69 acres ..... farms	-	2	2	1	2	-
acres irrigated	-	(D)	(D)	(D)	(D)	-
70 to 99 acres ..... farms	-	-	-	1	13	-
acres irrigated	-	-	-	(D)	442	-
100 to 139 acres ..... farms	-	-	-	-	7	-
acres irrigated	-	-	-	-	317	-
140 to 179 acres ..... farms	-	-	-	-	7	-
acres irrigated	-	-	-	-	167	-
180 to 219 acres ..... farms	-	-	-	1	11	-
acres irrigated	-	-	-	(D)	987	-
220 to 259 acres ..... farms	-	-	-	-	12	-
acres irrigated	-	-	-	-	1,512	-
260 to 499 acres ..... farms	-	2	-	2	35	-
acres irrigated	-	(D)	-	(D)	3,844	-
500 to 999 acres ..... farms	-	-	-	-	52	-
acres irrigated	-	-	-	-	16,816	-
1,000 to 1,999 acres ..... farms	-	-	1	1	43	-
acres irrigated	-	-	(D)	(D)	27,031	-
2,000 acres or more ..... farms	-	-	5	-	22	-
acres irrigated	-	-	(D)	-	24,340	-
Land with irrigation systems or equipment present (see text) ..... farms, 2022	16	7	10	50	260	4
acres, 2022	246	703	793	968	75,702	4

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Irrigated farms (see text) ..... number, 2022	20	18	30	100	27	13
2017	26	7	26	102	36	8
Land in irrigated farms ..... acres, 2022	2,157	33,982	61,691	108,756	405	13,558
2017	3,770	11,488	42,213	98,066	428	15,868
Harvested cropland ..... farms, 2022	20	18	30	100	27	13
2017	26	7	25	102	36	8
acres, 2022	951	26,346	44,806	93,349	92	12,289
2017	1,470	9,597	37,809	83,635	232	15,451
Other cropland, excluding cropland pastured ..... farms, 2022	6	3	16	41	7	11
2017	5	1	19	47	5	2
acres, 2022	104	52	6,172	2,610	(D)	341
2017	55	(D)	3,342	5,904	11	(D)
Pastureland, excluding woodland pastured ..... farms, 2022	8	6	6	29	1	-
2017	13	4	9	36	7	1
acres, 2022	355	2,753	(D)	6,502	(D)	-
2017	599	1,656	299	5,252	64	(D)
Irrigated land ..... acres, 2022	145	4,800	13,059	34,945	70	915
2017	385	2,161	5,580	32,031	90	1,065
Harvested cropland ..... farms, 2022	20	18	30	97	27	13
2017	26	7	25	101	36	8
acres, 2022	145	4,800	12,744	34,481	70	915
2017	(D)	2,161	5,558	31,871	90	1,065
Pastureland and other land ..... farms, 2022	-	-	5	8	-	-
2017	2	-	3	5	-	-
acres, 2022	-	-	315	464	-	-
2017	(D)	-	22	160	-	-
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	3	1	3	2	24	-
acres irrigated	3	(D)	3	(D)	(D)	-
10 to 49 acres ..... farms	7	2	-	7	1	-
acres irrigated	14	(D)	-	147	(D)	-
50 to 69 acres ..... farms	3	-	-	-	-	-
acres irrigated	27	-	-	-	-	-
70 to 99 acres ..... farms	1	-	4	2	-	6
acres irrigated	(D)	-	34	(D)	-	6
100 to 139 acres ..... farms	-	-	4	4	-	-
acres irrigated	-	-	6	159	-	-
140 to 179 acres ..... farms	2	1	-	3	2	-
acres irrigated	(D)	(D)	-	288	(D)	-
180 to 219 acres ..... farms	1	-	-	6	-	-
acres irrigated	(D)	-	-	238	-	-
220 to 259 acres ..... farms	1	-	-	1	-	-
acres irrigated	(D)	-	-	(D)	-	-
260 to 499 acres ..... farms	1	1	5	17	-	-
acres irrigated	(D)	(D)	1,033	2,553	-	-
500 to 999 acres ..... farms	1	1	1	21	-	2
acres irrigated	(D)	(D)	(D)	5,023	-	(D)
1,000 to 1,999 acres ..... farms	-	7	2	20	-	3
acres irrigated	-	2,564	(D)	8,363	-	(D)
2,000 acres or more ..... farms	-	5	11	17	-	2
acres irrigated	-	1,993	9,873	17,874	-	(D)
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	5	1	2	-	27	-
acres irrigated	5	(D)	(D)	-	45	-
10 to 49 acres ..... farms	9	1	3	9	8	1
acres irrigated	(D)	(D)	26	58	(D)	(D)
50 to 69 acres ..... farms	-	-	2	-	-	-
acres irrigated	-	-	(D)	-	-	-
70 to 99 acres ..... farms	1	-	1	1	-	-
acres irrigated	(D)	-	(D)	(D)	-	-
100 to 139 acres ..... farms	3	-	3	2	-	-
acres irrigated	62	-	3	(D)	-	-
140 to 179 acres ..... farms	3	1	-	5	-	-
acres irrigated	4	(D)	-	321	-	-
180 to 219 acres ..... farms	-	-	-	3	1	-
acres irrigated	-	-	-	(D)	(D)	-
220 to 259 acres ..... farms	3	-	-	4	-	-
acres irrigated	5	-	-	402	-	-
260 to 499 acres ..... farms	-	-	2	20	-	-
acres irrigated	-	-	(D)	3,194	-	-
500 to 999 acres ..... farms	1	-	4	23	-	-
acres irrigated	(D)	-	(D)	6,011	-	-
1,000 to 1,999 acres ..... farms	1	2	2	21	-	2
acres irrigated	(D)	(D)	(D)	4,763	-	(D)
2,000 acres or more ..... farms	-	2	7	14	-	5
acres irrigated	-	(D)	4,756	16,878	-	(D)
Land with irrigation systems or equipment present (see text) ..... farms, 2022	30	19	34	108	32	14
acres, 2022	206	4,980	19,469	37,148	83	1,255

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
Irrigated farms (see text) ..... number, 2022	21	14	55	9	-	72
2017	6	9	35	4	5	66
Land in irrigated farms ..... acres, 2022	3,986	12,818	31,531	(D)	-	15,431
2017	474	23,544	24,405	(D)	795	11,374
Harvested cropland ..... farms, 2022	20	14	55	3	-	72
2017	6	8	35	4	5	66
acres, 2022	3,896	12,151	29,299	(D)	-	9,390
2017	(D)	22,445	23,626	(D)	(D)	(D)
Other cropland, excluding cropland pastured ..... farms, 2022	2	-	21	8	-	15
2017	1	6	13	-	1	22
acres, 2022	(D)	-	495	20	-	294
2017	(D)	971	140	-	(D)	364
Pastureland, excluding woodland pastured ..... farms, 2022	2	2	15	2	-	25
2017	1	1	1	1	4	12
acres, 2022	(D)	(D)	99	(D)	-	328
2017	(D)	(D)	(D)	(D)	120	307
Irrigated land ..... acres, 2022	376	1,935	2,271	(D)	-	(D)
2017	48	1,214	2,830	(D)	37	(D)
Harvested cropland ..... farms, 2022	20	14	55	2	-	72
2017	6	8	35	3	5	65
acres, 2022	(D)	1,935	2,267	(D)	-	(D)
2017	48	(D)	2,830	(D)	37	(D)
Pastureland and other land ..... farms, 2022	1	-	4	7	-	3
2017	-	1	-	1	-	1
acres, 2022	(D)	-	4	(D)	-	3
2017	-	(D)	-	(D)	-	(D)
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	6	-	12	6	-	15
acres irrigated	6	-	(D)	6	-	17
10 to 49 acres ..... farms	7	6	22	-	-	28
acres irrigated	130	67	80	-	-	46
50 to 69 acres ..... farms	-	-	6	-	-	5
acres irrigated	-	-	155	-	-	6
70 to 99 acres ..... farms	-	-	1	-	-	5
acres irrigated	-	-	(D)	-	-	62
100 to 139 acres ..... farms	-	-	1	-	-	6
acres irrigated	-	-	(D)	-	-	(D)
140 to 179 acres ..... farms	1	-	-	-	-	-
acres irrigated	(D)	-	-	-	-	-
180 to 219 acres ..... farms	-	1	-	-	-	4
acres irrigated	-	(D)	-	-	-	(D)
220 to 259 acres ..... farms	-	-	-	-	-	3
acres irrigated	-	-	-	-	-	35
260 to 499 acres ..... farms	3	3	4	-	-	4
acres irrigated	(D)	(D)	675	-	-	301
500 to 999 acres ..... farms	4	-	-	1	-	-
acres irrigated	4	-	-	(D)	-	-
1,000 to 1,999 acres ..... farms	-	1	1	-	-	-
acres irrigated	-	(D)	(D)	-	-	-
2,000 acres or more ..... farms	-	3	8	2	-	2
acres irrigated	-	1,419	1,183	(D)	-	(D)
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	3	1	7	2	-	16
acres irrigated	(D)	(D)	8	(D)	-	16
10 to 49 acres ..... farms	-	1	12	-	4	21
acres irrigated	-	(D)	91	-	(D)	27
50 to 69 acres ..... farms	-	-	2	-	-	9
acres irrigated	-	-	(D)	-	-	54
70 to 99 acres ..... farms	-	-	1	-	-	4
acres irrigated	-	-	(D)	-	-	27
100 to 139 acres ..... farms	-	1	1	-	-	10
acres irrigated	-	(D)	(D)	-	-	14
140 to 179 acres ..... farms	3	-	-	-	-	-
acres irrigated	(D)	-	-	-	-	-
180 to 219 acres ..... farms	-	-	-	-	-	3
acres irrigated	-	-	-	-	-	4
220 to 259 acres ..... farms	-	-	-	-	-	1
acres irrigated	-	-	-	-	-	(D)
260 to 499 acres ..... farms	-	1	1	-	-	-
acres irrigated	-	(D)	(D)	-	-	-
500 to 999 acres ..... farms	-	-	1	-	1	1
acres irrigated	-	-	(D)	-	(D)	(D)
1,000 to 1,999 acres ..... farms	-	-	7	-	-	-
acres irrigated	-	-	1,492	-	-	-
2,000 acres or more ..... farms	-	5	3	2	-	1
acres irrigated	-	1,160	807	(D)	-	(D)
Land with irrigation systems or equipment present (see text) ..... farms, 2022	22	20	62	9	3	80
acres, 2022	486	1,941	2,361	(D)	6	(D)

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Irrigated farms (see text) ..... number, 2022	27	96	13	325	18	55
2017	16	92	5	341	18	60
Land in irrigated farms ..... acres, 2022	1,142	52,859	15,194	196,325	11,184	95,434
2017	285	56,873	6,109	166,345	5,166	77,266
Harvested cropland ..... farms, 2022	27	94	13	324	18	55
2017	16	88	3	340	18	60
acres, 2022	509	43,957	14,158	170,622	10,823	89,392
2017	68	47,845	5,703	138,624	4,845	72,260
Other cropland, excluding cropland pastured ..... farms, 2022	11	38	5	88	10	28
2017	8	31	2	116	5	20
acres, 2022	78	3,389	(D)	4,484	153	1,934
2017	44	1,624	(D)	4,819	112	648
Pastureland, excluding woodland pastured ..... farms, 2022	10	25	-	140	1	6
2017	2	13	3	127	2	11
acres, 2022	204	2,536	-	7,715	(D)	1,717
2017	(D)	1,860	11	9,284	(D)	2,288
Irrigated land ..... acres, 2022	154	37,673	1,062	58,778	2,337	22,814
2017	37	36,442	531	51,762	1,953	21,283
Harvested cropland ..... farms, 2022	26	94	13	324	18	55
2017	16	88	3	337	18	59
acres, 2022	(D)	37,573	1,062	58,201	2,337	22,814
2017	37	36,415	(D)	51,502	1,953	(D)
Pastureland and other land ..... farms, 2022	1	7	-	15	-	-
2017	-	5	2	8	-	1
acres, 2022	(D)	100	-	577	-	-
2017	-	27	(D)	260	-	(D)
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	5	18	7	20	2	6
acres irrigated	7	37	(D)	35	(D)	6
10 to 49 acres ..... farms	17	13	1	41	5	3
acres irrigated	55	49	(D)	233	38	116
50 to 69 acres ..... farms	-	2	-	4	1	-
acres irrigated	-	(D)	-	102	(D)	-
70 to 99 acres ..... farms	1	4	-	13	1	-
acres irrigated	(D)	77	-	367	(D)	-
100 to 139 acres ..... farms	1	8	-	15	-	-
acres irrigated	(D)	249	-	1,006	-	-
140 to 179 acres ..... farms	1	1	-	12	-	2
acres irrigated	(D)	(D)	-	762	-	(D)
180 to 219 acres ..... farms	1	2	-	23	2	-
acres irrigated	(D)	(D)	-	1,816	(D)	-
220 to 259 acres ..... farms	-	5	-	16	1	3
acres irrigated	-	519	-	1,126	(D)	(D)
260 to 499 acres ..... farms	1	9	-	70	1	4
acres irrigated	(D)	1,823	-	8,855	(D)	645
500 to 999 acres ..... farms	-	11	-	60	2	8
acres irrigated	-	6,860	-	11,699	(D)	1,951
1,000 to 1,999 acres ..... farms	-	21	-	34	-	13
acres irrigated	-	22,331	-	11,122	-	3,619
2,000 acres or more ..... farms	-	2	5	17	3	16
acres irrigated	-	(D)	1,028	21,655	1,284	16,276
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	3	15	3	8	2	1
acres irrigated	6	42	(D)	13	(D)	(D)
10 to 49 acres ..... farms	13	11	-	27	2	2
acres irrigated	31	79	-	127	(D)	(D)
50 to 69 acres ..... farms	-	1	-	9	-	-
acres irrigated	-	(D)	-	140	-	-
70 to 99 acres ..... farms	-	6	-	6	2	-
acres irrigated	-	347	-	136	(D)	-
100 to 139 acres ..... farms	-	1	-	14	-	1
acres irrigated	-	(D)	-	975	-	(D)
140 to 179 acres ..... farms	-	3	-	12	1	2
acres irrigated	-	522	-	760	(D)	(D)
180 to 219 acres ..... farms	-	4	-	24	-	2
acres irrigated	-	255	-	2,557	-	(D)
220 to 259 acres ..... farms	-	2	-	37	7	6
acres irrigated	-	(D)	-	3,090	1,378	504
260 to 499 acres ..... farms	-	5	-	104	2	9
acres irrigated	-	1,057	-	12,138	(D)	855
500 to 999 acres ..... farms	-	20	-	64	1	15
acres irrigated	-	8,969	-	11,568	(D)	4,722
1,000 to 1,999 acres ..... farms	-	22	-	23	1	13
acres irrigated	-	20,935	-	7,306	(D)	5,644
2,000 acres or more ..... farms	-	2	2	13	-	9
acres irrigated	-	(D)	(D)	12,952	-	8,954
Land with irrigation systems or equipment present (see text) ..... farms, 2022	33	110	13	349	20	59
acres, 2022	176	38,954	1,154	64,197	2,457	24,258

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Irrigated farms (see text) ..... number, 2022	73	84	3	41	50	14
2017	103	91	4	22	66	3
Land in irrigated farms ..... acres, 2022	91,540	61,950	(D)	11,081	51,947	1,094
2017	117,963	55,088	8,077	9,489	38,527	1,947
Harvested cropland ..... farms, 2022	73	84	3	39	50	14
2017	103	91	4	22	66	3
acres, 2022	82,603	52,098	(D)	8,849	45,381	1,061
2017	111,405	41,957	7,802	6,445	31,417	1,589
Other cropland, excluding cropland pastured ..... farms, 2022	35	22	1	7	17	5
2017	54	30	1	9	20	-
acres, 2022	3,469	1,247	(D)	264	1,150	10
2017	2,037	3,243	(D)	(D)	837	-
Pastureland, excluding woodland pastured ..... farms, 2022	10	32	-	5	21	2
2017	20	56	1	8	28	1
acres, 2022	2,253	3,418	-	373	1,638	(D)
2017	2,005	3,452	(D)	69	2,086	(D)
Irrigated land ..... acres, 2022	22,593	17,221	44	2,185	32,840	967
2017	26,837	12,934	794	1,735	15,735	(D)
Harvested cropland ..... farms, 2022	73	82	3	38	50	14
2017	103	87	4	22	66	2
acres, 2022	(D)	17,106	44	2,121	(D)	967
2017	(D)	12,827	794	1,735	15,500	(D)
Pastureland and other land ..... farms, 2022	1	6	-	3	1	-
2017	2	4	-	-	3	1
acres, 2022	(D)	115	-	64	(D)	-
2017	(D)	107	-	-	235	(D)
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	-	3	-	14	-	5
acres irrigated	-	(D)	-	15	-	5
10 to 49 acres ..... farms	6	7	-	5	-	2
acres irrigated	174	18	-	18	-	(D)
50 to 69 acres ..... farms	-	2	-	-	-	-
acres irrigated	-	(D)	-	-	-	-
70 to 99 acres ..... farms	-	5	-	3	4	-
acres irrigated	-	181	-	(D)	(D)	-
100 to 139 acres ..... farms	2	5	-	2	1	6
acres irrigated	(D)	262	-	(D)	(D)	(D)
140 to 179 acres ..... farms	1	5	2	4	-	-
acres irrigated	(D)	193	(D)	301	-	-
180 to 219 acres ..... farms	3	5	-	1	6	-
acres irrigated	222	651	-	(D)	465	-
220 to 259 acres ..... farms	5	5	-	1	1	1
acres irrigated	645	668	-	(D)	(D)	(D)
260 to 499 acres ..... farms	15	10	-	5	13	-
acres irrigated	1,955	1,015	-	539	2,335	-
500 to 999 acres ..... farms	11	11	-	3	5	-
acres irrigated	2,085	1,596	-	774	1,126	-
1,000 to 1,999 acres ..... farms	14	17	1	3	10	-
acres irrigated	3,622	5,238	(D)	(D)	7,830	-
2,000 acres or more ..... farms	16	9	-	-	10	-
acres irrigated	13,726	7,392	-	-	20,869	-
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	3	1	-	1	-	-
acres irrigated	9	(D)	-	(D)	-	-
10 to 49 acres ..... farms	-	11	-	9	4	1
acres irrigated	-	21	-	9	4	(D)
50 to 69 acres ..... farms	-	3	-	-	-	-
acres irrigated	-	(D)	-	-	-	-
70 to 99 acres ..... farms	-	4	-	-	1	-
acres irrigated	-	4	-	-	(D)	-
100 to 139 acres ..... farms	1	3	-	2	3	-
acres irrigated	(D)	100	-	(D)	71	-
140 to 179 acres ..... farms	3	8	-	-	1	-
acres irrigated	241	555	-	-	(D)	-
180 to 219 acres ..... farms	2	4	-	-	2	-
acres irrigated	(D)	174	-	-	(D)	-
220 to 259 acres ..... farms	2	1	-	2	3	-
acres irrigated	(D)	(D)	-	(D)	90	-
260 to 499 acres ..... farms	30	22	1	1	33	-
acres irrigated	3,915	2,392	(D)	(D)	4,479	-
500 to 999 acres ..... farms	14	14	-	4	8	2
acres irrigated	3,102	1,555	-	1,106	2,685	(D)
1,000 to 1,999 acres ..... farms	34	16	1	2	8	-
acres irrigated	9,481	5,471	(D)	(D)	3,242	-
2,000 acres or more ..... farms	14	4	2	1	3	-
acres irrigated	9,749	2,611	(D)	(D)	4,993	-
Land with irrigation systems or equipment present (see text) ..... farms, 2022	84	90	4	46	57	14
acres, 2022	25,666	18,278	76	2,309	33,912	971

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Table 10. **Irrigation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Irrigated farms (see text) ..... number, 2022	78	35	9	31	119	5
2017	94	30	10	16	97	8
Land in irrigated farms ..... acres, 2022	11,654	35,867	13,372	1,461	26,781	2,354
2017	19,281	38,854	11,569	1,007	45,820	2,442
Harvested cropland ..... farms, 2022	78	35	9	25	119	5
2017	94	30	10	16	95	8
acres, 2022	9,018	35,330	12,503	308	22,499	2,125
2017	15,969	36,979	10,060	167	42,098	2,151
Other cropland, excluding cropland pastured ..... farms, 2022	22	3	6	10	33	3
2017	36	11	3	4	15	2
acres, 2022	486	16	343	88	911	90
2017	540	878	789	(D)	800	(D)
Pastureland, excluding woodland pastured ..... farms, 2022	5	1	-	11	34	1
2017	15	7	1	4	27	5
acres, 2022	49	(D)	-	225	835	(D)
2017	201	66	(D)	55	457	105
Irrigated land ..... acres, 2022	2,840	8,318	515	46	7,775	807
2017	4,127	6,828	1,227	27	6,837	535
Harvested cropland ..... farms, 2022	78	35	9	23	118	5
2017	92	30	10	16	93	8
acres, 2022	(D)	8,318	515	38	7,751	807
2017	(D)	6,828	1,227	27	6,791	535
Pastureland and other land ..... farms, 2022	1	-	-	8	6	-
2017	2	-	-	-	7	-
acres, 2022	(D)	-	-	8	24	-
2017	(D)	-	-	-	46	-
2022 irrigated acres by size of farm:						
1 to 9 acres ..... farms	27	4	-	10	25	-
acres irrigated	54	4	-	14	29	-
10 to 49 acres ..... farms	25	4	4	11	34	2
acres irrigated	149	40	9	16	245	(D)
50 to 69 acres ..... farms	11	-	-	2	11	-
acres irrigated	172	-	-	(D)	166	-
70 to 99 acres ..... farms	2	-	-	1	5	-
acres irrigated	(D)	-	-	(D)	76	-
100 to 139 acres ..... farms	1	-	-	6	4	-
acres irrigated	(D)	-	-	6	189	-
140 to 179 acres ..... farms	-	1	-	-	4	-
acres irrigated	-	(D)	-	-	277	-
180 to 219 acres ..... farms	1	-	-	-	7	-
acres irrigated	(D)	-	-	-	779	-
220 to 259 acres ..... farms	-	-	-	-	2	1
acres irrigated	-	-	-	-	(D)	(D)
260 to 499 acres ..... farms	3	-	-	1	9	-
acres irrigated	(D)	-	-	(D)	1,110	-
500 to 999 acres ..... farms	3	15	-	-	10	1
acres irrigated	(D)	2,773	-	-	3,019	(D)
1,000 to 1,999 acres ..... farms	5	2	3	-	6	1
acres irrigated	1,538	(D)	(D)	-	1,416	(D)
2,000 acres or more ..... farms	-	9	2	-	2	-
acres irrigated	-	5,349	(D)	-	(D)	-
2017 irrigated acres by size of farm:						
1 to 9 acres ..... farms	31	1	3	5	16	1
acres irrigated	47	(D)	(D)	9	27	(D)
10 to 49 acres ..... farms	24	1	-	7	25	-
acres irrigated	80	(D)	-	11	201	-
50 to 69 acres ..... farms	8	-	-	1	4	3
acres irrigated	68	-	-	(D)	141	75
70 to 99 acres ..... farms	11	-	-	1	7	-
acres irrigated	46	-	-	(D)	232	-
100 to 139 acres ..... farms	2	-	1	-	3	-
acres irrigated	(D)	-	(D)	-	102	-
140 to 179 acres ..... farms	-	4	-	-	3	-
acres irrigated	-	(D)	-	-	103	-
180 to 219 acres ..... farms	1	-	-	1	1	2
acres irrigated	(D)	-	-	(D)	(D)	(D)
220 to 259 acres ..... farms	1	-	-	-	2	-
acres irrigated	(D)	-	-	-	(D)	-
260 to 499 acres ..... farms	3	-	-	1	11	-
acres irrigated	(D)	-	-	(D)	943	-
500 to 999 acres ..... farms	4	11	-	-	4	1
acres irrigated	856	2,384	-	-	372	(D)
1,000 to 1,999 acres ..... farms	8	3	3	-	15	1
acres irrigated	1,776	850	707	-	3,615	(D)
2,000 acres or more ..... farms	1	10	3	-	6	-
acres irrigated	(D)	3,430	516	-	860	-
Land with irrigation systems or equipment present (see text) ..... farms, 2022	82	36	12	33	120	6
acres, 2022	2,964	8,563	530	347	7,921	827

Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
INVENTORY					
Cattle and calves ..... farms, 2022	16,823	180	43	295	222
2017	20,969	213	63	308	272
number, 2022	2,121,625	7,879	886	30,827	13,648
2017	2,337,505	8,615	1,031	26,645	16,451
Farms by inventory:					
1 to 9 ..... farms, 2022	3,446	46	20	60	37
2017	4,141	45	29	52	59
number, 2022	17,165	(D)	81	312	(D)
2017	20,640	231	(D)	301	322
10 to 19 ..... farms, 2022	2,534	41	10	56	44
2017	3,109	53	16	57	42
number, 2022	34,775	584	141	800	595
2017	42,745	760	220	766	587
20 to 49 ..... farms, 2022	4,022	51	9	53	68
2017	5,084	64	16	80	87
number, 2022	126,869	1,469	344	1,706	2,156
2017	160,321	1,908	489	2,613	2,636
50 to 99 ..... farms, 2022	2,582	26	2	46	41
2017	3,336	30	2	57	37
number, 2022	177,582	1,788	(D)	3,330	2,733
2017	232,916	2,089	(D)	4,000	2,495
100 to 199 ..... farms, 2022	1,927	12	2	44	15
2017	2,715	18	-	36	29
number, 2022	263,233	1,782	(D)	5,757	1,966
2017	370,565	2,312	-	4,744	3,571
200 to 499 ..... farms, 2022	1,348	3	-	23	15
2017	1,682	2	-	20	15
number, 2022	397,131	(D)	-	6,075	4,617
2017	499,079	(D)	-	6,058	4,377
500 or more ..... farms, 2022	964	1	-	13	2
2017	902	1	-	6	3
number, 2022	1,104,870	(D)	-	12,847	(D)
2017	1,011,239	(D)	-	8,163	2,463
Cows and heifers that calved ..... farms, 2022	13,439	163	29	263	207
2017	16,346	193	39	272	248
number, 2022	824,165	3,744	475	15,693	7,090
2017	826,015	4,357	(D)	12,433	9,884
Beef cows ..... farms, 2022	11,691	161	29	233	206
2017	13,339	191	39	234	243
number, 2022	364,629	3,739	475	7,232	7,080
2017	368,214	4,240	(D)	6,154	9,801
2022 farms by inventory:					
1 to 9 ..... farms	3,718	69	16	74	47
number	17,682	(D)	99	342	216
10 to 19 ..... farms	2,619	31	3	48	43
number	35,814	423	(D)	679	582
20 to 49 ..... farms	3,494	44	8	60	77
number	104,830	1,316	226	1,903	2,276
50 to 99 ..... farms	1,205	13	2	39	29
number	79,467	817	(D)	2,712	1,879
100 to 199 ..... farms	470	1	-	9	7
number	59,183	(D)	-	996	1,017
200 to 499 ..... farms	149	3	-	3	2
number	41,955	600	-	600	(D)
500 or more ..... farms	36	-	-	-	1
number	25,698	-	-	-	(D)
Milk cows ..... farms, 2022	2,185	5	-	43	6
2017	3,644	9	2	52	12
number, 2022	459,536	5	-	8,461	10
2017	457,801	117	(D)	6,279	83
2022 farms by inventory:					
1 to 9 ..... farms	328	5	-	8	6
number	966	5	-	(D)	10
10 to 19 ..... farms	82	-	-	-	-
number	1,107	-	-	-	-
20 to 49 ..... farms	233	-	-	8	-
number	8,110	-	-	294	-
50 to 99 ..... farms	573	-	-	14	-
number	41,268	-	-	970	-
100 to 199 ..... farms	418	-	-	3	-
number	54,967	-	-	390	-
200 to 499 ..... farms	390	-	-	2	-
number	119,479	-	-	(D)	-
500 or more ..... farms	161	-	-	8	-
number	233,639	-	-	6,159	-
Other cattle ..... farms, 2022	14,574	150	33	263	177
2017	18,140	173	48	240	223
number, 2022	1,297,460	4,135	411	15,134	6,558
2017	1,511,490	4,258	(D)	14,212	6,567
2022 farms by inventory:					
1 to 9 ..... farms	4,477	70	18	98	73
number	20,327	(D)	81	452	(D)
10 to 19 ..... farms	2,483	29	8	42	25
number	33,446	351	94	565	370
20 to 49 ..... farms	3,199	31	7	53	51
number	97,678	844	236	1,697	1,607
50 to 99 ..... farms	1,799	10	-	36	12
number	122,364	642	-	2,416	786
100 to 199 ..... farms	1,173	6	-	19	7
number	156,424	748	-	2,375	871
200 to 499 ..... farms	859	3	-	10	8
number	256,663	636	-	3,221	2,116
500 or more ..... farms	584	1	-	5	1
number	610,558	(D)	-	4,408	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
INVENTORY						
Cattle and calves	farms, 2022	288	59	87	208	220
	2017	362	94	122	266	271
	number, 2022	44,073	4,375	5,372	33,601	7,167
	2017	33,372	13,273	12,160	42,072	9,957
Farms by inventory:						
1 to 9	farms, 2022	65	6	28	25	49
	2017	56	11	31	35	58
	number, 2022	328	34	102	142	259
	2017	321	28	198	182	330
10 to 19	farms, 2022	62	10	14	18	45
	2017	57	10	17	30	48
	number, 2022	832	135	194	240	616
	2017	826	137	249	425	643
20 to 49	farms, 2022	58	16	25	45	87
	2017	104	19	38	42	90
	number, 2022	1,795	559	774	1,533	2,632
	2017	3,306	639	1,214	1,431	2,593
50 to 99	farms, 2022	49	13	7	35	29
	2017	58	22	17	58	61
	number, 2022	3,063	972	436	2,544	2,068
	2017	4,182	1,461	1,038	4,199	4,105
100 to 199	farms, 2022	30	10	9	38	6
	2017	57	16	14	45	11
	number, 2022	4,103	1,538	1,216	5,634	672
	2017	7,694	2,154	1,643	5,758	1,453
200 to 499	farms, 2022	12	4	-	32	4
	2017	15	7	3	31	3
	number, 2022	3,322	1,137	-	9,941	920
	2017	4,229	2,694	(D)	11,038	833
500 or more	farms, 2022	12	-	4	15	-
	2017	15	9	2	25	-
	number, 2022	30,630	-	2,650	13,567	-
	2017	12,814	6,160	(D)	19,039	-
Cows and heifers that calved	farms, 2022	230	47	54	125	208
	2017	288	63	79	154	249
	number, 2022	20,960	1,562	897	8,754	3,955
	2017	14,417	2,563	1,723	8,420	5,879
Beef cows	farms, 2022	191	47	53	91	206
	2017	204	57	67	104	243
	number, 2022	3,799	1,562	(D)	4,057	(D)
	2017	4,013	2,545	1,347	2,664	5,312
2022 farms by inventory:						
1 to 9	farms	81	12	23	14	67
	number	(D)	75	106	71	(D)
10 to 19	farms	47	8	16	17	65
	number	626	95	234	220	882
20 to 49	farms	49	16	11	39	62
	number	1,511	496	254	1,246	1,892
50 to 99	farms	12	8	1	13	12
	number	884	556	(D)	834	835
100 to 199	farms	1	3	2	5	-
	number	(D)	340	(D)	666	-
200 to 499	farms	1	-	-	2	-
	number	(D)	-	-	(D)	-
500 or more	farms	-	-	-	1	-
	number	-	-	-	(D)	-
Milk cows	farms, 2022	45	-	1	38	3
	2017	86	6	12	54	12
	number, 2022	17,161	-	(D)	4,697	(D)
	2017	10,404	18	376	5,756	567
2022 farms by inventory:						
1 to 9	farms	5	-	-	1	2
	number	16	-	-	(D)	(D)
10 to 19	farms	-	-	1	-	1
	number	-	-	(D)	-	(D)
20 to 49	farms	10	-	-	1	-
	number	372	-	-	(D)	-
50 to 99	farms	11	-	-	10	-
	number	830	-	-	(D)	-
100 to 199	farms	7	-	-	22	-
	number	862	-	-	3,006	-
200 to 499	farms	8	-	-	4	-
	number	2,194	-	-	956	-
500 or more	farms	4	-	-	-	-
	number	12,887	-	-	-	-
Other cattle	farms, 2022	241	55	76	194	186
	2017	312	84	112	249	224
	number, 2022	23,113	2,813	4,475	24,847	3,212
	2017	18,955	10,710	10,437	33,652	4,078
2022 farms by inventory:						
1 to 9	farms	89	11	29	31	81
	number	405	(D)	113	155	376
10 to 19	farms	48	10	21	21	52
	number	593	128	312	279	658
20 to 49	farms	31	11	10	52	43
	number	1,006	306	317	1,614	1,251
50 to 99	farms	47	15	6	36	6
	number	3,118	1,026	384	2,469	329
100 to 199	farms	7	7	6	22	4
	number	882	956	699	2,948	598
200 to 499	farms	15	1	-	20	-
	number	4,070	(D)	-	5,697	-
500 or more	farms	4	-	4	12	-
	number	13,039	-	2,650	11,685	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
INVENTORY						
Cattle and calves ..... farms, 2022	173	216	46	168	118	196
2017	252	204	88	276	167	201
number, 2022	19,459	15,184	16,299	5,723	7,952	16,505
2017	22,107	20,897	22,613	10,016	9,974	16,450
Farms by inventory:						
1 to 9 ..... farms, 2022	35	49	14	63	29	31
2017	46	32	11	104	50	38
number, 2022	186	237	63	(D)	128	112
2017	242	176	48	460	200	173
10 to 19 ..... farms, 2022	19	41	7	45	18	18
2017	37	37	15	68	26	22
number, 2022	245	596	78	607	228	244
2017	504	534	224	906	355	328
20 to 49 ..... farms, 2022	31	56	11	35	20	45
2017	59	68	25	59	36	43
number, 2022	1,007	1,915	280	1,148	603	1,321
2017	1,857	2,345	765	1,943	1,133	1,315
50 to 99 ..... farms, 2022	28	31	6	10	19	59
2017	29	27	15	24	33	47
number, 2022	1,975	2,023	442	589	1,337	3,915
2017	1,865	1,939	1,036	1,826	2,328	3,248
100 to 199 ..... farms, 2022	25	22	-	13	24	27
2017	49	19	3	9	13	33
number, 2022	3,483	2,667	-	1,857	3,616	3,821
2017	7,082	2,660	306	(D)	(D)	4,211
200 to 499 ..... farms, 2022	29	10	4	-	8	11
2017	28	14	11	11	7	15
number, 2022	8,028	2,966	1,336	-	2,040	3,360
2017	7,304	4,139	4,181	3,015	2,151	4,901
500 or more ..... farms, 2022	6	7	4	2	-	5
2017	4	7	8	1	2	3
number, 2022	4,535	4,780	14,100	(D)	-	3,732
2017	3,253	9,104	16,053	(D)	(D)	2,274
Cows and heifers that calved ..... farms, 2022	139	199	25	133	106	184
2017	195	186	61	212	138	186
number, 2022	8,367	8,872	(D)	2,860	3,949	9,602
2017	9,583	9,829	9,667	4,164	5,106	9,286
Beef cows ..... farms, 2022	100	199	24	120	94	178
2017	126	183	60	197	123	179
number, 2022	2,250	8,782	536	1,648	3,379	9,563
2017	2,081	9,407	(D)	2,412	4,058	8,944
2022 farms by inventory:						
1 to 9 ..... farms	39	51	12	60	31	30
number	171	245	(D)	253	(D)	133
10 to 19 ..... farms	26	40	4	30	15	16
number	357	563	57	401	208	232
20 to 49 ..... farms	24	65	6	26	22	82
number	804	1,895	190	697	673	2,555
50 to 99 ..... farms	7	25	-	4	14	27
number	352	1,865	-	297	955	1,897
100 to 199 ..... farms	4	10	2	-	11	17
number	566	1,273	(D)	-	1,180	2,225
200 to 499 ..... farms	-	8	-	-	1	3
number	-	2,941	-	-	(D)	864
500 or more ..... farms	-	-	-	-	-	3
number	-	-	-	-	-	1,657
Milk cows ..... farms, 2022	41	3	1	16	14	11
2017	78	8	1	19	23	12
number, 2022	6,117	90	(D)	1,212	570	39
2017	7,502	422	(D)	1,752	1,048	342
2022 farms by inventory:						
1 to 9 ..... farms	2	-	-	8	6	10
number	(D)	-	-	24	(D)	(D)
10 to 19 ..... farms	1	-	-	-	-	1
number	(D)	-	-	-	-	(D)
20 to 49 ..... farms	5	3	-	2	2	-
number	(D)	90	-	(D)	(D)	-
50 to 99 ..... farms	10	-	-	2	6	-
number	697	-	-	(D)	498	-
100 to 199 ..... farms	12	-	-	2	-	-
number	1,440	-	-	(D)	-	-
200 to 499 ..... farms	11	-	-	2	-	-
number	3,755	-	-	(D)	-	-
500 or more ..... farms	-	-	1	-	-	-
number	-	-	(D)	-	-	-
Other cattle ..... farms, 2022	156	192	40	120	107	171
2017	225	175	68	220	152	165
number, 2022	11,092	6,312	(D)	2,863	4,003	6,903
2017	12,524	11,068	12,946	5,852	4,868	7,164
2022 farms by inventory:						
1 to 9 ..... farms	38	91	16	53	39	52
number	(D)	365	67	(D)	(D)	(D)
10 to 19 ..... farms	27	30	1	32	18	23
number	345	411	(D)	424	274	277
20 to 49 ..... farms	29	45	13	21	20	57
number	879	1,149	366	656	743	1,732
50 to 99 ..... farms	24	12	4	9	16	25
number	1,526	864	318	591	1,078	1,688
100 to 199 ..... farms	18	3	-	3	13	10
number	2,539	526	-	380	1,460	1,391
200 to 499 ..... farms	19	11	2	2	1	3
number	5,018	2,997	(D)	(D)	(D)	992
500 or more ..... farms	1	-	4	-	-	1
number	(D)	-	6,100	-	-	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
INVENTORY						
Cattle and calves ... farms, 2022	4	121	163	189	179	238
2017	3	149	194	190	174	273
number, 2022	49	18,565	6,631	33,205	23,457	14,600
2017	29	32,153	7,353	22,749	16,238	19,943
Farms by inventory:						
1 to 9 ... farms, 2022	1	19	53	45	47	60
2017	2	29	65	53	38	52
number, 2022	(D)	99	255	221	261	247
2017	(D)	135	370	243	187	260
10 to 19 ... farms, 2022	3	19	39	23	22	41
2017	1	16	30	14	28	45
number, 2022	(D)	261	506	305	312	574
2017	(D)	223	428	192	382	666
20 to 49 ... farms, 2022	-	38	37	38	39	64
2017	-	32	66	41	49	70
number, 2022	-	1,258	1,097	1,051	1,264	1,864
2017	-	1,041	1,993	1,200	1,602	2,244
50 to 99 ... farms, 2022	-	13	17	19	22	47
2017	-	23	14	38	29	64
number, 2022	-	843	1,223	1,263	1,556	3,131
2017	-	1,505	1,009	2,784	2,190	4,425
100 to 199 ... farms, 2022	-	14	11	24	27	14
2017	-	10	14	18	10	27
number, 2022	-	2,046	1,442	3,288	3,883	1,604
2017	-	1,374	1,698	2,423	1,159	3,889
200 to 499 ... farms, 2022	-	13	6	19	13	3
2017	-	21	4	17	11	8
number, 2022	-	4,524	2,108	6,601	3,481	800
2017	-	7,686	(D)	4,363	3,110	2,065
500 or more ... farms, 2022	-	5	-	21	9	9
2017	-	18	1	9	9	7
number, 2022	-	9,534	-	20,476	12,700	6,380
2017	-	20,189	(D)	11,544	7,608	6,394
Cows and heifers that calved ... farms, 2022	4	94	137	115	131	180
2017	3	105	177	117	132	222
number, 2022	49	2,983	3,823	6,912	8,365	6,522
2017	(D)	3,180	4,203	5,492	6,467	7,486
Beef cows ... farms, 2022	4	87	134	95	107	162
2017	3	92	172	90	112	174
number, 2022	(D)	2,184	3,089	1,769	1,821	3,553
2017	(D)	2,563	3,659	1,915	2,160	3,875
2022 farms by inventory:						
1 to 9 ... farms	1	26	43	47	47	59
number	(D)	104	232	(D)	233	259
10 to 19 ... farms	3	15	49	22	24	31
number	43	205	672	276	324	430
20 to 49 ... farms	-	33	29	17	29	61
number	-	942	876	513	796	1,841
50 to 99 ... farms	-	13	7	8	7	8
number	-	933	488	548	468	500
100 to 199 ... farms	-	-	6	-	-	2
number	-	-	821	-	-	(D)
200 to 499 ... farms	-	-	-	1	-	1
number	-	-	-	(D)	-	(D)
500 or more ... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Milk cows ... farms, 2022	1	10	5	26	28	22
2017	-	15	10	28	28	65
number, 2022	(D)	799	734	5,143	6,544	2,969
2017	-	617	544	3,577	4,307	3,611
2022 farms by inventory:						
1 to 9 ... farms	1	1	2	2	4	8
number	(D)	(D)	(D)	(D)	4	38
10 to 19 ... farms	-	-	-	-	-	3
number	-	-	-	-	-	36
20 to 49 ... farms	-	1	-	4	1	1
number	-	(D)	-	(D)	(D)	(D)
50 to 99 ... farms	-	4	-	6	12	3
number	-	(D)	-	471	965	168
100 to 199 ... farms	-	4	-	4	6	2
number	-	460	-	560	(D)	(D)
200 to 499 ... farms	-	-	3	9	3	2
number	-	-	(D)	3,322	784	(D)
500 or more ... farms	-	-	-	1	2	3
number	-	-	-	(D)	(D)	1,725
Other cattle ... farms, 2022	-	110	119	163	157	208
2017	1	131	146	171	152	237
number, 2022	-	15,582	2,808	26,293	15,092	8,078
2017	(D)	28,973	3,150	17,257	9,771	12,457
2022 farms by inventory:						
1 to 9 ... farms	-	35	60	42	47	83
number	-	168	252	202	215	(D)
10 to 19 ... farms	-	23	23	19	28	32
number	-	341	300	246	356	419
20 to 49 ... farms	-	22	22	33	21	55
number	-	654	616	918	610	1,592
50 to 99 ... farms	-	8	5	26	24	23
number	-	584	296	1,696	1,588	1,524
100 to 199 ... farms	-	7	6	3	26	4
number	-	947	702	356	3,499	520
200 to 499 ... farms	-	10	3	24	3	10
number	-	3,530	642	7,906	754	3,118
500 or more ... farms	-	5	-	16	8	1
number	-	9,358	-	14,969	8,070	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
INVENTORY						
Cattle and calves ..... farms, 2022	91	546	150	475	47	66
2017	111	647	234	589	55	103
number, 2022	6,228	60,869	9,173	68,383	12,644	3,300
2017	13,657	59,346	18,170	70,463	14,559	5,431
Farms by inventory:						
1 to 9 ..... farms, 2022	29	103	39	67	20	30
2017	27	135	73	79	8	25
number, 2022	173	431	247	360	80	153
2017	131	557	348	435	(D)	108
10 to 19 ..... farms, 2022	14	71	25	61	3	8
2017	23	78	37	76	5	21
number, 2022	198	988	305	797	45	124
2017	335	1,136	496	1,053	82	267
20 to 49 ..... farms, 2022	25	153	46	106	12	8
2017	23	169	54	141	17	21
number, 2022	721	5,080	1,450	3,313	431	243
2017	684	5,373	1,658	4,316	550	631
50 to 99 ..... farms, 2022	14	86	29	87	4	9
2017	13	97	30	101	20	13
number, 2022	970	5,783	1,847	6,371	(D)	521
2017	927	6,888	2,155	7,086	1,508	890
100 to 199 ..... farms, 2022	4	66	1	61	6	7
2017	13	90	24	96	2	20
number, 2022	(D)	9,068	(D)	8,548	(D)	1,115
2017	1,643	11,881	3,079	13,839	(D)	2,705
200 to 499 ..... farms, 2022	2	46	8	60	-	4
2017	4	57	12	60	-	3
number, 2022	(D)	15,724	2,615	17,567	-	1,144
2017	1,113	16,950	4,444	16,828	-	830
500 or more ..... farms, 2022	3	21	2	33	2	-
2017	8	21	4	36	3	-
number, 2022	3,244	23,795	(D)	31,427	(D)	-
2017	8,824	16,561	5,990	26,906	12,046	-
Cows and heifers that calved ..... farms, 2022	61	458	107	349	32	48
2017	69	528	173	427	43	73
number, 2022	2,645	27,182	3,654	26,891	(D)	1,114
2017	3,235	27,169	3,916	26,528	9,536	1,946
Beef cows ..... farms, 2022	58	422	104	263	28	46
2017	61	443	166	319	39	57
number, 2022	(D)	18,415	3,277	8,311	458	612
2017	1,091	16,206	3,225	8,146	(D)	830
2022 farms by inventory:						
1 to 9 ..... farms	24	95	43	55	12	24
number	125	421	212	(D)	(D)	(D)
10 to 19 ..... farms	15	88	20	67	4	15
number	197	1,253	260	914	58	203
20 to 49 ..... farms	15	133	31	96	10	5
number	454	3,949	824	2,980	220	(D)
50 to 99 ..... farms	4	70	7	33	2	2
number	(D)	4,665	519	2,069	(D)	(D)
100 to 199 ..... farms	-	25	-	10	-	-
number	-	3,549	-	1,316	-	-
200 to 499 ..... farms	-	7	2	2	-	-
number	-	2,092	(D)	(D)	-	-
500 or more ..... farms	-	4	1	-	-	-
number	-	2,486	(D)	-	-	-
Milk cows ..... farms, 2022	3	67	4	95	4	6
2017	10	125	7	135	4	18
number, 2022	(D)	8,767	377	18,580	(D)	502
2017	2,144	10,963	691	18,382	(D)	1,116
2022 farms by inventory:						
1 to 9 ..... farms	-	34	1	8	-	2
number	-	(D)	(D)	18	-	(D)
10 to 19 ..... farms	-	1	-	6	-	-
number	-	(D)	-	96	-	-
20 to 49 ..... farms	-	6	-	11	-	-
number	-	180	-	435	-	-
50 to 99 ..... farms	2	5	-	11	-	-
number	(D)	267	-	892	-	-
100 to 199 ..... farms	-	3	3	28	2	4
number	-	380	(D)	3,675	(D)	(D)
200 to 499 ..... farms	-	13	-	24	-	-
number	-	3,617	-	6,888	-	-
500 or more ..... farms	1	5	-	7	2	-
number	(D)	4,258	-	6,576	(D)	-
Other cattle ..... farms, 2022	77	477	124	432	39	55
2017	88	580	195	515	47	89
number, 2022	3,583	33,687	5,519	41,492	(D)	2,186
2017	10,422	32,177	14,254	43,935	5,023	3,485
2022 farms by inventory:						
1 to 9 ..... farms	35	140	45	89	15	29
number	173	648	(D)	427	48	115
10 to 19 ..... farms	7	98	25	72	7	6
number	(D)	1,316	332	1,020	101	(D)
20 to 49 ..... farms	22	94	30	101	7	6
number	598	2,569	967	3,259	166	207
50 to 99 ..... farms	8	64	14	54	5	5
number	499	4,259	834	3,822	387	364
100 to 199 ..... farms	2	39	6	70	4	7
number	(D)	5,665	967	9,282	552	1,001
200 to 499 ..... farms	-	32	3	31	-	2
number	-	9,496	1,331	8,910	-	(D)
500 or more ..... farms	3	10	1	15	1	-
number	1,861	9,734	(D)	14,772	(D)	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
INVENTORY						
Cattle and calves ... farms, 2022	306	142	171	160	119	192
2017	397	162	241	139	134	304
number, 2022	46,700	5,981	7,620	5,421	15,036	6,258
2017	43,648	6,841	7,650	4,558	16,055	11,724
Farms by inventory:						
1 to 9 ... farms, 2022	33	32	66	41	11	64
2017	37	33	113	36	24	119
number, 2022	146	163	311	188	54	(D)
2017	197	156	582	180	161	499
10 to 19 ... farms, 2022	28	38	44	39	15	44
2017	59	42	50	39	20	53
number, 2022	404	501	602	497	199	554
2017	804	597	672	553	261	746
20 to 49 ... farms, 2022	70	45	38	50	29	47
2017	76	51	45	42	37	63
number, 2022	2,338	1,454	1,175	1,741	892	1,530
2017	2,348	1,647	1,306	1,422	1,223	1,812
50 to 99 ... farms, 2022	67	14	11	23	34	27
2017	105	17	22	13	16	38
number, 2022	4,517	995	760	1,537	2,012	1,935
2017	7,695	1,181	1,355	904	1,073	2,332
100 to 199 ... farms, 2022	49	6	9	3	14	9
2017	53	14	9	7	17	26
number, 2022	6,598	1,140	1,152	378	1,853	1,110
2017	7,387	1,935	(D)	(D)	2,431	3,418
200 to 499 ... farms, 2022	35	7	2	4	6	-
2017	58	5	1	2	7	3
number, 2022	10,236	1,728	(D)	1,080	1,476	-
2017	16,503	1,325	(D)	(D)	1,734	(D)
500 or more ... farms, 2022	24	-	1	-	10	1
2017	9	-	1	-	13	2
number, 2022	22,461	-	(D)	-	8,550	(D)
2017	8,714	-	(D)	-	9,172	(D)
Cows and heifers that calved ... farms, 2022	270	122	141	144	85	175
2017	331	146	198	131	97	259
number, 2022	21,209	3,055	3,689	2,736	3,312	3,495
2017	17,038	3,559	3,674	2,598	3,406	5,474
Beef cows ... farms, 2022	222	121	136	144	83	172
2017	272	141	194	131	96	243
number, 2022	7,524	(D)	1,735	2,731	(D)	(D)
2017	7,861	3,148	(D)	2,594	(D)	5,077
2022 farms by inventory:						
1 to 9 ... farms	30	42	77	53	10	73
number	(D)	(D)	318	(D)	56	352
10 to 19 ... farms	45	31	33	32	19	42
number	678	390	435	442	254	578
20 to 49 ... farms	98	34	19	51	37	39
number	2,988	1,028	562	1,513	1,127	1,083
50 to 99 ... farms	41	8	7	7	12	17
number	2,716	658	420	464	784	1,048
100 to 199 ... farms	7	6	-	1	4	-
number	746	600	-	(D)	561	-
200 to 499 ... farms	1	-	-	-	1	1
number	(D)	-	-	-	(D)	(D)
500 or more ... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Milk cows ... farms, 2022	58	5	9	3	2	3
2017	74	10	9	4	1	20
number, 2022	13,685	(D)	1,954	5	(D)	(D)
2017	9,177	411	(D)	4	(D)	397
2022 farms by inventory:						
1 to 9 ... farms	3	4	4	3	-	2
number	3	6	10	5	-	(D)
10 to 19 ... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
20 to 49 ... farms	11	-	2	-	-	1
number	371	-	(D)	-	-	(D)
50 to 99 ... farms	10	-	2	-	-	-
number	660	-	(D)	-	-	-
100 to 199 ... farms	10	1	-	-	2	-
number	1,415	(D)	-	-	(D)	-
200 to 499 ... farms	18	-	-	-	-	-
number	6,326	-	-	-	-	-
500 or more ... farms	6	-	1	-	-	-
number	4,910	-	(D)	-	-	-
Other cattle ... farms, 2022	278	115	133	141	109	151
2017	352	139	191	106	119	224
number, 2022	25,491	2,926	3,931	2,685	11,724	2,763
2017	26,610	3,282	3,976	1,960	12,649	6,250
2022 farms by inventory:						
1 to 9 ... farms	48	46	71	73	19	84
number	209	260	316	308	(D)	379
10 to 19 ... farms	39	37	20	32	18	23
number	557	497	(D)	433	243	314
20 to 49 ... farms	80	18	28	29	39	34
number	2,420	519	826	880	1,142	1,035
50 to 99 ... farms	47	7	9	3	17	7
number	3,075	630	542	204	1,118	450
100 to 199 ... farms	31	7	4	2	6	2
number	4,568	1,020	570	(D)	784	(D)
200 to 499 ... farms	27	-	-	2	1	1
number	8,139	-	-	(D)	(D)	(D)
500 or more ... farms	6	-	1	-	9	-
number	6,523	-	(D)	-	8,010	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
INVENTORY						
Cattle and calves ..... farms, 2022	256	56	58	83	9	37
2017	307	61	62	134	12	26
number, 2022	41,065	8,448	3,251	8,186	62	1,693
2017	46,849	10,911	3,939	15,540	129	(D)
Farms by inventory:						
1 to 9 ..... farms, 2022	55	6	6	9	7	9
2017	72	6	13	3	7	5
number, 2022	264	22	31	47	(D)	50
2017	340	30	82	(D)	(D)	15
10 to 19 ..... farms, 2022	37	10	15	8	2	3
2017	51	4	11	16	4	7
number, 2022	479	139	(D)	113	(D)	(D)
2017	660	65	149	226	60	110
20 to 49 ..... farms, 2022	70	4	19	22	-	18
2017	59	9	16	43	1	4
number, 2022	2,226	121	573	617	-	555
2017	1,864	287	590	1,397	(D)	(D)
50 to 99 ..... farms, 2022	44	8	8	22	-	3
2017	53	12	8	37	-	6
number, 2022	3,001	673	517	1,556	-	223
2017	3,583	809	585	2,659	-	436
100 to 199 ..... farms, 2022	17	10	9	15	-	3
2017	37	14	9	13	-	3
number, 2022	2,235	1,152	1,181	1,725	-	375
2017	5,090	1,899	1,235	(D)	-	(D)
200 to 499 ..... farms, 2022	15	14	-	4	-	1
2017	16	10	5	20	-	1
number, 2022	3,444	3,442	-	1,300	-	(D)
2017	4,738	3,253	1,298	5,845	-	(D)
500 or more ..... farms, 2022	18	4	1	3	-	-
2017	19	6	-	2	-	-
number, 2022	29,416	2,899	(D)	2,828	-	-
2017	30,574	4,568	-	(D)	-	-
Cows and heifers that calved ..... farms, 2022	200	54	57	76	7	37
2017	216	57	60	117	12	26
number, 2022	20,014	4,879	1,770	4,027	20	1,109
2017	17,866	5,625	2,351	6,102	69	854
Beef cows ..... farms, 2022	174	54	57	75	7	37
2017	167	57	59	104	12	26
number, 2022	3,910	4,867	(D)	(D)	20	1,109
2017	3,534	(D)	2,022	5,516	(D)	854
2022 farms by inventory:						
1 to 9 ..... farms	59	11	15	10	7	11
number	277	(D)	84	47	20	46
10 to 19 ..... farms	51	8	15	22	-	4
number	742	110	219	265	-	50
20 to 49 ..... farms	46	13	17	24	-	18
number	1,477	533	406	878	-	558
50 to 99 ..... farms	14	7	5	12	-	2
number	849	493	288	766	-	(D)
100 to 199 ..... farms	4	6	4	4	-	2
number	565	823	416	608	-	(D)
200 to 499 ..... farms	-	8	1	2	-	-
number	-	2,255	(D)	(D)	-	-
500 or more ..... farms	-	1	-	1	-	-
number	-	(D)	-	(D)	-	-
Milk cows ..... farms, 2022	30	3	2	1	-	-
2017	55	1	5	13	2	-
number, 2022	16,104	12	(D)	(D)	-	-
2017	14,332	(D)	329	586	(D)	-
2022 farms by inventory:						
1 to 9 ..... farms	2	3	-	-	-	-
number	(D)	12	-	-	-	-
10 to 19 ..... farms	3	-	1	-	-	-
number	53	-	(D)	-	-	-
20 to 49 ..... farms	1	-	-	1	-	-
number	(D)	-	-	(D)	-	-
50 to 99 ..... farms	8	-	1	-	-	-
number	624	-	(D)	-	-	-
100 to 199 ..... farms	4	-	-	-	-	-
number	520	-	-	-	-	-
200 to 499 ..... farms	6	-	-	-	-	-
number	2,189	-	-	-	-	-
500 or more ..... farms	6	-	-	-	-	-
number	12,658	-	-	-	-	-
Other cattle ..... farms, 2022	231	50	49	76	5	26
2017	272	55	55	122	10	22
number, 2022	21,051	3,569	1,481	4,159	42	584
2017	28,983	5,286	1,588	9,438	60	(D)
2022 farms by inventory:						
1 to 9 ..... farms	71	13	20	11	3	18
number	306	71	(D)	(D)	(D)	(D)
10 to 19 ..... farms	46	6	8	18	2	-
number	642	84	104	239	(D)	-
20 to 49 ..... farms	54	9	14	30	-	7
number	1,571	361	493	1,032	-	237
50 to 99 ..... farms	27	11	6	10	-	-
number	1,695	727	389	622	-	-
100 to 199 ..... farms	14	6	-	1	-	-
number	1,838	797	-	(D)	-	-
200 to 499 ..... farms	8	5	1	5	-	1
number	2,300	1,529	(D)	1,347	-	(D)
500 or more ..... farms	11	-	-	1	-	-
number	12,699	-	-	(D)	-	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
INVENTORY						
Cattle and calves ..... farms, 2022	149	121	210	198	63	164
2017	140	189	257	295	79	152
number, 2022	11,800	17,734	57,000	17,922	5,169	10,835
2017	13,173	22,401	57,633	26,379	5,460	10,636
Farms by inventory:						
1 to 9 ..... farms, 2022	39	10	31	43	12	26
2017	37	19	37	62	9	17
number, 2022	234	49	151	212	57	125
2017	219	102	142	327	54	104
10 to 19 ..... farms, 2022	28	14	14	42	13	24
2017	18	13	15	57	22	22
number, 2022	382	221	200	546	187	326
2017	217	195	199	763	307	327
20 to 49 ..... farms, 2022	22	31	43	47	15	40
2017	39	67	39	61	23	50
number, 2022	636	1,116	1,372	1,487	541	1,253
2017	1,240	2,392	1,401	1,841	763	1,621
50 to 99 ..... farms, 2022	25	25	20	29	8	47
2017	10	29	38	51	9	25
number, 2022	1,721	1,571	1,462	1,840	582	3,064
2017	676	1,941	2,675	3,592	653	1,865
100 to 199 ..... farms, 2022	21	22	26	16	8	17
2017	22	32	34	43	9	28
number, 2022	2,948	3,174	3,409	2,096	994	(D)
2017	3,006	4,759	4,232	5,580	(D)	3,550
200 to 499 ..... farms, 2022	11	10	24	8	7	9
2017	11	22	59	9	6	9
number, 2022	3,379	2,704	6,926	1,931	2,808	2,605
2017	3,542	7,015	17,119	2,963	2,021	(D)
500 or more ..... farms, 2022	3	9	52	13	-	1
2017	3	7	35	12	1	1
number, 2022	2,500	8,899	43,480	9,810	-	(D)
2017	4,273	5,997	31,865	11,313	(D)	(D)
Cows and heifers that calved ..... farms, 2022	95	107	129	135	56	157
2017	88	144	136	206	74	142
number, 2022	3,659	7,953	6,032	5,909	2,645	5,860
2017	4,120	7,097	7,715	9,210	2,528	5,741
Beef cows ..... farms, 2022	86	101	127	106	49	151
2017	67	131	132	134	68	136
number, 2022	2,114	5,105	5,621	1,343	(D)	5,290
2017	1,147	5,073	5,908	1,852	2,171	5,463
2022 farms by inventory:						
1 to 9 ..... farms	28	10	31	51	12	29
number	(D)	61	139	(D)	(D)	(D)
10 to 19 ..... farms	22	25	22	30	9	38
number	278	383	296	406	140	512
20 to 49 ..... farms	23	37	35	24	12	57
number	660	1,163	918	611	405	1,826
50 to 99 ..... farms	11	15	21	1	10	16
number	751	1,125	1,114	(D)	580	1,092
100 to 199 ..... farms	2	10	14	-	3	9
number	(D)	1,279	1,814	-	456	1,140
200 to 499 ..... farms	-	4	4	-	3	2
number	-	1,094	1,340	-	690	(D)
500 or more ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Milk cows ..... farms, 2022	16	8	5	30	7	6
2017	24	15	15	74	9	6
number, 2022	1,545	2,848	411	4,566	(D)	570
2017	2,973	2,024	1,807	7,358	357	278
2022 farms by inventory:						
1 to 9 ..... farms	-	2	1	4	6	-
number	-	(D)	(D)	24	14	-
10 to 19 ..... farms	1	-	-	-	-	3
number	(D)	-	-	-	-	45
20 to 49 ..... farms	4	1	-	7	-	-
number	153	(D)	-	(D)	-	-
50 to 99 ..... farms	7	-	2	10	-	-
number	524	-	(D)	674	-	-
100 to 199 ..... farms	2	-	2	4	-	3
number	(D)	-	(D)	540	-	525
200 to 499 ..... farms	2	4	-	3	1	-
number	(D)	(D)	-	660	(D)	-
500 or more ..... farms	-	1	-	2	-	-
number	-	(D)	-	(D)	-	-
Other cattle ..... farms, 2022	140	99	191	173	53	131
2017	119	174	238	268	72	141
number, 2022	8,141	9,781	50,968	12,013	2,524	4,975
2017	9,053	15,304	49,918	17,169	2,932	4,895
2022 farms by inventory:						
1 to 9 ..... farms	49	8	30	52	23	27
number	(D)	47	102	225	124	(D)
10 to 19 ..... farms	23	18	20	28	5	33
number	286	267	234	360	74	435
20 to 49 ..... farms	24	36	38	50	8	40
number	704	1,015	1,154	1,442	295	1,194
50 to 99 ..... farms	26	18	15	12	10	22
number	1,747	1,180	986	705	674	1,606
100 to 199 ..... farms	6	9	22	14	3	8
number	721	1,350	3,083	1,706	475	1,120
200 to 499 ..... farms	11	6	21	7	4	-
number	2,972	1,722	7,570	2,045	882	-
500 or more ..... farms	1	4	45	10	-	1
number	(D)	4,200	37,839	5,530	-	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
INVENTORY						
Cattle and calves ... farms, 2022	115	227	210	668	223	165
2017	147	270	303	903	288	201
number, 2022	12,977	34,907	12,633	70,675	21,245	53,015
2017	21,069	30,487	17,357	87,791	29,733	53,129
Farms by inventory:						
1 to 9 ... farms, 2022	20	67	55	113	54	25
2017	36	81	82	162	60	18
number, 2022	90	309	252	656	265	151
2017	214	388	444	895	288	104
10 to 19 ... farms, 2022	18	20	51	99	37	15
2017	19	41	51	150	54	9
number, 2022	285	270	718	1,353	487	218
2017	255	597	679	2,070	756	121
20 to 49 ... farms, 2022	32	58	62	170	60	27
2017	36	62	83	265	87	33
number, 2022	1,042	1,764	1,908	5,276	1,916	951
2017	1,078	1,801	2,381	8,347	2,691	1,138
50 to 99 ... farms, 2022	18	32	15	113	26	23
2017	18	37	45	143	25	32
number, 2022	1,086	2,283	(D)	7,483	1,771	1,682
2017	1,276	2,521	3,066	9,624	1,804	2,271
100 to 199 ... farms, 2022	8	22	18	87	19	16
2017	11	20	29	112	28	38
number, 2022	1,058	2,973	2,497	11,681	2,384	2,180
2017	1,491	2,717	3,647	15,804	4,221	5,027
200 to 499 ... farms, 2022	13	7	8	58	17	21
2017	14	11	10	51	14	45
number, 2022	4,112	1,700	2,239	15,485	5,453	6,002
2017	3,838	2,918	2,960	15,093	5,244	14,776
500 or more ... farms, 2022	6	21	1	28	10	38
2017	13	18	3	20	20	26
number, 2022	5,304	25,608	(D)	28,741	8,969	41,831
2017	12,917	19,545	4,180	35,958	14,729	29,692
Cows and heifers that calved ... farms, 2022	79	178	189	603	137	120
2017	87	185	258	774	179	113
number, 2022	2,362	14,678	4,258	34,827	6,002	9,586
2017	2,123	10,694	5,575	43,243	6,405	8,817
Beef cows ... farms, 2022	74	144	180	509	115	110
2017	83	142	236	615	150	89
number, 2022	1,697	4,189	3,069	15,105	2,305	6,348
2017	1,666	2,787	3,919	15,438	2,927	5,053
2022 farms by inventory:						
1 to 9 ... farms	26	61	84	131	41	24
number	137	(D)	(D)	703	192	(D)
10 to 19 ... farms	17	34	37	126	40	13
number	217	431	506	1,689	552	183
20 to 49 ... farms	28	39	48	167	27	35
number	914	1,158	1,223	4,793	764	1,084
50 to 99 ... farms	2	5	10	60	4	19
number	(D)	266	760	3,972	249	1,232
100 to 199 ... farms	-	3	-	20	2	11
number	-	380	-	2,468	(D)	1,344
200 to 499 ... farms	1	-	1	5	1	7
number	(D)	-	(D)	1,480	(D)	1,794
500 or more ... farms	-	2	-	-	-	1
number	-	(D)	-	-	-	(D)
Milk cows ... farms, 2022	11	39	16	132	24	12
2017	4	46	34	214	33	24
number, 2022	665	10,489	1,189	19,722	3,697	3,238
2017	457	7,907	1,656	27,805	3,478	3,764
2022 farms by inventory:						
1 to 9 ... farms	2	10	4	8	2	-
number	(D)	25	8	13	(D)	-
10 to 19 ... farms	6	-	2	8	3	-
number	60	-	(D)	127	32	-
20 to 49 ... farms	-	4	2	17	5	-
number	-	108	(D)	593	135	-
50 to 99 ... farms	1	9	3	50	6	3
number	(D)	590	206	3,528	448	219
100 to 199 ... farms	-	3	5	23	2	2
number	-	375	875	2,981	(D)	(D)
200 to 499 ... farms	2	7	-	19	4	6
number	(D)	2,910	-	5,167	1,147	2,019
500 or more ... farms	-	6	-	7	2	1
number	-	6,481	-	7,313	(D)	(D)
Other cattle ... farms, 2022	104	193	169	571	210	158
2017	117	239	236	740	251	194
number, 2022	10,615	20,229	8,375	35,848	15,243	43,429
2017	18,946	19,793	11,782	44,548	23,328	44,312
2022 farms by inventory:						
1 to 9 ... farms	35	59	77	160	72	33
number	131	248	407	634	329	161
10 to 19 ... farms	23	37	44	112	35	16
number	321	501	618	1,457	502	203
20 to 49 ... farms	15	41	23	129	55	38
number	467	1,197	675	3,875	1,666	1,294
50 to 99 ... farms	5	17	16	79	14	11
number	285	1,198	1,171	5,283	917	875
100 to 199 ... farms	7	17	6	51	10	12
number	938	2,196	944	6,065	1,381	1,461
200 to 499 ... farms	14	3	2	27	18	18
number	3,973	882	(D)	7,060	5,523	5,057
500 or more ... farms	5	19	1	13	6	30
number	4,500	14,007	(D)	11,474	4,925	34,378

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
INVENTORY						
Cattle and calves ..... farms, 2022	117	195	68	313	689	68
2017	167	239	87	417	900	125
number, 2022	22,187	74,944	3,536	45,167	70,204	7,058
2017	26,541	92,426	3,707	44,266	78,216	8,656
Farms by inventory:						
1 to 9 ..... farms, 2022	26	21	17	54	131	9
2017	24	44	29	90	201	22
number, 2022	129	100	79	282	690	55
2017	109	189	133	444	1,044	124
10 to 19 ..... farms, 2022	14	20	11	39	101	6
2017	20	22	8	59	127	16
number, 2022	185	295	141	552	1,409	85
2017	274	311	94	818	1,640	218
20 to 49 ..... farms, 2022	33	35	18	89	169	28
2017	45	37	28	100	214	40
number, 2022	987	1,126	520	2,866	5,359	906
2017	1,480	1,100	919	3,100	6,733	1,325
50 to 99 ..... farms, 2022	12	21	12	65	115	13
2017	29	29	17	66	131	26
number, 2022	(D)	1,471	894	4,834	7,743	939
2017	2,029	2,122	1,265	4,517	9,109	1,894
100 to 199 ..... farms, 2022	9	22	6	20	90	4
2017	23	16	-	53	111	15
number, 2022	1,364	2,828	910	2,735	12,645	550
2017	3,604	2,209	-	7,212	14,718	(D)
200 to 499 ..... farms, 2022	19	27	4	24	59	4
2017	21	48	5	37	93	2
number, 2022	5,093	7,560	992	7,846	17,388	1,666
2017	5,503	15,373	1,296	10,518	25,866	(D)
500 or more ..... farms, 2022	4	49	-	22	24	4
2017	5	43	-	12	23	4
number, 2022	(D)	61,564	-	26,052	24,970	2,857
2017	13,542	71,122	-	17,657	19,106	2,517
Cows and heifers that calved ..... farms, 2022	77	134	55	258	597	66
2017	97	144	77	347	746	115
number, 2022	13,221	14,534	1,740	20,078	29,256	3,706
2017	12,676	11,663	1,765	18,694	32,420	4,451
Beef cows ..... farms, 2022	58	116	49	228	506	66
2017	59	124	71	278	585	112
number, 2022	1,105	6,864	1,652	8,815	16,973	3,706
2017	1,110	5,094	1,673	8,034	18,079	4,428
2022 farms by inventory:						
1 to 9 ..... farms	18	13	17	63	139	11
number	(D)	(D)	85	305	(D)	(D)
10 to 19 ..... farms	22	39	9	50	118	13
number	275	554	121	731	1,605	177
20 to 49 ..... farms	13	27	13	73	156	30
number	316	788	441	2,049	4,522	909
50 to 99 ..... farms	2	19	5	27	62	4
number	(D)	1,303	368	1,663	4,340	285
100 to 199 ..... farms	3	13	5	12	24	1
number	345	1,671	637	1,347	3,188	(D)
200 to 499 ..... farms	-	3	-	1	5	7
number	-	900	-	(D)	1,183	2,142
500 or more ..... farms	-	2	-	2	2	-
number	-	(D)	-	(D)	(D)	-
Milk cows ..... farms, 2022	19	18	6	41	108	-
2017	38	23	6	77	195	5
number, 2022	12,116	7,670	88	11,263	12,283	-
2017	11,566	6,569	92	10,660	14,341	23
2022 farms by inventory:						
1 to 9 ..... farms	4	2	-	6	7	-
number	12	(D)	-	(D)	9	-
10 to 19 ..... farms	-	-	4	-	4	-
number	-	-	(D)	-	56	-
20 to 49 ..... farms	1	1	2	4	21	-
number	(D)	(D)	(D)	159	613	-
50 to 99 ..... farms	1	1	-	1	42	-
number	(D)	(D)	-	(D)	3,086	-
100 to 199 ..... farms	9	4	-	4	20	-
number	1,214	526	-	520	2,840	-
200 to 499 ..... farms	3	5	-	22	8	-
number	(D)	1,689	-	6,138	2,310	-
500 or more ..... farms	1	5	-	4	6	-
number	(D)	5,350	-	4,360	3,369	-
Other cattle ..... farms, 2022	97	178	64	271	590	52
2017	155	218	69	359	759	111
number, 2022	8,966	60,410	1,796	25,089	40,948	3,352
2017	13,865	80,763	1,942	25,572	45,796	4,205
2022 farms by inventory:						
1 to 9 ..... farms	19	36	24	64	186	14
number	(D)	154	(D)	298	827	56
10 to 19 ..... farms	18	18	15	50	102	7
number	241	270	210	670	1,423	115
20 to 49 ..... farms	22	27	15	78	125	16
number	715	871	540	2,442	3,563	473
50 to 99 ..... farms	9	23	8	33	89	8
number	623	1,758	565	2,170	6,372	541
100 to 199 ..... farms	18	15	1	14	51	3
number	2,598	1,789	(D)	1,790	6,827	522
200 to 499 ..... farms	10	20	1	25	20	4
number	2,869	6,507	(D)	7,032	5,896	1,645
500 or more ..... farms	1	39	-	7	17	-
number	(D)	49,061	-	10,687	16,040	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
INVENTORY						
Cattle and calves ... farms, 2022	308	197	151	194	-	67
2017	378	222	197	231	1	70
number, 2022	19,294	62,663	13,468	19,845	-	10,937
2017	21,016	59,712	13,730	27,195	(D)	6,448
Farms by inventory:						
1 to 9 ... farms, 2022	88	24	25	40	-	14
2017	78	23	40	30	-	17
number, 2022	478	103	141	181	-	68
2017	423	115	196	167	-	67
10 to 19 ... farms, 2022	45	9	26	35	-	3
2017	94	21	17	36	-	8
number, 2022	619	130	336	495	-	45
2017	1,311	269	213	485	-	104
20 to 49 ... farms, 2022	84	33	21	46	-	13
2017	98	38	63	47	-	15
number, 2022	2,492	1,098	685	1,346	-	399
2017	3,002	1,355	2,238	1,502	-	501
50 to 99 ... farms, 2022	37	39	40	30	-	19
2017	60	24	37	44	-	17
number, 2022	2,420	2,577	2,924	2,163	-	1,279
2017	4,201	1,499	2,523	2,875	-	1,223
100 to 199 ... farms, 2022	32	28	26	24	-	3
2017	26	42	29	33	-	6
number, 2022	4,087	3,778	3,566	3,307	-	451
2017	3,417	5,490	3,837	4,473	-	800
200 to 499 ... farms, 2022	15	33	8	14	-	9
2017	16	42	7	34	1	4
number, 2022	4,268	9,346	2,235	4,814	-	3,150
2017	3,905	14,782	1,976	9,224	(D)	1,014
500 or more ... farms, 2022	7	31	5	5	-	6
2017	6	32	4	7	-	3
number, 2022	4,930	45,631	3,581	7,539	-	5,545
2017	4,757	36,202	2,747	8,469	-	2,739
Cows and heifers that calved ... farms, 2022	275	147	138	178	-	63
2017	339	157	183	199	1	64
number, 2022	9,833	20,611	6,939	8,701	-	3,554
2017	10,842	16,091	7,362	9,569	(D)	3,190
Beef cows ... farms, 2022	260	133	128	166	-	60
2017	297	140	151	169	-	62
number, 2022	6,864	10,011	5,981	5,753	-	2,282
2017	7,147	9,181	5,896	6,123	-	(D)
2022 farms by inventory:						
1 to 9 ... farms	100	21	31	50	-	12
number	(D)	(D)	151	(D)	-	62
10 to 19 ... farms	50	17	12	43	-	7
number	681	251	156	582	-	93
20 to 49 ... farms	68	41	40	44	-	28
number	1,932	1,346	1,391	1,439	-	1,019
50 to 99 ... farms	24	19	35	19	-	8
number	1,440	1,219	2,079	1,273	-	494
100 to 199 ... farms	16	23	5	6	-	5
number	1,806	3,127	574	875	-	614
200 to 499 ... farms	2	10	5	3	-	-
number	(D)	2,895	1,630	757	-	-
500 or more ... farms	-	2	-	1	-	-
number	-	(D)	-	(D)	-	-
Milk cows ... farms, 2022	24	14	15	15	-	3
2017	49	17	41	41	1	3
number, 2022	2,969	10,600	958	2,948	-	1,272
2017	3,695	6,910	1,466	3,446	(D)	(D)
2022 farms by inventory:						
1 to 9 ... farms	6	-	7	-	-	-
number	(D)	-	(D)	-	-	-
10 to 19 ... farms	-	-	3	1	-	-
number	-	-	36	(D)	-	-
20 to 49 ... farms	5	-	1	-	-	-
number	177	-	(D)	-	-	-
50 to 99 ... farms	6	-	3	6	-	-
number	400	-	225	(D)	-	-
100 to 199 ... farms	2	4	-	6	-	-
number	(D)	440	-	852	-	-
200 to 499 ... farms	5	5	-	1	-	3
number	2,185	1,680	-	(D)	-	1,272
500 or more ... farms	-	5	1	1	-	-
number	-	8,480	(D)	(D)	-	-
Other cattle ... farms, 2022	245	186	132	152	-	52
2017	301	202	173	204	1	51
number, 2022	9,461	42,052	6,529	11,144	-	7,383
2017	10,174	43,621	6,368	17,626	(D)	3,258
2022 farms by inventory:						
1 to 9 ... farms	83	29	43	50	-	15
number	(D)	119	(D)	(D)	-	81
10 to 19 ... farms	61	27	17	30	-	4
number	807	361	229	380	-	50
20 to 49 ... farms	53	38	33	33	-	15
number	1,590	1,184	1,145	1,152	-	526
50 to 99 ... farms	21	20	24	19	-	5
number	1,173	1,349	1,631	1,268	-	433
100 to 199 ... farms	19	32	10	6	-	3
number	2,538	4,173	1,280	973	-	480
200 to 499 ... farms	6	21	4	12	-	7
number	1,935	6,669	1,284	3,251	-	2,996
500 or more ... farms	2	19	1	2	-	3
number	(D)	28,197	(D)	(D)	-	2,817

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
INVENTORY						
Cattle and calves ..... farms, 2022	214	125	224	201	172	254
2017	221	148	335	271	177	304
number, 2022	49,053	26,887	16,167	70,805	16,286	11,243
2017	46,505	25,596	20,496	93,683	16,046	10,408
Farms by inventory:						
1 to 9 ..... farms, 2022	24	18	63	24	33	76
2017	24	22	104	22	16	105
number, 2022	146	100	280	123	154	(D)
2017	144	106	457	126	82	574
10 to 19 ..... farms, 2022	28	15	43	19	18	50
2017	17	20	66	22	22	76
number, 2022	414	196	609	259	243	688
2017	259	291	892	288	292	1,041
20 to 49 ..... farms, 2022	47	34	50	29	25	63
2017	55	34	63	36	40	59
number, 2022	1,545	1,142	1,478	923	891	2,128
2017	1,722	1,122	2,005	1,258	1,311	1,766
50 to 99 ..... farms, 2022	40	13	27	18	45	31
2017	30	32	48	42	56	45
number, 2022	2,911	947	1,965	1,269	2,872	2,203
2017	2,052	1,949	3,579	2,942	4,029	3,333
100 to 199 ..... farms, 2022	22	18	24	27	31	28
2017	30	15	39	29	27	13
number, 2022	2,975	2,289	3,169	3,619	3,858	3,285
2017	4,721	1,819	5,896	3,743	3,720	1,715
200 to 499 ..... farms, 2022	20	9	11	32	16	4
2017	38	16	9	53	12	5
number, 2022	5,766	2,710	3,263	9,469	4,971	1,220
2017	12,462	4,409	2,454	18,886	3,357	(D)
500 or more ..... farms, 2022	33	18	6	52	4	2
2017	27	9	6	67	4	1
number, 2022	35,296	19,503	5,403	55,143	3,297	(D)
2017	25,145	15,900	5,213	66,440	3,255	(D)
Cows and heifers that calved ..... farms, 2022	132	74	156	113	165	230
2017	126	89	245	138	168	281
number, 2022	8,645	5,026	7,443	9,522	9,477	5,950
2017	5,881	4,431	8,861	9,441	8,504	5,755
Beef cows ..... farms, 2022	125	63	124	102	161	225
2017	110	66	199	125	158	272
number, 2022	7,583	2,677	2,218	5,168	9,135	4,971
2017	4,209	1,579	2,839	5,561	7,706	4,991
2022 farms by inventory:						
1 to 9 ..... farms	27	22	39	21	36	93
number	(D)	102	155	115	(D)	431
10 to 19 ..... farms	28	7	40	22	17	44
number	391	(D)	506	322	222	613
20 to 49 ..... farms	40	21	37	24	49	62
number	1,239	568	1,015	859	1,587	2,027
50 to 99 ..... farms	15	11	8	18	29	21
number	1,086	644	542	1,101	1,972	1,292
100 to 199 ..... farms	10	-	-	13	22	5
number	1,355	-	-	1,464	2,646	608
200 to 499 ..... farms	3	1	-	4	7	-
number	1,057	(D)	-	1,307	1,914	-
500 or more ..... farms	2	1	-	-	1	-
number	(D)	(D)	-	-	(D)	-
Milk cows ..... farms, 2022	9	11	43	11	6	13
2017	20	25	70	18	18	11
number, 2022	1,062	2,349	5,225	4,354	342	979
2017	1,672	2,852	6,022	3,880	798	764
2022 farms by inventory:						
1 to 9 ..... farms	2	-	8	-	1	8
number	(D)	-	(D)	-	(D)	(D)
10 to 19 ..... farms	-	2	1	-	-	-
number	-	(D)	(D)	-	-	-
20 to 49 ..... farms	-	-	4	-	2	-
number	-	-	125	-	(D)	-
50 to 99 ..... farms	4	1	17	2	2	3
number	(D)	(D)	1,157	(D)	(D)	261
100 to 199 ..... farms	-	2	4	-	1	-
number	-	(D)	534	-	(D)	-
200 to 499 ..... farms	3	6	7	7	-	2
number	740	2,061	2,088	2,332	-	(D)
500 or more ..... farms	-	-	2	2	-	-
number	-	-	(D)	(D)	-	-
Other cattle ..... farms, 2022	201	120	184	186	157	218
2017	210	130	291	256	155	233
number, 2022	40,408	21,861	8,724	61,283	6,809	5,293
2017	40,624	21,165	11,635	84,242	7,542	4,653
2022 farms by inventory:						
1 to 9 ..... farms	37	32	66	38	63	100
number	220	169	312	171	276	493
10 to 19 ..... farms	29	16	33	16	18	40
number	386	205	441	237	(D)	540
20 to 49 ..... farms	58	22	41	19	40	44
number	1,729	719	1,161	618	1,074	1,357
50 to 99 ..... farms	23	15	23	19	20	28
number	1,616	1,026	1,416	1,307	1,480	1,664
100 to 199 ..... farms	12	12	11	16	6	3
number	1,617	1,630	1,701	1,773	766	405
200 to 499 ..... farms	14	11	7	37	9	3
number	4,184	3,100	1,893	12,109	2,328	834
500 or more ..... farms	28	12	3	41	1	-
number	30,656	15,012	1,800	45,068	(D)	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
INVENTORY						
Cattle and calves ... farms, 2022	147	102	226	1,258	145	82
2017	199	117	289	1,522	194	120
number, 2022	10,819	11,468	28,226	187,176	6,622	53,804
2017	15,279	8,972	34,346	198,361	13,069	58,256
Farms by inventory:						
1 to 9 ... farms, 2022	49	48	27	178	51	12
2017	50	51	52	175	61	15
number, 2022	234	247	162	935	(D)	59
2017	276	267	301	738	294	87
10 to 19 ... farms, 2022	30	11	29	145	28	12
2017	40	25	46	181	23	16
number, 2022	385	150	409	2,074	362	166
2017	535	318	639	2,447	349	220
20 to 49 ... farms, 2022	30	15	69	276	38	16
2017	38	17	61	297	43	20
number, 2022	846	444	2,120	8,514	1,231	469
2017	1,134	593	1,781	9,541	1,320	641
50 to 99 ... farms, 2022	11	6	35	183	12	3
2017	23	-	47	243	20	17
number, 2022	770	409	2,509	12,786	911	205
2017	1,535	-	3,001	17,609	1,443	1,031
100 to 199 ... farms, 2022	12	6	29	253	9	9
2017	24	11	42	382	34	22
number, 2022	1,799	648	4,043	35,443	1,234	1,323
2017	3,326	1,214	6,209	53,054	4,814	2,883
200 to 499 ... farms, 2022	10	5	21	150	5	16
2017	20	7	20	187	9	16
number, 2022	2,615	1,418	6,774	42,078	1,358	5,305
2017	4,992	2,610	5,903	50,869	2,649	4,707
500 or more ... farms, 2022	5	11	16	73	2	14
2017	4	6	21	57	4	14
number, 2022	4,170	8,152	12,209	85,346	(D)	46,277
2017	3,481	3,970	16,512	64,103	2,200	48,687
Cows and heifers that calved ... farms, 2022	103	73	165	951	121	52
2017	151	96	184	1,134	159	70
number, 2022	3,604	1,207	11,222	73,991	3,038	27,960
2017	5,084	1,529	10,797	77,867	5,661	28,367
Beef cows ... farms, 2022	85	69	133	636	112	44
2017	120	84	143	578	120	60
number, 2022	1,188	1,063	3,250	16,101	1,531	(D)
2017	1,775	820	3,609	11,343	2,143	(D)
2022 farms by inventory:						
1 to 9 ... farms	44	44	39	241	63	14
number	233	195	215	1,220	290	64
10 to 19 ... farms	27	12	35	162	21	13
number	333	180	437	2,233	303	189
20 to 49 ... farms	10	9	48	161	24	7
number	266	268	1,432	4,507	666	214
50 to 99 ... farms	2	2	8	51	4	4
number	(D)	(D)	494	3,130	272	270
100 to 199 ... farms	2	1	1	11	-	5
number	(D)	(D)	(D)	1,276	-	554
200 to 499 ... farms	-	1	2	5	-	1
number	-	(D)	(D)	1,127	-	(D)
500 or more ... farms	-	-	-	5	-	-
number	-	-	-	2,608	-	-
Milk cows ... farms, 2022	20	4	34	362	11	8
2017	33	12	44	624	40	10
number, 2022	2,416	144	7,972	57,890	1,507	(D)
2017	3,309	709	7,188	66,524	3,518	(D)
2022 farms by inventory:						
1 to 9 ... farms	3	2	-	13	2	-
number	11	(D)	-	68	(D)	-
10 to 19 ... farms	-	-	6	9	-	-
number	-	-	60	123	-	-
20 to 49 ... farms	-	-	2	31	1	2
number	-	-	(D)	1,206	(D)	(D)
50 to 99 ... farms	7	2	8	164	1	1
number	499	(D)	530	11,809	(D)	(D)
100 to 199 ... farms	6	-	2	94	5	-
number	674	-	(D)	12,446	795	-
200 to 499 ... farms	4	-	11	34	2	4
number	1,232	-	3,425	11,274	(D)	1,328
500 or more ... farms	-	-	5	17	-	1
number	-	-	3,655	20,964	-	(D)
Other cattle ... farms, 2022	120	79	191	1,136	122	72
2017	161	87	267	1,393	169	115
number, 2022	7,215	10,261	17,004	113,185	3,584	25,844
2017	10,195	7,443	23,549	120,494	7,408	29,889
2022 farms by inventory:						
1 to 9 ... farms	47	40	39	222	54	17
number	206	148	214	1,057	(D)	(D)
10 to 19 ... farms	27	11	37	173	23	9
number	340	148	478	2,323	318	113
20 to 49 ... farms	15	6	46	234	25	9
number	419	211	1,511	7,378	750	266
50 to 99 ... farms	13	4	27	221	9	2
number	931	302	1,932	15,530	576	(D)
100 to 199 ... farms	10	3	14	168	9	7
number	1,220	300	2,093	22,858	1,116	915
200 to 499 ... farms	5	5	21	74	2	18
number	1,301	1,500	6,500	21,405	(D)	5,474
500 or more ... farms	3	10	7	44	-	10
number	2,798	7,652	4,276	42,634	-	18,819

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
INVENTORY						
Cattle and calves ..... farms, 2022	110	600	19	317	180	101
2017	136	745	26	373	218	150
number, 2022	31,135	50,660	12,129	64,958	9,719	9,649
2017	31,353	55,660	13,432	56,163	12,818	12,802
Farms by inventory:						
1 to 9 ..... farms, 2022	25	125	2	19	47	29
2017	14	127	3	27	35	45
number, 2022	126	616	(D)	104	236	141
2017	74	632	15	119	190	223
10 to 19 ..... farms, 2022	11	120	1	32	23	13
2017	14	118	4	43	31	16
number, 2022	163	1,594	(D)	448	325	173
2017	221	1,568	(D)	575	475	226
20 to 49 ..... farms, 2022	24	130	4	62	65	29
2017	40	214	9	85	78	39
number, 2022	716	4,069	120	1,974	2,083	958
2017	1,162	6,759	273	2,805	2,256	1,177
50 to 99 ..... farms, 2022	19	101	1	64	20	5
2017	16	140	3	79	38	12
number, 2022	1,479	7,033	(D)	4,407	(D)	388
2017	1,091	9,865	(D)	5,832	2,537	814
100 to 199 ..... farms, 2022	15	71	4	52	11	12
2017	30	105	2	71	23	23
number, 2022	1,812	9,951	(D)	7,266	1,575	1,296
2017	3,913	14,270	(D)	10,506	(D)	3,215
200 to 499 ..... farms, 2022	4	40	5	60	13	6
2017	9	23	1	48	12	7
number, 2022	1,016	11,621	1,120	18,561	3,365	1,753
2017	2,618	7,649	(D)	13,945	3,365	1,787
500 or more ..... farms, 2022	12	13	2	28	1	7
2017	13	18	4	20	1	8
number, 2022	25,823	15,776	(D)	32,198	(D)	4,940
2017	22,274	14,917	12,423	22,381	(D)	5,360
Cows and heifers that calved ..... farms, 2022	94	507	12	274	161	60
2017	108	646	14	308	198	82
number, 2022	15,216	22,274	(D)	34,034	4,833	1,927
2017	15,545	25,800	(D)	25,695	6,813	2,698
Beef cows ..... farms, 2022	90	413	11	190	148	58
2017	88	474	13	192	165	63
number, 2022	(D)	10,533	756	6,489	3,720	1,730
2017	3,057	11,302	(D)	5,438	4,237	1,316
2022 farms by inventory:						
1 to 9 ..... farms	31	139	2	39	50	26
number	(D)	716	(D)	216	(D)	126
10 to 19 ..... farms	13	113	1	27	29	11
number	192	1,493	(D)	366	402	155
20 to 49 ..... farms	31	108	1	82	50	14
number	1,002	3,238	(D)	2,531	1,498	355
50 to 99 ..... farms	7	33	2	32	17	2
number	426	2,306	(D)	2,136	1,184	(D)
100 to 199 ..... farms	8	16	5	10	-	3
number	1,072	1,700	570	1,240	-	420
200 to 499 ..... farms	-	4	-	-	2	2
number	-	1,080	-	-	(D)	(D)
500 or more ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Milk cows ..... farms, 2022	5	141	1	103	17	3
2017	23	222	1	133	38	21
number, 2022	(D)	11,741	(D)	27,545	1,113	197
2017	12,488	14,498	(D)	20,257	2,576	1,382
2022 farms by inventory:						
1 to 9 ..... farms	-	47	-	1	4	-
number	-	141	-	(D)	21	-
10 to 19 ..... farms	-	6	-	-	-	-
number	-	104	-	-	-	-
20 to 49 ..... farms	-	21	-	4	6	1
number	-	789	-	(D)	(D)	(D)
50 to 99 ..... farms	1	34	-	21	6	2
number	(D)	2,308	-	1,650	467	(D)
100 to 199 ..... farms	-	24	-	31	-	-
number	-	2,990	-	4,172	-	-
200 to 499 ..... farms	2	5	-	34	1	-
number	(D)	1,431	-	9,250	(D)	-
500 or more ..... farms	2	4	1	12	-	-
number	(D)	3,978	(D)	12,336	-	-
Other cattle ..... farms, 2022	103	494	18	299	144	89
2017	127	643	24	347	184	136
number, 2022	15,919	28,386	(D)	30,924	4,886	7,722
2017	15,808	29,860	(D)	30,468	6,005	10,104
2022 farms by inventory:						
1 to 9 ..... farms	30	173	2	59	65	28
number	(D)	791	(D)	251	263	106
10 to 19 ..... farms	17	82	1	32	23	18
number	245	1,087	(D)	475	318	257
20 to 49 ..... farms	24	120	4	61	33	17
number	851	3,659	131	2,032	913	496
50 to 99 ..... farms	13	57	-	61	11	8
number	1,050	3,773	-	4,198	776	548
100 to 199 ..... farms	7	32	9	51	8	9
number	829	4,308	1,110	6,800	950	1,015
200 to 499 ..... farms	1	22	-	26	4	3
number	(D)	6,523	-	7,030	1,666	860
500 or more ..... farms	11	8	2	9	-	6
number	12,480	8,245	(D)	10,138	-	4,440

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
INVENTORY						
Cattle and calves ..... farms, 2022	71	58	37	443	337	143
2017	117	64	29	514	412	170
number, 2022	2,133	5,979	3,241	85,123	27,929	19,424
2017	5,466	3,654	2,763	70,460	31,648	27,915
Farms by inventory:						
1 to 9 ..... farms, 2022	29	17	7	57	99	34
2017	34	18	7	60	125	20
number, 2022	(D)	(D)	27	254	444	152
2017	154	70	41	268	551	90
10 to 19 ..... farms, 2022	18	17	7	57	48	15
2017	26	10	5	50	49	25
number, 2022	244	203	96	831	687	202
2017	342	113	65	658	656	361
20 to 49 ..... farms, 2022	12	10	13	99	90	28
2017	22	19	4	130	115	37
number, 2022	349	341	475	3,423	2,518	830
2017	681	695	126	4,035	3,436	1,240
50 to 99 ..... farms, 2022	6	8	6	71	38	26
2017	20	9	9	109	40	30
number, 2022	491	532	363	5,019	2,343	1,866
2017	1,356	584	708	7,425	2,746	2,094
100 to 199 ..... farms, 2022	5	-	2	42	29	16
2017	11	5	3	77	38	21
number, 2022	664	-	(D)	5,719	4,304	1,987
2017	1,355	668	(D)	10,478	5,142	2,858
200 to 499 ..... farms, 2022	1	2	-	61	17	14
2017	3	2	-	55	37	15
number, 2022	(D)	(D)	-	18,517	5,415	4,490
2017	(D)	(D)	-	16,173	11,056	4,225
500 or more ..... farms, 2022	-	4	2	56	16	10
2017	1	1	1	33	8	22
number, 2022	-	4,159	(D)	51,360	12,218	9,897
2017	(D)	(D)	(D)	31,423	8,061	17,047
Cows and heifers that calved ..... farms, 2022	57	37	28	356	244	105
2017	97	50	22	429	293	121
number, 2022	1,016	587	1,800	41,145	10,278	6,509
2017	2,774	1,315	1,527	32,575	9,251	4,936
Beef cows ..... farms, 2022	52	37	28	243	202	94
2017	82	45	22	300	237	112
number, 2022	655	587	1,800	7,763	2,518	3,842
2017	1,916	(D)	(D)	8,543	2,922	3,508
2022 farms by inventory:						
1 to 9 ..... farms	37	15	8	56	104	25
number	(D)	(D)	29	(D)	395	(D)
10 to 19 ..... farms	7	11	3	49	47	23
number	(D)	131	46	717	663	300
20 to 49 ..... farms	7	10	14	100	48	26
number	217	329	491	3,134	1,257	819
50 to 99 ..... farms	-	1	-	26	3	12
number	-	(D)	-	1,638	203	820
100 to 199 ..... farms	1	-	1	10	-	6
number	(D)	-	(D)	1,251	-	794
200 to 499 ..... farms	-	-	1	1	-	1
number	-	-	(D)	(D)	-	(D)
500 or more ..... farms	-	-	1	1	-	1
number	-	-	(D)	(D)	-	(D)
Milk cows ..... farms, 2022	5	-	-	137	47	11
2017	17	6	1	160	69	9
number, 2022	361	-	-	33,382	7,760	2,667
2017	858	(D)	(D)	24,032	6,329	1,428
2022 farms by inventory:						
1 to 9 ..... farms	-	-	-	23	2	4
number	-	-	-	93	(D)	4
10 to 19 ..... farms	-	-	-	3	2	-
number	-	-	-	34	(D)	-
20 to 49 ..... farms	3	-	-	8	2	-
number	(D)	-	-	263	(D)	-
50 to 99 ..... farms	-	-	-	13	13	3
number	-	-	-	990	947	(D)
100 to 199 ..... farms	2	-	-	22	11	-
number	(D)	-	-	2,695	1,440	-
200 to 499 ..... farms	-	-	-	46	14	3
number	-	-	-	13,555	3,455	1,100
500 or more ..... farms	-	-	-	22	3	1
number	-	-	-	15,752	1,816	(D)
Other cattle ..... farms, 2022	60	48	33	398	278	127
2017	96	58	27	462	334	154
number, 2022	1,117	5,392	1,441	43,978	17,651	12,915
2017	2,692	2,339	1,236	37,885	22,397	22,979
2022 farms by inventory:						
1 to 9 ..... farms	31	20	10	92	95	43
number	120	100	65	462	454	210
10 to 19 ..... farms	15	12	10	59	48	15
number	209	168	146	792	617	211
20 to 49 ..... farms	7	9	10	83	62	29
number	196	317	253	2,651	1,741	991
50 to 99 ..... farms	4	1	1	52	30	15
number	252	(D)	(D)	3,786	1,931	947
100 to 199 ..... farms	3	-	1	43	19	11
number	340	-	(D)	5,726	2,474	1,329
200 to 499 ..... farms	-	2	-	44	19	7
number	-	(D)	-	13,790	5,384	2,457
500 or more ..... farms	-	4	1	25	5	7
number	-	4,099	(D)	16,771	5,050	6,770

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
INVENTORY - Con.					
Cattle and calves - Con.					
Cattle on feed ..... farms, 2022	2,553	7	-	14	5
2017	3,220	3	8	16	3
number, 2022	520,056	190	-	2,985	307
2017	596,367	125	276	1,969	336
2022 farms by inventory:					
1 to 19 ..... farms	317	2	-	4	2
number	4,493	(D)	-	(D)	(D)
20 to 49 ..... farms	750	5	-	6	2
number	23,213	(D)	-	180	(D)
50 to 99 ..... farms	528	-	-	-	-
number	35,398	-	-	-	-
100 to 199 ..... farms	338	-	-	-	-
number	44,618	-	-	-	-
200 to 499 ..... farms	300	-	-	1	1
number	88,605	-	-	(D)	(D)
500 or more ..... farms	320	-	-	3	-
number	323,729	-	-	2,400	-
SALES					
Milk sold from cows ..... farms, 2022	1,893	2	-	35	3
2017	3,349	7	2	46	4
$1,000, 2022	2,504,638	(D)	-	46,172	(D)
2017	1,737,886	233	(D)	23,150	(D)
Cattle and calves sold ..... farms, 2022	14,649	149	32	269	194
2017	18,474	174	55	258	241
number, 2022	1,599,910	3,418	413	20,809	7,762
2017	1,683,259	4,582	607	14,357	9,597
$1,000, 2022	2,094,135	3,717	399	26,963	10,579
2017	1,886,939	3,920	489	13,665	9,689
2022 farms by number sold:					
1 to 9 ..... farms	4,154	65	20	84	48
number	19,214	(D)	111	367	(D)
10 to 19 ..... farms	2,404	21	7	32	43
number	32,563	269	(D)	424	594
20 to 49 ..... farms	3,610	50	4	72	70
number	112,647	1,531	158	2,259	2,195
50 to 99 ..... farms	1,896	8	1	44	18
number	129,777	484	(D)	3,047	1,375
100 to 199 ..... farms	1,147	2	-	12	6
number	151,529	(D)	-	1,465	790
200 to 499 ..... farms	827	3	-	12	8
number	244,770	600	-	3,668	1,697
500 or more ..... farms	611	-	-	13	1
number	909,410	-	-	9,579	(D)
Calves weighing less than 500 pounds, sold ..... farms, 2022	4,938	44	8	107	67
2017	6,226	71	12	109	56
number, 2022	345,069	574	114	3,617	1,077
2017	289,516	1,194	(D)	2,816	813
2022 farms by number sold:					
1 to 9 ..... farms	1,922	20	4	40	34
number	8,142	(D)	16	149	104
10 to 19 ..... farms	892	10	-	25	20
number	11,721	123	-	318	287
20 to 49 ..... farms	1,142	13	4	24	9
number	34,096	295	98	777	300
50 to 99 ..... farms	440	1	-	11	2
number	28,293	(D)	-	716	(D)
100 to 199 ..... farms	299	-	-	-	2
number	40,976	-	-	-	(D)
200 to 499 ..... farms	169	-	-	7	-
number	46,929	-	-	1,657	-
500 or more ..... farms	74	-	-	-	-
number	174,912	-	-	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	13,933	139	31	268	179
2017	17,228	160	51	236	228
number, 2022	1,254,841	2,844	299	17,192	6,685
2017	1,393,743	3,388	(D)	11,541	8,784
2022 farms by number sold:					
1 to 9 ..... farms	4,363	68	19	95	46
number	19,343	237	(D)	(D)	(D)
10 to 19 ..... farms	2,440	24	11	35	36
number	32,731	317	153	447	514
20 to 49 ..... farms	3,462	34	1	75	71
number	105,838	1,081	(D)	2,339	2,112
50 to 99 ..... farms	1,615	9	-	36	13
number	108,535	534	-	2,351	908
100 to 199 ..... farms	923	4	-	2	4
number	122,548	675	-	(D)	494
200 to 499 ..... farms	633	-	-	19	8
number	190,849	-	-	5,785	1,697
500 or more ..... farms	497	-	-	6	1
number	674,997	-	-	5,680	(D)
Cattle on feed sold ..... farms, 2022	2,685	10	2	22	15
2017	3,434	10	8	13	7
number, 2022	636,782	258	(D)	6,370	720
2017	708,257	113	208	2,548	380
2022 farms by number sold:					
1 to 19 ..... farms	420	4	2	11	8
number	6,010	60	(D)	(D)	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
INVENTORY - Con.					
Cattle and calves - Con.					
Cattle on feed ..... farms, 2022	57	10	12	62	1
2017	66	21	26	98	9
number, 2022	4,157	406	2,603	11,481	(D)
2017	3,395	1,065	5,959	22,794	187
2022 farms by inventory:					
1 to 19 ..... farms	8	4	1	3	1
number	116	58	(D)	54	(D)
20 to 49 ..... farms	16	3	2	20	-
number	518	128	(D)	617	-
50 to 99 ..... farms	21	3	4	11	-
number	1,347	220	269	787	-
100 to 199 ..... farms	6	-	1	6	-
number	873	-	(D)	858	-
200 to 499 ..... farms	6	-	3	14	-
number	1,303	-	975	4,029	-
500 or more ..... farms	-	-	1	8	-
number	-	-	(D)	5,136	-
SALES					
Milk sold from cows ..... farms, 2022	42	-	1	38	1
2017	86	-	8	49	12
$1,000, 2022	90,851	-	(D)	25,439	(D)
2017	36,923	-	435	21,526	1,801
Cattle and calves sold ..... farms, 2022	242	58	71	196	173
2017	317	89	110	261	209
number, 2022	20,763	3,656	4,370	32,017	4,283
2017	11,031	12,093	7,307	44,550	4,827
$1,000, 2022	18,961	3,843	7,133	51,134	4,495
2017	9,957	(D)	9,686	61,418	3,938
2022 farms by number sold:					
1 to 9 ..... farms	85	18	27	35	78
number	419	124	(D)	187	(D)
10 to 19 ..... farms	36	2	17	19	29
number	475	(D)	(D)	270	380
20 to 49 ..... farms	61	13	13	43	47
number	2,116	399	428	1,307	1,329
50 to 99 ..... farms	32	14	5	46	14
number	2,244	997	356	3,036	1,014
100 to 199 ..... farms	13	9	5	16	3
number	1,720	1,214	584	2,110	361
200 to 499 ..... farms	11	2	3	19	2
number	2,671	(D)	840	5,672	(D)
500 or more ..... farms	4	-	1	18	-
number	11,118	-	(D)	19,435	-
Calves weighing less than 500 pounds, sold ..... farms, 2022	94	18	22	53	74
2017	148	18	12	71	104
number, 2022	8,054	654	341	2,097	1,075
2017	2,823	2,588	281	3,048	1,264
2022 farms by number sold:					
1 to 9 ..... farms	39	4	15	10	51
number	159	26	94	54	185
10 to 19 ..... farms	10	5	3	4	8
number	150	78	(D)	58	112
20 to 49 ..... farms	36	5	3	29	6
number	1,125	150	97	909	155
50 to 99 ..... farms	4	2	-	4	9
number	232	(D)	-	216	623
100 to 199 ..... farms	1	2	1	6	-
number	(D)	(D)	(D)	860	-
200 to 499 ..... farms	2	-	-	-	-
number	(D)	-	-	-	-
500 or more ..... farms	2	-	-	-	-
number	(D)	-	-	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	223	56	60	190	163
2017	289	87	106	244	182
number, 2022	12,709	3,002	4,029	29,920	3,208
2017	8,208	9,505	7,026	41,502	3,563
2022 farms by number sold:					
1 to 9 ..... farms	91	22	24	36	79
number	(D)	139	(D)	189	352
10 to 19 ..... farms	32	4	13	19	34
number	369	(D)	170	266	399
20 to 49 ..... farms	51	11	10	56	43
number	1,633	323	342	1,689	1,167
50 to 99 ..... farms	24	10	6	32	3
number	1,537	743	416	2,023	190
100 to 199 ..... farms	10	7	3	14	2
number	1,380	856	370	1,818	(D)
200 to 499 ..... farms	13	2	3	17	2
number	3,379	(D)	840	5,600	(D)
500 or more ..... farms	2	-	1	16	-
number	(D)	-	(D)	18,335	-
Cattle on feed sold ..... farms, 2022	53	5	14	61	7
2017	56	21	28	95	3
number, 2022	4,191	286	3,024	16,001	122
2017	2,612	1,265	4,194	36,337	72
2022 farms by number sold:					
1 to 19 ..... farms	6	1	3	7	4
number	92	(D)	34	101	56

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	35	4	9	16	16	3
2017	53	10	17	14	11	2
number, 2022	3,345	84	1,024	592	375	(D)
2017	4,157	512	5,556	538	997	(D)
2022 farms by inventory:						
1 to 19 ..... farms	3	-	2	9	8	2
number	45	-	(D)	139	(D)	(D)
20 to 49 ..... farms	12	4	5	4	7	-
number	350	84	102	132	195	-
50 to 99 ..... farms	6	-	-	1	1	-
number	400	-	-	(D)	(D)	-
100 to 199 ..... farms	11	-	-	2	-	1
number	1,550	-	-	(D)	-	(D)
200 to 499 ..... farms	2	-	2	-	-	-
number	(D)	-	(D)	-	-	-
500 or more ..... farms	1	-	-	-	-	-
number	(D)	-	-	-	-	-
SALES						
Milk sold from cows ..... farms, 2022	39	3	1	10	10	3
2017	76	6	1	17	11	8
$1,000, 2022	30,134	505	(D)	6,674	2,858	(D)
2017	27,684	1,383	(D)	5,853	3,445	1,159
Cattle and calves sold ..... farms, 2022	160	194	42	142	106	174
2017	218	183	83	203	133	192
number, 2022	10,832	8,179	15,913	2,340	3,987	10,267
2017	9,076	13,077	16,980	6,457	5,428	8,942
$1,000, 2022	13,706	8,617	13,307	2,470	3,822	9,595
2017	9,185	14,247	(D)	6,285	5,609	7,799
2022 farms by number sold:						
1 to 9 ..... farms	40	55	16	68	34	37
number	(D)	254	81	(D)	(D)	152
10 to 19 ..... farms	29	41	12	33	27	20
number	358	519	149	435	363	274
20 to 49 ..... farms	30	49	4	31	17	62
number	896	1,679	81	866	552	1,972
50 to 99 ..... farms	22	25	4	8	13	36
number	1,556	1,475	282	568	822	2,687
100 to 199 ..... farms	28	16	-	2	13	12
number	3,756	2,009	-	(D)	1,490	1,561
200 to 499 ..... farms	9	8	-	-	2	4
number	3,051	2,243	-	-	(D)	1,150
500 or more ..... farms	2	-	6	-	-	3
number	(D)	-	15,320	-	-	2,471
Calves weighing less than 500 pounds, sold ..... farms, 2022	45	96	6	43	31	77
2017	66	73	26	78	37	61
number, 2022	2,140	1,408	(D)	553	938	3,122
2017	1,864	1,884	4,473	1,250	710	2,027
2022 farms by number sold:						
1 to 9 ..... farms	13	55	1	28	19	20
number	71	214	(D)	104	87	106
10 to 19 ..... farms	5	13	2	7	2	16
number	69	(D)	(D)	(D)	(D)	209
20 to 49 ..... farms	18	23	2	2	7	24
number	536	607	(D)	(D)	330	629
50 to 99 ..... farms	-	4	-	6	-	10
number	-	220	-	304	-	624
100 to 199 ..... farms	5	-	-	-	1	4
number	618	-	-	-	(D)	584
200 to 499 ..... farms	4	1	-	-	2	3
number	846	(D)	-	-	(D)	970
500 or more ..... farms	-	-	1	-	-	-
number	-	-	(D)	-	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	152	181	40	137	102	171
2017	214	163	82	192	118	185
number, 2022	8,692	6,771	(D)	1,787	3,049	7,145
2017	7,212	11,193	12,507	5,207	4,718	6,915
2022 farms by number sold:						
1 to 9 ..... farms	44	59	17	78	35	41
number	201	244	87	314	164	(D)
10 to 19 ..... farms	26	35	9	31	22	25
number	326	466	111	416	292	348
20 to 49 ..... farms	31	55	6	24	18	69
number	922	1,790	(D)	707	560	2,095
50 to 99 ..... farms	20	13	2	2	19	23
number	1,486	768	(D)	(D)	1,173	1,514
100 to 199 ..... farms	23	12	-	2	8	9
number	3,085	1,510	-	(D)	860	1,204
200 to 499 ..... farms	8	7	-	-	-	2
number	2,672	1,993	-	-	-	(D)
500 or more ..... farms	-	-	6	-	-	2
number	-	-	7,987	-	-	(D)
Cattle on feed sold ..... farms, 2022	42	11	7	16	11	3
2017	55	12	16	14	14	1
number, 2022	3,105	688	1,992	392	224	128
2017	4,027	990	6,183	467	1,583	(D)
2022 farms by number sold:						
1 to 19 ..... farms	8	2	2	6	8	-
number	(D)	(D)	(D)	(D)	112	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	-	23	-	55	40	26
2017	-	43	1	55	27	42
number, 2022	-	10,945	-	13,046	5,233	2,629
2017	-	22,367	(D)	10,968	5,551	5,611
2022 farms by inventory:						
1 to 19 ..... farms	-	6	-	4	9	1
number	-	(D)	-	45	118	(D)
20 to 49 ..... farms	-	2	-	20	7	4
number	-	(D)	-	533	199	138
50 to 99 ..... farms	-	-	-	5	11	15
number	-	-	-	302	736	1,045
100 to 199 ..... farms	-	4	-	5	7	1
number	-	400	-	616	880	(D)
200 to 499 ..... farms	-	6	-	16	-	4
number	-	2,670	-	5,167	-	800
500 or more ..... farms	-	5	-	5	6	1
number	-	7,748	-	6,383	3,300	(D)
SALES						
Milk sold from cows ..... farms, 2022	-	10	5	24	24	14
2017	-	12	6	28	18	63
$1,000, 2022	-	4,221	3,356	26,179	36,858	15,225
2017	-	1,863	1,654	14,777	16,704	12,013
Cattle and calves sold ..... farms, 2022	5	101	119	162	161	183
2017	2	147	169	174	159	242
number, 2022	224	25,392	4,168	27,808	14,323	8,560
2017	(D)	33,313	4,332	26,856	11,482	10,179
$1,000, 2022	174	47,886	3,386	48,460	(D)	10,582
2017	(D)	51,202	3,576	30,931	10,546	11,942
2022 farms by number sold:						
1 to 9 ..... farms	2	23	54	50	59	63
number	(D)	154	(D)	215	292	(D)
10 to 19 ..... farms	1	18	19	22	16	31
number	(D)	255	250	270	202	399
20 to 49 ..... farms	-	22	19	35	35	54
number	-	643	591	980	1,044	1,674
50 to 99 ..... farms	-	15	10	8	21	20
number	-	1,013	670	572	1,483	1,208
100 to 199 ..... farms	2	11	16	11	8	6
number	(D)	1,481	2,215	1,350	1,106	885
200 to 499 ..... farms	-	5	1	21	14	7
number	-	1,680	(D)	5,391	3,420	2,558
500 or more ..... farms	-	7	-	15	8	2
number	-	20,166	-	19,030	6,776	(D)
Calves weighing less than 500 pounds, sold ..... farms, 2022	5	27	53	32	66	51
2017	1	25	87	34	71	80
number, 2022	111	684	1,536	1,211	4,723	1,670
2017	(D)	739	1,450	1,036	3,773	1,325
2022 farms by number sold:						
1 to 9 ..... farms	3	8	22	10	17	23
number	(D)	(D)	57	(D)	47	(D)
10 to 19 ..... farms	-	4	6	5	14	18
number	-	47	82	60	(D)	236
20 to 49 ..... farms	-	13	14	13	14	5
number	-	343	412	388	468	154
50 to 99 ..... farms	2	-	5	-	7	1
number	(D)	-	343	-	425	(D)
100 to 199 ..... farms	-	2	6	3	10	-
number	-	(D)	642	460	1,200	-
200 to 499 ..... farms	-	-	-	1	3	4
number	-	-	-	(D)	650	1,142
500 or more ..... farms	-	-	-	-	1	-
number	-	-	-	-	(D)	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	5	96	103	153	149	171
2017	2	144	147	166	141	227
number, 2022	113	24,708	2,632	26,597	9,600	6,890
2017	(D)	32,574	2,882	25,820	7,709	8,854
2022 farms by number sold:						
1 to 9 ..... farms	3	24	46	46	56	61
number	(D)	144	149	194	289	(D)
10 to 19 ..... farms	-	18	18	22	23	26
number	-	252	237	286	285	349
20 to 49 ..... farms	-	25	18	34	33	55
number	-	810	491	1,021	1,013	1,639
50 to 99 ..... farms	2	8	15	10	13	14
number	(D)	525	1,015	726	783	884
100 to 199 ..... farms	-	9	6	8	10	9
number	-	1,131	740	1,111	1,210	1,370
200 to 499 ..... farms	-	5	-	19	7	5
number	-	1,680	-	4,729	1,560	1,373
500 or more ..... farms	-	7	-	14	7	1
number	-	20,166	-	18,530	4,460	(D)
Cattle on feed sold ..... farms, 2022	-	25	-	54	29	29
2017	-	46	3	61	27	37
number, 2022	-	19,950	-	12,387	5,334	2,936
2017	-	27,570	(D)	18,399	4,094	4,718
2022 farms by number sold:						
1 to 19 ..... farms	-	3	-	5	1	3
number	-	(D)	-	(D)	(D)	39

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	14	78	34	107	7	11
2017	29	84	46	140	7	4
number, 2022	1,643	10,438	3,166	14,818	526	954
2017	7,530	8,237	6,875	17,293	1,478	310
2022 farms by inventory:						
1 to 19 ..... farms	1	13	4	14	3	1
number	(D)	(D)	62	208	44	(D)
20 to 49 ..... farms	7	16	15	27	-	2
number	220	482	511	735	-	(D)
50 to 99 ..... farms	4	19	10	22	2	4
number	248	1,091	547	1,547	(D)	230
100 to 199 ..... farms	-	20	2	22	2	4
number	-	2,940	(D)	2,913	(D)	660
200 to 499 ..... farms	-	8	2	15	-	-
number	-	2,124	(D)	3,970	-	-
500 or more ..... farms	2	2	1	7	-	-
number	(D)	(D)	(D)	5,445	-	-
SALES						
Milk sold from cows ..... farms, 2022	3	32	3	89	4	4
2017	8	76	12	124	4	16
$1,000, 2022	(D)	49,239	2,429	102,446	(D)	2,573
2017	9,279	40,004	2,879	77,800	(D)	3,568
Cattle and calves sold ..... farms, 2022	89	480	135	463	44	50
2017	104	565	200	549	51	82
number, 2022	7,211	34,707	7,607	45,736	12,043	1,357
2017	9,943	38,703	15,053	40,236	8,839	2,562
$1,000, 2022	10,927	44,995	10,895	57,220	5,937	1,599
2017	13,184	38,972	16,614	37,710	5,237	2,609
2022 farms by number sold:						
1 to 9 ..... farms	42	112	52	94	14	24
number	195	497	266	442	70	111
10 to 19 ..... farms	10	89	23	81	8	8
number	(D)	1,302	(D)	1,076	96	(D)
20 to 49 ..... farms	20	107	37	122	12	7
number	654	3,112	1,157	3,677	414	185
50 to 99 ..... farms	7	71	14	57	3	9
number	510	4,869	996	3,881	235	726
100 to 199 ..... farms	3	67	1	56	5	2
number	354	8,968	(D)	7,425	(D)	(D)
200 to 499 ..... farms	2	21	4	37	-	-
number	(D)	6,116	1,266	9,561	-	-
500 or more ..... farms	5	13	4	16	2	-
number	4,684	9,843	3,460	19,674	(D)	-
Calves weighing less than 500 pounds, sold ..... farms, 2022	13	127	32	154	16	15
2017	21	160	47	207	18	23
number, 2022	905	4,884	706	9,142	(D)	246
2017	910	7,380	1,634	9,752	(D)	404
2022 farms by number sold:						
1 to 9 ..... farms	8	64	16	47	4	7
number	23	292	79	234	16	(D)
10 to 19 ..... farms	-	17	9	35	4	3
number	-	204	99	451	54	36
20 to 49 ..... farms	2	18	3	25	4	3
number	(D)	579	95	706	132	60
50 to 99 ..... farms	2	12	2	31	2	2
number	(D)	774	(D)	2,208	(D)	(D)
100 to 199 ..... farms	-	13	1	5	-	-
number	-	1,833	(D)	543	-	-
200 to 499 ..... farms	-	2	1	7	-	-
number	-	(D)	(D)	1,810	-	-
500 or more ..... farms	1	1	-	4	2	-
number	(D)	(D)	-	3,190	(D)	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	86	470	126	446	43	48
2017	94	527	186	526	49	79
number, 2022	6,306	29,823	6,901	36,594	(D)	1,111
2017	9,033	31,323	13,419	30,484	(D)	2,158
2022 farms by number sold:						
1 to 9 ..... farms	39	121	48	112	13	24
number	172	538	(D)	530	67	(D)
10 to 19 ..... farms	12	93	25	72	10	8
number	(D)	1,302	318	981	122	102
20 to 49 ..... farms	20	101	34	127	10	9
number	654	2,962	1,087	3,881	281	257
50 to 99 ..... farms	7	70	10	63	7	5
number	512	4,616	660	4,330	507	424
100 to 199 ..... farms	1	58	3	30	1	2
number	(D)	7,763	462	3,866	(D)	(D)
200 to 499 ..... farms	3	17	2	31	1	-
number	1,098	5,147	(D)	8,537	(D)	-
500 or more ..... farms	4	10	4	11	1	-
number	3,584	7,495	3,460	14,469	(D)	-
Cattle on feed sold ..... farms, 2022	16	68	32	111	9	9
2017	31	95	50	152	7	14
number, 2022	4,097	10,138	3,315	15,054	513	531
2017	7,164	8,650	6,393	15,288	1,398	930
2022 farms by number sold:						
1 to 19 ..... farms	1	7	6	15	1	2
number	(D)	108	104	218	(D)	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	48	-	14	2	24	3
2017	62	2	18	4	26	8
number, 2022	7,406	-	496	(D)	3,861	164
2017	4,539	(D)	733	70	6,540	804
2022 farms by inventory:						
1 to 19 ..... farms	7	-	4	2	5	-
number	89	-	47	(D)	74	-
20 to 49 ..... farms	14	-	7	-	4	2
number	467	-	263	-	139	(D)
50 to 99 ..... farms	9	-	3	-	8	1
number	586	-	186	-	462	(D)
100 to 199 ..... farms	11	-	-	-	4	-
number	1,554	-	-	-	516	-
200 to 499 ..... farms	3	-	-	-	-	-
number	780	-	-	-	-	-
500 or more ..... farms	4	-	-	-	3	-
number	3,930	-	-	-	2,670	-
SALES						
Milk sold from cows ..... farms, 2022	56	3	7	-	2	1
2017	67	5	5	-	1	20
$1,000, 2022	72,666	(D)	(D)	-	(D)	(D)
2017	39,254	(D)	(D)	-	(D)	3,128
Cattle and calves sold ..... farms, 2022	288	103	141	120	115	154
2017	376	146	173	108	118	212
number, 2022	37,367	3,312	2,831	2,625	19,896	3,081
2017	25,003	3,304	3,157	2,422	14,159	6,867
$1,000, 2022	41,840	3,188	3,157	(D)	26,858	3,272
2017	26,310	(D)	(D)	1,993	18,737	7,684
2022 farms by number sold:						
1 to 9 ..... farms	51	35	79	45	28	73
number	265	167	(D)	187	(D)	(D)
10 to 19 ..... farms	39	22	32	20	15	33
number	559	303	415	263	196	424
20 to 49 ..... farms	71	31	20	42	33	35
number	2,181	1,022	642	1,134	1,020	1,060
50 to 99 ..... farms	63	-	9	9	19	9
number	4,313	-	478	605	1,276	563
100 to 199 ..... farms	32	15	-	4	7	3
number	4,443	1,820	-	436	1,038	430
200 to 499 ..... farms	15	-	-	-	2	1
number	4,211	-	-	-	(D)	(D)
500 or more ..... farms	17	-	1	-	11	-
number	21,395	-	(D)	-	15,718	-
Calves weighing less than 500 pounds, sold ..... farms, 2022	103	32	45	28	27	61
2017	111	52	46	40	28	113
number, 2022	5,856	463	768	428	908	531
2017	4,632	651	918	639	762	2,026
2022 farms by number sold:						
1 to 9 ..... farms	30	16	36	16	12	39
number	(D)	(D)	130	(D)	44	172
10 to 19 ..... farms	13	9	6	5	4	16
number	175	114	74	67	61	205
20 to 49 ..... farms	34	5	2	6	7	6
number	1,027	105	(D)	200	175	154
50 to 99 ..... farms	11	1	-	-	2	-
number	802	(D)	-	-	(D)	-
100 to 199 ..... farms	8	1	-	1	-	-
number	1,034	(D)	-	(D)	-	-
200 to 499 ..... farms	6	-	-	-	2	-
number	2,139	-	-	-	(D)	-
500 or more ..... farms	1	-	1	-	-	-
number	(D)	-	(D)	-	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	280	98	129	118	112	144
2017	356	126	154	95	106	167
number, 2022	31,511	2,849	2,063	2,197	18,988	2,550
2017	20,371	2,653	2,239	1,783	13,397	4,841
2022 farms by number sold:						
1 to 9 ..... farms	58	37	74	49	34	79
number	261	(D)	(D)	(D)	176	(D)
10 to 19 ..... farms	39	22	29	20	14	31
number	533	303	362	259	198	387
20 to 49 ..... farms	88	24	17	39	28	24
number	2,791	736	510	1,014	776	710
50 to 99 ..... farms	44	2	8	8	20	6
number	2,837	(D)	421	535	1,350	374
100 to 199 ..... farms	27	13	-	2	5	3
number	3,945	1,500	-	(D)	770	430
200 to 499 ..... farms	11	-	1	-	-	1
number	2,429	-	(D)	-	-	(D)
500 or more ..... farms	13	-	-	-	11	-
number	18,715	-	-	-	15,718	-
Cattle on feed sold ..... farms, 2022	56	-	12	5	25	4
2017	64	4	11	5	26	15
number, 2022	9,468	-	312	98	6,871	175
2017	4,909	54	433	118	8,262	1,137
2022 farms by number sold:						
1 to 19 ..... farms	2	-	4	2	7	3
number	(D)	-	(D)	(D)	103	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	33	4	1	10	-	2
2017	43	1	-	25	-	-
number, 2022	1,903	640	(D)	1,404	-	(D)
2017	6,374	(D)	-	3,072	-	-
2022 farms by inventory:						
1 to 19 ..... farms	6	-	-	3	-	-
number	(D)	-	-	55	-	-
20 to 49 ..... farms	16	-	1	3	-	2
number	498	-	(D)	79	-	(D)
50 to 99 ..... farms	9	-	-	1	-	-
number	586	-	-	(D)	-	-
100 to 199 ..... farms	-	3	-	1	-	-
number	-	(D)	-	(D)	-	-
200 to 499 ..... farms	1	1	-	1	-	-
number	(D)	(D)	-	(D)	-	-
500 or more ..... farms	1	-	-	1	-	-
number	(D)	-	-	(D)	-	-
SALES						
Milk sold from cows ..... farms, 2022	30	1	2	1	-	-
2017	55	-	5	13	-	-
$1,000, 2022	91,700	(D)	(D)	(D)	-	-
2017	53,493	-	990	1,405	-	-
Cattle and calves sold ..... farms, 2022	219	46	50	81	4	32
2017	279	62	52	135	6	22
number, 2022	28,697	4,761	1,527	4,486	6	928
2017	32,371	6,201	1,719	9,719	(D)	795
$1,000, 2022	23,837	5,622	1,555	5,596	15	(D)
2017	31,464	5,568	1,382	10,741	35	637
2022 farms by number sold:						
1 to 9 ..... farms	76	5	18	21	4	12
number	323	(D)	(D)	105	6	(D)
10 to 19 ..... farms	34	4	15	11	-	5
number	457	55	188	149	-	68
20 to 49 ..... farms	55	11	9	25	-	10
number	1,531	373	269	810	-	307
50 to 99 ..... farms	24	10	4	14	-	3
number	1,661	770	258	906	-	(D)
100 to 199 ..... farms	6	11	3	7	-	2
number	815	1,702	380	864	-	(D)
200 to 499 ..... farms	11	4	1	2	-	-
number	2,696	1,213	(D)	(D)	-	-
500 or more ..... farms	13	1	-	1	-	-
number	21,214	(D)	-	(D)	-	-
Calves weighing less than 500 pounds, sold ..... farms, 2022	59	21	13	23	-	12
2017	76	23	17	43	1	11
number, 2022	12,411	657	389	842	-	234
2017	6,906	1,102	375	968	(D)	111
2022 farms by number sold:						
1 to 9 ..... farms	21	3	5	9	-	3
number	100	(D)	16	(D)	-	14
10 to 19 ..... farms	7	3	-	6	-	4
number	92	42	-	90	-	65
20 to 49 ..... farms	12	13	5	3	-	5
number	380	416	145	107	-	155
50 to 99 ..... farms	4	1	3	4	-	-
number	233	(D)	228	226	-	-
100 to 199 ..... farms	6	1	-	-	-	-
number	798	(D)	-	-	-	-
200 to 499 ..... farms	5	-	-	1	-	-
number	1,270	-	-	(D)	-	-
500 or more ..... farms	4	-	-	-	-	-
number	9,538	-	-	-	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	210	43	48	77	4	31
2017	266	59	49	131	6	22
number, 2022	16,286	4,104	1,138	3,644	6	694
2017	25,465	5,099	1,344	8,751	(D)	684
2022 farms by number sold:						
1 to 9 ..... farms	85	3	19	21	4	16
number	379	20	(D)	94	6	46
10 to 19 ..... farms	27	5	15	9	-	4
number	362	(D)	198	119	-	(D)
20 to 49 ..... farms	55	12	9	25	-	9
number	1,585	423	252	788	-	332
50 to 99 ..... farms	21	9	4	14	-	-
number	1,361	667	244	798	-	-
100 to 199 ..... farms	6	9	-	5	-	2
number	708	1,285	-	579	-	(D)
200 to 499 ..... farms	9	4	1	2	-	-
number	2,491	1,136	(D)	(D)	-	-
500 or more ..... farms	7	1	-	1	-	-
number	9,400	(D)	-	(D)	-	-
Cattle on feed sold ..... farms, 2022	37	4	2	13	-	2
2017	48	1	-	32	-	1
number, 2022	1,936	216	(D)	1,337	-	(D)
2017	5,021	(D)	-	3,651	-	(D)
2022 farms by number sold:						
1 to 19 ..... farms	9	-	1	4	-	-
number	137	-	(D)	60	-	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	41	24	95	36	3	2
2017	46	54	87	52	5	8
number, 2022	4,785	5,233	42,443	2,955	132	(D)
2017	6,006	9,949	33,003	4,814	279	341
2022 farms by inventory:						
1 to 19 ..... farms	7	7	2	8	-	-
number	(D)	99	(D)	102	-	-
20 to 49 ..... farms	16	4	9	13	3	-
number	511	85	(D)	463	132	-
50 to 99 ..... farms	7	5	8	8	-	2
number	458	283	610	434	-	(D)
100 to 199 ..... farms	6	4	14	3	-	-
number	748	566	1,906	376	-	-
200 to 499 ..... farms	4	-	21	2	-	-
number	1,510	-	7,380	(D)	-	-
500 or more ..... farms	1	4	41	2	-	-
number	(D)	4,200	32,177	(D)	-	-
SALES						
Milk sold from cows ..... farms, 2022	16	6	4	28	5	6
2017	23	14	11	69	6	6
$1,000, 2022	7,935	16,060	1,836	26,070	(D)	(D)
2017	10,764	7,794	7,167	26,207	1,269	938
Cattle and calves sold ..... farms, 2022	131	121	193	160	51	143
2017	140	178	234	265	68	164
number, 2022	6,788	16,073	56,835	51,962	2,334	5,985
2017	11,107	16,029	63,820	33,510	2,725	7,034
$1,000, 2022	10,425	21,574	104,979	36,404	(D)	6,133
2017	12,890	21,316	90,729	28,849	(D)	5,380
2022 farms by number sold:						
1 to 9 ..... farms	50	20	29	56	9	33
number	(D)	121	95	(D)	(D)	193
10 to 19 ..... farms	19	24	12	29	9	20
number	259	348	120	395	107	296
20 to 49 ..... farms	31	26	39	44	16	59
number	1,048	820	1,239	1,315	527	1,790
50 to 99 ..... farms	17	22	24	10	11	19
number	1,107	1,472	1,635	676	630	1,366
100 to 199 ..... farms	8	13	24	10	5	7
number	1,041	1,996	3,043	1,275	797	866
200 to 499 ..... farms	5	7	27	1	1	5
number	1,613	2,554	10,145	(D)	(D)	1,474
500 or more ..... farms	1	9	38	10	-	-
number	(D)	8,762	40,558	47,671	-	-
Calves weighing less than 500 pounds, sold ..... farms, 2022	31	44	28	45	14	61
2017	34	36	36	104	17	62
number, 2022	540	3,619	965	44,815	240	1,351
2017	1,595	1,024	1,249	24,012	416	2,609
2022 farms by number sold:						
1 to 9 ..... farms	15	14	8	17	7	23
number	(D)	75	37	(D)	(D)	(D)
10 to 19 ..... farms	8	3	4	11	6	18
number	100	(D)	57	138	68	256
20 to 49 ..... farms	6	12	13	8	-	15
number	131	352	338	195	-	422
50 to 99 ..... farms	-	5	-	3	-	3
number	-	295	-	190	-	252
100 to 199 ..... farms	2	6	2	-	1	2
number	(D)	889	(D)	-	(D)	(D)
200 to 499 ..... farms	-	1	1	2	-	-
number	-	(D)	(D)	(D)	-	-
500 or more ..... farms	-	3	-	4	-	-
number	-	1,500	-	43,600	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	127	115	186	146	49	142
2017	134	169	228	237	64	151
number, 2022	6,248	12,454	55,870	7,147	2,094	4,634
2017	9,512	15,005	62,571	9,498	2,309	4,425
2022 farms by number sold:						
1 to 9 ..... farms	49	21	30	53	9	46
number	(D)	122	90	(D)	47	220
10 to 19 ..... farms	21	28	12	30	10	28
number	292	391	134	411	126	411
20 to 49 ..... farms	26	24	40	38	13	45
number	837	717	1,233	977	434	1,390
50 to 99 ..... farms	17	19	17	9	12	14
number	1,047	1,352	1,206	610	690	907
100 to 199 ..... farms	10	10	22	9	5	6
number	1,307	1,470	2,797	1,225	797	856
200 to 499 ..... farms	3	5	28	1	-	3
number	1,067	1,956	10,482	(D)	-	850
500 or more ..... farms	1	8	37	6	-	-
number	(D)	6,446	39,928	3,460	-	-
Cattle on feed sold ..... farms, 2022	32	29	97	38	4	2
2017	50	56	98	61	5	10
number, 2022	3,985	6,391	46,271	3,040	164	(D)
2017	6,338	8,918	44,723	5,294	327	306
2022 farms by number sold:						
1 to 19 ..... farms	6	7	-	13	1	-
number	96	96	-	(D)	(D)	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	26	44	9	75	44	40
2017	45	52	27	98	70	64
number, 2022	5,727	9,551	169	9,242	5,363	18,964
2017	11,072	7,743	2,336	9,407	12,776	22,026
2022 farms by inventory:						
1 to 19 ..... farms	5	6	6	11	3	-
number	75	(D)	69	162	52	-
20 to 49 ..... farms	5	17	2	32	17	10
number	169	599	(D)	1,040	502	303
50 to 99 ..... farms	4	2	1	21	4	4
number	231	(D)	(D)	1,465	254	349
100 to 199 ..... farms	4	4	-	2	9	3
number	590	592	-	(D)	1,203	390
200 to 499 ..... farms	4	8	-	2	11	10
number	1,232	2,120	-	(D)	3,352	2,655
500 or more ..... farms	4	7	-	7	-	13
number	3,430	6,050	-	5,880	-	15,267
SALES						
Milk sold from cows ..... farms, 2022	3	29	10	126	22	12
2017	4	42	30	203	26	24
$1,000, 2022	2,976	60,288	5,542	100,743	20,014	17,141
2017	1,615	30,966	5,264	102,285	14,487	13,158
Cattle and calves sold ..... farms, 2022	109	188	146	594	192	160
2017	128	233	235	793	255	202
number, 2022	19,542	21,012	9,039	36,149	15,338	52,003
2017	25,810	25,307	13,730	39,741	26,647	59,583
$1,000, 2022	32,544	28,356	10,806	42,892	18,153	74,114
2017	35,881	27,020	13,258	34,723	29,195	73,798
2022 farms by number sold:						
1 to 9 ..... farms	28	64	57	146	61	30
number	(D)	273	(D)	667	270	138
10 to 19 ..... farms	18	39	45	114	40	14
number	231	516	618	1,456	550	180
20 to 49 ..... farms	29	34	18	172	49	34
number	947	1,104	494	5,156	1,455	1,146
50 to 99 ..... farms	8	17	11	86	10	20
number	473	1,148	697	5,955	674	1,234
100 to 199 ..... farms	2	9	11	44	14	15
number	(D)	1,156	1,628	5,587	2,226	1,866
200 to 499 ..... farms	18	11	1	18	12	20
number	5,100	3,128	(D)	4,900	3,292	5,331
500 or more ..... farms	6	14	3	14	6	27
number	12,417	13,687	5,064	12,428	6,871	42,108
Calves weighing less than 500 pounds, sold ..... farms, 2022	32	46	51	261	54	36
2017	29	90	78	355	64	45
number, 2022	692	4,967	3,403	8,965	7,312	2,620
2017	454	5,445	2,730	10,168	9,327	10,629
2022 farms by number sold:						
1 to 9 ..... farms	14	16	29	77	23	7
number	(D)	(D)	147	(D)	110	37
10 to 19 ..... farms	7	7	9	71	8	3
number	91	79	114	929	(D)	32
20 to 49 ..... farms	9	9	5	66	14	11
number	279	270	140	1,797	359	334
50 to 99 ..... farms	-	5	2	28	-	7
number	-	315	(D)	1,713	-	405
100 to 199 ..... farms	2	2	3	10	1	3
number	(D)	(D)	402	1,116	(D)	486
200 to 499 ..... farms	-	4	2	8	4	5
number	-	1,364	(D)	2,403	1,189	1,326
500 or more ..... farms	-	3	1	1	4	-
number	-	2,568	(D)	(D)	5,400	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	105	178	136	549	177	153
2017	120	219	209	707	233	191
number, 2022	18,850	16,045	5,636	27,184	8,026	49,383
2017	25,356	19,862	11,000	29,573	17,320	48,954
2022 farms by number sold:						
1 to 9 ..... farms	35	66	57	161	63	30
number	168	276	(D)	682	(D)	135
10 to 19 ..... farms	20	32	41	129	43	19
number	245	413	542	1,656	595	251
20 to 49 ..... farms	19	39	16	135	34	37
number	612	1,143	455	3,891	856	1,192
50 to 99 ..... farms	5	11	14	72	11	15
number	318	830	942	4,988	765	1,053
100 to 199 ..... farms	4	7	7	33	15	13
number	540	956	987	4,277	2,307	1,782
200 to 499 ..... farms	16	12	-	9	10	14
number	4,570	3,920	-	2,727	2,689	4,062
500 or more ..... farms	6	11	1	10	1	25
number	12,397	8,507	(D)	8,963	(D)	40,908
Cattle on feed sold ..... farms, 2022	30	37	14	81	49	43
2017	45	52	31	97	85	77
number, 2022	10,269	9,559	521	9,959	4,016	23,282
2017	17,001	6,920	2,760	7,927	14,135	28,889
2022 farms by number sold:						
1 to 19 ..... farms	5	4	5	18	7	3
number	(D)	(D)	73	268	84	41

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	28	70	2	50	69	6
2017	49	47	4	58	53	4
number, 2022	2,894	44,392	(D)	8,988	5,635	483
2017	4,316	44,897	147	7,929	4,257	204
2022 farms by inventory:						
1 to 19 ..... farms	4	3	-	3	6	2
number	58	30	-	34	(D)	(D)
20 to 49 ..... farms	9	8	2	21	25	-
number	327	253	(D)	656	754	-
50 to 99 ..... farms	7	13	-	19	27	1
number	520	964	-	1,306	1,770	(D)
100 to 199 ..... farms	3	5	-	2	6	3
number	531	705	-	(D)	771	390
200 to 499 ..... farms	5	7	-	3	2	-
number	1,458	2,190	-	1,092	(D)	-
500 or more ..... farms	-	34	-	2	3	-
number	-	40,250	-	(D)	1,750	-
SALES						
Milk sold from cows ..... farms, 2022	15	16	6	37	101	-
2017	38	21	6	91	173	-
$1,000, 2022	69,353	39,788	431	60,043	65,233	-
2017	42,509	23,126	207	42,709	48,329	-
Cattle and calves sold ..... farms, 2022	96	181	61	284	645	61
2017	151	214	79	372	771	96
number, 2022	19,612	91,598	2,024	24,718	45,931	4,427
2017	13,156	95,476	1,891	24,289	40,413	4,562
$1,000, 2022	11,633	156,367	1,995	28,223	52,067	3,944
2017	13,973	131,710	(D)	26,362	38,422	4,390
2022 farms by number sold:						
1 to 9 ..... farms	24	26	19	71	206	11
number	115	148	84	355	995	66
10 to 19 ..... farms	10	21	13	77	101	14
number	143	337	180	1,073	1,437	185
20 to 49 ..... farms	25	31	17	60	167	16
number	754	1,093	477	1,757	4,777	409
50 to 99 ..... farms	15	22	5	33	85	12
number	1,179	1,742	392	2,239	5,979	744
100 to 199 ..... farms	13	16	7	15	52	-
number	(D)	1,988	891	2,107	6,684	-
200 to 499 ..... farms	8	26	-	21	17	5
number	2,176	8,491	-	6,035	4,989	1,394
500 or more ..... farms	1	39	-	7	17	3
number	(D)	77,799	-	11,152	21,070	1,629
Calves weighing less than 500 pounds, sold ..... farms, 2022	28	50	22	97	237	19
2017	43	54	26	120	293	24
number, 2022	11,876	5,433	389	6,396	7,195	1,278
2017	4,852	4,165	124	4,564	7,678	550
2022 farms by number sold:						
1 to 9 ..... farms	3	19	10	41	103	7
number	8	123	(D)	156	444	(D)
10 to 19 ..... farms	4	10	7	18	38	7
number	58	(D)	80	226	497	86
20 to 49 ..... farms	10	2	3	7	58	-
number	283	(D)	97	178	1,826	-
50 to 99 ..... farms	3	4	1	11	21	2
number	235	252	(D)	919	1,203	(D)
100 to 199 ..... farms	5	11	1	17	9	-
number	560	1,759	(D)	2,503	1,300	-
200 to 499 ..... farms	2	3	-	1	8	3
number	(D)	900	-	(D)	1,925	984
500 or more ..... farms	1	1	-	2	-	-
number	(D)	(D)	-	(D)	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	89	166	58	263	619	61
2017	144	194	74	350	718	94
number, 2022	7,736	86,165	1,635	18,322	38,736	3,149
2017	8,304	91,311	1,767	19,725	32,735	4,012
2022 farms by number sold:						
1 to 9 ..... farms	24	19	23	70	227	11
number	(D)	107	96	360	980	(D)
10 to 19 ..... farms	13	15	10	70	100	19
number	190	248	136	962	1,394	243
20 to 49 ..... farms	28	34	15	62	157	16
number	883	1,135	415	1,883	4,720	495
50 to 99 ..... farms	11	22	5	37	82	7
number	851	1,613	397	2,581	5,435	424
100 to 199 ..... farms	7	24	5	8	26	1
number	1,024	3,140	591	961	3,447	(D)
200 to 499 ..... farms	5	13	-	11	13	7
number	1,166	4,323	-	3,622	3,223	1,819
500 or more ..... farms	1	39	-	5	14	-
number	(D)	75,599	-	7,953	19,537	-
Cattle on feed sold ..... farms, 2022	32	75	4	54	73	8
2017	49	60	8	61	62	8
number, 2022	2,687	72,014	80	9,820	5,171	434
2017	3,803	63,377	275	9,517	4,939	212
2022 farms by number sold:						
1 to 19 ..... farms	5	2	-	12	8	2
number	67	(D)	-	(D)	103	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	29	43	7	15	-	4
2017	17	49	1	42	-	3
number, 2022	2,221	23,524	892	4,578	-	1,513
2017	670	22,403	(D)	7,683	-	(D)
2022 farms by inventory:						
1 to 19 ..... farms	5	2	-	1	-	1
number	69	(D)	-	(D)	-	(D)
20 to 49 ..... farms	16	5	-	1	-	-
number	500	(D)	-	(D)	-	-
50 to 99 ..... farms	5	8	2	5	-	-
number	342	584	(D)	(D)	-	-
100 to 199 ..... farms	-	4	4	4	-	-
number	-	588	472	476	-	-
200 to 499 ..... farms	1	8	1	3	-	-
number	(D)	2,084	(D)	790	-	-
500 or more ..... farms	2	16	-	1	-	3
number	(D)	20,086	-	(D)	-	(D)
SALES						
Milk sold from cows ..... farms, 2022	19	14	11	15	-	3
2017	43	17	29	32	1	2
$1,000, 2022	16,186	58,159	3,062	16,530	-	7,696
2017	12,303	32,039	4,797	13,651	(D)	(D)
Cattle and calves sold ..... farms, 2022	256	183	145	159	-	56
2017	303	221	174	211	1	61
number, 2022	9,186	44,970	7,065	13,420	-	6,935
2017	8,483	61,558	9,488	16,737	(D)	4,387
$1,000, 2022	9,936	67,805	7,003	18,590	-	9,786
2017	(D)	70,440	9,947	18,897	(D)	3,787
2022 farms by number sold:						
1 to 9 ..... farms	102	26	43	36	-	4
number	429	116	203	213	-	21
10 to 19 ..... farms	41	18	12	26	-	6
number	565	249	(D)	352	-	76
20 to 49 ..... farms	71	40	57	52	-	28
number	2,256	1,300	1,962	1,757	-	967
50 to 99 ..... farms	18	22	19	22	-	5
number	1,114	1,465	1,286	1,393	-	358
100 to 199 ..... farms	15	30	7	12	-	7
number	1,732	3,768	1,197	1,581	-	893
200 to 499 ..... farms	9	30	6	8	-	3
number	3,090	10,170	1,643	1,890	-	1,020
500 or more ..... farms	-	17	1	3	-	3
number	-	27,902	(D)	6,234	-	3,600
Calves weighing less than 500 pounds, sold ..... farms, 2022	114	51	69	55	-	18
2017	127	61	58	72	1	20
number, 2022	2,250	6,632	2,006	1,894	-	1,050
2017	2,396	5,485	1,419	3,123	(D)	928
2022 farms by number sold:						
1 to 9 ..... farms	54	15	33	23	-	6
number	172	49	(D)	113	-	26
10 to 19 ..... farms	30	6	14	7	-	3
number	393	(D)	208	83	-	32
20 to 49 ..... farms	20	8	12	21	-	2
number	561	280	363	665	-	(D)
50 to 99 ..... farms	4	8	5	2	-	1
number	280	419	332	(D)	-	(D)
100 to 199 ..... farms	6	7	3	-	-	5
number	844	949	361	-	-	633
200 to 499 ..... farms	-	5	2	1	-	1
number	-	1,320	(D)	(D)	-	(D)
500 or more ..... farms	-	2	-	1	-	-
number	-	(D)	-	(D)	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	243	181	134	147	-	53
2017	275	213	171	194	1	58
number, 2022	6,936	38,338	5,059	11,526	-	5,885
2017	6,087	56,073	8,069	13,614	(D)	3,459
2022 farms by number sold:						
1 to 9 ..... farms	105	25	46	42	-	4
number	441	104	222	(D)	-	19
10 to 19 ..... farms	49	20	8	16	-	6
number	670	272	107	224	-	92
20 to 49 ..... farms	55	43	54	55	-	28
number	1,575	1,317	1,713	1,724	-	941
50 to 99 ..... farms	17	25	16	13	-	6
number	1,102	1,712	1,099	781	-	413
100 to 199 ..... farms	11	27	7	10	-	6
number	1,355	3,348	1,183	1,345	-	820
200 to 499 ..... farms	6	26	3	10	-	-
number	1,793	8,723	735	2,711	-	-
500 or more ..... farms	-	15	-	1	-	3
number	-	22,862	-	(D)	-	3,600
Cattle on feed sold ..... farms, 2022	22	45	9	20	-	4
2017	16	49	10	50	-	4
number, 2022	1,982	24,994	627	6,511	-	3,613
2017	603	25,081	1,948	7,231	-	(D)
2022 farms by number sold:						
1 to 19 ..... farms	2	4	-	1	-	1
number	(D)	(D)	-	(D)	-	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	70	42	29	72	6	5
2017	78	45	45	80	13	2
number, 2022	35,028	17,145	1,808	48,852	888	118
2017	27,009	15,477	2,242	49,782	509	(D)
2022 farms by inventory:						
1 to 19 ..... farms	5	9	5	1	-	1
number	72	142	84	(D)	-	(D)
20 to 49 ..... farms	12	5	12	2	3	4
number	389	164	322	(D)	71	(D)
50 to 99 ..... farms	12	7	5	8	2	-
number	881	397	287	600	(D)	-
100 to 199 ..... farms	3	5	7	4	-	-
number	398	590	1,115	420	-	-
200 to 499 ..... farms	12	4	-	20	-	-
number	3,632	840	-	6,281	-	-
500 or more ..... farms	26	12	-	37	1	-
number	29,656	15,012	-	41,479	(D)	-
SALES						
Milk sold from cows ..... farms, 2022	7	12	35	11	5	7
2017	20	25	66	18	17	6
$1,000, 2022	4,231	17,361	29,046	25,652	1,370	5,076
2017	5,843	10,768	24,234	14,544	2,229	2,636
Cattle and calves sold ..... farms, 2022	208	111	179	191	140	190
2017	229	125	250	274	158	222
number, 2022	58,478	35,071	7,377	81,116	9,593	5,763
2017	56,943	19,931	8,065	119,209	7,980	4,279
$1,000, 2022	101,077	57,418	8,410	149,641	10,928	6,175
2017	77,427	27,795	7,465	149,784	7,070	3,562
2022 farms by number sold:						
1 to 9 ..... farms	38	26	63	25	20	82
number	185	109	(D)	136	(D)	310
10 to 19 ..... farms	23	19	30	18	11	34
number	314	281	407	257	170	465
20 to 49 ..... farms	55	15	50	25	37	49
number	1,810	528	1,721	737	1,211	1,634
50 to 99 ..... farms	25	15	13	24	45	20
number	1,788	884	744	1,764	3,061	1,446
100 to 199 ..... farms	21	7	18	18	23	1
number	2,849	864	2,371	2,092	2,948	(D)
200 to 499 ..... farms	15	16	4	33	3	2
number	4,412	4,805	1,132	10,088	824	(D)
500 or more ..... farms	31	13	1	48	1	2
number	47,120	27,600	(D)	66,042	(D)	(D)
Calves weighing less than 500 pounds, sold ..... farms, 2022	49	37	47	38	71	82
2017	58	36	58	36	76	81
number, 2022	1,578	1,952	1,673	4,073	1,710	1,170
2017	2,071	2,089	2,013	9,743	1,684	835
2022 farms by number sold:						
1 to 9 ..... farms	12	13	12	4	15	48
number	54	41	(D)	16	(D)	195
10 to 19 ..... farms	17	7	10	4	13	14
number	219	89	143	(D)	169	206
20 to 49 ..... farms	11	8	17	8	41	17
number	309	286	523	298	1,378	469
50 to 99 ..... farms	6	2	6	6	2	1
number	396	(D)	423	382	(D)	(D)
100 to 199 ..... farms	2	5	-	6	-	2
number	(D)	825	-	616	-	(D)
200 to 499 ..... farms	1	2	2	9	-	-
number	(D)	(D)	(D)	2,112	-	-
500 or more ..... farms	-	-	-	1	-	-
number	-	-	-	(D)	-	-
Cattle weighing 500 pounds or more, sold ..... farms, 2022	202	104	171	188	139	175
2017	213	120	236	266	154	206
number, 2022	56,900	33,119	5,704	77,043	7,883	4,593
2017	54,872	17,842	6,052	109,466	6,296	3,444
2022 farms by number sold:						
1 to 9 ..... farms	42	24	65	25	23	80
number	197	110	274	136	(D)	(D)
10 to 19 ..... farms	27	16	31	20	20	39
number	373	226	425	267	304	560
20 to 49 ..... farms	51	21	48	31	34	35
number	1,715	672	1,521	952	1,194	1,043
50 to 99 ..... farms	19	14	10	24	46	16
number	1,318	910	657	1,720	2,836	1,035
100 to 199 ..... farms	20	5	13	16	14	3
number	2,765	628	1,734	1,898	1,791	480
200 to 499 ..... farms	12	11	4	29	1	-
number	3,412	3,506	1,093	9,197	(D)	-
500 or more ..... farms	31	13	-	43	1	2
number	47,120	27,067	-	62,873	(D)	(D)
Cattle on feed sold ..... farms, 2022	78	44	35	77	9	15
2017	90	46	51	85	7	6
number, 2022	43,693	27,713	2,246	65,609	1,667	370
2017	40,299	13,492	2,338	61,153	340	196
2022 farms by number sold:						
1 to 19 ..... farms	5	8	11	3	2	9
number	69	134	156	34	(D)	(D)

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	22	9	60	296	23	25
2017	37	12	98	328	23	54
number, 2022	2,016	4,315	5,268	42,573	985	11,014
2017	4,151	4,173	12,828	37,416	1,306	14,585
2022 farms by inventory:						
1 to 19 ..... farms	2	1	4	27	4	3
number	(D)	(D)	(D)	364	61	(D)
20 to 49 ..... farms	7	-	31	87	8	4
number	201	-	789	2,627	253	130
50 to 99 ..... farms	8	3	10	72	11	1
number	572	(D)	756	4,940	671	(D)
100 to 199 ..... farms	1	-	8	57	-	1
number	(D)	-	1,278	6,916	-	(D)
200 to 499 ..... farms	4	1	5	30	-	12
number	1,106	(D)	1,374	8,815	-	3,734
500 or more ..... farms	-	4	2	23	-	4
number	-	3,800	(D)	18,911	-	6,926
SALES						
Milk sold from cows ..... farms, 2022	17	4	28	349	9	8
2017	33	12	44	629	40	9
$1,000, 2022	14,085	694	45,450	303,340	7,076	(D)
2017	12,185	1,946	26,263	254,768	13,178	(D)
Cattle and calves sold ..... farms, 2022	109	73	209	1,112	120	75
2017	176	93	267	1,372	159	106
number, 2022	8,139	9,353	20,460	109,820	3,156	39,461
2017	9,979	6,465	26,187	111,909	4,550	39,892
$1,000, 2022	10,423	15,838	(D)	136,194	3,476	(D)
2017	12,636	7,550	34,126	112,985	(D)	(D)
2022 farms by number sold:						
1 to 9 ..... farms	42	32	49	254	53	15
number	199	111	214	1,235	214	73
10 to 19 ..... farms	27	14	34	139	26	11
number	361	203	473	1,877	348	164
20 to 49 ..... farms	22	3	53	265	23	8
number	682	127	1,560	8,709	692	252
50 to 99 ..... farms	8	6	30	227	14	11
number	565	369	2,159	15,115	1,142	711
100 to 199 ..... farms	2	5	20	110	2	4
number	(D)	553	2,845	14,037	(D)	654
200 to 499 ..... farms	7	9	14	78	2	14
number	(D)	2,690	5,169	22,438	(D)	4,298
500 or more ..... farms	1	4	9	39	-	12
number	(D)	5,300	8,040	46,409	-	33,309
Calves weighing less than 500 pounds, sold ..... farms, 2022	27	16	66	439	28	18
2017	62	25	70	518	54	12
number, 2022	828	122	4,622	26,610	781	(D)
2017	1,329	417	4,895	22,514	866	(D)
2022 farms by number sold:						
1 to 9 ..... farms	11	12	21	139	15	4
number	(D)	61	94	568	65	8
10 to 19 ..... farms	5	3	9	61	4	3
number	74	(D)	100	851	42	40
20 to 49 ..... farms	6	1	15	130	2	6
number	162	(D)	430	3,946	(D)	162
50 to 99 ..... farms	2	-	11	59	5	-
number	(D)	-	670	3,609	353	-
100 to 199 ..... farms	3	-	2	25	2	4
number	394	-	(D)	3,299	(D)	538
200 to 499 ..... farms	-	-	7	15	-	-
number	-	-	1,735	4,673	-	-
500 or more ..... farms	-	-	1	10	-	1
number	-	-	(D)	9,664	-	(D)
Cattle weighing 500 pounds or more, sold ..... farms, 2022	102	67	199	1,056	118	75
2017	164	86	255	1,316	153	103
number, 2022	7,311	9,231	15,838	83,210	2,375	(D)
2017	8,650	6,048	21,292	89,395	3,684	(D)
2022 farms by number sold:						
1 to 9 ..... farms	43	30	46	261	55	16
number	(D)	91	178	1,242	(D)	(D)
10 to 19 ..... farms	25	10	44	170	28	15
number	326	138	601	2,256	358	213
20 to 49 ..... farms	20	4	46	282	21	5
number	597	162	1,333	8,924	605	138
50 to 99 ..... farms	5	5	30	162	13	9
number	321	297	2,149	10,527	1,061	573
100 to 199 ..... farms	4	5	15	89	1	8
number	617	553	2,360	11,148	(D)	1,094
200 to 499 ..... farms	4	9	13	62	-	10
number	1,252	2,690	4,724	17,651	-	3,320
500 or more ..... farms	1	4	5	30	-	12
number	(D)	5,300	4,493	31,462	-	20,809
Cattle on feed sold ..... farms, 2022	20	14	61	299	23	23
2017	41	13	102	329	19	59
number, 2022	2,826	5,740	5,815	43,900	943	14,605
2017	6,679	3,940	13,133	39,565	1,039	16,967
2022 farms by number sold:						
1 to 19 ..... farms	3	5	12	32	4	3
number	46	74	(D)	444	(D)	42

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	17	51	6	67	7	19
2017	29	66	10	59	9	42
number, 2022	4,406	5,225	1,239	6,200	636	4,119
2017	4,190	5,236	3,426	5,950	186	6,511
2022 farms by inventory:						
1 to 19 ..... farms	2	3	-	7	-	1
number	(D)	(D)	-	(D)	-	(D)
20 to 49 ..... farms	5	19	1	22	1	7
number	170	657	(D)	831	(D)	203
50 to 99 ..... farms	4	10	2	16	-	2
number	322	704	(D)	1,000	-	(D)
100 to 199 ..... farms	-	11	2	12	6	4
number	-	1,460	(D)	1,351	(D)	440
200 to 499 ..... farms	2	7	-	9	-	2
number	(D)	1,750	-	2,404	-	(D)
500 or more ..... farms	4	1	1	1	-	3
number	3,480	(D)	(D)	(D)	-	2,700
SALES						
Milk sold from cows ..... farms, 2022	5	96	1	105	13	3
2017	21	216	1	133	30	21
$1,000, 2022	(D)	64,862	(D)	147,991	(D)	657
2017	46,721	52,897	(D)	81,834	8,964	4,266
Cattle and calves sold ..... farms, 2022	93	484	18	298	151	81
2017	133	650	26	340	198	135
number, 2022	24,850	23,937	11,481	32,247	6,057	9,701
2017	22,818	26,790	9,706	24,331	6,547	14,457
$1,000, 2022	21,545	26,725	(D)	29,358	5,822	15,237
2017	25,177	22,946	(D)	20,144	5,598	16,856
2022 farms by number sold:						
1 to 9 ..... farms	29	149	2	38	35	23
number	(D)	718	(D)	192	140	116
10 to 19 ..... farms	13	102	2	45	37	21
number	182	1,352	(D)	654	508	277
20 to 49 ..... farms	25	98	5	96	54	11
number	885	3,079	174	3,130	1,580	341
50 to 99 ..... farms	8	77	4	44	14	9
number	468	5,173	320	3,224	953	700
100 to 199 ..... farms	7	34	3	43	6	5
number	829	4,403	(D)	6,426	780	520
200 to 499 ..... farms	2	19	-	21	5	6
number	(D)	5,064	-	6,138	2,096	1,894
500 or more ..... farms	9	5	2	11	-	6
number	21,734	4,148	(D)	12,483	-	5,853
Calves weighing less than 500 pounds, sold ..... farms, 2022	21	194	4	133	74	17
2017	34	282	7	169	93	32
number, 2022	(D)	6,131	(D)	11,309	1,420	3,548
2017	(D)	6,713	(D)	8,087	2,168	2,762
2022 farms by number sold:						
1 to 9 ..... farms	10	85	1	34	41	6
number	42	(D)	(D)	138	202	28
10 to 19 ..... farms	8	38	2	18	11	2
number	96	494	(D)	215	(D)	(D)
20 to 49 ..... farms	-	47	-	27	17	5
number	-	1,458	-	810	464	140
50 to 99 ..... farms	-	10	-	31	3	-
number	-	670	-	2,079	184	-
100 to 199 ..... farms	1	8	-	12	1	-
number	(D)	1,012	-	1,454	(D)	-
200 to 499 ..... farms	-	4	-	7	1	1
number	-	920	-	1,629	(D)	(D)
500 or more ..... farms	2	2	1	4	-	3
number	(D)	(D)	(D)	4,984	-	3,150
Cattle weighing 500 pounds or more, sold ..... farms, 2022	92	455	18	290	139	80
2017	125	594	23	323	178	128
number, 2022	(D)	17,806	(D)	20,938	4,637	6,153
2017	(D)	20,077	(D)	16,244	4,379	11,695
2022 farms by number sold:						
1 to 9 ..... farms	31	175	3	42	52	28
number	149	834	10	211	192	132
10 to 19 ..... farms	11	87	2	49	25	18
number	141	1,111	(D)	689	344	236
20 to 49 ..... farms	26	88	4	102	44	15
number	923	2,528	150	3,104	1,252	471
50 to 99 ..... farms	6	66	4	44	10	6
number	336	4,630	320	3,180	718	470
100 to 199 ..... farms	8	20	3	29	4	5
number	929	2,379	500	3,965	611	520
200 to 499 ..... farms	1	16	-	21	4	5
number	(D)	4,407	-	7,256	1,520	1,624
500 or more ..... farms	9	3	2	3	-	3
number	11,867	1,917	(D)	2,533	-	2,700
Cattle on feed sold ..... farms, 2022	17	59	7	64	13	19
2017	44	54	10	66	12	35
number, 2022	4,872	4,886	2,114	5,296	408	4,357
2017	9,445	5,065	3,899	5,078	225	7,765
2022 farms by number sold:						
1 to 19 ..... farms	2	15	-	7	2	5
number	(D)	(D)	-	96	(D)	80

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
INVENTORY - Con.						
Cattle and calves - Con.						
Cattle on feed ..... farms, 2022	5	9	8	77	64	15
2017	10	6	1	97	65	52
number, 2022	321	3,779	238	6,118	7,677	3,136
2017	533	(D)	(D)	8,848	7,167	13,517
2022 farms by inventory:						
1 to 19 ..... farms	1	3	4	12	5	3
number	(D)	46	50	190	(D)	37
20 to 49 ..... farms	-	2	2	32	28	6
number	-	(D)	(D)	976	807	234
50 to 99 ..... farms	4	-	2	13	13	-
number	(D)	-	(D)	950	773	-
100 to 199 ..... farms	-	-	-	11	11	2
number	-	-	-	1,522	1,414	(D)
200 to 499 ..... farms	-	2	-	9	2	1
number	-	(D)	-	2,480	(D)	(D)
500 or more ..... farms	-	2	-	-	5	3
number	-	(D)	-	-	3,850	2,175
SALES						
Milk sold from cows ..... farms, 2022	5	-	-	114	45	7
2017	17	2	1	136	61	9
$1,000, 2022	1,683	-	-	185,343	42,129	13,914
2017	2,312	(D)	(D)	98,915	24,295	5,733
Cattle and calves sold ..... farms, 2022	55	58	32	402	275	123
2017	96	58	28	467	347	157
number, 2022	1,231	6,691	1,716	40,872	23,909	18,823
2017	2,118	2,971	896	31,335	21,657	22,467
$1,000, 2022	1,321	7,633	2,013	39,569	23,989	23,279
2017	1,853	4,114	857	27,640	22,027	30,936
2022 farms by number sold:						
1 to 9 ..... farms	28	26	11	71	113	33
number	134	(D)	31	322	471	178
10 to 19 ..... farms	9	11	9	62	48	13
number	(D)	136	136	886	665	162
20 to 49 ..... farms	9	10	4	105	60	35
number	279	266	120	3,280	1,864	1,188
50 to 99 ..... farms	7	5	5	49	22	12
number	495	293	311	3,390	1,656	868
100 to 199 ..... farms	2	-	-	47	10	8
number	(D)	-	-	6,582	1,233	1,036
200 to 499 ..... farms	-	2	3	55	17	10
number	-	(D)	1,118	16,470	4,770	3,165
500 or more ..... farms	-	4	-	13	5	12
number	-	5,321	-	9,942	13,250	12,226
Calves weighing less than 500 pounds, sold ..... farms, 2022	19	17	10	163	72	33
2017	34	13	6	203	101	40
number, 2022	362	214	247	14,649	12,249	3,629
2017	707	82	22	9,675	3,393	970
2022 farms by number sold:						
1 to 9 ..... farms	10	8	4	38	26	17
number	53	31	(D)	161	(D)	87
10 to 19 ..... farms	1	4	4	21	14	2
number	(D)	43	62	(D)	184	(D)
20 to 49 ..... farms	6	5	-	30	9	6
number	178	140	-	958	298	146
50 to 99 ..... farms	2	-	1	19	13	1
number	(D)	-	(D)	1,121	872	(D)
100 to 199 ..... farms	-	-	1	39	5	4
number	-	-	(D)	6,192	720	685
200 to 499 ..... farms	-	-	-	14	2	-
number	-	-	-	4,384	(D)	-
500 or more ..... farms	-	-	-	2	3	3
number	-	-	-	(D)	9,600	2,601
Cattle weighing 500 pounds or more, sold ..... farms, 2022	51	49	31	387	271	115
2017	92	56	28	417	332	150
number, 2022	869	6,477	1,469	26,223	11,660	15,194
2017	1,411	2,889	874	21,660	18,264	21,497
2022 farms by number sold:						
1 to 9 ..... farms	28	21	11	74	115	31
number	146	(D)	32	323	467	140
10 to 19 ..... farms	10	8	8	67	60	13
number	108	106	113	940	829	157
20 to 49 ..... farms	9	14	6	109	51	32
number	315	397	200	3,500	1,594	1,068
50 to 99 ..... farms	2	-	3	58	20	14
number	(D)	-	174	3,931	1,415	970
100 to 199 ..... farms	2	-	-	55	12	10
number	(D)	-	-	7,915	1,638	1,250
200 to 499 ..... farms	-	2	3	17	8	6
number	-	(D)	950	4,956	2,067	2,020
500 or more ..... farms	-	4	-	7	5	9
number	-	5,321	-	4,658	3,650	9,589
Cattle on feed sold ..... farms, 2022	5	11	9	79	66	15
2017	10	6	2	99	67	54
number, 2022	304	3,583	422	5,772	6,765	5,145
2017	504	(D)	(D)	8,555	8,615	16,615
2022 farms by number sold:						
1 to 19 ..... farms	-	6	5	11	16	-
number	-	80	(D)	169	244	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
SALES - Con.					
Cattle and calves sold - Con.					
Cattle on feed sold - Con.					
2022 farms by number sold: - Con.					
20 to 49 ... farms	831	6	-	1	-
number	25,602	198	-	(D)	-
50 to 99 ... farms	457	-	-	-	6
number	31,055	-	-	-	492
100 to 199 ... farms	341	-	-	-	1
number	44,451	-	-	-	(D)
200 to 499 ... farms	313	-	-	7	-
number	94,435	-	-	2,446	-
500 or more ... farms	323	-	-	3	-
number	435,229	-	-	3,750	-

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
SALES - Con.					
Cattle and calves sold - Con.					
Cattle on feed sold - Con.					
2022 farms by number sold: - Con.					
20 to 49 ... farms	26	1	4	16	3
number	879	(D)	143	475	66
50 to 99 ... farms	6	3	2	11	-
number	399	(D)	(D)	781	-
100 to 199 ... farms	7	-	1	4	-
number	940	-	(D)	490	-
200 to 499 ... farms	8	-	3	12	-
number	1,881	-	840	3,918	-
500 or more ... farms	-	-	1	11	-
number	-	-	(D)	10,236	-

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ... farms	12	4	3	9	3	2
number	332	(D)	60	255	112	(D)
50 to 99 ... farms	9	-	-	1	-	1
number	630	-	-	(D)	-	(D)
100 to 199 ... farms	12	5	-	-	-	-
number	1,592	500	-	-	-	-
200 to 499 ... farms	1	-	-	-	-	-
number	(D)	-	-	-	-	-
500 or more ... farms	-	-	2	-	-	-
number	-	-	(D)	-	-	-

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ... farms	-	6	-	18	14	10
number	-	230	-	524	529	343
50 to 99 ... farms	-	2	-	2	-	11
number	-	(D)	-	(D)	-	738
100 to 199 ... farms	-	3	-	8	2	2
number	-	305	-	1,026	(D)	(D)
200 to 499 ... farms	-	4	-	16	6	2
number	-	1,476	-	4,059	1,260	(D)
500 or more ... farms	-	7	-	5	6	1
number	-	17,766	-	6,572	3,300	(D)

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ... farms	8	14	14	35	5	3
number	261	337	476	1,041	158	89
50 to 99 ... farms	3	19	9	20	2	2
number	(D)	1,262	602	1,323	(D)	(D)
100 to 199 ... farms	-	17	-	22	1	2
number	-	2,230	-	2,986	(D)	(D)
200 to 499 ... farms	-	7	-	12	-	-
number	-	2,478	-	3,200	-	-
500 or more ... farms	4	4	3	7	-	-
number	3,584	3,723	2,133	6,286	-	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ..... farms	24	-	7	3	7	-
number	710	-	224	(D)	235	-
50 to 99 ..... farms	8	-	1	-	6	-
number	(D)	-	(D)	-	449	-
100 to 199 ..... farms	13	-	-	-	-	1
number	1,610	-	-	-	-	(D)
200 to 499 ..... farms	5	-	-	-	-	-
number	1,224	-	-	-	-	-
500 or more ..... farms	4	-	-	-	5	-
number	5,395	-	-	-	6,084	-

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ..... farms	17	3	1	5	-	2
number	451	(D)	(D)	119	-	(D)
50 to 99 ..... farms	7	1	-	2	-	-
number	456	(D)	-	(D)	-	-
100 to 199 ..... farms	2	-	-	-	-	-
number	(D)	-	-	-	-	-
200 to 499 ..... farms	2	-	-	1	-	-
number	(D)	-	-	(D)	-	-
500 or more ..... farms	-	-	-	1	-	-
number	-	-	-	(D)	-	-

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ..... farms	14	9	9	8	-	2
number	541	232	306	215	-	(D)
50 to 99 ..... farms	1	1	10	7	3	-
number	(D)	(D)	846	454	(D)	-
100 to 199 ..... farms	8	2	18	8	-	-
number	985	(D)	2,304	1,028	-	-
200 to 499 ..... farms	2	5	27	-	-	-
number	(D)	2,182	9,865	-	-	-
500 or more ..... farms	1	5	33	2	-	-
number	(D)	3,450	32,950	(D)	-	-

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ..... farms	7	13	4	28	19	9
number	218	461	104	860	462	295
50 to 99 ..... farms	2	2	5	19	6	8
number	(D)	(D)	344	1,256	391	641
100 to 199 ..... farms	-	3	-	6	10	-
number	-	396	-	717	1,528	-
200 to 499 ..... farms	12	8	-	3	7	11
number	3,616	2,410	-	678	1,551	3,014
500 or more ..... farms	4	7	-	7	-	12
number	6,219	6,050	-	6,180	-	19,291

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ..... farms	9	10	4	18	39	3
number	246	(D)	80	494	1,169	(D)
50 to 99 ..... farms	10	14	-	12	14	-
number	677	975	-	751	835	-
100 to 199 ..... farms	3	4	-	3	9	3
number	531	525	-	320	1,102	300
200 to 499 ..... farms	5	11	-	7	1	-
number	1,166	3,616	-	2,091	(D)	-
500 or more ..... farms	-	34	-	2	2	-
number	-	66,577	-	(D)	(D)	-

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Table 11. **Cattle and Calves - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ... farms	10	2	5	4	-	-
number	(D)	(D)	215	95	-	-
50 to 99 ... farms	7	10	2	3	-	-
number	468	849	(D)	167	-	-
100 to 199 ... farms	-	4	2	8	-	-
number	-	520	(D)	1,013	-	-
200 to 499 ... farms	3	15	-	3	-	-
number	1,168	5,065	-	(D)	-	-
500 or more ... farms	-	10	-	1	-	3
number	-	18,429	-	(D)	-	(D)

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ... farms	16	8	8	4	2	4
number	537	260	283	125	(D)	134
50 to 99 ... farms	10	6	4	5	4	2
number	673	356	247	291	267	(D)
100 to 199 ... farms	9	5	12	5	-	-
number	1,366	613	1,560	670	-	-
200 to 499 ... farms	11	5	-	20	-	-
number	3,484	1,458	-	6,344	-	-
500 or more ... farms	27	12	-	40	1	-
number	37,564	24,892	-	58,145	(D)	-

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ... farms	7	1	21	103	14	2
number	233	(D)	589	3,165	458	(D)
50 to 99 ... farms	4	1	15	65	4	1
number	236	(D)	1,173	4,129	320	(D)
100 to 199 ... farms	3	2	7	44	1	3
number	460	(D)	1,078	5,398	(D)	482
200 to 499 ... farms	2	1	4	32	-	8
number	(D)	(D)	1,270	8,457	-	2,720
500 or more ... farms	1	4	2	23	-	6
number	(D)	5,090	(D)	22,307	-	11,226

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ... farms	5	14	4	22	10	2
number	170	509	150	740	314	(D)
50 to 99 ... farms	4	15	-	17	1	2
number	246	1,013	-	1,252	(D)	(D)
100 to 199 ... farms	2	9	2	12	-	4
number	(D)	1,201	(D)	1,550	-	426
200 to 499 ... farms	-	5	-	6	-	3
number	-	1,327	-	1,658	-	964
500 or more ... farms	4	1	1	-	-	3
number	4,218	(D)	(D)	-	-	2,700

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
SALES - Con.						
Cattle and calves sold - Con.						
Cattle on feed sold - Con.						
2022 farms by number sold: - Con.						
20 to 49 ... farms	2	1	3	33	25	8
number	(D)	(D)	95	924	702	276
50 to 99 ... farms	1	-	-	12	13	1
number	(D)	-	-	746	870	(D)
100 to 199 ... farms	2	-	-	20	3	2
number	(D)	-	-	2,985	337	(D)
200 to 499 ... farms	-	2	1	3	4	-
number	-	(D)	(D)	948	962	-
500 or more ... farms	-	2	-	-	5	4
number	-	(D)	-	-	3,650	4,589

Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
INVENTORY						
Total hogs and pigs	farms, 2022	2,928	18	12	11	16
	2017	3,225	19	13	12	20
	number, 2022	8,873,776	171	231	24,991	209
	2017	8,467,361	217	146	(D)	190
Farms by inventory:						
1 to 24	farms, 2022	893	17	10	6	15
	2017	1,036	17	12	6	17
	number, 2022	6,064	(D)	(D)	71	(D)
	2017	6,989	(D)	(D)	44	56
25 to 49	farms, 2022	93	-	-	2	-
	2017	131	2	-	2	3
	number, 2022	3,051	-	-	(D)	-
	2017	4,217	(D)	-	(D)	134
50 to 99	farms, 2022	71	-	2	-	-
	2017	84	-	1	2	-
	number, 2022	4,708	-	(D)	-	-
	2017	5,596	-	(D)	(D)	-
100 to 199	farms, 2022	65	1	-	-	1
	2017	89	-	-	1	-
	number, 2022	8,229	(D)	-	-	(D)
	2017	12,738	-	-	(D)	-
200 to 499	farms, 2022	116	-	-	-	-
	2017	137	-	-	-	-
	number, 2022	35,806	-	-	-	-
	2017	44,021	-	-	-	-
500 to 999	farms, 2022	154	-	-	-	-
	2017	200	-	-	-	-
	number, 2022	104,640	-	-	-	-
	2017	136,876	-	-	-	-
1,000 or more	farms, 2022	1,536	-	-	3	-
	2017	1,548	-	-	1	-
	number, 2022	8,711,278	-	-	(D)	-
	2017	8,256,924	-	-	(D)	-
SALES						
Hogs and pigs sold	farms, 2022	3,352	18	11	21	17
	2017	3,562	19	11	20	17
	number, 2022	28,535,462	219	85	(D)	245
	2017	27,228,111	367	97	(D)	325
	$1,000, 2022	4,666,832	53	21	12,020	45
	2017	3,165,075	61	14	(D)	42
2022 farms by number sold:						
1 to 24	farms	1,015	16	9	16	16
	number	7,215	(D)	(D)	104	(D)
25 to 49	farms	134	1	2	-	-
	number	4,264	(D)	(D)	-	-
50 to 99	farms	80	1	-	1	-
	number	5,560	(D)	-	(D)	-
100 to 199	farms	67	-	-	1	1
	number	10,110	-	-	(D)	(D)
200 to 499	farms	83	-	-	-	-
	number	26,276	-	-	-	-
500 to 999	farms	63	-	-	-	-
	number	44,352	-	-	-	-
1,000 or more	farms	1,910	-	-	3	-
	number	28,437,685	-	-	(D)	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
INVENTORY						
Total hogs and pigs	farms, 2022	36	7	94	66	10
	2017	26	7	108	61	11
	number, 2022	34,685	45,114	669,744	244,365	60
	2017	25,398	47,084	599,573	282,668	491
Farms by inventory:						
1 to 24	farms, 2022	26	-	4	15	10
	2017	11	1	13	4	7
	number, 2022	148	-	6	(D)	60
	2017	85	(D)	142	(D)	54
25 to 49	farms, 2022	1	1	-	-	-
	2017	3	-	-	-	2
	number, 2022	(D)	(D)	-	-	-
	2017	97	-	-	-	(D)
50 to 99	farms, 2022	-	-	-	-	-
	2017	2	-	-	-	1
	number, 2022	-	-	-	-	-
	2017	(D)	-	-	-	(D)
100 to 199	farms, 2022	-	-	-	2	-
	2017	-	-	-	1	-
	number, 2022	-	-	-	(D)	-
	2017	-	-	-	(D)	-
200 to 499	farms, 2022	2	1	1	7	-
	2017	1	-	8	3	1
	number, 2022	(D)	(D)	(D)	1,933	-
	2017	(D)	-	2,645	1,147	(D)
500 to 999	farms, 2022	-	-	6	5	-
	2017	-	-	5	10	-
	number, 2022	-	-	(D)	3,145	-
	2017	-	-	3,540	6,090	-
1,000 or more	farms, 2022	7	5	83	37	-
	2017	9	6	82	43	-
	number, 2022	33,872	(D)	664,638	238,967	-
	2017	24,800	(D)	593,246	275,210	-
SALES						
Hogs and pigs sold	farms, 2022	27	9	114	75	12
	2017	28	12	110	73	24
	number, 2022	65,247	101,629	2,198,966	867,498	89
	2017	59,842	113,171	1,956,597	836,873	748
	$1,000, 2022	15,284	21,766	355,237	130,536	(D)
	2017	9,156	18,495	256,983	106,448	160
2022 farms by number sold:						
1 to 24	farms	14	3	4	10	12
	number	100	(D)	(D)	(D)	89
25 to 49	farms	2	-	1	6	-
	number	(D)	-	(D)	164	-
50 to 99	farms	2	-	-	-	-
	number	(D)	-	-	-	-
100 to 199	farms	-	-	-	4	-
	number	-	-	-	500	-
200 to 499	farms	2	1	-	5	-
	number	(D)	(D)	-	1,568	-
500 to 999	farms	-	-	-	2	-
	number	-	-	-	(D)	-
1,000 or more	farms	7	5	109	48	-
	number	64,200	101,389	2,198,907	864,005	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
INVENTORY						
Total hogs and pigs ..... farms, 2022	13	12	19	19	6	7
2017	17	19	30	52	23	12
number, 2022	25,743	222	61,623	484	13,515	538
2017	9,908	137	54,121	1,056	22,530	(D)
Farms by inventory:						
1 to 24 ..... farms, 2022	6	10	2	18	3	3
2017	4	18	8	49	17	9
number, 2022	51	(D)	(D)	(D)	15	18
2017	(D)	(D)	(D)	471	(D)	84
25 to 49 ..... farms, 2022	2	-	-	-	-	-
2017	-	1	-	-	-	-
number, 2022	(D)	-	-	-	-	-
2017	-	(D)	-	-	-	-
50 to 99 ..... farms, 2022	-	2	-	-	-	2
2017	-	-	-	1	-	1
number, 2022	-	(D)	-	-	-	(D)
2017	-	-	-	(D)	-	(D)
100 to 199 ..... farms, 2022	1	-	3	-	-	-
2017	3	-	1	-	-	-
number, 2022	(D)	-	400	-	-	-
2017	335	-	(D)	-	-	-
200 to 499 ..... farms, 2022	-	-	2	1	-	2
2017	1	-	3	2	-	1
number, 2022	-	-	(D)	(D)	-	(D)
2017	(D)	-	850	(D)	-	(D)
500 to 999 ..... farms, 2022	-	-	1	-	-	-
2017	5	-	6	-	1	-
number, 2022	-	-	(D)	-	-	-
2017	2,500	-	3,000	-	(D)	-
1,000 or more ..... farms, 2022	4	-	11	-	3	-
2017	4	-	12	-	5	1
number, 2022	25,500	-	59,653	-	13,500	-
2017	6,600	-	50,098	-	21,956	(D)
SALES						
Hogs and pigs sold ..... farms, 2022	12	10	30	18	11	7
2017	17	20	33	45	18	13
number, 2022	40,048	182	425,372	1,169	19,537	870
2017	21,642	273	128,749	2,277	58,008	3,512
$1,000, 2022	8,823	22	44,468	295	4,211	250
2017	3,491	32	18,924	395	7,910	(D)
2022 farms by number sold:						
1 to 24 ..... farms	5	7	3	17	8	3
number	34	22	42	(D)	37	10
25 to 49 ..... farms	2	1	2	-	-	-
number	(D)	(D)	(D)	-	-	-
50 to 99 ..... farms	-	2	1	-	-	-
number	-	(D)	(D)	-	-	-
100 to 199 ..... farms	1	-	2	-	-	2
number	(D)	-	(D)	-	-	(D)
200 to 499 ..... farms	-	-	2	-	-	2
number	-	-	(D)	-	-	(D)
500 to 999 ..... farms	-	-	2	1	-	-
number	-	-	(D)	(D)	-	-
1,000 or more ..... farms	4	-	18	-	3	-
number	39,832	-	422,906	-	19,500	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
INVENTORY							
Total hogs and pigs	farms, 2022	1	50	3	19	37	15
	2017	-	52	15	28	52	13
	number, 2022	(D)	341,754	25	4,808	243,721	1,179
	2017	-	356,536	267	14,493	169,168	1,089
Farms by inventory:							
1 to 24	farms, 2022	1	3	3	13	8	9
	2017	-	-	14	11	7	9
	number, 2022	(D)	(D)	25	81	38	21
	2017	-	-	(D)	(D)	28	49
25 to 49	farms, 2022	-	2	-	-	2	2
	2017	-	2	-	6	2	2
	number, 2022	-	(D)	-	-	(D)	(D)
	2017	-	(D)	-	228	(D)	(D)
50 to 99	farms, 2022	-	-	-	2	-	2
	2017	-	-	-	-	-	1
	number, 2022	-	-	-	(D)	-	(D)
	2017	-	-	-	-	-	(D)
100 to 199	farms, 2022	-	-	-	1	6	-
	2017	-	-	1	4	8	-
	number, 2022	-	-	-	(D)	894	-
	2017	-	-	(D)	580	1,208	-
200 to 499	farms, 2022	-	-	-	-	-	2
	2017	-	8	-	-	2	-
	number, 2022	-	-	-	-	-	(D)
	2017	-	2,900	-	-	(D)	-
500 to 999	farms, 2022	-	3	-	1	2	-
	2017	-	4	-	2	2	1
	number, 2022	-	1,803	-	(D)	(D)	-
	2017	-	(D)	-	(D)	(D)	(D)
1,000 or more	farms, 2022	-	42	-	2	19	-
	2017	-	38	-	5	31	-
	number, 2022	-	339,847	-	(D)	241,533	-
	2017	-	351,016	-	11,700	166,130	-
SALES							
Hogs and pigs sold	farms, 2022	1	61	4	24	49	13
	2017	-	55	16	41	54	25
	number, 2022	(D)	1,438,910	48	16,751	391,126	2,202
	2017	-	1,109,333	278	26,473	511,747	1,054
	$1,000, 2022	(D)	180,937	12	3,959	74,426	480
	2017	-	125,203	(D)	4,132	58,578	228
2022 farms by number sold:							
1 to 24	farms	1	8	3	17	13	7
	number	(D)	28	(D)	62	(D)	34
25 to 49	farms	-	-	1	1	-	-
	number	-	-	(D)	(D)	-	-
50 to 99	farms	-	-	-	-	6	2
	number	-	-	-	-	372	(D)
100 to 199	farms	-	-	-	1	2	2
	number	-	-	-	(D)	(D)	(D)
200 to 499	farms	-	-	-	2	-	-
	number	-	-	-	(D)	-	-
500 to 999	farms	-	-	-	-	-	2
	number	-	-	-	-	-	(D)
1,000 or more	farms	-	53	-	3	28	-
	number	-	1,438,882	-	(D)	390,496	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
INVENTORY							
Total hogs and pigs	farms, 2022	65	84	60	62	1	7
	2017	67	81	92	51	3	9
	number, 2022	278,094	135,192	224,400	99,919	(D)	48
	2017	211,593	143,545	291,430	103,073	23,320	55
Farms by inventory:							
1 to 24	farms, 2022	1	29	11	21	-	7
	2017	-	28	28	24	-	9
	number, 2022	(D)	172	101	(D)	-	48
	2017	-	265	345	118	-	55
25 to 49	farms, 2022	-	8	2	6	-	-
	2017	3	7	-	2	-	-
	number, 2022	-	282	(D)	201	-	-
	2017	(D)	220	-	(D)	-	-
50 to 99	farms, 2022	-	3	-	-	-	-
	2017	1	7	1	1	-	-
	number, 2022	-	160	-	-	-	-
	2017	(D)	456	(D)	(D)	-	-
100 to 199	farms, 2022	2	-	1	-	-	-
	2017	-	4	1	-	-	-
	number, 2022	(D)	-	(D)	-	-	-
	2017	-	578	(D)	-	-	-
200 to 499	farms, 2022	6	4	3	1	-	-
	2017	4	3	2	2	-	-
	number, 2022	1,500	1,150	900	(D)	-	-
	2017	1,090	1,050	(D)	(D)	-	-
500 to 999	farms, 2022	3	8	9	3	-	-
	2017	14	6	15	3	-	-
	number, 2022	1,710	4,772	6,057	2,730	-	-
	2017	9,840	3,973	10,439	2,220	-	-
1,000 or more	farms, 2022	53	32	34	31	1	-
	2017	45	26	45	19	3	-
	number, 2022	274,674	128,656	217,185	96,419	(D)	-
	2017	200,513	137,003	279,711	99,992	23,320	-
SALES							
Hogs and pigs sold	farms, 2022	83	92	69	91	4	14
	2017	71	81	107	77	7	14
	number, 2022	982,656	317,527	638,353	364,058	(D)	84
	2017	761,520	369,385	970,847	276,256	40,574	193
	$1,000, 2022	188,115	68,777	126,036	86,869	(D)	25
	2017	83,938	48,135	112,857	36,370	6,194	35
2022 farms by number sold:							
1 to 24	farms	4	24	11	40	3	14
	number	(D)	(D)	(D)	256	19	84
25 to 49	farms	-	2	-	2	-	-
	number	-	(D)	-	(D)	-	-
50 to 99	farms	1	10	-	1	-	-
	number	(D)	728	-	(D)	-	-
100 to 199	farms	-	3	1	-	-	-
	number	-	574	(D)	-	-	-
200 to 499	farms	4	-	-	-	-	-
	number	1,364	-	-	-	-	-
500 to 999	farms	6	5	5	-	-	-
	number	3,000	3,372	3,500	-	-	-
1,000 or more	farms	68	48	52	48	1	-
	number	978,191	312,595	634,617	363,702	(D)	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
INVENTORY							
Total hogs and pigs	farms, 2022	10	4	42	20	71	25
	2017	12	10	24	13	71	39
	number, 2022	18,419	16	20,543	123	229,617	(D)
	2017	12,703	1,052	(D)	161	278,724	902
Farms by inventory:							
1 to 24	farms, 2022	3	4	35	20	16	17
	2017	5	5	23	11	6	34
	number, 2022	19	16	(D)	123	(D)	135
	2017	(D)	(D)	158	(D)	6	177
25 to 49	farms, 2022	-	-	-	-	2	6
	2017	-	1	-	1	2	3
	number, 2022	-	-	-	-	(D)	230
	2017	-	(D)	-	(D)	(D)	(D)
50 to 99	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	1	2	-
	number, 2022	-	-	-	-	-	-
	2017	-	-	-	(D)	(D)	-
100 to 199	farms, 2022	-	-	-	-	-	1
	2017	2	-	-	-	2	-
	number, 2022	-	-	-	-	-	(D)
	2017	(D)	-	-	-	(D)	-
200 to 499	farms, 2022	-	-	-	-	-	-
	2017	-	4	-	-	5	2
	number, 2022	-	-	-	-	-	-
	2017	-	1,000	-	-	1,740	(D)
500 to 999	farms, 2022	-	-	2	-	8	-
	2017	-	-	-	-	4	-
	number, 2022	-	-	(D)	-	5,050	-
	2017	-	-	-	-	2,900	-
1,000 or more	farms, 2022	7	-	5	-	45	1
	2017	5	-	1	-	50	-
	number, 2022	18,400	-	19,000	-	224,313	(D)
	2017	12,350	-	(D)	-	273,674	-
SALES							
Hogs and pigs sold	farms, 2022	19	5	50	21	73	26
	2017	18	9	41	26	74	40
	number, 2022	41,958	82	151,249	248	734,275	(D)
	2017	27,021	869	(D)	226	779,543	2,307
	$1,000, 2022	8,172	13	11,232	52	114,644	(D)
	2017	4,489	87	1,143	40	99,912	119
2022 farms by number sold:							
1 to 24	farms	8	3	33	19	7	19
	number	46	(D)	(D)	(D)	45	131
25 to 49	farms	-	2	10	2	2	4
	number	-	(D)	266	(D)	(D)	136
50 to 99	farms	4	-	-	-	6	1
	number	312	-	-	-	510	(D)
100 to 199	farms	-	-	-	-	-	1
	number	-	-	-	-	-	(D)
200 to 499	farms	-	-	2	-	2	-
	number	-	-	(D)	-	(D)	-
500 to 999	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
1,000 or more	farms	7	-	5	-	56	1
	number	41,600	-	150,000	-	733,160	(D)

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
INVENTORY						
Total hogs and pigs ..... farms, 2022	32	1	4	50	2	3
2017	24	1	4	37	4	2
number, 2022	137,155	(D)	15	159,369	(D)	6
2017	85,372	(D)	6	148,837	21	(D)
Farms by inventory:						
1 to 24 ..... farms, 2022	9	1	4	9	2	3
2017	5	1	4	6	4	2
number, 2022	(D)	(D)	15	164	(D)	6
2017	18	(D)	6	47	21	(D)
25 to 49 ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
50 to 99 ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	1	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	(D)	-	-
100 to 199 ..... farms, 2022	-	-	-	2	-	-
2017	-	-	-	2	-	-
number, 2022	-	-	-	(D)	-	-
2017	-	-	-	(D)	-	-
200 to 499 ..... farms, 2022	1	-	-	1	-	-
2017	-	-	-	1	-	-
number, 2022	(D)	-	-	(D)	-	-
2017	-	-	-	(D)	-	-
500 to 999 ..... farms, 2022	-	-	-	-	-	-
2017	5	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	2,996	-	-	-	-	-
1,000 or more ..... farms, 2022	22	-	-	38	-	-
2017	14	-	-	27	-	-
number, 2022	136,744	-	-	158,662	-	-
2017	82,358	-	-	148,185	-	-
SALES						
Hogs and pigs sold ..... farms, 2022	26	-	7	62	4	4
2017	24	1	3	35	6	5
number, 2022	182,144	-	36	591,377	74	20
2017	192,573	(D)	14	436,147	41	41
$1,000, 2022	37,015	-	15	93,960	18	4
2017	30,699	(D)	6	63,250	7	(D)
2022 farms by number sold:						
1 to 24 ..... farms	3	-	7	10	2	4
number	6	-	36	84	(D)	20
25 to 49 ..... farms	-	-	-	5	2	-
number	-	-	-	130	(D)	-
50 to 99 ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
100 to 199 ..... farms	-	-	-	2	-	-
number	-	-	-	(D)	-	-
200 to 499 ..... farms	1	-	-	1	-	-
number	(D)	-	-	(D)	-	-
500 to 999 ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
1,000 or more ..... farms	22	-	-	44	-	-
number	(D)	-	-	590,416	-	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
INVENTORY						
Total hogs and pigs ..... farms, 2022	74	20	82	15	4	3
2017	62	20	78	25	4	5
number, 2022	109,236	131,627	444,988	7,779	57	9
2017	98,131	118,694	251,248	6,901	16	(D)
Farms by inventory:						
1 to 24 ..... farms, 2022	14	-	2	6	3	3
2017	14	7	11	13	4	2
number, 2022	176	-	(D)	41	(D)	9
2017	33	(D)	60	59	16	(D)
25 to 49 ..... farms, 2022	5	-	2	2	1	-
2017	3	1	7	3	-	1
number, 2022	(D)	-	(D)	(D)	(D)	-
2017	92	(D)	231	100	-	(D)
50 to 99 ..... farms, 2022	2	-	-	2	-	-
2017	2	1	2	1	-	1
number, 2022	(D)	-	-	(D)	-	-
2017	(D)	(D)	(D)	(D)	-	(D)
100 to 199 ..... farms, 2022	6	-	2	1	-	-
2017	3	-	3	3	-	-
number, 2022	642	-	(D)	(D)	-	-
2017	433	-	332	(D)	-	-
200 to 499 ..... farms, 2022	14	-	2	2	-	-
2017	1	-	1	3	-	-
number, 2022	4,281	-	(D)	(D)	-	-
2017	(D)	-	(D)	760	-	-
500 to 999 ..... farms, 2022	7	4	10	-	-	-
2017	13	-	5	-	-	-
number, 2022	4,925	2,300	6,270	-	-	-
2017	9,220	-	3,211	-	-	-
1,000 or more ..... farms, 2022	26	16	64	2	-	-
2017	26	11	49	2	-	1
number, 2022	98,959	129,327	437,573	(D)	-	-
2017	87,795	118,603	246,894	(D)	-	(D)
SALES						
Hogs and pigs sold ..... farms, 2022	87	21	92	22	4	5
2017	85	15	86	20	-	7
number, 2022	442,256	833,130	1,346,361	14,187	19	13
2017	415,315	544,131	922,055	13,365	-	(D)
$1,000, 2022	53,975	65,905	289,712	2,431	3	3
2017	34,564	43,532	100,539	1,627	-	(D)
2022 farms by number sold:						
1 to 24 ..... farms	25	1	5	16	4	5
number	232	(D)	66	86	19	13
25 to 49 ..... farms	3	-	1	-	-	-
number	(D)	-	(D)	-	-	-
50 to 99 ..... farms	3	-	1	2	-	-
number	201	-	(D)	(D)	-	-
100 to 199 ..... farms	6	-	-	1	-	-
number	1,152	-	-	(D)	-	-
200 to 499 ..... farms	3	-	1	-	-	-
number	1,200	-	(D)	-	-	-
500 to 999 ..... farms	2	4	-	1	-	-
number	(D)	(D)	-	(D)	-	-
1,000 or more ..... farms	45	16	84	2	-	-
number	437,972	829,363	1,345,829	(D)	-	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
INVENTORY						
Total hogs and pigs ..... farms, 2022	157	20	21	48	82	60
2017	166	29	30	58	91	66
number, 2022	845,233	1,752	127	59,596	237,896	198,432
2017	827,589	5,135	589	59,080	307,898	205,046
Farms by inventory:						
1 to 24 ..... farms, 2022	-	14	21	17	13	1
2017	5	16	25	33	5	2
number, 2022	-	82	127	116	(D)	(D)
2017	44	102	199	227	25	(D)
25 to 49 ..... farms, 2022	1	3	-	-	2	-
2017	-	8	4	1	4	-
number, 2022	(D)	90	-	-	(D)	-
2017	-	213	(D)	(D)	103	-
50 to 99 ..... farms, 2022	-	-	-	2	-	-
2017	-	-	-	1	1	-
number, 2022	-	-	-	(D)	-	-
2017	-	-	-	(D)	(D)	-
100 to 199 ..... farms, 2022	1	2	-	2	3	2
2017	-	2	-	2	2	1
number, 2022	(D)	(D)	-	(D)	400	(D)
2017	-	(D)	-	(D)	(D)	(D)
200 to 499 ..... farms, 2022	2	-	-	4	4	8
2017	3	1	1	-	10	9
number, 2022	(D)	-	-	1,804	1,800	2,200
2017	834	(D)	(D)	-	3,080	(D)
500 to 999 ..... farms, 2022	4	-	-	1	9	3
2017	3	-	-	4	9	5
number, 2022	2,300	-	-	(D)	6,081	1,500
2017	2,453	-	-	3,200	6,490	3,280
1,000 or more ..... farms, 2022	149	1	-	22	51	46
2017	155	2	-	17	60	49
number, 2022	842,013	(D)	-	56,536	229,466	194,506
2017	824,258	(D)	-	55,246	297,880	198,784
SALES						
Hogs and pigs sold ..... farms, 2022	175	26	26	54	88	70
2017	168	47	32	64	100	64
number, 2022	2,742,812	(D)	361	148,794	774,484	584,268
2017	2,913,151	15,450	390	171,600	1,013,666	551,066
$1,000, 2022	445,664	664	(D)	33,665	134,977	104,413
2017	330,132	1,459	75	20,515	116,536	64,623
2022 farms by number sold:						
1 to 24 ..... farms	1	22	19	18	18	7
number	(D)	211	(D)	111	113	(D)
25 to 49 ..... farms	-	1	6	-	-	-
number	-	(D)	184	-	-	-
50 to 99 ..... farms	-	-	1	-	2	1
number	-	-	(D)	-	(D)	(D)
100 to 199 ..... farms	-	-	-	5	2	-
number	-	-	-	705	(D)	-
200 to 499 ..... farms	3	2	-	4	3	-
number	(D)	(D)	-	1,034	1,290	-
500 to 999 ..... farms	-	-	-	-	4	3
number	-	-	-	-	2,497	2,300
1,000 or more ..... farms	171	1	-	27	59	59
number	2,742,088	(D)	-	146,944	770,134	581,851

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
INVENTORY							
Total hogs and pigs	farms, 2022	88	132	10	23	30	2
	2017	76	112	7	22	88	3
	number, 2022	405,026	504,733	(D)	37,041	599	(D)
	2017	267,990	393,029	(D)	23,691	11,746	(D)
Farms by inventory:							
1 to 24	farms, 2022	-	20	3	12	27	2
	2017	2	9	3	9	65	2
	number, 2022	-	286	13	93	157	(D)
	2017	(D)	113	(D)	74	376	(D)
25 to 49	farms, 2022	-	-	-	-	2	-
	2017	-	-	-	-	3	-
	number, 2022	-	-	-	-	(D)	-
	2017	-	-	-	-	(D)	-
50 to 99	farms, 2022	-	4	5	5	-	-
	2017	-	2	2	-	10	-
	number, 2022	-	274	368	430	-	-
	2017	-	(D)	(D)	-	618	-
100 to 199	farms, 2022	2	-	-	-	-	-
	2017	3	1	-	6	-	-
	number, 2022	(D)	-	-	-	-	-
	2017	(D)	(D)	-	1,020	-	-
200 to 499	farms, 2022	7	6	-	-	1	-
	2017	6	5	-	-	1	-
	number, 2022	2,725	1,623	-	-	(D)	-
	2017	2,020	1,597	-	-	(D)	-
500 to 999	farms, 2022	2	6	-	-	-	-
	2017	2	7	1	-	1	1
	number, 2022	(D)	3,180	-	-	-	-
	2017	(D)	4,132	(D)	-	(D)	(D)
1,000 or more	farms, 2022	77	96	2	6	-	-
	2017	63	88	1	7	8	-
	number, 2022	400,615	499,370	(D)	36,518	-	-
	2017	264,398	386,922	(D)	22,597	9,750	-
SALES							
Hogs and pigs sold	farms, 2022	102	145	10	31	43	1
	2017	83	113	7	24	97	3
	number, 2022	1,081,058	1,520,981	(D)	66,891	1,225	(D)
	2017	847,203	1,210,144	4,990	62,187	28,172	(D)
	$1,000, 2022	206,204	269,479	(D)	(D)	249	(D)
	2017	117,238	145,149	650	9,247	3,940	(D)
2022 farms by number sold:							
1 to 24	farms	2	11	3	20	40	1
	number	(D)	151	11	(D)	(D)	(D)
25 to 49	farms	2	2	2	-	2	-
	number	(D)	(D)	(D)	-	(D)	-
50 to 99	farms	-	5	1	2	-	-
	number	-	290	(D)	(D)	-	-
100 to 199	farms	-	2	2	-	-	-
	number	-	(D)	(D)	-	-	-
200 to 499	farms	1	8	-	3	-	-
	number	(D)	2,424	-	720	-	-
500 to 999	farms	9	-	-	-	1	-
	number	7,000	-	-	-	(D)	-
1,000 or more	farms	88	117	2	6	-	-
	number	1,073,668	1,517,706	(D)	65,822	-	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
INVENTORY							
Total hogs and pigs	farms, 2022	23	34	28	15	-	2
	2017	26	54	20	30	1	1
	number, 2022	202	303,763	1,862	68,364	-	(D)
	2017	207	361,314	18,081	104,433	(D)	(D)
Farms by inventory:							
1 to 24	farms, 2022	23	-	23	7	-	2
	2017	26	5	14	14	-	1
	number, 2022	202	-	118	37	-	(D)
	2017	207	30	59	108	-	(D)
25 to 49	farms, 2022	-	-	3	-	-	-
	2017	-	1	-	-	1	-
	number, 2022	-	-	(D)	-	-	-
	2017	-	(D)	-	-	(D)	-
50 to 99	farms, 2022	-	2	1	-	-	-
	2017	-	2	-	-	-	-
	number, 2022	-	(D)	(D)	-	-	-
	2017	-	(D)	-	-	-	-
100 to 199	farms, 2022	-	2	-	-	-	-
	2017	-	3	-	-	-	-
	number, 2022	-	(D)	-	-	-	-
	2017	-	400	-	-	-	-
200 to 499	farms, 2022	-	2	-	-	-	-
	2017	-	2	-	3	-	-
	number, 2022	-	(D)	-	-	-	-
	2017	-	(D)	-	1,000	-	-
500 to 999	farms, 2022	-	4	-	-	-	-
	2017	-	3	-	-	-	-
	number, 2022	-	2,690	-	-	-	-
	2017	-	2,250	-	-	-	-
1,000 or more	farms, 2022	-	24	1	8	-	-
	2017	-	38	6	13	-	-
	number, 2022	-	300,258	(D)	68,327	-	-
	2017	-	357,604	18,022	103,325	-	-
SALES							
Hogs and pigs sold	farms, 2022	32	32	27	14	-	2
	2017	27	52	23	33	1	1
	number, 2022	352	1,355,511	575	199,280	-	(D)
	2017	463	1,396,691	54,223	494,802	(D)	(D)
	$1,000, 2022	(D)	125,456	116	28,615	-	(D)
	2017	53	121,537	9,526	37,980	(D)	(D)
2022 farms by number sold:							
1 to 24	farms	27	-	22	5	-	2
	number	204	-	125	(D)	-	(D)
25 to 49	farms	5	-	3	-	-	-
	number	148	-	(D)	-	-	-
50 to 99	farms	-	-	-	1	-	-
	number	-	-	-	(D)	-	-
100 to 199	farms	-	-	1	-	-	-
	number	-	-	(D)	-	-	-
200 to 499	farms	-	1	1	-	-	-
	number	-	(D)	(D)	-	-	-
500 to 999	farms	-	2	-	-	-	-
	number	-	(D)	-	-	-	-
1,000 or more	farms	-	29	-	8	-	-
	number	-	1,353,711	-	199,200	-	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
INVENTORY							
Total hogs and pigs	farms, 2022	100	57	41	101	14	33
	2017	89	74	55	84	6	38
	number, 2022	352,676	253,395	149,572	400,859	13,262	266
	2017	197,170	313,786	167,191	299,729	33	292
Farms by inventory:							
1 to 24	farms, 2022	8	2	12	-	7	32
	2017	12	8	20	-	6	36
	number, 2022	48	(D)	100	-	(D)	(D)
	2017	(D)	57	124	-	33	(D)
25 to 49	farms, 2022	-	3	-	-	1	-
	2017	1	6	4	-	-	2
	number, 2022	-	86	-	-	(D)	-
	2017	(D)	150	130	-	-	(D)
50 to 99	farms, 2022	3	1	-	-	-	-
	2017	-	5	1	1	-	-
	number, 2022	160	(D)	-	-	-	-
	2017	-	320	(D)	(D)	-	-
100 to 199	farms, 2022	-	4	-	-	-	1
	2017	3	1	-	-	-	-
	number, 2022	-	454	-	-	-	(D)
	2017	320	(D)	-	-	-	-
200 to 499	farms, 2022	3	1	-	10	-	-
	2017	11	2	2	1	-	-
	number, 2022	940	(D)	-	2,760	-	-
	2017	3,691	(D)	(D)	(D)	-	-
500 to 999	farms, 2022	6	1	4	3	-	-
	2017	13	4	2	9	-	-
	number, 2022	3,974	(D)	3,275	1,500	-	-
	2017	10,584	2,260	(D)	(D)	-	-
1,000 or more	farms, 2022	80	45	25	88	6	-
	2017	49	48	26	73	-	-
	number, 2022	347,554	251,615	146,197	396,599	13,200	-
	2017	182,470	310,046	164,457	293,237	-	-
SALES							
Hogs and pigs sold	farms, 2022	111	63	46	111	13	34
	2017	98	71	65	93	11	40
	number, 2022	944,475	881,984	412,853	1,071,609	2,454	465
	2017	493,283	1,410,317	638,371	784,148	62	464
	$1,000, 2022	204,628	114,133	59,704	221,506	635	116
	2017	77,569	145,969	56,954	110,442	20	95
2022 farms by number sold:							
1 to 24	farms	11	4	14	4	6	25
	number	(D)	18	121	36	(D)	(D)
25 to 49	farms	4	3	-	-	-	8
	number	110	96	-	-	-	226
50 to 99	farms	-	-	3	-	-	1
	number	-	-	195	-	-	(D)
100 to 199	farms	2	4	-	-	1	-
	number	(D)	598	-	-	(D)	-
200 to 499	farms	-	2	-	-	6	-
	number	-	(D)	-	-	2,328	-
500 to 999	farms	4	1	-	4	-	-
	number	2,113	(D)	-	3,100	-	-
1,000 or more	farms	90	49	29	103	-	-
	number	941,801	880,272	412,537	1,068,473	-	-

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
INVENTORY						
Total hogs and pigs ..... farms, 2022	6	19	46	84	48	43
2017	19	22	53	92	65	60
number, 2022	(D)	(D)	79,804	65,897	116,411	210,165
2017	(D)	(D)	106,688	84,707	141,317	169,272
Farms by inventory:						
1 to 24 ..... farms, 2022	4	15	17	45	8	-
2017	14	20	7	48	11	8
number, 2022	68	75	(D)	341	50	-
2017	208	135	67	292	131	54
25 to 49 ..... farms, 2022	-	2	1	3	1	-
2017	3	-	4	4	1	6
number, 2022	-	(D)	(D)	92	(D)	-
2017	88	-	128	108	(D)	180
50 to 99 ..... farms, 2022	-	-	4	7	4	2
2017	1	-	-	4	1	-
number, 2022	-	-	256	434	228	(D)
2017	(D)	-	-	300	(D)	-
100 to 199 ..... farms, 2022	-	-	1	3	2	-
2017	-	-	1	6	2	7
number, 2022	-	-	(D)	395	(D)	-
2017	-	-	(D)	956	(D)	1,300
200 to 499 ..... farms, 2022	1	-	-	5	-	3
2017	-	-	-	5	1	3
number, 2022	(D)	-	-	1,717	-	(D)
2017	-	-	-	1,500	(D)	969
500 to 999 ..... farms, 2022	-	-	4	10	9	7
2017	-	-	2	8	8	7
number, 2022	-	-	3,154	5,418	6,982	6,811
2017	-	-	(D)	5,440	5,259	4,545
1,000 or more ..... farms, 2022	1	2	19	11	24	31
2017	1	2	39	17	41	29
number, 2022	(D)	(D)	76,115	57,500	108,824	202,528
2017	(D)	(D)	104,792	76,111	135,398	162,224
SALES						
Hogs and pigs sold ..... farms, 2022	13	26	49	95	64	47
2017	24	28	55	98	78	55
number, 2022	1,053	5,736	449,393	153,660	444,668	819,759
2017	(D)	5,803	492,109	271,773	353,740	643,914
$1,000, 2022	(D)	1,436	48,308	24,644	96,951	122,341
2017	(D)	1,034	53,168	32,114	61,133	54,098
2022 farms by number sold:						
1 to 24 ..... farms	9	19	19	52	15	-
number	71	156	90	414	103	-
25 to 49 ..... farms	-	3	1	10	2	-
number	-	104	(D)	367	(D)	-
50 to 99 ..... farms	2	-	-	2	1	2
number	(D)	-	-	(D)	(D)	(D)
100 to 199 ..... farms	-	2	3	1	1	-
number	-	(D)	370	(D)	(D)	-
200 to 499 ..... farms	1	-	2	4	4	3
number	(D)	-	(D)	1,337	1,616	(D)
500 to 999 ..... farms	1	-	-	2	-	-
number	(D)	-	-	(D)	-	-
1,000 or more ..... farms	-	2	24	24	41	42
number	-	(D)	448,426	149,802	442,664	818,615

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
INVENTORY							
Total hogs and pigs	farms, 2022	14	54	6	36	13	51
	2017	10	47	12	19	17	73
	number, 2022	26,698	7,175	12,478	41,069	153	216,305
	2017	15,538	10,740	35,141	11,603	181	271,933
Farms by inventory:							
1 to 24	farms, 2022	4	45	-	10	12	6
	2017	6	29	3	4	14	7
	number, 2022	24	242	-	(D)	(D)	(D)
	2017	38	163	36	23	49	117
25 to 49	farms, 2022	3	3	-	10	-	1
	2017	-	3	-	2	2	1
	number, 2022	90	78	-	324	-	(D)
	2017	-	104	-	(D)	(D)	(D)
50 to 99	farms, 2022	-	-	-	-	1	-
	2017	-	8	-	4	1	3
	number, 2022	-	-	-	-	(D)	-
	2017	-	542	-	309	(D)	150
100 to 199	farms, 2022	-	2	1	5	-	-
	2017	-	1	-	3	-	4
	number, 2022	-	(D)	(D)	564	-	-
	2017	-	(D)	-	360	-	632
200 to 499	farms, 2022	-	1	-	2	-	-
	2017	-	2	3	2	-	1
	number, 2022	-	(D)	-	(D)	-	-
	2017	-	(D)	1,050	(D)	-	(D)
500 to 999	farms, 2022	-	2	-	-	-	3
	2017	-	1	-	2	-	1
	number, 2022	-	(D)	-	-	-	2,095
	2017	-	(D)	-	(D)	-	(D)
1,000 or more	farms, 2022	7	1	5	9	-	41
	2017	4	3	6	2	-	56
	number, 2022	26,584	(D)	(D)	39,740	-	214,046
	2017	15,500	8,480	34,055	(D)	-	269,753
SALES							
Hogs and pigs sold	farms, 2022	13	44	6	35	7	62
	2017	8	48	12	31	19	76
	number, 2022	76,620	(D)	49,373	180,203	194	597,022
	2017	47,812	25,311	62,099	(D)	280	901,923
	$1,000, 2022	(D)	4,977	(D)	17,905	30	101,100
	2017	6,430	4,348	9,089	3,564	37	98,675
2022 farms by number sold:							
1 to 24	farms	5	35	-	7	6	16
	number	(D)	190	-	36	(D)	(D)
25 to 49	farms	-	2	-	12	-	-
	number	-	(D)	-	376	-	-
50 to 99	farms	1	1	1	-	-	1
	number	(D)	(D)	(D)	-	-	(D)
100 to 199	farms	-	2	-	3	1	-
	number	-	(D)	-	541	(D)	-
200 to 499	farms	-	1	-	2	-	-
	number	-	(D)	-	(D)	-	-
500 to 999	farms	-	-	-	2	-	-
	number	-	-	-	(D)	-	-
1,000 or more	farms	7	3	5	9	-	45
	number	76,500	(D)	(D)	177,200	-	596,679

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Table 12. **Hogs and Pigs - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
INVENTORY						
Total hogs and pigs ..... farms, 2022	14	47	8	28	34	44
2017	10	69	8	18	37	40
number, 2022	338	248,970	22	55,794	4,681	214,088
2017	103	381,830	48	112,381	1,045	164,594
Farms by inventory:						
1 to 24 ..... farms, 2022	12	7	8	16	28	8
2017	9	4	8	4	30	12
number, 2022	(D)	41	22	80	(D)	32
2017	(D)	(D)	48	37	151	96
25 to 49 ..... farms, 2022	1	-	-	5	-	2
2017	-	-	-	5	2	4
number, 2022	(D)	-	-	153	-	(D)
2017	-	-	-	126	(D)	135
50 to 99 ..... farms, 2022	-	4	-	2	5	2
2017	1	1	-	1	3	1
number, 2022	-	244	-	(D)	377	(D)
2017	(D)	(D)	-	(D)	211	(D)
100 to 199 ..... farms, 2022	-	-	-	-	-	2
2017	-	-	-	1	1	-
number, 2022	-	-	-	-	-	(D)
2017	-	-	-	(D)	(D)	-
200 to 499 ..... farms, 2022	1	1	-	2	-	-
2017	-	4	-	-	-	1
number, 2022	(D)	(D)	-	(D)	-	-
2017	-	1,200	-	-	-	(D)
500 to 999 ..... farms, 2022	-	2	-	-	-	2
2017	-	3	-	1	1	1
number, 2022	-	(D)	-	-	-	(D)
2017	-	2,925	-	(D)	(D)	(D)
1,000 or more ..... farms, 2022	-	33	-	3	1	28
2017	-	57	-	6	-	21
number, 2022	-	246,735	-	55,061	(D)	211,930
2017	-	377,616	-	111,458	-	163,283
SALES						
Hogs and pigs sold ..... farms, 2022	13	67	1	29	49	51
2017	12	70	8	26	45	49
number, 2022	204	806,631	(D)	67,929	(D)	593,648
2017	139	974,114	95	188,043	2,215	431,904
$1,000, 2022	(D)	133,773	(D)	9,026	(D)	104,253
2017	26	117,348	14	19,956	(D)	48,142
2022 farms by number sold:						
1 to 24 ..... farms	12	5	1	19	41	13
number	(D)	40	(D)	(D)	256	(D)
25 to 49 ..... farms	-	1	-	5	4	2
number	-	(D)	-	166	153	(D)
50 to 99 ..... farms	-	2	-	-	2	4
number	-	(D)	-	-	(D)	317
100 to 199 ..... farms	1	3	-	-	1	-
number	(D)	490	-	-	(D)	-
200 to 499 ..... farms	-	2	-	2	-	-
number	-	(D)	-	(D)	-	-
500 to 999 ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
1,000 or more ..... farms	-	54	-	3	1	32
number	-	805,427	-	66,841	(D)	593,177

Table 13. **Sheep and Lambs - Inventory, Sales, and Wool Production: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
Sheep and lambs inventory ..... farms, 2022	2,137	11	11	15	17
2017	2,248	13	21	23	34
number, 2022	109,592	125	176	243	370
2017	116,311	267	411	316	2,191
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	326	2	3	5	3
2017	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	9,346	(D)	12	71	(D)
2017	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:					
1 to 24 ..... farms	1,328	11	10	13	9
number	13,576	125	(D)	(D)	(D)
25 to 99 ..... farms	574	-	1	2	7
number	27,026	-	(D)	(D)	224
100 to 299 ..... farms	181	-	-	-	1
number	27,203	-	-	-	(D)
300 to 999 ..... farms	43	-	-	-	-
number	23,042	-	-	-	-
1,000 or more ..... farms	11	-	-	-	-
number	18,745	-	-	-	-
Sheep and lambs sold ..... farms, 2022	1,500	3	10	8	13
2017	1,694	21	7	10	22
number, 2022	92,512	10	154	85	577
2017	109,315	202	73	352	1,325
$1,000, 2022	18,840	1	29	14	77
2017	18,886	47	12	62	158
Wool production [1] ..... farms, 2022	996	7	10	5	11
2017	1,029	10	7	9	26
pounds, 2022	552,126	555	666	250	1,885
2017	620,989	494	1,125	1,613	6,972
$1,000, 2022	259	(D)	(D)	-	(D)
2017	419	1	1	2	3

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
Sheep and lambs inventory ..... farms, 2022	27	1	27	16	22
2017	20	7	28	19	40
number, 2022	407	(D)	2,361	1,240	590
2017	990	536	3,322	1,119	1,096
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	2	1	6	1	2
2017	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	(D)	(D)	166	(D)	(D)
2017	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:					
1 to 24 ..... farms	20	-	13	6	14
number	133	-	(D)	(D)	(D)
25 to 99 ..... farms	7	1	9	5	6
number	274	(D)	423	250	262
100 to 299 ..... farms	-	-	3	4	2
number	-	-	504	595	(D)
300 to 999 ..... farms	-	-	2	1	-
number	-	-	(D)	(D)	-
1,000 or more ..... farms	-	-	-	-	-
number	-	-	-	-	-
Sheep and lambs sold ..... farms, 2022	11	1	17	13	13
2017	16	6	27	13	29
number, 2022	209	(D)	1,625	1,565	280
2017	606	259	2,587	1,976	517
$1,000, 2022	24	(D)	311	277	39
2017	97	34	457	356	77
Wool production [1] ..... farms, 2022	5	-	10	8	13
2017	12	3	19	8	22
pounds, 2022	1,143	-	11,105	6,640	1,506
2017	6,253	1,140	15,108	8,055	14,206
$1,000, 2022	(D)	-	7	6	(D)
2017	3	1	6	13	10

See footnote(s) at end of table.

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Table 13. **Sheep and Lambs - Inventory, Sales, and Wool Production: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Sheep and lambs inventory	farms, 2022	33	9	20	52	18	29
	2017	20	13	24	51	5	15
	number, 2022	2,127	152	1,928	1,126	492	1,108
	2017	836	589	2,272	1,282	233	827
Hair sheep and wool-hair crosses (see text)	farms, 2022	8	-	1	5	1	3
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
	number, 2022	521	-	(D)	(D)	(D)	73
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:							
1 to 24	farms	18	6	9	41	13	14
	number	(D)	54	140	(D)	128	74
25 to 99	farms	8	3	-	10	4	15
	number	408	98	-	534	(D)	1,034
100 to 299	farms	5	-	11	1	1	-
	number	745	-	1,788	(D)	(D)	-
300 to 999	farms	2	-	-	-	-	-
	number	(D)	-	-	-	-	-
1,000 or more	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Sheep and lambs sold	farms, 2022	25	1	20	39	16	17
	2017	13	6	13	33	7	15
	number, 2022	1,706	(D)	2,252	468	462	334
	2017	582	105	2,378	1,070	143	674
	$1,000, 2022	321	(D)	437	106	74	53
	2017	111	17	459	210	15	119
Wool production [1]	farms, 2022	18	2	14	18	5	12
	2017	11	6	11	14	1	11
	pounds, 2022	7,611	(D)	14,316	4,266	2,617	4,247
	2017	4,057	2,107	10,337	4,629	(D)	5,049
	$1,000, 2022	10	-	7	3	-	4
	2017	5	2	4	2	-	7

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Sheep and lambs inventory	farms, 2022	-	16	6	52	28	26
	2017	-	17	16	32	26	14
	number, 2022	-	3,718	78	972	665	1,885
	2017	-	2,707	323	1,024	548	778
Hair sheep and wool-hair crosses (see text)	farms, 2022	-	-	2	2	3	9
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
	number, 2022	-	-	(D)	(D)	60	786
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:							
1 to 24	farms	-	9	5	36	23	20
	number	-	(D)	(D)	276	291	157
25 to 99	farms	-	2	1	16	4	2
	number	-	(D)	(D)	696	(D)	(D)
100 to 299	farms	-	-	-	-	1	1
	number	-	-	-	-	(D)	(D)
300 to 999	farms	-	4	-	-	-	3
	number	-	2,304	-	-	-	1,554
1,000 or more	farms	-	1	-	-	-	-
	number	-	(D)	-	-	-	-
Sheep and lambs sold	farms, 2022	-	10	9	30	14	14
	2017	-	18	13	25	20	10
	number, 2022	-	3,800	106	765	380	1,360
	2017	-	3,288	198	566	428	527
	$1,000, 2022	-	717	22	129	100	202
	2017	-	675	29	93	79	86
Wool production [1]	farms, 2022	-	7	2	22	14	3
	2017	-	9	9	13	11	9
	pounds, 2022	-	18,788	(D)	3,783	2,184	3,075
	2017	-	19,155	1,121	3,591	2,315	2,630
	$1,000, 2022	-	6	(D)	2	(D)	(D)
	2017	-	14	1	4	3	3

See footnote(s) at end of table.

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Table 13. **Sheep and Lambs - Inventory, Sales, and Wool Production: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Sheep and lambs inventory	farms, 2022	15	74	27	81	2	35
	2017	31	73	29	93	5	13
	number, 2022	506	2,932	583	3,045	(D)	472
	2017	655	3,163	889	2,624	(D)	332
Hair sheep and wool-hair crosses (see text)	farms, 2022	-	9	-	20	-	2
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
	number, 2022	-	182	-	457	-	(D)
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:							
1 to 24	farms	10	39	16	42	-	31
	number	(D)	(D)	114	(D)	-	198
25 to 99	farms	4	24	11	35	-	3
	number	253	1,119	469	1,455	-	(D)
100 to 299	farms	1	10	-	3	1	1
	number	(D)	1,060	-	497	(D)	(D)
300 to 999	farms	-	1	-	1	-	-
	number	-	(D)	-	(D)	-	-
1,000 or more	farms	-	-	-	-	1	-
	number	-	-	-	-	(D)	-
Sheep and lambs sold	farms, 2022	10	48	17	52	2	11
	2017	23	46	27	76	2	13
	number, 2022	533	1,713	653	1,778	(D)	238
	2017	542	8,130	5,856	1,890	(D)	335
	$1,000, 2022	103	335	121	401	(D)	48
	2017	76	1,012	746	334	(D)	48
Wool production [1]	farms, 2022	7	41	16	27	2	19
	2017	9	24	10	39	2	11
	pounds, 2022	1,797	12,414	3,264	10,529	(D)	1,617
	2017	1,515	20,245	4,635	12,778	(D)	1,472
	$1,000, 2022	(D)	7	2	5	(D)	2
	2017	2	19	6	12	(D)	2

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Sheep and lambs inventory	farms, 2022	23	6	43	25	23	44
	2017	17	19	50	28	13	24
	number, 2022	686	243	688	563	1,816	697
	2017	595	511	705	533	1,388	519
Hair sheep and wool-hair crosses (see text)	farms, 2022	5	-	7	7	8	2
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
	number, 2022	95	-	48	69	280	(D)
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:							
1 to 24	farms	11	4	32	19	1	37
	number	(D)	(D)	277	205	(D)	433
25 to 99	farms	10	1	11	6	15	7
	number	301	(D)	411	358	(D)	264
100 to 299	farms	2	1	-	-	7	-
	number	(D)	(D)	-	-	1,020	-
300 to 999	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
1,000 or more	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Sheep and lambs sold	farms, 2022	16	12	20	13	22	27
	2017	16	14	19	15	12	13
	number, 2022	609	196	440	499	1,478	319
	2017	536	284	223	244	962	314
	$1,000, 2022	97	37	101	119	321	54
	2017	106	44	34	32	157	56
Wool production [1]	farms, 2022	10	4	17	14	20	17
	2017	8	14	19	9	9	12
	pounds, 2022	2,984	1,572	4,145	3,821	4,937	2,145
	2017	1,970	1,736	2,111	926	13,015	2,360
	$1,000, 2022	(D)	(D)	1	(D)	2	2
	2017	1	1	1	1	10	4

See footnote(s) at end of table.

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Table 13. **Sheep and Lambs - Inventory, Sales, and Wool Production: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Sheep and lambs inventory ..... farms, 2022	32	5	-	5	2	-
2017	56	3	-	22	2	-
number, 2022	939	43	-	270	(D)	-
2017	4,101	34	-	1,508	(D)	-
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	2	-	-	-	-	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	(D)	-	-	-	-	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	21	5	-	2	2	-
number	(D)	43	-	(D)	(D)	-
25 to 99 ..... farms	10	-	-	2	-	-
number	376	-	-	(D)	-	-
100 to 299 ..... farms	-	-	-	1	-	-
number	-	-	-	(D)	-	-
300 to 999 ..... farms	1	-	-	-	-	-
number	(D)	-	-	-	-	-
1,000 or more ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Sheep and lambs sold ..... farms, 2022	18	2	-	3	-	2
2017	36	4	-	19	-	-
number, 2022	3,445	(D)	-	(D)	-	(D)
2017	7,337	112	-	1,211	-	-
$1,000, 2022	1,027	(D)	-	(D)	-	(D)
2017	1,318	21	-	247	-	-
Wool production [1] ..... farms, 2022	12	1	-	3	2	-
2017	19	-	-	15	-	-
pounds, 2022	11,772	(D)	-	(D)	(D)	-
2017	37,201	-	-	9,417	-	-
$1,000, 2022	(D)	(D)	-	(D)	-	-
2017	16	-	-	11	-	-

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Sheep and lambs inventory ..... farms, 2022	22	13	38	38	3	6
2017	27	15	32	29	16	8
number, 2022	1,187	2,775	8,724	4,738	(D)	427
2017	1,023	2,942	4,354	987	376	479
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	5	1	6	8	-	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	302	(D)	300	110	-	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	12	-	15	30	2	3
number	133	-	(D)	287	(D)	27
25 to 99 ..... farms	4	3	15	5	-	-
number	180	(D)	767	173	-	-
100 to 299 ..... farms	6	8	2	-	1	3
number	874	1,325	(D)	-	(D)	400
300 to 999 ..... farms	-	2	3	-	-	-
number	-	(D)	1,680	-	-	-
1,000 or more ..... farms	-	-	3	3	-	-
number	-	-	5,550	4,278	-	-
Sheep and lambs sold ..... farms, 2022	19	13	36	20	2	6
2017	23	13	33	18	13	10
number, 2022	696	1,799	8,761	4,598	(D)	343
2017	785	3,122	3,829	372	372	489
$1,000, 2022	133	336	1,959	1,018	(D)	62
2017	125	624	784	54	59	70
Wool production [1] ..... farms, 2022	13	12	23	9	1	6
2017	16	13	23	5	7	6
pounds, 2022	5,201	19,117	60,950	26,204	(D)	3,093
2017	6,042	15,901	28,290	883	1,635	1,689
$1,000, 2022	6	5	19	1	(D)	1
2017	2	7	30	2	1	(D)

See footnote(s) at end of table.

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Table 13. **Sheep and Lambs - Inventory, Sales, and Wool Production: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Sheep and lambs inventory ..... farms, 2022	13	30	18	29	17	13
2017	32	22	38	39	30	26
number, 2022	1,819	771	644	1,099	434	3,361
2017	1,170	1,158	768	1,080	1,633	5,101
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	2	-	7	2	1	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	(D)	-	127	(D)	(D)	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	5	21	14	16	12	2
number	(D)	253	(D)	182	165	(D)
25 to 99 ..... farms	4	9	3	10	5	3
number	140	518	208	462	269	(D)
100 to 299 ..... farms	3	-	1	3	-	3
number	661	-	(D)	455	-	537
300 to 999 ..... farms	1	-	-	-	-	5
number	(D)	-	-	-	-	2,690
1,000 or more ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Sheep and lambs sold ..... farms, 2022	10	19	10	25	14	14
2017	30	17	26	38	28	26
number, 2022	698	509	596	814	219	3,496
2017	1,507	877	765	594	1,017	4,624
$1,000, 2022	180	97	126	157	41	712
2017	312	155	84	91	169	916
Wool production [1] ..... farms, 2022	5	18	5	19	10	11
2017	14	17	13	19	15	15
pounds, 2022	11,828	6,501	2,645	3,977	1,693	20,191
2017	2,648	6,305	2,558	3,819	5,370	37,868
$1,000, 2022	(D)	2	2	3	1	7
2017	2	4	3	4	5	29

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Sheep and lambs inventory ..... farms, 2022	22	26	8	24	84	4
2017	19	28	7	44	62	4
number, 2022	609	990	896	479	3,933	125
2017	979	1,805	323	923	2,162	35
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	4	-	-	4	11	2
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	90	-	-	52	316	(D)
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	15	19	3	16	50	2
number	(D)	210	60	138	543	(D)
25 to 99 ..... farms	5	4	2	8	25	2
number	255	270	(D)	341	1,380	(D)
100 to 299 ..... farms	2	3	2	-	6	-
number	(D)	510	(D)	-	750	-
300 to 999 ..... farms	-	-	1	-	3	-
number	-	-	(D)	-	1,260	-
1,000 or more ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Sheep and lambs sold ..... farms, 2022	17	11	8	16	58	4
2017	12	27	7	34	51	3
number, 2022	430	691	514	252	3,454	84
2017	514	2,686	169	604	1,547	39
$1,000, 2022	73	108	70	37	683	9
2017	92	425	25	96	285	5
Wool production [1] ..... farms, 2022	8	9	5	12	47	2
2017	7	25	4	21	28	1
pounds, 2022	2,461	5,356	4,636	1,632	22,848	(D)
2017	839	10,621	1,752	3,174	12,680	(D)
$1,000, 2022	(D)	1	4	2	18	-
2017	1	11	2	3	12	(D)

See footnote(s) at end of table.

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Table 13. **Sheep and Lambs - Inventory, Sales, and Wool Production: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Sheep and lambs inventory ..... farms, 2022	47	40	28	16	-	5
2017	44	32	23	23	1	4
number, 2022	1,219	4,162	809	903	-	161
2017	901	3,964	481	867	(D)	102
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	5	4	2	-	-	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	70	462	(D)	-	-	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	29	18	10	9	-	2
number	(D)	309	126	168	-	(D)
25 to 99 ..... farms	17	14	18	4	-	3
number	814	866	683	245	-	(D)
100 to 299 ..... farms	1	4	-	3	-	-
number	(D)	497	-	490	-	-
300 to 999 ..... farms	-	4	-	-	-	-
number	-	2,490	-	-	-	-
1,000 or more ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Sheep and lambs sold ..... farms, 2022	27	37	23	16	-	12
2017	28	25	14	14	1	3
number, 2022	1,095	3,400	659	1,007	-	147
2017	337	3,433	600	929	(D)	33
$1,000, 2022	145	883	89	137	-	31
2017	42	746	96	178	(D)	5
Wool production [1] ..... farms, 2022	33	27	15	9	-	3
2017	11	13	9	7	-	3
pounds, 2022	7,111	25,760	3,362	5,568	-	(D)
2017	2,458	22,939	2,835	4,827	-	521
$1,000, 2022	2	10	(D)	2	-	-
2017	4	14	2	4	-	-

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
Sheep and lambs inventory ..... farms, 2022	31	43	38	15	23	39
2017	35	33	62	18	13	28
number, 2022	2,056	6,685	1,841	665	1,016	401
2017	2,416	13,779	3,084	2,057	375	564
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	-	12	11	4	6	2
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	-	72	559	119	78	(D)
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	16	16	24	8	15	37
number	(D)	(D)	(D)	(D)	(D)	(D)
25 to 99 ..... farms	5	7	8	5	2	2
number	311	384	328	261	(D)	(D)
100 to 299 ..... farms	9	18	5	2	6	-
number	1,194	2,778	850	(D)	720	-
300 to 999 ..... farms	1	1	1	-	-	-
number	(D)	(D)	(D)	-	-	-
1,000 or more ..... farms	-	1	-	-	-	-
number	-	(D)	-	-	-	-
Sheep and lambs sold ..... farms, 2022	28	35	26	11	18	15
2017	32	38	40	18	11	24
number, 2022	2,036	6,735	1,048	392	577	180
2017	2,206	11,821	1,191	2,010	481	232
$1,000, 2022	382	1,309	302	72	117	35
2017	391	1,877	206	369	82	34
Wool production [1] ..... farms, 2022	16	27	18	5	10	21
2017	35	25	14	14	4	25
pounds, 2022	7,655	34,904	9,045	1,232	4,848	2,179
2017	12,737	88,674	8,921	8,510	1,216	2,671
$1,000, 2022	10	8	6	(D)	2	2
2017	10	7	6	6	1	3

See footnote(s) at end of table.

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Table 13. **Sheep and Lambs - Inventory, Sales, and Wool Production: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Sheep and lambs inventory ..... farms, 2022	36	36	17	72	16	12
2017	29	37	23	89	23	18
number, 2022	950	328	468	3,665	291	256
2017	518	929	1,147	2,610	793	429
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	7	10	-	20	-	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	95	132	-	522	-	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	29	34	9	47	14	10
number	400	(D)	99	(D)	(D)	(D)
25 to 99 ..... farms	4	2	8	18	1	1
number	112	(D)	369	771	(D)	(D)
100 to 299 ..... farms	3	-	-	6	1	1
number	438	-	-	712	(D)	(D)
300 to 999 ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
1,000 or more ..... farms	-	-	-	1	-	-
number	-	-	-	(D)	-	-
Sheep and lambs sold ..... farms, 2022	34	15	16	60	8	8
2017	21	18	21	57	16	17
number, 2022	606	321	330	4,266	128	129
2017	288	312	776	2,787	587	335
$1,000, 2022	115	61	57	771	22	13
2017	44	37	120	511	95	48
Wool production [1] ..... farms, 2022	12	6	17	25	2	10
2017	17	9	11	23	12	11
pounds, 2022	3,452	522	2,975	18,081	(D)	1,508
2017	1,230	2,785	3,212	13,028	3,527	2,761
$1,000, 2022	1	(D)	3	5	(D)	1
2017	2	2	2	6	5	3

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Sheep and lambs inventory ..... farms, 2022	6	75	1	30	20	17
2017	8	73	2	34	19	22
number, 2022	110	2,228	(D)	1,099	2,098	746
2017	338	3,016	(D)	547	877	888
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	3	19	-	11	8	2
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	99	298	-	263	463	(D)
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	3	47	-	18	4	7
number	11	445	-	(D)	24	(D)
25 to 99 ..... farms	3	24	1	10	10	8
number	99	1,225	(D)	505	448	344
100 to 299 ..... farms	-	4	-	2	3	2
number	-	558	-	(D)	450	(D)
300 to 999 ..... farms	-	-	-	-	3	-
number	-	-	-	-	1,176	-
1,000 or more ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Sheep and lambs sold ..... farms, 2022	-	49	1	23	18	14
2017	4	48	2	22	24	20
number, 2022	-	1,644	(D)	820	1,529	513
2017	(D)	1,823	(D)	313	546	528
$1,000, 2022	-	267	(D)	113	350	112
2017	(D)	258	(D)	47	100	87
Wool production [1] ..... farms, 2022	-	26	1	9	11	5
2017	2	30	-	6	10	12
pounds, 2022	-	7,379	(D)	3,333	8,008	2,117
2017	(D)	11,888	-	1,801	3,227	3,179
$1,000, 2022	-	4	(D)	(D)	15	3
2017	(D)	7	-	(D)	3	3

See footnote(s) at end of table.

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Table 13. **Sheep and Lambs - Inventory, Sales, and Wool Production: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Sheep and lambs inventory ..... farms, 2022	39	18	4	33	59	35
2017	29	11	6	41	52	22
number, 2022	361	2,624	190	2,553	1,413	1,924
2017	680	496	51	3,049	992	1,917
Hair sheep and wool-hair crosses (see text) ..... farms, 2022	8	3	-	6	9	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
number, 2022	107	120	-	98	152	-
2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
2022 farms by inventory:						
1 to 24 ..... farms	36	9	1	24	48	5
number	281	100	(D)	(D)	592	54
25 to 99 ..... farms	3	3	3	8	8	25
number	80	157	(D)	352	371	1,120
100 to 299 ..... farms	-	3	-	-	3	5
number	-	600	-	-	450	750
300 to 999 ..... farms	-	3	-	-	-	-
number	-	1,767	-	-	-	-
1,000 or more ..... farms	-	-	-	1	-	-
number	-	-	-	(D)	-	-
Sheep and lambs sold ..... farms, 2022	24	15	10	23	47	26
2017	26	7	1	19	35	20
number, 2022	302	2,090	91	2,540	746	1,399
2017	765	312	(D)	(D)	450	1,492
$1,000, 2022	73	462	15	547	145	274
2017	125	50	(D)	(D)	72	263
Wool production [1] ..... farms, 2022	8	10	3	8	27	19
2017	14	3	1	13	15	10
pounds, 2022	760	9,463	1,321	(D)	5,591	8,310
2017	4,111	697	(D)	25,379	2,375	9,236
$1,000, 2022	(Z)	1	(Z)	1	3	8
2017	1	1	(D)	(D)	3	1

[1] Data are for farms with production, not necessarily sold.

Table 14. **All Goats - Inventory and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
State Total					
Minnesota 2022	2,326	50,691	1,215	38,339	8,735
2017	1,996	36,312	1,072	20,644	3,082
Counties, 2022					
Aitkin	28	618	18	259	37
Anoka	23	173	6	28	8
Becker	9	236	6	28	7
Beltrami	16	115	7	46	7
Benton	39	639	15	479	135
Big Stone	8	106	2	(D)	(D)
Blue Earth	17	144	5	112	49
Brown	11	213	-	-	-
Carlton	25	308	8	9,482	1,603
Carver	26	441	11	298	62
Cass	40	570	15	200	42
Chippewa	2	(D)	-	-	-
Chisago	64	758	37	290	67
Clay	6	(D)	3	(D)	(D)
Clearwater	34	611	18	194	33
Cottonwood	7	77	4	32	6
Crow Wing	20	376	10	146	19
Dakota	42	362	16	95	18
Dodge	23	902	16	428	121
Douglas	58	749	35	609	146
Faribault	16	336	8	102	26
Fillmore	67	2,045	42	1,209	262
Freeborn	18	(D)	9	3,198	748
Goodhue	108	3,273	69	1,447	329
Grant	12	553	9	134	33
Hennepin	37	345	17	132	17
Houston	22	394	22	226	34
Hubbard	27	384	22	113	38
Isanti	54	592	31	236	53
Itasca	22	311	7	27	4
Jackson	12	90	7	50	10
Kanabec	33	242	12	71	13
Kandiyohi	45	1,643	34	554	112
Kittson	2	(D)	1	(D)	(D)
Koochiching	7	29	-	-	-
Lac qui Parle	4	32	7	19	5
Lake of the Woods	2	(D)	2	(D)	(D)
Le Sueur	26	507	13	165	29
Lincoln	7	260	1	(D)	(D)
Lyon	15	641	5	219	92
McLeod	47	830	11	2,054	1,004
Marshall	7	63	1	(D)	(D)
Martin	13	191	6	97	38
Meeker	23	264	6	111	29
Mille Lacs	42	889	23	300	65
Morrison	48	894	23	300	54
Mower	41	937	33	316	75
Murray	19	754	14	352	69
Nicollet	5	78	4	36	4
Nobles	28	672	12	152	45
Norman	10	138	4	78	9
Olmsted	58	993	31	397	122
Otter Tail	61	1,162	43	654	122
Pennington	4	90	3	22	3
Pine	48	644	20	211	57
Pipestone	17	417	11	181	31
Polk	39	714	14	251	72
Pope	19	459	8	116	23
Red Lake	12	349	10	91	11
Redwood	19	1,059	13	1,202	208
Renville	23	425	6	232	35
Rice	30	1,539	16	1,200	270
Rock	8	222	7	258	96
Roseau	28	494	16	230	48
St. Louis	51	549	30	334	52
Scott	45	1,091	29	510	130
Sherburne	66	479	25	202	46
Sibley	24	655	21	351	64
Stearns	87	1,488	42	488	105
Steele	10	332	9	554	169
Stevens	5	96	2	(D)	(D)
Swift	10	284	4	55	11
Todd	97	4,939	61	3,263	572
Wabasha	38	663	20	264	43
Wadena	24	111	3	7	1
Waseca	24	1,274	17	679	223
Washington	17	438	8	804	363
Watonwan	14	320	9	172	41
Wilkin	3	46	8	52	8
Winona	54	1,171	18	656	153
Wright	62	550	22	127	31
Yellow Medicine	12	196	2	(D)	(D)

Table 15. **Milk Goats - Inventory and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area		Inventory		Sales		
		Farms	Number	Farms	Number	Value ($1,000)
State Total						
Minnesota	2022	734	14,638	389	8,331	2,127
	2017	698	13,342	368	5,854	1,083
Counties, 2022						
Aitkin		17	157	10	57	11
Anoka		2	(D)	5	(D)	(D)
Becker		1	(D)	2	(D)	(D)
Beltrami		4	18	4	15	3
Benton		14	(D)	2	(D)	(D)
Blue Earth		5	22	2	(D)	(D)
Brown		6	120	-	-	-
Carlton		14	(D)	4	8	1
Carver		2	(D)	2	(D)	(D)
Cass		16	(D)	8	62	13
Chisago		19	356	14	104	19
Clay		3	13	2	(D)	(D)
Clearwater		15	62	1	(D)	(D)
Crow Wing		4	33	7	62	10
Dakota		10	128	3	29	5
Dodge		8	49	5	31	8
Douglas		8	96	8	157	26
Faribault		6	180	4	53	14
Fillmore		26	(D)	21	418	123
Freeborn		8	95	5	509	156
Goodhue		17	240	12	178	51
Grant		3	63	-	-	-
Hennepin		26	281	15	110	14
Houston		5	104	4	46	7
Hubbard		15	127	11	21	3
Isanti		16	(D)	6	42	12
Itasca		12	190	4	22	3
Kanabec		9	45	5	27	4
Kandiyohi		9	231	5	29	3
Kittson		1	(D)	1	(D)	(D)
Koochiching		7	(D)	-	-	-
Le Sueur		13	(D)	8	67	8
Lyon		5	173	2	(D)	(D)
McLeod		6	348	4	128	44
Marshall		6	(D)	-	-	-
Martin		4	83	3	50	13
Meeker		8	22	-	-	-
Mille Lacs		21	195	6	38	9
Morrison		28	(D)	11	218	41
Mower		14	241	8	128	38
Murray		7	35	6	30	4
Nobles		4	(D)	1	(D)	(D)
Olmsted		14	240	10	69	15
Otter Tail		17	321	10	114	17
Pennington		1	(D)	1	(D)	(D)
Pine		27	208	6	56	12
Polk		11	390	6	183	57
Pope		9	83	1	(D)	(D)
Red Lake		2	(D)	-	-	-
Redwood		4	(D)	2	(D)	(D)
Renville		6	12	-	-	-
Rice		10	(D)	8	211	(D)
Roseau		11	87	8	(D)	(D)
St. Louis		31	317	17	(D)	(D)
Scott		17	218	11	88	19
Sherburne		23	190	13	98	25
Sibley		11	353	11	216	31
Stearns		11	252	4	96	24
Steele		1	(D)	-	-	-
Stevens		2	(D)	-	-	-
Swift		2	(D)	-	-	-
Todd		44	3,328	31	1,895	359
Wabasha		5	28	1	(D)	(D)
Wadena		3	(D)	-	-	-
Waseca		7	836	4	512	182
Washington		6	52	4	(D)	(D)
Watonwan		1	(D)	1	(D)	(D)
Wilkin		-	-	6	(D)	(D)
Winona		17	638	4	445	124
Wright		15	61	9	43	9
Yellow Medicine		2	(D)	-	-	-

Table 16. **Angora Goats - Inventory and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Angora goats					Mohair		
	Inventory		Sales			Clipped [1]		Value ($1,000)
	Farms	Number	Farms	Number	Value ($1,000)	Farms	Pounds	
State Total								
Minnesota 2022	117	1,274	33	378	45	39	8,636	7
2017	157	1,095	29	222	20	42	4,105	27
Counties, 2022								
Aitkin	3	153	3	15	3	3	900	5
Anoka	1	(D)	-	-	-	-	-	-
Becker	-	-	2	(D)	(D)	-	-	-
Beltrami	8	27	1	(D)	(D)	-	-	-
Benton	2	(D)	-	-	-	-	-	-
Carlton	2	(D)	-	-	-	2	(D)	-
Cass	1	(D)	-	-	-	-	-	-
Crow Wing	6	18	-	-	-	-	-	-
Dakota	3	57	3	3	1	3	150	1
Dodge	3	3	-	-	-	-	-	-
Fillmore	1	(D)	-	-	-	-	-	-
Goodhue	4	63	-	-	-	4	396	-
Hennepin	3	18	-	-	-	-	-	-
Hubbard	3	156	-	-	-	3	1,560	-
Isanti	2	(D)	-	-	-	2	(D)	-
Itasca	4	12	-	-	-	4	60	-
Kanabec	5	20	-	-	-	-	-	-
Kittson	1	(D)	-	-	-	-	-	-
Koochiching	1	(D)	-	-	-	-	-	-
Le Sueur	1	(D)	-	-	-	-	-	-
McLeod	4	28	-	-	-	-	-	-
Meeker	3	30	-	-	-	-	-	-
Mille Lacs	7	61	6	20	3	2	(D)	-
Morrison	2	(D)	-	-	-	-	-	-
Otter Tail	4	44	4	15	2	2	(D)	(D)
Rice	1	(D)	1	(D)	(D)	1	(D)	-
Rock	1	(D)	-	-	-	-	-	-
Roseau	5	25	1	(D)	(D)	-	-	-
St. Louis	2	(D)	1	(D)	(D)	1	(D)	(D)
Scott	3	57	3	21	3	3	540	1
Stearns	8	77	4	28	3	-	-	-
Wabasha	3	6	-	-	-	-	-	-
Wadena	2	(D)	-	-	-	-	-	-
Waseca	1	(D)	1	(D)	(D)	1	(D)	-
Washington	-	-	-	-	-	-	-	(Z)
Winona	1	(D)	-	-	-	-	-	-
Wright	14	109	3	10	1	8	660	-
Yellow Medicine	2	(D)	-	-	-	-	-	-

[1] Data are for farms with production, not necessarily sold.

Table 17. **Meat Goats and Other Goats - Inventory and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area		Inventory		Sales		
		Farms	Number	Farms	Number	Value ($1,000)
State Total						
Minnesota	2022	1,726	34,779	870	29,630	6,563
	2017	1,362	21,875	758	14,568	1,979
Counties, 2022						
Aitkin		16	308	5	187	23
Anoka		20	(D)	1	(D)	(D)
Becker		8	(D)	4	(D)	6
Beltrami		7	70	2	(D)	(D)
Benton		24	551	14	(D)	(D)
Big Stone		8	106	2	(D)	(D)
Blue Earth		12	122	3	(D)	(D)
Brown		11	93	-	-	-
Carlton		21	170	4	9,474	1,602
Carver		24	(D)	9	(D)	(D)
Cass		32	408	13	138	30
Chippewa		2	(D)	-	-	-
Chisago		49	402	24	186	48
Clay		3	(D)	1	(D)	(D)
Clearwater		27	549	17	(D)	(D)
Cottonwood		7	77	4	32	6
Crow Wing		10	325	3	84	9
Dakota		35	177	10	63	12
Dodge		18	850	11	397	113
Douglas		52	653	29	452	121
Faribault		11	156	5	49	12
Fillmore		48	1,026	29	791	138
Freeborn		12	(D)	6	2,689	592
Goodhue		96	2,970	57	1,269	278
Grant		9	490	9	134	33
Hennepin		13	46	3	22	3
Houston		17	290	19	180	27
Hubbard		17	101	11	92	35
Isanti		36	437	26	194	41
Itasca		13	109	3	5	1
Jackson		12	90	7	50	10
Kanabec		22	177	8	44	9
Kandiyohi		41	1,412	32	525	109
Kittson		1	(D)	-	-	-
Koochiching		1	(D)	-	-	-
Lac qui Parle		4	32	7	19	5
Lake of the Woods		2	(D)	2	(D)	(D)
Le Sueur		13	354	6	98	21
Lincoln		7	260	1	(D)	(D)
Lyon		10	468	3	(D)	(D)
McLeod		40	454	7	1,926	960
Marshall		1	(D)	1	(D)	(D)
Martin		10	108	4	47	24
Meeker		12	212	6	111	29
Mille Lacs		21	633	15	242	53
Morrison		33	580	12	82	13
Mower		32	696	28	188	37
Murray		18	719	14	322	65
Nicollet		5	78	4	36	4
Nobles		25	(D)	12	(D)	(D)
Norman		10	138	4	78	9
Olmsted		52	753	23	328	107
Otter Tail		47	797	33	525	103
Pennington		3	(D)	2	(D)	(D)
Pine		38	436	17	155	44
Pipestone		17	417	11	181	31
Polk		32	324	8	68	15
Pope		11	376	8	(D)	(D)
Red Lake		10	(D)	10	91	11
Redwood		16	(D)	12	(D)	(D)
Renville		23	413	6	232	35
Rice		23	1,177	8	(D)	(D)
Rock		7	(D)	7	258	96
Roseau		24	382	13	211	45
St. Louis		21	(D)	12	214	32
Scott		25	816	15	401	108
Sherburne		47	289	15	104	21
Sibley		13	302	10	135	33
Stearns		73	1,159	36	364	78
Steele		10	(D)	9	554	169
Stevens		3	(D)	2	(D)	(D)
Swift		8	(D)	4	55	11
Todd		63	1,611	38	1,368	214
Wabasha		32	629	19	(D)	(D)
Wadena		19	85	3	7	1
Waseca		16	(D)	12	(D)	(D)
Washington		11	386	4	(D)	(D)
Watonwan		13	(D)	8	(D)	(D)
Wilkin		3	46	2	(D)	(D)
Winona		41	(D)	14	211	29
Wright		39	380	10	74	22
Yellow Medicine		8	136	2	(D)	(D)

Table 18. **Equine - Inventory and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
HORSES AND PONIES					
State Total					
Minnesota 2022	6,988	40,131	1,171	4,403	18,000
2017	8,000	46,879	1,363	5,367	14,065
Counties, 2022					
Aitkin	64	229	7	46	(D)
Anoka	102	912	21	65	443
Becker	118	504	6	20	(D)
Beltrami	115	468	18	48	149
Benton	96	647	18	93	(D)
Big Stone	17	83	3	17	(D)
Blue Earth	73	342	10	28	(D)
Brown	33	106	2	(D)	(D)
Carlton	118	556	8	65	(D)
Carver	91	531	7	8	32
Cass	97	767	9	54	(D)
Chippewa	24	119	2	(D)	(D)
Chisago	154	731	26	66	370
Clay	81	463	16	42	(D)
Clearwater	82	579	13	77	290
Cook	8	16	1	(D)	(D)
Cottonwood	29	190	4	45	(D)
Crow Wing	88	400	19	39	(D)
Dakota	109	882	19	60	166
Dodge	67	315	10	21	50
Douglas	87	450	9	24	(D)
Faribault	24	72	10	20	17
Fillmore	219	1,685	64	523	1,063
Freeborn	63	408	11	63	788
Goodhue	172	751	25	73	(D)
Grant	22	152	3	14	(D)
Hennepin	120	1,008	22	74	(D)
Houston	106	536	20	67	(D)
Hubbard	72	349	23	192	(D)
Isanti	222	1,553	36	135	566
Itasca	89	426	11	29	100
Jackson	48	318	6	24	78
Kanabec	132	694	41	153	(D)
Kandiyohi	141	657	20	46	143
Kittson	34	213	4	10	28
Koochiching	35	177	3	3	6
Lac qui Parle	27	93	3	(D)	(D)
Lake	7	28	-	-	-
Lake of the Woods	18	73	-	-	-
Le Sueur	63	376	20	66	576
Lincoln	15	49	1	(D)	(D)
Lyon	49	128	7	9	(D)
McLeod	70	361	15	171	244
Mahnomen	20	84	4	8	27
Marshall	50	197	9	10	12
Martin	20	91	2	(D)	(D)
Meeker	69	364	20	43	(D)
Mille Lacs	117	547	17	99	157
Morrison	156	824	25	88	246
Mower	91	390	31	50	(D)
Murray	48	195	1	(D)	(D)
Nicollet	33	121	3	(D)	60
Nobles	30	107	10	12	12
Norman	29	185	4	6	4
Olmsted	154	795	34	69	654
Otter Tail	252	1,372	34	138	295
Pennington	15	43	6	15	30
Pine	147	700	26	83	265
Pipestone	53	248	2	(D)	(D)
Polk	93	566	21	62	169
Pope	66	376	12	86	(D)
Red Lake	24	141	8	8	79
Redwood	31	207	5	19	(D)
Renville	40	189	4	7	52
Rice	106	548	14	18	43
Rock	40	120	4	12	128
Roseau	70	364	10	25	68
St. Louis	175	991	32	92	756
Scott	146	1,115	30	126	582
Sherburne	99	592	11	11	(D)
Sibley	62	191	6	12	187
Stearns	238	1,367	28	114	397
Steele	51	173	5	8	16
Stevens	26	86	4	10	177
Swift	20	95	4	6	29
Todd	269	1,545	47	132	(D)
Traverse	12	41	2	(D)	(D)
Wabasha	59	370	8	25	(D)
Wadena	83	384	6	12	(D)
Waseca	42	118	4	6	9
Washington	128	1,555	42	140	1,584
Watonwan	18	133	1	(D)	(D)
Wilkin	23	144	-	-	-

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Table 18. **Equine - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
HORSES AND PONIES - Con.					
Counties, 2022 - Con.					
Winona	103	1,050	18	110	(D)
Wright	217	1,721	31	153	756
Yellow Medicine	62	289	13	33	(D)
MULES, BURROS, AND DONKEYS					
State Total					
Minnesota 2022	1,319	3,060	135	325	147
2017	1,405	3,247	119	425	124
Counties, 2022					
Aitkin	20	36	2	(D)	(D)
Anoka	18	59	-	-	-
Becker	14	17	2	(D)	(D)
Beltrami	12	23	3	5	2
Benton	17	35	2	(D)	(D)
Big Stone	3	9	1	(D)	(D)
Blue Earth	12	14	-	-	-
Brown	5	9	-	-	-
Carlton	21	39	2	(D)	(D)
Carver	16	31	-	-	-
Cass	38	102	2	(D)	(D)
Chippewa	2	(D)	-	-	-
Chisago	20	29	-	-	-
Clay	10	25	2	(D)	(D)
Clearwater	10	16	3	6	2
Cook	2	(D)	-	-	-
Cottonwood	4	22	1	(D)	(D)
Crow Wing	9	20	1	(D)	(D)
Dakota	21	29	3	6	3
Dodge	27	49	5	8	4
Douglas	18	32	2	(D)	(D)
Faribault	4	(D)	-	-	-
Fillmore	41	106	3	9	4
Freeborn	18	44	-	-	-
Goodhue	38	59	1	(D)	(D)
Grant	3	39	2	(D)	(D)
Hennepin	13	34	1	(D)	(D)
Houston	10	27	1	(D)	(D)
Hubbard	8	18	-	-	-
Isanti	45	108	4	6	4
Itasca	20	61	-	-	-
Jackson	18	57	4	6	2
Kanabec	9	16	1	(D)	(D)
Kandiyohi	36	93	2	(D)	(D)
Kittson	12	17	6	(D)	2
Koochiching	10	19	-	-	-
Lake of the Woods	2	(D)	-	-	-
Le Sueur	13	24	-	-	-
Lincoln	3	7	-	-	-
Lyon	6	9	1	(D)	(D)
McLeod	30	66	-	-	-
Mahnomen	1	(D)	-	-	-
Marshall	8	11	-	-	-
Martin	2	(D)	-	-	-
Meeker	17	28	-	-	-
Mille Lacs	19	34	-	-	-
Morrison	43	87	2	(D)	(D)
Mower	29	128	11	58	25
Nicollet	3	7	-	-	-
Nobles	15	43	3	7	2
Norman	3	6	-	-	-
Olmsted	36	64	-	-	-
Otter Tail	62	110	7	16	4
Pine	35	105	4	6	2
Pipestone	2	(D)	-	-	-
Polk	7	12	3	(D)	1
Pope	7	9	-	-	-
Red Lake	10	30	6	(D)	1
Redwood	7	37	-	-	-
Renville	3	(D)	-	-	-
Rice	18	67	-	-	-
Rock	10	18	-	-	-
Roseau	9	28	-	-	-
St. Louis	27	65	6	12	2
Scott	21	36	-	-	-
Sherburne	18	41	6	(D)	3
Sibley	10	33	-	-	-
Stearns	42	109	4	7	(D)
Steele	14	49	-	-	-
Stevens	9	18	5	15	6
Swift	5	6	-	-	-
Todd	49	117	1	(D)	(D)
Traverse	5	23	2	(D)	(D)
Wabasha	4	5	-	-	-
Wadena	20	56	2	(D)	(D)
Waseca	4	8	1	(D)	(D)

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Table 18. **Equine - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
MULES, BURROS, AND DONKEYS - Con.					
Counties, 2022 - Con.					
Washington	11	23	-	-	-
Watonwan	10	26	-	-	-
Wilkin	2	(D)	-	-	-
Winona	14	38	-	-	-
Wright	47	96	7	(D)	5
Yellow Medicine	23	42	8	14	7

Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
INVENTORY						
Any poultry	farms, 2022	6,943	81	59	64	85
	2017	6,198	84	60	70	111
Layers	farms, 2022	6,146	77	56	53	64
	2017	5,245	76	55	56	103
	number, 2022	14,553,497	1,681	1,883	1,156	1,469
	2017	10,849,607	2,375	1,172	1,958	3,672
2022 farms by inventory:						
1 to 49		5,412	65	44	47	60
50 to 99		472	12	9	6	2
100 to 399		161	-	3	-	2
400 to 3,199		36	-	-	-	-
3,200 to 9,999		8	-	-	-	-
10,000 to 19,999		24	-	-	-	-
20,000 to 49,999		4	-	-	-	-
50,000 to 99,999		5	-	-	-	-
100,000 or more		24	-	-	-	-
Pullets for laying flock replacement	farms, 2022	723	10	7	11	14
	2017	615	13	10	6	13
	number, 2022	4,185,443	156	203	800	707
	2017	4,636,614	261	183	104	115
Broilers and other meat-type chickens	farms, 2022	1,285	13	4	14	30
	2017	1,290	18	6	17	27
	number, 2022	7,767,645	834	186	328	1,349
	2017	11,068,267	1,405	60	681	1,931
Turkeys	farms, 2022	623	12	18	5	4
	2017	666	23	5	11	20
	number, 2022	14,927,734	92	118	357,337	6
	2017	18,110,298	100	29	578,604	132
Ducks, geese, and other miscellaneous poultry	farms, 2022	1,873	25	15	13	19
	2017	1,553	32	13	22	42
NUMBER SOLD						
Any poultry sold	farms, 2022	4,445	53	40	32	42
	2017	4,175	60	42	44	78
Layers sold	farms, 2022	664	7	2	-	10
	2017	702	10	5	1	10
	number, 2022	7,016,481	130	(D)	-	211
	2017	4,223,081	134	80	(D)	465
Pullets for laying flock replacement sold	farms, 2022	102	-	-	-	1
	2017	93	-	-	-	-
	number, 2022	8,319,040	-	-	-	(D)
	2017	9,562,724	-	-	-	-
Broilers and other meat-type chickens sold	farms, 2022	1,028	11	5	2	9
	2017	1,049	24	6	-	11
	number, 2022	41,793,592	1,620	395	(D)	301
	2017	60,397,850	4,362	60	-	1,475
2022 farms by number sold:						
1 to 1,999		900	11	5	2	9
2,000 to 59,999		11	-	-	-	-
60,000 to 99,999		-	-	-	-	-
100,000 to 199,999		2	-	-	-	-
200,000 to 499,999		100	-	-	-	-
500,000 or more		15	-	-	-	-
Turkeys sold	farms, 2022	379	8	4	8	2
	2017	486	15	2	12	-
	number, 2022	39,460,145	150,042	71	1,007,488	(D)
	2017	48,194,708	(D)	(D)	1,273,399	-
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	462	2	-	-	3
	2017	448	9	5	4	11

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item			Benton	Big Stone	Blue Earth	Brown	Carlton
INVENTORY							
Any poultry	farms,	2022	109	17	54	52	110
		2017	115	21	59	41	106
Layers	farms,	2022	76	14	49	43	106
		2017	65	20	48	29	100
	number,	2022	31,573	273	(D)	2,231	3,822
		2017	1,431	388	541,472	1,372	4,912
2022 farms by inventory:							
1 to 49			68	14	42	26	87
50 to 99			4	-	5	6	15
100 to 399			2	-	1	11	1
400 to 3,199			-	-	-	-	3
3,200 to 9,999			-	-	-	-	-
10,000 to 19,999			2	-	-	-	-
20,000 to 49,999			-	-	-	-	-
50,000 to 99,999			-	-	-	-	-
100,000 or more			-	-	1	-	-
Pullets for laying flock replacement	farms,	2022	8	1	8	4	15
		2017	11	1	4	1	10
	number,	2022	(D)	(D)	51	285	110
		2017	215,710	(D)	56	(D)	214
Broilers and other meat-type chickens	farms,	2022	42	2	5	1	26
		2017	57	2	9	9	22
	number,	2022	1,295,994	(D)	270	(D)	959
		2017	2,676,887	(D)	553	118	1,392
Turkeys	farms,	2022	2	2	6	5	2
		2017	-	1	11	5	7
	number,	2022	(D)	(D)	(D)	103,255	(D)
		2017	-	(D)	131,772	225,034	44
Ducks, geese, and other miscellaneous poultry	farms,	2022	35	9	22	17	39
		2017	14	4	16	7	12
NUMBER SOLD							
Any poultry sold	farms,	2022	70	10	31	43	70
		2017	92	17	54	33	83
Layers sold	farms,	2022	5	2	7	8	16
		2017	6	1	8	5	11
	number,	2022	30,059	(D)	126	315	1,389
		2017	92	(D)	447	302	754
Pullets for laying flock replacement sold	farms,	2022	3	-	-	2	-
		2017	5	-	2	-	2
	number,	2022	(D)	-	-	(D)	-
		2017	215,078	-	(D)	-	(D)
Broilers and other meat-type chickens sold	farms,	2022	31	1	4	4	19
		2017	55	-	20	9	25
	number,	2022	7,126,050	(D)	790	455	1,399
		2017	14,201,235	-	1,686	461,110	3,834
2022 farms by number sold:							
1 to 1,999			8	1	4	4	19
2,000 to 59,999			-	-	-	-	-
60,000 to 99,999			-	-	-	-	-
100,000 to 199,999			1	-	-	-	-
200,000 to 499,999			21	-	-	-	-
500,000 or more			1	-	-	-	-
Turkeys sold	farms,	2022	-	2	4	7	2
		2017	-	1	9	6	6
	number,	2022	-	(D)	(D)	373,679	(D)
		2017	-	(D)	335,528	1,002,765	159
Ducks, geese, and other miscellaneous poultry sold	farms,	2022	8	1	9	4	10
		2017	5	-	2	4	3

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
INVENTORY						
Any poultry ..... farms, 2022	93	118	24	188	58	42
2017	67	68	36	162	52	51
Layers ..... farms, 2022	88	111	19	175	52	38
2017	62	59	33	158	48	50
number, 2022	1,809	2,539	360	4,324	830,278	851
2017	1,248	1,455	532	4,202	767,536	(D)
2022 farms by inventory:						
1 to 49	85	102	17	153	32	33
50 to 99	-	9	2	11	13	5
100 to 399	3	-	-	11	2	-
400 to 3,199	-	-	-	-	-	-
3,200 to 9,999	-	-	-	-	-	-
10,000 to 19,999	-	-	-	-	-	-
20,000 to 49,999	-	-	-	-	-	-
50,000 to 99,999	-	-	-	-	1	-
100,000 or more	-	-	-	-	4	-
Pullets for laying flock replacement ..... farms, 2022	9	18	4	24	9	12
2017	2	10	5	31	10	9
number, 2022	75	475	64	323	385,566	292
2017	(D)	220	53	504	(D)	135
Broilers and other meat-type chickens ..... farms, 2022	10	23	2	40	3	8
2017	13	8	3	30	9	8
number, 2022	212	970	(D)	1,137	(D)	1,180
2017	525	630	155	1,959	5,820	860
Turkeys ..... farms, 2022	6	9	9	12	1	2
2017	4	2	2	13	6	8
number, 2022	43	(D)	109,546	93	(D)	(D)
2017	94	(D)	(D)	138	(D)	74
Ducks, geese, and other miscellaneous poultry ..... farms, 2022	20	37	6	54	20	16
2017	13	22	13	17	17	8
NUMBER SOLD						
Any poultry sold ..... farms, 2022	38	71	16	116	51	26
2017	27	43	25	98	42	28
Layers sold ..... farms, 2022	5	21	3	4	14	2
2017	9	12	7	24	8	8
number, 2022	46	894	12	149	(D)	(D)
2017	133	239	116	1,046	(D)	88
Pullets for laying flock replacement sold ..... farms, 2022	-	3	-	-	5	-
2017	-	-	-	5	1	4
number, 2022	-	36	-	-	1,739,261	-
2017	-	-	-	104	(D)	20
Broilers and other meat-type chickens sold ..... farms, 2022	3	14	2	13	3	11
2017	4	8	5	21	8	6
number, 2022	36	613	(D)	344	200	1,233
2017	210	671	228	1,388	(D)	1,000
2022 farms by number sold:						
1 to 1,999	3	14	2	13	3	11
2,000 to 59,999	-	-	-	-	-	-
60,000 to 99,999	-	-	-	-	-	-
100,000 to 199,999	-	-	-	-	-	-
200,000 to 499,999	-	-	-	-	-	-
500,000 or more	-	-	-	-	-	-
Turkeys sold ..... farms, 2022	-	5	5	2	2	2
2017	2	1	2	6	4	3
number, 2022	-	(D)	258,144	(D)	(D)	(D)
2017	(D)	(D)	(D)	(D)	(D)	44
Ducks, geese, and other miscellaneous poultry sold ..... farms, 2022	2	9	-	14	10	2
2017	7	8	3	5	8	4

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
INVENTORY							
Any poultry	farms, 2022	7	30	66	112	77	101
	2017	15	29	65	81	80	59
Layers	farms, 2022	7	22	53	104	69	96
	2017	15	23	59	76	65	57
	number, 2022	92	805	919	7,046	3,073	2,500
	2017	183	605	1,129	2,645	3,341	1,418
2022 farms by inventory:							
1 to 49		7	18	51	91	62	89
50 to 99		-	2	2	7	3	6
100 to 399		-	2	-	3	-	1
400 to 3,199		-	-	-	3	4	-
3,200 to 9,999		-	-	-	-	-	-
10,000 to 19,999		-	-	-	-	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	-	-	-	-
100,000 or more		-	-	-	-	-	-
Pullets for laying flock replacement	farms, 2022	-	5	4	16	13	8
	2017	3	1	12	13	5	9
	number, 2022	-	161	32	888	188	167
	2017	60	(D)	155	192	60	265
Broilers and other meat-type chickens	farms, 2022	-	8	20	27	15	29
	2017	1	14	18	27	13	4
	number, 2022	-	(D)	57,351	2,695	3,592	1,615
	2017	(D)	148,229	134,787	522	272	225
Turkeys	farms, 2022	-	7	9	17	8	1
	2017	-	4	3	5	14	-
	number, 2022	-	126,710	86	(D)	(D)	(D)
	2017	-	86,045	37	(D)	330,719	-
Ducks, geese, and other miscellaneous poultry	farms, 2022	1	11	20	20	31	34
	2017	-	2	18	21	28	13
NUMBER SOLD							
Any poultry sold	farms, 2022	4	32	48	72	40	62
	2017	10	26	44	62	46	44
Layers sold	farms, 2022	-	-	14	14	1	11
	2017	2	3	5	17	3	13
	number, 2022	-	-	564	2,520	(D)	274
	2017	(D)	70	61	1,108	(D)	305
Pullets for laying flock replacement sold	farms, 2022	-	-	5	2	-	3
	2017	-	-	-	-	1	2
	number, 2022	-	-	45	(D)	-	180
	2017	-	-	-	-	(D)	(D)
Broilers and other meat-type chickens sold	farms, 2022	1	14	23	10	16	16
	2017	2	6	18	15	11	17
	number, 2022	(D)	492,832	348,661	1,923	1,760	2,375
	2017	(D)	780,070	817,180	795	6,700	1,920
2022 farms by number sold:							
1 to 1,999		1	11	19	10	16	16
2,000 to 59,999		-	1	3	-	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	1	-	-	-	-
200,000 to 499,999		-	1	1	-	-	-
500,000 or more		-	-	-	-	-	-
Turkeys sold	farms, 2022	-	4	5	4	4	1
	2017	1	5	3	2	13	4
	number, 2022	-	466,100	36	(D)	(D)	(D)
	2017	(D)	356,227	87	(D)	766,112	20
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	-	5	12	7	9	5
	2017	-	8	4	6	12	5

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
INVENTORY							
Any poultry	farms, 2022	36	138	54	177	18	114
	2017	42	132	66	184	15	33
Layers	farms, 2022	36	128	47	151	18	106
	2017	26	118	57	165	13	32
	number, 2022	785	18,326	1,417	11,070	796	2,556
	2017	531	8,312	1,374	4,368	375	1,018
2022 farms by inventory:							
1 to 49		30	110	40	131	14	92
50 to 99		5	10	3	14	-	7
100 to 399		1	4	4	1	4	7
400 to 3,199		-	1	-	5	-	-
3,200 to 9,999		-	3	-	-	-	-
10,000 to 19,999		-	-	-	-	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	-	-	-	-
100,000 or more		-	-	-	-	-	-
Pullets for laying flock replacement	farms, 2022	3	23	1	20	1	11
	2017	3	17	2	11	2	1
	number, 2022	80	16,328	(D)	535	(D)	148
	2017	110	11,436	(D)	453	(D)	(D)
Broilers and other meat-type chickens	farms, 2022	4	19	4	36	5	19
	2017	13	38	9	28	4	6
	number, 2022	80	1,406	105	1,945	222	814
	2017	930	1,553	470	1,837	(D)	320
Turkeys	farms, 2022	-	6	8	12	2	11
	2017	1	10	5	12	1	3
	number, 2022	-	(D)	59,210	(D)	(D)	205
	2017	(D)	(D)	113,000	543,043	(D)	110
Ducks, geese, and other miscellaneous poultry	farms, 2022	6	50	8	37	7	20
	2017	14	18	24	48	2	3
NUMBER SOLD							
Any poultry sold	farms, 2022	20	86	29	99	7	81
	2017	12	94	48	113	14	28
Layers sold	farms, 2022	-	15	3	10	1	16
	2017	2	12	10	21	3	14
	number, 2022	-	22,759	(D)	173	(D)	425
	2017	(D)	4,164	151	438	80	209
Pullets for laying flock replacement sold	farms, 2022	-	4	1	2	1	3
	2017	-	4	-	-	-	3
	number, 2022	-	1,820	(D)	(D)	(D)	30
	2017	-	22,024	-	-	-	250
Broilers and other meat-type chickens sold	farms, 2022	6	17	8	27	3	14
	2017	2	17	2	31	1	9
	number, 2022	694	1,432	930	2,469	160	672
	2017	(D)	519	(D)	4,993	(D)	1,405
2022 farms by number sold:							
1 to 1,999		6	17	8	27	3	14
2,000 to 59,999		-	-	-	-	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	-	-	-	-	-
500,000 or more		-	-	-	-	-	-
Turkeys sold	farms, 2022	-	3	5	10	1	20
	2017	-	8	6	10	-	5
	number, 2022	-	(D)	174,000	(D)	(D)	318
	2017	-	595,795	345,899	1,199,007	-	297
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	1	8	1	17	-	6
	2017	1	6	11	6	1	-

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
INVENTORY						
Any poultry ..... farms, 2022	63	46	199	94	32	129
2017	66	85	134	81	28	118
Layers ..... farms, 2022	59	42	196	90	29	113
2017	60	76	123	80	16	116
number, 2022	1,471	756	4,592	2,312	(D)	29,040
2017	1,155	1,589	2,303	2,377	(D)	13,862
2022 farms by inventory:						
1 to 49	55	40	177	77	27	85
50 to 99	1	2	15	11	1	11
100 to 399	3	-	4	2	-	5
400 to 3,199	-	-	-	-	-	12
3,200 to 9,999	-	-	-	-	-	-
10,000 to 19,999	-	-	-	-	-	-
20,000 to 49,999	-	-	-	-	1	-
50,000 to 99,999	-	-	-	-	-	-
100,000 or more	-	-	-	-	-	-
Pullets for laying flock replacement ..... farms, 2022	13	5	17	6	1	10
2017	5	7	4	3	-	15
number, 2022	1,245	66	302	58	(D)	275
2017	91	154	16	(D)	-	117
Broilers and other meat-type chickens ..... farms, 2022	9	6	26	21	2	18
2017	13	26	10	9	4	10
number, 2022	4,312	142	2,751	1,660	(D)	998
2017	313	973	175	207	330	466
Turkeys ..... farms, 2022	5	-	15	3	1	5
2017	3	8	9	1	1	4
number, 2022	(D)	-	(D)	15	(D)	22
2017	(D)	65	(D)	(D)	(D)	47
Ducks, geese, and other miscellaneous poultry ..... farms, 2022	5	11	59	21	8	45
2017	24	22	61	4	11	33
NUMBER SOLD						
Any poultry sold ..... farms, 2022	43	28	130	67	25	82
2017	41	52	81	48	14	72
Layers sold ..... farms, 2022	10	4	11	13	1	13
2017	4	6	20	6	1	18
number, 2022	426	52	1,284	207	(D)	9,313
2017	(D)	233	248	126	(D)	5,615
Pullets for laying flock replacement sold ..... farms, 2022	-	-	-	2	-	7
2017	-	1	-	-	-	3
number, 2022	-	-	-	(D)	-	58
2017	-	(D)	-	-	-	25
Broilers and other meat-type chickens sold ..... farms, 2022	3	1	26	25	3	24
2017	1	10	19	3	3	17
number, 2022	142	(D)	2,162	1,648	145	4,322
2017	(D)	605	3,119	256	85	7,359
2022 farms by number sold:						
1 to 1,999	3	1	26	25	3	24
2,000 to 59,999	-	-	-	-	-	-
60,000 to 99,999	-	-	-	-	-	-
100,000 to 199,999	-	-	-	-	-	-
200,000 to 499,999	-	-	-	-	-	-
500,000 or more	-	-	-	-	-	-
Turkeys sold ..... farms, 2022	3	-	10	-	2	3
2017	1	3	5	-	-	6
number, 2022	(D)	-	(D)	-	(D)	60
2017	(D)	25	(D)	-	-	96
Ducks, geese, and other miscellaneous poultry sold ..... farms, 2022	3	2	9	9	5	8
2017	2	2	8	1	1	7

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
INVENTORY							
Any poultry	farms, 2022	115	12	37	31	17	21
	2017	83	8	17	26	17	15
Layers	farms, 2022	90	9	36	17	17	19
	2017	69	7	17	24	16	11
	number, 2022	1,746	138	1,210	281	663	412
	2017	1,275	150	482	323	885	310
2022 farms by inventory:							
1 to 49		84	9	31	17	12	19
50 to 99		6	-	2	-	4	-
100 to 399		-	-	3	-	1	-
400 to 3,199		-	-	-	-	-	-
3,200 to 9,999		-	-	-	-	-	-
10,000 to 19,999		-	-	-	-	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	-	-	-	-
100,000 or more		-	-	-	-	-	-
Pullets for laying flock replacement	farms, 2022	5	-	5	7	4	-
	2017	8	-	4	4	8	6
	number, 2022	51	-	225	100	92	-
	2017	59	-	230	35	355	84
Broilers and other meat-type chickens	farms, 2022	17	5	5	6	4	8
	2017	15	2	3	5	-	9
	number, 2022	461	75	225	1,503	1,020	400
	2017	408	(D)	660	1,382	-	85
Turkeys	farms, 2022	13	1	-	2	3	5
	2017	23	-	-	3	5	3
	number, 2022	2,441,677	(D)	-	(D)	40	26
	2017	2,294,399	-	-	(D)	11	9
Ducks, geese, and other miscellaneous poultry	farms, 2022	36	4	13	4	2	1
	2017	17	4	4	10	8	4
NUMBER SOLD							
Any poultry sold	farms, 2022	76	6	27	9	19	9
	2017	57	4	14	10	16	10
Layers sold	farms, 2022	6	-	1	-	-	-
	2017	3	-	4	-	-	-
	number, 2022	109	-	(D)	-	-	-
	2017	80	-	150	-	-	-
Pullets for laying flock replacement sold	farms, 2022	2	-	-	-	-	-
	2017	-	-	2	-	-	-
	number, 2022	(D)	-	-	-	-	-
	2017	-	-	(D)	-	-	-
Broilers and other meat-type chickens sold	farms, 2022	8	1	6	1	4	2
	2017	5	-	3	5	-	4
	number, 2022	278	(D)	1,070	(D)	160	(D)
	2017	470	-	510	1,978	-	175
2022 farms by number sold:							
1 to 1,999		8	1	6	1	4	2
2,000 to 59,999		-	-	-	-	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	-	-	-	-	-
500,000 or more		-	-	-	-	-	-
Turkeys sold	farms, 2022	13	-	-	2	-	-
	2017	15	-	-	2	-	2
	number, 2022	5,754,490	-	-	(D)	-	-
	2017	5,656,936	-	-	(D)	-	(D)
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	1	-	-	-	1	-
	2017	2	-	-	-	1	2

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
INVENTORY							
Any poultry	farms, 2022	79	10	40	93	11	27
	2017	76	17	27	84	14	24
Layers	farms, 2022	69	10	33	83	11	24
	2017	65	17	22	74	13	24
	number, 2022	1,489	166	(D)	3,374	386	497
	2017	3,762	312	(D)	2,899	453	831
2022 farms by inventory:							
1 to 49		63	10	31	70	5	24
50 to 99		4	-	-	7	6	-
100 to 399		2	-	1	5	-	-
400 to 3,199		-	-	-	1	-	-
3,200 to 9,999		-	-	-	-	-	-
10,000 to 19,999		-	-	-	-	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	1	-	-	-
100,000 or more		-	-	-	-	-	-
Pullets for laying flock replacement	farms, 2022	8	-	3	11	-	-
	2017	21	2	4	7	2	2
	number, 2022	(D)	-	12	165	-	-
	2017	2,501	(D)	100	101	(D)	(D)
Broilers and other meat-type chickens	farms, 2022	13	2	7	15	6	2
	2017	10	2	5	12	1	8
	number, 2022	328	(D)	490	455	155	(D)
	2017	290	(D)	325	456	(D)	333
Turkeys	farms, 2022	11	-	4	6	-	-
	2017	14	-	4	6	-	1
	number, 2022	68,794	-	506,333	(D)	-	-
	2017	101,014	-	522,333	129	-	(D)
Ducks, geese, and other miscellaneous poultry	farms, 2022	29	3	8	39	5	13
	2017	28	10	2	29	3	4
NUMBER SOLD							
Any poultry sold	farms, 2022	58	3	22	49	8	14
	2017	53	9	12	48	9	21
Layers sold	farms, 2022	7	-	3	9	-	-
	2017	14	1	3	9	-	1
	number, 2022	357	-	(D)	279	-	-
	2017	379	(D)	(D)	140	-	(D)
Pullets for laying flock replacement sold	farms, 2022	3	-	2	3	-	1
	2017	5	-	-	2	-	-
	number, 2022	(D)	-	(D)	30	-	(D)
	2017	1,439	-	-	(D)	-	-
Broilers and other meat-type chickens sold	farms, 2022	23	-	4	10	-	1
	2017	12	1	3	15	2	9
	number, 2022	5,347	-	780	2,537	-	(D)
	2017	2,790	(D)	75	2,440	(D)	411
2022 farms by number sold:							
1 to 1,999		23	-	4	9	-	1
2,000 to 59,999		-	-	-	1	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	-	-	-	-	-
500,000 or more		-	-	-	-	-	-
Turkeys sold	farms, 2022	11	-	4	-	-	1
	2017	10	-	4	-	-	4
	number, 2022	270,584	-	1,950,000	-	-	(D)
	2017	300,188	-	1,948,000	-	-	405,033
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	5	1	-	8	2	-
	2017	5	3	-	13	-	-

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
INVENTORY							
Any poultry	farms, 2022	38	89	123	288	94	24
	2017	29	89	125	271	90	20
Layers	farms, 2022	36	75	119	195	87	23
	2017	23	76	115	127	80	13
	number, 2022	908	5,700,533	362,928	312,324	2,624	638
	2017	621	(D)	2,874	240,598	2,294	962
2022 farms by inventory:							
1 to 49		35	71	103	151	74	22
50 to 99		1	-	11	23	10	-
100 to 399		-	-	2	5	3	1
400 to 3,199		-	-	-	-	-	-
3,200 to 9,999		-	-	-	-	-	-
10,000 to 19,999		-	-	-	15	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	-	-	-	-
100,000 or more		-	4	3	1	-	-
Pullets for laying flock replacement	farms, 2022	4	5	15	35	6	2
	2017	5	5	10	9	5	6
	number, 2022	74	1,143,304	457	315,310	63	(D)
	2017	86	(D)	337	400,154	84	570
Broilers and other meat-type chickens	farms, 2022	15	17	19	111	8	2
	2017	8	14	22	130	10	8
	number, 2022	1,181	1,070	(D)	3,651,676	112	(D)
	2017	488	621	97,176	4,838,537	352	560
Turkeys	farms, 2022	8	13	2	35	7	2
	2017	7	11	10	40	6	1
	number, 2022	36	(D)	(D)	961,670	(D)	(D)
	2017	102,010	1,041,083	129	1,477,183	363,016	(D)
Ducks, geese, and other miscellaneous poultry	farms, 2022	11	16	37	77	28	1
	2017	1	18	41	34	31	7
NUMBER SOLD							
Any poultry sold	farms, 2022	26	61	72	216	64	10
	2017	25	59	80	220	53	15
Layers sold	farms, 2022	1	5	6	37	9	1
	2017	3	15	20	21	11	-
	number, 2022	(D)	1,572,157	208	951,221	448	(D)
	2017	80	(D)	394	121,995	423	-
Pullets for laying flock replacement sold	farms, 2022	-	3	1	7	6	-
	2017	-	3	1	3	3	-
	number, 2022	-	1,603,938	(D)	1,126,000	36	-
	2017	-	(D)	(D)	1,350,000	30	-
Broilers and other meat-type chickens sold	farms, 2022	6	14	16	91	6	5
	2017	7	10	22	107	7	4
	number, 2022	552	2,565	(D)	20,650,190	208	530
	2017	665	595	501,435	26,026,113	175	283
2022 farms by number sold:							
1 to 1,999		6	14	15	32	6	5
2,000 to 59,999		-	-	-	1	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	-	-	49	-	-
500,000 or more		-	-	1	9	-	-
Turkeys sold	farms, 2022	-	7	4	21	1	1
	2017	6	13	4	35	3	1
	number, 2022	-	(D)	61	2,637,081	(D)	(D)
	2017	300,000	2,350,217	39	4,208,015	725,000	(D)
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	1	7	6	43	3	-
	2017	1	8	19	22	7	-

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
INVENTORY						
Any poultry ..... farms, 2022	43	56	21	116	221	14
2017	26	41	17	125	204	23
Layers ..... farms, 2022	34	45	18	109	201	14
2017	23	32	16	112	166	22
number, 2022	1,978,554	1,585	387	1,977	4,145	238
2017	(D)	835	477	2,185	3,960	382
2022 farms by inventory:						
1 to 49	30	39	16	101	189	14
50 to 99	1	5	2	8	9	-
100 to 399	-	-	-	-	3	-
400 to 3,199	-	1	-	-	-	-
3,200 to 9,999	-	-	-	-	-	-
10,000 to 19,999	-	-	-	-	-	-
20,000 to 49,999	-	-	-	-	-	-
50,000 to 99,999	-	-	-	-	-	-
100,000 or more	3	-	-	-	-	-
Pullets for laying flock replacement ..... farms, 2022	2	6	3	16	18	2
2017	7	16	2	9	14	-
number, 2022	(D)	540	(D)	225	234	(D)
2017	960,046	378	(D)	178	202	-
Broilers and other meat-type chickens ..... farms, 2022	1	12	6	13	22	-
2017	2	10	-	5	39	-
number, 2022	(D)	1,120	153	523	677	-
2017	(D)	783	-	42	1,927	-
Turkeys ..... farms, 2022	5	7	1	8	11	4
2017	-	9	1	12	20	2
number, 2022	5	(D)	(D)	(D)	880,267	14
2017	-	186,011	(D)	(D)	831,000	(D)
Ducks, geese, and other miscellaneous poultry ..... farms, 2022	8	14	2	40	47	6
2017	2	4	2	43	50	5
NUMBER SOLD						
Any poultry sold ..... farms, 2022	18	36	15	56	127	8
2017	21	32	14	52	105	11
Layers sold ..... farms, 2022	5	3	3	11	13	-
2017	1	7	2	10	10	3
number, 2022	2,357,913	69	30	121	519	-
2017	(D)	169	(D)	156	628	66
Pullets for laying flock replacement sold ..... farms, 2022	1	1	-	-	-	-
2017	3	8	-	1	2	-
number, 2022	(D)	(D)	-	-	-	-
2017	2,060,000	61	-	(D)	(D)	-
Broilers and other meat-type chickens sold ..... farms, 2022	4	14	3	14	13	-
2017	4	9	1	8	17	-
number, 2022	386	1,090	(D)	456	300	-
2017	800	765	(D)	395	1,881	-
2022 farms by number sold:						
1 to 1,999	4	14	3	14	13	-
2,000 to 59,999	-	-	-	-	-	-
60,000 to 99,999	-	-	-	-	-	-
100,000 to 199,999	-	-	-	-	-	-
200,000 to 499,999	-	-	-	-	-	-
500,000 or more	-	-	-	-	-	-
Turkeys sold ..... farms, 2022	-	1	1	2	14	-
2017	-	7	1	2	16	-
number, 2022	-	(D)	(D)	(D)	2,974,018	-
2017	-	588,005	(D)	(D)	2,900,118	-
Ducks, geese, and other miscellaneous poultry sold ..... farms, 2022	2	2	-	8	11	-
2017	1	-	-	8	8	-

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
INVENTORY							
Any poultry	farms, 2022	162	30	63	55	-	5
	2017	119	36	50	39	4	5
Layers	farms, 2022	156	27	53	50	-	5
	2017	116	34	48	34	3	5
	number, 2022	2,845	517	1,082	866	-	85
	2017	(D)	1,264	2,178	802	9	126
2022 farms by inventory:							
1 to 49		153	22	49	50	-	5
50 to 99		1	5	4	-	-	-
100 to 399		2	-	-	-	-	-
400 to 3,199		-	-	-	-	-	-
3,200 to 9,999		-	-	-	-	-	-
10,000 to 19,999		-	-	-	-	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	-	-	-	-
100,000 or more		-	-	-	-	-	-
Pullets for laying flock replacement	farms, 2022	15	1	6	8	-	-
	2017	16	-	6	3	-	-
	number, 2022	231	(D)	72	82	-	-
	2017	216	-	630	(D)	-	-
Broilers and other meat-type chickens	farms, 2022	37	3	9	10	-	-
	2017	17	2	16	9	1	2
	number, 2022	1,067	520	272	425	-	-
	2017	472	(D)	1,109	(D)	(D)	(D)
Turkeys	farms, 2022	21	4	12	3	-	-
	2017	25	1	1	4	1	1
	number, 2022	109	(D)	74	(D)	-	-
	2017	206	(D)	(D)	(D)	(D)	(D)
Ducks, geese, and other miscellaneous poultry	farms, 2022	48	5	19	8	-	-
	2017	55	9	13	1	-	3
NUMBER SOLD							
Any poultry sold	farms, 2022	85	16	46	31	-	3
	2017	82	12	37	31	1	5
Layers sold	farms, 2022	14	5	20	3	-	-
	2017	18	2	8	11	-	-
	number, 2022	160	109	1,739	(D)	-	-
	2017	(D)	(D)	172	240	-	-
Pullets for laying flock replacement sold	farms, 2022	-	-	3	-	-	-
	2017	2	-	-	-	-	-
	number, 2022	-	-	180	-	-	-
	2017	(D)	-	-	-	-	-
Broilers and other meat-type chickens sold	farms, 2022	14	5	9	8	-	-
	2017	21	1	14	10	-	1
	number, 2022	1,238	434	366	(D)	-	-
	2017	1,735	(D)	1,210	(D)	-	(D)
2022 farms by number sold:							
1 to 1,999		14	5	9	7	-	-
2,000 to 59,999		-	-	-	1	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	-	-	-	-	-
500,000 or more		-	-	-	-	-	-
Turkeys sold	farms, 2022	3	1	4	3	-	-
	2017	6	1	2	1	1	1
	number, 2022	6	(D)	34	(D)	-	-
	2017	104	(D)	(D)	(D)	(D)	(D)
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	6	-	5	-	-	-
	2017	18	-	1	1	-	1

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
INVENTORY							
Any poultry	farms, 2022	66	43	153	31	56	225
	2017	62	42	149	35	32	173
Layers	farms, 2022	47	37	139	29	48	216
	2017	43	34	142	35	24	164
	number, 2022	852	930	5,350	523	1,076	6,331
	2017	4,107	(D)	4,558	707	620	4,777
2022 farms by inventory:							
1 to 49		45	34	120	27	47	181
50 to 99		2	3	17	1	1	30
100 to 399		-	-	1	1	-	5
400 to 3,199		-	-	1	-	-	-
3,200 to 9,999		-	-	-	-	-	-
10,000 to 19,999		-	-	-	-	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	-	-	-	-
100,000 or more		-	-	-	-	-	-
Pullets for laying flock replacement	farms, 2022	6	4	10	-	-	30
	2017	1	2	13	2	4	22
	number, 2022	52	(D)	87	-	-	441
	2017	(D)	(D)	157	(D)	40	642
Broilers and other meat-type chickens	farms, 2022	2	10	35	7	8	39
	2017	17	15	31	-	5	49
	number, 2022	(D)	992	9,942	152	748	2,240
	2017	1,788	1,272	1,501	-	560	4,884
Turkeys	farms, 2022	23	5	12	1	7	12
	2017	18	5	26	1	5	23
	number, 2022	350,724	198,652	483,223	(D)	(D)	65
	2017	552,612	272,511	387,497	(D)	253,000	325
Ducks, geese, and other miscellaneous poultry	farms, 2022	18	8	32	6	18	69
	2017	17	3	44	14	3	36
NUMBER SOLD							
Any poultry sold	farms, 2022	38	28	97	12	39	177
	2017	45	31	77	16	25	122
Layers sold	farms, 2022	4	1	21	2	3	26
	2017	1	4	31	-	5	17
	number, 2022	48	(D)	2,013	(D)	71	1,453
	2017	(D)	(D)	1,637	-	42	597
Pullets for laying flock replacement sold	farms, 2022	-	1	6	-	-	-
	2017	-	2	-	-	-	4
	number, 2022	-	(D)	180	-	-	-
	2017	-	(D)	-	-	-	(D)
Broilers and other meat-type chickens sold	farms, 2022	3	7	44	6	7	34
	2017	2	15	30	1	6	19
	number, 2022	(D)	690	22,101	109	572	3,397
	2017	(D)	1,142	1,832	(D)	576	1,090
2022 farms by number sold:							
1 to 1,999		3	7	43	6	7	34
2,000 to 59,999		-	-	1	-	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	-	-	-	-	-
500,000 or more		-	-	-	-	-	-
Turkeys sold	farms, 2022	17	3	20	-	5	8
	2017	13	5	22	-	6	9
	number, 2022	1,076,278	(D)	1,058,586	-	690,020	95
	2017	1,455,600	1,162,301	988,534	-	621,500	87
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	4	-	13	1	7	12
	2017	-	1	18	-	-	9

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
INVENTORY							
Any poultry	farms, 2022	135	130	76	376	70	22
	2017	96	96	65	384	67	28
Layers	farms, 2022	131	120	69	298	49	18
	2017	86	85	55	259	47	22
	number, 2022	3,977	(D)	(D)	897,819	588	280
	2017	5,639	(D)	(D)	1,033,055	986	567
2022 farms by inventory:							
1 to 49		113	106	63	246	49	18
50 to 99		13	6	5	28	-	-
100 to 399		5	7	-	7	-	-
400 to 3,199		-	-	-	-	-	-
3,200 to 9,999		-	-	-	3	-	-
10,000 to 19,999		-	-	-	7	-	-
20,000 to 49,999		-	-	-	3	-	-
50,000 to 99,999		-	1	-	2	-	-
100,000 or more		-	-	1	2	-	-
Pullets for laying flock replacement	farms, 2022	10	31	15	35	-	2
	2017	3	10	4	29	3	-
	number, 2022	470	498	210	(D)	-	(D)
	2017	(D)	(D)	(D)	176,594	30	-
Broilers and other meat-type chickens	farms, 2022	13	36	11	83	18	2
	2017	6	18	19	109	14	-
	number, 2022	1,660	(D)	204	1,987,410	1,170	(D)
	2017	620	113,085	1,038	2,892,957	86	-
Turkeys	farms, 2022	11	15	15	40	14	-
	2017	8	4	-	46	10	-
	number, 2022	104	67	76	1,796,151	190,562	-
	2017	96	36	-	2,734,124	332,296	-
Ducks, geese, and other miscellaneous poultry	farms, 2022	45	47	30	86	16	4
	2017	30	25	20	82	8	8
NUMBER SOLD							
Any poultry sold	farms, 2022	104	90	44	271	33	12
	2017	71	77	34	276	40	15
Layers sold	farms, 2022	26	16	9	50	-	-
	2017	6	7	7	41	9	3
	number, 2022	864	227	116	794,462	-	-
	2017	1,256	92	(D)	802,719	52	169
Pullets for laying flock replacement sold	farms, 2022	-	6	1	3	-	-
	2017	-	2	1	6	-	-
	number, 2022	-	60	(D)	384,000	-	-
	2017	-	(D)	(D)	228,030	-	-
Broilers and other meat-type chickens sold	farms, 2022	11	21	8	76	14	8
	2017	15	17	5	85	17	7
	number, 2022	1,935	(D)	350	11,989,349	1,520	446
	2017	1,052	554,370	197	16,427,473	1,012	1,318
2022 farms by number sold:							
1 to 1,999		11	20	8	44	14	8
2,000 to 59,999		-	-	-	1	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	1	-	27	-	-
500,000 or more		-	-	-	4	-	-
Turkeys sold	farms, 2022	12	10	2	25	7	-
	2017	8	7	-	37	10	2
	number, 2022	125	67	(D)	5,442,631	(D)	-
	2017	386	145	-	6,518,966	991,894	(D)
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	10	12	8	37	6	-
	2017	12	12	3	32	2	1

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
INVENTORY							
Any poultry	farms, 2022	31	259	2	56	69	59
	2017	41	198	9	68	71	65
Layers	farms, 2022	17	236	2	56	56	49
	2017	28	166	8	61	70	41
	number, 2022	459	2,036,330	(D)	1,886	3,421	1,087
	2017	633	6,018	176	1,630	2,562	782
2022 farms by inventory:							
1 to 49		13	206	2	47	50	44
50 to 99		4	17	-	5	-	4
100 to 399		-	9	-	4	2	1
400 to 3,199		-	1	-	-	4	-
3,200 to 9,999		-	-	-	-	-	-
10,000 to 19,999		-	-	-	-	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	-	-	-	-
100,000 or more		-	3	-	-	-	-
Pullets for laying flock replacement	farms, 2022	-	24	-	6	5	3
	2017	6	26	2	6	2	4
	number, 2022	-	469,885	-	130	50	58
	2017	120	906	(D)	126	(D)	52
Broilers and other meat-type chickens	farms, 2022	6	45	-	4	9	6
	2017	4	49	2	14	32	3
	number, 2022	530	3,864	-	205	240	95
	2017	478	5,078	(D)	424	1,437	(D)
Turkeys	farms, 2022	9	21	-	5	2	7
	2017	19	20	1	2	7	18
	number, 2022	1,219,997	1,231,838	-	25	(D)	181,705
	2017	1,400,496	899,194	(D)	(D)	(D)	422,016
Ducks, geese, and other miscellaneous poultry	farms, 2022	6	60	-	20	16	18
	2017	18	45	-	16	20	18
NUMBER SOLD							
Any poultry sold	farms, 2022	22	180	2	30	44	29
	2017	32	129	7	47	51	44
Layers sold	farms, 2022	2	39	1	9	9	1
	2017	1	29	3	11	3	7
	number, 2022	(D)	904,848	(D)	344	208	(D)
	2017	(D)	670	42	163	550	143
Pullets for laying flock replacement sold	farms, 2022	-	3	-	-	1	1
	2017	-	-	-	-	-	1
	number, 2022	-	1,159,743	-	-	(D)	(D)
	2017	-	-	-	-	-	(D)
Broilers and other meat-type chickens sold	farms, 2022	5	38	-	5	8	2
	2017	3	41	1	9	15	4
	number, 2022	275	2,868	-	246	367	(D)
	2017	420	6,134	(D)	(D)	713	240
2022 farms by number sold:							
1 to 1,999		5	38	-	5	8	2
2,000 to 59,999		-	-	-	-	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	-	-	-	-	-
500,000 or more		-	-	-	-	-	-
Turkeys sold	farms, 2022	9	12	-	-	1	7
	2017	12	13	1	-	7	20
	number, 2022	2,176,635	2,578,868	-	-	(D)	432,025
	2017	2,745,787	2,719,685	(D)	-	(D)	1,220,203
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	3	20	-	2	2	5
	2017	2	22	-	5	3	3

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Table 19. **Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
INVENTORY							
Any poultry	farms, 2022	73	37	12	117	222	41
	2017	78	20	11	78	167	26
Layers	farms, 2022	67	31	12	116	213	38
	2017	71	11	11	74	144	21
	number, 2022	1,544	1,426	341	12,886	(D)	664
	2017	2,064	244	498	6,274	(D)	659
2022 farms by inventory:							
1 to 49		59	22	12	102	198	38
50 to 99		5	6	-	8	9	-
100 to 399		3	3	-	4	4	-
400 to 3,199		-	-	-	-	-	-
3,200 to 9,999		-	-	-	2	-	-
10,000 to 19,999		-	-	-	-	-	-
20,000 to 49,999		-	-	-	-	-	-
50,000 to 99,999		-	-	-	-	-	-
100,000 or more		-	-	-	-	2	-
Pullets for laying flock replacement	farms, 2022	4	3	6	6	23	2
	2017	11	1	-	12	20	2
	number, 2022	43	180	60	94	(D)	(D)
	2017	63	(D)	-	(D)	(D)	(D)
Broilers and other meat-type chickens	farms, 2022	5	15	1	21	41	2
	2017	6	-	-	20	24	1
	number, 2022	578	4,844	(D)	2,975	2,152	(D)
	2017	1,520	-	-	1,052	(D)	(D)
Turkeys	farms, 2022	1	2	-	1	25	2
	2017	1	7	-	5	23	4
	number, 2022	(D)	(D)	-	(D)	260	(D)
	2017	(D)	(D)	-	(D)	311	(D)
Ducks, geese, and other miscellaneous poultry	farms, 2022	19	9	6	35	31	9
	2017	25	10	2	10	55	4
NUMBER SOLD							
Any poultry sold	farms, 2022	56	24	13	68	149	29
	2017	64	16	11	49	144	19
Layers sold	farms, 2022	10	-	4	11	12	3
	2017	9	-	4	14	24	4
	number, 2022	513	-	24	1,093	197	100
	2017	192	-	160	(D)	744	590
Pullets for laying flock replacement sold	farms, 2022	-	-	-	1	2	-
	2017	-	-	-	7	2	-
	number, 2022	-	-	-	(D)	(D)	-
	2017	-	-	-	76	(D)	-
Broilers and other meat-type chickens sold	farms, 2022	4	11	-	21	36	8
	2017	13	8	-	16	27	5
	number, 2022	125	4,224	-	11,919	2,365	1,900
	2017	1,436	420	-	1,234	(D)	1,145
2022 farms by number sold:							
1 to 1,999		4	11	-	19	36	8
2,000 to 59,999		-	-	-	2	-	-
60,000 to 99,999		-	-	-	-	-	-
100,000 to 199,999		-	-	-	-	-	-
200,000 to 499,999		-	-	-	-	-	-
500,000 or more		-	-	-	-	-	-
Turkeys sold	farms, 2022	-	2	-	2	14	1
	2017	-	1	-	2	26	7
	number, 2022	-	(D)	-	(D)	200	(D)
	2017	-	(D)	-	(D)	156,318	(D)
Ducks, geese, and other miscellaneous poultry sold	farms, 2022	12	2	-	5	6	2
	2017	6	3	-	3	28	3

Table 20. **Miscellaneous Poultry - Inventory and Number Sold: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sold	
	Farms	Number	Farms	Number
CHUKARS				
State Total				
Minnesota 2022	28	35,131	31	188,427
2017	20	22,951	21	68,805
Counties, 2022				
Carver	3	217	2	(D)
Chisago	3	630	3	630
Crow Wing	2	(D)	2	(D)
Fillmore	-	-	3	900
Itasca	1	(D)	1	(D)
Mahnomen	-	-	2	(D)
Morrison	3	351	2	(D)
Otter Tail	3	110	2	(D)
St. Louis	1	(D)	-	-
Scott	3	35	5	14,108
Todd	7	32,432	7	162,536
Waseca	1	(D)	1	(D)
Washington	1	(D)	1	(D)
DUCKS				
State Total				
Minnesota 2022	834	18,056	191	41,771
2017	718	24,337	203	52,635
Counties, 2022				
Aitkin	12	461	2	(D)
Anoka	8	142	-	-
Becker	8	29	-	-
Beltrami	10	68	1	(D)
Benton	13	110	2	(D)
Blue Earth	14	35	1	(D)
Brown	5	163	1	(D)
Carlton	19	402	8	74
Carver	8	124	2	(D)
Cass	13	76	8	132
Chisago	31	681	10	193
Clay	5	34	-	-
Clearwater	4	30	-	-
Cook	1	(D)	-	-
Cottonwood	3	71	2	(D)
Crow Wing	7	7,508	7	31,716
Dakota	14	220	3	(D)
Dodge	18	173	9	121
Douglas	12	89	2	(D)
Faribault	5	37	1	(D)
Fillmore	24	140	2	(D)
Freeborn	8	45	1	(D)
Goodhue	20	200	7	62
Grant	2	(D)	-	-
Hennepin	4	32	4	68
Houston	2	(D)	1	(D)
Hubbard	5	36	-	-
Isanti	18	140	6	60
Itasca	12	166	6	40
Jackson	5	34	-	-
Kanabec	19	163	6	106
Kandiyohi	11	273	-	-
Kittson	4	38	-	-
Koochiching	3	4	-	-
Lac qui Parle	1	(D)	-	-
Le Sueur	22	161	2	(D)
Lincoln	1	(D)	1	(D)
McLeod	15	212	3	105
Mahnomen	3	33	-	-
Marshall	7	54	-	-
Martin	5	31	1	(D)
Meeker	8	86	3	6
Mille Lacs	15	180	4	40
Morrison	25	310	7	25
Mower	14	107	3	40
Murray	1	(D)	-	-
Nicollet	4	43	1	(D)
Nobles	6	72	1	(D)
Olmsted	21	171	5	51
Otter Tail	18	155	1	(D)
Pennington	6	32	-	-
Pine	28	367	3	100
Pipestone	3	105	-	-
Polk	6	34	3	24
Redwood	11	72	-	-
Renville	5	66	-	-
Rice	16	227	8	61
Rock	4	35	-	-
Roseau	11	72	2	(D)
St. Louis	28	220	8	40
Scott	27	167	4	218

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Table 20. **Miscellaneous Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sold	
	Farms	Number	Farms	Number
DUCKS - Con.				
Counties, 2022 - Con.				
Sherburne	33	231	9	94
Sibley	19	610	8	90
Stearns	30	485	8	106
Steele	4	35	2	(D)
Swift	5	43	2	(D)
Todd	21	329	3	180
Wabasha	11	175	-	-
Wadena	4	180	2	(D)
Waseca	7	83	-	-
Washington	1	(D)	-	-
Watonwan	5	55	2	(D)
Winona	13	140	2	(D)
Wright	16	67	1	(D)
Yellow Medicine	7	32	-	-
EMUS				
State Total				
Minnesota 2022	31	117	1	(D)
2017	24	87	8	32
Counties, 2022				
Aitkin	4	24	-	-
Benton	2	(D)	-	-
Chisago	2	(D)	-	-
Crow Wing	2	(D)	-	-
Dakota	2	(D)	-	-
Kandiyohi	2	(D)	-	-
McLeod	2	(D)	-	-
Otter Tail	4	(D)	-	-
Pine	1	(D)	-	-
Sibley	2	(D)	-	-
Stearns	5	16	-	-
Todd	1	(D)	1	(D)
Washington	2	(D)	-	-
GEESE				
State Total				
Minnesota 2022	354	2,700	57	637
2017	320	2,417	67	706
Counties, 2022				
Anoka	3	30	-	-
Becker	5	25	-	-
Beltrami	7	9	1	(D)
Benton	4	31	-	-
Blue Earth	5	10	1	(D)
Carlton	15	147	6	24
Carver	2	(D)	-	-
Cass	13	47	6	28
Chisago	14	55	6	54
Clay	3	6	-	-
Clearwater	2	(D)	-	-
Cook	1	(D)	-	-
Cottonwood	4	74	3	6
Crow Wing	7	263	3	150
Dakota	9	42	-	-
Dodge	5	46	2	(D)
Douglas	5	22	-	-
Faribault	1	(D)	-	-
Fillmore	5	34	-	-
Goodhue	3	14	-	-
Hennepin	3	3	-	-
Houston	2	(D)	1	(D)
Hubbard	2	(D)	2	(D)
Isanti	4	6	-	-
Itasca	8	32	-	-
Jackson	4	20	-	-
Kanabec	14	320	2	(D)
Kandiyohi	10	48	-	-
Koochiching	6	12	-	-
Lac qui Parle	2	(D)	-	-
Le Sueur	4	23	-	-
McLeod	3	11	1	(D)
Marshall	2	(D)	-	-
Martin	1	(D)	-	-
Meeker	2	(D)	-	-
Mille Lacs	11	50	2	(D)
Morrison	12	118	3	26
Mower	4	38	2	(D)
Nobles	1	(D)	-	-
Olmsted	7	21	-	-
Otter Tail	4	16	2	(D)
Pennington	2	(D)	-	-
Pine	13	97	-	-

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Table 20. **Miscellaneous Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sold	
	Farms	Number	Farms	Number
GEESE - Con.				
Counties, 2022 - Con.				
Polk	1	(D)	-	-
Redwood	2	(D)	-	-
Renville	3	6	-	-
Rice	2	(D)	-	-
Rock	3	18	-	-
Roseau	4	12	-	-
St. Louis	14	81	-	-
Scott	4	56	-	-
Sherburne	21	110	4	4
Sibley	17	150	2	(D)
Stearns	15	119	2	(D)
Swift	1	(D)	-	-
Todd	5	84	3	9
Wabasha	4	30	-	-
Waseca	6	45	-	-
Watonwan	3	18	-	-
Winona	9	50	3	18
Wright	4	20	-	-
Yellow Medicine	2	(D)	-	-
GUINEAS				
State Total				
Minnesota 2022	518	5,198	65	1,261
2017	436	3,619	54	1,247
Counties, 2022				
Aitkin	7	122	-	-
Anoka	10	48	-	-
Becker	4	21	-	-
Beltrami	3	41	-	-
Benton	12	149	-	-
Blue Earth	6	24	-	-
Brown	5	26	-	-
Carlton	9	60	2	(D)
Carver	5	15	-	-
Cass	11	65	-	-
Chippewa	2	(D)	-	-
Chisago	14	258	-	-
Clay	5	102	2	(D)
Cottonwood	3	16	-	-
Crow Wing	4	22	4	72
Dakota	4	34	-	-
Dodge	13	64	-	-
Douglas	21	147	3	120
Fillmore	7	36	-	-
Freeborn	2	(D)	-	-
Goodhue	10	112	4	12
Hennepin	3	9	-	-
Hubbard	4	42	-	-
Isanti	17	230	-	-
Itasca	7	20	-	-
Kanabec	6	88	-	-
Kandiyohi	10	84	-	-
Kittson	2	(D)	-	-
Koochiching	10	96	-	-
Lac qui Parle	3	70	-	-
Lake of the Woods	1	(D)	-	-
Le Sueur	9	59	1	(D)
Lincoln	1	(D)	1	(D)
Lyon	5	13	-	-
McLeod	19	163	-	-
Mahnomen	1	(D)	-	-
Marshall	7	82	-	-
Martin	6	75	-	-
Meeker	4	38	-	-
Mille Lacs	16	174	5	40
Morrison	24	227	-	-
Mower	9	32	-	-
Murray	1	(D)	-	-
Nobles	4	80	-	-
Olmsted	14	97	2	(D)
Otter Tail	8	49	3	5
Pennington	2	(D)	-	-
Pine	7	44	-	-
Pipestone	2	(D)	-	-
Polk	8	8	3	108
Redwood	10	72	4	8
Renville	6	102	-	-
Rice	8	175	5	150
Roseau	7	41	2	(D)
St. Louis	19	124	2	(D)
Scott	5	26	-	-
Sherburne	5	10	-	-
Sibley	2	(D)	-	-
Stearns	27	438	3	54
Steele	7	244	-	-
Stevens	2	(D)	-	-

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Table 20. **Miscellaneous Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sold	
	Farms	Number	Farms	Number
GUINEAS - Con.				
Counties, 2022 - Con.				
Swift	1	(D)	1	(D)
Todd	9	144	5	(D)
Wabasha	4	34	2	(D)
Waseca	4	44	2	(D)
Washington	9	213	7	97
Watonwan	5	72	2	(D)
Winona	12	62	-	-
Wright	4	6	-	-
Yellow Medicine	5	35	-	-
HUNGARIAN PARTRIDGE				
State Total				
Minnesota 2022	1	(D)	-	-
2017	2	(D)	1	(D)
Counties, 2022				
Todd	1	(D)	-	-
OSTRICHES				
State Total				
Minnesota 2022	6	8	-	-
2017	5	9	-	-
Counties, 2022				
Kandiyohi	2	(D)	-	-
Stearns	2	(D)	-	-
Washington	2	(D)	-	-
PEACOCKS OR PEAHENS				
State Total				
Minnesota 2022	197	1,331	23	192
2017	194	1,143	34	183
Counties, 2022				
Aitkin	9	108	-	-
Anoka	2	(D)	-	-
Becker	1	(D)	-	-
Benton	2	(D)	-	-
Blue Earth	4	16	-	-
Brown	3	42	-	-
Carlton	2	(D)	-	-
Carver	3	30	-	-
Cass	7	24	2	(D)
Chippewa	2	(D)	-	-
Chisago	2	(D)	-	-
Crow Wing	7	73	-	-
Dakota	2	(D)	-	-
Dodge	19	89	-	-
Douglas	2	(D)	-	-
Fillmore	5	31	-	-
Freeborn	1	(D)	1	(D)
Goodhue	2	(D)	-	-
Hennepin	10	52	2	(D)
Isanti	6	24	-	-
Jackson	2	(D)	-	-
Kanabec	1	(D)	3	39
Kandiyohi	8	30	-	-
Lac qui Parle	2	(D)	-	-
Le Sueur	2	(D)	1	(D)
McLeod	8	80	2	(D)
Marshall	2	(D)	-	-
Martin	1	(D)	-	-
Mille Lacs	6	56	4	20
Morrison	3	9	1	(D)
Mower	4	24	-	-
Murray	1	(D)	-	-
Olmsted	4	18	-	-
Otter Tail	2	(D)	-	-
Pine	6	21	-	-
Polk	1	(D)	3	48
Rice	6	12	-	-
Roseau	2	(D)	-	-
St. Louis	7	48	-	-
Scott	2	(D)	-	-
Sherburne	2	(D)	1	(D)
Sibley	5	40	-	-
Stearns	12	71	3	9
Stevens	2	(D)	-	-
Todd	9	47	-	-
Wabasha	2	(D)	-	-
Waseca	2	(D)	-	-
Wright	2	(D)	-	-

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Table 20. **Miscellaneous Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sold	
	Farms	Number	Farms	Number
PHEASANTS				
State Total				
Minnesota 2022	105	145,319	67	368,058
2017	92	159,951	63	572,704
Counties, 2022				
Aitkin	6	44	-	-
Beltrami	1	(D)	1	(D)
Blue Earth	-	-	1	(D)
Carlton	2	(D)	-	-
Carver	3	1,220	2	(D)
Chisago	10	3,435	3	3,312
Clay	6	60	6	30
Crow Wing	7	650	5	6,650
Dakota	2	(D)	-	-
Douglas	1	(D)	-	-
Fillmore	1	(D)	4	825
Goodhue	-	-	6	156
Isanti	6	12	-	-
Jackson	2	(D)	-	-
McLeod	7	51	1	(D)
Mahnomen	-	-	2	(D)
Meeker	1	(D)	1	(D)
Morrison	5	51,010	6	67,756
Nicollet	1	(D)	1	(D)
Olmsted	-	-	1	(D)
Otter Tail	3	1,008	5	10,525
Redwood	3	18	-	-
Renville	1	(D)	-	-
Rice	3	204	2	(D)
St. Louis	5	15	-	-
Scott	3	750	3	50,325
Sibley	2	(D)	-	-
Stearns	11	16,280	7	10,574
Stevens	2	(D)	-	-
Todd	7	(D)	4	42,038
Waseca	-	-	2	(D)
Washington	2	(D)	2	(D)
Wright	2	(D)	2	(D)
PIGEONS OR SQUAB				
State Total				
Minnesota 2022	44	2,224	14	794
2017	67	4,468	21	1,790
Counties, 2022				
Becker	2	(D)	-	-
Crow Wing	2	(D)	-	-
Dodge	2	(D)	-	-
Houston	1	(D)	1	(D)
Kanabec	8	110	2	(D)
Kandiyohi	1	(D)	1	(D)
Lake	1	(D)	1	(D)
Le Sueur	2	(D)	-	-
Meeker	3	60	3	30
Mille Lacs	1	(D)	1	(D)
Morrison	1	(D)	-	-
Nicollet	2	(D)	-	-
Otter Tail	3	(D)	-	-
Pine	6	12	-	-
Rice	1	(D)	-	-
Sibley	1	(D)	-	-
Stearns	3	75	-	-
Todd	2	(D)	1	(D)
Washington	2	(D)	2	(D)
Watonwan	-	-	2	(D)
QUAIL				
State Total				
Minnesota 2022	83	268,222	39	232,512
2017	26	16,133	15	(D)
Counties, 2022				
Aitkin	1	(D)	-	-
Blue Earth	7	458	2	(D)
Carlton	6	1,800	6	1,800
Cass	3	30	-	-
Chisago	3	78	3	78
Clay	6	60	-	-
Crow Wing	-	-	3	90
Dakota	1	(D)	1	(D)
Douglas	3	21	-	-
Fillmore	2	(D)	2	(D)
Isanti	6	24	-	-
Koochiching	2	(D)	-	-
McLeod	1	(D)	1	(D)

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Table 20. **Miscellaneous Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sold	
	Farms	Number	Farms	Number
QUAIL - Con.				
Counties, 2022 - Con.				
Morrison	1	(D)	-	-
Otter Tail	2	(D)	-	-
Pine	3	150	3	600
Polk	-	-	3	78
Roseau	3	450	3	900
St. Louis	4	80	-	-
Scott	1	(D)	3	1,800
Sibley	12	246	-	-
Stearns	6	94	2	(D)
Steele	4	264,000	4	212,000
Todd	1	(D)	1	(D)
Waseca	1	(D)	1	(D)
Washington	-	-	1	(D)
Wright	4	120	-	-
RHEAS				
State Total				
Minnesota 2022	-	-	-	-
2017	4	20	-	-
ROOSTERS				
State Total				
Minnesota 2022	689	114,472	143	120,655
2017	485	38,609	113	32,204
Counties, 2022				
Aitkin	4	8	-	-
Anoka	6	34	-	-
Becker	2	(D)	-	-
Beltrami	9	70	-	-
Benton	18	14,608	8	22,552
Big Stone	9	11	1	(D)
Blue Earth	5	12	5	22
Brown	6	10	-	-
Carlton	19	37	2	(D)
Carver	1	(D)	-	-
Cass	19	76	5	41
Chippewa	4	20	-	-
Chisago	25	80	1	(D)
Clay	6	58	4	36
Clearwater	12	78	2	(D)
Cottonwood	3	3	-	-
Crow Wing	4	8	2	(D)
Dakota	4	14	4	8
Dodge	8	20	-	-
Douglas	8	20	-	-
Faribault	1	(D)	-	-
Fillmore	32	130	4	49
Goodhue	11	27	8	16
Grant	5	19	-	-
Hennepin	7	21	1	(D)
Houston	2	(D)	-	-
Hubbard	4	10	-	-
Isanti	34	(D)	3	6
Itasca	6	56	2	(D)
Jackson	5	(D)	5	(D)
Kanabec	12	163	3	45
Kandiyohi	16	41	-	-
Koochiching	6	6	-	-
Lake	1	(D)	-	-
Le Sueur	12	49	2	(D)
Lincoln	2	(D)	-	-
Lyon	4	4	-	-
McLeod	10	49	3	90
Mahnomen	2	(D)	-	-
Marshall	1	(D)	-	-
Martin	1	(D)	-	-
Meeker	3	3	-	-
Mille Lacs	17	58	-	-
Morrison	42	65,050	26	66,656
Mower	15	59	-	-
Nicollet	1	(D)	-	-
Nobles	11	31	1	(D)
Norman	2	(D)	-	-
Olmsted	10	40	2	(D)
Otter Tail	17	47	-	-
Pine	4	65	-	-
Polk	6	12	5	544
Pope	8	64	-	-
Redwood	8	10	4	52
Renville	5	27	-	-
Rice	10	80	1	(D)
Rock	2	(D)	1	(D)
Roseau	4	8	-	-
St. Louis	32	118	-	-

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Table 20. **Miscellaneous Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sold	
	Farms	Number	Farms	Number
ROOSTERS - Con.				
Counties, 2022 - Con.				
Scott	20	53	1	(D)
Sherburne	18	73	2	(D)
Sibley	13	111	6	150
Stearns	24	27,873	19	25,452
Steele	2	(D)	-	-
Swift	1	(D)	-	-
Todd	18	72	4	(D)
Wabasha	2	(D)	-	-
Wadena	12	33	-	-
Washington	3	7	1	(D)
Watonwan	4	4	-	-
Wilkin	6	42	-	-
Winona	14	43	-	-
Wright	9	34	3	61
Yellow Medicine	-	-	2	(D)
OTHER POULTRY				
State Total				
Minnesota 2022	-	-	5	19
2017	7	30	-	-
Counties, 2022				
Brown	-	-	3	(D)
St. Louis	-	-	2	(D)
POULTRY HATCHED				
State Total				
Minnesota 2022	(X)	(X)	933	163,542,456
2017	(X)	(X)	865	155,673,316
Counties, 2022				
Aitkin	(X)	(X)	12	174
Anoka	(X)	(X)	4	234
Becker	(X)	(X)	6	(D)
Beltrami	(X)	(X)	6	365
Benton	(X)	(X)	17	75,978,800
Big Stone	(X)	(X)	1	(D)
Blue Earth	(X)	(X)	9	678
Brown	(X)	(X)	4	307
Carlton	(X)	(X)	10	166
Carver	(X)	(X)	13	720
Cass	(X)	(X)	31	1,021
Chippewa	(X)	(X)	6	440
Chisago	(X)	(X)	33	1,030
Clay	(X)	(X)	12	312
Clearwater	(X)	(X)	6	138
Cook	(X)	(X)	1	(D)
Cottonwood	(X)	(X)	7	330
Crow Wing	(X)	(X)	17	178,253
Dakota	(X)	(X)	14	544
Dodge	(X)	(X)	18	235
Douglas	(X)	(X)	18	566
Fillmore	(X)	(X)	21	17,398
Freeborn	(X)	(X)	3	(D)
Goodhue	(X)	(X)	22	1,258
Grant	(X)	(X)	4	105
Hennepin	(X)	(X)	12	755
Houston	(X)	(X)	6	1,006
Hubbard	(X)	(X)	2	(D)
Isanti	(X)	(X)	21	1,858
Itasca	(X)	(X)	10	152
Jackson	(X)	(X)	8	(D)
Kanabec	(X)	(X)	11	656
Kandiyohi	(X)	(X)	28	(D)
Kittson	(X)	(X)	2	(D)
Koochiching	(X)	(X)	9	267
Lake	(X)	(X)	2	(D)
Lake of the Woods	(X)	(X)	6	120
Le Sueur	(X)	(X)	11	371
Lincoln	(X)	(X)	3	117
Lyon	(X)	(X)	1	(D)
McLeod	(X)	(X)	15	832
Marshall	(X)	(X)	1	(D)
Martin	(X)	(X)	1	(D)
Meeker	(X)	(X)	2	(D)
Mille Lacs	(X)	(X)	24	481
Morrison	(X)	(X)	40	1,680
Mower	(X)	(X)	12	804
Nicollet	(X)	(X)	2	(D)
Norman	(X)	(X)	4	304
Olmsted	(X)	(X)	14	168
Otter Tail	(X)	(X)	24	(D)
Pennington	(X)	(X)	2	(D)
Pine	(X)	(X)	25	1,186

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Table 20. **Miscellaneous Poultry - Inventory and Number Sold: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sold	
	Farms	Number	Farms	Number
POULTRY HATCHED - Con.				
Counties, 2022 - Con.				
Polk	(X)	(X)	15	1,752
Pope	(X)	(X)	8	486
Redwood	(X)	(X)	5	33
Renville	(X)	(X)	5	1,180
Rice	(X)	(X)	18	1,047
Rock	(X)	(X)	1	(D)
Roseau	(X)	(X)	10	2,154
St. Louis	(X)	(X)	38	540
Scott	(X)	(X)	25	556
Sherburne	(X)	(X)	24	442
Sibley	(X)	(X)	15	280
Stearns	(X)	(X)	51	2,326
Steele	(X)	(X)	9	240,041
Swift	(X)	(X)	2	(D)
Todd	(X)	(X)	33	22,576
Traverse	(X)	(X)	1	(D)
Wabasha	(X)	(X)	9	149
Wadena	(X)	(X)	6	460
Waseca	(X)	(X)	4	(D)
Washington	(X)	(X)	6	400
Watonwan	(X)	(X)	6	300
Wilkin	(X)	(X)	8	300
Winona	(X)	(X)	13	215
Wright	(X)	(X)	26	158,595
Yellow Medicine	(X)	(X)	2	(D)

Table 21. **Colonies of Honey Bees - Inventory and Honey Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Colonies inventory		Honey collected [1]		Honey sales	
	Farms	Number	Farms	Pounds	Farms	Value ($1,000)
State Total						
Minnesota 2022	1,398	121,824	1,075	8,865,510	801	23,517
2017	1,063	45,905	830	7,653,535	599	14,148
Counties, 2022						
Aitkin	22	12,121	19	109,009	12	302
Anoka	27	278	20	10,405	18	32
Becker	13	62	7	(D)	6	(D)
Beltrami	13	2,056	11	77,334	8	7
Benton	14	1,105	13	69,804	10	166
Big Stone	1	(D)	1	(D)	1	(D)
Blue Earth	17	45	14	1,827	11	5
Brown	6	18	6	1,270	4	2
Carlton	32	95	15	1,797	11	4
Carver	21	415	12	41,916	12	126
Cass	21	301	16	9,255	10	42
Chippewa	4	7	3	260	2	(D)
Chisago	37	248	22	12,214	21	56
Clay	13	3,224	13	199,996	9	693
Clearwater	6	(D)	4	(D)	2	(D)
Cook	2	(D)	-	-	-	-
Cottonwood	8	282	7	15,888	6	88
Crow Wing	13	5,825	13	368,983	10	986
Dakota	29	2,397	20	166,774	19	707
Dodge	14	(D)	11	(D)	11	(D)
Douglas	14	57	9	1,115	8	5
Faribault	3	4	2	(D)	1	(D)
Fillmore	45	641	38	45,560	25	113
Freeborn	8	40	5	1,590	3	3
Goodhue	17	(D)	15	(D)	10	(D)
Grant	4	1,802	2	(D)	2	(D)
Hennepin	60	476	48	56,905	43	164
Houston	12	21	6	395	-	-
Hubbard	10	20	9	1,138	8	3
Isanti	48	237	40	20,791	24	51
Itasca	14	(D)	13	(D)	5	(D)
Jackson	2	(D)	2	(D)	2	(D)
Kanabec	22	205	15	60,434	12	170
Kandiyohi	33	6,499	31	310,026	15	617
Kittson	1	(D)	1	(D)	1	(D)
Koochiching	6	36	3	1,296	3	5
Lac qui Parle	5	(D)	5	(D)	2	(D)
Lake	3	9	3	240	3	1
Lake of the Woods	3	10	1	(D)	1	(D)
Le Sueur	8	28	5	733	2	(D)
Lincoln	5	95	5	3,236	5	13
Lyon	1	(D)	1	(D)	1	(D)
McLeod	20	67	18	20,510	16	59
Marshall	2	(D)	7	(D)	1	(D)
Martin	10	174	13	6,520	11	43
Meeker	38	178	25	5,710	15	11
Mille Lacs	31	596	19	24,962	15	84
Morrison	35	2,604	28	181,255	27	513
Mower	8	23	5	1,110	1	(D)
Murray	2	(D)	1	(D)	1	(D)
Nicollet	1	(D)	1	(D)	1	(D)
Nobles	11	15	7	795	7	2
Norman	2	(D)	2	(D)	2	(D)
Olmsted	44	272	44	40,448	35	105
Otter Tail	35	6,451	37	1,047,933	21	2,687
Pennington	7	82	5	1,046	5	3
Pine	31	303	12	22,560	9	(D)
Pipestone	2	(D)	-	-	-	-
Polk	8	18,807	11	1,306,060	11	2,766
Pope	19	9,419	10	540,502	9	1,512
Red Lake	2	(D)	2	(D)	2	(D)
Redwood	15	112	12	5,639	10	13
Renville	5	26	4	1,464	3	2
Rice	28	815	24	33,085	21	118
Rock	7	8	1	(D)	-	-
Roseau	2	(D)	2	(D)	1	(D)
St. Louis	66	270	42	9,861	30	42
Scott	39	1,111	25	51,678	19	219
Sherburne	21	248	15	18,522	13	50
Sibley	4	8	4	(D)	3	(Z)
Stearns	57	4,124	49	822,792	38	2,239
Steele	2	(D)	2	(D)	1	(D)
Stevens	3	5	2	(D)	2	(D)
Swift	1	(D)	-	-	-	-
Todd	20	149	20	437,163	15	1,217
Traverse	2	(D)	2	(D)	2	(D)
Wabasha	25	73	15	4,527	8	14
Wadena	13	63	9	1,593	1	(D)
Waseca	4	241	3	5,400	3	13
Washington	49	2,058	41	104,387	36	342
Wilkin	4	10	2	(D)	1	(D)
Winona	20	63	15	5,263	10	12

See footnote(s) at end of table.

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Table 21. **Colonies of Honey Bees - Inventory and Honey Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Colonies inventory		Honey collected [1]		Honey sales	
	Farms	Number	Farms	Pounds	Farms	Value ($1,000)
Counties, 2022 - Con.						
Wright	55	829	44	34,995	33	90
Yellow Medicine	11	105	9	3,206	3	13

[1] Data are for farms with production, not necessarily sold.

Table 22. **Aquaculture Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area		Farms	Value ($1,000)
CATFISH			
State Total			
Minnesota	2022	-	-
	2017	1	(D)
TROUT			
State Total			
Minnesota	2022	10	1,728
	2017	9	741
Counties, 2022			
Cass		2	(D)
Fillmore		3	(D)
Ramsey		1	(D)
Winona		4	553
OTHER FOOD FISH			
State Total			
Minnesota	2022	4	(D)
	2017	4	144
Counties, 2022			
Douglas		1	(D)
St. Louis		2	(D)
Stearns		1	(D)
BAITFISH			
State Total			
Minnesota	2022	27	4,425
	2017	18	4,344
Counties, 2022			
Big Stone		4	480
Clay		2	(D)
Crow Wing		2	(D)
Douglas		6	440
Fillmore		2	(D)
Kandiyohi		5	2,501
Mahnomen		1	(D)
Otter Tail		4	(D)
Todd		1	(D)
CRUSTACEANS			
State Total			
Minnesota	2022	6	(D)
	2017	1	(D)
Counties, 2022			
Crow Wing		2	(D)
Fillmore		2	(D)
Lyon		1	(D)
Otter Tail		1	(D)
ORNAMENTAL FISH			
State Total			
Minnesota	2022	6	20
	2017	3	205
Counties, 2022			
Fillmore		2	(D)
Houston		1	(D)
McLeod		1	(D)
Washington		2	(D)
SPORT OR GAME FISH			
State Total			
Minnesota	2022	51	13,480
	2017	29	6,028
Counties, 2022			
Aitkin		1	(D)
Becker		2	(D)
Beltrami		2	(D)
Benton		1	(D)
Big Stone		1	(D)
Cass		1	(D)
Cottonwood		2	(D)
Crow Wing		2	(D)
Douglas		10	4,252
Fillmore		1	(D)
Hubbard		1	(D)
Itasca		2	(D)
Kandiyohi		3	1,101
Koochiching		1	(D)
Lake		1	(D)
Lake of the Woods		1	(D)
Le Sueur		2	(D)
McLeod		1	(D)
Marshall		3	2
Mille Lacs		1	(D)
Morrison		1	(D)
Otter Tail		2	(D)
Pine		1	(D)
Pope		2	(D)
Ramsey		1	(D)
St. Louis		2	(D)
Scott		1	(D)
Todd		2	(D)
OTHER AQUACULTURE PRODUCTS			
State Total			
Minnesota	2022	8	11
	2017	-	-
Counties, 2022			
Fillmore		2	(D)
Hennepin		3	2
McLeod		1	(D)
Pope		2	(D)

Table 23. **Miscellaneous Livestock and Animal Specialties - Inventory and Sales: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
ALPACAS					
State Total					
Minnesota 2022	214	2,266	49	308	202
2017	211	2,014	46	239	338
Counties, 2022					
Aitkin	2	(D)	-	-	-
Anoka	9	48	6	54	24
Beltrami	7	56	-	-	-
Benton	2	(D)	-	-	-
Blue Earth	9	42	-	-	-
Carlton	6	54	2	(D)	(D)
Carver	1	(D)	-	-	-
Chippewa	3	40	-	-	-
Chisago	14	184	2	(D)	(D)
Dakota	6	154	2	(D)	(D)
Dodge	12	80	-	-	-
Douglas	2	(D)	-	-	-
Faribault	2	(D)	-	-	-
Fillmore	3	(D)	-	-	-
Freeborn	-	-	1	(D)	(D)
Goodhue	10	158	-	-	-
Hennepin	7	35	1	(D)	(D)
Hubbard	2	(D)	-	-	-
Isanti	9	201	7	51	86
Itasca	4	28	4	20	7
Jackson	1	(D)	1	(D)	(D)
Kandiyohi	8	28	-	-	-
Le Sueur	1	(D)	-	-	-
Lyon	4	26	-	-	-
McLeod	21	231	4	8	3
Martin	-	-	1	(D)	(D)
Meeker	2	(D)	1	(D)	(D)
Mille Lacs	8	212	6	18	9
Nobles	2	(D)	-	-	-
Olmsted	1	(D)	1	(D)	(D)
Otter Tail	4	24	-	-	-
Pennington	2	(D)	-	-	-
Pipestone	2	(D)	2	(D)	(D)
Pope	1	(D)	1	(D)	(D)
Rice	3	18	-	-	-
St. Louis	6	76	2	(D)	(D)
Scott	1	(D)	-	-	-
Stearns	4	48	-	-	-
Steele	1	(D)	1	(D)	(D)
Todd	2	(D)	-	-	-
Washington	1	(D)	-	-	-
Watonwan	5	10	-	-	-
Winona	1	(D)	-	-	-
Wright	21	140	4	19	(D)
Yellow Medicine	2	(D)	-	-	-
BISON					
State Total					
Minnesota 2022	53	3,109	35	1,349	2,854
2017	67	2,897	50	779	1,660
Counties, 2022					
Becker	3	(D)	4	332	515
Beltrami	2	(D)	1	(D)	(D)
Blue Earth	1	(D)	-	-	-
Brown	6	380	4	148	600
Carlton	4	48	-	-	-
Clearwater	1	(D)	1	(D)	(D)
Cottonwood	2	(D)	1	(D)	(D)
Crow Wing	2	(D)	-	-	-
Goodhue	2	(D)	2	(D)	(D)
Houston	1	(D)	1	(D)	(D)
Itasca	-	-	1	(D)	(D)
Le Sueur	2	(D)	2	(D)	(D)
Lyon	1	(D)	1	(D)	(D)
Mahnomen	2	(D)	1	(D)	(D)
Morrison	2	(D)	2	(D)	(D)
Nobles	1	(D)	1	(D)	(D)
Olmsted	2	(D)	2	(D)	(D)
Polk	1	(D)	1	(D)	(D)
Pope	4	80	-	-	-
Redwood	2	(D)	-	-	-
Renville	2	(D)	2	(D)	(D)
Rice	1	(D)	1	(D)	(D)
Rock	1	(D)	1	(D)	(D)
St. Louis	2	(D)	1	(D)	(D)
Todd	2	(D)	2	(D)	(D)
Traverse	2	(D)	2	(D)	(D)
Washington	1	(D)	-	-	-
Winona	1	(D)	1	(D)	(D)

See footnote(s) at end of table.

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Table 23. **Miscellaneous Livestock and Animal Specialties - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
DEER IN CAPTIVITY					
State Total					
Minnesota 2022	93	3,057	62	717	1,422
2017	138	4,186	67	698	1,196
Counties, 2022					
Aitkin	2	(D)	-	-	-
Benton	2	(D)	2	(D)	(D)
Blue Earth	2	(D)	2	(D)	(D)
Chisago	5	215	5	40	88
Crow Wing	6	204	4	20	52
Itasca	6	420	8	178	267
Kanabec	2	(D)	-	-	-
Kandiyohi	2	(D)	2	(D)	(D)
Le Sueur	2	(D)	2	(D)	(D)
Lincoln	3	360	3	45	225
McLeod	8	56	-	-	-
Meeker	1	(D)	-	-	-
Mille Lacs	10	146	6	18	33
Morrison	2	(D)	-	-	-
Pine	6	276	-	-	-
Polk	6	180	6	42	54
Rice	4	200	4	80	200
Roseau	6	212	4	12	13
Scott	-	-	6	60	90
Stearns	4	30	-	-	-
Steele	8	358	6	168	324
Traverse	2	(D)	-	-	-
Wright	4	102	2	(D)	(D)
ELK IN CAPTIVITY					
State Total					
Minnesota 2022	62	2,773	39	557	1,484
2017	89	3,858	57	755	1,921
Counties, 2022					
Cass	1	(D)	1	(D)	(D)
Clearwater	2	(D)	2	(D)	(D)
Dakota	2	(D)	2	(D)	(D)
Douglas	4	602	4	62	126
Goodhue	2	(D)	5	73	134
Houston	1	(D)	1	(D)	(D)
Jackson	-	-	2	(D)	(D)
Kandiyohi	1	(D)	1	(D)	(D)
Koochiching	1	(D)	-	-	-
Lake of the Woods	1	(D)	-	-	-
McLeod	6	30	-	-	-
Mille Lacs	5	125	-	-	-
Morrison	2	(D)	2	(D)	(D)
Nobles	6	300	-	-	-
Olmsted	1	(D)	-	-	-
Otter Tail	1	(D)	-	-	-
Pine	2	(D)	2	(D)	(D)
Redwood	1	(D)	1	(D)	(D)
Rice	2	(D)	-	-	-
St. Louis	2	(D)	-	-	-
Stearns	5	171	2	(D)	(D)
Steele	8	398	8	72	132
Todd	4	251	4	103	199
Wabasha	1	(D)	1	(D)	(D)
Wright	1	(D)	1	(D)	(D)
LLAMAS					
State Total					
Minnesota 2022	122	872	28	121	131
2017	139	679	16	39	26
Counties, 2022					
Anoka	3	57	-	-	-
Becker	2	(D)	-	-	-
Benton	4	33	-	-	-
Carver	3	149	2	(D)	(D)
Chippewa	2	(D)	-	-	-
Chisago	5	(D)	1	(D)	(D)
Cottonwood	1	(D)	-	-	-
Dakota	7	24	-	-	-
Dodge	1	(D)	-	-	-
Douglas	4	6	-	-	-
Fillmore	2	(D)	-	-	-
Goodhue	4	7	-	-	-
Hennepin	7	55	-	-	-
Houston	2	(D)	-	-	-
Hubbard	1	(D)	-	-	-
Isanti	7	126	6	24	24

See footnote(s) at end of table.

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Table 23. **Miscellaneous Livestock and Animal Specialties - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
LLAMAS - Con.					
Counties, 2022 - Con.					
Kanabec	1	(D)	-	-	-
Kandiyohi	2	(D)	2	(D)	(D)
McLeod	6	14	2	(D)	(D)
Martin	3	6	-	-	-
Mille Lacs	2	(D)	-	-	-
Morrison	3	9	-	-	-
Mower	11	185	10	40	59
Norman	2	(D)	2	(D)	(D)
Olmsted	2	(D)	-	-	-
Otter Tail	1	(D)	1	(D)	(D)
Polk	1	(D)	-	-	-
St. Louis	4	10	-	-	-
Scott	6	(D)	-	-	-
Sherburne	3	13	1	(D)	(D)
Stearns	1	(D)	-	-	-
Waseca	3	9	-	-	-
Washington	1	(D)	1	(D)	(D)
Winona	2	(D)	-	-	-
Wright	11	21	-	-	-
Yellow Medicine	2	(D)	-	-	-
RABBITS, LIVE					
State Total					
Minnesota 2022	153	4,328	59	6,851	106
2017	189	5,663	88	4,960	66
Counties, 2022					
Aitkin	2	(D)	2	(D)	(D)
Becker	2	(D)	-	-	-
Beltrami	2	(D)	-	-	-
Blue Earth	5	115	5	50	1
Cass	7	340	7	76	2
Cook	1	(D)	1	(D)	(D)
Crow Wing	7	180	5	87	2
Dakota	6	360	-	-	-
Douglas	7	81	3	18	(Z)
Faribault	1	(D)	-	-	-
Fillmore	6	878	2	(D)	(D)
Freeborn	4	26	1	(D)	(D)
Goodhue	3	22	-	-	-
Hubbard	3	81	3	99	1
Itasca	2	(D)	-	-	-
Kanabec	11	78	1	(D)	(D)
Koochiching	2	(D)	-	-	-
Le Sueur	1	(D)	-	-	-
McLeod	4	34	-	-	-
Meeker	3	108	-	-	-
Mille Lacs	1	(D)	1	(D)	(D)
Morrison	4	10	-	-	-
Mower	2	(D)	2	(D)	(D)
Nicollet	2	(D)	-	-	-
Nobles	10	64	-	-	-
Otter Tail	3	(D)	2	(D)	(D)
Pine	9	305	4	795	15
Pipestone	2	(D)	2	(D)	(D)
Renville	1	(D)	1	(D)	(D)
Rice	2	(D)	3	29	(D)
Roseau	2	(D)	-	-	-
St. Louis	7	39	4	4	(Z)
Sherburne	3	15	-	-	-
Sibley	6	60	6	24	(Z)
Stearns	4	95	1	(D)	(D)
Todd	1	(D)	-	-	-
Wabasha	2	(D)	-	-	-
Wadena	2	(D)	2	(D)	(D)
Waseca	2	(D)	-	-	-
Winona	1	(D)	-	-	-
Wright	6	(D)	1	(D)	(D)
Yellow Medicine	2	(D)	-	-	-
EQUINE PRODUCTS					
State Total					
Minnesota 2022	(NA)	(NA)	185	(X)	1,113
2017	(NA)	(NA)	211	(X)	1,947
Counties, 2022					
Anoka	(NA)	(NA)	2	(X)	(D)
Beltrami	(NA)	(NA)	6	(X)	8
Benton	(NA)	(NA)	6	(X)	24
Blue Earth	(NA)	(NA)	1	(X)	(D)
Brown	(NA)	(NA)	1	(X)	(D)
Carver	(NA)	(NA)	3	(X)	41
Cass	(NA)	(NA)	5	(X)	14

See footnote(s) at end of table.

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Table 23. **Miscellaneous Livestock and Animal Specialties - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area		Inventory		Sales		
		Farms	Number	Farms	Number	Value ($1,000)
EQUINE PRODUCTS - Con.						
Counties, 2022 - Con.						
Chisago		(NA)	(NA)	6	(X)	4
Clay		(NA)	(NA)	3	(X)	4
Clearwater		(NA)	(NA)	2	(X)	(D)
Cottonwood		(NA)	(NA)	3	(X)	15
Douglas		(NA)	(NA)	1	(X)	(D)
Fillmore		(NA)	(NA)	5	(X)	19
Freeborn		(NA)	(NA)	2	(X)	(D)
Goodhue		(NA)	(NA)	5	(X)	7
Grant		(NA)	(NA)	2	(X)	(D)
Hennepin		(NA)	(NA)	10	(X)	25
Houston		(NA)	(NA)	2	(X)	(D)
Isanti		(NA)	(NA)	17	(X)	22
Itasca		(NA)	(NA)	2	(X)	(D)
Kanabec		(NA)	(NA)	7	(X)	21
Kandiyohi		(NA)	(NA)	3	(X)	2
Lake of the Woods		(NA)	(NA)	1	(X)	(D)
Mahnomen		(NA)	(NA)	1	(X)	(D)
Mille Lacs		(NA)	(NA)	5	(X)	6
Morrison		(NA)	(NA)	3	(X)	2
Mower		(NA)	(NA)	1	(X)	(D)
Olmsted		(NA)	(NA)	2	(X)	(D)
Otter Tail		(NA)	(NA)	8	(X)	78
Pine		(NA)	(NA)	7	(X)	76
Polk		(NA)	(NA)	2	(X)	(D)
Pope		(NA)	(NA)	4	(X)	4
Red Lake		(NA)	(NA)	6	(X)	30
Rice		(NA)	(NA)	2	(X)	(D)
St. Louis		(NA)	(NA)	5	(X)	14
Scott		(NA)	(NA)	7	(X)	28
Stearns		(NA)	(NA)	3	(X)	15
Todd		(NA)	(NA)	16	(X)	143
Wabasha		(NA)	(NA)	1	(X)	(D)
Waseca		(NA)	(NA)	1	(X)	(D)
Washington		(NA)	(NA)	3	(X)	17
Watonwan		(NA)	(NA)	1	(X)	(D)
Winona		(NA)	(NA)	2	(X)	(D)
Wright		(NA)	(NA)	10	(X)	44
OTHER LIVESTOCK						
State Total						
Minnesota	2022	38	(X)	10	(X)	44
	2017	62	(X)	10	(X)	31,655
Counties, 2022						
Anoka		2	(X)	-	(X)	-
Crow Wing		2	(X)	2	(X)	(D)
Fillmore		2	(X)	2	(X)	(D)
Hennepin		7	(X)	-	(X)	-
Kandiyohi		2	(X)	2	(X)	(D)
McLeod		6	(X)	-	(X)	-
Meeker		1	(X)	-	(X)	-
Scott		2	(X)	2	(X)	(D)
Stearns		4	(X)	-	(X)	-
Washington		3	(X)	-	(X)	-
Winona		2	(X)	2	(X)	(D)
Wright		5	(X)	-	(X)	-
OTHER LIVESTOCK PRODUCTS [1]						
State Total						
Minnesota	2022	(NA)	(NA)	185	(X)	27,256
	2017	(NA)	(NA)	136	(X)	23,230
Counties, 2022						
Aitkin		(NA)	(NA)	4	(X)	8
Anoka		(NA)	(NA)	4	(X)	(Z)
Beltrami		(NA)	(NA)	4	(X)	1
Benton		(NA)	(NA)	2	(X)	(D)
Big Stone		(NA)	(NA)	3	(X)	(D)
Blue Earth		(NA)	(NA)	2	(X)	(D)
Brown		(NA)	(NA)	6	(X)	16,942
Carver		(NA)	(NA)	3	(X)	(D)
Cass		(NA)	(NA)	3	(X)	(Z)
Chippewa		(NA)	(NA)	2	(X)	(D)
Chisago		(NA)	(NA)	2	(X)	(D)
Cook		(NA)	(NA)	1	(X)	(D)
Cottonwood		(NA)	(NA)	2	(X)	(D)
Crow Wing		(NA)	(NA)	-	(X)	(D)
Dakota		(NA)	(NA)	6	(X)	8
Dodge		(NA)	(NA)	6	(X)	3
Douglas		(NA)	(NA)	2	(X)	(D)
Faribault		(NA)	(NA)	1	(X)	(D)
Fillmore		(NA)	(NA)	8	(X)	32
Goodhue		(NA)	(NA)	6	(X)	27

See footnote(s) at end of table.

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Table 23. **Miscellaneous Livestock and Animal Specialties - Inventory and Sales: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Inventory		Sales		
	Farms	Number	Farms	Number	Value ($1,000)
OTHER LIVESTOCK PRODUCTS [1] - Con.					
Counties, 2022 - Con.					
Hennepin	(NA)	(NA)	3	(X)	(Z)
Isanti	(NA)	(NA)	2	(X)	(D)
Jackson	(NA)	(NA)	3	(X)	35
Kanabec	(NA)	(NA)	5	(X)	1
Kandiyohi	(NA)	(NA)	2	(X)	(D)
Lake of the Woods	(NA)	(NA)	1	(X)	(D)
Le Sueur	(NA)	(NA)	9	(X)	534
Lincoln	(NA)	(NA)	2	(X)	(D)
Lyon	(NA)	(NA)	-	(X)	(D)
McLeod	(NA)	(NA)	-	(X)	(Z)
Martin	(NA)	(NA)	3	(X)	60
Meeker	(NA)	(NA)	7	(X)	(D)
Mille Lacs	(NA)	(NA)	1	(X)	(D)
Morrison	(NA)	(NA)	3	(X)	26
Mower	(NA)	(NA)	1	(X)	23
Nicollet	(NA)	(NA)	8	(X)	601
Norman	(NA)	(NA)	3	(X)	(D)
Olmsted	(NA)	(NA)	5	(X)	340
Otter Tail	(NA)	(NA)	1	(X)	(D)
Pine	(NA)	(NA)	2	(X)	(D)
Pipestone	(NA)	(NA)	2	(X)	(D)
Pope	(NA)	(NA)	1	(X)	(D)
Redwood	(NA)	(NA)	11	(X)	219
Renville	(NA)	(NA)	2	(X)	(D)
Rice	(NA)	(NA)	2	(X)	(D)
Rock	(NA)	(NA)	1	(X)	(D)
St. Louis	(NA)	(NA)	3	(X)	3
Sherburne	(NA)	(NA)	2	(X)	(D)
Sibley	(NA)	(NA)	6	(X)	75
Stearns	(NA)	(NA)	10	(X)	2,371
Steele	(NA)	(NA)	1	(X)	(D)
Stevens	(NA)	(NA)	2	(X)	(D)
Todd	(NA)	(NA)	3	(X)	(D)
Wabasha	(NA)	(NA)	1	(X)	(D)
Waseca	(NA)	(NA)	2	(X)	(D)
Washington	(NA)	(NA)	3	(X)	4
Watonwan	(NA)	(NA)	1	(X)	(D)
Winona	(NA)	(NA)	2	(X)	(D)
Wright	(NA)	(NA)	1	(X)	(D)
Yellow Medicine	(NA)	(NA)	1	(X)	(D)

[1] Data are for farms with production, not necessarily sold.

Table 24. **Selected Crops Harvested: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Harvested cropland	farms	47,549	396	259	597	473
	acres	19,662,443	48,445	17,836	242,439	73,854
Irrigated	farms	3,551	34	64	39	45
	acres	644,857	4,443	3,990	8,911	4,050
Barley for grain	farms	336	-	-	1	4
	acres	55,330	-	-	(D)	200
	bushels	4,011,381	-	-	(D)	12,522
Irrigated	farms	10	-	-	-	-
	acres	116	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		72	-	-	-	-
25 to 99 acres		96	-	-	-	3
100 to 249 acres		94	-	-	1	1
250 to 499 acres		53	-	-	-	-
500 to 999 acres		17	-	-	-	-
1,000 acres or more		4	-	-	-	-
Corn for grain	farms	24,697	25	32	164	32
	acres	7,732,455	905	3,750	72,931	1,975
	bushels	1,478,451,268	131,840	502,239	12,090,339	256,010
Irrigated	farms	1,341	-	2	4	-
	acres	302,897	-	(D)	157	-
Farms by acres harvested:						
1 to 24 acres		2,863	16	17	35	14
25 to 99 acres		6,867	8	8	31	9
100 to 249 acres		6,444	-	2	34	8
250 to 499 acres		4,136	1	3	20	1
500 to 999 acres		2,538	-	2	19	-
1,000 acres or more		1,849	-	-	25	-
Corn for silage or greenchop	farms	2,768	18	6	51	15
	acres	313,974	648	119	8,207	1,173
	tons	6,334,518	7,309	852	145,196	17,496
Irrigated	farms	108	-	1	7	-
	acres	13,135	-	(D)	1,007	-
Farms by acres harvested:						
1 to 24 acres		848	10	4	8	-
25 to 99 acres		1,133	7	2	24	14
100 to 249 acres		452	1	-	9	-
250 to 499 acres		218	-	-	3	-
500 to 999 acres		86	-	-	7	1
1,000 acres or more		31	-	-	-	-
Dry edible beans, excluding chickpeas and limas	farms	573	-	-	14	-
	acres	210,162	-	-	7,575	-
	cwt	5,278,245	-	-	155,605	-
Irrigated	farms	95	-	-	2	-
	acres	39,931	-	-	(D)	-
Farms by acres harvested:						
1 to 24 acres		34	-	-	-	-
25 to 99 acres		118	-	-	1	-
100 to 249 acres		146	-	-	2	-
250 to 499 acres		140	-	-	7	-
500 to 999 acres		100	-	-	3	-
1,000 acres or more		35	-	-	1	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	23,394	358	139	414	358
	acres	1,392,072	37,051	3,857	37,073	32,939
	tons, dry equivalent	3,565,994	54,042	10,153	81,264	55,330
Irrigated	farms	675	13	3	15	2
	acres	32,954	352	22	1,232	(D)
Farms by acres harvested:						
1 to 24 acres		11,106	97	107	110	101
25 to 99 acres		8,179	157	26	174	144
100 to 249 acres		3,115	71	3	92	82
250 to 499 acres		780	19	3	28	25
500 to 999 acres		188	13	-	10	5
1,000 acres or more		26	1	-	-	1
Oats for grain	farms	2,329	23	-	28	52
	acres	126,011	1,222	-	1,367	3,919
	bushels	9,470,546	91,150	-	66,886	219,833
Irrigated	farms	66	-	-	-	-
	acres	3,194	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		906	9	-	10	8
25 to 99 acres		1,097	8	-	12	26
100 to 249 acres		286	6	-	6	15
250 to 499 acres		29	-	-	-	3
500 to 999 acres		8	-	-	-	-
1,000 acres or more		3	-	-	-	-
Sorghum for grain	farms	12	-	2	1	-
	acres	364	-	(D)	(D)	-
	bushels	24,260	-	(D)	(D)	-
Irrigated	farms	-	-	-	-	-
	acres	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		7	-	2	-	-
25 to 99 acres		4	-	-	1	-
100 to 249 acres		1	-	-	-	-
250 to 499 acres		-	-	-	-	-
500 to 999 acres		-	-	-	-	-
1,000 acres or more		-	-	-	-	-
Soybeans for beans	farms	25,337	29	27	182	90
	acres	7,597,171	3,967	4,195	82,288	16,300
	bushels	373,669,175	108,033	187,975	3,504,122	487,568

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Harvested cropland	farms	541	290	768	756	377
	acres	95,943	213,843	437,712	260,346	30,672
Irrigated	farms	62	11	25	35	23
	acres	19,401	2,092	3,269	3,293	(D)
Barley for grain	farms	2	-	1	3	-
	acres	(D)	-	(D)	31	-
	bushels	(D)	-	(D)	2,604	-
Irrigated	farms	-	-	-	-	-
	acres	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		-	-	-	3	-
25 to 99 acres		2	-	1	-	-
100 to 249 acres		-	-	-	-	-
250 to 499 acres		-	-	-	-	-
500 to 999 acres		-	-	-	-	-
1,000 acres or more		-	-	-	-	-
Corn for grain	farms	263	206	553	624	9
	acres	36,233	89,282	219,446	131,214	245
	bushels	6,414,145	15,223,986	46,453,017	26,682,697	29,238
Irrigated	farms	30	10	13	21	-
	acres	10,241	1,385	2,355	1,629	-
Farms by acres harvested:						
1 to 24 acres		75	8	42	42	5
25 to 99 acres		100	37	126	195	4
100 to 249 acres		62	65	143	216	-
250 to 499 acres		15	31	116	121	-
500 to 999 acres		5	45	54	39	-
1,000 acres or more		6	20	72	11	-
Corn for silage or greenchop	farms	50	13	4	52	12
	acres	7,256	3,412	248	4,988	286
	tons	147,700	26,144	(D)	96,399	4,536
Irrigated	farms	7	-	-	1	-
	acres	486	-	-	(D)	-
Farms by acres harvested:						
1 to 24 acres		13	3	2	13	8
25 to 99 acres		26	2	1	23	3
100 to 249 acres		3	2	1	13	1
250 to 499 acres		6	-	-	2	-
500 to 999 acres		-	6	-	-	-
1,000 acres or more		2	-	-	1	-
Dry edible beans, excluding chickpeas and limas	farms	2	1	-	5	8
	acres	(D)	(D)	-	401	16
	cwt	(D)	(D)	-	20,501	300
Irrigated	farms	1	-	-	4	1
	acres	(D)	-	-	(D)	(D)
Farms by acres harvested:						
1 to 24 acres		-	-	-	1	8
25 to 99 acres		-	-	-	3	-
100 to 249 acres		-	-	-	1	-
250 to 499 acres		-	-	-	-	-
500 to 999 acres		1	1	-	-	-
1,000 acres or more		1	-	-	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	354	78	132	201	350
	acres	16,115	5,970	2,898	6,860	28,711
	tons, dry equivalent	37,028	18,704	8,376	27,917	43,598
Irrigated	farms	27	-	1	9	3
	acres	1,645	-	(D)	179	202
Farms by acres harvested:						
1 to 24 acres		159	37	104	131	93
25 to 99 acres		158	28	23	53	156
100 to 249 acres		32	3	5	15	88
250 to 499 acres		3	9	-	1	10
500 to 999 acres		2	-	-	1	3
1,000 acres or more		-	1	-	-	-
Oats for grain	farms	28	3	17	27	13
	acres	473	86	627	806	860
	bushels	21,962	4,863	56,304	76,450	69,075
Irrigated	farms	-	-	-	3	-
	acres	-	-	-	6	-
Farms by acres harvested:						
1 to 24 acres		23	1	8	15	8
25 to 99 acres		5	2	9	12	2
100 to 249 acres		-	-	-	-	-
250 to 499 acres		-	-	-	-	3
500 to 999 acres		-	-	-	-	-
1,000 acres or more		-	-	-	-	-
Sorghum for grain	farms	-	-	-	-	-
	acres	-	-	-	-	-
	bushels	-	-	-	-	-
Irrigated	farms	-	-	-	-	-
	acres	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		-	-	-	-	-
25 to 99 acres		-	-	-	-	-
100 to 249 acres		-	-	-	-	-
250 to 499 acres		-	-	-	-	-
500 to 999 acres		-	-	-	-	-
1,000 acres or more		-	-	-	-	-
Soybeans for beans	farms	235	238	600	605	2
	acres	27,857	111,535	212,796	111,584	(D)
	bushels	1,231,840	4,631,099	12,522,067	6,101,554	(D)

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Harvested cropland	farms	473	371	395	551	498	298
	acres	129,717	46,589	316,194	53,977	476,475	62,929
Irrigated	farms	18	28	15	70	30	22
	acres	(D)	(D)	2,442	2,042	2,899	6,958
Barley for grain	farms	2	-	-	-	4	1
	acres	(D)	-	-	-	829	(D)
	bushels	(D)	-	-	-	60,664	(D)
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	1	-
25 to 99 acres		2	-	-	-	-	1
100 to 249 acres		-	-	-	-	1	-
250 to 499 acres		-	-	-	-	2	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Corn for grain	farms	243	25	320	159	234	17
	acres	60,960	2,436	163,441	19,816	144,928	3,368
	bushels	11,439,765	222,624	32,869,161	3,206,533	25,402,028	528,337
Irrigated	farms	-	-	9	3	6	2
	acres	-	-	1,504	900	810	(D)
Farms by acres harvested:							
1 to 24 acres		34	9	23	50	10	1
25 to 99 acres		83	11	56	68	41	11
100 to 249 acres		62	1	75	23	43	2
250 to 499 acres		33	3	61	9	51	2
500 to 999 acres		17	1	48	6	42	-
1,000 acres or more		14	-	57	3	47	1
Corn for silage or greenchop	farms	39	14	13	15	19	11
	acres	1,863	573	4,759	399	1,137	672
	tons	28,692	10,826	103,841	5,723	21,217	9,656
Irrigated	farms	-	1	-	-	-	-
	acres	-	(D)	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		15	5	2	8	4	4
25 to 99 acres		22	8	-	6	14	5
100 to 249 acres		2	1	3	1	-	2
250 to 499 acres		-	-	2	-	1	-
500 to 999 acres		-	-	6	-	-	-
1,000 acres or more		-	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas	farms	2	-	32	1	3	3
	acres	(D)	-	10,892	(D)	757	342
	cwt	(D)	-	393,901	(D)	15,381	11,023
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		2	-	11	1	-	2
100 to 249 acres		-	-	3	-	1	1
250 to 499 acres		-	-	9	-	2	-
500 to 999 acres		-	-	9	-	-	-
1,000 acres or more		-	-	-	-	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	294	322	76	297	194	253
	acres	12,681	33,900	4,661	9,384	15,971	31,653
	tons, dry equivalent	43,689	49,840	11,135	19,935	47,445	62,668
Irrigated	farms	1	4	-	1	1	4
	acres	(D)	49	-	(D)	(D)	204
Farms by acres harvested:							
1 to 24 acres		168	80	44	180	67	56
25 to 99 acres		91	133	17	101	68	79
100 to 249 acres		27	72	8	16	46	78
250 to 499 acres		6	23	7	-	12	35
500 to 999 acres		2	14	-	-	1	5
1,000 acres or more		-	-	-	-	-	-
Oats for grain	farms	6	8	2	9	28	15
	acres	108	384	(D)	215	2,213	1,357
	bushels	8,602	17,773	(D)	20,647	117,970	120,420
Irrigated	farms	-	1	-	-	-	-
	acres	-	(D)	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		5	4	1	5	2	4
25 to 99 acres		1	4	1	4	20	5
100 to 249 acres		-	-	-	-	6	6
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Sorghum for grain	farms	-	-	-	2	-	-
	acres	-	-	-	(D)	-	-
	bushels	-	-	-	(D)	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	2	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	229	17	305	173	313	47
	acres	52,608	1,554	99,594	21,438	193,698	13,593
	bushels	2,929,606	50,484	5,009,898	905,331	8,326,903	496,802

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Harvested cropland ..... farms	21	548	327	657	436	660
acres	228	351,380	37,686	175,486	255,854	176,176
Irrigated ..... farms	7	15	22	262	19	46
acres	17	2,909	(D)	59,839	(D)	6,903
Barley for grain ..... farms	-	1	-	4	-	-
acres	-	(D)	-	88	-	-
bushels	-	(D)	-	4,050	-	-
Irrigated ..... farms	-	-	-	2	-	-
acres	-	-	-	(D)	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	2	-	-
25 to 99 acres	-	1	-	2	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Corn for grain ..... farms	-	436	52	330	281	283
acres	-	181,404	7,339	87,720	140,265	73,291
bushels	-	37,787,711	876,782	16,360,503	29,571,963	12,507,296
Irrigated ..... farms	-	12	3	127	2	19
acres	-	2,732	1,137	30,872	(D)	4,139
Farms by acres harvested:						
1 to 24 acres	-	10	20	22	34	49
25 to 99 acres	-	92	17	130	69	86
100 to 249 acres	-	113	2	81	45	78
250 to 499 acres	-	96	13	53	49	30
500 to 999 acres	-	75	-	28	47	18
1,000 acres or more	-	50	-	16	37	22
Corn for silage or greenchop ..... farms	-	17	16	24	25	20
acres	-	2,971	1,151	3,897	2,374	1,287
tons	-	43,247	17,190	85,914	54,144	21,680
Irrigated ..... farms	-	-	-	7	-	-
acres	-	-	-	1,779	-	-
Farms by acres harvested:						
1 to 24 acres	-	7	11	1	5	13
25 to 99 acres	-	2	2	13	14	3
100 to 249 acres	-	4	-	3	4	2
250 to 499 acres	-	2	3	6	1	1
500 to 999 acres	-	2	-	-	1	1
1,000 acres or more	-	-	-	1	-	-
Dry edible beans, excluding chickpeas and limas ..... farms	-	-	2	14	2	4
acres	-	-	(D)	1,068	(D)	178
cwt	-	-	(D)	31,834	(D)	6,520
Irrigated ..... farms	-	-	-	4	-	-
acres	-	-	-	464	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	2	-	2	2
25 to 99 acres	-	-	-	11	-	2
100 to 249 acres	-	-	-	3	-	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop ..... farms	13	132	260	246	212	338
acres	204	3,357	17,548	8,477	6,261	13,046
tons, dry equivalent	120	11,507	28,458	24,927	24,726	32,220
Irrigated ..... farms	1	-	-	42	6	10
acres	(D)	-	-	2,202	77	137
Farms by acres harvested:						
1 to 24 acres	9	90	87	173	145	202
25 to 99 acres	4	40	122	51	54	104
100 to 249 acres	-	2	33	19	11	28
250 to 499 acres	-	-	17	1	-	4
500 to 999 acres	-	-	1	2	2	-
1,000 acres or more	-	-	-	-	-	-
Oats for grain ..... farms	-	8	26	27	15	59
acres	-	552	1,502	673	580	2,850
bushels	-	53,100	58,406	42,128	54,602	130,308
Irrigated ..... farms	-	-	3	4	-	-
acres	-	-	465	40	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	12	17	5	19
25 to 99 acres	-	8	8	10	10	34
100 to 249 acres	-	-	6	-	-	6
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Sorghum for grain ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
bushels	-	-	-	-	-	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Soybeans for beans ..... farms	-	438	29	326	255	371
acres	-	161,145	5,821	54,577	102,376	74,900
bushels	-	8,673,177	134,182	2,819,858	6,145,192	3,154,860

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Harvested cropland	farms	640	1,002	670	1,059	282	373
	acres	356,884	347,026	312,957	341,371	281,684	17,928
Irrigated	farms	14	46	23	51	38	95
	acres	(D)	(D)	3,444	6,101	7,390	449
Barley for grain	farms	-	5	3	3	1	-
	acres	-	301	124	(D)	(D)	-
	bushels	-	18,300	5,878	(D)	(D)	-
Irrigated	farms	-	-	-	1	-	-
	acres	-	-	-	(D)	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	2	-	-
25 to 99 acres		-	5	3	-	1	-
100 to 249 acres		-	-	-	1	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Corn for grain	farms	484	644	477	703	197	58
	acres	177,166	182,006	162,436	182,876	133,860	4,368
	bushels	38,066,534	36,758,109	33,828,505	37,497,055	24,677,288	727,930
Irrigated	farms	4	1	15	24	27	1
	acres	632	(D)	2,131	4,974	3,983	(D)
Farms by acres harvested:							
1 to 24 acres		15	91	33	108	14	18
25 to 99 acres		94	188	115	244	36	27
100 to 249 acres		144	169	130	166	34	10
250 to 499 acres		128	108	107	93	33	2
500 to 999 acres		70	42	55	51	37	1
1,000 acres or more		33	46	37	41	43	-
Corn for silage or greenchop	farms	5	88	10	97	8	4
	acres	(D)	8,120	650	7,437	1,380	262
	tons	(D)	169,889	12,160	178,562	26,728	6,000
Irrigated	farms	-	-	-	-	1	-
	acres	-	-	-	-	(D)	-
Farms by acres harvested:							
1 to 24 acres		2	34	4	30	3	-
25 to 99 acres		2	31	4	49	-	4
100 to 249 acres		-	12	2	13	3	-
250 to 499 acres		-	11	-	3	1	-
500 to 999 acres		1	-	-	2	1	-
1,000 acres or more		-	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas	farms	-	3	-	4	7	-
	acres	-	171	-	116	3,799	-
	cwt	-	10,420	-	7,584	143,163	-
Irrigated	farms	-	-	-	-	1	-
	acres	-	-	-	-	(D)	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	3	-	4	1	-
100 to 249 acres		-	-	-	-	2	-
250 to 499 acres		-	-	-	-	1	-
500 to 999 acres		-	-	-	-	2	-
1,000 acres or more		-	-	-	-	1	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	78	591	226	546	67	193
	acres	2,015	33,931	4,732	25,556	2,540	4,944
	tons, dry equivalent	5,912	131,742	12,830	117,740	8,388	11,430
Irrigated	farms	5	7	6	8	4	4
	acres	117	108	40	275	161	50
Farms by acres harvested:							
1 to 24 acres		55	268	181	260	40	146
25 to 99 acres		19	240	40	221	23	35
100 to 249 acres		4	62	3	57	2	10
250 to 499 acres		-	15	2	7	2	2
500 to 999 acres		-	6	-	1	-	-
1,000 acres or more		-	-	-	-	-	-
Oats for grain	farms	9	69	24	57	1	3
	acres	195	2,785	1,386	1,471	(D)	161
	bushels	16,487	265,569	105,989	82,172	(D)	7,130
Irrigated	farms	-	-	2	1	-	-
	acres	-	-	(D)	(D)	-	-
Farms by acres harvested:							
1 to 24 acres		4	39	19	42	1	-
25 to 99 acres		5	21	2	15	-	3
100 to 249 acres		-	9	-	-	-	-
250 to 499 acres		-	-	3	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Sorghum for grain	farms	-	1	-	-	-	-
	acres	-	(D)	-	-	-	-
	bushels	-	(D)	-	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	1	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	552	513	472	622	222	68
	acres	171,786	117,291	138,846	118,627	119,553	7,169
	bushels	10,642,575	6,869,263	7,992,460	7,114,715	5,270,661	347,164

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Harvested cropland	farms	525	231	584	330	653	432
	acres	117,902	47,705	64,610	42,596	349,235	53,672
Irrigated	farms	20	42	55	35	9	30
	acres	(D)	(D)	2,657	(D)	1,530	150
Barley for grain	farms	1	2	-	1	-	-
	acres	(D)	(D)	-	(D)	-	-
	bushels	(D)	(D)	-	(D)	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	1	-	-	-	-
25 to 99 acres		1	1	-	1	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Corn for grain	farms	311	47	136	12	556	69
	acres	52,132	12,273	24,352	1,483	176,899	12,558
	bushels	10,310,358	2,093,412	3,476,006	174,888	36,322,400	1,881,809
Irrigated	farms	3	14	11	-	6	-
	acres	65	9,784	1,169	-	450	-
Farms by acres harvested:							
1 to 24 acres		48	16	40	2	34	17
25 to 99 acres		131	13	44	5	148	25
100 to 249 acres		84	7	27	2	152	11
250 to 499 acres		33	8	18	3	104	13
500 to 999 acres		7	-	2	-	87	-
1,000 acres or more		8	3	5	-	31	3
Corn for silage or greenchop	farms	67	15	9	5	19	9
	acres	6,454	1,206	1,493	258	416	222
	tons	163,203	9,214	34,293	3,205	9,250	3,771
Irrigated	farms	-	1	1	-	-	-
	acres	-	(D)	(D)	-	-	-
Farms by acres harvested:							
1 to 24 acres		29	-	4	1	16	3
25 to 99 acres		16	14	4	3	2	6
100 to 249 acres		15	1	-	1	1	-
250 to 499 acres		6	-	-	-	-	-
500 to 999 acres		1	-	-	-	-	-
1,000 acres or more		-	-	1	-	-	-
Dry edible beans, excluding chickpeas and limas	farms	-	6	1	-	1	-
	acres	-	8,926	(D)	-	(D)	-
	cwt	-	240,573	(D)	-	(D)	-
Irrigated	farms	-	6	1	-	-	-
	acres	-	8,226	(D)	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	1	-	-	-	-
100 to 249 acres		-	-	1	-	1	-
250 to 499 acres		-	1	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	4	-	-	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	405	175	375	283	121	345
	acres	29,275	12,356	13,174	27,535	3,973	20,630
	tons, dry equivalent	103,956	16,135	24,434	40,777	10,761	32,686
Irrigated	farms	5	11	14	6	-	2
	acres	58	1,217	229	196	-	(D)
Farms by acres harvested:							
1 to 24 acres		133	57	230	90	86	165
25 to 99 acres		180	76	117	101	22	123
100 to 249 acres		72	34	19	61	12	41
250 to 499 acres		16	8	8	24	1	12
500 to 999 acres		4	-	1	7	-	4
1,000 acres or more		-	-	-	-	-	-
Oats for grain	farms	30	28	13	18	7	25
	acres	923	1,558	523	932	215	1,561
	bushels	62,118	94,603	17,638	60,106	21,130	85,962
Irrigated	farms	-	6	1	-	-	-
	acres	-	420	(D)	-	-	-
Farms by acres harvested:							
1 to 24 acres		18	7	5	4	3	6
25 to 99 acres		11	21	8	11	4	13
100 to 249 acres		-	-	-	3	-	6
250 to 499 acres		1	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	236	11	160	23	545	81
	acres	27,414	2,225	22,282	4,743	167,355	15,789
	bushels	1,515,776	104,399	855,736	132,109	9,093,623	631,938

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Harvested cropland	farms	728	342	147	521	19	126
	acres	396,375	418,170	23,979	340,540	144	57,749
Irrigated	farms	62	10	3	18	7	1
	acres	27,812	(D)	4	4,325	10	(D)
Barley for grain	farms	1	14	1	2	-	10
	acres	(D)	3,452	(D)	(D)	-	2,807
	bushels	(D)	291,930	(D)	(D)	-	196,425
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		1	-	-	-	-	-
25 to 99 acres		-	1	1	2	-	3
100 to 249 acres		-	6	-	-	-	2
250 to 499 acres		-	7	-	-	-	3
500 to 999 acres		-	-	-	-	-	1
1,000 acres or more		-	-	-	-	-	1
Corn for grain	farms	421	38	7	424	-	3
	acres	194,117	13,946	440	165,302	-	1,125
	bushels	37,614,584	2,052,239	66,618	30,408,622	-	176,125
Irrigated	farms	43	2	-	13	-	-
	acres	15,729	(D)	-	1,828	-	-
Farms by acres harvested:							
1 to 24 acres		48	2	1	22	-	-
25 to 99 acres		111	3	4	87	-	-
100 to 249 acres		88	7	2	110	-	-
250 to 499 acres		54	15	-	85	-	2
500 to 999 acres		61	9	-	81	-	1
1,000 acres or more		59	2	-	39	-	-
Corn for silage or greenchop	farms	43	10	2	6	-	-
	acres	9,182	427	(D)	430	-	-
	tons	204,359	9,123	(D)	8,840	-	-
Irrigated	farms	1	-	-	-	-	-
	acres	(D)	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		9	2	-	-	-	-
25 to 99 acres		14	8	-	5	-	-
100 to 249 acres		10	-	2	1	-	-
250 to 499 acres		3	-	-	-	-	-
500 to 999 acres		6	-	-	-	-	-
1,000 acres or more		1	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas	farms	28	2	-	5	-	1
	acres	10,840	(D)	-	1,961	-	(D)
	cwt	288,549	(D)	-	93,742	-	(D)
Irrigated	farms	5	-	-	1	-	-
	acres	3,371	-	-	(D)	-	-
Farms by acres harvested:							
1 to 24 acres		4	-	-	-	-	-
25 to 99 acres		5	-	-	-	-	-
100 to 249 acres		9	-	-	3	-	-
250 to 499 acres		7	1	-	1	-	1
500 to 999 acres		2	1	-	-	-	-
1,000 acres or more		1	-	-	1	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	335	93	121	115	11	70
	acres	16,369	13,484	13,342	5,056	126	7,218
	tons, dry equivalent	44,647	35,349	27,039	15,739	115	14,231
Irrigated	farms	14	4	-	-	-	-
	acres	549	36	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		186	24	28	59	9	20
25 to 99 acres		109	38	47	44	2	21
100 to 249 acres		29	16	30	10	-	21
250 to 499 acres		7	5	13	1	-	7
500 to 999 acres		4	9	3	1	-	1
1,000 acres or more		-	1	-	-	-	-
Oats for grain	farms	6	17	4	13	-	18
	acres	209	1,386	74	955	-	2,790
	bushels	10,388	129,942	2,534	58,536	-	290,213
Irrigated	farms	-	-	-	1	-	-
	acres	-	-	-	(D)	-	-
Farms by acres harvested:							
1 to 24 acres		1	4	2	1	-	1
25 to 99 acres		5	9	2	9	-	11
100 to 249 acres		-	4	-	3	-	3
250 to 499 acres		-	-	-	-	-	2
500 to 999 acres		-	-	-	-	-	1
1,000 acres or more		-	-	-	-	-	-
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	416	213	19	446	-	50
	acres	135,404	140,224	6,914	164,409	-	21,884
	bushels	6,723,133	6,275,192	212,020	7,715,294	-	794,930

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Harvested cropland	farms	523	351	639	570	197	717
	acres	159,857	153,500	360,873	218,209	171,244	646,007
Irrigated	farms	22	7	11	22	1	12
	acres	(D)	184	1,482	(D)	(D)	(D)
Barley for grain	farms	-	-	-	-	13	49
	acres	-	-	-	-	2,787	13,099
	bushels	-	-	-	-	224,371	934,242
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	1
25 to 99 acres		-	-	-	-	1	3
100 to 249 acres		-	-	-	-	9	26
250 to 499 acres		-	-	-	-	2	14
500 to 999 acres		-	-	-	-	1	5
1,000 acres or more		-	-	-	-	-	-
Corn for grain	farms	288	254	517	327	75	78
	acres	75,924	74,109	180,786	113,705	42,747	28,255
	bushels	15,528,082	13,230,886	32,297,253	22,618,847	8,327,208	4,162,308
Irrigated	farms	9	1	3	-	-	-
	acres	1,098	(D)	(D)	-	-	-
Farms by acres harvested:							
1 to 24 acres		31	14	31	46	2	3
25 to 99 acres		105	70	82	108	10	11
100 to 249 acres		71	67	143	60	24	28
250 to 499 acres		39	63	150	47	7	25
500 to 999 acres		25	32	91	25	17	6
1,000 acres or more		17	8	20	41	15	5
Corn for silage or greenchop	farms	20	38	43	21	9	10
	acres	701	3,437	4,236	1,593	578	762
	tons	14,129	62,053	80,414	32,931	10,976	8,713
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		12	11	5	8	3	1
25 to 99 acres		6	18	19	8	5	5
100 to 249 acres		2	4	17	3	1	4
250 to 499 acres		-	4	1	1	-	-
500 to 999 acres		-	1	1	1	-	-
1,000 acres or more		-	-	-	-	-	-
Dry edible beans, excluding chickpeas and limas	farms	-	-	1	7	32	29
	acres	-	-	(D)	2,011	9,571	10,752
	cwt	-	-	(D)	68,277	242,599	258,531
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	1	2	-	-
25 to 99 acres		-	-	-	1	4	4
100 to 249 acres		-	-	-	-	10	5
250 to 499 acres		-	-	-	3	13	15
500 to 999 acres		-	-	-	-	5	4
1,000 acres or more		-	-	-	1	-	1
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	240	135	198	281	92	239
	acres	4,654	5,326	7,154	8,110	7,261	22,450
	tons, dry equivalent	11,139	16,775	25,991	27,383	17,652	60,430
Irrigated	farms	2	-	-	5	1	4
	acres	(D)	-	-	28	(D)	301
Farms by acres harvested:							
1 to 24 acres		194	64	107	196	23	76
25 to 99 acres		35	57	78	68	31	85
100 to 249 acres		11	14	13	11	34	50
250 to 499 acres		-	-	-	5	4	25
500 to 999 acres		-	-	-	1	-	3
1,000 acres or more		-	-	-	-	-	-
Oats for grain	farms	28	10	23	21	32	74
	acres	975	1,367	1,297	389	3,107	9,096
	bushels	50,149	160,046	119,334	31,984	297,987	840,276
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		14	3	3	14	4	8
25 to 99 acres		14	6	17	7	9	39
100 to 249 acres		-	-	3	-	18	25
250 to 499 acres		-	-	-	-	1	-
500 to 999 acres		-	1	-	-	-	1
1,000 acres or more		-	-	-	-	-	1
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	336	271	533	345	141	474
	acres	75,175	67,229	165,332	88,037	67,294	254,815
	bushels	4,331,080	2,918,612	7,769,052	4,910,620	3,008,680	9,638,917

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Harvested cropland ..... farms	650	602	488	1,288	716	608
acres	422,048	242,801	55,469	190,224	333,878	298,402
Irrigated ..... farms	11	74	19	130	51	2
acres	532	12,676	467	18,283	(D)	(D)
Barley for grain ..... farms	-	3	2	3	3	3
acres	-	325	(D)	144	(D)	68
bushels	-	24,528	(D)	8,900	(D)	3,600
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	2	-	2	3
25 to 99 acres	-	2	-	3	-	-
100 to 249 acres	-	1	-	-	1	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Corn for grain ..... farms	512	359	117	613	500	488
acres	223,294	114,219	14,937	74,544	174,442	144,562
bushels	49,177,589	20,704,602	2,226,698	12,179,959	37,444,843	26,301,852
Irrigated ..... farms	6	35	1	66	26	-
acres	527	7,651	(D)	9,620	3,649	-
Farms by acres harvested:						
1 to 24 acres	19	41	33	144	54	39
25 to 99 acres	94	114	50	246	102	120
100 to 249 acres	157	84	16	151	183	136
250 to 499 acres	92	58	12	49	70	107
500 to 999 acres	82	31	4	16	47	65
1,000 acres or more	68	31	2	7	44	21
Corn for silage or greenchop ..... farms	5	31	25	148	24	39
acres	553	6,435	2,147	13,093	2,582	4,055
tons	12,742	130,352	41,871	248,318	56,666	59,225
Irrigated ..... farms	-	4	-	8	-	-
acres	-	960	-	1,681	-	-
Farms by acres harvested:						
1 to 24 acres	1	6	9	53	12	11
25 to 99 acres	-	11	11	63	5	14
100 to 249 acres	4	2	3	18	3	10
250 to 499 acres	-	8	1	9	3	4
500 to 999 acres	-	4	1	4	1	-
1,000 acres or more	-	-	-	1	-	-
Dry edible beans, excluding chickpeas and limas ..... farms	1	2	-	6	-	1
acres	(D)	(D)	-	2,563	-	(D)
cwt	(D)	(D)	-	87,016	-	(D)
Irrigated ..... farms	-	2	-	1	-	-
acres	-	(D)	-	(D)	-	-
Farms by acres harvested:						
1 to 24 acres	1	-	-	-	-	-
25 to 99 acres	-	2	-	1	-	-
100 to 249 acres	-	-	-	2	-	1
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	3	-	-
1,000 acres or more	-	-	-	-	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop ..... farms	94	279	387	994	239	214
acres	2,328	15,701	19,030	57,013	6,705	10,009
tons, dry equivalent	4,819	44,283	37,147	132,991	21,271	30,468
Irrigated ..... farms	-	16	3	48	4	-
acres	-	1,068	159	2,038	89	-
Farms by acres harvested:						
1 to 24 acres	68	171	190	389	168	110
25 to 99 acres	21	72	141	417	58	68
100 to 249 acres	5	19	48	168	9	35
250 to 499 acres	-	14	7	16	3	1
500 to 999 acres	-	2	1	3	1	-
1,000 acres or more	-	1	-	1	-	-
Oats for grain ..... farms	11	23	23	65	23	33
acres	365	579	1,018	1,485	844	1,472
bushels	33,912	47,185	41,616	69,070	71,022	113,737
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	3	14	13	38	18	4
25 to 99 acres	8	8	4	27	2	29
100 to 249 acres	-	1	6	-	3	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Sorghum for grain ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
bushels	-	-	-	-	-	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Soybeans for beans ..... farms	533	340	126	361	480	491
acres	191,866	100,336	17,351	34,256	136,298	137,597
bushels	11,501,189	4,794,286	648,085	1,564,338	8,033,769	6,391,086

--continued

Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Harvested cropland	farms	510	716	344	782	1,598	213
	acres	253,410	334,873	428,145	238,968	472,434	187,360
Irrigated	farms	16	4	9	40	242	1
	acres	246	599	559	(D)	70,051	(D)
Barley for grain	farms	2	-	18	-	11	16
	acres	(D)	-	4,648	-	1,398	5,630
	bushels	(D)	-	405,295	-	100,821	415,080
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	3	-	2	-
25 to 99 acres		2	-	3	-	4	1
100 to 249 acres		-	-	9	-	4	5
250 to 499 acres		-	-	1	-	-	7
500 to 999 acres		-	-	-	-	1	3
1,000 acres or more		-	-	2	-	-	-
Corn for grain	farms	399	583	170	442	741	20
	acres	126,724	167,428	88,569	121,676	173,119	7,016
	bushels	25,977,990	30,637,107	14,837,436	25,031,695	28,762,851	1,027,438
Irrigated	farms	-	3	2	7	145	-
	acres	-	369	(D)	396	35,122	-
Farms by acres harvested:							
1 to 24 acres		32	18	12	75	113	-
25 to 99 acres		102	152	16	125	245	1
100 to 249 acres		136	192	40	120	206	7
250 to 499 acres		62	126	40	60	99	9
500 to 999 acres		29	60	35	34	45	3
1,000 acres or more		38	35	27	28	33	-
Corn for silage or greenchop	farms	36	50	14	42	136	9
	acres	7,850	10,362	2,469	6,019	7,113	845
	tons	161,003	214,288	47,312	147,799	136,066	8,915
Irrigated	farms	-	-	-	-	10	-
	acres	-	-	-	-	1,137	-
Farms by acres harvested:							
1 to 24 acres		2	15	7	17	55	1
25 to 99 acres		14	10	2	11	64	5
100 to 249 acres		13	10	1	7	12	3
250 to 499 acres		4	11	2	3	5	-
500 to 999 acres		-	2	2	4	-	-
1,000 acres or more		3	2	-	-	-	-
Dry edible beans, excluding chickpeas and limas	farms	-	-	12	3	46	4
	acres	-	-	4,773	333	15,001	1,793
	cwt	-	-	101,402	7,954	358,998	43,345
Irrigated	farms	-	-	1	-	24	-
	acres	-	-	(D)	-	8,733	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	1	-
25 to 99 acres		-	-	2	2	14	-
100 to 249 acres		-	-	2	1	13	1
250 to 499 acres		-	-	5	-	7	1
500 to 999 acres		-	-	2	-	10	2
1,000 acres or more		-	-	1	-	1	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	134	215	108	438	1,032	95
	acres	4,505	7,170	9,084	19,009	73,435	13,969
	tons, dry equivalent	10,159	23,059	23,527	71,139	177,089	37,558
Irrigated	farms	-	-	-	7	81	-
	acres	-	-	-	62	5,249	-
Farms by acres harvested:							
1 to 24 acres		100	133	42	269	378	16
25 to 99 acres		20	64	38	115	422	32
100 to 249 acres		11	16	18	44	179	35
250 to 499 acres		3	2	8	8	49	6
500 to 999 acres		-	-	2	2	3	5
1,000 acres or more		-	-	-	-	1	1
Oats for grain	farms	11	14	16	41	134	26
	acres	723	654	947	1,978	8,081	4,426
	bushels	45,672	87,908	94,426	167,527	519,046	370,583
Irrigated	farms	-	-	-	-	12	-
	acres	-	-	-	-	624	-
Farms by acres harvested:							
1 to 24 acres		7	6	2	11	32	-
25 to 99 acres		-	5	11	27	66	12
100 to 249 acres		4	3	3	3	33	12
250 to 499 acres		-	-	-	-	3	1
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	1
Sorghum for grain	farms	-	-	-	1	2	-
	acres	-	-	-	(D)	(D)	-
	bushels	-	-	-	(D)	(D)	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	1	2	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	403	586	262	407	693	124
	acres	111,495	148,252	172,160	79,016	159,496	87,787
	bushels	6,503,844	7,097,059	7,482,259	4,670,907	6,567,089	3,141,123

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Harvested cropland	farms	620	412	890	470	40	213
	acres	75,570	181,999	904,276	220,081	108	154,337
Irrigated	farms	20	18	30	97	27	13
	acres	145	4,800	12,744	34,481	70	915
Barley for grain	farms	4	2	22	1	1	7
	acres	126	(D)	5,457	(D)	(D)	1,425
	bushels	(D)	(D)	361,640	(D)	(D)	94,975
Irrigated	farms	-	-	-	1	1	-
	acres	-	-	-	(D)	(D)	-
Farms by acres harvested:							
1 to 24 acres		3	-	-	1	1	3
25 to 99 acres		-	2	-	-	-	-
100 to 249 acres		1	-	12	-	-	1
250 to 499 acres		-	-	9	-	-	2
500 to 999 acres		-	-	1	-	-	1
1,000 acres or more		-	-	-	-	-	-
Corn for grain	farms	107	277	183	271	-	45
	acres	12,696	85,909	90,389	102,075	-	13,891
	bushels	1,780,538	14,810,917	14,278,511	17,738,290	-	2,315,235
Irrigated	farms	-	12	7	63	-	1
	acres	-	3,592	1,386	20,765	-	(D)
Farms by acres harvested:							
1 to 24 acres		25	10	9	26	-	3
25 to 99 acres		39	67	32	64	-	11
100 to 249 acres		29	96	37	74	-	12
250 to 499 acres		11	69	51	44	-	12
500 to 999 acres		2	18	28	36	-	4
1,000 acres or more		1	17	26	27	-	3
Corn for silage or greenchop	farms	38	39	12	34	-	9
	acres	3,333	7,390	927	2,984	-	1,607
	tons	55,814	120,243	19,342	52,908	-	27,782
Irrigated	farms	-	-	-	5	-	-
	acres	-	-	-	509	-	-
Farms by acres harvested:							
1 to 24 acres		12	9	5	12	-	1
25 to 99 acres		17	10	3	17	-	5
100 to 249 acres		3	10	4	3	-	-
250 to 499 acres		6	5	-	1	-	3
500 to 999 acres		-	4	-	-	-	-
1,000 acres or more		-	1	-	1	-	-
Dry edible beans, excluding chickpeas and limas	farms	-	-	100	11	-	4
	acres	-	-	55,891	4,957	-	2,008
	cwt	-	-	1,071,414	109,418	-	35,158
Irrigated	farms	-	-	1	4	-	1
	acres	-	-	(D)	1,872	-	(D)
Farms by acres harvested:							
1 to 24 acres		-	-	2	1	-	-
25 to 99 acres		-	-	7	1	-	-
100 to 249 acres		-	-	13	5	-	1
250 to 499 acres		-	-	30	-	-	2
500 to 999 acres		-	-	35	3	-	-
1,000 acres or more		-	-	13	1	-	1
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	528	228	220	229	-	77
	acres	45,525	11,017	19,520	17,386	-	6,937
	tons, dry equivalent	78,101	27,534	60,995	49,962	-	20,638
Irrigated	farms	7	2	3	23	-	-
	acres	99	(D)	18	1,195	-	-
Farms by acres harvested:							
1 to 24 acres		172	123	73	91	-	22
25 to 99 acres		216	75	87	90	-	30
100 to 249 acres		97	25	48	38	-	16
250 to 499 acres		36	4	7	4	-	9
500 to 999 acres		6	1	4	5	-	-
1,000 acres or more		1	-	1	1	-	-
Oats for grain	farms	20	28	15	30	1	12
	acres	501	1,370	3,647	1,362	(D)	1,812
	bushels	27,265	124,983	284,041	81,918	(D)	204,850
Irrigated	farms	-	-	-	1	1	-
	acres	-	-	-	(D)	(D)	-
Farms by acres harvested:							
1 to 24 acres		14	10	1	11	1	2
25 to 99 acres		6	12	5	19	-	7
100 to 249 acres		-	6	3	-	-	-
250 to 499 acres		-	-	3	-	-	3
500 to 999 acres		-	-	3	-	-	-
1,000 acres or more		-	-	-	-	-	-
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	90	283	580	304	-	152
	acres	11,638	73,765	325,204	83,190	-	65,417
	bushels	433,252	3,267,256	12,771,360	3,572,368	-	2,502,348

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Harvested cropland	farms	983	734	818	443	490	635
	acres	509,922	571,420	197,825	235,233	339,987	70,850
Irrigated	farms	20	14	55	2	-	72
	acres	(D)	1,935	2,267	(D)	-	(D)
Barley for grain	farms	2	4	1	-	18	11
	acres	(D)	12	(D)	-	6,436	218
	bushels	(D)	550	(D)	-	490,002	13,058
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		1	4	-	-	-	8
25 to 99 acres		-	-	1	-	6	3
100 to 249 acres		1	-	-	-	3	-
250 to 499 acres		-	-	-	-	4	-
500 to 999 acres		-	-	-	-	4	-
1,000 acres or more		-	-	-	-	1	-
Corn for grain	farms	833	564	419	337	41	-
	acres	257,104	271,325	96,895	120,530	12,134	-
	bushels	48,880,497	53,676,916	20,234,092	23,596,331	1,715,961	-
Irrigated	farms	5	7	12	2	-	-
	acres	132	1,780	1,248	(D)	-	-
Farms by acres harvested:							
1 to 24 acres		58	16	79	17	11	-
25 to 99 acres		151	91	160	85	12	-
100 to 249 acres		267	160	97	100	4	-
250 to 499 acres		199	138	29	68	6	-
500 to 999 acres		118	88	26	40	3	-
1,000 acres or more		40	71	28	27	5	-
Corn for silage or greenchop	farms	40	23	34	46	15	11
	acres	3,939	1,964	2,345	6,639	1,290	332
	tons	58,901	45,026	48,820	166,296	22,476	5,352
Irrigated	farms	-	2	-	-	-	-
	acres	-	(D)	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		12	7	12	9	5	5
25 to 99 acres		20	11	13	18	4	6
100 to 249 acres		1	3	8	12	6	-
250 to 499 acres		7	1	1	5	-	-
500 to 999 acres		-	1	-	1	-	-
1,000 acres or more		-	-	-	1	-	-
Dry edible beans, excluding chickpeas and limas	farms	1	49	-	-	2	-
	acres	(D)	10,429	-	-	(D)	-
	cwt	(D)	304,399	-	-	(D)	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	14	-	-	-	-
100 to 249 acres		1	22	-	-	1	-
250 to 499 acres		-	10	-	-	1	-
500 to 999 acres		-	3	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	173	133	383	197	262	510
	acres	4,263	4,039	11,080	8,005	30,953	59,337
	tons, dry equivalent	13,848	13,912	31,527	33,188	58,696	92,598
Irrigated	farms	1	-	7	-	-	9
	acres	(D)	-	17	-	-	553
Farms by acres harvested:							
1 to 24 acres		127	88	244	114	47	128
25 to 99 acres		35	39	118	62	101	212
100 to 249 acres		10	4	19	16	81	109
250 to 499 acres		1	1	2	5	30	40
500 to 999 acres		-	1	-	-	3	13
1,000 acres or more		-	-	-	-	-	8
Oats for grain	farms	13	17	24	10	54	37
	acres	390	560	360	690	6,502	2,298
	bushels	29,722	37,042	34,153	80,024	535,248	147,772
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		5	10	22	7	3	9
25 to 99 acres		8	7	2	1	25	19
100 to 249 acres		-	-	-	1	22	9
250 to 499 acres		-	-	-	1	1	-
500 to 999 acres		-	-	-	-	2	-
1,000 acres or more		-	-	-	-	1	-
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	847	579	426	320	238	2
	acres	231,905	221,215	84,766	97,893	131,263	(D)
	bushels	11,457,738	11,855,304	4,981,172	5,299,981	4,945,922	(D)

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Harvested cropland	farms	442	325	670	2,118	442	326
	acres	81,167	57,043	333,743	458,204	215,514	283,965
Irrigated	farms	26	94	13	324	18	55
	acres	(D)	37,573	1,062	58,201	2,337	22,814
Barley for grain	farms	-	-	6	28	-	-
	acres	-	-	239	954	-	-
	bushels	-	-	14,443	48,972	-	-
Irrigated	farms	-	-	-	5	-	-
	acres	-	-	-	90	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	1	17	-	-
25 to 99 acres		-	-	5	9	-	-
100 to 249 acres		-	-	-	2	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Corn for grain	farms	182	96	497	1,223	277	224
	acres	37,043	24,604	177,256	183,737	118,042	126,102
	bushels	6,481,477	4,212,532	35,479,978	32,564,050	24,945,640	22,496,743
Irrigated	farms	2	43	5	199	5	36
	acres	(D)	18,174	1,028	30,299	918	13,901
Farms by acres harvested:							
1 to 24 acres		45	24	60	167	25	8
25 to 99 acres		64	21	124	555	78	33
100 to 249 acres		37	15	140	324	75	52
250 to 499 acres		16	18	74	105	28	40
500 to 999 acres		9	13	40	59	33	52
1,000 acres or more		11	5	59	13	38	39
Corn for silage or greenchop	farms	17	10	39	317	15	30
	acres	1,647	1,190	2,783	34,145	667	11,002
	tons	36,761	23,084	63,302	674,802	12,126	239,448
Irrigated	farms	-	5	-	26	-	3
	acres	-	550	-	1,665	-	212
Farms by acres harvested:							
1 to 24 acres		4	2	16	73	7	5
25 to 99 acres		7	3	12	163	5	12
100 to 249 acres		6	4	9	50	3	9
250 to 499 acres		-	1	2	22	-	1
500 to 999 acres		-	-	-	5	-	-
1,000 acres or more		-	-	-	4	-	3
Dry edible beans, excluding chickpeas and limas	farms	-	3	-	9	1	31
	acres	-	(D)	-	3,215	(D)	13,869
	cwt	-	(D)	-	105,383	(D)	323,840
Irrigated	farms	-	1	-	4	-	17
	acres	-	(D)	-	(D)	-	4,810
Farms by acres harvested:							
1 to 24 acres		-	2	-	-	1	-
25 to 99 acres		-	-	-	3	-	3
100 to 249 acres		-	1	-	4	-	12
250 to 499 acres		-	-	-	1	-	10
500 to 999 acres		-	-	-	-	-	3
1,000 acres or more		-	-	-	1	-	3
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	277	156	261	1,490	183	103
	acres	7,048	4,555	7,790	90,305	4,085	10,836
	tons, dry equivalent	19,797	6,748	24,003	269,036	11,414	38,674
Irrigated	farms	-	7	-	104	3	6
	acres	-	172	-	6,261	38	464
Farms by acres harvested:							
1 to 24 acres		198	97	167	610	137	47
25 to 99 acres		60	51	73	629	38	32
100 to 249 acres		16	7	19	203	7	14
250 to 499 acres		3	1	2	33	1	7
500 to 999 acres		-	-	-	12	-	-
1,000 acres or more		-	-	-	3	-	3
Oats for grain	farms	18	8	16	293	5	1
	acres	539	431	309	11,452	314	(D)
	bushels	41,721	21,401	24,207	744,283	31,310	(D)
Irrigated	farms	-	-	-	15	-	-
	acres	-	-	-	367	-	-
Farms by acres harvested:							
1 to 24 acres		4	1	11	122	2	-
25 to 99 acres		14	7	5	163	-	1
100 to 249 acres		-	-	-	4	3	-
250 to 499 acres		-	-	-	4	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Sorghum for grain	farms	-	-	2	-	-	-
	acres	-	-	(D)	-	-	-
	bushels	-	-	(D)	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	2	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	158	73	467	876	280	212
	acres	34,096	13,826	132,175	113,387	88,651	103,077
	bushels	1,638,236	571,707	7,416,746	5,367,293	5,489,870	4,561,223

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Harvested cropland	farms	445	1,179	229	604	333	453
	acres	302,409	175,396	257,835	167,885	71,052	235,748
Irrigated	farms	73	82	3	38	50	14
	acres	(D)	17,106	44	2,121	(D)	967
Barley for grain	farms	-	15	-	12	2	-
	acres	-	758	-	718	(D)	-
	bushels	-	41,875	-	42,924	(D)	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	3	-	4	2	-
25 to 99 acres		-	9	-	5	-	-
100 to 249 acres		-	3	-	3	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Corn for grain	farms	357	502	185	424	92	331
	acres	157,921	57,958	115,605	76,700	19,535	120,236
	bushels	29,433,661	9,404,011	18,589,545	15,537,718	3,334,062	26,432,335
Irrigated	farms	48	40	-	11	37	1
	acres	13,234	7,390	-	1,475	13,676	(D)
Farms by acres harvested:							
1 to 24 acres		26	150	5	65	14	24
25 to 99 acres		70	187	16	140	48	100
100 to 249 acres		106	105	34	143	8	73
250 to 499 acres		54	40	58	34	12	65
500 to 999 acres		55	12	32	35	4	32
1,000 acres or more		46	8	40	7	6	37
Corn for silage or greenchop	farms	40	112	22	73	29	11
	acres	9,735	9,516	6,967	11,700	2,294	321
	tons	223,033	174,415	144,063	268,431	35,946	4,824
Irrigated	farms	4	4	-	-	8	-
	acres	429	1,843	-	-	319	-
Farms by acres harvested:							
1 to 24 acres		8	42	-	9	7	7
25 to 99 acres		11	43	5	36	20	4
100 to 249 acres		5	20	9	9	1	-
250 to 499 acres		13	3	4	15	-	-
500 to 999 acres		2	2	1	4	1	-
1,000 acres or more		1	2	3	-	-	-
Dry edible beans, excluding chickpeas and limas	farms	29	3	3	2	9	1
	acres	7,659	3,972	1,862	(D)	3,450	(D)
	cwt	207,377	122,550	71,780	(D)	83,754	(D)
Irrigated	farms	6	-	-	-	7	-
	acres	765	-	-	-	(D)	-
Farms by acres harvested:							
1 to 24 acres		1	-	-	-	-	-
25 to 99 acres		3	-	-	-	3	-
100 to 249 acres		15	-	-	2	-	-
250 to 499 acres		7	-	1	-	-	1
500 to 999 acres		3	-	2	-	6	-
1,000 acres or more		-	3	-	-	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	115	865	57	386	293	105
	acres	7,336	45,723	5,718	31,201	20,167	2,289
	tons, dry equivalent	27,478	105,683	23,724	125,045	39,325	7,161
Irrigated	farms	4	40	-	2	21	-
	acres	189	3,295	-	(D)	1,102	-
Farms by acres harvested:							
1 to 24 acres		54	388	23	128	101	74
25 to 99 acres		32	344	8	148	120	27
100 to 249 acres		27	109	18	80	66	4
250 to 499 acres		1	22	8	25	4	-
500 to 999 acres		1	2	-	5	1	-
1,000 acres or more		-	-	-	-	1	-
Oats for grain	farms	24	121	3	59	48	2
	acres	976	5,271	600	1,826	3,102	(D)
	bushels	82,301	355,300	60,000	168,701	188,693	(D)
Irrigated	farms	-	-	-	2	6	-
	acres	-	-	-	(D)	492	-
Farms by acres harvested:							
1 to 24 acres		10	51	-	23	9	2
25 to 99 acres		14	56	-	36	33	-
100 to 249 acres		-	14	3	-	6	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Sorghum for grain	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
	bushels	-	-	-	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	332	401	196	291	57	326
	acres	107,709	46,542	118,079	39,729	16,495	108,599
	bushels	4,887,338	1,965,831	4,916,309	2,308,568	716,736	6,850,400

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Harvested cropland	farms	392	390	260	742	995	588
	acres	33,731	241,723	358,050	198,115	171,228	316,017
Irrigated	farms	78	35	9	23	118	5
	acres	(D)	8,318	515	38	7,751	807
Barley for grain	farms	-	-	8	2	-	-
	acres	-	-	1,143	(D)	-	-
	bushels	-	-	82,662	(D)	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	1	-	-	-
25 to 99 acres		-	-	4	2	-	-
100 to 249 acres		-	-	1	-	-	-
250 to 499 acres		-	-	2	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Corn for grain	farms	84	294	168	505	383	438
	acres	12,821	135,115	108,649	89,443	68,316	156,080
	bushels	2,197,670	28,429,538	16,711,248	17,257,708	12,038,709	28,714,015
Irrigated	farms	6	24	3	-	38	3
	acres	1,265	6,255	264	-	4,188	454
Farms by acres harvested:							
1 to 24 acres		20	22	3	91	106	22
25 to 99 acres		27	44	22	200	123	93
100 to 249 acres		21	80	28	108	81	119
250 to 499 acres		9	66	43	61	41	116
500 to 999 acres		6	46	36	40	15	59
1,000 acres or more		1	36	36	5	17	29
Corn for silage or greenchop	farms	6	6	11	117	54	27
	acres	362	215	1,714	15,647	4,679	5,463
	tons	7,080	6,520	38,303	368,279	87,370	116,988
Irrigated	farms	-	1	-	-	-	-
	acres	-	(D)	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	5	3	33	26	10
25 to 99 acres		6	-	3	35	14	6
100 to 249 acres		-	1	4	25	10	7
250 to 499 acres		-	-	-	17	3	1
500 to 999 acres		-	-	1	7	1	-
1,000 acres or more		-	-	-	-	-	3
Dry edible beans, excluding chickpeas and limas	farms	2	-	7	1	3	7
	acres	(D)	-	1,581	(D)	208	756
	cwt	(D)	-	37,781	(D)	5,124	35,581
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		2	-	-	-	-	1
25 to 99 acres		-	-	-	-	2	5
100 to 249 acres		-	-	5	1	1	-
250 to 499 acres		-	-	2	-	-	1
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	169	63	58	517	611	160
	acres	5,600	1,009	5,133	42,174	18,476	6,779
	tons, dry equivalent	9,607	2,426	10,051	179,296	43,500	22,154
Irrigated	farms	1	3	2	2	23	1
	acres	(D)	(D)	(D)	(D)	362	(D)
Farms by acres harvested:							
1 to 24 acres		112	47	26	185	417	95
25 to 99 acres		45	15	22	210	154	43
100 to 249 acres		9	1	1	82	34	21
250 to 499 acres		3	-	7	33	6	1
500 to 999 acres		-	-	2	7	-	-
1,000 acres or more		-	-	-	-	-	-
Oats for grain	farms	16	12	5	42	37	14
	acres	997	534	153	1,138	2,094	945
	bushels	62,085	38,253	11,520	70,208	154,236	116,718
Irrigated	farms	-	1	-	-	6	-
	acres	-	(D)	-	-	636	-
Farms by acres harvested:							
1 to 24 acres		6	5	2	32	14	10
25 to 99 acres		1	7	3	10	14	-
100 to 249 acres		9	-	-	-	9	4
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Sorghum for grain	farms	-	-	-	-	1	-
	acres	-	-	-	-	(D)	-
	bushels	-	-	-	-	(D)	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	1	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Soybeans for beans	farms	83	298	197	376	369	458
	acres	11,080	101,160	148,655	45,868	73,396	140,040
	bushels	520,912	5,872,100	5,701,794	2,695,843	3,776,548	6,624,270

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Soybeans for beans - Con.						
Irrigated	farms	892	-	1	11	-
	acres	122,734	-	(D)	842	-
Farms by acres harvested:						
1 to 24 acres		2,307	4	2	11	17
25 to 99 acres		7,345	16	18	49	33
100 to 249 acres		6,879	7	4	52	29
250 to 499 acres		4,297	1	-	22	3
500 to 999 acres		2,864	-	2	20	6
1,000 acres or more		1,645	1	1	28	2
Sugarbeets for sugar	farms	1,106	-	-	14	-
	acres	446,627	-	-	5,503	-
	tons	11,642,041	-	-	164,645	-
Irrigated	farms	31	-	-	-	-
	acres	10,798	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		35	-	-	1	-
25 to 99 acres		158	-	-	-	-
100 to 249 acres		312	-	-	8	-
250 to 499 acres		281	-	-	1	-
500 to 999 acres		238	-	-	2	-
1,000 acres or more		82	-	-	2	-
Sunflower seed, all	farms	221	1	-	1	-
	acres	66,924	(D)	-	(D)	-
	pounds	151,726,117	(D)	-	(D)	-
Irrigated	farms	2	-	-	-	-
	acres	(D)	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		8	1	-	-	-
25 to 99 acres		53	-	-	-	-
100 to 249 acres		62	-	-	-	-
250 to 499 acres		49	-	-	1	-
500 to 999 acres		44	-	-	-	-
1,000 acres or more		5	-	-	-	-
Wheat for grain, all	farms	3,669	1	-	99	25
	acres	1,268,681	(D)	-	23,468	9,873
	bushels	82,039,945	(D)	-	1,521,552	505,116
Irrigated	farms	52	-	-	1	2
	acres	6,251	-	-	(D)	(D)
Farms by acres harvested:						
1 to 24 acres		416	1	-	3	1
25 to 99 acres		1,023	-	-	27	6
100 to 249 acres		809	-	-	38	9
250 to 499 acres		544	-	-	21	3
500 to 999 acres		557	-	-	7	4
1,000 acres or more		320	-	-	3	2
Vegetables harvested for sale	farms	2,620	27	38	16	24
	acres	205,632	53	1,757	(D)	27
Farms by acres harvested:						
0.1 to 4.9 acres		1,339	26	25	13	24
5.0 to 24.9 acres		235	1	7	-	-
25.0 to 99.9 acres		476	-	4	-	-
100.0 to 249.9 acres		369	-	-	1	-
250.0 to 499.9 acres		141	-	1	1	-
500.0 acres or more		60	-	1	1	-
500.0 to 749.9 acres		24	-	-	-	-
750.0 to 999.9 acres		16	-	-	-	-
1,000.0 acres or more		20	-	1	1	-
Land in orchards	farms	1,174	13	11	21	10
	acres	5,049	31	28	37	9
Irrigated	farms	204	3	1	1	3
	acres	778	(D)	(D)	(D)	(D)
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres		927	11	11	18	9
5.0 to 24.9 acres		212	2	-	3	1
25.0 to 99.9 acres		32	-	-	-	-
100.0 to 249.9 acres		3	-	-	-	-
250.0 to 499.9 acres		-	-	-	-	-
500.0 acres or more		-	-	-	-	-
500.0 to 749.9 acres		-	-	-	-	-
750.0 to 999.9 acres		-	-	-	-	-
1,000.0 acres or more		-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Soybeans for beans - Con.						
Irrigated	farms	17	7	3	15	-
	acres	1,462	706	(D)	1,076	-
Farms by acres harvested:						
1 to 24 acres		35	6	42	37	-
25 to 99 acres		121	51	132	202	2
100 to 249 acres		54	55	183	225	-
250 to 499 acres		22	53	114	113	-
500 to 999 acres		-	42	60	22	-
1,000 acres or more		3	31	69	6	-
Sugarbeets for sugar	farms	-	2	-	1	-
	acres	-	(D)	-	(D)	-
	tons	-	(D)	-	(D)	-
Irrigated	farms	-	-	-	-	-
	acres	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		-	-	-	-	-
25 to 99 acres		-	-	-	-	-
100 to 249 acres		-	2	-	1	-
250 to 499 acres		-	-	-	-	-
500 to 999 acres		-	-	-	-	-
1,000 acres or more		-	-	-	-	-
Sunflower seed, all	farms	-	-	-	-	1
	acres	-	-	-	-	(D)
	pounds	-	-	-	-	(D)
Irrigated	farms	-	-	-	-	-
	acres	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres		-	-	-	-	1
25 to 99 acres		-	-	-	-	-
100 to 249 acres		-	-	-	-	-
250 to 499 acres		-	-	-	-	-
500 to 999 acres		-	-	-	-	-
1,000 acres or more		-	-	-	-	-
Wheat for grain, all	farms	12	41	6	27	3
	acres	206	2,492	102	930	(D)
	bushels	9,327	133,362	5,951	44,762	505
Irrigated	farms	-	-	-	1	-
	acres	-	-	-	(D)	-
Farms by acres harvested:						
1 to 24 acres		8	13	6	12	3
25 to 99 acres		4	23	-	12	-
100 to 249 acres		-	3	-	3	-
250 to 499 acres		-	2	-	-	-
500 to 999 acres		-	-	-	-	-
1,000 acres or more		-	-	-	-	-
Vegetables harvested for sale	farms	20	4	39	31	25
	acres	4,158	15	1,355	3,248	45
Farms by acres harvested:						
0.1 to 4.9 acres		13	3	17	1	23
5.0 to 24.9 acres		-	1	8	3	2
25.0 to 99.9 acres		2	-	12	19	-
100.0 to 249.9 acres		-	-	1	6	-
250.0 to 499.9 acres		2	-	-	1	-
500.0 acres or more		3	-	1	1	-
500.0 to 749.9 acres		2	-	1	-	-
750.0 to 999.9 acres		-	-	-	1	-
1,000.0 acres or more		1	-	-	-	-
Land in orchards	farms	7	2	29	4	11
	acres	12	(D)	76	26	21
Irrigated	farms	3	-	-	-	-
	acres	6	-	-	-	-
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres		7	2	26	3	8
5.0 to 24.9 acres		-	-	3	1	3
25.0 to 99.9 acres		-	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-
250.0 to 499.9 acres		-	-	-	-	-
500.0 acres or more		-	-	-	-	-
500.0 to 749.9 acres		-	-	-	-	-
750.0 to 999.9 acres		-	-	-	-	-
1,000.0 acres or more		-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Soybeans for beans - Con.						
Irrigated ..... farms	-	-	2	2	6	2
acres	-	-	(D)	(D)	461	(D)
Farms by acres harvested:						
1 to 24 acres	22	8	17	44	18	2
25 to 99 acres	97	4	68	72	37	19
100 to 249 acres	48	4	85	34	75	11
250 to 499 acres	38	-	74	13	51	8
500 to 999 acres	14	1	42	8	71	5
1,000 acres or more	10	-	19	2	61	2
Sugarbeets for sugar ..... farms	-	-	89	-	70	-
acres	-	-	29,626	-	39,558	-
tons	-	-	818,710	-	1,073,071	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	1	-	-	-
25 to 99 acres	-	-	15	-	11	-
100 to 249 acres	-	-	22	-	10	-
250 to 499 acres	-	-	28	-	20	-
500 to 999 acres	-	-	23	-	14	-
1,000 acres or more	-	-	-	-	15	-
Sunflower seed, all ..... farms	-	-	-	-	22	1
acres	-	-	-	-	8,598	(D)
pounds	-	-	-	-	22,687,794	(D)
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	1	-
25 to 99 acres	-	-	-	-	3	-
100 to 249 acres	-	-	-	-	4	1
250 to 499 acres	-	-	-	-	7	-
500 to 999 acres	-	-	-	-	6	-
1,000 acres or more	-	-	-	-	1	-
Wheat for grain, all ..... farms	22	10	25	4	199	19
acres	537	705	1,164	141	65,878	3,402
bushels	18,676	23,855	47,916	(D)	4,108,121	187,283
Irrigated ..... farms	-	-	-	-	10	-
acres	-	-	-	-	582	-
Farms by acres harvested:						
1 to 24 acres	11	-	9	3	13	-
25 to 99 acres	11	7	15	-	35	7
100 to 249 acres	-	3	1	1	62	9
250 to 499 acres	-	-	-	-	54	2
500 to 999 acres	-	-	-	-	21	1
1,000 acres or more	-	-	-	-	14	-
Vegetables harvested for sale ..... farms	26	14	17	37	26	21
acres	83	(D)	2,082	73	1,828	1,421
Farms by acres harvested:						
0.1 to 4.9 acres	17	12	5	35	18	14
5.0 to 24.9 acres	9	1	3	2	3	3
25.0 to 99.9 acres	-	-	2	-	1	-
100.0 to 249.9 acres	-	-	5	-	-	-
250.0 to 499.9 acres	-	-	1	-	3	4
500.0 acres or more	-	1	1	-	1	-
500.0 to 749.9 acres	-	1	-	-	1	-
750.0 to 999.9 acres	-	-	1	-	-	-
1,000.0 acres or more	-	-	-	-	-	-
Land in orchards ..... farms	24	23	13	38	13	-
acres	173	22	46	186	15	-
Irrigated ..... farms	6	7	2	10	-	-
acres	9	9	(D)	27	-	-
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	17	23	9	21	13	-
5.0 to 24.9 acres	6	-	4	16	-	-
25.0 to 99.9 acres	1	-	-	1	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Soybeans for beans - Con.						
Irrigated ..... farms	-	3	3	96	6	10
acres	-	87	1,140	11,491	364	906
Farms by acres harvested:						
1 to 24 acres	-	25	4	64	23	65
25 to 99 acres	-	76	9	108	58	131
100 to 249 acres	-	141	7	88	60	93
250 to 499 acres	-	80	3	44	43	45
500 to 999 acres	-	77	6	17	40	26
1,000 acres or more	-	39	-	5	31	11
Sugarbeets for sugar ..... farms	-	1	-	-	-	6
acres	-	(D)	-	-	-	3,780
tons	-	(D)	-	-	-	98,280
Irrigated ..... farms	-	-	-	-	-	6
acres	-	-	-	-	-	1,596
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	1	-	-	-	-
500 to 999 acres	-	-	-	-	-	6
1,000 acres or more	-	-	-	-	-	-
Sunflower seed, all ..... farms	1	-	9	-	-	-
acres	(D)	-	1,632	-	-	-
pounds	(D)	-	2,358,000	-	-	-
Irrigated ..... farms	1	-	-	-	-	-
acres	(D)	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	1	-	-	-	-	-
25 to 99 acres	-	-	3	-	-	-
100 to 249 acres	-	-	6	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Wheat for grain, all ..... farms	-	14	3	18	2	73
acres	-	922	474	646	(D)	5,821
bushels	-	42,551	22,260	22,225	(D)	266,592
Irrigated ..... farms	-	-	-	3	-	-
acres	-	-	-	(D)	-	-
Farms by acres harvested:						
1 to 24 acres	-	2	-	9	-	12
25 to 99 acres	-	8	-	8	2	40
100 to 249 acres	-	4	3	1	-	20
250 to 499 acres	-	-	-	-	-	1
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Vegetables harvested for sale ..... farms	9	6	26	176	27	22
acres	8	462	58	18,755	4,619	116
Farms by acres harvested:						
0.1 to 4.9 acres	9	3	24	63	3	17
5.0 to 24.9 acres	-	-	2	18	4	3
25.0 to 99.9 acres	-	-	-	26	6	2
100.0 to 249.9 acres	-	3	-	47	10	-
250.0 to 499.9 acres	-	-	-	19	2	-
500.0 acres or more	-	-	-	3	2	-
500.0 to 749.9 acres	-	-	-	-	1	-
750.0 to 999.9 acres	-	-	-	3	-	-
1,000.0 acres or more	-	-	-	-	1	-
Land in orchards ..... farms	2	4	15	35	8	22
acres	(D)	4	26	198	9	98
Irrigated ..... farms	1	-	1	9	-	4
acres	(D)	-	(D)	28	-	31
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	2	4	13	22	8	17
5.0 to 24.9 acres	-	-	2	11	-	5
25.0 to 99.9 acres	-	-	-	2	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Soybeans for beans - Con.						
Irrigated ..... farms	3	1	11	9	24	1
acres	358	(D)	1,267	565	3,190	(D)
Farms by acres harvested:						
1 to 24 acres	51	54	34	88	8	15
25 to 99 acres	117	209	118	253	49	30
100 to 249 acres	171	107	148	158	51	13
250 to 499 acres	120	82	95	75	38	9
500 to 999 acres	66	34	55	33	35	1
1,000 acres or more	27	27	22	15	41	-
Sugarbeets for sugar ..... farms	-	-	-	-	16	-
acres	-	-	-	-	8,337	-
tons	-	-	-	-	191,836	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	3	-
100 to 249 acres	-	-	-	-	1	-
250 to 499 acres	-	-	-	-	7	-
500 to 999 acres	-	-	-	-	3	-
1,000 acres or more	-	-	-	-	2	-
Sunflower seed, all ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
pounds	-	-	-	-	-	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Wheat for grain, all ..... farms	1	6	3	24	43	5
acres	(D)	619	(D)	931	7,963	113
bushels	(D)	27,912	(D)	38,626	471,155	4,500
Irrigated ..... farms	-	-	-	1	1	-
acres	-	-	-	(D)	(D)	-
Farms by acres harvested:						
1 to 24 acres	-	1	2	6	3	2
25 to 99 acres	1	4	-	17	14	3
100 to 249 acres	-	-	1	1	16	-
250 to 499 acres	-	1	-	-	8	-
500 to 999 acres	-	-	-	-	2	-
1,000 acres or more	-	-	-	-	-	-
Vegetables harvested for sale ..... farms	45	52	35	60	3	79
acres	4,571	965	5,675	3,560	(D)	391
Farms by acres harvested:						
0.1 to 4.9 acres	3	40	2	19	3	62
5.0 to 24.9 acres	2	6	6	2	-	13
25.0 to 99.9 acres	28	4	15	26	-	4
100.0 to 249.9 acres	9	1	9	13	-	-
250.0 to 499.9 acres	2	1	1	-	-	-
500.0 acres or more	1	-	2	-	-	-
500.0 to 749.9 acres	1	-	1	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	1	-	-	-
Land in orchards ..... farms	2	28	9	34	1	55
acres	(D)	155	22	164	(D)	118
Irrigated ..... farms	-	2	-	3	-	9
acres	-	(D)	-	11	-	4
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	2	24	7	22	-	52
5.0 to 24.9 acres	-	1	2	11	1	2
25.0 to 99.9 acres	-	3	-	1	-	1
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Soybeans for beans - Con.						
Irrigated ..... farms	7	3	11	-	7	-
acres	314	1,065	739	-	1,059	-
Farms by acres harvested:						
1 to 24 acres	53	3	48	2	23	17
25 to 99 acres	115	3	56	9	137	27
100 to 249 acres	34	3	34	4	174	18
250 to 499 acres	26	-	13	3	104	16
500 to 999 acres	7	2	6	5	82	-
1,000 acres or more	1	-	3	-	25	3
Sugarbeets for sugar ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
tons	-	-	-	-	-	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Sunflower seed, all ..... farms	-	3	-	-	-	6
acres	-	25	-	-	-	246
pounds	-	29,800	-	-	-	486,000
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	3	-	-	-	-
25 to 99 acres	-	-	-	-	-	6
100 to 249 acres	-	-	-	-	-	-
250 to 499 acres	-	-	-	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Wheat for grain, all ..... farms	7	6	7	1	7	15
acres	309	314	680	(D)	250	2,243
bushels	18,202	10,275	22,654	(D)	13,405	44,104
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	2	2	-	-	1	1
25 to 99 acres	5	3	4	-	6	6
100 to 249 acres	-	1	2	-	-	7
250 to 499 acres	-	-	1	-	-	1
500 to 999 acres	-	-	-	1	-	-
1,000 acres or more	-	-	-	-	-	-
Vegetables harvested for sale ..... farms	6	12	29	33	3	32
acres	(D)	(D)	82	318	(D)	69
Farms by acres harvested:						
0.1 to 4.9 acres	5	11	20	27	3	29
5.0 to 24.9 acres	-	-	9	3	-	3
25.0 to 99.9 acres	-	-	-	3	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	1	1	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	1	1	-	-	-	-
Land in orchards ..... farms	8	10	23	8	2	11
acres	121	41	72	7	(D)	56
Irrigated ..... farms	1	1	3	6	1	5
acres	(D)	(D)	4	(D)	(D)	24
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	5	8	19	8	1	7
5.0 to 24.9 acres	1	2	4	-	1	4
25.0 to 99.9 acres	2	-	-	-	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Soybeans for beans - Con.						
Irrigated ..... farms	20	1	-	12	-	-
acres	3,234	(D)	-	2,272	-	-
Farms by acres harvested:						
1 to 24 acres	49	8	1	25	-	9
25 to 99 acres	95	22	3	99	-	8
100 to 249 acres	110	40	3	120	-	9
250 to 499 acres	67	35	10	90	-	12
500 to 999 acres	72	60	-	72	-	4
1,000 acres or more	23	48	2	40	-	8
Sugarbeets for sugar ..... farms	31	90	-	2	-	-
acres	17,441	30,086	-	(D)	-	-
tons	494,986	865,108	-	(D)	-	-
Irrigated ..... farms	1	-	-	1	-	-
acres	(D)	-	-	(D)	-	-
Farms by acres harvested:						
1 to 24 acres	2	-	-	-	-	-
25 to 99 acres	4	13	-	-	-	-
100 to 249 acres	3	29	-	-	-	-
250 to 499 acres	6	35	-	2	-	-
500 to 999 acres	14	11	-	-	-	-
1,000 acres or more	2	2	-	-	-	-
Sunflower seed, all ..... farms	-	24	-	1	-	4
acres	-	9,401	-	(D)	-	2,037
pounds	-	20,588,806	-	(D)	-	4,074,592
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	2	-	-	-	1
100 to 249 acres	-	9	-	-	-	-
250 to 499 acres	-	8	-	1	-	-
500 to 999 acres	-	4	-	-	-	2
1,000 acres or more	-	1	-	-	-	1
Wheat for grain, all ..... farms	38	214	7	22	-	20
acres	2,963	170,257	1,308	970	-	11,175
bushels	140,190	11,514,162	79,500	45,939	-	725,625
Irrigated ..... farms	-	1	-	2	-	-
acres	-	(D)	-	(D)	-	-
Farms by acres harvested:						
1 to 24 acres	7	12	-	10	-	3
25 to 99 acres	21	5	-	10	-	2
100 to 249 acres	10	37	6	2	-	3
250 to 499 acres	-	22	1	-	-	4
500 to 999 acres	-	77	-	-	-	3
1,000 acres or more	-	61	-	-	-	5
Vegetables harvested for sale ..... farms	49	4	1	2	8	2
acres	9,583	1,308	(D)	(D)	10	(D)
Farms by acres harvested:						
0.1 to 4.9 acres	9	-	1	2	8	-
5.0 to 24.9 acres	3	-	-	-	-	1
25.0 to 99.9 acres	6	1	-	-	-	-
100.0 to 249.9 acres	20	-	-	-	-	-
250.0 to 499.9 acres	6	2	-	-	-	-
500.0 acres or more	5	1	-	-	-	1
500.0 to 749.9 acres	3	-	-	-	-	1
750.0 to 999.9 acres	-	1	-	-	-	-
1,000.0 acres or more	2	-	-	-	-	-
Land in orchards ..... farms	19	-	-	3	5	2
acres	44	-	-	23	7	(D)
Irrigated ..... farms	1	-	-	1	-	-
acres	(D)	-	-	(D)	-	-
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	17	-	-	1	5	2
5.0 to 24.9 acres	2	-	-	2	-	-
25.0 to 99.9 acres	-	-	-	-	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Soybeans for beans - Con.						
Irrigated ..... farms	7	1	7	1	-	4
acres	1,175	(D)	1,338	(D)	-	1,740
Farms by acres harvested:						
1 to 24 acres	43	11	18	46	4	2
25 to 99 acres	128	92	116	129	29	79
100 to 249 acres	87	84	152	63	24	105
250 to 499 acres	39	51	167	47	47	106
500 to 999 acres	22	26	62	40	25	115
1,000 acres or more	17	7	18	20	12	67
Sugarbeets for sugar ..... farms	-	-	1	1	13	126
acres	-	-	(D)	(D)	2,859	49,535
tons	-	-	(D)	(D)	79,311	1,341,709
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	3
25 to 99 acres	-	-	-	-	-	26
100 to 249 acres	-	-	-	-	12	38
250 to 499 acres	-	-	1	-	1	23
500 to 999 acres	-	-	-	1	-	27
1,000 acres or more	-	-	-	-	-	9
Sunflower seed, all ..... farms	-	-	-	-	2	39
acres	-	-	-	-	(D)	13,662
pounds	-	-	-	-	(D)	31,458,017
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	-	5
100 to 249 acres	-	-	-	-	-	13
250 to 499 acres	-	-	-	-	-	10
500 to 999 acres	-	-	-	-	2	11
1,000 acres or more	-	-	-	-	-	-
Wheat for grain, all ..... farms	20	32	22	26	93	404
acres	1,017	1,977	1,363	984	32,220	217,709
bushels	63,906	103,898	80,045	51,869	2,208,782	13,634,836
Irrigated ..... farms	-	-	-	-	-	2
acres	-	-	-	-	-	(D)
Farms by acres harvested:						
1 to 24 acres	4	14	5	12	-	-
25 to 99 acres	15	12	13	11	18	67
100 to 249 acres	1	5	4	3	30	84
250 to 499 acres	-	1	-	-	31	96
500 to 999 acres	-	-	-	-	11	94
1,000 acres or more	-	-	-	-	3	63
Vegetables harvested for sale ..... farms	15	6	1	43	4	9
acres	1,296	2	(D)	2,866	(D)	367
Farms by acres harvested:						
0.1 to 4.9 acres	3	6	1	18	4	4
5.0 to 24.9 acres	-	-	-	7	-	1
25.0 to 99.9 acres	8	-	-	7	-	4
100.0 to 249.9 acres	3	-	-	9	-	-
250.0 to 499.9 acres	1	-	-	1	-	-
500.0 acres or more	-	-	-	1	-	-
500.0 to 749.9 acres	-	-	-	1	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-
Land in orchards ..... farms	8	8	1	14	-	-
acres	66	45	(D)	59	-	-
Irrigated ..... farms	1	3	-	3	-	-
acres	(D)	30	-	7	-	-
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	5	5	1	12	-	-
5.0 to 24.9 acres	2	3	-	1	-	-
25.0 to 99.9 acres	1	-	-	1	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Soybeans for beans - Con.							
Irrigated	farms	-	21	2	51	14	-
	acres	-	1,788	(D)	4,348	1,876	-
Farms by acres harvested:							
1 to 24 acres		27	31	23	73	31	30
25 to 99 acres		112	120	50	186	130	122
100 to 249 acres		168	84	31	78	170	147
250 to 499 acres		94	43	17	13	66	112
500 to 999 acres		89	36	4	10	62	61
1,000 acres or more		43	26	1	1	21	19
Sugarbeets for sugar	farms	-	2	-	-	-	-
	acres	-	(D)	-	-	-	-
	tons	-	(D)	-	-	-	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	1	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	1	-	-	-	-
Sunflower seed, all	farms	-	-	3	4	3	-
	acres	-	-	72	230	144	-
	pounds	-	-	17,900	460,000	270,000	-
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	1	-	-	-
25 to 99 acres		-	-	2	4	3	-
100 to 249 acres		-	-	-	-	-	-
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Wheat for grain, all	farms	2	13	10	19	8	4
	acres	(D)	513	435	1,764	376	286
	bushels	(D)	24,196	10,650	42,079	18,044	15,317
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	4	1	1	5	-
25 to 99 acres		2	9	9	9	1	3
100 to 249 acres		-	-	-	9	2	1
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Vegetables harvested for sale	farms	41	36	19	18	79	7
	acres	3,384	2,824	82	3,653	11,790	34
Farms by acres harvested:							
0.1 to 4.9 acres		2	28	15	10	11	2
5.0 to 24.9 acres		1	-	4	2	2	5
25.0 to 99.9 acres		25	1	-	1	22	-
100.0 to 249.9 acres		12	3	-	3	25	-
250.0 to 499.9 acres		1	3	-	-	18	-
500.0 acres or more		-	1	-	2	1	-
500.0 to 749.9 acres		-	-	-	-	-	-
750.0 to 999.9 acres		-	-	-	-	1	-
1,000.0 acres or more		-	1	-	2	-	-
Land in orchards	farms	2	26	13	11	13	2
	acres	(D)	56	58	19	48	(D)
Irrigated	farms	-	12	1	4	-	-
	acres	-	4	(D)	4	-	-
Farms by bearing and nonbearing acres:							
0.1 to 4.9 acres		1	21	8	10	11	2
5.0 to 24.9 acres		1	5	5	1	2	-
25.0 to 99.9 acres		-	-	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-	-
250.0 to 499.9 acres		-	-	-	-	-	-
500.0 acres or more		-	-	-	-	-	-
500.0 to 749.9 acres		-	-	-	-	-	-
750.0 to 999.9 acres		-	-	-	-	-	-
1,000.0 acres or more		-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Soybeans for beans - Con.						
Irrigated ..... farms	1	3	2	8	114	-
acres	(D)	222	(D)	439	14,449	-
Farms by acres harvested:						
1 to 24 acres	46	22	13	71	76	3
25 to 99 acres	119	152	20	131	226	22
100 to 249 acres	128	225	43	114	198	13
250 to 499 acres	49	118	56	54	109	32
500 to 999 acres	25	47	62	27	62	17
1,000 acres or more	36	22	68	10	22	37
Sugarbeets for sugar ..... farms	1	-	86	-	3	1
acres	(D)	-	39,058	-	978	(D)
tons	(D)	-	1,003,105	-	23,116	(D)
Irrigated ..... farms	-	-	2	-	1	-
acres	-	-	(D)	-	(D)	-
Farms by acres harvested:						
1 to 24 acres	-	-	4	-	-	-
25 to 99 acres	1	-	9	-	2	-
100 to 249 acres	-	-	23	-	-	-
250 to 499 acres	-	-	26	-	-	1
500 to 999 acres	-	-	17	-	1	-
1,000 acres or more	-	-	7	-	-	-
Sunflower seed, all ..... farms	-	-	12	-	6	4
acres	-	-	3,678	-	411	934
pounds	-	-	8,564,000	-	806,550	1,680,000
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	3	-	4	-
100 to 249 acres	-	-	2	-	2	3
250 to 499 acres	-	-	5	-	-	1
500 to 999 acres	-	-	2	-	-	-
1,000 acres or more	-	-	-	-	-	-
Wheat for grain, all ..... farms	22	5	203	4	176	100
acres	629	515	101,089	84	20,131	57,079
bushels	40,127	40,545	6,851,314	4,900	992,388	3,373,899
Irrigated ..... farms	-	-	1	-	8	-
acres	-	-	(D)	-	1,348	-
Farms by acres harvested:						
1 to 24 acres	6	1	4	2	33	1
25 to 99 acres	16	1	29	2	90	7
100 to 249 acres	-	3	49	-	30	31
250 to 499 acres	-	-	47	-	19	18
500 to 999 acres	-	-	43	-	3	23
1,000 acres or more	-	-	31	-	1	20
Vegetables harvested for sale ..... farms	28	3	9	128	44	6
acres	980	12	118	10,570	(D)	17
Farms by acres harvested:						
0.1 to 4.9 acres	18	2	6	33	28	5
5.0 to 24.9 acres	-	1	-	6	13	1
25.0 to 99.9 acres	6	-	3	53	1	-
100.0 to 249.9 acres	4	-	-	29	-	-
250.0 to 499.9 acres	-	-	-	5	-	-
500.0 acres or more	-	-	-	2	2	-
500.0 to 749.9 acres	-	-	-	1	-	-
750.0 to 999.9 acres	-	-	-	1	-	-
1,000.0 acres or more	-	-	-	-	2	-
Land in orchards ..... farms	6	3	2	41	38	11
acres	3	(D)	(D)	141	91	23
Irrigated ..... farms	2	-	-	2	7	-
acres	(D)	-	-	(D)	18	-
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	6	2	2	32	34	9
5.0 to 24.9 acres	-	1	-	8	4	2
25.0 to 99.9 acres	-	-	-	1	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Soybeans for beans - Con.						
Irrigated ..... farms	-	4	6	47	-	3
acres	-	992	3,634	6,674	-	396
Farms by acres harvested:						
1 to 24 acres	19	17	11	27	-	6
25 to 99 acres	33	65	92	85	-	14
100 to 249 acres	25	113	115	97	-	54
250 to 499 acres	8	48	117	40	-	38
500 to 999 acres	4	26	158	43	-	29
1,000 acres or more	1	14	87	12	-	11
Sugarbeets for sugar ..... farms	-	-	249	4	-	2
acres	-	-	96,745	418	-	(D)
tons	-	-	2,452,048	11,960	-	(D)
Irrigated ..... farms	-	-	1	-	-	-
acres	-	-	(D)	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	12	-	-	-
25 to 99 acres	-	-	42	3	-	-
100 to 249 acres	-	-	57	-	-	1
250 to 499 acres	-	-	57	1	-	-
500 to 999 acres	-	-	66	-	-	1
1,000 acres or more	-	-	15	-	-	-
Sunflower seed, all ..... farms	-	1	25	-	-	5
acres	-	(D)	7,106	-	-	1,288
pounds	-	(D)	16,952,154	-	-	2,659,200
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	1	3	-	-	2
100 to 249 acres	-	-	12	-	-	1
250 to 499 acres	-	-	6	-	-	2
500 to 999 acres	-	-	3	-	-	-
1,000 acres or more	-	-	1	-	-	-
Wheat for grain, all ..... farms	8	7	531	47	1	140
acres	349	486	278,518	3,192	(D)	55,005
bushels	13,565	19,920	20,189,206	140,742	(D)	3,470,736
Irrigated ..... farms	-	-	1	4	1	1
acres	-	-	(D)	171	(D)	(D)
Farms by acres harvested:						
1 to 24 acres	1	2	12	7	1	6
25 to 99 acres	7	4	77	27	-	37
100 to 249 acres	-	-	117	12	-	32
250 to 499 acres	-	1	89	1	-	26
500 to 999 acres	-	-	163	-	-	28
1,000 acres or more	-	-	73	-	-	11
Vegetables harvested for sale ..... farms	20	4	27	18	29	-
acres	52	(D)	5,237	4,399	49	-
Farms by acres harvested:						
0.1 to 4.9 acres	18	3	15	4	28	-
5.0 to 24.9 acres	1	1	-	-	1	-
25.0 to 99.9 acres	1	-	1	3	-	-
100.0 to 249.9 acres	-	-	-	4	-	-
250.0 to 499.9 acres	-	-	8	6	-	-
500.0 acres or more	-	-	3	1	-	-
500.0 to 749.9 acres	-	-	2	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	1	1	-	-
Land in orchards ..... farms	31	-	5	6	-	-
acres	59	-	9	5	-	-
Irrigated ..... farms	4	-	-	-	-	-
acres	2	-	-	-	-	-
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	27	-	5	6	-	-
5.0 to 24.9 acres	4	-	-	-	-	-
25.0 to 99.9 acres	-	-	-	-	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
Soybeans for beans - Con.						
Irrigated ..... farms	2	1	1	1	-	-
acres	(D)	(D)	(D)	(D)	-	-
Farms by acres harvested:						
1 to 24 acres	41	27	56	10	7	-
25 to 99 acres	176	132	170	71	51	-
100 to 249 acres	307	131	121	118	47	-
250 to 499 acres	203	163	34	70	43	2
500 to 999 acres	91	78	26	32	48	-
1,000 acres or more	29	48	19	19	42	-
Sugarbeets for sugar ..... farms	33	87	-	-	2	-
acres	6,901	35,122	-	-	(D)	-
tons	174,072	894,561	-	-	(D)	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	12	-	-	-	-	-
25 to 99 acres	1	19	-	-	-	-
100 to 249 acres	8	24	-	-	2	-
250 to 499 acres	11	27	-	-	-	-
500 to 999 acres	1	9	-	-	-	-
1,000 acres or more	-	8	-	-	-	-
Sunflower seed, all ..... farms	-	-	-	1	20	-
acres	-	-	-	(D)	8,098	-
pounds	-	-	-	(D)	19,033,933	-
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	5	-
100 to 249 acres	-	-	-	-	4	-
250 to 499 acres	-	-	-	-	3	-
500 to 999 acres	-	-	-	1	7	-
1,000 acres or more	-	-	-	-	1	-
Wheat for grain, all ..... farms	17	45	13	2	187	5
acres	506	3,050	368	(D)	89,637	64
bushels	24,819	175,764	20,706	(D)	5,754,165	1,683
Irrigated ..... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	8	15	9	-	-	5
25 to 99 acres	9	27	3	2	34	-
100 to 249 acres	-	2	1	-	46	-
250 to 499 acres	-	-	-	-	41	-
500 to 999 acres	-	-	-	-	43	-
1,000 acres or more	-	1	-	-	23	-
Vegetables harvested for sale ..... farms	20	152	44	11	3	76
acres	2,910	25,545	683	17	8	114
Farms by acres harvested:						
0.1 to 4.9 acres	6	9	31	11	3	73
5.0 to 24.9 acres	-	1	7	-	-	3
25.0 to 99.9 acres	2	53	4	-	-	-
100.0 to 249.9 acres	11	64	2	-	-	-
250.0 to 499.9 acres	-	21	-	-	-	-
500.0 acres or more	1	4	-	-	-	-
500.0 to 749.9 acres	-	1	-	-	-	-
750.0 to 999.9 acres	1	1	-	-	-	-
1,000.0 acres or more	-	2	-	-	-	-
Land in orchards ..... farms	10	8	37	-	1	46
acres	13	16	276	-	(D)	67
Irrigated ..... farms	4	-	5	-	-	2
acres	4	-	21	-	-	(D)
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	10	6	29	-	1	40
5.0 to 24.9 acres	-	2	4	-	-	6
25.0 to 99.9 acres	-	-	4	-	-	-
100.0 to 249.9 acres	-	-	-	-	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Soybeans for beans - Con.							
Irrigated	farms	-	26	1	97	5	18
	acres	-	8,629	(D)	8,983	918	2,632
Farms by acres harvested:							
1 to 24 acres		17	16	46	121	18	6
25 to 99 acres		73	21	143	426	93	32
100 to 249 acres		31	18	119	231	77	47
250 to 499 acres		11	11	84	56	32	45
500 to 999 acres		20	6	40	32	42	60
1,000 acres or more		6	1	35	10	18	22
Sugarbeets for sugar	farms	-	-	19	12	-	34
	acres	-	-	6,049	10,294	-	10,884
	tons	-	-	150,505	302,794	-	280,943
Irrigated	farms	-	-	-	7	-	6
	acres	-	-	-	5,490	-	780
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	1	-	-	-
100 to 249 acres		-	-	11	5	-	18
250 to 499 acres		-	-	-	-	-	7
500 to 999 acres		-	-	7	-	-	8
1,000 acres or more		-	-	-	7	-	1
Sunflower seed, all	farms	-	-	-	-	-	2
	acres	-	-	-	-	-	(D)
	pounds	-	-	-	-	-	(D)
Irrigated	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Farms by acres harvested:							
1 to 24 acres		-	-	-	-	-	-
25 to 99 acres		-	-	-	-	-	-
100 to 249 acres		-	-	-	-	-	2
250 to 499 acres		-	-	-	-	-	-
500 to 999 acres		-	-	-	-	-	-
1,000 acres or more		-	-	-	-	-	-
Wheat for grain, all	farms	5	3	25	55	14	41
	acres	131	(D)	1,312	2,568	1,017	7,848
	bushels	5,052	3,456	78,957	123,260	53,104	462,844
Irrigated	farms	-	-	-	4	-	1
	acres	-	-	-	568	-	(D)
Farms by acres harvested:							
1 to 24 acres		3	2	10	20	6	2
25 to 99 acres		2	-	8	33	4	22
100 to 249 acres		-	-	7	-	4	8
250 to 499 acres		-	1	-	1	-	2
500 to 999 acres		-	-	-	1	-	7
1,000 acres or more		-	-	-	-	-	-
Vegetables harvested for sale	farms	29	51	53	75	21	9
	acres	182	9,233	5,875	3,503	2,618	3
Farms by acres harvested:							
0.1 to 4.9 acres		22	28	11	48	5	9
5.0 to 24.9 acres		4	2	1	5	2	-
25.0 to 99.9 acres		3	1	16	12	5	-
100.0 to 249.9 acres		-	5	22	7	6	-
250.0 to 499.9 acres		-	11	2	1	3	-
500.0 acres or more		-	4	1	2	-	-
500.0 to 749.9 acres		-	2	-	1	-	-
750.0 to 999.9 acres		-	1	1	1	-	-
1,000.0 acres or more		-	1	-	-	-	-
Land in orchards	farms	34	28	1	35	4	2
	acres	110	47	(D)	103	26	(D)
Irrigated	farms	7	12	-	12	-	-
	acres	20	21	-	25	-	-
Farms by bearing and nonbearing acres:							
0.1 to 4.9 acres		25	26	1	30	2	2
5.0 to 24.9 acres		9	2	-	5	2	-
25.0 to 99.9 acres		-	-	-	-	-	-
100.0 to 249.9 acres		-	-	-	-	-	-
250.0 to 499.9 acres		-	-	-	-	-	-
500.0 acres or more		-	-	-	-	-	-
500.0 to 749.9 acres		-	-	-	-	-	-
750.0 to 999.9 acres		-	-	-	-	-	-
1,000.0 acres or more		-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Soybeans for beans - Con.						
Irrigated ..... farms	43	14	2	4	33	7
acres	7,630	3,390	(D)	272	10,548	860
Farms by acres harvested:						
1 to 24 acres	33	67	-	34	3	20
25 to 99 acres	68	193	20	124	25	80
100 to 249 acres	79	96	40	87	7	113
250 to 499 acres	86	29	48	33	6	49
500 to 999 acres	45	15	48	12	13	31
1,000 acres or more	21	1	40	1	3	33
Sugarbeets for sugar ..... farms	19	-	10	-	-	-
acres	8,256	-	4,248	-	-	-
tons	236,427	-	86,066	-	-	-
Irrigated ..... farms	4	-	-	-	-	-
acres	212	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	9	-	2	-	-	-
250 to 499 acres	3	-	6	-	-	-
500 to 999 acres	4	-	1	-	-	-
1,000 acres or more	3	-	1	-	-	-
Sunflower seed, all ..... farms	-	-	3	-	7	-
acres	-	-	912	-	479	-
pounds	-	-	1,824,000	-	658,014	-
Irrigated ..... farms	-	-	-	-	1	-
acres	-	-	-	-	(D)	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	6	-
100 to 249 acres	-	-	-	-	1	-
250 to 499 acres	-	-	3	-	-	-
500 to 999 acres	-	-	-	-	-	-
1,000 acres or more	-	-	-	-	-	-
Wheat for grain, all ..... farms	22	43	20	3	11	4
acres	1,921	2,712	3,762	110	1,230	100
bushels	93,639	111,215	189,957	7,608	72,238	6,040
Irrigated ..... farms	1	-	-	-	5	-
acres	(D)	-	-	-	855	-
Farms by acres harvested:						
1 to 24 acres	5	10	1	1	3	1
25 to 99 acres	10	26	5	2	4	3
100 to 249 acres	5	5	9	-	1	-
250 to 499 acres	2	2	4	-	3	-
500 to 999 acres	-	-	1	-	-	-
1,000 acres or more	-	-	-	-	-	-
Vegetables harvested for sale ..... farms	8	42	1	72	8	51
acres	859	1,294	(D)	5,495	2,968	3,434
Farms by acres harvested:						
0.1 to 4.9 acres	4	34	1	10	3	14
5.0 to 24.9 acres	-	5	-	12	2	2
25.0 to 99.9 acres	1	1	-	29	-	24
100.0 to 249.9 acres	-	-	-	16	-	10
250.0 to 499.9 acres	3	1	-	4	-	1
500.0 acres or more	-	1	-	1	3	-
500.0 to 749.9 acres	-	-	-	1	1	-
750.0 to 999.9 acres	-	1	-	-	1	-
1,000.0 acres or more	-	-	-	-	1	-
Land in orchards ..... farms	1	24	2	22	3	7
acres	(D)	107	(D)	454	6	28
Irrigated ..... farms	-	3	1	6	-	-
acres	-	9	(D)	(D)	-	-
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	1	20	1	10	3	5
5.0 to 24.9 acres	-	3	1	7	-	2
25.0 to 99.9 acres	-	1	-	4	-	-
100.0 to 249.9 acres	-	-	-	1	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

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Table 24. **Selected Crops Harvested: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Soybeans for beans - Con.						
Irrigated ... farms	2	16	2	-	25	2
acres	(D)	1,313	(D)	-	1,533	(D)
Farms by acres harvested:						
1 to 24 acres	19	25	8	49	58	42
25 to 99 acres	31	56	14	179	156	106
100 to 249 acres	18	79	39	101	93	110
250 to 499 acres	8	70	39	35	30	117
500 to 999 acres	7	46	43	11	13	60
1,000 acres or more	-	22	54	1	19	23
Sugarbeets for sugar ... farms	-	-	71	-	-	8
acres	-	-	33,147	-	-	2,469
tons	-	-	685,888	-	-	62,592
Irrigated ... farms	-	-	2	-	-	-
acres	-	-	(D)	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	6	-	-	2
100 to 249 acres	-	-	24	-	-	1
250 to 499 acres	-	-	13	-	-	4
500 to 999 acres	-	-	21	-	-	1
1,000 acres or more	-	-	7	-	-	-
Sunflower seed, all ... farms	-	-	7	-	-	3
acres	-	-	3,892	-	-	807
pounds	-	-	9,927,600	-	-	1,251,640
Irrigated ... farms	-	-	-	-	-	-
acres	-	-	-	-	-	-
Farms by acres harvested:						
1 to 24 acres	-	-	-	-	-	-
25 to 99 acres	-	-	-	-	-	-
100 to 249 acres	-	-	-	-	-	2
250 to 499 acres	-	-	2	-	-	-
500 to 999 acres	-	-	5	-	-	1
1,000 acres or more	-	-	-	-	-	-
Wheat for grain, all ... farms	8	16	139	4	32	29
acres	237	571	53,565	210	1,653	2,038
bushels	6,836	13,176	3,055,031	7,840	84,564	100,867
Irrigated ... farms	-	-	1	-	-	-
acres	-	-	(D)	-	-	-
Farms by acres harvested:						
1 to 24 acres	5	8	1	1	11	9
25 to 99 acres	3	8	11	2	18	15
100 to 249 acres	-	-	58	1	3	3
250 to 499 acres	-	-	36	-	-	2
500 to 999 acres	-	-	24	-	-	-
1,000 acres or more	-	-	9	-	-	-
Vegetables harvested for sale ... farms	74	25	1	45	58	11
acres	926	3,197	(D)	2,529	878	16
Farms by acres harvested:						
0.1 to 4.9 acres	53	10	1	22	47	11
5.0 to 24.9 acres	16	3	-	-	6	-
25.0 to 99.9 acres	3	4	-	18	3	-
100.0 to 249.9 acres	1	4	-	3	1	-
250.0 to 499.9 acres	1	2	-	2	-	-
500.0 acres or more	-	2	-	-	1	-
500.0 to 749.9 acres	-	1	-	-	1	-
750.0 to 999.9 acres	-	1	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-
Land in orchards ... farms	47	3	-	35	56	2
acres	394	2	-	501	282	(D)
Irrigated ... farms	14	-	-	2	13	-
acres	164	-	-	(D)	78	-
Farms by bearing and nonbearing acres:						
0.1 to 4.9 acres	25	3	-	17	45	2
5.0 to 24.9 acres	19	-	-	14	7	-
25.0 to 99.9 acres	3	-	-	2	4	-
100.0 to 249.9 acres	-	-	-	2	-	-
250.0 to 499.9 acres	-	-	-	-	-	-
500.0 acres or more	-	-	-	-	-	-
500.0 to 749.9 acres	-	-	-	-	-	-
750.0 to 999.9 acres	-	-	-	-	-	-
1,000.0 acres or more	-	-	-	-	-	-

Table 25. **Field Crops: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
AUSTRIAN WINTER PEAS (CWT)										
State Total										
Minnesota	1	(D)	(D)	-	-	-	-	-	-	-
Counties										
Olmsted	1	(D)	(D)	-	-	-	-	-	-	-
BARLEY FOR GRAIN (BUSHELS)										
State Total										
Minnesota	336	55,330	4,011,381	10	116	552	67,521	5,369,559	8	886
Counties										
Becker	1	(D)	(D)	-	-	3	69	5,568	-	-
Beltrami	4	200	12,522	-	-	5	232	15,448	-	-
Benton	2	(D)	(D)	-	-	5	199	12,561	-	-
Blue Earth	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Brown	3	31	2,604	-	-	4	97	5,888	-	-
Carlton	-	-	-	-	-	3	47	2,256	-	-
Carver	2	(D)	(D)	-	-	-	-	-	-	-
Cass	-	-	-	-	-	2	(D)	(D)	1	(D)
Chippewa	-	-	-	-	-	1	(D)	(D)	-	-
Chisago	-	-	-	-	-	1	(D)	(D)	-	-
Clay	4	829	60,664	-	-	6	1,200	103,358	-	-
Clearwater	1	(D)	(D)	-	-	3	92	6,720	-	-
Cottonwood	1	(D)	(D)	-	-	3	36	2,490	-	-
Dakota	4	88	4,050	2	(D)	3	244	12,150	1	(D)
Dodge	-	-	-	-	-	4	184	9,437	-	-
Douglas	-	-	-	-	-	2	(D)	(D)	-	-
Faribault	-	-	-	-	-	3	129	9,073	-	-
Fillmore	5	301	18,300	-	-	6	226	19,175	-	-
Freeborn	3	124	5,878	-	-	4	61	2,886	-	-
Goodhue	3	(D)	(D)	1	(D)	8	396	25,384	-	-
Grant	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Hennepin	-	-	-	-	-	3	5	116	-	-
Houston	1	(D)	(D)	-	-	3	40	1,360	-	-
Hubbard	2	(D)	(D)	-	-	-	-	-	-	-
Itasca	1	(D)	(D)	-	-	3	10	332	-	-
Jackson	-	-	-	-	-	2	(D)	(D)	-	-
Kanabec	-	-	-	-	-	3	20	1,800	-	-
Kandiyohi	1	(D)	(D)	-	-	4	116	6,455	1	(D)
Kittson	14	3,452	291,930	-	-	15	3,251	284,900	-	-
Koochiching	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Lac qui Parle	2	(D)	(D)	-	-	7	142	3,660	-	-
Lake of the Woods	10	2,807	196,425	-	-	3	1,328	122,640	-	-
Le Sueur	-	-	-	-	-	2	(D)	(D)	-	-
Lincoln	-	-	-	-	-	1	(D)	(D)	-	-
Lyon	-	-	-	-	-	2	(D)	(D)	-	-
McLeod	-	-	-	-	-	3	50	2,840	-	-
Mahnomen	13	2,787	224,371	-	-	2	(D)	(D)	-	-
Marshall	49	13,099	934,242	-	-	60	16,770	1,436,587	-	-
Martin	-	-	-	-	-	2	(D)	(D)	-	-
Meeker	3	325	24,528	-	-	5	308	21,603	-	-
Mille Lacs	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Morrison	3	144	8,900	-	-	15	236	12,004	-	-
Mower	3	(D)	(D)	-	-	6	349	17,414	-	-
Murray	3	68	3,600	-	-	1	(D)	(D)	-	-
Nicollet	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Norman	18	4,648	405,295	-	-	22	4,963	419,928	-	-
Olmsted	-	-	-	-	-	8	108	5,039	-	-
Otter Tail	11	1,398	100,821	-	-	16	1,115	84,118	3	(D)
Pennington	16	5,630	415,080	-	-	23	6,448	595,022	-	-
Pine	4	126	(D)	-	-	6	126	6,058	-	-
Pipestone	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Polk	22	5,457	361,640	-	-	19	5,331	464,200	-	-
Pope	1	(D)	(D)	1	(D)	-	-	-	-	-
Ramsey	1	(D)	(D)	1	(D)	1	(D)	(D)	-	-
Red Lake	7	1,425	94,975	-	-	16	3,863	362,568	-	-
Redwood	2	(D)	(D)	-	-	-	-	-	-	-
Renville	4	12	550	-	-	8	274	14,282	-	-
Rice	1	(D)	(D)	-	-	6	151	6,050	-	-
Roseau	18	6,436	490,002	-	-	28	9,689	619,549	-	-
St. Louis	11	218	13,058	-	-	8	212	6,490	-	-
Scott	-	-	-	-	-	2	(D)	(D)	-	-
Sibley	6	239	14,443	-	-	9	634	37,713	-	-
Stearns	28	954	48,972	5	90	65	1,693	102,326	-	-
Steele	-	-	-	-	-	2	(D)	(D)	-	-
Stevens	-	-	-	-	-	1	(D)	(D)	-	-
Swift	-	-	-	-	-	1	(D)	(D)	-	-
Todd	15	758	41,875	-	-	36	1,273	63,419	1	(D)
Wabasha	12	718	42,924	-	-	18	581	27,950	-	-
Wadena	2	(D)	(D)	-	-	1	(D)	(D)	1	(D)
Washington	-	-	-	-	-	4	46	2,950	-	-
Watonwan	-	-	-	-	-	1	(D)	(D)	-	-
Wilkin	8	1,143	82,662	-	-	18	2,404	202,458	-	-
Winona	2	(D)	(D)	-	-	14	451	19,725	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
BARLEY FOR GRAIN (BUSHELS) - Con.										
Counties - Con.										
Wright	-	-	-	-	-	2	(D)	(D)	-	-
Yellow Medicine	-	-	-	-	-	1	(D)	(D)	-	-
BUCKWHEAT (BUSHELS)										
State Total										
Minnesota	15	4,328	93,305	2	(D)	26	2,909	59,341	1	(D)
Counties										
Blue Earth	-	-	-	-	-	1	(D)	(D)	-	-
Clay	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Crow Wing	-	-	-	-	-	2	(D)	(D)	-	-
Dakota	-	-	-	-	-	1	(D)	(D)	-	-
Faribault	-	-	-	-	-	1	(D)	(D)	-	-
Kittson	5	144	2,512	-	-	-	-	-	-	-
Lac qui Parle	-	-	-	-	-	3	495	1,900	-	-
Lake of the Woods	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Le Sueur	-	-	-	-	-	1	(D)	(D)	-	-
Mahnomen	1	(D)	(D)	-	-	-	-	-	-	-
Mille Lacs	-	-	-	-	-	1	(D)	(D)	-	-
Morrison	1	(D)	(D)	-	-	-	-	-	-	-
Norman	-	-	-	-	-	1	(D)	(D)	-	-
Otter Tail	2	(D)	(D)	2	(D)	2	(D)	(D)	1	(D)
St. Louis	-	-	-	-	-	6	42	756	-	-
Sibley	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Steele	1	(D)	(D)	-	-	-	-	-	-	-
Stevens	-	-	-	-	-	1	(D)	(D)	-	-
Wadena	-	-	-	-	-	1	(D)	(D)	-	-
Wilkin	-	-	-	-	-	1	(D)	(D)	-	-
CAMELINA (POUNDS)										
State Total										
Minnesota	2	(D)	(D)	-	-	-	-	-	-	-
Counties										
Big Stone	2	(D)	(D)	-	-	-	-	-	-	-
CANOLA (POUNDS)										
State Total										
Minnesota	184	65,913	147,784,049	1	(D)	112	32,391	67,729,542	-	-
Counties										
Aitkin	-	-	-	-	-	1	(D)	(D)	-	-
Beltrami	7	2,152	3,221,174	-	-	2	(D)	(D)	-	-
Clay	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Clearwater	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Kittson	64	28,631	65,838,892	-	-	34	10,604	22,937,966	-	-
Koochiching	-	-	-	-	-	1	(D)	(D)	-	-
Lake of the Woods	12	2,581	6,456,849	-	-	-	-	-	-	-
Marshall	50	13,466	26,755,150	-	-	18	5,026	9,841,253	-	-
Meeker	-	-	-	-	-	3	105	105,000	-	-
Otter Tail	-	-	-	-	-	2	(D)	(D)	-	-
Pennington	7	3,667	8,134,853	-	-	5	1,538	4,172,800	-	-
Polk	1	(D)	(D)	-	-	-	-	-	-	-
Pope	1	(D)	(D)	1	(D)	2	(D)	(D)	-	-
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Roseau	40	13,808	33,758,520	-	-	39	12,726	25,987,286	-	-
St. Louis	-	-	-	-	-	1	(D)	(D)	-	-
CHICKPEAS, ALL (CWT)										
State Total										
Minnesota	1	(D)	(D)	-	-	3	180	3,856	2	(D)
Counties										
Crow Wing	-	-	-	-	-	1	(D)	(D)	1	(D)
Mahnomen	-	-	-	-	-	1	(D)	(D)	-	-
Otter Tail	1	(D)	(D)	-	-	1	(D)	(D)	1	(D)
CORN FOR GRAIN (BUSHELS)										
State Total										
Minnesota	24,697	7,732,455	1,478,451,268	1,341	302,897	28,086	7,790,541	1,494,241,562	1,417	288,250
Counties										
Aitkin	25	905	131,840	-	-	21	877	125,068	-	-
Anoka	32	3,750	502,239	2	(D)	59	10,990	1,762,557	6	1,703
Becker	164	72,931	12,090,339	4	157	151	59,859	9,713,439	8	1,291
Beltrami	32	1,975	256,010	-	-	25	2,057	258,648	-	-
Benton	263	36,233	6,414,145	30	10,241	353	56,554	8,640,821	29	6,548

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
CORN FOR GRAIN (BUSHELS) - Con.										
Counties - Con.										
Big Stone	206	89,282	15,223,986	10	1,385	238	96,272	17,299,191	8	2,403
Blue Earth	553	219,446	46,453,017	13	2,355	541	168,936	34,834,244	9	1,481
Brown	624	131,214	26,682,697	21	1,629	675	150,466	30,030,304	26	2,305
Carlton	9	245	29,238	-	-	6	183	27,220	-	-
Carver	243	60,960	11,439,765	-	-	359	64,404	12,823,369	4	280
Cass	25	2,436	222,624	-	-	18	3,127	466,732	1	(D)
Chippewa	320	163,441	32,869,161	9	1,504	378	141,971	28,879,671	10	2,467
Chisago	159	19,816	3,206,533	3	900	219	25,848	4,090,380	2	(D)
Clay	234	144,928	25,402,028	6	810	256	159,122	25,224,229	7	1,096
Clearwater	17	3,368	528,337	2	(D)	32	3,992	583,027	1	(D)
Cottonwood	436	181,404	37,787,711	12	2,732	493	169,117	34,570,141	7	1,733
Crow Wing	52	7,339	876,782	3	1,137	56	6,571	1,076,258	7	2,770
Dakota	330	87,720	16,360,503	127	30,872	335	103,411	20,733,764	132	34,801
Dodge	281	140,265	29,571,963	2	(D)	297	123,561	26,414,536	7	4,735
Douglas	283	73,291	12,507,296	19	4,139	333	63,660	10,870,370	23	1,662
Faribault	484	177,166	38,066,534	4	632	551	197,833	41,460,923	1	(D)
Fillmore	644	182,006	36,758,109	1	(D)	634	136,887	28,118,083	1	(D)
Freeborn	477	162,436	33,828,505	15	2,131	577	189,595	39,339,079	14	1,430
Goodhue	703	182,876	37,497,055	24	4,974	723	153,611	32,039,120	26	3,237
Grant	197	133,860	24,677,288	27	3,983	219	122,615	23,136,130	24	3,491
Hennepin	58	4,368	727,930	1	(D)	93	11,342	2,035,931	-	-
Houston	311	52,132	10,310,358	3	65	383	43,258	8,211,854	-	-
Hubbard	47	12,273	2,093,412	14	9,784	31	11,214	2,154,201	9	9,091
Isanti	136	24,352	3,476,006	11	1,169	179	35,966	5,418,224	22	2,968
Itasca	12	1,483	174,888	-	-	10	803	95,000	-	-
Jackson	556	176,899	36,322,400	6	450	518	159,138	31,740,839	-	-
Kanabec	69	12,558	1,881,809	-	-	107	18,313	2,933,151	8	1,204
Kandiyohi	421	194,117	37,614,584	43	15,729	464	169,607	32,950,026	37	16,823
Kittson	38	13,946	2,052,239	2	(D)	62	18,449	2,462,356	3	1,360
Koochiching	7	440	66,618	-	-	9	2,254	(D)	-	-
Lac qui Parle	424	165,302	30,408,622	13	1,828	501	163,114	30,545,651	20	2,602
Lake of the Woods	3	1,125	176,125	-	-	3	(D)	(D)	-	-
Le Sueur	288	75,924	15,528,082	9	1,098	362	95,406	19,372,272	4	736
Lincoln	254	74,109	13,230,886	1	(D)	353	115,033	20,517,179	1	(D)
Lyon	517	180,786	32,297,253	3	(D)	574	177,305	32,869,877	3	82
McLeod	327	113,705	22,618,847	-	-	413	115,814	22,964,323	1	(D)
Mahnomen	75	42,747	8,327,208	-	-	94	49,366	7,520,754	-	-
Marshall	78	28,255	4,162,308	-	-	139	55,840	7,678,799	2	(D)
Martin	512	223,294	49,177,589	6	527	629	241,276	51,272,047	3	290
Meeker	359	114,219	20,704,602	35	7,651	426	107,299	20,150,391	32	5,493
Mille Lacs	117	14,937	2,226,698	1	(D)	163	30,423	4,099,395	5	290
Morrison	613	74,544	12,179,959	66	9,620	663	71,970	11,746,855	93	15,941
Mower	500	174,442	37,444,843	26	3,649	556	210,179	43,850,891	15	2,007
Murray	488	144,562	26,301,852	-	-	547	168,160	32,647,621	-	-
Nicollet	399	126,724	25,977,990	-	-	471	123,854	25,474,206	-	-
Nobles	583	167,428	30,637,107	3	369	600	185,989	36,007,959	-	-
Norman	170	88,569	14,837,436	2	(D)	180	94,013	14,809,071	4	800
Olmsted	442	121,676	25,031,695	7	396	480	110,854	23,123,331	-	-
Otter Tail	741	173,119	28,762,851	145	35,122	781	168,402	28,739,618	143	31,347
Pennington	20	7,016	1,027,438	-	-	25	9,725	1,183,225	-	-
Pine	107	12,696	1,780,538	-	-	103	9,756	1,303,624	-	-
Pipestone	277	85,909	14,810,917	12	3,592	349	94,639	17,342,841	4	1,107
Polk	183	90,389	14,278,511	7	1,386	195	91,599	13,089,484	6	1,073
Pope	271	102,075	17,738,290	63	20,765	329	115,033	21,602,483	61	16,748
Ramsey	-	-	-	-	-	1	(D)	(D)	1	(D)
Red Lake	45	13,891	2,315,235	1	(D)	48	21,089	2,791,679	1	(D)
Redwood	833	257,104	48,880,497	5	132	776	232,908	46,446,172	1	(D)
Renville	564	271,325	53,676,916	7	1,780	642	264,229	54,452,778	3	406
Rice	419	96,895	20,234,092	12	1,248	499	86,122	17,189,758	11	1,989
Rock	337	120,530	23,596,331	2	(D)	470	127,899	25,785,916	1	(D)
Roseau	41	12,134	1,715,961	-	-	35	12,289	1,538,280	-	-
St. Louis	-	-	-	-	-	3	340	47,640	-	-
Scott	182	37,043	6,481,477	2	(D)	247	38,670	7,345,268	-	-
Sherburne	96	24,604	4,212,532	43	18,174	105	27,579	4,977,778	48	17,120
Sibley	497	177,256	35,479,978	5	1,028	544	161,804	32,780,760	2	(D)
Stearns	1,223	183,737	32,564,050	199	30,299	1,461	182,828	31,850,522	228	26,863
Steele	277	118,042	24,945,640	5	918	311	119,624	25,078,747	9	1,509
Stevens	224	126,102	22,496,743	36	13,901	292	124,239	22,352,001	46	13,745
Swift	357	157,921	29,433,661	48	13,234	408	148,393	28,510,884	78	16,740
Todd	502	57,958	9,404,011	40	7,390	585	54,679	8,457,691	41	5,163
Traverse	185	115,605	18,589,545	-	-	223	138,917	25,793,048	-	-
Wabasha	424	76,700	15,537,718	11	1,475	452	68,810	13,838,435	10	1,545
Wadena	92	19,535	3,334,062	37	13,676	110	15,828	2,517,862	35	5,941
Waseca	331	120,236	26,432,335	1	(D)	406	113,225	23,872,853	2	(D)
Washington	84	12,821	2,197,670	6	1,265	129	21,650	4,187,419	12	2,242
Watonwan	294	135,115	28,429,538	24	6,255	313	123,668	26,907,121	23	4,587
Wilkin	168	108,649	16,711,248	3	264	204	115,407	21,100,394	5	718
Winona	505	89,443	17,257,708	-	-	524	72,401	13,769,697	-	-
Wright	383	68,316	12,038,709	38	4,188	477	71,881	13,076,198	28	2,681
Yellow Medicine	438	156,080	28,714,015	3	454	480	158,044	30,656,178	3	304

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
DRY EDIBLE BEANS, EXCLUDING CHICKPEAS AND LIMAS (CWT)										
State Total										
Minnesota	573	210,162	5,278,245	95	39,931	506	160,604	3,520,202	101	41,653
Counties										
Becker	14	7,575	155,605	2	(D)	5	3,822	119,752	5	3,794
Beltrami	-	-	-	-	-	1	(D)	(D)	-	-
Benton	2	(D)	(D)	1	(D)	2	(D)	(D)	2	(D)
Big Stone	1	(D)	(D)	-	-	4	960	(D)	1	(D)
Brown	5	401	20,501	4	(D)	-	-	-	-	-
Carlton	8	16	300	1	(D)	-	-	-	-	-
Carver	2	(D)	(D)	-	-	-	-	-	-	-
Cass	-	-	-	-	-	1	(D)	(D)	1	(D)
Chippewa	32	10,892	393,901	-	-	31	6,310	163,565	1	(D)
Chisago	1	(D)	(D)	-	-	3	81	2,316	-	-
Clay	3	757	15,381	-	-	6	1,188	24,770	-	-
Clearwater	3	342	11,023	-	-	-	-	-	-	-
Crow Wing	2	(D)	(D)	-	-	1	(D)	(D)	1	(D)
Dakota	14	1,068	31,834	4	464	1	(D)	(D)	-	-
Dodge	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Douglas	4	178	6,520	-	-	4	212	6,840	-	-
Faribault	-	-	-	-	-	2	(D)	(D)	-	-
Fillmore	3	171	10,420	-	-	-	-	-	-	-
Freeborn	-	-	-	-	-	2	(D)	(D)	-	-
Goodhue	4	116	7,584	-	-	2	(D)	(D)	-	-
Grant	7	3,799	143,163	1	(D)	9	2,584	52,858	-	-
Hennepin	-	-	-	-	-	1	(D)	(D)	-	-
Houston	-	-	-	-	-	1	(D)	(D)	-	-
Hubbard	6	8,926	240,573	6	8,226	7	8,412	254,049	6	(D)
Isanti	1	(D)	(D)	1	(D)	2	(D)	(D)	2	(D)
Jackson	1	(D)	(D)	-	-	-	-	-	-	-
Kandiyohi	28	10,840	288,549	5	3,371	30	9,522	202,234	5	2,695
Kittson	2	(D)	(D)	-	-	4	872	16,685	-	-
Lac qui Parle	5	1,961	93,742	1	(D)	6	362	11,298	-	-
Lake of the Woods	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Lyon	1	(D)	(D)	-	-	2	(D)	(D)	-	-
McLeod	7	2,011	68,277	-	-	9	1,734	42,116	-	-
Mahnomen	32	9,571	242,599	-	-	9	4,059	80,919	-	-
Marshall	29	10,752	258,531	-	-	22	8,046	119,010	-	-
Martin	1	(D)	(D)	-	-	-	-	-	-	-
Meeker	2	(D)	(D)	2	(D)	5	466	10,866	4	(D)
Morrison	6	2,563	87,016	1	(D)	12	4,271	90,610	12	3,592
Murray	1	(D)	(D)	-	-	-	-	-	-	-
Norman	12	4,773	101,402	1	(D)	11	4,433	86,205	-	-
Olmsted	3	333	7,954	-	-	2	(D)	(D)	-	-
Otter Tail	46	15,001	358,998	24	8,733	39	14,437	295,160	24	11,088
Pennington	4	1,793	43,345	-	-	8	2,661	38,780	-	-
Polk	100	55,891	1,071,414	1	(D)	98	43,110	826,136	2	(D)
Pope	11	4,957	109,418	4	1,872	10	5,769	142,647	7	2,530
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	4	2,008	35,158	1	(D)	11	3,768	71,062	5	653
Redwood	1	(D)	(D)	-	-	-	-	-	-	-
Renville	49	10,429	304,399	-	-	48	7,819	205,059	-	-
Roseau	2	(D)	(D)	-	-	-	-	-	-	-
Sherburne	3	(D)	(D)	1	(D)	2	(D)	(D)	2	(D)
Stearns	9	3,215	105,383	4	(D)	10	2,090	53,261	3	(D)
Steele	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Stevens	31	13,869	323,840	17	4,810	30	8,868	215,982	9	1,470
Swift	29	7,659	207,377	6	765	14	3,998	116,837	3	540
Todd	3	3,972	122,550	-	-	11	1,271	27,273	2	(D)
Traverse	3	1,862	71,780	-	-	2	(D)	(D)	-	-
Wabasha	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Wadena	9	3,450	83,754	7	(D)	8	1,856	36,252	3	284
Waseca	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Washington	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Wilkin	7	1,581	37,781	-	-	4	745	13,507	1	(D)
Winona	1	(D)	(D)	-	-	3	30	990	-	-
Wright	3	208	5,124	-	-	-	-	-	-	-
Yellow Medicine	7	756	35,581	-	-	3	266	7,336	-	-
DRY EDIBLE PEAS (CWT)										
State Total										
Minnesota	35	5,781	148,841	7	1,230	66	11,187	302,729	5	2,591
Counties										
Becker	1	(D)	(D)	-	-	4	286	5,344	-	-
Blue Earth	-	-	-	-	-	1	(D)	(D)	1	(D)
Brown	-	-	-	-	-	2	(D)	(D)	-	-
Carlton	1	(D)	(D)	-	-	-	-	-	-	-
Chippewa	-	-	-	-	-	4	622	14,146	-	-
Clay	-	-	-	-	-	1	(D)	(D)	-	-
Crow Wing	3	936	25,695	3	678	1	(D)	(D)	1	(D)
Dakota	3	453	2,418	-	-	1	(D)	(D)	1	(D)
Faribault	-	-	-	-	-	1	(D)	(D)	-	-
Goodhue	4	310	10,176	-	-	5	325	9,475	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
DRY EDIBLE PEAS (CWT) - Con.										
Counties - Con.										
Hubbard	-	-	-	-	-	3	210	2,440	-	-
Kandiyohi	2	(D)	(D)	2	(D)	2	(D)	(D)	-	-
Mahnomen	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Marshall	-	-	-	-	-	5	382	7,948	-	-
Martin	-	-	-	-	-	2	(D)	(D)	-	-
Morrison	-	-	-	-	-	1	(D)	(D)	-	-
Mower	4	380	7,980	-	-	1	(D)	(D)	-	-
Olmsted	-	-	-	-	-	2	(D)	(D)	-	-
Otter Tail	4	218	5,304	-	-	6	583	13,110	2	(D)
Pennington	1	(D)	(D)	-	-	4	1,223	35,889	-	-
Pipestone	-	-	-	-	-	2	(D)	(D)	-	-
Polk	6	1,787	45,466	-	-	8	2,256	51,540	-	-
Red Lake	-	-	-	-	-	1	(D)	(D)	-	-
Renville	1	(D)	(D)	-	-	-	-	-	-	-
Stearns	2	(D)	(D)	2	(D)	4	150	3,812	-	-
Steele	-	-	-	-	-	2	(D)	(D)	-	-
Wadena	2	(D)	(D)	-	-	-	-	-	-	-
Watonwan	-	-	-	-	-	1	(D)	(D)	-	-
Winona	-	-	-	-	-	1	(D)	(D)	-	-
DRY LIMA BEANS (CWT)										
State Total										
Minnesota	2	(D)	(D)	-	-	-	-	-	-	-
Counties										
Olmsted	1	(D)	(D)	-	-	-	-	-	-	-
Winona	1	(D)	(D)	-	-	-	-	-	-	-
DRY SOUTHERN PEAS (COWPEAS) (BUSHELS)										
State Total										
Minnesota	-	-	-	-	-	1	(D)	(D)	-	-
Counties										
Chisago	-	-	-	-	-	1	(D)	(D)	-	-
EMMER AND SPELT (BUSHELS)										
State Total										
Minnesota	3	90	7,200	-	-	2	(D)	(D)	-	-
Counties										
Stearns	-	-	-	-	-	1	(D)	(D)	-	-
Wadena	2	(D)	(D)	-	-	-	-	-	-	-
Winona	1	(D)	(D)	-	-	1	(D)	(D)	-	-
FLAXSEED (BUSHELS)										
State Total										
Minnesota	19	2,215	49,189	-	-	23	2,709	78,848	-	-
Counties										
Becker	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Clay	2	(D)	(D)	-	-	8	350	7,753	-	-
Crow Wing	3	168	3,072	-	-	-	-	-	-	-
Kittson	-	-	-	-	-	1	(D)	(D)	-	-
Lake of the Woods	-	-	-	-	-	2	(D)	(D)	-	-
Marshall	2	(D)	(D)	-	-	3	270	9,450	-	-
Roseau	11	1,617	39,287	-	-	8	1,557	49,943	-	-
HEMP FOR FIBER (POUNDS) (SEE TEXT)										
State Total										
Minnesota	1	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Counties										
St. Louis	1	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
HEMP FOR FLORAL (CBD AND OTHER CANNABINOID USAGE) (POUNDS) (SEE TEXT)										
State Total										
Minnesota	72	195	126,586	41	69	(NA)	(NA)	(NA)	(NA)	(NA)
Counties										
Aitkin	2	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Carver	1	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
HEMP FOR FLORAL (CBD AND OTHER CANNABINOID USAGE) (POUNDS) (SEE TEXT) - Con.										
Counties - Con.										
Chisago	2	(D)	(D)	2	(D)	(NA)	(NA)	(NA)	(NA)	(NA)
Dakota	1	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Goodhue	2	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Grant	3	3	150	3	3	(NA)	(NA)	(NA)	(NA)	(NA)
Hennepin	5	5	10,000	5	5	(NA)	(NA)	(NA)	(NA)	(NA)
Houston	2	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Kanabec	1	(D)	(D)	1	(D)	(NA)	(NA)	(NA)	(NA)	(NA)
Lyon	2	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Mille Lacs	1	(D)	(D)	1	(D)	(NA)	(NA)	(NA)	(NA)	(NA)
Mower	7	7	700	7	7	(NA)	(NA)	(NA)	(NA)	(NA)
Otter Tail	8	22	21,560	2	(D)	(NA)	(NA)	(NA)	(NA)	(NA)
Pine	1	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Ramsey	3	3	6,000	3	3	(NA)	(NA)	(NA)	(NA)	(NA)
Red Lake	8	8	1,872	8	8	(NA)	(NA)	(NA)	(NA)	(NA)
Rice	3	3	450	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
St. Louis	3	3	450	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Scott	2	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Stearns	1	(D)	(D)	1	(D)	(NA)	(NA)	(NA)	(NA)	(NA)
Todd	2	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Washington	4	4	200	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Wright	8	10	30,000	8	10	(NA)	(NA)	(NA)	(NA)	(NA)
OTHER HEMP USAGE (POUNDS) (SEE TEXT)										
State Total										
Minnesota	2	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Counties										
Fillmore	1	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
Goodhue	1	(D)	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)
LENTILS (CWT)										
State Total										
Minnesota	-	-	-	-	-	3	241	2,952	1	(D)
Counties										
Clearwater	-	-	-	-	-	1	(D)	(D)	-	-
Crow Wing	-	-	-	-	-	1	(D)	(D)	1	(D)
Renville	-	-	-	-	-	1	(D)	(D)	-	-
MUSTARD SEED (POUNDS)										
State Total										
Minnesota	-	-	-	-	-	1	(D)	(D)	-	-
Counties										
Wadena	-	-	-	-	-	1	(D)	(D)	-	-
OATS FOR GRAIN (BUSHELS)										
State Total										
Minnesota	2,329	126,011	9,470,546	66	3,194	2,532	84,616	6,494,938	24	891
Counties										
Aitkin	23	1,222	91,150	-	-	22	612	24,946	-	-
Anoka	-	-	-	-	-	9	145	5,536	-	-
Becker	28	1,367	66,886	-	-	49	1,983	102,277	-	-
Beltrami	52	3,919	219,833	-	-	38	1,667	101,260	-	-
Benton	28	473	21,962	-	-	35	637	33,240	-	-
Big Stone	3	86	4,863	-	-	6	163	16,040	-	-
Blue Earth	17	627	56,304	-	-	16	1,311	135,938	1	(D)
Brown	27	806	76,450	3	6	31	641	62,499	-	-
Carlton	13	860	69,075	-	-	19	442	20,190	-	-
Carver	6	108	8,602	-	-	31	603	35,650	-	-
Cass	8	384	17,773	1	(D)	3	67	2,220	-	-
Chippewa	2	(D)	(D)	-	-	6	125	7,929	-	-
Chisago	9	215	20,647	-	-	8	163	9,620	-	-
Clay	28	2,213	117,970	-	-	11	577	44,660	-	-
Clearwater	15	1,357	120,420	-	-	20	1,267	113,301	-	-
Cottonwood	8	552	53,100	-	-	8	115	12,472	-	-
Crow Wing	26	1,502	58,406	3	465	28	1,085	65,747	-	-
Dakota	27	673	42,128	4	40	14	277	23,716	3	90
Dodge	15	580	54,602	-	-	20	436	32,623	-	-
Douglas	59	2,850	130,308	-	-	53	1,186	85,380	-	-
Faribault	9	195	16,487	-	-	27	827	70,938	-	-
Fillmore	69	2,785	265,569	-	-	81	1,570	118,289	-	-
Freeborn	24	1,386	105,989	2	(D)	19	281	27,682	-	-
Goodhue	57	1,471	82,172	1	(D)	59	1,210	82,792	-	-
Grant	1	(D)	(D)	-	-	2	(D)	(D)	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
OATS FOR GRAIN (BUSHELS) - Con.										
Counties - Con.										
Hennepin	3	161	7,130	-	-	11	205	13,260	-	-
Houston	30	923	62,118	-	-	66	1,615	84,073	-	-
Hubbard	28	1,558	94,603	6	420	16	784	41,377	-	-
Isanti	13	523	17,638	1	(D)	6	150	6,300	-	-
Itasca	18	932	60,106	-	-	14	516	30,980	-	-
Jackson	7	215	21,130	-	-	24	317	33,267	-	-
Kanabec	25	1,561	85,962	-	-	22	466	30,341	-	-
Kandiyohi	6	209	10,388	-	-	29	998	67,016	-	-
Kittson	17	1,386	129,942	-	-	20	1,564	104,328	-	-
Koochiching	4	74	2,534	-	-	10	220	11,385	-	-
Lac qui Parle	13	955	58,536	1	(D)	10	465	23,580	-	-
Lake of the Woods	18	2,790	290,213	-	-	7	775	72,860	-	-
Le Sueur	28	975	50,149	-	-	16	223	19,868	-	-
Lincoln	10	1,367	160,046	-	-	21	1,821	179,127	-	-
Lyon	23	1,297	119,334	-	-	12	373	46,625	-	-
McLeod	21	389	31,984	-	-	23	523	40,897	-	-
Mahnomen	32	3,107	297,987	-	-	5	157	(D)	-	-
Marshall	74	9,096	840,276	-	-	32	2,555	204,987	-	-
Martin	11	365	33,912	-	-	8	266	25,077	-	-
Meeker	23	579	47,185	-	-	24	897	71,474	1	(D)
Mille Lacs	23	1,018	41,616	-	-	18	436	21,936	-	-
Morrison	65	1,485	69,070	-	-	101	2,478	167,653	2	(D)
Mower	23	844	71,022	-	-	20	617	43,777	-	-
Murray	33	1,472	113,737	-	-	34	1,047	125,654	-	-
Nicollet	11	723	45,672	-	-	17	474	39,646	-	-
Nobles	14	654	87,908	-	-	18	555	76,764	-	-
Norman	16	947	94,426	-	-	11	536	44,784	-	-
Olmsted	41	1,978	167,527	-	-	50	1,288	104,404	-	-
Otter Tail	134	8,081	519,046	12	624	156	6,926	512,676	2	(D)
Pennington	26	4,426	370,583	-	-	11	847	82,929	-	-
Pine	20	501	27,265	-	-	41	762	34,771	-	-
Pipestone	28	1,370	124,983	-	-	19	518	51,990	-	-
Polk	15	3,647	284,041	-	-	21	1,846	131,013	-	-
Pope	30	1,362	81,918	1	(D)	26	1,625	142,699	-	-
Ramsey	1	(D)	(D)	1	(D)	1	(D)	(D)	-	-
Red Lake	12	1,812	204,850	-	-	4	515	41,450	-	-
Redwood	13	390	29,722	-	-	22	558	50,688	-	-
Renville	17	560	37,042	-	-	18	394	37,180	-	-
Rice	24	360	34,153	-	-	34	559	39,306	-	-
Rock	10	690	80,024	-	-	13	1,544	159,277	-	-
Roseau	54	6,502	535,248	-	-	38	4,138	379,646	-	-
St. Louis	37	2,298	147,772	-	-	33	713	39,402	-	-
Scott	18	539	41,721	-	-	28	498	41,436	-	-
Sherburne	8	431	21,401	-	-	5	100	8,168	-	-
Sibley	16	309	24,207	-	-	25	569	46,981	-	-
Stearns	293	11,452	744,283	15	367	327	11,100	916,516	11	238
Steele	5	314	31,310	-	-	13	353	26,384	-	-
Stevens	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Swift	24	976	82,301	-	-	6	180	10,812	-	-
Todd	121	5,271	355,300	-	-	122	2,983	194,557	-	-
Traverse	3	600	60,000	-	-	2	(D)	(D)	-	-
Wabasha	59	1,826	168,701	2	(D)	66	1,781	137,758	-	-
Wadena	48	3,102	188,693	6	492	40	1,272	67,922	2	(D)
Waseca	2	(D)	(D)	-	-	13	223	22,777	2	(D)
Washington	16	997	62,085	-	-	27	1,023	43,961	-	-
Watonwan	12	534	38,253	1	(D)	11	199	18,478	-	-
Wilkin	5	153	11,520	-	-	4	99	9,920	-	-
Winona	42	1,138	70,208	-	-	82	2,249	147,608	-	-
Wright	37	2,094	154,236	6	636	51	777	56,281	-	-
Yellow Medicine	14	945	116,718	-	-	11	185	16,857	-	-
POPCORN (POUNDS, SHELLED)										
State Total										
Minnesota	5	11	2,485	1	(D)	5	15	(D)	-	-
Counties										
Dakota	-	-	-	-	-	1	(D)	(D)	-	-
Lac qui Parle	2	(D)	(D)	-	-	-	-	-	-	-
Martin	-	-	-	-	-	3	(D)	180	-	-
Nicollet	2	(D)	(D)	-	-	-	-	-	-	-
Ramsey	1	(D)	(D)	1	(D)	1	(D)	(D)	-	-
PROSO MILLET (BUSHELS)										
State Total										
Minnesota	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Counties										
Otter Tail	-	-	-	-	-	1	(D)	(D)	-	-
Polk	2	(D)	(D)	-	-	-	-	-	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
RAPESEED (POUNDS)										
State Total										
Minnesota	-	-	-	-	-	1	(D)	(D)	1	(D)
Counties										
Benton	-	-	-	-	-	1	(D)	(D)	1	(D)
RYE FOR GRAIN (BUSHELS)										
State Total										
Minnesota	580	37,506	2,020,506	18	787	404	20,301	837,792	5	265
Counties										
Aitkin	4	68	2,634	-	-	1	(D)	(D)	-	-
Anoka	10	122	3,120	-	-	13	526	24,231	-	-
Becker	4	138	5,700	-	-	2	(D)	(D)	-	-
Beltrami	11	184	5,200	-	-	1	(D)	(D)	-	-
Benton	6	605	36,208	-	-	10	633	28,247	3	(D)
Big Stone	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Blue Earth	1	(D)	(D)	-	-	5	150	12,335	-	-
Brown	3	56	1,557	-	-	-	-	-	-	-
Carlton	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Cass	-	-	-	-	-	1	(D)	(D)	-	-
Chisago	8	330	(D)	-	-	6	152	5,045	-	-
Clay	3	216	6,280	-	-	1	(D)	(D)	-	-
Clearwater	4	201	10,229	-	-	-	-	-	-	-
Cottonwood	2	(D)	(D)	-	-	-	-	-	-	-
Crow Wing	1	(D)	(D)	-	-	11	1,005	40,484	-	-
Dakota	7	126	6,267	1	(D)	1	(D)	(D)	-	-
Dodge	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Douglas	11	391	21,675	-	-	10	1,842	99,965	-	-
Faribault	3	173	5,792	-	-	7	80	4,850	-	-
Fillmore	10	459	27,721	-	-	6	452	18,400	-	-
Freeborn	3	282	23,986	-	-	1	(D)	(D)	-	-
Goodhue	7	298	16,194	1	(D)	7	355	17,922	-	-
Grant	4	204	13,198	-	-	2	(D)	(D)	-	-
Hennepin	1	(D)	(D)	-	-	3	(D)	(D)	-	-
Houston	2	(D)	(D)	-	-	8	178	5,946	-	-
Hubbard	-	-	-	-	-	15	504	17,420	-	-
Isanti	15	580	19,563	-	-	24	1,194	43,385	-	-
Jackson	-	-	-	-	-	6	90	4,500	-	-
Kanabec	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Kandiyohi	2	(D)	(D)	-	-	3	51	2,800	-	-
Kittson	5	561	37,405	-	-	1	(D)	(D)	-	-
Koochiching	2	(D)	(D)	-	-	-	-	-	-	-
Lac qui Parle	3	64	2,820	-	-	2	(D)	(D)	-	-
Lake of the Woods	1	(D)	(D)	-	-	-	-	-	-	-
Le Sueur	7	160	5,200	-	-	-	-	-	-	-
Lincoln	-	-	-	-	-	1	(D)	(D)	-	-
Lyon	4	271	11,935	-	-	-	-	-	-	-
McLeod	1	(D)	(D)	-	-	-	-	-	-	-
Mahnomen	17	1,328	70,104	-	-	3	(D)	(D)	-	-
Marshall	9	(D)	(D)	-	-	3	185	7,800	-	-
Martin	3	300	12,000	-	-	-	-	-	-	-
Meeker	12	540	37,574	-	-	3	154	4,868	-	-
Mille Lacs	2	(D)	(D)	-	-	4	218	7,600	-	-
Morrison	29	932	34,767	-	-	34	1,823	68,650	2	(D)
Mower	9	749	40,707	-	-	2	(D)	(D)	-	-
Murray	3	195	8,584	-	-	2	(D)	(D)	-	-
Nicollet	5	280	14,886	-	-	2	(D)	(D)	-	-
Nobles	5	460	22,900	-	-	1	(D)	(D)	-	-
Norman	14	1,549	83,222	-	-	2	(D)	(D)	-	-
Olmsted	5	131	3,725	-	-	1	(D)	(D)	-	-
Otter Tail	38	1,847	85,192	1	(D)	23	971	31,040	-	-
Pennington	3	(D)	(D)	-	-	-	-	-	-	-
Pine	9	258	7,832	-	-	-	-	-	-	-
Pipestone	15	1,905	124,581	-	-	2	(D)	(D)	-	-
Polk	13	1,534	58,970	-	-	12	549	22,723	-	-
Pope	9	438	17,093	-	-	5	115	6,325	-	-
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	3	657	59,100	-	-	-	-	-	-	-
Redwood	6	417	26,584	-	-	1	(D)	(D)	-	-
Renville	3	64	1,900	-	-	-	-	-	-	-
Rice	9	106	4,800	-	-	-	-	-	-	-
Rock	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Roseau	26	3,509	225,715	-	-	1	(D)	(D)	-	-
St. Louis	3	21	420	-	-	6	39	450	-	-
Scott	6	168	2,991	-	-	6	192	5,575	-	-
Sherburne	12	820	36,979	4	185	27	1,425	49,320	-	-
Sibley	6	140	5,730	-	-	-	-	-	-	-
Stearns	40	4,692	288,417	2	(D)	49	2,713	99,716	-	-
Steele	-	-	-	-	-	3	116	4,488	-	-
Stevens	-	-	-	-	-	1	(D)	(D)	-	-
Swift	1	(D)	(D)	1	(D)	-	-	-	-	-
Todd	39	1,174	48,976	-	-	26	1,349	29,624	-	-
Traverse	2	(D)	(D)	-	-	-	-	-	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
RYE FOR GRAIN (BUSHELS) - Con.										
Counties - Con.										
Wabasha	9	209	9,029	-	-	11	196	7,809	-	-
Wadena	24	950	18,447	1	(D)	9	256	11,221	-	-
Waseca	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Washington	6	103	6,873	-	-	4	58	2,800	-	-
Watonwan	5	76	5,677	1	(D)	-	-	-	-	-
Wilkin	3	(D)	20,599	-	-	-	-	-	-	-
Winona	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Wright	14	639	27,087	6	300	2	(D)	(D)	-	-
Yellow Medicine	8	593	33,232	-	-	1	(D)	(D)	-	-
SORGHUM FOR GRAIN (BUSHELS)										
State Total										
Minnesota	12	364	24,260	-	-	12	526	44,880	2	(D)
Counties										
Anoka	2	(D)	(D)	-	-	-	-	-	-	-
Becker	1	(D)	(D)	-	-	-	-	-	-	-
Chisago	2	(D)	(D)	-	-	-	-	-	-	-
Fillmore	1	(D)	(D)	-	-	-	-	-	-	-
Olmsted	1	(D)	(D)	-	-	-	-	-	-	-
Otter Tail	2	(D)	(D)	-	-	-	-	-	-	-
Pope	-	-	-	-	-	2	(D)	(D)	-	-
Renville	-	-	-	-	-	2	(D)	(D)	-	-
Scott	-	-	-	-	-	2	(D)	(D)	-	-
Sibley	2	(D)	(D)	-	-	-	-	-	-	-
Stearns	-	-	-	-	-	3	305	28,100	2	(D)
Washington	-	-	-	-	-	2	(D)	(D)	-	-
Wright	1	(D)	(D)	-	-	1	(D)	(D)	-	-
SOYBEANS FOR BEANS (BUSHELS)										
State Total										
Minnesota	25,337	7,597,171	373,669,175	892	122,734	27,865	8,142,472	376,505,537	950	128,172
Counties										
Aitkin	29	3,967	108,033	-	-	18	4,995	172,084	-	-
Anoka	27	4,195	187,975	1	(D)	38	5,489	232,213	4	301
Becker	182	82,288	3,504,122	11	842	191	86,237	3,089,889	5	3,332
Beltrami	90	16,300	487,568	-	-	80	17,782	475,414	-	-
Benton	235	27,857	1,231,840	17	1,462	325	54,340	2,081,362	20	2,867
Big Stone	238	111,535	4,631,099	7	706	262	117,604	5,420,748	8	1,358
Blue Earth	600	212,796	12,522,067	3	(D)	545	161,950	9,246,445	-	-
Brown	605	111,584	6,101,554	15	1,076	668	134,274	7,223,683	14	933
Carlton	2	(D)	(D)	-	-	-	-	-	-	-
Carver	229	52,608	2,929,606	-	-	264	48,084	2,413,639	2	(D)
Cass	17	1,554	50,484	-	-	5	(D)	(D)	1	(D)
Chippewa	305	99,594	5,009,898	2	(D)	356	109,184	5,308,475	3	245
Chisago	173	21,438	905,331	2	(D)	237	31,368	1,210,601	3	(D)
Clay	313	193,698	8,326,903	6	461	375	210,459	7,864,217	7	880
Clearwater	47	13,593	496,802	2	(D)	64	16,293	505,157	-	-
Cottonwood	438	161,145	8,673,177	3	87	474	152,023	8,528,137	2	(D)
Crow Wing	29	5,821	134,182	3	1,140	30	4,855	236,011	7	638
Dakota	326	54,577	2,819,858	96	11,491	315	65,489	3,373,894	103	15,933
Dodge	255	102,376	6,145,192	6	364	261	92,757	5,040,411	-	-
Douglas	371	74,900	3,154,860	10	906	405	82,326	3,510,498	21	1,288
Faribault	552	171,786	10,642,575	3	358	526	171,440	9,833,806	-	-
Fillmore	513	117,291	6,869,263	1	(D)	463	82,605	4,342,668	-	-
Freeborn	472	138,846	7,992,460	11	1,267	560	157,334	8,562,606	3	221
Goodhue	622	118,627	7,114,715	9	565	615	113,522	6,122,650	15	1,433
Grant	222	119,553	5,270,661	24	3,190	245	126,077	5,768,640	23	2,127
Hennepin	68	7,169	347,164	1	(D)	91	14,765	712,695	-	-
Houston	236	27,414	1,515,776	7	314	264	24,820	1,234,243	-	-
Hubbard	11	2,225	104,399	3	1,065	14	1,540	57,390	4	728
Isanti	160	22,282	855,736	11	739	192	35,367	1,231,602	5	198
Itasca	23	4,743	132,109	-	-	15	2,818	71,205	-	-
Jackson	545	167,355	9,093,623	7	1,059	534	158,909	8,738,101	-	-
Kanabec	81	15,789	631,938	-	-	101	16,812	678,742	6	786
Kandiyohi	416	135,404	6,723,133	20	3,234	441	128,626	5,883,274	24	3,158
Kittson	213	140,224	6,275,192	1	(D)	214	150,649	4,579,395	2	(D)
Koochiching	19	6,914	212,020	-	-	13	3,829	116,393	-	-
Lac qui Parle	446	164,409	7,715,294	12	2,272	513	165,882	7,989,923	18	2,419
Lake of the Woods	50	21,884	794,930	-	-	48	32,859	959,811	-	-
Le Sueur	336	75,175	4,331,080	7	1,175	386	99,778	5,414,062	5	540
Lincoln	271	67,229	2,918,612	1	(D)	352	105,213	4,981,525	-	-
Lyon	533	165,332	7,769,052	7	1,338	562	154,568	7,848,062	2	(D)
McLeod	345	88,037	4,910,620	1	(D)	443	97,909	4,596,643	-	-
Mahnomen	141	67,294	3,008,680	-	-	148	83,420	2,808,440	-	-
Marshall	474	254,815	9,638,917	4	1,740	447	321,603	9,562,795	1	(D)
Martin	533	191,866	11,501,189	-	-	603	179,087	10,346,314	2	(D)
Meeker	340	100,336	4,794,286	21	1,788	415	110,033	5,056,740	19	1,513
Mille Lacs	126	17,351	648,085	2	(D)	155	25,469	866,492	2	(D)
Morrison	361	34,256	1,564,338	51	4,348	448	38,723	1,526,903	70	6,338

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
SOYBEANS FOR BEANS (BUSHELS) - Con.										
Counties - Con.										
Mower	480	136,298	8,033,769	14	1,876	568	170,760	9,067,637	13	1,450
Murray	491	137,597	6,391,086	-	-	553	161,709	8,479,082	-	-
Nicollet	403	111,495	6,503,844	1	(D)	469	103,642	5,835,913	-	-
Nobles	586	148,252	7,097,059	3	222	585	176,225	9,212,296	-	-
Norman	262	172,160	7,482,259	2	(D)	323	216,652	7,359,227	1	(D)
Olmsted	407	79,016	4,670,907	8	439	417	69,899	3,731,461	-	-
Otter Tail	693	159,496	6,567,089	114	14,449	676	179,243	7,512,012	102	19,680
Pennington	124	87,787	3,141,123	-	-	197	110,456	2,860,427	-	-
Pine	90	11,638	433,252	-	-	110	11,569	400,298	-	-
Pipestone	283	73,765	3,267,256	4	992	310	83,912	4,360,226	3	892
Polk	580	325,204	12,771,360	6	3,634	575	311,160	10,772,149	3	396
Pope	304	83,190	3,572,368	47	6,674	313	93,627	4,284,557	55	7,472
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	152	65,417	2,502,348	3	396	144	71,818	2,289,799	1	(D)
Redwood	847	231,905	11,457,738	2	(D)	784	216,964	11,354,746	1	(D)
Renville	579	221,215	11,855,304	1	(D)	651	228,655	11,814,235	1	(D)
Rice	426	84,766	4,981,172	1	(D)	508	73,043	3,731,692	3	372
Rock	320	97,893	5,299,981	1	(D)	467	113,772	6,425,767	1	(D)
Roseau	238	131,263	4,945,922	-	-	252	188,292	5,449,071	-	-
St. Louis	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Scott	158	34,096	1,638,236	-	-	251	38,130	1,914,638	-	-
Sherburne	73	13,826	571,707	26	8,629	86	19,533	906,445	41	11,657
Sibley	467	132,175	7,416,746	1	(D)	527	131,259	7,155,182	-	-
Stearns	876	113,387	5,367,293	97	8,983	995	114,288	5,280,674	132	10,211
Steele	280	88,651	5,489,870	5	918	283	88,042	4,749,632	2	(D)
Stevens	212	103,077	4,561,223	18	2,632	278	117,546	5,257,845	31	4,306
Swift	332	107,709	4,887,338	43	7,630	361	111,264	5,251,564	54	8,355
Todd	401	46,542	1,965,831	14	3,390	449	48,600	1,910,373	27	3,133
Traverse	196	118,079	4,916,309	2	(D)	260	167,575	7,748,116	2	(D)
Wabasha	291	39,729	2,308,568	4	272	332	40,860	2,236,324	-	-
Wadena	57	16,495	716,736	33	10,548	72	14,188	616,385	33	5,183
Waseca	326	108,599	6,850,400	7	860	388	95,958	5,390,080	-	-
Washington	83	11,080	520,912	2	(D)	121	19,583	933,902	5	541
Watonwan	298	101,160	5,872,100	16	1,313	305	103,896	6,046,601	12	1,955
Wilkin	197	148,655	5,701,794	2	(D)	244	170,393	6,735,179	1	(D)
Winona	376	45,868	2,695,843	-	-	336	34,666	1,780,849	-	-
Wright	369	73,396	3,776,548	25	1,533	454	87,051	4,006,310	24	1,669
Yellow Medicine	458	140,040	6,624,270	2	(D)	498	153,832	7,603,239	1	(D)
SUGARBEETS FOR SUGAR (TONS)										
State Total										
Minnesota	1,106	446,627	11,642,041	31	10,798	1,107	423,096	12,544,950	32	8,808
Counties										
Becker	14	5,503	164,645	-	-	10	4,504	137,775	-	-
Benton	-	-	-	-	-	1	(D)	(D)	1	(D)
Big Stone	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Brown	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Chippewa	89	29,626	818,710	-	-	94	31,659	964,940	3	(D)
Clay	70	39,558	1,073,071	-	-	95	40,195	1,239,757	-	-
Cottonwood	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Douglas	6	3,780	98,280	6	1,596	-	-	-	-	-
Grant	16	8,337	191,836	-	-	27	11,822	358,332	1	(D)
Kandiyohi	31	17,441	494,986	1	(D)	44	18,874	580,961	4	(D)
Kittson	90	30,086	865,108	-	-	73	21,670	575,467	-	-
Lac qui Parle	2	(D)	(D)	1	(D)	1	(D)	(D)	-	-
Lyon	1	(D)	(D)	-	-	3	506	14,438	-	-
McLeod	1	(D)	(D)	-	-	5	1,747	56,110	-	-
Mahnomen	13	2,859	79,311	-	-	7	2,773	83,090	-	-
Marshall	126	49,535	1,341,709	-	-	87	40,562	1,116,843	1	(D)
Meeker	2	(D)	(D)	-	-	8	2,233	66,716	-	-
Nicollet	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Norman	86	39,058	1,003,105	2	(D)	86	40,603	1,234,341	2	(D)
Otter Tail	3	978	23,116	1	(D)	2	(D)	(D)	1	(D)
Pennington	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Polk	249	96,745	2,452,048	1	(D)	235	87,000	2,714,375	2	(D)
Pope	4	418	11,960	-	-	7	1,871	53,419	2	(D)
Red Lake	2	(D)	(D)	-	-	4	1,493	44,881	-	-
Redwood	33	6,901	174,072	-	-	20	5,710	162,528	-	-
Renville	87	35,122	894,561	-	-	121	45,729	1,299,319	2	(D)
Roseau	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Sibley	19	6,049	150,505	-	-	11	2,953	86,591	-	-
Stearns	12	10,294	302,794	7	5,490	4	3,140	94,420	2	(D)
Stevens	34	10,884	280,943	6	780	18	5,433	164,846	9	947
Swift	19	8,256	236,427	4	212	18	5,198	152,663	2	(D)
Traverse	10	4,248	86,066	-	-	14	5,452	158,811	-	-
Wilkin	71	33,147	685,888	2	(D)	96	37,204	1,055,343	-	-
Yellow Medicine	8	2,469	62,592	-	-	8	1,930	48,943	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
SUNFLOWER SEED, ALL (POUNDS)										
State Total										
Minnesota	221	66,924	151,726,117	2	(D)	165	36,214	74,066,478	4	266
Counties										
Aitkin	1	(D)	(D)	-	-	-	-	-	-	-
Becker	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Beltrami	-	-	-	-	-	1	(D)	(D)	-	-
Carlton	1	(D)	(D)	-	-	-	-	-	-	-
Clay	22	8,598	22,687,794	-	-	9	2,181	4,636,519	-	-
Clearwater	1	(D)	(D)	-	-	-	-	-	-	-
Cook	1	(D)	(D)	1	(D)	-	-	-	-	-
Crow Wing	9	1,632	2,358,000	-	-	1	(D)	(D)	-	-
Douglas	-	-	-	-	-	2	(D)	(D)	-	-
Grant	-	-	-	-	-	2	(D)	(D)	-	-
Hubbard	3	25	29,800	-	-	2	(D)	(D)	-	-
Kanabec	6	246	486,000	-	-	-	-	-	-	-
Kittson	24	9,401	20,588,806	-	-	21	4,548	9,405,403	-	-
Lac qui Parle	1	(D)	(D)	-	-	-	-	-	-	-
Lake of the Woods	4	2,037	4,074,592	-	-	2	(D)	(D)	-	-
Mahnomen	2	(D)	(D)	-	-	3	643	1,596,564	-	-
Marshall	39	13,662	31,458,017	-	-	21	6,189	13,859,659	-	-
Mille Lacs	3	72	17,900	-	-	4	(D)	11,400	-	-
Morrison	4	230	460,000	-	-	5	585	1,520,404	-	-
Mower	3	144	270,000	-	-	-	-	-	-	-
Norman	12	3,678	8,564,000	-	-	5	447	917,075	-	-
Otter Tail	6	411	806,550	-	-	5	206	349,769	2	(D)
Pennington	4	934	1,680,000	-	-	1	(D)	(D)	-	-
Pipestone	1	(D)	(D)	-	-	-	-	-	-	-
Polk	25	7,106	16,952,154	-	-	19	4,620	9,389,510	1	(D)
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	5	1,288	2,659,200	-	-	2	(D)	(D)	-	-
Rock	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Roseau	20	8,098	19,033,933	-	-	18	7,502	16,952,022	-	-
St. Louis	-	-	-	-	-	2	(D)	(D)	-	-
Steele	-	-	-	-	-	5	175	156,490	-	-
Stevens	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Todd	-	-	-	-	-	3	209	332,953	-	-
Traverse	3	912	1,824,000	-	-	1	(D)	(D)	-	-
Wadena	7	479	658,014	1	(D)	13	780	737,612	1	(D)
Washington	-	-	-	-	-	2	(D)	(D)	-	-
Wilkin	7	3,892	9,927,600	-	-	11	3,124	5,116,901	-	-
Yellow Medicine	3	807	1,251,640	-	-	1	(D)	(D)	-	-
SUNFLOWER SEED, OIL VARIETIES (POUNDS)										
State Total										
Minnesota	207	62,065	139,161,307	2	(D)	148	33,562	70,823,217	3	(D)
Counties										
Aitkin	1	(D)	(D)	-	-	-	-	-	-	-
Becker	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Beltrami	-	-	-	-	-	1	(D)	(D)	-	-
Carlton	1	(D)	(D)	-	-	-	-	-	-	-
Clay	22	8,598	22,687,794	-	-	9	2,181	4,636,519	-	-
Clearwater	1	(D)	(D)	-	-	-	-	-	-	-
Cook	1	(D)	(D)	1	(D)	-	-	-	-	-
Crow Wing	9	1,632	2,358,000	-	-	1	(D)	(D)	-	-
Douglas	-	-	-	-	-	2	(D)	(D)	-	-
Grant	-	-	-	-	-	1	(D)	(D)	-	-
Hubbard	3	25	29,800	-	-	2	(D)	(D)	-	-
Kanabec	6	246	486,000	-	-	-	-	-	-	-
Kittson	24	9,401	20,588,806	-	-	21	4,548	9,405,403	-	-
Lac qui Parle	1	(D)	(D)	-	-	-	-	-	-	-
Lake of the Woods	4	2,037	4,074,592	-	-	2	(D)	(D)	-	-
Mahnomen	2	(D)	(D)	-	-	3	643	1,596,564	-	-
Marshall	39	(D)	(D)	-	-	21	6,189	13,859,659	-	-
Mille Lacs	3	72	17,900	-	-	2	(D)	(D)	-	-
Morrison	4	230	460,000	-	-	5	585	1,520,404	-	-
Norman	8	1,708	2,358,000	-	-	5	447	917,075	-	-
Otter Tail	6	411	806,550	-	-	4	(D)	(D)	2	(D)
Pennington	4	934	1,680,000	-	-	1	(D)	(D)	-	-
Pipestone	1	(D)	(D)	-	-	-	-	-	-	-
Polk	24	(D)	(D)	-	-	17	(D)	(D)	-	-
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	5	1,288	2,659,200	-	-	2	(D)	(D)	-	-
Rock	1	(D)	(D)	-	-	-	-	-	-	-
Roseau	15	6,502	15,031,763	-	-	18	7,502	16,952,022	-	-
St. Louis	-	-	-	-	-	2	(D)	(D)	-	-
Stevens	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Todd	-	-	-	-	-	3	209	332,953	-	-
Traverse	3	912	1,824,000	-	-	1	(D)	(D)	-	-
Wadena	7	479	658,014	1	(D)	13	780	737,612	1	(D)
Wilkin	7	3,892	9,927,600	-	-	9	(D)	(D)	-	-
Yellow Medicine	2	(D)	(D)	-	-	-	-	-	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
SUNFLOWER SEED, NON-OIL VARIETIES (POUNDS)										
State Total										
Minnesota	15	4,859	12,564,810	-	-	17	2,652	3,243,261	1	(D)
Counties										
Grant	-	-	-	-	-	1	(D)	(D)	-	-
Marshall	1	(D)	(D)	-	-	-	-	-	-	-
Mille Lacs	-	-	-	-	-	2	(D)	(D)	-	-
Mower	3	144	270,000	-	-	-	-	-	-	-
Norman	4	1,970	6,206,000	-	-	-	-	-	-	-
Otter Tail	-	-	-	-	-	1	(D)	(D)	-	-
Polk	1	(D)	(D)	-	-	2	(D)	(D)	1	(D)
Rock	-	-	-	-	-	1	(D)	(D)	-	-
Roseau	5	1,596	4,002,170	-	-	-	-	-	-	-
Steele	-	-	-	-	-	5	175	156,490	-	-
Washington	-	-	-	-	-	2	(D)	(D)	-	-
Wilkin	-	-	-	-	-	2	(D)	(D)	-	-
Yellow Medicine	1	(D)	(D)	-	-	1	(D)	(D)	-	-
TRITICALE FOR GRAIN (BUSHELS)										
State Total										
Minnesota	10	284	15,214	1	(D)	18	825	60,097	-	-
Counties										
Becker	2	(D)	(D)	-	-	-	-	-	-	-
Clearwater	-	-	-	-	-	1	(D)	(D)	-	-
Crow Wing	-	-	-	-	-	3	226	10,212	-	-
Dakota	1	(D)	(D)	1	(D)	-	-	-	-	-
Douglas	2	(D)	(D)	-	-	-	-	-	-	-
Freeborn	2	(D)	(D)	-	-	-	-	-	-	-
Goodhue	2	(D)	(D)	-	-	-	-	-	-	-
Lyon	-	-	-	-	-	2	(D)	(D)	-	-
Norman	-	-	-	-	-	1	(D)	(D)	-	-
Rock	-	-	-	-	-	6	174	17,400	-	-
Stearns	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Steele	-	-	-	-	-	1	(D)	(D)	-	-
Todd	-	-	-	-	-	1	(D)	(D)	-	-
Winona	-	-	-	-	-	2	(D)	(D)	-	-
WHEAT FOR GRAIN, ALL (BUSHELS)										
State Total										
Minnesota	3,669	1,268,681	82,039,945	52	6,251	4,284	1,197,036	79,313,793	45	6,999
Counties										
Aitkin	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Anoka	-	-	-	-	-	2	(D)	(D)	-	-
Becker	99	23,468	1,521,552	1	(D)	132	29,990	1,938,965	3	2,316
Beltrami	25	9,873	505,116	2	(D)	20	6,305	385,774	-	-
Benton	12	206	9,327	-	-	7	278	9,341	-	-
Big Stone	41	2,492	133,362	-	-	85	11,930	675,227	-	-
Blue Earth	6	102	5,951	-	-	8	(D)	63,315	-	-
Brown	27	930	44,762	1	(D)	35	996	51,262	-	-
Carlton	3	(D)	505	-	-	1	(D)	(D)	-	-
Carver	22	537	18,676	-	-	23	518	27,002	-	-
Cass	10	705	23,855	-	-	-	-	-	-	-
Chippewa	25	1,164	47,916	-	-	43	2,224	129,532	-	-
Chisago	4	141	(D)	-	-	10	281	8,104	-	-
Clay	199	65,878	4,108,121	10	582	236	70,262	4,479,793	2	(D)
Clearwater	19	3,402	187,283	-	-	28	4,556	264,851	-	-
Cottonwood	14	922	42,551	-	-	15	1,395	82,778	-	-
Crow Wing	3	474	22,260	-	-	3	(D)	(D)	-	-
Dakota	18	646	22,225	3	(D)	22	620	27,374	-	-
Dodge	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Douglas	73	5,821	266,592	-	-	122	10,702	562,137	-	-
Faribault	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Fillmore	6	619	27,912	-	-	-	-	-	-	-
Freeborn	3	(D)	(D)	-	-	3	206	4,170	-	-
Goodhue	24	931	38,626	1	(D)	1	(D)	(D)	-	-
Grant	43	7,963	471,155	1	(D)	85	12,993	826,139	-	-
Hennepin	5	113	4,500	-	-	7	157	7,662	-	-
Houston	7	309	18,202	-	-	3	45	2,610	-	-
Hubbard	6	314	10,275	-	-	5	1,203	(D)	1	(D)
Isanti	7	680	22,654	-	-	4	420	27,592	-	-
Itasca	1	(D)	(D)	-	-	4	(D)	(D)	-	-
Jackson	7	250	13,405	-	-	8	90	3,605	-	-
Kanabec	15	2,243	44,104	-	-	9	642	34,714	-	-
Kandiyohi	38	2,963	140,190	-	-	39	2,482	137,437	2	(D)
Kittson	214	170,257	11,514,162	1	(D)	158	96,775	6,580,132	-	-
Koochiching	7	1,308	79,500	-	-	7	965	47,148	-	-
Lac qui Parle	22	970	45,939	2	(D)	66	3,300	179,132	-	-
Lake of the Woods	20	11,175	725,625	-	-	31	7,628	449,357	-	-
Le Sueur	20	1,017	63,906	-	-	29	661	43,630	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
WHEAT FOR GRAIN, ALL (BUSHELS) - Con.										
Counties - Con.										
Lincoln	32	1,977	103,898	-	-	61	4,460	274,911	-	-
Lyon	22	1,363	80,045	-	-	38	2,859	155,912	-	-
McLeod	26	984	51,869	-	-	55	1,675	74,029	-	-
Mahnomen	93	32,220	2,208,782	-	-	99	24,808	1,565,759	-	-
Marshall	404	217,709	13,634,836	2	(D)	360	189,873	12,732,501	1	(D)
Martin	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Meeker	13	513	24,196	-	-	34	1,155	67,200	-	-
Mille Lacs	10	435	10,650	-	-	9	492	22,148	-	-
Morrison	19	1,764	42,079	-	-	25	1,449	62,330	-	-
Mower	8	376	18,044	-	-	5	118	6,739	-	-
Murray	4	286	15,317	-	-	7	389	26,298	-	-
Nicollet	22	629	40,127	-	-	29	1,016	59,396	-	-
Nobles	5	515	40,545	-	-	11	493	38,689	-	-
Norman	203	101,089	6,851,314	1	(D)	231	104,755	7,050,610	-	-
Olmsted	4	84	4,900	-	-	4	121	3,796	-	-
Otter Tail	176	20,131	992,388	8	1,348	268	30,196	1,660,210	13	2,935
Pennington	100	57,079	3,373,899	-	-	123	60,631	4,116,652	-	-
Pine	8	349	13,565	-	-	5	280	9,711	-	-
Pipestone	7	486	19,920	-	-	24	2,049	129,122	-	-
Polk	531	278,518	20,189,206	1	(D)	486	254,680	18,362,532	2	(D)
Pope	47	3,192	140,742	4	171	63	5,318	281,606	1	(D)
Ramsey	1	(D)	(D)	1	(D)	1	(D)	(D)	1	(D)
Red Lake	140	55,005	3,470,736	1	(D)	118	56,595	3,570,094	-	-
Redwood	17	506	24,819	-	-	32	1,255	56,939	-	-
Renville	45	3,050	175,764	-	-	41	2,290	134,865	2	(D)
Rice	13	368	20,706	-	-	15	345	20,353	-	-
Rock	2	(D)	(D)	-	-	-	-	-	-	-
Roseau	187	89,637	5,754,165	-	-	162	74,791	5,214,325	-	-
St. Louis	5	64	1,683	-	-	1	(D)	(D)	-	-
Scott	5	131	5,052	-	-	16	396	17,451	-	-
Sherburne	3	(D)	3,456	-	-	5	757	(D)	2	(D)
Sibley	25	1,312	78,957	-	-	34	1,154	71,615	-	-
Stearns	55	2,568	123,260	4	568	89	4,758	268,801	5	91
Steele	14	1,017	53,104	-	-	8	409	19,098	-	-
Stevens	41	7,848	462,844	1	(D)	78	10,109	598,637	1	(D)
Swift	22	1,921	93,639	1	(D)	44	4,275	268,922	1	(D)
Todd	43	2,712	111,215	-	-	65	5,753	242,010	2	(D)
Traverse	20	3,762	189,957	-	-	54	10,414	691,239	-	-
Wabasha	3	110	7,608	-	-	6	188	7,752	-	-
Wadena	11	1,230	72,238	5	855	12	501	24,099	2	(D)
Waseca	4	100	6,040	-	-	9	102	5,611	2	(D)
Washington	8	237	6,836	-	-	-	-	-	-	-
Watonwan	16	571	13,176	-	-	10	318	12,907	-	-
Wilkin	139	53,565	3,055,031	1	(D)	173	59,026	3,791,610	1	(D)
Winona	4	210	7,840	-	-	7	148	5,763	-	-
Wright	32	1,653	84,564	-	-	29	1,750	83,628	1	(D)
Yellow Medicine	29	2,038	100,867	-	-	80	4,104	265,041	-	-
WINTER WHEAT FOR GRAIN (BUSHELS)										
State Total										
Minnesota	102	(D)	342,295	1	(D)	161	5,069	251,488	1	(D)
Counties										
Aitkin	-	-	-	-	-	1	(D)	(D)	-	-
Anoka	-	-	-	-	-	2	(D)	(D)	-	-
Becker	-	-	-	-	-	3	81	3,370	-	-
Benton	3	48	2,008	-	-	1	(D)	(D)	-	-
Big Stone	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Brown	-	-	-	-	-	1	(D)	(D)	-	-
Carlton	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Carver	1	(D)	(D)	-	-	4	30	2,184	-	-
Cass	1	(D)	(D)	-	-	-	-	-	-	-
Chippewa	-	-	-	-	-	6	102	2,688	-	-
Chisago	2	(D)	(D)	-	-	3	70	1,394	-	-
Clay	4	220	10,488	-	-	3	(D)	(D)	-	-
Clearwater	-	-	-	-	-	2	(D)	(D)	-	-
Crow Wing	3	474	22,260	-	-	-	-	-	-	-
Dakota	1	(D)	(D)	1	(D)	6	(D)	(D)	-	-
Dodge	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Douglas	-	-	-	-	-	7	298	11,260	-	-
Fillmore	1	(D)	(D)	-	-	-	-	-	-	-
Goodhue	3	140	7,488	-	-	-	-	-	-	-
Grant	2	(D)	(D)	-	-	3	(D)	(D)	-	-
Houston	1	(D)	(D)	-	-	3	45	2,610	-	-
Jackson	-	-	-	-	-	6	(D)	(D)	-	-
Kandiyohi	-	-	-	-	-	2	(D)	(D)	-	-
Kittson	1	(D)	(D)	-	-	-	-	-	-	-
Lac qui Parle	2	(D)	(D)	-	-	5	159	8,651	-	-
Le Sueur	9	686	50,600	-	-	5	146	7,812	-	-
Lyon	8	495	35,711	-	-	-	-	-	-	-
McLeod	1	(D)	(D)	-	-	5	128	4,974	-	-
Marshall	4	217	(D)	-	-	1	(D)	(D)	-	-
Mille Lacs	-	-	-	-	-	2	(D)	(D)	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
WINTER WHEAT FOR GRAIN (BUSHELS) - Con.										
Counties - Con.										
Mower	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Murray	1	(D)	(D)	-	-	-	-	-	-	-
Nicollet	3	90	6,750	-	-	4	92	6,116	-	-
Nobles	3	(D)	(D)	-	-	-	-	-	-	-
Norman	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Olmsted	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Otter Tail	1	(D)	(D)	-	-	17	541	22,274	-	-
Pine	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Polk	3	330	15,143	-	-	1	(D)	(D)	-	-
Pope	-	-	-	-	-	3	(D)	(D)	-	-
Ramsey	-	-	-	-	-	1	(D)	(D)	1	(D)
Red Lake	-	-	-	-	-	2	(D)	(D)	-	-
Renville	1	(D)	(D)	-	-	-	-	-	-	-
Rice	5	(D)	(D)	-	-	-	-	-	-	-
Roseau	6	168	12,600	-	-	-	-	-	-	-
Scott	-	-	-	-	-	6	141	4,874	-	-
Sherburne	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Sibley	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Stearns	1	(D)	(D)	-	-	7	186	7,926	-	-
Steele	3	116	1,915	-	-	1	(D)	(D)	-	-
Stevens	-	-	-	-	-	6	244	15,531	-	-
Swift	-	-	-	-	-	1	(D)	(D)	-	-
Todd	7	256	21,720	-	-	3	76	3,890	-	-
Traverse	-	-	-	-	-	2	(D)	(D)	-	-
Wabasha	-	-	-	-	-	1	(D)	(D)	-	-
Wadena	1	(D)	(D)	-	-	-	-	-	-	-
Watonwan	-	-	-	-	-	5	76	4,560	-	-
Wilkin	1	(D)	(D)	-	-	-	-	-	-	-
Winona	1	(D)	(D)	-	-	3	92	3,079	-	-
Wright	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Yellow Medicine	-	-	-	-	-	14	458	27,294	-	-
DURUM WHEAT FOR GRAIN (BUSHELS)										
State Total										
Minnesota	31	(D)	54,556	-	-	14	1,413	85,479	-	-
Counties										
Cass	5	(D)	(D)	-	-	-	-	-	-	-
Clay	-	-	-	-	-	1	(D)	(D)	-	-
Dakota	-	-	-	-	-	1	(D)	(D)	-	-
Grant	-	-	-	-	-	1	(D)	(D)	-	-
Hennepin	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Kandiyohi	1	(D)	(D)	-	-	-	-	-	-	-
Kittson	1	(D)	(D)	-	-	-	-	-	-	-
Lac qui Parle	1	(D)	(D)	-	-	-	-	-	-	-
Mille Lacs	-	-	-	-	-	2	(D)	(D)	-	-
Norman	3	(D)	(D)	-	-	-	-	-	-	-
Otter Tail	11	(D)	(D)	-	-	-	-	-	-	-
Polk	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	-	-	-	-	-	6	(D)	(D)	-	-
Renville	2	(D)	(D)	-	-	-	-	-	-	-
Stearns	2	(D)	(D)	-	-	-	-	-	-	-
Todd	3	46	1,098	-	-	-	-	-	-	-
Wilkin	1	(D)	(D)	-	-	1	(D)	(D)	-	-
OTHER SPRING WHEAT FOR GRAIN (BUSHELS)										
State Total										
Minnesota	3,557	1,261,299	81,643,094	51	(D)	4,130	1,190,554	78,976,826	45	(D)
Counties										
Aitkin	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Becker	99	23,468	1,521,552	1	(D)	129	29,909	1,935,595	3	2,316
Beltrami	25	9,873	505,116	2	(D)	20	6,305	385,774	-	-
Benton	9	158	7,319	-	-	6	(D)	(D)	-	-
Big Stone	39	(D)	(D)	-	-	84	(D)	(D)	-	-
Blue Earth	6	102	5,951	-	-	8	(D)	63,315	-	-
Brown	27	930	44,762	1	(D)	34	(D)	(D)	-	-
Carlton	2	(D)	(D)	-	-	-	-	-	-	-
Carver	21	(D)	(D)	-	-	19	488	24,818	-	-
Cass	4	348	17,406	-	-	-	-	-	-	-
Chippewa	25	1,164	47,916	-	-	37	2,122	126,844	-	-
Chisago	2	(D)	(D)	-	-	7	211	6,710	-	-
Clay	197	65,658	4,097,633	10	582	236	69,923	4,457,276	2	(D)
Clearwater	19	3,402	187,283	-	-	26	(D)	(D)	-	-
Cottonwood	14	922	42,551	-	-	15	1,395	82,778	-	-
Crow Wing	-	-	-	-	-	3	(D)	(D)	-	-
Dakota	17	(D)	(D)	2	(D)	15	385	16,270	-	-
Douglas	73	5,821	266,592	-	-	115	10,404	550,877	-	-
Faribault	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Fillmore	6	(D)	(D)	-	-	-	-	-	-	-
Freeborn	3	(D)	(D)	-	-	3	206	4,170	-	-

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Table 25. **Field Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
OTHER SPRING WHEAT FOR GRAIN (BUSHELS) - Con.										
Counties - Con.										
Goodhue	21	791	31,138	1	(D)	1	(D)	(D)	-	-
Grant	41	(D)	(D)	1	(D)	81	12,859	819,162	-	-
Hennepin	4	(D)	(D)	-	-	6	(D)	(D)	-	-
Houston	6	(D)	(D)	-	-	-	-	-	-	-
Hubbard	6	314	10,275	-	-	5	1,203	(D)	1	(D)
Isanti	7	680	22,654	-	-	4	420	27,592	-	-
Itasca	1	(D)	(D)	-	-	4	(D)	(D)	-	-
Jackson	7	250	13,405	-	-	2	(D)	(D)	-	-
Kanabec	15	2,243	44,104	-	-	9	642	34,714	-	-
Kandiyohi	37	(D)	(D)	-	-	37	(D)	(D)	2	(D)
Kittson	213	(D)	(D)	1	(D)	158	96,775	6,580,132	-	-
Koochiching	7	1,308	79,500	-	-	7	965	47,148	-	-
Lac qui Parle	19	(D)	45,394	2	(D)	62	3,141	170,481	-	-
Lake of the Woods	20	11,175	725,625	-	-	31	7,628	449,357	-	-
Le Sueur	11	331	13,306	-	-	26	515	35,818	-	-
Lincoln	32	1,977	103,898	-	-	61	4,460	274,911	-	-
Lyon	19	868	44,334	-	-	38	2,859	155,912	-	-
McLeod	26	(D)	(D)	-	-	50	1,547	69,055	-	-
Mahnomen	93	32,220	2,208,782	-	-	99	24,808	1,565,759	-	-
Marshall	403	217,492	(D)	2	(D)	359	(D)	(D)	1	(D)
Martin	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Meeker	13	513	24,196	-	-	34	1,155	67,200	-	-
Mille Lacs	10	435	10,650	-	-	5	340	16,878	-	-
Morrison	19	1,764	42,079	-	-	25	1,449	62,330	-	-
Mower	6	(D)	(D)	-	-	4	(D)	(D)	-	-
Murray	3	(D)	(D)	-	-	7	389	26,298	-	-
Nicollet	19	539	33,377	-	-	25	924	53,280	-	-
Nobles	2	(D)	(D)	-	-	11	493	38,689	-	-
Norman	200	100,864	6,842,971	1	(D)	231	(D)	(D)	-	-
Olmsted	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Otter Tail	164	19,455	974,124	8	1,348	253	29,655	1,637,936	13	2,935
Pennington	100	57,079	3,373,899	-	-	123	60,631	4,116,652	-	-
Pine	6	(D)	(D)	-	-	4	(D)	(D)	-	-
Pipestone	7	486	19,920	-	-	24	2,049	129,122	-	-
Polk	530	278,188	20,174,063	1	(D)	486	(D)	(D)	2	(D)
Pope	47	3,192	140,742	4	171	61	(D)	(D)	1	(D)
Ramsey	1	(D)	(D)	1	(D)	1	(D)	(D)	1	(D)
Red Lake	140	55,005	3,470,736	1	(D)	112	55,518	3,501,793	-	-
Redwood	17	506	24,819	-	-	32	1,255	56,939	-	-
Renville	42	2,979	173,104	-	-	41	2,290	134,865	2	(D)
Rice	9	(D)	(D)	-	-	15	345	20,353	-	-
Rock	2	(D)	(D)	-	-	-	-	-	-	-
Roseau	181	89,469	5,741,565	-	-	162	74,791	5,214,325	-	-
St. Louis	5	64	1,683	-	-	1	(D)	(D)	-	-
Scott	5	131	5,052	-	-	10	255	12,577	-	-
Sherburne	3	(D)	(D)	-	-	4	(D)	(D)	2	(D)
Sibley	23	(D)	(D)	-	-	32	(D)	(D)	-	-
Stearns	52	2,500	120,828	4	568	82	4,572	260,875	5	91
Steele	11	901	51,189	-	-	8	(D)	(D)	-	-
Stevens	41	7,848	462,844	1	(D)	74	9,865	583,106	1	(D)
Swift	22	1,921	93,639	1	(D)	43	(D)	(D)	1	(D)
Todd	35	2,410	88,397	-	-	62	5,677	238,120	2	(D)
Traverse	20	3,762	189,957	-	-	52	(D)	(D)	-	-
Wabasha	3	110	7,608	-	-	5	(D)	(D)	-	-
Wadena	10	(D)	(D)	5	855	12	501	24,099	2	(D)
Waseca	4	100	6,040	-	-	9	102	5,611	2	(D)
Washington	8	237	6,836	-	-	-	-	-	-	-
Watonwan	16	571	13,176	-	-	5	242	8,347	-	-
Wilkin	137	(D)	(D)	1	(D)	172	(D)	(D)	1	(D)
Winona	3	(D)	(D)	-	-	4	56	2,684	-	-
Wright	30	(D)	(D)	-	-	28	(D)	(D)	1	(D)
Yellow Medicine	29	2,038	100,867	-	-	68	3,646	237,747	-	-
WILD RICE (CWT)										
State Total										
Minnesota	35	41,543	236,372	35	41,543	26	36,568	129,397	26	36,568
Counties										
Aitkin	5	4,014	31,714	5	4,014	3	2,941	16,614	3	2,941
Beltrami	18	3,908	40,323	18	3,908	8	3,433	16,775	8	3,433
Carlton	-	-	-	-	-	1	(D)	(D)	1	(D)
Cass	1	(D)	(D)	1	(D)	1	(D)	(D)	1	(D)
Clearwater	4	6,463	62,500	4	6,463	3	4,814	39,509	3	4,814
Crow Wing	-	-	-	-	-	1	(D)	(D)	1	(D)
Hubbard	1	(D)	(D)	1	(D)	1	(D)	(D)	1	(D)
Itasca	2	(D)	(D)	2	(D)	1	(D)	(D)	1	(D)
Lake of the Woods	-	-	-	-	-	3	1,185	17,775	3	1,185
Otter Tail	-	-	-	-	-	2	(D)	(D)	2	(D)
Polk	3	6,684	75,000	3	6,684	1	(D)	(D)	1	(D)
St. Louis	1	(D)	(D)	1	(D)	1	(D)	(D)	1	(D)

Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
FIELD AND GRASS SEED CROPS, ALL										
State Total										
Minnesota	155	66,601	(X)	6	505	137	37,056	(X)	4	535
Counties										
Aitkin	3	63	(X)	-	-	-	-	(X)	-	-
Anoka	-	-	(X)	-	-	2	(D)	(X)	-	-
Beltrami	5	1,045	(X)	-	-	1	(D)	(X)	-	-
Big Stone	2	(D)	(X)	-	-	-	-	(X)	-	-
Chisago	-	-	(X)	-	-	1	(D)	(X)	-	-
Clay	-	-	(X)	-	-	2	(D)	(X)	-	-
Clearwater	-	-	(X)	-	-	2	(D)	(X)	-	-
Crow Wing	-	-	(X)	-	-	2	(D)	(X)	-	-
Dakota	1	(D)	(X)	-	-	2	(D)	(X)	-	-
Dodge	-	-	(X)	-	-	6	234	(X)	-	-
Faribault	2	(D)	(X)	-	-	1	(D)	(X)	-	-
Fillmore	1	(D)	(X)	-	-	1	(D)	(X)	-	-
Houston	1	(D)	(X)	-	-	3	312	(X)	-	-
Isanti	1	(D)	(X)	-	-	1	(D)	(X)	-	-
Kanabec	2	(D)	(X)	-	-	-	-	(X)	-	-
Kittson	2	(D)	(X)	-	-	2	(D)	(X)	1	(D)
Koochiching	7	1,324	(X)	-	-	1	(D)	(X)	-	-
Lake of the Woods	15	4,792	(X)	-	-	7	1,757	(X)	-	-
Mahnomen	1	(D)	(X)	-	-	5	86	(X)	-	-
Marshall	12	9,531	(X)	-	-	20	8,785	(X)	-	-
Meeker	1	(D)	(X)	-	-	1	(D)	(X)	-	-
Morrison	2	(D)	(X)	-	-	-	-	(X)	-	-
Mower	-	-	(X)	-	-	2	(D)	(X)	-	-
Nicollet	3	90	(X)	3	90	-	-	(X)	-	-
Norman	-	-	(X)	-	-	2	(D)	(X)	-	-
Otter Tail	2	(D)	(X)	2	(D)	-	-	(X)	-	-
Pennington	7	2,721	(X)	-	-	3	1,214	(X)	-	-
Polk	5	4,220	(X)	-	-	2	(D)	(X)	-	-
Red Lake	12	3,436	(X)	-	-	6	864	(X)	1	(D)
Rock	1	(D)	(X)	-	-	1	(D)	(X)	-	-
Roseau	59	33,675	(X)	-	-	45	17,491	(X)	-	-
St. Louis	-	-	(X)	-	-	6	234	(X)	-	-
Sherburne	3	519	(X)	1	(D)	3	1,020	(X)	-	-
Stearns	-	-	(X)	-	-	2	(D)	(X)	1	(D)
Todd	-	-	(X)	-	-	1	(D)	(X)	-	-
Wadena	-	-	(X)	-	-	1	(D)	(X)	1	(D)
Washington	-	-	(X)	-	-	2	(D)	(X)	-	-
Wright	1	(D)	(X)	-	-	1	(D)	(X)	-	-
Yellow Medicine	4	26	(X)	-	-	-	-	(X)	-	-
BIRDSFOOT TREFOIL SEED (POUNDS)										
State Total										
Minnesota	-	-	-	-	-	8	104	6,240	-	-
Counties										
Clearwater	-	-	-	-	-	2	(D)	(D)	-	-
St. Louis	-	-	-	-	-	6	(D)	(D)	-	-
BROMEGRASS SEED (POUNDS)										
State Total										
Minnesota	1	(D)	(D)	-	-	2	(D)	(D)	1	(D)
Counties										
Houston	-	-	-	-	-	1	(D)	(D)	-	-
Stearns	-	-	-	-	-	1	(D)	(D)	1	(D)
Yellow Medicine	1	(D)	(D)	-	-	-	-	-	-	-
FESCUE SEED (POUNDS)										
State Total										
Minnesota	12	5,119	5,604,932	-	-	5	675	(D)	1	(D)
Counties										
Mahnomen	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Marshall	2	(D)	(D)	-	-	-	-	-	-	-
Pennington	5	(D)	1,495,190	-	-	1	(D)	(D)	-	-
Polk	1	(D)	(D)	-	-	-	-	-	-	-
Red Lake	2	(D)	(D)	-	-	1	(D)	(D)	1	(D)
Roseau	1	(D)	(D)	-	-	-	-	-	-	-
Wright	-	-	-	-	-	1	(D)	(D)	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
KENTUCKY BLUEGRASS SEED (POUNDS)										
State Total										
Minnesota	7	2,588	875,630	-	-	7	1,484	316,580	-	-
Counties										
Anoka	-	-	-	-	-	2	(D)	(D)	-	-
Roseau	7	2,588	875,630	-	-	5	(D)	(D)	-	-
ORCHARDGRASS SEED (POUNDS)										
State Total										
Minnesota	2	(D)	(D)	-	-	-	-	-	-	-
Counties										
Kanabec	2	(D)	(D)	-	-	-	-	-	-	-
RED CLOVER SEED (POUNDS)										
State Total										
Minnesota	2	(D)	(D)	-	-	10	309	31,800	-	-
Counties										
Beltrami	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Crow Wing	-	-	-	-	-	2	(D)	(D)	-	-
St. Louis	-	-	-	-	-	6	(D)	10,800	-	-
Todd	-	-	-	-	-	1	(D)	(D)	-	-
RYEGRASS SEED (POUNDS)										
State Total										
Minnesota	112	53,935	51,155,950	-	-	93	27,908	27,187,045	-	-
Counties										
Beltrami	3	(D)	718,533	-	-	-	-	-	-	-
Chisago	-	-	-	-	-	1	(D)	(D)	-	-
Dodge	-	-	-	-	-	6	234	273,756	-	-
Fillmore	-	-	-	-	-	1	(D)	(D)	-	-
Houston	-	-	-	-	-	1	(D)	(D)	-	-
Isanti	1	(D)	(D)	-	-	-	-	-	-	-
Kittson	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Koochiching	7	1,324	1,493,350	-	-	1	(D)	(D)	-	-
Lake of the Woods	15	(D)	3,877,414	-	-	6	(D)	1,220,652	-	-
Marshall	10	(D)	10,578,150	-	-	20	8,785	10,589,372	-	-
Morrison	1	(D)	(D)	-	-	-	-	-	-	-
Pennington	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Polk	1	(D)	(D)	-	-	-	-	-	-	-
Red Lake	11	(D)	1,883,995	-	-	5	(D)	602,376	-	-
Rock	-	-	-	-	-	1	(D)	(D)	-	-
Roseau	57	(D)	28,177,617	-	-	41	15,213	13,143,606	-	-
St. Louis	-	-	-	-	-	6	42	10,080	-	-
Sherburne	1	(D)	(D)	-	-	-	-	-	-	-
Stearns	-	-	-	-	-	1	(D)	(D)	-	-
Wright	1	(D)	(D)	-	-	-	-	-	-	-
TIMOTHY SEED (POUNDS)										
State Total										
Minnesota	-	-	-	-	-	3	530	191,000	-	-
Counties										
Lake of the Woods	-	-	-	-	-	1	(D)	(D)	-	-
Norman	-	-	-	-	-	1	(D)	(D)	-	-
Roseau	-	-	-	-	-	1	(D)	(D)	-	-
VETCH SEED (POUNDS)										
State Total										
Minnesota	10	259	63,096	-	-	9	395	170,587	1	(D)
Counties										
Aitkin	3	63	26,460	-	-	-	-	-	-	-
Crow Wing	-	-	-	-	-	2	(D)	(D)	-	-
Faribault	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Houston	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Meeker	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Mower	-	-	-	-	-	2	(D)	(D)	-	-
Wadena	-	-	-	-	-	1	(D)	(D)	1	(D)
Yellow Medicine	3	(D)	3,000	-	-	-	-	-	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
WHEATGRASS SEED (POUNDS)										
State Total										
Minnesota	7	215	155,280	3	90	2	(D)	(D)	-	-
Counties										
Big Stone	2	(D)	(D)	-	-	-	-	-	-	-
Dakota	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Nicollet	3	90	90,000	3	90	-	-	-	-	-
Rock	1	(D)	(D)	-	-	-	-	-	-	-
Roseau	-	-	-	-	-	1	(D)	(D)	-	-
OTHER FIELD AND GRASS SEED CROPS (POUNDS)										
State Total										
Minnesota	12	4,322	1,478,589	3	415	18	5,321	2,272,250	1	(D)
Counties										
Clay	-	-	-	-	-	2	(D)	(D)	-	-
Dakota	-	-	-	-	-	1	(D)	(D)	-	-
Fillmore	1	(D)	(D)	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	1	(D)	(D)	-	-
Kittson	-	-	-	-	-	1	(D)	(D)	1	(D)
Lake of the Woods	1	(D)	(D)	-	-	-	-	-	-	-
Mahnomen	-	-	-	-	-	3	(D)	1,200	-	-
Morrison	1	(D)	(D)	-	-	-	-	-	-	-
Norman	-	-	-	-	-	1	(D)	(D)	-	-
Otter Tail	2	(D)	(D)	2	(D)	-	-	-	-	-
Polk	3	(D)	(D)	-	-	2	(D)	(D)	-	-
Roseau	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Sherburne	2	(D)	(D)	1	(D)	3	1,020	153,000	-	-
Washington	-	-	-	-	-	2	(D)	(D)	-	-
Wright	1	(D)	(D)	-	-	-	-	-	-	-
FORAGE - LAND USED FOR ALL HAY AND HAYLAGE, GRASS SILAGE, AND GREENCHOP (TONS, DRY EQUIVALENT)										
State Total										
Minnesota	23,394	1,392,072	3,565,994	675	32,954	25,835	1,448,195	3,877,087	479	26,872
Counties										
Aitkin	358	37,051	54,042	13	352	354	34,574	56,926	-	-
Anoka	139	3,857	10,153	3	22	155	5,857	11,690	4	42
Becker	414	37,073	81,264	15	1,232	440	32,358	73,481	9	748
Beltrami	358	32,939	55,330	2	(D)	344	34,128	71,498	1	(D)
Benton	354	16,115	37,028	27	1,645	459	20,256	53,395	23	963
Big Stone	78	5,970	18,704	-	-	100	4,108	11,039	1	(D)
Blue Earth	132	2,898	8,376	1	(D)	147	3,659	8,387	-	-
Brown	201	6,860	27,917	9	179	229	6,800	25,869	4	190
Carlton	350	28,711	43,598	3	202	426	34,755	66,240	-	-
Carver	294	12,681	43,689	1	(D)	359	12,340	46,658	1	(D)
Cass	322	33,900	49,840	4	49	291	33,959	54,786	5	407
Chippewa	76	4,661	11,135	-	-	83	3,834	10,055	1	(D)
Chisago	297	9,384	19,935	1	(D)	345	11,798	27,898	4	118
Clay	194	15,971	47,445	1	(D)	197	16,780	52,141	3	259
Clearwater	253	31,653	62,668	4	204	250	31,895	78,944	1	(D)
Cook	13	204	120	1	(D)	8	(D)	(D)	-	-
Cottonwood	132	3,357	11,507	-	-	143	3,540	10,732	4	17
Crow Wing	260	17,548	28,458	-	-	304	21,486	33,907	-	-
Dakota	246	8,477	24,927	42	2,202	259	7,864	27,512	30	1,454
Dodge	212	6,261	24,726	6	77	192	5,544	20,128	2	(D)
Douglas	338	13,046	32,220	10	137	374	16,013	47,580	5	173
Faribault	78	2,015	5,912	5	117	94	2,391	8,777	-	-
Fillmore	591	33,931	131,742	7	108	619	30,469	128,940	3	45
Freeborn	226	4,732	12,830	6	40	216	4,679	16,853	-	-
Goodhue	546	25,556	117,740	8	275	599	25,760	92,531	2	(D)
Grant	67	2,540	8,388	4	161	59	2,278	8,113	2	(D)
Hennepin	193	4,944	11,430	4	50	199	6,556	14,351	-	-
Houston	405	29,275	103,956	5	58	478	28,938	100,635	8	73
Hubbard	175	12,356	16,135	11	1,217	224	15,402	22,618	13	883
Isanti	375	13,174	24,434	14	229	369	10,965	23,863	2	(D)
Itasca	283	27,535	40,777	6	196	248	20,724	31,775	-	-
Jackson	121	3,973	10,761	-	-	151	4,089	12,384	-	-
Kanabec	345	20,630	32,686	2	(D)	439	24,495	41,053	4	88
Kandiyohi	335	16,369	44,647	14	549	310	16,930	54,017	8	528
Kittson	93	13,484	35,349	4	36	103	16,793	31,194	-	-
Koochiching	121	13,342	27,039	-	-	128	15,868	30,517	-	-
Lac qui Parle	115	5,056	15,739	-	-	179	7,725	24,739	1	(D)
Lake	11	126	115	-	-	21	945	1,416	-	-
Lake of the Woods	70	7,218	14,231	-	-	56	7,095	9,140	-	-
Le Sueur	240	4,654	11,139	2	(D)	248	4,637	14,345	-	-
Lincoln	135	5,326	16,775	-	-	197	9,149	29,549	-	-
Lyon	198	7,154	25,991	-	-	235	7,404	28,247	-	-
McLeod	281	8,110	27,383	5	28	317	11,348	35,035	-	-
Mahnomen	92	7,261	17,652	1	(D)	122	7,159	18,380	1	(D)

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
FORAGE - LAND USED FOR ALL HAY AND HAYLAGE, GRASS SILAGE, AND GREENCHOP (TONS, DRY EQUIVALENT) - Con.										
Counties - Con.										
Marshall	239	22,450	60,430	4	301	209	22,680	50,736	1	(D)
Martin	94	2,328	4,819	-	-	114	2,515	6,639	1	(D)
Meeker	279	15,701	44,283	16	1,068	277	10,431	30,781	5	522
Mille Lacs	387	19,030	37,147	3	159	463	21,050	36,337	3	74
Morrison	994	57,013	132,991	48	2,038	1,190	65,403	152,176	34	1,745
Mower	239	6,705	21,271	4	89	286	9,026	31,638	4	189
Murray	214	10,009	30,468	-	-	225	10,101	40,156	-	-
Nicollet	134	4,505	10,159	-	-	169	5,618	23,033	-	-
Nobles	215	7,170	23,059	-	-	216	8,043	30,251	1	(D)
Norman	108	9,084	23,527	-	-	103	7,263	16,823	-	-
Olmsted	438	19,009	71,139	7	62	465	20,491	75,918	-	-
Otter Tail	1,032	73,435	177,089	81	5,249	1,125	81,319	237,962	71	6,289
Pennington	95	13,969	37,558	-	-	144	22,228	64,447	-	-
Pine	528	45,525	78,101	7	99	597	41,642	85,099	5	322
Pipestone	228	11,017	27,534	2	(D)	253	10,325	43,843	2	(D)
Polk	220	19,520	60,995	3	18	242	27,595	63,554	-	-
Pope	229	17,386	49,962	23	1,195	253	13,150	42,104	17	886
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	77	6,937	20,638	-	-	69	5,081	14,667	-	-
Redwood	173	4,263	13,848	1	(D)	195	7,134	22,184	-	-
Renville	133	4,039	13,912	-	-	136	4,553	15,344	1	(D)
Rice	383	11,080	31,527	7	17	439	13,113	37,152	-	-
Rock	197	8,005	33,188	-	-	280	7,463	23,034	-	-
Roseau	262	30,953	58,696	-	-	264	31,777	68,329	-	-
St. Louis	510	59,337	92,598	9	553	494	45,623	76,298	4	(D)
Scott	277	7,048	19,797	-	-	341	10,047	27,537	-	-
Sherburne	156	4,555	6,748	7	172	155	5,696	12,254	13	562
Sibley	261	7,790	24,003	-	-	303	7,649	23,262	-	-
Stearns	1,490	90,305	269,036	104	6,261	1,695	95,352	306,700	101	5,580
Steele	183	4,085	11,414	3	38	194	5,409	15,632	3	140
Stevens	103	10,836	38,674	6	464	109	9,301	29,300	3	(D)
Swift	115	7,336	27,478	4	189	131	6,806	22,131	4	292
Todd	865	45,723	105,683	40	3,295	933	49,406	126,633	18	1,337
Traverse	57	5,718	23,724	-	-	50	3,610	11,097	1	(D)
Wabasha	386	31,201	125,045	2	(D)	415	29,597	111,908	1	(D)
Wadena	293	20,167	39,325	21	1,102	328	23,457	43,833	27	1,387
Waseca	105	2,289	7,161	-	-	165	3,386	12,197	2	(D)
Washington	169	5,600	9,607	1	(D)	238	8,517	20,324	2	(D)
Watonwan	63	1,009	2,426	3	(D)	73	928	2,417	-	-
Wilkin	58	5,133	10,051	2	(D)	61	6,015	19,198	2	(D)
Winona	517	42,174	179,296	2	(D)	595	38,502	163,440	2	(D)
Wright	611	18,476	43,500	23	362	614	18,285	44,200	6	181
Yellow Medicine	160	6,779	22,154	1	(D)	156	9,050	28,817	3	75
HAY - ALL HAY INCLUDING ALFALFA AND OTHER DRY HAY (TONS, DRY)										
State Total										
Minnesota	21,207	1,134,538	2,629,928	530	19,607	23,737	1,210,924	3,002,173	386	17,270
Counties										
Aitkin	308	34,387	48,129	8	92	306	32,434	53,942	-	-
Anoka	136	3,794	9,851	3	22	148	5,699	11,315	4	42
Becker	383	30,629	66,414	7	452	404	27,776	59,826	5	130
Beltrami	324	29,805	49,875	2	(D)	319	31,234	64,623	1	(D)
Benton	325	12,270	22,268	16	631	423	17,195	41,405	22	853
Big Stone	74	5,547	18,494	-	-	97	3,838	10,610	1	(D)
Blue Earth	124	2,807	7,957	1	(D)	135	3,501	7,703	-	-
Brown	184	5,343	18,397	7	49	208	5,501	18,756	4	115
Carlton	302	24,468	32,151	3	202	389	30,210	57,454	-	-
Carver	272	9,948	25,838	1	(D)	330	9,400	32,946	1	(D)
Cass	305	31,831	46,996	1	(D)	270	32,582	52,765	5	407
Chippewa	54	1,228	4,392	-	-	79	3,121	8,303	1	(D)
Chisago	277	8,572	15,896	1	(D)	331	10,733	24,410	2	(D)
Clay	178	14,686	43,200	1	(D)	185	16,066	49,403	3	259
Clearwater	238	28,106	57,666	4	204	241	31,417	76,189	1	(D)
Cook	10	123	89	-	-	7	(D)	(D)	-	-
Cottonwood	116	2,902	8,313	-	-	134	3,001	8,184	2	(D)
Crow Wing	221	15,146	25,059	-	-	273	20,033	31,245	-	-
Dakota	223	6,335	15,322	33	1,172	249	6,377	21,251	27	950
Dodge	192	4,795	14,923	4	67	180	3,470	11,147	2	(D)
Douglas	311	11,628	29,912	10	137	362	15,244	43,424	5	140
Faribault	59	1,246	2,874	3	47	78	1,720	6,378	-	-
Fillmore	559	26,845	91,253	6	41	590	22,308	87,522	3	45
Freeborn	211	4,309	12,003	6	40	191	3,771	14,216	-	-
Goodhue	506	18,623	64,893	8	254	543	17,996	62,254	2	(D)
Grant	60	2,420	8,129	2	(D)	59	2,243	7,780	2	(D)
Hennepin	172	4,396	9,836	3	43	186	5,696	12,853	-	-
Houston	375	19,044	59,923	3	(D)	428	20,099	59,488	8	73
Hubbard	152	10,243	13,566	9	797	215	14,682	21,391	13	588
Isanti	350	12,595	23,119	14	229	345	10,144	21,095	-	-
Itasca	242	24,547	36,202	3	180	223	19,136	29,070	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
HAY - ALL HAY INCLUDING ALFALFA AND OTHER DRY HAY (TONS, DRY) - Con.										
Counties - Con.										
Jackson	115	3,683	8,943	-	-	138	3,759	10,659	-	-
Kanabec	311	18,463	29,654	2	(D)	405	23,142	39,667	4	88
Kandiyohi	302	10,865	27,746	12	429	289	11,232	33,451	8	478
Kittson	86	12,822	34,694	4	36	92	15,930	30,789	-	-
Koochiching	107	12,090	22,545	-	-	117	14,952	29,624	-	-
Lac qui Parle	106	4,633	14,072	-	-	162	7,027	23,437	1	(D)
Lake	7	85	70	-	-	18	882	1,355	-	-
Lake of the Woods	56	6,179	11,427	-	-	46	6,553	8,551	-	-
Le Sueur	222	3,814	9,049	1	(D)	228	3,608	10,923	-	-
Lincoln	120	4,266	12,395	-	-	189	8,399	25,733	-	-
Lyon	185	6,275	21,966	-	-	222	6,438	23,695	-	-
McLeod	268	6,272	20,126	5	28	296	7,518	21,355	-	-
Mahnomen	91	7,023	16,954	1	(D)	116	6,556	16,898	-	-
Marshall	224	21,264	57,129	4	301	192	20,963	45,502	1	(D)
Martin	90	1,905	4,529	-	-	98	2,003	5,259	1	(D)
Meeker	258	12,662	29,117	13	468	264	7,779	21,242	2	(D)
Mille Lacs	344	16,437	30,255	3	115	421	18,838	32,866	3	74
Morrison	891	45,301	93,819	29	1,327	1,048	52,040	117,088	20	1,016
Mower	210	4,496	14,901	3	45	268	6,799	22,058	2	(D)
Murray	205	8,907	26,672	-	-	221	8,378	33,857	-	-
Nicollet	107	3,305	6,407	-	-	153	4,182	17,570	-	-
Nobles	178	5,244	13,612	-	-	199	6,574	21,454	1	(D)
Norman	102	8,724	23,075	-	-	101	7,173	16,675	-	-
Olmsted	402	13,696	44,221	7	62	425	13,489	40,744	-	-
Otter Tail	964	62,598	135,626	67	3,484	1,057	72,158	198,408	56	4,702
Pennington	93	13,668	37,257	-	-	141	21,217	59,694	-	-
Pine	487	40,366	69,074	7	99	547	35,414	68,917	4	82
Pipestone	207	7,632	18,361	2	(D)	230	8,907	33,722	2	(D)
Polk	217	18,475	56,843	3	18	231	25,686	57,601	-	-
Pope	210	13,980	42,178	20	1,019	239	11,859	37,411	15	694
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	67	5,777	17,016	-	-	58	4,255	11,859	-	-
Redwood	148	3,255	9,845	1	(D)	189	6,515	19,800	-	-
Renville	129	3,035	10,013	-	-	130	3,561	11,852	-	-
Rice	357	9,427	23,578	5	7	409	10,309	27,418	-	-
Rock	179	6,805	25,792	-	-	263	5,972	18,340	-	-
Roseau	251	29,365	52,488	-	-	249	30,480	66,516	-	-
St. Louis	446	53,962	82,601	9	310	427	40,796	71,183	3	(D)
Scott	255	5,392	12,397	-	-	319	8,049	19,895	-	-
Sherburne	143	4,177	6,381	6	152	144	4,861	10,867	13	562
Sibley	241	5,949	17,186	-	-	272	6,001	16,783	-	-
Stearns	1,297	58,717	161,344	80	3,201	1,502	67,771	192,443	73	2,564
Steele	166	3,073	9,244	3	38	179	4,294	11,420	3	140
Stevens	85	4,215	13,064	4	(D)	98	3,704	12,478	2	(D)
Swift	105	4,867	13,767	4	189	113	4,541	13,923	4	292
Todd	792	36,617	80,963	35	1,852	884	41,416	102,759	13	547
Traverse	46	4,221	17,144	-	-	44	2,628	9,010	1	(D)
Wabasha	325	17,579	59,770	1	(D)	336	16,881	54,708	-	-
Wadena	257	16,881	32,855	16	690	296	20,828	36,543	23	1,006
Waseca	86	1,737	5,322	-	-	150	2,870	10,970	2	(D)
Washington	155	5,275	8,256	1	(D)	227	7,717	17,828	2	(D)
Watonwan	60	995	2,124	3	(D)	71	900	2,387	-	-
Wilkin	51	4,811	9,204	1	(D)	54	5,867	18,775	2	(D)
Winona	445	23,740	94,270	2	(D)	524	20,730	71,862	2	(D)
Wright	556	14,300	29,150	16	201	568	15,344	32,647	6	181
Yellow Medicine	157	6,618	20,497	1	(D)	149	8,381	26,411	3	75
ALFALFA HAY (TONS, DRY)										
State Total										
Minnesota	15,333	744,117	1,971,568	421	15,949	17,865	828,937	2,345,020	338	15,364
Counties										
Aitkin	105	8,026	10,736	-	-	126	7,006	13,319	-	-
Anoka	81	2,123	7,055	1	(D)	109	4,074	7,553	3	(D)
Becker	302	23,909	57,250	7	452	342	21,512	50,062	5	130
Beltrami	252	21,430	37,366	1	(D)	270	27,116	58,820	-	-
Benton	185	6,358	12,242	16	(D)	239	9,340	26,359	19	719
Big Stone	64	4,067	15,691	-	-	80	2,377	8,642	1	(D)
Blue Earth	92	1,559	3,955	-	-	104	2,550	5,651	-	-
Brown	117	3,289	13,964	3	9	150	4,316	16,034	4	115
Carlton	156	13,759	18,633	3	202	209	14,405	31,824	-	-
Carver	196	7,996	21,457	1	(D)	252	7,085	27,267	1	(D)
Cass	129	8,529	14,314	1	(D)	115	10,178	22,270	4	(D)
Chippewa	45	1,111	4,265	-	-	66	1,568	5,296	1	(D)
Chisago	172	5,549	11,516	1	(D)	244	7,389	18,855	2	(D)
Clay	151	11,282	37,493	-	-	161	12,794	44,643	3	259
Clearwater	213	22,312	46,754	2	(D)	215	24,797	59,486	1	(D)
Cook	1	(D)	(D)	-	-	-	-	-	-	-
Cottonwood	74	1,734	5,494	-	-	105	1,842	5,965	2	(D)
Crow Wing	94	5,585	8,174	-	-	124	6,749	11,140	-	-
Dakota	179	4,818	12,849	26	895	196	5,312	19,312	25	632
Dodge	145	3,690	12,831	1	(D)	137	2,553	8,354	1	(D)
Douglas	247	9,339	26,674	9	(D)	311	13,288	40,225	5	140

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
ALFALFA HAY (TONS, DRY) - Con.										
Counties - Con.										
Faribault	32	690	1,654	1	(D)	57	1,256	4,833	-	-
Fillmore	517	23,886	82,190	6	41	551	20,719	83,369	3	45
Freeborn	160	3,170	8,940	2	(D)	149	2,750	11,883	-	-
Goodhue	447	16,385	60,462	8	158	469	14,946	54,944	2	(D)
Grant	54	2,214	7,853	2	(D)	55	1,980	7,425	2	(D)
Hennepin	114	3,302	7,833	3	43	137	3,870	8,980	-	-
Houston	323	16,795	53,258	3	(D)	399	17,766	53,997	8	73
Hubbard	69	3,624	5,386	9	614	127	7,608	12,934	8	535
Isanti	258	8,109	18,300	6	(D)	280	7,485	17,288	-	-
Itasca	123	8,983	15,853	-	-	118	8,627	16,298	-	-
Jackson	78	2,130	7,464	-	-	106	2,802	8,981	-	-
Kanabec	140	7,497	13,354	-	-	158	8,574	18,097	1	(D)
Kandiyohi	248	8,437	23,132	12	429	244	8,735	28,949	8	478
Kittson	65	5,786	22,416	4	36	78	9,262	21,060	-	-
Koochiching	75	7,726	13,800	-	-	101	13,116	27,355	-	-
Lac qui Parle	88	3,708	11,851	-	-	135	5,191	19,047	-	-
Lake	1	(D)	(D)	-	-	5	(D)	(D)	-	-
Lake of the Woods	42	4,271	9,002	-	-	28	3,237	4,480	-	-
Le Sueur	163	2,763	6,830	1	(D)	150	2,608	8,356	-	-
Lincoln	100	3,562	10,949	-	-	156	6,328	21,622	-	-
Lyon	146	4,496	16,039	-	-	190	5,600	22,390	-	-
McLeod	183	4,283	15,617	-	-	223	5,701	17,067	-	-
Mahnomen	83	6,406	16,009	1	(D)	102	5,968	15,837	-	-
Marshall	205	19,390	53,706	4	301	174	18,643	41,646	1	(D)
Martin	63	1,085	2,415	-	-	67	1,147	3,610	1	(D)
Meeker	186	10,226	25,237	11	458	185	5,480	16,830	2	(D)
Mille Lacs	161	8,115	17,905	3	(D)	195	7,346	16,086	3	74
Morrison	526	23,122	52,966	23	1,007	657	27,771	73,367	18	976
Mower	172	3,540	10,539	3	45	226	6,061	20,408	2	(D)
Murray	161	7,063	22,114	-	-	177	7,049	30,443	-	-
Nicollet	79	2,458	4,593	-	-	122	3,597	15,857	-	-
Nobles	106	3,662	10,324	-	-	131	4,616	17,260	-	-
Norman	83	6,636	19,635	-	-	92	6,446	15,524	-	-
Olmsted	345	11,942	39,294	-	-	365	11,353	36,216	-	-
Otter Tail	799	48,662	114,330	65	2,971	909	59,345	178,277	54	4,505
Pennington	76	10,801	31,625	-	-	140	18,676	50,033	-	-
Pine	263	20,784	39,620	1	(D)	307	16,599	37,218	-	-
Pipestone	147	5,217	13,087	1	(D)	159	6,839	29,270	2	(D)
Polk	201	16,789	54,817	3	18	207	21,755	51,846	-	-
Pope	182	10,944	36,629	18	904	200	9,854	34,059	15	574
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	64	5,088	15,721	-	-	57	4,040	11,234	-	-
Redwood	116	2,192	7,442	1	(D)	168	4,287	15,534	-	-
Renville	101	2,274	8,562	-	-	119	3,170	11,242	-	-
Rice	307	7,952	20,880	4	(D)	330	7,483	20,845	-	-
Rock	98	2,957	10,254	-	-	137	3,524	12,953	-	-
Roseau	209	20,606	39,590	-	-	230	24,090	56,868	-	-
St. Louis	166	16,944	25,767	5	119	183	14,065	25,922	-	-
Scott	189	4,038	9,774	-	-	237	6,678	16,766	-	-
Sherburne	100	2,330	4,152	6	152	106	3,686	9,573	12	(D)
Sibley	177	4,121	12,531	-	-	213	4,682	13,755	-	-
Stearns	970	44,601	135,951	76	3,045	1,236	54,108	163,595	65	2,257
Steele	126	2,030	5,761	3	38	144	2,864	8,209	2	(D)
Stevens	72	3,246	10,708	2	(D)	90	3,160	11,505	2	(D)
Swift	93	4,118	12,674	3	(D)	93	3,987	12,930	3	(D)
Todd	546	23,369	59,750	30	1,622	655	27,778	79,831	8	301
Traverse	40	3,936	16,698	-	-	40	2,473	8,764	1	(D)
Wabasha	304	16,307	57,056	1	(D)	308	15,187	49,982	-	-
Wadena	157	7,832	18,589	11	278	198	10,463	21,502	21	973
Waseca	68	1,423	4,447	-	-	117	2,356	9,952	2	(D)
Washington	106	3,578	6,341	-	-	168	5,534	14,391	2	(D)
Watonwan	48	679	1,674	3	(D)	56	704	2,061	-	-
Wilkin	42	3,961	8,346	1	(D)	49	5,213	17,961	2	(D)
Winona	398	19,656	81,306	2	(D)	477	18,613	66,674	2	(D)
Wright	438	10,923	24,358	10	165	439	11,341	24,856	6	181
Yellow Medicine	134	4,786	17,426	1	(D)	128	6,338	23,637	3	75
OTHER DRY HAY (TONS, DRY)										
State Total										
Minnesota	8,556	390,421	658,360	153	3,658	9,043	381,987	657,153	80	1,906
Counties										
Aitkin	227	26,361	37,393	8	92	235	25,428	40,623	-	-
Anoka	71	1,671	2,796	2	(D)	61	1,625	3,762	1	(D)
Becker	133	6,720	9,164	-	-	123	6,264	9,764	-	-
Beltrami	103	8,375	12,509	1	(D)	98	4,118	5,803	1	(D)
Benton	180	5,912	10,026	1	(D)	259	7,855	15,046	4	134
Big Stone	15	1,480	2,803	-	-	28	1,461	1,968	-	-
Blue Earth	47	1,248	4,002	1	(D)	57	951	2,052	-	-
Brown	85	2,054	4,433	4	40	79	1,185	2,722	-	-
Carlton	184	10,709	13,518	-	-	255	15,805	25,630	-	-
Carver	122	1,952	4,381	-	-	141	2,315	5,679	-	-
Cass	219	23,302	32,682	-	-	204	22,404	30,495	1	(D)
Chippewa	14	117	127	-	-	24	1,553	3,007	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
OTHER DRY HAY (TONS, DRY) - Con.										
Counties - Con.										
Chisago	132	3,023	4,380	-	-	117	3,344	5,555	-	-
Clay	64	3,404	5,707	1	(D)	59	3,272	4,760	-	-
Clearwater	62	5,794	10,912	2	(D)	64	6,620	16,703	-	-
Cook	9	(D)	(D)	-	-	7	(D)	(D)	-	-
Cottonwood	49	1,168	2,819	-	-	51	1,159	2,219	-	-
Crow Wing	145	9,561	16,885	-	-	194	13,284	20,105	-	-
Dakota	74	1,517	2,473	15	277	72	1,065	1,939	6	318
Dodge	66	1,105	2,092	3	(D)	58	917	2,793	1	(D)
Douglas	89	2,289	3,238	1	(D)	100	1,956	3,199	-	-
Faribault	34	556	1,220	2	(D)	28	464	1,545	-	-
Fillmore	90	2,959	9,063	-	-	95	1,589	4,153	-	-
Freeborn	71	1,139	3,063	4	(D)	59	1,021	2,333	-	-
Goodhue	122	2,238	4,431	3	96	126	3,050	7,310	-	-
Grant	13	206	276	-	-	17	263	355	-	-
Hennepin	73	1,094	2,003	-	-	78	1,826	3,873	-	-
Houston	113	2,249	6,665	2	(D)	92	2,333	5,491	-	-
Hubbard	98	6,619	8,180	3	183	125	7,074	8,457	6	53
Isanti	131	4,486	4,819	8	(D)	102	2,659	3,807	-	-
Itasca	170	15,564	20,349	3	180	139	10,509	12,772	-	-
Jackson	52	1,553	1,479	-	-	54	957	1,678	-	-
Kanabec	204	10,966	16,300	2	(D)	286	14,568	21,570	3	(D)
Kandiyohi	94	2,428	4,614	-	-	86	2,497	4,502	-	-
Kittson	32	7,036	12,278	-	-	32	6,668	9,729	-	-
Koochiching	52	4,364	8,745	-	-	33	1,836	2,269	-	-
Lac qui Parle	35	925	2,221	-	-	46	1,836	4,390	1	(D)
Lake	6	(D)	(D)	-	-	14	(D)	(D)	-	-
Lake of the Woods	21	1,908	2,425	-	-	21	3,316	4,071	-	-
Le Sueur	86	1,051	2,219	1	(D)	96	1,000	2,567	-	-
Lincoln	33	704	1,446	-	-	65	2,071	4,111	-	-
Lyon	54	1,779	5,927	-	-	53	838	1,305	-	-
McLeod	126	1,989	4,509	5	28	128	1,817	4,288	-	-
Mahnomen	19	617	945	-	-	27	588	1,061	-	-
Marshall	36	1,874	3,423	-	-	45	2,320	3,856	-	-
Martin	38	820	2,114	-	-	45	856	1,649	-	-
Meeker	108	2,436	3,880	4	10	102	2,299	4,412	-	-
Mille Lacs	213	8,322	12,350	1	(D)	266	11,492	16,780	-	-
Morrison	543	22,179	40,853	12	320	566	24,269	43,721	4	40
Mower	63	956	4,362	-	-	52	738	1,650	-	-
Murray	76	1,844	4,558	-	-	77	1,329	3,414	-	-
Nicollet	38	847	1,814	-	-	44	585	1,713	-	-
Nobles	84	1,582	3,288	-	-	97	1,958	4,194	1	(D)
Norman	38	2,088	3,440	-	-	22	727	1,151	-	-
Olmsted	85	1,754	4,927	7	62	106	2,136	4,528	-	-
Otter Tail	291	13,936	21,296	8	513	268	12,813	20,131	6	197
Pennington	31	2,867	5,632	-	-	21	2,541	9,661	-	-
Pine	282	19,582	29,454	6	(D)	326	18,815	31,699	4	82
Pipestone	97	2,415	5,274	1	(D)	94	2,068	4,452	-	-
Polk	32	1,686	2,026	-	-	53	3,931	5,755	-	-
Pope	71	3,036	5,549	5	115	84	2,005	3,352	6	120
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	11	689	1,295	-	-	4	215	625	-	-
Redwood	40	1,063	2,403	-	-	36	2,228	4,266	-	-
Renville	46	761	1,451	-	-	29	391	610	-	-
Rice	82	1,475	2,698	1	(D)	125	2,826	6,573	-	-
Rock	96	3,848	15,538	-	-	151	2,448	5,387	-	-
Roseau	92	8,759	12,898	-	-	48	6,390	9,648	-	-
St. Louis	336	37,018	56,834	5	191	289	26,731	45,261	3	(D)
Scott	96	1,354	2,623	-	-	110	1,371	3,129	-	-
Sherburne	62	1,847	2,229	-	-	57	1,175	1,294	1	(D)
Sibley	100	1,828	4,655	-	-	90	1,319	3,028	-	-
Stearns	533	14,116	25,393	9	156	540	13,663	28,848	21	307
Steele	65	1,043	3,483	-	-	68	1,430	3,211	1	(D)
Stevens	20	969	2,356	2	(D)	11	544	973	-	-
Swift	18	749	1,093	1	(D)	31	554	993	1	(D)
Todd	357	13,248	21,213	5	230	367	13,638	22,928	5	246
Traverse	8	285	446	-	-	11	155	246	-	-
Wabasha	53	1,272	2,714	-	-	72	1,694	4,726	-	-
Wadena	144	9,049	14,266	6	412	142	10,365	15,041	3	33
Waseca	19	314	875	-	-	46	514	1,018	-	-
Washington	65	1,697	1,915	1	(D)	84	2,183	3,437	-	-
Watonwan	17	316	450	-	-	19	196	326	-	-
Wilkin	22	850	858	-	-	15	654	814	-	-
Winona	98	4,084	12,964	1	(D)	91	2,117	5,188	-	-
Wright	185	3,377	4,792	6	36	215	4,003	7,791	-	-
Yellow Medicine	46	1,832	3,071	-	-	35	2,043	2,774	-	-
ALL HAYLAGE, GRASS SILAGE, AND GREENCHOP (TONS, GREEN)										
State Total										
Minnesota	4,152	305,999	1,893,891	211	14,317	4,365	284,273	1,770,188	160	11,280
Counties										
Aitkin	68	3,265	11,967	5	260	58	2,325	6,055	-	-
Anoka	4	(D)	612	-	-	10	159	762	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
ALL HAYLAGE, GRASS SILAGE, AND GREENCHOP (TONS, GREEN) - Con.										
Counties - Con.										
Becker	63	6,976	30,037	9	849	69	5,243	27,631	5	618
Beltrami	52	3,611	11,036	-	-	49	3,354	13,901	-	-
Benton	72	4,882	29,866	18	1,324	78	3,920	24,261	8	410
Big Stone	6	423	426	-	-	12	287	866	-	-
Blue Earth	10	151	850	-	-	19	278	1,386	-	-
Brown	39	2,107	19,262	2	(D)	40	1,569	14,388	1	(D)
Carlton	85	4,622	23,173	-	-	77	4,814	17,783	-	-
Carver	55	4,400	36,123	-	-	78	3,772	27,741	-	-
Cass	33	2,201	5,754	3	9	36	1,434	4,089	-	-
Chippewa	23	3,433	13,644	-	-	4	(D)	(D)	-	-
Chisago	36	927	8,165	-	-	38	1,377	7,065	2	(D)
Clay	25	1,507	8,583	-	-	18	1,042	5,543	-	-
Clearwater	25	3,622	10,117	-	-	34	1,259	5,575	-	-
Cook	3	(D)	(D)	1	(D)	3	(D)	(D)	-	-
Cottonwood	24	725	6,467	-	-	18	679	5,157	2	(D)
Crow Wing	45	2,430	6,873	-	-	42	1,799	5,385	-	-
Dakota	46	2,591	19,439	15	1,217	33	1,861	12,673	9	600
Dodge	43	1,997	19,839	2	(D)	40	2,191	18,178	-	-
Douglas	52	1,683	4,671	-	-	45	1,754	8,409	1	(D)
Faribault	21	849	6,151	2	(D)	25	821	4,857	-	-
Fillmore	104	9,712	81,915	1	(D)	125	10,597	83,807	-	-
Freeborn	20	425	1,678	-	-	29	954	5,340	-	-
Goodhue	119	10,214	106,909	3	121	138	9,688	61,242	-	-
Grant	9	140	518	2	(D)	2	(D)	(D)	1	(D)
Hennepin	29	855	3,227	1	(D)	26	946	3,032	-	-
Houston	90	11,346	89,080	2	(D)	117	10,256	83,243	-	-
Hubbard	36	2,236	5,196	2	(D)	24	912	2,475	3	295
Isanti	36	694	2,675	-	-	31	854	5,602	2	(D)
Itasca	56	3,232	9,268	3	16	41	1,825	5,484	-	-
Jackson	14	351	3,676	-	-	18	362	3,493	-	-
Kanabec	41	2,312	6,143	-	-	39	1,373	2,815	-	-
Kandiyohi	51	6,068	34,186	2	(D)	60	6,403	41,606	1	(D)
Kittson	10	682	1,328	-	-	13	863	819	-	-
Koochiching	22	1,437	9,092	-	-	21	1,026	1,805	-	-
Lac qui Parle	14	523	3,371	-	-	27	708	2,645	-	-
Lake	6	51	92	-	-	3	63	122	-	-
Lake of the Woods	19	1,039	5,676	-	-	10	542	1,190	-	-
Le Sueur	39	1,051	4,229	1	(D)	38	1,286	6,929	-	-
Lincoln	23	1,395	8,861	-	-	24	1,097	7,721	-	-
Lyon	24	1,171	8,144	-	-	34	1,433	9,208	-	-
McLeod	40	2,157	14,684	-	-	59	4,119	27,682	-	-
Mahnomen	8	348	1,412	-	-	6	603	2,997	1	(D)
Marshall	23	1,736	6,677	-	-	21	1,918	10,591	-	-
Martin	6	423	583	-	-	17	512	2,796	-	-
Meeker	43	5,856	30,691	3	600	40	3,288	19,308	3	(D)
Mille Lacs	64	2,711	13,945	1	(D)	62	2,456	7,013	-	-
Morrison	216	13,120	79,245	20	713	240	14,662	70,988	20	871
Mower	46	2,456	12,890	1	(D)	44	2,973	19,394	2	(D)
Murray	37	2,180	7,679	-	-	28	2,619	12,743	-	-
Nicollet	34	1,362	7,595	-	-	26	1,489	11,045	-	-
Nobles	47	2,578	19,124	-	-	30	2,283	17,804	-	-
Norman	13	360	914	-	-	5	124	303	-	-
Olmsted	70	6,427	54,470	-	-	95	8,519	71,160	-	-
Otter Tail	169	14,111	83,882	26	1,854	175	13,222	80,042	23	2,006
Pennington	7	301	612	-	-	8	1,211	(D)	-	-
Pine	67	6,273	18,261	-	-	107	6,742	32,750	1	(D)
Pipestone	43	3,618	18,564	-	-	37	2,176	20,471	-	-
Polk	17	1,359	8,397	-	-	22	2,354	12,053	-	-
Pope	40	3,766	15,754	4	181	41	1,807	9,495	8	196
Red Lake	15	1,410	7,336	-	-	12	856	5,681	-	-
Redwood	34	1,074	8,107	-	-	17	659	4,824	-	-
Renville	19	1,343	7,888	-	-	35	1,605	7,054	1	(D)
Rice	46	2,280	16,082	2	(D)	62	3,425	19,695	-	-
Rock	35	1,798	14,959	-	-	48	1,692	9,498	-	-
Roseau	17	2,033	12,560	-	-	27	1,634	3,669	-	-
St. Louis	119	6,811	20,224	4	249	101	5,392	10,353	1	(D)
Scott	40	2,044	14,961	-	-	37	2,359	15,451	-	-
Sherburne	14	378	742	1	(D)	15	850	2,811	-	-
Sibley	42	2,281	13,790	-	-	44	1,771	13,099	-	-
Stearns	423	35,764	217,850	42	3,215	469	34,749	231,180	49	3,506
Steele	28	1,059	4,399	-	-	30	1,617	8,519	-	-
Stevens	25	6,621	51,802	2	(D)	22	5,639	34,031	1	(D)
Swift	30	3,189	27,740	-	-	32	2,495	16,611	-	-
Todd	134	9,723	50,008	10	1,443	161	9,083	48,280	7	946
Traverse	15	2,278	13,312	-	-	10	1,212	4,227	-	-
Wabasha	131	16,370	132,053	1	(D)	143	15,071	115,717	1	(D)
Wadena	63	3,506	13,092	8	438	50	2,904	14,739	6	407
Waseca	30	553	3,719	-	-	21	522	2,477	-	-
Washington	28	557	2,733	-	-	35	902	5,059	-	-
Watonwan	6	144	613	-	-	4	28	62	-	-
Wilkin	8	324	(D)	1	(D)	9	364	857	-	-
Winona	147	20,575	172,037	1	(D)	163	20,051	185,261	-	-
Wright	111	4,825	29,060	10	182	84	3,533	23,374	1	(D)
Yellow Medicine	10	431	3,353	-	-	25	799	4,863	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
HAYLAGE OR GREENCHOP FROM ALFALFA OR ALFALFA MIXTURES (TONS, GREEN)										
State Total										
Minnesota	2,114	216,094	1,522,392	149	12,058	2,736	216,829	1,542,528	146	9,924
Counties										
Aitkin	9	293	(D)	-	-	8	249	813	-	-
Anoka	1	(D)	(D)	-	-	4	79	(D)	-	-
Becker	33	4,785	20,642	9	849	36	3,756	23,266	4	(D)
Beltrami	17	2,103	6,328	-	-	20	2,014	11,062	-	-
Benton	38	3,778	27,339	14	1,310	62	3,615	23,698	8	410
Big Stone	-	-	-	-	-	9	71	(D)	-	-
Blue Earth	5	96	(D)	-	-	3	145	1,043	-	-
Brown	18	1,110	7,660	-	-	32	1,478	14,065	1	(D)
Carlton	21	820	3,756	-	-	33	1,307	7,566	-	-
Carver	42	4,078	35,072	-	-	51	3,207	25,718	-	-
Cass	4	155	598	-	-	9	34	192	-	-
Chippewa	15	3,353	13,507	-	-	1	(D)	(D)	-	-
Chisago	18	726	7,676	-	-	19	959	6,332	-	-
Clay	8	778	7,032	-	-	4	590	2,376	-	-
Clearwater	6	813	4,289	-	-	22	1,187	5,491	-	-
Cook	2	(D)	(D)	-	-	-	-	-	-	-
Cottonwood	11	563	5,942	-	-	12	428	3,897	2	(D)
Crow Wing	16	1,103	3,801	-	-	8	519	2,393	-	-
Dakota	27	2,350	18,578	10	1,194	23	1,735	12,127	9	600
Dodge	22	1,696	17,841	-	-	30	1,914	16,343	-	-
Douglas	27	610	2,799	-	-	29	1,479	7,860	1	(D)
Faribault	9	493	3,615	-	-	12	673	4,660	-	-
Fillmore	78	8,759	75,409	-	-	103	9,513	79,391	-	-
Freeborn	8	255	1,442	-	-	17	712	4,730	-	-
Goodhue	102	8,862	98,498	3	(D)	120	7,987	54,036	-	-
Grant	2	(D)	(D)	-	-	2	(D)	(D)	1	(D)
Hennepin	12	579	3,067	-	-	15	692	2,781	-	-
Houston	77	10,195	84,612	2	(D)	105	9,184	76,199	-	-
Hubbard	7	550	1,685	1	(D)	11	410	1,610	2	(D)
Isanti	21	425	1,662	-	-	9	619	(D)	-	-
Itasca	18	1,589	5,553	-	-	12	461	2,110	-	-
Jackson	10	315	3,511	-	-	12	314	3,340	-	-
Kanabec	7	425	1,248	-	-	7	304	1,300	-	-
Kandiyohi	33	5,384	31,879	2	(D)	47	6,146	39,870	1	(D)
Kittson	1	(D)	(D)	-	-	4	296	296	-	-
Koochiching	7	689	4,028	-	-	11	744	1,353	-	-
Lac qui Parle	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Lake of the Woods	4	(D)	178	-	-	2	(D)	(D)	-	-
Le Sueur	7	306	1,582	-	-	24	1,018	5,879	-	-
Lincoln	13	1,221	8,488	-	-	16	692	5,654	-	-
Lyon	14	666	4,534	-	-	30	1,276	8,251	-	-
McLeod	13	1,898	14,007	-	-	43	3,750	26,367	-	-
Mahnomen	2	(D)	(D)	-	-	2	(D)	(D)	-	-
Marshall	6	532	5,023	-	-	6	607	1,622	-	-
Martin	3	399	525	-	-	1	(D)	(D)	-	-
Meeker	29	5,580	30,234	3	600	33	2,334	15,203	3	117
Mille Lacs	15	914	6,886	1	(D)	22	1,109	4,722	-	-
Morrison	107	8,969	64,548	15	653	149	10,514	59,662	20	871
Mower	25	2,055	11,110	1	(D)	32	2,800	18,439	2	(D)
Murray	13	1,568	5,929	-	-	25	2,357	10,874	-	-
Nicollet	17	1,091	6,580	-	-	22	1,204	10,741	-	-
Nobles	13	1,860	14,436	-	-	16	2,036	16,837	-	-
Norman	6	133	617	-	-	3	(D)	(D)	-	-
Olmsted	52	5,892	51,851	-	-	76	7,624	66,371	-	-
Otter Tail	102	10,451	69,129	24	(D)	123	11,481	75,292	23	(D)
Pennington	-	-	-	-	-	5	(D)	462	-	-
Pine	23	3,776	13,493	-	-	55	3,142	22,503	-	-
Pipestone	31	2,875	17,052	-	-	11	1,623	17,371	-	-
Polk	6	1,036	7,289	-	-	10	1,599	10,480	-	-
Pope	14	1,817	13,016	2	(D)	20	1,283	8,615	8	184
Red Lake	6	914	6,388	-	-	2	(D)	(D)	-	-
Redwood	12	592	3,084	-	-	9	418	3,682	-	-
Renville	11	1,153	5,982	-	-	24	1,401	6,268	-	-
Rice	30	2,083	15,131	2	(D)	36	2,772	18,614	-	-
Rock	8	798	3,962	-	-	21	1,167	6,700	-	-
Roseau	5	947	(D)	-	-	9	472	1,908	-	-
St. Louis	25	1,727	11,131	3	(D)	12	500	1,102	-	-
Scott	19	1,586	10,781	-	-	30	2,128	14,932	-	-
Sherburne	1	(D)	(D)	1	(D)	4	(D)	(D)	-	-
Sibley	20	1,681	12,843	-	-	16	1,468	11,836	-	-
Stearns	291	28,608	180,322	37	2,894	398	30,903	212,720	48	3,246
Steele	8	455	2,414	-	-	26	1,395	7,089	-	-
Stevens	17	5,814	35,177	2	(D)	21	(D)	(D)	1	(D)
Swift	17	2,993	26,226	-	-	17	2,188	15,217	-	-
Todd	51	5,521	37,543	7	1,293	86	6,620	40,683	7	(D)
Traverse	9	1,488	(D)	-	-	8	(D)	(D)	-	-
Wabasha	105	14,636	116,004	-	-	123	12,474	103,396	1	(D)
Wadena	24	1,596	9,235	6	(D)	27	1,491	10,986	3	251
Waseca	3	(D)	(D)	-	-	16	437	2,228	-	-
Washington	11	371	2,491	-	-	13	539	4,131	-	-
Watonwan	2	(D)	(D)	-	-	-	-	-	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
HAYLAGE OR GREENCHOP FROM ALFALFA OR ALFALFA MIXTURES (TONS, GREEN) - Con.										
Counties - Con.										
Wilkin	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Winona	132	17,571	153,630	1	(D)	159	19,137	179,624	-	-
Wright	53	3,359	23,684	3	12	42	2,796	20,718	1	(D)
Yellow Medicine	4	247	1,133	-	-	7	294	2,120	-	-
ALL OTHER HAYLAGE, GRASS SILAGE, AND GREENCHOP (TONS, GREEN)										
State Total										
Minnesota	2,310	89,905	371,499	67	2,259	1,953	67,444	227,660	25	1,356
Counties										
Aitkin	60	2,972	(D)	5	260	50	2,076	5,242	-	-
Anoka	3	44	(D)	-	-	6	80	(D)	-	-
Becker	32	2,191	9,395	-	-	40	1,487	4,365	1	(D)
Beltrami	43	1,508	4,708	-	-	31	1,340	2,839	-	-
Benton	35	1,104	2,527	4	14	20	305	563	-	-
Big Stone	6	423	426	-	-	3	216	(D)	-	-
Blue Earth	6	55	(D)	-	-	16	133	343	-	-
Brown	23	997	11,602	2	(D)	8	91	323	-	-
Carlton	68	3,802	19,417	-	-	54	3,507	10,217	-	-
Carver	19	322	1,051	-	-	39	565	2,023	-	-
Cass	29	2,046	5,156	3	9	36	1,400	3,897	-	-
Chippewa	8	80	137	-	-	3	(D)	(D)	-	-
Chisago	18	201	489	-	-	19	418	733	2	(D)
Clay	23	729	1,551	-	-	14	452	3,167	-	-
Clearwater	22	2,809	5,828	-	-	12	72	84	-	-
Cook	1	(D)	(D)	1	(D)	3	(D)	(D)	-	-
Cottonwood	15	162	525	-	-	8	251	1,260	-	-
Crow Wing	32	1,327	3,072	-	-	35	1,280	2,992	-	-
Dakota	21	241	861	5	23	14	126	546	-	-
Dodge	23	301	1,998	2	(D)	12	277	1,835	-	-
Douglas	32	1,073	1,872	-	-	24	275	549	-	-
Faribault	14	356	2,536	2	(D)	13	148	197	-	-
Fillmore	31	953	6,506	1	(D)	39	1,084	4,416	-	-
Freeborn	12	170	236	-	-	14	242	610	-	-
Goodhue	27	1,352	8,411	2	(D)	31	1,701	7,206	-	-
Grant	7	(D)	(D)	2	(D)	-	-	-	-	-
Hennepin	17	276	160	1	(D)	13	254	251	-	-
Houston	20	1,151	4,468	-	-	21	1,072	7,044	-	-
Hubbard	30	1,686	3,511	2	(D)	19	502	865	1	(D)
Isanti	15	269	1,013	-	-	24	235	(D)	2	(D)
Itasca	38	1,643	3,715	3	16	29	1,364	3,374	-	-
Jackson	6	36	165	-	-	6	48	153	-	-
Kanabec	35	1,887	4,895	-	-	33	1,069	1,515	-	-
Kandiyohi	21	684	2,307	-	-	16	257	1,736	-	-
Kittson	10	(D)	(D)	-	-	11	567	523	-	-
Koochiching	16	748	5,064	-	-	10	282	452	-	-
Lac qui Parle	14	(D)	(D)	-	-	27	(D)	(D)	-	-
Lake	6	51	92	-	-	3	63	122	-	-
Lake of the Woods	15	(D)	5,498	-	-	8	(D)	(D)	-	-
Le Sueur	35	745	2,647	1	(D)	17	268	1,050	-	-
Lincoln	10	174	373	-	-	12	405	2,067	-	-
Lyon	12	505	3,610	-	-	8	157	957	-	-
McLeod	31	259	677	-	-	23	369	1,315	-	-
Mahnomen	7	(D)	(D)	-	-	5	(D)	(D)	1	(D)
Marshall	17	1,204	1,654	-	-	16	1,311	8,969	-	-
Martin	3	24	58	-	-	16	(D)	(D)	-	-
Meeker	18	276	457	-	-	9	954	4,105	1	(D)
Mille Lacs	53	1,797	7,059	-	-	45	1,347	2,291	-	-
Morrison	116	4,151	14,697	5	60	102	4,148	11,326	-	-
Mower	27	401	1,780	-	-	14	173	955	-	-
Murray	24	612	1,750	-	-	4	262	1,869	-	-
Nicollet	20	271	1,015	-	-	5	285	304	-	-
Nobles	34	718	4,688	-	-	16	247	967	-	-
Norman	7	227	297	-	-	2	(D)	(D)	-	-
Olmsted	22	535	2,619	-	-	27	895	4,789	-	-
Otter Tail	85	3,660	14,753	2	(D)	62	1,741	4,750	2	(D)
Pennington	7	301	612	-	-	3	(D)	(D)	-	-
Pine	48	2,497	4,768	-	-	60	3,600	10,247	1	(D)
Pipestone	15	743	1,512	-	-	28	553	3,100	-	-
Polk	12	323	1,108	-	-	15	755	1,573	-	-
Pope	33	1,949	2,738	2	(D)	26	524	880	4	12
Red Lake	9	496	948	-	-	10	(D)	(D)	-	-
Redwood	24	482	5,023	-	-	10	241	1,142	-	-
Renville	8	190	1,906	-	-	20	204	786	1	(D)
Rice	16	197	951	-	-	28	653	1,081	-	-
Rock	27	1,000	10,997	-	-	27	525	2,798	-	-
Roseau	12	1,086	(D)	-	-	20	1,162	1,761	-	-
St. Louis	95	5,084	9,093	1	(D)	90	4,892	9,251	1	(D)
Scott	24	458	4,180	-	-	12	231	519	-	-
Sherburne	13	(D)	(D)	-	-	12	(D)	(D)	-	-
Sibley	26	600	947	-	-	29	303	1,263	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
ALL OTHER HAYLAGE, GRASS SILAGE, AND GREENCHOP (TONS, GREEN) - Con.										
Counties - Con.										
Stearns	165	7,156	37,528	7	321	106	3,846	18,460	4	260
Steele	22	604	1,985	-	-	6	222	1,430	-	-
Stevens	13	807	16,625	-	-	1	(D)	(D)	-	-
Swift	13	196	1,514	-	-	15	307	1,394	-	-
Todd	97	4,202	12,465	3	150	82	2,463	7,597	1	(D)
Traverse	6	790	(D)	-	-	2	(D)	(D)	-	-
Wabasha	41	1,734	16,049	1	(D)	39	2,597	12,321	-	-
Wadena	45	1,910	3,857	2	(D)	26	1,413	3,753	3	156
Waseca	27	(D)	(D)	-	-	11	85	249	-	-
Washington	18	186	242	-	-	23	363	928	-	-
Watonwan	4	(D)	(D)	-	-	4	28	62	-	-
Wilkin	7	(D)	(D)	1	(D)	8	(D)	(D)	-	-
Winona	36	3,004	18,407	-	-	21	914	5,637	-	-
Wright	67	1,466	5,376	7	170	54	737	2,656	-	-
Yellow Medicine	6	184	2,220	-	-	18	505	2,743	-	-
CORN FOR SILAGE OR GREENCHOP (TONS)										
State Total										
Minnesota	2,768	313,974	6,334,518	108	13,135	4,606	330,543	6,702,696	176	15,332
Counties										
Aitkin	18	648	7,309	-	-	24	838	13,618	-	-
Anoka	6	119	852	1	(D)	3	46	607	-	-
Becker	51	8,207	145,196	7	1,007	82	5,436	98,529	3	576
Beltrami	15	1,173	17,496	-	-	15	1,398	16,605	-	-
Benton	50	7,256	147,700	7	486	113	6,629	123,986	11	616
Big Stone	13	3,412	26,144	-	-	5	209	3,080	-	-
Blue Earth	4	248	(D)	-	-	13	311	6,291	-	-
Brown	52	4,988	96,399	1	(D)	81	5,130	112,535	2	(D)
Carlton	12	286	4,536	-	-	15	537	9,529	-	-
Carver	39	1,863	28,692	-	-	69	2,452	50,398	-	-
Cass	14	573	10,826	1	(D)	36	2,580	35,726	1	(D)
Chippewa	13	4,759	103,841	-	-	10	4,364	92,363	-	-
Chisago	15	399	5,723	-	-	39	1,454	27,653	-	-
Clay	19	1,137	21,217	-	-	23	1,322	28,211	-	-
Clearwater	11	672	9,656	-	-	18	1,348	24,324	-	-
Cottonwood	17	2,971	43,247	-	-	34	1,804	30,883	-	-
Crow Wing	16	1,151	17,190	-	-	10	434	8,087	-	-
Dakota	24	3,897	85,914	7	1,779	36	2,301	55,872	13	1,082
Dodge	25	2,374	54,144	-	-	20	933	25,289	-	-
Douglas	20	1,287	21,680	-	-	65	3,038	59,108	4	98
Faribault	5	(D)	(D)	-	-	6	755	(D)	-	-
Fillmore	88	8,120	169,889	-	-	167	8,469	187,424	-	-
Freeborn	10	650	12,160	-	-	11	1,070	20,520	-	-
Goodhue	97	7,437	178,562	-	-	173	9,888	234,567	6	90
Grant	8	1,380	26,728	1	(D)	8	667	15,668	-	-
Hennepin	4	262	6,000	-	-	23	575	9,987	-	-
Houston	67	6,454	163,203	-	-	99	6,144	135,427	-	-
Hubbard	15	1,206	9,214	1	(D)	18	703	9,904	1	(D)
Isanti	9	1,493	34,293	1	(D)	16	1,158	21,431	1	(D)
Itasca	5	258	3,205	-	-	3	94	874	-	-
Jackson	19	416	9,250	-	-	19	1,057	18,638	-	-
Kanabec	9	222	3,771	-	-	23	609	8,521	-	-
Kandiyohi	43	9,182	204,359	1	(D)	73	8,357	191,413	-	-
Kittson	10	427	9,123	-	-	11	994	14,354	-	-
Koochiching	2	(D)	(D)	-	-	5	469	5,535	-	-
Lac qui Parle	6	430	8,840	-	-	17	1,219	25,056	1	(D)
Le Sueur	20	701	14,129	-	-	31	1,025	21,642	1	(D)
Lincoln	38	3,437	62,053	-	-	39	2,224	42,567	-	-
Lyon	43	4,236	80,414	-	-	50	3,716	68,147	-	-
McLeod	21	1,593	32,931	-	-	49	4,279	98,118	-	-
Mahnomen	9	578	10,976	-	-	15	739	13,364	-	-
Marshall	10	762	8,713	-	-	18	1,181	16,466	-	-
Martin	5	553	12,742	-	-	11	913	18,771	-	-
Meeker	31	6,435	130,352	4	960	48	5,482	112,570	3	651
Mille Lacs	25	2,147	41,871	-	-	45	2,804	47,094	-	-
Morrison	148	13,093	248,318	8	1,681	262	21,105	364,971	14	2,259
Mower	24	2,582	56,666	-	-	57	2,975	64,016	-	-
Murray	39	4,055	59,225	-	-	66	4,595	99,409	-	-
Nicollet	36	7,850	161,003	-	-	42	3,160	72,337	-	-
Nobles	50	10,362	214,288	-	-	62	9,386	197,274	1	(D)
Norman	14	2,469	47,312	-	-	18	417	4,726	-	-
Olmsted	42	6,019	147,799	-	-	89	3,958	85,928	-	-
Otter Tail	136	7,113	136,066	10	1,137	246	13,658	282,850	24	1,540
Pennington	9	845	8,915	-	-	6	679	8,214	-	-
Pine	38	3,333	55,814	-	-	77	4,339	73,285	-	-
Pipestone	39	7,390	120,243	-	-	70	6,599	141,701	1	(D)
Polk	12	927	19,342	-	-	16	778	14,466	-	-
Pope	34	2,984	52,908	5	509	70	4,788	88,194	7	406
Ramsey	-	-	-	-	-	1	(D)	(D)	-	-
Red Lake	9	1,607	27,782	-	-	10	1,313	30,628	-	-
Redwood	40	3,939	58,901	-	-	47	3,715	87,720	-	-

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Table 26. **Field Seeds, Grass Seeds, Forage, Hay, and Silage: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
CORN FOR SILAGE OR GREENCHOP (TONS) - Con.										
Counties - Con.										
Renville	23	1,964	45,026	2	(D)	40	1,835	34,859	-	-
Rice	34	2,345	48,820	-	-	48	2,698	57,345	-	-
Rock	46	6,639	166,296	-	-	74	8,309	173,965	-	-
Roseau	15	1,290	22,476	-	-	18	1,135	11,716	-	-
St. Louis	11	332	5,352	-	-	2	(D)	(D)	-	-
Scott	17	1,647	36,761	-	-	40	2,546	66,919	-	-
Sherburne	10	1,190	23,084	5	550	19	1,785	38,420	8	780
Sibley	39	2,783	63,302	-	-	52	3,764	81,223	-	-
Stearns	317	34,145	674,802	26	1,665	584	40,242	809,038	36	2,889
Steele	15	667	12,126	-	-	40	1,716	35,482	-	-
Stevens	30	11,002	239,448	3	212	48	12,955	278,403	10	641
Swift	40	9,735	223,033	4	429	46	5,892	138,659	1	(D)
Todd	112	9,516	174,415	4	1,843	238	10,736	203,081	13	945
Traverse	22	6,967	144,063	-	-	9	4,715	95,726	-	-
Wabasha	73	11,700	268,431	-	-	141	10,308	238,090	1	(D)
Wadena	29	2,294	35,946	8	319	49	3,088	52,389	7	257
Waseca	11	321	4,824	-	-	28	3,037	37,750	-	-
Washington	6	362	7,080	-	-	24	524	10,324	-	-
Watonwan	6	215	6,520	1	(D)	7	266	5,856	-	-
Wilkin	11	1,714	38,303	-	-	4	139	2,504	-	-
Winona	117	15,647	368,279	-	-	177	15,252	340,874	-	-
Wright	54	4,679	87,370	-	-	68	8,807	163,011	6	1,380
Yellow Medicine	27	5,463	116,988	-	-	22	1,924	31,343	-	-
SORGHUM FOR SILAGE OR GREENCHOP (TONS)										
State Total										
Minnesota	54	1,394	11,883	2	(D)	41	850	7,990	-	-
Counties										
Becker	3	92	460	-	-	2	(D)	(D)	-	-
Benton	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Blue Earth	3	45	450	-	-	-	-	-	-	-
Brown	-	-	-	-	-	2	(D)	(D)	-	-
Chisago	1	(D)	(D)	-	-	-	-	-	-	-
Clearwater	1	(D)	(D)	-	-	-	-	-	-	-
Douglas	2	(D)	(D)	-	-	-	-	-	-	-
Fillmore	-	-	-	-	-	3	13	85	-	-
Goodhue	1	(D)	(D)	-	-	-	-	-	-	-
Lac qui Parle	1	(D)	(D)	-	-	-	-	-	-	-
Mille Lacs	-	-	-	-	-	2	(D)	(D)	-	-
Morrison	4	40	513	-	-	8	239	2,633	-	-
Nobles	-	-	-	-	-	2	(D)	(D)	-	-
Olmsted	3	34	214	-	-	-	-	-	-	-
Otter Tail	7	113	1,272	-	-	2	(D)	(D)	-	-
Pine	2	(D)	(D)	-	-	-	-	-	-	-
Pipestone	1	(D)	(D)	-	-	-	-	-	-	-
Polk	1	(D)	(D)	-	-	-	-	-	-	-
Pope	4	92	886	-	-	-	-	-	-	-
Renville	2	(D)	(D)	-	-	-	-	-	-	-
Rice	1	(D)	(D)	-	-	-	-	-	-	-
Sibley	1	(D)	(D)	-	-	-	-	-	-	-
Stearns	10	413	4,984	2	(D)	8	173	2,236	-	-
Steele	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Todd	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Wabasha	1	(D)	(D)	-	-	-	-	-	-	-
Washington	1	(D)	(D)	-	-	3	33	173	-	-
Winona	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Wright	-	-	-	-	-	3	29	166	-	-

Table 27. **Other Crops: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
CORN, TRADITIONAL OR INDIAN (POUNDS)										
State Total										
Minnesota	6	8	4,416	3	4	4	4	2,852	2	(D)
Counties										
Anoka	1	(D)	(D)	1	(D)	1	(D)	(D)	1	(D)
Carlton	1	(D)	(D)	-	-	-	-	-	-	-
Cook	1	(D)	(D)	1	(D)	-	-	-	-	-
Dakota	-	-	-	-	-	1	(D)	(D)	1	(D)
Olmsted	1	(D)	(D)	-	-	2	(D)	(D)	-	-
Sherburne	1	(D)	(D)	1	(D)	-	-	-	-	-
Stearns	1	(D)	(D)	-	-	-	-	-	-	-
HERBS, DRIED (POUNDS)										
State Total										
Minnesota	2	(D)	(D)	-	-	1	(D)	(D)	-	-
Counties										
Carlton	1	(D)	(D)	-	-	-	-	-	-	-
Le Sueur	1	(D)	(D)	-	-	1	(D)	(D)	-	-
HOPS (POUNDS)										
State Total										
Minnesota	20	12	10,797	17	12	37	59	79,260	26	48
Counties										
Anoka	3	2	6,000	3	2	8	10	6,600	8	10
Benton	-	-	-	-	-	1	(D)	(D)	1	(D)
Blue Earth	-	-	-	-	-	3	3	4,500	3	3
Dakota	2	(D)	(D)	2	(D)	-	-	-	-	-
Grant	-	-	-	-	-	1	(D)	(D)	-	-
Houston	-	-	-	-	-	6	6	1,200	-	-
Kandiyohi	2	(D)	(D)	2	(D)	3	3	600	1	(D)
Martin	3	(Z)	594	3	(Z)	-	-	-	-	-
Morrison	-	-	-	-	-	2	(D)	(D)	2	(D)
Nicollet	-	-	-	-	-	1	(D)	(D)	1	(D)
Olmsted	4	4	940	4	4	-	-	-	-	-
Pine	-	-	-	-	-	2	(D)	(D)	-	-
Sherburne	-	-	-	-	-	1	(D)	(D)	1	(D)
Steele	-	-	-	-	-	1	(D)	(D)	1	(D)
Wabasha	3	(Z)	1,200	-	-	-	-	-	-	-
Washington	3	2	1,200	3	2	8	8	3,440	8	8
MINT FOR OIL, ALL (POUNDS OF OIL)										
State Total										
Minnesota	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Counties										
Kittson	1	(D)	(D)	-	-	1	(D)	(D)	-	-
MINT FOR OIL, PEPPERMINT (POUNDS OF OIL)										
State Total										
Minnesota	1	(D)	(D)	-	-	1	(D)	(D)	-	-
Counties										
Kittson	1	(D)	(D)	-	-	1	(D)	(D)	-	-
SWITCHGRASS (TONS)										
State Total										
Minnesota	1	(D)	(D)	-	-	-	-	-	-	-
Counties										
Morrison	1	(D)	(D)	-	-	-	-	-	-	-
OTHER CROPS										
State Total										
Minnesota	18	5,208	(X)	-	-	11	738	(X)	-	-
Counties										
Carlton	1	(D)	(X)	-	-	-	-	(X)	-	-
Cass	1	(D)	(X)	-	-	2	(D)	(X)	-	-
Chippewa	-	-	(X)	-	-	2	(D)	(X)	-	-
Crow Wing	3	672	(X)	-	-	-	-	(X)	-	-
Freeborn	-	-	(X)	-	-	2	(D)	(X)	-	-

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Table 27. **Other Crops: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Harvested			Irrigated		Harvested			Irrigated	
	Farms	Acres	Quantity	Farms	Acres	Farms	Acres	Quantity	Farms	Acres
OTHER CROPS - Con.										
Counties - Con.										
Grant	6	3,966	(X)	-	-	-	-	(X)	-	-
Hubbard	1	(D)	(X)	-	-	-	-	(X)	-	-
Lac qui Parle	2	(D)	(X)	-	-	-	-	(X)	-	-
Mower	-	-	(X)	-	-	2	(D)	(X)	-	-
Pine	3	48	(X)	-	-	-	-	(X)	-	-
Polk	1	(D)	(X)	-	-	1	(D)	(X)	-	-
Todd	-	-	(X)	-	-	2	(D)	(X)	-	-

Table 28. **Land Used for Vegetables and Vegetables Harvested for Sale: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Land used for vegetables (see text)				Vegetables harvested (see text) (acres)	Land used for vegetables (see text)				Vegetables harvested (see text) (acres)
	Harvested		Irrigated			Harvested		Irrigated		
	Farms	Acres	Farms	Acres		Farms	Acres	Farms	Acres	
State Total										
Minnesota	2,620	196,718	764	54,640	205,632	2,840	207,071	706	51,939	212,474
Counties										
Aitkin	27	46	9	19	53	24	39	7	16	41
Anoka	38	1,744	16	537	1,757	24	650	10	(D)	657
Becker	16	(D)	6	(D)	(D)	23	(D)	11	(D)	(D)
Beltrami	24	25	13	13	27	23	30	8	16	32
Benton	20	4,108	9	3,930	4,158	17	4,007	8	3,619	4,007
Big Stone	4	15	-	-	15	3	3	-	-	(D)
Blue Earth	39	1,349	9	(D)	1,355	18	1,240	1	(D)	1,246
Brown	31	3,248	2	(D)	3,248	128	11,469	8	635	11,535
Carlton	25	40	7	5	45	25	75	14	26	80
Carver	26	82	5	8	83	22	128	3	5	134
Cass	14	(D)	13	(D)	(D)	19	155	9	(D)	157
Chippewa	17	2,079	4	(D)	2,082	21	2,325	3	(D)	2,538
Chisago	37	67	16	39	73	47	1,295	13	68	1,311
Clay	26	1,828	11	(D)	1,828	18	2,454	8	(D)	2,454
Clearwater	21	1,418	5	24	1,421	11	(D)	2	(D)	(D)
Cook	9	7	5	5	8	9	9	8	(D)	11
Cottonwood	6	461	1	(D)	462	11	739	4	5	743
Crow Wing	26	57	14	37	58	18	40	8	29	44
Dakota	176	15,322	104	10,046	18,755	172	14,470	79	9,651	16,613
Dodge	27	4,619	1	(D)	4,619	29	3,501	1	(D)	4,267
Douglas	22	113	11	73	116	18	106	9	60	108
Faribault	45	4,571	1	(D)	4,571	62	5,722	1	(D)	5,726
Fillmore	52	959	20	115	965	55	1,396	11	314	1,406
Freeborn	35	4,550	-	-	5,675	44	7,391	7	6	7,410
Goodhue	60	3,234	6	242	3,560	62	4,272	15	498	4,520
Grant	3	9	2	(D)	(D)	11	(D)	3	2	(D)
Hennepin	79	383	43	56	391	83	345	16	137	353
Houston	6	(D)	2	(D)	(D)	16	(D)	6	6	(D)
Hubbard	12	(D)	3	(D)	(D)	13	(D)	7	(D)	(D)
Isanti	29	82	9	25	82	18	141	13	122	164
Itasca	33	310	10	7	318	18	173	10	48	177
Jackson	3	3	-	-	(D)	5	48	-	-	48
Kanabec	32	65	12	27	69	24	44	12	18	47
Kandiyohi	49	9,483	14	2,402	9,583	39	5,775	11	1,427	5,782
Kittson	4	1,308	4	(D)	1,308	4	1,873	2	(D)	1,873
Koochiching	1	(D)	-	-	(D)	7	9	1	(D)	11
Lac qui Parle	2	(D)	-	-	(D)	12	9	7	6	11
Lake	8	7	4	7	10	9	10	5	6	10
Lake of the Woods	2	(D)	1	(D)	(D)	5	(D)	-	-	(D)
Le Sueur	15	1,280	6	302	1,296	36	2,168	3	(D)	2,173
Lincoln	6	2	-	-	2	3	4	-	-	7
Lyon	1	(D)	-	-	(D)	-	-	-	-	-
McLeod	43	2,859	8	20	2,866	46	2,601	10	9	2,607
Mahnomen	4	5	-	-	(D)	5	(D)	-	-	(D)
Marshall	9	367	4	14	367	7	319	3	(D)	321
Martin	41	3,345	-	-	3,384	46	3,088	3	4	3,090
Meeker	36	2,625	15	1,068	2,824	40	2,626	15	803	2,630
Mille Lacs	19	76	4	41	82	20	53	7	16	62
Morrison	18	3,651	9	473	3,653	25	1,707	14	392	1,710
Mower	79	11,517	7	925	11,790	93	12,449	10	1,429	13,027
Murray	7	32	2	(D)	34	6	12	-	-	12
Nicollet	28	977	6	9	980	24	793	1	(D)	794
Nobles	3	12	1	(D)	12	6	71	3	20	71
Norman	9	118	5	31	118	6	50	-	-	50
Olmsted	128	10,405	6	12	10,570	115	10,257	1	(D)	10,514
Otter Tail	44	(D)	12	(D)	(D)	46	(D)	16	(D)	(D)
Pennington	6	15	-	-	17	7	14	2	(D)	15
Pine	20	50	4	6	52	16	35	9	12	37
Pipestone	4	(D)	-	-	(D)	3	(D)	1	(D)	(D)
Polk	27	5,237	6	815	5,237	29	4,616	5	(D)	4,620
Pope	18	3,784	12	3,246	4,399	28	4,859	17	3,973	4,860
Ramsey	29	44	19	30	49	37	83	18	19	86
Red Lake	-	-	-	-	-	13	1,016	2	(D)	1,016
Redwood	20	2,800	3	2	2,910	69	6,413	-	-	6,484
Renville	152	24,885	4	(D)	25,545	168	25,185	1	(D)	25,199
Rice	44	683	9	176	683	31	368	5	(D)	448
Rock	11	17	-	-	17	2	(D)	-	-	(D)
Roseau	3	6	-	-	8	17	23	4	12	24
St. Louis	76	104	31	33	114	66	112	31	26	127
Scott	29	166	12	30	182	21	79	11	26	81
Sherburne	51	9,203	40	8,780	9,233	57	10,366	35	7,161	10,371
Sibley	53	5,801	6	3	5,875	44	5,616	-	-	5,869
Stearns	75	3,022	32	1,406	3,503	66	3,283	36	2,866	3,288
Steele	21	2,288	3	398	2,618	35	4,829	4	135	4,989
Stevens	9	3	7	(D)	3	3	4	-	-	6
Swift	8	859	1	(D)	859	11	475	3	9	479
Todd	42	1,292	14	(D)	1,294	44	1,432	13	1,361	1,437
Traverse	1	(D)	-	-	(D)	4	3	-	-	(D)
Wabasha	72	5,161	6	128	5,495	96	6,548	6	3	6,790
Wadena	8	2,967	4	(D)	2,968	14	(D)	5	(D)	(D)
Waseca	51	3,401	2	(D)	3,434	48	4,132	2	(D)	4,133
Washington	74	867	31	506	926	101	1,093	31	473	1,103

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Table 28. **Land Used for Vegetables and Vegetables Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Land used for vegetables (see text)				Vegetables harvested (see text) (acres)	Land used for vegetables (see text)				Vegetables harvested (see text) (acres)
	Harvested		Irrigated			Harvested		Irrigated		
	Farms	Acres	Farms	Acres		Farms	Acres	Farms	Acres	
Counties - Con.										
Watonwan	25	3,062	7	(D)	3,197	19	2,716	4	312	2,723
Wilkin	1	(D)	-	-	(D)	3	(D)	-	-	(D)
Winona	45	2,526	8	9	2,529	32	971	1	(D)	972
Wright	58	783	24	(D)	878	56	724	33	(D)	747
Yellow Medicine	11	15	2	(D)	16	9	22	-	-	22

Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
VEGETABLES HARVESTED FOR SALE												
State Total												
Minnesota	2,620	205,632	1,632	23,564	1,026	182,068	2,840	212,474	1,634	28,581	1,257	183,892
Counties												
Aitkin	27	53	27	53	-	-	24	41	24	41	-	-
Anoka	38	1,757	32	1,755	7	2	24	657	24	657	-	-
Becker	16	(D)	13	5	4	(D)	23	(D)	21	44	2	(D)
Beltrami	24	27	24	(D)	1	(D)	23	32	23	(D)	2	(D)
Benton	20	4,158	15	(D)	5	(D)	17	4,007	14	(D)	3	(D)
Big Stone	4	15	4	15	-	-	3	(D)	3	(D)	-	-
Blue Earth	39	1,355	27	185	12	1,170	18	1,246	9	124	9	1,123
Brown	31	3,248	2	(D)	30	(D)	128	11,535	13	26	116	11,509
Carlton	25	45	25	45	-	-	25	80	25	80	-	-
Carver	26	83	26	(D)	2	(D)	22	134	22	(D)	1	(D)
Cass	14	(D)	13	24	1	(D)	19	157	19	156	3	1
Chippewa	17	2,082	8	(D)	9	(D)	21	2,538	7	7	14	2,531
Chisago	37	73	37	(D)	2	(D)	47	1,311	47	1,311	-	-
Clay	26	1,828	25	(D)	1	(D)	18	2,454	15	1,229	4	1,225
Clearwater	21	1,421	20	(D)	2	(D)	11	(D)	11	750	1	(D)
Cook	9	8	9	8	-	-	9	11	9	11	-	-
Cottonwood	6	462	3	6	3	456	11	743	8	19	3	724
Crow Wing	26	58	26	58	-	-	18	44	18	44	-	-
Dakota	176	18,755	82	788	95	17,968	172	16,613	93	2,544	81	14,069
Dodge	27	4,619	4	18	23	4,601	29	4,267	7	28	22	4,239
Douglas	22	116	22	(D)	1	(D)	18	108	18	108	-	-
Faribault	45	4,571	5	121	40	4,450	62	5,726	2	(D)	60	(D)
Fillmore	52	965	46	267	7	698	55	1,406	39	486	19	919
Freeborn	35	5,675	9	133	26	5,543	44	7,410	15	(D)	31	(D)
Goodhue	60	3,560	21	49	39	3,511	62	4,520	23	93	41	4,427
Grant	3	(D)	3	(D)	-	-	11	(D)	10	17	1	(D)
Hennepin	79	391	79	391	-	-	83	353	83	353	-	-
Houston	6	(D)	5	9	2	(D)	16	(D)	15	30	1	(D)
Hubbard	12	(D)	11	13	1	(D)	13	(D)	13	(D)	2	(D)
Isanti	29	82	24	67	9	15	18	164	18	164	-	-
Itasca	33	318	33	318	-	-	18	177	18	177	-	-
Jackson	3	(D)	3	(D)	-	-	5	48	5	48	-	-
Kanabec	32	69	32	69	-	-	24	47	24	47	-	-
Kandiyohi	49	9,583	12	51	37	9,532	39	5,782	11	(D)	29	(D)
Kittson	4	1,308	2	(D)	2	(D)	4	1,873	-	-	4	1,873
Koochiching	1	(D)	1	(D)	-	-	7	11	7	11	-	-
Lac qui Parle	2	(D)	2	(D)	-	-	12	11	12	11	-	-
Lake	8	10	8	10	-	-	9	10	9	10	-	-
Lake of the Woods	2	(D)	2	(D)	-	-	5	(D)	5	(D)	-	-
Le Sueur	15	1,296	3	8	12	1,288	36	2,173	17	162	22	2,010
Lincoln	6	2	6	2	-	-	3	7	3	7	-	-
Lyon	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	43	2,866	26	121	17	2,745	46	2,607	28	123	18	2,484
Mahnomen	4	(D)	4	(D)	-	-	5	(D)	4	6	1	(D)
Marshall	9	367	9	367	-	-	7	321	6	(D)	1	(D)
Martin	41	3,384	2	(D)	39	(D)	46	3,090	5	15	41	3,075
Meeker	36	2,824	29	41	8	2,783	40	2,630	25	238	15	2,392
Mille Lacs	19	82	19	82	-	-	20	62	20	62	-	-
Morrison	18	3,653	16	(D)	3	(D)	25	1,710	20	56	5	1,654
Mower	79	11,790	13	33	66	11,756	93	13,027	18	146	79	12,881
Murray	7	34	7	34	-	-	6	12	6	12	-	-
Nicollet	28	980	19	46	10	934	24	794	11	35	14	759
Nobles	3	12	3	12	-	-	6	71	6	71	-	-
Norman	9	118	7	(D)	2	(D)	6	50	6	50	-	-
Olmsted	128	10,570	41	337	91	10,233	115	10,514	27	208	89	10,306
Otter Tail	44	(D)	42	259	2	(D)	46	(D)	44	127	2	(D)
Pennington	6	17	6	17	-	-	7	15	7	15	-	-
Pine	20	52	20	52	-	-	16	37	16	37	-	-
Pipestone	4	(D)	4	(D)	-	-	3	(D)	3	(D)	-	-
Polk	27	5,237	21	3,318	7	1,919	29	4,620	27	(D)	2	(D)
Pope	18	4,399	4	1	14	4,398	28	4,860	8	22	20	4,838
Ramsey	29	49	29	49	3	(Z)	37	86	37	86	-	-
Red Lake	-	-	-	-	-	-	13	1,016	7	(D)	6	(D)
Redwood	20	2,910	6	5	14	2,904	69	6,484	1	(D)	68	(D)
Renville	152	25,545	11	(D)	141	(D)	168	25,199	7	207	161	24,992
Rice	44	683	38	105	7	579	31	448	29	(D)	2	(D)
Rock	11	17	11	17	-	-	2	(D)	2	(D)	-	-
Roseau	3	8	3	8	-	-	17	24	17	24	-	-
St. Louis	76	114	76	(D)	1	(D)	66	127	64	114	7	12
Scott	29	182	27	(D)	3	(D)	21	81	20	(D)	1	(D)
Sherburne	51	9,233	42	4,384	9	4,849	57	10,371	44	5,445	14	4,925
Sibley	53	5,875	12	26	41	5,849	44	5,869	4	3	40	5,866
Stearns	75	3,503	57	211	19	3,292	66	3,288	52	210	14	3,078
Steele	21	2,618	7	19	14	2,599	35	4,989	10	32	25	4,957
Stevens	9	3	9	3	-	-	3	6	3	6	-	-
Swift	8	859	4	7	4	852	11	479	8	17	3	462
Todd	42	1,294	41	(D)	1	(D)	44	1,437	44	1,437	-	-
Traverse	1	(D)	1	(D)	-	-	4	(D)	4	(D)	-	-
Wabasha	72	5,495	14	42	58	5,453	96	6,790	23	428	81	6,361
Wadena	8	2,968	6	(D)	3	(D)	14	(D)	12	(D)	3	3,002
Waseca	51	3,434	18	57	35	3,377	48	4,133	6	19	42	4,114

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
VEGETABLES HARVESTED FOR SALE - Con.												
Counties - Con.												
Washington	74	926	74	926	3	1	101	1,103	100	1,095	3	8
Watonwan	25	3,197	9	24	16	3,173	19	2,723	2	(D)	17	(D)
Wilkin	1	(D)	1	(D)	-	-	3	(D)	2	(D)	2	(D)
Winona	45	2,529	25	162	20	2,367	32	972	25	247	7	725
Wright	58	878	56	(D)	2	(D)	56	747	56	(D)	3	(D)
Yellow Medicine	11	16	11	16	-	-	9	22	9	22	-	-
ARTICHOKES, EXCLUDING JERUSALEM												
State Total												
Minnesota	3	(Z)	3	(Z)	-	-	12	1	12	1	-	-
Counties												
Isanti	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Kanabec	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Otter Tail	1	(D)	1	(D)	-	-	-	-	-	-	-	-
St. Louis	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Scott	-	-	-	-	-	-	6	(D)	6	(D)	-	-
Washington	-	-	-	-	-	-	1	(D)	1	(D)	-	-
ASPARAGUS, BEARING AGE												
State Total												
Minnesota	194	141	193	(D)	1	(D)	215	128	215	128	-	-
Counties												
Aitkin	-	-	-	-	-	-	5	1	5	1	-	-
Anoka	1	(D)	1	(D)	-	-	5	3	5	3	-	-
Becker	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Beltrami	3	(D)	2	(D)	1	(D)	2	(D)	2	(D)	-	-
Benton	1	(D)	1	(D)	-	-	4	3	4	3	-	-
Brown	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Carlton	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Carver	2	(D)	2	(D)	-	-	4	1	4	1	-	-
Cass	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Chippewa	7	1	7	1	-	-	4	3	4	3	-	-
Chisago	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Clay	-	-	-	-	-	-	3	4	3	4	-	-
Clearwater	5	3	5	3	-	-	2	(D)	2	(D)	-	-
Cook	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Dakota	15	16	15	16	-	-	8	22	8	22	-	-
Dodge	1	(D)	1	(D)	-	-	4	(D)	4	(D)	-	-
Douglas	2	(D)	2	(D)	-	-	3	(D)	3	(D)	-	-
Faribault	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Fillmore	6	1	6	1	-	-	17	10	17	10	-	-
Freeborn	1	(D)	1	(D)	-	-	3	(D)	3	(D)	-	-
Goodhue	4	1	4	1	-	-	-	-	-	-	-	-
Hennepin	7	2	7	2	-	-	3	1	3	1	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Isanti	3	3	3	3	-	-	3	(Z)	3	(Z)	-	-
Itasca	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Jackson	2	(D)	2	(D)	-	-	4	10	4	10	-	-
Kanabec	5	1	5	1	-	-	-	-	-	-	-	-
Kandiyohi	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Koochiching	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Lac qui Parle	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Lincoln	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
McLeod	2	(D)	2	(D)	-	-	11	6	11	6	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	2	(D)	-	-	5	3	5	3	-	-
Morrison	1	(D)	1	(D)	-	-	5	2	5	2	-	-
Mower	2	(D)	2	(D)	-	-	7	1	7	1	-	-
Murray	2	(D)	2	(D)	-	-	5	(D)	5	(D)	-	-
Nicollet	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Nobles	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Olmsted	7	4	7	4	-	-	6	1	6	1	-	-
Otter Tail	3	(D)	3	(D)	-	-	2	(D)	2	(D)	-	-
Pennington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Pine	4	1	4	1	-	-	4	2	4	2	-	-
Pipestone	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Polk	3	1	3	1	-	-	-	-	-	-	-	-
Pope	-	-	-	-	-	-	3	1	3	1	-	-
Renville	3	1	3	1	-	-	-	-	-	-	-	-
Rock	6	4	6	4	-	-	-	-	-	-	-	-
St. Louis	9	1	9	1	-	-	8	1	8	1	-	-
Scott	3	(Z)	3	(Z)	-	-	10	1	10	1	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
ASPARAGUS, BEARING AGE - Con.												
Counties - Con.												
Sherburne	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	11	5	11	5	-	-	6	2	6	2	-	-
Steele	4	1	4	1	-	-	4	(D)	4	(D)	-	-
Swift	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Todd	5	(D)	5	(D)	-	-	1	(D)	1	(D)	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	7	2	7	2	-	-	2	(D)	2	(D)	-	-
Wadena	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Waseca	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
Washington	8	4	8	4	-	-	10	9	10	9	-	-
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	2	(D)	2	(D)	-	-	12	5	12	5	-	-
Wright	4	(D)	4	(D)	-	-	3	(D)	3	(D)	-	-
BEANS, LIMA												
State Total												
Minnesota	20	505	14	1	6	504	5	(D)	3	1	2	(D)
Counties												
Cass	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Chippewa	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Dakota	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Otter Tail	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Pine	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Redwood	2	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Renville	4	(D)	-	-	4	(D)	-	-	-	-	-	-
Scott	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Washington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
BEANS, SNAP (BUSH AND POLE)												
State Total												
Minnesota	390	2,553	370	276	22	2,278	529	4,465	497	461	32	4,005
Counties												
Aitkin	15	3	15	3	-	-	12	2	12	2	-	-
Anoka	5	1	5	1	-	-	11	7	11	7	-	-
Becker	2	(D)	2	(D)	-	-	7	2	7	2	-	-
Beltrami	4	1	3	(D)	1	(D)	3	(Z)	3	(Z)	-	-
Benton	6	(D)	6	(D)	-	-	5	(D)	5	(D)	-	-
Blue Earth	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Brown	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Carlton	11	2	11	2	-	-	8	1	8	1	-	-
Carver	6	1	6	1	-	-	4	1	4	1	-	-
Cass	7	1	7	1	-	-	7	(D)	7	(D)	-	-
Chippewa	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Chisago	3	1	3	1	-	-	12	3	12	3	-	-
Clay	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Clearwater	8	2	8	2	-	-	2	(D)	2	(D)	-	-
Cook	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	3	(Z)	3	(Z)	-	-	6	1	6	1	-	-
Dakota	24	1,074	11	(D)	13	(D)	58	2,096	41	59	17	2,037
Dodge	1	(D)	-	-	1	(D)	4	(D)	3	(Z)	1	(D)
Douglas	5	1	5	1	-	-	4	1	4	1	-	-
Fillmore	11	3	11	3	-	-	16	8	16	8	-	-
Freeborn	1	(D)	1	(D)	-	-	7	1	7	1	-	-
Goodhue	3	(D)	1	(D)	2	(D)	7	229	4	(Z)	3	229
Grant	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hennepin	16	3	16	3	-	-	26	14	26	14	-	-
Houston	3	(D)	2	(D)	1	(D)	8	(D)	7	2	1	(D)
Hubbard	4	1	4	1	-	-	5	2	5	2	-	-
Isanti	4	(D)	2	(D)	2	(D)	8	1	8	1	-	-
Itasca	9	2	9	2	-	-	10	1	10	1	-	-
Kanabec	6	2	6	2	-	-	6	1	6	1	-	-
Kandiyohi	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Koochiching	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	6	1	6	1	-	-
Lake	3	1	3	1	-	-	4	1	4	1	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Lincoln	-	-	-	-	-	-	1	(D)	1	(D)	-	-
McLeod	8	2	8	2	-	-	15	4	15	4	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	7	1	7	1	-	-	10	1	10	1	-	-
Mille Lacs	1	(D)	1	(D)	-	-	5	2	5	2	-	-
Morrison	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Mower	2	(D)	2	(D)	-	-	7	(D)	5	1	2	(D)
Murray	5	6	5	6	-	-	-	-	-	-	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
BEANS, SNAP (BUSH AND POLE) - Con.												
Counties - Con.												
Nicollet	5	1	5	(D)	1	(D)	5	2	5	2	-	-
Nobles	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Norman	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Olmsted	9	2	9	2	-	-	17	(D)	16	4	1	(D)
Otter Tail	8	2	8	2	-	-	9	4	9	4	-	-
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	3	1	3	1	-	-	9	4	9	4	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	3	1	3	1	-	-	5	2	5	2	-	-
Pope	-	-	-	-	-	-	4	1	4	1	-	-
Ramsey	14	5	14	5	-	-	11	4	11	4	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Renville	10	(D)	10	(D)	-	-	-	-	-	-	-	-
Rice	2	(D)	2	(D)	-	-	9	2	9	2	-	-
Roseau	3	(Z)	3	(Z)	-	-	10	1	10	1	-	-
St. Louis	24	5	24	(D)	1	(D)	24	5	23	(D)	1	(D)
Scott	14	2	14	2	-	-	5	1	5	1	-	-
Sherburne	6	4	6	4	-	-	20	597	15	(D)	5	(D)
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	8	4	8	4	-	-	17	10	17	10	-	-
Steele	4	1	4	1	-	-	6	1	6	1	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Todd	6	2	6	2	-	-	2	(D)	2	(D)	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Wadena	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Waseca	14	2	14	2	-	-	4	(Z)	4	(Z)	-	-
Washington	24	(D)	24	(D)	-	-	31	(D)	31	(D)	-	-
Watonwan	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	4	2	4	2	-	-	4	4	4	4	-	-
Wright	14	(D)	14	(D)	-	-	16	(D)	15	4	1	(D)
Yellow Medicine	8	3	8	3	-	-	1	(D)	1	(D)	-	-
BEETS												
State Total												
Minnesota	305	595	303	(D)	3	(D)	322	351	319	(D)	3	(D)
Counties												
Aitkin	7	1	7	1	-	-	2	(D)	2	(D)	-	-
Anoka	3	(D)	3	(D)	-	-	7	3	7	3	-	-
Becker	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Beltrami	4	1	3	(D)	1	(D)	4	(Z)	4	(Z)	-	-
Brown	-	-	-	-	-	-	5	1	5	1	-	-
Carlton	7	1	7	1	-	-	9	2	9	2	-	-
Carver	3	1	3	1	-	-	3	1	3	1	-	-
Cass	5	1	5	1	-	-	-	-	-	-	-	-
Chippewa	7	(D)	6	1	1	(D)	2	(D)	1	(D)	1	(D)
Chisago	7	1	7	1	-	-	15	(D)	15	(D)	-	-
Clay	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Clearwater	8	3	8	3	-	-	2	(D)	2	(D)	-	-
Cook	3	(Z)	3	(Z)	-	-	3	(D)	3	(D)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Dakota	13	5	13	5	-	-	23	23	23	23	-	-
Dodge	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Douglas	5	1	5	1	-	-	4	1	4	1	-	-
Fillmore	12	5	12	5	-	-	11	11	11	11	-	-
Freeborn	-	-	-	-	-	-	7	1	7	1	-	-
Goodhue	-	-	-	-	-	-	4	1	4	1	-	-
Hennepin	4	(Z)	4	(Z)	-	-	12	4	12	4	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Isanti	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Itasca	6	1	6	1	-	-	8	1	8	1	-	-
Jackson	-	-	-	-	-	-	4	(D)	4	(D)	-	-
Kanabec	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Koochiching	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Lake	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
McLeod	5	2	5	2	-	-	7	2	7	2	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	4	(Z)	4	(Z)	-	-	7	1	7	1	-	-
Mille Lacs	3	1	3	1	-	-	7	1	7	1	-	-
Morrison	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Murray	4	1	4	1	-	-	-	-	-	-	-	-
Nicollet	8	1	8	(D)	1	(D)	3	(Z)	3	(Z)	-	-
Nobles	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	10	4	10	4	-	-	15	3	15	3	-	-
Otter Tail	9	1	9	1	-	-	5	1	5	1	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pine	3	1	3	1	-	-	2	(D)	2	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
BEETS - Con.												
Counties - Con.												
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Pope	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Ramsey	14	2	14	2	-	-	5	1	5	1	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Renville	10	5	10	5	-	-	1	(D)	1	(D)	-	-
Rice	3	1	3	1	-	-	11	2	11	2	-	-
Roseau	3	(Z)	3	(Z)	-	-	4	1	4	1	-	-
St. Louis	28	3	28	3	-	-	18	2	16	(D)	2	(D)
Scott	4	1	4	1	-	-	7	1	7	1	-	-
Sherburne	4	3	4	3	-	-	4	1	4	1	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	4	2	4	2	-	-	11	1	11	1	-	-
Steele	4	1	4	1	-	-	5	1	5	1	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	6	1	6	1	-	-
Todd	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Wabasha	5	2	5	2	-	-	2	(D)	2	(D)	-	-
Waseca	9	1	9	1	-	-	3	(Z)	3	(Z)	-	-
Washington	18	6	18	6	-	-	23	6	23	6	-	-
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	12	2	12	2	-	-	6	5	6	5	-	-
Wright	5	3	5	3	-	-	7	1	7	1	-	-
Yellow Medicine	4	(D)	4	(D)	-	-	1	(D)	1	(D)	-	-
BROCCOLI												
State Total												
Minnesota	254	(D)	254	(D)	-	-	306	170	306	170	-	-
Counties												
Aitkin	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Anoka	3	2	3	2	-	-	12	7	12	7	-	-
Becker	-	-	-	-	-	-	3	1	3	1	-	-
Beltrami	3	(Z)	3	(Z)	-	-	3	(D)	3	(D)	-	-
Benton	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Blue Earth	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Brown	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Carlton	3	(D)	3	(D)	-	-	8	9	8	9	-	-
Carver	4	3	4	3	-	-	3	1	3	1	-	-
Cass	-	-	-	-	-	-	3	1	3	1	-	-
Chippewa	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chisago	1	(D)	1	(D)	-	-	10	1	10	1	-	-
Clay	10	3	10	3	-	-	2	(D)	2	(D)	-	-
Clearwater	4	1	4	1	-	-	-	-	-	-	-	-
Cook	4	(Z)	4	(Z)	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Dakota	22	11	22	11	-	-	26	27	26	27	-	-
Dodge	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Douglas	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
Fillmore	13	22	13	22	-	-	13	47	13	47	-	-
Freeborn	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Goodhue	-	-	-	-	-	-	5	2	5	2	-	-
Hennepin	4	(Z)	4	(Z)	-	-	9	5	9	5	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Isanti	2	(D)	2	(D)	-	-	8	1	8	1	-	-
Itasca	4	1	4	1	-	-	12	2	12	2	-	-
Kanabec	5	1	5	1	-	-	5	1	5	1	-	-
Kandiyohi	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Koochiching	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lake	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Le Sueur	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
McLeod	7	2	7	2	-	-	7	4	7	4	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mille Lacs	3	1	3	1	-	-	6	1	6	1	-	-
Morrison	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Mower	3	1	3	1	-	-	3	1	3	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	6	1	6	1	-	-	12	1	12	1	-	-
Otter Tail	5	1	5	1	-	-	4	1	4	1	-	-
Pennington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Pine	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	-	-	-	-	-	-	3	1	3	1	-	-
Pope	-	-	-	-	-	-	4	1	4	1	-	-
Ramsey	14	2	14	2	-	-	7	2	7	2	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
BROCCOLI - Con.												
Counties - Con.												
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	2	(D)	2	(D)	-	-	12	9	12	9	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	17	3	17	3	-	-	15	2	15	2	-	-
Scott	16	2	16	2	-	-	6	1	6	1	-	-
Sherburne	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	5	2	5	2	-	-	9	2	9	2	-	-
Steele	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Todd	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Wabasha	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Waseca	12	1	12	1	-	-	1	(D)	1	(D)	-	-
Washington	9	3	9	3	-	-	24	12	24	12	-	-
Winona	8	2	8	2	-	-	7	(D)	7	(D)	-	-
Wright	7	8	7	8	-	-	14	3	14	3	-	-
BRUSSELS SPROUTS												
State Total												
Minnesota	101	25	101	25	-	-	142	44	142	44	-	-
Counties												
Aitkin	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Anoka	1	(D)	1	(D)	-	-	6	2	6	2	-	-
Beltrami	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Blue Earth	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Brown	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Carlton	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
Carver	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Chippewa	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Clay	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Clearwater	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Cook	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Dakota	7	3	7	3	-	-	15	21	15	21	-	-
Douglas	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
Fillmore	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Freeborn	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Goodhue	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Hennepin	4	(Z)	4	(Z)	-	-	8	3	8	3	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Isanti	-	-	-	-	-	-	5	1	5	1	-	-
Itasca	3	(Z)	3	(Z)	-	-	4	1	4	1	-	-
Kanabec	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Koochiching	-	-	-	-	-	-	1	(D)	1	(D)	-	-
McLeod	3	(D)	3	(D)	-	-	2	(D)	2	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Morrison	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mower	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	3	1	3	1	-	-	-	-	-	-	-	-
Olmsted	3	2	3	2	-	-	4	(Z)	4	(Z)	-	-
Otter Tail	4	1	4	1	-	-	4	1	4	1	-	-
Pine	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Ramsey	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
St. Louis	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Scott	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Sherburne	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	2	(D)	2	(D)	-	-	7	1	7	1	-	-
Steele	-	-	-	-	-	-	3	1	3	1	-	-
Swift	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Todd	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Wabasha	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Waseca	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Washington	10	2	10	2	-	-	20	3	20	3	-	-
Winona	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Wright	4	(D)	4	(D)	-	-	5	1	5	1	-	-
CABBAGE, CHINESE (NAPPA, BOK CHOY, ETC.)												
State Total												
Minnesota	108	28	108	28	-	-	157	35	157	35	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
CABBAGE, CHINESE (NAPPA, BOK CHOY, ETC.) - Con.												
Counties												
Aitkin	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Anoka	2	(D)	2	(D)	-	-	4	1	4	1	-	-
Becker	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Beltrami	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Benton	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Carlton	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Carver	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Cook	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Dakota	5	2	5	2	-	-	24	7	24	7	-	-
Douglas	4	1	4	1	-	-	-	-	-	-	-	-
Fillmore	12	6	12	6	-	-	8	7	8	7	-	-
Freeborn	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Goodhue	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hennepin	1	(D)	1	(D)	-	-	17	6	17	6	-	-
Hubbard	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Isanti	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Itasca	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
Kanabec	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Koochiching	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Lake	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	3	(D)	3	(D)	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Morrison	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mower	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Olmsted	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Otter Tail	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Ramsey	8	1	8	1	-	-	8	1	8	1	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	8	1	8	1	-	-	2	(D)	2	(D)	-	-
Scott	5	1	5	1	-	-	2	(D)	2	(D)	-	-
Sherburne	-	-	-	-	-	-	4	1	4	1	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
Steele	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	3	(D)	3	(D)	-	-
Todd	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Waseca	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Washington	5	1	5	1	-	-	16	3	16	3	-	-
Winona	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Wright	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
CABBAGE, HEAD												
State Total												
Minnesota	290	309	290	308	3	(Z)	304	421	302	(D)	3	(D)
Counties												
Aitkin	10	1	10	1	-	-	3	1	3	1	-	-
Anoka	10	(D)	10	(D)	-	-	10	(D)	10	(D)	-	-
Becker	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Beltrami	4	1	4	1	-	-	4	1	4	1	-	-
Benton	5	(D)	5	(D)	-	-	1	(D)	1	(D)	-	-
Blue Earth	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Brown	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Carlton	5	1	5	1	-	-	12	10	12	10	-	-
Carver	3	2	3	2	-	-	3	1	3	1	-	-
Cass	4	1	4	1	-	-	3	1	3	1	-	-
Chippewa	5	1	5	1	-	-	-	-	-	-	-	-
Chisago	3	(Z)	3	(Z)	-	-	13	2	13	2	-	-
Clay	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Clearwater	7	4	7	4	-	-	3	(D)	3	(D)	-	-
Cook	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Cottonwood	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Crow Wing	3	(Z)	3	(Z)	-	-	6	1	6	1	-	-
Dakota	14	(D)	14	(D)	-	-	21	(D)	21	(D)	-	-
Dodge	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Douglas	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
Fillmore	5	(D)	5	(D)	-	-	10	39	10	39	-	-
Freeborn	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Goodhue	-	-	-	-	-	-	4	1	4	1	-	-
Hennepin	4	(Z)	4	(Z)	-	-	12	6	12	6	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Isanti	1	(D)	1	(D)	-	-	6	2	6	2	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
CABBAGE, HEAD - Con.												
Counties - Con.												
Itasca	5	1	5	1	-	-	5	1	5	1	-	-
Kanabec	9	3	9	3	-	-	5	2	5	2	-	-
Kandiyohi	3	(D)	3	(D)	-	-	1	(D)	1	(D)	-	-
Koochiching	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	5	1	5	1	-	-
Lake	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Lake of the Woods	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
McLeod	5	2	5	2	-	-	5	3	5	3	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mille Lacs	4	2	4	2	-	-	8	1	8	1	-	-
Morrison	4	1	4	1	-	-	-	-	-	-	-	-
Mower	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Olmsted	10	22	10	22	-	-	9	1	9	1	-	-
Otter Tail	7	3	7	3	-	-	5	3	5	3	-	-
Pennington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Pine	3	(Z)	3	(Z)	-	-	5	1	5	1	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Pope	-	-	-	-	-	-	4	1	4	1	-	-
Ramsey	14	2	14	2	3	(Z)	4	3	4	3	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Renville	4	(D)	4	(D)	-	-	1	(D)	1	(D)	-	-
Rice	4	3	4	3	-	-	15	4	15	4	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	27	3	27	3	-	-	18	3	16	(D)	2	(D)
Scott	14	2	14	2	-	-	2	(D)	2	(D)	-	-
Sherburne	3	(D)	3	(D)	-	-	1	(D)	1	(D)	-	-
Stearns	9	2	9	2	-	-	13	5	13	5	-	-
Steele	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Swift	-	-	-	-	-	-	4	1	4	1	-	-
Todd	1	(D)	1	(D)	-	-	3	(D)	3	(D)	-	-
Wabasha	3	1	3	1	-	-	4	1	4	1	-	-
Waseca	12	1	12	1	-	-	-	-	-	-	-	-
Washington	7	2	7	2	-	-	17	11	17	(D)	1	(D)
Winona	9	3	9	3	-	-	12	19	12	19	-	-
Wright	5	(D)	5	(D)	-	-	10	2	10	2	-	-
Yellow Medicine	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
CABBAGE, MUSTARD												
State Total												
Minnesota	17	3	17	3	(X)	(X)	15	4	15	4	(X)	(X)
Counties												
Anoka	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Dakota	3	(Z)	3	(Z)	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Kanabec	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
McLeod	1	(D)	1	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Nobles	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Otter Tail	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Ramsey	5	1	5	1	(X)	(X)	-	-	-	-	(X)	(X)
Scott	1	(D)	1	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Sherburne	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Stevens	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Waseca	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Washington	4	(Z)	4	(Z)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
CANTALOUPES AND MUSKMELONS												
State Total												
Minnesota	155	124	155	124	-	-	170	117	170	117	-	-
Counties												
Aitkin	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Anoka	5	(D)	5	(D)	-	-	8	9	8	9	-	-
Becker	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Beltrami	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Blue Earth	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Brown	-	-	-	-	-	-	6	1	6	1	-	-
Carlton	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Carver	3	1	3	1	-	-	1	(D)	1	(D)	-	-
Cass	5	1	5	1	-	-	-	-	-	-	-	-
Chippewa	8	2	8	2	-	-	1	(D)	1	(D)	-	-
Chisago	-	-	-	-	-	-	3	1	3	1	-	-
Clay	7	1	7	1	-	-	3	(D)	3	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cook	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Cottonwood	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Crow Wing	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
CANTALOUPES AND MUSKMELONS - Con.												
Counties - Con.												
Dakota	5	1	5	1	-	-	6	2	6	2	-	-
Dodge	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Douglas	6	2	6	2	-	-	2	(D)	2	(D)	-	-
Fillmore	5	6	5	6	-	-	6	17	6	17	-	-
Freeborn	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Goodhue	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Hennepin	5	1	5	1	-	-	7	7	7	7	-	-
Houston	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Isanti	1	(D)	1	(D)	-	-	6	2	6	2	-	-
Itasca	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Jackson	-	-	-	-	-	-	4	(D)	4	(D)	-	-
Kanabec	7	2	7	2	-	-	2	(D)	2	(D)	-	-
Kandiyohi	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Lac qui Parle	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lake	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Le Sueur	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
McLeod	4	2	4	2	-	-	6	2	6	2	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	2	(D)	2	(D)	-	-	3	2	3	2	-	-
Mille Lacs	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Morrison	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Murray	4	1	4	1	-	-	-	-	-	-	-	-
Nicollet	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Nobles	1	(D)	1	(D)	-	-	3	(D)	3	(D)	-	-
Norman	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Olmsted	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Otter Tail	6	3	6	3	-	-	4	3	4	3	-	-
Pine	5	1	5	1	-	-	7	1	7	1	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	1	(D)	1	(D)	-	-	4	2	4	2	-	-
Pope	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	1	(D)	1	(D)	-	-	7	2	7	2	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Scott	4	3	4	3	-	-	3	1	3	1	-	-
Sherburne	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	4	1	4	1	-	-	4	1	4	1	-	-
Steele	-	-	-	-	-	-	3	1	3	1	-	-
Swift	3	1	3	1	-	-	-	-	-	-	-	-
Todd	1	(D)	1	(D)	-	-	10	2	10	2	-	-
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Wadena	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Waseca	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Washington	7	5	7	5	-	-	17	8	17	8	-	-
Winona	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Wright	7	(D)	7	(D)	-	-	7	7	7	7	-	-
CARROTS												
State Total												
Minnesota	336	1,194	332	512	4	682	364	947	359	398	5	548
Counties												
Aitkin	7	1	7	1	-	-	10	1	10	1	-	-
Anoka	2	(D)	2	(D)	-	-	9	6	9	6	-	-
Beltrami	4	1	3	(D)	1	(D)	11	1	11	1	-	-
Brown	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Carlton	8	4	8	4	-	-	9	4	9	4	-	-
Carver	8	2	8	2	-	-	6	1	6	1	-	-
Cass	11	1	11	1	-	-	7	1	7	1	-	-
Chippewa	4	(D)	3	(Z)	1	(D)	2	(D)	1	(D)	1	(D)
Chisago	2	(D)	2	(D)	-	-	16	(D)	16	(D)	-	-
Clay	12	1	12	1	-	-	3	(Z)	3	(Z)	-	-
Clearwater	8	2	8	2	-	-	-	-	-	-	-	-
Cook	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Crow Wing	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Dakota	11	8	11	8	-	-	15	29	15	29	-	-
Dodge	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Douglas	9	(D)	9	(D)	-	-	4	(Z)	4	(Z)	-	-
Faribault	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Fillmore	5	(D)	5	(D)	-	-	14	37	14	37	-	-
Freeborn	1	(D)	-	-	1	(D)	8	(D)	6	1	2	(D)
Goodhue	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Hennepin	10	1	10	1	-	-	12	3	12	3	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Isanti	1	(D)	1	(D)	-	-	6	1	6	1	-	-
Itasca	5	1	5	1	-	-	10	1	10	1	-	-
Kanabec	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Kandiyohi	3	(D)	3	(D)	-	-	-	-	-	-	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
CARROTS - Con.												
Counties - Con.												
Koochiching	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Lac qui Parle	-	-	-	-	-	-	11	5	11	5	-	-
Lake	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Lincoln	-	-	-	-	-	-	2	(D)	2	(D)	-	-
McLeod	4	2	4	2	-	-	2	(D)	2	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	3	(Z)	3	(Z)	-	-	7	1	7	1	-	-
Mille Lacs	3	1	3	1	-	-	7	1	7	1	-	-
Morrison	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mower	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	5	1	5	1	-	-	-	-	-	-	-	-
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	7	2	7	2	-	-	13	4	13	4	-	-
Otter Tail	12	2	12	2	-	-	5	1	5	1	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pine	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	3	1	3	1	-	-	-	-	-	-	-	-
Pope	-	-	-	-	-	-	4	1	4	1	-	-
Ramsey	6	1	6	1	-	-	10	2	10	2	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	9	1	9	1	-	-	10	2	10	2	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	31	4	31	4	-	-	28	7	28	7	-	-
Scott	7	1	7	1	-	-	3	1	3	1	-	-
Sherburne	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Sibley	7	(D)	7	(D)	-	-	-	-	-	-	-	-
Stearns	7	2	7	2	-	-	7	2	7	2	-	-
Steele	5	(D)	4	1	1	(D)	8	151	6	(D)	2	(D)
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	4	1	4	1	-	-
Todd	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Wabasha	5	2	5	2	-	-	2	(D)	2	(D)	-	-
Wadena	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Waseca	12	1	12	1	-	-	1	(D)	1	(D)	-	-
Washington	29	10	29	10	-	-	26	10	26	10	-	-
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	7	3	7	3	-	-	7	18	7	18	-	-
Wright	14	6	14	6	-	-	11	1	11	1	-	-
Yellow Medicine	-	-	-	-	-	-	1	(D)	1	(D)	-	-
CAULIFLOWER												
State Total												
Minnesota	145	47	145	47	-	-	179	59	179	59	-	-
Counties												
Aitkin	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Anoka	2	(D)	2	(D)	-	-	6	3	6	3	-	-
Becker	-	-	-	-	-	-	3	1	3	1	-	-
Beltrami	-	-	-	-	-	-	4	1	4	1	-	-
Brown	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Carlton	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Carver	6	5	6	5	-	-	3	(Z)	3	(Z)	-	-
Chippewa	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chisago	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Clay	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cook	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Crow Wing	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Dakota	10	6	10	6	-	-	11	14	11	14	-	-
Dodge	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Douglas	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Fillmore	12	3	12	3	-	-	9	5	9	5	-	-
Freeborn	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Goodhue	-	-	-	-	-	-	4	1	4	1	-	-
Hennepin	4	(Z)	4	(Z)	-	-	8	5	8	5	-	-
Hubbard	6	1	6	1	-	-	-	-	-	-	-	-
Isanti	1	(D)	1	(D)	-	-	6	1	6	1	-	-
Itasca	2	(D)	2	(D)	-	-	7	1	7	1	-	-
Kanabec	5	1	5	1	-	-	2	(D)	2	(D)	-	-
Lake	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	3	2	3	2	-	-	4	2	4	2	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Mille Lacs	3	1	3	1	-	-	4	1	4	1	-	-
Mower	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	-	-	-	-	-	-	7	1	7	1	-	-
Otter Tail	4	1	4	1	-	-	5	1	5	1	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
CAULIFLOWER - Con.												
Counties - Con.												
Pennington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Pine	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Ramsey	-	-	-	-	-	-	4	2	4	2	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	7	1	7	1	-	-	9	2	9	2	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	10	1	10	1	-	-	8	1	8	1	-	-
Scott	5	2	5	2	-	-	2	(D)	2	(D)	-	-
Sherburne	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	5	1	5	1	-	-	9	2	9	2	-	-
Steele	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Todd	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Wabasha	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Waseca	5	1	5	1	-	-	1	(D)	1	(D)	-	-
Washington	9	2	9	2	-	-	19	9	19	9	-	-
Winona	-	-	-	-	-	-	5	3	5	3	-	-
Wright	2	(D)	2	(D)	-	-	3	1	3	1	-	-
CELERY												
State Total												
Minnesota	105	22	105	22	-	-	88	16	88	16	-	-
Counties												
Aitkin	3	(Z)	3	(Z)	-	-	3	1	3	1	-	-
Anoka	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Beltrami	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Brown	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Carlton	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Carver	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Cass	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chippewa	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chisago	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Clay	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Dakota	4	(D)	4	(D)	-	-	6	1	6	1	-	-
Fillmore	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Freeborn	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Goodhue	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hennepin	8	1	8	1	-	-	5	2	5	2	-	-
Hubbard	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Itasca	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Kanabec	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lake	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mille Lacs	-	-	-	-	-	-	3	(D)	3	(D)	-	-
Morrison	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mower	-	-	-	-	-	-	3	1	3	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Norman	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Olmsted	4	(Z)	4	(Z)	-	-	3	(Z)	3	(Z)	-	-
Otter Tail	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Pine	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Ramsey	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	20	2	20	2	-	-	4	1	4	1	-	-
Scott	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Sherburne	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Wadena	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Waseca	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Washington	7	2	7	2	-	-	6	1	6	1	-	-
Winona	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Wright	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Yellow Medicine	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
CHICORY												
State Total												
Minnesota	5	1	5	1	-	-	3	(Z)	3	(Z)	(X)	(X)

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
CHICORY - Con.												
Counties												
Carver	-	-	-	-	-	-	2	(D)	2	(D)	(X)	(X)
Houston	2	(D)	2	(D)	-	-	-	-	-	-	(X)	(X)
Kanabec	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
Meeker	-	-	-	-	-	-	1	(D)	1	(D)	(X)	(X)
Otter Tail	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
Rice	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
COLLARDS												
State Total												
Minnesota	53	14	53	14	-	-	33	9	33	9	-	-
Counties												
Aitkin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Anoka	5	2	5	2	-	-	-	-	-	-	-	-
Carlton	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Cass	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Chisago	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Dakota	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Fillmore	2	(D)	2	(D)	-	-	3	3	3	3	-	-
Goodhue	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hennepin	10	1	10	1	-	-	2	(D)	2	(D)	-	-
Isanti	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Itasca	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Kanabec	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Koochiching	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lake	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
McLeod	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	-	-	-	-	-	-	3	1	3	1	-	-
Olmsted	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Scott	3	1	3	1	-	-	4	1	4	1	-	-
Stearns	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Wabasha	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Washington	12	5	12	5	-	-	7	2	7	2	-	-
CUCUMBERS AND PICKLES												
State Total												
Minnesota	425	200	417	198	13	3	549	326	539	323	17	3
Counties												
Aitkin	17	5	17	5	-	-	10	2	10	2	-	-
Anoka	6	18	6	(D)	1	(D)	9	18	9	18	-	-
Becker	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Beltrami	8	1	7	(D)	1	(D)	6	1	5	(D)	1	(D)
Benton	7	(D)	7	(D)	-	-	3	(D)	3	(D)	-	-
Blue Earth	1	(D)	1	(D)	-	-	3	2	3	2	-	-
Brown	-	-	-	-	-	-	5	1	5	1	-	-
Carlton	3	1	3	1	-	-	3	(Z)	3	(Z)	-	-
Carver	5	2	3	(D)	2	(D)	6	1	6	1	-	-
Cass	7	1	7	1	-	-	3	5	3	3	3	1
Chippewa	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Chisago	7	1	7	1	-	-	27	6	27	6	-	-
Clay	5	1	5	1	-	-	5	2	5	2	-	-
Clearwater	8	3	8	3	-	-	3	2	3	2	-	-
Cook	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Crow Wing	3	(Z)	3	(Z)	-	-	5	1	5	1	-	-
Dakota	25	13	25	13	-	-	65	84	65	84	-	-
Dodge	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Douglas	5	1	5	1	-	-	4	1	4	1	-	-
Faribault	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Fillmore	15	7	15	(D)	1	(D)	14	16	11	(D)	3	(D)
Freeborn	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Goodhue	-	-	-	-	-	-	4	1	4	1	-	-
Grant	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Hennepin	24	5	24	5	-	-	43	10	43	10	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	4	1	4	1	-	-	4	1	4	1	-	-
Isanti	4	1	1	(D)	4	(D)	9	3	9	3	-	-
Itasca	15	3	15	3	-	-	10	1	10	1	-	-
Jackson	-	-	-	-	-	-	4	2	4	2	-	-
Kanabec	10	2	10	2	-	-	4	1	4	1	-	-
Kandiyohi	1	(D)	1	(D)	-	-	4	(D)	4	(D)	-	-
Koochiching	-	-	-	-	-	-	3	1	3	1	-	-
Lac qui Parle	-	-	-	-	-	-	6	1	6	1	-	-
Lake	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	5	2	5	1	3	(Z)
McLeod	12	4	12	4	-	-	10	4	10	4	-	-
Marshall	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	3	1	3	1	-	-	7	1	7	1	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
CUCUMBERS AND PICKLES - Con.												
Counties - Con.												
Mille Lacs	4	2	4	2	-	-	9	3	9	3	-	-
Morrison	6	1	6	1	-	-	13	4	13	4	-	-
Mower	2	(D)	2	(D)	-	-	11	2	9	(D)	2	(D)
Murray	5	3	5	3	-	-	1	(D)	1	(D)	-	-
Nicollet	7	1	7	1	-	-	4	1	4	1	-	-
Nobles	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Norman	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	10	(D)	10	(D)	-	-	11	1	11	1	-	-
Otter Tail	13	3	13	3	-	-	11	2	11	2	-	-
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	6	1	6	1	-	-	8	2	8	2	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	-	-	-	-	-	-	3	2	3	2	-	-
Pope	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	3	(D)	3	(D)	-	-	11	3	11	3	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Renville	10	(D)	10	(D)	-	-	1	(D)	1	(D)	-	-
Rice	9	2	9	(D)	1	(D)	15	4	15	4	-	-
Roseau	-	-	-	-	-	-	4	2	4	2	-	-
St. Louis	37	6	37	6	-	-	26	5	22	4	4	(Z)
Scott	6	6	6	(D)	1	(D)	7	1	7	1	-	-
Sherburne	6	4	6	4	-	-	9	4	9	4	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	14	3	14	3	-	-	16	3	16	3	-	-
Steele	4	1	4	1	-	-	5	1	5	1	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Todd	11	1	11	1	-	-	4	1	4	1	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Wadena	1	(D)	1	(D)	-	-	4	3	4	3	-	-
Waseca	7	1	7	1	-	-	1	(D)	1	(D)	-	-
Washington	26	11	26	11	-	-	26	10	26	10	-	-
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Winona	7	3	7	3	-	-	11	11	11	11	-	-
Wright	6	4	4	(D)	2	(D)	16	4	16	4	-	-
Yellow Medicine	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
DAIKON												
State Total												
Minnesota	34	6	34	6	-	-	41	9	41	9	-	-
Counties												
Aitkin	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Anoka	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Carlton	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Chisago	-	-	-	-	-	-	3	1	3	1	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Dakota	2	(D)	2	(D)	-	-	6	3	6	3	-	-
Fillmore	3	1	3	1	-	-	4	1	4	1	-	-
Goodhue	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hennepin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Kanabec	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Meeker	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mower	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Olmsted	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Otter Tail	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Pine	-	-	-	-	-	-	2	(D)	2	(D)	-	-
St. Louis	5	1	5	1	-	-	-	-	-	-	-	-
Scott	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Stearns	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	3	1	3	1	-	-
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Waseca	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Washington	4	1	4	1	-	-	3	1	3	1	-	-
Winona	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Wright	1	(D)	1	(D)	-	-	-	-	-	-	-	-
EGGPLANT												
State Total												
Minnesota	169	50	169	50	-	-	192	59	192	59	-	-
Counties												
Aitkin	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Anoka	9	1	9	1	-	-	6	3	6	3	-	-
Beltrami	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Blue Earth	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Brown	-	-	-	-	-	-	1	(D)	1	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
EGGPLANT - Con.												
Counties - Con.												
Carlton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Carver	4	1	4	1	-	-	4	(Z)	4	(Z)	-	-
Cass	3	1	3	1	-	-	-	-	-	-	-	-
Chisago	1	(D)	1	(D)	-	-	6	2	6	2	-	-
Clay	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Dakota	14	6	14	6	-	-	26	11	26	11	-	-
Dodge	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Douglas	4	1	4	1	-	-	-	-	-	-	-	-
Fillmore	11	2	11	2	-	-	6	(D)	6	(D)	-	-
Goodhue	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Hennepin	11	3	11	3	-	-	6	1	6	1	-	-
Houston	2	(D)	2	(D)	-	-	6	1	6	1	-	-
Isanti	-	-	-	-	-	-	7	1	7	1	-	-
Itasca	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Kanabec	6	1	6	1	-	-	3	1	3	1	-	-
Koochiching	-	-	-	-	-	-	3	1	3	1	-	-
Lac qui Parle	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	4	2	4	2	-	-	3	(D)	3	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Mille Lacs	2	(D)	2	(D)	-	-	3	(D)	3	(D)	-	-
Morrison	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mower	3	1	3	1	-	-	3	1	3	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	4	(Z)	4	(Z)	-	-	4	1	4	1	-	-
Otter Tail	5	1	5	1	-	-	4	1	4	1	-	-
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Pope	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	3	(Z)	3	(Z)	-	-	7	(D)	7	(D)	-	-
Redwood	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Rice	6	1	6	1	-	-	5	2	5	2	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	6	1	6	1	-	-	4	1	4	1	-	-
Scott	5	1	5	1	-	-	2	(D)	2	(D)	-	-
Sherburne	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Steele	4	1	4	1	-	-	-	-	-	-	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Todd	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	5	1	5	1	-	-	2	(D)	2	(D)	-	-
Waseca	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Washington	19	12	19	12	-	-	27	15	27	15	-	-
Winona	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Wright	4	3	4	3	-	-	5	1	5	1	-	-
ESCAROLE AND ENDIVE												
State Total												
Minnesota	8	1	8	1	(X)	(X)	6	1	6	1	(X)	(X)
Counties												
Carver	1	(D)	1	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Crow Wing	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Fillmore	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Houston	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Isanti	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Washington	4	(Z)	4	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
GARLIC												
State Total												
Minnesota	316	81	316	78	7	3	224	52	221	51	4	(Z)
Counties												
Aitkin	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Anoka	4	1	4	1	-	-	8	1	8	1	-	-
Becker	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Beltrami	6	3	6	3	-	-	4	1	4	(D)	1	(D)
Benton	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Big Stone	3	(D)	3	(D)	-	-	1	(D)	1	(D)	-	-
Carlton	6	1	6	1	-	-	5	1	5	1	-	-
Carver	1	(D)	1	(D)	-	-	4	1	4	1	-	-
Cass	6	1	6	1	-	-	-	-	-	-	-	-
Chippewa	7	1	7	1	-	-	-	-	-	-	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
GARLIC - Con.												
Counties - Con.												
Chisago	5	2	5	(D)	2	(D)	8	3	8	3	-	-
Clay	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Clearwater	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Cook	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	6	1	6	1	-	-	8	1	8	1	-	-
Dakota	17	5	17	5	-	-	7	2	7	2	-	-
Dodge	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Douglas	5	1	5	1	-	-	3	(Z)	3	(Z)	-	-
Faribault	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Fillmore	9	1	9	(D)	1	(D)	15	2	15	2	-	-
Goodhue	5	4	5	4	-	-	7	1	7	1	-	-
Grant	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Hennepin	17	2	17	2	-	-	4	(Z)	4	(Z)	-	-
Houston	2	(D)	2	(D)	-	-	6	1	6	1	-	-
Hubbard	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Isanti	10	5	10	3	3	2	5	1	5	1	-	-
Itasca	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Kanabec	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Lake	5	1	5	1	-	-	3	(Z)	3	(Z)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	5	2	5	2	-	-	1	(D)	1	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	13	4	13	4	-	-	2	(D)	2	(D)	-	-
Mille Lacs	3	1	3	1	-	-	4	(Z)	4	(Z)	-	-
Morrison	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Mower	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Murray	4	(D)	4	(D)	-	-	-	-	-	-	-	-
Nicollet	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nobles	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	10	2	10	2	-	-	6	1	6	1	-	-
Otter Tail	5	2	5	2	-	-	4	1	4	1	-	-
Pine	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Ramsey	-	-	-	-	-	-	8	2	8	2	-	-
Redwood	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Rice	14	2	14	2	-	-	9	2	9	2	-	-
St. Louis	25	7	25	7	-	-	17	13	14	(D)	3	(D)
Scott	4	1	4	1	-	-	6	2	6	2	-	-
Sherburne	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
Stearns	10	5	10	5	-	-	2	(D)	2	(D)	-	-
Steele	2	(D)	2	(D)	-	-	7	1	7	1	-	-
Stevens	7	(D)	7	(D)	-	-	-	-	-	-	-	-
Swift	3	1	3	1	-	-	3	(Z)	3	(Z)	-	-
Todd	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	8	2	8	2	-	-	4	2	4	2	-	-
Waseca	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Washington	23	3	23	3	-	-	20	4	20	4	-	-
Winona	5	1	5	1	-	-	1	(D)	1	(D)	-	-
Wright	22	5	22	5	-	-	5	1	5	1	-	-
Yellow Medicine	2	(D)	2	(D)	-	-	-	-	-	-	-	-
GINGER ROOT												
State Total												
Minnesota	8	1	8	1	-	-	6	1	6	1	-	-
Counties												
Crow Wing	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Dakota	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Goodhue	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Kanabec	1	(D)	1	(D)	-	-	-	-	-	-	-	-
St. Louis	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Scott	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Washington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Winona	-	-	-	-	-	-	1	(D)	1	(D)	-	-
GINSENG, CULTIVATED ONLY (SEE TEXT)												
State Total												
Minnesota	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Counties												
Fillmore	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Freeborn	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Washington	-	-	-	-	-	-	1	(D)	-	-	1	(D)
GOURDS (SEE TEXT)												
State Total												
Minnesota	138	84	138	84	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
GOURDS (SEE TEXT) - Con.												
Counties												
Aitkin	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Anoka	4	18	4	18	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Becker	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Beltrami	9	1	9	1	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Benton	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Blue Earth	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Carver	4	4	4	4	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Cass	3	(Z)	3	(Z)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Chisago	6	2	6	2	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Clay	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Crow Wing	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Dakota	4	1	4	1	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Faribault	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Fillmore	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Goodhue	3	2	3	2	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Hennepin	27	11	27	11	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Itasca	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
McLeod	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Morrison	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Mower	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Murray	3	5	3	5	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Nobles	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Olmsted	6	3	6	3	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Otter Tail	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Pennington	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Pine	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Ramsey	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Renville	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Rice	7	2	7	2	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Roseau	3	(Z)	3	(Z)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Scott	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Sherburne	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Stearns	5	2	5	2	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Todd	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Wabasha	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Waseca	9	2	9	2	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Washington	4	5	4	5	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Wright	4	(D)	4	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Yellow Medicine	7	1	7	1	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
HERBS, FRESH CUT												
State Total												
Minnesota	219	49	219	49	(X)	(X)	247	80	247	80	(X)	(X)
Counties												
Aitkin	8	1	8	1	(X)	(X)	3	1	3	1	(X)	(X)
Anoka	5	2	5	2	(X)	(X)	7	4	7	4	(X)	(X)
Becker	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Beltrami	1	(D)	1	(D)	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Benton	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Blue Earth	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Carlton	3	(Z)	3	(Z)	(X)	(X)	8	1	8	1	(X)	(X)
Carver	2	(D)	2	(D)	(X)	(X)	4	1	4	1	(X)	(X)
Cass	7	1	7	1	(X)	(X)	-	-	-	-	(X)	(X)
Chisago	7	1	7	1	(X)	(X)	6	2	6	2	(X)	(X)
Clearwater	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Cook	2	(D)	2	(D)	(X)	(X)	4	(Z)	4	(Z)	(X)	(X)
Cottonwood	1	(D)	1	(D)	(X)	(X)	5	1	5	1	(X)	(X)
Crow Wing	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Dakota	11	2	11	2	(X)	(X)	18	20	18	20	(X)	(X)
Fillmore	13	14	13	14	(X)	(X)	9	12	9	12	(X)	(X)
Goodhue	1	(D)	1	(D)	(X)	(X)	4	1	4	1	(X)	(X)
Hennepin	24	2	24	2	(X)	(X)	30	4	30	4	(X)	(X)
Houston	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Isanti	1	(D)	1	(D)	(X)	(X)	4	1	4	1	(X)	(X)
Itasca	6	1	6	1	(X)	(X)	8	1	8	1	(X)	(X)
Kanabec	4	1	4	1	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Lake	2	(D)	2	(D)	(X)	(X)	5	1	5	1	(X)	(X)
Le Sueur	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
McLeod	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Marshall	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Meeker	3	(Z)	3	(Z)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Mille Lacs	2	(D)	2	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Morrison	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Mower	1	(D)	1	(D)	(X)	(X)	3	1	3	1	(X)	(X)
Murray	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Nicollet	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Norman	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Olmsted	13	1	13	1	(X)	(X)	9	1	9	1	(X)	(X)
Otter Tail	2	(D)	2	(D)	(X)	(X)	4	1	4	1	(X)	(X)
Pennington	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Pine	2	(D)	2	(D)	(X)	(X)	7	1	7	1	(X)	(X)
Pipestone	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Polk	-	-	-	-	(X)	(X)	7	1	7	1	(X)	(X)

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
HERBS, FRESH CUT - Con.												
Counties - Con.												
Ramsey	1	(D)	1	(D)	(X)	(X)	13	1	13	1	(X)	(X)
Red Lake	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Redwood	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Rice	7	1	7	1	(X)	(X)	11	2	11	2	(X)	(X)
Roseau	3	(Z)	3	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
St. Louis	13	1	13	1	(X)	(X)	15	2	15	2	(X)	(X)
Scott	4	(Z)	4	(Z)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Sherburne	1	(D)	1	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Stearns	6	1	6	1	(X)	(X)	6	1	6	1	(X)	(X)
Steele	-	-	-	-	(X)	(X)	5	1	5	1	(X)	(X)
Swift	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Todd	11	1	11	1	(X)	(X)	4	(Z)	4	(Z)	(X)	(X)
Traverse	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Wabasha	11	4	11	4	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Waseca	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Washington	20	2	20	2	(X)	(X)	10	2	10	2	(X)	(X)
Winona	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Wright	4	1	4	1	(X)	(X)	9	2	9	2	(X)	(X)
HONEYDEW MELONS												
State Total												
Minnesota	38	8	38	8	-	-	51	7	51	7	(X)	(X)
Counties												
Anoka	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
Beltrami	-	-	-	-	-	-	3	(Z)	3	(Z)	(X)	(X)
Carver	1	(D)	1	(D)	-	-	1	(D)	1	(D)	(X)	(X)
Cass	3	1	3	1	-	-	-	-	-	-	(X)	(X)
Chisago	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
Clay	-	-	-	-	-	-	2	(D)	2	(D)	(X)	(X)
Cottonwood	-	-	-	-	-	-	3	(Z)	3	(Z)	(X)	(X)
Douglas	-	-	-	-	-	-	1	(D)	1	(D)	(X)	(X)
Freeborn	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
Hennepin	2	(D)	2	(D)	-	-	-	-	-	-	(X)	(X)
Isanti	-	-	-	-	-	-	2	(D)	2	(D)	(X)	(X)
Itasca	-	-	-	-	-	-	1	(D)	1	(D)	(X)	(X)
Kanabec	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
McLeod	3	1	3	1	-	-	-	-	-	-	(X)	(X)
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	(X)	(X)
Meeker	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
Mille Lacs	-	-	-	-	-	-	1	(D)	1	(D)	(X)	(X)
Morrison	1	(D)	1	(D)	-	-	-	-	-	-	(X)	(X)
Mower	1	(D)	1	(D)	-	-	2	(D)	2	(D)	(X)	(X)
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	(X)	(X)
Pine	-	-	-	-	-	-	1	(D)	1	(D)	(X)	(X)
Polk	2	(D)	2	(D)	-	-	-	-	-	-	(X)	(X)
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	(X)	(X)
Rice	2	(D)	2	(D)	-	-	6	1	6	1	(X)	(X)
St. Louis	3	(Z)	3	(Z)	-	-	-	-	-	-	(X)	(X)
Scott	1	(D)	1	(D)	-	-	1	(D)	1	(D)	(X)	(X)
Sherburne	2	(D)	2	(D)	-	-	-	-	-	-	(X)	(X)
Stearns	4	(Z)	4	(Z)	-	-	3	(Z)	3	(Z)	(X)	(X)
Steele	-	-	-	-	-	-	5	1	5	1	(X)	(X)
Swift	-	-	-	-	-	-	2	(D)	2	(D)	(X)	(X)
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	(X)	(X)
Waseca	-	-	-	-	-	-	1	(D)	1	(D)	(X)	(X)
Washington	4	(Z)	4	(Z)	-	-	6	1	6	1	(X)	(X)
Wright	1	(D)	1	(D)	-	-	6	2	6	2	(X)	(X)
HORSERADISH												
State Total												
Minnesota	29	(D)	28	3	1	(D)	28	3	27	(D)	1	(D)
Counties												
Carlton	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Chisago	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Clearwater	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Cook	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Dakota	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Goodhue	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Hennepin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Houston	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hubbard	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Itasca	2	(D)	2	(D)	-	-	-	-	-	-	-	-
McLeod	1	(D)	1	(D)	-	-	6	(D)	6	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Mille Lacs	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Mower	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Otter Tail	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Rice	1	(D)	1	(D)	-	-	-	-	-	-	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
HORSERADISH - Con.												
Counties - Con.												
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	1	(D)	1	(D)	-	-	2	(D)	1	(D)	1	(D)
Stearns	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Wadena	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Washington	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Winona	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Wright	-	-	-	-	-	-	2	(D)	2	(D)	-	-
KALE												
State Total												
Minnesota	242	52	242	52	-	-	230	80	230	80	-	-
Counties												
Aitkin	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Anoka	5	1	5	1	-	-	9	4	9	4	-	-
Beltrami	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Brown	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Carlton	16	2	16	2	-	-	10	1	10	1	-	-
Carver	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Cass	7	1	7	1	-	-	3	2	3	2	-	-
Chippewa	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Chisago	4	1	4	1	-	-	3	1	3	1	-	-
Clay	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cook	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Crow Wing	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Dakota	19	3	19	3	-	-	10	2	10	2	-	-
Dodge	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Douglas	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
Fillmore	5	(D)	5	(D)	-	-	10	31	10	31	-	-
Freeborn	-	-	-	-	-	-	5	1	5	1	-	-
Goodhue	-	-	-	-	-	-	5	1	5	1	-	-
Grant	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Hennepin	20	2	20	2	-	-	3	(Z)	3	(Z)	-	-
Houston	2	(D)	2	(D)	-	-	6	1	6	1	-	-
Hubbard	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Isanti	3	(Z)	3	(Z)	-	-	5	1	5	1	-	-
Itasca	5	1	5	1	-	-	2	(D)	2	(D)	-	-
Kanabec	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Koochiching	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lake	3	(Z)	3	(Z)	-	-	4	(Z)	4	(Z)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Mille Lacs	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
Morrison	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Murray	4	1	4	1	-	-	-	-	-	-	-	-
Nicollet	4	(Z)	4	(Z)	-	-	4	(Z)	4	(Z)	-	-
Nobles	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	6	1	6	1	-	-	11	1	11	1	-	-
Otter Tail	6	1	6	1	-	-	3	1	3	1	-	-
Pine	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Pope	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	7	1	7	1	-	-	15	2	15	2	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	8	2	8	2	-	-	9	1	9	1	-	-
St. Louis	20	2	20	2	-	-	11	1	11	1	-	-
Scott	4	1	4	1	-	-	3	1	3	1	-	-
Sherburne	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Stearns	4	1	4	1	-	-	6	1	6	1	-	-
Steele	2	(D)	2	(D)	-	-	5	(D)	5	(D)	-	-
Swift	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Todd	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	9	2	9	2	-	-	-	-	-	-	-	-
Waseca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Washington	22	8	22	8	-	-	15	11	15	11	-	-
Winona	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
Wright	5	1	5	1	-	-	7	2	7	2	-	-
LETTUCE, ALL												
State Total												
Minnesota	322	94	322	94	(X)	(X)	289	97	289	97	(X)	(X)
Counties												
Aitkin	8	2	8	2	(X)	(X)	9	1	9	1	(X)	(X)
Anoka	5	2	5	2	(X)	(X)	9	5	9	5	(X)	(X)

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
LETTUCE, ALL - Con.												
Counties - Con.												
Beltrami	3	(Z)	3	(Z)	(X)	(X)	10	2	10	2	(X)	(X)
Carlton	4	1	4	1	(X)	(X)	9	2	9	2	(X)	(X)
Carver	3	(D)	3	(D)	(X)	(X)	6	2	6	2	(X)	(X)
Cass	6	2	6	2	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Chippewa	1	(D)	1	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Chisago	7	1	7	1	(X)	(X)	15	3	15	3	(X)	(X)
Clay	8	2	8	2	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Clearwater	4	1	4	1	(X)	(X)	-	-	-	-	(X)	(X)
Cook	5	1	5	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Cottonwood	-	-	-	-	(X)	(X)	3	1	3	1	(X)	(X)
Crow Wing	3	(Z)	3	(Z)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Dakota	22	6	22	6	(X)	(X)	14	8	14	8	(X)	(X)
Dodge	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Douglas	4	1	4	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Fillmore	9	7	9	7	(X)	(X)	15	13	15	13	(X)	(X)
Freeborn	-	-	-	-	(X)	(X)	7	1	7	1	(X)	(X)
Goodhue	3	1	3	1	(X)	(X)	5	1	5	1	(X)	(X)
Grant	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Hennepin	26	5	26	5	(X)	(X)	11	4	11	4	(X)	(X)
Houston	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Hubbard	2	(D)	2	(D)	(X)	(X)	3	2	3	2	(X)	(X)
Isanti	1	(D)	1	(D)	(X)	(X)	7	1	7	1	(X)	(X)
Itasca	7	2	7	2	(X)	(X)	3	1	3	1	(X)	(X)
Kanabec	5	2	5	2	(X)	(X)	3	1	3	1	(X)	(X)
Lac qui Parle	-	-	-	-	(X)	(X)	5	1	5	1	(X)	(X)
Lake	4	1	4	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Le Sueur	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Lincoln	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
McLeod	3	(D)	3	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Marshall	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Meeker	3	1	3	1	(X)	(X)	7	3	7	3	(X)	(X)
Mille Lacs	3	3	3	3	(X)	(X)	5	1	5	1	(X)	(X)
Morrison	2	(D)	2	(D)	(X)	(X)	3	(D)	3	(D)	(X)	(X)
Mower	3	(D)	3	(D)	(X)	(X)	5	1	5	1	(X)	(X)
Murray	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Nicollet	4	1	4	1	(X)	(X)	5	2	5	2	(X)	(X)
Norman	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Olmsted	6	4	6	4	(X)	(X)	6	2	6	2	(X)	(X)
Otter Tail	8	1	8	1	(X)	(X)	5	1	5	1	(X)	(X)
Pennington	1	(D)	1	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Pine	4	(Z)	4	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
Pipestone	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Polk	2	(D)	2	(D)	(X)	(X)	3	3	3	3	(X)	(X)
Ramsey	7	2	7	2	(X)	(X)	14	3	14	3	(X)	(X)
Red Lake	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Renville	3	(Z)	3	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
Rice	9	2	9	2	(X)	(X)	10	2	10	2	(X)	(X)
Roseau	3	1	3	1	(X)	(X)	-	-	-	-	(X)	(X)
St. Louis	21	4	21	4	(X)	(X)	16	4	16	4	(X)	(X)
Scott	6	2	6	2	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Sherburne	3	(D)	3	(D)	(X)	(X)	3	2	3	2	(X)	(X)
Sibley	6	(D)	6	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Stearns	3	(D)	3	(D)	(X)	(X)	8	3	8	3	(X)	(X)
Steele	2	(D)	2	(D)	(X)	(X)	5	2	5	2	(X)	(X)
Swift	-	-	-	-	(X)	(X)	4	1	4	1	(X)	(X)
Todd	8	2	8	2	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Wabasha	10	4	10	4	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Waseca	10	2	10	2	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Washington	20	8	20	8	(X)	(X)	16	6	16	6	(X)	(X)
Winona	10	2	10	2	(X)	(X)	5	4	5	4	(X)	(X)
Wright	14	3	14	3	(X)	(X)	6	2	6	2	(X)	(X)
LETTUCE, HEAD												
State Total												
Minnesota	163	30	163	30	(X)	(X)	96	22	96	22	(X)	(X)
Counties												
Aitkin	3	(Z)	3	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
Anoka	3	1	3	1	(X)	(X)	3	1	3	1	(X)	(X)
Beltrami	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Carlton	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Carver	2	(D)	2	(D)	(X)	(X)	3	1	3	1	(X)	(X)
Cass	3	(Z)	3	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
Chippewa	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Chisago	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Clay	8	1	8	1	(X)	(X)	-	-	-	-	(X)	(X)
Cook	3	(Z)	3	(Z)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Cottonwood	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Crow Wing	3	(Z)	3	(Z)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Dakota	15	3	15	3	(X)	(X)	6	(D)	6	(D)	(X)	(X)
Douglas	4	1	4	1	(X)	(X)	-	-	-	-	(X)	(X)
Fillmore	5	3	5	3	(X)	(X)	7	1	7	1	(X)	(X)
Freeborn	-	-	-	-	(X)	(X)	4	(Z)	4	(Z)	(X)	(X)
Goodhue	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
LETTUCE, HEAD - Con.												
Counties - Con.												
Hennepin	12	2	12	2	(X)	(X)	3	(D)	3	(D)	(X)	(X)
Houston	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Isanti	-	-	-	-	(X)	(X)	4	(Z)	4	(Z)	(X)	(X)
Kanabec	5	1	5	1	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Lake	3	(D)	3	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Le Sueur	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
McLeod	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Marshall	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Meeker	3	(Z)	3	(Z)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Mille Lacs	2	(D)	2	(D)	(X)	(X)	5	1	5	1	(X)	(X)
Mower	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Murray	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Nicollet	3	(Z)	3	(Z)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Olmsted	4	2	4	2	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Otter Tail	2	(D)	2	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Pipestone	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Polk	-	-	-	-	(X)	(X)	3	2	3	2	(X)	(X)
Ramsey	6	2	6	2	(X)	(X)	7	1	7	1	(X)	(X)
Rice	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Roseau	3	(Z)	3	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
St. Louis	13	1	13	1	(X)	(X)	8	2	8	2	(X)	(X)
Scott	3	(D)	3	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Sherburne	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Sibley	6	(D)	6	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Stearns	1	(D)	1	(D)	(X)	(X)	4	1	4	1	(X)	(X)
Steele	2	(D)	2	(D)	(X)	(X)	5	1	5	1	(X)	(X)
Todd	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Wabasha	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Waseca	5	1	5	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Washington	13	2	13	2	(X)	(X)	6	2	6	2	(X)	(X)
Winona	6	1	6	1	(X)	(X)	3	(D)	3	(D)	(X)	(X)
Wright	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
LETTUCE, LEAF												
State Total												
Minnesota	221	41	221	41	(X)	(X)	232	54	232	54	(X)	(X)
Counties												
Aitkin	7	1	7	1	(X)	(X)	9	(D)	9	(D)	(X)	(X)
Anoka	3	1	3	1	(X)	(X)	9	2	9	2	(X)	(X)
Beltrami	3	(D)	3	(D)	(X)	(X)	10	1	10	1	(X)	(X)
Carlton	2	(D)	2	(D)	(X)	(X)	9	1	9	1	(X)	(X)
Carver	2	(D)	2	(D)	(X)	(X)	4	1	4	1	(X)	(X)
Cass	6	1	6	1	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Chippewa	1	(D)	1	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Chisago	3	(D)	3	(D)	(X)	(X)	11	(D)	11	(D)	(X)	(X)
Clay	7	1	7	1	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Clearwater	4	(D)	4	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Cook	3	1	3	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Cottonwood	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Crow Wing	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Dakota	10	2	10	2	(X)	(X)	11	7	11	7	(X)	(X)
Dodge	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Douglas	4	1	4	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Fillmore	8	2	8	2	(X)	(X)	12	7	12	7	(X)	(X)
Freeborn	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Goodhue	3	(D)	3	(D)	(X)	(X)	5	(D)	5	(D)	(X)	(X)
Grant	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Hennepin	18	2	18	2	(X)	(X)	10	(D)	10	(D)	(X)	(X)
Houston	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Hubbard	2	(D)	2	(D)	(X)	(X)	3	2	3	2	(X)	(X)
Isanti	1	(D)	1	(D)	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Itasca	7	(D)	7	(D)	(X)	(X)	3	(D)	3	(D)	(X)	(X)
Kanabec	3	1	3	1	(X)	(X)	3	(D)	3	(D)	(X)	(X)
Lac qui Parle	-	-	-	-	(X)	(X)	5	1	5	1	(X)	(X)
Lake	4	(Z)	4	(Z)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Le Sueur	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
McLeod	3	(D)	3	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Marshall	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Meeker	3	(D)	3	(D)	(X)	(X)	7	(D)	7	(D)	(X)	(X)
Mille Lacs	3	(D)	3	(D)	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Morrison	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Mower	2	(D)	2	(D)	(X)	(X)	5	1	5	1	(X)	(X)
Murray	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Nicollet	4	(Z)	4	(Z)	(X)	(X)	4	(D)	4	(D)	(X)	(X)
Olmsted	4	2	4	2	(X)	(X)	5	(D)	5	(D)	(X)	(X)
Otter Tail	8	(D)	8	(D)	(X)	(X)	4	(D)	4	(D)	(X)	(X)
Pennington	1	(D)	1	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Pine	4	(Z)	4	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
Pipestone	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Polk	2	(D)	2	(D)	(X)	(X)	3	2	3	2	(X)	(X)
Ramsey	4	(Z)	4	(Z)	(X)	(X)	5	1	5	1	(X)	(X)
Red Lake	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
LETTUCE, LEAF - Con.												
Counties - Con.												
Renville	3	(Z)	3	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
Rice	7	1	7	1	(X)	(X)	9	(D)	9	(D)	(X)	(X)
Roseau	3	(Z)	3	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
St. Louis	16	2	16	2	(X)	(X)	11	1	11	1	(X)	(X)
Scott	5	1	5	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Sherburne	1	(D)	1	(D)	(X)	(X)	3	2	3	2	(X)	(X)
Stearns	3	(D)	3	(D)	(X)	(X)	7	1	7	1	(X)	(X)
Steele	2	(D)	2	(D)	(X)	(X)	5	1	5	1	(X)	(X)
Swift	-	-	-	-	(X)	(X)	4	(Z)	4	(Z)	(X)	(X)
Todd	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Wabasha	9	(D)	9	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Waseca	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Washington	16	3	16	3	(X)	(X)	12	3	12	3	(X)	(X)
Winona	4	1	4	1	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Wright	3	1	3	1	(X)	(X)	3	(D)	3	(D)	(X)	(X)
LETTUCE, ROMAINE												
State Total												
Minnesota	152	23	152	23	(X)	(X)	111	22	111	22	(X)	(X)
Counties												
Aitkin	5	1	5	1	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Anoka	5	1	5	1	(X)	(X)	5	1	5	1	(X)	(X)
Beltrami	1	(D)	1	(D)	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Carlton	3	(D)	3	(D)	(X)	(X)	4	1	4	1	(X)	(X)
Carver	1	(D)	1	(D)	(X)	(X)	4	1	4	1	(X)	(X)
Cass	5	1	5	1	(X)	(X)	-	-	-	-	(X)	(X)
Chisago	6	1	6	1	(X)	(X)	5	1	5	1	(X)	(X)
Clearwater	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Cook	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Cottonwood	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Dakota	7	1	7	1	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Douglas	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Fillmore	4	2	4	2	(X)	(X)	8	5	8	5	(X)	(X)
Freeborn	-	-	-	-	(X)	(X)	4	(Z)	4	(Z)	(X)	(X)
Goodhue	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Grant	-	-	-	-	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Hennepin	12	1	12	1	(X)	(X)	-	-	-	-	(X)	(X)
Isanti	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Itasca	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Kanabec	4	(Z)	4	(Z)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Lake	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Le Sueur	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Lincoln	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
McLeod	2	(D)	2	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Marshall	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Meeker	1	(D)	1	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Mille Lacs	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Morrison	1	(D)	1	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Mower	-	-	-	-	(X)	(X)	3	1	3	1	(X)	(X)
Murray	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Nicollet	-	-	-	-	(X)	(X)	4	(Z)	4	(Z)	(X)	(X)
Norman	2	(D)	2	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Olmsted	6	1	6	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Otter Tail	1	(D)	1	(D)	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Pennington	1	(D)	1	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Pipestone	1	(D)	1	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Ramsey	-	-	-	-	(X)	(X)	9	1	9	1	(X)	(X)
Rice	7	(D)	7	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Roseau	3	(Z)	3	(Z)	(X)	(X)	-	-	-	-	(X)	(X)
St. Louis	9	1	9	1	(X)	(X)	3	1	3	1	(X)	(X)
Scott	1	(D)	1	(D)	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Sherburne	3	(D)	3	(D)	(X)	(X)	-	-	-	-	(X)	(X)
Stearns	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Steele	2	(D)	2	(D)	(X)	(X)	5	1	5	1	(X)	(X)
Swift	-	-	-	-	(X)	(X)	3	(Z)	3	(Z)	(X)	(X)
Todd	6	(D)	6	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)
Waseca	10	1	10	1	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Washington	14	2	14	2	(X)	(X)	6	1	6	1	(X)	(X)
Winona	6	1	6	1	(X)	(X)	3	1	3	1	(X)	(X)
Wright	10	(D)	10	(D)	(X)	(X)	4	1	4	1	(X)	(X)
MUSTARD GREENS												
State Total												
Minnesota	43	14	43	14	-	-	51	12	51	12	-	-
Counties												
Aitkin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Anoka	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Beltrami	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Carver	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Cass	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
MUSTARD GREENS - Con.												
Counties - Con.												
Chisago	-	-	-	-	-	-	3	1	3	1	-	-
Cottonwood	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Dakota	5	5	5	5	-	-	5	4	5	4	-	-
Fillmore	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Goodhue	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Hennepin	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Isanti	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Kanabec	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Lake	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
McLeod	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Otter Tail	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Scott	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Steele	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Swift	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Wabasha	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Washington	7	2	7	2	-	-	5	1	5	1	-	-
Winona	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Wright	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
OKRA												
State Total												
Minnesota	44	11	43	(D)	1	(D)	48	16	48	16	-	-
Counties												
Aitkin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Anoka	10	2	10	2	-	-	3	(Z)	3	(Z)	-	-
Beltrami	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Blue Earth	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Chippewa	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Chisago	6	2	6	2	-	-	1	(D)	1	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Dakota	4	3	4	3	-	-	9	9	9	9	-	-
Dodge	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Fillmore	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Goodhue	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Hennepin	7	2	7	2	-	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Lac qui Parle	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Mower	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Olmsted	-	-	-	-	-	-	4	1	4	1	-	-
Otter Tail	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Pine	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Polk	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Ramsey	-	-	-	-	-	-	3	(D)	3	(D)	-	-
Rice	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Washington	4	(Z)	4	(Z)	-	-	5	2	5	2	-	-
Wright	1	(D)	1	(D)	-	-	-	-	-	-	-	-
ONIONS, DRY												
State Total												
Minnesota	292	308	290	(D)	2	(D)	340	292	340	292	-	-
Counties												
Aitkin	6	1	6	1	-	-	10	2	10	2	-	-
Anoka	5	10	5	10	-	-	6	5	6	5	-	-
Beltrami	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Big Stone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Blue Earth	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Brown	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Carlton	5	1	5	1	-	-	4	1	4	1	-	-
Carver	7	8	7	8	-	-	3	1	3	1	-	-
Cass	3	(Z)	3	(Z)	-	-	6	2	6	2	-	-
Chippewa	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Chisago	4	2	4	2	-	-	4	2	4	2	-	-
Clay	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Cook	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Cottonwood	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
Crow Wing	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Dakota	20	8	20	8	-	-	25	39	25	39	-	-
Dodge	1	(D)	1	(D)	-	-	4	4	4	4	-	-
Douglas	4	1	4	1	-	-	6	2	6	2	-	-
Faribault	-	-	-	-	-	-	1	(D)	1	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
ONIONS, DRY - Con.												
Counties - Con.												
Fillmore	9	5	9	5	-	-	17	5	17	5	-	-
Freeborn	2	(D)	1	(D)	1	(D)	1	(D)	1	(D)	-	-
Goodhue	6	1	6	1	-	-	5	1	5	1	-	-
Grant	1	(D)	1	(D)	-	-	9	5	9	5	-	-
Hennepin	6	3	6	3	-	-	13	3	13	3	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Isanti	3	(Z)	3	(Z)	-	-	7	2	7	2	-	-
Itasca	7	2	7	2	-	-	9	1	9	1	-	-
Kanabec	5	1	5	1	-	-	3	(D)	3	(D)	-	-
Kandiyohi	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Lake	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Le Sueur	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Lincoln	-	-	-	-	-	-	1	(D)	1	(D)	-	-
McLeod	5	2	5	2	-	-	3	(D)	3	(D)	-	-
Marshall	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Meeker	6	1	6	1	-	-	8	1	8	1	-	-
Mille Lacs	3	1	3	1	-	-	8	3	8	3	-	-
Morrison	3	1	3	1	-	-	-	-	-	-	-	-
Mower	3	1	3	1	-	-	11	2	11	2	-	-
Murray	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Nicollet	6	1	6	1	-	-	6	1	6	1	-	-
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Norman	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Olmsted	11	(D)	11	(D)	-	-	12	5	12	5	-	-
Otter Tail	9	2	9	2	-	-	4	1	4	1	-	-
Pennington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Pine	4	1	4	1	-	-	4	1	4	1	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	2	(D)	2	(D)	-	-	4	4	4	4	-	-
Pope	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	-	-	-	-	-	-	3	2	3	2	-	-
Redwood	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Renville	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Rice	4	4	4	4	-	-	6	3	6	3	-	-
Rock	3	2	3	2	-	-	-	-	-	-	-	-
Roseau	-	-	-	-	-	-	4	1	4	1	-	-
St. Louis	24	3	24	3	-	-	14	2	14	2	-	-
Scott	6	3	6	3	-	-	4	1	4	1	-	-
Sherburne	9	5	9	5	-	-	12	11	12	11	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	6	2	6	2	-	-	11	2	11	2	-	-
Steele	3	(D)	2	(D)	1	(D)	5	2	5	2	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	5	1	5	1	-	-
Todd	8	1	8	1	-	-	11	2	11	2	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	8	2	8	2	-	-	-	-	-	-	-	-
Wadena	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Waseca	7	1	7	1	-	-	3	(Z)	3	(Z)	-	-
Washington	25	7	25	7	-	-	13	7	13	7	-	-
Watonwan	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	1	(D)	1	(D)	-	-	4	5	4	5	-	-
Wright	3	(D)	3	(D)	-	-	12	4	12	4	-	-
Yellow Medicine	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
ONIONS, GREEN												
State Total												
Minnesota	209	60	209	60	-	-	230	67	230	67	-	-
Counties												
Aitkin	7	1	7	1	-	-	2	(D)	2	(D)	-	-
Anoka	2	(D)	2	(D)	-	-	5	2	5	2	-	-
Beltrami	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Brown	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Carlton	7	1	7	1	-	-	6	1	6	1	-	-
Carver	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Cass	11	1	11	1	-	-	2	(D)	2	(D)	-	-
Chippewa	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chisago	5	1	5	1	-	-	6	(D)	6	(D)	-	-
Clay	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Clearwater	4	1	4	1	-	-	-	-	-	-	-	-
Cook	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Cottonwood	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Dakota	15	6	15	6	-	-	25	4	25	4	-	-
Fillmore	3	(Z)	3	(Z)	-	-	5	1	5	1	-	-
Goodhue	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
Hennepin	8	2	8	2	-	-	35	5	35	5	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	5	1	5	1	-	-
Itasca	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Kanabec	3	(Z)	3	(Z)	-	-	3	1	3	1	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
ONIONS, GREEN - Con.												
Counties - Con.												
Koochiching	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Lac qui Parle	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Lake	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	-	-	3	(D)	3	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Morrison	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	1	(D)	1	(D)	-	-	7	1	7	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Olmsted	6	1	6	1	-	-	4	(Z)	4	(Z)	-	-
Otter Tail	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pine	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pope	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Ramsey	-	-	-	-	-	-	8	1	8	1	-	-
Rice	6	1	6	1	-	-	8	2	8	2	-	-
St. Louis	14	2	14	2	-	-	11	5	11	5	-	-
Scott	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Sherburne	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Stearns	3	2	3	2	-	-	4	(Z)	4	(Z)	-	-
Steele	4	1	4	1	-	-	5	1	5	1	-	-
Swift	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Todd	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Wadena	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Waseca	10	1	10	1	-	-	1	(D)	1	(D)	-	-
Washington	31	8	31	8	-	-	23	7	23	7	-	-
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	12	1	12	1	-	-	4	4	4	4	-	-
Wright	10	1	10	1	-	-	4	1	4	1	-	-
PARSLEY												
State Total												
Minnesota	110	20	110	20	-	-	108	20	108	20	-	-
Counties												
Aitkin	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Anoka	4	(Z)	4	(Z)	-	-	5	1	5	1	-	-
Beltrami	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Carlton	2	(D)	2	(D)	-	-	6	1	6	1	-	-
Carver	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Cass	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chisago	3	1	3	1	-	-	-	-	-	-	-	-
Cook	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Cottonwood	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Dakota	6	1	6	1	-	-	6	1	6	1	-	-
Douglas	4	1	4	1	-	-	-	-	-	-	-	-
Fillmore	4	(D)	4	(D)	-	-	7	8	7	8	-	-
Goodhue	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Hennepin	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Itasca	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Kanabec	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Lake	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Morrison	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Olmsted	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Otter Tail	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Pine	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Pope	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	-	-	-	-	-	-	10	1	10	1	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	7	1	7	1	-	-	6	1	6	1	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	15	2	15	2	-	-	2	(D)	2	(D)	-	-
Scott	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Stearns	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Steele	-	-	-	-	-	-	3	1	3	1	-	-
Swift	-	-	-	-	-	-	5	1	5	1	-	-
Todd	5	1	5	1	-	-	-	-	-	-	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
PARSLEY - Con.												
Counties - Con.												
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Waseca	5	1	5	1	-	-	1	(D)	1	(D)	-	-
Washington	10	1	10	1	-	-	8	1	8	1	-	-
Wright	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
PARSNIPS (SEE TEXT)												
State Total												
Minnesota	21	2	21	2	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Counties												
Anoka	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Carlton	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Cook	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Dakota	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Kanabec	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Meeker	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Morrison	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Otter Tail	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
St. Louis	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Waseca	5	1	5	1	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Washington	4	(Z)	4	(Z)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
PEAS, CHINESE (SUGAR AND SNOW)												
State Total												
Minnesota	121	671	111	28	10	644	159	1,030	142	235	17	795
Counties												
Aitkin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Anoka	4	3	4	3	-	-	5	4	5	4	-	-
Beltrami	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Benton	3	81	1	(D)	2	(D)	1	(D)	1	(D)	-	-
Blue Earth	5	5	5	5	-	-	1	(D)	-	-	1	(D)
Brown	7	(D)	-	-	7	(D)	3	114	-	-	3	114
Carlton	3	(Z)	3	(Z)	-	-	5	1	5	1	-	-
Carver	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Cass	4	1	4	1	-	-	-	-	-	-	-	-
Chisago	1	(D)	1	(D)	-	-	8	1	8	1	-	-
Clay	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cook	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Dakota	2	(D)	2	(D)	-	-	8	2	8	2	-	-
Dodge	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Fillmore	4	(Z)	4	(Z)	-	-	4	8	4	8	-	-
Goodhue	-	-	-	-	-	-	5	(D)	4	(Z)	1	(D)
Hennepin	4	(Z)	4	(Z)	-	-	2	(D)	2	(D)	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Itasca	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Kanabec	4	(Z)	4	(Z)	-	-	5	1	5	1	-	-
Lake	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	2	(D)	-	-	2	(D)
McLeod	4	(D)	3	(D)	1	(D)	2	(D)	1	(D)	1	(D)
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	2	(D)	2	(D)	-	-	6	185	6	185	-	-
Mille Lacs	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Morrison	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Mower	-	-	-	-	-	-	5	133	3	(D)	2	(D)
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	-	-	-	-	-	-	8	1	8	1	-	-
Otter Tail	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	2	(D)	2	(D)	-	-	6	1	6	1	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Renville	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Rice	6	1	6	1	-	-	7	1	7	1	-	-
St. Louis	9	1	9	1	-	-	3	(Z)	3	(Z)	-	-
Scott	8	1	8	1	-	-	2	(D)	2	(D)	-	-
Stearns	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Steele	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Todd	4	(Z)	4	(Z)	-	-	8	12	8	12	-	-
Wabasha	2	(D)	2	(D)	-	-	5	(D)	-	-	5	(D)
Waseca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Washington	15	3	15	3	-	-	2	(D)	2	(D)	-	-
Wright	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
PEAS, GREEN												
State Total												
Minnesota	599	47,364	108	20	491	47,345	697	44,463	163	53	536	44,410
Counties												
Aitkin	3	(D)	3	(D)	-	-	1	(D)	1	(D)	-	-
Anoka	1	(D)	1	(D)	-	-	4	2	4	2	-	-
Beltrami	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Benton	1	(D)	-	-	1	(D)	2	(D)	2	(D)	-	-
Blue Earth	6	(D)	-	-	6	(D)	3	340	-	-	3	340
Brown	11	877	-	-	11	877	66	3,677	-	-	66	3,677
Carlton	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Carver	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cass	1	(D)	1	(D)	-	-	5	2	5	2	-	-
Chippewa	3	(Z)	3	(Z)	-	-	3	(D)	1	(D)	2	(D)
Chisago	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Clay	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cook	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Cottonwood	2	(D)	-	-	2	(D)	4	(D)	3	(Z)	1	(D)
Dakota	76	(D)	5	1	71	(D)	58	5,324	7	1	51	5,323
Dodge	7	(D)	-	-	7	(D)	11	(D)	-	-	11	(D)
Faribault	13	724	-	-	13	724	22	1,556	-	-	22	1,556
Fillmore	1	(D)	1	(D)	-	-	10	542	1	(D)	9	(D)
Freeborn	4	(D)	-	-	4	(D)	10	742	7	1	3	741
Goodhue	30	1,657	2	(D)	28	(D)	16	1,100	-	-	16	1,100
Hennepin	11	2	11	2	-	-	4	1	4	1	-	-
Houston	1	(D)	-	-	1	(D)	1	(D)	-	-	1	(D)
Isanti	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Itasca	4	2	4	2	-	-	3	(Z)	3	(Z)	-	-
Kanabec	5	1	5	1	-	-	4	2	4	2	-	-
Kandiyohi	17	2,373	-	-	17	2,373	17	1,766	-	-	17	1,766
Koochiching	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Lac qui Parle	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Le Sueur	10	859	-	-	10	859	9	596	-	-	9	596
McLeod	6	(D)	-	-	6	(D)	3	(D)	2	(D)	1	(D)
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Martin	15	(D)	-	-	15	(D)	21	1,016	1	(D)	20	(D)
Meeker	11	667	3	(Z)	8	667	12	582	1	(D)	11	(D)
Mille Lacs	-	-	-	-	-	-	5	1	5	1	-	-
Morrison	4	(D)	2	(D)	2	(D)	-	-	-	-	-	-
Mower	30	2,531	-	-	30	2,531	36	2,309	8	1	28	2,307
Nicollet	8	403	3	(D)	5	(D)	7	195	3	(D)	4	(D)
Norman	2	(D)	-	-	2	(D)	1	(D)	1	(D)	-	-
Olmsted	47	(D)	-	-	47	(D)	53	3,420	5	3	48	3,417
Otter Tail	6	1	6	1	-	-	5	1	5	1	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pine	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Polk	-	-	-	-	-	-	10	2	10	2	-	-
Pope	12	2,024	-	-	12	2,024	17	2,246	3	1	14	2,245
Ramsey	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	11	(D)	-	-	11	(D)	38	(D)	1	(D)	37	1,959
Renville	89	8,373	3	(Z)	86	8,373	68	7,071	-	-	68	7,071
Rice	2	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)
Roseau	-	-	-	-	-	-	4	2	4	2	-	-
St. Louis	5	1	5	1	-	-	8	3	7	(D)	1	(D)
Scott	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Sherburne	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Sibley	27	1,596	6	1	21	1,595	18	1,483	-	-	18	1,483
Stearns	17	1,573	2	(D)	15	(D)	16	(D)	8	1	8	(D)
Steele	12	953	2	(D)	10	(D)	15	1,736	4	1	11	1,735
Todd	6	1	6	1	-	-	1	(D)	1	(D)	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	26	1,367	1	(D)	25	(D)	38	1,616	2	(D)	38	(D)
Wadena	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Waseca	3	(D)	-	-	3	(D)	8	410	3	8	5	402
Washington	11	2	11	2	-	-	10	3	10	3	-	-
Watonwan	8	(D)	-	-	8	(D)	7	(D)	-	-	7	(D)
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	14	1,243	1	(D)	13	(D)	9	279	4	1	5	278
Wright	3	1	3	1	-	-	6	2	6	2	-	-
PEAS, SOUTHERN (COWPEAS) - BLACKEYED, CROWDER, ETC.												
State Total												
Minnesota	4	(Z)	4	(Z)	-	-	8	2	8	2	-	-
Counties												
Clay	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Dakota	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Dodge	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Houston	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Isanti	-	-	-	-	-	-	2	(D)	2	(D)	-	-
St. Louis	-	-	-	-	-	-	1	(D)	1	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
PEAS, SOUTHERN (COWPEAS) - BLACKEYED, CROWDER, ETC. - Con.												
Counties - Con.												
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Washington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
PEPPERS, BELL (EXCLUDING PIMIENTOS)												
State Total												
Minnesota	439	348	434	347	5	1	489	391	487	390	5	1
Counties												
Aitkin	12	3	12	3	-	-	4	1	4	1	-	-
Anoka	4	(D)	4	(D)	-	-	14	38	14	38	-	-
Becker	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Beltrami	5	1	5	1	-	-	10	1	10	1	-	-
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Blue Earth	6	5	6	5	-	-	2	(D)	2	(D)	-	-
Brown	-	-	-	-	-	-	5	1	5	1	-	-
Carlton	2	(D)	2	(D)	-	-	15	3	15	3	-	-
Carver	7	1	7	1	-	-	6	1	6	1	-	-
Cass	8	1	8	1	-	-	-	-	-	-	-	-
Chippewa	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chisago	14	4	14	4	-	-	20	4	20	4	-	-
Clay	3	(Z)	3	(Z)	-	-	3	2	3	2	-	-
Clearwater	4	1	4	1	-	-	-	-	-	-	-	-
Cook	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Cottonwood	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Crow Wing	1	(D)	1	(D)	-	-	4	1	4	1	-	-
Dakota	32	57	32	57	-	-	50	60	50	60	-	-
Dodge	-	-	-	-	-	-	4	1	4	1	-	-
Douglas	5	1	5	1	-	-	3	(Z)	3	(Z)	-	-
Fillmore	18	9	18	9	-	-	16	16	16	16	-	-
Freeborn	1	(D)	1	(D)	-	-	4	1	4	1	-	-
Goodhue	3	(D)	3	(D)	-	-	7	1	7	1	-	-
Grant	2	(D)	2	(D)	-	-	7	1	7	1	-	-
Hennepin	19	5	19	5	-	-	19	5	19	5	-	-
Houston	3	(Z)	3	(Z)	-	-	6	1	6	1	-	-
Hubbard	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Isanti	4	(D)	1	(D)	3	(D)	6	1	6	1	-	-
Itasca	14	3	14	3	-	-	11	1	11	1	-	-
Kanabec	14	3	14	3	-	-	7	1	7	1	-	-
Kandiyohi	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Koochiching	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	5	1	5	1	-	-
Lake	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	6	4	6	(D)	3	(D)
Lincoln	-	-	-	-	-	-	1	(D)	1	(D)	-	-
McLeod	8	2	8	2	-	-	7	3	7	3	-	-
Marshall	3	(D)	3	(D)	-	-	3	1	3	1	-	-
Martin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Meeker	9	1	9	1	-	-	7	2	7	2	-	-
Mille Lacs	6	2	6	2	-	-	8	1	8	1	-	-
Morrison	3	1	3	1	-	-	10	4	10	4	-	-
Mower	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Murray	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Nicollet	6	1	6	1	-	-	2	(D)	2	(D)	-	-
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	14	5	14	5	-	-	14	3	14	3	-	-
Otter Tail	6	1	6	1	-	-	8	3	8	3	-	-
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	10	1	10	1	-	-	8	2	8	2	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	-	-	-	-	-	-	7	1	7	1	-	-
Pope	3	(Z)	3	(Z)	-	-	3	1	3	1	-	-
Ramsey	5	(D)	5	(D)	-	-	11	2	11	2	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Renville	10	7	10	7	-	-	1	(D)	1	(D)	-	-
Rice	11	4	11	4	-	-	13	3	13	3	-	-
Rock	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	18	2	18	2	-	-	8	1	7	(D)	1	(D)
Scott	17	4	17	4	-	-	4	1	4	1	-	-
Sherburne	7	10	7	10	-	-	13	11	13	11	-	-
Sibley	7	1	7	1	-	-	2	(D)	2	(D)	-	-
Stearns	10	2	10	2	-	-	14	3	14	3	-	-
Steele	2	(D)	2	(D)	-	-	6	1	6	1	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	5	1	5	1	-	-
Todd	15	2	15	2	-	-	6	1	6	1	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	10	2	10	2	-	-	1	(D)	1	(D)	-	-
Wadena	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Waseca	5	1	5	1	-	-	1	(D)	1	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
PEPPERS, BELL (EXCLUDING PIMIENTOS) - Con.												
Counties - Con.												
Washington	26	73	26	73	-	-	46	80	45	(D)	1	(D)
Winona	1	(D)	1	(D)	-	-	3	(D)	3	(D)	-	-
Wright	8	22	6	(D)	2	(D)	6	2	6	2	-	-
Yellow Medicine	6	(D)	6	(D)	-	-	1	(D)	1	(D)	-	-
PEPPERS, OTHER THAN BELL (INCLUDING CHILE)												
State Total												
Minnesota	294	79	280	77	14	1	305	(D)	303	(D)	3	(D)
Counties												
Aitkin	7	1	7	1	-	-	3	1	3	1	-	-
Anoka	13	3	7	(D)	6	(D)	7	4	7	4	-	-
Becker	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Beltrami	4	1	3	(D)	1	(D)	4	(Z)	4	(Z)	-	-
Benton	3	(D)	3	(D)	-	-	1	(D)	1	(D)	-	-
Blue Earth	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Brown	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Carlton	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Carver	5	1	5	1	-	-	4	(Z)	4	(Z)	-	-
Cass	7	1	7	1	-	-	-	-	-	-	-	-
Chippewa	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Chisago	2	(D)	2	(D)	-	-	15	3	15	3	-	-
Clay	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cook	-	-	-	-	-	-	3	(D)	3	(D)	-	-
Cottonwood	-	-	-	-	-	-	5	1	5	1	-	-
Crow Wing	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Dakota	26	16	26	16	-	-	33	21	33	21	-	-
Dodge	-	-	-	-	-	-	4	1	4	1	-	-
Douglas	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Fillmore	13	2	13	2	-	-	7	2	7	2	-	-
Goodhue	1	(D)	1	(D)	-	-	2	(D)	2	(D)	1	(D)
Grant	2	(D)	2	(D)	-	-	7	1	7	1	-	-
Hennepin	10	2	10	2	-	-	28	6	28	6	-	-
Houston	2	(D)	2	(D)	-	-	6	1	6	1	-	-
Hubbard	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Isanti	4	(Z)	1	(D)	3	(D)	6	2	6	2	-	-
Itasca	7	1	7	1	-	-	3	(Z)	3	(Z)	-	-
Kanabec	9	1	9	1	-	-	5	1	5	1	-	-
Kandiyohi	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Lac qui Parle	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Lake	3	(Z)	3	(Z)	-	-	4	(Z)	4	(Z)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Marshall	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Mille Lacs	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Morrison	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Mower	2	(D)	2	(D)	-	-	11	1	11	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	6	1	6	1	-	-	4	(Z)	4	(Z)	-	-
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	10	2	10	2	-	-	7	1	7	1	-	-
Otter Tail	8	1	8	1	-	-	4	1	4	1	-	-
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	4	(Z)	4	(Z)	-	-	5	1	5	1	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pope	-	-	-	-	-	-	3	1	3	1	-	-
Ramsey	15	2	15	2	-	-	9	3	9	3	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Renville	4	2	4	2	-	-	-	-	-	-	-	-
Rice	1	(D)	1	(D)	-	-	6	(D)	6	(D)	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	22	2	22	2	-	-	4	(Z)	3	(D)	1	(D)
Scott	4	1	4	1	-	-	4	1	4	1	-	-
Sherburne	6	5	6	5	-	-	10	6	10	6	-	-
Sibley	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Stearns	8	2	8	2	-	-	7	1	7	1	-	-
Steele	4	1	4	1	-	-	7	2	7	2	-	-
Swift	-	-	-	-	-	-	6	1	6	1	-	-
Todd	9	1	9	1	-	-	1	(D)	1	(D)	-	-
Wabasha	3	2	3	2	-	-	3	1	3	1	-	-
Waseca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Washington	12	12	12	12	-	-	16	8	15	(D)	1	(D)
Watonwan	4	(D)	-	-	4	(D)	-	-	-	-	-	-
Winona	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Wright	7	3	7	3	-	-	5	1	5	1	-	-
Yellow Medicine	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
POTATOES												
State Total												
Minnesota	509	49,008	474	13,882	39	35,127	577	46,278	526	16,942	57	29,336
Counties												
Aitkin	11	4	11	4	-	-	12	11	12	11	-	-
Anoka	6	(D)	6	(D)	-	-	6	16	6	16	-	-
Becker	3	(D)	-	-	3	(D)	8	(D)	6	2	2	(D)
Beltrami	4	2	4	2	-	-	4	(Z)	4	(Z)	-	-
Benton	4	2,664	1	(D)	3	(D)	6	2,935	3	(D)	3	(D)
Blue Earth	7	4	7	4	-	-	1	(D)	1	(D)	-	-
Brown	-	-	-	-	-	-	3	(D)	3	(D)	-	-
Carlton	8	4	8	4	-	-	8	6	8	6	-	-
Carver	4	1	4	1	-	-	5	1	5	1	-	-
Cass	5	(D)	4	1	1	(D)	6	(D)	6	(D)	-	-
Chippewa	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Chisago	5	1	5	1	-	-	12	34	12	34	-	-
Clay	10	1,778	9	(D)	1	(D)	11	2,374	8	1,149	4	1,225
Clearwater	12	1,054	12	(D)	1	(D)	6	(D)	6	(D)	1	(D)
Cook	4	1	4	1	-	-	4	3	4	3	-	-
Cottonwood	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Crow Wing	1	(D)	1	(D)	-	-	6	1	6	1	-	-
Dakota	28	(D)	27	12	1	(D)	31	1,311	31	1,311	-	-
Dodge	1	(D)	1	(D)	-	-	4	(D)	4	(D)	-	-
Douglas	6	1	6	1	-	-	9	3	9	3	-	-
Faribault	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Fillmore	11	7	11	7	-	-	9	5	9	5	-	-
Freeborn	4	(D)	2	(D)	2	(D)	9	804	8	(D)	1	(D)
Goodhue	8	7	8	7	-	-	3	(D)	3	(D)	-	-
Grant	2	(D)	2	(D)	-	-	7	8	7	8	-	-
Hennepin	14	3	14	3	-	-	7	8	7	8	-	-
Houston	1	(D)	1	(D)	-	-	3	5	3	5	-	-
Hubbard	7	(D)	6	2	1	(D)	4	(D)	4	(D)	2	(D)
Isanti	4	3	4	3	-	-	8	(D)	8	(D)	-	-
Itasca	15	264	15	264	-	-	11	(D)	11	(D)	-	-
Jackson	-	-	-	-	-	-	4	5	4	5	-	-
Kanabec	16	5	16	5	-	-	13	4	13	4	-	-
Kandiyohi	2	(D)	2	(D)	-	-	5	(D)	4	(D)	1	(D)
Kittson	4	1,308	2	(D)	2	(D)	4	1,873	-	-	4	1,873
Koochiching	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Lac qui Parle	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Lake	3	(Z)	3	(Z)	-	-	3	1	3	1	-	-
Lake of the Woods	2	(D)	2	(D)	-	-	3	(D)	3	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	4	4	4	4	-	-
Lincoln	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
McLeod	5	5	5	5	-	-	6	9	6	9	-	-
Mahnomen	2	(D)	2	(D)	-	-	1	(D)	-	-	1	(D)
Marshall	4	352	4	352	-	-	4	299	3	(D)	1	(D)
Martin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	8	1	8	1	-	-	4	2	4	2	-	-
Mille Lacs	6	3	6	3	-	-	9	3	9	3	-	-
Morrison	11	2,664	10	(D)	2	(D)	11	1,655	6	1	5	1,654
Mower	3	(Z)	3	(Z)	-	-	11	2	11	2	-	-
Murray	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Nicollet	5	1	5	1	-	-	3	(Z)	3	(Z)	-	-
Nobles	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Norman	5	(D)	5	(D)	-	-	2	(D)	2	(D)	-	-
Olmsted	19	16	19	16	-	-	17	7	17	7	-	-
Otter Tail	13	(D)	11	(D)	2	(D)	14	(D)	12	8	2	(D)
Pennington	3	(D)	3	(D)	-	-	5	1	5	1	-	-
Pine	8	2	8	2	-	-	2	(D)	2	(D)	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	13	4,904	9	(D)	5	(D)	14	4,574	12	(D)	2	(D)
Pope	1	(D)	-	-	1	(D)	6	1,283	2	(D)	4	(D)
Ramsey	3	(Z)	3	(Z)	-	-	11	8	11	8	-	-
Red Lake	-	-	-	-	-	-	10	1,013	4	(D)	6	(D)
Redwood	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Renville	9	3	9	3	-	-	-	-	-	-	-	-
Rice	8	4	8	4	-	-	7	1	7	1	-	-
Rock	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Roseau	3	(Z)	3	(Z)	-	-	8	6	8	6	-	-
St. Louis	24	13	24	13	-	-	24	23	23	(D)	1	(D)
Scott	5	1	5	1	-	-	2	(D)	2	(D)	-	-
Sherburne	33	9,063	24	4,214	9	4,849	40	9,568	32	5,274	9	4,294
Stearns	17	73	17	73	-	-	16	(D)	14	17	2	(D)
Steele	3	(D)	2	(D)	1	(D)	8	393	6	(D)	2	(D)
Stevens	-	-	-	-	-	-	3	1	3	1	-	-
Swift	-	-	-	-	-	-	6	2	6	2	-	-
Todd	13	(D)	12	(D)	1	(D)	16	1,340	16	1,340	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	3	1	3	1	-	-	3	2	3	2	-	-
Wadena	5	2,948	3	(D)	3	(D)	6	(D)	4	(D)	3	3,002
Waseca	5	1	5	1	-	-	2	(D)	2	(D)	-	-
Washington	18	12	18	12	-	-	29	26	29	26	-	-
Wilkin	-	-	-	-	-	-	2	(D)	1	(D)	1	(D)
Winona	8	3	8	3	-	-	6	6	6	6	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
POTATOES - Con.												
Counties - Con.												
Wright	7	7	7	7	-	-	11	13	11	13	-	-
Yellow Medicine	8	3	8	3	-	-	1	(D)	1	(D)	-	-
PUMPKINS												
State Total												
Minnesota	627	2,018	621	2,018	6	1	569	1,827	569	(D)	1	(D)
Counties												
Aitkin	9	5	9	5	-	-	4	3	4	3	-	-
Anoka	20	131	14	130	6	1	12	112	12	112	-	-
Becker	7	1	7	1	-	-	8	10	8	10	-	-
Beltrami	12	3	12	3	-	-	17	5	17	5	-	-
Benton	4	(D)	4	(D)	-	-	7	322	7	322	-	-
Blue Earth	12	116	12	116	-	-	8	16	8	16	-	-
Brown	2	(D)	2	(D)	-	-	10	14	10	14	-	-
Carlton	15	2	15	2	-	-	12	2	12	2	-	-
Carver	14	19	14	19	-	-	11	62	11	62	-	-
Cass	5	1	5	1	-	-	5	7	5	7	-	-
Chippewa	8	(D)	8	(D)	-	-	2	(D)	2	(D)	-	-
Chisago	33	33	33	33	-	-	27	174	27	174	-	-
Clay	12	11	12	11	-	-	6	2	6	2	-	-
Clearwater	1	(D)	1	(D)	-	-	3	(D)	3	(D)	-	-
Cook	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
Cottonwood	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Crow Wing	10	30	10	30	-	-	5	(D)	5	(D)	-	-
Dakota	26	30	26	30	-	-	12	(D)	12	(D)	-	-
Dodge	1	(D)	1	(D)	-	-	4	(D)	4	(D)	-	-
Douglas	4	19	4	19	-	-	8	25	8	25	-	-
Faribault	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Fillmore	25	38	25	38	-	-	8	6	8	6	-	-
Freeborn	4	12	4	12	-	-	7	(D)	7	(D)	-	-
Goodhue	11	8	11	8	-	-	14	10	14	10	-	-
Grant	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Hennepin	43	173	43	173	-	-	18	84	18	84	-	-
Houston	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Hubbard	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Isanti	5	35	5	35	-	-	7	(D)	7	(D)	-	-
Itasca	13	14	13	14	-	-	12	6	12	6	-	-
Kanabec	7	2	7	2	-	-	2	(D)	2	(D)	-	-
Kandiyohi	6	11	6	11	-	-	4	(D)	4	(D)	-	-
Koochiching	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Lac qui Parle	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
Lake	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
McLeod	9	6	9	6	-	-	16	8	16	8	-	-
Mahnomen	2	(D)	2	(D)	-	-	4	(D)	4	(D)	-	-
Marshall	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Martin	1	(D)	1	(D)	-	-	3	(D)	3	(D)	-	-
Meeker	7	5	7	5	-	-	12	12	12	12	-	-
Mille Lacs	3	2	3	2	-	-	5	10	5	10	-	-
Morrison	4	(D)	4	(D)	-	-	6	5	6	5	-	-
Mower	4	1	4	1	-	-	9	6	9	6	-	-
Murray	4	1	4	1	-	-	1	(D)	1	(D)	-	-
Nicollet	14	9	14	9	-	-	8	1	8	1	-	-
Nobles	2	(D)	2	(D)	-	-	4	44	4	44	-	-
Norman	2	(D)	2	(D)	-	-	6	(D)	6	(D)	-	-
Olmsted	11	90	11	90	-	-	11	15	11	15	-	-
Otter Tail	25	62	25	62	-	-	19	18	19	18	-	-
Pennington	4	7	4	7	-	-	5	(D)	5	(D)	-	-
Pine	5	(D)	5	(D)	-	-	8	1	8	1	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	4	8	4	8	-	-	6	(D)	6	(D)	-	-
Pope	-	-	-	-	-	-	5	1	5	1	-	-
Ramsey	1	(D)	1	(D)	-	-	4	2	4	2	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Renville	4	(D)	4	(D)	-	-	2	(D)	2	(D)	-	-
Rice	26	42	26	42	-	-	19	22	19	22	-	-
Rock	5	5	5	5	-	-	2	(D)	2	(D)	-	-
Roseau	3	(Z)	3	(Z)	-	-	6	3	6	3	-	-
St. Louis	24	13	24	13	-	-	17	13	17	13	-	-
Scott	7	30	7	30	-	-	4	(D)	4	(D)	-	-
Sherburne	4	15	4	15	-	-	12	36	12	36	-	-
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	27	47	27	47	-	-	32	(D)	32	(D)	-	-
Steele	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	3	(D)	3	(D)	-	-	5	1	5	1	-	-
Todd	9	24	9	24	-	-	5	(D)	5	(D)	-	-
Traverse	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Wabasha	9	2	9	2	-	-	2	(D)	2	(D)	-	-
Wadena	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Waseca	6	(D)	6	(D)	-	-	2	(D)	2	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
PUMPKINS - Con.												
Counties - Con.												
Washington	36	159	36	159	-	-	26	119	26	119	-	-
Watonwan	9	16	9	16	-	-	1	(D)	1	(D)	-	-
Wilkin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Winona	2	(D)	2	(D)	-	-	3	(D)	3	(D)	-	-
Wright	16	254	16	254	-	-	29	213	29	213	-	-
Yellow Medicine	4	3	4	3	-	-	1	(D)	1	(D)	-	-
RADISHES												
State Total												
Minnesota	206	(D)	206	(D)	-	-	270	(D)	270	(D)	-	-
Counties												
Aitkin	12	2	12	2	-	-	5	1	5	1	-	-
Anoka	3	(D)	3	(D)	-	-	5	1	5	1	-	-
Beltrami	2	(D)	2	(D)	-	-	9	1	9	1	-	-
Brown	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Carlton	2	(D)	2	(D)	-	-	13	1	13	1	-	-
Carver	3	(Z)	3	(Z)	-	-	4	(Z)	4	(Z)	-	-
Cass	8	1	8	1	-	-	-	-	-	-	-	-
Chippewa	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chisago	4	1	4	1	-	-	20	(D)	20	(D)	-	-
Clay	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Clearwater	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Cook	3	(Z)	3	(Z)	-	-	4	(Z)	4	(Z)	-	-
Cottonwood	-	-	-	-	-	-	5	1	5	1	-	-
Crow Wing	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Dakota	12	2	12	2	-	-	11	2	11	2	-	-
Dodge	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Douglas	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Fillmore	7	1	7	1	-	-	9	2	9	2	-	-
Freeborn	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Goodhue	3	(Z)	3	(Z)	-	-	5	1	5	1	-	-
Grant	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Hennepin	8	1	8	1	-	-	10	1	10	1	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Isanti	4	(Z)	4	(Z)	-	-	5	1	5	1	-	-
Itasca	11	5	11	5	-	-	1	(D)	1	(D)	-	-
Kanabec	5	1	5	1	-	-	2	(D)	2	(D)	-	-
Lake	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	3	(D)	3	(D)	-	-	2	(D)	2	(D)	-	-
Mahnomen	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	3	(Z)	3	(Z)	-	-	7	1	7	1	-	-
Mille Lacs	3	1	3	1	-	-	4	(Z)	4	(Z)	-	-
Morrison	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Mower	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Murray	4	1	4	1	-	-	-	-	-	-	-	-
Nicollet	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Nobles	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	4	1	4	1	-	-	13	1	13	1	-	-
Otter Tail	7	(D)	7	(D)	-	-	4	1	4	1	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pine	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	-	-	-	-	-	-	5	1	5	1	-	-
Pope	-	-	-	-	-	-	3	1	3	1	-	-
Ramsey	4	(Z)	4	(Z)	-	-	13	2	13	2	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	9	1	9	1	-	-	9	2	9	2	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	16	2	16	2	-	-	7	2	7	2	-	-
Scott	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Sherburne	1	(D)	1	(D)	-	-	6	2	6	2	-	-
Sibley	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Stearns	7	5	7	5	-	-	8	2	8	2	-	-
Steele	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	5	1	5	1	-	-
Todd	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Wabasha	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Waseca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Washington	12	3	12	3	-	-	16	4	16	4	-	-
Winona	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wright	3	2	3	2	-	-	9	3	9	3	-	-
RHUBARB												
State Total												
Minnesota	216	73	210	72	6	2	193	72	192	(D)	1	(D)

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
RHUBARB - Con.												
Counties												
Aitkin	7	2	7	2	-	-	9	1	9	1	-	-
Anoka	9	(D)	9	(D)	-	-	10	(D)	10	(D)	-	-
Beltrami	4	2	4	2	-	-	4	1	4	1	-	-
Benton	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Carlton	1	(D)	1	(D)	-	-	10	1	10	1	-	-
Carver	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Cass	4	1	4	1	-	-	-	-	-	-	-	-
Chippewa	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Chisago	8	1	8	1	-	-	5	1	5	1	-	-
Clay	4	(Z)	4	(Z)	-	-	3	(Z)	3	(Z)	-	-
Clearwater	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cook	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Cottonwood	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Crow Wing	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Dakota	17	4	17	4	-	-	10	5	10	5	-	-
Douglas	5	2	4	(D)	1	(D)	-	-	-	-	-	-
Fillmore	11	1	11	1	-	-	8	1	8	1	-	-
Freeborn	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Goodhue	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
Hennepin	4	1	4	1	-	-	3	(Z)	3	(Z)	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hubbard	-	-	-	-	-	-	6	9	6	9	-	-
Isanti	7	1	4	(D)	3	(D)	5	1	5	1	-	-
Itasca	8	1	8	1	-	-	-	-	-	-	-	-
Kanabec	6	1	6	1	-	-	-	-	-	-	-	-
Lac qui Parle	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lake	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
McLeod	2	(D)	2	(D)	-	-	3	(D)	3	(D)	-	-
Marshall	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Mower	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	10	3	10	3	-	-	5	1	5	1	-	-
Otter Tail	5	1	5	1	-	-	3	1	3	1	-	-
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Ramsey	1	(D)	1	(D)	-	-	8	1	8	1	-	-
Redwood	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	6	1	6	1	-	-	6	1	6	1	-	-
Roseau	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
St. Louis	13	1	13	1	-	-	6	1	5	(D)	1	(D)
Scott	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Sherburne	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Sibley	-	-	-	-	-	-	4	(D)	4	(D)	-	-
Stearns	3	1	3	1	-	-	6	1	6	1	-	-
Steele	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Stevens	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Swift	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Todd	5	1	5	1	-	-	4	(Z)	4	(Z)	-	-
Wabasha	6	1	6	1	-	-	-	-	-	-	-	-
Wadena	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Waseca	5	1	5	1	-	-	1	(D)	1	(D)	-	-
Washington	15	5	15	5	-	-	12	5	12	5	-	-
Winona	-	-	-	-	-	-	7	1	7	1	-	-
Wright	4	(D)	2	(D)	2	(D)	3	2	3	2	-	-
SPINACH												
State Total												
Minnesota	155	31	155	31	-	-	163	44	163	44	-	-
Counties												
Aitkin	3	(Z)	3	(Z)	-	-	3	1	3	1	-	-
Anoka	1	(D)	1	(D)	-	-	6	3	6	3	-	-
Beltrami	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Brown	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Carlton	2	(D)	2	(D)	-	-	11	1	11	1	-	-
Carver	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Cass	6	1	6	1	-	-	-	-	-	-	-	-
Chippewa	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Chisago	3	1	3	1	-	-	-	-	-	-	-	-
Cook	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Cottonwood	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Crow Wing	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Dakota	11	1	11	1	-	-	7	1	7	1	-	-
Douglas	4	1	4	1	-	-	-	-	-	-	-	-
Fillmore	4	1	4	1	-	-	8	4	8	4	-	-
Goodhue	2	(D)	2	(D)	-	-	5	1	5	1	-	-
Hennepin	7	2	7	2	-	-	4	1	4	1	-	-
Houston	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Isanti	3	(Z)	3	(Z)	-	-	5	1	5	1	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
SPINACH - Con.												
Counties - Con.												
Itasca	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
Kanabec	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Kandiyohi	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Lake	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
Morrison	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Olmsted	8	1	8	1	-	-	7	1	7	1	-	-
Otter Tail	2	(D)	2	(D)	-	-	4	1	4	1	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pine	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Ramsey	4	(Z)	4	(Z)	-	-	10	1	10	1	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	8	1	8	1	-	-	9	2	9	2	-	-
Rock	3	3	3	3	-	-	-	-	-	-	-	-
Roseau	3	(Z)	3	(Z)	-	-	4	1	4	1	-	-
St. Louis	7	1	7	1	-	-	4	1	4	1	-	-
Scott	4	(D)	4	(D)	-	-	2	(D)	2	(D)	-	-
Sibley	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Stearns	2	(D)	2	(D)	-	-	9	2	9	2	-	-
Steele	-	-	-	-	-	-	3	1	3	1	-	-
Swift	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Todd	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Traverse	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wabasha	3	1	3	1	-	-	2	(D)	2	(D)	-	-
Waseca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Washington	22	4	22	4	-	-	11	2	11	2	-	-
Winona	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Wright	4	1	4	1	-	-	5	1	5	1	-	-
SQUASH (INCLUDING ZUCCHINI) (SEE TEXT)												
State Total												
Minnesota	539	652	539	652	-	-	682	921	682	920	1	(D)
Counties												
Aitkin	8	4	8	4	-	-	5	3	5	3	-	-
Anoka	14	67	14	67	-	-	13	82	13	82	-	-
Becker	6	1	6	1	-	-	12	3	12	3	-	-
Beltrami	8	4	8	4	-	-	9	10	9	10	-	-
Benton	4	(D)	4	(D)	-	-	7	(D)	7	(D)	-	-
Blue Earth	4	7	4	7	-	-	4	(D)	4	(D)	-	-
Brown	-	-	-	-	-	-	5	1	5	1	-	-
Carlton	15	3	15	3	-	-	14	5	14	5	-	-
Carver	11	10	11	10	-	-	9	5	9	5	-	-
Cass	8	1	8	1	-	-	7	3	7	3	-	-
Chippewa	6	7	6	7	-	-	1	(D)	1	(D)	-	-
Chisago	14	6	14	6	-	-	33	(D)	33	(D)	-	-
Clay	3	(D)	3	(D)	-	-	5	4	5	4	-	-
Clearwater	5	4	5	4	-	-	6	10	6	10	-	-
Cook	5	1	5	1	-	-	4	1	4	1	-	-
Cottonwood	1	(D)	1	(D)	-	-	7	2	7	2	-	-
Crow Wing	11	8	11	8	-	-	6	4	6	4	-	-
Dakota	29	26	29	26	-	-	37	111	37	111	-	-
Dodge	1	(D)	1	(D)	-	-	5	2	5	2	-	-
Douglas	8	7	8	7	-	-	8	9	8	9	-	-
Fillmore	17	8	17	8	-	-	13	50	13	50	-	-
Freeborn	1	(D)	1	(D)	-	-	4	1	4	1	-	-
Goodhue	8	6	8	6	-	-	9	4	9	4	-	-
Grant	2	(D)	2	(D)	-	-	4	1	4	1	-	-
Hennepin	26	15	26	15	-	-	22	10	22	10	-	-
Houston	2	(D)	2	(D)	-	-	9	3	9	3	-	-
Hubbard	2	(D)	2	(D)	-	-	5	(D)	5	(D)	1	(D)
Isanti	4	1	4	1	-	-	11	12	11	12	-	-
Itasca	8	2	8	2	-	-	12	2	12	2	-	-
Jackson	-	-	-	-	-	-	4	5	4	5	-	-
Kanabec	14	7	14	7	-	-	18	10	18	10	-	-
Kandiyohi	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Koochiching	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Lac qui Parle	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Lake	4	1	4	1	-	-	5	1	5	1	-	-
Lake of the Woods	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	7	10	7	10	-	-
Lincoln	-	-	-	-	-	-	1	(D)	1	(D)	-	-
McLeod	12	11	12	11	-	-	7	12	7	12	-	-
Mahnomen	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
SQUASH (INCLUDING ZUCCHINI) (SEE TEXT) - Con.												
Counties - Con.												
Marshall	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Martin	-	-	-	-	-	-	3	(D)	3	(D)	-	-
Meeker	7	1	7	1	-	-	2	(D)	2	(D)	-	-
Mille Lacs	12	7	12	7	-	-	12	4	12	4	-	-
Morrison	2	(D)	2	(D)	-	-	11	7	11	7	-	-
Mower	3	(Z)	3	(Z)	-	-	11	3	11	3	-	-
Murray	7	7	7	7	-	-	1	(D)	1	(D)	-	-
Nicollet	6	(D)	6	(D)	-	-	8	3	8	3	-	-
Nobles	2	(D)	2	(D)	-	-	4	9	4	9	-	-
Norman	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Olmsted	13	16	13	16	-	-	17	20	17	20	-	-
Otter Tail	20	25	20	25	-	-	18	19	18	19	-	-
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	9	4	9	4	-	-	11	4	11	4	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	2	(D)	2	(D)	-	-	7	3	7	3	-	-
Pope	3	(Z)	3	(Z)	-	-	5	4	5	4	-	-
Ramsey	11	4	11	4	-	-	15	12	15	12	-	-
Red Lake	-	-	-	-	-	-	4	(D)	4	1	-	-
Redwood	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Renville	4	(D)	4	(D)	-	-	1	(D)	1	(D)	-	-
Rice	12	6	12	6	-	-	19	10	19	10	-	-
Rock	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Roseau	3	(Z)	3	(Z)	-	-	7	3	7	3	-	-
St. Louis	36	6	36	6	-	-	17	8	17	8	-	-
Scott	7	3	7	3	-	-	8	3	8	3	-	-
Sherburne	11	21	11	21	-	-	9	10	9	10	-	-
Sibley	1	(D)	1	(D)	-	-	4	1	4	1	-	-
Stearns	13	4	13	4	-	-	21	5	21	5	-	-
Steele	2	(D)	2	(D)	-	-	6	2	6	2	-	-
Stevens	-	-	-	-	-	-	3	1	3	1	-	-
Swift	4	(D)	4	(D)	-	-	5	2	5	2	-	-
Todd	7	3	7	3	-	-	16	13	16	13	-	-
Wabasha	3	2	3	2	-	-	5	4	5	4	-	-
Wadena	3	(D)	3	(D)	-	-	4	(D)	4	(D)	-	-
Waseca	4	4	4	4	-	-	3	1	3	1	-	-
Washington	43	25	43	25	-	-	45	32	45	32	-	-
Wilkin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Winona	2	(D)	2	(D)	-	-	12	39	12	39	-	-
Wright	12	88	12	88	-	-	21	(D)	21	(D)	-	-
Yellow Medicine	-	-	-	-	-	-	1	(D)	1	(D)	-	-
SWEET CORN (SEE TEXT)												
State Total												
Minnesota	1,243	96,990	496	2,453	750	94,536	1,531	107,955	557	3,447	985	104,508
Counties												
Aitkin	10	4	10	4	-	-	10	3	10	3	-	-
Anoka	15	(D)	15	(D)	-	-	11	215	11	215	-	-
Becker	-	-	-	-	-	-	5	12	5	12	-	-
Beltrami	2	(D)	2	(D)	-	-	4	1	4	1	-	-
Benton	13	(D)	13	(D)	-	-	7	(D)	7	(D)	-	-
Blue Earth	10	650	3	(D)	7	(D)	9	767	3	(D)	6	(D)
Brown	17	1,906	-	-	17	1,906	100	7,720	8	1	92	7,718
Carlton	8	8	8	8	-	-	6	19	6	19	-	-
Carver	4	10	4	10	-	-	11	47	10	(D)	1	(D)
Cass	4	2	4	2	-	-	5	9	5	9	-	-
Chippewa	9	1,221	1	(D)	8	(D)	16	1,991	2	(D)	14	(D)
Chisago	19	4	19	4	-	-	6	13	6	13	-	-
Clay	11	20	11	20	-	-	5	16	5	16	-	-
Clearwater	13	11	13	11	-	-	3	2	3	2	-	-
Cook	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	4	256	1	(D)	3	(D)	10	553	7	(D)	3	(D)
Crow Wing	10	14	10	14	-	-	6	9	6	9	-	-
Dakota	103	8,886	29	333	74	8,554	103	7,068	40	360	63	6,708
Dodge	21	2,676	2	(D)	19	(D)	25	2,222	4	(D)	21	(D)
Douglas	9	69	9	69	-	-	9	47	9	47	-	-
Faribault	35	3,726	-	-	35	3,726	53	4,123	1	(D)	52	(D)
Fillmore	22	740	17	(D)	5	(D)	17	431	9	53	8	378
Freeborn	29	4,023	6	40	23	3,983	34	5,487	4	(D)	30	(D)
Goodhue	29	1,746	6	13	23	1,733	43	3,112	5	(D)	39	(D)
Grant	2	(D)	2	(D)	-	-	3	(D)	2	(D)	1	(D)
Hennepin	10	100	10	100	-	-	34	125	34	125	-	-
Houston	1	(D)	1	(D)	-	-	3	8	3	8	-	-
Hubbard	2	(D)	2	(D)	-	-	1	(D)	1	(D)	1	(D)
Isanti	6	16	6	16	-	-	7	(D)	7	(D)	-	-
Itasca	5	3	5	3	-	-	9	13	9	13	-	-
Jackson	1	(D)	1	(D)	-	-	5	19	5	19	-	-
Kanabec	16	15	16	15	-	-	12	9	12	9	-	-
Kandiyohi	37	7,185	3	26	34	7,159	22	2,922	4	5	18	2,916
Lac qui Parle	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lake	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Le Sueur	6	429	-	-	6	429	22	1,348	7	86	15	1,261

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
SWEET CORN (SEE TEXT) - Con.												
Counties - Con.												
Lincoln	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Lyon	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	22	2,137	8	36	14	2,101	30	2,411	12	(D)	18	(D)
Marshall	1	(D)	1	(D)	-	-	3	(D)	3	(D)	-	-
Martin	33	2,684	1	(D)	32	(D)	37	2,063	4	(D)	33	(D)
Meeker	17	2,132	10	16	7	2,116	17	1,827	6	(D)	11	(D)
Mille Lacs	14	24	14	24	-	-	8	16	8	16	-	-
Morrison	4	(D)	4	(D)	-	-	4	(D)	4	(D)	-	-
Mower	66	9,249	9	24	57	9,226	77	10,491	9	(D)	69	(D)
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nicollet	11	544	5	13	6	531	18	580	7	(D)	12	(D)
Nobles	-	-	-	-	-	-	3	10	3	10	-	-
Norman	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	89	6,075	22	57	68	6,019	86	6,726	15	102	72	6,624
Otter Tail	13	26	13	26	-	-	13	37	13	37	-	-
Pennington	1	(D)	1	(D)	-	-	5	10	5	10	-	-
Pine	11	5	11	5	-	-	7	6	7	6	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	7	(D)	5	5	2	(D)	12	13	12	13	-	-
Pope	9	(D)	1	(D)	8	(D)	14	1,313	2	(D)	12	(D)
Ramsey	3	(D)	3	(D)	-	-	9	13	9	13	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	14	1,803	-	-	14	1,803	52	4,523	1	(D)	51	(D)
Renville	116	16,588	4	(D)	112	(D)	146	17,852	3	(D)	143	(D)
Rice	9	445	4	(D)	5	(D)	8	(D)	6	12	2	(D)
Rock	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Roseau	-	-	-	-	-	-	3	3	3	3	-	-
St. Louis	7	5	7	5	-	-	13	9	13	9	-	-
Scott	14	95	12	(D)	2	(D)	13	43	12	(D)	1	(D)
Sherburne	17	50	17	50	-	-	7	85	6	(D)	1	(D)
Sibley	42	4,263	6	10	36	4,254	36	4,383	-	-	36	4,383
Stearns	24	1,739	13	(D)	11	(D)	28	1,259	20	63	8	1,196
Steele	13	1,443	1	(D)	12	(D)	21	2,683	4	1	17	2,682
Swift	4	852	-	-	4	852	7	462	4	(Z)	3	462
Todd	28	49	28	49	-	-	18	23	18	23	-	-
Wabasha	52	4,087	3	(D)	49	(D)	78	4,994	12	395	72	4,599
Wadena	4	11	4	11	-	-	2	(D)	2	(D)	-	-
Waseca	34	3,103	2	(D)	34	(D)	44	3,718	3	6	41	3,712
Washington	27	388	27	388	-	-	45	463	45	463	-	-
Watonwan	14	2,153	5	(D)	9	(D)	13	1,889	-	-	13	1,889
Wilkin	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Winona	17	1,208	3	(D)	14	(D)	14	470	8	23	6	447
Wright	15	251	15	251	-	-	11	(D)	11	(D)	-	-
Yellow Medicine	-	-	-	-	-	-	1	(D)	1	(D)	-	-
SWEET POTATOES												
State Total												
Minnesota	58	23	58	23	-	-	82	33	82	33	-	-
Counties												
Aitkin	2	(D)	2	(D)	-	-	3	(Z)	3	(Z)	-	-
Anoka	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Chippewa	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Clay	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Clearwater	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Crow Wing	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Dakota	11	2	11	2	-	-	15	11	15	11	-	-
Dodge	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Douglas	4	1	4	1	-	-	-	-	-	-	-	-
Fillmore	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Goodhue	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Hennepin	10	3	10	3	-	-	4	1	4	1	-	-
Isanti	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Kanabec	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Meeker	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Mille Lacs	-	-	-	-	-	-	5	1	5	1	-	-
Mower	-	-	-	-	-	-	3	1	3	1	-	-
Murray	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Otter Tail	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Pine	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Ramsey	-	-	-	-	-	-	3	1	3	1	-	-
Rice	1	(D)	1	(D)	-	-	6	1	6	1	-	-
St. Louis	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Scott	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Sherburne	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Stearns	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Waseca	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Washington	5	2	5	2	-	-	15	8	15	8	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
SWEET POTATOES - Con.												
Counties - Con.												
Winona	1	(D)	1	(D)	-	-	3	(D)	3	(D)	-	-
Wright	-	-	-	-	-	-	2	(D)	2	(D)	-	-
TOMATOES IN THE OPEN												
State Total												
Minnesota	592	300	581	298	18	2	670	350	663	348	11	2
Counties												
Aitkin	8	1	8	1	-	-	10	3	10	3	-	-
Anoka	16	13	10	12	6	1	8	6	8	6	-	-
Becker	2	(D)	2	(D)	-	-	11	6	11	6	-	-
Beltrami	4	2	4	2	-	-	10	1	10	1	-	-
Benton	3	(D)	3	(D)	-	-	2	(D)	2	(D)	-	-
Big Stone	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Blue Earth	7	6	7	6	-	-	3	3	3	3	-	-
Brown	-	-	-	-	-	-	10	3	10	3	-	-
Carlton	7	3	7	3	-	-	16	2	16	2	-	-
Carver	9	5	9	5	-	-	5	1	5	1	-	-
Cass	6	1	6	1	-	-	-	-	-	-	-	-
Chippewa	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Chisago	12	3	12	3	-	-	23	7	23	7	-	-
Clay	10	2	10	2	-	-	5	5	5	5	-	-
Clearwater	5	3	5	3	-	-	3	(D)	3	(D)	-	-
Cook	3	(Z)	3	(Z)	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	3	1	3	1	-	-	-	-	-	-	-	-
Crow Wing	3	(Z)	3	(Z)	-	-	6	2	6	2	-	-
Dakota	40	34	40	34	-	-	57	66	57	66	-	-
Dodge	1	(D)	1	(D)	-	-	4	1	4	1	-	-
Douglas	4	1	4	1	-	-	8	4	8	4	-	-
Fillmore	18	12	18	12	-	-	21	31	21	31	-	-
Freeborn	1	(D)	1	(D)	-	-	6	1	6	1	-	-
Goodhue	5	1	5	1	-	-	6	2	6	2	-	-
Grant	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Hennepin	28	13	28	13	-	-	47	16	47	16	-	-
Houston	1	(D)	1	(D)	1	(D)	10	3	10	3	-	-
Hubbard	6	1	6	1	-	-	5	3	5	3	-	-
Isanti	6	1	3	(Z)	3	(Z)	8	7	8	7	-	-
Itasca	13	1	13	1	-	-	9	1	9	1	-	-
Jackson	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Kanabec	14	2	14	2	-	-	12	3	12	3	-	-
Kandiyohi	2	(D)	2	(D)	-	-	4	1	4	(D)	1	(D)
Koochiching	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Lac qui Parle	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Lake	1	(D)	1	(D)	-	-	9	2	9	2	-	-
Le Sueur	1	(D)	1	(D)	-	-	8	7	8	6	3	(Z)
Lincoln	4	(D)	4	(D)	-	-	2	(D)	2	(D)	-	-
McLeod	12	5	12	5	-	-	14	4	14	4	-	-
Mahnomen	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Marshall	4	4	4	4	-	-	2	(D)	2	(D)	-	-
Martin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Meeker	12	3	12	3	-	-	7	2	7	2	-	-
Mille Lacs	6	4	6	4	-	-	5	4	5	4	-	-
Morrison	3	1	3	1	-	-	15	6	15	6	-	-
Mower	4	1	4	1	-	-	11	1	11	1	-	-
Murray	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Nicollet	11	2	11	2	-	-	4	1	4	1	-	-
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	18	35	18	(D)	2	(D)	16	15	16	15	-	-
Otter Tail	20	25	20	25	-	-	23	4	23	4	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pine	10	2	10	2	-	-	10	2	10	2	-	-
Pipestone	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Polk	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pope	3	(D)	3	(D)	-	-	5	2	5	2	-	-
Ramsey	12	4	12	4	-	-	19	2	19	2	-	-
Red Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Redwood	4	(Z)	4	(Z)	-	-	1	(D)	1	(D)	-	-
Renville	9	1	9	1	-	-	-	-	-	-	-	-
Rice	11	3	11	3	-	-	13	6	13	6	-	-
Rock	3	3	3	3	-	-	2	(D)	2	(D)	-	-
Roseau	3	(Z)	3	(Z)	-	-	4	(Z)	4	(Z)	-	-
St. Louis	29	4	29	4	-	-	17	2	13	2	4	(Z)
Scott	20	8	20	(D)	1	(D)	9	2	9	2	-	-
Sherburne	14	17	14	17	-	-	11	9	11	9	-	-
Sibley	7	1	7	1	-	-	-	-	-	-	-	-
Stearns	19	7	19	7	-	-	15	3	15	3	-	-
Steele	2	(D)	2	(D)	-	-	8	2	8	2	-	-
Stevens	-	-	-	-	-	-	3	1	3	1	-	-
Swift	1	(D)	1	(D)	-	-	6	1	6	1	-	-
Todd	9	1	9	1	-	-	6	1	6	1	-	-
Wabasha	9	2	9	2	-	-	4	3	4	3	-	-
Wadena	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Waseca	10	1	10	1	-	-	1	(D)	1	(D)	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
TOMATOES IN THE OPEN - Con.												
Counties - Con.												
Washington	35	27	35	27	3	1	36	22	35	(D)	1	(D)
Wilkin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Winona	15	6	15	6	-	-	15	16	15	16	-	-
Wright	17	15	15	(D)	2	(D)	27	16	25	(D)	2	(D)
Yellow Medicine	6	1	6	1	-	-	7	3	7	3	-	-
TURNIP GREENS												
State Total												
Minnesota	19	4	19	4	-	-	30	6	30	6	-	-
Counties												
Anoka	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Beltrami	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Carlton	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Carver	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Chisago	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Dakota	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Hennepin	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Isanti	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Kanabec	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Olmsted	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Otter Tail	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Stearns	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Washington	2	(D)	2	(D)	-	-	7	2	7	2	-	-
Wright	-	-	-	-	-	-	1	(D)	1	(D)	-	-
TURNIPS												
State Total												
Minnesota	90	18	90	18	-	-	102	16	102	16	-	-
Counties												
Aitkin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Anoka	1	(D)	1	(D)	-	-	3	1	3	1	-	-
Beltrami	1	(D)	1	(D)	-	-	3	(Z)	3	(Z)	-	-
Brown	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Carlton	2	(D)	2	(D)	-	-	4	(Z)	4	(Z)	-	-
Carver	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Chisago	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Clay	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Cook	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	-	-	-	-	-	-	7	1	7	1	-	-
Dakota	11	2	11	2	-	-	3	(Z)	3	(Z)	-	-
Fillmore	2	(D)	2	(D)	-	-	4	2	4	2	-	-
Goodhue	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Hennepin	2	(D)	2	(D)	-	-	6	1	6	1	-	-
Isanti	3	(Z)	3	(Z)	-	-	5	1	5	1	-	-
Itasca	7	3	7	3	-	-	1	(D)	1	(D)	-	-
Kanabec	3	(Z)	3	(Z)	-	-	2	(D)	2	(D)	-	-
Lake	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Olmsted	-	-	-	-	-	-	5	1	5	1	-	-
Otter Tail	5	3	5	3	-	-	3	1	3	1	-	-
Pine	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Polk	3	1	3	1	-	-	-	-	-	-	-	-
Ramsey	3	(Z)	3	(Z)	-	-	8	1	8	1	-	-
Rice	-	-	-	-	-	-	6	1	6	1	-	-
St. Louis	9	1	9	1	-	-	6	1	6	1	-	-
Scott	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Sherburne	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Stearns	7	2	7	2	-	-	5	1	5	1	-	-
Swift	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Wadena	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Washington	10	1	10	1	-	-	5	1	5	1	-	-
Wright	3	1	3	1	-	-	3	1	3	1	-	-
WATERCRESS												
State Total												
Minnesota	2	(D)	2	(D)	(X)	(X)	6	1	6	1	(X)	(X)
Counties												
Goodhue	-	-	-	-	(X)	(X)	3	(D)	3	(D)	(X)	(X)
Kandiyohi	-	-	-	-	(X)	(X)	1	(D)	1	(D)	(X)	(X)
Wright	2	(D)	2	(D)	(X)	(X)	2	(D)	2	(D)	(X)	(X)

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
WATERMELONS												
State Total												
Minnesota	209	237	209	237	-	-	253	136	253	136	-	-
Counties												
Anoka	6	(D)	6	(D)	-	-	7	11	7	11	-	-
Becker	-	-	-	-	-	-	4	1	4	1	-	-
Beltrami	3	(Z)	3	(Z)	-	-	9	(D)	9	(D)	-	-
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Blue Earth	2	(D)	2	(D)	-	-	4	(D)	4	(D)	-	-
Brown	-	-	-	-	-	-	6	1	6	1	-	-
Carver	5	5	5	5	-	-	1	(D)	1	(D)	-	-
Cass	3	1	3	1	-	-	-	-	-	-	-	-
Chippewa	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Chisago	12	3	12	3	-	-	10	2	10	2	-	-
Clay	5	2	5	2	-	-	2	(D)	2	(D)	-	-
Clearwater	4	1	4	1	-	-	-	-	-	-	-	-
Cook	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Cottonwood	1	(D)	1	(D)	-	-	7	(D)	7	(D)	-	-
Crow Wing	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Dakota	15	3	15	3	-	-	9	1	9	1	-	-
Dodge	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Douglas	9	2	9	2	-	-	2	(D)	2	(D)	-	-
Fillmore	9	8	9	8	-	-	7	19	7	19	-	-
Freeborn	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Goodhue	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Grant	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Hennepin	10	13	10	13	-	-	11	4	11	4	-	-
Houston	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Hubbard	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Isanti	4	(D)	4	(D)	-	-	5	1	5	1	-	-
Itasca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Kanabec	10	8	10	8	-	-	1	(D)	1	(D)	-	-
Kandiyohi	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Lake	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	4	2	4	2	-	-	3	(D)	3	(D)	-	-
Martin	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Meeker	3	(Z)	3	(Z)	-	-	3	2	3	2	-	-
Mille Lacs	4	4	4	4	-	-	1	(D)	1	(D)	-	-
Morrison	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	1	(D)	1	(D)	-	-	5	1	5	1	-	-
Murray	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Nicollet	2	(D)	2	(D)	-	-	6	2	6	2	-	-
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Norman	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Olmsted	3	2	3	2	-	-	6	(D)	6	(D)	-	-
Otter Tail	8	5	8	5	-	-	9	3	9	3	-	-
Pennington	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Pine	5	1	5	1	-	-	8	1	8	1	-	-
Pipestone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Polk	3	(Z)	3	(Z)	-	-	8	2	8	2	-	-
Pope	-	-	-	-	-	-	3	1	3	1	-	-
Ramsey	4	1	4	1	-	-	13	2	13	2	-	-
Redwood	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Renville	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Rice	8	1	8	1	-	-	8	2	8	2	-	-
Roseau	3	(Z)	3	(Z)	-	-	3	1	3	1	-	-
St. Louis	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Scott	3	2	3	2	-	-	3	1	3	1	-	-
Sherburne	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Sibley	1	(D)	1	(D)	-	-	4	(Z)	4	(Z)	-	-
Stearns	6	2	6	2	-	-	13	2	13	2	-	-
Steele	2	(D)	2	(D)	-	-	3	1	3	1	-	-
Swift	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Todd	3	(D)	3	(D)	-	-	4	2	4	2	-	-
Traverse	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Wabasha	2	(D)	2	(D)	-	-	4	(D)	4	(D)	-	-
Waseca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Washington	14	5	14	5	-	-	19	4	19	4	-	-
Watonwan	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	-	-	-	-	-	-	4	(D)	4	(D)	-	-
Wright	2	(D)	2	(D)	-	-	6	(D)	6	(D)	-	-
OTHER VEGETABLES												
State Total												
Minnesota	123	184	123	184	-	-	167	336	167	336	-	-
Counties												
Aitkin	6	4	6	4	-	-	1	(D)	1	(D)	-	-
Anoka	10	10	10	10	-	-	2	(D)	2	(D)	-	-
Becker	1	(D)	1	(D)	-	-	3	2	3	2	-	-
Beltrami	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Benton	1	(D)	1	(D)	-	-	-	-	-	-	-	-

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Table 29. **Vegetables, Potatoes, and Melons Harvested for Sale: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total harvested		Harvested for fresh market		Harvested for processing		Total harvested		Harvested for fresh market		Harvested for processing	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
OTHER VEGETABLES - Con.												
Counties - Con.												
Blue Earth	6	6	6	6	-	-	-	-	-	-	-	-
Carlton	1	(D)	1	(D)	-	-	8	2	8	2	-	-
Carver	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Chisago	2	(D)	2	(D)	-	-	4	(D)	4	(D)	-	-
Clearwater	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Cook	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Crow Wing	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Dakota	15	78	15	78	-	-	24	13	24	13	-	-
Fillmore	-	-	-	-	-	-	6	16	6	16	-	-
Freeborn	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Goodhue	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Hennepin	8	7	8	7	-	-	13	10	13	10	-	-
Houston	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hubbard	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Isanti	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Itasca	6	3	6	3	-	-	6	1	6	1	-	-
Jackson	-	-	-	-	-	-	4	2	4	2	-	-
Kanabec	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Lake	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lake of the Woods	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Le Sueur	-	-	-	-	-	-	1	(D)	1	(D)	-	-
McLeod	3	2	3	2	-	-	5	11	5	11	-	-
Mahnomen	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Mille Lacs	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Morrison	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Mower	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Nobles	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	5	(D)	5	(D)	-	-	1	(D)	1	(D)	-	-
Otter Tail	1	(D)	1	(D)	-	-	6	5	6	5	-	-
Pine	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Polk	3	2	3	2	-	-	1	(D)	1	(D)	-	-
Pope	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Ramsey	9	6	9	6	-	-	5	5	5	5	-	-
Renville	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Rice	-	-	-	-	-	-	5	4	5	4	-	-
St. Louis	7	9	7	9	-	-	10	8	10	8	-	-
Scott	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Sherburne	-	-	-	-	-	-	7	12	7	12	-	-
Stevens	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Todd	1	(D)	1	(D)	-	-	3	2	3	2	-	-
Wabasha	-	-	-	-	-	-	3	1	3	1	-	-
Wadena	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Waseca	5	8	5	8	-	-	-	-	-	-	-	-
Washington	6	2	6	2	-	-	15	10	15	10	-	-
Watonwan	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Wright	7	9	7	9	-	-	2	(D)	2	(D)	-	-
Yellow Medicine	-	-	-	-	-	-	1	(D)	1	(D)	-	-

Table 30. **Land in Orchards: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022				2017			
	Total		Irrigated		Total		Irrigated	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
State Total								
Minnesota	1,174	5,049	204	778	1,061	4,767	154	891
Counties								
Aitkin	13	31	3	(D)	12	20	1	(D)
Anoka	11	28	1	(D)	12	32	3	2
Becker	21	37	1	(D)	22	52	5	(D)
Beltrami	10	9	3	(D)	14	20	-	-
Benton	7	12	3	6	2	(D)	1	(D)
Big Stone	2	(D)	-	-	14	26	1	(D)
Blue Earth	29	76	-	-	34	95	2	(D)
Brown	4	26	-	-	6	21	-	-
Carlton	11	21	-	-	10	21	4	7
Carver	24	173	6	9	25	145	5	25
Cass	23	22	7	9	14	19	4	6
Chippewa	13	46	2	(D)	6	4	-	-
Chisago	38	186	10	27	52	161	7	6
Clay	13	15	-	-	7	3	-	-
Clearwater	-	-	-	-	4	(D)	-	-
Cook	2	(D)	1	(D)	9	4	-	-
Cottonwood	4	4	-	-	6	24	-	-
Crow Wing	15	26	1	(D)	10	8	2	(D)
Dakota	35	198	9	28	21	103	6	55
Dodge	8	9	-	-	4	13	-	-
Douglas	22	98	4	31	13	54	2	(D)
Faribault	2	(D)	-	-	1	(D)	-	-
Fillmore	28	155	2	(D)	25	144	1	(D)
Freeborn	9	22	-	-	9	16	-	-
Goodhue	34	164	3	11	43	110	1	(D)
Grant	1	(D)	-	-	1	(D)	-	-
Hennepin	55	118	9	4	26	123	2	(D)
Houston	8	121	1	(D)	11	(D)	1	(D)
Hubbard	10	41	1	(D)	11	21	-	-
Isanti	23	72	3	4	15	31	2	(D)
Itasca	8	7	6	(D)	13	10	7	3
Jackson	2	(D)	1	(D)	-	-	-	-
Kanabec	11	56	5	24	7	19	2	(D)
Kandiyohi	19	44	1	(D)	8	39	-	-
Koochiching	-	-	-	-	2	(D)	-	-
Lac qui Parle	3	23	1	(D)	8	25	4	8
Lake	5	7	-	-	5	9	-	-
Lake of the Woods	2	(D)	-	-	-	-	-	-
Le Sueur	8	66	1	(D)	14	96	2	(D)
Lincoln	8	45	3	30	2	(D)	-	-
Lyon	1	(D)	-	-	1	(D)	-	-
McLeod	14	59	3	7	16	73	2	(D)
Mahnomen	-	-	-	-	2	(D)	-	-
Marshall	-	-	-	-	4	(D)	-	-
Martin	2	(D)	-	-	4	18	2	(D)
Meeker	26	56	12	4	17	29	3	4
Mille Lacs	13	58	1	(D)	19	45	3	(D)
Morrison	11	19	4	4	10	18	4	6
Mower	13	48	-	-	18	77	6	1
Murray	2	(D)	-	-	5	4	-	-
Nicollet	6	3	2	(D)	3	(D)	-	-
Nobles	3	(D)	-	-	7	69	-	-
Norman	2	(D)	-	-	1	(D)	1	(D)
Olmsted	41	141	2	(D)	39	126	2	(D)
Otter Tail	38	91	7	18	28	55	2	(D)
Pennington	11	23	-	-	3	(D)	-	-
Pine	31	59	4	2	15	26	4	4
Pipestone	-	-	-	-	1	(D)	-	-
Polk	5	9	-	-	9	16	-	-
Pope	6	5	-	-	5	4	2	(D)
Ramsey	-	-	-	-	14	18	6	10
Red Lake	-	-	-	-	3	(D)	-	-
Redwood	10	13	4	4	5	10	2	(D)
Renville	8	16	-	-	3	(D)	-	-
Rice	37	276	5	21	27	197	6	47
Roseau	1	(D)	-	-	2	(D)	-	-
St. Louis	46	67	2	(D)	34	55	2	(D)
Scott	34	110	7	20	24	236	1	(D)
Sherburne	28	47	12	21	9	30	1	(D)
Sibley	1	(D)	-	-	3	(D)	-	-
Stearns	35	103	12	25	24	163	3	30
Steele	4	26	-	-	9	30	-	-
Stevens	2	(D)	-	-	1	(D)	-	-
Swift	1	(D)	-	-	3	2	-	-
Todd	24	107	3	9	25	43	3	(D)
Traverse	2	(D)	1	(D)	2	(D)	1	(D)
Wabasha	22	454	6	(D)	18	374	1	(D)
Wadena	3	6	-	-	8	13	-	-
Waseca	7	28	-	-	1	(D)	-	-
Washington	47	394	14	164	59	402	15	206
Watonwan	3	2	-	-	1	(D)	-	-
Wilkin	-	-	-	-	4	(D)	3	(D)
Winona	35	501	2	(D)	29	490	1	(D)

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Table 30. **Land in Orchards: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022				2017			
	Total		Irrigated		Total		Irrigated	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
Counties - Con.								
Wright	56	282	13	78	47	373	13	175
Yellow Medicine	2	(D)	-	-	1	(D)	-	-

Table 31. **Fruits and Nuts: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
NONCITRUS, ALL												
State Total												
Minnesota	1,126	4,724	931	3,739	588	985	1,028	4,589	814	3,687	556	903
Counties												
Aitkin	13	(D)	8	26	10	(D)	12	20	11	14	11	6
Anoka	11	28	11	23	4	5	12	32	8	15	5	17
Becker	21	37	19	28	11	10	22	52	15	36	14	16
Beltrami	10	(D)	10	(D)	-	-	14	(D)	11	(D)	7	15
Benton	7	12	7	12	-	-	2	(D)	2	(D)	2	(D)
Big Stone	2	(D)	2	(D)	2	(D)	14	26	14	23	9	3
Blue Earth	29	76	19	50	17	25	34	95	30	77	21	18
Brown	4	26	4	(D)	1	(D)	6	21	6	13	5	8
Carlton	11	21	11	(D)	4	(D)	10	21	5	12	8	9
Carver	24	173	23	159	11	15	25	(D)	21	109	14	(D)
Cass	23	22	9	8	18	14	14	19	8	7	11	13
Chippewa	13	(D)	11	37	10	(D)	6	4	6	3	4	1
Chisago	38	186	27	122	30	64	52	(D)	38	107	27	(D)
Clay	13	15	7	8	10	7	7	3	4	(D)	4	(D)
Clearwater	-	-	-	-	-	-	4	(D)	2	(D)	2	(D)
Cook	2	(D)	2	(D)	-	-	9	4	9	4	-	-
Cottonwood	4	4	4	4	-	-	6	(D)	6	16	2	(D)
Crow Wing	15	18	12	12	9	6	10	8	7	6	5	3
Dakota	35	(D)	26	132	19	(D)	21	(D)	19	85	10	(D)
Dodge	8	9	7	7	6	2	4	13	4	13	-	-
Douglas	22	98	21	83	14	16	13	54	7	35	12	20
Faribault	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Fillmore	25	152	23	124	13	28	20	107	20	95	5	12
Freeborn	4	12	4	12	-	-	9	16	9	9	9	7
Goodhue	34	(D)	30	136	21	(D)	43	(D)	37	85	24	(D)
Grant	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)	-	-
Hennepin	51	(D)	47	91	19	(D)	26	123	21	89	9	34
Houston	8	121	8	(D)	2	(D)	10	(D)	7	(D)	5	16
Hubbard	10	(D)	9	21	7	(D)	11	21	3	(D)	10	(D)
Isanti	22	(D)	22	60	14	(D)	13	(D)	13	21	9	(D)
Itasca	8	7	8	6	4	1	13	(D)	7	8	9	(D)
Jackson	2	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Kanabec	11	(D)	11	33	9	(D)	7	19	2	(D)	6	(D)
Kandiyohi	19	44	11	32	12	12	8	(D)	4	(D)	4	(D)
Koochiching	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Lac qui Parle	3	23	3	(D)	1	(D)	8	25	7	20	6	5
Lake	5	7	5	(D)	1	(D)	5	9	4	6	4	3
Lake of the Woods	2	(D)	2	(D)	2	(D)	-	-	-	-	-	-
Le Sueur	8	66	8	(D)	1	(D)	14	96	14	73	9	23
Lincoln	8	45	6	42	5	3	2	(D)	1	(D)	1	(D)
Lyon	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
McLeod	14	59	13	52	8	7	16	(D)	10	56	12	(D)
Mahnomen	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Marshall	-	-	-	-	-	-	4	(D)	3	(D)	3	(D)
Martin	2	(D)	2	(D)	-	-	4	18	4	(D)	2	(D)
Meeker	24	(D)	17	47	13	(D)	17	26	15	23	11	4
Mille Lacs	10	43	10	(D)	4	(D)	19	45	13	26	8	19
Morrison	11	19	10	11	6	8	10	18	8	12	5	6
Mower	10	(D)	9	(D)	2	(D)	12	31	12	(D)	2	(D)
Murray	2	(D)	2	(D)	-	-	5	4	5	4	-	-
Nicollet	6	3	6	3	-	-	3	(D)	3	(D)	1	(D)
Nobles	3	(D)	3	(D)	1	(D)	7	69	7	49	6	21
Norman	2	(D)	-	-	2	(D)	1	(D)	1	(D)	-	-
Olmsted	36	129	31	116	13	14	34	103	27	85	15	18
Otter Tail	38	(D)	22	48	32	(D)	27	(D)	17	31	16	(D)
Pennington	11	23	9	(D)	2	(D)	3	(D)	2	(D)	1	(D)
Pine	31	53	14	29	22	24	15	26	12	21	7	6
Pipestone	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Polk	5	9	5	(D)	2	(D)	9	16	8	(D)	2	(D)
Pope	6	5	1	(D)	6	(D)	5	4	2	(D)	3	(D)
Ramsey	-	-	-	-	-	-	14	18	14	15	4	3
Red Lake	-	-	-	-	-	-	3	(D)	2	(D)	1	(D)
Redwood	10	13	10	12	4	1	5	10	5	7	4	3
Renville	8	16	8	16	-	-	3	(D)	3	(D)	1	(D)
Rice	34	264	29	215	15	49	26	(D)	25	169	12	(D)
Roseau	1	(D)	1	(D)	1	(D)	2	(D)	-	-	2	(D)
St. Louis	46	66	40	51	22	15	34	(D)	25	(D)	23	28
Scott	34	108	34	87	14	21	24	236	18	(D)	13	(D)
Sherburne	27	(D)	21	29	13	(D)	8	(D)	8	17	5	(D)
Sibley	-	-	-	-	-	-	3	(D)	1	(D)	2	(D)
Stearns	34	(D)	24	63	22	(D)	24	163	20	151	7	12
Steele	4	26	4	(D)	2	(D)	8	(D)	6	(D)	4	18
Stevens	2	(D)	2	(D)	-	-	1	(D)	-	-	1	(D)
Swift	1	(D)	1	(D)	1	(D)	3	2	-	-	3	2
Todd	24	(D)	20	64	16	(D)	25	43	15	25	16	18
Traverse	2	(D)	2	(D)	-	-	2	(D)	2	(D)	1	(D)
Wabasha	17	378	16	331	6	48	16	(D)	12	317	8	(D)
Wadena	3	6	3	(D)	1	(D)	8	13	7	(D)	4	(D)
Waseca	7	28	6	(D)	2	(D)	1	(D)	1	(D)	-	-
Washington	46	(D)	32	261	33	(D)	53	384	44	327	26	57
Watonwan	3	1	3	1	3	(Z)	-	-	-	-	-	-
Wilkin	-	-	-	-	-	-	4	(D)	1	(D)	4	3
Winona	25	415	25	376	9	40	28	(D)	24	461	12	(D)

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
NONCITRUS, ALL - Con.												
Counties - Con.												
Wright	56	282	52	213	22	70	47	(D)	43	314	22	(D)
Yellow Medicine	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
APPLES												
State Total												
Minnesota	751	3,219	600	2,567	393	651	706	3,600	545	2,931	394	669
Counties												
Aitkin	8	24	7	(D)	5	(D)	8	11	8	(D)	8	(D)
Anoka	7	13	7	(D)	1	(D)	10	24	6	13	5	12
Becker	13	28	11	22	3	6	13	36	11	26	6	10
Beltrami	9	9	9	9	-	-	14	20	10	5	7	15
Benton	3	6	3	6	-	-	1	(D)	1	(D)	1	(D)
Big Stone	1	(D)	1	(D)	1	(D)	11	21	11	(D)	6	(D)
Blue Earth	13	6	-	-	13	6	11	35	7	27	10	9
Brown	4	(D)	4	(D)	-	-	5	(D)	5	(D)	5	(D)
Carlton	9	11	9	(D)	2	(D)	5	(D)	-	-	5	(D)
Carver	16	89	15	76	9	13	21	107	18	79	11	28
Cass	22	21	8	(D)	18	(D)	10	16	6	(D)	9	(D)
Chippewa	5	7	5	(D)	2	(D)	2	(D)	2	(D)	-	-
Chisago	23	112	20	62	15	50	39	83	28	51	18	32
Clay	13	4	3	1	10	3	-	-	-	-	-	-
Clearwater	-	-	-	-	-	-	4	(D)	2	(D)	2	(D)
Cook	2	(D)	2	(D)	-	-	9	4	9	4	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Crow Wing	7	7	7	4	6	3	6	5	3	(D)	4	(D)
Dakota	23	124	18	93	11	31	14	59	12	51	6	8
Dodge	7	8	7	(D)	5	(D)	4	(D)	4	(D)	-	-
Douglas	10	26	8	21	7	5	10	(D)	2	(D)	9	10
Fillmore	16	134	14	(D)	11	(D)	10	85	10	(D)	4	(D)
Freeborn	-	-	-	-	-	-	8	(D)	8	(D)	8	(D)
Goodhue	21	38	16	34	16	4	28	38	21	28	17	10
Hennepin	30	82	28	65	17	17	16	107	11	(D)	8	(D)
Houston	6	113	6	(D)	2	(D)	7	(D)	4	(D)	5	16
Hubbard	8	22	7	13	7	10	11	16	3	(D)	10	(D)
Isanti	19	29	19	26	6	3	12	13	12	10	7	3
Itasca	5	3	4	(D)	3	(D)	5	7	5	7	3	1
Kanabec	8	36	8	(D)	7	(D)	6	(D)	1	(D)	6	9
Kandiyohi	16	37	9	(D)	9	(D)	5	35	4	(D)	1	(D)
Koochiching	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Lac qui Parle	1	(D)	1	(D)	-	-	5	8	4	(D)	5	(D)
Lake	5	(D)	5	(D)	-	-	5	(D)	4	6	3	(D)
Lake of the Woods	2	(D)	2	(D)	2	(D)	-	-	-	-	-	-
Le Sueur	5	(D)	5	33	1	(D)	7	72	7	(D)	6	(D)
Lincoln	2	(D)	-	-	2	(D)	1	(D)	-	-	1	(D)
McLeod	8	19	7	16	4	3	12	31	8	22	6	9
Marshall	-	-	-	-	-	-	4	(D)	3	(D)	3	(D)
Martin	1	(D)	1	(D)	-	-	4	18	4	(D)	2	(D)
Meeker	17	(D)	10	23	10	(D)	10	9	10	(D)	4	(D)
Mille Lacs	6	31	6	(D)	2	(D)	17	43	11	24	8	19
Morrison	6	12	5	(D)	6	(D)	6	11	3	8	4	4
Mower	4	(D)	4	(D)	1	(D)	4	21	4	(D)	1	(D)
Nicollet	5	(D)	5	(D)	-	-	3	(D)	3	(D)	1	(D)
Nobles	2	(D)	2	(D)	1	(D)	7	69	7	49	6	21
Norman	2	(D)	-	-	2	(D)	1	(D)	1	(D)	-	-
Olmsted	30	102	27	92	10	11	22	84	15	75	12	8
Otter Tail	27	58	13	27	23	31	5	16	3	12	5	5
Pennington	11	23	9	(D)	2	(D)	3	(D)	2	(D)	1	(D)
Pine	20	40	11	21	14	19	13	22	10	(D)	7	(D)
Polk	4	(D)	4	3	2	(D)	4	(D)	3	(Z)	1	(D)
Pope	5	(D)	-	-	5	(D)	3	(D)	2	(D)	1	(D)
Ramsey	-	-	-	-	-	-	14	15	14	(D)	4	(D)
Red Lake	-	-	-	-	-	-	3	(D)	2	(D)	1	(D)
Redwood	6	9	6	8	4	1	5	10	5	7	4	3
Rice	16	228	13	185	8	44	18	179	18	154	10	26
Roseau	1	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)
St. Louis	39	42	34	30	13	11	27	43	21	22	19	21
Scott	30	87	30	77	5	10	14	214	14	(D)	6	(D)
Sherburne	22	31	21	(D)	2	(D)	8	26	8	(D)	5	(D)
Stearns	24	65	18	49	15	16	17	131	13	119	7	12
Steele	2	(D)	2	(D)	-	-	3	(D)	3	(D)	-	-
Swift	1	(D)	1	(D)	1	(D)	3	1	-	-	3	1
Todd	18	83	14	58	16	25	24	37	14	23	14	15
Wabasha	15	370	14	(D)	6	(D)	14	347	11	(D)	7	(D)
Wadena	3	(D)	3	5	1	(D)	8	8	7	(D)	4	(D)
Waseca	4	20	3	(D)	2	(D)	-	-	-	-	-	-
Washington	27	242	20	206	18	36	43	364	34	312	18	52
Watonwan	3	1	3	1	3	(Z)	-	-	-	-	-	-
Wilkin	-	-	-	-	-	-	4	2	1	(D)	4	(D)
Winona	16	347	16	314	5	33	19	414	16	403	9	11
Wright	35	230	27	168	20	62	35	346	31	288	16	58
Yellow Medicine	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
APRICOTS												
State Total												
Minnesota	22	(D)	13	3	11	(D)	22	11	10	5	19	7
Counties												
Anoka	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Becker	2	(D)	-	-	2	(D)	1	(D)	-	-	1	(D)
Brown	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Carver	1	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)
Chippewa	4	(D)	2	(D)	2	(D)	1	(D)	-	-	1	(D)
Chisago	1	(D)	1	(D)	-	-	2	(D)	1	(D)	2	(D)
Douglas	3	(D)	3	(D)	-	-	1	(D)	1	(D)	1	(D)
Goodhue	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Hennepin	5	(D)	3	1	2	(D)	-	-	-	-	-	-
Hubbard	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Lake	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Mille Lacs	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Ramsey	-	-	-	-	-	-	2	(D)	-	-	2	(D)
St. Louis	1	(D)	-	-	1	(D)	1	(D)	-	-	1	(D)
Stearns	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Todd	2	(D)	2	(D)	-	-	1	(D)	-	-	1	(D)
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Winona	1	(D)	1	(D)	1	(D)	3	6	3	3	3	3
CHERRIES, SWEET												
State Total												
Minnesota	52	12	22	6	33	6	24	15	9	3	19	12
Counties												
Anoka	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Blue Earth	4	(Z)	-	-	4	(Z)	-	-	-	-	-	-
Carver	1	(D)	1	(D)	1	(D)	2	(D)	2	(D)	2	(D)
Cass	4	(D)	-	-	4	(D)	-	-	-	-	-	-
Chippewa	2	(D)	-	-	2	(D)	3	1	3	1	-	-
Chisago	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Dakota	2	(D)	-	-	2	(D)	2	(D)	2	(D)	2	(D)
Fillmore	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Goodhue	1	(D)	1	(D)	1	(D)	7	1	-	-	7	1
Hennepin	3	(D)	1	(D)	2	(D)	-	-	-	-	-	-
Isanti	4	1	-	-	4	1	-	-	-	-	-	-
Itasca	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Lake of the Woods	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Mahnomen	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Norman	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Olmsted	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Pine	2	(D)	-	-	2	(D)	-	-	-	-	-	-
St. Louis	3	(D)	3	(D)	-	-	4	1	1	(D)	3	(D)
Sherburne	5	2	5	2	-	-	-	-	-	-	-	-
Stearns	6	1	1	(D)	6	(D)	-	-	-	-	-	-
Todd	3	2	3	2	-	-	1	(D)	1	(D)	-	-
Wright	3	(D)	3	(D)	-	-	-	-	-	-	-	-
CHERRIES, TART												
State Total												
Minnesota	123	54	77	42	58	12	103	40	65	26	49	14
Counties												
Aitkin	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Anoka	3	(D)	3	(D)	-	-	-	-	-	-	-	-
Beltrami	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Benton	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Blue Earth	4	(Z)	-	-	4	(Z)	-	-	-	-	-	-
Brown	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Carlton	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Carver	1	(D)	1	(D)	1	(D)	5	1	4	(D)	1	(D)
Cass	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Chippewa	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Chisago	2	(D)	-	-	2	(D)	6	1	5	(D)	1	(D)
Crow Wing	6	3	3	(Z)	3	3	1	(D)	1	(D)	1	(D)
Dakota	7	1	7	1	-	-	4	(D)	2	(D)	2	(D)
Dodge	4	(D)	-	-	4	(D)	-	-	-	-	-	-
Douglas	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Fillmore	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Goodhue	5	16	4	(D)	2	(D)	7	1	7	1	-	-
Hennepin	11	3	9	3	3	1	1	(D)	1	(D)	-	-
Hubbard	3	(D)	1	(D)	2	(D)	4	2	1	(D)	4	(D)
Isanti	3	1	3	(Z)	3	1	1	(D)	-	-	1	(D)
Itasca	3	(D)	3	(D)	1	(D)	1	(D)	1	(D)	1	(D)
Kandiyohi	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Lake	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Lake of the Woods	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Le Sueur	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	4	1	4	(D)	1	(D)	4	(D)	2	(D)	2	(D)
Meeker	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Mille Lacs	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
CHERRIES, TART - Con.												
Counties - Con.												
Morrison	3	(D)	2	(D)	1	(D)	3	(D)	-	-	3	(D)
Mower	2	(D)	2	(D)	-	-	6	(D)	6	(D)	-	-
Nicollet	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	5	(D)	1	(D)	4	(Z)	5	1	1	(D)	4	(D)
Otter Tail	1	(D)	1	(D)	-	-	8	10	5	10	3	1
Pine	6	(D)	3	(D)	4	(Z)	4	(D)	3	(D)	1	(D)
Ramsey	-	-	-	-	-	-	5	(D)	3	(D)	2	(D)
Rice	-	-	-	-	-	-	3	(D)	3	(D)	-	-
St. Louis	10	4	7	(D)	3	(D)	6	1	2	(D)	4	(D)
Scott	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Sibley	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Stearns	6	1	1	(D)	5	(D)	2	(D)	2	(D)	-	-
Swift	1	(D)	-	-	1	(D)	3	1	-	-	3	1
Todd	5	1	3	(D)	3	(D)	1	(D)	-	-	1	(D)
Wadena	-	-	-	-	-	-	2	(D)	1	(D)	2	(D)
Washington	9	4	9	(D)	2	(D)	2	(D)	1	(D)	2	(D)
Wilkin	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Winona	1	(D)	1	(D)	-	-	3	3	3	3	-	-
Wright	-	-	-	-	-	-	3	1	3	(D)	2	(D)
GRAPES (INCLUDE MUSCADINE) (SEE TEXT)												
State Total												
Minnesota	433	1,290	361	1,045	173	246	327	816	261	657	138	160
Counties												
Aitkin	5	(D)	2	(D)	3	(Z)	2	(D)	2	(D)	-	-
Anoka	6	10	6	(D)	2	(D)	5	6	2	(D)	3	(D)
Becker	11	(D)	9	5	8	(D)	8	7	3	(D)	7	(D)
Beltrami	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Benton	4	6	4	6	-	-	-	-	-	-	-	-
Big Stone	1	(D)	1	(D)	1	(D)	3	(D)	3	(D)	2	(D)
Blue Earth	20	65	19	50	8	15	23	59	23	50	11	10
Brown	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Carlton	2	(D)	2	(D)	2	(D)	3	12	3	(D)	1	(D)
Carver	9	(D)	9	(D)	2	(D)	11	36	7	30	7	7
Cass	1	(D)	-	-	1	(D)	3	(D)	3	(D)	-	-
Chippewa	8	36	6	30	6	7	1	(D)	1	(D)	-	-
Chisago	20	65	12	56	12	9	20	71	13	53	12	18
Clay	10	10	4	8	6	2	3	(D)	-	-	3	(D)
Clearwater	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Cottonwood	4	4	4	4	-	-	4	(D)	4	(D)	-	-
Crow Wing	5	6	5	6	-	-	4	(D)	4	(D)	-	-
Dakota	19	66	17	38	6	28	4	34	4	(D)	2	(D)
Douglas	14	71	14	61	7	9	4	33	4	(D)	4	(D)
Faribault	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Fillmore	9	(D)	9	(D)	2	(D)	10	21	10	(D)	1	(D)
Freeborn	4	12	4	12	-	-	1	(D)	1	(D)	1	(D)
Goodhue	18	101	14	83	10	17	20	65	14	54	7	11
Grant	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)	-	-
Hennepin	15	16	13	(D)	2	(D)	6	8	6	8	-	-
Houston	4	8	4	8	-	-	3	3	3	3	-	-
Hubbard	3	(D)	3	(D)	-	-	1	(D)	-	-	1	(D)
Isanti	12	36	12	31	8	5	2	(D)	2	(D)	2	(D)
Itasca	4	(D)	4	(D)	2	(D)	2	(D)	2	(D)	-	-
Jackson	2	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Kanabec	2	(D)	2	(D)	2	(D)	1	(D)	1	(D)	-	-
Kandiyohi	3	(D)	2	(D)	3	(D)	1	(D)	-	-	1	(D)
Lac qui Parle	2	(D)	2	(D)	1	(D)	3	(D)	3	(D)	1	(D)
Lake	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Le Sueur	5	3	5	3	-	-	7	(D)	7	(D)	3	(D)
Lincoln	6	(D)	6	42	3	(D)	1	(D)	1	(D)	-	-
Lyon	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
McLeod	3	(D)	3	(D)	-	-	5	(D)	3	(D)	5	5
Martin	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Meeker	9	28	9	25	5	4	7	15	7	14	3	1
Mille Lacs	6	(D)	6	5	2	(D)	3	(D)	3	(D)	-	-
Morrison	5	6	4	(D)	1	(D)	4	6	3	(D)	1	(D)
Mower	6	16	5	(D)	1	(D)	2	(D)	2	(D)	1	(D)
Murray	2	(D)	2	(D)	-	-	5	4	5	4	-	-
Nobles	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	7	22	7	(D)	1	(D)	12	15	11	(D)	3	(D)
Otter Tail	8	23	6	17	7	6	16	19	9	10	10	9
Pine	10	4	3	3	7	1	5	1	5	(D)	2	(D)
Pipestone	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Polk	1	(D)	1	(D)	-	-	5	(D)	5	(D)	1	(D)
Pope	1	(D)	1	(D)	1	(D)	2	(D)	-	-	2	(D)
Ramsey	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Redwood	4	4	4	4	-	-	-	-	-	-	-	-
Renville	8	16	8	16	-	-	3	(D)	3	(D)	1	(D)
Rice	21	(D)	19	27	7	(D)	9	14	8	(D)	2	(D)
Roseau	-	-	-	-	-	-	1	(D)	-	-	1	(D)
St. Louis	9	2	6	(D)	3	(D)	7	2	7	(D)	2	(D)
Scott	3	10	3	(D)	3	(D)	10	(D)	4	16	6	(D)
Sherburne	11	4	-	-	11	4	1	(D)	1	(D)	-	-
Sibley	-	-	-	-	-	-	1	(D)	1	(D)	-	-

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
GRAPES (INCLUDE MUSCADINE) (SEE TEXT) - Con.												
Counties - Con.												
Stearns	8	13	8	12	3	1	7	(D)	7	(D)	-	-
Steele	2	(D)	2	(D)	2	(D)	5	22	3	4	4	18
Stevens	2	(D)	2	(D)	-	-	1	(D)	-	-	1	(D)
Todd	1	(D)	1	(D)	-	-	2	(D)	1	(D)	2	(D)
Traverse	2	(D)	2	(D)	-	-	2	(D)	2	(D)	1	(D)
Wabasha	5	8	5	(D)	1	(D)	3	(D)	2	(D)	1	(D)
Wadena	1	(D)	1	(D)	-	-	2	(D)	1	(D)	1	(D)
Waseca	3	9	3	9	-	-	1	(D)	1	(D)	-	-
Washington	21	120	10	42	12	78	14	19	13	(D)	6	(D)
Wilkin	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Winona	12	64	12	(D)	5	(D)	9	60	8	50	4	10
Wright	26	40	26	(D)	1	(D)	16	23	14	22	4	1
KIWIFRUIT												
State Total												
Minnesota	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Counties												
Fillmore	1	(D)	-	-	1	(D)	-	-	-	-	-	-
PEACHES, ALL												
State Total												
Minnesota	17	(D)	5	1	13	(D)	19	3	2	(D)	17	(D)
Counties												
Carver	1	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)
Chippewa	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Chisago	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Douglas	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Fillmore	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Goodhue	1	(D)	-	-	1	(D)	6	1	-	-	6	1
Hennepin	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	1	(D)	-	-	1	(D)
McLeod	1	(D)	1	(D)	-	-	2	(D)	-	-	2	(D)
Meeker	-	-	-	-	-	-	3	1	-	-	3	1
Scott	4	(D)	-	-	4	(D)	-	-	-	-	-	-
Washington	2	(D)	-	-	2	(D)	3	(D)	-	-	3	(D)
Winona	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
PEACHES, CLINGSTONE												
State Total												
Minnesota	10	(D)	4	(D)	7	(D)	6	1	2	(D)	4	(D)
Counties												
Carver	1	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)
Chisago	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Fillmore	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Hennepin	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Scott	3	1	-	-	3	1	-	-	-	-	-	-
Washington	-	-	-	-	-	-	3	(D)	-	-	3	(D)
Winona	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
PEACHES, FREESTONE												
State Total												
Minnesota	11	(D)	2	(D)	9	(D)	13	2	-	-	13	2
Counties												
Chippewa	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Chisago	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Douglas	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Fillmore	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Goodhue	1	(D)	-	-	1	(D)	6	1	-	-	6	1
Hennepin	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	1	(D)	-	-	1	(D)
McLeod	1	(D)	1	(D)	-	-	2	(D)	-	-	2	(D)
Meeker	-	-	-	-	-	-	3	1	-	-	3	1
Scott	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Washington	2	(D)	-	-	2	(D)	-	-	-	-	-	-
PEARS, ALL												
State Total												
Minnesota	156	70	93	32	100	37	91	36	47	20	50	16
Counties												
Anoka	1	(D)	1	(D)	1	(D)	2	(D)	1	(D)	1	(D)
Becker	2	(D)	-	-	2	(D)	1	(D)	-	-	1	(D)
Big Stone	1	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
PEARS, ALL - Con.												
Counties - Con.												
Blue Earth	12	3	4	(Z)	12	3	-	-	-	-	-	-
Brown	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Carver	2	(D)	2	(D)	1	(D)	1	(D)	-	-	1	(D)
Chippewa	2	(D)	2	(D)	-	-	1	(D)	-	-	1	(D)
Chisago	7	6	4	4	3	2	7	1	7	(D)	1	(D)
Crow Wing	3	(Z)	3	(Z)	-	-	3	(D)	-	-	3	(D)
Dakota	7	1	4	(D)	3	(D)	1	(D)	1	(D)	-	-
Dodge	2	(D)	1	(D)	2	(D)	-	-	-	-	-	-
Douglas	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Fillmore	1	(D)	-	-	1	(D)	2	(D)	2	(D)	-	-
Freeborn	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Goodhue	2	(D)	2	(D)	-	-	7	1	-	-	7	1
Hennepin	7	4	5	(D)	3	(D)	2	(D)	2	(D)	-	-
Hubbard	-	-	-	-	-	-	2	(D)	1	(D)	2	(D)
Isanti	4	(D)	-	-	4	(D)	2	(D)	-	-	2	(D)
Itasca	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Kanabec	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Kandiyohi	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Lac qui Parle	1	(D)	1	(D)	-	-	4	(D)	4	(D)	-	-
Lake	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Le Sueur	2	(D)	2	(D)	1	(D)	-	-	-	-	-	-
McLeod	6	5	6	(D)	6	(D)	9	2	3	1	7	1
Mille Lacs	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Morrison	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Mower	4	2	3	(D)	1	(D)	3	(D)	3	(D)	-	-
Olmsted	3	(D)	1	(D)	2	(D)	4	(D)	-	-	4	(D)
Otter Tail	8	4	4	(D)	8	(D)	1	(D)	-	-	1	(D)
Pine	5	3	1	(D)	4	(D)	1	(D)	-	-	1	(D)
Rice	3	(D)	3	(D)	-	-	1	(D)	1	(D)	-	-
St. Louis	12	5	4	3	8	2	8	3	2	(D)	8	(D)
Scott	8	(D)	3	(D)	6	3	4	(D)	3	1	1	(D)
Stearns	11	1	4	(D)	8	(D)	2	(D)	2	(D)	-	-
Todd	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Wadena	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Washington	13	8	12	(D)	6	(D)	4	(D)	1	(D)	3	(D)
Winona	5	1	5	1	-	-	6	(D)	6	(D)	-	-
Wright	14	9	12	4	12	5	2	(D)	2	(D)	-	-
PEARS, BARTLETT												
State Total												
Minnesota	45	14	20	7	27	8	11	2	7	1	4	(Z)
Counties												
Blue Earth	12	3	4	(Z)	8	2	-	-	-	-	-	-
Carver	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Chippewa	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Crow Wing	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Dodge	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Douglas	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Fillmore	1	(D)	-	-	1	(D)	2	(D)	2	(D)	-	-
Goodhue	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Hennepin	3	(D)	1	(D)	3	(D)	-	-	-	-	-	-
Lac qui Parle	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Mower	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Otter Tail	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Pine	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Rice	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Scott	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	4	(Z)	-	-	4	(Z)	-	-	-	-	-	-
Washington	6	5	3	3	4	2	1	(D)	1	(D)	-	-
Winona	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Wright	5	1	5	1	-	-	2	(D)	2	(D)	-	-
PEARS, OTHER THAN BARTLETT												
State Total												
Minnesota	127	56	74	26	80	30	84	34	42	18	48	16
Counties												
Anoka	1	(D)	1	(D)	1	(D)	2	(D)	1	(D)	1	(D)
Becker	2	(D)	-	-	2	(D)	1	(D)	-	-	1	(D)
Big Stone	1	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)
Blue Earth	4	(Z)	-	-	4	(Z)	-	-	-	-	-	-
Brown	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Carver	2	(D)	2	(D)	1	(D)	1	(D)	-	-	1	(D)
Chippewa	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Chisago	7	6	4	4	3	2	7	1	7	(D)	1	(D)
Crow Wing	3	(Z)	3	(Z)	-	-	1	(D)	-	-	1	(D)
Dakota	7	1	4	(D)	3	(D)	1	(D)	1	(D)	-	-
Dodge	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Fillmore	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Freeborn	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Goodhue	2	(D)	2	(D)	-	-	7	(D)	-	-	7	(D)
Hennepin	6	(D)	4	(D)	2	(D)	2	(D)	2	(D)	-	-
Hubbard	-	-	-	-	-	-	2	(D)	1	(D)	2	(D)

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
PEARS, OTHER THAN BARTLETT - Con.												
Counties - Con.												
Isanti	4	(D)	-	-	4	(D)	2	(D)	-	-	2	(D)
Itasca	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Kanabec	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Kandiyohi	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Lac qui Parle	-	-	-	-	-	-	4	(D)	4	(D)	-	-
Lake	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Le Sueur	2	(D)	2	(D)	1	(D)	-	-	-	-	-	-
McLeod	6	5	6	(D)	6	(D)	9	2	3	1	7	1
Mille Lacs	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Morrison	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Mower	3	(D)	3	(D)	-	-	3	(D)	3	(D)	-	-
Olmsted	3	(D)	1	(D)	2	(D)	4	(D)	-	-	4	(D)
Otter Tail	8	(D)	4	(D)	8	(D)	1	(D)	-	-	1	(D)
Pine	3	(D)	1	(D)	2	(D)	1	(D)	-	-	1	(D)
Rice	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
St. Louis	12	5	4	3	8	2	8	3	2	(D)	8	(D)
Scott	7	(D)	2	(D)	6	3	4	(D)	3	1	1	(D)
Stearns	7	1	4	(D)	4	(D)	2	(D)	2	(D)	-	-
Todd	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Wadena	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Washington	9	3	9	(D)	4	(D)	3	(D)	-	-	3	(D)
Winona	3	(D)	3	(D)	-	-	4	(D)	4	(D)	-	-
Wright	14	8	8	3	12	5	2	(D)	2	(D)	-	-
PERSIMMONS												
State Total												
Minnesota	6	3	-	-	6	3	-	-	-	-	-	-
Counties												
Scott	3	(D)	-	-	3	(D)	-	-	-	-	-	-
Todd	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Wright	2	(D)	-	-	2	(D)	-	-	-	-	-	-
PLUMS AND PRUNES												
State Total												
Minnesota	150	64	93	42	90	22	135	48	80	28	69	19
Counties												
Aitkin	3	(D)	2	(D)	2	(D)	5	(D)	5	(D)	-	-
Anoka	-	-	-	-	-	-	3	(D)	2	(D)	1	(D)
Becker	-	-	-	-	-	-	3	(D)	2	(D)	1	(D)
Beltrami	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Blue Earth	4	(Z)	-	-	4	(Z)	-	-	-	-	-	-
Brown	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Carlton	4	(D)	4	(D)	-	-	-	-	-	-	-	-
Carver	2	(D)	2	(D)	2	(D)	1	(D)	-	-	1	(D)
Cass	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Chippewa	4	1	-	-	4	1	4	(Z)	1	(D)	3	(D)
Chisago	5	3	2	(D)	3	(D)	14	3	13	(D)	2	(D)
Clay	-	-	-	-	-	-	4	(D)	4	(D)	1	(D)
Crow Wing	6	1	3	(Z)	3	1	1	(D)	1	(D)	-	-
Dakota	5	1	2	(D)	3	(D)	-	-	-	-	-	-
Dodge	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Douglas	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Fillmore	-	-	-	-	-	-	3	(D)	1	(D)	2	(D)
Freeborn	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Goodhue	6	4	6	3	6	1	7	3	6	1	7	1
Hennepin	6	2	4	2	3	(Z)	1	(D)	1	(D)	1	(D)
Hubbard	-	-	-	-	-	-	3	(D)	-	-	3	(D)
Isanti	13	4	9	3	11	1	3	(D)	3	(D)	-	-
Itasca	2	(D)	2	(D)	-	-	8	1	2	(D)	6	(D)
Kanabec	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Kandiyohi	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Lake	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Le Sueur	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
McLeod	6	1	6	(D)	2	(D)	5	1	1	(D)	5	(D)
Marshall	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Meeker	-	-	-	-	-	-	5	(D)	2	(D)	3	(D)
Mille Lacs	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Morrison	1	(D)	-	-	1	(D)	2	(D)	2	(D)	-	-
Mower	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Nicollet	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Olmsted	6	3	1	(D)	5	(D)	6	1	-	-	6	1
Otter Tail	7	4	5	(D)	6	(D)	3	1	-	-	3	1
Pennington	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Pine	1	(D)	1	(D)	-	-	4	2	4	2	-	-
Ramsey	-	-	-	-	-	-	6	2	6	2	-	-
Red Lake	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Rice	4	2	4	(D)	1	(D)	2	(D)	2	(D)	-	-
Roseau	-	-	-	-	-	-	1	(D)	-	-	1	(D)
St. Louis	5	(D)	3	(D)	3	(Z)	8	5	3	1	7	4
Scott	1	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
PLUMS AND PRUNES - Con.												
Counties - Con.												
Sherburne	5	(D)	5	(D)	-	-	-	-	-	-	-	-
Stearns	15	2	3	1	12	1	2	(D)	2	(D)	-	-
Todd	11	3	7	2	5	1	4	1	3	(D)	1	(D)
Wadena	1	(D)	1	(D)	1	(D)	2	(D)	2	(D)	-	-
Washington	6	9	5	5	6	4	1	(D)	-	-	1	(D)
Wilkin	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Winona	2	(D)	2	(D)	-	-	3	(D)	1	(D)	2	(D)
Wright	6	1	2	(D)	4	(D)	5	1	3	1	4	(Z)
PLUMS												
State Total												
Minnesota	150	64	93	42	90	22	134	(D)	79	(D)	68	(D)
Counties												
Aitkin	3	(D)	2	(D)	2	(D)	5	(D)	5	(D)	-	-
Anoka	-	-	-	-	-	-	3	(D)	2	(D)	1	(D)
Becker	-	-	-	-	-	-	3	(D)	2	(D)	1	(D)
Beltrami	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Blue Earth	4	(Z)	-	-	4	(Z)	-	-	-	-	-	-
Brown	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Carlton	4	(D)	4	(D)	-	-	-	-	-	-	-	-
Carver	2	(D)	2	(D)	2	(D)	1	(D)	-	-	1	(D)
Cass	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Chippewa	4	1	-	-	4	1	4	(Z)	1	(D)	3	(D)
Chisago	5	3	2	(D)	3	(D)	14	3	13	(D)	2	(D)
Clay	-	-	-	-	-	-	4	(D)	4	(D)	1	(D)
Crow Wing	6	1	3	(Z)	3	1	1	(D)	1	(D)	-	-
Dakota	5	1	2	(D)	3	(D)	-	-	-	-	-	-
Dodge	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Douglas	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Fillmore	-	-	-	-	-	-	3	(D)	1	(D)	2	(D)
Freeborn	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Goodhue	6	4	6	3	6	1	7	3	6	1	7	1
Hennepin	6	2	4	2	3	(Z)	-	-	-	-	-	-
Hubbard	-	-	-	-	-	-	3	(D)	-	-	3	(D)
Isanti	13	4	9	3	11	1	3	(D)	3	(D)	-	-
Itasca	2	(D)	2	(D)	-	-	8	1	2	(D)	6	(D)
Kanabec	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Kandiyohi	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Lake	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Le Sueur	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
McLeod	6	1	6	(D)	2	(D)	5	1	1	(D)	5	(D)
Marshall	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Meeker	-	-	-	-	-	-	5	(D)	2	(D)	3	(D)
Mille Lacs	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Morrison	1	(D)	-	-	1	(D)	2	(D)	2	(D)	-	-
Mower	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Nicollet	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Olmsted	6	3	1	(D)	5	(D)	6	1	-	-	6	1
Otter Tail	7	4	5	(D)	6	(D)	3	1	-	-	3	1
Pennington	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Pine	1	(D)	1	(D)	-	-	4	2	4	2	-	-
Ramsey	-	-	-	-	-	-	6	2	6	2	-	-
Red Lake	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Rice	4	2	4	(D)	1	(D)	2	(D)	2	(D)	-	-
Roseau	-	-	-	-	-	-	1	(D)	-	-	1	(D)
St. Louis	5	(D)	3	(D)	3	(Z)	8	5	3	1	7	4
Scott	1	(D)	1	(D)	1	(D)	1	(D)	-	-	1	(D)
Sherburne	5	(D)	5	(D)	-	-	-	-	-	-	-	-
Stearns	15	2	3	1	12	1	2	(D)	2	(D)	-	-
Todd	11	3	7	2	5	1	4	1	3	(D)	1	(D)
Wadena	1	(D)	1	(D)	1	(D)	2	(D)	2	(D)	-	-
Washington	6	9	5	5	6	4	1	(D)	-	-	1	(D)
Wilkin	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Winona	2	(D)	2	(D)	-	-	3	(D)	1	(D)	2	(D)
Wright	6	1	2	(D)	4	(D)	5	1	3	1	4	(Z)
PRUNES												
State Total												
Minnesota	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Counties												
Hennepin	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
OTHER NONCITRUS FRUIT (SEE TEXT)												
State Total												
Minnesota	20	5	5	2	16	3	10	21	8	(D)	4	(D)

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
OTHER NONCITRUS FRUIT (SEE TEXT) - Con.												
Counties												
Aitkin	-	-	-	-	-	-	3	(D)	2	(D)	3	(D)
Becker	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Beltrami	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Clay	6	1	-	-	6	1	-	-	-	-	-	-
Goodhue	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Hennepin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
McLeod	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Otter Tail	1	(D)	1	(D)	-	-	1	(D)	-	-	1	(D)
Rice	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Sherburne	4	(D)	-	-	4	(D)	-	-	-	-	-	-
Stearns	5	1	-	-	5	1	2	(D)	2	(D)	-	-
NUTS, ALL												
State Total												
Minnesota	109	325	55	102	72	223	65	177	28	119	49	58
Counties												
Aitkin	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Beltrami	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Carver	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Cass	3	1	3	1	-	-	-	-	-	-	-	-
Chippewa	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Chisago	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Crow Wing	8	8	5	5	8	4	-	-	-	-	-	-
Dakota	3	(D)	-	-	3	(D)	2	(D)	-	-	2	(D)
Fillmore	8	3	8	(D)	2	(D)	8	37	6	30	6	7
Freeborn	5	10	5	10	-	-	-	-	-	-	-	-
Goodhue	2	(D)	2	(D)	2	(D)	1	(D)	-	-	1	(D)
Hennepin	4	(D)	2	(D)	2	(D)	-	-	-	-	-	-
Houston	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hubbard	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Isanti	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Itasca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Kanabec	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Kandiyohi	-	-	-	-	-	-	2	(D)	-	-	2	(D)
McLeod	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Meeker	2	(D)	2	(D)	-	-	5	2	2	(D)	3	(D)
Mille Lacs	3	15	-	-	3	15	-	-	-	-	-	-
Mower	3	(D)	-	-	3	(D)	6	46	4	(D)	6	(D)
Norman	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Olmsted	11	12	6	6	8	5	9	24	4	17	6	7
Otter Tail	1	(D)	-	-	1	(D)	1	(D)	-	-	1	(D)
Pine	8	5	2	(D)	7	(D)	-	-	-	-	-	-
Rice	3	12	-	-	3	12	1	(D)	1	(D)	-	-
St. Louis	4	1	4	(D)	1	(D)	2	(D)	-	-	2	(D)
Scott	4	2	-	-	4	2	-	-	-	-	-	-
Sherburne	2	(D)	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Steele	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Todd	2	(D)	2	(D)	2	(D)	-	-	-	-	-	-
Wabasha	7	75	4	40	3	36	2	(D)	2	(D)	-	-
Washington	1	(D)	1	(D)	-	-	7	18	1	(D)	7	(D)
Watonwan	3	1	3	1	-	-	1	(D)	1	(D)	-	-
Wilkin	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Winona	10	86	1	(D)	10	(D)	1	(D)	1	(D)	1	(D)
Wright	-	-	-	-	-	-	2	(D)	-	-	2	(D)
CHESTNUTS												
State Total												
Minnesota	24	(D)	5	(D)	21	54	8	(D)	1	(D)	8	4
Counties												
Carver	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Fillmore	-	-	-	-	-	-	3	(D)	1	(D)	3	(D)
Goodhue	2	(D)	2	(D)	2	(D)	-	-	-	-	-	-
Hennepin	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Mower	2	(D)	-	-	2	(D)	2	(D)	-	-	2	(D)
Olmsted	3	(D)	-	-	3	(D)	2	(D)	-	-	2	(D)
Pine	6	(D)	-	-	6	(D)	-	-	-	-	-	-
Scott	3	(D)	-	-	3	(D)	-	-	-	-	-	-
Todd	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Wabasha	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Watonwan	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
HAZELNUTS (FILBERTS)												
State Total												
Minnesota	63	123	43	(D)	31	(D)	47	131	18	99	36	32

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
HAZELNUTS (FILBERTS) - Con.												
Counties												
Aitkin	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Carver	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Cass	3	1	3	1	-	-	-	-	-	-	-	-
Chippewa	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Chisago	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Crow Wing	8	8	5	5	8	4	-	-	-	-	-	-
Dakota	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Fillmore	8	3	8	(D)	2	(D)	8	(D)	6	(D)	6	(D)
Freeborn	5	10	5	10	-	-	-	-	-	-	-	-
Goodhue	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Hennepin	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Houston	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hubbard	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Kanabec	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Kandiyohi	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Meeker	2	(D)	2	(D)	-	-	4	(D)	2	(D)	2	(D)
Mille Lacs	3	15	-	-	3	15	-	-	-	-	-	-
Mower	3	(D)	-	-	3	(D)	4	(D)	2	(D)	4	(D)
Olmsted	7	(D)	4	(D)	4	(D)	8	21	3	(D)	6	(D)
Otter Tail	1	(D)	-	-	1	(D)	-	-	-	-	-	-
St. Louis	4	1	4	(D)	1	(D)	2	(D)	-	-	2	(D)
Sherburne	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Stearns	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Steele	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Todd	2	(D)	2	(D)	1	(D)	-	-	-	-	-	-
Wabasha	4	(D)	3	(D)	1	(D)	2	(D)	2	(D)	-	-
Washington	-	-	-	-	-	-	6	(D)	-	-	6	(D)
Watonwan	3	(Z)	3	(Z)	-	-	1	(D)	1	(D)	-	-
Wilkin	-	-	-	-	-	-	1	(D)	-	-	1	(D)
PECANS, ALL												
State Total												
Minnesota	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Counties												
Olmsted	-	-	-	-	-	-	2	(D)	-	-	2	(D)
PECANS, IMPROVED												
State Total												
Minnesota	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Counties												
Olmsted	-	-	-	-	-	-	2	(D)	-	-	2	(D)
WALNUTS, ENGLISH												
State Total												
Minnesota	29	142	8	26	24	115	14	26	7	7	10	19
Counties												
Beltrami	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Chisago	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Dakota	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Isanti	1	(D)	-	-	1	(D)	2	(D)	-	-	2	(D)
Itasca	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Mower	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Norman	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Olmsted	4	6	2	(D)	4	(D)	2	(D)	-	-	2	(D)
Otter Tail	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Rice	3	12	-	-	3	12	-	-	-	-	-	-
Scott	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Sherburne	1	(D)	1	(D)	-	-	1	(D)	1	(D)	1	(D)
Sibley	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Stearns	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Wabasha	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Washington	1	(D)	1	(D)	-	-	1	(D)	1	(D)	1	(D)
Watonwan	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Winona	10	86	1	(D)	10	(D)	1	(D)	1	(D)	1	(D)
OTHER NUTS												
State Total												
Minnesota	2	(D)	2	(D)	1	(D)	15	(D)	6	(D)	12	(D)
Counties												
Chisago	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Fillmore	-	-	-	-	-	-	3	(D)	1	(D)	3	1
McLeod	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Meeker	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Mower	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Olmsted	-	-	-	-	-	-	3	(D)	1	(D)	2	(D)

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Table 31. **Fruits and Nuts: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age acres		Nonbearing age acres		Total		Bearing age acres		Nonbearing age acres	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
OTHER NUTS - Con.												
Counties - Con.												
Pine	2	(D)	2	(D)	1	(D)	-	-	-	-	-	-
Rice	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Wright	-	-	-	-	-	-	2	(D)	-	-	2	(D)

Table 32. **Land in Berries: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022				2017			
	Total		Irrigated		Total		Irrigated	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
State Total								
Minnesota	578	1,129	185	426	638	1,002	196	440
Counties								
Aitkin	4	(D)	3	(D)	11	66	2	(D)
Anoka	8	28	3	18	10	16	5	10
Becker	8	4	-	-	5	4	1	(D)
Beltrami	10	8	3	(D)	17	17	2	(D)
Benton	2	(D)	2	(D)	2	(D)	1	(D)
Big Stone	1	(D)	-	-	-	-	-	-
Blue Earth	9	5	-	-	13	2	-	-
Brown	4	1	-	-	5	5	-	-
Carlton	14	138	8	14	15	36	5	(D)
Carver	3	(D)	2	(D)	7	17	2	(D)
Cass	10	12	7	6	8	8	5	7
Chippewa	6	2	-	-	5	2	-	-
Chisago	16	15	4	7	20	23	8	9
Clay	9	2	-	-	6	3	-	-
Clearwater	3	(D)	3	(D)	5	(D)	1	(D)
Cook	6	(D)	2	(D)	3	(D)	2	(D)
Cottonwood	3	(D)	-	-	5	12	2	(D)
Crow Wing	17	16	3	4	8	10	4	3
Dakota	25	51	15	31	14	54	10	47
Dodge	9	9	-	-	4	8	-	-
Douglas	13	36	3	(D)	11	8	3	6
Fillmore	17	12	3	2	21	7	3	1
Freeborn	5	4	-	-	9	8	2	(D)
Goodhue	6	10	2	(D)	15	6	7	2
Grant	-	-	-	-	2	(D)	2	(D)
Hennepin	29	24	13	7	13	43	8	8
Houston	-	-	-	-	8	33	-	-
Hubbard	11	(D)	10	(D)	10	18	3	13
Isanti	32	33	2	(D)	14	18	12	(D)
Itasca	8	6	6	(D)	13	10	7	4
Jackson	-	-	-	-	6	1	-	-
Kanabec	9	(D)	1	(D)	7	(D)	2	(D)
Kandiyohi	2	(D)	1	(D)	4	(D)	1	(D)
Koochiching	4	4	2	(D)	3	(D)	2	(D)
Lac qui Parle	2	(D)	-	-	5	2	-	-
Lake	2	(D)	-	-	-	-	-	-
Lake of the Woods	2	(D)	-	-	1	(D)	-	-
Le Sueur	-	-	-	-	3	5	3	5
Lincoln	2	(D)	-	-	-	-	-	-
McLeod	10	20	5	17	6	24	3	(D)
Mahnomen	-	-	-	-	2	(D)	-	-
Marshall	-	-	-	-	3	(D)	-	-
Martin	1	(D)	-	-	-	-	-	-
Meeker	7	7	5	(D)	9	28	3	2
Mille Lacs	3	(D)	1	(D)	13	12	9	9
Morrison	3	(D)	1	(D)	5	3	2	(D)
Mower	5	5	-	-	10	1	6	1
Murray	-	-	-	-	3	(Z)	-	-
Nicollet	8	1	4	1	3	(D)	-	-
Nobles	1	(D)	-	-	2	(D)	-	-
Norman	2	(D)	-	-	1	(D)	1	(D)
Olmsted	25	19	1	(D)	30	42	1	(D)
Otter Tail	9	16	2	(D)	13	18	2	(D)
Pennington	1	(D)	-	-	2	(D)	-	-
Pine	12	17	2	(D)	15	8	3	(D)
Pipestone	1	(D)	1	(D)	-	-	-	-
Polk	4	3	-	-	8	(D)	2	(D)
Pope	5	(D)	1	(D)	5	5	3	(D)
Ramsey	11	(D)	9	(D)	7	2	3	(Z)
Redwood	2	(D)	2	(D)	4	17	2	(D)
Renville	-	-	-	-	1	(D)	1	(D)
Rice	13	26	2	(D)	4	21	2	(D)
Roseau	-	-	-	-	2	(D)	-	-
St. Louis	31	37	6	6	33	40	9	8
Scott	4	1	-	-	8	6	1	(D)
Sherburne	21	18	9	4	7	15	3	8
Sibley	-	-	-	-	3	(D)	-	-
Stearns	22	26	13	19	12	17	6	7
Steele	-	-	-	-	6	10	-	-
Stevens	2	(D)	2	(D)	-	-	-	-
Swift	1	(D)	-	-	5	2	-	-
Todd	10	(D)	1	(D)	11	6	-	-
Wabasha	4	4	1	(D)	5	2	2	(D)
Wadena	2	(D)	-	-	11	16	2	(D)
Waseca	3	1	-	-	2	(D)	-	-
Washington	20	99	15	88	43	100	13	77
Watonwan	3	2	-	-	-	-	-	-
Wilkin	-	-	-	-	2	(D)	-	-
Winona	13	15	2	(D)	16	18	1	(D)
Wright	8	(D)	2	(D)	17	36	11	34
Yellow Medicine	-	-	-	-	1	(D)	-	-

Table 33. **Berries: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age		Nonbearing age		Total		Bearing age		Nonbearing age	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
ARONIA BERRIES												
State Total												
Minnesota	49	30	44	26	11	4	65	93	52	46	36	47
Counties												
Aitkin	-	-	-	-	-	-	3	2	-	-	3	2
Beltrami	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Brown	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Carver	1	(D)	1	(D)	-	-	1	(D)	-	-	1	(D)
Chippewa	2	(D)	2	(D)	-	-	3	(D)	3	(D)	3	1
Chisago	2	(D)	2	(D)	-	-	1	(D)	1	(D)	1	(D)
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	3	2	3	(Z)	3	1	1	(D)	-	-	1	(D)
Dakota	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Douglas	4	(D)	4	(D)	-	-	2	(D)	2	(D)	-	-
Fillmore	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Freeborn	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Houston	-	-	-	-	-	-	7	(D)	7	15	7	(D)
Hubbard	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Isanti	4	(Z)	4	(Z)	-	-	1	(D)	-	-	1	(D)
Jackson	-	-	-	-	-	-	6	1	6	1	-	-
Kandiyohi	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Koochiching	2	(D)	2	(D)	2	(D)	-	-	-	-	-	-
McLeod	1	(D)	1	(D)	-	-	1	(D)	-	-	1	(D)
Mahnomen	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Martin	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Meeker	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Mower	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Murray	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Nicollet	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Olmsted	5	3	3	(D)	2	(D)	7	1	4	(Z)	3	(Z)
Otter Tail	5	3	5	3	-	-	-	-	-	-	-	-
Pine	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Rice	1	(D)	1	(D)	-	-	-	-	-	-	-	-
St. Louis	3	(D)	2	(D)	1	(D)	3	(D)	3	(D)	-	-
Stearns	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Steele	-	-	-	-	-	-	3	9	3	9	-	-
Wadena	1	(D)	1	(D)	-	-	8	12	8	3	6	9
Waseca	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Winona	2	(D)	2	(D)	-	-	2	(D)	2	(D)	2	(D)
Wright	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
BLACKBERRIES AND DEWBERRIES (INCLUDING MARIONBERRIES)												
State Total												
Minnesota	33	13	22	9	16	4	23	37	19	(D)	7	(D)
Counties												
Big Stone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Carver	-	-	-	-	-	-	3	1	2	(D)	3	(D)
Cass	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Crow Wing	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Dakota	1	(D)	1	(D)	-	-	2	(D)	-	-	2	(D)
Fillmore	1	(D)	1	(D)	1	(D)	3	1	3	1	-	-
Hennepin	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Houston	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Isanti	3	(Z)	-	-	3	(Z)	1	(D)	1	(D)	-	-
McLeod	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Mower	2	(D)	2	(D)	2	(D)	-	-	-	-	-	-
Olmsted	1	(D)	1	(D)	-	-	2	(D)	1	(D)	1	(D)
Otter Tail	1	(D)	-	-	1	(D)	1	(D)	1	(D)	1	(D)
Pine	1	(D)	-	-	1	(D)	1	(D)	1	(D)	-	-
Polk	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Pope	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Rice	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Sherburne	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Stearns	9	(D)	5	1	4	(D)	-	-	-	-	-	-
Wabasha	3	(D)	3	(Z)	1	(D)	-	-	-	-	-	-
Washington	1	(D)	1	(D)	-	-	6	(D)	6	(D)	-	-
BLUEBERRIES, ALL												
State Total												
Minnesota	174	340	111	296	87	44	180	124	137	91	66	34
Counties												
Aitkin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Anoka	3	5	3	5	-	-	1	(D)	-	-	1	(D)
Becker	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Beltrami	3	3	3	3	-	-	6	(D)	6	(D)	-	-
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	1	(D)
Blue Earth	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Carlton	14	62	7	41	11	20	8	8	6	7	4	1
Carver	1	(D)	1	(D)	-	-	3	1	2	(D)	3	(D)
Cass	7	5	6	(D)	5	(D)	5	6	5	6	-	-
Chippewa	2	(D)	-	-	2	(D)	1	(D)	-	-	1	(D)

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Table 33. **Berries: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age		Nonbearing age		Total		Bearing age		Nonbearing age	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
BLUEBERRIES, ALL - Con.												
Counties - Con.												
Chisago	4	(D)	2	(D)	2	(D)	11	(D)	11	5	5	(D)
Clay	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Crow Wing	8	4	2	(D)	7	(D)	5	3	4	(D)	1	(D)
Dakota	13	17	13	(D)	1	(D)	6	10	4	6	3	5
Dodge	4	2	4	2	-	-	3	(D)	3	(D)	-	-
Douglas	4	10	4	10	-	-	1	(D)	1	(D)	1	(D)
Fillmore	3	(D)	1	(D)	3	1	4	(Z)	-	-	4	(Z)
Goodhue	2	(D)	2	(D)	2	(D)	8	(D)	1	(D)	7	(D)
Hennepin	9	2	4	1	5	1	2	(D)	2	(D)	-	-
Houston	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Hubbard	5	(D)	2	(D)	5	1	4	(D)	2	(D)	2	(D)
Isanti	9	3	-	-	9	3	3	(D)	2	(D)	1	(D)
Itasca	6	3	6	(D)	1	(D)	11	6	10	(D)	1	(D)
Koochiching	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	4	(Z)	-	-	4	(Z)
Lake	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	1	(D)	1	(D)	1	(D)	2	(D)	-	-	2	(D)
Mahnomen	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	-	-	1	(D)	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	1	(D)	1	(D)	10	9	10	(D)	1	(D)
Morrison	2	(D)	2	(D)	-	-	5	2	4	(D)	1	(D)
Norman	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Olmsted	3	2	1	(D)	3	(D)	4	(D)	3	1	1	(D)
Otter Tail	2	(D)	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)
Pine	10	(D)	4	(D)	8	(D)	6	1	4	(D)	2	(D)
Renville	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Rice	3	(D)	2	(D)	2	(D)	3	(D)	3	(D)	1	(D)
St. Louis	19	16	17	14	4	1	13	8	13	(D)	1	(D)
Scott	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Sherburne	5	(D)	5	(D)	-	-	5	(D)	5	(D)	-	-
Stearns	3	8	3	8	-	-	1	(D)	-	-	1	(D)
Todd	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Wabasha	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wadena	1	(D)	1	(D)	-	-	2	(D)	-	-	2	(D)
Waseca	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Washington	7	16	3	(D)	4	(D)	24	15	18	(D)	7	(D)
Winona	4	(D)	4	5	1	(D)	4	3	4	1	4	3
Wright	3	(D)	1	(D)	2	(D)	1	(D)	1	(D)	-	-
BLUEBERRIES, TAME												
State Total												
Minnesota	165	292	103	(D)	84	(D)	169	121	132	89	60	32
Counties												
Aitkin	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Anoka	3	5	3	5	-	-	1	(D)	-	-	1	(D)
Beltrami	3	3	3	3	-	-	6	(D)	6	(D)	-	-
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	1	(D)
Carlton	13	(D)	6	(D)	10	(D)	8	8	6	7	4	1
Carver	1	(D)	1	(D)	-	-	3	1	2	(D)	3	(D)
Cass	7	5	6	(D)	5	(D)	5	6	5	6	-	-
Chippewa	2	(D)	-	-	2	(D)	1	(D)	-	-	1	(D)
Chisago	4	(D)	2	(D)	2	(D)	11	(D)	11	5	5	(D)
Clay	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Crow Wing	8	3	2	(D)	7	(D)	5	3	4	(D)	1	(D)
Dakota	13	17	13	(D)	1	(D)	6	10	4	6	3	5
Dodge	4	2	4	2	-	-	3	(D)	3	(D)	-	-
Douglas	4	10	4	10	-	-	1	(D)	1	(D)	1	(D)
Fillmore	3	(D)	1	(D)	3	1	4	(Z)	-	-	4	(Z)
Goodhue	2	(D)	2	(D)	2	(D)	8	1	1	(D)	7	(D)
Hennepin	9	2	4	1	5	1	2	(D)	2	(D)	-	-
Houston	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Hubbard	5	(D)	2	(D)	5	1	4	(D)	2	(D)	2	(D)
Isanti	9	3	-	-	9	3	3	(D)	2	(D)	1	(D)
Itasca	6	3	6	(D)	1	(D)	11	6	10	(D)	1	(D)
Koochiching	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Lac qui Parle	-	-	-	-	-	-	4	(Z)	-	-	4	(Z)
Lake	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	1	(D)	1	(D)	1	(D)	2	(D)	-	-	2	(D)
Mahnomen	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Marshall	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Meeker	1	(D)	-	-	1	(D)	1	(D)	1	(D)	-	-
Mille Lacs	2	(D)	1	(D)	1	(D)	10	9	10	(D)	1	(D)
Morrison	2	(D)	2	(D)	-	-	5	(D)	4	(D)	1	(D)
Norman	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Olmsted	3	2	1	(D)	3	(D)	4	(D)	3	1	1	(D)
Otter Tail	2	(D)	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)
Pine	9	5	2	(D)	8	(D)	5	(D)	3	1	2	(D)
Renville	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Rice	3	(D)	2	(D)	2	(D)	3	(D)	3	(D)	1	(D)
St. Louis	16	11	14	10	4	1	9	(D)	9	(D)	1	(D)
Scott	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Sherburne	5	(D)	5	(D)	-	-	5	(D)	5	(D)	-	-
Stearns	3	8	3	8	-	-	1	(D)	-	-	1	(D)

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Table 33. **Berries: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age		Nonbearing age		Total		Bearing age		Nonbearing age	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
BLUEBERRIES, TAME - Con.												
Counties - Con.												
Todd	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Wabasha	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Wadena	1	(D)	1	(D)	-	-	2	(D)	-	-	2	(D)
Washington	7	16	3	(D)	4	(D)	18	(D)	18	(D)	1	(D)
Winona	4	(D)	4	5	1	(D)	4	3	4	1	4	3
Wright	3	(D)	1	(D)	2	(D)	1	(D)	1	(D)	-	-
BLUEBERRIES, WILD												
State Total												
Minnesota	16	48	8	(D)	9	(D)	13	3	5	1	8	2
Counties												
Becker	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Blue Earth	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Carlton	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Crow Wing	6	1	-	-	6	1	-	-	-	-	-	-
Goodhue	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Morrison	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Pine	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
St. Louis	3	5	3	5	-	-	4	(D)	4	(D)	-	-
Waseca	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Washington	-	-	-	-	-	-	6	(D)	-	-	6	(D)
CRANBERRIES												
State Total												
Minnesota	10	(D)	5	(D)	8	4	9	(D)	4	(D)	8	4
Counties												
Aitkin	1	(D)	1	(D)	-	-	1	(D)	1	(D)	-	-
Carver	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Crow Wing	3	2	3	(D)	3	(D)	3	2	3	1	3	1
Olmsted	3	(Z)	-	-	3	(Z)	-	-	-	-	-	-
Otter Tail	-	-	-	-	-	-	3	(D)	-	-	3	(D)
Pine	1	(D)	-	-	1	(D)	1	(D)	-	-	1	(D)
St. Louis	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Sherburne	1	(D)	-	-	1	(D)	-	-	-	-	-	-
CURRANTS (BLACK OR RED)												
State Total												
Minnesota	44	17	42	(D)	6	(D)	59	31	52	17	34	14
Counties												
Anoka	-	-	-	-	-	-	3	(D)	3	2	2	(D)
Carver	3	(Z)	3	(Z)	-	-	3	(D)	2	(D)	3	(Z)
Chippewa	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Chisago	4	(D)	4	(D)	-	-	2	(D)	2	(D)	2	(D)
Crow Wing	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Dakota	3	(D)	3	(D)	-	-	2	(D)	2	(D)	-	-
Fillmore	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Hennepin	3	(D)	3	(D)	-	-	1	(D)	1	(D)	1	(D)
Houston	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Hubbard	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Isanti	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Itasca	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Kanabec	5	1	5	1	-	-	-	-	-	-	-	-
Kandiyohi	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Lac qui Parle	-	-	-	-	-	-	4	(Z)	4	(Z)	-	-
Lake	1	(D)	1	(D)	-	-	-	-	-	-	-	-
McLeod	3	1	3	1	3	1	1	(D)	1	(D)	-	-
Meeker	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Morrison	-	-	-	-	-	-	4	(D)	4	(D)	-	-
Olmsted	1	(D)	1	(D)	-	-	3	(D)	2	(D)	2	(D)
Pine	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Renville	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Rice	2	(D)	2	(D)	-	-	-	-	-	-	-	-
St. Louis	9	4	8	(D)	2	(D)	10	8	10	3	10	5
Scott	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Stearns	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Todd	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Wabasha	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Wadena	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Washington	1	(D)	1	(D)	-	-	4	4	4	4	-	-
Winona	2	(D)	2	(D)	-	-	1	(D)	1	(D)	1	(D)
Wright	1	(D)	1	(D)	-	-	1	(D)	1	(D)	1	(D)
ELDERBERRIES												
State Total												
Minnesota	91	51	55	18	40	34	46	(D)	28	9	26	(D)

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Table 33. **Berries: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age		Nonbearing age		Total		Bearing age		Nonbearing age	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
ELDERBERRIES - Con.												
Counties												
Aitkin	-	-	-	-	-	-	3	2	-	-	3	2
Becker	3	(D)	2	(D)	1	(D)	-	-	-	-	-	-
Beltrami	2	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Blue Earth	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Carlton	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Carver	2	(D)	2	(D)	-	-	3	1	2	(D)	3	(D)
Chisago	3	(D)	2	(D)	1	(D)	1	(D)	1	(D)	1	(D)
Clay	6	(D)	6	(D)	-	-	-	-	-	-	-	-
Clearwater	2	(D)	-	-	2	(D)	-	-	-	-	-	-
Crow Wing	3	(D)	-	-	3	(D)	-	-	-	-	-	-
Dakota	4	1	4	1	-	-	3	(D)	1	(D)	3	(Z)
Douglas	3	(D)	2	(D)	1	(D)	-	-	-	-	-	-
Fillmore	5	1	5	1	-	-	-	-	-	-	-	-
Goodhue	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Hennepin	5	(D)	2	(D)	3	(Z)	-	-	-	-	-	-
Houston	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Hubbard	4	4	-	-	4	4	2	(D)	-	-	2	(D)
Isanti	4	(Z)	4	(Z)	-	-	1	(D)	-	-	1	(D)
Kanabec	6	1	5	(D)	1	(D)	1	(D)	-	-	1	(D)
Kandiyohi	1	(D)	-	-	1	(D)	-	-	-	-	-	-
McLeod	4	3	4	2	3	1	1	(D)	1	(D)	1	(D)
Marshall	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Meeker	-	-	-	-	-	-	4	1	4	(D)	2	(D)
Mower	1	(D)	1	(D)	-	-	6	1	6	1	-	-
Olmsted	3	(D)	1	(D)	2	(D)	1	(D)	-	-	1	(D)
Pine	7	1	-	-	7	1	1	(D)	-	-	1	(D)
Polk	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Pope	3	(Z)	3	(Z)	-	-	-	-	-	-	-	-
Roseau	-	-	-	-	-	-	1	(D)	-	-	1	(D)
St. Louis	3	1	3	1	-	-	6	(D)	6	(D)	-	-
Sherburne	4	6	3	(D)	1	(D)	-	-	-	-	-	-
Todd	3	1	-	-	3	1	-	-	-	-	-	-
Wabasha	2	(D)	2	(D)	1	(D)	-	-	-	-	-	-
Washington	4	16	-	-	4	16	5	(D)	3	2	3	(D)
Winona	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
GOOSEBERRIES (SEE TEXT)												
State Total												
Minnesota	11	4	6	(D)	8	(D)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Counties												
Dakota	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Kandiyohi	1	(D)	-	-	1	(D)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
McLeod	3	1	3	1	3	(Z)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Olmsted	2	(D)	-	-	2	(D)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
St. Louis	2	(D)	2	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Wright	2	(D)	-	-	2	(D)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
LOGANBERRIES												
State Total												
Minnesota	3	(D)	1	(D)	2	(D)	1	(D)	-	-	1	(D)
Counties												
Carver	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Crow Wing	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Mower	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Pine	1	(D)	-	-	1	(D)	-	-	-	-	-	-
MULBERRIES (SEE TEXT)												
State Total												
Minnesota	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Counties												
Cottonwood	1	(D)	1	(D)	-	-	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
RASPBERRIES, ALL												
State Total												
Minnesota	270	177	242	137	80	40	312	196	264	138	107	58
Counties												
Aitkin	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Anoka	5	5	5	3	3	3	5	2	5	(D)	3	(D)
Becker	6	2	6	(D)	1	(D)	2	(D)	2	(D)	2	(D)
Beltrami	4	1	4	1	-	-	12	(D)	5	(D)	7	1
Benton	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Big Stone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Blue Earth	7	2	6	(D)	1	(D)	10	1	10	1	-	-
Brown	4	1	4	1	-	-	2	(D)	2	(D)	-	-
Carlton	9	(D)	8	(D)	5	(D)	5	(D)	3	4	2	(D)

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Table 33. **Berries: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age		Nonbearing age		Total		Bearing age		Nonbearing age	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
RASPBERRIES, ALL - Con.												
Counties - Con.												
Carver	2	(D)	2	(D)	-	-	5	14	4	(D)	1	(D)
Cass	5	(D)	4	(D)	1	(D)	7	1	7	1	-	-
Chippewa	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Chisago	5	2	5	2	-	-	15	7	15	(D)	2	(D)
Clay	8	(D)	8	(D)	-	-	3	(D)	3	(D)	-	-
Clearwater	-	-	-	-	-	-	4	1	4	1	-	-
Cook	4	(D)	4	(D)	-	-	2	(D)	2	(D)	-	-
Cottonwood	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Crow Wing	3	4	3	4	-	-	5	4	5	(D)	2	(D)
Dakota	12	4	12	(D)	1	(D)	7	3	7	3	-	-
Douglas	8	6	6	(D)	2	(D)	5	2	5	2	-	-
Fillmore	7	4	7	(D)	2	(D)	12	5	12	5	-	-
Freeborn	5	4	5	4	-	-	8	(D)	8	(D)	-	-
Goodhue	2	(D)	2	(D)	1	(D)	13	4	-	-	13	4
Grant	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Hennepin	6	7	4	(D)	6	(D)	7	9	6	(D)	3	(D)
Hubbard	5	1	2	(D)	3	(D)	6	1	3	(Z)	3	(Z)
Isanti	16	5	16	3	9	2	5	(D)	5	(D)	-	-
Itasca	6	(D)	4	(Z)	2	(D)	6	(D)	6	(D)	-	-
Kandiyohi	1	(D)	-	-	1	(D)	1	(D)	-	-	1	(D)
Koochiching	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Lac qui Parle	2	(D)	2	(D)	-	-	4	1	4	(Z)	4	(Z)
Lake of the Woods	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Le Sueur	-	-	-	-	-	-	3	5	3	3	3	3
Lincoln	2	(D)	-	-	2	(D)	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	2	(D)	-	-	-	-	-	-
Marshall	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Meeker	5	(D)	5	2	1	(D)	3	(D)	1	(D)	2	(D)
Mille Lacs	2	(D)	2	(D)	-	-	4	(D)	4	(D)	-	-
Morrison	1	(D)	-	-	1	(D)	1	(D)	-	-	1	(D)
Mower	3	(D)	1	(D)	2	(D)	4	1	4	(D)	2	(D)
Nicollet	4	1	3	(D)	1	(D)	2	(D)	2	(D)	-	-
Nobles	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Olmsted	13	5	13	4	6	1	13	2	13	(D)	1	(D)
Otter Tail	4	(D)	3	(D)	1	(D)	4	(D)	4	(D)	3	(D)
Pennington	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Pine	4	2	4	(D)	2	(D)	2	(D)	2	(D)	-	-
Pipestone	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Polk	-	-	-	-	-	-	3	(Z)	3	(Z)	-	-
Pope	1	(D)	1	(D)	1	(D)	4	(D)	2	(D)	2	(D)
Ramsey	9	(D)	9	(D)	-	-	-	-	-	-	-	-
Redwood	-	-	-	-	-	-	3	3	3	3	-	-
Renville	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Rice	10	15	10	9	5	7	4	(D)	4	5	1	(D)
Roseau	-	-	-	-	-	-	2	(D)	1	(D)	1	(D)
St. Louis	11	9	11	(D)	1	(D)	10	16	10	12	4	4
Scott	4	(D)	4	(D)	1	(D)	7	(D)	7	5	4	(D)
Sherburne	12	4	11	(D)	1	(D)	1	(D)	1	(D)	-	-
Sibley	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Stearns	13	8	9	6	6	1	12	14	12	11	5	3
Steele	-	-	-	-	-	-	3	1	3	1	-	-
Stevens	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Swift	1	(D)	1	(D)	-	-	5	2	4	(D)	1	(D)
Todd	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Wabasha	3	2	3	(D)	1	(D)	-	-	-	-	-	-
Wadena	1	(D)	1	(D)	-	-	9	3	9	2	6	1
Waseca	3	(D)	2	(D)	1	(D)	1	(D)	1	(D)	-	-
Washington	6	(D)	6	12	2	(D)	28	20	20	18	15	2
Wilkin	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Winona	10	5	10	(D)	1	(D)	12	5	12	3	3	2
Wright	2	(D)	-	-	2	(D)	9	(D)	6	4	5	(D)
STRAWBERRIES												
State Total												
Minnesota	218	401	184	308	85	93	232	423	193	329	104	94
Counties												
Aitkin	2	(D)	2	(D)	-	-	5	(D)	5	(D)	1	(D)
Anoka	4	18	4	(D)	1	(D)	6	8	5	6	4	2
Becker	3	(D)	3	(D)	-	-	1	(D)	1	(D)	-	-
Beltrami	2	(D)	1	(D)	2	(D)	11	(D)	5	(D)	6	1
Benton	1	(D)	1	(D)	-	-	1	(D)	1	(D)	1	(D)
Big Stone	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Blue Earth	1	(D)	1	(D)	-	-	3	(Z)	-	-	3	(Z)
Brown	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Carlton	10	(D)	3	(D)	10	10	6	(D)	6	(D)	2	(D)
Carver	2	(D)	1	(D)	1	(D)	3	1	2	(D)	3	(D)
Cass	8	7	7	3	8	4	4	(Z)	4	(Z)	-	-
Chippewa	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Chisago	8	8	6	(D)	2	(D)	6	(D)	6	4	4	(D)
Clay	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Clearwater	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)
Cook	2	(D)	2	(D)	2	(D)	1	(D)	1	(D)	1	(D)
Cottonwood	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Crow Wing	1	(D)	-	-	1	(D)	4	(D)	3	(D)	1	(D)

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Table 33. **Berries: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022						2017					
	Total		Bearing age		Nonbearing age		Total		Bearing age		Nonbearing age	
	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres	Farms	Acres
STRAWBERRIES - Con.												
Counties - Con.												
Dakota	10	28	10	(D)	2	(D)	7	36	6	32	6	4
Dodge	9	7	9	7	-	-	1	(D)	1	(D)	1	(D)
Douglas	7	17	6	13	3	4	7	4	7	(D)	1	(D)
Fillmore	5	6	5	(D)	1	(D)	8	(D)	8	(D)	-	-
Freeborn	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Goodhue	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Grant	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Hennepin	20	6	18	5	6	1	4	(D)	4	(D)	1	(D)
Hubbard	2	(D)	2	(D)	1	(D)	3	(D)	1	(D)	3	(D)
Isanti	11	9	2	(D)	10	(D)	8	17	8	(D)	1	(D)
Itasca	7	2	5	1	3	1	9	3	8	(D)	2	(D)
Kanabec	3	(D)	3	(D)	-	-	7	(D)	1	(D)	6	(D)
Kandiyohi	2	(D)	1	(D)	2	(D)	3	(D)	3	(D)	1	(D)
Koochiching	1	(D)	1	(D)	-	-	2	(D)	2	(D)	2	(D)
Lac qui Parle	-	-	-	-	-	-	5	1	5	1	-	-
Lake of the Woods	2	(D)	2	(D)	-	-	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	2	(D)	2	(D)	2	(D)	1	(D)
Marshall	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Meeker	4	4	4	(D)	4	(D)	3	1	3	(D)	2	(D)
Mille Lacs	1	(D)	1	(D)	-	-	6	(D)	5	(D)	1	(D)
Mower	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Nicollet	4	(Z)	4	(Z)	-	-	-	-	-	-	-	-
Nobles	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Norman	2	(D)	2	(D)	-	-	1	(D)	1	(D)	-	-
Olmsted	7	6	7	(D)	1	(D)	15	37	14	22	7	15
Otter Tail	3	(D)	2	(D)	1	(D)	6	(D)	6	8	4	(D)
Pennington	1	(D)	1	(D)	-	-	2	(D)	2	(D)	-	-
Pine	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Polk	3	(D)	3	(D)	1	(D)	4	1	4	1	-	-
Pope	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)	1	(D)
Ramsey	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Redwood	2	(D)	2	(D)	-	-	3	14	3	6	3	8
Renville	-	-	-	-	-	-	1	(D)	1	(D)	-	-
Rice	6	7	6	(D)	2	(D)	3	14	3	(D)	1	(D)
Roseau	-	-	-	-	-	-	1	(D)	1	(D)	-	-
St. Louis	7	4	7	(D)	2	(D)	6	7	6	(D)	1	(D)
Scott	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Sherburne	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Sibley	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Stearns	12	9	8	7	6	2	7	(D)	7	(D)	-	-
Todd	6	1	6	(D)	2	(D)	6	2	6	2	-	-
Wabasha	2	(D)	2	(D)	-	-	2	(D)	2	(D)	-	-
Waseca	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Washington	11	54	10	43	5	11	14	51	8	37	13	14
Wilkin	-	-	-	-	-	-	2	(D)	1	(D)	1	(D)
Winona	1	(D)	1	(D)	1	(D)	5	(D)	5	2	3	(D)
Wright	4	(D)	4	(D)	1	(D)	11	30	7	23	8	7
Yellow Medicine	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
OTHER BERRIES (SEE TEXT)												
State Total												
Minnesota	30	44	19	13	19	31	51	29	32	14	27	15
Counties												
Aitkin	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Becker	2	(D)	2	(D)	-	-	2	(D)	1	(D)	1	(D)
Carlton	4	17	3	6	4	11	3	(D)	1	(D)	3	4
Carver	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Clay	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Dakota	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Douglas	2	(D)	2	(D)	-	-	1	(D)	-	-	1	(D)
Hennepin	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Houston	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Hubbard	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Isanti	8	16	-	-	8	16	1	(D)	1	(D)	-	-
Kandiyohi	1	(D)	1	(D)	-	-	-	-	-	-	-	-
Lake	1	(D)	-	-	1	(D)	-	-	-	-	-	-
McLeod	2	(D)	2	(D)	-	-	-	-	-	-	-	-
Meeker	-	-	-	-	-	-	2	(D)	2	(D)	2	(D)
Nobles	-	-	-	-	-	-	2	(D)	2	(D)	-	-
Olmsted	-	-	-	-	-	-	3	(D)	2	(D)	1	(D)
Otter Tail	-	-	-	-	-	-	4	1	4	(D)	1	(D)
Pine	-	-	-	-	-	-	6	3	-	-	6	3
Pope	-	-	-	-	-	-	2	(D)	-	-	2	(D)
Ramsey	-	-	-	-	-	-	7	2	7	2	-	-
St. Louis	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Sherburne	1	(D)	-	-	1	(D)	-	-	-	-	-	-
Stearns	1	(D)	1	(D)	1	(D)	-	-	-	-	-	-
Todd	-	-	-	-	-	-	1	(D)	1	(D)	1	(D)
Wadena	-	-	-	-	-	-	6	(D)	6	(D)	-	-
Watonwan	3	2	3	(Z)	3	1	-	-	-	-	-	-
Wilkin	-	-	-	-	-	-	1	(D)	-	-	1	(D)
Winona	2	(D)	2	(D)	-	-	1	(D)	1	(D)	1	(D)
Wright	1	(D)	1	(D)	-	-	-	-	-	-	-	-

Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017**

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
BEDDING/GARDEN PLANTS, CUT FLOWERS AND CUT FLORIST GREENS, FOLIAGE PLANTS, POTTED FLOWERING PLANTS, AND OTHER FLORICULTURE AND BEDDING CROPS, TOTAL								
State Total								
Minnesota	605	13,099,758	528	605	139,921,406	490	14,692,175	416
Counties								
Aitkin	7	8,724	(D)	7	(D)	5	(D)	(D)
Anoka	27	1,492,539	25	27	28,210,698	18	708,284	13
Becker	6	(D)	-	6	14,000,000	7	(D)	5
Beltrami	11	(D)	4	11	163,594	7	12,240	-
Benton	2	(D)	-	2	(D)	9	15,032	(D)
Blue Earth	10	(D)	(D)	10	(D)	3	180,750	-
Brown	1	(D)	-	1	(D)	3	530	-
Carlton	5	(D)	1	5	(D)	1	(D)	-
Carver	2	(D)	(D)	2	(D)	1	(D)	-
Cass	3	7,429	(D)	3	(D)	2	-	(D)
Chippewa	-	-	-	-	-	2	(D)	-
Chisago	18	136,682	11	18	802,739	13	54,980	7
Clay	5	(D)	9	5	1,803,298	5	(D)	5
Clearwater	2	(D)	(D)	2	(D)	3	4,501	(D)
Cook	2	(D)	(D)	2	(D)	4	(D)	3
Cottonwood	3	(D)	(D)	3	(D)	2	(D)	(D)
Crow Wing	6	72,210	-	6	477,700	9	66,673	2
Dakota	37	1,002,916	61	37	10,064,847	27	1,124,887	53
Dodge	7	(D)	4	7	(D)	1	(D)	-
Douglas	5	18,892	(D)	5	201,292	7	61,300	(D)
Faribault	3	(D)	(D)	3	(D)	2	(D)	-
Fillmore	11	9,080	(D)	11	74,087	11	9,200	7
Freeborn	8	(D)	1	8	(D)	2	(D)	-
Goodhue	7	(D)	4	7	(D)	14	(D)	8
Hennepin	27	1,876,017	15	27	28,776,033	31	2,811,270	19
Houston	2	(D)	(D)	2	(D)	12	6,672	9
Hubbard	1	(D)	-	1	(D)	4	(D)	-
Isanti	8	9,792	13	8	(D)	10	(D)	(D)
Itasca	20	60,856	7	20	358,990	11	21,100	7
Jackson	1	(D)	-	1	(D)	2	(D)	-
Kanabec	9	17,566	(D)	9	125,556	5	(D)	11
Kandiyohi	4	(D)	7	4	(D)	-	-	-
Kittson	2	(D)	-	2	(D)	1	(D)	-
Lac qui Parle	-	-	-	-	-	2	(D)	-
Lake	3	(D)	(D)	3	(D)	6	16,352	1
Lake of the Woods	-	-	-	-	-	1	(D)	-
Le Sueur	10	(D)	5	10	36,880	9	19,654	(D)
Lincoln	2	(D)	-	2	(D)	1	(D)	-
Lyon	1	(D)	-	1	(D)	1	(D)	-
McLeod	6	(D)	4	6	(D)	4	(D)	(D)
Marshall	2	(D)	-	2	(D)	1	(D)	-
Martin	5	(D)	5	5	(D)	6	(D)	(D)
Meeker	8	3,520	10	8	53,030	7	9,740	-
Mille Lacs	11	13,796	9	11	256,303	5	(D)	(D)
Morrison	9	14,050	7	9	104,360	8	63,592	4
Mower	-	-	-	-	-	1	(D)	-
Murray	-	-	-	-	-	2	(D)	-
Nicollet	8	66,000	(D)	8	381,204	6	36,000	-
Nobles	1	-	(D)	1	(D)	-	-	-
Norman	1	(D)	(D)	1	(D)	5	15,080	(D)
Olmsted	10	113,776	4	10	(D)	3	(D)	(D)
Otter Tail	14	171,275	12	14	1,286,531	16	147,580	6
Pennington	-	-	-	-	-	4	-	(Z)
Pine	6	39,005	-	6	(D)	7	46,467	-
Pipestone	2	(D)	(D)	2	(D)	1	(D)	-
Polk	2	(D)	(D)	2	(D)	6	52,758	(D)
Pope	3	27,800	(D)	3	(D)	4	33,300	(D)
Ramsey	16	210,400	4	16	2,391,840	12	96,824	3
Redwood	2	(D)	(D)	2	(D)	-	-	-
Renville	1	(D)	-	1	(D)	-	-	-
Rice	22	729,960	18	22	14,032,806	7	494,852	(D)
Rock	3	-	3	3	12,000	2	(D)	-
Roseau	-	-	-	-	-	1	-	(D)
St. Louis	43	232,250	19	43	2,043,269	29	316,006	36
Scott	13	77,356	14	13	496,623	9	123,441	17
Sherburne	13	614,900	19	13	3,697,200	16	363,610	10
Sibley	1	(D)	(D)	1	(D)	2	(D)	(D)
Stearns	22	221,026	13	22	2,234,218	5	115,656	(D)
Steele	3	(D)	(D)	3	(D)	3	(D)	(D)
Stevens	3	(D)	1	3	(D)	1	(D)	(D)
Swift	1	-	(D)	1	(D)	3	-	1
Todd	5	(D)	(D)	5	(D)	6	25,400	(D)
Wabasha	19	29,921	8	19	503,324	5	(D)	(D)
Wadena	2	(D)	(D)	2	(D)	1	-	(D)
Waseca	7	1,500	(D)	7	16,680	-	-	-
Washington	26	182,585	28	26	1,114,065	21	339,318	16
Watonwan	6	8,660	8	6	(D)	1	(D)	-
Wilkin	7	(D)	14	7	(D)	-	-	-
Winona	11	63,438	(D)	11	510,178	13	93,120	5
Wright	13	(D)	7	13	(D)	13	(D)	16

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
BEDDING/GARDEN PLANTS - ANNUALS, HERBACEOUS PERENNIALS, VEGETABLE PLANTS (INCLUDING HANGING BASKETS)								
State Total								
Minnesota	391	8,459,412	229	391	95,906,823	364	9,771,478	226
Counties								
Aitkin	6	2,288	-	6	13,728	1	(D)	(D)
Anoka	18	1,297,562	17	18	26,851,650	13	(D)	11
Becker	6	(D)	-	6	(D)	5	(D)	(D)
Beltrami	5	(D)	-	5	(D)	7	12,240	-
Benton	2	(D)	-	2	(D)	7	15,032	(D)
Blue Earth	9	(D)	(D)	9	(D)	3	140,750	-
Brown	1	(D)	-	1	(D)	3	(D)	-
Carlton	1	(D)	-	1	(D)	1	(D)	-
Carver	2	(D)	-	2	(D)	1	(D)	-
Cass	3	7,429	(D)	3	(D)	-	-	-
Chippewa	-	-	-	-	-	2	(D)	-
Chisago	13	136,682	(D)	13	754,212	7	54,980	(D)
Clay	3	(D)	(D)	3	(D)	5	(D)	5
Clearwater	1	(D)	-	1	(D)	2	(D)	-
Cook	1	(D)	-	1	(D)	-	-	-
Cottonwood	2	(D)	(D)	2	(D)	2	(D)	(D)
Crow Wing	6	(D)	-	6	(D)	9	66,673	2
Dakota	21	921,059	25	21	9,414,842	22	812,623	23
Dodge	1	(D)	-	1	(D)	1	(D)	-
Douglas	3	14,192	-	3	119,152	4	(D)	-
Faribault	2	(D)	-	2	(D)	2	(D)	-
Fillmore	7	(D)	(D)	7	69,050	9	(D)	(D)
Freeborn	4	(D)	(D)	4	(D)	1	(D)	-
Goodhue	3	(D)	(D)	3	(D)	9	(D)	(D)
Hennepin	15	956,496	4	15	13,565,283	27	2,242,374	14
Houston	2	(D)	(D)	2	(D)	5	6,672	(D)
Hubbard	1	(D)	-	1	(D)	4	(D)	-
Isanti	5	(D)	-	5	(D)	8	(D)	(D)
Itasca	13	34,740	(D)	13	180,490	3	(D)	-
Jackson	1	(D)	-	1	(D)	2	(D)	-
Kanabec	7	9,114	(D)	7	63,284	5	(D)	11
Kandiyohi	4	(D)	(D)	4	16,500	-	-	-
Kittson	2	(D)	-	2	(D)	-	-	-
Lac qui Parle	-	-	-	-	-	2	(D)	-
Lake	3	(D)	(D)	3	(D)	3	8,560	-
Lake of the Woods	-	-	-	-	-	1	(D)	-
Le Sueur	1	(D)	-	1	(D)	2	(D)	-
Lincoln	2	(D)	-	2	(D)	1	(D)	-
Lyon	1	(D)	-	1	(D)	1	(D)	-
McLeod	6	(D)	4	6	(D)	3	(D)	(D)
Marshall	2	(D)	-	2	(D)	1	(D)	-
Martin	3	(D)	(D)	3	(D)	2	(D)	-
Meeker	5	3,380	4	5	30,042	7	(D)	-
Mille Lacs	3	1,196	-	3	2,303	5	(D)	-
Morrison	9	(D)	3	9	82,100	7	(D)	4
Mower	-	-	-	-	-	1	(D)	-
Murray	-	-	-	-	-	2	(D)	-
Nicollet	6	21,996	-	6	131,976	6	36,000	-
Nobles	1	-	(D)	1	(D)	-	-	-
Norman	1	(D)	(D)	1	(D)	5	(D)	(D)
Olmsted	6	113,776	(D)	6	(D)	1	(D)	(D)
Otter Tail	11	(D)	6	11	1,036,376	15	(D)	6
Pennington	-	-	-	-	-	4	-	(Z)
Pine	6	(D)	-	6	(D)	7	46,467	-
Pipestone	2	(D)	(D)	2	(D)	1	(D)	-
Polk	2	(D)	(D)	2	(D)	6	34,812	-
Pope	2	(D)	-	2	(D)	2	(D)	(D)
Ramsey	10	150,100	(D)	10	2,245,500	10	83,000	3
Redwood	2	(D)	(D)	2	(D)	-	-	-
Renville	1	(D)	-	1	(D)	-	-	-
Rice	6	(D)	(D)	6	3,538,386	6	(D)	(D)
Rock	-	-	-	-	-	2	(D)	-
Roseau	-	-	-	-	-	1	-	(D)
St. Louis	33	184,854	8	33	1,708,052	22	272,756	(D)
Scott	7	64,036	(D)	7	391,061	6	89,661	(D)
Sherburne	11	292,400	(D)	11	1,507,050	11	(D)	(D)
Sibley	-	-	-	-	-	1	-	(D)
Stearns	16	(D)	(D)	16	(D)	5	(D)	(D)
Steele	1	(D)	-	1	(D)	1	(D)	-
Stevens	3	(D)	1	3	(D)	1	(D)	(D)
Todd	5	(D)	(D)	5	(D)	4	(D)	-
Wabasha	11	(D)	(D)	11	308,070	3	(D)	(D)
Wadena	2	(D)	(D)	2	(D)	-	-	-
Waseca	5	1,500	-	5	(D)	-	-	-
Washington	10	(D)	(D)	10	944,300	14	(D)	10
Watonwan	2	(D)	-	2	(D)	1	(D)	-
Wilkin	7	(D)	14	7	(D)	-	-	-
Winona	9	(D)	(D)	9	(D)	9	(D)	(D)
Wright	8	(D)	5	8	(D)	12	(D)	(D)

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
CUT FLOWERS AND CUT FLORIST GREENS								
State Total								
Minnesota	218	394,932	178	218	9,190,414	99	404,204	118
Counties								
Aitkin	5	2,436	(D)	5	12,200	4	-	(Z)
Anoka	6	-	(D)	6	33,600	4	-	(D)
Beltrami	6	-	4	6	(D)	-	-	-
Benton	-	-	-	-	-	2	-	(D)
Carlton	4	-	1	4	4,840	-	-	-
Carver	1	-	(D)	1	(D)	-	-	-
Cass	-	-	-	-	-	2	-	(D)
Chisago	5	-	6	5	(D)	5	-	4
Clearwater	1	(D)	(D)	1	(D)	1	(D)	(D)
Cook	-	-	-	-	-	1	(D)	-
Cottonwood	2	(D)	(D)	2	(D)	1	(D)	-
Dakota	11	(D)	23	11	100,740	2	-	(D)
Dodge	4	-	4	4	40,000	-	-	-
Douglas	2	(D)	(D)	2	(D)	2	(D)	(D)
Fillmore	2	-	(D)	2	(D)	2	-	(D)
Freeborn	1	-	(D)	1	(D)	-	-	-
Goodhue	4	-	(D)	4	19,212	4	(D)	(D)
Hennepin	6	(D)	(D)	6	(D)	4	(D)	(D)
Houston	1	-	(D)	1	(D)	7	-	(D)
Isanti	4	(D)	(D)	4	96,800	2	(D)	(D)
Itasca	16	2,116	5	16	36,500	10	(D)	7
Kanabec	2	(D)	-	2	(D)	-	-	-
Kandiyohi	2	-	(D)	2	(D)	-	-	-
Lake	1	(D)	-	1	(D)	2	(D)	-
Le Sueur	9	-	5	9	(D)	7	(D)	(D)
Meeker	3	-	6	3	22,218	-	-	-
Mille Lacs	9	(D)	9	9	(D)	2	-	(D)
Nicollet	1	-	(D)	1	(D)	-	-	-
Olmsted	4	-	2	4	10,240	2	-	(D)
Otter Tail	4	(D)	6	4	(D)	-	-	-
Pope	1	(D)	(D)	1	(D)	2	(D)	(D)
Ramsey	6	300	(D)	6	5,340	2	(D)	-
Redwood	1	(D)	-	1	(D)	-	-	-
Rice	14	8,000	(D)	14	216,920	1	(D)	(D)
St. Louis	27	6,858	10	27	97,960	12	(D)	13
Scott	4	(D)	6	4	48,000	2	(D)	(D)
Sherburne	1	-	(D)	1	(D)	-	-	-
Sibley	1	(D)	(D)	1	(D)	1	(D)	(D)
Stearns	7	(D)	(D)	7	(D)	-	-	-
Steele	2	-	(D)	2	(D)	2	-	(D)
Swift	1	-	(D)	1	(D)	3	-	1
Todd	-	-	-	-	-	1	-	(D)
Wabasha	7	(D)	7	7	167,000	-	-	-
Wadena	1	(D)	(D)	1	(D)	1	-	(D)
Waseca	2	-	(D)	2	(D)	-	-	-
Washington	17	(D)	24	17	(D)	3	-	(D)
Watonwan	4	(D)	(D)	4	69,000	-	-	-
Winona	-	-	-	-	-	2	(D)	(D)
Wright	6	(D)	2	6	14,880	1	-	(D)
FOLIAGE PLANTS, INDOOR (INCLUDING HANGING BASKETS)								
State Total								
Minnesota	69	1,070,501	5	69	6,635,408	36	908,430	3
Counties								
Aitkin	4	2,000	-	4	11,000	2	(D)	-
Anoka	1	(D)	-	1	(D)	2	(D)	-
Benton	1	(D)	-	1	(D)	-	-	-
Blue Earth	-	-	-	-	-	2	(D)	-
Carver	1	(D)	(D)	1	(D)	-	-	-
Chisago	2	-	(D)	2	(D)	-	-	-
Clay	1	(D)	-	1	(D)	-	-	-
Clearwater	1	(D)	-	1	(D)	-	-	-
Cook	1	-	(D)	1	(D)	-	-	-
Cottonwood	1	(D)	-	1	(D)	-	-	-
Dakota	1	(D)	-	1	(D)	6	94,032	-
Dodge	2	(D)	-	2	(D)	-	-	-
Fillmore	2	(D)	-	2	(D)	-	-	-
Freeborn	5	-	(D)	5	1,850	-	-	-
Goodhue	1	(D)	-	1	(D)	-	-	-
Hennepin	5	(D)	(Z)	5	(D)	-	-	-
Hubbard	-	-	-	-	-	1	(D)	-
Itasca	3	6,000	-	3	33,000	1	(D)	-
Kanabec	4	(D)	-	4	(D)	2	(D)	-
Kandiyohi	2	(D)	-	2	(D)	-	-	-
Kittson	-	-	-	-	-	1	(D)	-
Lake	-	-	-	-	-	3	(D)	(Z)
Marshall	2	(D)	-	2	(D)	-	-	-
Meeker	2	(D)	-	2	(D)	-	-	-
Morrison	6	-	2	6	6,660	-	-	-

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
FOLIAGE PLANTS, INDOOR (INCLUDING HANGING BASKETS) - Con.								
Counties - Con.								
Nicollet	6	22,002	-	6	(D)	-	-	-
Olmsted	1	-	(D)	1	(D)	-	-	-
Pipestone	1	(D)	-	1	(D)	-	-	-
Polk	1	(D)	-	1	(D)	2	(D)	-
Ramsey	-	-	-	-	-	3	(D)	-
Renville	1	(D)	-	1	(D)	-	-	-
Rice	1	(D)	-	1	(D)	1	(D)	-
St. Louis	3	(D)	-	3	(D)	7	(D)	3
Scott	2	(D)	-	2	(D)	1	(D)	-
Sherburne	3	(D)	-	3	(D)	-	-	-
Stearns	-	-	-	-	-	1	(D)	-
Wilkin	1	(D)	-	1	(D)	-	-	-
Wright	1	(D)	-	1	(D)	1	(D)	-
POTTED FLOWERING PLANTS								
State Total								
Minnesota	121	2,981,019	34	121	23,692,175	85	3,323,647	24
Counties								
Aitkin	4	2,000	-	4	(D)	2	(D)	-
Anoka	4	(D)	(D)	4	1,297,134	5	(D)	(D)
Becker	1	(D)	-	1	(D)	1	(D)	-
Benton	1	(D)	-	1	(D)	-	-	-
Blue Earth	-	-	-	-	-	2	(D)	-
Brown	-	-	-	-	-	1	(D)	-
Carver	1	(D)	(D)	1	(D)	-	-	-
Chisago	-	-	-	-	-	1	-	(D)
Clay	2	(D)	-	2	(D)	1	(D)	-
Clearwater	1	(D)	-	1	(D)	-	-	-
Cook	1	-	(D)	1	(D)	3	-	3
Cottonwood	1	(D)	-	1	(D)	1	(D)	-
Crow Wing	1	(D)	-	1	(D)	-	-	-
Dakota	3	(D)	(D)	3	(D)	8	198,032	(D)
Dodge	1	(D)	-	1	(D)	-	-	-
Douglas	2	(D)	-	2	(D)	1	-	(D)
Faribault	1	-	(D)	1	(D)	-	-	-
Fillmore	-	-	-	-	-	1	(D)	-
Freeborn	1	(D)	-	1	(D)	2	(D)	-
Goodhue	1	(D)	-	1	(D)	2	-	(D)
Hennepin	14	587,688	(D)	14	(D)	3	(D)	(D)
Houston	-	-	-	-	-	1	-	(D)
Hubbard	-	-	-	-	-	2	(D)	-
Itasca	4	18,000	(D)	4	109,000	-	-	-
Kanabec	4	4,311	-	4	32,861	2	(D)	-
Kandiyohi	2	(D)	-	2	(D)	-	-	-
Kittson	-	-	-	-	-	1	(D)	-
Lake	1	(D)	-	1	(D)	5	5,396	(Z)
Le Sueur	-	-	-	-	-	2	(D)	-
Marshall	2	(D)	-	2	(D)	-	-	-
Martin	1	(D)	-	1	(D)	4	17,000	(D)
Meeker	2	(D)	-	2	(D)	1	(D)	-
Mille Lacs	1	(D)	-	1	(D)	-	-	-
Morrison	8	(D)	2	8	15,600	2	(D)	-
Nicollet	7	22,002	(D)	7	125,014	-	-	-
Norman	-	-	-	-	-	1	(D)	-
Olmsted	3	-	(D)	3	1,236	-	-	-
Otter Tail	1	(D)	-	1	(D)	1	(D)	-
Pine	1	(D)	-	1	(D)	-	-	-
Pipestone	1	(D)	-	1	(D)	-	-	-
Polk	1	(D)	-	1	(D)	3	(D)	(D)
Ramsey	4	60,000	(D)	4	141,000	3	(D)	-
Renville	1	(D)	-	1	(D)	-	-	-
Rice	4	145,680	(D)	4	5,477,500	1	(D)	-
Rock	3	-	3	3	12,000	-	-	-
St. Louis	16	35,034	1	16	198,616	7	33,350	(D)
Scott	1	(D)	-	1	(D)	1	(D)	-
Sherburne	3	(D)	-	3	(D)	5	(D)	-
Stearns	2	(D)	-	2	(D)	2	(D)	-
Todd	-	-	-	-	-	1	(D)	-
Wabasha	2	-	(D)	2	(D)	1	(D)	-
Washington	2	-	(D)	2	(D)	2	(D)	(D)
Watonwan	2	-	(D)	2	(D)	-	-	-
Wilkin	1	(D)	-	1	(D)	-	-	-
Winona	-	-	-	-	-	2	-	(D)
Wright	1	(D)	-	1	(D)	1	(D)	-
OTHER FLORICULTURE AND BEDDING CROPS								
State Total								
Minnesota	32	193,894	83	32	4,496,586	37	284,416	46

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
OTHER FLORICULTURE AND BEDDING CROPS - Con.								
Counties								
Anoka	4	(D)	(D)	4	(D)	2	(D)	(D)
Becker	-	-	-	-	-	2	-	(D)
Blue Earth	1	-	(D)	1	(D)	-	-	-
Clay	2	(D)	(D)	2	(D)	-	-	-
Dakota	6	(D)	(D)	6	27,426	8	20,200	(D)
Goodhue	1	(D)	-	1	(D)	4	(D)	4
Hennepin	1	(D)	(D)	1	(D)	2	(D)	-
Isanti	2	-	(D)	2	(D)	-	-	-
McLeod	-	-	-	-	-	2	-	(D)
Martin	2	-	(D)	2	(D)	2	-	(D)
Morrison	-	-	-	-	-	1	(D)	-
Otter Tail	-	-	-	-	-	1	(D)	-
Rice	2	(D)	-	2	(D)	-	-	-
St. Louis	2	(D)	-	2	(D)	2	-	(D)
Scott	3	-	(D)	3	(D)	2	(D)	(D)
Sherburne	-	-	-	-	-	2	(D)	(D)
Sibley	-	-	-	-	-	1	-	(D)
Stearns	3	(D)	(D)	3	27,108	-	-	-
Todd	-	-	-	-	-	1	(D)	-
Wabasha	1	-	(D)	1	(D)	2	-	(D)
Washington	-	-	-	-	-	3	(D)	(D)
Winona	2	(D)	(D)	2	(D)	-	-	-
NURSERY STOCK CROPS								
State Total								
Minnesota	325	1,497,053	6,690	325	146,712,916	263	646,291	5,271
Counties								
Aitkin	1	-	(D)	1	(D)	1	-	(D)
Anoka	9	(D)	144	9	(D)	5	(D)	53
Becker	5	-	2	5	(D)	-	-	-
Beltrami	1	-	(D)	1	(D)	2	-	(D)
Benton	4	-	(D)	4	(D)	2	-	(D)
Big Stone	3	-	3	3	33,000	-	-	-
Blue Earth	10	-	28	10	(D)	3	(D)	(D)
Brown	-	-	-	-	-	3	206	-
Carlton	2	-	(D)	2	(D)	3	-	2
Carver	12	21,789	429	12	4,510,794	10	25,840	214
Cass	2	-	(D)	2	(D)	1	-	(D)
Chippewa	-	-	-	-	-	1	-	(D)
Chisago	21	(D)	85	21	(D)	8	(D)	10
Clearwater	4	-	4	4	193,600	2	-	(D)
Cottonwood	1	(D)	(D)	1	(D)	2	(D)	(D)
Crow Wing	5	-	(D)	5	(D)	4	-	18
Dakota	18	(D)	1,764	18	93,011,118	16	(D)	1,817
Douglas	4	(D)	(D)	4	(D)	4	-	1
Fillmore	13	(D)	24	13	265,722	7	(D)	5
Freeborn	5	-	2	5	(D)	-	-	-
Goodhue	2	-	(D)	2	(D)	3	-	22
Hennepin	11	(D)	219	11	(D)	16	(D)	104
Houston	1	-	(D)	1	(D)	3	-	5
Hubbard	2	(D)	(D)	2	(D)	6	-	26
Isanti	6	(D)	(D)	6	2,287,700	6	-	265
Itasca	4	(D)	1	4	(D)	2	(D)	(D)
Kanabec	8	(D)	46	8	(D)	5	-	136
Kandiyohi	3	-	(D)	3	(D)	1	-	(D)
Kittson	2	-	(D)	2	(D)	1	-	(D)
Lake	3	(D)	1	3	(D)	-	-	-
Le Sueur	4	-	42	4	322,000	3	(D)	(D)
Lincoln	-	-	-	-	-	1	-	(D)
Lyon	2	-	(D)	2	(D)	2	-	(D)
McLeod	3	-	11	3	121,000	4	(D)	(D)
Marshall	2	-	(D)	2	(D)	-	-	-
Martin	4	-	18	4	(D)	2	-	(D)
Meeker	5	(D)	(D)	5	240,059	8	-	25
Mille Lacs	-	-	-	-	-	1	-	(D)
Morrison	13	(D)	34	13	316,600	9	-	62
Nobles	1	-	(D)	1	(D)	1	-	(D)
Norman	-	-	-	-	-	1	-	(D)
Olmsted	5	-	25	5	(D)	7	-	22
Otter Tail	12	(D)	340	12	(D)	7	(D)	230
Pine	4	(D)	(D)	4	(D)	8	-	156
Pipestone	5	-	9	5	102,300	2	-	(D)
Polk	4	14,296	-	4	55,740	2	(D)	-
Ramsey	1	(D)	-	1	(D)	4	130,680	(D)
Red Lake	-	-	-	-	-	1	-	(D)
Redwood	6	(D)	31	6	(D)	-	-	-
Renville	1	(D)	-	1	(D)	-	-	-
Rice	6	(D)	673	6	7,492,000	5	25,000	366
Roseau	1	-	(D)	1	(D)	1	-	(D)
St. Louis	14	26,920	80	14	988,200	14	19,350	54
Scott	8	(D)	51	8	301,691	6	-	55
Sherburne	5	-	79	5	869,000	6	-	145
Sibley	-	-	-	-	-	1	-	(D)

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
NURSERY STOCK CROPS - Con.								
Counties - Con.								
Stearns	12	(D)	74	12	(D)	9	18,000	74
Steele	1	-	(D)	1	(D)	3	-	3
Stevens	2	(D)	(D)	2	(D)	1	(D)	(D)
Swift	1	-	(D)	1	(D)	1	-	(D)
Todd	2	-	(D)	2	(D)	4	-	4
Wabasha	7	-	4	7	(D)	-	-	-
Waseca	-	-	-	-	-	1	-	(D)
Washington	8	(D)	645	8	(D)	15	1,562	663
Watonwan	-	-	-	-	-	1	(D)	(D)
Wilkin	1	-	(D)	1	(D)	-	-	-
Winona	11	(D)	19	11	296,600	4	(D)	10
Wright	12	(D)	221	12	2,334,000	11	(D)	91
AQUATIC PLANTS								
State Total								
Minnesota	8	400	1	8	8,682	7	(D)	3
Counties								
Carver	-	-	-	-	-	1	-	(D)
Chisago	3	-	(D)	3	1,382	-	-	-
Dakota	-	-	-	-	-	1	(D)	-
Dodge	-	-	-	-	-	1	(D)	-
Fillmore	2	(D)	-	2	(D)	-	-	-
Hennepin	1	-	(D)	1	(D)	2	(D)	(D)
Houston	1	-	(D)	1	(D)	1	-	(D)
Pine	-	-	-	-	-	1	(D)	-
Renville	1	(D)	-	1	(D)	-	-	-
HEMP CLONES OR TRANSPLANTS SOLD FOR TRANSPLANTS TO OTHERS (SEE TEXT)								
State Total								
Minnesota	9	2,500	(X)	9	13,750	(NA)	(NA)	(X)
Counties								
Carver	1	(D)	(X)	1	(D)	(NA)	(NA)	(X)
Ramsey	3	(D)	(X)	3	(D)	(NA)	(NA)	(X)
Waseca	5	1,500	(X)	5	7,500	(NA)	(NA)	(X)
HEMP COMPLETE GROWS (SEE TEXT)								
State Total								
Minnesota	38	61,906	(X)	38	640,128	(NA)	(NA)	(X)
Counties								
Chisago	8	13,800	(X)	8	84,000	(NA)	(NA)	(X)
Dakota	6	21,000	(X)	6	(D)	(NA)	(NA)	(X)
Isanti	1	(D)	(X)	1	(D)	(NA)	(NA)	(X)
Kanabec	1	(D)	(X)	1	(D)	(NA)	(NA)	(X)
Le Sueur	7	(D)	(X)	7	310,800	(NA)	(NA)	(X)
Ramsey	3	2,700	(X)	3	(D)	(NA)	(NA)	(X)
Waseca	5	4,500	(X)	5	36,000	(NA)	(NA)	(X)
Wright	7	2,166	(X)	7	(D)	(NA)	(NA)	(X)
HEMP SEEDS (SEE TEXT)								
State Total								
Minnesota	8	2,400	-	8	27,600	(NA)	(NA)	(NA)
Counties								
Ramsey	3	900	-	3	10,350	(NA)	(NA)	(NA)
Waseca	5	1,500	-	5	17,250	(NA)	(NA)	(NA)
BULBS, CORMS, RHIZOMES, AND TUBERS - DRY								
State Total								
Minnesota	18	(D)	20	18	108,378	30	1,575	29
Counties								
Anoka	-	-	-	-	-	1	-	(D)
Clay	1	(D)	-	1	(D)	3	-	1
Crow Wing	-	-	-	-	-	1	-	(D)
Dakota	-	-	-	-	-	1	(D)	-
Fillmore	-	-	-	-	-	1	(D)	-
Itasca	-	-	-	-	-	2	-	(D)
Kandiyohi	2	(D)	-	2	(D)	-	-	-
Marshall	-	-	-	-	-	1	-	(D)
Meeker	2	(D)	-	2	(D)	-	-	-
Morrison	-	-	-	-	-	2	(D)	-
Olmsted	-	-	-	-	-	2	(D)	(D)
Ramsey	3	-	(D)	3	3,000	-	-	-

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
BULBS, CORMS, RHIZOMES, AND TUBERS - DRY - Con.								
Counties - Con.								
Renville	1	(D)	-	1	(D)	-	-	-
Rice	-	-	-	-	-	1	-	(D)
St. Louis	3	-	2	3	(D)	6	(D)	5
Sherburne	-	-	-	-	-	4	60	(D)
Stearns	-	-	-	-	-	1	(D)	-
Steele	1	-	(D)	1	(D)	-	-	-
Waseca	4	-	8	4	40,000	-	-	-
Washington	-	-	-	-	-	1	-	(D)
Wright	1	(D)	(D)	1	(D)	3	-	(D)
CUTTINGS, SEEDLINGS, LINERS, AND PLUGS								
State Total								
Minnesota	18	394,871	(D)	18	9,921,875	15	534,684	6
Counties								
Benton	-	-	-	-	-	1	(D)	(D)
Blue Earth	-	-	-	-	-	1	-	(D)
Crow Wing	-	-	-	-	-	1	-	(D)
Dakota	1	(D)	-	1	(D)	1	(D)	-
Freeborn	-	-	-	-	-	1	(D)	-
Hennepin	1	(D)	-	1	(D)	1	(D)	-
Jackson	1	(D)	-	1	(D)	1	(D)	-
Kanabec	1	(D)	-	1	(D)	-	-	-
Lincoln	2	(D)	-	2	(D)	-	-	-
McLeod	2	-	(D)	2	(D)	-	-	-
Meeker	2	(D)	-	2	(D)	-	-	-
Morrison	2	(D)	-	2	(D)	1	-	(D)
Rice	-	-	-	-	-	1	(D)	-
St. Louis	2	(D)	(D)	2	(D)	-	-	-
Scott	1	(D)	-	1	(D)	1	(D)	-
Todd	1	(D)	-	1	(D)	1	(D)	-
Washington	2	(D)	-	2	(D)	4	(D)	(D)
FLOWER SEEDS								
State Total								
Minnesota	21	(D)	451	21	767,180	27	(D)	545
Counties								
Anoka	1	(D)	-	1	(D)	1	(D)	-
Becker	-	-	-	-	-	2	-	(D)
Benton	1	-	(D)	1	(D)	1	(D)	(D)
Clay	1	(D)	-	1	(D)	-	-	-
Crow Wing	2	(D)	-	2	(D)	1	-	(D)
Dakota	-	-	-	-	-	1	(D)	-
Faribault	1	-	(D)	1	(D)	2	-	(D)
Houston	-	-	-	-	-	1	(D)	-
Kittson	-	-	-	-	-	1	-	(D)
Lac qui Parle	1	-	(D)	1	(D)	-	-	-
Le Sueur	1	-	(D)	1	(D)	2	-	(D)
Mahnomen	1	-	(D)	1	(D)	3	-	30
Martin	-	-	-	-	-	1	-	(D)
Meeker	2	(D)	-	2	(D)	-	-	-
Morrison	-	-	-	-	-	1	-	(D)
Polk	1	-	(D)	1	(D)	-	-	-
Pope	1	-	(D)	1	(D)	-	-	-
Ramsey	-	-	-	-	-	1	(D)	-
Renville	1	(D)	-	1	(D)	-	-	-
St. Louis	-	-	-	-	-	1	(D)	-
Sherburne	1	-	(D)	1	(D)	5	60	(D)
Todd	1	-	(D)	1	(D)	-	-	-
Wadena	1	-	(D)	1	(D)	-	-	-
Washington	1	-	(D)	1	(D)	-	-	-
Winona	3	-	87	3	(D)	2	-	(D)
Yellow Medicine	-	-	-	-	-	1	-	(D)
TOBACCO TRANSPLANTS TO FARM FIELDS								
State Total								
Minnesota	1	(D)	-	1	(D)	-	-	-
Counties								
Otter Tail	1	(D)	-	1	(D)	-	-	-
VEGETABLE SEEDS (SEE TEXT)								
State Total								
Minnesota	41	25,833	(X)	41	39,172	24	15,218	(X)
Counties								
Anoka	-	-	(X)	-	-	1	(D)	(X)
Blue Earth	-	-	(X)	-	-	1	-	(X)

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
VEGETABLE SEEDS (SEE TEXT) - Con.								
Counties - Con.								
Carlton	3	1,760	(X)	3	2,960	-	-	(X)
Cass	1	(D)	(X)	1	(D)	-	-	(X)
Chisago	5	1,009	(X)	5	3,058	1	-	(X)
Clay	-	-	(X)	-	-	3	-	(X)
Clearwater	3	1,050	(X)	3	2,100	-	-	(X)
Crow Wing	-	-	(X)	-	-	1	-	(X)
Dakota	-	-	(X)	-	-	1	(D)	(X)
Fillmore	5	790	(X)	5	1,820	1	(D)	(X)
Grant	-	-	(X)	-	-	1	-	(X)
Hubbard	1	(D)	(X)	1	(D)	-	-	(X)
Itasca	1	(D)	(X)	1	(D)	-	-	(X)
Kanabec	1	(D)	(X)	1	(D)	2	-	(X)
Kandiyohi	1	(D)	(X)	1	(D)	-	-	(X)
Kittson	-	-	(X)	-	-	1	(D)	(X)
Lake	1	(D)	(X)	1	(D)	-	-	(X)
Lincoln	2	(D)	(X)	2	(D)	-	-	(X)
Meeker	2	(D)	(X)	2	(D)	-	-	(X)
Morrison	-	-	(X)	-	-	1	-	(X)
Pine	-	-	(X)	-	-	3	(D)	(X)
Ramsey	3	900	(X)	3	1,800	1	(D)	(X)
St. Louis	2	(D)	(X)	2	(D)	1	(D)	(X)
Sherburne	1	(D)	(X)	1	(D)	-	-	(X)
Stearns	2	(D)	(X)	2	(D)	1	(D)	(X)
Steele	-	-	(X)	-	-	2	-	(X)
Wadena	1	(D)	(X)	1	(D)	2	(D)	(X)
Waseca	5	1,500	(X)	5	3,000	-	-	(X)
Washington	1	(D)	(X)	1	(D)	-	-	(X)
VEGETABLE TRANSPLANTS TO FARM FIELDS								
State Total								
Minnesota	105	121,962	(X)	105	292,388	61	64,655	(X)
Counties								
Aitkin	3	918	(X)	3	3,352	3	(D)	(X)
Anoka	2	(D)	(X)	2	(D)	3	(D)	(X)
Beltrami	3	(D)	(X)	3	(D)	-	-	(X)
Benton	1	(D)	(X)	1	(D)	-	-	(X)
Carlton	2	(D)	(X)	2	(D)	1	(D)	(X)
Cass	1	(D)	(X)	1	(D)	-	-	(X)
Chisago	-	-	(X)	-	-	4	-	(X)
Clay	-	-	(X)	-	-	3	-	(X)
Clearwater	1	(D)	(X)	1	(D)	-	-	(X)
Cook	1	(D)	(X)	1	(D)	-	-	(X)
Cottonwood	2	(D)	(X)	2	(D)	4	2,544	(X)
Crow Wing	1	(D)	(X)	1	(D)	-	-	(X)
Fillmore	8	9,752	(X)	8	23,211	2	(D)	(X)
Freeborn	1	(D)	(X)	1	(D)	-	-	(X)
Goodhue	1	(D)	(X)	1	(D)	1	(D)	(X)
Hennepin	4	1,600	(X)	4	3,840	-	-	(X)
Hubbard	1	(D)	(X)	1	(D)	-	-	(X)
Isanti	4	1,946	(X)	4	4,670	4	2,214	(X)
Itasca	4	4,080	(X)	4	8,700	1	(D)	(X)
Kanabec	6	18,500	(X)	6	44,550	2	(D)	(X)
Lake	1	(D)	(X)	1	(D)	-	-	(X)
Le Sueur	-	-	(X)	-	-	3	2,596	(X)
Lincoln	2	(D)	(X)	2	(D)	-	-	(X)
Meeker	3	(D)	(X)	3	(D)	1	(D)	(X)
Mille Lacs	1	(D)	(X)	1	(D)	4	218	(X)
Morrison	-	-	(X)	-	-	2	(D)	(X)
Nicollet	3	4,500	(X)	3	3,495	-	-	(X)
Olmsted	4	6,203	(X)	4	14,887	-	-	(X)
Otter Tail	3	(D)	(X)	3	(D)	2	(D)	(X)
Pine	-	-	(X)	-	-	2	(D)	(X)
Ramsey	6	4,500	(X)	6	12,660	3	7,110	(X)
Rice	1	(D)	(X)	1	(D)	4	9,063	(X)
St. Louis	13	6,742	(X)	13	15,031	-	-	(X)
Scott	1	(D)	(X)	1	(D)	2	(D)	(X)
Sherburne	5	2,188	(X)	5	4,835	5	300	(X)
Wabasha	1	(D)	(X)	1	(D)	-	-	(X)
Waseca	5	1,500	(X)	5	3,600	-	-	(X)
Washington	5	22,625	(X)	5	62,300	5	4,600	(X)
Watonwan	2	(D)	(X)	2	(D)	-	-	(X)
Winona	1	(D)	(X)	1	(D)	-	-	(X)
Wright	2	(D)	(X)	2	(D)	-	-	(X)
SOD HARVESTED OR INTENDED FOR SALE IN FUTURE YEARS (SEE TEXT)								
State Total								
Minnesota	52	(X)	8,604	52	47,606,894	(NA)	(X)	(NA)
Counties								
Aitkin	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Anoka	11	(X)	3,189	11	22,418,008	(NA)	(X)	(NA)

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
SOD HARVESTED OR INTENDED FOR SALE IN FUTURE YEARS (SEE TEXT) - Con.								
Counties - Con.								
Benton	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Blue Earth	-	(X)	-	-	-	(NA)	(X)	(NA)
Carlton	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Carver	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Chisago	2	(X)	(D)	2	(D)	(NA)	(X)	(NA)
Dakota	6	(X)	1,235	6	5,699,670	(NA)	(X)	(NA)
Faribault	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Freeborn	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Goodhue	-	(X)	-	-	-	(NA)	(X)	(NA)
Hennepin	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Houston	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Le Sueur	-	(X)	-	-	-	(NA)	(X)	(NA)
McLeod	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Mille Lacs	-	(X)	-	-	-	(NA)	(X)	(NA)
Nicollet	-	(X)	-	-	-	(NA)	(X)	(NA)
Pennington	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Polk	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Ramsey	-	(X)	-	-	-	(NA)	(X)	(NA)
Renville	-	(X)	-	-	-	(NA)	(X)	(NA)
Rice	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Scott	2	(X)	(D)	2	(D)	(NA)	(X)	(NA)
Sherburne	3	(X)	(D)	3	(D)	(NA)	(X)	(NA)
Stearns	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Steele	3	(X)	495	3	2,389,880	(NA)	(X)	(NA)
Wadena	-	(X)	-	-	-	(NA)	(X)	(NA)
Waseca	6	(X)	480	6	960,000	(NA)	(X)	(NA)
Washington	3	(X)	70	3	660,980	(NA)	(X)	(NA)
Winona	1	(X)	(D)	1	(D)	(NA)	(X)	(NA)
Wright	2	(X)	(D)	2	(D)	(NA)	(X)	(NA)
TOTAL GREENHOUSE VEGETABLES AND FRESH CUT HERBS								
State Total								
Minnesota	275	3,709,397	(X)	275	39,093,358	304	2,504,364	(X)
Counties								
Aitkin	6	18,184	(X)	6	70,345	7	11,040	(X)
Anoka	15	98,822	(X)	15	325,424	9	50,786	(X)
Becker	1	(D)	(X)	1	(D)	3	4,800	(X)
Beltrami	6	14,138	(X)	6	(D)	13	16,800	(X)
Benton	1	(D)	(X)	1	(D)	1	(D)	(X)
Big Stone	1	(D)	(X)	1	(D)	-	-	(X)
Blue Earth	6	2,592	(X)	6	9,000	1	(D)	(X)
Carlton	8	20,620	(X)	8	73,146	8	30,928	(X)
Cass	7	18,644	(X)	7	96,541	3	5,484	(X)
Chisago	13	36,571	(X)	13	125,454	13	34,410	(X)
Clay	1	(D)	(X)	1	(D)	-	-	(X)
Clearwater	7	18,614	(X)	7	68,874	2	(D)	(X)
Cook	2	(D)	(X)	2	(D)	6	6,296	(X)
Cottonwood	2	(D)	(X)	2	(D)	4	6,104	(X)
Crow Wing	6	8,989	(X)	6	(D)	7	75,317	(X)
Dakota	11	298,510	(X)	11	1,499,716	14	68,050	(X)
Dodge	1	(D)	(X)	1	(D)	-	-	(X)
Douglas	1	(D)	(X)	1	(D)	4	17,946	(X)
Faribault	-	-	(X)	-	-	1	(D)	(X)
Fillmore	8	49,513	(X)	8	259,679	4	8,560	(X)
Freeborn	-	-	(X)	-	-	2	(D)	(X)
Goodhue	7	10,572	(X)	7	48,500	4	6,692	(X)
Grant	-	-	(X)	-	-	1	(D)	(X)
Hennepin	8	18,867	(X)	8	66,621	17	51,900	(X)
Houston	2	(D)	(X)	2	(D)	11	6,850	(X)
Hubbard	1	(D)	(X)	1	(D)	3	(D)	(X)
Isanti	9	32,418	(X)	9	126,316	10	51,012	(X)
Itasca	14	19,002	(X)	14	73,483	11	9,948	(X)
Jackson	1	(D)	(X)	1	(D)	1	(D)	(X)
Kanabec	4	13,311	(X)	4	54,053	2	(D)	(X)
Kandiyohi	1	(D)	(X)	1	(D)	-	-	(X)
Kittson	-	-	(X)	-	-	1	(D)	(X)
Koochiching	2	(D)	(X)	2	(D)	-	-	(X)
Lake	2	(D)	(X)	2	(D)	4	2,232	(X)
Le Sueur	2	(D)	(X)	2	(D)	3	950	(X)
Lincoln	2	(D)	(X)	2	(D)	-	-	(X)
McLeod	2	(D)	(X)	2	(D)	2	(D)	(X)
Marshall	1	(D)	(X)	1	(D)	1	(D)	(X)
Martin	1	(D)	(X)	1	(D)	1	(D)	(X)
Meeker	3	(D)	(X)	3	(D)	1	(D)	(X)
Mille Lacs	3	9,565	(X)	3	(D)	3	7,194	(X)
Morrison	2	(D)	(X)	2	(D)	2	(D)	(X)
Nicollet	3	17,280	(X)	3	49,371	-	-	(X)
Nobles	-	-	(X)	-	-	1	(D)	(X)
Olmsted	4	9,047	(X)	4	90,099	4	(D)	(X)
Otter Tail	8	12,927	(X)	8	65,870	6	23,220	(X)
Pennington	1	(D)	(X)	1	(D)	-	-	(X)
Pine	-	-	(X)	-	-	7	(D)	(X)

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
TOTAL GREENHOUSE VEGETABLES AND FRESH CUT HERBS - Con.								
Counties - Con.								
Pipestone	2	(D)	(X)	2	(D)	2	(D)	(X)
Polk	4	(D)	(X)	4	(D)	6	20,450	(X)
Ramsey	3	714	(X)	3	1,500	14	73,657	(X)
Redwood	1	(D)	(X)	1	(D)	-	-	(X)
Renville	1	(D)	(X)	1	(D)	-	-	(X)
Rice	2	(D)	(X)	2	(D)	9	37,090	(X)
St. Louis	34	61,830	(X)	34	278,093	23	76,833	(X)
Scott	4	(D)	(X)	4	(D)	-	-	(X)
Sherburne	6	7,816	(X)	6	27,646	8	94,130	(X)
Stearns	3	6,972	(X)	3	32,299	7	140,948	(X)
Steele	6	(D)	(X)	6	(D)	2	(D)	(X)
Todd	4	35,084	(X)	4	150,548	11	68,000	(X)
Wabasha	1	(D)	(X)	1	(D)	1	(D)	(X)
Wadena	1	(D)	(X)	1	(D)	1	(D)	(X)
Washington	11	97,830	(X)	11	398,058	9	47,300	(X)
Watonwan	2	(D)	(X)	2	(D)	1	(D)	(X)
Winona	2	(D)	(X)	2	(D)	3	15,916	(X)
Wright	2	(D)	(X)	2	(D)	8	22,060	(X)
Yellow Medicine	-	-	(X)	-	-	1	(D)	(X)
GREENHOUSE TOMATOES								
State Total								
Minnesota	226	2,697,020	(X)	226	(D)	227	1,956,248	(X)
Counties								
Aitkin	6	7,536	(X)	6	47,567	7	11,040	(X)
Anoka	8	39,586	(X)	8	206,729	8	30,948	(X)
Becker	1	(D)	(X)	1	(D)	2	(D)	(X)
Beltrami	6	8,175	(X)	6	52,805	4	2,743	(X)
Benton	1	(D)	(X)	1	(D)	1	(D)	(X)
Blue Earth	6	2,592	(X)	6	9,000	1	(D)	(X)
Carlton	8	6,632	(X)	8	43,771	8	13,374	(X)
Cass	7	11,619	(X)	7	76,686	3	5,484	(X)
Chisago	12	10,812	(X)	12	71,360	7	21,075	(X)
Clay	1	(D)	(X)	1	(D)	-	-	(X)
Clearwater	7	12,325	(X)	7	(D)	2	(D)	(X)
Cook	2	(D)	(X)	2	(D)	3	432	(X)
Cottonwood	1	(D)	(X)	1	(D)	4	3,052	(X)
Crow Wing	6	1,394	(X)	6	(D)	7	9,899	(X)
Dakota	10	218,860	(X)	10	1,114,976	10	46,196	(X)
Dodge	1	(D)	(X)	1	(D)	-	-	(X)
Douglas	1	(D)	(X)	1	(D)	3	5,204	(X)
Faribault	-	-	(X)	-	-	1	(D)	(X)
Fillmore	7	36,048	(X)	7	231,384	4	(D)	(X)
Goodhue	3	6,616	(X)	3	40,193	4	5,844	(X)
Grant	-	-	(X)	-	-	1	(D)	(X)
Hennepin	3	(D)	(X)	3	(D)	5	6,500	(X)
Houston	-	-	(X)	-	-	6	900	(X)
Hubbard	1	(D)	(X)	1	(D)	3	(D)	(X)
Isanti	9	12,198	(X)	9	90,113	10	31,409	(X)
Itasca	9	7,764	(X)	9	51,242	4	(D)	(X)
Jackson	1	(D)	(X)	1	(D)	1	(D)	(X)
Kanabec	3	5,800	(X)	3	38,280	-	-	(X)
Kandiyohi	1	(D)	(X)	1	(D)	-	-	(X)
Kittson	-	-	(X)	-	-	1	(D)	(X)
Koochiching	2	(D)	(X)	2	(D)	-	-	(X)
Lake	2	(D)	(X)	2	(D)	3	396	(X)
Le Sueur	2	(D)	(X)	2	(D)	3	(D)	(X)
Lincoln	2	(D)	(X)	2	(D)	-	-	(X)
McLeod	2	(D)	(X)	2	(D)	1	(D)	(X)
Marshall	1	(D)	(X)	1	(D)	1	(D)	(X)
Martin	1	(D)	(X)	1	(D)	1	(D)	(X)
Meeker	3	580	(X)	3	3,828	1	(D)	(X)
Mille Lacs	3	4,455	(X)	3	29,404	3	(D)	(X)
Morrison	1	(D)	(X)	1	(D)	2	(D)	(X)
Nicollet	3	8,640	(X)	3	31,227	-	-	(X)
Nobles	-	-	(X)	-	-	1	(D)	(X)
Olmsted	3	(D)	(X)	3	(D)	3	1,000	(X)
Otter Tail	7	8,662	(X)	7	58,234	6	11,228	(X)
Pennington	1	(D)	(X)	1	(D)	-	-	(X)
Pine	-	-	(X)	-	-	7	(D)	(X)
Pipestone	1	(D)	(X)	1	(D)	2	(D)	(X)
Polk	4	(D)	(X)	4	(D)	6	15,099	(X)
Ramsey	-	-	(X)	-	-	7	57,735	(X)
Redwood	1	(D)	(X)	1	(D)	-	-	(X)
Renville	1	(D)	(X)	1	(D)	-	-	(X)
Rice	2	(D)	(X)	2	(D)	7	32,972	(X)
St. Louis	32	21,946	(X)	32	150,136	20	35,000	(X)
Scott	1	(D)	(X)	1	(D)	-	-	(X)
Sherburne	1	(D)	(X)	1	(D)	8	85,660	(X)
Stearns	3	(D)	(X)	3	(D)	7	(D)	(X)
Steele	5	(D)	(X)	5	(D)	2	(D)	(X)
Todd	4	(D)	(X)	4	87,644	7	27,040	(X)
Wabasha	1	(D)	(X)	1	(D)	1	(D)	(X)

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
GREENHOUSE TOMATOES - Con.								
Counties - Con.								
Wadena	1	(D)	(X)	1	(D)	1	(D)	(X)
Washington	10	43,170	(X)	10	284,922	6	23,000	(X)
Watonwan	2	(D)	(X)	2	(D)	1	(D)	(X)
Winona	1	(D)	(X)	1	(D)	2	(D)	(X)
Wright	2	(D)	(X)	2	(D)	7	9,820	(X)
Yellow Medicine	-	-	(X)	-	-	1	(D)	(X)
OTHER GREENHOUSE VEGETABLES AND FRESH CUT HERBS								
State Total								
Minnesota	199	1,012,377	(X)	199	(D)	220	548,116	(X)
Counties								
Aitkin	6	10,648	(X)	6	22,778	-	-	(X)
Anoka	11	59,236	(X)	11	118,695	5	19,838	(X)
Becker	-	-	(X)	-	-	1	(D)	(X)
Beltrami	5	5,963	(X)	5	(D)	13	14,057	(X)
Benton	1	(D)	(X)	1	(D)	1	(D)	(X)
Big Stone	1	(D)	(X)	1	(D)	-	-	(X)
Carlton	5	13,988	(X)	5	29,375	7	17,554	(X)
Cass	7	7,025	(X)	7	19,855	-	-	(X)
Chisago	8	25,759	(X)	8	54,094	12	13,335	(X)
Clay	1	(D)	(X)	1	(D)	-	-	(X)
Clearwater	5	6,289	(X)	5	(D)	2	(D)	(X)
Cook	1	(D)	(X)	1	(D)	6	5,864	(X)
Cottonwood	2	(D)	(X)	2	(D)	4	3,052	(X)
Crow Wing	4	7,595	(X)	4	13,661	5	65,418	(X)
Dakota	8	79,650	(X)	8	384,740	10	21,854	(X)
Douglas	1	(D)	(X)	1	(D)	4	12,742	(X)
Faribault	-	-	(X)	-	-	1	(D)	(X)
Fillmore	5	13,465	(X)	5	28,295	1	(D)	(X)
Freeborn	-	-	(X)	-	-	2	(D)	(X)
Goodhue	6	3,956	(X)	6	8,307	3	848	(X)
Grant	-	-	(X)	-	-	1	(D)	(X)
Hennepin	7	(D)	(X)	7	(D)	13	45,400	(X)
Houston	2	(D)	(X)	2	(D)	5	5,950	(X)
Hubbard	1	(D)	(X)	1	(D)	3	5,440	(X)
Isanti	8	20,220	(X)	8	36,203	9	19,603	(X)
Itasca	13	11,238	(X)	13	22,241	9	(D)	(X)
Jackson	1	(D)	(X)	1	(D)	1	(D)	(X)
Kanabec	4	7,511	(X)	4	15,773	2	(D)	(X)
Kittson	-	-	(X)	-	-	1	(D)	(X)
Koochiching	2	(D)	(X)	2	(D)	-	-	(X)
Lake	2	(D)	(X)	2	(D)	4	1,836	(X)
Le Sueur	1	(D)	(X)	1	(D)	1	(D)	(X)
McLeod	1	(D)	(X)	1	(D)	1	(D)	(X)
Marshall	1	(D)	(X)	1	(D)	1	(D)	(X)
Meeker	1	(D)	(X)	1	(D)	1	(D)	(X)
Mille Lacs	3	5,110	(X)	3	(D)	2	(D)	(X)
Morrison	1	(D)	(X)	1	(D)	2	(D)	(X)
Nicollet	3	8,640	(X)	3	18,144	-	-	(X)
Olmsted	1	(D)	(X)	1	(D)	1	(D)	(X)
Otter Tail	4	4,265	(X)	4	7,636	5	11,992	(X)
Pine	-	-	(X)	-	-	4	(D)	(X)
Pipestone	1	(D)	(X)	1	(D)	1	(D)	(X)
Polk	4	(D)	(X)	4	(D)	3	5,351	(X)
Ramsey	3	714	(X)	3	1,500	11	15,922	(X)
Redwood	1	(D)	(X)	1	(D)	-	-	(X)
Renville	1	(D)	(X)	1	(D)	-	-	(X)
Rice	1	(D)	(X)	1	(D)	8	4,118	(X)
St. Louis	23	39,884	(X)	23	127,957	20	41,833	(X)
Scott	4	1,220	(X)	4	2,562	-	-	(X)
Sherburne	5	(D)	(X)	5	(D)	4	8,470	(X)
Stearns	1	(D)	(X)	1	(D)	4	(D)	(X)
Steele	4	(D)	(X)	4	(D)	1	(D)	(X)
Todd	4	(D)	(X)	4	62,904	7	40,960	(X)
Wabasha	1	(D)	(X)	1	(D)	1	(D)	(X)
Wadena	1	(D)	(X)	1	(D)	1	(D)	(X)
Washington	7	54,660	(X)	7	113,136	8	24,300	(X)
Watonwan	2	(D)	(X)	2	(D)	-	-	(X)
Winona	2	(D)	(X)	2	(D)	3	(D)	(X)
Wright	1	(D)	(X)	1	(D)	4	12,240	(X)
Yellow Medicine	-	-	(X)	-	-	1	(D)	(X)
GREENHOUSE FRUITS AND BERRIES								
State Total								
Minnesota	53	207,992	(X)	53	673,700	38	68,997	(X)
Counties								
Aitkin	1	(D)	(X)	1	(D)	-	-	(X)
Anoka	3	5,370	(X)	3	18,258	3	4,965	(X)
Becker	-	-	(X)	-	-	1	(D)	(X)
Beltrami	-	-	(X)	-	-	2	(D)	(X)

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Table 34. **Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2022 and 2017** (continued)

[Totals may not add due to rounding. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017		
	Farms	Sq. ft. under glass or other protection	Acres in the open	Value of sales		Farms	Sq. ft. under glass or other protection	Acres in the open
				Farms	Dollars			
GREENHOUSE FRUITS AND BERRIES - Con.								
Counties - Con.								
Big Stone	1	(D)	(X)	1	(D)	-	-	(X)
Chippewa	-	-	(X)	-	-	1	(D)	(X)
Chisago	2	(D)	(X)	2	(D)	1	(D)	(X)
Clay	1	(D)	(X)	1	(D)	2	(D)	(X)
Cook	1	(D)	(X)	1	(D)	-	-	(X)
Crow Wing	-	-	(X)	-	-	2	(D)	(X)
Dakota	9	53,100	(X)	9	154,540	2	(D)	(X)
Douglas	2	(D)	(X)	2	(D)	3	6,750	(X)
Fillmore	2	(D)	(X)	2	(D)	-	-	(X)
Goodhue	1	(D)	(X)	1	(D)	2	(D)	(X)
Hennepin	-	-	(X)	-	-	2	(D)	(X)
Hubbard	1	(D)	(X)	1	(D)	2	(D)	(X)
Itasca	6	9,109	(X)	6	30,971	-	-	(X)
Lincoln	2	(D)	(X)	2	(D)	-	-	(X)
McLeod	2	(D)	(X)	2	(D)	-	-	(X)
Martin	1	(D)	(X)	1	(D)	1	(D)	(X)
Meeker	2	(D)	(X)	2	(D)	-	-	(X)
Mille Lacs	1	(D)	(X)	1	(D)	2	(D)	(X)
Otter Tail	2	(D)	(X)	2	(D)	1	(D)	(X)
Polk	1	(D)	(X)	1	(D)	1	(D)	(X)
Renville	1	(D)	(X)	1	(D)	-	-	(X)
Rice	1	(D)	(X)	1	(D)	-	-	(X)
St. Louis	-	-	(X)	-	-	8	19,979	(X)
Sherburne	3	4,320	(X)	3	14,688	-	-	(X)
Steele	1	(D)	(X)	1	(D)	-	-	(X)
Stevens	2	(D)	(X)	2	(D)	-	-	(X)
Todd	3	1,276	(X)	3	4,338	-	-	(X)
Washington	1	(D)	(X)	1	(D)	1	(D)	(X)
Winona	-	-	(X)	-	-	1	(D)	(X)
MUSHROOMS								
State Total								
Minnesota	34	85,172	(X)	34	5,940,836	7	11,145	(X)
Counties								
Beltrami	1	(D)	(X)	1	(D)	-	-	(X)
Blue Earth	1	(D)	(X)	1	(D)	-	-	(X)
Chisago	3	1,200	(X)	3	60,000	-	-	(X)
Fillmore	6	3,792	(X)	6	201,210	-	-	(X)
Hennepin	3	60,000	(X)	3	3,900,000	2	(D)	(X)
Itasca	2	(D)	(X)	2	(D)	-	-	(X)
Kanabec	3	300	(X)	3	900	-	-	(X)
McLeod	3	(D)	(X)	3	(D)	-	-	(X)
Morrison	1	(D)	(X)	1	(D)	-	-	(X)
Olmsted	2	(D)	(X)	2	(D)	1	(D)	(X)
Otter Tail	1	(D)	(X)	1	(D)	2	(D)	(X)
Sherburne	2	(D)	(X)	2	(D)	-	-	(X)
Stearns	1	(D)	(X)	1	(D)	1	(D)	(X)
Wabasha	1	(D)	(X)	1	(D)	-	-	(X)
Washington	1	(D)	(X)	1	(D)	-	-	(X)
Wright	3	9,000	(X)	3	237,000	1	(D)	(X)
MUSHROOM SPAWN								
State Total								
Minnesota	2	(X)	(X)	2	(D)	-	(X)	(X)
Counties								
Fillmore	2	(X)	(X)	2	(D)	-	(X)	(X)

Table 35. **Cultivated Christmas Trees: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017			
	Acres in production			Trees cut		Acres in production		Trees cut	
	Farms	Acres	Acres irrigated	Farms	Number	Farms	Acres	Farms	Number
State Total									
Minnesota	378	7,127	626	243	153,600	321	7,337	209	182,532
Counties									
Aitkin	7	(D)	-	4	(D)	6	139	6	2,435
Anoka	8	576	75	7	24,600	9	543	7	(D)
Becker	13	174	-	3	(D)	5	77	1	(D)
Beltrami	5	86	-	2	(D)	3	15	1	(D)
Benton	3	350	(D)	2	(D)	9	370	7	3,350
Blue Earth	4	30	(D)	1	(D)	-	-	-	-
Brown	1	(D)	-	-	-	1	(D)	1	(D)
Carlton	7	72	-	5	790	8	113	5	431
Carver	1	(D)	-	-	-	2	(D)	-	-
Cass	8	51	-	5	74	4	7	3	194
Chisago	12	273	-	12	1,401	14	147	12	2,202
Clay	-	-	-	-	-	1	(D)	1	(D)
Clearwater	1	(D)	-	-	-	-	-	-	-
Crow Wing	11	107	6	6	190	3	(D)	3	88
Dakota	-	-	-	-	-	5	73	4	536
Dodge	3	10	-	3	130	2	(D)	2	(D)
Douglas	4	11	-	1	(D)	3	114	1	(D)
Fillmore	1	(D)	-	1	(D)	1	(D)	1	(D)
Goodhue	8	76	-	3	1,151	8	38	2	(D)
Hennepin	4	30	-	4	90	4	12	2	(D)
Houston	1	(D)	-	-	-	1	(D)	-	-
Hubbard	5	190	160	-	-	-	-	-	-
Isanti	24	802	(D)	19	37,941	13	1,577	9	55,770
Itasca	9	567	-	5	5,656	7	113	5	2,287
Kanabec	9	94	-	5	438	7	60	5	616
Kandiyohi	2	(D)	-	2	(D)	2	(D)	1	(D)
Kittson	4	60	-	-	-	-	-	-	-
Koochiching	1	(D)	-	1	(D)	1	(D)	1	(D)
Lake	-	-	-	-	-	2	(D)	2	(D)
Lake of the Woods	4	52	-	2	(D)	2	(D)	-	-
Le Sueur	2	(D)	-	1	(D)	1	(D)	1	(D)
Lincoln	-	-	-	-	-	1	(D)	-	-
McLeod	2	(D)	-	1	(D)	1	(D)	1	(D)
Martin	1	(D)	-	1	(D)	1	(D)	1	(D)
Meeker	3	(D)	-	3	(D)	7	198	7	7,400
Mille Lacs	9	137	-	8	3,083	6	131	5	3,154
Morrison	7	99	(D)	6	828	12	139	7	1,502
Mower	1	(D)	-	-	-	-	-	-	-
Nicollet	1	(D)	-	-	-	2	(D)	2	(D)
Olmsted	18	136	-	10	1,327	14	60	9	424
Otter Tail	21	382	(D)	16	6,769	15	214	4	4,750
Pine	12	339	(D)	9	4,946	16	465	12	7,969
Pope	5	58	(D)	5	4,350	3	24	3	500
Red Lake	-	-	-	-	-	1	(D)	1	(D)
Redwood	1	(D)	-	1	(D)	1	(D)	1	(D)
Rice	15	114	12	5	1,500	5	54	2	(D)
Rock	1	(D)	-	-	-	-	-	-	-
Roseau	9	111	-	6	240	4	101	3	28
St. Louis	24	185	(D)	15	3,642	21	304	5	3,049
Scott	4	101	-	3	1,029	5	152	5	2,457
Sherburne	10	465	106	8	9,753	18	998	12	48,378
Stearns	11	55	-	7	65	10	68	3	(D)
Steele	-	-	-	-	-	1	(D)	-	-
Stevens	-	-	-	-	-	1	(D)	1	(D)
Todd	7	182	-	2	(D)	6	131	3	(D)
Wabasha	13	146	-	8	1,160	5	62	5	635
Wadena	-	-	-	-	-	2	(D)	1	(D)
Washington	19	262	9	17	8,555	15	291	14	6,656
Wilkin	-	-	-	-	-	1	(D)	-	-
Winona	8	32	(D)	6	132	11	41	11	2,590
Wright	14	125	(D)	12	1,921	11	86	8	(D)
Yellow Medicine	-	-	-	-	-	1	(D)	-	-

Table 36. **Short Rotation Woody Crops: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022					2017				
	Acres in production			Acres harvested		Acres in production			Acres harvested	
	Farms	Acres	Acres irrigated	Farms	Acres	Farms	Acres	Acres irrigated	Farms	Acres
State Total										
Minnesota	5	290	-	1	(D)	77	1,808	24	28	110
Counties										
Aitkin	-	-	-	-	-	2	(D)	-	-	-
Becker	-	-	-	-	-	1	(D)	-	-	-
Beltrami	-	-	-	-	-	1	(D)	-	-	-
Blue Earth	-	-	-	-	-	2	(D)	-	2	(D)
Carlton	2	(D)	-	-	-	-	-	-	-	-
Chisago	-	-	-	-	-	3	114	(D)	3	6
Clearwater	-	-	-	-	-	2	(D)	-	-	-
Crow Wing	-	-	-	-	-	2	(D)	-	2	(D)
Dakota	-	-	-	-	-	2	(D)	-	1	(D)
Douglas	2	(D)	-	-	-	2	(D)	-	-	-
Fillmore	-	-	-	-	-	2	(D)	-	2	(D)
Goodhue	-	-	-	-	-	1	(D)	-	-	-
Houston	-	-	-	-	-	1	(D)	-	1	(D)
Hubbard	-	-	-	-	-	4	40	-	-	-
Isanti	-	-	-	-	-	2	(D)	-	-	-
Itasca	-	-	-	-	-	1	(D)	-	1	(D)
Kanabec	-	-	-	-	-	2	(D)	-	-	-
Kandiyohi	-	-	-	-	-	2	(D)	-	-	-
Lake of the Woods	-	-	-	-	-	3	80	-	-	-
Mahnomen	-	-	-	-	-	1	(D)	-	1	(D)
Marshall	-	-	-	-	-	2	(D)	(D)	2	(D)
Mille Lacs	-	-	-	-	-	1	(D)	-	-	-
Morrison	1	(D)	-	1	(D)	2	(D)	-	2	(D)
Olmsted	-	-	-	-	-	1	(D)	-	1	(D)
Otter Tail	-	-	-	-	-	6	111	-	-	-
Pine	-	-	-	-	-	3	50	-	1	(D)
Polk	-	-	-	-	-	1	(D)	-	-	-
Rice	-	-	-	-	-	1	(D)	-	-	-
Roseau	-	-	-	-	-	2	(D)	-	1	(D)
St. Louis	-	-	-	-	-	3	(D)	-	1	(D)
Sherburne	-	-	-	-	-	1	(D)	-	-	-
Sibley	-	-	-	-	-	1	(D)	-	1	(D)
Stearns	-	-	-	-	-	3	11	(D)	1	(D)
Todd	-	-	-	-	-	6	228	-	2	(D)
Wabasha	-	-	-	-	-	2	(D)	-	-	-
Wadena	-	-	-	-	-	2	(D)	-	-	-
Washington	-	-	-	-	-	1	(D)	-	-	-
Winona	-	-	-	-	-	3	13	-	3	7

Table 37. **Maple Syrup: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	2022			2017		
	Farms	Number of taps	Syrup produced (gallons)	Farms	Number of taps	Syrup produced (gallons)
State Total						
Minnesota	364	97,822	21,507	291	99,205	19,102
Counties						
Aitkin	12	(D)	(D)	10	6,216	(D)
Anoka	14	556	102	6	165	23
Becker	12	1,757	299	4	1,604	128
Beltrami	6	646	112	2	(D)	(D)
Benton	-	-	-	2	(D)	(D)
Blue Earth	4	(D)	(D)	2	(D)	(D)
Brown	-	-	-	3	114	6
Carlton	17	4,706	1,089	12	5,014	851
Carver	7	908	172	2	(D)	(D)
Cass	5	(D)	(D)	4	10,219	826
Chisago	29	10,667	1,160	26	8,176	1,134
Clearwater	2	(D)	(D)	1	(D)	(D)
Cook	3	(D)	(D)	3	(D)	(D)
Crow Wing	6	995	281	7	540	79
Dakota	6	288	61	1	(D)	(D)
Dodge	-	-	-	2	(D)	(D)
Douglas	7	3,910	580	6	350	52
Fillmore	5	163	38	4	1,480	172
Goodhue	9	200	74	9	1,027	159
Hennepin	12	7,200	994	7	1,520	516
Houston	2	(D)	(D)	2	(D)	(D)
Hubbard	4	181	26	4	200	28
Isanti	6	585	118	8	1,765	222
Itasca	18	5,146	1,215	7	3,980	1,077
Kanabec	7	1,030	169	8	600	92
Kandiyohi	1	(D)	(D)	2	(D)	(D)
Lake	1	(D)	(D)	4	2,700	325
Lake of the Woods	1	(D)	(D)	-	-	-
Le Sueur	4	218	80	4	311	95
McLeod	7	94	32	5	1,480	350
Mahnomen	3	750	159	2	(D)	(D)
Martin	2	(D)	(D)	-	-	-
Meeker	1	(D)	(D)	1	(D)	(D)
Mille Lacs	8	1,863	454	9	1,110	131
Morrison	10	764	283	6	419	87
Mower	-	-	-	1	(D)	(D)
Murray	-	-	-	1	(D)	(D)
Nicollet	4	300	92	1	(D)	(D)
Nobles	1	(D)	(D)	-	-	-
Olmsted	8	164	34	4	250	52
Otter Tail	9	4,132	911	19	3,570	484
Pine	9	2,525	680	7	970	105
Polk	-	-	-	2	(D)	(D)
Ramsey	1	(D)	(D)	-	-	-
Renville	-	-	-	1	(D)	(D)
Rice	7	1,545	610	10	1,140	363
Rock	-	-	-	1	(D)	(D)
St. Louis	34	7,080	1,405	11	7,092	914
Scott	1	(D)	(D)	4	600	60
Sherburne	1	(D)	(D)	1	(D)	(D)
Sibley	3	230	58	1	(D)	(D)
Stearns	11	3,398	(D)	8	4,444	983
Steele	1	(D)	(D)	1	(D)	(D)
Stevens	2	(D)	(D)	-	-	-
Todd	5	(D)	(D)	10	2,183	372
Wabasha	1	(D)	(D)	2	(D)	(D)
Wadena	2	(D)	(D)	4	(D)	(D)
Waseca	1	(D)	(D)	1	(D)	(D)
Washington	16	2,588	598	3	380	(D)
Wilkin	1	(D)	(D)	-	-	-
Winona	4	140	38	-	-	-
Wright	11	700	119	17	1,692	356
Yellow Medicine	-	-	-	6	120	12

Table 38. **Commodities Raised and Delivered Under Production Contracts: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Number
BROILERS AND OTHER MEAT-TYPE CHICKENS		
State Total		
Minnesota	119	41,480,700
Counties		
Benton	23	7,125,000
Cottonwood	3	490,000
Crow Wing	1	(D)
Mille Lacs	1	(D)
Morrison	58	20,610,700
Sherburne	1	(D)
Stearns	32	11,983,000
EGGS, CHICKEN (DOZENS)		
State Total		
Minnesota	39	51,924,410
Counties		
Benton	2	(D)
Blue Earth	1	(D)
Fillmore	2	(D)
Morrison	18	19,724,180
Sherburne	1	(D)
Sibley	1	(D)
Stearns	13	17,283,110
Waseca	1	(D)
LAYERS		
State Total		
Minnesota	36	1,727,454
Counties		
Benton	2	(D)
Fillmore	2	(D)
Morrison	18	925,394
Stearns	13	764,100
Waseca	1	(D)
PULLETS FOR LAYING FLOCK REPLACEMENT		
State Total		
Minnesota	13	3,754,000
Counties		
Benton	3	(D)
Morrison	5	(D)
Nicollet	1	(D)
Renville	1	(D)
Stearns	3	384,000
TURKEYS		
State Total		
Minnesota	60	5,699,214
Counties		
Aitkin	5	150,000
Becker	1	(D)
Brown	1	(D)
Cass	1	(D)
Chippewa	2	(D)
Dodge	1	(D)
Douglas	1	(D)
Fillmore	1	(D)
Freeborn	5	174,000
Houston	1	(D)
Kandiyohi	4	713,300
Lac qui Parle	2	(D)
Le Sueur	6	270,500
Meeker	1	(D)
Morrison	3	318,000
Mower	1	(D)
Otter Tail	2	(D)
Redwood	6	72,000
Renville	1	(D)
Rice	1	(D)
Roseau	1	(D)
Stearns	5	797,414
TURKEYS - Con.		
Counties - Con.		
Steele	1	(D)
Swift	2	(D)
Todd	1	(D)
Waseca	4	282,000
CUSTOM FED CATTLE SHIPPED DIRECTLY FOR SLAUGHTER		
State Total		
Minnesota	59	44,297
Counties		
Brown	4	1,521
Faribault	2	(D)
Fillmore	5	1,250
Houston	2	(D)
Lincoln	1	(D)
Lyon	3	2,750
Martin	2	(D)
Mower	4	710
Murray	4	1,100
Nobles	5	11,455
Redwood	2	(D)
Renville	1	(D)
Rock	15	11,515
Stearns	2	(D)
Steele	2	(D)
Stevens	1	(D)
Swift	1	(D)
Waseca	3	2,700
HOGS AND PIGS		
State Total		
Minnesota	1,294	12,102,347
Counties		
Becker	1	(D)
Benton	5	28,200
Big Stone	1	(D)
Blue Earth	78	1,093,337
Brown	34	376,154
Chippewa	14	118,100
Cottonwood	42	416,012
Dakota	1	(D)
Dodge	26	310,496
Douglas	2	(D)
Faribault	40	594,643
Fillmore	40	168,507
Freeborn	39	309,468
Goodhue	42	268,142
Houston	1	(D)
Isanti	5	150,000
Jackson	40	287,733
Kandiyohi	12	61,950
Lac qui Parle	36	452,800
Le Sueur	27	100,689
Lincoln	6	71,700
Lyon	40	481,480
McLeod	1	(D)
Martin	128	1,159,794
Meeker	1	(D)
Morrison	24	94,750
Mower	37	351,905
Murray	36	234,683
Nicollet	69	496,263
Nobles	71	678,040
Norman	1	(D)
Olmsted	2	(D)
Pipestone	13	124,940
Pope	2	(D)
Redwood	59	530,727
Renville	38	391,366
Rice	21	214,950
Rock	66	447,146
Sibley	18	193,730
Stearns	18	70,426
Steele	38	438,164
Stevens	13	52,627
Traverse	3	14,400

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Table 38. **Commodities Raised and Delivered Under Production Contracts: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Number
HOGS AND PIGS - Con.		
Counties - Con.		
Wabasha	9	177,200
Waseca	30	276,037
Watonwan	44	382,010
Yellow Medicine	20	318,640
REPLACEMENT DAIRY HEIFERS		
State Total		
Minnesota	122	58,947
Counties		
Beltrami	6	180
Big Stone	1	(D)
Brown	3	150
Chisago	2	(D)
Fillmore	5	422
Freeborn	1	(D)
Goodhue	13	9,030
Houston	7	10,211
Kandiyohi	5	5,900
Le Sueur	4	196
McLeod	4	1,610
Mille Lacs	5	5,280
Morrison	1	(D)
Murray	1	(D)
Nobles	4	4,200
Olmsted	2	(D)
Otter Tail	11	1,040
Pipestone	3	820
Pope	1	(D)
Renville	2	(D)
Rice	2	(D)
Rock	4	900
Stearns	7	1,560
Swift	1	(D)
Todd	3	850
Wabasha	5	800
Waseca	3	3,150
Winona	10	4,501
Wright	1	(D)
Yellow Medicine	5	4,300
OTHER CATTLE, SHEEP, LIVESTOCK, OR POULTRY		
State Total		
Minnesota	25	(X)
Counties		
Cass	5	(X)
Cottonwood	2	(X)
Lincoln	1	(X)
Lyon	6	(X)

Geographic area	Farms	Number
OTHER CATTLE, SHEEP, LIVESTOCK, OR POULTRY - Con.		
Counties - Con.		
Murray	3	(X)
Nobles	1	(X)
Sherburne	2	(X)
Wadena	3	(X)
Yellow Medicine	2	(X)
GRAINS, OILSEEDS, VEGETABLES, MELONS, POTATOES, AND OTHER CROPS		
State Total		
Minnesota	951	(X)
Counties		
Benton	1	(X)
Big Stone	1	(X)
Blue Earth	12	(X)
Brown	24	(X)
Chippewa	9	(X)
Cottonwood	4	(X)
Dakota	93	(X)
Dodge	23	(X)
Faribault	40	(X)
Fillmore	5	(X)
Freeborn	26	(X)
Goodhue	41	(X)
Houston	1	(X)
Jackson	2	(X)
Kandiyohi	37	(X)
Le Sueur	12	(X)
McLeod	17	(X)
Martin	39	(X)
Meeker	8	(X)
Morrison	2	(X)
Mower	66	(X)
Nicollet	9	(X)
Norman	2	(X)
Olmsted	89	(X)
Polk	2	(X)
Pope	13	(X)
Redwood	14	(X)
Renville	142	(X)
Rice	10	(X)
Scott	2	(X)
Sibley	41	(X)
Stearns	20	(X)
Steele	14	(X)
Swift	4	(X)
Wabasha	58	(X)
Waseca	35	(X)
Watonwan	12	(X)
Wilkin	1	(X)
Winona	20	(X)

Table 39. **Machinery and Equipment on Operation: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment	farms, 2022	65,531	449	355	952	608
	2017	68,788	462	360	942	582
	$1,000, 2022	17,904,134	40,480	42,750	209,307	61,968
	2017	15,385,551	33,278	44,122	143,035	39,100
Average per farm	dollars, 2022	273,216	90,155	120,422	219,860	101,921
	2017	223,666	72,031	122,561	151,842	67,182
Farms by value group:						
$1 to $9,999	2022	7,121	37	41	143	72
	2017	8,823	74	61	164	76
$10,000 to $19,999	2022	6,447	55	43	85	68
	2017	7,585	65	32	155	105
$20,000 to $29,999	2022	5,450	29	43	126	54
	2017	6,334	55	51	92	80
$30,000 to $49,999	2022	6,933	72	57	113	105
	2017	7,589	80	46	107	85
$50,000 to $69,999	2022	5,828	58	55	87	65
	2017	5,747	55	45	104	66
$70,000 to $99,999	2022	4,678	52	26	67	50
	2017	4,827	25	21	54	47
$100,000 to $199,999	2022	9,020	101	36	128	123
	2017	8,734	68	63	109	79
$200,000 to $499,999	2022	9,719	40	36	104	52
	2017	9,982	36	24	76	38
$500,000 or more	2022	10,335	5	18	99	19
	2017	9,167	4	17	81	6
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups	farms, 2022	51,156	362	273	667	493
	2017	54,590	381	277	685	502
	number, 2022	127,301	691	524	1,713	916
	2017	127,910	604	531	1,630	931
Tractors	farms, 2022	52,770	399	280	705	507
	2017	56,422	405	287	753	526
	number, 2022	184,473	1,254	659	2,327	1,475
	2017	198,583	1,132	838	2,314	1,404
Less than 40 horsepower (PTO)	farms, 2022	22,815	222	151	333	228
	2017	25,328	231	157	338	230
	number, 2022	36,863	392	240	569	370
	2017	40,957	351	261	522	331
40 to 99 horsepower (PTO)	farms, 2022	35,619	329	189	478	365
	2017	39,967	331	202	528	379
	number, 2022	60,537	605	295	771	637
	2017	70,470	583	417	902	659
100 horsepower (PTO) or more	farms, 2022	31,912	137	69	323	220
	2017	34,377	123	81	355	187
	number, 2022	87,073	257	124	987	468
	2017	87,156	198	160	890	414
Grain and bean combines, self-propelled	farms, 2022	21,753	40	25	189	123
	2017	24,390	46	56	203	84
	number, 2022	25,736	42	31	267	157
	2017	27,944	47	65	265	112
Cotton pickers and strippers, self-propelled	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
	number, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Forage harvesters, self-propelled	farms, 2022	2,195	10	5	29	25
	2017	2,854	16	10	43	26
	number, 2022	2,384	14	5	30	30
	2017	3,075	19	10	55	28
Hay balers	farms, 2022	19,296	242	110	335	266
	2017	22,933	247	127	365	284
	number, 2022	24,300	329	134	423	338
	2017	29,164	314	163	488	362
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups	farms	13,424	67	52	134	69
	number	17,745	72	77	195	74
Tractors	farms	7,605	55	47	89	35
	number	12,615	67	71	151	70
Less than 40 horsepower (PTO)	farms	2,008	9	21	18	11
	number	2,302	9	21	19	35
40 to 99 horsepower (PTO)	farms	2,626	41	25	33	24
	number	3,059	45	32	33	28
100 horsepower (PTO) or more	farms	4,117	12	13	48	7
	number	7,254	13	18	99	7
Grain and bean combines	farms	2,584	-	1	15	-
	number	2,858	-	(D)	21	-
Cotton pickers and strippers	farms	-	-	-	-	-
	number	-	-	-	-	-
Forage harvesters, self-propelled	farms	175	1	-	2	1
	number	191	(D)	-	(D)	(D)
Hay balers	farms	1,673	15	9	25	11
	number	1,791	15	10	26	11

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
VALUE OF MACHINERY AND EQUIPMENT					
Estimated market value of all machinery and equipment ..... farms, 2022	687	392	1,019	973	463
2017	816	438	982	1,040	529
$1,000, 2022	135,496	162,740	409,468	259,726	42,696
2017	147,971	135,226	279,123	251,240	37,105
Average per farm ..... dollars, 2022	197,229	415,153	401,833	266,933	92,216
2017	181,337	308,736	284,239	241,577	70,143
Farms by value group:					
$1 to $9,999 2022	43	39	71	117	33
2017	111	36	78	89	62
$10,000 to $19,999 2022	73	32	59	39	55
2017	74	33	93	71	84
$20,000 to $29,999 2022	61	27	67	62	58
2017	82	46	86	73	60
$30,000 to $49,999 2022	110	17	131	56	65
2017	85	53	108	110	94
$50,000 to $69,999 2022	56	30	83	83	65
2017	90	25	109	54	45
$70,000 to $99,999 2022	45	38	53	60	46
2017	47	38	54	109	59
$100,000 to $199,999 2022	121	37	134	145	77
2017	134	51	101	156	87
$200,000 to $499,999 2022	120	58	155	217	57
2017	105	63	161	222	36
$500,000 or more 2022	58	114	266	194	7
2017	88	93	192	156	2
SELECTED MACHINERY AND EQUIPMENT					
Trucks, including pickups ..... farms, 2022	563	315	810	782	376
2017	668	339	791	852	435
number, 2022	1,049	1,140	2,313	1,949	563
2017	1,143	1,102	2,146	2,112	663
Tractors ..... farms, 2022	579	310	848	806	379
2017	713	351	795	868	470
number, 2022	2,060	1,200	3,099	3,112	1,094
2017	2,571	1,265	2,909	3,554	1,320
Less than 40 horsepower (PTO) ..... farms, 2022	312	110	352	300	222
2017	367	127	362	416	265
number, 2022	539	166	586	471	364
2017	603	217	581	690	433
40 to 99 horsepower (PTO) ..... farms, 2022	423	186	584	553	288
2017	534	233	567	667	362
number, 2022	741	310	924	949	543
2017	936	353	978	1,210	668
100 horsepower (PTO) or more ..... farms, 2022	330	245	570	645	115
2017	427	258	534	677	139
number, 2022	780	724	1,589	1,692	187
2017	1,032	695	1,350	1,654	219
Grain and bean combines, self-propelled ..... farms, 2022	213	204	482	504	21
2017	303	183	469	569	38
number, 2022	231	264	536	555	22
2017	340	226	497	607	38
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-
2017	-	-	-	-	-
number, 2022	-	-	-	-	-
2017	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	45	4	15	32	18
2017	66	1	25	53	14
number, 2022	52	5	15	32	20
2017	72	(D)	28	53	14
Hay balers ..... farms, 2022	312	85	159	232	240
2017	385	105	199	310	331
number, 2022	392	104	190	276	333
2017	498	123	251	371	460
2022 INVENTORY					
Manufactured 2017 to 2022:					
Trucks, including pickups ..... farms	130	100	288	166	66
number	168	158	395	216	76
Tractors ..... farms	61	49	153	72	80
number	87	91	242	99	92
Less than 40 horsepower (PTO) ..... farms	23	15	35	16	27
number	24	15	42	17	30
40 to 99 horsepower (PTO) ..... farms	27	12	50	18	37
number	28	16	55	20	40
100 horsepower (PTO) or more ..... farms	27	29	88	52	19
number	35	60	145	62	22
Grain and bean combines ..... farms	3	27	84	63	-
number	3	34	86	68	-
Cotton pickers and strippers ..... farms	-	-	-	-	-
number	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	2	1	-	-	-
number	(D)	(D)	-	-	-
Hay balers ..... farms	33	6	2	15	36
number	34	6	(D)	15	37

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	606	488	563	740	655	404
2017	689	432	623	821	692	414
$1,000, 2022	158,429	47,814	274,154	77,167	254,196	61,416
2017	150,229	36,234	219,908	77,622	254,351	47,029
Average per farm ..... dollars, 2022	261,434	97,980	486,951	104,280	388,085	152,019
2017	218,040	83,876	352,983	94,546	367,559	113,597
Farms by value group:						
$1 to $9,999 2022	73	59	63	81	50	39
2017	94	67	66	143	68	71
$10,000 to $19,999 2022	56	56	43	111	61	42
2017	62	70	52	125	61	60
$20,000 to $29,999 2022	30	43	26	55	65	46
2017	50	45	60	102	77	62
$30,000 to $49,999 2022	77	68	73	114	51	43
2017	61	70	70	116	39	33
$50,000 to $69,999 2022	55	62	25	103	47	35
2017	80	34	34	66	45	23
$70,000 to $99,999 2022	56	63	38	79	23	54
2017	45	33	46	47	56	41
$100,000 to $199,999 2022	81	77	59	86	89	61
2017	97	67	65	118	101	58
$200,000 to $499,999 2022	90	52	92	89	96	61
2017	99	34	84	78	80	51
$500,000 or more 2022	88	8	144	22	173	23
2017	101	12	146	26	165	15
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	488	411	441	561	545	318
2017	551	350	485	672	598	337
number, 2022	975	672	1,474	946	2,202	768
2017	1,009	573	1,606	1,021	2,073	705
Tractors ..... farms, 2022	517	412	444	597	575	325
2017	599	358	481	695	585	359
number, 2022	1,924	1,019	1,557	1,541	2,519	1,081
2017	2,288	959	1,806	2,005	2,286	1,068
Less than 40 horsepower (PTO) ..... farms, 2022	245	167	146	295	273	141
2017	302	182	194	357	236	165
number, 2022	465	245	211	424	521	223
2017	489	272	303	588	456	245
40 to 99 horsepower (PTO) ..... farms, 2022	389	320	260	396	353	234
2017	469	286	300	493	332	282
number, 2022	735	585	374	661	672	420
2017	936	504	473	850	585	482
100 horsepower (PTO) or more ..... farms, 2022	286	121	324	222	376	173
2017	350	95	356	274	429	174
number, 2022	724	189	972	456	1,326	438
2017	863	183	1,030	567	1,245	341
Grain and bean combines, self-propelled ..... farms, 2022	211	27	235	129	293	59
2017	289	23	262	173	334	72
number, 2022	241	30	257	146	455	81
2017	316	24	288	210	455	101
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	41	14	8	11	11	17
2017	51	10	4	19	12	20
number, 2022	45	15	9	11	14	20
2017	51	12	(D)	22	12	20
Hay balers ..... farms, 2022	272	236	82	224	169	202
2017	318	226	85	294	190	206
number, 2022	344	296	96	288	209	253
2017	426	281	97	388	231	251
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	99	78	153	151	162	53
number	146	84	225	169	219	81
Tractors ..... farms	70	48	97	69	93	30
number	115	59	226	82	194	41
Less than 40 horsepower (PTO) ..... farms	19	21	16	24	33	8
number	21	24	20	24	36	10
40 to 99 horsepower (PTO) ..... farms	36	24	24	30	35	5
number	51	29	27	32	36	8
100 horsepower (PTO) or more ..... farms	26	5	66	23	54	20
number	43	6	179	26	122	23
Grain and bean combines ..... farms	20	-	55	2	21	1
number	20	-	62	(D)	26	(D)
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	11	-	2	-	2	1
number	11	-	(D)	-	(D)	(D)
Hay balers ..... farms	27	12	1	15	17	29
number	32	12	(D)	15	18	29

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	25	742	426	841	614	980
2017	32	744	494	820	611	960
$1,000, 2022	2,163	345,752	49,626	199,084	217,546	154,227
2017	638	289,389	46,021	186,486	173,216	133,108
Average per farm ..... dollars, 2022	86,505	465,973	116,492	236,723	354,310	157,375
2017	19,944	388,964	93,161	227,421	283,496	138,654
Farms by value group:						
$1 to $9,999 2022	2	91	62	86	60	172
2017	12	106	77	105	45	184
$10,000 to $19,999 2022	1	40	49	73	44	110
2017	8	38	80	94	77	132
$20,000 to $29,999 2022	2	30	55	82	44	96
2017	6	37	46	65	65	104
$30,000 to $49,999 2022	5	48	55	100	71	114
2017	4	56	73	102	69	98
$50,000 to $69,999 2022	6	43	40	111	60	94
2017	-	37	53	83	77	82
$70,000 to $99,999 2022	6	42	52	35	43	75
2017	1	42	44	45	46	53
$100,000 to $199,999 2022	1	93	63	115	107	97
2017	1	70	68	96	63	112
$200,000 to $499,999 2022	2	134	33	143	51	148
2017	-	153	41	120	51	124
$500,000 or more 2022	-	221	17	96	134	74
2017	-	205	12	110	118	71
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	19	594	349	660	504	682
2017	22	605	416	613	482	703
number, 2022	26	1,909	599	1,656	1,218	1,509
2017	33	1,718	655	1,589	1,189	1,418
Tractors ..... farms, 2022	20	578	360	682	514	749
2017	19	612	423	629	486	764
number, 2022	45	2,380	1,057	2,404	1,911	2,254
2017	32	2,430	1,244	2,320	1,813	2,620
Less than 40 horsepower (PTO) ..... farms, 2022	17	216	194	338	249	327
2017	17	235	242	309	261	386
number, 2022	34	330	299	523	378	517
2017	24	383	428	556	415	688
40 to 99 horsepower (PTO) ..... farms, 2022	9	375	260	451	336	500
2017	5	400	303	449	341	564
number, 2022	(D)	645	500	829	636	855
2017	(D)	675	596	819	567	938
100 horsepower (PTO) or more ..... farms, 2022	1	482	125	370	317	395
2017	1	508	139	347	309	416
number, 2022	(D)	1,405	258	1,052	897	882
2017	(D)	1,372	220	945	831	994
Grain and bean combines, self-propelled ..... farms, 2022	-	353	42	241	210	263
2017	-	400	46	244	218	305
number, 2022	-	398	51	257	243	308
2017	-	435	50	264	251	349
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	-	24	15	19	22	39
2017	-	30	18	19	17	48
number, 2022	-	24	15	21	22	47
2017	-	32	20	19	18	52
Hay balers ..... farms, 2022	10	164	209	194	168	284
2017	5	165	232	206	161	320
number, 2022	12	197	254	233	208	356
2017	9	190	296	264	205	414
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	1	199	60	194	139	146
number	(D)	422	83	336	172	197
Tractors ..... farms	4	132	48	148	97	122
number	(D)	324	52	335	148	154
Less than 40 horsepower (PTO) ..... farms	4	16	16	58	32	43
number	(D)	16	(D)	72	32	46
40 to 99 horsepower (PTO) ..... farms	-	28	32	48	31	52
number	-	30	34	78	37	55
100 horsepower (PTO) or more ..... farms	-	109	2	83	45	38
number	-	278	(D)	185	79	53
Grain and bean combines ..... farms	-	81	4	41	49	12
number	-	81	4	44	55	12
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	-	3	-	6	-	8
number	-	3	-	6	-	10
Hay balers ..... farms	-	29	18	19	6	22
number	-	39	18	19	9	22

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	773	1,458	908	1,406	529	511
2017	822	1,400	1,076	1,461	524	467
$1,000, 2022	306,051	391,562	303,555	385,283	197,819	53,901
2017	289,545	259,554	269,432	321,382	156,670	62,265
Average per farm ..... dollars, 2022	395,926	268,561	334,311	274,028	373,950	105,481
2017	352,244	185,396	250,401	219,974	298,988	133,330
Farms by value group:						
$1 to $9,999 2022	68	99	82	129	56	79
2017	40	172	126	156	53	66
$10,000 to $19,999 2022	62	118	78	135	78	73
2017	57	149	119	130	65	58
$20,000 to $29,999 2022	48	161	54	96	53	63
2017	36	135	94	112	46	35
$30,000 to $49,999 2022	43	176	78	147	66	52
2017	101	171	89	133	64	65
$50,000 to $69,999 2022	67	124	72	144	41	84
2017	53	151	70	139	42	58
$70,000 to $99,999 2022	32	122	36	103	21	36
2017	65	102	54	141	36	25
$100,000 to $199,999 2022	89	205	139	167	47	58
2017	81	174	155	222	51	71
$200,000 to $499,999 2022	151	212	192	233	65	46
2017	196	181	191	263	75	67
$500,000 or more 2022	213	241	177	252	102	20
2017	193	165	178	165	92	22
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	683	1,122	723	1,180	352	370
2017	685	1,081	862	1,258	376	324
number, 2022	1,900	2,417	2,018	2,625	1,019	621
2017	1,930	2,072	2,154	2,557	1,161	574
Tractors ..... farms, 2022	666	1,179	732	1,194	342	363
2017	669	1,134	853	1,266	372	337
number, 2022	2,447	3,854	2,696	4,126	1,075	876
2017	2,624	3,693	3,112	4,266	1,402	905
Less than 40 horsepower (PTO) ..... farms, 2022	256	458	303	520	145	219
2017	247	417	355	516	155	176
number, 2022	430	723	477	816	188	317
2017	397	619	664	842	299	276
40 to 99 horsepower (PTO) ..... farms, 2022	420	782	451	793	204	221
2017	428	849	558	899	232	198
number, 2022	660	1,232	786	1,371	268	374
2017	812	1,511	890	1,565	348	365
100 horsepower (PTO) or more ..... farms, 2022	496	664	549	725	226	109
2017	526	626	583	757	252	134
number, 2022	1,357	1,899	1,433	1,939	619	185
2017	1,415	1,563	1,558	1,859	755	264
Grain and bean combines, self-propelled ..... farms, 2022	411	433	430	425	176	45
2017	459	407	470	450	218	72
number, 2022	442	512	485	482	251	49
2017	497	436	503	486	261	74
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	23	60	8	48	6	14
2017	13	53	29	61	10	17
number, 2022	23	68	9	57	7	14
2017	14	54	29	69	10	18
Hay balers ..... farms, 2022	89	428	205	380	54	127
2017	108	486	213	472	64	157
number, 2022	96	546	261	449	77	163
2017	126	590	266	570	96	209
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	255	364	210	289	145	73
number	350	488	267	329	189	170
Tractors ..... farms	123	199	103	181	71	49
number	234	305	158	318	140	68
Less than 40 horsepower (PTO) ..... farms	30	47	31	61	27	29
number	31	50	33	67	27	35
40 to 99 horsepower (PTO) ..... farms	41	61	19	52	10	14
number	53	76	31	63	10	21
100 horsepower (PTO) or more ..... farms	76	120	65	104	40	12
number	150	179	94	188	103	12
Grain and bean combines ..... farms	76	69	54	76	24	-
number	81	69	57	83	26	-
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	-	5	-	7	2	-
number	-	7	-	7	(D)	-
Hay balers ..... farms	3	50	3	43	5	13
number	3	50	3	47	6	13

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	797	336	814	424	845	531
2017	890	384	805	337	799	624
$1,000, 2022	165,816	46,646	94,946	42,532	299,422	54,356
2017	116,513	41,105	81,041	22,648	246,677	55,642
Average per farm ..... dollars, 2022	208,050	138,828	116,641	100,310	354,345	102,366
2017	130,913	107,044	100,672	67,203	308,732	89,170
Farms by value group:						
$1 to $9,999 2022	76	34	99	57	23	68
2017	111	72	125	79	97	96
$10,000 to $19,999 2022	87	49	57	55	84	84
2017	120	70	102	26	37	106
$20,000 to $29,999 2022	74	57	99	33	64	81
2017	93	36	105	35	73	75
$30,000 to $49,999 2022	99	51	99	69	73	74
2017	142	63	153	61	73	106
$50,000 to $69,999 2022	90	27	94	42	74	40
2017	81	35	87	42	64	42
$70,000 to $99,999 2022	58	33	89	44	46	46
2017	55	36	38	24	40	68
$100,000 to $199,999 2022	123	50	158	60	115	74
2017	122	42	103	44	93	60
$200,000 to $499,999 2022	95	15	94	49	160	38
2017	122	18	56	24	165	60
$500,000 or more 2022	95	20	25	15	206	26
2017	44	12	36	2	157	11
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	601	265	623	344	719	403
2017	621	329	655	262	650	501
number, 2022	1,029	551	1,089	670	1,915	699
2017	1,025	545	1,074	478	1,829	729
Tractors ..... farms, 2022	650	284	663	352	671	436
2017	734	312	686	279	620	538
number, 2022	2,261	704	1,628	964	2,674	1,271
2017	2,342	802	1,797	816	2,554	1,467
Less than 40 horsepower (PTO) ..... farms, 2022	279	140	312	182	249	210
2017	290	159	329	169	250	259
number, 2022	395	194	488	300	446	359
2017	432	229	499	325	426	412
40 to 99 horsepower (PTO) ..... farms, 2022	490	202	483	248	431	321
2017	558	224	511	206	427	420
number, 2022	928	324	775	448	686	553
2017	1,077	354	788	369	797	717
100 horsepower (PTO) or more ..... farms, 2022	357	83	197	110	536	161
2017	395	102	266	79	495	185
number, 2022	938	186	365	216	1,542	359
2017	833	219	510	122	1,331	338
Grain and bean combines, self-propelled ..... farms, 2022	173	50	118	64	443	73
2017	190	39	149	31	407	97
number, 2022	204	85	137	80	485	85
2017	212	46	174	36	437	108
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	30	15	9	30	20	22
2017	44	16	27	15	19	38
number, 2022	30	18	10	33	20	24
2017	46	16	32	18	19	39
Hay balers ..... farms, 2022	305	158	312	204	159	267
2017	349	187	343	172	186	327
number, 2022	383	197	403	281	193	333
2017	451	236	458	241	231	426
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	134	48	137	72	219	67
number	158	53	146	100	262	74
Tractors ..... farms	109	19	112	51	108	37
number	144	24	165	61	190	43
Less than 40 horsepower (PTO) ..... farms	22	6	51	29	17	15
number	22	6	55	31	20	15
40 to 99 horsepower (PTO) ..... farms	41	8	63	23	31	17
number	45	8	86	23	41	20
100 horsepower (PTO) or more ..... farms	58	9	22	7	83	7
number	77	10	24	7	129	8
Grain and bean combines ..... farms	10	3	11	-	83	1
number	10	5	11	-	84	(D)
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	3	-	2	1	-	3
number	3	-	(D)	(D)	-	3
Hay balers ..... farms	26	16	14	25	7	22
number	29	16	15	25	7	22

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	1,252	613	190	735	34	186
2017	1,219	526	181	852	42	134
$1,000, 2022	374,900	242,719	22,933	267,030	1,220	44,965
2017	317,270	168,152	15,472	234,565	2,061	23,090
Average per farm ..... dollars, 2022	299,441	395,953	120,698	363,305	35,884	241,747
2017	260,271	319,681	85,478	275,311	49,065	172,314
Farms by value group:						
$1 to $9,999 2022	187	58	15	67	3	21
2017	280	57	27	102	4	18
$10,000 to $19,999 2022	174	56	26	51	8	25
2017	167	63	25	83	9	10
$20,000 to $29,999 2022	152	60	20	52	7	12
2017	98	61	16	79	5	10
$30,000 to $49,999 2022	102	76	20	79	7	25
2017	109	51	20	74	6	14
$50,000 to $69,999 2022	72	58	26	68	2	25
2017	65	49	26	38	9	12
$70,000 to $99,999 2022	85	39	12	46	6	16
2017	77	28	18	54	3	15
$100,000 to $199,999 2022	139	34	47	81	1	15
2017	112	44	31	92	5	31
$200,000 to $499,999 2022	149	81	14	122	-	23
2017	131	67	15	156	1	13
$500,000 or more 2022	192	151	10	169	-	24
2017	180	106	3	174	-	11
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	896	435	163	561	31	143
2017	885	388	152	656	36	119
number, 2022	2,365	1,574	322	1,670	46	368
2017	2,248	1,518	284	1,905	49	317
Tractors ..... farms, 2022	927	473	169	575	29	156
2017	888	420	167	680	27	119
number, 2022	3,112	1,636	549	2,058	49	526
2017	3,093	1,617	508	2,638	84	430
Less than 40 horsepower (PTO) ..... farms, 2022	454	141	97	180	22	75
2017	415	138	85	270	23	52
number, 2022	697	217	142	287	32	102
2017	707	226	147	416	40	80
40 to 99 horsepower (PTO) ..... farms, 2022	587	253	136	338	10	103
2017	611	254	124	455	18	91
number, 2022	947	337	255	535	(D)	172
2017	1,049	392	245	731	(D)	146
100 horsepower (PTO) or more ..... farms, 2022	511	337	78	437	3	107
2017	511	332	70	555	3	80
number, 2022	1,468	1,082	152	1,236	(D)	252
2017	1,337	999	116	1,491	(D)	204
Grain and bean combines, self-propelled ..... farms, 2022	359	219	39	350	-	63
2017	363	202	37	448	-	53
number, 2022	417	300	46	397	-	79
2017	419	274	44	511	-	73
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	39	8	9	7	-	2
2017	53	16	6	8	2	8
number, 2022	41	10	9	7	-	(D)
2017	53	17	8	10	(D)	12
Hay balers ..... farms, 2022	267	69	101	119	6	60
2017	330	95	104	173	12	37
number, 2022	336	101	138	140	7	79
2017	416	124	147	217	(D)	53
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	217	166	44	184	6	40
number	294	218	52	256	8	62
Tractors ..... farms	126	120	24	84	2	29
number	296	179	36	115	(D)	47
Less than 40 horsepower (PTO) ..... farms	35	36	9	18	2	4
number	50	41	9	22	(D)	4
40 to 99 horsepower (PTO) ..... farms	45	22	11	13	-	21
number	53	22	14	13	-	21
100 horsepower (PTO) or more ..... farms	67	77	6	60	-	13
number	193	116	13	80	-	22
Grain and bean combines ..... farms	42	29	1	44	-	7
number	49	35	(D)	45	-	14
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	2	-	-	-	-	-
number	(D)	-	-	-	-	-
Hay balers ..... farms	17	9	9	11	-	2
number	19	9	11	14	-	(D)

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	896	598	869	801	268	1,072
2017	937	670	893	880	311	1,083
$1,000, 2022	160,835	163,147	330,494	232,663	88,361	376,367
2017	169,256	175,385	268,240	199,409	78,137	297,411
Average per farm ..... dollars, 2022	179,503	272,822	380,315	290,466	329,705	351,089
2017	180,636	261,768	300,380	226,601	251,243	274,618
Farms by value group:						
$1 to $9,999 2022	163	68	95	138	19	80
2017	133	64	39	107	39	124
$10,000 to $19,999 2022	104	77	74	83	25	141
2017	104	70	98	123	26	99
$20,000 to $29,999 2022	63	45	39	78	10	66
2017	130	83	61	89	33	127
$30,000 to $49,999 2022	96	56	53	60	24	98
2017	124	50	94	63	33	124
$50,000 to $69,999 2022	82	28	64	47	27	60
2017	88	45	51	71	29	101
$70,000 to $99,999 2022	82	32	42	73	20	53
2017	53	45	43	46	41	62
$100,000 to $199,999 2022	108	99	98	92	28	166
2017	82	65	119	113	29	92
$200,000 to $499,999 2022	123	85	181	110	72	204
2017	121	145	202	161	35	176
$500,000 or more 2022	75	108	223	120	43	204
2017	102	103	186	107	46	178
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	614	420	709	625	221	823
2017	709	500	738	729	254	797
number, 2022	1,365	992	1,993	1,517	653	3,075
2017	1,630	1,235	1,885	1,541	756	2,801
Tractors ..... farms, 2022	652	436	720	626	233	879
2017	718	538	741	772	273	806
number, 2022	2,115	1,662	2,945	2,361	752	3,529
2017	2,552	2,046	2,955	2,970	897	3,151
Less than 40 horsepower (PTO) ..... farms, 2022	313	159	252	318	63	310
2017	387	187	292	376	105	332
number, 2022	545	270	428	484	94	473
2017	663	296	491	673	147	484
40 to 99 horsepower (PTO) ..... farms, 2022	457	291	461	449	136	486
2017	533	386	510	577	174	471
number, 2022	750	510	828	789	200	694
2017	983	742	861	1,059	276	794
100 horsepower (PTO) or more ..... farms, 2022	366	323	567	403	160	677
2017	405	428	596	467	172	623
number, 2022	820	882	1,689	1,088	458	2,362
2017	906	1,008	1,603	1,238	474	1,873
Grain and bean combines, self-propelled ..... farms, 2022	247	220	437	300	139	464
2017	350	297	483	351	140	422
number, 2022	288	262	472	334	185	662
2017	389	323	527	387	188	612
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	17	20	42	22	6	23
2017	38	22	48	44	11	26
number, 2022	17	21	42	23	6	28
2017	39	24	50	45	13	30
Hay balers ..... farms, 2022	188	166	264	276	67	216
2017	260	214	293	365	114	201
number, 2022	224	195	320	342	81	269
2017	319	268	358	466	134	267
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	182	118	184	147	69	257
number	208	143	269	206	92	375
Tractors ..... farms	72	57	97	85	38	116
number	106	95	146	192	72	250
Less than 40 horsepower (PTO) ..... farms	19	16	20	27	2	30
number	24	19	20	31	(D)	39
40 to 99 horsepower (PTO) ..... farms	40	12	29	28	12	42
number	44	12	29	51	(D)	44
100 horsepower (PTO) or more ..... farms	19	38	66	56	27	80
number	38	64	97	110	57	167
Grain and bean combines ..... farms	22	22	53	40	9	24
number	22	27	55	42	12	37
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	-	1	-	7	-	-
number	-	(D)	-	8	-	-
Hay balers ..... farms	7	12	35	23	2	18
number	8	14	35	31	(D)	18

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	823	991	603	1,571	999	789
2017	911	1,026	707	1,760	1,068	864
$1,000, 2022	368,209	278,031	83,609	293,758	330,749	262,673
2017	352,537	210,130	73,158	275,392	298,558	273,299
Average per farm ..... dollars, 2022	447,399	280,556	138,655	186,988	331,080	332,919
2017	386,978	204,806	103,477	156,473	279,549	316,318
Farms by value group:						
$1 to $9,999 2022	26	161	81	123	89	82
2017	75	144	116	189	110	117
$10,000 to $19,999 2022	42	113	48	145	79	61
2017	69	143	106	182	109	61
$20,000 to $29,999 2022	48	115	69	150	67	56
2017	47	104	126	158	65	80
$30,000 to $49,999 2022	67	93	82	181	116	52
2017	61	130	96	237	99	49
$50,000 to $69,999 2022	47	84	100	142	72	73
2017	56	68	48	149	90	38
$70,000 to $99,999 2022	58	37	44	147	75	52
2017	43	103	46	170	77	50
$100,000 to $199,999 2022	126	132	81	280	107	99
2017	125	112	70	298	118	142
$200,000 to $499,999 2022	167	117	61	250	195	144
2017	206	103	55	248	204	130
$500,000 or more 2022	242	139	37	153	199	170
2017	229	119	44	129	196	197
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	679	715	475	1,314	792	612
2017	779	791	592	1,474	900	653
number, 2022	2,208	1,692	776	2,425	1,907	1,711
2017	2,255	1,690	969	2,502	2,171	1,694
Tractors ..... farms, 2022	662	737	508	1,334	772	620
2017	774	824	586	1,532	911	661
number, 2022	2,600	2,622	1,429	4,682	2,828	2,475
2017	2,968	2,684	1,833	5,292	3,290	2,786
Less than 40 horsepower (PTO) ..... farms, 2022	282	334	253	598	296	235
2017	291	392	286	757	436	282
number, 2022	481	568	398	1,016	502	442
2017	448	593	476	1,233	700	417
40 to 99 horsepower (PTO) ..... farms, 2022	408	493	351	1,051	488	394
2017	521	595	436	1,204	614	460
number, 2022	617	836	577	1,878	876	712
2017	875	995	740	2,234	1,031	789
100 horsepower (PTO) or more ..... farms, 2022	531	449	213	713	533	463
2017	627	461	255	850	626	519
number, 2022	1,502	1,218	454	1,788	1,450	1,321
2017	1,645	1,096	617	1,825	1,559	1,580
Grain and bean combines, self-propelled ..... farms, 2022	399	319	118	446	378	379
2017	523	354	165	489	462	419
number, 2022	449	372	147	524	411	426
2017	555	413	197	541	496	461
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	17	34	20	119	16	35
2017	11	36	38	143	50	29
number, 2022	18	42	20	127	16	35
2017	15	36	40	152	53	29
Hay balers ..... farms, 2022	141	216	297	772	215	181
2017	162	314	368	907	261	235
number, 2022	170	268	365	994	273	229
2017	191	373	488	1,131	344	278
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	233	185	78	241	229	191
number	314	208	90	273	296	264
Tractors ..... farms	88	119	65	146	112	118
number	144	228	81	177	182	244
Less than 40 horsepower (PTO) ..... farms	15	33	29	36	34	12
number	19	33	38	36	38	14
40 to 99 horsepower (PTO) ..... farms	25	42	31	79	37	38
number	29	45	35	79	39	39
100 horsepower (PTO) or more ..... farms	64	64	8	48	53	94
number	96	150	8	62	105	191
Grain and bean combines ..... farms	61	60	-	15	43	78
number	66	68	-	15	47	94
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	-	1	-	11	1	1
number	-	(D)	-	13	(D)	(D)
Hay balers ..... farms	4	28	16	84	13	13
number	5	31	18	87	13	14

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	660	938	435	1,102	2,497	322
2017	688	885	505	1,138	2,543	409
$1,000, 2022	287,567	371,336	229,143	258,228	446,155	101,201
2017	206,065	353,984	207,500	209,945	383,195	94,789
Average per farm ..... dollars, 2022	435,707	395,880	526,764	234,326	178,676	314,288
2017	299,514	399,982	410,892	184,486	150,686	231,758
Farms by value group:						
$1 to $9,999 2022	50	57	23	152	340	35
2017	45	87	35	149	391	44
$10,000 to $19,999 2022	48	65	37	95	315	54
2017	36	52	44	102	410	45
$20,000 to $29,999 2022	33	53	26	87	239	26
2017	34	55	31	122	274	25
$30,000 to $49,999 2022	44	104	59	119	357	21
2017	65	60	42	168	285	47
$50,000 to $69,999 2022	48	58	35	124	244	10
2017	47	40	35	122	243	28
$70,000 to $99,999 2022	28	55	9	81	157	17
2017	51	34	20	71	194	51
$100,000 to $199,999 2022	98	147	32	144	292	44
2017	138	128	56	152	269	45
$200,000 to $499,999 2022	161	167	52	149	314	52
2017	131	164	106	123	267	59
$500,000 or more 2022	150	232	162	151	239	63
2017	141	265	136	129	210	65
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	558	727	372	882	1,844	227
2017	602	738	432	885	1,900	342
number, 2022	1,466	1,941	1,992	1,803	4,133	833
2017	1,524	1,852	1,902	1,773	4,139	1,109
Tractors ..... farms, 2022	569	737	382	900	2,021	256
2017	612	758	429	930	2,006	358
number, 2022	2,384	2,801	1,809	2,840	6,248	977
2017	2,586	3,052	1,841	3,087	6,555	1,357
Less than 40 horsepower (PTO) ..... farms, 2022	269	219	129	430	912	110
2017	288	258	145	425	893	160
number, 2022	534	347	236	640	1,334	155
2017	484	407	221	625	1,388	249
40 to 99 horsepower (PTO) ..... farms, 2022	419	459	233	591	1,432	145
2017	463	506	259	646	1,431	247
number, 2022	743	784	395	963	2,313	254
2017	880	865	412	1,204	2,604	419
100 horsepower (PTO) or more ..... farms, 2022	415	578	315	470	1,051	187
2017	482	625	329	508	1,081	251
number, 2022	1,107	1,670	1,178	1,237	2,601	568
2017	1,222	1,780	1,208	1,258	2,563	689
Grain and bean combines, self-propelled ..... farms, 2022	330	455	269	302	653	129
2017	417	476	291	328	735	188
number, 2022	353	496	417	338	797	188
2017	428	537	474	355	850	257
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	18	39	8	28	87	12
2017	12	42	9	56	123	15
number, 2022	23	41	13	28	90	15
2017	13	47	9	56	135	18
Hay balers ..... farms, 2022	158	182	95	286	863	93
2017	174	238	119	409	1,032	116
number, 2022	189	227	121	351	1,123	112
2017	233	282	144	515	1,339	143
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	195	218	109	234	368	62
number	267	285	141	275	439	80
Tractors ..... farms	97	125	35	135	213	31
number	201	212	65	192	278	40
Less than 40 horsepower (PTO) ..... farms	19	7	6	48	79	9
number	29	12	6	52	83	9
40 to 99 horsepower (PTO) ..... farms	34	42	11	43	78	11
number	55	58	11	47	84	12
100 horsepower (PTO) or more ..... farms	61	87	29	61	77	16
number	117	142	48	93	111	19
Grain and bean combines ..... farms	52	68	30	30	34	12
number	53	76	35	30	35	15
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	6	11	-	2	2	1
number	8	11	-	(D)	(D)	(D)
Hay balers ..... farms	23	29	4	24	71	6
number	26	38	4	24	77	6

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	728	529	1,223	821	47	274
2017	823	594	1,258	833	55	263
$1,000, 2022	78,647	188,858	631,119	183,466	1,407	105,358
2017	60,408	204,327	492,393	212,297	2,512	80,458
Average per farm ..... dollars, 2022	108,032	357,010	516,042	223,467	29,945	384,518
2017	73,400	343,986	391,409	254,858	45,670	305,925
Farms by value group:						
$1 to $9,999 2022	79	73	91	138	17	7
2017	143	55	138	162	15	24
$10,000 to $19,999 2022	65	11	90	84	8	11
2017	143	61	126	77	15	21
$20,000 to $29,999 2022	81	48	93	97	4	9
2017	109	55	116	50	6	11
$30,000 to $49,999 2022	105	29	101	96	11	24
2017	118	32	136	84	8	33
$50,000 to $69,999 2022	98	35	77	70	1	30
2017	87	42	89	61	1	16
$70,000 to $99,999 2022	84	43	80	44	3	24
2017	56	34	70	41	5	16
$100,000 to $199,999 2022	121	85	157	80	3	62
2017	97	68	131	129	3	52
$200,000 to $499,999 2022	66	109	144	103	-	50
2017	53	136	147	102	1	36
$500,000 or more 2022	29	96	390	109	-	57
2017	17	111	305	127	1	54
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	577	465	981	584	17	240
2017	658	483	943	617	37	229
number, 2022	987	1,126	4,337	1,433	36	810
2017	981	1,221	3,728	1,487	65	745
Tractors ..... farms, 2022	623	449	1,004	588	10	238
2017	699	492	987	649	24	224
number, 2022	1,974	1,644	4,250	1,930	20	955
2017	2,160	1,713	3,872	2,268	31	840
Less than 40 horsepower (PTO) ..... farms, 2022	290	161	383	226	5	79
2017	360	168	385	278	14	86
number, 2022	457	274	595	339	6	126
2017	575	245	584	417	18	109
40 to 99 horsepower (PTO) ..... farms, 2022	489	300	527	412	10	163
2017	564	313	570	453	10	163
number, 2022	939	481	826	620	(D)	260
2017	1,113	519	959	775	13	258
100 horsepower (PTO) or more ..... farms, 2022	275	315	772	358	1	181
2017	260	366	702	401	-	165
number, 2022	578	889	2,829	971	(D)	569
2017	472	949	2,329	1,076	-	473
Grain and bean combines, self-propelled ..... farms, 2022	104	214	606	221	-	141
2017	124	251	504	237	-	123
number, 2022	120	234	937	270	-	210
2017	138	275	737	282	-	189
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	41	25	20	21	-	9
2017	47	27	29	42	-	8
number, 2022	44	26	23	27	-	9
2017	58	30	34	47	-	8
Hay balers ..... farms, 2022	396	202	197	176	-	72
2017	447	207	214	258	1	66
number, 2022	511	240	249	224	-	86
2017	595	242	286	336	(D)	73
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	76	109	330	150	4	52
number	82	183	478	199	(D)	70
Tractors ..... farms	61	60	158	92	3	19
number	97	93	281	152	(D)	21
Less than 40 horsepower (PTO) ..... farms	15	12	23	25	-	1
number	17	15	24	27	-	(D)
40 to 99 horsepower (PTO) ..... farms	28	15	43	27	3	5
number	29	18	45	27	(D)	(D)
100 horsepower (PTO) or more ..... farms	28	42	108	54	-	13
number	51	60	212	98	-	(D)
Grain and bean combines ..... farms	7	21	68	37	-	2
number	7	24	96	42	-	(D)
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	4	1	1	3	-	2
number	4	(D)	(D)	4	-	(D)
Hay balers ..... farms	25	21	7	15	-	3
number	26	21	7	15	-	3

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	1,323	931	1,111	573	751	821
2017	1,133	1,025	1,241	701	842	779
$1,000, 2022	490,671	471,272	235,260	234,510	225,261	68,608
2017	357,601	385,574	180,494	225,799	154,914	48,219
Average per farm ..... dollars, 2022	370,878	506,200	211,755	409,268	299,948	83,566
2017	315,623	376,170	145,442	322,110	183,983	61,899
Farms by value group:						
$1 to $9,999 2022	141	91	146	33	52	109
2017	136	135	213	54	166	139
$10,000 to $19,999 2022	98	63	114	45	73	124
2017	54	87	181	59	90	113
$20,000 to $29,999 2022	46	49	112	31	56	91
2017	53	28	112	29	67	112
$30,000 to $49,999 2022	88	50	102	54	78	107
2017	112	81	141	69	94	131
$50,000 to $69,999 2022	74	59	117	42	75	94
2017	60	47	114	42	86	76
$70,000 to $99,999 2022	60	48	66	48	73	85
2017	73	55	74	53	65	65
$100,000 to $199,999 2022	204	89	177	81	125	107
2017	139	131	162	86	83	88
$200,000 to $499,999 2022	301	187	157	98	124	92
2017	255	195	161	149	110	50
$500,000 or more 2022	311	295	120	141	95	12
2017	251	266	83	160	81	5
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	1,068	738	839	499	586	660
2017	912	849	937	583	647	619
number, 2022	2,951	2,623	1,792	1,311	1,741	1,119
2017	2,346	2,838	1,862	1,397	1,802	996
Tractors ..... farms, 2022	1,046	713	869	470	632	682
2017	935	841	978	583	705	622
number, 2022	4,009	2,861	2,693	1,831	2,186	1,876
2017	3,791	3,181	2,940	2,294	2,341	1,669
Less than 40 horsepower (PTO) ..... farms, 2022	366	262	399	140	222	415
2017	374	343	453	167	268	380
number, 2022	560	435	629	268	373	617
2017	580	537	710	289	431	619
40 to 99 horsepower (PTO) ..... farms, 2022	702	463	562	285	425	455
2017	687	524	637	390	522	462
number, 2022	1,165	756	946	486	705	895
2017	1,159	877	1,070	665	850	793
100 horsepower (PTO) or more ..... farms, 2022	828	570	470	382	409	201
2017	753	653	519	466	435	160
number, 2022	2,284	1,670	1,118	1,077	1,108	364
2017	2,052	1,767	1,160	1,340	1,060	257
Grain and bean combines, self-propelled ..... farms, 2022	697	464	342	240	267	61
2017	665	551	406	335	270	55
number, 2022	753	537	379	253	414	63
2017	728	636	430	356	382	57
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	39	17	40	37	32	32
2017	35	18	42	49	46	23
number, 2022	43	17	45	37	35	36
2017	37	18	43	49	49	28
Hay balers ..... farms, 2022	268	156	304	146	242	403
2017	227	159	373	204	245	392
number, 2022	315	203	370	177	328	548
2017	290	196	452	233	319	536
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	318	264	167	160	204	124
number	435	351	202	210	257	145
Tractors ..... farms	148	140	105	85	93	90
number	288	258	198	162	140	109
Less than 40 horsepower (PTO) ..... farms	27	9	24	6	23	51
number	31	9	33	11	23	58
40 to 99 horsepower (PTO) ..... farms	54	19	39	21	39	29
number	87	20	46	26	39	32
100 horsepower (PTO) or more ..... farms	112	117	67	68	40	15
number	170	229	119	125	78	19
Grain and bean combines ..... farms	100	75	23	46	29	5
number	100	89	26	50	53	5
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	4	-	3	9	1	-
number	8	-	3	9	(D)	-
Hay balers ..... farms	19	6	20	29	18	38
number	19	6	20	40	20	40

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	624	494	860	2,695	721	500
2017	740	501	898	2,951	744	553
$1,000, 2022	105,424	82,965	300,378	593,687	217,310	180,393
2017	89,060	94,130	254,312	548,519	187,138	160,098
Average per farm ..... dollars, 2022	168,948	167,945	349,277	220,292	301,401	360,785
2017	120,351	187,885	283,199	185,876	251,529	289,508
Farms by value group:						
$1 to $9,999 2022	113	65	71	226	110	55
2017	76	70	96	327	86	91
$10,000 to $19,999 2022	56	72	84	221	93	52
2017	115	100	71	268	73	50
$20,000 to $29,999 2022	52	43	61	223	43	34
2017	67	28	76	262	86	33
$30,000 to $49,999 2022	68	51	76	266	86	30
2017	88	79	57	298	89	41
$50,000 to $69,999 2022	83	74	62	250	52	56
2017	108	71	70	259	57	33
$70,000 to $99,999 2022	39	51	59	284	29	46
2017	68	43	59	229	43	26
$100,000 to $199,999 2022	91	49	103	497	93	30
2017	96	39	137	518	80	82
$200,000 to $499,999 2022	74	50	146	392	104	84
2017	82	27	176	469	113	78
$500,000 or more 2022	48	39	198	336	111	113
2017	40	44	156	321	117	119
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	471	382	704	2,152	532	370
2017	576	398	750	2,395	585	410
number, 2022	837	831	1,899	3,904	1,321	1,213
2017	973	956	1,790	3,914	1,519	1,272
Tractors ..... farms, 2022	467	366	703	2,287	569	361
2017	610	403	748	2,536	621	398
number, 2022	1,316	1,045	2,719	8,801	2,017	1,375
2017	1,876	1,260	3,031	9,562	2,214	1,573
Less than 40 horsepower (PTO) ..... farms, 2022	222	205	276	1,099	252	115
2017	289	228	370	1,291	286	158
number, 2022	331	326	555	1,859	421	150
2017	444	415	657	2,177	458	241
40 to 99 horsepower (PTO) ..... farms, 2022	289	233	475	1,748	423	256
2017	459	260	526	1,973	456	284
number, 2022	517	395	811	3,126	702	401
2017	806	512	959	3,559	828	448
100 horsepower (PTO) or more ..... farms, 2022	199	140	520	1,470	331	262
2017	295	124	543	1,644	367	304
number, 2022	468	324	1,353	3,816	894	824
2017	626	333	1,415	3,826	928	884
Grain and bean combines, self-propelled ..... farms, 2022	152	88	419	781	248	189
2017	206	90	476	942	275	244
number, 2022	171	101	458	841	277	239
2017	219	104	518	1,010	315	285
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	11	9	22	214	16	8
2017	26	24	20	245	11	16
number, 2022	13	9	24	235	17	10
2017	27	25	21	260	11	22
Hay balers ..... farms, 2022	174	121	235	1,106	158	102
2017	283	142	328	1,411	169	123
number, 2022	224	145	288	1,425	204	124
2017	362	188	405	1,817	225	164
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	150	105	239	414	150	130
number	189	157	382	468	196	155
Tractors ..... farms	69	72	107	237	90	64
number	89	117	208	349	167	127
Less than 40 horsepower (PTO) ..... farms	28	35	16	63	23	5
number	36	41	26	64	26	9
40 to 99 horsepower (PTO) ..... farms	20	24	23	79	37	10
number	24	28	23	102	37	12
100 horsepower (PTO) or more ..... farms	25	26	84	122	46	61
number	29	48	159	183	104	106
Grain and bean combines ..... farms	15	8	64	31	33	18
number	17	8	64	31	34	22
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	1	-	-	7	2	1
number	(D)	-	-	7	(D)	(D)
Hay balers ..... farms	12	7	15	160	10	4
number	13	7	15	169	10	4

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	708	1,529	358	743	442	622
2017	759	1,604	410	809	516	729
$1,000, 2022	263,470	211,245	162,359	231,856	63,638	200,840
2017	232,152	178,593	198,518	197,951	45,921	204,115
Average per farm ..... dollars, 2022	372,132	138,159	453,517	312,053	143,977	322,894
2017	305,866	111,342	484,191	244,686	88,995	279,994
Farms by value group:						
$1 to $9,999 2022	81	198	41	86	77	73
2017	141	191	24	82	110	56
$10,000 to $19,999 2022	89	193	34	43	73	54
2017	75	216	31	69	69	79
$20,000 to $29,999 2022	64	151	24	44	34	41
2017	64	157	35	74	55	74
$30,000 to $49,999 2022	45	175	30	73	44	59
2017	44	233	34	89	75	67
$50,000 to $69,999 2022	48	161	20	50	33	38
2017	58	158	45	40	49	52
$70,000 to $99,999 2022	48	137	15	35	44	28
2017	50	153	14	74	34	67
$100,000 to $199,999 2022	78	253	30	125	54	85
2017	73	235	33	108	69	67
$200,000 to $499,999 2022	77	171	63	143	59	122
2017	130	201	74	165	46	122
$500,000 or more 2022	178	90	101	144	24	122
2017	124	60	120	108	9	145
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	490	1,137	257	606	368	511
2017	543	1,246	344	679	420	574
number, 2022	1,585	2,078	1,066	1,381	695	1,559
2017	1,569	2,128	1,299	1,575	733	1,599
Tractors ..... farms, 2022	530	1,252	254	655	379	514
2017	581	1,361	339	696	425	592
number, 2022	1,915	3,963	1,011	2,920	1,200	2,015
2017	2,134	4,515	1,296	2,855	1,249	2,176
Less than 40 horsepower (PTO) ..... farms, 2022	173	574	85	287	168	245
2017	244	652	133	288	154	271
number, 2022	260	956	120	535	264	499
2017	446	1,084	192	487	253	428
40 to 99 horsepower (PTO) ..... farms, 2022	347	941	127	493	289	369
2017	357	1,026	174	547	327	413
number, 2022	526	1,608	199	1,009	546	630
2017	587	1,872	271	1,183	646	756
100 horsepower (PTO) or more ..... farms, 2022	371	609	195	447	168	341
2017	407	761	252	486	182	393
number, 2022	1,129	1,399	692	1,376	390	886
2017	1,101	1,559	833	1,185	350	992
Grain and bean combines, self-propelled ..... farms, 2022	289	308	171	247	96	282
2017	300	456	225	268	103	339
number, 2022	325	364	216	282	110	307
2017	329	533	268	286	119	356
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	13	47	1	52	20	9
2017	32	78	8	66	37	18
number, 2022	16	50	(D)	56	21	10
2017	34	82	9	73	39	24
Hay balers ..... farms, 2022	89	681	42	272	226	146
2017	156	824	54	332	263	174
number, 2022	103	852	48	342	298	177
2017	194	1,042	64	417	344	210
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	179	165	89	151	57	156
number	221	180	130	171	83	222
Tractors ..... farms	126	115	69	76	24	82
number	206	175	110	97	35	170
Less than 40 horsepower (PTO) ..... farms	17	38	18	19	5	31
number	21	45	18	21	8	45
40 to 99 horsepower (PTO) ..... farms	36	65	23	17	17	19
number	36	70	29	18	18	25
100 horsepower (PTO) or more ..... farms	82	41	39	45	6	51
number	149	60	63	58	9	100
Grain and bean combines ..... farms	54	11	24	14	10	54
number	57	14	27	15	10	55
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	-	3	-	4	1	-
number	-	3	-	4	(D)	-
Hay balers ..... farms	11	45	8	34	23	6
number	11	48	8	34	23	7

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
VALUE OF MACHINERY AND EQUIPMENT						
Estimated market value of all machinery and equipment ..... farms, 2022	525	512	358	993	1,310	847
2017	612	497	390	1,034	1,338	852
$1,000, 2022	59,204	213,589	185,963	257,758	226,809	268,428
2017	68,502	190,103	172,673	187,970	201,816	235,079
Average per farm ..... dollars, 2022	112,770	417,167	519,451	259,575	173,136	316,916
2017	111,931	382,501	442,751	181,789	150,834	275,914
Farms by value group:						
$1 to $9,999 2022	100	29	26	77	182	97
2017	99	36	42	140	196	102
$10,000 to $19,999 2022	58	46	45	88	189	70
2017	95	44	20	103	186	48
$20,000 to $29,999 2022	44	36	21	67	121	73
2017	68	35	26	75	141	98
$30,000 to $49,999 2022	79	57	40	101	169	76
2017	66	35	25	95	177	77
$50,000 to $69,999 2022	46	27	10	104	112	72
2017	68	40	18	119	109	53
$70,000 to $99,999 2022	29	17	20	74	89	41
2017	50	38	24	65	114	37
$100,000 to $199,999 2022	96	68	35	158	189	89
2017	69	63	55	159	144	88
$200,000 to $499,999 2022	42	88	39	175	153	133
2017	69	85	62	192	186	197
$500,000 or more 2022	31	144	122	149	106	196
2017	28	121	118	86	85	152
SELECTED MACHINERY AND EQUIPMENT						
Trucks, including pickups ..... farms, 2022	371	413	266	784	981	671
2017	501	419	312	837	1,021	647
number, 2022	642	1,360	1,464	1,515	1,768	1,725
2017	967	1,232	1,450	1,501	1,856	1,781
Tractors ..... farms, 2022	399	406	266	861	1,021	665
2017	500	423	309	885	1,084	664
number, 2022	1,000	1,777	1,084	3,125	3,109	2,315
2017	1,560	1,731	1,326	3,183	3,406	2,306
Less than 40 horsepower (PTO) ..... farms, 2022	237	197	83	316	526	245
2017	327	175	92	360	533	225
number, 2022	333	353	125	490	814	369
2017	520	306	152	533	811	372
40 to 99 horsepower (PTO) ..... farms, 2022	242	279	99	593	726	402
2017	342	320	163	637	832	453
number, 2022	409	469	153	1,040	1,201	622
2017	658	578	249	1,266	1,438	705
100 horsepower (PTO) or more ..... farms, 2022	126	318	216	548	471	472
2017	167	297	263	564	536	477
number, 2022	258	955	806	1,595	1,094	1,324
2017	382	847	925	1,384	1,157	1,229
Grain and bean combines, self-propelled ..... farms, 2022	57	258	175	255	293	369
2017	108	262	235	281	371	389
number, 2022	61	326	257	271	327	404
2017	119	289	327	287	409	440
Cotton pickers and strippers, self-propelled ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
number, 2022	-	-	-	-	-	-
2017	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms, 2022	3	1	6	60	50	23
2017	14	10	5	101	57	30
number, 2022	4	(D)	7	60	52	23
2017	14	10	5	111	63	32
Hay balers ..... farms, 2022	113	66	51	357	444	170
2017	193	87	52	456	519	216
number, 2022	144	78	66	448	578	204
2017	267	115	62	584	665	250
2022 INVENTORY						
Manufactured 2017 to 2022:						
Trucks, including pickups ..... farms	122	105	91	211	213	262
number	148	153	147	262	284	312
Tractors ..... farms	45	55	42	142	131	110
number	100	96	58	214	186	175
Less than 40 horsepower (PTO) ..... farms	23	11	12	22	29	22
number	30	14	12	22	36	22
40 to 99 horsepower (PTO) ..... farms	22	8	-	60	67	39
number	31	8	-	68	72	41
100 horsepower (PTO) or more ..... farms	25	41	30	74	49	66
number	39	74	46	124	78	112
Grain and bean combines ..... farms	8	50	24	15	19	57
number	12	56	25	17	19	60
Cotton pickers and strippers ..... farms	-	-	-	-	-	-
number	-	-	-	-	-	-
Forage harvesters, self-propelled ..... farms	-	-	-	18	1	-
number	-	-	-	18	(D)	-
Hay balers ..... farms	9	1	2	41	36	14
number	13	(D)	(D)	45	37	15

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
2022 INVENTORY - Con.						
Manufactured prior to 2017:						
Trucks, including pickups	farms	46,077	323	246	622	457
	number	109,556	619	447	1,518	842
Tractors	farms	50,098	388	263	676	491
	number	171,858	1,187	588	2,176	1,405
Less than 40 horsepower (PTO)	farms	21,180	215	138	315	223
	number	34,561	383	219	550	335
40 to 99 horsepower (PTO)	farms	33,666	306	175	457	351
	number	57,478	560	263	738	609
100 horsepower (PTO) or more	farms	30,494	129	60	309	214
	number	79,819	244	106	888	461
Grain and bean combines	farms	19,502	40	24	178	123
	number	22,878	42	(D)	246	157
Cotton pickers and strippers	farms	-	-	-	-	-
	number	-	-	-	-	-
Forage harvesters, self-propelled	farms	2,027	10	5	27	24
	number	2,193	(D)	5	(D)	(D)
Hay balers	farms	17,962	229	104	312	256
	number	22,509	314	124	397	327

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
2022 INVENTORY - Con.						
Manufactured prior to 2017:						
Trucks, including pickups	farms	493	291	720	728	344
	number	881	982	1,918	1,733	487
Tractors	farms	546	301	794	793	348
	number	1,973	1,109	2,857	3,013	1,002
Less than 40 horsepower (PTO)	farms	290	102	327	286	202
	number	515	151	544	454	334
40 to 99 horsepower (PTO)	farms	404	178	548	542	262
	number	713	294	869	929	503
100 horsepower (PTO) or more	farms	316	235	539	631	107
	number	745	664	1,444	1,630	165
Grain and bean combines	farms	210	181	412	441	21
	number	228	230	450	487	22
Cotton pickers and strippers	farms	-	-	-	-	-
	number	-	-	-	-	-
Forage harvesters, self-propelled	farms	43	3	15	32	18
	number	(D)	(D)	15	32	20
Hay balers	farms	288	82	157	219	211
	number	358	98	(D)	261	296

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	426	367	396	481	493	314
	number	829	588	1,249	777	1,983	687
Tractors	farms	491	384	398	559	538	317
	number	1,809	960	1,331	1,459	2,325	1,040
Less than 40 horsepower (PTO)	farms	229	150	133	273	240	136
	number	444	221	191	400	485	213
40 to 99 horsepower (PTO)	farms	364	301	237	373	329	229
	number	684	556	347	629	636	412
100 horsepower (PTO) or more	farms	272	119	289	210	361	169
	number	681	183	793	430	1,204	415
Grain and bean combines	farms	197	27	183	127	279	59
	number	221	30	195	(D)	429	(D)
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	32	14	6	11	9	16
	number	34	15	(D)	11	(D)	(D)
Hay balers	farms	251	226	81	212	154	181
	number	312	284	(D)	273	191	224

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	18	532	331	573	452	611
	number	(D)	1,487	516	1,320	1,046	1,312
Tractors	farms	16	550	337	620	486	678
	number	(D)	2,056	1,005	2,069	1,763	2,100
Less than 40 horsepower (PTO)	farms	13	206	184	284	218	290
	number	(D)	314	(D)	451	346	471
40 to 99 horsepower (PTO)	farms	9	358	239	421	322	452
	number	(D)	615	466	751	599	800
100 horsepower (PTO) or more	farms	1	438	124	335	303	375
	number	(D)	1,127	(D)	867	818	829
Grain and bean combines	farms	-	272	38	202	163	252
	number	-	317	47	213	188	296
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	-	21	15	13	22	31
	number	-	21	15	15	22	37
Hay balers	farms	10	136	193	180	162	262
	number	12	158	236	214	199	334

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	609	967	661	1,058	337	322
	number	1,550	1,929	1,751	2,296	830	451
Tractors	farms	631	1,130	714	1,138	318	342
	number	2,213	3,549	2,538	3,808	935	808
Less than 40 horsepower (PTO)	farms	232	417	290	473	125	199
	number	399	673	444	749	161	282
40 to 99 horsepower (PTO)	farms	385	737	438	755	196	213
	number	607	1,156	755	1,308	258	353
100 horsepower (PTO) or more	farms	465	622	536	703	217	102
	number	1,207	1,720	1,339	1,751	516	173
Grain and bean combines	farms	339	385	388	365	164	45
	number	361	443	428	399	225	49
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	23	55	8	44	4	14
	number	23	61	9	50	(D)	14
Hay balers	farms	86	387	202	344	49	114
	number	93	496	258	402	71	150

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	529	234	546	306	672	371
	number	871	498	943	570	1,653	625
Tractors	farms	618	274	586	326	655	422
	number	2,117	680	1,463	903	2,484	1,228
Less than 40 horsepower (PTO)	farms	260	134	268	166	238	200
	number	373	188	433	269	426	344
40 to 99 horsepower (PTO)	farms	460	195	428	227	408	308
	number	883	316	689	425	645	533
100 horsepower (PTO) or more	farms	343	77	184	109	522	158
	number	861	176	341	209	1,413	351
Grain and bean combines	farms	167	49	108	64	368	72
	number	194	80	126	80	401	(D)
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	27	15	7	29	20	19
	number	27	18	(D)	(D)	20	21
Hay balers	farms	286	142	305	186	156	253
	number	354	181	388	256	186	311

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	823	385	138	515	26	128
	number	2,071	1,356	270	1,414	38	306
Tractors	farms	878	436	160	554	27	145
	number	2,816	1,457	513	1,943	(D)	479
Less than 40 horsepower (PTO)	farms	422	123	90	164	20	71
	number	647	176	133	265	(D)	98
40 to 99 horsepower (PTO)	farms	550	236	131	331	10	85
	number	894	315	241	522	(D)	151
100 horsepower (PTO) or more	farms	483	312	76	423	3	107
	number	1,275	966	139	1,156	(D)	230
Grain and bean combines	farms	327	191	38	310	-	56
	number	368	265	(D)	352	-	65
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	37	8	9	7	-	2
	number	(D)	10	9	7	-	(D)
Hay balers	farms	251	67	94	108	6	58
	number	317	92	127	126	7	(D)

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	520	377	651	556	202	762
	number	1,157	849	1,724	1,311	561	2,700
Tractors	farms	606	416	687	605	219	844
	number	2,009	1,567	2,799	2,169	680	3,279
Less than 40 horsepower (PTO)	farms	296	143	234	300	61	285
	number	521	251	408	453	(D)	434
40 to 99 horsepower (PTO)	farms	422	280	438	431	126	451
	number	706	498	799	738	(D)	650
100 horsepower (PTO) or more	farms	354	303	551	390	150	643
	number	782	818	1,592	978	401	2,195
Grain and bean combines	farms	225	199	385	269	137	443
	number	266	235	417	292	173	625
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	17	19	42	15	6	23
	number	17	(D)	42	15	6	28
Hay balers	farms	181	159	233	256	65	203
	number	216	181	285	311	(D)	251

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	605	625	438	1,196	704	562
	number	1,894	1,484	686	2,152	1,611	1,447
Tractors	farms	647	687	484	1,272	738	596
	number	2,456	2,394	1,348	4,505	2,646	2,231
Less than 40 horsepower (PTO)	farms	268	305	234	567	268	230
	number	462	535	360	980	464	428
40 to 99 horsepower (PTO)	farms	385	458	332	991	471	373
	number	588	791	542	1,799	837	673
100 horsepower (PTO) or more	farms	517	416	208	700	511	442
	number	1,406	1,068	446	1,726	1,345	1,130
Grain and bean combines	farms	338	274	118	431	338	304
	number	383	304	147	509	364	332
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	17	33	20	108	15	34
	number	18	(D)	20	114	(D)	(D)
Hay balers	farms	137	189	286	701	202	168
	number	165	237	347	907	260	215

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	484	672	353	753	1,699	207
	number	1,199	1,656	1,851	1,528	3,694	753
Tractors	farms	537	687	376	853	1,921	245
	number	2,183	2,589	1,744	2,648	5,970	937
Less than 40 horsepower (PTO)	farms	253	212	123	387	842	102
	number	505	335	230	588	1,251	146
40 to 99 horsepower (PTO)	farms	389	423	227	553	1,369	135
	number	688	726	384	916	2,229	242
100 horsepower (PTO) or more	farms	377	552	305	450	1,027	178
	number	990	1,528	1,130	1,144	2,490	549
Grain and bean combines	farms	278	390	241	272	632	120
	number	300	420	382	308	762	173
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	12	28	8	26	85	11
	number	15	30	13	(D)	(D)	(D)
Hay balers	farms	137	160	94	268	817	89
	number	163	189	117	327	1,046	106

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	540	431	915	528	14	224
	number	905	943	3,859	1,234	(D)	740
Tractors	farms	600	432	979	557	7	237
	number	1,877	1,551	3,969	1,778	(D)	934
Less than 40 horsepower (PTO)	farms	278	152	364	206	5	78
	number	440	259	571	312	6	(D)
40 to 99 horsepower (PTO)	farms	470	289	496	390	7	158
	number	910	463	781	593	10	(D)
100 horsepower (PTO) or more	farms	257	302	747	342	1	177
	number	527	829	2,617	873	(D)	(D)
Grain and bean combines	farms	97	194	551	192	-	140
	number	113	210	841	228	-	(D)
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	37	24	19	18	-	7
	number	40	(D)	(D)	23	-	(D)
Hay balers	farms	372	185	190	168	-	69
	number	485	219	242	209	-	83

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	960	681	750	456	513	599
	number	2,516	2,272	1,590	1,101	1,484	974
Tractors	farms	995	688	818	452	598	631
	number	3,721	2,603	2,495	1,669	2,046	1,767
Less than 40 horsepower (PTO)	farms	341	257	377	134	206	367
	number	529	426	596	257	350	559
40 to 99 horsepower (PTO)	farms	657	452	526	270	401	439
	number	1,078	736	900	460	666	863
100 horsepower (PTO) or more	farms	790	527	435	365	395	194
	number	2,114	1,441	999	952	1,030	345
Grain and bean combines	farms	609	400	322	197	242	56
	number	653	448	353	203	361	58
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	35	17	37	28	31	32
	number	35	17	42	28	(D)	36
Hay balers	farms	251	150	285	121	229	381
	number	296	197	350	137	308	508

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Table 39. **Machinery and Equipment on Operation: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	378	320	634	1,930	475	327
	number	648	674	1,517	3,436	1,125	1,058
Tractors	farms	424	325	681	2,204	536	350
	number	1,227	928	2,511	8,452	1,850	1,248
Less than 40 horsepower (PTO)	farms	200	177	265	1,043	233	110
	number	295	285	529	1,795	395	141
40 to 99 horsepower (PTO)	farms	269	215	457	1,688	394	251
	number	493	367	788	3,024	665	389
100 horsepower (PTO) or more	farms	187	130	495	1,439	311	252
	number	439	276	1,194	3,633	790	718
Grain and bean combines	farms	137	81	362	752	219	173
	number	154	93	394	810	243	217
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	10	9	22	208	14	7
	number	(D)	9	24	228	(D)	(D)
Hay balers	farms	164	116	222	976	148	98
	number	211	138	273	1,256	194	120

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	452	1,069	229	562	331	472
	number	1,364	1,898	936	1,210	612	1,337
Tractors	farms	491	1,206	225	626	363	497
	number	1,709	3,788	901	2,823	1,165	1,845
Less than 40 horsepower (PTO)	farms	159	546	67	268	164	214
	number	239	911	102	514	256	454
40 to 99 horsepower (PTO)	farms	316	901	107	477	276	358
	number	490	1,538	170	991	528	605
100 horsepower (PTO) or more	farms	352	593	184	431	163	320
	number	980	1,339	629	1,318	381	786
Grain and bean combines	farms	238	300	150	233	89	229
	number	268	350	189	267	100	252
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	13	44	1	48	19	9
	number	16	47	(D)	52	(D)	10
Hay balers	farms	79	652	36	244	213	140
	number	92	804	40	308	275	170

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
2022 INVENTORY - Con.							
Manufactured prior to 2017:							
Trucks, including pickups	farms	290	393	251	683	879	580
	number	494	1,207	1,317	1,253	1,484	1,413
Tractors	farms	371	394	257	804	979	623
	number	900	1,681	1,026	2,911	2,923	2,140
Less than 40 horsepower (PTO)	farms	217	187	71	295	510	233
	number	303	339	113	468	778	347
40 to 99 horsepower (PTO)	farms	229	274	99	548	681	367
	number	378	461	153	972	1,129	581
100 horsepower (PTO) or more	farms	105	310	210	534	449	445
	number	219	881	760	1,471	1,016	1,212
Grain and bean combines	farms	49	218	162	243	288	320
	number	49	270	232	254	308	344
Cotton pickers and strippers	farms	-	-	-	-	-	-
	number	-	-	-	-	-	-
Forage harvesters, self-propelled	farms	3	1	6	42	49	23
	number	4	(D)	7	42	(D)	23
Hay balers	farms	107	65	51	326	421	158
	number	131	(D)	(D)	403	541	189

Table 40. **Fertilizers and Chemicals Applied: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Commercial fertilizer, lime, and soil conditioners	farms, 2022	34,208	110	159	340	194
	2017	37,969	113	169	367	190
	acres treated, 2022	14,076,782	14,094	14,451	150,619	42,495
	2017	14,641,179	15,984	19,859	144,958	44,288
Cropland fertilized, except cropland pasture	farms, 2022	33,266	107	149	317	185
	2017	37,001	102	146	357	182
	acres treated, 2022	14,003,664	13,502	14,298	148,419	41,718
	2017	14,550,746	14,775	19,691	142,338	42,862
Pastureland and rangeland fertilized	farms, 2022	2,136	15	23	38	18
	2017	2,636	20	33	41	24
	acres treated, 2022	73,118	592	153	2,200	777
	2017	90,433	1,209	168	2,620	1,426
Manure	farms, 2022	13,721	105	61	192	88
	2017	16,229	90	72	190	105
	acres treated, 2022	1,453,615	3,149	578	13,665	5,594
	2017	1,690,674	3,762	926	12,964	4,497
Organic fertilizer	farms, 2022	1,053	14	7	7	5
	2017	1,123	11	4	8	6
	acres treated, 2022	135,551	396	96	(D)	28
	2017	139,319	194	11	247	(D)
Acres treated to control-						
Insects	farms, 2022	13,847	26	35	103	54
	2017	18,339	10	30	160	53
	acres, 2022	5,229,304	5,580	5,452	48,070	16,979
	2017	7,867,716	6,652	5,453	82,942	20,217
Weeds, grass, or brush	farms, 2022	34,397	70	112	337	180
	2017	34,699	55	111	319	114
	acres, 2022	17,661,145	9,133	13,527	200,608	38,720
	2017	18,000,973	13,258	21,942	180,020	31,921
Nematodes	farms, 2022	3,288	7	5	30	10
	2017	2,707	2	2	15	-
	acres, 2022	977,113	1,342	(D)	9,845	2,530
	2017	786,555	(D)	(D)	5,945	-
Diseases in crops and orchards	farms, 2022	5,080	6	12	51	7
	2017	4,417	5	18	61	12
	acres, 2022	2,350,398	148	632	23,100	5,429
	2017	2,183,439	(D)	261	35,403	5,514
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	1,762	5	8	28	4
	2017	655	3	8	5	1
	acres on which used, 2022	318,341	146	(D)	5,128	43
	2017	182,352	12	25	(D)	(D)

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Commercial fertilizer, lime, and soil conditioners	farms, 2022	340	245	659	685	149
	2017	458	278	609	739	180
	acres treated, 2022	75,073	156,481	311,250	191,241	9,631
	2017	99,805	160,985	236,984	213,124	10,104
Cropland fertilized, except cropland pasture	farms, 2022	330	237	649	680	140
	2017	437	273	599	736	160
	acres treated, 2022	74,710	156,417	310,764	191,153	9,146
	2017	99,011	160,780	236,723	212,997	9,448
Pastureland and rangeland fertilized	farms, 2022	26	8	19	8	22
	2017	57	9	15	8	37
	acres treated, 2022	363	64	486	88	485
	2017	794	205	261	127	656
Manure	farms, 2022	231	54	207	209	135
	2017	240	73	231	276	132
	acres treated, 2022	20,074	3,649	40,796	20,343	4,468
	2017	17,314	8,576	36,215	35,515	3,321
Organic fertilizer	farms, 2022	2	6	22	10	3
	2017	18	4	15	19	11
	acres treated, 2022	(D)	1,120	1,453	1,215	82
	2017	1,002	428	4,928	2,580	231
Acres treated to control-						
Insects	farms, 2022	48	94	356	357	20
	2017	64	125	421	503	9
	acres, 2022	18,938	39,773	173,712	82,241	401
	2017	18,746	56,477	168,861	134,114	717
Weeds, grass, or brush	farms, 2022	334	262	694	712	46
	2017	414	272	599	714	43
	acres, 2022	80,680	199,140	429,331	253,190	1,184
	2017	122,397	220,649	328,129	283,255	2,389
Nematodes	farms, 2022	14	15	93	84	5
	2017	15	16	79	90	-
	acres, 2022	2,317	6,589	30,795	15,033	75
	2017	3,052	7,933	27,597	17,931	-
Diseases in crops and orchards	farms, 2022	20	22	121	90	10
	2017	14	30	79	47	4
	acres, 2022	7,825	9,312	68,474	19,455	163
	2017	4,323	10,200	46,456	6,753	474
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	13	7	34	26	9
	2017	2	-	9	4	-
	acres on which used, 2022	2,055	1,138	10,496	3,171	159
	2017	(D)	-	1,599	(D)	-

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Table 40. **Fertilizers and Chemicals Applied: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Commercial fertilizer, lime, and soil conditioners	farms, 2022	310	129	358	287	391	133
	2017	408	145	430	422	446	162
	acres treated, 2022	103,541	21,363	225,293	39,166	313,692	28,547
	2017	99,457	20,085	225,252	57,801	358,488	36,455
Cropland fertilized, except cropland pasture	farms, 2022	305	116	349	269	382	127
	2017	396	136	421	402	440	154
	acres treated, 2022	103,343	19,388	225,047	38,758	313,111	27,959
	2017	99,226	17,835	225,115	56,941	357,710	34,084
Pastureland and rangeland fertilized	farms, 2022	15	14	14	35	12	10
	2017	16	22	13	62	27	25
	acres treated, 2022	198	1,975	246	408	581	588
	2017	231	2,250	137	860	778	2,371
Manure	farms, 2022	160	71	80	128	78	88
	2017	222	93	110	159	101	83
	acres treated, 2022	12,160	2,606	24,805	3,236	4,783	4,170
	2017	15,027	4,255	20,797	4,127	8,489	3,593
Organic fertilizer	farms, 2022	12	4	4	25	9	18
	2017	20	3	15	22	11	8
	acres treated, 2022	989	4	(D)	480	4,950	1,508
	2017	2,286	115	2,534	426	3,402	1,323
Acres treated to control-							
Insects	farms, 2022	117	13	195	57	133	23
	2017	131	14	257	69	320	31
	acres, 2022	14,544	(D)	82,397	1,859	103,899	4,637
	2017	30,111	1,368	118,651	15,246	226,433	13,221
Weeds, grass, or brush	farms, 2022	312	85	385	279	396	110
	2017	380	70	418	333	437	107
	acres, 2022	117,558	13,875	287,321	42,065	418,203	27,434
	2017	116,204	12,823	302,730	60,589	482,155	39,290
Nematodes	farms, 2022	33	11	30	4	36	5
	2017	19	-	34	11	41	4
	acres, 2022	4,369	1,199	13,266	(D)	11,732	676
	2017	2,129	-	14,174	857	15,158	635
Diseases in crops and orchards	farms, 2022	44	10	70	27	79	16
	2017	56	5	81	25	128	11
	acres, 2022	12,556	780	27,013	301	57,406	5,701
	2017	9,614	(D)	40,083	3,435	83,386	8,106
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	10	6	18	11	25	9
	2017	3	2	16	8	5	1
	acres on which used, 2022	259	856	3,826	648	5,895	1,117
	2017	25	(D)	2,630	148	2,110	(D)

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Commercial fertilizer, lime, and soil conditioners	farms, 2022	4	489	140	492	338	427
	2017	3	519	165	505	350	463
	acres treated, 2022	8	247,480	24,441	146,096	207,868	128,831
	2017	(D)	214,527	21,449	156,300	183,250	136,067
Cropland fertilized, except cropland pasture	farms, 2022	4	488	129	473	330	409
	2017	2	518	152	490	346	455
	acres treated, 2022	8	247,222	23,459	145,747	207,458	127,391
	2017	(D)	213,688	19,544	155,818	183,122	134,522
Pastureland and rangeland fertilized	farms, 2022	-	6	19	29	15	39
	2017	1	20	29	41	8	37
	acres treated, 2022	-	258	982	349	410	1,440
	2017	(D)	839	1,905	482	128	1,545
Manure	farms, 2022	8	141	82	137	153	169
	2017	5	180	99	170	155	212
	acres treated, 2022	93	25,703	6,304	14,596	21,357	8,451
	2017	(D)	27,159	4,087	9,969	21,265	14,563
Organic fertilizer	farms, 2022	6	20	3	30	11	7
	2017	7	13	11	26	4	18
	acres treated, 2022	8	5,649	(D)	224	3,670	(D)
	2017	47	(D)	140	1,308	236	989
Acres treated to control-							
Insects	farms, 2022	3	294	23	252	179	207
	2017	2	361	28	167	205	147
	acres, 2022	7	144,997	874	45,122	124,210	49,202
	2017	(D)	134,223	1,467	48,736	111,309	29,201
Weeds, grass, or brush	farms, 2022	2	514	93	457	326	484
	2017	-	524	102	416	321	491
	acres, 2022	(D)	335,941	21,140	162,934	245,700	160,325
	2017	-	310,951	12,830	183,490	210,336	156,903
Nematodes	farms, 2022	-	77	-	68	53	35
	2017	-	44	6	29	41	11
	acres, 2022	-	37,977	-	10,087	25,269	9,025
	2017	-	10,957	2,400	5,121	15,662	1,878
Diseases in crops and orchards	farms, 2022	-	80	9	88	90	38
	2017	2	32	8	68	68	32
	acres, 2022	-	55,658	2,155	16,144	68,922	6,969
	2017	(D)	10,631	(D)	15,383	41,051	5,349
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	-	11	8	51	23	14
	2017	-	2	2	13	11	1
	acres on which used, 2022	-	1,894	368	5,935	5,934	1,260
	2017	-	(D)	(D)	730	2,595	(D)

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Table 40. **Fertilizers and Chemicals Applied: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Commercial fertilizer, lime, and soil conditioners	farms, 2022	569	756	575	858	252	165
	2017	591	825	668	901	268	181
	acres treated, 2022	260,847	276,985	234,415	277,787	192,372	11,221
	2017	268,963	222,079	281,369	243,586	223,602	24,975
Cropland fertilized, except cropland pasture	farms, 2022	563	727	565	827	247	152
	2017	582	784	664	858	267	169
	acres treated, 2022	260,735	271,007	234,155	275,552	192,263	10,954
	2017	268,679	214,984	280,824	241,606	223,407	24,703
Pastureland and rangeland fertilized	farms, 2022	7	96	20	89	7	18
	2017	12	160	20	93	3	21
	acres treated, 2022	112	5,978	260	2,235	109	267
	2017	284	7,095	545	1,980	195	272
Manure	farms, 2022	144	399	165	426	40	78
	2017	147	434	211	505	45	85
	acres treated, 2022	21,857	28,856	16,389	31,675	2,829	2,538
	2017	31,557	31,833	24,058	35,192	2,349	4,329
Organic fertilizer	farms, 2022	13	35	12	25	5	21
	2017	6	49	12	25	4	18
	acres treated, 2022	2,489	4,267	3,891	2,852	451	739
	2017	1,412	4,626	292	1,500	750	336
Acres treated to control-							
Insects	farms, 2022	285	314	257	465	102	86
	2017	407	363	373	419	183	57
	acres, 2022	115,851	100,528	115,739	124,351	50,959	1,506
	2017	179,261	87,017	172,882	105,474	109,528	5,414
Weeds, grass, or brush	farms, 2022	605	782	589	839	258	174
	2017	571	693	615	843	255	150
	acres, 2022	348,606	315,627	305,354	316,905	263,759	12,937
	2017	354,421	229,374	334,291	278,780	229,726	26,728
Nematodes	farms, 2022	63	92	74	91	24	29
	2017	64	52	77	52	17	11
	acres, 2022	22,705	20,937	29,565	21,105	13,377	397
	2017	16,931	9,608	27,396	21,036	19,366	1,299
Diseases in crops and orchards	farms, 2022	108	184	114	189	24	47
	2017	95	86	86	103	34	34
	acres, 2022	55,779	87,258	66,313	46,547	8,284	764
	2017	63,812	18,523	37,394	13,525	29,316	896
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	22	32	30	34	15	25
	2017	6	10	6	18	1	6
	acres on which used, 2022	2,835	3,854	8,625	2,907	2,251	443
	2017	2,981	1,590	3,105	203	(D)	25

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Commercial fertilizer, lime, and soil conditioners	farms, 2022	391	98	301	103	588	150
	2017	450	129	366	76	550	187
	acres treated, 2022	92,418	34,812	50,688	16,562	241,623	29,788
	2017	77,988	33,970	77,951	12,356	247,731	37,142
Cropland fertilized, except cropland pasture	farms, 2022	380	90	286	87	584	139
	2017	433	125	335	72	550	179
	acres treated, 2022	90,191	34,172	49,860	15,661	241,060	29,079
	2017	74,695	33,196	77,297	11,638	246,360	33,841
Pastureland and rangeland fertilized	farms, 2022	48	14	37	29	17	15
	2017	67	17	51	18	17	20
	acres treated, 2022	2,227	640	828	901	563	709
	2017	3,293	774	654	718	1,371	3,301
Manure	farms, 2022	248	61	160	79	153	117
	2017	290	76	145	55	137	102
	acres treated, 2022	28,560	5,520	5,099	1,589	21,617	2,978
	2017	27,619	7,889	4,197	1,074	19,587	4,088
Organic fertilizer	farms, 2022	20	5	19	9	9	8
	2017	28	3	29	4	5	6
	acres treated, 2022	3,117	(D)	396	487	2,891	(D)
	2017	4,082	(D)	828	(D)	395	161
Acres treated to control-							
Insects	farms, 2022	140	19	56	18	313	28
	2017	137	23	51	12	422	9
	acres, 2022	24,405	14,127	4,162	(D)	105,520	5,024
	2017	24,565	8,658	5,945	1,642	178,853	1,030
Weeds, grass, or brush	farms, 2022	391	84	274	72	629	129
	2017	399	66	281	44	551	123
	acres, 2022	86,731	33,834	48,161	13,953	342,148	33,163
	2017	76,340	28,184	75,509	10,942	304,706	37,051
Nematodes	farms, 2022	30	5	15	6	68	8
	2017	38	1	18	3	83	1
	acres, 2022	5,310	(D)	1,348	273	17,532	207
	2017	5,040	(D)	3,072	(D)	20,761	(D)
Diseases in crops and orchards	farms, 2022	40	6	19	12	62	13
	2017	47	7	11	6	50	7
	acres, 2022	8,699	(D)	1,993	392	16,204	2,153
	2017	7,032	10,856	164	(D)	8,629	1,369
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	10	7	16	7	20	1
	2017	7	4	4	3	3	1
	acres on which used, 2022	596	(D)	407	396	2,573	(D)
	2017	1,660	(D)	57	3	1,181	(D)

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Table 40. **Fertilizers and Chemicals Applied: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Commercial fertilizer, lime, and soil conditioners	farms, 2022	539	289	35	476	6	63
	2017	564	259	47	548	13	57
	acres treated, 2022	282,048	316,384	7,768	248,357	6	32,388
	2017	257,674	236,982	10,135	273,992	(D)	34,728
Cropland fertilized, except cropland pasture	farms, 2022	525	286	31	470	4	61
	2017	542	257	35	545	8	55
	acres treated, 2022	281,552	315,829	(D)	248,015	(D)	32,264
	2017	256,562	236,282	8,955	273,384	(D)	34,673
Pastureland and rangeland fertilized	farms, 2022	29	6	8	12	2	3
	2017	45	7	16	14	5	4
	acres treated, 2022	496	555	(D)	342	(D)	124
	2017	1,112	700	1,180	608	(D)	55
Manure	farms, 2022	213	27	13	100	-	15
	2017	252	27	34	135	13	7
	acres treated, 2022	37,503	2,209	591	19,671	-	699
	2017	41,158	1,234	2,192	19,825	125	263
Organic fertilizer	farms, 2022	18	3	-	17	3	-
	2017	10	3	5	11	6	-
	acres treated, 2022	1,603	600	-	2,131	5	-
	2017	1,816	207	1,180	1,262	12	-
Acres treated to control-							
Insects	farms, 2022	230	144	17	285	3	26
	2017	319	181	14	365	5	44
	acres, 2022	120,145	162,052	4,331	107,353	5	14,452
	2017	124,126	182,464	3,161	139,347	(D)	37,044
Weeds, grass, or brush	farms, 2022	591	301	32	491	2	69
	2017	538	238	26	546	4	57
	acres, 2022	366,547	380,251	10,809	331,167	(D)	45,608
	2017	320,903	317,144	10,332	322,899	(D)	49,005
Nematodes	farms, 2022	47	22	-	34	-	4
	2017	43	18	-	58	-	-
	acres, 2022	17,008	15,899	-	16,846	-	136
	2017	10,710	5,797	-	13,892	-	-
Diseases in crops and orchards	farms, 2022	63	131	8	39	-	7
	2017	57	111	3	32	-	18
	acres, 2022	56,803	141,042	6,104	19,672	-	7,486
	2017	21,016	106,696	898	4,520	-	19,072
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	39	15	8	11	-	9
	2017	11	14	2	7	-	1
	acres on which used, 2022	7,259	13,869	1,518	519	-	2,842
	2017	3,086	7,340	(D)	1,040	-	(D)

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Commercial fertilizer, lime, and soil conditioners	farms, 2022	377	322	564	398	151	574
	2017	422	388	611	493	177	535
	acres treated, 2022	116,554	113,136	270,077	158,275	130,109	509,106
	2017	139,999	168,076	263,852	165,664	130,778	538,078
Cropland fertilized, except cropland pasture	farms, 2022	371	317	558	392	151	565
	2017	413	383	604	482	177	525
	acres treated, 2022	116,319	111,960	268,233	158,207	129,309	508,187
	2017	139,841	166,966	263,213	165,502	130,404	534,965
Pastureland and rangeland fertilized	farms, 2022	24	18	25	10	4	16
	2017	14	26	22	16	6	44
	acres treated, 2022	235	1,176	1,844	68	800	919
	2017	158	1,110	639	162	374	3,113
Manure	farms, 2022	156	111	210	214	27	76
	2017	196	154	235	223	55	90
	acres treated, 2022	11,926	13,504	43,953	13,561	1,812	5,187
	2017	11,943	17,880	34,347	17,639	2,085	7,766
Organic fertilizer	farms, 2022	10	9	9	12	2	9
	2017	21	13	11	7	-	2
	acres treated, 2022	99	2,688	2,004	2,582	(D)	501
	2017	6,305	1,213	3,370	357	-	(D)
Acres treated to control-							
Insects	farms, 2022	144	156	332	140	51	225
	2017	176	163	341	159	132	387
	acres, 2022	42,928	43,505	123,944	44,672	18,300	190,040
	2017	58,060	79,851	120,470	56,520	80,977	421,934
Weeds, grass, or brush	farms, 2022	403	340	592	443	158	567
	2017	434	374	589	466	171	498
	acres, 2022	152,976	150,051	351,775	208,560	160,852	577,037
	2017	188,191	217,928	326,473	208,644	168,154	657,894
Nematodes	farms, 2022	46	25	83	45	16	49
	2017	20	30	81	29	10	30
	acres, 2022	29,946	4,850	22,807	16,481	2,386	19,786
	2017	6,045	8,433	26,459	8,249	2,319	21,039
Diseases in crops and orchards	farms, 2022	44	23	54	46	54	157
	2017	44	15	35	43	46	219
	acres, 2022	12,721	8,823	23,656	16,084	22,309	121,605
	2017	16,048	2,589	13,984	22,269	18,331	211,482
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	26	14	12	32	7	29
	2017	14	-	3	7	4	39
	acres on which used, 2022	1,133	1,732	687	3,448	514	12,563
	2017	362	-	1,910	975	810	23,423

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Table 40. **Fertilizers and Chemicals Applied: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Commercial fertilizer, lime, and soil conditioners	farms, 2022	588	478	221	789	594	526
	2017	683	505	252	961	658	581
	acres treated, 2022	305,474	170,669	35,137	125,378	262,090	202,346
	2017	305,802	175,316	59,494	144,099	300,713	253,898
Cropland fertilized, except cropland pasture	farms, 2022	588	465	213	773	587	519
	2017	679	487	243	942	652	580
	acres treated, 2022	305,327	170,309	34,733	123,749	261,607	201,728
	2017	305,528	174,879	58,900	142,091	300,429	252,642
Pastureland and rangeland fertilized	farms, 2022	7	19	17	58	23	22
	2017	12	29	28	75	28	16
	acres treated, 2022	147	360	404	1,629	483	618
	2017	274	437	594	2,008	284	1,256
Manure	farms, 2022	208	174	138	492	216	149
	2017	279	233	174	608	252	199
	acres treated, 2022	40,016	22,554	7,181	45,647	23,251	21,158
	2017	65,229	23,006	10,761	60,259	24,078	33,183
Organic fertilizer	farms, 2022	7	19	11	26	14	7
	2017	10	10	12	27	24	19
	acres treated, 2022	586	6,226	2,009	1,456	2,104	1,757
	2017	2,041	4,058	609	3,015	1,150	4,426
Acres treated to control-							
Insects	farms, 2022	260	136	26	154	318	247
	2017	517	236	29	201	368	407
	acres, 2022	88,434	44,519	1,182	13,849	131,742	80,499
	2017	219,103	83,593	4,213	26,121	176,591	154,446
Weeds, grass, or brush	farms, 2022	611	472	195	727	597	550
	2017	677	493	205	782	631	580
	acres, 2022	405,789	227,334	34,616	122,758	316,002	283,816
	2017	407,115	221,881	58,728	141,449	374,004	324,956
Nematodes	farms, 2022	62	33	11	25	95	59
	2017	91	51	2	15	74	89
	acres, 2022	12,404	19,548	264	2,995	23,198	22,878
	2017	23,975	13,960	(D)	2,995	22,111	26,084
Diseases in crops and orchards	farms, 2022	89	24	15	34	153	65
	2017	54	26	11	14	127	42
	acres, 2022	28,840	15,414	(D)	2,680	65,962	17,205
	2017	18,631	10,956	1,302	1,214	71,405	8,006
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	19	22	11	31	53	9
	2017	6	2	-	11	10	6
	acres on which used, 2022	1,568	4,491	164	3,249	11,576	1,116
	2017	323	(D)	-	1,314	1,154	930

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Commercial fertilizer, lime, and soil conditioners	farms, 2022	439	633	287	566	1,097	155
	2017	533	632	361	577	1,176	231
	acres treated, 2022	189,394	233,190	291,332	189,427	331,322	136,816
	2017	169,763	265,293	326,757	181,741	376,034	178,312
Cropland fertilized, except cropland pasture	farms, 2022	434	626	286	544	1,044	154
	2017	529	624	358	553	1,146	229
	acres treated, 2022	188,601	232,242	291,214	188,518	325,637	136,339
	2017	169,659	264,083	326,168	179,816	372,017	176,354
Pastureland and rangeland fertilized	farms, 2022	10	28	3	40	122	8
	2017	10	26	16	71	110	21
	acres treated, 2022	793	948	118	909	5,685	477
	2017	104	1,210	589	1,925	4,017	1,958
Manure	farms, 2022	167	248	45	231	464	24
	2017	234	262	49	285	546	45
	acres treated, 2022	23,692	47,489	2,623	15,940	32,702	1,571
	2017	30,368	53,240	1,842	20,848	40,430	3,006
Organic fertilizer	farms, 2022	12	13	-	17	22	3
	2017	10	20	-	22	25	3
	acres treated, 2022	986	4,024	-	1,794	3,638	3
	2017	957	2,952	-	671	1,598	1,692
Acres treated to control-							
Insects	farms, 2022	139	301	125	261	309	39
	2017	323	441	292	268	487	178
	acres, 2022	25,909	103,883	133,160	66,603	63,574	49,639
	2017	83,366	162,138	279,060	89,901	172,435	139,584
Weeds, grass, or brush	farms, 2022	451	661	295	559	1,138	160
	2017	517	598	349	532	1,085	202
	acres, 2022	245,670	321,068	386,489	217,897	390,323	169,205
	2017	228,418	345,484	459,229	196,832	413,770	192,624
Nematodes	farms, 2022	38	87	30	72	43	9
	2017	68	76	23	34	56	5
	acres, 2022	7,387	32,161	13,950	17,032	8,910	5,713
	2017	14,827	21,817	6,848	5,818	17,701	1,437
Diseases in crops and orchards	farms, 2022	59	88	90	114	99	36
	2017	38	57	157	66	89	69
	acres, 2022	21,881	55,688	61,197	42,536	28,395	30,908
	2017	6,695	16,096	133,441	19,858	30,115	57,287
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	14	30	24	48	44	5
	2017	4	7	14	6	24	6
	acres on which used, 2022	1,434	2,517	8,499	4,739	10,534	1,217
	2017	(D)	266	13,249	257	7,353	2,944

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Table 40. **Fertilizers and Chemicals Applied: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Commercial fertilizer, lime, and soil conditioners	farms, 2022	273	312	769	380	16	176
	2017	298	376	727	427	20	174
	acres treated, 2022	35,840	131,415	673,185	163,638	208	117,018
	2017	32,852	146,762	690,763	204,929	108	133,326
Cropland fertilized, except cropland pasture	farms, 2022	261	304	759	375	16	172
	2017	281	363	708	406	20	172
	acres treated, 2022	34,947	129,405	672,486	163,245	208	116,364
	2017	31,340	144,666	689,127	203,481	108	133,130
Pastureland and rangeland fertilized	farms, 2022	33	33	25	15	-	13
	2017	43	40	38	38	-	6
	acres treated, 2022	893	2,010	699	393	-	654
	2017	1,512	2,096	1,636	1,448	-	196
Manure	farms, 2022	165	160	97	122	4	37
	2017	197	185	104	186	13	43
	acres treated, 2022	6,324	33,980	12,952	16,666	13	2,538
	2017	8,867	30,388	9,803	25,119	(D)	3,600
Organic fertilizer	farms, 2022	15	7	13	5	6	-
	2017	20	7	15	8	8	2
	acres treated, 2022	480	1,979	12,824	16	6	-
	2017	869	313	14,729	245	10	(D)
Acres treated to control-							
Insects	farms, 2022	20	107	377	152	13	66
	2017	36	204	563	258	6	119
	acres, 2022	1,463	42,592	330,387	42,394	23	27,737
	2017	2,896	70,745	525,869	104,076	36	86,635
Weeds, grass, or brush	farms, 2022	193	340	772	410	12	183
	2017	200	380	679	417	6	159
	acres, 2022	29,580	173,113	815,754	194,626	(D)	144,668
	2017	25,598	191,769	799,109	229,707	(D)	161,941
Nematodes	farms, 2022	4	25	60	27	-	7
	2017	-	42	66	14	-	11
	acres, 2022	270	6,512	33,848	7,402	-	3,236
	2017	-	13,208	26,427	3,576	-	3,791
Diseases in crops and orchards	farms, 2022	10	16	282	38	4	35
	2017	10	27	338	37	4	54
	acres, 2022	241	4,223	255,577	10,321	4	18,212
	2017	133	5,421	325,043	10,619	38	40,702
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	13	9	83	15	-	8
	2017	3	1	52	7	1	10
	acres on which used, 2022	531	600	28,833	3,044	-	2,695
	2017	(D)	(D)	25,152	1,712	(D)	2,842

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Commercial fertilizer, lime, and soil conditioners	farms, 2022	909	663	523	391	336	175
	2017	816	719	635	533	340	149
	acres treated, 2022	345,842	368,622	136,895	161,900	225,720	15,609
	2017	323,099	383,327	133,819	180,465	273,519	9,102
Cropland fertilized, except cropland pasture	farms, 2022	900	648	509	376	327	161
	2017	812	719	612	507	322	140
	acres treated, 2022	345,352	368,429	136,645	159,429	225,253	15,052
	2017	322,732	383,255	133,424	178,699	272,223	8,512
Pastureland and rangeland fertilized	farms, 2022	20	19	23	41	16	32
	2017	20	5	35	56	30	18
	acres treated, 2022	490	193	250	2,471	467	557
	2017	367	72	395	1,766	1,296	590
Manure	farms, 2022	255	134	227	173	79	159
	2017	273	185	280	279	68	123
	acres treated, 2022	38,421	25,769	20,364	30,225	4,929	5,149
	2017	37,534	40,496	23,644	47,815	6,508	4,180
Organic fertilizer	farms, 2022	11	4	21	13	-	22
	2017	11	6	21	18	11	24
	acres treated, 2022	2,874	(D)	1,567	1,736	-	55
	2017	2,321	3,068	3,902	4,021	1,599	694
Acres treated to control-							
Insects	farms, 2022	460	404	179	140	143	34
	2017	521	500	223	245	235	21
	acres, 2022	139,636	172,979	53,293	59,027	120,656	(D)
	2017	168,091	213,932	51,657	87,426	254,284	(D)
Weeds, grass, or brush	farms, 2022	930	677	558	397	344	83
	2017	793	684	586	533	306	38
	acres, 2022	490,193	525,088	187,305	225,405	285,669	9,850
	2017	453,635	542,439	156,969	242,782	330,148	9,957
Nematodes	farms, 2022	126	126	64	23	11	9
	2017	108	81	35	33	17	2
	acres, 2022	30,202	44,240	13,245	4,939	1,941	19
	2017	33,719	36,047	5,383	6,235	8,188	(D)
Diseases in crops and orchards	farms, 2022	147	174	89	50	64	11
	2017	83	119	56	32	122	8
	acres, 2022	47,016	81,102	24,091	31,913	59,812	29
	2017	30,043	46,397	12,114	6,792	133,420	171
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	27	85	38	6	31	5
	2017	2	9	16	4	37	2
	acres on which used, 2022	4,146	16,801	5,705	760	14,629	65
	2017	(D)	8,597	2,118	(D)	12,608	(D)

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Table 40. **Fertilizers and Chemicals Applied: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Commercial fertilizer, lime, and soil conditioners	farms, 2022	256	170	540	1,526	340	278
	2017	349	199	594	1,808	371	316
	acres treated, 2022	60,938	47,119	232,219	318,445	171,404	220,868
	2017	52,625	60,238	225,592	329,051	174,269	215,824
Cropland fertilized, except cropland pasture	farms, 2022	228	160	532	1,496	339	278
	2017	323	188	581	1,775	360	310
	acres treated, 2022	60,554	44,625	231,776	315,587	171,077	220,727
	2017	51,979	60,095	225,406	326,548	174,023	215,314
Pastureland and rangeland fertilized	farms, 2022	34	14	24	110	9	6
	2017	45	15	24	104	19	15
	acres treated, 2022	384	2,494	443	2,858	327	141
	2017	646	143	186	2,503	246	510
Manure	farms, 2022	126	68	195	1,031	132	111
	2017	175	75	263	1,222	182	104
	acres treated, 2022	7,350	4,448	24,423	114,996	16,523	21,025
	2017	9,189	3,943	30,229	131,231	22,549	20,310
Organic fertilizer	farms, 2022	12	15	2	78	8	10
	2017	10	4	10	46	3	6
	acres treated, 2022	402	1,069	(D)	5,399	511	476
	2017	521	63	1,588	4,524	85	2,585
Acres treated to control-							
Insects	farms, 2022	81	59	161	501	159	139
	2017	110	69	256	485	192	201
	acres, 2022	8,600	16,958	38,577	66,710	88,139	71,853
	2017	18,316	22,666	99,337	86,350	106,348	95,979
Weeds, grass, or brush	farms, 2022	254	177	555	1,572	347	289
	2017	329	153	581	1,693	347	327
	acres, 2022	73,053	50,293	310,464	354,026	211,528	272,982
	2017	72,165	61,247	290,313	360,361	201,767	276,591
Nematodes	farms, 2022	23	22	57	96	61	21
	2017	5	12	34	44	37	15
	acres, 2022	6,432	9,077	9,800	15,807	27,523	7,758
	2017	490	4,578	6,636	4,337	17,942	5,276
Diseases in crops and orchards	farms, 2022	30	30	81	105	75	33
	2017	21	30	52	76	57	33
	acres, 2022	1,520	10,985	29,936	19,472	47,401	7,263
	2017	1,101	6,975	15,407	16,082	26,727	14,037
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	12	24	24	56	12	16
	2017	8	23	3	16	4	13
	acres on which used, 2022	490	9,502	3,103	5,318	1,570	7,360
	2017	224	6,843	(D)	2,186	628	5,556

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Commercial fertilizer, lime, and soil conditioners	farms, 2022	388	713	204	479	183	400
	2017	468	838	272	555	218	464
	acres treated, 2022	227,032	119,528	177,847	132,166	44,383	176,715
	2017	229,201	122,249	244,988	125,845	44,179	155,322
Cropland fertilized, except cropland pasture	farms, 2022	387	690	204	472	165	395
	2017	466	807	270	550	210	458
	acres treated, 2022	226,864	118,269	177,847	130,913	43,207	176,642
	2017	228,311	119,876	244,777	124,356	43,112	155,170
Pastureland and rangeland fertilized	farms, 2022	5	51	-	42	42	6
	2017	9	86	3	54	27	9
	acres treated, 2022	168	1,259	-	1,253	1,176	73
	2017	890	2,373	211	1,489	1,067	152
Manure	farms, 2022	86	430	33	297	99	121
	2017	140	507	27	313	125	189
	acres treated, 2022	15,067	28,279	6,038	29,494	3,051	25,481
	2017	26,581	40,160	2,188	32,685	5,869	35,074
Organic fertilizer	farms, 2022	3	28	2	28	6	7
	2017	6	17	-	16	16	17
	acres treated, 2022	(D)	1,480	(D)	1,525	640	842
	2017	3,038	861	-	1,182	419	3,592
Acres treated to control-							
Insects	farms, 2022	192	176	87	191	43	198
	2017	319	277	165	201	59	258
	acres, 2022	78,173	21,367	52,034	38,032	13,472	85,970
	2017	117,202	38,889	144,281	39,560	13,930	85,991
Weeds, grass, or brush	farms, 2022	426	696	210	483	165	407
	2017	464	759	263	501	158	452
	acres, 2022	294,026	123,811	249,101	130,967	44,796	233,150
	2017	280,959	131,757	321,889	127,134	37,186	209,199
Nematodes	farms, 2022	59	30	18	48	6	48
	2017	50	13	29	35	5	50
	acres, 2022	21,542	3,823	8,221	6,213	3,047	9,043
	2017	15,029	984	14,156	4,225	750	13,422
Diseases in crops and orchards	farms, 2022	46	43	17	88	9	74
	2017	52	29	23	43	16	68
	acres, 2022	18,868	6,301	18,080	16,270	3,493	45,269
	2017	17,472	3,117	12,866	6,925	8,403	24,665
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	28	30	4	40	7	12
	2017	7	2	5	14	5	2
	acres on which used, 2022	9,780	2,073	474	3,174	3,009	1,549
	2017	2,009	(D)	1,721	808	3,257	(D)

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Table 40. **Fertilizers and Chemicals Applied: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Commercial fertilizer, lime, and soil conditioners	farms, 2022	211	321	228	580	605	511
	2017	293	328	266	621	681	537
	acres treated, 2022	24,184	173,135	225,076	154,117	123,987	243,765
	2017	42,772	163,446	256,891	128,119	146,693	247,444
Cropland fertilized, except cropland pasture	farms, 2022	192	320	223	550	533	508
	2017	271	326	266	610	664	534
	acres treated, 2022	23,572	(D)	225,014	152,096	122,873	241,355
	2017	41,556	163,367	(D)	125,828	146,162	246,376
Pastureland and rangeland fertilized	farms, 2022	38	1	6	72	91	19
	2017	48	5	1	65	41	32
	acres treated, 2022	612	(D)	62	2,021	1,114	2,410
	2017	1,216	79	(D)	2,291	531	1,068
Manure	farms, 2022	86	98	24	343	319	145
	2017	121	122	20	391	361	139
	acres treated, 2022	1,384	20,306	5,198	52,294	20,014	16,387
	2017	2,905	24,107	2,039	41,138	23,154	26,405
Organic fertilizer	farms, 2022	16	6	1	45	14	6
	2017	20	3	1	48	28	7
	acres treated, 2022	393	231	(D)	4,935	2,590	(D)
	2017	293	(D)	(D)	4,415	1,251	1,961
Acres treated to control-							
Insects	farms, 2022	102	180	79	179	192	293
	2017	84	249	156	225	170	336
	acres, 2022	6,994	81,224	71,808	41,014	32,200	107,147
	2017	12,395	103,870	109,468	45,105	29,892	132,924
Weeds, grass, or brush	farms, 2022	225	339	239	551	614	528
	2017	234	321	259	523	606	525
	acres, 2022	27,626	232,637	335,860	154,720	144,828	300,147
	2017	45,741	217,952	386,482	124,386	168,026	313,234
Nematodes	farms, 2022	22	55	22	62	43	58
	2017	4	47	20	46	11	62
	acres, 2022	1,890	18,117	11,902	8,619	7,168	21,384
	2017	769	13,094	10,754	2,646	1,346	15,984
Diseases in crops and orchards	farms, 2022	42	38	54	100	40	55
	2017	43	25	75	55	56	48
	acres, 2022	2,691	15,200	29,067	20,883	2,988	22,501
	2017	1,469	9,727	46,336	7,155	5,068	13,702
Chemicals used to control growth, thin fruit, ripen, or defoliate	farms, 2022	24	22	4	30	40	6
	2017	14	1	3	9	18	1
	acres on which used, 2022	887	3,686	2,220	3,075	1,673	337
	2017	357	(D)	1,273	2,299	432	(D)

Table 41. **Land Use Practices: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Land drained by tile	farms, 2022	19,088	11	18	80	14
	2017	21,249	14	19	50	15
	acres, 2022	8,247,260	2,452	3,230	29,866	7,345
	2017	8,079,984	4,628	3,489	15,075	4,195
Average per farm	acres, 2022	432	223	179	373	525
	2017	380	331	184	302	280
Land artificially drained by ditches	farms, 2022	9,435	81	62	82	87
	2017	10,845	124	66	99	82
	acres, 2022	4,560,910	20,362	6,909	50,239	40,030
	2017	4,674,449	23,165	6,369	53,023	33,815
Average per farm	acres, 2022	483	251	111	613	460
	2017	431	187	97	536	412
Land under conservation easement	farms, 2022	4,909	11	5	68	21
	2017	2,522	10	1	31	17
	acres, 2022	282,171	1,170	306	5,368	1,958
	2017	218,215	666	(D)	2,842	2,383
Average per farm	acres, 2022	57	106	61	79	93
	2017	87	67	(D)	92	140
Cropland on which no-till practices were used	farms, 2022	6,845	37	47	59	32
	2017	5,815	19	31	43	15
	acres, 2022	1,194,987	1,061	1,740	4,506	4,089
	2017	1,091,337	888	3,442	4,492	1,319
Average per farm	acres, 2022	175	29	37	76	128
	2017	188	47	111	104	88
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	15,574	32	34	130	65
	2017	16,704	21	47	108	58
	acres, 2022	7,881,385	5,780	4,484	73,459	16,459
	2017	8,214,896	2,062	10,521	79,709	19,857
Average per farm	acres, 2022	506	181	132	565	253
	2017	492	98	224	738	342
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	22,330	108	98	280	177
	2017	22,993	94	73	275	112
	acres, 2022	9,573,777	8,174	8,265	135,078	25,992
	2017	9,499,259	11,341	7,423	113,968	16,367
Average per farm	acres, 2022	429	76	84	482	147
	2017	413	121	102	414	146
Cropland planted to a cover crop (excluding CRP)	farms, 2022	6,050	42	39	64	44
	2017	5,302	29	28	59	41
	acres, 2022	760,423	807	580	3,438	4,169
	2017	579,147	313	566	6,367	1,178
Average per farm	acres, 2022	126	19	15	54	95
	2017	109	11	20	108	29
Use of precision agriculture practices (see text)	farms, 2022	15,460	18	9	118	58
	2017	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Land drained by tile	farms, 2022	87	130	584	574	4
	2017	109	129	574	637	4
	acres, 2022	13,879	47,775	333,692	179,771	58
	2017	13,746	47,058	263,965	229,441	261
Average per farm	acres, 2022	160	368	571	313	15
	2017	126	365	460	360	65
Land artificially drained by ditches	farms, 2022	128	94	86	141	44
	2017	122	135	100	170	59
	acres, 2022	10,226	77,335	32,358	31,421	2,343
	2017	10,534	75,656	30,902	49,682	3,882
Average per farm	acres, 2022	80	823	376	223	53
	2017	86	560	309	292	66
Land under conservation easement	farms, 2022	26	62	112	89	5
	2017	12	54	27	39	-
	acres, 2022	532	5,698	3,344	3,050	252
	2017	259	5,893	967	1,614	-
Average per farm	acres, 2022	20	92	30	34	50
	2017	22	109	36	41	-
Cropland on which no-till practices were used	farms, 2022	52	62	91	101	28
	2017	59	71	57	120	12
	acres, 2022	5,260	11,874	25,888	16,759	975
	2017	14,773	15,865	11,602	25,480	259
Average per farm	acres, 2022	101	192	284	166	35
	2017	250	223	204	212	22
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	139	136	284	290	17
	2017	190	147	296	389	32
	acres, 2022	24,251	92,697	187,687	114,591	317
	2017	60,835	102,604	157,240	146,975	1,500
Average per farm	acres, 2022	174	682	661	395	19
	2017	320	698	531	378	47
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	302	130	458	454	78
	2017	299	160	361	437	55
	acres, 2022	54,671	107,378	222,427	124,823	2,386
	2017	53,295	110,317	170,875	132,489	2,203
Average per farm	acres, 2022	181	826	486	275	31
	2017	178	689	473	303	40
Cropland planted to a cover crop (excluding CRP)	farms, 2022	66	45	40	61	37
	2017	51	29	43	85	55
	acres, 2022	6,524	3,579	6,241	6,696	651
	2017	3,244	10,598	8,665	4,336	716
Average per farm	acres, 2022	99	80	156	110	18
	2017	64	365	202	51	13
Use of precision agriculture practices (see text)	farms, 2022	81	146	415	342	15
	2017	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Land drained by tile	farms, 2022	275	3	275	59	128	3
	2017	369	4	338	80	127	9
	acres, 2022	90,843	25	209,554	2,439	50,838	(D)
	2017	80,420	194	190,474	5,114	41,742	(D)
Average per farm	acres, 2022	330	8	762	41	397	(D)
	2017	218	49	564	64	329	(D)
Land artificially drained by ditches	farms, 2022	104	28	103	87	194	42
	2017	136	36	125	130	237	27
	acres, 2022	24,439	3,126	41,828	10,165	215,588	17,215
	2017	16,589	2,407	56,542	14,991	227,373	12,436
Average per farm	acres, 2022	235	112	406	117	1,111	410
	2017	122	67	452	115	959	461
Land under conservation easement	farms, 2022	37	10	75	17	58	9
	2017	21	5	44	12	30	8
	acres, 2022	926	1,025	2,261	1,456	2,806	1,865
	2017	446	1,025	2,703	362	2,331	291
Average per farm	acres, 2022	25	103	30	86	48	207
	2017	21	205	61	30	78	36
Cropland on which no-till practices were used	farms, 2022	29	43	22	87	76	16
	2017	42	23	40	105	52	6
	acres, 2022	1,911	1,839	4,404	7,316	26,649	477
	2017	3,569	768	4,333	9,449	21,178	282
Average per farm	acres, 2022	66	43	200	84	351	30
	2017	85	33	108	90	407	47
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	129	46	157	128	140	45
	2017	166	28	163	165	176	33
	acres, 2022	62,904	4,484	134,322	27,298	129,115	17,372
	2017	45,077	6,873	101,919	41,606	157,572	11,232
Average per farm	acres, 2022	488	97	856	213	922	386
	2017	272	245	625	252	895	340
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	225	86	253	160	283	90
	2017	268	75	301	165	295	112
	acres, 2022	55,136	9,519	175,370	11,989	311,665	16,704
	2017	69,089	13,338	195,108	13,178	314,124	25,944
Average per farm	acres, 2022	245	111	693	75	1,101	186
	2017	258	178	648	80	1,065	232
Cropland planted to a cover crop (excluding CRP)	farms, 2022	37	45	56	74	73	41
	2017	44	30	83	54	60	30
	acres, 2022	1,375	800	12,348	1,395	11,669	2,443
	2017	584	790	21,548	939	9,497	2,706
Average per farm	acres, 2022	37	18	221	19	160	60
	2017	13	26	260	17	158	90
Use of precision agriculture practices (see text)	farms, 2022	116	14	186	45	194	23
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Land drained by tile	farms, 2022	1	455	4	150	297	193
	2017	-	461	5	141	317	245
	acres, 2022	(D)	276,488	877	36,785	206,560	70,447
	2017	-	229,841	379	31,482	172,698	59,446
Average per farm	acres, 2022	(D)	608	219	245	695	365
	2017	-	499	76	223	545	243
Land artificially drained by ditches	farms, 2022	1	68	16	52	35	129
	2017	-	71	28	60	47	142
	acres, 2022	(D)	25,741	634	5,579	11,916	16,416
	2017	-	10,915	1,674	8,458	15,391	20,317
Average per farm	acres, 2022	(D)	379	40	107	340	127
	2017	-	154	60	141	327	143
Land under conservation easement	farms, 2022	-	82	23	39	44	112
	2017	-	31	9	41	16	63
	acres, 2022	-	4,087	3,248	2,579	1,322	6,426
	2017	-	3,318	932	3,405	294	6,021
Average per farm	acres, 2022	-	50	141	66	30	57
	2017	-	107	104	83	18	96
Cropland on which no-till practices were used	farms, 2022	5	112	52	96	57	101
	2017	5	84	38	81	39	76
	acres, 2022	35	22,556	9,349	19,838	18,958	15,432
	2017	10	22,787	4,238	12,305	19,477	9,115
Average per farm	acres, 2022	7	201	180	207	333	153
	2017	2	271	112	152	499	120
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	4	233	33	239	166	225
	2017	3	256	30	254	170	219
	acres, 2022	6	152,694	6,453	88,037	121,748	67,244
	2017	10	167,930	7,414	104,654	98,031	68,384
Average per farm	acres, 2022	2	655	196	368	733	299
	2017	3	656	247	412	577	312
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	3	284	95	286	189	349
	2017	-	319	75	267	208	338
	acres, 2022	(D)	174,079	6,584	60,935	111,162	85,465
	2017	-	135,478	5,506	72,575	104,751	88,607
Average per farm	acres, 2022	(D)	613	69	213	588	245
	2017	-	425	73	272	504	262
Cropland planted to a cover crop (excluding CRP)	farms, 2022	3	40	44	107	35	104
	2017	2	36	30	97	42	51
	acres, 2022	9	5,501	1,999	17,999	5,435	8,878
	2017	(D)	7,008	3,381	11,174	2,880	2,773
Average per farm	acres, 2022	3	138	45	168	155	85
	2017	(D)	195	113	115	69	54
Use of precision agriculture practices (see text)	farms, 2022	-	328	24	205	207	148
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Land drained by tile	farms, 2022	531	256	534	386	156	103
	2017	536	197	649	403	195	107
	acres, 2022	259,020	77,909	238,358	142,151	122,838	7,029
	2017	277,273	36,844	286,040	93,093	109,054	16,897
Average per farm	acres, 2022	488	304	446	368	787	68
	2017	517	187	441	231	559	158
Land artificially drained by ditches	farms, 2022	118	50	129	73	136	66
	2017	127	63	160	92	159	53
	acres, 2022	63,660	7,121	42,415	10,191	108,396	1,788
	2017	51,510	9,948	50,748	9,294	122,385	3,329
Average per farm	acres, 2022	539	142	329	140	797	27
	2017	406	158	317	101	770	63
Land under conservation easement	farms, 2022	57	111	119	106	99	31
	2017	33	52	47	38	44	12
	acres, 2022	1,354	3,355	6,057	3,717	5,075	818
	2017	714	3,574	1,482	2,257	3,533	949
Average per farm	acres, 2022	24	30	51	35	51	26
	2017	22	69	32	59	80	79
Cropland on which no-till practices were used	farms, 2022	107	284	104	220	67	55
	2017	97	219	123	211	30	22
	acres, 2022	25,498	56,670	27,224	26,741	7,611	879
	2017	30,821	39,381	31,308	22,980	7,990	2,038
Average per farm	acres, 2022	238	200	262	122	114	16
	2017	318	180	255	109	266	93
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	298	433	270	526	111	95
	2017	309	461	334	497	116	59
	acres, 2022	185,545	191,917	104,997	209,764	134,328	8,815
	2017	186,918	139,133	173,006	171,822	101,761	11,523
Average per farm	acres, 2022	623	443	389	399	1,210	93
	2017	605	302	518	346	877	195
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	346	299	356	428	153	82
	2017	345	295	351	389	182	141
	acres, 2022	144,870	73,580	177,825	88,562	139,299	4,252
	2017	160,769	56,170	152,644	93,915	170,000	15,052
Average per farm	acres, 2022	419	246	500	207	910	52
	2017	466	190	435	241	934	107
Cropland planted to a cover crop (excluding CRP)	farms, 2022	54	182	67	169	43	48
	2017	53	160	69	157	52	37
	acres, 2022	9,104	15,218	13,347	14,205	6,385	791
	2017	8,765	8,853	10,366	9,124	8,434	1,640
Average per farm	acres, 2022	169	84	199	84	148	16
	2017	165	55	150	58	162	44
Use of precision agriculture practices (see text)	farms, 2022	392	325	349	442	145	23
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item			Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Land drained by tile	farms	2022	54	1	50	5	513	11
		2017	33	2	63	1	520	26
	acres	2022	3,697	(D)	7,380	105	252,980	2,263
		2017	2,720	(D)	8,113	(D)	254,250	2,161
Average per farm	acres	2022	68	(D)	148	21	493	206
		2017	82	(D)	129	(D)	489	83
Land artificially drained by ditches	farms	2022	43	2	78	29	106	60
		2017	30	2	72	13	106	82
	acres	2022	4,315	(D)	3,770	903	28,981	3,988
		2017	2,267	(D)	12,476	867	24,780	4,001
Average per farm	acres	2022	100	(D)	48	31	273	66
		2017	76	(D)	173	67	234	49
Land under conservation easement	farms	2022	88	6	16	6	57	10
		2017	31	11	6	2	43	6
	acres	2022	2,996	892	772	57	2,423	849
		2017	2,676	945	286	(D)	7,434	107
Average per farm	acres	2022	34	149	48	10	43	85
		2017	86	86	48	(D)	173	18
Cropland on which no-till practices were used	farms	2022	197	13	93	27	119	61
		2017	208	25	90	27	85	54
	acres	2022	30,425	1,090	9,702	2,938	46,637	9,521
		2017	26,197	1,220	9,625	2,351	31,756	3,021
Average per farm	acres	2022	154	84	104	109	392	156
		2017	126	49	107	87	374	56
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms	2022	213	27	113	26	290	45
		2017	253	27	114	17	277	49
	acres	2022	45,577	12,488	22,088	4,031	160,816	18,974
		2017	41,631	3,735	41,470	1,508	154,298	18,135
Average per farm	acres	2022	214	463	195	155	555	422
		2017	165	138	364	89	557	370
Cropland on which intensive or conventional tillage practices were used (see text)	farms	2022	121	90	181	77	351	126
		2017	145	74	160	53	317	154
	acres	2022	18,177	23,726	21,414	9,569	138,721	6,657
		2017	14,306	27,582	25,444	9,509	134,500	18,300
Average per farm	acres	2022	150	264	118	124	395	53
		2017	99	373	159	179	424	119
Cropland planted to a cover crop (excluding CRP)	farms	2022	104	26	48	28	44	35
		2017	78	31	63	26	60	31
	acres	2022	7,431	543	4,103	490	11,789	1,682
		2017	3,280	2,491	1,458	877	13,176	853
Average per farm	acres	2022	71	21	85	18	268	48
		2017	42	80	23	34	220	28
Use of precision agriculture practices (see text)	farms	2022	91	25	50	13	370	42
		2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Land drained by tile	farms, 2022	425	48	8	347	2	14
	2017	442	25	2	417	-	7
	acres, 2022	260,802	14,771	3,626	174,434	(D)	11,923
	2017	214,782	5,825	(D)	168,470	-	8,112
Average per farm	acres, 2022	614	308	453	503	(D)	852
	2017	486	233	(D)	404	-	1,159
Land artificially drained by ditches	farms, 2022	178	208	23	145	5	75
	2017	187	182	27	189	1	62
	acres, 2022	77,846	314,200	4,900	53,554	26	27,451
	2017	47,036	216,395	3,573	33,787	(D)	31,447
Average per farm	acres, 2022	437	1,511	213	369	5	366
	2017	252	1,189	132	179	(D)	507
Land under conservation easement	farms, 2022	139	48	8	95	-	14
	2017	84	14	3	68	2	1
	acres, 2022	5,962	5,269	924	5,945	-	1,442
	2017	7,145	3,839	444	5,838	(D)	(D)
Average per farm	acres, 2022	43	110	116	63	-	103
	2017	85	274	148	86	(D)	(D)
Cropland on which no-till practices were used	farms, 2022	86	37	6	85	2	18
	2017	85	19	2	119	3	7
	acres, 2022	26,858	6,786	102	20,245	(D)	2,385
	2017	22,319	6,209	(D)	25,203	(D)	2,038
Average per farm	acres, 2022	312	183	17	238	(D)	133
	2017	263	327	(D)	212	(D)	291
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	240	120	9	208	3	25
	2017	265	89	21	285	1	15
	acres, 2022	145,142	131,100	3,652	148,473	5	24,166
	2017	151,687	102,131	(D)	158,411	(D)	11,361
Average per farm	acres, 2022	605	1,093	406	714	2	967
	2017	572	1,148	(D)	556	(D)	757
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	364	195	69	323	1	73
	2017	317	189	34	345	-	61
	acres, 2022	214,078	272,100	9,553	170,487	(D)	28,749
	2017	174,207	207,706	9,004	155,089	-	38,003
Average per farm	acres, 2022	588	1,395	138	528	(D)	394
	2017	550	1,099	265	450	-	623
Cropland planted to a cover crop (excluding CRP)	farms, 2022	93	50	12	44	3	19
	2017	68	16	20	53	8	8
	acres, 2022	15,395	7,829	350	6,700	3	5,422
	2017	12,214	3,028	711	2,759	46	879
Average per farm	acres, 2022	166	157	29	152	1	285
	2017	180	189	36	52	6	110
Use of precision agriculture practices (see text)	farms, 2022	248	167	18	281	-	24
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Land drained by tile	farms, 2022	407	262	521	392	49	98
	2017	433	313	557	502	64	78
	acres, 2022	120,625	88,605	248,846	156,993	23,698	51,305
	2017	131,038	125,339	242,699	147,606	21,550	39,337
Average per farm	acres, 2022	296	338	478	400	484	524
	2017	303	400	436	294	337	504
Land artificially drained by ditches	farms, 2022	140	93	114	135	80	494
	2017	157	101	95	162	107	464
	acres, 2022	31,333	18,206	38,090	46,193	89,251	470,756
	2017	27,494	14,829	40,094	41,453	70,631	487,110
Average per farm	acres, 2022	224	196	334	342	1,116	953
	2017	175	147	422	256	660	1,050
Land under conservation easement	farms, 2022	135	64	99	79	27	75
	2017	48	24	42	35	20	53
	acres, 2022	2,743	3,794	6,243	8,851	5,460	7,873
	2017	2,185	2,405	3,151	1,427	4,459	9,389
Average per farm	acres, 2022	20	59	63	112	202	105
	2017	46	100	75	41	223	177
Cropland on which no-till practices were used	farms, 2022	94	56	99	37	12	52
	2017	57	53	91	53	14	62
	acres, 2022	9,443	15,736	25,248	2,418	2,414	12,170
	2017	8,242	15,783	20,568	4,723	881	27,851
Average per farm	acres, 2022	100	281	255	65	201	234
	2017	145	298	226	89	63	449
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	202	129	316	140	66	223
	2017	250	179	246	182	73	230
	acres, 2022	58,419	66,356	175,274	70,132	40,246	197,201
	2017	117,837	92,677	153,093	75,070	59,950	263,690
Average per farm	acres, 2022	289	514	555	501	610	884
	2017	471	518	622	412	821	1,146
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	223	182	319	317	125	461
	2017	238	244	376	387	119	344
	acres, 2022	89,026	68,881	156,467	139,901	124,495	430,567
	2017	74,066	122,305	167,084	148,893	107,005	368,435
Average per farm	acres, 2022	399	378	490	441	996	934
	2017	311	501	444	385	899	1,071
Cropland planted to a cover crop (excluding CRP)	farms, 2022	68	39	83	39	26	130
	2017	45	37	46	48	42	69
	acres, 2022	5,489	6,424	9,282	1,964	4,629	53,929
	2017	1,490	8,780	5,969	2,056	9,139	21,578
Average per farm	acres, 2022	81	165	112	50	178	415
	2017	33	237	130	43	218	313
Use of precision agriculture practices (see text)	farms, 2022	183	150	383	176	85	341
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Land drained by tile	farms, 2022	513	348	56	136	564	399
	2017	644	386	79	147	669	489
	acres, 2022	332,672	130,508	4,166	13,357	250,540	185,549
	2017	349,232	138,661	6,833	10,779	316,253	247,046
Average per farm	acres, 2022	648	375	74	98	444	465
	2017	542	359	86	73	473	505
Land artificially drained by ditches	farms, 2022	94	129	103	180	93	66
	2017	131	157	154	218	86	82
	acres, 2022	42,790	33,734	5,708	12,969	31,420	14,842
	2017	36,895	38,253	16,837	14,082	14,338	15,521
Average per farm	acres, 2022	455	262	55	72	338	225
	2017	282	244	109	65	167	189
Land under conservation easement	farms, 2022	81	97	16	61	73	69
	2017	33	50	16	35	50	41
	acres, 2022	2,528	3,260	610	9,247	3,258	2,268
	2017	1,782	1,758	143	3,713	2,845	9,920
Average per farm	acres, 2022	31	34	38	152	45	33
	2017	54	35	9	106	57	242
Cropland on which no-till practices were used	farms, 2022	76	50	46	119	99	137
	2017	43	60	42	128	96	102
	acres, 2022	16,979	9,344	3,930	8,932	11,395	26,857
	2017	6,704	15,972	6,437	8,870	27,696	17,714
Average per farm	acres, 2022	223	187	85	75	115	196
	2017	156	266	153	69	289	174
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	297	171	91	306	270	263
	2017	370	207	79	410	275	310
	acres, 2022	198,184	77,744	13,436	55,680	173,501	130,705
	2017	231,602	98,702	20,299	82,619	175,056	163,955
Average per farm	acres, 2022	667	455	148	182	643	497
	2017	626	477	257	202	637	529
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	346	322	168	579	384	321
	2017	355	327	213	627	405	291
	acres, 2022	205,346	143,530	23,171	80,504	144,587	133,225
	2017	187,025	117,630	36,718	62,418	196,177	155,591
Average per farm	acres, 2022	593	446	138	139	377	415
	2017	527	360	172	100	484	535
Cropland planted to a cover crop (excluding CRP)	farms, 2022	34	62	51	133	67	60
	2017	41	64	28	134	89	60
	acres, 2022	2,382	7,045	951	5,301	12,958	7,151
	2017	2,005	4,945	799	9,008	6,787	9,458
Average per farm	acres, 2022	70	114	19	40	193	119
	2017	49	77	29	67	76	158
Use of precision agriculture practices (see text)	farms, 2022	365	163	47	141	371	318
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Land drained by tile	farms, 2022	386	517	62	265	243	13
	2017	499	565	49	289	224	14
	acres, 2022	187,091	223,809	33,180	58,233	58,972	3,373
	2017	200,775	259,230	18,943	44,521	53,066	9,494
Average per farm	acres, 2022	485	433	535	220	243	259
	2017	402	459	387	154	237	678
Land artificially drained by ditches	farms, 2022	104	78	180	56	225	141
	2017	115	91	227	80	271	217
	acres, 2022	27,198	16,393	263,700	3,651	37,996	141,648
	2017	40,359	18,534	250,517	9,790	47,186	164,738
Average per farm	acres, 2022	262	210	1,465	65	169	1,005
	2017	351	204	1,104	122	174	759
Land under conservation easement	farms, 2022	56	63	32	59	235	28
	2017	15	49	16	41	113	11
	acres, 2022	3,083	907	2,058	2,321	15,234	3,287
	2017	904	5,971	1,619	957	16,402	2,227
Average per farm	acres, 2022	55	14	64	39	65	117
	2017	60	122	101	23	145	202
Cropland on which no-till practices were used	farms, 2022	48	109	26	156	195	22
	2017	40	81	28	166	174	11
	acres, 2022	4,542	18,573	3,341	20,311	24,215	8,925
	2017	6,413	26,336	12,112	18,337	33,515	1,001
Average per farm	acres, 2022	95	170	129	130	124	406
	2017	160	325	433	110	193	91
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	192	246	138	375	514	64
	2017	213	298	168	340	502	78
	acres, 2022	104,862	123,097	132,410	154,209	220,475	73,864
	2017	111,190	170,822	167,783	139,492	204,850	86,167
Average per farm	acres, 2022	546	500	959	411	429	1,154
	2017	522	573	999	410	408	1,105
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	324	425	224	222	748	107
	2017	348	385	237	218	784	163
	acres, 2022	141,962	188,106	287,999	50,511	176,896	96,063
	2017	116,825	177,103	289,447	42,054	194,118	112,594
Average per farm	acres, 2022	438	443	1,286	228	236	898
	2017	336	460	1,221	193	248	691
Cropland planted to a cover crop (excluding CRP)	farms, 2022	43	47	91	140	243	25
	2017	32	45	46	131	186	16
	acres, 2022	6,418	6,910	23,567	16,822	21,132	4,804
	2017	3,708	6,473	13,400	9,397	19,501	1,562
Average per farm	acres, 2022	149	147	259	120	87	192
	2017	116	144	291	72	105	98
Use of precision agriculture practices (see text)	farms, 2022	242	409	177	237	339	79
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Land drained by tile	farms, 2022	23	227	97	193	-	31
	2017	29	268	92	238	6	30
	acres, 2022	1,014	74,633	70,241	63,901	-	16,305
	2017	1,676	87,332	41,522	71,116	6	15,526
Average per farm	acres, 2022	44	329	724	331	-	526
	2017	58	326	451	299	1	518
Land artificially drained by ditches	farms, 2022	70	37	480	82	1	98
	2017	83	41	505	119	3	125
	acres, 2022	5,088	8,618	586,862	11,410	(D)	78,959
	2017	7,273	11,907	569,173	24,113	30	98,386
Average per farm	acres, 2022	73	233	1,223	139	(D)	806
	2017	88	290	1,127	203	10	787
Land under conservation easement	farms, 2022	15	32	43	136	-	3
	2017	6	25	37	78	-	10
	acres, 2022	1,928	2,463	4,660	11,529	-	222
	2017	357	778	4,231	7,359	-	919
Average per farm	acres, 2022	129	77	108	85	-	74
	2017	60	31	114	94	-	92
Cropland on which no-till practices were used	farms, 2022	96	109	71	78	12	20
	2017	54	81	73	66	15	15
	acres, 2022	7,101	26,558	25,539	17,897	(D)	10,120
	2017	2,638	14,076	33,516	16,983	85	10,540
Average per farm	acres, 2022	74	244	360	229	(D)	506
	2017	49	174	459	257	6	703
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	46	166	362	193	4	84
	2017	60	162	284	216	6	76
	acres, 2022	5,386	76,919	349,750	106,061	9	63,148
	2017	9,456	86,070	306,497	128,278	94	72,044
Average per farm	acres, 2022	117	463	966	550	2	752
	2017	158	531	1,079	594	16	948
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	202	168	519	214	11	109
	2017	196	221	528	231	10	96
	acres, 2022	21,862	70,276	519,449	83,793	54	78,696
	2017	20,391	89,072	477,123	89,625	41	80,879
Average per farm	acres, 2022	108	418	1,001	392	5	722
	2017	104	403	904	388	4	842
Cropland planted to a cover crop (excluding CRP)	farms, 2022	71	51	173	70	14	24
	2017	47	78	145	67	8	20
	acres, 2022	1,554	8,768	53,713	7,748	15	5,957
	2017	1,483	4,278	53,860	5,883	(D)	3,381
Average per farm	acres, 2022	22	172	310	111	1	248
	2017	32	55	371	88	(D)	169
Use of precision agriculture practices (see text)	farms, 2022	38	160	431	176	7	81
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Land drained by tile	farms, 2022	807	596	484	270	21	21
	2017	747	669	564	378	13	13
	acres, 2022	392,433	434,370	126,526	93,136	7,828	(D)
	2017	362,433	455,647	118,220	99,704	5,979	470
Average per farm	acres, 2022	486	729	261	345	373	(D)
	2017	485	681	210	264	460	36
Land artificially drained by ditches	farms, 2022	183	180	154	32	249	85
	2017	139	216	192	53	268	119
	acres, 2022	64,654	152,656	14,813	3,799	201,552	13,221
	2017	63,341	170,291	14,421	10,590	229,786	9,395
Average per farm	acres, 2022	353	848	96	119	809	156
	2017	456	788	75	200	857	79
Land under conservation easement	farms, 2022	132	124	88	39	51	8
	2017	56	70	21	12	24	13
	acres, 2022	5,342	9,779	2,942	1,890	4,773	770
	2017	4,370	6,256	1,238	1,849	3,185	730
Average per farm	acres, 2022	40	79	33	48	94	96
	2017	78	89	59	154	133	56
Cropland on which no-till practices were used	farms, 2022	175	68	186	99	58	77
	2017	124	35	135	137	65	45
	acres, 2022	40,017	8,325	24,755	43,153	33,902	1,359
	2017	26,956	10,685	21,645	28,725	29,698	797
Average per farm	acres, 2022	229	122	133	436	585	18
	2017	217	305	160	210	457	18
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	378	250	279	211	153	46
	2017	369	259	285	299	113	9
	acres, 2022	169,512	214,213	86,602	120,988	120,541	2,872
	2017	182,320	187,381	71,914	111,087	124,480	(D)
Average per farm	acres, 2022	448	857	310	573	788	62
	2017	494	723	252	372	1,102	(D)
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	619	488	345	182	226	176
	2017	513	508	423	236	244	144
	acres, 2022	298,859	346,348	77,873	64,570	167,133	12,583
	2017	259,292	379,811	71,419	112,923	181,023	6,598
Average per farm	acres, 2022	483	710	226	355	740	71
	2017	505	748	169	478	742	46
Cropland planted to a cover crop (excluding CRP)	farms, 2022	84	108	107	60	55	75
	2017	60	108	108	58	64	68
	acres, 2022	12,263	33,935	10,076	8,514	5,315	1,738
	2017	6,041	37,900	7,018	4,281	7,147	1,425
Average per farm	acres, 2022	146	314	94	142	97	23
	2017	101	351	65	74	112	21
Use of precision agriculture practices (see text)	farms, 2022	552	372	223	195	141	15
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Land drained by tile	farms, 2022	205	17	488	734	349	222
	2017	254	20	580	860	407	220
	acres, 2022	50,310	847	223,753	133,547	140,652	154,320
	2017	50,610	569	226,553	124,490	159,045	115,438
Average per farm	acres, 2022	245	50	459	182	403	695
	2017	199	28	391	145	391	525
Land artificially drained by ditches	farms, 2022	71	42	146	512	77	123
	2017	99	38	160	530	107	166
	acres, 2022	8,973	2,612	41,878	44,842	24,796	51,499
	2017	11,355	2,592	59,921	48,573	24,431	81,950
Average per farm	acres, 2022	126	62	287	88	322	419
	2017	115	68	375	92	228	494
Land under conservation easement	farms, 2022	34	15	81	125	61	60
	2017	25	10	49	77	17	41
	acres, 2022	733	1,838	1,600	5,629	1,847	4,045
	2017	408	2,688	4,729	3,771	794	4,688
Average per farm	acres, 2022	22	123	20	45	30	67
	2017	16	269	97	49	47	114
Cropland on which no-till practices were used	farms, 2022	57	54	46	281	64	48
	2017	27	41	29	191	41	37
	acres, 2022	3,540	6,883	4,716	28,876	15,736	8,602
	2017	1,197	5,850	3,617	18,601	11,725	10,021
Average per farm	acres, 2022	62	127	103	103	246	179
	2017	44	143	125	97	286	271
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	87	80	221	731	169	106
	2017	149	65	250	833	155	120
	acres, 2022	37,005	24,056	147,553	157,038	119,051	89,000
	2017	48,504	32,443	117,705	152,583	99,369	111,751
Average per farm	acres, 2022	425	301	668	215	704	840
	2017	326	499	471	183	641	931
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	179	117	374	1,091	237	194
	2017	241	140	410	1,166	245	225
	acres, 2022	35,264	24,154	176,169	210,500	78,602	180,929
	2017	31,870	28,169	187,881	209,391	105,588	159,410
Average per farm	acres, 2022	197	206	471	193	332	933
	2017	132	201	458	180	431	708
Cropland planted to a cover crop (excluding CRP)	farms, 2022	62	58	53	304	51	71
	2017	41	78	45	264	34	47
	acres, 2022	4,036	12,946	8,965	22,139	8,544	22,416
	2017	1,020	12,794	5,627	17,017	3,740	8,709
Average per farm	acres, 2022	65	223	169	73	168	316
	2017	25	164	125	64	110	185
Use of precision agriculture practices (see text)	farms, 2022	78	35	254	424	175	194
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Land drained by tile	farms, 2022	286	150	92	110	4	372
	2017	330	162	96	111	1	450
	acres, 2022	177,780	11,834	37,093	19,911	114	193,096
	2017	154,478	12,998	31,759	13,124	(D)	186,807
Average per farm	acres, 2022	622	79	403	181	29	519
	2017	468	80	331	118	(D)	415
Land artificially drained by ditches	farms, 2022	118	155	129	39	26	85
	2017	180	214	158	60	52	103
	acres, 2022	57,277	11,095	145,327	6,340	3,912	21,419
	2017	47,655	14,087	178,450	6,640	2,951	28,854
Average per farm	acres, 2022	485	72	1,127	163	150	252
	2017	265	66	1,129	111	57	280
Land under conservation easement	farms, 2022	80	65	40	40	7	66
	2017	42	26	23	12	3	35
	acres, 2022	4,139	3,397	1,325	3,422	1,228	2,091
	2017	3,180	1,162	2,481	1,875	51	1,407
Average per farm	acres, 2022	52	52	33	86	175	32
	2017	76	45	108	156	17	40
Cropland on which no-till practices were used	farms, 2022	47	147	17	127	44	68
	2017	84	89	25	124	19	71
	acres, 2022	18,220	17,334	5,019	17,122	1,906	7,691
	2017	12,769	12,880	7,708	18,324	460	11,564
Average per farm	acres, 2022	388	118	295	135	43	113
	2017	152	145	308	148	24	163
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	164	266	80	276	70	227
	2017	208	262	104	306	61	270
	acres, 2022	105,839	49,188	96,003	77,196	32,066	148,652
	2017	116,713	41,564	130,881	77,441	14,166	116,473
Average per farm	acres, 2022	645	185	1,200	280	458	655
	2017	561	159	1,258	253	232	431
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	296	598	159	224	141	210
	2017	326	678	190	244	150	204
	acres, 2022	174,946	74,468	158,976	51,619	21,263	78,228
	2017	151,668	80,696	191,819	37,662	30,737	89,791
Average per farm	acres, 2022	591	125	1,000	230	151	373
	2017	465	119	1,010	154	205	440
Cropland planted to a cover crop (excluding CRP)	farms, 2022	50	131	60	114	51	46
	2017	38	124	16	121	66	35
	acres, 2022	6,990	6,243	12,942	10,182	1,918	4,898
	2017	7,108	5,808	5,880	9,327	5,809	1,986
Average per farm	acres, 2022	140	48	216	89	38	106
	2017	187	47	368	77	88	57
Use of precision agriculture practices (see text)	farms, 2022	220	140	119	167	34	242
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

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Table 41. **Land Use Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Land drained by tile	farms, 2022	28	299	90	61	390	401
	2017	31	307	92	58	490	460
	acres, 2022	2,087	191,233	40,995	7,798	84,687	176,789
	2017	749	168,829	34,074	3,936	87,735	200,525
Average per farm	acres, 2022	75	640	456	128	217	441
	2017	24	550	370	68	179	436
Land artificially drained by ditches	farms, 2022	23	39	146	51	195	114
	2017	49	43	174	37	157	137
	acres, 2022	296	5,309	189,959	8,690	31,991	39,723
	2017	747	12,086	223,712	5,951	16,080	52,937
Average per farm	acres, 2022	13	136	1,301	170	164	348
	2017	15	281	1,286	161	102	386
Land under conservation easement	farms, 2022	21	47	30	64	52	86
	2017	10	17	18	31	17	57
	acres, 2022	1,393	1,297	11,931	2,881	1,003	5,463
	2017	418	352	4,412	1,656	262	3,680
Average per farm	acres, 2022	66	28	398	45	19	64
	2017	42	21	245	53	15	65
Cropland on which no-till practices were used	farms, 2022	65	70	22	219	110	91
	2017	96	26	17	136	87	85
	acres, 2022	5,202	7,994	9,497	42,854	7,537	20,508
	2017	8,020	4,069	10,772	14,205	8,670	24,968
Average per farm	acres, 2022	80	114	432	196	69	225
	2017	84	157	634	104	100	294
Cropland on which conservation or reduced tillage, excluding no-till, practices were used (see text)	farms, 2022	118	194	78	336	249	223
	2017	101	187	104	342	241	258
	acres, 2022	15,076	113,230	108,645	78,495	53,626	164,590
	2017	32,484	121,635	129,298	77,289	90,435	140,791
Average per farm	acres, 2022	128	584	1,393	234	215	738
	2017	322	650	1,243	226	375	546
Cropland on which intensive or conventional tillage practices were used (see text)	farms, 2022	102	182	178	241	411	317
	2017	109	194	199	275	450	295
	acres, 2022	7,437	119,973	238,585	45,864	97,536	127,050
	2017	4,731	105,700	250,641	40,125	75,295	156,224
Average per farm	acres, 2022	73	659	1,340	190	237	401
	2017	43	545	1,260	146	167	530
Cropland planted to a cover crop (excluding CRP)	farms, 2022	73	34	63	221	104	65
	2017	83	21	44	138	86	62
	acres, 2022	1,684	4,552	20,902	27,032	4,609	9,348
	2017	2,130	1,401	16,957	6,836	3,571	6,442
Average per farm	acres, 2022	23	134	332	122	44	144
	2017	26	67	385	50	42	104
Use of precision agriculture practices (see text)	farms, 2022	35	212	137	194	173	333
	2017	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

Table 42. **Organic Agriculture: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES						
Total organic product sales	farms, 2022	577	6	5	3	-
	2017	639	1	4	3	-
	$1,000, 2022	121,783	187	50	718	-
	2017	101,325	(D)	120	14	-
By value of sales:						
$1 to $4,999	farms, 2022	65	3	2	-	-
	2017	116	1	1	3	-
	$1,000, 2022	131	2	(D)	-	-
	2017	227	(D)	(D)	14	-
$5,000 or more	farms, 2022	512	3	3	3	-
	2017	523	-	3	-	-
	$1,000, 2022	121,652	185	(D)	718	-
	2017	101,098	-	(D)	-	-
TYPE OF PRODUCTION						
USDA National Organic Program certified organic production	farms, 2022	582	3	5	2	-
	2017	647	-	3	1	-
USDA National Organic Program organic production exempt from certification	farms, 2022	55	3	-	1	1
	2017	88	1	2	3	-
Acres transitioning into USDA National Organic Program organic production	farms, 2022	121	3	-	-	-
	2017	167	-	-	-	3

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Table 42. **Organic Agriculture: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES						
Total organic product sales	farms, 2022	2	2	8	1	5
	2017	5	2	1	3	6
	$1,000, 2022	(D)	(D)	2,406	(D)	(D)
	2017	94	(D)	(D)	129	638
By value of sales:						
$1 to $4,999	farms, 2022	1	-	-	-	2
	2017	2	1	-	-	-
	$1,000, 2022	(D)	-	-	-	(D)
	2017	(D)	(D)	-	-	-
$5,000 or more	farms, 2022	1	2	8	1	3
	2017	3	1	1	3	6
	$1,000, 2022	(D)	(D)	2,406	(D)	(D)
	2017	(D)	(D)	(D)	129	638
TYPE OF PRODUCTION						
USDA National Organic Program certified organic production	farms, 2022	1	2	8	2	3
	2017	3	2	7	3	7
USDA National Organic Program organic production exempt from certification	farms, 2022	1	-	-	-	2
	2017	2	-	-	-	-
Acres transitioning into USDA National Organic Program organic production	farms, 2022	-	-	9	-	-
	2017	4	2	1	2	-

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES							
Total organic product sales	farms, 2022	1	3	1	6	10	1
	2017	7	1	6	5	11	3
	$1,000, 2022	(D)	45	(D)	(D)	4,889	(D)
	2017	124	(D)	630	143	2,790	(D)
By value of sales:							
$1 to $4,999	farms, 2022	1	-	-	4	-	1
	2017	4	-	1	-	1	2
	$1,000, 2022	(D)	-	-	4	-	(D)
	2017	7	-	(D)	-	(D)	(D)
$5,000 or more	farms, 2022	-	3	1	2	10	-
	2017	3	1	5	5	10	1
	$1,000, 2022	-	45	(D)	(D)	4,889	-
	2017	117	(D)	(D)	143	(D)	(D)
TYPE OF PRODUCTION							
USDA National Organic Program certified organic production	farms, 2022	1	3	1	5	10	1
	2017	3	1	4	5	12	2
USDA National Organic Program organic production exempt from certification	farms, 2022	1	-	-	4	-	-
	2017	4	-	3	1	-	1
Acres transitioning into USDA National Organic Program organic production	farms, 2022	-	-	1	-	2	-
	2017	-	-	4	1	4	-

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES							
Total organic product sales	farms, 2022	1	9	-	18	5	3
	2017	2	3	6	13	6	9
	$1,000, 2022	(D)	2,227	-	3,202	711	(D)
	2017	(D)	1,175	347	1,440	523	694
By value of sales:							
$1 to $4,999	farms, 2022	-	-	-	-	-	-
	2017	1	-	1	1	-	-
	$1,000, 2022	-	-	-	-	-	-
	2017	(D)	-	(D)	(D)	-	-
$5,000 or more	farms, 2022	1	9	-	18	5	3
	2017	1	3	5	12	6	9
	$1,000, 2022	(D)	2,227	-	3,202	711	(D)
	2017	(D)	1,175	(D)	(D)	523	694
TYPE OF PRODUCTION							
USDA National Organic Program certified organic production	farms, 2022	1	9	-	19	5	3
	2017	2	4	5	13	5	9
USDA National Organic Program organic production exempt from certification	farms, 2022	-	-	-	-	-	-
	2017	-	-	1	-	1	-
Acres transitioning into USDA National Organic Program organic production	farms, 2022	-	6	-	2	1	-
	2017	-	-	1	5	1	-

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Table 42. **Organic Agriculture: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES							
Total organic product sales	farms, 2022	7	34	11	19	-	-
	2017	5	33	8	29	-	4
	$1,000, 2022	1,536	5,869	4,456	8,401	-	-
	2017	2,363	9,290	1,426	7,682	-	70
By value of sales:							
$1 to $4,999	farms, 2022	-	6	-	-	-	-
	2017	-	4	-	10	-	1
	$1,000, 2022	-	18	-	-	-	-
	2017	-	10	-	6	-	(D)
$5,000 or more	farms, 2022	7	28	11	19	-	-
	2017	5	29	8	19	-	3
	$1,000, 2022	1,536	5,851	4,456	8,401	-	-
	2017	2,363	9,280	1,426	7,676	-	(D)
TYPE OF PRODUCTION							
USDA National Organic Program certified organic production	farms, 2022	7	33	11	19	-	-
	2017	5	42	12	31	-	3
USDA National Organic Program organic production exempt from certification	farms, 2022	-	4	1	-	1	-
	2017	-	2	-	10	-	1
Acres transitioning into USDA National Organic Program organic production	farms, 2022	-	9	3	3	1	3
	2017	-	12	6	3	1	-

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES							
Total organic product sales	farms, 2022	16	1	1	1	1	4
	2017	18	2	9	-	1	7
	$1,000, 2022	1,687	(D)	(D)	(D)	(D)	108
	2017	(D)	(D)	261	-	(D)	67
By value of sales:							
$1 to $4,999	farms, 2022	-	-	-	-	-	-
	2017	8	1	-	-	-	5
	$1,000, 2022	-	-	-	-	-	-
	2017	24	(D)	-	-	-	(D)
$5,000 or more	farms, 2022	16	1	1	1	1	4
	2017	10	1	9	-	1	2
	$1,000, 2022	1,687	(D)	(D)	(D)	(D)	108
	2017	(D)	(D)	261	-	(D)	(D)
TYPE OF PRODUCTION							
USDA National Organic Program certified organic production	farms, 2022	18	2	2	-	1	4
	2017	22	2	10	-	1	2
USDA National Organic Program organic production exempt from certification	farms, 2022	-	-	-	1	-	-
	2017	-	-	-	-	-	5
Acres transitioning into USDA National Organic Program organic production	farms, 2022	6	-	1	1	-	2
	2017	7	2	-	1	-	-

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES							
Total organic product sales	farms, 2022	7	-	1	13	3	-
	2017	5	-	-	11	2	-
	$1,000, 2022	1,298	-	(D)	3,491	6	-
	2017	575	-	-	812	(D)	-
By value of sales:							
$1 to $4,999	farms, 2022	-	-	-	-	3	-
	2017	-	-	-	-	2	-
	$1,000, 2022	-	-	-	-	6	-
	2017	-	-	-	-	(D)	-
$5,000 or more	farms, 2022	7	-	1	13	-	-
	2017	5	-	-	11	-	-
	$1,000, 2022	1,298	-	(D)	3,491	-	-
	2017	575	-	-	812	-	-
TYPE OF PRODUCTION							
USDA National Organic Program certified organic production	farms, 2022	7	-	1	13	-	-
	2017	7	-	-	11	-	-
USDA National Organic Program organic production exempt from certification	farms, 2022	-	-	-	-	3	-
	2017	-	-	-	-	2	-
Acres transitioning into USDA National Organic Program organic production	farms, 2022	2	-	-	2	-	-
	2017	2	1	-	2	-	-

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Table 42. **Organic Agriculture: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES						
Total organic product sales ..... farms, 2022	12	1	4	12	3	3
2017	8	3	3	9	2	2
$1,000, 2022	697	(D)	1,673	4,216	107	(D)
2017	276	418	2,534	1,419	(D)	(D)
By value of sales:						
$1 to $4,999 ..... farms, 2022	-	-	-	-	-	2
2017	3	-	-	-	-	-
$1,000, 2022	-	-	-	-	-	(D)
2017	9	-	-	-	-	-
$5,000 or more ..... farms, 2022	12	1	4	12	3	1
2017	5	3	3	9	2	2
$1,000, 2022	697	(D)	1,673	4,216	107	(D)
2017	267	418	2,534	1,419	(D)	(D)
TYPE OF PRODUCTION						
USDA National Organic Program certified organic production ..... farms, 2022	13	1	2	12	3	3
2017	5	3	3	9	2	2
USDA National Organic Program organic production exempt from certification ..... farms, 2022	-	-	2	-	-	-
2017	3	-	-	-	-	-
Acres transitioning into USDA National Organic Program organic production ..... farms, 2022	1	-	-	1	1	2
2017	1	-	-	2	3	-

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES						
Total organic product sales ..... farms, 2022	6	4	2	3	15	2
2017	3	7	6	6	12	10
$1,000, 2022	2,564	663	(D)	146	3,608	(D)
2017	284	1,033	30	574	302	4,157
By value of sales:						
$1 to $4,999 ..... farms, 2022	-	-	2	-	2	-
2017	-	-	4	2	6	1
$1,000, 2022	-	-	(D)	-	(D)	-
2017	-	-	(D)	(D)	6	(D)
$5,000 or more ..... farms, 2022	6	4	-	3	13	2
2017	3	7	2	4	6	9
$1,000, 2022	2,564	663	-	146	(D)	(D)
2017	284	1,033	(D)	(D)	296	(D)
TYPE OF PRODUCTION						
USDA National Organic Program certified organic production ..... farms, 2022	6	4	2	3	17	2
2017	4	7	2	9	9	10
USDA National Organic Program organic production exempt from certification ..... farms, 2022	-	-	2	-	-	-
2017	-	-	4	1	6	-
Acres transitioning into USDA National Organic Program organic production ..... farms, 2022	3	-	1	1	-	-
2017	-	-	1	5	9	-

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES						
Total organic product sales ..... farms, 2022	2	1	1	8	20	-
2017	1	1	4	13	29	-
$1,000, 2022	(D)	(D)	(D)	488	5,501	-
2017	(D)	(D)	96	1,166	3,293	-
By value of sales:						
$1 to $4,999 ..... farms, 2022	-	-	-	-	-	-
2017	-	-	-	4	3	-
$1,000, 2022	-	-	-	-	-	-
2017	-	-	-	5	6	-
$5,000 or more ..... farms, 2022	2	1	1	8	20	-
2017	1	1	4	9	26	-
$1,000, 2022	(D)	(D)	(D)	488	5,501	-
2017	(D)	(D)	96	1,161	3,287	-
TYPE OF PRODUCTION						
USDA National Organic Program certified organic production ..... farms, 2022	2	1	1	8	22	-
2017	1	1	4	11	31	-
USDA National Organic Program organic production exempt from certification ..... farms, 2022	-	-	-	3	-	-
2017	-	-	-	4	2	-
Acres transitioning into USDA National Organic Program organic production ..... farms, 2022	3	-	-	4	2	-
2017	2	-	-	6	2	-

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Table 42. **Organic Agriculture: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES						
Total organic product sales ..... farms, 2022	4	10	17	6	3	-
2017	1	5	18	6	8	-
$1,000, 2022	220	1,107	5,156	1,307	22	-
2017	(D)	1,265	6,530	2,038	45	-
By value of sales:						
$1 to $4,999 ..... farms, 2022	-	-	-	2	2	-
2017	1	-	2	-	5	-
$1,000, 2022	-	-	-	(D)	(D)	-
2017	(D)	-	(D)	-	9	-
$5,000 or more ..... farms, 2022	4	10	17	4	1	-
2017	-	5	16	6	3	-
$1,000, 2022	220	1,107	5,156	(D)	(D)	-
2017	-	1,265	(D)	2,038	36	-
TYPE OF PRODUCTION						
USDA National Organic Program certified organic production ..... farms, 2022	2	10	20	6	4	-
2017	-	5	18	8	5	-
USDA National Organic Program organic production exempt from certification ..... farms, 2022	2	-	-	-	-	-
2017	2	-	-	-	3	-
Acres transitioning into USDA National Organic Program organic production ..... farms, 2022	2	-	3	2	-	-
2017	2	-	6	5	-	-

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES						
Total organic product sales ..... farms, 2022	4	3	11	-	1	4
2017	4	1	11	1	3	6
$1,000, 2022	1,093	2,544	520	-	(D)	67
2017	1,235	(D)	832	(D)	57	15
By value of sales:						
$1 to $4,999 ..... farms, 2022	-	-	2	-	-	2
2017	-	-	-	-	-	6
$1,000, 2022	-	-	(D)	-	-	(D)
2017	-	-	-	-	-	15
$5,000 or more ..... farms, 2022	4	3	9	-	1	2
2017	4	1	11	1	3	-
$1,000, 2022	1,093	2,544	(D)	-	(D)	(D)
2017	1,235	(D)	832	(D)	57	-
TYPE OF PRODUCTION						
USDA National Organic Program certified organic production ..... farms, 2022	4	3	11	-	1	2
2017	4	1	12	1	3	3
USDA National Organic Program organic production exempt from certification ..... farms, 2022	-	-	2	-	-	2
2017	-	-	1	-	-	5
Acres transitioning into USDA National Organic Program organic production ..... farms, 2022	-	-	6	-	-	-
2017	-	-	6	-	-	6

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES						
Total organic product sales ..... farms, 2022	10	6	9	44	5	8
2017	15	4	8	55	10	3
$1,000, 2022	192	233	1,738	9,194	6,728	1,593
2017	1,371	5	905	9,317	3,234	851
By value of sales:						
$1 to $4,999 ..... farms, 2022	7	-	2	1	-	2
2017	5	4	-	6	2	-
$1,000, 2022	17	-	(D)	(D)	-	(D)
2017	15	5	-	11	(D)	-
$5,000 or more ..... farms, 2022	3	6	7	43	5	6
2017	10	-	8	49	8	3
$1,000, 2022	175	233	(D)	(D)	6,728	(D)
2017	1,356	-	905	9,306	(D)	851
TYPE OF PRODUCTION						
USDA National Organic Program certified organic production ..... farms, 2022	12	6	7	51	8	7
2017	10	2	8	54	10	4
USDA National Organic Program organic production exempt from certification ..... farms, 2022	5	-	2	3	-	2
2017	5	2	-	3	1	-
Acres transitioning into USDA National Organic Program organic production ..... farms, 2022	-	10	-	4	-	1
2017	3	-	-	3	1	2

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Table 42. **Organic Agriculture: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES							
Total organic product sales	farms, 2022	3	20	1	9	2	3
	2017	-	18	-	9	9	8
	$1,000, 2022	634	1,865	(D)	1,924	(D)	(D)
	2017	-	1,613	-	2,648	833	1,988
By value of sales:							
$1 to $4,999	farms, 2022	-	3	-	1	-	1
	2017	-	-	-	1	1	-
	$1,000, 2022	-	14	-	(D)	-	(D)
	2017	-	-	-	(D)	(D)	-
$5,000 or more	farms, 2022	3	17	1	8	2	2
	2017	-	18	-	8	8	8
	$1,000, 2022	634	1,851	(D)	(D)	(D)	(D)
	2017	-	1,613	-	(D)	(D)	1,988
TYPE OF PRODUCTION							
USDA National Organic Program certified organic production	farms, 2022	3	18	1	11	3	3
	2017	-	21	-	11	14	9
USDA National Organic Program organic production exempt from certification	farms, 2022	-	2	-	-	-	-
	2017	-	2	-	-	1	-
Acres transitioning into USDA National Organic Program organic production	farms, 2022	-	-	1	3	-	-
	2017	-	4	-	6	1	3

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
VALUE OF SALES OF CERTIFIED OR EXEMPT ORGANICALLY PRODUCED COMMODITIES							
Total organic product sales	farms, 2022	11	1	1	42	24	7
	2017	8	-	3	54	17	4
	$1,000, 2022	324	(D)	(D)	8,510	4,316	3,701
	2017	25	-	71	9,051	1,293	2,156
By value of sales:							
$1 to $4,999	farms, 2022	-	-	-	2	9	-
	2017	4	-	-	5	1	-
	$1,000, 2022	-	-	-	(D)	14	-
	2017	2	-	-	7	(D)	-
$5,000 or more	farms, 2022	11	1	1	40	15	7
	2017	4	-	3	49	16	4
	$1,000, 2022	324	(D)	(D)	(D)	4,302	3,701
	2017	23	-	71	9,043	(D)	2,156
TYPE OF PRODUCTION							
USDA National Organic Program certified organic production	farms, 2022	11	1	1	44	21	7
	2017	8	-	3	57	19	5
USDA National Organic Program organic production exempt from certification	farms, 2022	-	-	-	-	5	-
	2017	2	-	-	1	1	-
Acres transitioning into USDA National Organic Program organic production	farms, 2022	-	-	-	-	9	4
	2017	6	1	-	11	4	1

Table 43. **Selected Practices: 2022 and 2017**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	1,082	33	7	27	25
	2017	1,011	11	6	19	18
Harvested biomass for use in renewable energy	farms, 2022	522	5	5	13	3
	2017	322	4	1	3	4
Practiced rotational or management-intensive grazing	farms, 2022	4,750	81	33	87	69
	2017	5,201	78	42	70	110
Raised or sold veal calves	farms, 2022	49	-	-	-	-
	2017	134	-	2	2	1
On-farm packing facility	farms, 2022	465	7	10	6	2
	2017	387	7	10	4	3
Had a barn that was built prior to 1960	farms, 2022	14,459	139	47	161	91
	2017	17,870	143	47	192	112
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	20,377	129	79	280	185
	2017	22,553	166	108	308	196

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Table 43. **Selected Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Benton	Big Stone	Blue Earth	Brown	Carlton
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-
	2017	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	13	-	5	4	25
	2017	12	-	10	2	17
Harvested biomass for use in renewable energy	farms, 2022	12	1	7	13	8
	2017	1	-	-	7	1
Practiced rotational or management-intensive grazing	farms, 2022	57	17	31	36	94
	2017	50	15	27	41	112
Raised or sold veal calves	farms, 2022	-	-	-	-	-
	2017	1	-	-	-	-
On-farm packing facility	farms, 2022	3	1	7	4	16
	2017	4	5	2	5	12
Had a barn that was built prior to 1960	farms, 2022	137	84	189	234	120
	2017	191	129	204	288	165
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	202	152	362	301	122
	2017	227	176	311	305	157

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	11	18	-	27	8	10
	2017	18	15	4	10	12	12
Harvested biomass for use in renewable energy	farms, 2022	3	6	-	7	-	10
	2017	4	4	1	3	1	3
Practiced rotational or management-intensive grazing	farms, 2022	53	76	11	98	32	80
	2017	32	75	17	117	47	65
Raised or sold veal calves	farms, 2022	-	-	-	-	-	-
	2017	3	-	-	2	-	1
On-farm packing facility	farms, 2022	8	6	1	9	8	1
	2017	6	4	2	7	-	1
Had a barn that was built prior to 1960	farms, 2022	233	88	68	150	83	96
	2017	279	103	95	236	151	54
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	162	146	226	200	201	109
	2017	197	129	207	226	233	135

Item		Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	2	3	17	9	12	19
	2017	7	7	25	17	4	22
Harvested biomass for use in renewable energy	farms, 2022	1	4	8	4	4	12
	2017	3	-	8	1	-	-
Practiced rotational or management-intensive grazing	farms, 2022	1	24	45	71	52	65
	2017	2	19	74	63	45	85
Raised or sold veal calves	farms, 2022	-	-	-	-	4	-
	2017	-	-	-	-	2	3
On-farm packing facility	farms, 2022	3	3	4	29	5	3
	2017	5	2	3	11	-	4
Had a barn that was built prior to 1960	farms, 2022	4	226	67	207	178	208
	2017	2	207	112	204	146	251
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	4	282	117	281	196	317
	2017	6	226	146	244	209	324

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Table 43. **Selected Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	3	40	9	31	4	8
	2017	1	30	15	33	1	9
Harvested biomass for use in renewable energy	farms, 2022	4	18	3	8	-	6
	2017	-	13	6	9	-	8
Practiced rotational or management-intensive grazing	farms, 2022	18	158	34	181	11	47
	2017	12	169	40	181	11	43
Raised or sold veal calves	farms, 2022	-	9	-	-	-	-
	2017	-	18	-	1	-	-
On-farm packing facility	farms, 2022	-	15	1	4	2	19
	2017	1	22	6	6	5	15
Had a barn that was built prior to 1960	farms, 2022	169	408	206	524	86	131
	2017	169	450	266	626	99	125
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	266	462	313	403	191	154
	2017	282	418	369	431	192	132

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	27	14	14	20	6	6
	2017	13	16	15	16	4	12
Harvested biomass for use in renewable energy	farms, 2022	9	4	4	4	-	5
	2017	3	2	5	-	3	4
Practiced rotational or management-intensive grazing	farms, 2022	108	42	100	64	28	63
	2017	123	34	84	62	24	91
Raised or sold veal calves	farms, 2022	5	-	-	2	-	1
	2017	8	2	-	-	-	3
On-farm packing facility	farms, 2022	4	1	2	5	-	6
	2017	2	3	4	2	-	7
Had a barn that was built prior to 1960	farms, 2022	330	62	134	82	198	96
	2017	360	68	138	85	171	155
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	240	95	187	116	306	145
	2017	297	142	284	86	279	200

Item		Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	12	1	8	1	3	7
	2017	9	-	8	1	4	5
Harvested biomass for use in renewable energy	farms, 2022	13	8	2	3	1	5
	2017	7	-	-	1	-	2
Practiced rotational or management-intensive grazing	farms, 2022	75	22	29	11	2	10
	2017	61	20	27	21	7	12
Raised or sold veal calves	farms, 2022	-	-	-	-	-	-
	2017	3	2	-	-	-	-
On-farm packing facility	farms, 2022	-	1	-	5	4	1
	2017	2	2	-	5	2	-
Had a barn that was built prior to 1960	farms, 2022	255	54	19	144	7	30
	2017	267	49	31	222	2	20
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	372	241	51	240	5	51
	2017	399	243	44	345	12	50

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Table 43. **Selected Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	12	1	2	10	-	7
	2017	16	-	2	3	4	9
Harvested biomass for use in renewable energy	farms, 2022	4	4	4	6	-	6
	2017	3	4	6	-	-	4
Practiced rotational or management-intensive grazing	farms, 2022	46	32	49	40	11	52
	2017	42	40	27	37	23	54
Raised or sold veal calves	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	2	-	-
On-farm packing facility	farms, 2022	11	-	-	7	-	-
	2017	1	1	-	4	-	1
Had a barn that was built prior to 1960	farms, 2022	171	127	201	209	32	127
	2017	229	179	236	319	66	136
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	263	201	325	224	100	372
	2017	283	192	310	278	127	471

Item		Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	1	11	16	32	9	-
	2017	3	4	14	29	13	1
Harvested biomass for use in renewable energy	farms, 2022	5	7	7	20	5	6
	2017	9	7	7	18	5	2
Practiced rotational or management-intensive grazing	farms, 2022	27	64	85	144	51	21
	2017	19	60	97	154	42	27
Raised or sold veal calves	farms, 2022	-	-	-	3	-	-
	2017	-	2	3	12	6	3
On-farm packing facility	farms, 2022	1	1	6	1	1	-
	2017	2	5	3	4	3	-
Had a barn that was built prior to 1960	farms, 2022	176	186	174	362	206	165
	2017	216	247	203	469	295	217
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	276	313	165	464	304	261
	2017	377	347	221	568	366	321

Item		Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	3	2	9	21	63	-
	2017	-	1	8	39	52	2
Harvested biomass for use in renewable energy	farms, 2022	1	4	2	14	14	-
	2017	12	6	4	6	19	1
Practiced rotational or management-intensive grazing	farms, 2022	17	24	19	103	163	18
	2017	14	28	19	133	185	29
Raised or sold veal calves	farms, 2022	-	-	3	1	1	-
	2017	-	1	2	3	8	-
On-farm packing facility	farms, 2022	2	1	2	8	11	4
	2017	-	7	-	13	6	-
Had a barn that was built prior to 1960	farms, 2022	147	182	60	292	521	33
	2017	208	218	80	367	639	89
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	204	323	127	380	872	132
	2017	191	285	176	399	964	151

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Table 43. **Selected Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	23	1	17	3	-	6
	2017	15	2	17	13	6	5
Harvested biomass for use in renewable energy	farms, 2022	12	2	11	4	-	2
	2017	2	-	9	3	-	2
Practiced rotational or management-intensive grazing	farms, 2022	104	54	49	75	-	26
	2017	120	51	63	74	-	23
Raised or sold veal calves	farms, 2022	-	-	-	-	-	-
	2017	-	2	1	2	-	-
On-farm packing facility	farms, 2022	9	1	7	1	10	-
	2017	4	4	3	-	3	-
Had a barn that was built prior to 1960	farms, 2022	178	137	163	142	2	39
	2017	229	199	209	206	6	36
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	201	158	451	248	11	93
	2017	232	228	475	310	8	110

Item		Redwood	Renville	Rice	Rock	Roseau	St. Louis
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	6	-	37	-	17	41
	2017	4	8	19	5	7	42
Harvested biomass for use in renewable energy	farms, 2022	6	3	5	6	11	18
	2017	4	3	2	-	3	13
Practiced rotational or management-intensive grazing	farms, 2022	33	22	73	35	45	124
	2017	27	23	68	51	70	128
Raised or sold veal calves	farms, 2022	1	-	-	-	2	-
	2017	-	-	2	1	-	1
On-farm packing facility	farms, 2022	5	1	17	-	3	19
	2017	2	2	22	-	-	11
Had a barn that was built prior to 1960	farms, 2022	257	179	272	165	77	180
	2017	249	256	377	225	118	190
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	417	285	331	141	264	198
	2017	368	309	379	242	354	235

Item		Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	22	20	9	33	4	3
	2017	6	12	4	38	4	1
Harvested biomass for use in renewable energy	farms, 2022	1	9	9	23	1	2
	2017	4	2	6	10	2	-
Practiced rotational or management-intensive grazing	farms, 2022	68	74	37	173	27	26
	2017	75	60	43	195	28	43
Raised or sold veal calves	farms, 2022	-	-	2	3	3	-
	2017	-	-	4	7	2	-
On-farm packing facility	farms, 2022	6	17	-	10	3	-
	2017	8	8	-	9	1	5
Had a barn that was built prior to 1960	farms, 2022	121	95	245	740	174	97
	2017	189	86	357	985	207	154
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	184	111	239	740	234	181
	2017	204	159	243	834	216	211

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Table 43. **Selected Practices: 2022 and 2017** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	5	27	2	18	16	1
	2017	4	43	2	23	10	5
Harvested biomass for use in renewable energy	farms, 2022	3	11	-	4	5	5
	2017	-	5	-	3	1	-
Practiced rotational or management-intensive grazing	farms, 2022	17	148	3	58	53	17
	2017	39	188	13	87	71	26
Raised or sold veal calves	farms, 2022	-	-	-	6	-	-
	2017	-	4	-	3	-	-
On-farm packing facility	farms, 2022	-	9	-	15	-	7
	2017	-	6	2	6	-	1
Had a barn that was built prior to 1960	farms, 2022	115	322	41	273	75	189
	2017	163	426	55	361	138	211
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	238	472	111	236	116	182
	2017	265	499	124	274	173	233

Item		Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Received irrigation water from the U.S. Bureau of Reclamation	farms, 2022	-	-	-	-	-	-
	2017	-	-	-	-	-	-
Practiced alley cropping, silvopasture, forest farming, or had riparian forest buffers or windbreaks	farms, 2022	20	7	3	25	26	2
	2017	23	-	-	31	14	8
Harvested biomass for use in renewable energy	farms, 2022	8	5	4	4	13	3
	2017	2	1	1	13	6	-
Practiced rotational or management-intensive grazing	farms, 2022	74	16	8	100	109	20
	2017	110	9	2	147	94	35
Raised or sold veal calves	farms, 2022	-	-	-	3	-	-
	2017	-	-	-	9	-	-
On-farm packing facility	farms, 2022	22	-	-	16	22	3
	2017	23	-	-	10	23	3
Had a barn that was built prior to 1960	farms, 2022	140	93	47	306	301	178
	2017	168	114	51	372	318	188
Aware of right to appeal an adverse program decision to USDA's National Appeals Division	farms, 2022	118	163	136	296	341	284
	2017	179	132	135	288	368	298

Table 44. **Farms by North American Industry Classification System: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
Total farms	65,531	449	355	952	608
Oilseed and grain farming (1111)	26,315	28	50	179	111
Vegetable and melon farming (1112)	1,072	10	17	4	7
Fruit and tree nut farming (1113)	972	7	11	24	10
Greenhouse, nursery, and floriculture production (1114)	971	11	52	18	12
Other crop farming (1119)	18,104	248	79	436	216
Tobacco farming (11191)	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	18,104	248	79	436	216
Beef cattle ranching and farming (112111)	6,753	97	24	161	160
Cattle feedlots (112112)	892	2	-	15	6
Dairy cattle and milk production (11212)	1,713	-	-	32	3
Hog and pig farming (1122)	1,855	1	2	7	1
Poultry and egg production (1123)	1,724	21	20	18	9
Sheep and goat farming (1124)	1,456	2	12	12	3
Aquaculture and other animal production (1125, 1129)	3,704	22	88	46	70

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Table 44. **Farms by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
Total farms	687	392	1,019	973	463
Oilseed and grain farming (1111)	250	245	593	594	9
Vegetable and melon farming (1112)	13	1	19	2	11
Fruit and tree nut farming (1113)	5	1	22	3	14
Greenhouse, nursery, and floriculture production (1114)	8	2	7	-	5
Other crop farming (1119)	147	81	196	177	211
Tobacco farming (11191)	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	147	81	196	177	211
Beef cattle ranching and farming (112111)	107	33	31	55	127
Cattle feedlots (112112)	12	1	1	20	3
Dairy cattle and milk production (11212)	38	-	-	33	-
Hog and pig farming (1122)	8	4	95	41	-
Poultry and egg production (1123)	37	-	10	19	39
Sheep and goat farming (1124)	16	8	9	6	6
Aquaculture and other animal production (1125, 1129)	46	16	36	23	38

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
Total farms	606	488	563	740	655	404
Oilseed and grain farming (1111)	230	27	325	194	321	50
Vegetable and melon farming (1112)	15	4	7	23	17	11
Fruit and tree nut farming (1113)	21	25	9	32	3	-
Greenhouse, nursery, and floriculture production (1114)	12	14	-	50	5	7
Other crop farming (1119)	154	192	159	125	174	134
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	154	192	159	125	174	134
Beef cattle ranching and farming (112111)	64	144	13	100	56	154
Cattle feedlots (112112)	3	10	5	4	3	2
Dairy cattle and milk production (11212)	32	3	1	9	8	1
Hog and pig farming (1122)	3	1	17	8	5	-
Poultry and egg production (1123)	15	27	6	51	22	8
Sheep and goat farming (1124)	24	11	8	50	9	19
Aquaculture and other animal production (1125, 1129)	33	30	13	94	32	18

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
Total farms	25	742	426	841	614	980
Oilseed and grain farming (1111)	-	441	38	329	258	394
Vegetable and melon farming (1112)	6	3	12	75	6	10
Fruit and tree nut farming (1113)	6	4	19	39	9	22
Greenhouse, nursery, and floriculture production (1114)	-	1	19	54	4	6
Other crop farming (1119)	8	145	144	82	123	323
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	8	145	144	82	123	323
Beef cattle ranching and farming (112111)	5	55	109	70	77	103
Cattle feedlots (112112)	-	10	-	20	4	8
Dairy cattle and milk production (11212)	-	8	3	22	22	15
Hog and pig farming (1122)	-	40	2	2	25	-
Poultry and egg production (1123)	-	10	15	35	15	36
Sheep and goat farming (1124)	-	9	11	39	22	17
Aquaculture and other animal production (1125, 1129)	-	16	54	74	49	46

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
Total farms	773	1,458	908	1,406	529	511
Oilseed and grain farming (1111)	545	583	495	648	229	66
Vegetable and melon farming (1112)	7	19	11	18	2	55
Fruit and tree nut farming (1113)	2	16	9	28	1	49
Greenhouse, nursery, and floriculture production (1114)	4	17	5	12	-	32
Other crop farming (1119)	77	381	213	199	243	119
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	77	381	213	199	243	119
Beef cattle ranching and farming (112111)	49	211	45	155	20	26
Cattle feedlots (112112)	8	21	9	29	4	5
Dairy cattle and milk production (11212)	3	29	3	77	4	4
Hog and pig farming (1122)	59	37	52	51	1	2
Poultry and egg production (1123)	-	23	12	31	3	16
Sheep and goat farming (1124)	7	36	23	63	6	26
Aquaculture and other animal production (1125, 1129)	12	85	31	95	16	111

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Table 44. **Farms by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
Total farms	797	336	814	424	845	531
Oilseed and grain farming (1111)	239	40	179	23	561	86
Vegetable and melon farming (1112)	4	4	13	14	-	10
Fruit and tree nut farming (1113)	6	14	25	2	2	11
Greenhouse, nursery, and floriculture production (1114)	3	8	36	24	1	14
Other crop farming (1119)	291	116	205	183	134	161
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	291	116	205	183	134	161
Beef cattle ranching and farming (112111)	94	101	106	90	37	119
Cattle feedlots (112112)	25	-	3	1	10	-
Dairy cattle and milk production (11212)	53	1	3	-	2	1
Hog and pig farming (1122)	7	-	24	9	55	7
Poultry and egg production (1123)	15	2	52	23	11	45
Sheep and goat farming (1124)	17	14	31	7	18	18
Aquaculture and other animal production (1125, 1129)	43	36	137	48	14	59

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
Total farms	1,252	613	190	735	34	186
Oilseed and grain farming (1111)	445	250	20	439	-	55
Vegetable and melon farming (1112)	4	4	1	2	5	2
Fruit and tree nut farming (1113)	17	-	3	1	-	2
Greenhouse, nursery, and floriculture production (1114)	5	6	3	-	3	2
Other crop farming (1119)	472	311	106	198	9	87
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	472	311	106	198	9	87
Beef cattle ranching and farming (112111)	103	32	21	33	4	22
Cattle feedlots (112112)	10	-	1	-	-	2
Dairy cattle and milk production (11212)	26	-	2	1	-	-
Hog and pig farming (1122)	20	-	-	42	2	-
Poultry and egg production (1123)	30	1	17	4	7	7
Sheep and goat farming (1124)	39	1	-	4	-	2
Aquaculture and other animal production (1125, 1129)	81	8	16	11	4	5

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
Total farms	896	598	869	801	268	1,072
Oilseed and grain farming (1111)	330	276	477	361	141	500
Vegetable and melon farming (1112)	2	3	-	21	2	4
Fruit and tree nut farming (1113)	6	8	1	6	-	-
Greenhouse, nursery, and floriculture production (1114)	14	2	2	5	1	3
Other crop farming (1119)	345	216	192	196	72	448
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	345	216	192	196	72	448
Beef cattle ranching and farming (112111)	52	48	67	64	28	89
Cattle feedlots (112112)	7	7	27	5	4	2
Dairy cattle and milk production (11212)	16	5	2	21	1	6
Hog and pig farming (1122)	36	20	56	6	-	-
Poultry and egg production (1123)	27	-	10	11	5	3
Sheep and goat farming (1124)	15	3	21	47	2	6
Aquaculture and other animal production (1125, 1129)	46	10	14	58	12	11

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
Total farms	823	991	603	1,571	999	789
Oilseed and grain farming (1111)	491	383	135	443	485	461
Vegetable and melon farming (1112)	3	11	16	8	28	7
Fruit and tree nut farming (1113)	1	20	11	3	9	2
Greenhouse, nursery, and floriculture production (1114)	8	7	12	19	-	-
Other crop farming (1119)	103	353	217	415	209	161
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	103	353	217	415	209	161
Beef cattle ranching and farming (112111)	39	84	80	271	93	38
Cattle feedlots (112112)	8	10	6	23	14	20
Dairy cattle and milk production (11212)	2	29	12	111	17	10
Hog and pig farming (1122)	150	9	4	25	56	47
Poultry and egg production (1123)	5	37	29	154	12	1
Sheep and goat farming (1124)	8	16	15	20	22	15
Aquaculture and other animal production (1125, 1129)	5	32	66	79	54	27

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Table 44. **Farms by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
Total farms	660	938	435	1,102	2,497	322
Oilseed and grain farming (1111)	385	540	272	425	800	130
Vegetable and melon farming (1112)	14	-	-	34	27	3
Fruit and tree nut farming (1113)	2	1	-	35	29	10
Greenhouse, nursery, and floriculture production (1114)	6	1	1	19	30	1
Other crop farming (1119)	92	136	104	284	1,013	123
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	92	136	104	284	1,013	123
Beef cattle ranching and farming (112111)	31	49	35	112	268	35
Cattle feedlots (112112)	5	43	-	11	21	2
Dairy cattle and milk production (11212)	10	18	6	35	96	-
Hog and pig farming (1122)	80	98	1	6	7	2
Poultry and egg production (1123)	11	17	7	11	38	6
Sheep and goat farming (1124)	12	20	5	29	48	3
Aquaculture and other animal production (1125, 1129)	12	15	4	101	120	7

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
Total farms	728	529	1,223	821	47	274
Oilseed and grain farming (1111)	96	261	620	322	1	167
Vegetable and melon farming (1112)	13	1	13	3	26	-
Fruit and tree nut farming (1113)	18	-	2	2	2	-
Greenhouse, nursery, and floriculture production (1114)	18	5	6	7	8	-
Other crop farming (1119)	304	72	397	311	8	51
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	304	72	397	311	8	51
Beef cattle ranching and farming (112111)	142	60	86	85	-	36
Cattle feedlots (112112)	5	23	2	3	-	3
Dairy cattle and milk production (11212)	18	14	9	13	-	3
Hog and pig farming (1122)	4	28	13	8	-	-
Poultry and egg production (1123)	13	5	17	20	-	2
Sheep and goat farming (1124)	28	34	12	10	-	1
Aquaculture and other animal production (1125, 1129)	69	26	46	37	2	11

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
Total farms	1,323	931	1,111	573	751	821
Oilseed and grain farming (1111)	843	586	460	262	261	15
Vegetable and melon farming (1112)	4	10	16	8	3	52
Fruit and tree nut farming (1113)	8	7	38	-	-	19
Greenhouse, nursery, and floriculture production (1114)	6	1	21	1	5	46
Other crop farming (1119)	240	189	320	59	306	368
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	240	189	320	59	306	368
Beef cattle ranching and farming (112111)	43	21	69	63	106	115
Cattle feedlots (112112)	33	21	17	54	5	4
Dairy cattle and milk production (11212)	7	7	27	8	3	5
Hog and pig farming (1122)	84	41	19	82	-	10
Poultry and egg production (1123)	13	5	39	4	21	62
Sheep and goat farming (1124)	24	31	27	15	9	19
Aquaculture and other animal production (1125, 1129)	18	12	58	17	32	106

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
Total farms	624	494	860	2,695	721	500
Oilseed and grain farming (1111)	176	89	503	904	281	229
Vegetable and melon farming (1112)	18	33	13	45	5	5
Fruit and tree nut farming (1113)	19	24	-	26	2	2
Greenhouse, nursery, and floriculture production (1114)	18	30	1	27	9	3
Other crop farming (1119)	140	86	157	657	241	154
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	140	86	157	657	241	154
Beef cattle ranching and farming (112111)	52	59	67	322	65	25
Cattle feedlots (112112)	6	7	12	99	8	13
Dairy cattle and milk production (11212)	17	4	29	331	9	7
Hog and pig farming (1122)	1	10	25	33	44	34
Poultry and egg production (1123)	37	44	22	130	13	-
Sheep and goat farming (1124)	36	25	5	24	12	9
Aquaculture and other animal production (1125, 1129)	104	83	26	97	32	19

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Table 44. **Farms by North American Industry Classification System: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
Total farms	708	1,529	358	743	442	622
Oilseed and grain farming (1111)	389	473	200	307	89	331
Vegetable and melon farming (1112)	3	15	-	9	4	23
Fruit and tree nut farming (1113)	-	18	-	20	2	4
Greenhouse, nursery, and floriculture production (1114)	-	10	-	26	1	15
Other crop farming (1119)	249	459	133	122	161	122
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	249	459	133	122	161	122
Beef cattle ranching and farming (112111)	33	235	6	69	108	28
Cattle feedlots (112112)	1	23	5	15	2	12
Dairy cattle and milk production (11212)	4	85	1	95	13	1
Hog and pig farming (1122)	8	5	4	10	-	51
Poultry and egg production (1123)	9	53	-	8	10	9
Sheep and goat farming (1124)	6	62	1	19	5	9
Aquaculture and other animal production (1125, 1129)	6	91	8	43	47	17

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
Total farms	525	512	358	993	1,310	847
Oilseed and grain farming (1111)	102	302	206	361	415	460
Vegetable and melon farming (1112)	55	10	1	14	33	6
Fruit and tree nut farming (1113)	49	-	-	37	53	2
Greenhouse, nursery, and floriculture production (1114)	45	6	7	19	37	-
Other crop farming (1119)	81	100	107	209	329	234
Tobacco farming (11191)	-	-	-	-	-	-
Cotton farming (11192)	-	-	-	-	-	-
Sugarcane farming, hay farming, and all other crop farming (11193, 11194, 11199)	81	100	107	209	329	234
Beef cattle ranching and farming (112111)	39	21	16	116	110	60
Cattle feedlots (112112)	2	1	6	14	19	5
Dairy cattle and milk production (11212)	5	-	-	113	44	5
Hog and pig farming (1122)	4	46	-	6	12	40
Poultry and egg production (1123)	8	9	1	25	48	1
Sheep and goat farming (1124)	27	7	6	32	33	16
Aquaculture and other animal production (1125, 1129)	108	10	8	47	177	18

Table 45. **Selected Operation and Producer Characteristics: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item		Minnesota	Aitkin	Anoka	Becker	Beltrami
FARMS						
Land in farms	farms	65,531	449	355	952	608
	acres	25,442,625	120,748	30,064	381,537	173,158
Harvested cropland	farms	47,549	396	259	597	473
	acres	19,662,443	48,445	17,836	242,439	73,854
OWNED AND RENTED LAND IN FARMS						
Owned land in farms	farms	60,960	437	333	925	596
	acres	13,006,137	89,540	19,483	236,786	130,211
Rented or leased land in farms	farms	25,135	122	76	273	169
	acres	12,436,488	31,208	10,581	144,751	42,947
TENURE						
Full owners	farms	40,396	327	279	679	439
	acres	5,657,674	57,056	(D)	129,768	69,705
Harvested cropland	farms	23,435	275	190	334	322
	acres	2,453,729	17,187	3,853	45,257	22,639
Part owners	farms	20,564	110	54	246	157
	acres	17,880,717	60,519	17,420	236,843	101,612
Owned land in farms	acres	7,348,463	32,484	9,058	107,018	60,506
Rented land in farms	acres	10,532,254	28,035	8,362	129,825	41,106
Harvested cropland	farms	19,918	109	49	241	144
	acres	15,440,721	28,753	12,080	183,037	50,432
Tenants	farms	4,571	12	22	27	12
	acres	1,904,234	3,173	(D)	14,926	1,841
Harvested cropland	farms	4,196	12	20	22	7
	acres	1,767,993	2,505	1,903	14,145	783
NUMBER OF TOTAL PRODUCERS						
Total producers	number	118,256	796	689	1,753	1,069
Farms by number of producers:						
1 producer		28,348	172	128	417	236
2 producers		28,866	239	177	422	317
3 producers		4,480	19	25	56	37
4 producers		2,500	10	10	35	6
5 or more producers		1,337	9	15	22	12
Total male producers	number	81,062	508	420	1,168	671
Farms by number of male producers:						
1 producer		49,919	358	253	742	521
2 producers		8,600	40	51	101	29
3 producers		2,596	22	9	24	23
4 producers		766	1	2	27	-
5 or more producers		459	-	6	4	4
Total female producers	number	37,193	288	269	585	398
Farms by number of female producers:						
1 producer		29,936	243	198	458	341
2 producers		2,374	18	13	23	24
3 producers		466	3	9	13	3
4 producers		138	-	2	2	-
5 or more producers		90	-	2	2	-
PRODUCER CHARACTERISTICS [1]						
Producers (see text)		114,868	783	657	1,657	1,053
Sex of producers:						
Male		79,245	500	403	1,132	659
Female		35,623	283	254	525	394
Hired managers		6,902	3	87	75	11
Primary occupation:						
Farming		51,122	278	267	599	397
Other		63,746	505	390	1,058	656
Place of residence:						
On farm operated		79,195	558	505	1,126	829
Not on farm operated		35,673	225	152	531	224
Days worked off farm:						
None		46,862	287	246	655	340
Any		68,006	496	411	1,002	713
1 to 49 days		9,840	75	59	115	151
50 to 99 days		4,745	39	21	67	55
100 to 199 days		8,361	78	74	131	67
200 days or more		45,060	304	257	689	440
Years on present farm:						
2 years or less		4,867	34	68	34	70
3 or 4 years		7,650	63	63	74	48
5 to 9 years		18,524	151	145	288	214
10 years or more		83,827	535	381	1,261	721
Average years on present farm		24.2	22.9	19.5	24.5	24.0
Years operating any farm:						
5 years or less		13,846	115	147	143	139
6 to 10 years		15,740	108	127	237	171
11 years or more		85,282	560	383	1,277	743

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
FARMS					
Land in farms ..... farms	687	392	1,019	973	463
acres	134,358	263,888	478,133	302,331	125,420
Harvested cropland ..... farms	541	290	768	756	377
acres	95,943	213,843	437,712	260,346	30,672
OWNED AND RENTED LAND IN FARMS					
Owned land in farms ..... farms	664	354	929	872	458
acres	93,270	129,166	183,148	152,923	107,120
Rented or leased land in farms ..... farms	222	193	467	486	150
acres	41,088	134,722	294,985	149,408	18,300
TENURE					
Full owners ..... farms	465	199	552	487	313
acres	47,248	49,349	64,886	66,137	(D)
Harvested cropland ..... farms	330	108	315	289	231
acres	25,962	29,716	39,433	42,183	(D)
Part owners ..... farms	199	155	377	385	145
acres	81,177	200,173	353,889	207,314	41,489
Owned land in farms ..... acres	46,022	79,817	118,262	86,786	23,851
Rented land in farms ..... acres	35,155	120,356	235,627	120,528	17,638
Harvested cropland ..... farms	190	150	365	371	143
acres	64,312	171,005	340,278	189,848	19,595
Tenants ..... farms	23	38	90	101	5
acres	5,933	14,366	59,358	28,880	(D)
Harvested cropland ..... farms	21	32	88	96	3
acres	5,669	13,122	58,001	28,315	(D)
NUMBER OF TOTAL PRODUCERS					
Total producers ..... number	1,163	666	1,853	1,753	829
Farms by number of producers:					
1 producer	318	190	446	468	165
2 producers	305	156	419	361	256
3 producers	37	34	89	73	29
4 producers	20	6	39	31	12
5 or more producers	7	6	26	40	1
Total male producers ..... number	743	483	1,325	1,260	497
Farms by number of male producers:					
1 producer	567	297	721	707	389
2 producers	61	53	183	167	38
3 producers	13	21	52	35	5
4 producers	-	-	18	18	-
5 or more producers	3	2	2	8	1
Total female producers ..... number	420	183	528	493	332
Farms by number of female producers:					
1 producer	342	143	424	347	295
2 producers	28	17	35	51	11
3 producers	3	2	8	4	5
4 producers	2	-	1	2	-
5 or more producers	1	-	1	3	-
PRODUCER CHARACTERISTICS [1]					
Producers (see text)	1,147	652	1,811	1,693	816
Sex of producers:					
Male	737	472	1,322	1,232	484
Female	410	180	489	461	332
Hired managers	80	55	159	113	15
Primary occupation:					
Farming	458	350	918	773	295
Other	689	302	893	920	521
Place of residence:					
On farm operated	935	419	1,040	1,018	726
Not on farm operated	212	233	771	675	90
Days worked off farm:					
None	404	305	770	683	266
Any	743	347	1,041	1,010	550
1 to 49 days	105	77	113	132	80
50 to 99 days	44	29	84	66	62
100 to 199 days	78	43	109	140	87
200 days or more	516	198	735	672	321
Years on present farm:					
2 years or less	49	39	107	75	29
3 or 4 years	58	19	127	87	75
5 to 9 years	215	75	242	210	155
10 years or more	825	519	1,335	1,321	557
Average years on present farm	23.3	25.6	24.1	25.6	21.9
Years operating any farm:					
5 years or less	152	72	245	191	121
6 to 10 years	143	62	178	228	119
11 years or more	852	518	1,388	1,274	576

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Carver	Cass	Chippewa	Chisago	Clay	Clearwater
FARMS							
Land in farms	farms	606	488	563	740	655	404
	acres	156,676	134,449	364,695	81,038	556,161	159,856
Harvested cropland	farms	473	371	395	551	498	298
	acres	129,717	46,589	316,194	53,977	476,475	62,929
OWNED AND RENTED LAND IN FARMS							
Owned land in farms	farms	568	476	519	725	584	392
	acres	83,565	97,088	129,168	51,714	213,048	111,918
Rented or leased land in farms	farms	211	141	275	195	329	139
	acres	73,111	37,361	235,527	29,324	343,113	47,938
TENURE							
Full owners	farms	395	347	288	545	326	265
	acres	31,549	59,892	36,207	26,686	55,876	58,701
Harvested cropland	farms	272	255	124	362	180	174
	acres	14,926	21,687	18,464	9,947	23,443	20,240
Part owners	farms	173	129	231	180	258	127
	acres	116,000	72,840	291,998	53,232	440,194	95,977
Owned land in farms	acres	52,016	37,196	92,961	25,028	157,172	53,217
Rented land in farms	acres	63,984	35,644	199,037	28,204	283,022	42,760
Harvested cropland	farms	167	108	229	175	251	116
	acres	106,130	24,535	264,592	43,414	394,842	40,217
Tenants	farms	38	12	44	15	71	12
	acres	9,127	1,717	36,490	1,120	60,091	5,178
Harvested cropland	farms	34	8	42	14	67	8
	acres	8,661	367	33,138	616	58,190	2,472
NUMBER OF TOTAL PRODUCERS							
Total producers	number	1,085	836	1,058	1,258	1,232	700
Farms by number of producers:							
1 producer		257	196	292	304	300	155
2 producers		274	252	179	380	247	214
3 producers		31	27	42	35	68	27
4 producers		36	10	26	18	25	7
5 or more producers		8	3	24	3	15	1
Total male producers	number	711	526	763	783	907	446
Farms by number of male producers:							
1 producer		462	411	412	597	456	355
2 producers		86	48	71	65	120	30
3 producers		15	1	34	17	39	9
4 producers		8	4	12	-	-	1
5 or more producers		-	-	7	1	9	-
Total female producers	number	374	310	295	475	325	254
Farms by number of female producers:							
1 producer		303	275	195	429	262	238
2 producers		34	13	29	23	26	6
3 producers		1	3	5	-	1	-
4 producers		-	-	-	-	2	1
5 or more producers		-	-	3	-	-	-
PRODUCER CHARACTERISTICS [1]							
Producers (see text)		1,074	833	976	1,253	1,158	696
Sex of producers:							
Male		706	526	722	780	842	445
Female		368	307	254	473	316	251
Hired managers		58	6	90	24	139	9
Primary occupation:							
Farming		485	314	452	456	608	255
Other		589	519	524	797	550	441
Place of residence:							
On farm operated		840	720	559	1,072	809	570
Not on farm operated		234	113	417	181	349	126
Days worked off farm:							
None		465	285	411	395	545	208
Any		609	548	565	858	613	488
1 to 49 days		79	57	88	114	83	69
50 to 99 days		61	48	51	41	43	35
100 to 199 days		60	84	56	100	83	88
200 days or more		409	359	370	603	404	296
Years on present farm:							
2 years or less		36	70	21	69	29	68
3 or 4 years		99	55	48	129	86	55
5 to 9 years		177	147	164	306	180	104
10 years or more		762	561	743	749	863	469
Average years on present farm		26.6	21.1	25.1	19.3	25.3	21.9
Years operating any farm:							
5 years or less		117	129	78	210	138	127
6 to 10 years		161	113	127	266	142	102
11 years or more		796	591	771	777	878	467

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
FARMS						
Land in farms ..... farms	25	742	426	841	614	980
acres	1,940	392,494	92,791	208,517	280,440	268,096
Harvested cropland ..... farms	21	548	327	657	436	660
acres	228	351,380	37,686	175,486	255,854	176,176
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	24	655	405	733	553	936
acres	1,814	178,616	66,392	120,583	113,350	165,178
Rented or leased land in farms ..... farms	3	380	105	316	251	296
acres	126	213,878	26,399	87,934	167,090	102,918
TENURE						
Full owners ..... farms	22	362	321	525	363	684
acres	1,776	54,487	48,072	56,787	33,015	82,998
Harvested cropland ..... farms	19	183	233	357	202	385
acres	(D)	34,511	10,139	39,201	20,862	28,062
Part owners ..... farms	2	293	84	208	190	252
acres	(D)	301,268	34,267	135,934	206,656	180,338
Owned land in farms ..... acres	(D)	124,129	18,320	63,796	80,335	82,180
Rented land in farms ..... acres	(D)	177,139	15,947	72,138	126,321	98,158
Harvested cropland ..... farms	2	285	75	201	181	240
acres	(D)	283,085	18,615	121,802	195,287	144,171
Tenants ..... farms	1	87	21	108	61	44
acres	(D)	36,739	10,452	15,796	40,769	4,760
Harvested cropland ..... farms	-	80	19	99	53	35
acres	-	33,784	8,932	14,483	39,705	3,943
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	47	1,329	711	1,630	1,126	1,827
Farms by number of producers:						
1 producer	8	338	183	311	254	408
2 producers	13	293	217	394	282	445
3 producers	3	76	16	73	37	51
4 producers	1	23	4	34	27	53
5 or more producers	-	12	6	29	14	23
Total male producers ..... number	30	967	443	1,097	742	1,272
Farms by number of male producers:						
1 producer	15	531	357	608	477	761
2 producers	6	112	43	118	75	102
3 producers	1	61	-	49	16	43
4 producers	-	3	-	14	13	21
5 or more producers	-	3	-	10	3	14
Total female producers ..... number	17	362	268	533	384	555
Farms by number of female producers:						
1 producer	17	286	222	367	295	470
2 producers	-	22	14	50	24	33
3 producers	-	5	6	15	11	1
4 producers	-	3	-	4	2	4
5 or more producers	-	1	-	1	-	-
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	47	1,292	705	1,570	1,093	1,755
Sex of producers:						
Male	30	949	443	1,069	737	1,233
Female	17	343	262	501	356	522
Hired managers	-	95	24	190	64	64
Primary occupation:						
Farming	18	694	273	720	551	599
Other	29	598	432	850	542	1,156
Place of residence:						
On farm operated	33	809	581	996	821	1,134
Not on farm operated	14	483	124	574	272	621
Days worked off farm:						
None	15	582	289	620	486	708
Any	32	710	416	950	607	1,047
1 to 49 days	5	132	38	116	71	184
50 to 99 days	4	58	32	70	24	78
100 to 199 days	4	79	58	85	67	113
200 days or more	19	441	288	679	445	672
Years on present farm:						
2 years or less	1	42	44	82	31	85
3 or 4 years	-	106	36	117	83	95
5 to 9 years	6	120	131	261	156	352
10 years or more	40	1,024	494	1,110	823	1,223
Average years on present farm	27.4	26.8	24.1	22.6	25.5	22.4
Years operating any farm:						
5 years or less	2	145	89	191	109	215
6 to 10 years	6	146	96	306	142	352
11 years or more	39	1,001	520	1,073	842	1,188

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
FARMS						
Land in farms ..... farms	773	1,458	908	1,406	529	511
acres	383,231	470,312	351,174	421,698	338,754	32,406
Harvested cropland ..... farms	640	1,002	670	1,059	282	373
acres	356,884	347,026	312,957	341,371	281,684	17,928
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	660	1,364	824	1,308	497	474
acres	146,635	262,223	151,288	223,022	147,998	22,475
Rented or leased land in farms ..... farms	468	526	419	566	187	94
acres	236,596	208,089	199,886	198,676	190,756	9,931
TENURE						
Full owners ..... farms	305	932	489	840	342	417
acres	35,617	115,309	57,347	92,467	48,353	17,096
Harvested cropland ..... farms	175	520	256	515	100	284
acres	26,268	46,610	34,771	45,921	15,460	5,680
Part owners ..... farms	355	432	335	468	155	57
acres	318,156	323,816	263,635	294,441	272,636	11,997
Owned land in farms ..... acres	111,018	146,914	93,941	130,555	99,645	5,379
Rented land in farms ..... acres	207,138	176,902	169,694	163,886	172,991	6,618
Harvested cropland ..... farms	353	406	331	454	152	55
acres	302,285	272,773	248,435	263,514	250,368	9,291
Tenants ..... farms	113	94	84	98	32	37
acres	29,458	31,187	30,192	34,790	17,765	3,313
Harvested cropland ..... farms	112	76	83	90	30	34
acres	28,331	27,643	29,751	31,936	15,856	2,957
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	1,322	2,670	1,515	2,520	960	950
Farms by number of producers:						
1 producer	383	615	424	572	242	198
2 producers	297	651	398	660	218	247
3 producers	50	86	56	110	32	41
4 producers	33	65	24	46	24	15
5 or more producers	10	41	6	18	13	10
Total male producers ..... number	949	1,829	1,048	1,696	657	580
Farms by number of male producers:						
1 producer	595	1,111	726	1,098	381	372
2 producers	118	207	110	176	84	55
3 producers	19	37	30	71	7	17
4 producers	13	33	3	5	15	8
5 or more producers	1	10	-	2	5	1
Total female producers ..... number	373	841	467	824	303	370
Farms by number of female producers:						
1 producer	301	658	396	671	228	306
2 producers	24	74	23	61	19	23
3 producers	2	9	7	3	3	1
4 producers	3	2	1	2	7	-
5 or more producers	1	-	-	2	-	1
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	1,299	2,599	1,508	2,478	922	915
Sex of producers:						
Male	936	1,788	1,044	1,681	647	562
Female	363	811	464	797	275	353
Hired managers	78	94	46	157	46	84
Primary occupation:						
Farming	741	1,179	779	1,194	368	326
Other	558	1,420	729	1,284	554	589
Place of residence:						
On farm operated	873	1,797	999	1,993	481	747
Not on farm operated	426	802	509	485	441	168
Days worked off farm:						
None	541	1,043	763	1,044	371	350
Any	758	1,556	745	1,434	551	565
1 to 49 days	135	247	112	205	93	96
50 to 99 days	59	76	46	110	65	33
100 to 199 days	124	196	91	194	62	75
200 days or more	440	1,037	496	925	331	361
Years on present farm:						
2 years or less	36	110	49	63	55	64
3 or 4 years	76	116	86	164	73	121
5 to 9 years	232	458	198	359	86	223
10 years or more	955	1,915	1,175	1,892	708	507
Average years on present farm	25.9	24.0	27.8	24.7	25.1	19.8
Years operating any farm:						
5 years or less	125	238	152	270	135	210
6 to 10 years	204	389	159	306	79	203
11 years or more	970	1,972	1,197	1,902	708	502

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
FARMS							
Land in farms	farms	797	336	814	424	845	531
	acres	223,021	98,144	101,666	96,375	384,337	99,182
Harvested cropland	farms	525	231	584	330	653	432
	acres	117,902	47,705	64,610	42,596	349,235	53,672
OWNED AND RENTED LAND IN FARMS							
Owned land in farms	farms	763	326	789	415	739	514
	acres	159,525	57,693	62,302	71,312	173,096	69,122
Rented or leased land in farms	farms	228	89	210	109	460	144
	acres	63,496	40,451	39,364	25,063	211,241	30,060
TENURE							
Full owners	farms	569	247	604	315	385	387
	acres	96,306	(D)	32,866	50,804	66,549	42,823
Harvested cropland	farms	308	150	397	222	205	304
	acres	26,766	(D)	8,551	16,497	47,504	13,218
Part owners	farms	194	79	185	100	354	127
	acres	111,203	52,665	67,611	45,285	282,137	55,029
Owned land in farms	acres	63,219	20,553	29,436	20,508	106,547	26,299
Rented land in farms	acres	47,984	32,112	38,175	24,777	175,590	28,730
Harvested cropland	farms	183	73	168	100	351	119
	acres	77,796	31,683	55,283	25,876	268,552	39,616
Tenants	farms	34	10	25	9	106	17
	acres	15,512	(D)	1,189	286	35,651	1,330
Harvested cropland	farms	34	8	19	8	97	9
	acres	13,340	(D)	776	223	33,179	838
NUMBER OF TOTAL PRODUCERS							
Total producers	number	1,564	617	1,414	748	1,549	947
Farms by number of producers:							
1 producer		301	146	318	153	388	197
2 producers		374	145	435	245	335	288
3 producers		56	16	39	15	78	23
4 producers		45	16	11	2	18	13
5 or more producers		21	13	11	9	26	10
Total male producers	number	1,017	386	871	452	1,171	587
Farms by number of male producers:							
1 producer		561	262	680	367	620	441
2 producers		131	40	74	25	114	51
3 producers		26	4	11	1	51	4
4 producers		16	8	1	8	7	8
5 or more producers		8	-	1	-	18	-
Total female producers	number	547	231	543	296	378	360
Farms by number of female producers:							
1 producer		419	172	437	271	325	315
2 producers		29	18	44	11	18	18
3 producers		4	6	1	1	4	1
4 producers		4	-	-	-	-	-
5 or more producers		7	1	3	-	1	1
PRODUCER CHARACTERISTICS [1]							
Producers (see text)		1,481	600	1,393	732	1,468	934
Sex of producers:							
Male		989	374	862	448	1,101	585
Female		492	226	531	284	367	349
Hired managers		72	10	39	11	91	15
Primary occupation:							
Farming		666	223	521	287	787	367
Other		815	377	872	445	681	567
Place of residence:							
On farm operated		1,050	510	1,227	590	860	810
Not on farm operated		431	90	166	142	608	124
Days worked off farm:							
None		646	235	449	241	727	353
Any		835	365	944	491	741	581
1 to 49 days		80	25	129	65	124	83
50 to 99 days		63	20	76	48	60	35
100 to 199 days		109	66	113	74	87	57
200 days or more		583	254	626	304	470	406
Years on present farm:							
2 years or less		44	43	88	43	47	53
3 or 4 years		103	33	189	46	78	65
5 to 9 years		218	119	282	125	243	232
10 years or more		1,116	405	834	518	1,100	584
Average years on present farm		24.2	21.2	19.0	21.9	27.5	20.5
Years operating any farm:							
5 years or less		153	90	293	97	153	127
6 to 10 years		179	90	271	93	214	198
11 years or more		1,149	420	829	542	1,101	609

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
FARMS						
Land in farms ..... farms	1,252	613	190	735	34	186
acres	494,447	602,709	60,919	410,959	1,422	109,394
Harvested cropland ..... farms	728	342	147	521	19	126
acres	396,375	418,170	23,979	340,540	144	57,749
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	1,191	582	186	664	34	177
acres	224,860	326,314	46,198	190,575	(D)	67,509
Rented or leased land in farms ..... farms	389	240	54	356	4	65
acres	269,587	276,395	14,721	220,384	(D)	41,885
TENURE						
Full owners ..... farms	863	373	136	379	30	121
acres	99,962	127,602	27,725	67,219	1,091	34,770
Harvested cropland ..... farms	364	109	94	169	15	66
acres	36,546	18,363	6,491	32,158	89	8,025
Part owners ..... farms	328	209	50	285	4	56
acres	350,570	442,723	30,359	325,341	331	68,370
Owned land in farms ..... acres	124,898	198,712	18,473	123,356	(D)	32,739
Rented land in farms ..... acres	225,672	244,011	11,886	201,985	(D)	35,631
Harvested cropland ..... farms	315	203	49	283	4	52
acres	319,303	369,003	14,908	291,453	55	44,126
Tenants ..... farms	61	31	4	71	-	9
acres	43,915	32,384	2,835	18,399	-	6,254
Harvested cropland ..... farms	49	30	4	69	-	8
acres	40,526	30,804	2,580	16,929	-	5,598
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	2,399	1,191	319	1,227	65	309
Farms by number of producers:						
1 producer	511	276	78	395	9	96
2 producers	540	199	98	243	21	68
3 producers	92	80	11	69	2	17
4 producers	80	27	3	11	2	3
5 or more producers	29	31	-	17	-	2
Total male producers ..... number	1,664	874	214	924	35	227
Farms by number of male producers:						
1 producer	861	399	162	535	29	151
2 producers	186	101	9	121	3	17
3 producers	85	47	10	37	-	12
4 producers	32	18	1	9	-	-
5 or more producers	5	12	-	-	-	1
Total female producers ..... number	735	317	105	303	30	82
Farms by number of female producers:						
1 producer	568	215	105	223	24	71
2 producers	44	35	-	21	-	3
3 producers	5	4	-	10	2	-
4 producers	9	5	-	2	-	-
5 or more producers	4	-	-	-	-	1
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	2,303	1,146	319	1,200	65	303
Sex of producers:						
Male	1,625	859	214	918	35	223
Female	678	287	105	282	30	80
Hired managers	213	91	2	71	2	9
Primary occupation:						
Farming	897	507	137	609	13	127
Other	1,406	639	182	591	52	176
Place of residence:						
On farm operated	1,446	491	241	665	61	197
Not on farm operated	857	655	78	535	4	106
Days worked off farm:						
None	900	455	126	570	11	95
Any	1,403	691	193	630	54	208
1 to 49 days	187	202	23	129	3	61
50 to 99 days	76	34	15	64	2	16
100 to 199 days	186	61	32	70	13	30
200 days or more	954	394	123	367	36	101
Years on present farm:						
2 years or less	125	20	9	39	-	40
3 or 4 years	187	100	12	28	7	24
5 to 9 years	386	192	62	146	14	27
10 years or more	1,605	834	236	987	44	212
Average years on present farm	23.4	23.2	24.9	26.7	19.0	22.4
Years operating any farm:						
5 years or less	343	145	23	73	9	57
6 to 10 years	302	134	52	173	8	37
11 years or more	1,658	867	244	954	48	209

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
FARMS							
Land in farms	farms	896	598	869	801	268	1,072
	acres	205,774	212,420	424,591	246,163	217,882	912,128
Harvested cropland	farms	523	351	639	570	197	717
	acres	159,857	153,500	360,873	218,209	171,244	646,007
OWNED AND RENTED LAND IN FARMS							
Owned land in farms	farms	822	554	760	748	252	991
	acres	103,490	113,711	167,969	118,971	122,106	479,754
Rented or leased land in farms	farms	276	218	475	286	124	464
	acres	102,284	98,709	256,622	127,192	95,776	432,374
TENURE							
Full owners	farms	620	380	394	515	144	608
	acres	53,648	63,907	66,747	47,088	53,921	189,431
Harvested cropland	farms	258	146	171	300	75	274
	acres	18,543	23,821	28,961	28,060	30,937	63,784
Part owners	farms	202	174	366	233	108	383
	acres	138,100	131,351	302,740	192,713	156,865	671,038
Owned land in farms	acres	49,842	49,804	101,222	71,883	68,185	290,323
Rented land in farms	acres	88,258	81,547	201,518	120,830	88,680	380,715
Harvested cropland	farms	193	168	362	224	107	367
	acres	128,473	115,881	279,004	183,958	133,377	539,639
Tenants	farms	74	44	109	53	16	81
	acres	14,026	17,162	55,104	6,362	7,096	51,659
Harvested cropland	farms	72	37	106	46	15	76
	acres	12,841	13,798	52,908	6,191	6,930	42,584
NUMBER OF TOTAL PRODUCERS							
Total producers	number	1,616	1,075	1,564	1,468	460	2,007
Farms by number of producers:							
1 producer		380	253	408	354	134	497
2 producers		414	267	314	329	99	416
3 producers		42	35	89	66	24	73
4 producers		38	36	40	27	5	48
5 or more producers		22	7	18	25	6	38
Total male producers	number	1,090	737	1,149	1,054	340	1,537
Farms by number of male producers:							
1 producer		677	425	615	609	222	715
2 producers		125	109	152	90	17	205
3 producers		23	22	66	43	18	54
4 producers		11	7	3	7	-	28
5 or more producers		10	-	4	18	6	24
Total female producers	number	526	338	415	414	120	470
Farms by number of female producers:							
1 producer		406	247	311	347	114	327
2 producers		38	31	31	20	3	34
3 producers		8	7	14	5	-	2
4 producers		5	2	-	-	-	6
5 or more producers		-	-	-	2	-	9
PRODUCER CHARACTERISTICS [1]							
Producers (see text)		1,574	1,064	1,535	1,418	448	1,892
Sex of producers:							
Male		1,066	732	1,140	1,015	334	1,493
Female		508	332	395	403	114	399
Hired managers		92	55	120	97	13	95
Primary occupation:							
Farming		576	429	814	640	197	936
Other		998	635	721	778	251	956
Place of residence:							
On farm operated		1,026	556	914	1,105	256	950
Not on farm operated		548	508	621	313	192	942
Days worked off farm:							
None		613	433	626	573	151	821
Any		961	631	909	845	297	1,071
1 to 49 days		89	118	122	113	32	191
50 to 99 days		50	45	40	65	35	83
100 to 199 days		86	68	87	115	32	91
200 days or more		736	400	660	552	198	706
Years on present farm:							
2 years or less		87	37	48	42	13	67
3 or 4 years		127	54	132	101	24	152
5 to 9 years		206	135	263	207	47	263
10 years or more		1,154	838	1,092	1,068	364	1,410
Average years on present farm		24.8	26.0	24.6	26.2	23.2	23.9
Years operating any farm:							
5 years or less		237	104	188	139	48	252
6 to 10 years		164	107	176	185	44	217
11 years or more		1,173	853	1,171	1,094	356	1,423

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
FARMS						
Land in farms ..... farms	823	991	603	1,571	999	789
acres	454,025	308,376	96,684	361,789	380,070	351,476
Harvested cropland ..... farms	650	602	488	1,288	716	608
acres	422,048	242,801	55,469	190,224	333,878	298,402
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	716	934	590	1,531	888	707
acres	163,304	164,459	62,481	275,706	153,106	167,146
Rented or leased land in farms ..... farms	470	305	190	484	442	403
acres	290,721	143,917	34,203	86,083	226,964	184,330
TENURE						
Full owners ..... farms	353	686	413	1,087	557	386
acres	47,753	85,210	36,282	160,242	63,213	51,268
Harvested cropland ..... farms	196	305	312	823	283	220
acres	32,189	40,096	11,970	52,972	40,572	33,276
Part owners ..... farms	363	248	177	444	331	321
acres	354,961	206,188	58,070	185,842	271,019	277,275
Owned land in farms ..... acres	115,551	79,249	26,199	115,464	89,893	115,878
Rented land in farms ..... acres	239,410	126,939	31,871	70,378	181,126	161,397
Harvested cropland ..... farms	359	243	165	427	324	319
acres	339,607	186,321	41,499	123,640	249,040	243,945
Tenants ..... farms	107	57	13	40	111	82
acres	51,311	16,978	2,332	15,705	45,838	22,933
Harvested cropland ..... farms	95	54	11	38	109	69
acres	50,252	16,384	2,000	13,612	44,266	21,181
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	1,492	1,698	1,063	2,713	1,801	1,313
Farms by number of producers:						
1 producer	402	448	231	708	425	411
2 producers	303	436	319	720	421	295
3 producers	52	73	26	77	100	44
4 producers	33	18	22	44	42	25
5 or more producers	33	16	5	22	11	14
Total male producers ..... number	1,117	1,133	681	1,830	1,241	922
Farms by number of male producers:						
1 producer	616	773	490	1,306	756	630
2 producers	114	136	73	149	147	88
3 producers	44	28	15	35	51	22
4 producers	12	1	-	12	7	5
5 or more producers	15	-	-	8	2	6
Total female producers ..... number	375	565	382	883	560	391
Farms by number of female producers:						
1 producer	290	467	331	782	446	296
2 producers	23	28	21	43	46	19
3 producers	9	10	3	5	4	13
4 producers	3	3	-	-	1	2
5 or more producers	-	-	-	-	1	2
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	1,428	1,675	1,055	2,643	1,779	1,289
Sex of producers:						
Male	1,070	1,127	679	1,782	1,233	912
Female	358	548	376	861	546	377
Hired managers	116	107	16	121	118	88
Primary occupation:						
Farming	756	709	406	1,217	828	664
Other	672	966	649	1,426	951	625
Place of residence:						
On farm operated	830	1,175	901	2,182	1,287	786
Not on farm operated	598	500	154	461	492	503
Days worked off farm:						
None	604	679	370	1,069	776	575
Any	824	996	685	1,574	1,003	714
1 to 49 days	112	123	115	226	118	129
50 to 99 days	38	82	40	123	92	53
100 to 199 days	91	117	86	200	108	86
200 days or more	583	674	444	1,025	685	446
Years on present farm:						
2 years or less	35	62	40	95	62	36
3 or 4 years	122	138	62	141	135	81
5 to 9 years	220	297	280	403	204	240
10 years or more	1,051	1,178	673	2,004	1,378	932
Average years on present farm	24.7	23.4	20.4	25.2	25.5	25.5
Years operating any farm:						
5 years or less	166	256	136	294	197	121
6 to 10 years	185	200	200	377	179	190
11 years or more	1,077	1,219	719	1,972	1,403	978

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
FARMS						
Land in farms ..... farms	660	938	435	1,102	2,497	322
acres	278,870	366,330	491,694	308,004	770,922	258,956
Harvested cropland ..... farms	510	716	344	782	1,598	213
acres	253,410	334,873	428,145	238,968	472,434	187,360
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	579	822	382	1,039	2,384	314
acres	107,209	154,055	184,210	159,372	491,557	134,140
Rented or leased land in farms ..... farms	321	474	252	381	755	123
acres	171,661	212,275	307,484	148,632	279,365	124,816
TENURE						
Full owners ..... farms	339	464	183	721	1,742	199
acres	39,903	57,846	47,561	71,020	255,061	51,750
Harvested cropland ..... farms	196	244	95	427	886	100
acres	26,021	43,476	22,141	33,485	70,273	18,437
Part owners ..... farms	240	358	199	318	642	115
acres	188,738	268,648	399,697	196,667	480,601	203,644
Owned land in farms ..... acres	67,306	96,209	136,649	88,352	236,496	82,390
Rented land in farms ..... acres	121,432	172,439	263,048	108,315	244,105	121,254
Harvested cropland ..... farms	236	356	199	299	611	106
acres	177,882	252,449	363,883	170,868	370,295	166,168
Tenants ..... farms	81	116	53	63	113	8
acres	50,229	39,836	44,436	40,317	35,260	3,562
Harvested cropland ..... farms	78	116	50	56	101	7
acres	49,507	38,948	42,121	34,615	31,866	2,755
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	1,181	1,831	738	2,012	4,520	559
Farms by number of producers:						
1 producer	288	406	229	394	1,119	144
2 producers	276	364	138	591	1,096	156
3 producers	61	76	46	54	140	5
4 producers	28	68	18	43	84	8
5 or more producers	7	24	4	20	58	9
Total male producers ..... number	855	1,333	564	1,333	3,102	381
Farms by number of male producers:						
1 producer	460	660	321	864	1,987	265
2 producers	131	157	69	152	277	30
3 producers	39	46	22	32	86	2
4 producers	4	23	7	11	15	1
5 or more producers	-	12	2	5	30	8
Total female producers ..... number	326	498	174	679	1,418	178
Farms by number of female producers:						
1 producer	261	373	138	579	1,159	152
2 producers	22	52	16	33	74	8
3 producers	7	2	-	10	18	2
4 producers	-	1	1	1	9	1
5 or more producers	-	2	-	-	4	-
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	1,163	1,730	731	1,990	4,299	539
Sex of producers:						
Male	851	1,245	558	1,319	2,951	363
Female	312	485	173	671	1,348	176
Hired managers	112	93	47	101	192	16
Primary occupation:						
Farming	612	829	414	818	1,630	233
Other	551	901	317	1,172	2,669	306
Place of residence:						
On farm operated	829	990	403	1,487	2,907	359
Not on farm operated	334	740	328	503	1,392	180
Days worked off farm:						
None	531	655	361	816	1,701	203
Any	632	1,075	370	1,174	2,598	336
1 to 49 days	70	159	78	141	408	68
50 to 99 days	46	71	18	68	172	14
100 to 199 days	88	104	60	119	303	25
200 days or more	428	741	214	846	1,715	229
Years on present farm:						
2 years or less	12	73	31	63	166	23
3 or 4 years	58	151	35	119	306	27
5 to 9 years	166	354	92	312	662	45
10 years or more	927	1,152	573	1,496	3,165	444
Average years on present farm	27.2	23.2	25.5	23.9	23.9	25.1
Years operating any farm:						
5 years or less	109	238	66	203	530	48
6 to 10 years	139	267	67	282	494	51
11 years or more	915	1,225	598	1,505	3,275	440

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
FARMS						
Land in farms ..... farms	728	529	1,223	821	47	274
acres	164,801	227,976	1,083,394	310,041	799	196,716
Harvested cropland ..... farms	620	412	890	470	40	213
acres	75,570	181,999	904,276	220,081	108	154,337
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	718	489	1,077	756	36	245
acres	123,705	115,579	467,811	163,866	(D)	115,283
Rented or leased land in farms ..... farms	232	250	675	247	14	142
acres	41,096	112,397	615,583	146,175	(D)	81,433
TENURE						
Full owners ..... farms	496	279	548	574	33	132
acres	63,388	44,595	129,755	92,042	(D)	44,756
Harvested cropland ..... farms	389	175	241	236	26	80
acres	15,300	28,096	52,552	31,304	81	28,384
Part owners ..... farms	222	210	529	182	3	113
acres	100,493	167,174	874,765	152,003	(D)	134,459
Owned land in farms ..... acres	60,317	70,984	338,056	71,824	6	70,527
Rented land in farms ..... acres	40,176	96,190	536,709	80,179	(D)	63,932
Harvested cropland ..... farms	222	203	512	170	3	108
acres	59,810	139,930	778,241	127,266	(D)	112,177
Tenants ..... farms	10	40	146	65	11	29
acres	920	16,207	78,874	65,996	(D)	17,501
Harvested cropland ..... farms	9	34	137	64	11	25
acres	460	13,973	73,483	61,511	(D)	13,776
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	1,250	899	2,394	1,502	81	457
Farms by number of producers:						
1 producer	304	253	517	348	22	138
2 producers	348	227	458	374	20	105
3 producers	54	26	130	52	3	25
4 producers	22	13	86	29	-	4
5 or more producers	-	10	32	18	2	2
Total male producers ..... number	772	617	1,762	1,049	37	347
Farms by number of male producers:						
1 producer	564	447	808	618	31	203
2 producers	77	43	251	116	3	42
3 producers	18	16	95	35	-	16
4 producers	-	4	21	9	-	-
5 or more producers	-	4	12	9	-	2
Total female producers ..... number	478	282	631	453	44	110
Farms by number of female producers:						
1 producer	410	232	461	366	34	94
2 producers	34	18	49	17	-	5
3 producers	-	2	10	6	-	2
4 producers	-	2	8	-	-	-
5 or more producers	-	-	2	7	2	-
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	1,250	877	2,295	1,440	79	447
Sex of producers:						
Male	772	605	1,707	1,016	37	343
Female	478	272	588	424	42	104
Hired managers	44	61	301	80	21	21
Primary occupation:						
Farming	488	464	1,169	474	34	223
Other	762	413	1,126	966	45	224
Place of residence:						
On farm operated	1,016	689	1,400	789	29	321
Not on farm operated	234	188	895	651	50	126
Days worked off farm:						
None	444	361	1,025	587	34	156
Any	806	516	1,270	853	45	291
1 to 49 days	91	75	244	115	2	28
50 to 99 days	77	39	122	57	-	12
100 to 199 days	137	65	101	82	12	73
200 days or more	501	337	803	599	31	178
Years on present farm:						
2 years or less	72	36	53	85	8	14
3 or 4 years	103	32	181	87	18	13
5 to 9 years	205	114	376	139	24	71
10 years or more	870	695	1,685	1,129	29	349
Average years on present farm	23.1	26.5	24.1	24.1	14.3	25.9
Years operating any farm:						
5 years or less	167	77	254	190	15	29
6 to 10 years	171	97	293	98	27	56
11 years or more	912	703	1,748	1,152	37	362

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
FARMS						
Land in farms ..... farms	1,323	931	1,111	573	751	821
acres	560,222	626,065	249,881	261,220	537,341	162,061
Harvested cropland ..... farms	983	734	818	443	490	635
acres	509,922	571,420	197,825	235,233	339,987	70,850
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	1,119	824	1,029	532	721	807
acres	219,768	234,298	133,188	120,310	326,638	128,640
Rented or leased land in farms ..... farms	736	519	361	290	272	172
acres	340,454	391,767	116,693	140,910	210,703	33,421
TENURE						
Full owners ..... farms	587	412	750	283	479	649
acres	86,363	77,406	66,839	34,995	147,176	84,095
Harvested cropland ..... farms	282	224	469	161	225	468
acres	58,954	54,489	32,667	24,044	44,814	27,131
Part owners ..... farms	532	412	279	249	242	158
acres	386,128	478,874	155,380	208,894	353,993	77,117
Owned land in farms ..... acres	133,405	156,892	66,349	85,315	179,462	44,545
Rented land in farms ..... acres	252,723	321,982	89,031	123,579	174,531	32,572
Harvested cropland ..... farms	518	406	274	245	237	158
acres	365,011	449,110	138,296	195,001	263,206	43,642
Tenants ..... farms	204	107	82	41	30	14
acres	87,731	69,785	27,662	17,331	36,172	849
Harvested cropland ..... farms	183	104	75	37	28	9
acres	85,957	67,821	26,862	16,188	31,967	77
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	2,472	1,614	2,015	1,050	1,288	1,448
Farms by number of producers:						
1 producer	602	457	448	242	368	308
2 producers	522	334	518	269	300	463
3 producers	83	94	81	36	53	23
4 producers	73	35	48	16	18	13
5 or more producers	43	11	16	10	12	14
Total male producers ..... number	1,843	1,155	1,349	728	910	869
Farms by number of male producers:						
1 producer	966	688	855	447	587	661
2 producers	181	139	148	73	91	56
3 producers	66	49	48	17	29	16
4 producers	54	8	6	1	6	-
5 or more producers	14	2	6	10	5	6
Total female producers ..... number	629	459	666	322	378	579
Farms by number of female producers:						
1 producer	482	360	546	280	307	519
2 producers	45	33	40	18	19	19
3 producers	9	4	8	2	7	6
4 producers	-	4	4	-	-	1
5 or more producers	6	1	-	-	2	-
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	2,359	1,591	1,983	992	1,247	1,411
Sex of producers:						
Male	1,789	1,147	1,331	686	896	844
Female	570	444	652	306	351	567
Hired managers	184	172	94	79	37	47
Primary occupation:						
Farming	1,142	781	718	484	516	534
Other	1,217	810	1,265	508	731	877
Place of residence:						
On farm operated	1,213	937	1,420	722	814	1,206
Not on farm operated	1,146	654	563	270	433	205
Days worked off farm:						
None	1,009	670	757	425	531	557
Any	1,350	921	1,226	567	716	854
1 to 49 days	223	172	180	61	96	111
50 to 99 days	94	65	44	36	41	59
100 to 199 days	196	94	128	69	91	164
200 days or more	837	590	874	401	488	520
Years on present farm:						
2 years or less	169	44	101	12	41	64
3 or 4 years	199	73	152	83	66	118
5 to 9 years	391	250	325	159	181	261
10 years or more	1,600	1,224	1,405	738	959	968
Average years on present farm	23.1	24.8	23.3	25.4	24.6	21.6
Years operating any farm:						
5 years or less	442	145	238	117	110	209
6 to 10 years	326	200	285	103	151	259
11 years or more	1,591	1,246	1,460	772	986	943

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
FARMS						
Land in farms ..... farms	624	494	860	2,695	721	500
acres	99,629	85,044	373,628	643,463	245,834	330,936
Harvested cropland ..... farms	442	325	670	2,118	442	326
acres	81,167	57,043	333,743	458,204	215,514	283,965
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	586	473	811	2,566	686	447
acres	44,837	52,731	177,013	442,876	127,544	115,521
Rented or leased land in farms ..... farms	193	124	344	892	236	233
acres	54,792	32,313	196,615	200,587	118,290	215,415
TENURE						
Full owners ..... farms	431	370	516	1,803	485	267
acres	22,591	19,599	70,880	229,546	44,576	44,281
Harvested cropland ..... farms	262	207	331	1,264	210	108
acres	10,698	5,531	46,837	118,130	21,978	23,074
Part owners ..... farms	155	103	295	763	201	180
acres	67,442	55,496	290,012	386,970	189,982	252,262
Owned land in farms ..... acres	22,246	33,132	106,133	213,330	82,968	71,240
Rented land in farms ..... acres	45,196	22,364	183,879	173,640	107,014	181,022
Harvested cropland ..... farms	145	97	293	737	198	176
acres	62,792	43,243	275,275	315,210	183,242	230,204
Tenants ..... farms	38	21	49	129	35	53
acres	9,596	9,949	12,736	26,947	11,276	34,393
Harvested cropland ..... farms	35	21	46	117	34	42
acres	7,677	8,269	11,631	24,864	10,294	30,687
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	1,124	894	1,521	4,826	1,270	1,015
Farms by number of producers:						
1 producer	238	182	386	1,097	323	193
2 producers	331	250	365	1,296	313	206
3 producers	23	39	63	165	44	47
4 producers	24	21	36	99	33	42
5 or more producers	8	2	10	38	8	12
Total male producers ..... number	694	567	1,028	3,250	877	751
Farms by number of male producers:						
1 producer	496	398	690	2,117	581	308
2 producers	55	43	95	359	74	95
3 producers	13	21	35	80	25	45
4 producers	4	5	7	19	13	12
5 or more producers	6	-	3	17	2	7
Total female producers ..... number	430	327	493	1,576	393	264
Farms by number of female producers:						
1 producer	357	283	401	1,326	327	219
2 producers	23	19	31	81	28	18
3 producers	9	2	1	15	2	-
4 producers	-	-	3	7	1	1
5 or more producers	-	-	3	3	-	1
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	1,097	891	1,489	4,732	1,245	962
Sex of producers:						
Male	678	565	1,014	3,211	857	706
Female	419	326	475	1,521	388	256
Hired managers	75	74	94	296	50	145
Primary occupation:						
Farming	410	351	722	2,190	508	489
Other	687	540	767	2,542	737	473
Place of residence:						
On farm operated	849	695	986	3,595	864	542
Not on farm operated	248	196	503	1,137	381	420
Days worked off farm:						
None	396	340	646	1,994	495	488
Any	701	551	843	2,738	750	474
1 to 49 days	74	52	76	311	102	100
50 to 99 days	25	51	64	148	39	38
100 to 199 days	104	92	118	352	70	59
200 days or more	498	356	585	1,927	539	277
Years on present farm:						
2 years or less	70	22	65	181	46	63
3 or 4 years	69	128	70	238	94	35
5 to 9 years	189	232	233	715	211	125
10 years or more	769	509	1,121	3,598	894	739
Average years on present farm	22.2	20.2	26.3	24.8	25.4	25.3
Years operating any farm:						
5 years or less	139	155	169	420	135	109
6 to 10 years	187	216	164	671	178	119
11 years or more	771	520	1,156	3,641	932	734

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
FARMS						
Land in farms ..... farms	708	1,529	358	743	442	622
acres	374,933	321,168	309,539	235,417	123,335	266,866
Harvested cropland ..... farms	445	1,179	229	604	333	453
acres	302,409	175,396	257,835	167,885	71,052	235,748
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	652	1,477	322	713	432	583
acres	204,595	230,876	119,159	151,887	86,198	127,918
Rented or leased land in farms ..... farms	274	459	168	291	132	245
acres	170,338	90,292	190,380	83,530	37,137	138,948
TENURE						
Full owners ..... farms	434	1,070	190	452	310	377
acres	77,597	138,405	37,654	70,615	50,320	53,735
Harvested cropland ..... farms	178	739	63	323	208	213
acres	34,949	45,700	18,310	33,854	14,393	35,711
Part owners ..... farms	218	407	132	261	122	206
acres	273,752	174,075	234,047	156,947	65,306	202,248
Owned land in farms ..... acres	126,998	92,471	81,505	81,272	35,878	74,183
Rented land in farms ..... acres	146,754	81,604	152,542	75,675	29,428	128,065
Harvested cropland ..... farms	213	392	131	253	115	202
acres	245,512	122,194	202,603	126,703	48,995	189,302
Tenants ..... farms	56	52	36	30	10	39
acres	23,584	8,688	37,838	7,855	7,709	10,883
Harvested cropland ..... farms	54	48	35	28	10	38
acres	21,948	7,502	36,922	7,328	7,664	10,735
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	1,386	2,715	588	1,330	721	1,144
Farms by number of producers:						
1 producer	312	657	176	311	209	264
2 producers	249	694	144	343	202	266
3 producers	72	75	29	42	16	48
4 producers	46	79	8	30	15	30
5 or more producers	29	24	1	17	-	14
Total male producers ..... number	996	1,825	405	909	483	791
Farms by number of male producers:						
1 producer	465	1,248	252	568	361	461
2 producers	115	118	54	123	43	100
3 producers	63	58	15	25	-	26
4 producers	18	27	-	5	9	13
5 or more producers	8	11	-	-	-	-
Total female producers ..... number	390	890	183	421	238	353
Farms by number of female producers:						
1 producer	250	757	154	340	226	258
2 producers	43	56	7	27	6	36
3 producers	18	7	5	9	-	3
4 producers	-	-	-	-	-	2
5 or more producers	-	-	-	-	-	1
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	1,326	2,682	587	1,311	721	1,116
Sex of producers:						
Male	969	1,800	405	905	483	788
Female	357	882	182	406	238	328
Hired managers	95	68	85	100	19	73
Primary occupation:						
Farming	575	1,160	316	654	313	557
Other	751	1,522	271	657	408	559
Place of residence:						
On farm operated	672	2,019	328	1,031	597	765
Not on farm operated	654	663	259	280	124	351
Days worked off farm:						
None	571	1,024	301	607	304	482
Any	755	1,658	286	704	417	634
1 to 49 days	152	191	26	109	60	100
50 to 99 days	30	94	29	41	36	50
100 to 199 days	84	222	49	100	67	76
200 days or more	489	1,151	182	454	254	408
Years on present farm:						
2 years or less	112	148	22	62	24	26
3 or 4 years	49	139	20	74	37	48
5 to 9 years	182	441	53	150	123	172
10 years or more	983	1,954	492	1,025	537	870
Average years on present farm	24.8	23.1	27.9	26.0	25.4	27.0
Years operating any farm:						
5 years or less	181	342	45	140	70	96
6 to 10 years	113	357	69	142	112	133
11 years or more	1,032	1,983	473	1,029	539	887

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
FARMS						
Land in farms ..... farms	525	512	358	993	1,310	847
acres	50,806	263,479	401,044	295,658	224,831	383,404
Harvested cropland ..... farms	392	390	260	742	995	588
acres	33,731	241,723	358,050	198,115	171,228	316,017
OWNED AND RENTED LAND IN FARMS						
Owned land in farms ..... farms	457	453	324	936	1,260	771
acres	28,809	105,530	161,812	186,649	111,252	180,842
Rented or leased land in farms ..... farms	180	264	182	385	386	387
acres	21,997	157,949	239,232	109,009	113,579	202,562
TENURE						
Full owners ..... farms	345	248	176	608	924	460
acres	14,423	34,333	43,186	87,244	56,006	73,731
Harvested cropland ..... farms	235	131	80	368	628	207
acres	3,983	24,258	28,319	31,135	22,692	40,994
Part owners ..... farms	112	205	148	328	336	311
acres	31,698	217,372	322,293	198,116	157,573	286,146
Owned land in farms ..... acres	14,386	71,197	118,626	99,405	55,246	107,111
Rented land in farms ..... acres	17,312	146,175	203,667	98,711	102,327	179,035
Harvested cropland ..... farms	104	200	146	322	322	308
acres	26,243	206,020	294,546	158,981	138,264	253,390
Tenants ..... farms	68	59	34	57	50	76
acres	4,685	11,774	35,565	10,298	11,252	23,527
Harvested cropland ..... farms	53	59	34	52	45	73
acres	3,505	11,445	35,185	7,999	10,272	21,633
NUMBER OF TOTAL PRODUCERS						
Total producers ..... number	967	928	663	1,968	2,379	1,540
Farms by number of producers:						
1 producer	193	261	167	356	554	383
2 producers	262	176	119	477	621	356
3 producers	44	36	45	82	56	53
4 producers	18	22	17	52	43	30
5 or more producers	8	17	10	26	36	25
Total male producers ..... number	577	697	502	1,358	1,516	1,056
Farms by number of male producers:						
1 producer	414	350	229	690	1,032	645
2 producers	44	90	80	195	135	120
3 producers	21	23	23	45	42	25
4 producers	3	2	1	21	16	1
5 or more producers	-	13	8	4	3	16
Total female producers ..... number	390	231	161	610	863	484
Farms by number of female producers:						
1 producer	292	171	122	421	683	377
2 producers	38	27	16	65	28	27
3 producers	4	2	1	14	28	10
4 producers	1	-	1	2	5	1
5 or more producers	1	-	-	1	1	3
PRODUCER CHARACTERISTICS [1]						
Producers (see text)	953	877	648	1,868	2,280	1,474
Sex of producers:						
Male	574	648	491	1,304	1,475	1,015
Female	379	229	157	564	805	459
Hired managers	85	47	64	158	73	69
Primary occupation:						
Farming	405	487	351	923	802	686
Other	548	390	297	945	1,478	788
Place of residence:						
On farm operated	743	574	318	1,363	1,727	890
Not on farm operated	210	303	330	505	553	584
Days worked off farm:						
None	313	400	327	850	762	564
Any	640	477	321	1,018	1,518	910
1 to 49 days	70	93	75	162	147	188
50 to 99 days	77	22	40	68	145	57
100 to 199 days	86	90	28	131	130	101
200 days or more	407	272	178	657	1,096	564
Years on present farm:						
2 years or less	45	22	14	88	90	65
3 or 4 years	107	37	46	143	117	78
5 to 9 years	202	169	84	232	503	215
10 years or more	599	649	504	1,405	1,570	1,116
Average years on present farm	21.0	25.8	25.3	23.8	23.0	25.8
Years operating any farm:						
5 years or less	189	104	70	214	232	143
6 to 10 years	173	124	102	203	467	197
11 years or more	591	649	476	1,451	1,581	1,134

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Minnesota	Aitkin	Anoka	Becker	Beltrami
PRODUCER CHARACTERISTICS [1] - Con.					
Years operating any farm: - Con.					
Average years on any farm	26.1	24.7	20.9	25.6	25.7
Age group:					
Under 25 years	1,900	8	6	27	14
25 to 34 years	9,374	42	85	87	73
35 to 44 years	16,237	99	155	193	146
45 to 54 years	16,743	127	70	271	148
55 to 64 years	29,818	195	140	424	257
65 to 74 years	27,187	205	136	417	253
75 years and over	13,609	107	65	238	162
Average age	57.1	59.0	53.5	58.9	58.4
Young producers (see text)	11,274	50	91	114	87
Producers of Hispanic, Latino, or Spanish origin	754	3	2	21	9
Producers by race:					
American Indian or Alaska Native	244	3	2	25	7
Asian	306	2	11	-	-
Black or African American	61	2	6	2	1
Native Hawaiian or Other Pacific Islander	43	-	-	-	-
White	113,864	775	636	1,613	1,036
More than one race reported	350	1	2	17	9
Military service:					
Never served or only on active duty for training in Reserves or National Guard (see text)	105,603	683	573	1,473	948
Active duty now or in the past (see text)	9,265	100	84	184	105
Number of persons living in producers' households	228,210	1,366	1,227	3,314	1,912
On farm involvement in decisionmaking:					
Day-to-day decisions	98,292	680	598	1,420	937
Land use and/or crop decisions	83,860	626	517	1,116	826
Livestock decisions	49,585	478	317	724	651
Marketing decisions (see text)	68,020	455	415	803	630
Record keeping and/or financial management	84,043	549	449	1,078	777
Estate planning or succession planning	64,079	408	341	892	553
INTERNET ACCESS					
Farms with-					
Internet access	53,964	363	318	721	488
Dial-up	1,876	27	18	32	14
Broadband (DSL, cable, fiber optic) (see text)	33,399	161	197	509	416
Cellular data plan (see text)	32,121	195	197	426	325
Satellite	8,385	72	21	39	22
Don't know	2,877	24	14	35	12
Other	346	1	-	-	2
TYPE OF ORGANIZATION					
Operation more than 50 percent owned by one producer's household and/or extended family — farms	62,111	433	348	901	598
Operation more than 50 percent owned by one producer's household and/or extended family — acres	22,990,670	119,559	27,851	348,942	163,190
Limited Liability Company — farms	4,803	25	68	88	22
Limited Liability Company — acres	2,179,815	8,003	3,650	43,025	1,278
OPERATION'S LEGAL STATUS FOR TAX PURPOSES					
Family or individual — farms	55,532	403	290	815	570
Family or individual — acres	17,410,756	103,131	(D)	272,940	148,877
Partnership — farms	5,022	21	29	82	11
Partnership — acres	4,452,974	8,966	3,134	74,572	10,538
Corporation:					
Family held — farms	3,375	16	27	41	16
Family held — acres	3,085,380	7,336	4,704	(D)	11,998
Other than family held — farms	428	3	8	1	3
Other than family held — acres	159,481	400	2,004	(D)	349
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	1,174	6	1	13	8
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — acres	334,034	915	(D)	2,238	1,396

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Benton	Big Stone	Blue Earth	Brown	Carlton
PRODUCER CHARACTERISTICS [1] - Con.					
Years operating any farm: - Con.					
Average years on any farm	25.0	27.8	27.0	27.4	24.0
Age group:					
Under 25 years	20	22	35	26	14
25 to 34 years	85	54	154	123	22
35 to 44 years	170	89	231	252	146
45 to 54 years	232	91	271	237	122
55 to 64 years	343	157	429	499	249
65 to 74 years	212	166	485	381	182
75 years and over	85	73	206	175	81
Average age	55.0	56.8	57.3	56.9	57.3
Young producers (see text)	105	76	189	149	36
Producers of Hispanic, Latino, or Spanish origin	26	1	4	1	9
Producers by race:					
American Indian or Alaska Native	2	-	-	1	20
Asian	-	-	3	-	-
Black or African American	-	-	2	-	1
Native Hawaiian or Other Pacific Islander	3	-	-	1	-
White	1,141	652	1,804	1,690	793
More than one race reported	1	-	2	1	2
Military service:					
Never served or only on active duty for training in Reserves or National Guard (see text)	1,046	614	1,667	1,566	721
Active duty now or in the past (see text)	101	38	144	127	95
Number of persons living in producers' households	2,388	1,436	3,522	3,364	1,517
On farm involvement in decisionmaking:					
Day-to-day decisions	1,014	575	1,503	1,396	745
Land use and/or crop decisions	828	491	1,361	1,172	660
Livestock decisions	648	199	516	535	575
Marketing decisions (see text)	628	407	1,081	1,048	526
Record keeping and/or financial management	798	500	1,337	1,229	613
Estate planning or succession planning	568	353	1,020	874	479
INTERNET ACCESS					
Farms with-					
Internet access	578	337	881	792	387
Dial-up	19	4	44	34	22
Broadband (DSL, cable, fiber optic) (see text)	396	288	529	510	178
Cellular data plan (see text)	324	213	510	484	239
Satellite	65	24	172	81	89
Don't know	28	5	49	40	16
Other	4	-	7	4	1
TYPE OF ORGANIZATION					
Operation more than 50 percent owned by one producer's household and/or extended family — farms	665	357	976	890	450
acres	127,078	232,978	447,531	272,542	77,212
Limited Liability Company — farms	59	21	94	82	35
acres	23,177	27,726	38,715	13,658	3,895
OPERATION'S LEGAL STATUS FOR TAX PURPOSES					
Family or individual — farms	610	328	850	803	434
acres	94,223	208,033	318,413	224,793	(D)
Partnership — farms	45	29	91	93	8
acres	24,382	25,127	107,142	31,881	(D)
Corporation:					
Family held — farms	21	16	52	58	17
acres	(D)	16,343	(D)	43,790	(D)
Other than family held — farms	5	10	6	8	-
acres	(D)	13,125	(D)	666	-
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	6	9	20	11	4
acres	424	1,260	2,420	1,201	(D)

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Carver	Cass	Chippewa	Chisago	Clay	Clearwater
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	28.8	23.9	27.2	21.0	26.9	23.1
Age group:						
Under 25 years	12	12	23	21	16	13
25 to 34 years	76	45	102	111	122	51
35 to 44 years	111	100	120	180	176	124
45 to 54 years	162	119	116	213	156	107
55 to 64 years	285	234	228	340	331	183
65 to 74 years	280	231	291	248	237	158
75 years and over	148	92	96	140	120	60
Average age	58.9	58.6	57.0	56.1	55.7	55.6
Young producers (see text)	88	57	125	132	138	64
Producers of Hispanic, Latino, or Spanish origin	5	7	2	9	7	4
Producers by race:						
American Indian or Alaska Native	-	9	1	6	2	9
Asian	2	3	-	26	-	-
Black or African American	-	-	-	-	-	-
Native Hawaiian or Other Pacific Islander	-	2	-	1	-	2
White	1,067	819	973	1,219	1,149	675
More than one race reported	5	-	2	1	7	10
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,019	736	891	1,130	1,077	632
Active duty now or in the past (see text)	55	97	85	123	81	64
Number of persons living in producers' households	1,993	1,443	1,992	2,299	2,337	1,436
On farm involvement in decisionmaking:						
Day-to-day decisions	952	746	780	1,138	1,009	588
Land use and/or crop decisions	765	650	664	950	868	490
Livestock decisions	504	583	217	705	402	434
Marketing decisions (see text)	651	542	557	732	778	434
Record keeping and/or financial management	768	584	673	863	883	493
Estate planning or succession planning	607	495	491	629	652	380
INTERNET ACCESS						
Farms with-						
Internet access	501	404	473	662	541	314
Dial-up	15	16	16	51	19	13
Broadband (DSL, cable, fiber optic) (see text)	338	317	277	419	349	232
Cellular data plan (see text)	281	212	280	354	322	217
Satellite	70	17	99	62	100	11
Don't know	22	12	32	54	14	19
Other	1	-	10	-	3	-
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	572	485	520	715	621	395
Operation more than 50 percent owned by one producer's household and/or extended family — acres	145,255	133,478	340,171	77,186	453,167	149,811
Limited Liability Company — farms	65	34	29	90	52	19
Limited Liability Company — acres	20,290	7,829	7,835	10,131	68,569	15,308
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	511	454	410	671	527	381
Family or individual — acres	94,043	101,484	203,677	63,367	339,718	133,355
Partnership — farms	53	18	82	33	52	12
Partnership — acres	42,722	16,590	85,170	11,589	109,884	12,321
Corporation:						
Family held — farms	23	5	51	21	63	2
Family held — acres	15,922	1,724	74,099	(D)	(D)	(D)
Other than family held — farms	3	5	4	2	2	-
Other than family held — acres	1,074	7,400	188	(D)	(D)	-
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	16	6	16	13	11	9
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — acres	2,915	7,251	1,561	661	3,384	(D)

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Cook	Cottonwood	Crow Wing	Dakota	Dodge	Douglas
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	28.6	28.8	26.0	24.7	28.8	24.4
Age group:						
Under 25 years	-	41	24	13	19	46
25 to 34 years	3	124	31	135	75	137
35 to 44 years	9	149	82	282	135	217
45 to 54 years	5	176	101	214	199	264
55 to 64 years	12	333	173	401	241	433
65 to 74 years	7	307	214	383	277	452
75 years and over	11	162	80	142	147	206
Average age	59.2	56.9	58.6	56.0	57.7	57.4
Young producers (see text)	3	165	55	148	94	183
Producers of Hispanic, Latino, or Spanish origin	-	2	2	19	4	13
Producers by race:						
American Indian or Alaska Native	1	-	4	-	1	6
Asian	-	1	-	51	-	-
Black or African American	-	-	1	-	-	-
Native Hawaiian or Other Pacific Islander	-	-	-	-	-	-
White	46	1,290	698	1,511	1,084	1,748
More than one race reported	-	1	2	8	8	1
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	40	1,226	640	1,474	1,003	1,591
Active duty now or in the past (see text)	7	66	65	96	90	164
Number of persons living in producers' households	75	2,642	1,239	3,371	2,145	3,375
On farm involvement in decisionmaking:						
Day-to-day decisions	43	1,062	641	1,352	970	1,490
Land use and/or crop decisions	39	989	541	1,164	797	1,245
Livestock decisions	18	405	412	644	529	670
Marketing decisions (see text)	26	846	434	1,097	709	905
Record keeping and/or financial management	37	1,058	525	1,245	854	1,178
Estate planning or succession planning	32	768	396	812	676	856
INTERNET ACCESS						
Farms with-						
Internet access	22	638	306	727	538	737
Dial-up	2	17	7	45	11	36
Broadband (DSL, cable, fiber optic) (see text)	14	304	242	346	312	490
Cellular data plan (see text)	12	416	176	430	306	416
Satellite	-	172	19	163	130	61
Don't know	-	50	13	56	36	51
Other	-	1	-	9	2	3
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	25	711	416	765	592	938
acres	1,940	381,740	88,189	180,912	223,543	257,730
Limited Liability Company — farms	4	55	27	93	50	91
acres	210	53,133	2,630	35,421	32,679	46,993
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	25	610	378	617	542	846
acres	1,940	284,322	74,263	119,465	174,284	217,587
Partnership — farms	-	62	8	106	49	81
acres	-	71,622	6,964	54,726	90,598	26,872
Corporation:						
Family held — farms	-	41	33	84	13	39
acres	-	31,010	(D)	24,471	12,238	21,888
Other than family held — farms	-	5	1	21	4	6
acres	-	474	(D)	884	1,687	790
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	-	24	6	13	6	8
acres	-	5,066	547	8,971	1,633	959

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Faribault	Fillmore	Freeborn	Goodhue	Grant	Hennepin
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	28.0	26.1	29.6	26.9	26.6	20.4
Age group:						
Under 25 years	18	34	17	46	12	17
25 to 34 years	174	216	105	203	58	73
35 to 44 years	191	295	186	347	151	142
45 to 54 years	149	426	216	355	140	149
55 to 64 years	289	698	362	689	201	229
65 to 74 years	305	617	380	584	235	185
75 years and over	173	313	242	254	125	120
Average age	56.0	57.4	59.3	56.6	57.8	56.6
Young producers (see text)	192	250	122	249	70	90
Producers of Hispanic, Latino, or Spanish origin	5	10	2	15	2	-
Producers by race:						
American Indian or Alaska Native	-	1	1	4	-	-
Asian	-	4	-	4	2	18
Black or African American	-	-	-	-	-	-
Native Hawaiian or Other Pacific Islander	-	-	-	-	-	-
White	1,298	2,587	1,506	2,458	908	891
More than one race reported	1	7	1	12	12	6
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,219	2,447	1,409	2,254	852	834
Active duty now or in the past (see text)	80	152	99	224	70	81
Number of persons living in producers' households	2,496	5,025	2,825	4,797	2,004	1,817
On farm involvement in decisionmaking:						
Day-to-day decisions	1,079	2,264	1,242	2,146	706	790
Land use and/or crop decisions	980	1,955	1,108	1,878	617	669
Livestock decisions	381	1,310	485	1,379	178	441
Marketing decisions (see text)	922	1,593	897	1,621	465	518
Record keeping and/or financial management	1,051	1,992	1,140	1,894	665	613
Estate planning or succession planning	830	1,449	927	1,520	548	459
INTERNET ACCESS						
Farms with-						
Internet access	695	1,163	782	1,234	434	429
Dial-up	20	39	18	73	13	7
Broadband (DSL, cable, fiber optic) (see text)	551	751	499	712	353	259
Cellular data plan (see text)	455	685	459	745	291	255
Satellite	76	234	95	244	36	59
Don't know	19	30	47	46	27	13
Other	2	4	9	4	-	-
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	737	1,381	866	1,340	491	493
acres	358,211	443,250	314,519	359,189	321,312	30,916
Limited Liability Company — farms	22	125	54	105	47	98
acres	24,718	69,897	35,547	27,376	38,954	5,112
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	668	1,224	796	1,216	452	428
acres	308,088	329,612	266,735	264,092	266,633	22,645
Partnership — farms	39	164	59	114	39	35
acres	48,247	115,669	61,378	111,658	44,564	6,504
Corporation:						
Family held — farms	46	34	37	53	15	32
acres	24,749	18,669	(D)	(D)	24,397	1,722
Other than family held — farms	9	13	2	2	9	8
acres	641	2,190	(D)	(D)	1,870	175
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	11	23	14	21	14	8
acres	1,506	4,172	2,057	6,306	1,290	1,360

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Houston	Hubbard	Isanti	Itasca	Jackson	Kanabec
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	27.0	23.3	20.6	23.9	29.1	23.1
Age group:						
Under 25 years	24	36	24	8	23	25
25 to 34 years	84	40	99	67	126	60
35 to 44 years	192	64	219	101	113	173
45 to 54 years	213	91	212	120	227	125
55 to 64 years	392	154	412	165	381	252
65 to 74 years	406	150	276	198	414	209
75 years and over	170	65	151	73	184	90
Average age	58.6	56.0	56.5	57.1	59.0	55.9
Young producers (see text)	108	76	123	75	149	85
Producers of Hispanic, Latino, or Spanish origin	5	3	2	8	9	6
Producers by race:						
American Indian or Alaska Native	-	3	6	13	-	1
Asian	4	-	-	1	-	4
Black or African American	1	-	5	-	-	-
Native Hawaiian or Other Pacific Islander	-	-	1	-	-	5
White	1,472	596	1,380	715	1,464	910
More than one race reported	4	1	1	3	4	14
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,367	528	1,245	663	1,354	811
Active duty now or in the past (see text)	114	72	148	69	114	123
Number of persons living in producers' households	2,918	988	2,464	1,299	2,756	1,714
On farm involvement in decisionmaking:						
Day-to-day decisions	1,301	484	1,284	669	1,230	820
Land use and/or crop decisions	1,092	430	1,045	591	1,125	662
Livestock decisions	774	376	822	476	443	567
Marketing decisions (see text)	805	289	867	482	985	568
Record keeping and/or financial management	1,074	390	970	558	1,136	621
Estate planning or succession planning	868	303	718	438	924	471
INTERNET ACCESS						
Farms with-						
Internet access	636	286	662	347	745	377
Dial-up	21	3	40	3	14	13
Broadband (DSL, cable, fiber optic) (see text)	436	222	380	279	453	183
Cellular data plan (see text)	349	157	426	207	475	249
Satellite	71	7	119	25	177	64
Don't know	48	16	14	10	39	18
Other	7	-	10	-	2	-
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	756	329	798	415	788	524
Operation more than 50 percent owned by one producer's household and/or extended family — acres	208,164	97,383	99,502	85,514	365,526	97,903
Limited Liability Company — farms	62	14	95	29	58	23
Limited Liability Company — acres	23,504	3,127	12,460	6,898	27,350	7,776
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	646	291	752	387	696	500
Family or individual — acres	160,094	66,268	77,779	(D)	282,854	78,218
Partnership — farms	81	16	36	14	63	11
Partnership — acres	36,032	3,237	16,939	10,547	33,597	8,998
Corporation:						
Family held — farms	50	20	15	17	51	13
Family held — acres	23,651	25,980	6,269	5,835	53,203	10,078
Other than family held — farms	-	-	7	-	7	3
Other than family held — acres	-	-	152	-	110	550
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	20	9	4	6	28	4
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — acres	3,244	2,659	527	(D)	14,573	1,338

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Kandiyohi	Kittson	Koochiching	Lac qui Parle	Lake	Lake of the Woods
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	25.0	25.3	26.5	29.3	20.4	23.9
Age group:						
Under 25 years	37	18	1	9	2	3
25 to 34 years	137	115	3	122	9	17
35 to 44 years	354	146	24	125	7	63
45 to 54 years	297	213	72	190	8	24
55 to 64 years	614	247	86	235	16	66
65 to 74 years	580	273	82	308	18	87
75 years and over	284	134	51	211	5	43
Average age	57.7	56.6	61.1	58.5	55.3	58.3
Young producers (see text)	174	133	4	131	11	20
Producers of Hispanic, Latino, or Spanish origin	8	7	1	9	-	3
Producers by race:						
American Indian or Alaska Native	3	-	8	6	1	2
Asian	2	-	3	-	-	-
Black or African American	-	-	-	-	-	-
Native Hawaiian or Other Pacific Islander	-	-	-	-	-	-
White	2,282	1,146	307	1,193	64	296
More than one race reported	16	-	1	1	-	5
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	2,140	1,032	280	1,093	63	291
Active duty now or in the past (see text)	163	114	39	107	2	12
Number of persons living in producers' households	4,691	2,638	525	2,693	97	609
On farm involvement in decisionmaking:						
Day-to-day decisions	1,868	943	288	972	55	273
Land use and/or crop decisions	1,592	823	247	914	52	239
Livestock decisions	828	244	165	262	36	125
Marketing decisions (see text)	1,137	587	178	708	32	184
Record keeping and/or financial management	1,528	824	220	905	53	230
Estate planning or succession planning	1,206	619	149	648	31	184
INTERNET ACCESS						
Farms with-						
Internet access	1,019	495	142	603	29	155
Dial-up	40	17	7	23	1	5
Broadband (DSL, cable, fiber optic) (see text)	553	372	79	490	24	95
Cellular data plan (see text)	570	338	85	366	10	88
Satellite	186	58	31	40	1	9
Don't know	67	26	4	22	-	13
Other	13	1	-	-	-	-
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family, farms	1,150	574	187	695	30	182
acres	438,994	543,568	59,990	377,809	1,408	101,130
Limited Liability Company, farms	101	28	7	29	2	4
acres	43,823	37,979	1,738	15,428	(D)	8,986
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual, farms	984	479	170	633	30	168
acres	251,193	360,630	(D)	330,901	1,408	(D)
Partnership, farms	141	70	5	52	-	4
acres	128,550	153,852	4,500	42,846	-	16,930
Corporation:						
Family held, farms	70	59	13	28	1	9
acres	89,208	(D)	10,565	31,808	(D)	25,814
Other than family held, farms	17	2	-	-	-	3
acres	19,844	(D)	-	-	-	1,215
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc., farms	40	3	2	22	3	2
acres	5,652	440	(D)	5,404	(D)	(D)

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Le Sueur	Lincoln	Lyon	McLeod	Mahnomen	Marshall
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	26.2	27.8	27.2	27.8	25.2	25.9
Age group:						
Under 25 years	10	5	29	43	-	13
25 to 34 years	91	92	141	129	35	190
35 to 44 years	179	105	273	143	74	269
45 to 54 years	241	142	235	213	97	289
55 to 64 years	461	304	339	363	108	458
65 to 74 years	351	248	324	335	85	464
75 years and over	241	168	194	192	49	209
Average age	59.3	59.5	55.7	57.6	55.9	56.6
Young producers (see text)	101	97	170	172	35	203
Producers of Hispanic, Latino, or Spanish origin	8	5	9	4	2	26
Producers by race:						
American Indian or Alaska Native	-	-	-	-	18	1
Asian	1	-	-	2	-	1
Black or African American	-	-	-	3	-	3
Native Hawaiian or Other Pacific Islander	-	-	-	1	-	-
White	1,571	1,064	1,534	1,411	421	1,883
More than one race reported	2	-	1	1	9	4
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,424	960	1,427	1,337	415	1,731
Active duty now or in the past (see text)	150	104	108	81	33	161
Number of persons living in producers' households	3,084	2,111	3,514	2,832	1,023	4,039
On farm involvement in decisionmaking:						
Day-to-day decisions	1,319	853	1,258	1,206	387	1,651
Land use and/or crop decisions	1,028	714	1,081	1,007	324	1,405
Livestock decisions	594	366	602	578	152	517
Marketing decisions (see text)	745	552	939	816	259	1,106
Record keeping and/or financial management	1,092	726	1,143	961	337	1,388
Estate planning or succession planning	873	541	905	779	275	988
INTERNET ACCESS						
Farms with-						
Internet access	721	470	782	637	215	824
Dial-up	25	15	8	38	6	23
Broadband (DSL, cable, fiber optic) (see text)	389	342	381	322	156	573
Cellular data plan (see text)	385	264	455	348	151	489
Satellite	135	31	214	104	10	103
Don't know	56	22	39	45	8	26
Other	5	5	7	4	-	7
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	825	540	826	759	257	969
Operation more than 50 percent owned by one producer's household and/or extended family — acres	189,116	199,931	382,994	227,061	196,815	802,502
Limited Liability Company — farms	70	26	35	50	13	30
Limited Liability Company — acres	31,721	19,381	24,796	29,270	2,999	11,576
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	754	475	726	702	234	859
Family or individual — acres	136,100	172,812	274,167	166,973	169,002	620,808
Partnership — farms	81	53	60	31	13	142
Partnership — acres	46,172	20,140	66,500	24,086	24,688	194,125
Corporation:						
Family held — farms	37	36	67	49	16	58
Family held — acres	21,666	14,029	(D)	(D)	22,486	91,230
Other than family held — farms	6	9	2	4	-	3
Other than family held — acres	165	757	(D)	(D)	-	760
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	18	25	14	15	5	10
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — acres	1,671	4,682	1,960	978	1,706	5,205

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Martin	Meeker	Mille Lacs	Morrison	Mower	Murray
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	27.3	25.4	22.7	26.5	27.6	27.5
Age group:						
Under 25 years	15	31	15	56	30	36
25 to 34 years	128	146	89	240	120	114
35 to 44 years	197	267	182	377	269	171
45 to 54 years	232	226	160	470	268	170
55 to 64 years	366	394	272	650	439	263
65 to 74 years	359	402	242	615	417	385
75 years and over	131	209	95	235	236	150
Average age	56.2	56.9	55.8	55.8	57.6	57.3
Young producers (see text)	143	177	104	296	150	150
Producers of Hispanic, Latino, or Spanish origin	17	7	7	13	12	2
Producers by race:						
American Indian or Alaska Native	4	1	4	2	1	1
Asian	-	2	-	1	3	2
Black or African American	-	-	-	-	3	-
Native Hawaiian or Other Pacific Islander	-	8	-	-	2	3
White	1,419	1,663	1,049	2,631	1,769	1,283
More than one race reported	5	1	2	9	1	-
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,327	1,562	949	2,355	1,609	1,174
Active duty now or in the past (see text)	101	113	106	288	170	115
Number of persons living in producers' households	3,023	3,291	1,967	5,040	3,477	2,545
On farm involvement in decisionmaking:						
Day-to-day decisions	1,204	1,451	935	2,344	1,586	1,084
Land use and/or crop decisions	1,033	1,167	801	1,944	1,293	896
Livestock decisions	458	675	627	1,601	758	465
Marketing decisions (see text)	933	890	659	1,581	1,113	781
Record keeping and/or financial management	1,041	1,172	752	1,920	1,339	969
Estate planning or succession planning	781	913	543	1,363	1,056	704
INTERNET ACCESS						
Farms with-						
Internet access	716	811	485	1,265	859	664
Dial-up	28	12	34	30	17	14
Broadband (DSL, cable, fiber optic) (see text)	394	524	300	740	509	322
Cellular data plan (see text)	463	420	299	760	472	439
Satellite	166	130	53	159	202	192
Don't know	40	31	22	87	34	56
Other	9	10	3	4	3	6
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	757	952	592	1,515	942	738
Operation more than 50 percent owned by one producer's household and/or extended family — acres	390,454	283,109	93,422	337,679	317,549	319,524
Limited Liability Company — farms	47	53	72	102	60	49
Limited Liability Company — acres	9,294	23,210	17,099	38,471	22,850	12,715
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	662	845	555	1,417	854	671
Family or individual — acres	298,507	187,074	80,933	284,203	259,042	261,607
Partnership — farms	71	61	25	91	85	60
Partnership — acres	69,352	65,769	7,641	48,034	67,767	39,653
Corporation:						
Family held — farms	71	59	14	43	37	34
Family held — acres	78,946	(D)	6,969	21,129	47,000	36,310
Other than family held — farms	13	3	-	7	7	3
Other than family held — acres	6,957	(D)	-	4,669	3,877	3,368
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	6	23	9	13	16	21
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — acres	263	3,358	1,141	3,754	2,384	10,538

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Nicollet	Nobles	Norman	Olmsted	Otter Tail	Pennington
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	29.0	26.0	28.2	26.1	25.8	26.4
Age group:						
Under 25 years	4	58	19	17	63	6
25 to 34 years	93	246	74	139	332	14
35 to 44 years	199	215	92	240	554	99
45 to 54 years	161	243	128	362	536	77
55 to 64 years	319	385	182	502	1,176	142
65 to 74 years	265	400	156	465	1,070	152
75 years and over	122	183	80	265	568	49
Average age	56.8	54.8	56.2	58.1	58.4	57.7
Young producers (see text)	97	304	93	156	395	20
Producers of Hispanic, Latino, or Spanish origin	2	9	1	12	20	2
Producers by race:						
American Indian or Alaska Native	2	-	1	6	4	-
Asian	6	-	6	5	14	3
Black or African American	-	-	-	-	-	-
Native Hawaiian or Other Pacific Islander	6	-	-	-	1	-
White	1,143	1,729	721	1,964	4,266	532
More than one race reported	6	1	3	15	14	4
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,077	1,636	687	1,835	3,881	481
Active duty now or in the past (see text)	86	94	44	155	418	58
Number of persons living in producers' households	2,358	3,527	1,575	3,776	8,358	1,030
On farm involvement in decisionmaking:						
Day-to-day decisions	1,044	1,423	600	1,693	3,600	474
Land use and/or crop decisions	867	1,186	541	1,432	3,192	396
Livestock decisions	484	615	184	886	1,774	191
Marketing decisions (see text)	768	1,055	464	1,183	2,186	287
Record keeping and/or financial management	866	1,269	538	1,470	3,046	406
Estate planning or succession planning	724	948	411	1,119	2,336	306
INTERNET ACCESS						
Farms with-						
Internet access	557	797	378	932	1,917	268
Dial-up	12	18	15	50	68	2
Broadband (DSL, cable, fiber optic) (see text)	311	443	270	528	1,263	201
Cellular data plan (see text)	339	533	256	506	1,118	121
Satellite	137	162	22	214	161	13
Don't know	35	45	35	39	131	30
Other	10	6	1	6	10	-
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family, farms	603	889	404	1,051	2,403	308
acres	258,042	344,682	432,864	266,817	718,212	248,000
Limited Liability Company, farms	40	64	26	87	119	13
acres	30,113	40,058	50,706	27,072	53,204	4,064
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual, farms	513	774	364	942	2,197	287
acres	163,065	273,491	335,577	190,237	579,968	208,808
Partnership, farms	55	87	42	105	153	22
acres	34,678	56,998	102,983	72,916	112,484	31,111
Corporation:						
Family held, farms	75	47	25	38	77	10
acres	79,665	30,987	52,936	(D)	58,706	18,808
Other than family held, farms	9	14	-	2	9	-
acres	228	410	-	(D)	2,522	-
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc., farms	8	16	4	15	61	3
acres	1,234	4,444	198	1,465	17,242	229

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Pine	Pipestone	Polk	Pope	Ramsey	Red Lake
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	25.3	28.2	26.8	25.8	16.5	27.6
Age group:						
Under 25 years	16	22	51	6	-	-
25 to 34 years	58	62	227	120	6	49
35 to 44 years	168	125	389	199	20	97
45 to 54 years	176	127	302	202	18	47
55 to 64 years	344	254	596	339	8	125
65 to 74 years	329	182	482	406	23	81
75 years and over	159	105	248	168	4	48
Average age	59.0	56.9	55.3	58.1	53.6	55.1
Young producers (see text)	74	84	278	126	6	49
Producers of Hispanic, Latino, or Spanish origin	17	8	18	6	1	2
Producers by race:						
American Indian or Alaska Native	2	-	1	5	-	-
Asian	7	-	4	1	2	-
Black or African American	-	-	-	-	-	-
Native Hawaiian or Other Pacific Islander	-	-	-	-	-	-
White	1,235	876	2,278	1,434	74	447
More than one race reported	6	1	12	-	3	-
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,112	823	2,122	1,326	77	419
Active duty now or in the past (see text)	138	54	173	114	2	28
Number of persons living in producers' households	2,167	1,655	4,773	2,953	153	1,027
On farm involvement in decisionmaking:						
Day-to-day decisions	1,125	742	1,928	1,183	70	378
Land use and/or crop decisions	950	627	1,730	963	68	335
Livestock decisions	789	440	650	555	18	165
Marketing decisions (see text)	779	565	1,361	710	61	301
Record keeping and/or financial management	896	664	1,722	1,039	62	354
Estate planning or succession planning	732	487	1,284	781	27	268
INTERNET ACCESS						
Farms with-						
Internet access	580	451	1,026	649	43	246
Dial-up	30	6	8	5	1	2
Broadband (DSL, cable, fiber optic) (see text)	244	254	777	433	35	199
Cellular data plan (see text)	339	295	717	345	27	150
Satellite	134	114	101	82	-	7
Don't know	21	13	54	48	-	6
Other	4	13	4	2	-	2
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	712	517	1,160	767	34	261
acres	150,570	216,133	973,461	271,079	312	190,766
Limited Liability Company — farms	34	35	82	73	4	31
acres	15,373	21,032	108,179	45,404	(D)	25,951
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	678	457	950	683	12	232
acres	134,793	170,587	604,608	199,649	(D)	(D)
Partnership — farms	18	35	141	67	1	29
acres	11,506	23,457	250,205	57,974	(D)	20,678
Corporation:						
Family held — farms	26	21	115	42	15	10
acres	15,016	30,007	(D)	41,533	180	(D)
Other than family held — farms	3	3	3	5	6	2
acres	(D)	123	(D)	3,553	21	(D)
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	3	13	14	24	13	1
acres	(D)	3,802	4,879	7,332	553	(D)

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Redwood	Renville	Rice	Rock	Roseau	St. Louis
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	25.2	27.0	25.4	27.9	26.7	22.8
Age group:						
Under 25 years	57	9	60	9	18	28
25 to 34 years	264	126	180	109	92	84
35 to 44 years	354	257	258	161	153	214
45 to 54 years	332	241	242	160	202	195
55 to 64 years	601	473	590	272	333	399
65 to 74 years	502	325	409	203	303	322
75 years and over	249	160	244	78	146	169
Average age	55.1	56.4	56.4	54.7	57.3	57.3
Young producers (see text)	321	135	240	118	110	112
Producers of Hispanic, Latino, or Spanish origin	5	2	28	6	11	9
Producers by race:						
American Indian or Alaska Native	2	-	-	-	1	11
Asian	5	-	4	-	-	7
Black or African American	-	-	14	-	-	3
Native Hawaiian or Other Pacific Islander	-	-	-	3	-	-
White	2,350	1,586	1,961	987	1,236	1,386
More than one race reported	2	5	4	2	10	4
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	2,212	1,501	1,817	931	1,150	1,255
Active duty now or in the past (see text)	147	90	166	61	97	156
Number of persons living in producers' households	5,205	3,436	3,765	2,123	2,520	2,459
On farm involvement in decisionmaking:						
Day-to-day decisions	1,919	1,315	1,709	826	1,076	1,321
Land use and/or crop decisions	1,613	1,149	1,498	654	872	1,140
Livestock decisions	746	472	879	490	474	944
Marketing decisions (see text)	1,457	1,029	1,181	653	672	865
Record keeping and/or financial management	1,769	1,197	1,441	774	934	1,069
Estate planning or succession planning	1,289	935	1,195	607	647	764
INTERNET ACCESS						
Farms with-						
Internet access	1,104	785	903	534	638	660
Dial-up	34	16	24	6	28	41
Broadband (DSL, cable, fiber optic) (see text)	682	461	536	446	487	309
Cellular data plan (see text)	634	456	524	322	391	408
Satellite	148	224	142	39	25	137
Don't know	78	29	41	13	39	14
Other	8	7	7	2	2	-
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family - farms	1,222	862	1,056	532	709	792
Operation more than 50 percent owned by one producer's household and/or extended family - acres	505,135	578,136	191,302	232,703	478,793	145,023
Limited Liability Company - farms	97	59	111	32	23	68
Limited Liability Company - acres	41,751	15,709	40,973	10,327	21,179	11,384
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual - farms	1,022	725	938	486	638	737
Family or individual - acres	341,571	359,514	148,032	186,495	343,255	127,471
Partnership - farms	132	89	95	35	53	22
Partnership - acres	111,375	124,585	75,851	35,550	102,737	11,663
Corporation:						
Family held - farms	137	98	53	38	47	40
Family held - acres	97,617	136,120	21,627	(D)	85,218	9,645
Other than family held - farms	5	7	16	2	4	9
Other than family held - acres	2,042	3,390	2,639	(D)	2,186	1,552
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. - farms	27	12	9	12	9	13
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. - acres	7,617	2,456	1,732	4,007	3,945	11,730

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Scott	Sherburne	Sibley	Stearns	Steele	Stevens
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	23.6	21.7	28.2	26.3	27.2	27.2
Age group:						
Under 25 years	12	13	23	60	13	20
25 to 34 years	81	90	114	389	108	98
35 to 44 years	105	168	213	675	210	170
45 to 54 years	177	130	172	768	140	107
55 to 64 years	356	217	404	1,384	300	185
65 to 74 years	241	162	416	960	290	241
75 years and over	125	111	147	496	184	141
Average age	58.0	55.2	57.4	56.3	57.6	56.6
Young producers (see text)	93	103	137	449	121	118
Producers of Hispanic, Latino, or Spanish origin	14	11	7	33	3	19
Producers by race:						
American Indian or Alaska Native	3	1	-	2	2	-
Asian	1	-	2	5	2	2
Black or African American	-	-	-	3	-	-
Native Hawaiian or Other Pacific Islander	-	-	-	-	-	-
White	1,092	890	1,487	4,713	1,238	959
More than one race reported	1	-	-	9	3	1
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,029	802	1,411	4,417	1,143	868
Active duty now or in the past (see text)	68	89	78	315	102	94
Number of persons living in producers' households	2,022	1,735	2,842	9,567	2,439	2,090
On farm involvement in decisionmaking:						
Day-to-day decisions	974	816	1,289	4,119	1,040	814
Land use and/or crop decisions	798	706	1,109	3,480	847	661
Livestock decisions	557	519	613	2,681	452	365
Marketing decisions (see text)	614	528	915	2,924	656	552
Record keeping and/or financial management	771	642	1,134	3,589	902	678
Estate planning or succession planning	644	470	877	2,748	707	573
INTERNET ACCESS						
Farms with-						
Internet access	559	393	722	2,166	578	426
Dial-up	17	27	28	84	2	7
Broadband (DSL, cable, fiber optic) (see text)	405	247	392	1,270	265	346
Cellular data plan (see text)	323	253	394	1,276	311	244
Satellite	50	42	146	290	177	22
Don't know	21	25	60	135	42	36
Other	3	1	3	20	14	-
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	593	475	811	2,573	691	453
Operation more than 50 percent owned by one producer's household and/or extended family — acres	88,523	76,025	350,377	585,566	219,685	273,880
Limited Liability Company — farms	83	58	67	213	40	49
Limited Liability Company — acres	27,268	6,852	47,318	91,302	43,894	45,658
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	525	408	717	2,327	617	383
Family or individual — acres	54,287	42,767	268,341	440,957	185,619	197,868
Partnership — farms	31	37	64	205	57	57
Partnership — acres	34,091	16,392	51,707	113,899	52,464	61,810
Corporation:						
Family held — farms	37	31	59	113	27	41
Family held — acres	(D)	20,207	50,479	77,878	4,518	66,355
Other than family held — farms	2	4	-	13	10	5
Other than family held — acres	(D)	3,460	-	2,494	2,627	400
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	29	14	20	37	10	14
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — acres	5,403	2,218	3,101	8,235	606	4,503

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Swift	Todd	Traverse	Wabasha	Wadena	Waseca
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	26.9	24.9	29.5	28.2	28.0	29.1
Age group:						
Under 25 years	39	57	4	41	13	14
25 to 34 years	64	293	34	81	40	62
35 to 44 years	229	370	83	183	108	160
45 to 54 years	150	399	70	138	116	165
55 to 64 years	315	648	164	403	175	326
65 to 74 years	352	666	138	334	147	243
75 years and over	177	249	94	131	122	146
Average age	58.2	55.6	59.4	57.3	58.4	58.3
Young producers (see text)	103	350	38	122	53	76
Producers of Hispanic, Latino, or Spanish origin	5	56	10	17	7	4
Producers by race:						
American Indian or Alaska Native	-	6	4	-	-	-
Asian	1	1	-	-	-	4
Black or African American	1	6	-	-	4	-
Native Hawaiian or Other Pacific Islander	-	-	-	-	-	1
White	1,323	2,667	582	1,310	713	1,107
More than one race reported	1	2	1	1	4	4
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	1,227	2,507	535	1,220	658	1,043
Active duty now or in the past (see text)	99	175	52	91	63	73
Number of persons living in producers' households	2,806	5,585	1,130	2,581	1,374	2,182
On farm involvement in decisionmaking:						
Day-to-day decisions	1,019	2,366	481	1,128	630	947
Land use and/or crop decisions	912	2,054	416	999	519	809
Livestock decisions	352	1,443	142	693	416	338
Marketing decisions (see text)	676	1,604	344	874	395	674
Record keeping and/or financial management	990	1,901	445	973	490	826
Estate planning or succession planning	694	1,463	365	814	329	681
INTERNET ACCESS						
Farms with-						
Internet access	568	1,108	278	627	322	508
Dial-up	8	48	3	18	7	17
Broadband (DSL, cable, fiber optic) (see text)	432	564	150	295	262	259
Cellular data plan (see text)	322	641	144	404	206	291
Satellite	29	183	81	151	3	132
Don't know	37	56	19	30	6	29
Other	5	5	-	2	-	11
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family — farms	636	1,476	330	713	427	584
acres	313,976	299,006	285,275	221,635	118,435	244,707
Limited Liability Company — farms	43	76	8	58	14	43
acres	20,052	24,129	18,319	28,117	5,329	31,650
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual — farms	549	1,397	268	645	399	517
acres	225,494	250,823	192,040	181,164	91,722	185,888
Partnership — farms	85	70	33	54	21	56
acres	73,700	39,592	49,001	28,301	16,324	62,322
Corporation:						
Family held — farms	54	36	33	29	12	21
acres	(D)	20,210	53,258	23,330	5,535	11,359
Other than family held — farms	2	12	5	-	3	10
acres	(D)	7,025	8,714	-	2,040	1,871
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. — farms	18	14	19	15	7	18
acres	4,294	3,518	6,526	2,622	7,714	5,426

See footnote(s) at end of table.

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Table 45. **Selected Operation and Producer Characteristics: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item	Washington	Watonwan	Wilkin	Winona	Wright	Yellow Medicine
PRODUCER CHARACTERISTICS [1] - Con.						
Years operating any farm: - Con.						
Average years on any farm	21.9	27.4	26.6	26.1	24.7	27.9
Age group:						
Under 25 years	11	12	6	35	20	15
25 to 34 years	66	92	62	142	178	145
35 to 44 years	120	133	127	289	323	212
45 to 54 years	118	106	87	243	348	187
55 to 64 years	259	236	164	464	644	342
65 to 74 years	261	214	117	465	469	340
75 years and over	118	84	85	230	298	233
Average age	58.5	55.7	55.4	57.3	57.2	57.6
Young producers (see text)	77	104	68	177	198	160
Producers of Hispanic, Latino, or Spanish origin	5	9	1	6	14	17
Producers by race:						
American Indian or Alaska Native	7	-	-	2	1	1
Asian	45	4	2	11	6	3
Black or African American	-	-	-	-	-	-
Native Hawaiian or Other Pacific Islander	1	-	-	2	-	-
White	896	873	645	1,848	2,264	1,462
More than one race reported	4	-	1	5	9	8
Military service:						
Never served or only on active duty for training in Reserves or National Guard (see text)	883	834	625	1,721	2,107	1,329
Active duty now or in the past (see text)	70	43	23	147	173	145
Number of persons living in producers' households	1,785	1,981	1,390	3,838	4,259	3,049
On farm involvement in decisionmaking:						
Day-to-day decisions	825	743	542	1,603	2,004	1,195
Land use and/or crop decisions	687	602	477	1,365	1,744	991
Livestock decisions	424	221	137	977	1,192	456
Marketing decisions (see text)	567	475	405	1,116	1,369	839
Record keeping and/or financial management	653	636	515	1,432	1,692	1,063
Estate planning or succession planning	478	472	376	983	1,345	905
INTERNET ACCESS						
Farms with-						
Internet access	454	443	311	815	1,094	714
Dial-up	8	8	23	35	87	14
Broadband (DSL, cable, fiber optic) (see text)	307	240	167	417	588	447
Cellular data plan (see text)	288	258	184	490	677	444
Satellite	60	102	46	190	143	156
Don't know	16	32	28	40	56	31
Other	-	1	2	12	9	11
TYPE OF ORGANIZATION						
Operation more than 50 percent owned by one producer's household and/or extended family - farms	494	483	325	914	1,271	799
Operation more than 50 percent owned by one producer's household and/or extended family - acres	44,528	234,233	303,996	265,245	217,841	351,258
Limited Liability Company - farms	113	30	24	124	120	29
Limited Liability Company - acres	6,193	14,207	19,225	51,666	28,731	9,117
OPERATION'S LEGAL STATUS FOR TAX PURPOSES						
Family or individual - farms	412	456	286	762	1,131	749
Family or individual - acres	36,777	210,284	(D)	160,844	178,534	311,268
Partnership - farms	42	25	43	159	71	50
Partnership - acres	3,604	37,925	96,488	80,483	18,594	44,603
Corporation:						
Family held - farms	55	17	27	47	68	31
Family held - acres	(D)	14,132	(D)	49,175	23,140	23,141
Other than family held - farms	3	7	1	4	12	-
Other than family held - acres	(D)	431	(D)	961	1,852	-
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. - farms	13	7	1	21	28	17
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc. - acres	1,026	707	(D)	4,195	2,711	4,392

[1] Data were collected for a maximum of four producers per farm.

Table 46. **Male Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Male producers	Land in farms (acres)
State Total			
Minnesota	62,332	79,245	25,033,191
Counties			
Aitkin	421	500	118,248
Anoka	321	403	28,616
Becker	898	1,132	369,301
Beltrami	577	659	168,879
Benton	644	737	130,180
Big Stone	373	472	262,508
Blue Earth	976	1,322	474,638
Brown	934	1,232	297,973
Carlton	433	484	121,727
Carver	571	706	152,829
Cass	464	526	131,643
Chippewa	536	722	361,567
Chisago	680	780	78,296
Clay	624	842	546,987
Clearwater	395	445	159,033
Cook	22	30	1,620
Cottonwood	710	949	387,775
Crow Wing	400	443	89,863
Dakota	799	1,069	204,331
Dodge	584	737	279,204
Douglas	941	1,233	264,310
Faribault	745	936	380,618
Fillmore	1,398	1,788	465,426
Freeborn	869	1,044	346,650
Goodhue	1,352	1,681	416,519
Grant	491	647	332,261
Hennepin	453	562	28,264
Houston	742	989	214,731
Hubbard	314	374	95,830
Isanti	767	862	99,674
Itasca	401	448	93,492
Jackson	810	1,101	377,550
Kanabec	504	585	97,373
Kandiyohi	1,169	1,625	486,802
Kittson	576	859	585,636
Koochiching	182	214	59,466
Lac qui Parle	701	918	403,757
Lake	32	35	1,410
Lake of the Woods	180	223	108,111
Le Sueur	846	1,066	202,274
Lincoln	563	732	205,216
Lyon	840	1,140	421,496
McLeod	767	1,015	244,661
Mahnomen	263	334	216,816
Marshall	1,026	1,493	902,530
Martin	801	1,070	451,643
Meeker	938	1,127	304,619
Mille Lacs	578	679	95,243
Morrison	1,510	1,782	353,048
Mower	963	1,233	370,719
Murray	751	912	348,013
Nicollet	634	851	276,483
Nobles	898	1,245	359,587
Norman	420	558	486,527
Olmsted	1,064	1,319	302,184
Otter Tail	2,395	2,951	758,383
Pennington	306	363	255,297
Pine	659	772	158,944
Pipestone	514	605	226,148
Polk	1,187	1,707	1,077,139
Pope	787	1,016	304,641
Ramsey	34	37	560
Red Lake	263	343	191,142
Redwood	1,281	1,789	555,241
Renville	885	1,147	611,465
Rice	1,063	1,331	245,593
Rock	548	686	259,250
Roseau	718	896	527,631
St. Louis	739	844	144,490
Scott	574	678	97,428
Sherburne	467	565	82,901
Sibley	830	1,014	370,832
Stearns	2,592	3,211	633,806
Steele	695	857	244,126
Stevens	467	706	328,230
Swift	669	969	371,329
Todd	1,462	1,800	312,225
Traverse	321	405	307,083
Wabasha	721	905	231,061
Wadena	413	483	117,929
Waseca	600	788	264,909
Washington	482	574	48,840
Watonwan	478	648	257,677
Wilkin	341	491	399,346
Winona	955	1,304	286,590
Wright	1,228	1,475	221,360
Yellow Medicine	807	1,015	377,438

Table 47. **Female Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Female producers	Land in farms (acres)
State Total			
Minnesota	32,729	35,623	9,634,361
Counties			
Aitkin	264	283	54,619
Anoka	224	254	12,219
Becker	487	525	127,734
Beltrami	367	394	96,339
Benton	376	410	68,539
Big Stone	162	180	66,581
Blue Earth	460	489	147,046
Brown	399	461	108,183
Carlton	311	332	47,899
Carver	338	368	68,434
Cass	291	307	68,543
Chippewa	226	254	96,537
Chisago	452	473	33,146
Clay	291	316	149,599
Clearwater	245	251	74,106
Cook	17	17	1,365
Cottonwood	315	343	134,905
Crow Wing	242	262	42,612
Dakota	430	501	64,541
Dodge	326	356	80,716
Douglas	492	522	124,246
Faribault	330	363	149,301
Fillmore	729	811	190,699
Freeborn	427	464	150,403
Goodhue	738	797	175,115
Grant	247	275	150,225
Hennepin	331	353	15,948
Houston	454	492	118,342
Hubbard	197	226	54,030
Isanti	485	531	38,603
Itasca	277	284	48,643
Jackson	348	367	117,163
Kanabec	329	349	54,152
Kandiyohi	624	678	161,169
Kittson	255	287	235,909
Koochiching	105	105	26,421
Lac qui Parle	250	282	129,623
Lake	26	30	1,206
Lake of the Woods	75	80	30,021
Le Sueur	457	508	65,800
Lincoln	285	332	96,960
Lyon	354	395	166,517
McLeod	374	403	71,733
Mahnomen	111	114	87,408
Marshall	363	399	269,332
Martin	324	358	153,907
Meeker	508	548	136,216
Mille Lacs	355	376	48,583
Morrison	820	861	166,072
Mower	494	546	150,995
Murray	324	377	116,924
Nicollet	290	312	96,932
Nobles	428	485	126,614
Norman	155	173	156,797
Olmsted	623	671	107,313
Otter Tail	1,253	1,348	322,826
Pennington	163	176	106,476
Pine	444	478	90,659
Pipestone	254	272	97,821
Polk	525	588	375,362
Pope	395	424	142,940
Ramsey	36	42	474
Red Lake	99	104	66,744
Redwood	524	570	197,305
Renville	399	444	219,979
Rice	598	652	94,701
Rock	294	306	101,387
Roseau	329	351	164,903
St. Louis	545	567	88,204
Scott	388	419	46,280
Sherburne	304	326	34,961
Sibley	439	475	137,843
Stearns	1,417	1,521	283,724
Steele	358	388	118,233
Stevens	238	256	94,275
Swift	304	357	136,094
Todd	820	882	158,079
Traverse	166	182	135,737
Wabasha	376	406	112,202
Wadena	232	238	47,916
Waseca	292	328	128,700
Washington	335	379	24,346
Watonwan	200	229	71,842
Wilkin	140	157	128,627
Winona	496	564	108,710
Wright	742	805	94,338
Yellow Medicine	417	459	169,688

Table 48. **Hispanic, Latino, or Spanish Origin Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Hispanic, Latino, or Spanish producers	Land in farms (acres)
State Total			
Minnesota	607	754	287,887
Counties			
Aitkin	3	3	956
Anoka	1	2	(D)
Becker	15	21	11,489
Beltrami	7	9	357
Benton	17	26	1,089
Big Stone	1	1	(D)
Blue Earth	4	4	201
Brown	1	1	(D)
Carlton	9	9	1,121
Carver	5	5	1,522
Cass	5	7	2,176
Chippewa	2	2	(D)
Chisago	7	9	517
Clay	7	7	3,288
Clearwater	4	4	430
Cottonwood	2	2	(D)
Crow Wing	2	2	(D)
Dakota	16	19	724
Dodge	4	4	(D)
Douglas	13	13	2,202
Faribault	5	5	4,047
Fillmore	8	10	2,288
Freeborn	2	2	(D)
Goodhue	15	15	19,356
Grant	2	2	(D)
Houston	5	5	1,223
Hubbard	3	3	(D)
Isanti	2	2	(D)
Itasca	8	8	288
Jackson	9	9	890
Kanabec	6	6	(D)
Kandiyohi	8	8	600
Kittson	7	7	18,558
Koochiching	1	1	(D)
Lac qui Parle	5	9	1,773
Lake of the Woods	3	3	(D)
Le Sueur	7	8	38
Lincoln	5	5	1,930
Lyon	3	9	1,426
McLeod	4	4	(D)
Mahnomen	2	2	(D)
Marshall	14	26	20,228
Martin	15	17	14,280
Meeker	7	7	129
Mille Lacs	7	7	552
Morrison	13	13	6,759
Mower	12	12	2,289
Murray	2	2	(D)
Nicollet	2	2	(D)
Nobles	7	9	1,470
Norman	1	1	(D)
Olmsted	9	12	3,425
Otter Tail	19	20	11,303
Pennington	2	2	(D)
Pine	11	17	2,143
Pipestone	4	8	1,571
Polk	11	18	20,351
Pope	6	6	817
Ramsey	1	1	(D)
Red Lake	2	2	(D)
Redwood	5	5	3,371
Renville	2	2	(D)
Rice	13	28	934
Rock	6	6	1,178
Roseau	10	11	8,554
St. Louis	8	9	1,237
Scott	14	14	383
Sherburne	11	11	(D)
Sibley	6	7	3,721
Stearns	22	33	9,518
Steele	3	3	(D)
Stevens	17	19	6,693
Swift	5	5	10,738
Todd	26	56	6,300
Traverse	9	10	8,621
Wabasha	14	17	4,679
Wadena	7	7	2,240
Waseca	4	4	(D)
Washington	5	5	328
Watonwan	9	9	(D)
Wilkin	1	1	(D)
Winona	6	6	1,816
Wright	13	14	416
Yellow Medicine	11	17	330

Table 49. **American Indian or Alaska Native Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	American Indian or Alaska Native producers [1]	Land in farms (acres)
State Total			
Minnesota	207	244	117,541
Counties			
Aitkin	3	3	(D)
Anoka	2	2	(D)
Becker	22	25	4,642
Beltrami	5	7	1,376
Benton	2	2	(D)
Brown	1	1	(D)
Carlton	11	20	(D)
Cass	7	9	(D)
Chippewa	1	1	(D)
Chisago	6	6	1,521
Clay	2	2	(D)
Clearwater	6	9	4,720
Cook	1	1	(D)
Crow Wing	4	4	(D)
Dodge	1	1	(D)
Douglas	6	6	60
Fillmore	1	1	(D)
Freeborn	1	1	(D)
Goodhue	4	4	(D)
Hubbard	1	3	(D)
Isanti	6	6	350
Itasca	11	13	(D)
Kanabec	1	1	(D)
Kandiyohi	2	3	(D)
Koochiching	8	8	380
Lac qui Parle	6	6	(D)
Lake	1	1	(D)
Lake of the Woods	2	2	(D)
Mahnomen	12	18	2,164
Marshall	1	1	(D)
Martin	2	4	(D)
Meeker	1	1	(D)
Mille Lacs	4	4	980
Morrison	2	2	(D)
Mower	1	1	(D)
Murray	1	1	(D)
Nicollet	2	2	(D)
Norman	1	1	(D)
Olmsted	4	6	349
Otter Tail	4	4	889
Pine	2	2	(D)
Polk	1	1	(D)
Pope	3	5	(D)
Redwood	2	2	(D)
Roseau	1	1	(D)
St. Louis	11	11	(D)
Scott	3	3	57
Sherburne	1	1	(D)
Stearns	2	2	(D)
Steele	2	2	(D)
Todd	6	6	954
Traverse	3	4	3,906
Washington	7	7	380
Winona	2	2	(D)
Wright	1	1	(D)
Yellow Medicine	1	1	(D)

[1] For any producer reporting race as American Indian or Alaska Native only.

Table 50. **Asian Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Asian producers [1]	Land in farms (acres)
State Total			
Minnesota	240	306	40,554
Counties			
Aitkin	2	2	(D)
Anoka	11	11	180
Blue Earth	2	3	(D)
Carver	2	2	(D)
Cass	3	3	1,095
Chisago	23	26	729
Cottonwood	1	1	(D)
Dakota	27	51	364
Fillmore	4	4	310
Goodhue	3	4	2,580
Grant	2	2	(D)
Hennepin	15	18	51
Houston	4	4	360
Itasca	1	1	(D)
Kanabec	3	4	172
Kandiyohi	2	2	(D)
Koochiching	3	3	880
Le Sueur	1	1	(D)
McLeod	2	2	(D)
Marshall	1	1	(D)
Meeker	2	2	(D)
Morrison	1	1	(D)
Mower	3	3	532
Murray	1	2	(D)
Nicollet	4	6	874
Norman	6	6	11,705
Olmsted	5	5	380
Otter Tail	14	14	3,122
Pennington	3	3	(D)
Pine	7	7	801
Polk	4	4	806
Pope	1	1	(D)
Ramsey	2	2	(D)
Redwood	5	5	(D)
Rice	4	4	168
St. Louis	7	7	427
Scott	1	1	(D)
Sibley	2	2	(D)
Stearns	4	5	321
Steele	2	2	(D)
Stevens	2	2	(D)
Swift	1	1	(D)
Todd	1	1	(D)
Waseca	2	4	(D)
Washington	23	45	409
Watonwan	2	4	(D)
Wilkin	2	2	(D)
Winona	9	11	548
Wright	6	6	66
Yellow Medicine	2	3	(D)

[1] For any producer reporting race as Asian only.

Table 51. **Black or African American Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Black or African American producers [1]	Land in farms (acres)
State Total			
Minnesota	46	61	5,943
Counties			
Aitkin	2	2	(D)
Anoka	3	6	24
Becker	2	2	(D)
Beltrami	1	1	(D)
Blue Earth	1	2	(D)
Carlton	1	1	(D)
Crow Wing	1	1	(D)
Houston	1	1	(D)
Isanti	3	5	238
McLeod	3	3	66
Marshall	3	3	(D)
Mower	3	3	(D)
Rice	9	14	279
St. Louis	3	3	180
Stearns	2	3	(D)
Swift	1	1	(D)
Todd	3	6	210
Wadena	4	4	680

[1] For any producer reporting race as Black or African American only.

Table 52. **Native Hawaiian or Other Pacific Islander Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Native Hawaiian or Other Pacific Islander producers [1]	Land in farms (acres)
State Total			
Minnesota	39	43	9,191
Counties			
Benton	3	3	94
Brown	1	1	(D)
Cass	2	2	(D)
Chisago	1	1	(D)
Clearwater	2	2	(D)
Isanti	1	1	(D)
Kanabec	5	5	130
McLeod	1	1	(D)
Meeker	4	8	712
Mower	2	2	(D)
Murray	3	3	3,830
Nicollet	6	6	72
Otter Tail	1	1	(D)
Rock	3	3	(D)
Waseca	1	1	(D)
Washington	1	1	(D)
Winona	2	2	(D)

[1] For any producer reporting race as Native Hawaiian or Other Pacific Islander only.

Table 53. **White Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	White producers [1]	Land in farms (acres)
State Total			
Minnesota	65,219	113,864	25,312,777
Counties			
Aitkin	447	775	118,902
Anoka	347	636	29,928
Becker	933	1,613	378,135
Beltrami	603	1,036	170,948
Benton	685	1,141	134,274
Big Stone	392	652	263,888
Blue Earth	1,017	1,804	477,653
Brown	971	1,690	301,479
Carlton	453	793	78,639
Carver	604	1,067	156,276
Cass	486	819	128,219
Chippewa	562	973	(D)
Chisago	731	1,219	80,771
Clay	652	1,149	555,270
Clearwater	400	675	157,774
Cook	25	46	1,940
Cottonwood	741	1,290	392,448
Crow Wing	425	698	92,706
Dakota	819	1,511	207,793
Dodge	613	1,084	278,440
Douglas	980	1,748	268,096
Faribault	772	1,298	(D)
Fillmore	1,453	2,587	469,958
Freeborn	907	1,506	351,014
Goodhue	1,400	2,458	418,950
Grant	529	908	338,754
Hennepin	505	891	32,388
Houston	795	1,472	222,819
Hubbard	335	596	97,444
Isanti	808	1,380	101,224
Itasca	419	715	89,864
Jackson	845	1,464	384,337
Kanabec	523	910	98,880
Kandiyohi	1,250	2,282	494,370
Kittson	613	1,146	602,709
Koochiching	188	307	60,431
Lac qui Parle	728	1,193	409,709
Lake	34	64	1,422
Lake of the Woods	185	296	108,754
Le Sueur	896	1,571	205,774
Lincoln	598	1,064	212,420
Lyon	869	1,534	424,591
McLeod	797	1,411	244,662
Mahnomen	256	421	215,912
Marshall	1,067	1,883	910,076
Martin	822	1,419	450,075
Meeker	989	1,663	308,221
Mille Lacs	602	1,049	96,424
Morrison	1,570	2,631	361,009
Mower	997	1,769	380,052
Murray	788	1,283	351,253
Nicollet	654	1,143	278,798
Nobles	938	1,729	366,330
Norman	431	721	487,984
Olmsted	1,094	1,964	307,620
Otter Tail	2,480	4,266	765,243
Pennington	321	532	258,891
Pine	721	1,235	164,273
Pipestone	528	876	(D)
Polk	1,220	2,278	1,075,777
Pope	818	1,434	309,681
Ramsey	45	74	797
Red Lake	274	447	196,716
Redwood	1,320	2,350	558,819
Renville	930	1,586	626,031
Rice	1,104	1,961	249,677
Rock	573	987	261,220
Roseau	747	1,236	536,905
St. Louis	817	1,386	154,610
Scott	620	1,092	99,129
Sherburne	494	890	85,044
Sibley	860	1,487	373,628
Stearns	2,690	4,713	642,710
Steele	717	1,238	245,794
Stevens	499	959	330,779
Swift	708	1,323	374,933
Todd	1,526	2,667	320,958
Traverse	357	582	309,489
Wabasha	743	1,310	235,417
Wadena	437	713	122,301
Waseca	621	1,107	265,266
Washington	504	896	50,465
Watonwan	510	873	(D)
Wilkin	358	645	401,044
Winona	989	1,848	295,356

See footnote(s) at end of table.

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Table 53. **White Producers: 2022** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	White producers [1]	Land in farms (acres)
Counties - Con.			
Wright	1,304	2,264	224,765
Yellow Medicine	841	1,462	380,966

[1] For any producer reporting race as White only.

Table 54. **Producers Reporting More Than One Race: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Producers reporting more than one race	Land in farms (acres)
State Total			
Minnesota	305	350	162,218
Counties			
Aitkin	1	1	(D)
Anoka	2	2	(D)
Becker	16	17	2,267
Beltrami	7	9	482
Benton	1	1	(D)
Blue Earth	2	2	(D)
Brown	1	1	(D)
Carlton	2	2	(D)
Carver	5	5	39
Chippewa	2	2	(D)
Chisago	1	1	(D)
Clay	7	7	3,561
Clearwater	10	10	4,582
Cottonwood	1	1	(D)
Crow Wing	2	2	(D)
Dakota	8	8	(D)
Dodge	6	8	(D)
Douglas	1	1	(D)
Faribault	1	1	(D)
Fillmore	5	7	347
Freeborn	1	1	(D)
Goodhue	6	12	5,211
Grant	6	12	12,894
Hennepin	6	6	30
Houston	3	4	258
Hubbard	1	1	(D)
Isanti	1	1	(D)
Itasca	3	3	365
Jackson	4	4	235
Kanabec	9	14	350
Kandiyohi	9	16	1,218
Koochiching	1	1	(D)
Lac qui Parle	1	1	(D)
Lake of the Woods	5	5	4,150
Le Sueur	2	2	(D)
Lyon	1	1	(D)
McLeod	1	1	(D)
Mahnomen	9	9	1,570
Marshall	4	4	2,833
Martin	5	5	9,600
Meeker	1	1	(D)
Mille Lacs	2	2	(D)
Morrison	8	9	1,475
Mower	1	1	(D)
Nicollet	6	6	72
Nobles	1	1	(D)
Norman	3	3	(D)
Olmsted	13	15	608
Otter Tail	14	14	3,995
Pennington	4	4	6,393
Pine	6	6	892
Pipestone	1	1	(D)
Polk	12	12	25,945
Ramsey	3	3	3
Redwood	2	2	(D)
Renville	4	5	563
Rice	3	4	144
Rock	2	2	(D)
Roseau	7	10	1,114
St. Louis	4	4	308
Scott	1	1	(D)
Stearns	9	9	596
Steele	3	3	(D)
Stevens	1	1	(D)
Swift	1	1	(D)
Todd	2	2	(D)
Traverse	1	1	(D)
Wabasha	1	1	(D)
Wadena	2	4	(D)
Waseca	4	4	373
Washington	4	4	224
Wilkin	1	1	(D)
Winona	5	5	786
Wright	9	9	155
Yellow Medicine	5	8	(D)

Table 55. **Producers with Military Service: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Producers with military service	Land in farms (acres)
State Total			
Minnesota	8,801	9,265	2,540,720
Counties			
Aitkin	100	100	20,620
Anoka	83	84	5,104
Becker	173	184	44,684
Beltrami	105	105	30,011
Benton	97	101	14,366
Big Stone	38	38	6,404
Blue Earth	142	144	62,383
Brown	124	127	40,733
Carlton	88	95	60,820
Carver	55	55	9,453
Cass	93	97	32,956
Chippewa	76	85	61,200
Chisago	114	123	13,506
Clay	77	81	20,833
Clearwater	56	64	18,326
Cook	6	7	510
Cottonwood	61	66	17,865
Crow Wing	62	65	10,752
Dakota	96	96	10,966
Dodge	88	90	33,117
Douglas	156	164	29,151
Faribault	66	80	29,031
Fillmore	152	152	47,521
Freeborn	96	99	24,898
Goodhue	207	224	61,835
Grant	66	70	24,125
Hennepin	74	81	4,334
Houston	99	114	20,776
Hubbard	67	72	11,586
Isanti	145	148	13,131
Itasca	67	69	11,541
Jackson	108	114	46,496
Kanabec	120	123	20,497
Kandiyohi	156	163	35,664
Kittson	86	114	37,045
Koochiching	33	39	4,795
Lac qui Parle	100	107	27,591
Lake	2	2	(D)
Lake of the Woods	12	12	6,990
Le Sueur	138	150	24,071
Lincoln	100	104	20,018
Lyon	94	108	25,845
McLeod	78	81	18,995
Mahnomen	31	33	6,834
Marshall	151	161	94,308
Martin	96	101	47,155
Meeker	106	113	27,592
Mille Lacs	101	106	9,022
Morrison	280	288	52,496
Mower	168	170	45,869
Murray	110	115	49,476
Nicollet	80	86	25,857
Nobles	90	94	44,687
Norman	42	44	33,826
Olmsted	152	155	25,554
Otter Tail	405	418	94,451
Pennington	57	58	31,574
Pine	136	138	33,102
Pipestone	51	54	13,000
Polk	170	173	116,311
Pope	111	114	24,024
Ramsey	2	2	(D)
Red Lake	28	28	28,849
Redwood	121	147	45,855
Renville	88	90	20,617
Rice	152	166	23,755
Rock	59	61	36,143
Roseau	93	97	47,392
St. Louis	146	156	27,716
Scott	62	68	2,497
Sherburne	82	89	9,389
Sibley	78	78	13,114
Stearns	304	315	55,379
Steele	101	102	24,937
Stevens	90	94	49,439
Swift	95	99	30,264
Todd	172	175	31,028
Traverse	49	52	46,277
Wabasha	85	91	28,131
Wadena	62	63	9,963
Waseca	73	73	20,142
Washington	70	70	4,180
Watonwan	43	43	11,457
Wilkin	22	23	22,652
Winona	135	147	27,338

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Table 55. **Producers with Military Service: 2022** (continued)

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Producers with military service	Land in farms (acres)
Counties - Con.			
Wright	167	173	24,545
Yellow Medicine	129	145	63,667

Table 56. **Young Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	Young producers	Land in farms (acres)
State Total			
Minnesota	8,554	11,274	3,762,834
Counties			
Aitkin	39	50	8,054
Anoka	57	91	7,696
Becker	90	114	31,775
Beltrami	72	87	14,837
Benton	86	105	27,702
Big Stone	68	76	41,555
Blue Earth	146	189	104,639
Brown	135	149	31,706
Carlton	26	36	5,821
Carver	69	88	33,712
Cass	52	57	19,068
Chippewa	80	125	68,466
Chisago	85	132	7,467
Clay	107	138	68,894
Clearwater	47	64	12,805
Cook	2	3	(D)
Cottonwood	120	165	96,663
Crow Wing	39	55	7,867
Dakota	120	148	24,980
Dodge	79	94	54,254
Douglas	134	183	52,736
Faribault	145	192	54,987
Fillmore	174	250	67,159
Freeborn	101	122	41,596
Goodhue	173	249	54,589
Grant	64	70	54,886
Hennepin	70	90	6,610
Houston	75	108	29,035
Hubbard	52	76	17,478
Isanti	94	123	18,822
Itasca	51	75	10,587
Jackson	121	149	54,348
Kanabec	70	85	13,144
Kandiyohi	126	174	37,546
Kittson	93	133	154,153
Koochiching	3	4	4,490
Lac qui Parle	120	131	92,109
Lake	7	11	560
Lake of the Woods	13	20	10,642
Le Sueur	77	101	30,565
Lincoln	76	97	27,528
Lyon	135	170	58,833
McLeod	130	172	41,845
Mahnomen	30	35	20,358
Marshall	162	203	150,235
Martin	111	143	54,607
Meeker	143	177	83,903
Mille Lacs	78	104	13,524
Morrison	217	296	59,854
Mower	111	150	40,170
Murray	110	150	50,619
Nicollet	76	97	18,914
Nobles	203	304	68,646
Norman	65	93	52,984
Olmsted	122	156	37,739
Otter Tail	310	395	103,579
Pennington	17	20	12,415
Pine	58	74	12,803
Pipestone	61	84	44,757
Polk	217	278	227,333
Pope	96	126	31,935
Ramsey	6	6	(D)
Red Lake	42	49	17,798
Redwood	244	321	90,706
Renville	110	135	59,353
Rice	164	240	52,784
Rock	93	118	26,255
Roseau	86	110	55,704
St. Louis	78	112	9,263
Scott	66	93	27,450
Sherburne	73	103	16,765
Sibley	107	137	35,683
Stearns	340	449	95,411
Steele	90	121	40,745
Stevens	88	118	62,483
Swift	84	103	48,991
Todd	243	350	52,638
Traverse	34	38	42,473
Wabasha	91	122	40,180
Wadena	43	53	23,517
Waseca	53	76	19,701
Washington	60	77	2,582
Watonwan	81	104	48,280
Wilkin	55	68	81,410
Winona	131	177	34,021
Wright	170	198	44,493
Yellow Medicine	112	160	47,359

Table 57. **New and Beginning Producers: 2022**

[Data were collected for a maximum of four producers per farm. For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Farms	New and beginning producers	Land in farms (acres)
State Total			
Minnesota	18,914	29,586	5,184,617
Counties			
Aitkin	136	223	24,126
Anoka	153	274	14,734
Becker	234	380	60,663
Beltrami	193	310	38,649
Benton	194	295	32,623
Big Stone	98	134	44,709
Blue Earth	288	423	99,690
Brown	283	419	49,227
Carlton	149	240	18,466
Carver	176	278	51,061
Cass	156	242	21,278
Chippewa	130	205	72,234
Chisago	296	476	19,938
Clay	175	280	84,529
Clearwater	135	229	34,481
Cook	4	8	255
Cottonwood	212	291	110,768
Crow Wing	116	185	14,497
Dakota	295	497	48,621
Dodge	169	251	57,107
Douglas	351	567	78,783
Faribault	228	329	70,946
Fillmore	378	627	89,082
Freeborn	216	311	56,860
Goodhue	370	576	66,338
Grant	147	214	71,845
Hennepin	242	413	11,390
Houston	201	332	47,077
Hubbard	105	180	21,726
Isanti	359	564	31,472
Itasca	121	190	19,977
Jackson	250	367	83,810
Kanabec	198	325	26,928
Kandiyohi	393	645	78,932
Kittson	163	279	155,533
Koochiching	47	75	12,335
Lac qui Parle	171	246	89,127
Lake	13	17	708
Lake of the Woods	54	94	22,569
Le Sueur	239	401	26,531
Lincoln	149	211	35,501
Lyon	253	364	107,394
McLeod	221	324	49,186
Mahnomen	63	92	31,972
Marshall	273	469	154,272
Martin	238	351	71,555
Meeker	316	456	102,227
Mille Lacs	206	336	29,435
Morrison	441	671	86,305
Mower	256	376	61,841
Murray	212	311	55,148
Nicollet	149	248	51,248
Nobles	304	505	86,781
Norman	94	133	68,541
Olmsted	312	485	52,770
Otter Tail	664	1,024	160,901
Pennington	68	99	46,461
Pine	223	338	27,559
Pipestone	126	174	53,692
Polk	364	547	284,783
Pope	196	288	37,289
Ramsey	27	42	290
Red Lake	70	85	32,305
Redwood	464	768	147,748
Renville	230	345	88,381
Rice	309	523	55,889
Rock	157	220	28,882
Roseau	180	261	84,672
St. Louis	273	468	25,724
Scott	203	326	29,409
Sherburne	211	371	28,023
Sibley	207	333	55,797
Stearns	705	1,091	137,483
Steele	200	313	51,543
Stevens	148	228	85,511
Swift	176	294	56,351
Todd	446	699	70,547
Traverse	82	114	72,057
Wabasha	188	282	57,721
Wadena	119	182	32,045
Waseca	149	229	30,590
Washington	210	362	9,186
Watonwan	160	228	77,113
Wilkin	103	172	103,460
Winona	275	417	66,987
Wright	420	699	74,012
Yellow Medicine	236	340	68,405

Appendix A.
Census of Agriculture Methodology

The purpose of a census is to enumerate all objects with a defined characteristic. For the census of agriculture, that goal is to account for "any place from which $1,000 or more of agricultural products were produced and sold, or normally would have been sold, during the census year." To do this, NASS creates a Census Mail List (CML) of agricultural operations that potentially meet the farm definition, collects agricultural information from those operations, reviews the data, corrects or completes the requested information, and combines the data to provide information on the characteristics of farm operations and farm producers at the national, State, and county levels. In this appendix, these census processes are described.

THE CENSUS POPULATION

The Census Mail List

The National Agricultural Statistics Service (NASS) maintains a list of farmers and ranchers from which the CML is compiled. The goal is to build as complete a list as possible of agricultural places that meet the farm definition. The CML compilation begins with the list used to define sampling populations for NASS surveys conducted for the agricultural estimates program. Each record on the list includes name, address, telephone number, and email plus additional information that is used to efficiently administer the census of agriculture and agricultural estimates programs.

NASS builds and improves the list on an ongoing basis by obtaining outside source lists. Sources include State and federal government lists, producer association lists, seed grower lists, pesticide applicator lists, veterinarian lists, marketing association lists, and a variety of other agriculture-related lists. NASS also obtains special commodity lists to address specific list deficiencies. These outside source lists are matched to the NASS list using record linkage programs. Most names on newly acquired sources are already on the NASS list. Records not on the NASS list are treated as potential farms until NASS can confirm their existence as a qualifying farm. Staff in NASS regional and field offices routinely contact these potential farms to determine whether they meet the farm definition. For the 2022 Census of Agriculture, NASS made a concerted effort to work with community-based organizations not only to improve list coverage for minorities but also to increase census awareness and participation.

List building activities for developing the 2022 CML started in 2019 by updating list information from respondents to the 2017 Census of Agriculture. Between 2017 and 2022, NASS conducted a series of National Agricultural Classification Surveys (NACS) on over 2.1 million records, which included nonrespondents from the 2017 census and newly added records from outside list sources. The NACS report forms collected information that was used to determine whether an operation met the farm definition. If the definition was met, the operation was added to the NASS list and subsequently to the CML. Addressees that were nonrespondents to a NACS were also added to the CML and identified with a special status code.

Measures were taken to improve name and address quality. Additional record linkage programs were run to detect and remove duplicate records both within each State and across States. List addresses were processed through software programs that utilize the United States Postal Service's National Change of Address System and the Locatable Address Conversion System to improve mail delivery. Records on the list with missing or invalid phone numbers were matched against a nationally available telephone database to obtain as many phone numbers as possible. To reduce costs, operations with characteristics that indicated they were unlikely to be farms, according to the farm definition, were removed from the list.

The official CML for the 2022 Census of Agriculture was established on September 3, 2022. The list contained 2,879,343 records. Of these, 2,079,333 records were thought to meet the NASS farm definition and 800,010 were potential farm records, which included NACS nonrespondents, other records added to the CML by the NASS regional field offices after the record linkage process, and late adds to the CML that were not included in any previous NACS or State screening survey.

Not on the Mail List (NML)

Extensive efforts are directed toward developing a CML that includes all farms in the U.S. However, some farms are not on the list, and some agricultural operations on the list are not farms. NASS uses its June Area Survey (JAS) to

quantify the number and types of farms not on the CML. The records in the JAS that are not on the CML are said to be in the Not-on-the-Mail List (NML) domain. If a JAS record in the NML domain is determined to be a farm during the census, it is an NML farm. The NML farms are used to measure coverage associated with the grown crops, farm numbers, and inventories of cattle. Sampled segments in the JAS are personally enumerated. Each operation identified within a segment boundary is known as a tract.

The 2022 JAS sample was increased to improve the farm counts for operations that produced specialty commodities or had socially disadvantaged or minority producers. The total JAS sample consisted of 14,015 segments of which 4,933 were additional ACES segments. This set of additional segments is referred to as the Agricultural Coverage Evaluation Survey (ACES) segments. The ACES segments were selected using a multivariate sampling design that targeted specific items at the U.S. level. The 2022 JAS consisted of sample segments from all States, with the exception of Alaska where NASS does not maintain an area frame.

During the JAS/ACES enumeration process, each tract is identified as either agricultural or non-agricultural. Each JAS/ACES agricultural tract is identified as a farm or non-farm in June based on the farm definition of $1,000 of sales or potential sales of agricultural products. Non-agricultural tracts are further classified into categories: with farm potential, with unknown farm potential, or with no farm potential. The names and addresses collected in the 2022 JAS/ACES were matched to the CML. Those from the 2022 JAS/ACES that did not match were determined to be in the NML domain and sent a yellow census report form so that they could be differentiated from the green report form sent to those addressees on the CML. Instructions on the census report form directed any respondent who received duplicate forms to complete the CML form and to mail all duplicate forms back together. Those who returned a CML and an NML form had been misclassified as NML and were removed from the NML domain.

The initial NML mailout consisted of 41,273 records. A total of 40,775 NML records were analyzed, of which 1,913 records were confirmed to be NML and in-scope.

The farm/nonfarm status of each NML domain operation was determined based on the reported data in the census form. An operation in the NML domain that was determined to be a farm is referred to as an NML farm. Characteristics of NML farms and their producers provided a measure of the undercoverage of farms present in the CML.

The percentage of farms not represented on the CML varied by State. In general, NML farms tended to be small in acreage, production, and sales of agricultural products. Farm operations were missing from the CML for various reasons, including the possibility that the operation started after development of the CML, the operation was so small that it did not appear in any agriculture-related source list, or the operation was misclassified as a nonfarm prior to census mailout. The CML was used with the NML in a capture-recapture framework to represent all farming operations across all States in the JAS sample.

DATA COLLECTION OUTREACH AND PROMOTIONAL EFFORTS

NASS planned and executed a multi-phase strategic communications campaign for the 2022 Census of Agriculture, to increase the level of awareness and response among all U.S. agricultural producers.

- Phase 1 ran from April 2021 − June 2022. It raised awareness about the census and list building, encouraged producers to sign up in response to NASS mailings and at community, association, and other stakeholder meetings where NASS partners reached out.

- Phase 2 ran from July 2022 − October 2022. It notified farm producers and agricultural organizations that the census would be mailed in November and encouraged communications regarding the census.

- Phase 3 ran from November 2022 – May 2023. It focused on census data collection with messaging urging response to remind producers that it was not too late to respond.

- Phase 4 ran from August 2023 – February 2024. It thanked producers for their participation and NASS partners for their support and informed everyone of the February 2024 data release plan.

The communications campaign focused on these primary areas: partnership building, local-level outreach, public relations, media relations, paid media, social media and some paid advertising. Some external support was provided by a private communications agency (i.e. primarily assisted with design and paid advertising).

The unifying force behind the 2022 communications campaign was the theme “Your Voice. Your Future. Your Opportunity.” This was accompanied by supporting messages and artwork that created a consistent look and feel for all census communications. All messages and materials served the purpose of inspiring action: Sign Up to Be Counted - Show the Value of Your Work - *Grow Your*

Farm Future - Shape Farm Policy/Programs - Respond to the Census of Agriculture - Be counted - The Census of Agriculture is Your Voice, Your Future, Your Opportunity.

Partnership and Local-Level Outreach

At the national level, NASS officials met with leaders from dozens of agricultural organizations, State Departments of Agriculture, and other USDA agencies to successfully secure their support in promoting the census among their constituencies. Stakeholders partnered with NASS to promote the 2022 Census of Agriculture through publications (e.g. newsletters), special mailings, speeches, social media, websites, and other communications. In addition, through grassroots-level outreach and efforts, NASS partnered with a number of community-based organizations to reach minority and limited-resource farmers and ranchers. National-level outreach was encouraged and mirrored at the regional, State, and local levels. Among the highlights of these partnership efforts was the production of multiple television and radio public service announcements featuring the U.S. Secretary of Agriculture, State secretaries, directors, and commissioners of agriculture and leaders from community-based organizations.

Coverage of American Indian and Alaska Native Farm Producers

To maximize coverage of American Indian and Alaska Native agricultural producers, special procedures were followed in the census. A concerted effort was made to get individual reports from every American Indian and Alaska Native farm or ranch producer in the country. If this was not possible within some reservations, a single reservation-level census report was obtained from knowledgeable reservation officials. These reports covered agricultural activity on the entire reservation. NASS staff reviewed these data and removed duplication with any data reported by American Indian or Alaska Native producers who responded on an individual census report form. Additionally, NASS obtained, from knowledgeable reservation officials, the count of American Indian and Alaska Native producers (on reservations) who were not counted through individual census report forms, but whose agricultural activity was included in the reservation-level report form.

Table D, **American Indian and Alaska Native Producers:** 2022 provides the number of producers (1) reported as American Indian or Alaska Native in the race category, either as a single race or in combination with other races, on the individual census report forms (for up to four per farm) and (2) identified as American Indian or Alaska Native producers farming on reservations by reservation officials. The count from the individual report forms is summarized in the "Individually reported" column. It includes up to four producers on or off reservations. The "Other" column provides counts of producers on reservations as reported by a reservation or tribal official. The "Total" column is simply a sum of the "Individually reported" and the "Other" columns. Tables in other parts of the publication count the reservation-level reports as single farms.

Public Relations

In the public relations arena, NASS worked with internal and external, national, regional, and local stakeholders to equip them with communications tools and resources to deliver the census communications message to their audiences. NASS utilized its Intranet, the Partner Tools section on the census webpage, and a regularly scheduled, newsletter-type email update to deliver materials to staff across its 12 regions, other USDA agencies and external stakeholders. The materials included but were not limited to: customizable news releases, public service announcement scripts, and a PowerPoint template; Secretary of Agriculture video public service announcements, and drop-in advertisements; informational, instructional, and testimonial videos; website buttons and banners; brochures in multiple languages; social media posts; flyers; posters; FAQ sheets, talking points, and more. In addition, at the national level, NASS issued six news releases during data collection (three more were produced before data collection to inform and prepare producers) citing department and agency spokespeople, published half a dozen timely and relevant pieces to the USDA blog highlighting the census, and conducted three social media campaigns. These public relations efforts at the national and local-levels helped ensure that NASS' message about the census was continually in the media, including print and online publications, a variety of social media, radio, and some television programs. Media outlets included both those specializing in agriculture and more general outlets.

Paid Media

With a very limited budget, NASS was able to apply a small portion of funds toward paid advertising. For the 2022 Census of Agriculture, NASS strategically advertised in regional print publications, online, and with national agriculture news services (i.e., TV, radio) to bolster reach both in general and within geographically specific, previously under-represented populations and lower response areas.

DATA COLLECTION

Method of Enumeration

Data collection was accomplished primarily by mail, Computer-Assisted Self Interview (CASI) on the Internet, and personal enumeration for special classes of records in the census operations. Personal enumeration (interviewing) involved the use of both Computer-Assisted Telephone Interview (CATI) and Computer-Assisted Personal Interview (CAPI) data collection instruments. Enumerators at the five NASS Data Collection Centers conducted CATI data collection. In addition, enumerators under contract with NASS through the National Association of State Departments of Agriculture (NASDA) conducted phone and personal interviews with respondents. For the 2022 Census of Agriculture, NASS implemented a pre-notification strategy to increase awareness, improve overall responses, and encourage respondents to report early to avoid continued correspondence. All records with an e-mail address received an e-mail message marketing the improved web form and announcing the census mail packets were coming.

Report Forms

Four versions of report forms were used for the 2022 Census of Agriculture:

- General form (22 - A100)
- Hawaii form (22 - A101)
- American Indian form (22 - A300)
- Farm Status form (22 - A400)

The general form facilitated reporting crops and livestock most commonly grown and raised in the U.S. The short form expedited reporting specific crops or livestock for pre-identified farms and ranches in the U.S. The Hawaii form targeted crops and livestock specifically grown or raised on farms and ranches in Hawaii. The American Indian form focused on crops and livestock for farms and ranches on reservations in Arizona, New Mexico, and Utah. All report forms allowed respondents to write in specific commodities that were not prelisted on their report form.

Report Form Mailings

Census data collection began on November 22, 2022. Nearly all producers on the CML received a letter inviting them to report online. They received a unique survey code and instructions for completing their census online. The letter encouraged producers to report online early to avoid receiving mail and phone follow-up. Approximately 3 million mail packets were mailed in December 2022. Each packet contained a cover letter, instruction sheet, a labeled report form, and a return envelope. The Census Bureau's National Processing Center (NPC) in Jeffersonville, IN was contracted to perform mail packet preparation, initial mailout, and two follow-up mailings to nonrespondents.

The initial mailout was followed by a thank-you reminder correspondence in January 2023. This pressure-sealed envelope reminded respondents of the approaching deadline and that they could report online. First follow-up mail packets were mailed in mid-February 2023 to approximately 1.5 million nonrespondents. Second follow-up mail packets were mailed in mid-March 2023 to approximately 1 million nonrespondents. A final mailing went to approximately 800,000 non-respondents. This mailing included a drastically reduced four-page questionnaire designed to primarily determine if the operation was a farm or not in business.

Nonresponse Follow-up

Operating concurrently with NPC's mail data collection efforts, NASS Data Collection Centers targeted selected groups of census nonrespondents for telephone enumeration. NASS regional field offices targeted selected groups of census nonrespondents for in-person enumeration. These efforts were referred to as:

- Must Case Follow-up
- American Indian Producer Follow-up
- National Nonresponse Follow-up
- Not on Mail List (NML) Follow-up

Must Case Follow-up. Must cases are known large or unique operations, the absence of which could have significantly affected the accuracy of census results. For the 2022 Census of Agriculture, 125,697 records were categorized as Must cases. Each active Must operation was accounted for by mail receipt, phone interview, or personal enumeration; if an operation was no longer in business, its nonfarm status was documented. Call centers conducted CATI calling of nonrespondent Must cases from March 2023 through May 2023, after the initial and first follow-up mailings. Following the CATI calling, the remaining nonresponse Must cases were assigned to regional field offices for personal enumeration. Because of the potential importance of Must cases, they were all accounted for and therefore not eligible for nonresponse weighting adjustment.

American Indian Producer Follow-up. The American Indian report form (22-A300) was mailed to all operations in Arizona, New Mexico and Utah thought to have an American Indian producer. It was included in the initial

mailout, but due to poor mail response, a personal enumeration data collection strategy was utilized with no additional mail follow-up. A concerted effort was made to get individual reports from every American Indian farm producer in the country. If this was not possible within a reservation, a single reservation-level census report was obtained from knowledgeable reservation officials. These reports covered agricultural activity on the entire reservation. NASS staff reviewed these data and removed any duplicate data reported by American Indian producers from that reservation who responded on an individual census report form. Additionally, NASS obtained, from knowledgeable reservation officials, the count of American Indian farm producers (on the reservations) who were not counted through individual census report forms, but whose agricultural activity was included in the reservation-level report form.

National Nonresponse Follow-up (Excludes Must Records). In April 2023, a group of records that were not part of other nonresponse data collection efforts were identified for additional phone contacts. In total, 82,237 records with specified demographics and/or eligibility for Census Special Studies (follow-ons) were made available for nonresponse Computer-Assisted Telephone Interviews (CATI).

Not-on-the-Mail List (NML) Follow-up. To account for farming operations not on the CML, NASS used its 2022 JAS sample from the NASS area frame, augmented with the ACES segments. Because the NASS area frame covers all land in the U.S. with the exception of Alaska, it includes all farms. As previously described, NASS conducted a record linkage operation between the CML records and the records from the 2022 JAS/ACES. Those 2022 JAS records that did not match records on the CML were designated as "Not-on-the-Mail List" (NML) records. These records were mailed a yellow census form so that it could be differentiated from the green forms mailed to CML records. The NML records were mailed at the same time as the census mailing and received the same follow-up procedures as the census mailing through the first follow-up in mid-February 2023. Beginning in March 2023, CATI was used for nonresponse follow-up for NML nonrespondents.

REPORT FORM PROCESSING

Data Capture

The Census Bureau's National Processing Center (NPC) in Jeffersonville, IN was contracted to process returned mail packets. NASS staff on site at the NPC provided technical guidance and monitored NPC processing activities. All report forms returned to the NPC were immediately checked in, using bar codes printed on the mailing label, and removed from follow-up report form mailings. All forms with any data were scanned and an image was made of each page of a report form. Optical Mark Recognition (OMR) was used to capture categorical responses and to identify the other answer zones in which some type of mark was present.

Data entry operators keyed data from the scanned images using OMR results that highlighted the areas of the report forms with respondent entries. The keyer evaluated the contents and captured pertinent responses. Ten percent of the captured data were keyed a second time for quality control. If differences existed between the first keyed value and the second, an adjudicator handled resolution. The decision of the adjudicator was used to grade the performance of the keyers, who were required to maintain a certain accuracy level.

The images and the captured data were transferred to NASS's centralized network and became available to NASS analysts on a flow basis. The images were available for use in all stages of review.

Editing Data

Captured data were processed through a computer formatting program that verified that records were valid – that the record ID number was on the list of census records, that the reported counties of operation and production were valid, and other related criteria. Rejected records were referred to analysts for correction. Accepted records were sent to a complex computer batch edit process. Each execution of the computer edit in batch mode consisted of records from only one State and flowed as the data were received from NPC, the NASS Computer-Assisted Self Interview (CASI), or the Computer-Assisted Telephone Interview (CATI) applications.

The computer edit determined whether a reporting operation met the qualifying criteria to be counted as a farm (in-scope). The edit examined each in-scope record for reasonableness and completeness and determined whether to accept the recorded value for each data item or take corrective action. Such corrective actions included removing erroneously reported values, replacing an unreasonable value with one consistent with other reported data, or providing a value for an item omitted by the respondent. To the extent possible, the computer edit determined a replacement value. Strategies for determining replacement values are discussed in the next section. Operations failing to meet the qualifying criteria for being classified as a farm were categorized as out-of-scope for the census. Records that NASS had reason to believe might have been erroneously classified as out-of-

scope (indications of recent and/or significant agricultural activity reported on NASS surveys, for example) were referred to analysts for verification.

The edit systematically checked reported data section-by-section with the overall objective of achieving an internally consistent and complete report. NASS subject-matter experts had previously defined the criteria for acceptable data. Problems that could not be resolved within the edit were referred to an analyst for intervention. Prior to the census mail-out, NASS established a group of analysts in a Census Editing Unit in the National Operations Center in St. Louis, MO who examined the scanned images, consulted additional sources of information, and determined an appropriate action. Regional field office analysts also participated using an interactive version of the edit program to submit corrected data and immediately re-edit the record to ensure a satisfactory solution.

Farm Status Form Editing

From the CML, 883,732 records were selected to receive a Farm Status form as a final follow-up form; this form was derived from the full census report form by selecting a subset of the questions on the full form. Since these questions were also asked on the general form, the edit was able to treat the Farm Status form responses as though they were incomplete general forms, as described in the previous paragraphs.

Imputing Data

The edit determined the best value to impute for reported responses that were deemed unreasonable and for required responses that were absent. If an item could not be calculated directly from other current responses, the edit determined whether acreage, production, or inventory items had been reported for that farm on a recent NASS crop or livestock survey. For producers who had not changed in five years, demographics such as race and gender were taken from the previous census. Administrative data from the Farm Service Agency were used for a few items, such as Conservation Reserve Program acreage. When deterministic edit logic and previously-reported data sources were unable to provide a current value, data from a reporting farm of similar type, size, and location were considered. In cases where automated imputation was unable to provide a consistent report, the record was referred to an analyst for resolution.

Separate system processes were established to efficiently provide data from a similar farm to the edit when donor imputation was required. The farm characteristics used to define similarity between a recipient record and its donor record were determined dynamically by the edit logic. Euclidean distance was used for similarity computations, with each contributing similarity characteristic scaled appropriately. The most similar farm based on this criterion (the "nearest neighbor") was identified and returned to the edit for use as a donor. The calculated distance between the centroids of the principal counties of production of the donor and recipient was always included as one of the measures of similarity.

To provide donors to the automated edit, a pool of successfully edited records was maintained for each section of the report form. These donor pools began with 2017 census data, reconfigured to emulate 2022 data and then edited using 2022 logic. Data from the 2020 Census Content Test were similarly remapped and edited before being added to the original donor pools. As 2022 records were successfully processed, they were added to the donor pools, which maintained the most recent data for each farm. Donor pools were updated approximately every other week, as determined by edit processing schedules. After several updates, all initial data records were dropped, leaving only 2022 records in the donor pools. After each update, donor pool records were grouped into strata containing farms in the same State of similar type and size, using a data-driven algorithm to define strata. Certain American Indian farms were treated as a separate group, effectively having their own donor pool.

In response to each donor request issued by the edit, a dedicated system process would search the appropriate stratum and respond with the most similar donor, while giving preference to more recent donors. In relatively rare instances where it was unable to provide a donor, the donor selection process issued an appropriate failure message to the edit. Imputation failures occurred for several different reasons. The requirement that an imputed value be positive could have ruled out all available donors, as could have the necessity for the donor record to satisfy a particular constraint – say, that the donor record has cattle, but no milk cows. In general, an imputation failure occurred if there were no satisfactory donors in the same profile as the report being edited. Records with imputation failures were either held until more records were available in the donor pool or referred to an analyst. In addition, when such a failure occurred in finding a donor for expenditure data, donor pool averages were provided in lieu of an individual donor, wherever possible. This "failover" utility was first introduced for the 2012 census imputation process, and significantly reduced the number of imputation failures among the expenditure and labor variables. During the early stages of editing, records requiring imputation for production (and hence yields) of field crops or hay, land values, or certain expenditure variables, were set aside or "parked." These records were edited when the donor pools contained only 2022 records, ensuring that 2022 data were

used in the imputations for the variables.

After receiving a donor's data, the edit substituted the values into the edited record. In many cases, the donor record's data value was scaled using another data field specified in the edit logic. In such cases, the size of the auxiliary field's value in the edited record, relative to its value in the donor record, was used to appropriately scale the donor record's value for the field to be imputed. The imputed data were then validated by the same edit logic to which reported data were subject. Since imputation was conducted independently for each occurrence, reports requiring multiple imputations may have drawn from multiple donors.

As was done for the 2017 Census, for records reporting three or more persons as producers, a different imputation process was used for certain items (specifically the items in question 3) in the Personal Characteristics Section. Records with one or two persons reported as producers had these data edited and imputed using the decision logic table edit and donor pool imputation process. Records with three or more persons reported as producers, and for which it was determined that these data were inconsistent or missing, had these data imputed using a fully conditional specification method. During the edit for records reporting three or more producers, the items needing imputation were marked, and the record was flagged. At the end of the data collection period, the data for these records (both the items needing to be imputed and the other variables needed by the model) were pulled and run through the imputation program. The resulting imputed values were loaded back to the records, and the records were made available for review.

Data Analysis

The complex edit ensured the full internal consistency of the record. Successfully completing the edit did not provide insight as to whether the report was reasonable compared to other reports in the county. Analysts were provided an additional set of tools, in the form of listings and graphs, to review record-level data across farms. These examinations revealed extreme outliers, large and small, or unique data distribution patterns that were possibly a result of reporting, recording, or handling errors. Potential problems were investigated and, when necessary, corrections were made, and the record interactively edited again.

When NASS summarizes data from the census of agriculture, each individual report is typically assigned to a single “principal” county. The principal county is the county in which the majority of an operation’s agricultural products are produced, as reported by the producer. For large operations that have significant production in multiple counties, their reports may be broken up into multiple source counties to more accurately summarize the data. Similarly, for large farms operating in more than one State, separate report forms are completed by State in order to assign the proper portion of the farm’s total agricultural production to each State in which the farm operates.

ACCOUNTING FOR UNDERCOVERAGE, NONRESPONSE, AND MISCLASSIFICATION

Although much effort has been expended making the CML as complete and accurate as possible, it does not include all U.S. farm operations, resulting in list undercoverage. Additionally, some farm operations on the CML did not respond to the census, despite numerous contact attempts. Finally, although each operation was classified as a farm or a nonfarm based on their census responses, some were misclassified; that is, some nonfarms were classified as farms and some farms were classified as nonfarms. NASS’s goal is to produce agricultural census totals for publication at the county level that are fully adjusted for these factors: list undercoverage, nonresponse, and misclassification.

In 2017, NASS used a series of models based on a subset of the responding census and all the JAS records in a capture-recapture framework to separately adjust for undercoverage, nonresponse, and misclassification. For the 2022 Census of Agriculture, the capture-recapture methodology was extended to model the probability of capture with a single model, thereby allowing the utilization of all census responses and JAS records in the adjustments. To implement capture-recapture methods, two independent samples are required. The 2022 Census of Agriculture (based on the CML) and the 2022 JAS (based on the area frame) were those two samples. Historically, NASS has been careful to maintain the independence of the CML and the area frame. Thus, the Census of Agriculture and the JAS were assumed to be independent after accounting for heterogeneity in the capture probabilities based on characteristics of records.

For a farm to be identified as a farm, and thus captured by the census, it must be on the CML, respond to the census report form, and be classified as a farm on the form. Thus, the capture probability π_C is of interest:

$\pi_C = \pi(\text{CML, Responded, Farm on Census}|\text{Farm})$

Two types of classification error can occur. First, a farm can be misclassified as a nonfarm. This type of misclassification is accounted for in determining the probability of capture π_C. The second type of classification

error results when a response to the census is classified as a farm operation when it does not meet the definition of a farm. That is, some farms on the CML may be misclassified from their census report response and may be nonfarms. To account for the misclassification of nonfarms as farms, the probability of a farm on the census being classified correctly must be estimated; that is,

$\pi_{CCFC} = \pi(\text{Farm} \mid \text{Farm on Census})$

where *CCFC* represents Correct Census Farm Classification. To adjust for undercoverage, nonresponse, and misclassification, each CML record classified as a farm based on its response to the census report form was given a weight of the ratio of the estimated probability of correct classification of a farm on the census and the estimated probability of capture $(\hat{\pi}_{CCFC}/\hat{\pi}_C$ where the hat symbol ($\hat{}$) denotes an estimate). To estimate the number of farms with a given set of characteristics, the weights of CML records responding as farms on the census and having that set of characteristics were summed.

This estimator is referred to as the capture-recapture estimator (*CR*):

$$CR = \sum_{i \in F} \frac{\hat{\pi}_{CCFC,i}}{\hat{\pi}_{C,i}}$$

where *F* is the set of all CML records classified as farms based on their responses to the census report form.

To estimate these probabilities $(\hat{\pi}_C \text{ and } \hat{\pi}_{CCFC})$, the records in the 2022 JAS sample were matched to the 2022 CML using probabilistic record linkage allowing the records only on the CML, JAS, and on both the CML and JAS to be identified. All CML records and JAS tracts were used to estimate the capture-recapture probabilities jointly.

Resolving Farm Status

The farm status based on census responses to either the CML or NML census data collection and the response on the JAS agreed in most cases; these records are referred to as having resolved farm status. However, in other cases, a record was identified as a farm (nonfarm) on the JAS and as a nonfarm (farm) on the CML or the NML. Such records are said to have conflicting or unresolved farm status. An operation identified as a farm is referred to as in-scope; an operation identified as a nonfarm is referred to as out-of-scope. From the set of matched records, two groups with conflicting farm status were identified: 1) in-scope JAS records that were out-of-scope on the census and 2) census in-scope and JAS out-of-scope records. The records with conflicting farm status were sent to NASS regional field offices for review. In each case, efforts were made to determine whether (1) the status had changed between June and December when the census was conducted, (2) the JAS farm status was correct, (3) the census farm status was correct, (4) the records were incorrectly matched, or (5) the farm status could not be resolved.

The probability that an operation is a farm was estimated for census and JAS by using a conditional logistic model. Only those records identified as a farm based on either their JAS response or their Census response were used to develop the model for estimating the probability a record is associated with a farm. Operations with matching farm status were considered as certain if the farm status agreed between the JAS and the CML. If the status between the JAS and CML was conflicting, then the operation was treated as uncertain during the modeling stages. Characteristics of the operations were considered as potential covariates in the model. Variable selection was conducted using a stepwise algorithm to maximize the conditional likelihood. The probability of being a farm is estimated for each record classified as a farm based on their JAS or census response. The estimated probability is used as a weight in all subsequent modeling.

Capture Probabilities

Recall that, for a farm to be identified as a farm, and thus captured, by the census, it must be on the CML, respond to either the census or JAS report form and, based on that response, be classified as a farm. Therefore, the probability of capture π_C may be written as

$\pi_C = \pi(\text{CML, Responded, Farm on Census}|\text{Farm})$
$= \pi(\text{CML}|\text{Farm})\pi(\text{Responded}|\text{CML, Farm})\pi(\text{Farm on Census}|\text{CML, Responded, Farm})$

Terms in the probability of capturing a farm depend on characteristics of the farm. These terms, as well as the corresponding terms associated with a farm being captured by the JAS, were jointly estimated from a single model. Using all Census and JAS data, model variables were selected by applying a stepwise variable selection algorithm and expert opinion. Estimation was based on a conditional weighted likelihood. The events of a farm being included in the CML, the JAS or both were included in the likelihood. The event of a farm not being included in either the JAS or the CML was excluded from the likelihood but was accounted for through the model's capture-recapture properties. Although the probability of capture is estimated for both CML and JAS records, only CML records with a census response are given a census weight; records with only a JAS response are not given a census weight or used further to produce census estimates.

Because Alaska is not included in the JAS and thus has no area frame, the Alaskan agricultural operations were not

included in the capture-recapture process. No adjustments were made for undercoverage or misclassification. To account for nonresponse, the CML records were divided into three groups: (1) the Must records, (2) the Criteria Records, and (3) the remaining CML records. The must records received a weight of one, thereby receiving no adjustment for nonresponse. The probability of response for each of the other two groups was the proportion of responders within the group. Each record within the group was then given a weight equal to the reciprocal of the probability of response.

Misclassification

An operation is misclassified if: (1) it meets the definition of a farm but is classified as a nonfarm on the census or (2) it does not meet the definition of a farm but is classified as a farm on the census. The first type of misclassification is accounted for when modeling the probability of capture. An adjustment is still needed for the misclassification of nonfarms as farms. As with farm status and capture, the probability of this misclassification depends on an operation's characteristics. Thus, a conditional logistic model was developed. Given that a farm on the CML was classified as a farm in the census, the probability of its being a farm was modeled based on its characteristics.

CALIBRATION

Each operation identified as being in-scope on the CML was given a weight equal to the probability of misclassifying a nonfarm as a farm on the census divided by the probability of capture. This weight accounted for undercoverage, nonresponse, and both types of misclassification.

The record weighting processes were initially applied at the State level to produce adjusted estimates of farm numbers, land in farms, and for 64 different categories of characteristics of the farm operation or the farm producer -- value of agricultural sales (10); age (2); female; race (3); Hispanic origin; 4 sales categories for each of 10 major commodities (40); and farm type groups (7). The State-level number of farms and land in farms were two additional adjusted estimates, resulting in 66 categories. To reduce the intercensal variation at the State level, the State targets were smoothed by averaging the 2022 estimates from capture-recapture and the published 2017 State estimates.

These State estimates were general purpose in that they did not provide any control over expected levels of commodity production of the individual farm operation. As a result of this limitation, the procedures could have over-adjusted or under-adjusted for commodity production. To address this, a second set of variables, known as commodity targets, was added to the calibration algorithm. These targets were commodity totals from administrative sources or from NASS surveys of nonfarm populations (e.g., USDA Farm Service Agency program data, Agricultural Marketing Service market orders, livestock slaughter data, cotton ginning data). The introduction of these commodity coverage targets strengthened the overall adjustment procedure by ensuring that major commodity totals remained within reasonable bounds of established benchmarks.

Each State was calibrated separately. The calibration algorithm addressed commodity coverage. The algorithm was controlled by the 65 State farm operation coverage targets and the State commodity coverage targets. Because calibration targets are estimates subject to uncertainty, NASS allowed some tolerance in the determination of the adjusted weights. Rather than forcing the total for each calibration variable computed using the adjusted weights to equal a specific amount, NASS allowed the estimated total to fall within a tolerance range.

To ensure that all subdomains for which NASS publishes summed to their grand total, integer weights were produced by a discrete calibration algorithm. This eliminated the need for rounding individual cell values and ensured that marginal totals always added correctly to the grand total. If a weight was initially not in the interval [1,6], it was trimmed so that it was in that interval. That is, adjusted weights less than 1 were set to 1, and those greater than 6 were set to 6. The remaining non-integer weights were then rounded sequentially to reduce the distance of the estimated totals from the targets.

Calibration adjustments began with the computation of a priority index for each record. The priority index was the absolute value of the gradient of the relative error associated with increasing or decreasing a record's weight by one. The record with the highest priority index was then selected as a candidate to increase or decrease its weight by one to reduce the cumulative distance from the targets as measured by the relative error. If the new value produced an improvement and satisfied the range restrictions, the weight was updated and new priorities were assigned; otherwise, the record with the next highest priority index was processed. This process was iteratively performed until convergence was attained. Because census data collection was assumed to be complete for very large and unique farms, their weights were set to 1 during the calibration adjustment process. For all other farms, the final census record weights were forced to be an integer number in the interval [1, 6]. The calibration process considered all targets simultaneously through the priority index. Although calibration was seldom able to adjust

weights so that all State targets were met, all targets were brought collectively as close to the targets as possible.

The proportions of selected census data items that were due to coverage, response, and classification adjustments are displayed in Tables A and C.

DISCLOSURE REVIEW

After tabulation and review of the aggregates, a comprehensive disclosure review was conducted. NASS is obligated to withhold, under Title 7, U.S. Code, any total that would reveal an individual's information or allow it to be closely estimated by the public. Farm counts are not considered sensitive and are not subject to disclosure controls. Cell suppression was used to protect the cells that were determined to be sensitive to a disclosure of information.

Based on agency standards, data cells were determined to be sensitive to a disclosure of information if they failed either of two rules. The threshold rule failed if the data cell contained less than three operations. For example, if only one farmer produced turkeys in a county, NASS could not publish the county total for turkey inventory without disclosing that individual's information. The dominance rule failed if the distribution of the data within the cell allowed a data user to estimate any respondent's data too closely. For example, if there are many farmers producing turkeys in a county and some of them were large enough to dominate the cell total, NASS could not publish the county total for turkey inventory without risking disclosing an individual respondent's data. In both of these situations, the data were suppressed and a "(D)" was placed in the cell in the census publication table. These data cells are referred to as primary suppressions.

Since most items were summed to marginal totals, primary suppressions within these summation relationships were protected by ensuring that there were additional suppressions within the linear relationship that provided adequate protection for the primary. A detailed computer routine selected additional data cells for suppression to ensure all primary suppressions were properly protected. These data cells are referred to as complementary suppressions. These cells are not themselves sensitive to a disclosure of information but were suppressed to protect other primary suppressions. A "(D)" was also placed in the cell of the census publication table to indicate a complementary suppression. A data user cannot determine whether a cell with a (D) represents a primary or a complementary suppression.

Regional field office analysts reviewed all complementary suppressions to ensure no cells had been withheld that were vital to the data users. In instances where complementary suppressions were deemed critically important to a State or county, analysts requested an override, and a different complementary cell was chosen.

CENSUS QUALITY

The purpose of the census of agriculture is to account for "any place from which $1,000 or more of agricultural products were produced and sold, or normally would have been sold, during the census year." To accomplish this, NASS develops a CML that contains identifying information for operations that have an indication of meeting the census definition, develops procedures to collect agricultural information from those records, establishes criteria for analyst review of the data, creates computer routines to correct or complete the requested information, and provides census estimates of the characteristics of farms and farm producers with associated measures of uncertainty.

It is not likely that either the CML includes all operations that meet the definition of a farm or that all those that do meet the definition of a farm respond to the census inquiry. The goal is to publish data with a high level of quality. The quality of a census may be measured in many ways. One of the first indicators used is a measure of the response to the census data collection as it has generally been thought that a high response rate indicates more complete coverage of the population of interest. This is a valid assumption if the enumeration list, the CML here, has complete coverage of the population of interest. In the case of the census of agriculture, the definition requiring advance knowledge of sales makes achieving a high level of coverage difficult. To ensure that the census of agriculture is as complete as possible, records are included that might not meet the census definition of a farm – in fact, almost 50 percent more records than the anticipated number of qualifying farm operations were included in the 2022 CML. A second indicator of quality then is the coverage of the farm population by the CML. Other indicators of quality relate to the accuracy and completeness of the data, and the validity of the procedures used in processing the data.

In some cases, NASS was able to produce measures of quality – such as the response rate to the data collection, the coverage of the census mail list, and the variability of the final adjusted estimates. In other cases, measures were not produced but descriptions of procedures that NASS used to reduce errors from the procedures were subsequently provided.

Census Response Rate

The response rate is one indicator of the quality of a data

collection. It is generally assumed that if a response rate is close to a full participation level of 100 percent, the potential for nonresponse bias is small, although this has been questioned in the literature. The response rate for the 2022 Census of Agriculture CML was 61.0 percent, as compared with the 2017 Census of Agriculture's response rate of 71.8 percent and 74.6 percent for the 2012 Census of Agriculture.

The 2022 Census of Agriculture's response rate used the fourth response rate formula (RR4) from the American Association of Public Opinion Research's Response Rate Standard Definitions manual:

$$RR4 = \frac{C_{adj}}{C_{adj} + R + NC + O + Replicated + e(U)}(100)$$

where
C_{adj} = number of fully and partially completed records, excluding replicated records
R = number of explicit refusals
NC = number of non-contacted operations known to be eligible
O = number of other types of nonrespondents
Replicated = number of replicated records
U = number of operations of unknown eligibility
$e(U)$ = estimated number of operations of unknown eligibility assumed to be eligible

Records were classified into the above variables based on the combination of their active status (AS) codes, in-scope status, and replication status. Active status refers to the eligibility status of records for selection on the CML. All replicated records were considered a form of nonresponse and were classified into other nonrespondents; in-scope status was considered immaterial.

Certain active status classifications indicated records of unknown agricultural status. These classifications included records to be removed from the CML but had data from outside sources indicating agricultural activity, new records from outside data sources, nonrespondents and refusals to the NACS, records for regional office handling only, and records with Farm Service Agency or Conservation Reserve Program data on operations that are not owned by the principal producer. These records were stratified (grouped) based on their probabilities of being in-scope had they responded. The estimated number of in-scope nonrespondents was calculated for the *h*th stratum (group) by the following formula:

$$e(U_h) = \left(\frac{C_{in-scope,h}}{C_h}\right)U_h$$

where
$e(U_h)$ = estimated number of operations of unknown eligibility assumed to be eligible in the *h*th group
$C_{in-scope,h}$ = the number of completed and in-scope census records in the *h*th group
C_h = the number of completed census records in the *h*th group
U_h = number of operations of unknown eligibility in the *h*th group

Census Coverage

As a side-product of the statistical adjustment used to account for undercoverage, nonresponse of farms on the CML, and misclassification of responses to the census, the proportion of the adjustments due to each of those factors can be derived. The percentage of final census estimates due to adjustments for undercoverage, nonresponse, and misclassification as well as the total percent adjustment for selected items are displayed in Tables A and C.

MEASURED ERRORS IN THE CENSUS PROCESS

NASS uses statistical procedures in compiling the CML, in its data collection procedures, in data editing and processing, and in compiling the final data. Additionally, it uses statistical procedures to both measure errors in the various processes when adjusting for those errors in the final data. One example is the statistical process used to account for undercoverage, nonresponse of farms on the CML, and misclassification of responses to the census. The basis of the undercoverage adjustment is the capture-recapture procedure that uses the area sample enumeration from the JAS. The largest contributors to error in the census estimates are due to the adjustments for nonresponse, undercoverage, misclassification, and integer calibration.

Variability in Census Estimates due to Statistical Adjustment

In conducting the 2022 Census of Agriculture, efforts were initiated to measure error associated with the adjustments for farm operations that were not on the CML; for farm operations that were on the CML but did not respond to the census report form; for farms and nonfarms that were misclassified as nonfarms and farms, respectively; and for integer calibration. These error measurements were developed from the standard error of the estimates at the national, State, and county levels and were expressed as coefficients of variation (CVs) at the national and State levels and as generalized coefficients of variation (GCVs) at the county levels.

The standard error of an estimate is an estimate of the

standard deviation of the sampling distribution of the estimator. In each case, standard errors were computed using an approach based on a delete-a-group jackknife methodology. To conduct the jackknifing, $k = 10$ mutually exclusive and exhaustive groups of records were formed. The groups were selected using a stratified random design so that each group reflected capture status by the CML and the JAS. Based on estimated weights for records in each group, a delete-a-group jackknife estimator of the variance would account for the uncertainty associated with modeling the capture-recapture probabilities and the uncertainty due to integer calibration. Therefore, the weights within each jackknife group were computed using the group-specific models and calibrated to match group-specific targets. For a given data item *i*, such as the number of farms, the estimate was computed at the specified geographical level, such as nation, State, or county, using the weights obtained for group *j*. Estimates of the variance and standard error associated with the estimator T_i are then, respectively,

$$\sigma_i^2 = \frac{k-1}{k}\sum_{j=1}^{k}\left(T_i^{(j)} - \sum_{l=1}^{k}\frac{T_i^{(l)}}{k}\right)^2; \quad SE(T_i) = \sqrt{\sigma_i^2}$$

Ten (10) calibration-adjusted jackknife groups were used to provide standard errors for 2022 State and national estimates (i.e., $k=10$). For the estimate of the number of farms with a given set of characteristics, only the CML records with those characteristics were used to obtain the overall estimate as well as the estimates from each calibrated jackknife group.

Note that the calibrated jackknife groups were only constructed once, and different subsets of the records were used to compute estimates and standard errors for the data items.

The CV is a measure of the relative amount of error associated with the sample estimate:

$$\mathrm{CV}_i = \frac{SE(T_i)}{T_i}100\%$$

where $SE(T_i)$ is the standard error of the capture-recapture estimate for data item *i*. This relative measure allows the reliability of a range of estimates to be compared. For example, the standard error is often larger for large population estimates than for small population estimates, but the large population estimates may have a smaller CV, indicating a more reliable estimate. For county-level estimates, a generalized coefficient of variation (GCV) was determined for each estimate within a State. A generalized variance function relates a function of the variance of an estimator to a function of the estimator. Within a State, the standard error of an estimate for a data item was often found to be linearly related to the estimate of that item with an intercept of zero. Based on this modeled relationship, the GCV is the slope of the line relating the standard error to the estimate, multiplied times 100 to represent the GCV as a percentage.

The standard error is the product of the CV (or GCV for county estimates) and the estimate divided by 100. As an example, if the GCV for a State is 25 percent and a county's estimate is 4, then the standard error is 25(4)/100 = 1. The standard error of an estimated data item from the census provides a measure of the uncertainty associated with that estimated data item due to the possible outcomes of the census collection, including incompleteness of the CML, nonresponse to the census, misclassification either as a farm or as a nonfarm, and the integer calibration. With 95 percent confidence, an estimate is within two standard errors of the true value being estimated. For this example, with 95 percent confidence, the estimate of 4 is within 2(1) = 2 of the true county value.

Note: The standard errors and consequently, the CVs tend to be substantially smaller than those reported for the 2017 Census of Agriculture. For 2017, the model of the probability of capture incorporated information from the approximately 40,000 respondents to the 2017 JAS and the census records matching a JAS record. In contrast, the models for the 2022 Census of Agriculture relied on information from the approximately 1 million responding CML records and the 2022 JAS, some of which were on both the CML and the JAS. The large increase in the number of records used in the modeling process led to a major decrease in the measures of uncertainty (standard errors and CVs).

Table B presents the fully adjusted estimates with the coefficient of variation for selected items.

NONMEASURED ERRORS IN THE CENSUS PROCESS

As noted in the previous section, errors can be introduced from adjustments for coverage, nonresponse, and misclassification and from integer calibration. These errors are measurable. However, nonsampling errors are imbedded in the census process that cannot be directly measured as part of the design of the census but must be contained to ensure an accurate count. Extensive efforts were made to compile a complete and accurate mail list for the census, to elicit response to the census, to design an understandable report form with clear instructions, to minimize processing errors through the use of quality control measures, to reduce matching error associated with the capture-recapture estimation process, and to minimize

error associated with identification of a respondent as a farm operation (referred to as classification error). The weight adjustment and tabulation processes recognize the presence of nonsampling errors; however, it is assumed that these errors are small and that, in total, the net effect is zero. In other words, the positive errors cancel the negative errors.

Respondent and Enumerator Error

Incorrect or incomplete responses to the census report form or to the questions posed by an enumerator can introduce error into the census data. Steps were taken in the design and execution of the Census of Agriculture to reduce errors from respondent reporting. Poor instructions and ambiguous definitions lead to misreporting. Respondents may not remember accurately, may estimate responses, or may record an item in the wrong cell. To reduce reporting and recording errors, the report form was tested prior to the census using industry-accepted cognitive testing procedures. Detailed instructions for completing the report form were provided to each respondent. Questions were phrased as clearly as possible based on previous tests of the report form. Computer-assisted telephone interviewing software included immediate integrity checks of recorded responses so suspect data could be verified or corrected. In addition, each respondent's answers were checked for completeness and consistency by the complex edit and imputation system.

Processing Error

Processing of each census report form was another potential source of nonsampling error. All mail returns that included multiple reports, respondent remarks, or that were marked out of business and report forms with no reported data were sent to an analyst for verification and appropriate action. Integrity checks were performed by the imaging system and data transfer functions. Standard quality control procedures were in place that required that randomly selected batches of data keyed from image be re-entered by a different operator to verify the work and evaluate key entry operators. All systems and programs were thoroughly tested before going on-line and were monitored throughout the processing period.

Developing accurate processing methods is complicated by the complex structure of agriculture. Among the complexities are the many places to be included, the variety of arrangements under which farms are operated, the continuing changes in the relationship of producers to the farm operated, the expiration of leases and the initiation or renewal of leases, the problem of obtaining a complete list of agriculture operations, the difficulty of contacting and identifying some types of contractor/contractee relationships, the producer's absence from the farm during the data collection period, and the producer's opinion that part or all of the operation does not qualify and should not be included in the census. During data collection and processing of the census, all operations underwent a number of quality control checks to ensure results were as accurate as possible.

Item Nonresponse

All item nonresponse actions provide another opportunity to introduce measurement errors. Regardless of whether previously reported data, administrative data, the nearest neighbor algorithm, the fully conditional specification method, or manual imputation is used to complete a nonresponse item, some risk exists that the imputed value does not equal the actual value. Previously reported and administrative data were used only when they related to the census reference period. A new nearest neighbor was randomly selected for each incident to eliminate the chance of a consistent bias.

Record Matching Error

The process of building and expanding the CML involves finding new list sources and checking for names not on the list. An automated processing system compared each new name to the existing CML names and "linked" like records for the purpose of preventing duplication. New names with strong links to a CML name were discarded and those with no links were added as potential farms. Names with weak links, possible matches, were reviewed by staff to determine whether the new name should be added. Despite this thorough review, some new names may have been erroneously added or deleted. Additions could contribute to duplication (overcoverage) whereas deletions could contribute to undercoverage. As a result, some names received more than one report form, and some farm producers did not receive a report form. Respondents were instructed to complete one form and return all forms so the duplication could be removed.

Another chance for error came when comparing June Area Survey tract producer names to the CML. Area producers whose names were not found on the CML were part of the measure of list incompleteness, or NML. Mistakes in determining overlap status resulted in overcounts (including a tract whose producer was on the CML) or undercounts (excluding a tract whose producer was not on the CML). All tracts determined to not be on the list were triple checked to eliminate, or at least minimize, any error. NML tract producers were mailed a report form printed in a different color. To identify duplication, all respondents who received multiple report forms were instructed to complete the CML version and return all forms so

duplication could be removed.

Records in the 2022 JAS were matched to the 2022 census using probabilistic record linkage. The records of operations with differing farm status were sent out to be reviewed by NASS regional field offices. If farm status could not be resolved, the probability of an operation being a farm was imputed using a missing data model. The uncertainty associated with this estimate apart from model uncertainty was accounted for, but errors not found through this process were not.

Table A. **Summary of State Coverage, Nonresponse, and Misclassification Adjustments: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
Farms ..... number	65,531	4,913	35.6	11.1	12.8	11.7
Land in farms ..... acres	25,442,625	7,766,836	31.9	1.6	5.7	24.5
Farms by size:						
1 to 9 acres ..... farms	4,401	1,621	55.9	25.2	18.0	12.8
acres	22,106	9,123	53.8	22.9	18.1	12.7
10 to 49 acres ..... farms	15,218	2,233	39.4	16.1	13.7	9.6
acres	398,319	56,793	36.3	14.9	12.5	8.9
50 to 69 acres ..... farms	3,598	527	31.3	12.7	10.7	7.9
acres	211,291	30,533	31.4	12.7	10.7	8.0
70 to 99 acres ..... farms	5,575	897	30.8	9.4	11.3	10.1
acres	455,348	72,388	30.8	9.4	11.2	10.2
100 to 139 acres ..... farms	4,857	817	30.0	10.0	10.8	9.2
acres	567,895	94,730	30.1	9.9	10.9	9.3
140 to 179 acres ..... farms	4,814	769	31.2	7.9	11.8	11.5
acres	757,338	120,866	31.2	7.9	11.8	11.5
180 to 219 acres ..... farms	2,981	426	31.9	6.9	12.5	12.5
acres	588,138	84,561	31.8	7.0	12.6	12.3
220 to 259 acres ..... farms	2,503	302	29.2	6.9	13.3	9.0
acres	594,776	71,591	29.2	6.9	13.2	9.0
260 to 499 acres ..... farms	8,699	1,505	34.7	4.3	19.3	11.1
acres	3,130,858	571,131	34.9	4.3	19.6	11.0
500 to 999 acres ..... farms	6,421	2,061	34.3	2.6	19.1	12.5
acres	4,468,495	1,449,070	34.2	2.5	19.4	12.3
1,000 to 1,999 acres ..... farms	3,752	1,273	32.8	1.2	11.5	20.1
acres	5,173,695	1,821,880	32.9	1.1	11.2	20.6
2,000 acres or more ..... farms	2,712	1,481	35.2	0.4	1.8	33.1
acres	9,074,366	4,251,485	29.3	0.2	0.8	28.3
Irrigated land use:						
Harvested cropland ..... farms	3,551	512	38.8	15.4	12.6	10.8
acres	644,857	159,218	30.6	0.8	3.5	26.3
Pastureland and other land ..... farms	160	16	43.7	9.6	29.2	5.0
acres	3,456	846	29.0	6.1	15.4	7.4
Market value of agricultural products sold $1,000	28,482,097	6,450	29.9	2.3	5.9	21.7
Farms by value of sales:						
Less than $1,000 ..... farms	15,502	994	30.9	14.5	9.9	6.5
$1,000	1,169	(Z)	51.0	26.7	19.0	5.3
$1,000 to $2,499 ..... farms	3,496	215	44.8	19.6	18.9	6.4
$1,000	5,706	(Z)	44.6	19.5	18.9	6.2
$2,500 to $4,999 ..... farms	3,533	157	42.5	18.5	17.2	6.7
$1,000	12,660	1	42.4	18.5	17.1	6.8
$5,000 to $9,999 ..... farms	4,091	262	41.5	17.4	15.5	8.6
$1,000	29,240	2	41.3	17.3	15.7	8.3
$10,000 to $19,999 ..... farms	4,177	815	36.2	14.8	14.2	7.2
$1,000	59,970	12	36.0	14.6	13.8	7.6
$20,000 to $24,999 ..... farms	1,385	286	35.7	15.8	14.4	5.6
$1,000	30,596	6	35.7	15.7	14.3	5.7
$25,000 to $39,999 ..... farms	2,858	765	35.1	13.9	11.4	9.8
$1,000	90,565	25	35.1	13.8	11.3	10.1
$40,000 to $49,999 ..... farms	1,410	424	36.4	13.4	15.7	7.3
$1,000	62,843	19	36.4	13.4	15.7	7.4
$50,000 to $99,999 ..... farms	5,328	954	42.7	11.2	13.8	17.7
$1,000	386,353	71	42.7	11.2	14.5	16.9
$100,000 to $249,999 ..... farms	6,767	1,706	30.8	6.2	12.4	12.2
$1,000	1,101,110	258	30.6	6.2	12.6	11.7
$250,000 to $499,999 ..... farms	5,372	1,548	36.4	3.9	20.5	12.0
$1,000	1,930,062	570	36.4	3.9	21.0	11.4
$500,000 to $999,999 ..... farms	4,483	1,083	32.4	2.9	15.5	14.0
$1,000	3,183,211	814	32.4	2.9	15.8	13.6
$1,000,000 or more ..... farms	7,129	1,764	35.1	2.3	8.5	24.4
$1,000	21,588,612	5,932	28.6	2.0	4.7	21.9
Farms by legal status for tax purposes:						
Family or individual ..... farms	55,532	3,830	34.9	13.1	14.0	7.9
acres	17,410,756	4,710,189	31.2	3.2	9.6	18.3
Partnership ..... farms	5,022	1,376	43.3	4.3	10.8	28.2
acres	4,452,974	1,772,269	34.0	0.4	2.6	31.0
Corporation:						
Family held ..... farms	3,375	634	37.9	5.1	8.5	24.3
acres	3,085,380	1,176,290	33.6	0.6	3.9	29.1
Other than family held ..... farms	428	101	42.8	11.3	12.8	18.7
acres	159,481	61,434	30.0	2.9	8.3	18.8
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc ..... farms	1,174	74	26.8	8.0	7.4	11.4
acres	334,034	127,117	22.7	4.1	6.8	11.7
Tenure:						
Full owners ..... farms	40,396	3,472	34.8	13.8	11.4	9.6
acres	5,657,674	1,011,691	28.9	6.3	7.5	15.1
Part owners ..... farms	20,564	3,482	35.2	3.8	15.7	15.7
acres	17,880,717	6,260,996	32.0	0.6	4.9	26.4
Tenants ..... farms	4,571	371	44.8	10.3	16.7	17.8
acres	1,904,234	604,177	39.8	4.3	14.2	21.2
Producers characteristics by- [1] (see text)						
Sex of operator:						
Male ..... farms	62,332	5,144	36.2	10.7	13.3	12.2
acres	25,033,191	7,778,945	32.1	1.6	5.8	24.7
Female ..... farms	32,729	1,994	35.4	14.2	13.7	7.5
acres	9,634,361	2,050,422	28.9	3.2	8.0	17.7
Primary occupation:						
Farming ..... farms	51,122	6,592	36.3	6.2	10.4	19.7
Other ..... farms	63,746	4,745	40.0	11.6	14.1	14.3

See footnote(s) at end of table.

--continued

Table A. **Summary of State Coverage, Nonresponse, and Misclassification Adjustments: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
Producers characteristics by- [1] (see text) - Con.							
Hispanic, Latino, or Spanish origin	farms	607	114	34.3	7.1	10.9	16.2
	acres	287,887	98,993	26.3	1.0	2.3	23.1
Race:							
American Indian or Alaska Native	farms	207	72	29.5	8.9	8.1	12.4
	acres	117,541	103,362	7.2	0.4	0.6	6.1
Asian	farms	240	48	47.9	19.2	13.3	15.4
	acres	40,554	24,932	33.4	0.8	1.2	31.4
Black or African American	farms	46	27	41.3	10.8	10.3	20.3
	acres	5,943	1,647	20.1	3.6	3.5	13.0
Native Hawaiian or Other Pacific Islander	farms	39	7	43.6	15.4	20.7	7.5
	acres	9,191	3,309	25.6	6.9	13.5	5.1
White	farms	65,219	4,899	35.6	11.1	12.9	11.7
	acres	25,312,777	7,750,788	32.0	1.7	5.8	24.6
More than one race reported	farms	305	77	31.5	12.1	12.1	7.3
	acres	162,218	119,471	19.3	1.3	1.7	16.3
Military service:							
Never served or only on active duty for training in the Reserves or National Guard (see text)	producers	105,603	9,918	38.7	9.2	12.5	17.0
Active duty now or in the past (see text)	producers	9,265	895	34.3	9.4	11.1	13.8
All producers by age group [1]:							
Under 25 years	farms	1,900	439	63.4	7.2	24.1	32.1
25 to 34 years	farms	9,374	1,556	57.7	13.1	16.3	28.3
35 to 44 years	farms	16,237	2,702	48.3	8.9	13.5	25.9
45 to 54 years	farms	16,743	1,626	40.4	10.2	18.0	12.1
55 to 64 years	farms	29,818	2,647	35.4	9.2	12.3	13.8
65 to 74 years	farms	27,187	2,216	31.9	9.1	9.4	13.3
75 years and over	farms	13,609	975	26.6	8.6	6.8	11.2
Net cash farm income of operations:							
Farms with gains of- [2]							
Less than $1,000	farms	1,541	84	31.6	12.8	9.7	9.0
	$1,000	775	(Z)	32.0	11.7	10.5	9.8
$1,000 to $4,999	farms	4,053	352	31.5	12.3	9.0	10.2
	$1,000	11,280	1	31.4	11.4	9.0	11.1
$5,000 to $9,999	farms	3,053	454	30.8	13.2	10.0	7.6
	$1,000	22,351	3	30.6	13.2	10.0	7.4
$10,000 to $24,999	farms	5,680	795	31.3	12.9	10.1	8.3
	$1,000	95,057	13	31.3	12.7	10.2	8.4
$25,000 to $49,999	farms	5,396	547	32.8	10.0	13.1	9.6
	$1,000	196,292	20	32.9	9.9	13.2	9.8
$50,000 or more	farms	21,773	2,374	32.9	3.7	12.0	17.2
	$1,000	9,745,519	2,341	31.0	2.6	6.4	22.0
Farms with losses of-							
Less than $1,000	farms	1,786	123	37.0	13.6	11.1	12.3
	$1,000	856	(Z)	37.1	13.6	11.6	11.8
$1,000 to $4,999	farms	6,380	573	39.7	18.8	14.5	6.5
	$1,000	18,668	2	40.5	19.0	15.3	6.3
$5,000 to $9,999	farms	5,021	555	43.1	19.6	17.5	6.0
	$1,000	36,645	4	43.3	19.8	17.5	6.0
$10,000 to $24,999	farms	5,999	557	42.2	18.6	16.3	7.3
	$1,000	95,543	9	42.4	18.4	16.5	7.5
$25,000 to $49,999	farms	2,539	234	45.3	14.4	18.2	12.7
	$1,000	87,840	8	45.2	13.9	17.5	13.8
$50,000 or more	farms	2,310	353	38.8	6.8	11.2	20.8
	$1,000	534,873	109	30.6	2.6	6.9	21.2
Livestock and poultry:							
Cattle and calves inventory	farms	16,823	968	37.1	27.2	6.6	3.2
	number	2,121,625	268,472	34.8	17.9	9.8	7.1
Beef cows inventory	farms	11,691	722	35.5	26.1	5.9	3.4
	number	364,629	38,419	33.0	17.1	9.0	6.8
Milk cows inventory	farms	2,185	65	40.5	22.9	14.6	3.1
	number	459,536	32,139	25.2	12.8	5.8	6.5
Hog and pigs inventory	farms	2,928	1,258	43.4	5.2	14.6	23.6
	number	8,873,776	5,727,658	22.5	1.2	3.6	17.7
Layers inventory	farms	6,146	559	51.8	19.3	26.9	5.6
	number	14,553,497	257,308	42.9	12.2	10.8	19.9
Broilers sold	farms	1,028	146	47.4	17.2	24.4	5.7
	number	41,793,592	10,736,727	20.0	4.0	12.4	3.6
Aquaculture sold	farms	98	42	36.7	10.8	17.0	8.9
	$1,000	19,763	6	39.7	15.5	9.8	14.4
Selected crops harvested:							
Corn for grain	farms	24,697	4,941	32.6	7.6	24.7	0.3
	acres	7,732,455	1,656,356	32.7	3.8	27.6	1.3
Durum wheat for grain	farms	31	13	45.2	6.9	7.9	30.4
	acres	(D)	(D)	(D)	(D)	(D)	(D)
Other spring wheat for grain	farms	3,557	2,270	36.1	1.0	4.2	30.9
	acres	1,261,299	687,161	27.7	0.1	0.9	26.7
Winter wheat for grain	farms	102	27	41.2	8.8	19.6	12.8
	acres	(D)	(D)	(D)	(D)	(D)	(D)
Sorghum for grain	farms	12	5	33.3	18.9	3.7	10.8
	acres	364	63	11.0	7.1	1.7	2.2
Soybeans for beans	farms	25,337	9,759	36.2	3.9	14.3	18.0
	acres	7,597,171	3,578,047	32.8	0.9	6.5	25.4
Rice	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Cotton	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-

See footnote(s) at end of table.

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Table A. **Summary of State Coverage, Nonresponse, and Misclassification Adjustments: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
Selected crops harvested: - Con.							
Peanuts	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Barley	farms	336	156	38.1	1.3	3.8	33.1
	acres	55,330	27,245	33.0	0.4	1.9	30.7
Oats	farms	2,329	1,032	50.3	11.7	18.2	20.4
	acres	126,011	34,117	58.5	4.5	11.6	42.4
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	23,394	1,682	35.7	16.0	12.7	7.0
	acres	1,392,072	250,302	33.9	10.5	12.5	10.9
Land in vegetables (see text)	farms	2,620	323	39.2	19.1	15.0	5.2
	acres	196,718	29,468	22.2	2.0	4.5	15.8
Potatoes	farms	509	183	36.9	15.0	12.0	9.9
	acres	49,008	24,632	8.3	0.3	0.3	7.8
Tomatoes in the open	farms	592	107	44.8	26.0	16.4	2.3
	acres	300	73	27.1	15.0	7.3	4.8
Sweet corn (see text)	farms	1,243	153	33.1	14.6	14.8	3.7
	acres	96,990	5,194	26.6	4.1	16.1	6.5
Lettuce	farms	322	61	44.7	29.5	13.3	1.8
	acres	94	17	34.8	22.0	9.4	3.4
Land in orchards (see text)	farms	1,174	91	42.2	25.0	13.1	4.0
	acres	5,049	316	24.3	10.2	5.4	8.7
Apples	farms	751	53	41.7	25.1	12.5	4.1
	acres	3,219	224	18.3	6.7	3.0	8.5
Grapes (including muscadine) (see text)	farms	433	41	44.8	25.1	15.5	4.2
	acres	1,290	95	34.5	17.9	10.4	6.2
Oranges	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Almonds	farms	-	-	-	-	-	-
	acres	-	-	-	-	-	-
Land in berries	farms	578	43	42.6	24.0	14.5	4.1
	acres	1,129	234	19.3	5.0	3.5	10.8

[1] Data were collected for a maximum of four producers per farm.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.

Table B. **Reliability Estimates of State Totals: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Item	Total	Coefficient of variation (percent)
Farms ..... number	65,531	7.5
Land in farms ..... acres	25,442,625	30.5
Farms by size:		
1 to 9 acres ..... farms	4,401	36.8
acres	22,106	41.3
10 to 49 acres ..... farms	15,218	14.7
acres	398,319	14.3
50 to 69 acres ..... farms	3,598	14.7
acres	211,291	14.5
70 to 99 acres ..... farms	5,575	16.1
acres	455,348	15.9
100 to 139 acres ..... farms	4,857	16.8
acres	567,895	16.7
140 to 179 acres ..... farms	4,814	16.0
acres	757,338	16.0
180 to 219 acres ..... farms	2,981	14.3
acres	588,138	14.4
220 to 259 acres ..... farms	2,503	12.1
acres	594,776	12.0
260 to 499 acres ..... farms	8,699	17.3
acres	3,130,858	18.2
500 to 999 acres ..... farms	6,421	32.1
acres	4,468,495	32.4
1,000 to 1,999 acres ..... farms	3,752	33.9
acres	5,173,695	35.2
2,000 acres or more ..... farms	2,712	54.6
acres	9,074,366	46.9
Irrigated land use:		
Harvested cropland ..... farms	3,551	14.4
acres	644,857	24.7
Pastureland and other land ..... farms	160	9.7
acres	3,456	24.5
Market value of agricultural products sold $1,000	28,482,097	22.6
Farms by value of sales:		
Less than $1,000 ..... farms	15,502	6.4
$1,000	1,169	19.1
$1,000 to $2,499 ..... farms	3,496	6.1
$1,000	5,706	6.6
$2,500 to $4,999 ..... farms	3,533	4.4
$1,000	12,660	4.4
$5,000 to $9,999 ..... farms	4,091	6.4
$1,000	29,240	7.0
$10,000 to $19,999 ..... farms	4,177	19.5
$1,000	59,970	19.9
$20,000 to $24,999 ..... farms	1,385	20.7
$1,000	30,596	21.0
$25,000 to $39,999 ..... farms	2,858	26.8
$1,000	90,565	27.1
$40,000 to $49,999 ..... farms	1,410	30.1
$1,000	62,843	30.1
$50,000 to $99,999 ..... farms	5,328	17.9
$1,000	386,353	18.3
$100,000 to $249,999 ..... farms	6,767	25.2
$1,000	1,101,110	23.4
$250,000 to $499,999 ..... farms	5,372	28.8
$1,000	1,930,062	29.5
$500,000 to $999,999 ..... farms	4,483	24.2
$1,000	3,183,211	25.6
$1,000,000 or more ..... farms	7,129	24.7
$1,000	21,588,612	27.5
Farms by legal status for tax purposes:		
Family or individual ..... farms	55,532	6.9
acres	17,410,756	27.1
Partnership ..... farms	5,022	27.4
acres	4,452,974	39.8
Corporation:		
Family held ..... farms	3,375	18.8
acres	3,085,380	38.1
Other than family held ..... farms	428	23.6
acres	159,481	38.5
Other - estate or trust, prison farm, grazing association, American Indian Reservation, etc ..... farms	1,174	6.3
acres	334,034	38.1
Tenure:		
Full owners ..... farms	40,396	8.6
acres	5,657,674	17.9
Part owners ..... farms	20,564	16.9
acres	17,880,717	35.0
Tenants ..... farms	4,571	8.1
acres	1,904,234	31.7
Producers characteristics by- [1] (see text)		
Sex of operator:		
Male ..... farms	62,332	8.3
acres	25,033,191	31.1
Female ..... farms	32,729	6.1
acres	9,634,361	21.3
Primary occupation:		
Farming ..... farms	51,122	12.9
Other ..... farms	63,746	7.4
Producers characteristics by- [1] (see text) - Con.		
Hispanic, Latino, or Spanish origin ..... farms	607	18.7
acres	287,887	34.4
Race:		
American Indian or Alaska Native ..... farms	207	34.7
acres	117,541	87.9
Asian ..... farms	240	19.9
acres	40,554	61.5
Black or African American ..... farms	46	58.7
acres	5,943	27.7
Native Hawaiian or Other Pacific Islander ..... farms	39	17.4
acres	9,191	36.0
White ..... farms	65,219	7.5
acres	25,312,777	30.6
More than one race reported ..... farms	305	25.1
acres	162,218	73.6
Military service:		
Never served or only on active duty for training in the Reserves or National Guard (see text) ..... producers	105,603	9.4
Active duty now or in the past (see text) ..... producers	9,265	9.7
All producers by age group [1]:		
Under 25 years ..... farms	1,900	23.1
25 to 34 years ..... farms	9,374	16.6
35 to 44 years ..... farms	16,237	16.6
45 to 54 years ..... farms	16,743	9.7
55 to 64 years ..... farms	29,818	8.9
65 to 74 years ..... farms	27,187	8.2
75 years and over ..... farms	13,609	7.2
Net cash farm income of operations:		
Farms with gains of- [2]		
Less than $1,000 ..... farms	1,541	5.4
$1,000	775	5.7
$1,000 to $4,999 ..... farms	4,053	8.7
$1,000	11,280	9.7
$5,000 to $9,999 ..... farms	3,053	14.9
$1,000	22,351	14.9
$10,000 to $24,999 ..... farms	5,680	14.0
$1,000	95,057	13.8
$25,000 to $49,999 ..... farms	5,396	10.1
$1,000	196,292	10.3
$50,000 or more ..... farms	21,773	10.9
$1,000	9,745,519	24.0
Farms with losses of-		
Less than $1,000 ..... farms	1,786	6.9
$1,000	856	8.3
$1,000 to $4,999 ..... farms	6,380	9.0
$1,000	18,668	9.5
$5,000 to $9,999 ..... farms	5,021	11.1
$1,000	36,645	11.0
$10,000 to $24,999 ..... farms	5,999	9.3
$1,000	95,543	9.0
$25,000 to $49,999 ..... farms	2,539	9.2
$1,000	87,840	9.4
$50,000 or more ..... farms	2,310	15.3
$1,000	534,873	20.4
Livestock and poultry:		
Cattle and calves inventory ..... farms	16,823	5.8
number	2,121,625	12.7
Beef cows inventory ..... farms	11,691	6.2
number	364,629	10.5
Milk cows inventory ..... farms	2,185	3.0
number	459,536	7.0
Hog and pigs inventory ..... farms	2,928	43.0
number	8,873,776	64.5
Layers inventory ..... farms	6,146	9.1
number	14,553,497	1.8
Broilers sold ..... farms	1,028	14.2
number	41,793,592	25.7
Aquaculture sold ..... farms	98	42.4
$1,000	19,763	32.7
Selected crops harvested:		
Corn for grain ..... farms	24,697	20.0
acres	7,732,455	21.4
Durum wheat for grain ..... farms	31	43.5
acres	(D)	(D)
Other spring wheat for grain ..... farms	3,557	63.8
acres	1,261,299	54.5
Winter wheat for grain ..... farms	102	26.2
acres	(D)	(D)
Sorghum for grain ..... farms	12	38.7
acres	364	17.4
Soybeans for beans ..... farms	25,337	38.5
acres	7,597,171	47.1
Rice ..... farms	-	-
acres	-	-

See footnote(s) at end of table.

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Table B. **Reliability Estimates of State Totals: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Item		Total	Coefficient of variation (percent)
Selected crops harvested: - Con.			
Cotton	farms	-	-
	acres	-	-
Peanuts	farms	-	-
	acres	-	-
Barley	farms	336	46.3
	acres	55,330	49.2
Oats	farms	2,329	44.3
	acres	126,011	27.1
Forage - land used for all hay and haylage, grass silage, and greenchop	farms	23,394	7.2
	acres	1,392,072	18.0
Land in vegetables (see text)	farms	2,620	12.3
	acres	196,718	15.0
Potatoes	farms	509	35.9
	acres	49,008	50.3
Tomatoes in the open	farms	592	18.1
	acres	300	24.4
Selected crops harvested: - Con. Land in vegetables (see text) - Con.			
Sweet corn (see text)	farms	1,243	12.3
	acres	96,990	5.4
Lettuce	farms	322	19.1
	acres	94	18.2
Land in orchards (see text)	farms	1,174	7.7
	acres	5,049	6.2
Apples	farms	751	7.1
	acres	3,219	7.0
Grapes (including muscadine) (see text)	farms	433	9.5
	acres	1,290	7.3
Oranges	farms	-	-
	acres	-	-
Almonds	farms	-	-
	acres	-	-
Land in berries	farms	578	7.4
	acres	1,129	20.7

[1] Data were collected for a maximum of four producers per farm.
[2] Farms with total production expenses equal to market value of agricultural products sold, government payments, and farm-related income are included as farms with gains of less than $1,000.

Table C. **Summary of Coverage, Nonresponse, and Misclassification Adjustments by County: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Total (number)	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
ALL FARMS (NUMBER)						
State Total						
Minnesota	65,531	4,913	35.6	11.1	12.8	11.7
Counties						
Aitkin	449	102	35.2	14.8	13.5	6.9
Anoka	355	56	47.3	16.1	21.8	9.3
Becker	952	177	33.1	14.9	9.4	8.8
Beltrami	608	129	42.1	18.8	14.0	9.2
Benton	687	105	31.7	14.3	13.3	4.1
Big Stone	392	88	29.3	7.5	11.2	10.6
Blue Earth	1,019	58	34.8	8.7	14.8	11.3
Brown	973	134	33.0	9.8	15.5	7.6
Carlton	463	64	35.9	16.3	15.4	4.2
Carver	606	119	32.5	13.0	16.7	2.9
Cass	488	99	39.3	17.6	17.1	4.6
Chippewa	563	32	29.7	12.8	11.3	5.6
Chisago	740	88	43.1	17.4	21.5	4.2
Clay	655	187	34.0	10.4	10.8	12.9
Clearwater	404	89	36.6	16.1	12.4	8.1
Cook	25	4	36.0	24.9	4.4	6.8
Cottonwood	742	61	33.2	10.7	14.2	8.3
Crow Wing	426	69	39.0	22.9	12.1	4.0
Dakota	841	105	43.5	17.2	19.1	7.2
Dodge	614	63	34.4	18.0	12.8	3.6
Douglas	980	160	38.3	13.7	15.6	8.9
Faribault	773	30	32.6	5.2	9.6	17.8
Fillmore	1,458	272	35.2	12.3	18.4	4.5
Freeborn	908	115	29.5	10.2	13.1	6.2
Goodhue	1,406	253	39.1	11.2	18.3	9.6
Grant	529	96	27.2	8.9	8.0	10.3
Hennepin	511	87	47.0	20.6	20.1	6.3
Houston	797	73	31.9	11.8	12.7	7.4
Hubbard	336	87	36.0	17.4	13.7	4.9
Isanti	814	93	45.6	19.0	21.0	5.6
Itasca	424	68	39.2	19.5	10.9	8.7
Jackson	845	47	33.4	8.7	16.6	8.1
Kanabec	531	57	37.1	12.5	16.7	7.9
Kandiyohi	1,252	116	34.5	8.9	10.6	15.0
Kittson	613	438	37.8	1.2	2.7	33.9
Koochiching	190	56	37.4	10.4	16.3	10.7
Lac qui Parle	735	136	31.3	8.6	16.3	6.4
Lake	34	7	41.2	29.0	6.5	5.7
Lake of the Woods	186	71	38.7	7.5	10.7	20.5
Le Sueur	896	43	29.5	7.8	8.2	13.5
Lincoln	598	69	28.4	10.8	10.1	7.5
Lyon	869	75	36.5	8.6	18.6	9.2
McLeod	801	98	35.6	13.7	12.4	9.4
Mahnomen	268	123	34.0	4.0	4.9	25.0
Marshall	1,072	644	39.6	3.4	5.0	31.2
Martin	823	48	36.0	6.5	16.1	13.3
Meeker	991	97	31.0	14.0	12.2	4.8
Mille Lacs	603	90	35.5	15.7	13.6	6.2
Morrison	1,571	333	35.5	15.2	15.4	4.8
Mower	999	76	35.1	10.9	16.1	8.1
Murray	789	51	30.8	5.8	11.3	13.7
Nicollet	660	40	35.3	9.7	17.7	8.0
Nobles	938	56	36.1	4.3	9.8	22.1
Norman	435	157	34.0	5.4	7.4	21.2
Olmsted	1,102	177	35.1	16.2	12.9	6.0
Otter Tail	2,497	466	36.2	12.0	9.9	14.3
Pennington	322	159	31.4	4.2	3.6	23.6
Pine	728	116	37.6	17.7	14.3	5.7
Pipestone	529	27	34.0	14.2	13.4	6.4
Polk	1,223	689	40.1	3.0	6.7	30.4
Pope	821	131	31.5	11.8	10.6	9.1
Ramsey	47	16	46.8	37.1	7.8	2.0
Red Lake	274	116	38.3	4.1	5.1	29.1
Redwood	1,323	229	38.3	6.1	15.8	16.4
Renville	931	102	31.4	6.4	18.2	6.7
Rice	1,111	96	34.5	13.9	13.6	7.0
Rock	573	55	36.3	14.5	12.1	9.6
Roseau	751	256	38.1	6.9	7.8	23.4
St. Louis	821	145	42.9	16.9	21.0	5.0
Scott	624	156	37.8	17.4	17.2	3.2
Sherburne	494	144	45.3	19.5	21.7	4.1
Sibley	860	101	32.4	13.0	12.2	7.2
Stearns	2,695	540	36.5	18.2	13.0	5.3
Steele	721	82	30.8	9.1	6.8	14.9
Stevens	500	84	33.2	8.2	9.2	15.8
Swift	708	137	30.6	7.4	9.0	14.3
Todd	1,529	186	38.8	14.7	14.3	9.7
Traverse	358	35	22.3	7.0	9.9	5.5
Wabasha	743	302	32.8	15.0	14.4	3.5
Wadena	442	76	36.0	14.3	15.0	6.6
Waseca	622	62	28.5	10.2	11.3	6.9
Washington	525	35	43.2	19.5	15.4	8.4
Watonwan	512	43	34.4	6.2	9.4	18.8

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Table C. **Summary of Coverage, Nonresponse, and Misclassification Adjustments by County: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Total (number)	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
ALL FARMS (NUMBER) - Con.						
Counties - Con.						
Wilkin	358	52	27.9	7.7	10.7	9.5
Winona	993	120	37.3	16.2	14.2	6.8
Wright	1,310	146	41.5	17.1	16.9	7.5
Yellow Medicine	847	34	30.5	5.2	6.8	18.5
LAND IN FARMS (ACRES)						
State Total						
Minnesota	25,442,625	7,766,836	31.9	1.6	5.7	24.5
Counties						
Aitkin	120,748	58,996	35.0	6.3	7.7	20.9
Anoka	30,064	6,763	32.6	7.1	10.2	15.3
Becker	381,537	113,499	26.9	6.3	9.4	11.2
Beltrami	173,158	74,113	38.6	8.3	14.7	15.7
Benton	134,358	12,733	24.0	7.4	11.8	4.8
Big Stone	263,888	119,437	27.1	2.5	12.9	11.7
Blue Earth	478,133	249,782	40.3	3.5	24.8	12.0
Brown	302,331	27,088	31.7	4.2	20.7	6.7
Carlton	125,420	106,585	19.2	8.2	7.4	3.7
Carver	156,676	61,200	33.7	2.7	27.8	3.3
Cass	134,449	67,817	35.3	10.4	16.4	8.5
Chippewa	364,695	124,972	35.2	7.0	23.4	4.9
Chisago	81,038	7,989	24.0	6.8	13.2	4.1
Clay	556,161	242,957	24.7	2.0	6.5	16.2
Clearwater	159,856	60,717	27.3	2.9	4.3	20.1
Cook	1,940	406	33.4	19.1	4.1	10.2
Cottonwood	392,494	169,783	37.7	4.9	25.7	7.1
Crow Wing	92,791	44,524	42.4	18.2	17.8	6.4
Dakota	208,517	12,872	26.6	5.8	15.0	5.8
Dodge	280,440	68,452	31.6	5.8	18.3	7.4
Douglas	268,096	126,217	39.8	7.1	22.1	10.6
Faribault	383,231	81,084	28.5	2.8	14.8	10.8
Fillmore	470,312	106,041	38.6	5.3	30.0	3.3
Freeborn	351,174	73,564	28.9	4.5	20.2	4.1
Goodhue	421,698	72,821	37.0	6.1	19.0	11.9
Grant	338,754	106,302	22.7	3.2	13.1	6.4
Hennepin	32,406	4,550	34.5	11.4	11.6	11.5
Houston	223,021	44,632	34.7	9.6	15.1	9.9
Hubbard	98,144	30,674	28.7	12.4	9.1	7.2
Isanti	101,666	36,131	28.9	6.6	11.9	10.5
Itasca	96,375	46,427	38.1	8.6	9.3	20.3
Jackson	384,337	137,483	32.5	3.4	23.1	5.9
Kanabec	99,182	21,314	28.1	6.2	17.3	4.6
Kandiyohi	494,447	200,515	36.2	3.7	13.0	19.4
Kittson	602,709	423,902	33.7	0.1	0.4	33.2
Koochiching	60,919	33,846	34.2	4.0	11.3	18.8
Lac qui Parle	410,959	167,126	32.9	3.3	26.7	2.9
Lake	1,422	577	32.3	18.3	5.5	8.5
Lake of the Woods	109,394	39,281	23.9	0.6	1.1	22.2
Le Sueur	205,774	78,875	31.0	5.8	15.0	10.1
Lincoln	212,420	43,568	21.6	3.9	13.6	4.1
Lyon	424,591	161,280	37.6	4.1	29.4	4.1
McLeod	246,163	94,064	39.8	6.5	22.0	11.3
Mahnomen	217,882	126,855	35.5	1.2	3.0	31.4
Marshall	912,128	527,835	31.5	0.4	1.5	29.7
Martin	454,025	159,503	34.4	2.6	24.4	7.4
Meeker	308,376	94,913	33.4	6.0	21.5	5.9
Mille Lacs	96,684	22,497	29.2	8.1	12.4	8.7
Morrison	361,789	62,967	33.0	8.9	16.1	8.0
Mower	380,070	87,812	32.2	4.6	22.1	5.5
Murray	351,476	120,952	31.1	3.6	18.8	8.6
Nicollet	278,870	126,521	38.5	4.0	31.7	2.8
Nobles	366,330	97,102	32.0	3.1	24.9	4.0
Norman	491,694	236,768	24.7	0.6	2.8	21.3
Olmsted	308,004	64,254	34.7	9.0	18.1	7.6
Otter Tail	770,922	267,108	34.6	1.1	2.2	31.3
Pennington	258,956	129,291	21.6	0.2	0.6	20.8
Pine	164,801	78,572	36.5	13.7	14.3	8.5
Pipestone	227,976	94,551	31.4	6.0	17.3	8.0
Polk	1,083,394	618,111	29.6	0.2	1.1	28.3
Pope	310,041	95,215	29.3	5.7	14.9	8.8
Ramsey	799	44	20.2	12.4	3.5	4.3
Red Lake	196,716	78,196	26.3	0.5	1.7	24.1
Redwood	560,222	233,071	36.1	3.8	27.6	4.8
Renville	626,065	129,381	28.1	3.4	19.6	5.1
Rice	249,881	66,673	34.9	6.3	21.6	7.0
Rock	261,220	61,232	32.1	4.1	21.4	6.6
Roseau	537,341	239,014	26.5	0.3	1.1	25.2
St. Louis	162,061	61,782	39.5	15.3	15.5	8.7
Scott	99,629	31,413	35.3	7.5	22.8	5.0
Sherburne	85,044	33,026	33.0	8.4	20.9	3.7
Sibley	373,628	96,474	33.5	6.3	22.5	4.8
Stearns	643,463	75,798	33.5	9.0	18.9	5.6
Steele	245,834	81,430	33.8	5.7	17.3	10.9
Stevens	330,936	142,582	35.8	2.3	14.8	18.7

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Table C. **Summary of Coverage, Nonresponse, and Misclassification Adjustments by County: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Total (number)	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
LAND IN FARMS (ACRES) - Con.						
Counties - Con.						
Swift	374,933	107,564	31.2	3.1	16.0	12.1
Todd	321,168	69,623	37.0	9.3	14.2	13.5
Traverse	309,539	71,559	20.7	2.5	14.6	3.6
Wabasha	235,417	100,410	32.8	7.2	21.6	4.0
Wadena	123,335	44,031	37.0	12.2	10.5	14.3
Waseca	266,866	131,871	35.7	3.4	21.1	11.1
Washington	50,806	9,031	22.6	2.9	6.5	13.2
Watonwan	263,479	67,007	33.2	2.4	23.9	6.9
Wilkin	401,044	92,817	17.5	1.1	7.1	9.3
Winona	295,658	42,343	39.0	8.5	20.1	10.4
Wright	224,831	66,251	35.2	7.7	13.4	14.2
Yellow Medicine	383,404	115,246	25.2	3.0	11.7	10.5
SALES ($1,000)						
State Total						
Minnesota	28,482,097	6,450	29.9	2.3	5.9	21.7
Counties						
Aitkin	22,332	7	40.7	2.6	18.1	20.1
Anoka	72,811	15	24.3	6.5	2.1	15.6
Becker	305,922	62	23.2	12.7	5.0	5.6
Beltrami	38,203	13	38.7	4.8	15.7	18.1
Benton	278,263	10	15.6	8.7	3.8	3.0
Big Stone	194,879	64	20.9	3.0	14.0	4.0
Blue Earth	838,011	368	32.6	1.9	8.1	22.6
Brown	485,455	102	29.6	4.3	14.8	10.5
Carlton	13,416	5	34.0	17.6	10.4	6.0
Carver	172,878	90	38.2	1.4	32.5	4.4
Cass	29,837	9	20.9	14.8	3.3	2.9
Chippewa	446,611	155	35.1	13.7	13.7	7.7
Chisago	54,864	6	20.2	6.5	10.9	2.9
Clay	466,030	203	23.0	9.4	4.3	9.3
Clearwater	46,418	17	23.0	0.5	0.9	21.6
Cook	506	(Z)	33.8	23.2	3.0	7.6
Cottonwood	601,642	218	31.1	4.2	6.6	20.3
Crow Wing	26,272	13	49.2	12.3	24.9	12.0
Dakota	364,822	25	25.0	5.8	6.3	12.9
Dodge	413,313	87	29.5	9.5	12.5	7.5
Douglas	168,616	67	42.8	4.8	34.4	3.6
Faribault	587,680	164	31.3	3.2	5.7	22.5
Fillmore	519,865	106	36.7	1.7	30.5	4.4
Freeborn	475,632	66	25.9	3.6	17.9	4.4
Goodhue	595,613	78	38.8	3.5	13.0	22.3
Grant	313,725	92	20.2	7.7	7.7	4.8
Hennepin	56,766	6	19.7	5.4	2.0	12.3
Houston	213,008	49	41.8	16.2	13.8	11.8
Hubbard	52,155	16	9.1	4.5	1.2	3.4
Isanti	73,159	39	25.5	2.2	10.7	12.6
Itasca	13,796	6	40.9	17.5	12.5	10.9
Jackson	501,296	157	32.2	4.3	13.1	14.8
Kanabec	32,517	7	26.8	2.6	22.6	1.6
Kandiyohi	715,674	159	25.2	5.5	4.3	15.4
Kittson	301,443	238	35.2	0.1	0.4	34.8
Koochiching	10,444	5	31.9	1.3	6.4	24.2
Lac qui Parle	394,270	212	38.3	6.0	29.6	2.7
Lake	468	(H)	8.6	5.8	1.4	1.4
Lake of the Woods	32,786	4	11.3	0.1	0.2	11.0
Le Sueur	239,195	108	35.1	2.2	3.8	29.1
Lincoln	229,846	72	19.9	5.2	2.3	12.4
Lyon	762,925	226	33.3	4.0	20.8	8.5
McLeod	286,425	109	42.0	5.9	26.9	9.2
Mahnomen	136,673	91	38.9	0.9	3.5	34.6
Marshall	420,392	230	28.0	0.2	1.1	26.6
Martin	943,050	410	32.3	4.0	14.3	14.0
Meeker	497,668	81	40.1	6.5	8.5	25.1
Mille Lacs	65,669	14	35.4	7.9	24.1	3.4
Morrison	538,309	136	25.2	5.8	13.3	6.1
Mower	529,254	159	29.0	2.2	12.1	14.7
Murray	451,948	163	29.6	2.8	9.5	17.4
Nicollet	596,399	220	30.6	3.7	19.5	7.4
Nobles	761,337	143	29.1	0.7	3.2	25.3
Norman	341,464	162	23.2	1.3	2.6	19.3
Olmsted	337,134	42	30.9	8.1	16.1	6.7
Otter Tail	551,279	99	29.1	1.6	1.3	26.1
Pennington	100,306	52	18.4	0.1	0.5	17.8
Pine	58,065	29	33.7	11.9	12.7	9.1
Pipestone	397,208	52	17.8	3.4	1.5	12.9
Polk	697,381	406	30.1	0.1	0.9	29.0
Pope	244,815	68	27.8	7.4	7.4	12.9
Ramsey	3,449	1	48.9	38.1	2.8	8.0
Red Lake	109,527	31	24.3	0.5	1.4	22.5
Redwood	804,002	304	41.9	1.1	4.1	36.7
Renville	810,285	147	25.4	3.2	10.4	11.8
Rice	356,823	90	34.2	5.6	21.3	7.3
Rock	624,006	212	35.4	3.0	8.2	24.3

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Table C. **Summary of Coverage, Nonresponse, and Misclassification Adjustments by County: 2022** (continued)

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	Total (number)	Standard error	Adjustment as percent of total	Percent of total adjustment from coverage	Percent of total adjustment from nonresponse	Percent of total adjustment from misclassification
SALES ($1,000) - Con.						
Counties - Con.						
Roseau	212,493	81	20.2	0.2	0.6	19.4
St. Louis	29,054	8	40.3	14.1	13.6	12.7
Scott	91,834	24	32.8	8.5	21.2	3.1
Sherburne	120,592	70	27.6	8.0	15.4	4.3
Sibley	484,129	114	32.8	1.7	2.4	28.7
Stearns	1,021,472	186	25.3	9.2	8.7	7.3
Steele	396,997	120	31.8	8.8	8.3	14.7
Stevens	583,773	202	27.8	3.9	4.4	19.5
Swift	453,273	100	24.4	7.2	9.0	8.2
Todd	346,248	50	33.3	13.9	10.9	8.4
Traverse	259,570	54	18.7	5.4	9.4	3.9
Wabasha	329,119	125	33.3	5.9	24.0	3.3
Wadena	105,639	45	24.0	15.0	2.0	7.1
Waseca	393,883	151	29.5	6.0	12.1	11.4
Washington	60,710	11	15.7	3.2	4.8	7.8
Watonwan	404,682	132	30.0	2.5	5.2	22.2
Wilkin	254,790	59	17.5	1.4	7.1	9.0
Winona	401,862	53	39.4	9.1	17.2	13.1
Wright	283,025	86	27.7	3.3	20.5	3.8
Yellow Medicine	422,723	106	21.7	0.6	2.2	18.9

Table D. **American Indian or Alaska Native Producers: 2022**

[For meaning of abbreviations and symbols, see introductory text.]

Geographic area	American Indian or Alaska Native farm producers			Geographic area	American Indian or Alaska Native farm producers		
	Total	Individually reported [1]	Other [2]		Total	Individually reported [1]	Other [2]
State Total				**Counties** - Con.			
Minnesota	467	467	-	Lyon	1	1	-
				McLeod	1	1	-
Counties				Mahnomen	27	27	-
				Marshall	4	4	-
Aitkin	4	4	-	Martin	9	9	-
Anoka	4	4	-	Meeker	2	2	-
Becker	40	40	-	Mille Lacs	5	5	-
Beltrami	12	12	-	Morrison	9	9	-
Benton	3	3	-	Mower	1	1	-
Brown	2	2	-	Murray	1	1	-
Carlton	22	22	-				
Carver	1	1	-	Nicollet	2	2	-
Cass	9	9	-	Nobles	1	1	-
Chippewa	1	1	-	Norman	4	4	-
				Olmsted	10	10	-
Chisago	6	6	-	Otter Tail	16	16	-
Clay	9	9	-	Pennington	1	1	-
Clearwater	14	14	-	Pine	8	8	-
Cook	1	1	-	Polk	13	13	-
Cottonwood	1	1	-	Pope	5	5	-
Crow Wing	6	6	-	Ramsey	3	3	-
Dakota	2	2	-				
Dodge	7	7	-	Redwood	2	2	-
Douglas	7	7	-	Renville	5	5	-
Faribault	1	1	-	Rice	1	1	-
				Roseau	11	11	-
Fillmore	8	8	-	St. Louis	14	14	-
Freeborn	2	2	-	Scott	4	4	-
Goodhue	6	6	-	Sherburne	1	1	-
Grant	12	12	-	Stearns	4	4	-
Houston	3	3	-	Steele	3	3	-
Hubbard	4	4	-	Todd	6	6	-
Isanti	7	7	-				
Itasca	16	16	-	Traverse	5	5	-
Jackson	4	4	-	Wabasha	1	1	-
Kanabec	13	13	-	Wadena	3	3	-
				Waseca	1	1	-
Kandiyohi	3	3	-	Washington	9	9	-
Koochiching	9	9	-	Wilkin	1	1	-
Lac qui Parle	7	7	-	Winona	7	7	-
Lake	1	1	-	Wright	4	4	-
Lake of the Woods	7	7	-	Yellow Medicine	8	8	-

[1] Data were collected for a maximum of four producers per farm.
[2] Data represent American Indian or Alaska Native farm or ranch producers on reservations who did not report individually. Data obtained by reservation officials.

Appendix B.
General Explanation and Census of Agriculture Report Form

DEVELOPMENT OF THE CENSUS REPORT FORMS

Before the release of the 2017 Census of Agriculture's results, NASS had already begun preparations for the 2022 Census of Agriculture. The 2022 Census Content Team and the Data Collection Testing Teams evaluated the content and report form design for the census. They reviewed the 2017 report forms, solicited input from both internal and external customers, and developed criteria for determining acceptable content for inclusion in the 2022 Census of Agriculture. The teams tested the effectiveness of the 2022 report forms in various modes of data collection (mail, telephone, personal interview, and web) and made recommendations to NASS senior executives for final determination.

Throughout development NASS sought the advice and input from the data user community. Integral partners included the Advisory Committee on Agriculture Statistics, State Departments of Agriculture and other State government officials, Federal agency officials, land grant universities, agricultural trade associations, media, and various community-based organizations.

NASS conducted usability testing to assess the user experience for the web report form in April and May 2020. In addition, NASS conducted two rounds of cognitive interviews for the paper report forms in April through August 2020; one to test new and modified questions, and one to test all sections of the report forms. In late 2020 through early 2021, NASS conducted a large-scale content test (OMB No. 0535-0243) of the general census of agriculture forms. This test began in late December 2020 when survey requests were mailed to a nationwide sample of approximately 36,000 farm producers. The paper, web, and telephone report forms were tested for question phrasing, reporting of new commodities, form design and flow, and respondent comprehension. Finally, in January through March 2022, NASS conducted a 15,000 record test of the web form to further evaluate the online submission system and functionality. Testing results from these activities helped determine final report form content and design. A sample copy of the 2022 report form and instruction sheet is included in this appendix.

DATA CHANGES

Following are descriptions of the report form changes and their effect on the publication tables.

Crop Data Changes

Added items include:

- Gourds
- Gooseberries
- Hemp was added to both the nursery section and the field crops section
- Longan
- Lychees
- Mulberries
- Parsnips
- Pawpaws
- Rambutan

Other changes include:

- Sod harvested or intended for sale in future years replaced sod harvested to include sod in production but not harvested.
- Vegetable seeds and Vegetable transplants to farm fields moved from Propagative Material Sold to Food Crops Grown Under Glass or Other Protection. Only square feet under protection were collected for these items.
- Vegetable seeds grown in the open were moved from the Nursery section and reported under the specific vegetable in the Vegetable section.

Items combined with another item(s) on the 2022 report form that were reported individually on the 2017 report form include:

- Black, red, and other raspberries were combined into raspberries, all
- Summer and winter squash were combined into squash (including zucchini)
- Sugarcane for sugar and sugarcane for seed were combined into sugarcane for sugar or seed

- Sweet corn for seed in the field crops section was combined into sweet corn in the vegetable section
- Temples are recorded under tangerines
- Cable, DSL, fiber optic were combined into broadband (high speed) internet

Livestock and Poultry Data Changes

Added item includes:

- Hair sheep or wool-hair crosses inventory

Economic, Energy, Land Use Practices, Selected Practices, Organic, Producer Characteristics, and Type of Organization/Legal Status Data Changes

Added items include:

- Land with irrigation systems or equipment
- Precision agricultural practices
- Producers' involvement in marketing decisions

Deleted items include:

- Biodiesel and ethanol production systems
- Indication that a person is a principal operator or spouse of a principal operator
- Number of acres irrigated in the past five years

DEFINITIONS AND EXPLANATIONS

The following definitions and explanations provide a detailed description of specific terms and phrases used in this publication. Items in the publication tables which carry the note ‘‘see text’’ also are explained. Report form section number references refer to the general version (22-A100). Many of the definitions and explanations are the same as those used in earlier censuses.

Acres and quantity harvested. Crops were reported in whole acres, except for the following crops that were reported in tenths of acres: tobacco, hops, nursery and greenhouse crops in the open, vegetables including potatoes and sweet potatoes, fruit and nut crops including land in orchards, and berries. Totals for crops reported in tenths of acres were rounded to whole acres at the aggregate level during the tabulation process. Nursery and greenhouse crops grown under glass or other protection were reported in square feet and are published in square feet.

If two or more crops were harvested from the same land during the year (double cropping), the acres were counted for each crop. Therefore, the total acres of all crops harvested could exceed the acres of cropland harvested. No double cropping is allowed for hay or fruit and nut crops.

When more than one cutting of hay was taken from the same acres, the acres were counted only once. If there were multiple cuttings of one type of hay production, e.g., two cuttings of alfalfa for dry hay, acreage was reported once, but the quantity harvested includes all cuttings. Acreage cut and tons harvested for both dry hay and haylage, silage, or greenchop were reported for each crop. For interplanted crops or ‘‘skip-row’’ crops, acres were reported according to the portion of the field occupied, whether by a crop or whether it was idle land. If a crop was interplanted in an orchard or vineyard and harvested, then the entire orchard or vineyard acreage was reported under the appropriate fruit crop and the interplanted estimated crop acreage was reported under the appropriate crop.

If a crop was planted but not harvested, the acres were not reported as harvested. These acres were reported in the Land Use section on the report form under the appropriate items – cropland on which all crops failed or were abandoned, cropland in summer fallow, cropland idle or used for cover crops or soil-improvement but not harvested and not pastured or grazed, or other pasture and grazing land that could have been used for crops without additional improvements. This does not include fruit and nut orchards, vineyards, berries, acres in production for cultivated Christmas trees, and acres in production for short rotation woody crops that were not harvested. Acreage in these commodities were included in cropland harvested regardless of whether the crop was harvested. Abandoned orchards were reported as cropland idle, not as harvested cropland, and the individual abandoned orchard crop acres were not reported.

Crops that were grazed by livestock were reported as “Other pasture and grazing land that could have been used for crops without additional improvements.” Crop residue left in fields after the 2022 harvest and later grazed by livestock were reported as cropland harvested and not as other pasture or grazing land that could have been used for crops.

Quantity harvested was not obtained for crops such as fruits, nuts, berries, vegetables, melons, nursery crops, and greenhouse crops.

Agri-tourism and recreational services. See Total income from farm-related sources.

Agricultural products sold directly to individuals for human consumption. See Value of food sold directly to consumers.

All haylage, grass silage, and greenchop (tons). See Haylage, grass silage, and greenchop, all.

All producers. See Producer.

All other production expenses. See Total farm production expenses.

American Indian and Alaska Native farm producers, total. Data are reported in Chapter 1, tables 52 through 77 and Chapter 2, tables 45 and 49. In Chapter 2, table 49 data are published for a maximum of four producers reported in the Personal Characteristics section of the report form. The individual producers were included on the census mail list for most reservations. Those reservations that did not include all the individual producers on the census mail list were identified and the data for the entire reservation, including the data for the producers that would have met the definition of a farm, were collected on one report form. The count of reservations and the number of producers that were reported on these reservations are included in Appendix A, Table D.

Amount from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement Programs. See Land enrolled in the Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), Farmable Wetlands Program (FWP), or Conservation Reserve Enhancement Program (CREP).

Amount from State and local government agricultural program payments. See Total income from farm-related sources.

Amount spent to repay CCC loans. See also Commodity Credit Corporation loans. Farming operations that receive a CCC loan can use cash to repay the loan, purchase certificates for use in the repayment, or deliver the pledged collateral as full payment at maturity. If a farmer uses cash instead of certificates to repay the loan, the farmer and the IRS receive an information return showing the market gain realized. The farmer can repay the loan to the CCC and then sell the grain, feed the grain, or store it. These provisions only apply until the maturity date of the loan. After the maturity date of the loan, the entire original loan principal and all accrued interest must be repaid or, as an alternative choice, the crop may be forfeited to CCC.

Animal production and aquaculture (112). See Farms by North American Industry Classification System (NAICS).

Any poultry sold. The number of farms with any poultry sold includes all farms with sales of poultry, poultry hatched, or eggs.

Aquaculture. Aquaculture is defined as the farming of fish, crustaceans, mollusks, and other aquaculture products. The aquaculture production reported in the census requires some form of intervention in the rearing process and requires inputs such as seeding, stocking, feeding, protection from predators, etc. It also requires ownership of the stock being cultivated and harvesting that is conducted in a controlled environment by the operation. The value of sales includes all sizes and eggs by species and includes aquaculture distributed for restoration, conservation, or recreational purposes, such as State and Federal hatcheries. Distributed fish with unknown values were assigned a value based on sales of farm-raised fish.

Aquaculture and other animal production (1125, 1129). See Farms by North American Industry Classification System (NAICS).

Aware of right to appeal an adverse program decision to USDA's National Appeals Division. The National Appeals Division (NAD) of the United States Department of Agriculture (USDA) provides an independent forum within USDA for program participants to seek administrative appeals of adverse agency decisions.

Bantams. See Layers.

Bees. See Colonies of honey bees and Honey collected.

Berries, all. Refer to Land in berries.

Breeding livestock. See Total farm production expenses.

Broadband. This item is the number of farms that reported using DSL, cable, or fiber optic connections to the internet.

By economic class. See Economic class of farms.

Cattle on feed. Cattle on feed are steers and heifers being fed a ration of grain, silage, hay and/or protein supplement for slaughter market that are expected to produce a carcass that will grade select or better. It excludes cattle being "backgrounded only" for later sale as feeders or later placement in another feedlot.

Cattle on feed sold. Data are for cattle on feed sold that weighed 500 pounds or more that were shipped directly

from the feedlot to the slaughter market. This category excludes cattle that were pastured only, owned cattle that were shipped from feedlots operated by others, background feeder cattle, and veal calves.

CCC loans. See Commodity Credit Corporation loans.

Cellular data plan. Mobile internet service for a cell phone or other device. This includes counts of farm operations that reported accessing the internet from a mobile device, such as cell phone or tablet. In 2017 this item was labeled mobile broadband plan for a computer or a cell phone. This is a wording change only; data are comparable.

Chemicals applied. For each type of chemical used, the acres treated were reported only once even if the acres were treated more than once. If multi-purpose chemicals were used, the acres treated for each purpose were reported. See Total farm production expenses; Chemicals.

Cherries. Cherries were reported as either sweet cherries or tart cherries. Combined crops or non-specified cherry acres were not options for the respondent. Total acres, bearing age acres, and nonbearing age acres were reported for each crop.

Christmas trees, cultivated. Data are for acres of Christmas trees-cut or to be cut-in production, acres irrigated, and number of trees cut. Sales data are included in the Cut Christmas trees and short rotation woody crops category.

Christmas trees, live. Data were reported as nursery stock and include Christmas trees sold live, generally balled and burlapped, from the operation.

Coffee. Data include trees grown in the open as well as under shade or in greenhouses. Data for coffee relate to the July 2021 through June 2022 harvest season.

Colonies of honey bees. Published colonies inventory is the total number of colonies owned on December 31, 2022. Bee operations with multiple locations reported inventory on the location where the bees were present and the inventory was tabulated in those counties. Inventories in 2022 were tabulated in the county where the operation had the largest value of all agricultural products raised or produced. Package bees were not included as separate colonies.

Commodities raised and delivered under production contracts. A production contract is an agreement between a producer or grower and a contractor (integrator) setting terms, conditions, and fees to be paid by the contractor to the operation for the production of crops, livestock, or poultry. The grower receives a payment or fee from the contractor, generally after delivery, which is less than the full market price of the commodity. A production contract involves the shifting of some risk and control from the grower to the contractor. Marketing contracts, futures contracts, forward contracts, or other contracts based strictly on price are not considered production contracts. Commodities sold to a co-op where some of the input items were purchased from the same co-op at a discount price were also excluded. Many operations produce commodities only under production contracts or only independently. Some operations may produce a commodity under production contract and also produce more of the same commodity that they sell independently. The production contract data are totals for the portion of agriculture production raised and delivered under production contract. Crops and livestock inventory, production, and value of sales are the total of all production, both independent and raised under production contract.

Custom fed cattle shipped directly for slaughter under a production contract. Cattle under production contract which were not shipped directly to slaughter were reported in either Replacement dairy heifers under production contract or in the Other cattle, sheep, livestock, or poultry under production contract category.

Grains, oilseeds, vegetables, melons, potatoes, and other crops under production contract. This category is the number of farms that produced and delivered any crop grown under a production contract. This item was reported as three different categories (grains and oilseeds, vegetables/melons/potatoes, and all other crops).

Layers under production contract. The production contract is based on eggs, but the layers are owned by the contractor and are also under contract. The layers are produced at the pullet farm, which may have a separate production contract.

Other cattle, sheep, livestock, or poultry under production contract. The data for commodities raised and delivered under a production contract include cattle which were not shipped directly to slaughter (backgrounding), sheep, livestock, and poultry not listed separately.

Commodity Credit Corporation loans. This category includes nonrecourse marketing loans for wheat, corn, sorghum, barley, oats, cotton, rice, soybeans, Austrian winter peas, honey, dry edible peas, lentils, chickpeas, peanuts, sunflower seed, flaxseed, canola and other rapeseed, safflower, mustard seed, crambe, sesame seed, wool, and mohair.

Corn, Traditional or Indian. Traditional corn is an open-pollinated (non-hybrid), non-GMO cultivar of Zea mays that was indigenously developed and consists of many heritage varieties of sizes, color, and drought tolerance. Traditional corn grown on southwest reservations has been passed from generation to generation through seed saving by American Indian and Hispanic communities. Traditional corn is culturally significant.

Cover crop seed purchased. See Total farm production expenses.

Crop and livestock insurance payments received. See Total income from farm-related sources.

Crop units of measure. The report form allowed the producer to report the quantity of field crops harvested in a unit of measure commonly used in the region. When the producer reported in units different than the unit of measure published, the quantity harvested was converted to the published unit of measure.

Crop year or season covered. Acres and quantity harvested are for the calendar year 2022 except for coffee. Data for coffee relate to July 2021 through June 2022.

Cropland, harvested. See Harvested cropland.

Cropland idle or used for cover crops or soil improvement but not harvested and not pastured or grazed. Cropland idle includes any other acreage which could have been used for crops without any additional improvement and which was not reported as cropland harvested, cropland on which all crops failed, cropland in summer fallow, or other pasture or grazing land that could have been used for crops without additional improvements. This category includes:

1. Land used for cover crops or soil improvement but not harvested or grazed.

2. Land in Federal or State conservation programs that was not hayed or grazed in 2022.

3. Land occupied with growing crops for harvest in 2023 or later years but not harvested or summer fallowed in 2022 (except fruit or nuts in an orchard, grove, or vineyard or berries being maintained for production). Examples are acreage planted in winter wheat, strawberries, etc., for harvest in 2023 and no crop was harvested from these acres in 2022.

4. Land in "skipped" rows between rows of crops or field strips.

Cropland in summer fallow. This includes cropland cultivated or treated with herbicides to control weeds and conserve moisture and not seeded or harvested in 2022. It includes cropland summer fallowed in 2022 and planted to a crop (i.e., winter wheat, etc.) for harvest in 2023.

Cropland, irrigated. See Irrigated land.

Cropland on which intensive tillage practices were used. See Land use practices.

Cropland on which reduced tillage, excluding no-till, practices were used. See Land use practices.

Cropland, other. See Other cropland.

Cropland, total. See Total cropland.

Cropland used only for pasture or grazing. See other pasture and grazing land that could have been used for crops without additional improvements.

Crustaceans. These are invertebrate animals with jointed legs and a hard-shelled segmented body. Examples include crawfish, lobster, prawns, shrimp, and softshell crabs.

Cultivated Christmas trees. See Christmas trees, cultivated.

Custom fed cattle shipped directly for slaughter. See Commodities raised and delivered under production contract.

Customwork and custom hauling. See Total farm production expenses.

Customwork and other agricultural services. See Total income from farm-related sources.

Cuttings, seedlings, liners, and plugs. See Nursery, greenhouse, floriculture, and sod.

Data are based on sample of farms. For censuses from 1987 through 2002, selected data items were collected from only a sample of farms. These data were subject to sampling error.

Depreciation expenses claimed. The calculation of total farm production expenses does not include depreciation because it is a capital expense. Depreciation allows the expensing of capital purchases over multiple years. It is not included in the calculation of Net cash farm income.

Dry edible beans, excluding chickpeas and limas. Dry edible beans do not include chickpeas, dry lima beans, or

dry southern (black eyed/cowpeas).

Ducks, geese, and other miscellaneous poultry. See Miscellaneous poultry.

Economic class of farms. Economic class data are the classification of farms by the sum of market value of agricultural products sold and Federal farm program payments. See Total market value of agricultural products sold and government payments. See Farms with sales and government payments of less than $1,000.

Energy. See Renewable energy producing systems.

Equine products. This category includes horse breeding fees, stud fees, semen, and other equine products and excludes boarding, training and riding facilities income.

Expenses. See Total farm production expenses.

Farm or ranch producer. See Producer.

Farms by combined government payments and market value of agricultural products sold. This category represents the value of products sold plus government payments. Total value of products sold combines total sales not under production contract and total sales under production contract. Government payments consist of government payments received from the Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), Farmable Wetlands Program (FWP), or Conservation Reserve Enhancement Program (CREP) plus government payments received from Federal programs other than the CRP, WRP, FWP, and CREP, and Commodity Credit Corporation loans.

Farms by economic class. See Economic class of farms and Total market value of agricultural products sold and government payments.

Farms by legal status. All farms were classified by legal status in the 2022 census. This section collects information for federal tax purposes to determine an operation's legal status. The classifications used were:

1. Family or individual (sole proprietorship), excluding partnership and corporation.

2. Partnership, including family partnership – in selected tables, partnership was further subclassified into:
   a. Registered under State law.
   b. Not registered under State law.

3. Corporation, including family corporations - in selected tables, corporation was further subclassified into:
   a. Family held or other than family held.
   b. More than 10 stockholders.

4. Other - estate or trust, prison farm, grazing association, American Indian reservation, etc.

Farms by North American Industry Classification System (NAICS). The NAICS classifies economic activities. It was jointly developed by Mexico, Canada, and the U.S. NAICS makes it possible to produce comparable industrial statistics for Mexico, Canada, and the U.S. For the 2022 census, all agricultural production establishments (farms, ranches, nurseries, greenhouses, etc.) were classified by type of activity or activities using the NAICS code. The 2022 census is the sixth census to use NAICS. Censuses prior to the 1997 census used the old Standard Industrial Classification (SIC) system to classify farms.

NAICS was developed to provide a consistent framework for the collection, analysis, and dissemination of industrial statistics used by government policy analysts, academia and researchers, the business community, and the public. It is the first industry classification system developed in accordance with a single principle of aggregation that production units using similar production processes should be grouped together. Though NAICS differs from other industry classification systems, statistics compiled on NAICS are comparable with statistics compiled according to the latest revision of the United Nations' International Standard Industrial Classification, Revision Four, (ISIC, Revision 4) for some 60 high level groupings. Following are explanations of the major classifications used in 2022.

Oilseed and grain farming (1111). Comprises establishments primarily engaged in (1) growing oilseed and/or grain crops and/or (2) producing oilseed and grain seeds. These crops have an annual life cycle and are typically grown in open fields. This category includes corn silage and grain silage.

Vegetable and melon farming (1121). Comprises establishments primarily engaged in one or more of the following: (1) growing vegetables and/or melon crops, (2) producing vegetable and melon seeds, and (3) growing vegetable and/or melon bedding plants.

Fruit and tree nut farming (1113). Comprises establishments primarily engaged in growing fruit and/or tree nut crops. These crops are generally not grown from seeds and have a perennial life cycle.

Greenhouse, nursery, and floriculture production (1114). Comprises establishments primarily engaged in growing crops of any kind under cover and/or growing nursery stock and flowers. ''Under cover'' is generally defined as greenhouses, cold frames, cloth houses, and lath houses. Crops grown are removed at various stages of maturity and have annual and perennial life cycles. The category includes short rotation woody crops and Christmas trees that have a growing and harvesting cycle of 10 years or less.

Other crop farming (1119). Comprises establishments primarily engaged in (1) growing crops such as tobacco, cotton, sugarcane, hay, sugarbeets, peanuts, agave, herbs and spices, and hay and grass seeds, or (2) growing a combination of the valid crops with no one crop or family of crops accounting for one-half of the establishment's agricultural production (value of crops for market). Crops not included in this category are oilseeds, grains, vegetables and melons, fruits, tree nuts, greenhouse, nursery and floriculture products.

All other crop farming (11199). Comprises establishments primarily engaged in (1) growing crops (except oilseeds and/or grains; vegetables and/or melons; fruits and/or tree nuts; greenhouse, nursery, and/or floriculture products; tobacco; cotton; sugarcane; or hay) or (2) growing a combination of crops (except a combination of oilseed(s) and grain(s)); and a combination of fruit(s) and tree nut(s) with no one crop or family of crops accounting for one-half of the establishment's agricultural production.

Animal production and aquaculture (112). Industries in the Animal Production and Aquaculture subsector raise or fatten animals for the sale of animals or animal products and/or raise aquatic plants and animals in controlled or selected aquatic environments for the sale of aquatic plants, animals, or their products. The subsector includes establishments, such as ranches, farms, and feedlots primarily engaged in keeping, grazing, breeding, or feeding animals. These animals are kept for the products they produce or for eventual sale. The animals are generally raised in various environments, from total confinement or captivity to feeding on an open range pasture. The industries in this subsector are grouped by important factors, such as suitable grazing or pasture land, specialized buildings, type of equipment, and the amount and types of labor required. Establishments are classified to the Animal Production and Aquaculture subsector when animal production (i.e., value of animals for market) accounts for one-half or more of the establishment's total agricultural production. Establishments with one-half or more animal production with no one animal product or family of animal products of an industry accounting for one half of the establishment's agricultural production are treated as combination animal farming classified to Industry 11299, All Other Animal Production.

Beef cattle ranching and farming (112111). Comprises establishments primarily engaged in raising cattle (including cattle for dairy herd replacements). Pastureland-only farms, those with only 100 or more acres of pastureland, were classified as "All other animal production farming (11299)."

Cattle feedlots (112112). Comprises establishments primarily engaged in feeding cattle for fattening.

Dairy cattle and milk production (11212). This industry comprises establishments primarily engaged in milking dairy cattle.

Hog and pig farming (1122). This industry comprises establishments primarily engaged in raising hogs and pigs. These establishments may include farming activities, such as breeding, farrowing, and the raising of weanling pigs, feeder pigs, or market size hogs.

Poultry and egg production (1123). This industry group comprises establishments primarily engaged in breeding, hatching, and raising poultry for meat or egg production.

Sheep and goat farming (1124). This industry group comprises establishments primarily engaged in raising sheep, lambs, and goats, or feeding lambs for fattening.

Aquaculture (1125). Comprises establishments primarily engaged in the farm raising of finfish, shellfish, or any other kind of animal aquaculture. These establishments use some form of intervention in the rearing process to enhance production, such as holding in captivity, regular stocking, feeding, and protecting from predators.

Other animal production (1129). Comprises establishments primarily engaged in raising animals and insects (except cattle, hogs and pigs, poultry, sheep and goats, and aquaculture) for sale or product production. These establishments are primarily engaged in one of the following: bees, horses and other equine, rabbits and other fur-bearing animals, etc. and producing products such as honey and other bee products. Establishments primarily engaged in raising a combination of animals with no one animal or family of animals accounting for one-half of the establishment's agricultural production are included in this industry group. Farms with only 100 acres or more of pastureland were classified as "All other animal production farming (11299)."

Farms by number of households sharing in net income of operation. Households that received funds because they

were only landlords, custom equipment producers, or provided other production services were not included. Published data can exceed the number of producers listed under Producers, all.

Farms by size. All farms were classified into size groups according to the total land area in the farm. The land area of a farm is an operating unit concept and includes land owned and operated as well as land rented from others. Land rented to or assigned to a tenant was considered part of the tenant's farm and not part of the owner's.

Farms by tenure of producer. All farms were classified by tenure of producers. The classifications used were:

- Full owners operated only land they owned.
- Part owners operated land they owned and also land they rented from others.
- Tenants operated only land they rented from others or worked on shares for others.

Farms with hired managers are classified according to the land ownership characteristics reported. For example, a corporation owns all the land used on the farm and hires a manager to run the farm. The hired manager is considered the farm producer, and the farm is classified with a tenure type of "full owner" even though the hired manager owns none of the land he/she operates.

Farms by typology group. The classifications were based on two criteria: who owned the operation and gross cash farm income (GCFI). GCFI included the producer's sales of crops and livestock, fees for delivering commodities under production contracts, government payments, and farm-related income. Family farms are defined by the operation reporting more than 50 percent of this operation was owned by an operator's household and/or extended family.

Small family farms. Farms defined by GCFI less than $349,000.

Midsize family farms. Farms defined by GCFI between $350,000 and $999,999.

Large family farms. Farms defined by GCFI between one million and five million or more.

Non-family farms. Farms defined as the producer and persons related to the producer do not own a majority of the business.

Farms by type of organization. The data categorizes an operation's ownership.

Operation more than 50 percent owned by one producer's household and/or extended family. The data are used to measure the producers' ownership interest in the organization. This item is operations with 50 percent or more ownership interest held by operator and/or persons related by blood, marriage, or adoption.

Limited Liability Company. This type of farm structure combines the pass-through taxation of a partnership or sole proprietorship with the limited liability of a corporation.

Farms by value of sales. See Market value of agricultural products sold.

Farms or farms reporting. The terms "farms" and "farms reporting" in the presentation of data are equivalent. Both represent the number of farms reporting the item. For example, if there are 3,710 farms in a State and 842 of them had 28,594 cattle and calves, the data for those farms reporting cattle and calves would appear as:

Cattle and calves farms 842
number . . . 28,594

Farms with sales and government payments of less than $1,000. This category includes farms with combined sales and government payments of less than $1,000 but having the potential for sales of $1,000 or more. It provides information on all items for farms that normally would be expected to sell agricultural products of $1,000.

Farms with sales of less than $1,000. This category includes farms with sales of less than $1,000 but having the potential for sales of $1,000 or more. Some of these farms had no sales in the census year. It provides information on all report form items for farms that normally would be expected to sell agricultural products of $1,000 or more.

Fertilizer. See Total farm production expenses; Fertilizer, lime, and soil conditioners.

Field and grass seed crops, all. Data are for all the field and grass seed crops not published as field crops and include field seed crops which did not have a specific code on the 2022 report form.

Food marketing practices. This section consists of sales of edible agricultural products that are both produced and sold by the operation directly to consumers (farmers markets, on farm stores or farm stand, roadside stands or stores, u-pick, CSA, online marketplaces, etc.) or retail markets, institutions, or food hubs for local or regionally branding. Retail and institutional establishments include supermarkets, supercenters, restaurants, caterers, independently owned grocery stores, food cooperatives, K-12 schools, colleges or universities, hospitals, workplace

cafeterias, prisons, foodbanks, etc.

Forage - land used for all hay and all haylage, grass silage, and greenchop. Data shown represent the area harvested with each acre counted only once if dry hay, haylage, grass silage, or greenchop were cut from the same acreage or if there were multiple cuttings of dry hay, haylage, grass silage, or greenchop. Data exclude corn silage and sorghum silage. Quantity produced is the sum of the quantity harvested of all hay including alfalfa, other dry hay, and all haylage, grass silage and greenchop after converting the all haylage, grass silage, and greenchop quantity harvested to a dry equivalent basis (13 percent moisture). The green tons of all haylage, grass silage, and greenchop harvested were multiplied by a factor of 0.4943 to convert to a dry equivalent. This conversion factor is based on the assumption that one ton of dry hay is 0.87 ton of dry matter, one ton of haylage or grass silage is 0.45 ton dry matter, and one ton of greenchop is 0.25 ton dry matter. The all haylage, grass silage, and greenchop quantity harvested is assumed to be comprised of 90 percent haylage and grass silage and 10 percent greenchop. Therefore, the conversion factor used to adjust all haylage, grass silage, and greenchop quantity harvested to a dry equivalent basis = [(0.45*0.9)+(0.25*0.1)]/0.87 = 0.4943.

Fruits and tree nuts. Total acres, bearing age acres, and nonbearing age acres were collected.

Geothermal/geoexchange systems. See Renewable energy producing systems.

Gooseberries. This is a new item for 2022. In 2017, gooseberries were reported in other berries.

Gourds. This is a new item for 2022. In 2017, gourds were reported in other vegetables.

Government payments. This category consists of payments from Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), Farmable Wetlands Program (FWP), and Conservation Reserve Enhancement Program (CREP); loan deficiency payments; disaster payments; other conservation programs; and all other Federal farm programs under which payments were made directly to farm producers, including those specified in the 2018 Agricultural Act (Farm Bill), including Agriculture Risk Coverage (ARC) and Price Loss Coverage (PLC). Commodity Credit Corporation (CCC) proceeds, amount from State and local government agricultural program payments, and Federal crop insurance payments were not tabulated in this category.

Grain and bean combines. Data were collected for self-propelled combines only.

Grains, oilseeds, dry beans, and dry peas sales. Data are for the total market value of cash grains sold, including corn for grain, seed, or silage; wheat for grain; soybeans for beans; sorghum for grain, seed, or silage; barley for grain; rice; oats for grain; and other grains. Also included is the total market value of cash oilseeds sold, including sunflower seed (oil and non-oil), flaxseed, canola, rapeseed, safflower seed, mustard seed, dry beans, and dry peas.

Grains, oilseeds, vegetables, melons, potatoes, and other crops. See Commodities raised and delivered under production contracts.

Grapes (including muscadine). This was updated in 2022 for clarification that muscadine grapes should be included. It is a wording change only; data are comparable.

Greenhouse fruits and berries. Data include strawberries, raspberries, etc. grown in greenhouses and high tunnels where the crops were always covered. See Nursery, greenhouse, floriculture, and sod.

Gross cash rent or share payments. See Total income from farm-related sources.

Hair sheep or wool-hair crosses. This is a new item for 2022.

Harvested cropland. This category includes land from which crops were harvested and hay was cut, land used to grow short rotation woody crops, Christmas trees, and land in orchards, groves, vineyards, berries, nurseries, and greenhouses. Land from which two or more crops were harvested was counted only once. Land in tapped maple trees was included in woodland not pastured. The 2022 census definition for harvested cropland is the same as the 2017 definition.

Hay - all hay including alfalfa, and other dry. Data shown represent the acreage and quantity harvested of all types of dry hay. The quantity harvested was reported in dry tons (dry weight at the time the hay was removed from the field for storage or feeding). If two or more cuttings of dry hay were made from the same field, the acreage was reported only once as acres harvested of the appropriate dry hay category but the production from all dry hay cuttings was combined in the corresponding quantity harvested. Straw acreage and production are excluded.

If dry hay was cut from the same land that haylage, grass silage, or greenchop was cut, the acreage and production for the dry hay was reported in the appropriate category of dry hay and the acreage and production for haylage, grass silage, or greenchop was reported in the appropriate

haylage, grass silage, or greenchop category. For example, if 20 acres of alfalfa were cut for hay and then the same land was used to produce alfalfa haylage, 20 acres and the quantity harvested of hay were reported as Alfalfa and alfalfa mixtures for dry hay and 20 acres and the quantity harvested of alfalfa haylage were reported as Haylage or greenchop from alfalfa or alfalfa mixtures.

Hay, other dry hay. Data shown represent acreage and dry tons of hay harvested from clover, fescue, lespedeza, timothy, Bermuda grass, Sudangrass, sorghum hay, and other types of legumes (excluding alfalfa) and tame grasses. Data include small grains harvested for hay including barley, oats, rye, and wheat as well as wild hay.

Haylage, grass silage, and greenchop, all. Data shown represent the acreage and quantity harvested of all types (alfalfa and all other haylage, grass silage, and greenchop). The quantity harvested was reported in green tons. If two or more cuttings of haylage, grass silage, or greenchop were made from the same field, the acreage was reported as acres harvested in the appropriate haylage category only once, and the tonnage from all cuttings was combined in the corresponding quantity harvested. Straw acreage and production is excluded.

Hemp. In 2022, hemp was added to the field crops and nursery sections. Hemp previously would have been reported in other nursery or field crops. Hemp was asked based on utilization of the crop. In the field crops section, four utilizations were asked: 1) hemp for fiber, 2) hemp for floral (CBD and other cannabinoid usage), 3) hemp for grain, and 4) other hemp usage. In the nursery section, three categories were asked: 1) hemp clones or transplants sold for transplant to others, 2) hemp complete grows, and 3) hemp seeds. In 2017 and prior years, hemp was included in other crops.

Hired farm labor. Data are for total hired farm workers, including paid family members, by number of days worked. Data exclude contract laborers.

Hired managers. A hired manager is someone who receives a wage to manage the farm operation. Up to four hired managers were reported for each farm operation.

Hispanic, Latino, or Spanish origin. Producers of Hispanic, Latino, or Spanish origin are found in all of the racial groups listed in the census and were tabulated according to the race reported, as well as on tables pertaining only to this group.

Hogs and pigs by type of operation. Hog and pig farms were classified by primary type of operation. Operation types were farrow to wean, farrow to feeder, farrow to finish, nursery, finish only, and other. Each description was accepted and the reported inventory and sales data were assigned to each reported type.

Hogs and pigs by type of producer. Hog and pig farms were classified by one type of producer. Producer types were independent grower, contractor or integrator, and contract grower (contractee). Each description was accepted and the reported inventory and sales data were assigned to each reported type.

Honey collected. Data are for pounds of honey collected but not necessarily sold. See Colonies of honey bees.

Income. Net cash farm income is published for the operation and producer. See Net cash farm income of the operations and Net cash farm income of the producers.

Income from farm-related sources. See Total income from farm-related sources.

Institutional, research, experimental, and American Indian Reservation farms. Data for these farms are combined into a single category. Research farms include farms operated by private companies as well as those operated by universities, colleges, and government organizations for the purpose of expanding agricultural knowledge.

Internet access. This item is the number of farms that reported using personal computers, laptops, or mobile devices (e.g., cell phones or tablets) to access the internet. This can be done using services such as broadband, dial-up, cellular , satellite, or other methods.

Involvement in decisionmaking. Questions were asked about each producer's involvement in farm-related decisions, including day-to-day decisions, land use and/or crop decisions, livestock decisions, record keeping and/or financial management, and estate planning or succession planning. Marketing decisions were added in 2022.

Irrigated farms. In 2017, this item was referred to as the number of farms with irrigation. This is a wording change only; data are comparable.

Irrigated land. This category includes all land watered by any artificial or controlled means, such as sprinklers, flooding, furrows or ditches, sub-irrigation, and spreader dikes. Included are supplemental, partial, and preplant irrigation. Each acre was counted only once regardless of the number of times it was irrigated or harvested. If an operation reported less than one acre irrigated, the irrigated land for the operation was rounded to one acre. Livestock lagoon wastewater distributed by sprinkler or flood

systems was also included.

Land area, approximate. The approximate land area represents the total land area as determined by records and calculations as of January 1, 2022. The proportion of land area in farms may exceed 100 percent because some operations have land in two or more counties, but all acres are tabulated in the principal county of operation. The approximate land area data were supplied by the U.S. Department of Commerce, Bureau of the Census. See Land in two or more counties.

Land enrolled in crop insurance programs. The data are for all land enrolled in any Federal, private, or other crop insurance program. It includes acreage of pasture/rangeland enrolled in crop insurance programs in areas where it is provided.

Land enrolled in the Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), Farmable Wetlands Program (FWP), or Conservation Reserve Enhancement Program (CREP). CRP is a program established by the USDA in 1985 that takes land prone to erosion out of production for 10 to 15 years and devotes it to conservation uses. In return, farmers receive an annual rental payment for carrying out approved conservation practices on the conservation acreage. The WRP, FWP, and CREP programs are included under the Conservation Reserve Program.

Operations with land enrolled in the CRP, WRP, FWP, or CREP were counted as farms, given they received $1,000 or more in government payments, even if they had no sales and otherwise lacked the potential to have $1,000 or more in sales.

Land in berries. Data are for total land in berries, including land on which all berry crops failed. Respondents reported bearing age acres and nonbearing acres by individual berry crops.

Land in farms. The acreage designated as ''land in farms'' consists primarily of agricultural land used for crops, pasture, or grazing. It also includes woodland and wasteland not actually under cultivation or used for pasture or grazing, provided it was part of the farm producer's total operation. Large acreages of woodland or wasteland held for nonagricultural purposes were deleted from individual reports during the edit process. Land in farms includes CRP, WRP, FWP, and CREP acres.

Land in farms is an operating unit concept and includes land owned and operated as well as land rented from others. Land used rent free was reported as land rented from others. All grazing land, except land used under government permits on a per-head basis, was included as ''land in farms'' provided it was part of a farm or ranch. Land under the exclusive use of a grazing association was reported by the grazing association and included as land in farms. All land in American Indian reservations used for growing crops, grazing livestock, or with the potential of grazing livestock was included as land in farms. Land in reservations not reported by reservation, individual American Indians, or non-Native Americans was reported in the name of the cooperative group that used the land. In a few instances, an entire American Indian reservation was reported as one farm.

Land in orchards. This category includes land in bearing age and nonbearing age fruit trees, citrus or other groves, vineyards, and nut trees of all ages, including land on which all fruit crops failed. Respondents also reported bearing age acres and nonbearing age acres by individual fruit and nut crops.

Land in two or more counties. With few exceptions, the land in each farm was tabulated as being in the producer's principal county. The principal county was defined as the one where the largest value of agricultural products was raised or produced. It was usually the county containing all or the largest proportion of the land in the farm or viewed by the respondent as his/her principal county. Reports received showing land in more than one county were separated into two or more reports if the data would substantially distort county totals.

Land use practices. Includes all agricultural land used for the production of agricultural commodities.

Drained by tile. Tile drainage is a practice that removes excess water from the soils subsurface.

Artificially drained by ditches. A field ditch installed for surface drainage for collecting excess surface or subsurface water in a field.

Conservation easement. A conservation easement is a legal agreement voluntarily entered into by a property owner and a qualified conservation organization such as a land trust or government agency. This category excludes land in CRP (Conservation Reserve Program) acres.

No-till practices used. Using no-till or minimum till is a practice used for weed control and helps reduce weed seed germination by not disturbing the soil.

Conservation or reduced tillage. Conserves the soil by reducing erosion and decreasing water pollution. Conservation tillage leaves 30 percent or more of the soil surface covered by crop residue after planting. Reduced

tillage leaves between 15 percent and up to 30 percent of the soil surface covered. In 2017, this category was labeled reduced (conservation tillage). This is a wording change only; data are comparable.

Intensive or conventional tillage. Refers to tillage operations that use standard practices which leaves less than 15 percent of the soil surface covered by crop residue. Intensive tillage often involves multiple operations with implements such as moldboard, disk, or chisel plow. In 2017, this category was labeled as intensive (conventional tillage). This is a wording change only; the data are comparable.

Cover crop. A crop planted primarily to manage soil fertility, soil quality, water, weeds, pests, diseases, or wildlife. This item does not include CRP acres.

Land used for vegetables. Data are for the total land used for vegetable and melon crops. The acres were reported only once, even though two or more harvests of a vegetable or more than one vegetable were harvested from the same acres. Respondents also reported harvested acres, acres harvested for fresh market, and acres harvested for processing by individual vegetable crops.

Land with irrigation systems or equipment present. This was a new question in 2022. Land includes acres irrigated in 2022 and acres that were not irrigated in 2022 but could have been irrigated, regardless of water rights.

Landlord's share of the total sales. Data represent the share of the operation's total sales that went to landlord(s).

Layers. This category includes table-egg type layers, hatching layers for meat-types, hatching layers for table egg types, and reported bantams.

Legal status for tax purposes. See Farms by legal status.

Less than $1,000. See Farms with sales and government payments of less than $1,000.

Livestock and poultry purchased or leased. See Total farm production expenses; Livestock and poultry purchased or leased.

Longan. This is a new item for 2022. In 2017, longan were reported in other non-citrus fruit.

Lychees. This is a new item for 2022. In 2017, lychees were reported in other non-citrus fruit.

Maple syrup. Data are for the number of taps set, syrup produced, and value of sales.

Market value of agricultural products sold. This category represents the gross market value before taxes and production expenses of all agricultural products sold or removed from the place in 2022, regardless of who received the payment. It is equivalent to total sales and it includes sales by the producers as well as the value of any shares received by partners, landlords, contractors, or others associated with the operation. It includes value of organic sales, direct sales and the value of commodities placed in the Commodity Credit Corporation (CCC) loan program. Market value of agricultural products sold does not include payments received for participation in other Federal farm programs. It does not include income from farm-related sources such as customwork and other agricultural services, or income from nonfarm sources.

The value of crops sold in 2022 does not necessarily represent the sales from crops harvested in 2022. Data may include sales from crops produced in earlier years and may exclude some crops produced in 2022 but held in storage and not sold. For commodities such as sugarbeets and wool sold through a co-op that made payments in several installments, respondents were requested to report the total value received in 2022.

The value of agricultural products sold was requested of all producers. If the producers failed to report this information, estimates were made based on the amount of crops harvested, livestock or poultry inventory, or number sold. Caution should be used when comparing sales in the 2022 census with sales reported in earlier censuses. Sales figures are expressed in current dollars and have not been adjusted for inflation or deflation. See Farms with sales and government payments of less than $1,000.

Market value of agricultural products sold and government payments. See Total market value of agricultural products sold and government payments.

Medical supplies, veterinary, and custom services for livestock. This category includes fees for medical supplies, veterinary care, and custom services such as artificial insemination (AI), banding, breeding fees, caponizing, carcass removal, castrating, custom feed processing, hormone injections, performance testing, pregnancy testing, seining, sheep shearing, and other such care. This category excludes manure removal. See Total farm production expenses.

Methane digesters. See Renewable energy producing systems.

Migrant farm labor on farms reporting only contract labor. Data are for those operations that did not have hired farm workers but reported that they did have migrant

contract workers on their operation in 2022.

Migrant farm labor on farms with hired labor. Producers were asked whether any hired or contract workers were migrant workers. A migrant farm worker is a farm worker whose employment required travel that prevented the worker from returning to his/her permanent place of residence the same day.

Migrant workers, total. Data are for total migrant farm workers whose employment requires travel that prevents the worker from returning to his or her permanent place of residence the same day.

Military service. A producer with military service is a person who currently or previously served on active duty in the U.S. Armed Forces. For publication purposes, two categories are included in the personal characteristics tables 1) Never served or only on active duty for training in the Reserves or National Guard, 2) Active duty now or in the past. The categories in 2017 were: Never served and Served. This is a wording change only; data are comparable.

Mink, live. The data are for inventory and sales of live mink. Number of farms producing mink pelts are included in livestock products.

Miscellaneous poultry. Data are for poultry other than chickens or turkeys. Data are published in Chapter 2, table 20.

Misreported or miscoded crops. In a few cases, data may have been reported on the wrong line, in the wrong section, or the wrong crop code may have been assigned to a write-in crop code. A few of these errors may not have been identified and corrected during processing which resulted in rare cases of inaccurately tabulated data. Reports with significant acres of unusual crops for the area were examined to minimize the possibility that they were in error.

Mollusks. These are invertebrate animals with a soft body covering and shells of 1-18 parts or sections. Examples include abalones, clams, mussels, oysters, and snails. See Aquaculture.

More than one race reported. This category represents producers who reported more than one race on the census form.

Mulberries. This is a new item for 2022. In 2017, mulberries were reported in other berries.

Mushroom spawn. Respondents reported only sales; growing area was not summarized.

Mushrooms. All mushroom crops were considered grown under glass or other protection and no mushroom data were published as area in the open. Those reporting mushrooms grown in the open area were converted to an equivalent area of square feet under protection proportional to their sales.

NAICS. See Farms by North American Industry Classification System (NAICS).

Net cash farm income of the operations. This concept is derived by subtracting total farm expenses from total sales, government payments, and other farm-related income. Depreciation is not used in the calculation of net cash farm income. Net cash farm income of the operation includes the value of commodities produced under production contract by the contract growers.

For publication purposes, farms are divided into two categories:

1. Farms with net gains (includes those operations that broke even).

2. Farms with net losses.

Net cash farm income of producers. This value is the producers' total revenue (fees for producing under a production contract, total sales not under a production contract, government payments, and farm-related income) minus total expenses paid by the producers. Net cash farm income of the producer includes the payments received for producing under a production contract and does not include value of commodities produced under production contract by the contract growers. Depreciation is not used in the calculation of net cash farm income.

For publication purposes, farms are divided into two categories:

1. Farms with net gains (includes those producers that broke even).

2. Farms with net losses.

New and beginning producers. It includes producers operating on any operation for 10 years or less. They may be on farms with producers who are not beginning producers.

Noncitrus fruit, all. This is a summation of all acres reported in the commodities defined as noncitrus such as apples, grapes, and plums.

Number of female producers. This item is the total count of female producers involved in decisions for the operation reported by the respondent. Detailed demographic data are only available for up to four producers per farm operation.

Number of male producers. This item is the total count of male producers involved in decisions for the operation reported by the respondent. Detailed demographic data are only available for up to four producers per farm operation.

Number of persons living in producers' households. This is the count of people living in the households of the producers on the farm. If producers on the farm are living in the same household, the count is not duplicated for each producer.

Number of producers. This item is the total count of producers involved in decisions for the operation reported by the respondent. Detailed demographic data are only available for up to four producers per farm operation.

Nursery, greenhouse, floriculture, and sod. Data are for total square feet under protection and acres in the open. Individual crop data were collected for area under glass or other protection, area in the open, and sales of aquatic plants, floriculture and bedding crops, nursery crops, sod, propagative materials, food crops grown under protection, and mushroom crops. Total sales data are the summation of all crops.

Nursery stock crops. Data include ornamentals, shrubs, shade trees, flowering trees, evergreens, live Christmas trees, fruit and nut trees and plants, vines, palms, ornamental grasses, and bare root herbaceous perennials.

Nuts, all. Data include all nut trees.

Occupation. See Producer characteristics.

Operation more than 50 percent owned by one producer's household and/or extended family. See Farms by type of organization.

Operations legal status for tax purposes. See Farms by legal status.

Oranges, all. All oranges are a summation of Valencia oranges and Other than Valencia oranges. Total acres, bearing age acres, and nonbearing age acres were collected by category.

Oranges, other than Valencia – include Navel. This includes all oranges other than Valencia type.

Organic agriculture. Respondents were instructed to indicate if they had organic production according to USDA's National Organic Program (NOP). Respondents reported whether their organic production was certified or exempt from certification and the sales from NOP produced commodities. They also reported whether they had acres transitioning into NOP production and the value of sales of USDA NOP certified or exempt organically produced commodities. Also see Total organic product sales.

Organic fertilizer used. These are the acres of cropland or pastureland on which approved organic fertilizers were applied.

Organic value of sales. See Total organic product sales.

Ornamental fish. This category includes various fish raised for water gardens, aquariums, etc. Examples include angel fish, guppies, koi, ornamental goldfish, and tropical fish. The value of sales was tabulated for each specified species.

Other animals and other animal products sold. This category includes number of farms and value of sales for all animals and animal products not listed elsewhere on that specific table.

Other aquaculture products. This category includes aquaculture not listed separately. Examples include the production of alligators, frogs, leeches, eels, live rock, salamanders, and turtles.

Other berries. This includes other berry varieties that were not pre-printed in the report form. In 2017, this category included gooseberries and mulberries which are reported separately in 2022. Data are not directly comparable.

Other cattle. Data include heifers that had not calved, steers, calves, and bulls.

Other cattle, sheep, livestock, or poultry. See Commodities raised and delivered under production contract.

Other citrus. Data relate to any citrus crop not having a specific code on the report form.

Other cropland. This includes all cropland other than harvested cropland or other pasture and grazing land that could have been used for crops without additional improvements. It includes cropland idle or used for cover crops or soil improvement, cropland on which all crops failed or were abandoned, and cropland in summer fallow.

Other crops. In Chapter 2, table 27, Other crops data relate to any field crops that did not have a specific code in the field crops section of the report form.

Other crops and hay. Data are for the total market value of all crops not categorized into one of the prelisted crop sales categories on the report form. This category includes crops such as grass seed, hay and grass silage, haylage, greenchop, hops, maple syrup, mint for oil, peanuts, sugarcane, sugarbeets, etc.

Other dry hay. See Hay, other dry.

Other farm related income sources. See Total income from farm-related sources.

Other field and grass seed crops. Data relate to any field or grass seed crop not having a specified code on the report form.

Other floriculture and bedding crops. Data relate to any floriculture and bedding crops not having a specific code on the report form.

Other food fish. Data are for fish, other than catfish and trout, raised on farms primarily for food. Examples include hybrid striped bass, perch, salmon, sturgeon, and tilapia.

Other greenhouse vegetables and fresh cut herbs. This category includes vegetable crops, other than tomatoes, that were grown under protection and fresh cut herbs grown under protection.

Other land. This category includes land in house lots, barn lots, ponds, roads, ditches, wasteland, etc. It includes those acres in the farm operation not classified as cropland, pastureland, or woodland. See Land in farms.

Other livestock. This category includes all livestock not having specific codes on the 2022 report form. In addition, package bees; bees, other than honey or package bees; laboratory animals; and worms are included. See Other animals and other animal products sold.

Other livestock and poultry purchased or leased. See Total farm production expenses.

Other livestock products. Data for this category include the number of farms that sold livestock products that did not have a specific code on the 2022 report form. In addition, beeswax, breeding fees, embryos, fur or pelts, horns, manure sold, and semen are included in this category. Data are for farms with production, not necessarily sold.

Other noncitrus fruit. Data relate to any noncitrus fruit not having a specific code on the census report form. Data are not directly comparable because several fruits were listed individually in 2022 and not included in other noncitrus item.

Other nuts. This category includes any nut crop not having a specific code on the report form.

Other pasture and grazing land that could have been used for crops without additional improvements. This category includes land used only for pasture or grazing that could have been used for crops without additional improvement. Also included are acres of crops grazed by livestock, but not harvested prior to grazing. However, cropland that was pastured before or after crops were harvested in 2022 was included as harvested cropland rather than cropland for pasture or grazing.

Other poultry. Data are for other poultry not having a specific code on the report form.

Other spring wheat for grain. Other spring wheat for grain was sometimes referred to as spring wheat for grain. Spring wheat is consistently referred to as other spring wheat for grain. See also Wheat for grain.

Other vegetables. Data shown for other vegetables relate to any vegetable not having a specific code on the census form.

Patronage dividends. See Total income from farm-related sources.

Parsnips. This is a new item for 2022. In 2017, parsnips were reported in other vegetables.

Payments received by the contractee for commodities produced under production contract. These data show the number of farms and the dollar amount the contractees received from contractors for commodities produced under contract. This is not the market value of the commodities delivered, but the payment or fee the producers received for commodities delivered.

Pawpaws. This is a new item for 2022. In 2017, pawpaws were reported in other non-citrus fruit.

Peacocks and peahens. Peacocks and peahens were reported as other poultry.

Peaches, all. Data were collected for pears as, Peaches, clingstone and Peaches, freestone, in all States including Hawaii.

Pears, all. Data were collected for Pears as, Bartlett and Pears, other than Bartlett in all States including Hawaii.

Peas, green. Excludes all dry peas which were collected in the field crop section. Also excluded are Chinese peas and southern peas which were reported separately.

Peas, southern (cowpeas) – blackeyed, crowder, etc. Excludes dry peas which were collected in the field crops section.

Pecans, all. All pecans are a summation of Pecans, improved and Pecans, native and seedling. Total acres, bearing acres, and nonbearing acres were collected by category.

Pecans, improved. Improved pecans are varieties that have been genetically altered through breeding and grafting techniques to produce more nuts, and nuts with a greater percentage of nut meat. See Pecans, all.

Pecans, native and seedlings. Native pecans are varieties that developed under natural conditions. Seedling pecans are produced from seed (the nut) and have not been budded or grafted. See Pecans, all.

Peppers, Bell (excluding pimientos). Pimientos were reported as Other vegetables.

Peppers, other than Bell (including chile). The data include all other peppers including chile. Pimientos were reported as Other vegetables.

Permanent pasture and rangeland, other than cropland and woodland pastured. This land use category encompasses grazable land that does not qualify as woodland pasture or cropland pasture. It may be irrigated or dry land. In some areas, it can be a high quality pasture that could not be cropped without improvements. In other areas, it is barely able to be grazed and is only marginally better than wasteland.

Plumcots, pluots, and other plum-apricot hybrids. This category includes everything that is not a plum or prune. Pluot is a registered trademark of plumcots, which are genetic crosses between plums and apricots.

Potatoes. Potato acres are included in the vegetable acres. Data are for total acres harvested, acres harvested for fresh market, and acres harvested for processing. Production was not collected.

Poultry hatched. This category includes all poultry hatched on the operation during the year. The number of poultry hatched is published under the sales heading.

Poultry, other. See Other poultry.

Precision agriculture. See Use of precision agriculture practices.

Primary occupation of producer. Data on primary occupation were obtained from up to four producers per farm. The primary occupation classifications used were:

1. *Farm or ranch work.* The producer spent 50 percent or more of his/her worktime during 2022 farming or ranching.

2. *Other.* The producer spent less than 50 percent of his/her worktime during 2022 farming or ranching.

Producer. The term producer designates a person who is involved in making decisions for the farm operation. Decisions may include decisions about such things as planting, harvesting, livestock management, and marketing. The producer may be the owner, a member of the owner's household, a hired manager, a tenant, a renter, or a sharecropper. If a person rents land to others or has land worked on shares by others, he/she is considered the producer only of the land which is retained for his/her own operation. The census collected information on the total number of male producers, the total number of female producers, and demographic information for up to four producers per farm.

Producer characteristics. Producers (up to four producers per farm) were asked to report primary occupation, sex, age, race, if they were of Hispanic, Latino or Spanish origin, place of residence, if retired from farming, number of days worked off farm, year in which his/her operation of the farm began, year began operating any farm, if they were a hired manager, if they had military service, and the number of persons living in their households. In addition, the total number of male and female producers was collected from each operation.

Producers, number. Demographic and other information were collected for up to four producers per farm. This may be fewer than the total number of producers on some farms.

Production contracts. See Commodities raised and delivered under production contracts.

Production expenses. See Total farm production expenses.

Pullets for laying flock replacement. Data are for pullet inventory and the number sold or moved for laying flock replacement.

Rabbits, live. The data are for inventory and sales of live rabbits. The number of rabbit pelts is included in Other livestock products**.**

Race of producer. With the exception of Hawaii, data were collected for American Indian and Alaska Native, Asian, Black or African American, Native Hawaiian and Other Pacific Islander, and White producers. Respondents were asked to mark one or more of the race categories. In Hawaii producer race data were collected for American Indian (included Alaska Native), Chinese, Filipino, Japanese, Korean, Other Asian, Black or African American, Native Hawaiian, other Pacific Islander, and White. The combination of Native Hawaiian and Other Pacific Islander is equivalent to the Native Hawaiian or Other Pacific Islander category on the other forms. The combination of the Chinese, Filipino, Japanese, Korean, and Other Asian categories is equivalent to the Asian category on the other forms. The Volume 1, Geographic Area Series, U.S. Summary publication only displays counts for the categories of Native Hawaiian and Other Pacific Islander and Asian. Data for the 11 Hawaii race categories are published in chapter 2 of the Hawaii publication of the Volume 1 series.

Rambutan. This is a new item for 2022. In 2017, rambutan were reported in other non-citrus fruit.

Raspberries, all. In 2022, data for black, red, and other raspberries were combined and reported as raspberries, all. Data are comparable to 2017.

Renewable energy producing systems. These types of systems produce power, heat, or mechanical energy by converting resources either to electricity or to motor power.

Geothermal/geoexchange system. A system that uses temperatures from the earth to reduce the operational costs of heating and cooling.

Methane digesters. It is a device which captures biogas resulting from the decomposition of manure, processing by-products, and other materials. Harvested biogas is used as a substitute for natural gas to power engines which generate electricity. It is fed into the natural gas pipeline or flared.

Small hydro system. A water driven system, which produces electricity, by the gravitational force of falling or flowing water. It excludes water driven systems that only provide mechanical power, such as turning a grinding stone for a flour mill.

Solar panels. A flat panel designed to capture the sun's energy. Includes photovoltaic systems, which convert light from the sun into electricity, and thermal systems that passively generate electricity.

Wind turbines. A device which converts wind power into electricity. Includes wind generators, wind power units, wind energy converters, and aero generators. Excludes windmills, which do not produce electricity.

Rental of farmland. See Total income from farm-related sources, Gross cash rent or share payments.

Sales, total. See Market value of agricultural products sold.

Sex of producers. This item pertains only to four producers from whom detailed demographic data were collected. Total male and female producer counts may be larger.

Sheep and lambs inventory. Data are for sheep and lambs of all ages owned regardless of location.

Short rotation woody crops. Data are for short rotation woody crops that grow from seed to a mature tree in 10 years or less. These are trees for use by the paper or pulp industry or as engineered wood. This does not include lumber. Acres in production were included in Cropland harvested in the Land use section of the report form.

Size of farm. See Farms by size.

Small hydro system. See Renewable energy producing systems.

Sod harvested or intended for sale in future years. This is a new item for 2022. It replaced sod harvested to include sod in production but not harvested. Data are not comparable.

Solar panel. See Renewable energy producing systems.

Sport or game fish. Data are for sport or game fish raised on farms to be used primarily for sport. Examples include bluegill, crappie, largemouth bass, smallmouth bass, sunfish, muskie, northern pike, and walleye.

Squash, all. All squash is a summation of summer squash and winter squash. Total acres, acres for fresh market, and acres for processing were collected by category. In 2017, the squash types were collected as separate items.

Sugarcane for sugar or seed. Sugarcane for sugar and sugarcane for seed were collected separately in 2017 but were combined in 2022 and collected as sugarcane for sugar or seed. Data are not comparable.

Sweet corn. Sweet corn includes sweet corn harvested for the fresh and processing markets as well as for seed. Sweet corn harvested for the fresh market includes seed grown in the open and the category is not comparable to 2017 for this category. See Vegetables harvested for fresh market.

Sweet corn for seed. Sweet corn for seed is not published as a separate data item in 2022. Sweet corn for seed is in the field crop section was combined into vegetable seeds in the vegetable section.

Sweet potatoes. Sweet potato acres are included in the vegetable acres. Data are for total acres harvested, acres harvested for fresh market, and acres harvested for processing. Production was not collected.

Tangerines. Data include temples.

Tenure. See Farms by tenure of producer.

Tobacco transplants. Data are for tobacco transplants that were sold for transplant to farm fields. Transplants grown for transplanting to the same operation were not reported or removed during data review.

Tomatoes in the open. Data are for tomatoes grown in the open and excludes tomatoes produced under glass or other protection.

Total cropland. This category includes cropland harvested, other pasture and grazing land that could have been used for crops without additional improvements, cropland on which all crops failed or were abandoned, cropland in summer fallow, and cropland idle or used for cover crops or soil improvement but not harvested and not pastured or grazed.

Total farm production expenses. Includes the production expenses provided by the producers, partners, landlords (excluding property taxes), and production contractors for the farm business in 2022. Tenant farmers reported expenses paid by landlords for the agricultural production on the operation, as well as their expenses. Farm or ranch producers who rented part of their land to others reported only the expenses for the land they actually used themselves and not expenses for land rented to others. The 2022 total farm production expenditure includes all farm-related expenses such as customwork, fuel costs, cost of cutting timber, services provided to hunters, cooperative membership fees, etc. However, if the income from these farm-related categories was not considered a part of the operation (i.e., if the income was regarded as derived from a separate business), then the associated expenses were not included. The contractor's portion of expenses was solely based on computer generated estimates for 2022. This item excludes expenses relating to non-farm activities such as trading and speculation in the commodities market or livestock trading activities. Explanations of selected production expenses are listed below.

All other production expenses. All other production expenses include all expenses not listed on the report form. Examples include storage and warehousing, marketing and ginning expenses, insurance, etc. Health insurance premiums and payroll taxes are reported in hired labor expenses.

Breeding livestock purchased or leased. These expenses include all breeding livestock and poultry purchased or leased during 2022 for production on the farm or ranch. The total includes amount spent for beef and dairy cows, heifers, bulls, sows, gilts, boars, rams, lambs, ewes, roosters, hens, layers, etc. Estimations of the value of livestock or poultry fed on a custom basis were to be made based on their value when they arrived on the farm or ranch.

Cash rent paid in 2022 for land and buildings. These data include the cost of renting land and buildings that were part of the operation. Rent paid for the producer's dwelling or other non-farm property and the value of the shares of crops and livestock paid to landlords were excluded.

Chemicals. These 2022, expenses include insecticides, herbicides, fungicides, and other pesticides, including costs of custom application. Data exclude commercial fertilizer purchased.

Contract labor. These data include payments made to contractors, crew leaders, cooperatives, or any other organization hired to furnish a crew of laborers to do a job that may involve one or more agricultural operations. In some cases, a crew leader may furnish some equipment. Data exclude expenses made on a contractual basis for repair or maintenance or for capital improvements, such as construction of farm buildings, installation of fences or irrigation systems, and land leveling.

Cover crop seed purchased. This expense category is a subset of total seeds, plants, vines, and trees expense. It includes the cost of all seeds, bulbs, plants, propagation materials, trees, seed treatments, seed cleaning costs, etc. for cover crops purchased during 2022.

Customwork and custom hauling. These expenses include costs incurred for having customwork done on the place and for renting machines to perform agricultural operations. The cost of cotton ginning is excluded. The cost of labor involved in the customwork service is included in the customwork expense. Some examples of

customwork are planting, spraying, harvesting, preparation of products for marketing, grinding and mixing feed, corn picking, grain drying, and silo filling. The cost of custom application of fertilizer and chemicals is included in expenditures for fertilizer and chemicals. The cost of hired labor for operating rented or hired machinery is included as a hired farm and ranch labor expense.

Feed purchased. These expenses include the cost of all feed purchased for livestock and poultry including grain, hay, silage, mixed feeds, concentrates, etc. during 2022.

Fertilizer, lime, and soil conditioners. These 2022 expenses include fertilizer, lime, rock phosphate, and gypsum and the costs of custom application.

Gasolines, fuels, and oils. These expenses include the cost of all gasoline, diesel, natural gas, LP gas, motor oil, and grease products for the farm during 2022. Expenses exclude fuel for personal use of automobiles by the family and others, fuel used for cooking and heating the farmhouse, and any other use outside of farmwork on the operation.

Hired farm labor. These 2022 expenses include the total amount paid for farm or ranch labor including regular workers, part-time workers, and members of the producer's family if they received payments for labor. Expenses include Social Security taxes, State taxes, unemployment tax, payment for sick leave or vacation pay, workman's compensation, insurance premiums, and pension plans.

Interest paid on debts. These expenses include interest and finance charges paid in 2022 for debts secured by real estate and on debt not secured by real estate. Interest expenses excluded from this category are non-farm interest expenses and interest expenses originating from machinery and equipment used for a separate customwork business or for other operations. Interest expense for the producer's dwelling, where the amount is separate from interest on farm land and buildings on the operation, is excluded. Interest paid on debts was reported in one of two categories:

1. *Secured by real estate.* These data include all interest expenses paid in 2022 on debts secured by real estate for the farm.

2. *Not secured by real estate.* These data include all interest expenses paid in 2022 on debts secured by machinery, tractors, trucks, other equipment, livestock, poultry, breeding stock, money borrowed for use as working capital, and interest paid on CCC loans for the farm.

Livestock and poultry purchased or leased. These data include Breeding livestock purchased or leased and Other livestock and poultry purchased or leased.

Medical supplies, veterinary, and custom services for livestock. This category includes fees for medical supplies, veterinary care, and custom services such as artificial insemination (AI), banding, breeding fees, caponizing, carcass removal, castrating, custom feed processing, hormone injections, performance testing, pregnancy testing, seining, sheep shearing, and other such care. This category excludes manure removal. See Total farm production expenses.

Other livestock and poultry purchased or leased. These expenses include all non-breeding livestock and poultry purchased or leased during 2022 for production on the farm or ranch. The total includes amounts spent for cattle, calves, hogs, pigs, sheep, hatchery eggs, etc.

Property taxes paid. These data include property taxes paid by the producers for the farm share of land, machinery, buildings, and livestock, excluding taxes paid by this producer's landlords.

Rent and lease expenses for machinery, equipment, and farm share of vehicles. These data include the farm share cost of renting or leasing machinery, equipment, and vehicles during 2022. Rental and lease expenses of items used only for custom hire are excluded here.

Repairs, supplies, and maintenance. These expenses include all costs for the repair and upkeep of buildings, motor vehicles, fences, and farm equipment used for the farm business during 2022. Repairs to equipment used both for the farm business and for performing customwork are included.

Seeds, plants, vines, and trees. These expenses include the cost of all seeds, bulbs, plants, propagation materials, trees, seed treatments, seed cleaning costs, etc. purchased during 2022. Excluded were items purchased for immediate resale or the value of seed grown on the operation.

Utilities. These data show the farm share cost of electricity, telephone charges, internet fees, and water purchased in 2022. Included in the water cost is water purchased for irrigation purposes, livestock watering, etc. Household utility costs were excluded from these items.

Total female producers. See Number of female producers.

Total greenhouse vegetables and fresh cut herbs. This category includes greenhouse tomatoes and other

greenhouse vegetables and fresh cut herbs.

Total horses and ponies. See Horses and ponies value of sales.

Total income from farm-related sources. This includes gross income from farm-related sources received in 2022 before taxes and expenses from the sales of farm byproducts and other sales and services closely related to the principal functions of the farm business. The data exclude income from employment or business activities, which were separate from the farm business.

Agri-tourism and recreational services. This income includes income from recreational services such as hunting, fishing, farm or wine tours, hay rides, etc.

Amount from State and local government agricultural program payments. This income includes State and local government agricultural program payments. Respondents were to exclude the State and local portion of Conservation Reserve Enhancement Program (CREP) payments if they were reported in the amount received for participation in CREP in section 6, item 2 of the report form.

Crop and livestock insurance payments received. This income includes insurance payments from crop and livestock losses.

Customwork and other agricultural services. This income includes gross receipts received by the farm producers for providing services for others such as planting, plowing, spraying, and harvesting. Income from customwork and other agricultural services is generally included in the agriculture census if it is closely related to the farming operation. However, it is excluded if it constituted a separate business or was conducted from another location.

Gross cash rent or share payments. This income includes gross cash or share payments received from renting out farmland, payments received from the lease or sale of allotments, and payments received for livestock pastured on a per-head, per month, or per pound basis. It excludes rental income from nonfarm property.

Other farm-related income sources. This is other income which is closely related to the agricultural operation. This income includes animal boarding, breeding fees (horse breeding or stud fees received were reported in the Value of Sales section in the Other animals and other animal products category), tobacco quota buyouts, State fuel tax refunds, farm generated energy, etc. Crop and livestock insurance payments received and amount from State and local government agricultural program payments were published separately.

Patronage dividends and refunds from cooperatives. This income includes payments to a farmer or rancher for business done with a cooperative to which he/she usually belongs. The payment is usually for goods sold through the co-op.

Sales of forest products. This income includes gross receipts from sales of standing timber, pulpwood, firewood, etc. from the farm or ranch operation. It excludes income from nonfarm timber tracts, sawmill businesses, cultivated Christmas trees, maple products, and short rotation woody crops.

Total market value of agricultural products sold and government payments. This category represents the value of products sold plus government payments. Total value of products sold combines total sales not under production contract and total sales under production contract. Government payments consist of government payments received from the Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), Farmable Wetlands Program (FWP), or Conservation Reserve Enhancement Program (CREP) plus government payments received from Federal programs other than the CRP, WRP, FWP, and CREP, and Commodity Credit Corporation loans.

Total male producers. See Number of male producers.

Total organic product sales. The data represent the value of organically produced agricultural commodities sold from operations during 2022. It includes only the value of those products that were produced as organic according to the National Organic Standards and sold by certified or exempt from certification farm operations.

Total payments received. See Commodities raised and delivered under production contracts.

Total producers. See Number of producers.

Total sales. See Market value of agricultural products sold.

Turkeys. Turkey data are a combination of turkeys for meat production, turkey hens and toms kept for breeding, and turkey brooders tabulated from three questions. Turkey brooders are immature birds sent to another farm for further growout to meat production or breeding. This may result in a turkey being sold more than once from different operations.

Type of organization. See Farms by type of organization.

Unpaid workers. Data include agricultural workers not on the payroll who performed activities or work on a farm or ranch.

Utilities. See Total farm production expenses.

Use of precision agriculture practices. This is a new item for 2022. The use of precision agricultural practices is defined as the use of practices that utilize technology to improve agricultural productivity or efficiency by connecting the practice to a digital environment for crop or livestock production. Several examples of precision agriculture practices are the use of global positioning (GPS) guidance systems, GPS yield monitoring and soil mapping, variable rate input applications, use of drones for scouting fields or monitoring livestock, electronic tagging, precision feeding, and robotic milking. Precision agriculture practices are not limited to these examples.

Value of commodities. Data show the number of farms and the market value of all commodities delivered under a production contract.

Value of food sold directly to consumers. Data represent the value of edible products, including value added products, produced and sold for human consumption directly to consumers at farmers markets, on-farm stores or farm stands, roadside stands or stores, u-pick, CSA (Community Supported Agriculture), online marketplaces, etc.

Value of food sold directly to retail markets, institutions, and food hubs for local or regionally branded products. Data represent the value of products, including value added products, produced and sold for human consumption directly to retail markets, institutions, or food hubs for locally or regionally branded products. Examples include supermarkets, restaurants, caterers, independently owned grocery stores, food cooperatives, K-12 schools, colleges or universities, hospitals, workplace cafeterias, prisons, food banks, etc.

Value of landlord's share of total sales. Data include the value of agricultural sales received by the landlords.

Value of organically produced commodities. See Total organic product sales.

Value of processed or value-added agricultural products sold. Data represent the value of products that originated from crop or livestock commodities produced on the operation. Through further manufacture or processing, these items are transformed into products worth more than the originally produced commodity.

Value of sales. See Market value of agricultural products sold.

Vegetable seeds. Include seed grown under protective cover for vegetable crops.

Vegetable transplants. Data are for vegetable transplants grown and sold from the operation for transplanting to fields on another operation.

Vegetables harvested for fresh market. Respondents reported the total vegetable acres harvested, harvested for fresh market, and harvested for processing. Data include vegetables harvested for seed and are not directly comparable to 2017.

Vegetables harvested for sale. The acres of vegetables harvested is the summation of the acres of individual vegetables harvested. All of the individual vegetable items may not be shown. When more than one vegetable crop was harvested from the same acreage, acres were counted for each crop.

Vegetables, melons, and potatoes. See Commodities raised and delivered under production contracts.

Vegetables, other. See Other vegetables.

Wheat for grain. Data were reported by type of wheat - Durum, winter, and other spring.

Wind turbines. See Renewable energy producing systems.

Woodland pastured. This category includes all woodland used for pasture or grazing during the census year. Woodland or forest land pastured under a per-head grazing permit was not counted as land in farms and, therefore, was not included in woodland pastured.

Woodland, total. This category includes natural or planted woodlots or timber tracts, cutover and deforested land with young growth which has or will have value for wood products, and woodland pastured. Land covered by sagebrush or mesquite was reported as Permanent pasture and rangeland or Other land. Land planted for Christmas tree production and short rotation woody crops was reported in Cropland harvested, and land in tapped maple trees was reported as Woodland not pastured.

Write-in crops. The respondent was asked to look at a list of crops in each section of the report form and write in the crop name and its code for all commodities produced. For crops that had no individual code listed on the report form, the respondent was to write in the crop name and code of the appropriate ''all other'' category for that section. Write-in crops coded as ''all other'' were reviewed and assigned a specific code when possible. Crops not assigned a specific code were left in the appropriate ''all other'' category.

Years operating any farm. This number is based on the year each producer began operating any farm operation.

Young producers. A young producer is defined as a producer 34 years of age or younger. This is a definition change from 2017. Young producers in 2017 included producers 35 years of age or younger. The data are not comparable.

OMB No. 0535-0226: Approval Expires 09/30/2024

UNITED STATES 2022 CENSUS OF AGRICULTURE

Form Number: 22-A100
(09/20/2021)





National Agricultural Statistics Service

Return your completed report to:

Census of Agriculture
1201 East 10th Street
Jeffersonville, IN 47132

OFFICE USE ONLY

0013		
0011	0012	
0014	0015	0016
0021	0022	0023

22-A100

Make corrections to name, address, and ZIP code if necessary.

Complete your report by mail or via the internet at **www.agcounts.usda.gov**.

- **Your mandatory report is due by February 6, 2023.**
- To fill out the paper form, use a black or blue ballpoint pen.
- **Duplicate forms?** If you received extra Census report forms for the SAME farming operation, return all report forms in the same envelope with this completed report.

Print the information below for the person completing this form:

9912 Respondent Name

9911 Respondent Phone – –

Check if cell phone ☐

1095 Respondent E-mail

9910 Date Completed (MM-DD-YYYY) – –

9937 Operation E-mail (if different from above)

9936 Operation Phone – –

Check if cell phone ☐

THANK YOU FOR YOUR COOPERATION.
Questions? Call us toll free at 1-888-424-7828.

¿Preguntas? Llámenos libre de cargos al 1-888-424-7828.

The information you provide will be used for statistical purposes only. Your response will be kept confidential and any person who willfully discloses ANY identifiable information about you or your operation is subject to a jail term, a fine, or both. This survey is conducted in accordance with the Confidential Information Protection and Statistical Efficiency Act of 2018, Title III of Pub. L. No. 115-435, codified in 44 U.S.C. Ch. 35 and other applicable Federal laws. For more information on how we protect your information please visit: https://www.nass.usda.gov/confidentiality. Response to this survey is required by law under Title 7 USC 2204(g) Public Law 105-113.

According to the Paperwork Reduction Act of 1995, an agency may not conduct or sponsor, and a person is not required to respond to, a collection of information unless it displays a valid OMB control number. The valid OMB number is 0535-0226. The time required to complete this information collection is estimated to average 50 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information.

22100010

SECTION 1 ACREAGE IN 2022

Report land owned, rented, or used by you, your spouse, or by the partnership, corporation, or organization named on the front of this form. Include ALL LAND, REGARDLESS OF LOCATION OR USE - cropland, Conservation Reserve Program (CRP) and Wetlands Reserve Program (WRP) land, pastureland, rangeland, woodland, idle land, farmsteads, etc.

	Mark "X" if None	BOX A
1. Number of acres OWNED 0043	☐	

2. Total number of acres RENTED or LEASED **FROM** OTHERS

INCLUDE
- *land worked by you on shares*
- *land used rent free in exchange for services, payment of taxes, etc.*
- *Federal, State, and railroad land leased on a per acre basis*
- *land rented or leased by you for cash*

EXCLUDE
- *land used on a fee per head or animal unit month (AUM) basis.. . . . . 0044* ☐

BOX B

3. Number of acres RENTED or LEASED **TO** OTHERS

INCLUDE ACRES
- *worked on shares by others*
- *subleased*
- *rented or leased to others for cash*
- *used rent free in exchange for services, payment of taxes, etc.*

EXCLUDE ACRES:
- *enrolled in Conservation Reserve Program (CRP)*
- *enrolled in Wetlands Reserve Program (WRP)*
- *enrolled in Farmable Wetlands Program (FWP)*
- *enrolled in Conservation Reserve Enhancement Program (CREP)*
- *rented or leased to others part of the year*
- *used on a fee per head or animal unit month (AUM) basis . . . . . 0045* ☐

BOX C

a. How many acres rented or leased to others (Box C above) did this operation own? 0053	Mark "X" if None ☐	Number of Acres

4. Enter the figures from the boxes above to determine your total acres operated:

BOX A		BOX B		BOX C			BOX D
	+		−		=	0046	

5. Does the figure in **Box D** = 0 or do you rent all your land to someone else?

☐ **Yes** - Refer to the instruction sheet to complete this form

☐ **No** - Continue

6. Did this operation pay on a fee per head or animal unit month (AUM) basis to use any land?

0040 1 ☐ **Yes** - Continue 3 ☐ **No** - Go to item 7

a. If yes, how many acres? 1160	Don't Know ☐	0041	Number of Acres

b. DO NOT include these acres in the boxes above. If you did, **GO BACK** and **EXCLUDE** them from the boxes above and recalculate BOX D.

7. Considering the total acres in Box D above, in what county was the largest value of this operation's agricultural products raised or produced?

	Principal County Name		State		Number of Acres
0055		0060		0056	

a. If this operation had agricultural activity in any **other** county, enter the county name(s), etc.

	Other County Name(s)		State		Number of Acres
3026		3031		0057	
3027		3032		0058	
3028		3033		0059	

22100028

SECTION 2 LAND USE IN 2022

Report how the acres in Box D on the previous page were used.
- Report acres in the first item that applies.
- Report acres only once.
- Report acres in CRP, WRP, FWP, and CREP in the most appropriate land use below.

		Mark "X" if None	Number of Acres
1.	**Cropland**		
	a. Cropland harvested *INCLUDE* • *land from which field crops were harvested or hay was cut* • *land used for vegetables* • *land used for nursery and greenhouses (rounded to the nearest acre)* • *land used for orchards, vineyards, citrus groves, Christmas trees, short rotation woody crops, fruits, nuts, and berries (bearing and nonbearing)* 0787	☐	
	b. Cropland on which all crops failed or were abandoned – Exclude land in orchards and vineyards 0790	☐	
	c. Cropland in summer fallow (cultivated cropland on which no crops or hay were harvested during the 2022 growing season) 0791	☐	
	d. Cropland idle or used for cover crops or soil-improvement but not harvested and not pastured or grazed 1062	☐	
2.	**Pasture**		
	a. Permanent pasture and rangeland 0796	☐	
	b. Woodland pastured 0794	☐	
	c. Other pasture and grazing land (including rotational pasture) that could have been used for crops without additional improvements. 0788	☐	
3.	**Woodland not pastured** *INCLUDE* • *woodlots* • *timber tracts* • *sugarbush*. 0795	☐	
4.	**All other land** *INCLUDE* • *farmsteads, home, and buildings* • *home gardens* • *livestock facilities* • *ponds* • *roads* • *wasteland, etc.* 0797	☐	

		BOX E
5.	**TOTAL ACRES -** Add items 1-4 to determine your total acres operated 0798	

6. Does **Box E** above = **Box D** on the previous page?

☐ **Yes -** Continue

☐ **No -** Go back and correct your figures. These figures should be the same.

The acres in Box E will be referred to as "this operation" for the remainder of this form.

22100036

SECTION 3 LAND RENTED OR LEASED FROM OTHERS FOR CASH

1. In 2022, did this operation **rent or lease** any cropland or pasture acres from others **for cash**? Exclude land rented or leased on a share basis, per head or AUM basis, free of charge, and rent that includes buildings, such as barns.

3420 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 4

		Mark "X" if None	Number of Acres
2.	How many acres of **non-irrigated cropland** were rented or leased for cash? Include fruit, nut, berry, vineyard, nursery, and hay land. 3421	☐	
3.	How many acres of **irrigated cropland** were rented or leased for cash? Include fruit, nut, berry, vineyard, nursery, and hay land. 3424	☐	
4.	How many acres of **permanent pasture, grazing, or grassland** were rented or leased for cash? Exclude Federal, State, and other types of land rented or leased on an animal unit month (AUM) basis 3427	☐	

SECTION 4 LAND USE PRACTICES

		Mark "X" if None	Number of Acres
1.	During 2022, considering the **total acres** on this operation, how many acres –		
a.	Were drained by tile? 3450	☐	
b.	Were artificially drained by ditches? 3451	☐	
c.	Were under a conservation easement? 3452	☐	
2.	During 2022, considering the **cropland acres** on this operation, [on] how many acres –		
a.	Were no-till practices used? 3455	☐	
b.	Were conservation or reduced tillage, excluding no-till, practices used? 3454	☐	
c.	Were intensive or conventional tillage practices used? 3453	☐	
d.	Were planted to a cover crop? (Cover crops are planted primarily for managing soil fertility, soil quality, and controlling weeds, pests, and diseases.) Exclude CRP acres 3456	☐	

3. At any time during 2022, did this operation use precision agriculture practices to manage crops or livestock? This would include the use of global positioning (GPS) guidance systems, GPS yield monitoring and soil mapping, variable rate input applications, use of drones for scouting fields or monitoring livestock, electronic tagging, precision feeding, robotic milking, etc. 1165 1 ☐ Yes 3 ☐ No

SECTION 5 IRRIGATION

1. Were any acres irrigated on this operation or were there any irrigation systems or irrigation equipment available on this operation in 2022?

INCLUDE
- *Sprinklers, drip or trickle irrigation, etc.*
- *Ditches or furrows, controlled and uncontrolled flooding, etc.*

EXCLUDE
- *Water used exclusively for home use*
- *Water used exclusively for aquaculture*

1166 1 ☐ **Yes** - Continue 3 ☐ **No** - Go to SECTION 6

		Number of Acres
2.	How many acres of harvested cropland were irrigated? 0680 ☐	
3.	How many acres of all other land were irrigated? Include pasture and rangeland, CRP and failed cropland, and all other non-harvested cropland 0681 ☐	
4.	How many acres on this operation have irrigation systems or equipment? Include all acres irrigated in 2022 and acres that could have been irrigated in 2022 using the existing irrigation systems available on the operation, regardless of water rights. 1167 ☐	

5. Do you intend to use the irrigation systems or irrigation equipment on this operation in the future? 1168 1 ☐ Yes 3 ☐ No

22100044

SECTION 6 CROP INSURANCE, CONSERVATION RESERVE PROGRAM AND OTHER GOVERNMENT PROGRAMS

		Mark "X" if None	Number of Acres
1.	How many acres in this operation were covered under any crop insurance policy in 2022? 1067	☐	
2.	How many acres in this operation were enrolled in the Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), Farmable Wetlands Program (FWP), or Conservation Reserve Enhancement Program (CREP) on September 30, 2022? 0683	☐	

		Mark "X" if None	Dollars
a.	What was the amount received in 2022 for participation in these programs? 0685	☐	$ .00
3.	What was the amount received in 2022 for all other Federal agricultural program payments? Exclude any type of insurance payments received. 1422	☐	$ .00
4.	What was the amount received in 2022 from state and local government agricultural program payments? 1423	☐	$ .00
5.	What was the total amount received in 2022 from Commodity Credit Corporation (CCC) loans for all commodities? 1411	☐	$ .00
6.	What was the total amount spent in 2022 to repay CCC loans? 1414	☐	$ .00

7. Do you know that you have the right to appeal an adverse program decision to USDA's National Appeals Division? 1416 1 ☐ Yes 3 ☐ No

SECTION 7 TYPE OF ORGANIZATION

1. In 2022, was more than 50 percent of this operation owned by an operator's household and/or extended family?

   Mark "yes" if more than 50 percent of the assets of this operation are owned by one of the operators, members of their household, and/or other persons related to them by blood, marriage, or adoption, including relatives not residing in his/her household. Consider only farm and ranch assets owned – not rented or leased – by this operation, and exclude the assets held by non-family landlords and contractors. 1672 1 ☐ Yes 3 ☐ No

		Number
2.	In 2022, how many households shared in the net farm income of this operation? 1608	

3. Was this operation organized as a Limited Liability Company (LLC) under State law? 1673 1 ☐ Yes 3 ☐ No

4. In 2022, what was this operation's legal status for tax purposes? Mark one answer only:

1671

1 ☐ Family or individual operation – Exclude partnerships and corporations.

2 ☐ Partnership operation – Include family partnerships.

- Is this partnership registered under state law? 1567 1 ☐ Yes 3 ☐ No

3 ☐ Incorporated under state law –

- Is this a family-held corporation? 1681 1 ☐ Yes 3 ☐ No
- Are there more than 10 stockholders? 1683 1 ☐ Yes 3 ☐ No

4 ☐ Other –

- Estate or trust. 1674 1 ☐ Yes 3 ☐ No
- Government facility, grazing association or American Indian reservation 1675 1 ☐ Yes 3 ☐ No
- Other, specify type. 1676

22100051

SECTION 8 PERSONAL CHARACTERISTICS

1. In 2022, how many men and women were involved in decisions for this operation (include family members and hired managers)? Exclude hired workers unless they were a hired manager or family member. 1571

Men	Women
1574	

2. Answer the following questions for up to four individuals who were involved in the decisions for this operation as of **December 31, 2022.**

	Person 1	Person 2	Person 3	Person 4
a. Full name	1836	1852	1872	1873
b. Sex	1926 1 ☐ Male 2 ☐ Female	1586 1 ☐ Male 2 ☐ Female	1597 1 ☐ Male 2 ☐ Female	1614 1 ☐ Male 2 ☐ Female
c. What was this person's age on December 31, 2022?	1925 ☐ age	1585 ☐ age	1596 ☐ age	1615 ☐ age
d. Is this person of Hispanic, Latino, or Spanish origin?	1927 Hispanic, Latino, or Spanish origin 1 ☐ Yes 3 ☐ No	1587 Hispanic, Latino, or Spanish origin 1 ☐ Yes 3 ☐ No	1598 Hispanic, Latino, or Spanish origin 1 ☐ Yes 3 ☐ No	1622 Hispanic, Latino, or Spanish origin 1 ☐ Yes 3 ☐ No
e. Race	Mark one or more. 2701 ☐ White 2702 ☐ Black or African American 2703 ☐ American Indian or Alaska Native. Specify tribe ↙ 2733 ☐ 2705 ☐ Asian 2704 ☐ Native Hawaiian or Other Pacific Islander	Mark one or more. 1801 ☐ White 1802 ☐ Black or African American 1803 ☐ American Indian or Alaska Native. Specify tribe ↙ 1833 ☐ 1805 ☐ Asian 1804 ☐ Native Hawaiian or Other Pacific Islander	Mark one or more. 1901 ☐ White 1902 ☐ Black or African American 1903 ☐ American Indian or Alaska Native. Specify tribe ↙ 1933 ☐ 1905 ☐ Asian 1904 ☐ Native Hawaiian or Other Pacific Islander	Mark one or more. 1616 ☐ White 1617 ☐ Black or African American 1618 ☐ American Indian or Alaska Native. Specify tribe ↙ 1619 ☐ 1620 ☐ Asian 1621 ☐ Native Hawaiian or Other Pacific Islander
f. At which occupation did this person spend the majority (50 percent or more) of his/her worktime in 2022?	1928 Mark one. 1 ☐ Farm or ranch work 2 ☐ Work other than farming or ranching	1580 Mark one. 1 ☐ Farm or ranch work 2 ☐ Work other than farming or ranching	1591 Mark one. 1 ☐ Farm or ranch work 2 ☐ Work other than farming or ranching	1623 Mark one. 1 ☐ Farm or ranch work 2 ☐ Work other than farming or ranching
g. Is this person retired from farming or ranching?	1924 1 ☐ Yes 3 ☐ No	1582 1 ☐ Yes 3 ☐ No	1593 1 ☐ Yes 3 ☐ No	1624 1 ☐ Yes 3 ☐ No
h. How many days did this person work off the farm in 2022? Include days in which the person worked at least four hours per day in an off-farm job. Include work on someone else's farm for pay	1929 Mark one. 1 ☐ None 2 ☐ 1 - 49 days 3 ☐ 50 - 99 days 4 ☐ 100 - 199 days 5 ☐ 200 days or more	1831 Mark one. 1 ☐ None 2 ☐ 1 - 49 days 3 ☐ 50 - 99 days 4 ☐ 100 - 199 days 5 ☐ 200 days or more	1931 Mark one. 1 ☐ None 2 ☐ 1 - 49 days 3 ☐ 50 - 99 days 4 ☐ 100 - 199 days 5 ☐ 200 days or more	1625 Mark one. 1 ☐ None 2 ☐ 1 - 49 days 3 ☐ 50 - 99 days 4 ☐ 100 - 199 days 5 ☐ 200 days or more

22100069

SECTION 8 CONTINUED –

	Person 1, continued	Person 2, continued	Person 3, continued	Person 4, continued
i. Did this person live on this operation at any time in 2022?	1923 1 ☐ Yes 3 ☐ No	1581 1 ☐ Yes 3 ☐ No	1592 1 ☐ Yes 3 ☐ No	1626 1 ☐ Yes 3 ☐ No
j. In what year did this person begin to operate any part of **THIS** operation?	1930	1584	1595	1627
k. In what year did this person begin to operate **ANY** farm operation?	2834	1851	1871	1628
l. Has this person ever served on active duty in the U.S. Armed Forces, Reserves, or National Guard?	1633 **Mark one.** 1 ☐ Never served in the military 2 ☐ Only on active duty for training in the Reserves or National Guard 3 ☐ Now on active duty 4 ☐ On active duty in the past, but not now	1634 **Mark one.** 1 ☐ Never served in the military 2 ☐ Only on active duty for training in the Reserves or National Guard 3 ☐ Now on active duty 4 ☐ On active duty in the past, but not now	1635 **Mark one.** 1 ☐ Never served in the military 2 ☐ Only on active duty for training in the Reserves or National Guard 3 ☐ Now on active duty 4 ☐ On active duty in the past, but not now	1636 **Mark one.** 1 ☐ Never served in the military 2 ☐ Only on active duty for training in the Reserves or National Guard 3 ☐ Now on active duty 4 ☐ On active duty in the past, but not now
m. How many people lived in this person's household in 2022?	Number living in household of Person 1 2577 number	Number living in household of Person 2. Enter "0" if Person 2 was counted in the previous column. 1589 number	Number living in household of Person 3. Enter "0" if Person 3 was counted in a previous column. 1600 number	Number living in household of Person 4. Enter "0" if Person 4 was counted in a previous column. 1637 number
n. Was this person hired and paid a salary or wages to manage this operation?	2576 1 ☐ Yes 3 ☐ No	1588 1 ☐ Yes 3 ☐ No	1599 1 ☐ Yes 3 ☐ No	1641 1 ☐ Yes 3 ☐ No

3. Was this person involved in these specific decisions as of **December 31, 2022**? For each person and for each item, **mark all that apply**.

	Person 1	Person 2	Person 3	Person 4
a. Day-to-day decisions	1642 1 ☐	1643 1 ☐	1644 1 ☐	1645 1 ☐
b. Land use and/or crop decisions, including planting, crop spraying, or other, e.g., grazing	1650 1 ☐	1651 1 ☐	1652 1 ☐	1653 1 ☐
c. Livestock decisions, including purchases, sales, breeding, and pasturing	1654 1 ☐	1655 1 ☐	1656 1 ☐	1657 1 ☐
d. Marketing decisions	1687 1 ☐	1688 1 ☐	1689 1 ☐	1690 1 ☐
e. Record keeping and/or financial management	1776 1 ☐	1777 1 ☐	1778 1 ☐	1779 1 ☐
f. Estate planning or succession planning	1757 1 ☐	1758 1 ☐	1759 1 ☐	1760 1 ☐

22100077

SECTION 9 HAY AND FORAGE CROPS

1. Were any hay or forage crops cut or harvested from this operation in 2022?

INCLUDE
- *your landlord's share and crops grown under contract*

EXCLUDE
- *crops grown on land rented to others*

1152 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 10

2. All land from which dry hay, haylage, grass silage, or greenchop was cut or forage was harvested in 2022. Exclude straw, corn silage, and sorghum silage. 1021	Mark "X" if None	Acres Harvested	Acres Irrigated
	☐		

3. Report gross value of hay and forage sold from this operation in 2022. Include the value of your landlord's share, marketing charges, taxes, hauling, etc. Exclude dollars for items produced under production contracts. 1328	Mark "X" if None	Gross Value of Sales (Dollars)
	☐	$ .00

For items 4 through 7, when both dry hay and haylage were cut from the same acres, report acres for each type. If two or more cuttings were made from the same acres, report acres for that item only once, but report total quantity harvested from all cuttings.

	Mark "X" if None	Acres Harvested	Acres Irrigated	Total Tons Harvested		OR	Total Number of Bales	Average Weight per Bale	
4. Alfalfa and alfalfa mixtures for dry hay. . . 0103	☐				Tons, dry	OR			Lbs., dry
5. Haylage or greenchop from alfalfa or alfalfa mixtures 1070	☐				Tons, green				
6. Other dry hay from barley, clover, fescue, lespedeza, oats, rye, timothy, wheat, wild, Bermuda grass, Sudangrass, etc. 4111	☐				Tons, dry	OR			Lbs., dry
7. All other haylage, grass silage, and greenchop. 1073	☐				Tons, green				

SECTION 10 CULTIVATED CHRISTMAS TREES, SHORT ROTATION WOODY CROPS, AND MAPLE SYRUP

1. Were any Christmas trees or woodland crops grown, harvested, or tapped on this operation in 2022?

INCLUDE
- *your landlord's share and crops grown under contract*

EXCLUDE
- *crops grown on land rented to others*

1153 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 11

For items 2 through 4, fill in the columns below for this operation in 2022.
- Include the value of your landlord's share, marketing charges, taxes, hauling, etc.
- Exclude from sales dollars for items produced under production contracts.

	Mark "X" if None	Acres in Production	Number of Trees Cut	Acres Irrigated	Gross Value of Sales (Dollars)
2. Cultivated Christmas trees - cut or to be cut. Exclude wild harvested trees. Report live trees sold in SECTION 12 . . . 1023	☐				$ .00

	Acres in Production	Acres Harvested	Acres Irrigated	Gross Value of Sales (Dollars)
3. Short rotation woody crops - trees with growth cycles of 10 years or less. Exclude nursery trees, evergreens for replanting, and timber. Report nursery stock in SECTION 12 . . . . . 1025 ☐ Specify crop ↙ 1097				$ .00

	Number of Taps	Syrup Produced		Gross Value of Sales (Dollars)
4. Maple syrup . . . . . 0800 ☐			Gallons	$ .00

22100085

SECTION 11 FIELD CROPS

1. Were any field crops, such as corn, soybeans, wheat, etc., harvested from this operation in 2022?

INCLUDE
- *your landlord's share and crops grown under contract*

EXCLUDE
- *crops grown on land rented to others*
- *home gardens*

1011 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 12

	Acres Harvested	Acres Irrigated
2. Acres from which field crops were harvested in 2022. Report multiple cropped acreage only once. 1780		

3. Fill in the columns below for all field crops harvested from this operation in 2022. For those crops not printed in the table, enter the crop name and code from the list below.
- Report production in the units specified next to the crop.
- Include the value of your landlord's share, marketing charges, taxes, hauling, etc.
- Exclude from sales dollars for items produced under production contracts.

Enter Field Crop Name	Enter Code	Acres Harvested	Total Production Harvested		Acres Irrigated	Gross Value of Sales (Dollars)
Corn for grain or seed	0067			Bu.		$ .00
Soybeans for beans or seed	0088			Bu.		$ .00
Wheat, winter for grain or seed	0572			Bu.		$ .00
Other field crops, specify below:						
						$ .00
						$ .00
						$ .00
						$ .00
						$ .00
						$ .00

If more space is needed, use a separate sheet of paper.

FIELD CROPS	CODE
All hay including alfalfa and other - report in SECTION 9	
Alfalfa seed (pounds)	542
Bahia grass seed (pounds)	551
Barley for grain or seed (bushels)	079
Beans, dry edible - exclude chickpeas and limas (hundredweight)	554
Bentgrass seed (pounds)	560
Bermuda grass seed (pounds)	563
Birdsfoot trefoil seed (pounds)	566
Bromegrass seed (pounds)	569
Buckwheat (bushels)	575
Camelina (pounds)	608
Canola, edible (pounds)	614
Chickpeas, all (garbanzos) (hundredweight)	2816
Clover, crimson clover seed (pounds)	593
Clover, red clover seed (pounds)	671
Clover, white clover seed (pounds)	761
Corn for silage or greenchop (tons)	070
Cotton, Pima (bales) - include cottonseed in value of sales only	644
Cotton, Upland (bales) - include cottonseed in value of sales only	581
Dill for oil (pounds)	596
Emmer and spelt (bushels)	599
Fescue seed (pounds)	602
Flaxseed (bushels)	605
Guar (pounds)	617

FIELD CROPS	CODE
Hemp for fiber (pounds)	2615
Hemp for floral (CBD or other cannabinoid usage) (pounds)	2620
Hemp for grain (pounds)	2625
Hemp for other utilizations, specify above (pounds)	2630
Hemp seeds - report in SECTION 12	
Herbs, dried (pounds)	620
Hops (pounds) - Report to the nearest tenth acre	623
Indian corn (pounds)	695
Jojoba (pounds)	626
Kentucky bluegrass seed (pounds)	629
Lentils (hundredweight)	635
Lespedeza seed (pounds)	638
Lima beans, dry (hundredweight)	557
Mint, peppermint (pounds of oil)	047
Mint, spearmint (pounds of oil)	050
Mint, tea leaves (pounds)	767
Miscanthus (tons)	641
Mustard seed (pounds)	650
Oats for grain or seed (bushels)	076
Orchardgrass seed (pounds)	653
Peanuts for nuts (pounds)	656
Peas, Austrian winter peas (hundredweight)	548
Peas, dry edible (hundredweight)	659
Peas, dry southern/cowpeas (bushels)	584
Popcorn (pounds shelled)	662
Potatoes - report in SECTION 13	
Proso millet for grain or seed (bushels)	665

FIELD CROPS	CODE
Rapeseed (pounds)	668
Rice (hundredweight)	677
Rye for grain or seed - exclude ryegrass (bushels)	686
Ryegrass seed (pounds)	689
Safflower (pounds)	692
Sesame (pounds)	701
Sorghum for grain or seed - include milo (bushels)	082
Sorghum for silage or greenchop - exclude sorghum-sudan crosses (tons)	085
Sorghum for syrup (gallons)	704
Sudangrass seed (pounds)	713
Sugarbeets for seed (pounds)	716
Sugarbeets for sugar (tons)	719
Sugarcane for sugar or seed (tons)	2290
Sunflower seed, non-oil variety (pounds)	776
Sunflower seed, oil variety (pounds)	773
Switchgrass (tons)	647
Timothy seed (pounds)	746
Tobacco (pounds) - Report to the nearest tenth acre	094
Triticale for grain (bushels)	749
Vetch seed (pounds)	755
Wheat, durum for grain or seed (bushels)	578
Wheat, other spring for grain or seed (bushels)	728
Wheatgrass seed (pounds)	758
Wild rice (hundredweight)	764
Other seeds, specify above (pounds)	770
Other field crop, specify above (pounds)	752

22100093

SECTION 12 NURSERY, GREENHOUSE, FLORICULTURE, SOD, MUSHROOMS, VEGETABLE SEEDS, AND PROPAGATIVE MATERIALS

1. Were any nursery, floriculture, or greenhouse crops, including ornamental plants, flowers, mushrooms, aquatic plants, sod, vegetable seeds under protective cover, food and other crops grown under protective cover, flower seeds, or other propagative materials grown for sale on this operation in 2022? Report food crops temporarily covered for early germination, frost protection, etc. in SECTION 13 or 14.

INCLUDE
- *crops produced, including under contract*
- *food crops grown in greenhouses, caves, and high tunnels where crops were always covered*

EXCLUDE
- *home garden, personal or home use crops*
- *finished plants purchased from others and resold*
- *vegetable seeds grown in the open*

1032 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 13

2. Report total area and irrigated area on which nursery, greenhouse, floriculture, mushrooms, and propagative materials were grown under glass or other protection in 2022 . . . . . 0474 ☐ Mark "X" if None

Square Feet Under Glass or Other Protection	
Total Area	Irrigated Area

3. Report total acres and irrigated acres on which nursery, floriculture, sod, mushrooms, and propagative materials were grown in the open in 2022 . . . . . 0476 ☐

Acres in the Open			
Total Acres	Tenths	Irrigated Acres	Tenths

4. Fill in the columns below for all nursery, greenhouse, floriculture, sod, mushrooms, vegetable seeds grown under protection, and propagative materials grown for sale on this operation in 2022. Enter the crop name and code from the table below.
- Include the value of your landlord's share, marketing charges, taxes, hauling, etc.
- Exclude from sales dollars for items produced under production contracts.

Enter Nursery, Greenhouse, Floriculture, Sod, Mushroom, Vegetable Seed, or Propagative Material Name	Enter Code	Square Feet Under Glass or Other Protection	Acres in the Open		Gross Value of Sales (Dollars)
			Acres	Tenths	
					$ .00
					$ .00
					$ .00
					$ .00
					$ .00
					$ .00

If more space is needed, use a separate sheet of paper.

FLORICULTURE AND BEDDING CROPS	CODE
Bedding/Garden plants - annuals, herbaceous perennials, vegetable plants - Include hanging baskets	0479
Cut flowers and cut florist greens	0485
Foliage plants, indoor - Include hanging baskets	0707
Potted flowering plants	0710
Other floriculture and bedding, specify above	1015

NURSERY CROPS	CODE
Nursery stock – ornamentals, shrubs, shade trees, flowering trees, evergreens, live Christmas trees, fruit and nut trees and plants, vines, palms, ornamental grasses, and bareroot herbaceous perennials	0488
Aquatic plants	0880

HEMP	CODE
Hemp clones or transplants sold for transplant to others	2640
Hemp complete grows	2655
Hemp seeds	2685

SOD	CODE
Sod harvested or intended for sale in future years	1897

PROPAGATIVE MATERIAL SOLD	CODE
Bulbs, corms, rhizomes, and tubers, dry	0482
Cuttings, seedlings, liners, plugs	1002
Flower seeds	0882
Tobacco plants sold for transplant to farm fields	1004

FOOD CROPS GROWN UNDER GLASS OR OTHER PROTECTION	CODE
Fruits and berries	1008
Tomatoes	1019
Vegetable seeds	0884
Vegetable transplants to farm fields	1006
Other vegetables and fresh cut herbs	0503

MUSHROOM CROPS	CODE
Mushrooms - Report growing area and sales	0494
Mushroom spawn - Report sales only	2495

22100101

SECTION 13 VEGETABLES, POTATOES, AND MELONS

1. Were any vegetables, vegetable seeds grown in the open, potatoes, sweet corn, or melons harvested from this operation in 2022? Report crops grown under glass or other protection in SECTION 12.

INCLUDE
- *crops grown under contract*
- *crops grown for seed*

EXCLUDE
- *home garden, personal or home use crops*

1101 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 14

2. Acres from which vegetables, potatoes, and melons were harvested in 2022. Exclude home gardens. Report multiple cropped acreage only once 0375

Acres Harvested		Acres Irrigated	
Acres	Tenths	Acres	Tenths

3. Report gross value of vegetables, potatoes, and melons sold from this operation in 2022. Include the value of your landlord's share, marketing charges, taxes, hauling, etc. Exclude dollars for items produced under production contracts 1388

Mark "X" if None ☐

Gross Value of Sales (Dollars)
$ .00

4. Fill in the columns below for all vegetables, potatoes, and melons harvested from this operation in 2022. Enter the crop name and code from the table below.
- If more than one vegetable crop was harvested from the same acres, report acres for each crop.
- For two or more pickings of the same crop, report the area harvested only once.
- Processing refers to vegetables that have been altered by heat, pressure, or freezing.

Enter Vegetable, Potato, or Melon Name	Enter Code	Total Acres Harvested		Acres Harvested for Fresh Market		Acres Harvested for Processing	
		Acres	Tenths	Acres	Tenths	Acres	Tenths

If more space is needed, use a separate sheet of paper.

CROP NAME	CODE	CROP NAME	CODE	CROP NAME	CODE
Artichokes - exclude Jerusalem	0377	Garlic	0421	Peppers, bell - exclude pimientos	0443
Asparagus, bearing age	0418	Ginger root	0611	Peppers, other than bell - include chile	0445
Beans, lima	0429	Ginseng, cultivated only	0446	Potatoes	0097
Beans, snap (bush and pole)	0381	Gourds	0422	Pumpkins	0449
Beets	0383	Herbs, fresh cut	0455	Radishes	0451
Broccoli	0385	Honeydew melons	0423	Rhubarb	0453
Brussels sprouts	0387	Horseradish	0424	Spinach	0457
Cabbage, Chinese (nappa, bok choy, etc.)	0389	Kale	0425	Squash (including zucchini)	0459
Cabbage, head	0391	Lettuce, head	0428	Sweet corn	0461
Cabbage, mustard	0393	Lettuce, leaf	0430	Sweet potatoes	0100
Cantaloupes and muskmelons	0395	Lettuce, Romaine	0432	Taro	0743
Carrots	0397	Mustard greens	0431	Tomatoes in the open	0463
Cauliflower	0399	Okra	0437	Turnip greens	0467
Celery	0401	Onions, dry	0433	Turnips	0465
Chicory	0403	Onions, green	0435	Watercress	0471
Collards	0407	Parsley	0439	Watermelons	0473
Cucumbers and pickles	0411	Parsnips	1465	Other vegetables, specify above	0475
Daikon	0413	Peas, Chinese (sugar, snow)	0405		
Eggplant	0415	Peas, green	0441		
Escarole and endive	0417	Peas, southern (cowpeas) - blackeyed, crowder, etc	0409		

22100119

SECTION 14 FRUIT, NUTS, AND BERRIES

1. Were any fruit or nut trees, including grapevines, or berries on this operation in 2022?

INCLUDE
- *crops grown under contract*

EXCLUDE
- *abandoned acres*
- *home garden, personal or home use crops*

1039 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 15

2. Acres and irrigated acres in bearing and nonbearing fruit orchards, vineyards, nut trees, and berries in 2022. Exclude home gardens, personal or home use 0121

FRUIT AND NUTS				BERRIES			
Total Acres		Irrigated Acres		Total Acres		Irrigated Acres	
Acres	Tenths	Acres	Tenths	Acres	Tenths	Acres	Tenths

3. Report gross value of fruit, nuts, and berries sold from this operation in 2022. Include the value of your landlord's share, marketing charges, taxes, hauling, etc. Exclude dollars for items produced under production contracts 1329

Mark "X" if None	FRUIT AND NUTS Gross Value of Sales (Dollars)	Mark "X" if None	BERRIES Gross Value of Sales (Dollars)
☐	$ .00	☐	$ .00

4. Fill in the columns below for all fruit, nut trees, and berries on this operation in 2022. Enter the crop name and code from the table below.
- Include acres even if not harvested because of low prices, damage from hail, frost, etc.

Enter Fruit, Nut, or Berry Name	Enter Code	Total Acres		Bearing Age Acres		Nonbearing Age Acres	
		Acres	Tenths	Acres	Tenths	Acres	Tenths

If more space is needed, use a separate sheet of paper.

NON-CITRUS FRUIT	CODE
Apples	0123
Apricots	0129
Avocados	0135
Bananas	0141
Cherimoyas	0293
Cherries, sweet	0345
Cherries, tart	0587
Coffee (2021-2022 crop)	0153
Dates	0159
Figs	0165
Grapes (include muscadine)	0366
Guavas	0183
Kiwifruit	0189
Longan	2248
Lychees	2258
Mangos	0195
Nectarines	0201
Olives	0207
Papayas	0213
Passion fruit	0219
Paw paws	2268
Peaches, clingstone	0222
Peaches, freestone	0216
Pears, Bartlett	0234
Pears, other than Bartlett	0240
Persimmons	0237

NON-CITRUS FRUIT	CODE
Pineapples	1297
Plumcots, pluots, other plum/apricot hybrids	0264
Plums	0243
Pomegranates	0255
Prunes	0249
Rambutan	2278
Other non-citrus fruits, specify above	0261

CITRUS FRUIT	CODE
Grapefruit	0267
Kumquats	0273
Lemons	0279
Limes	0285
Tangelos	0303
Tangerines (Mandarins)	0309
Oranges, Valencia	0150
Oranges, other than Valencia - include Navel	0174
Other citrus fruit, specify above	0315

NUTS	CODE
Almonds	0321
Chestnuts	0324
Hazelnuts (Filberts)	0327
Macadamia nuts	0333
Pecans, improved	0336
Pecans, native and seedling	0342
Pistachios	0351
Walnuts, English	0357
Other nuts, specify above	0363

BERRIES	CODE
Aronia berries	0507
Blackberries and dewberries - include marionberries	0509
Blueberries, tame	0512
Blueberries, wild	0515
Boysenberries	0518
Cranberries	0521
Currants (black or red)	0524
Elderberries	0508
Gooseberries	2540
Loganberries	0530
Mulberries	2550
Raspberries, all	2570
Strawberries	0536
Other berries, specify above	0539

22100127

SECTION 15 CATTLE AND CALVES

1. Did you or anyone else have any cattle or calves, including dairy cattle, on this operation in 2022?

INCLUDE
- *cattle on this operation*
- *cattle on public or industrial property under a grazing permit*
- *cattle on land used rent free by this operation*
- *cattle grown or fed on this operation for others on a custom or contract basis*

EXCLUDE
- *cattle grown or fed by someone else on a custom or contract basis*

1201 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 16

2. Of the total number of cattle and calves on hand December 31, 2022, how many were –

		Mark "X" if None	Number on this operation **December 31, 2022**
a. Beef cows? Include beef heifers that had calved. Exclude heifers that had not calved, steers, calves, and bulls.	0804	☐	
b. Milk cows kept for production of milk? Include dry milk cows and milk heifers that had calved.	0805	☐	
c. Other cattle and calves? Include heifers that had not calved, steers, calves, and bulls	1206	☐	
d. **TOTAL** cattle and calves on hand December 31, 2022. Add items 2a, 2b, and 2c	0803	☐	

3. Of the cattle and calves sold or moved from this operation during 2022, how many were –

		Total number sold or moved in 2022
a. Calves sold or moved from this operation in 2022 weighing less than 500 pounds?	0808 ☐	
b. Cattle sold or moved from this operation in 2022, including calves weighing 500 pounds or more?	0810 ☐	

4. Report gross value of sales of cattle and calves in 2022. Include the value of your landlord's share, marketing charges, taxes, hauling, etc. Exclude dollars for items produced under production contracts.

INCLUDE
- *beef and dairy cattle for breeding stock, and beef and dairy cull animals*
- *fed cattle, stockers, and feeders*
- *veal calves, etc..*

		Gross Value of Sales (Dollars)
	1339 ☐	$ .00
5. Sales of milk from cows	1380 ☐	$ .00

6. **CATTLE IN FEEDLOTS FOR SLAUGHTER MARKET**

INCLUDE
- *steers and heifers for slaughter market fed a ration of grain or other concentrates that are expected to produce a carcass that will grade select or better*

EXCLUDE
- *cows and bulls*
- *cattle being backgrounded, pastured only, fed for home use, or veal*

		Number on this operation **December 31, 2022**
a. How many steers and heifers reported in item 2c above were on feed December 31, 2022, and were or will be shipped directly from your feedlot to slaughter market? Exclude cattle being backgrounded.	1207 ☐	

		Number sold or moved in 2022
b. How many of the steers and heifers sold during 2022 reported in item 3b above were shipped directly from your feedlot to a slaughter market? Exclude any of your cattle custom fed in feedlots operated by others. Exclude cattle sold as feeders	0812 ☐	

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SECTION 16 HOGS AND PIGS

1. Did you or anyone else have any hogs or pigs on this operation in 2022? If you are a contractor or integrator, report only the hogs on the land you operate.

INCLUDE
- *hogs grown for others on a contract basis*

EXCLUDE
- *hogs grown by someone else on a custom or contract basis*

1211 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 17

		Mark "X" if None	Number on this operation **December 31, 2022**
2.	Total number of hogs and pigs on hand December 31, 2022. 0815	☐	

			Total number sold or moved in 2022
3.	Number of hogs and pigs sold or moved from this operation during 2022, including feeder pigs 0820	☐	

			Gross Value of Sales (Dollars)
4.	Report gross value of sales for hogs and pigs sold from this operation in 2022. Include the value of your landlord's share, marketing charges, taxes, hauling, etc. Exclude dollars for items produced under production contracts 1341	☐	$ .00

5. Mark **one** item which best describes this type of operation:

1241 ☐ Farrow to wean 1242 ☐ Farrow to finish 1243 ☐ Finish only

1244 ☐ Farrow to feeder 1245 ☐ Nursery 1246 ☐ Other, specify → 1118

6. Mark **one** item which best describes this type of producer:

1214 ☐ Independent grower 1216 ☐ Contract grower (contractee) 1215 ☐ Contractor or integrator

SECTION 17 HORSES, PONIES, MULES, BURROS, AND DONKEYS

1. Did you or anyone else have any horses, ponies, mules, burros, or donkeys on this operation in 2022?

1247 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 18

Report inventory and sales for this operation in 2022.
- Include the value of your landlord's share, marketing charges, taxes, hauling, etc.

		Mark "X" if None	Number on this operation **December 31, 2022**	Total Number Sold in 2022	Gross Value of Sales in 2022 (Dollars)
2.	Horses and ponies OWNED by this operation. 0872	☐			$ .00
3.	Horses and ponies NOT owned by this operation. 0822	☐			$ .00
4.	Mules, burros, and donkeys. 0833	☐			$ .00

		Mark "X" if None	Gross Value of Sales in 2022 (Dollars)
5.	Horse breeding or stud fees, semen, and other equine products (Exclude income from boarding, training, or riding facilities which should be reported in SECTION 34, item 7). 1406	☐	$ .00

22100143

SECTION 18 SHEEP AND GOATS

1. Did this operation own or custom feed for others any sheep, lambs, goats, or kids in 2022, regardless of location?

INCLUDE
- *sheep and goats on public or industrial property under a grazing permit*
- *sheep and goats on land used rent free by this operation*
- *sheep and goats grown or fed on this operation for others on a custom or contract basis*

EXCLUDE
- *sheep and goats grown or fed by someone else on a custom or contract basis*

1102 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 19

Report for this operation in 2022.
- Include in the value of sales the value of your landlord's share, marketing charges, taxes, hauling, etc.

		Mark "X" if None	Number owned or custom fed on **December 31, 2022**	Total number sold or moved in 2022	Gross Value of Sales (Dollars)
2.	Sheep and lambs 0824	☐			$ .00
	a. Hair sheep or wool-hair crosses 0818	☐			
3.	Goats and kids				
	a. Angora goats and kids 0847	☐			$ .00
	b. Milk goats and kids. 0843	☐			$ .00
	c. Meat goats and kids, other goats and kids. 0851	☐			$ .00

		Mark "X" if None	Total amount produced in 2022	Total amount sold or moved in 2022	Gross Value of Sales (Dollars)
4.	Sheep and goat products				
	a. Wool shorn 0828	☐	lbs.	lbs.	$ .00
	b. Mohair clipped 0849	☐	lbs.	lbs.	$ .00
	c. Milk from sheep and goats . . 1389	☐	. . . . .		$ .00

SECTION 19 AQUACULTURE

1. Did you or anyone else have any aquaculture on this operation in 2022? Include production for others on a contract basis.

1157 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 20

2. Fill in the columns below for all aquaculture raised on this operation in 2022. Report aquatic plants in SECTION 12.
- Include the value of your landlord's share, marketing charges, taxes, hauling, etc.
- Include all sizes for each type.
- Include food size, fingerlings, fry, and eggs.
- Exclude wild-caught products.

Enter Aquaculture Type	Enter Code	Total pounds sold or moved in 2022		Total number sold or moved in 2022	Gross Value of Sales (Dollars)
			OR		$ .00
			OR		$ .00
			OR		$ .00
			OR		$ .00

If more space is needed, use a separate sheet of paper.

AQUACULTURE	CODE	AQUACULTURE	CODE	AQUACULTURE	CODE
Catfish	0860	Crustaceans (crawfish for food, shrimp, softshell crabs, etc.)	0902	Sport or game fish	0984
Trout	0863	Mollusks (clams, oysters, etc.)	0978	Other aquaculture products - include algae, alligators, caviar, turtles, etc., specify above	0869
Other food fish - include salmon, specify in table	0896	Ornamental fish	0980		
Baitfish - include crawfish for bait	0900				

22100150

SECTION 20 POULTRY

1. Did you or anyone else have any poultry, such as chickens, turkeys, ducks, emus, ostriches, etc., on this operation in 2022? Include poultry grown for others on a contract basis.

1217 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 21

2. VALUE OF SALES - Report gross value of sales for poultry, chicks, eggs, and other poultry products. Include the value of your landlord's share, marketing charges, taxes, hauling, etc. Exclude dollars for items produced under production contracts. 1344

Mark "X" if None	Gross Value of Sales (Dollars)
☐	$ .00

3. CHICKENS

		Mark "X" if None	Number on this operation December 31, 2022	Total number sold or moved from this operation in 2022
a.	Broilers, fryers, and other chickens raised for meat production, including capons and roasters. 0898	☐		
b.	Table egg layers – Include those for home use. 1229	☐		
c.	Hatching layers for meat-types – Include layers for broilers, roasters, and other meat-types 1231	☐		
d.	Hatching layers for table eggs 1233	☐		
e.	Pullets for laying flock replacement 1221	☐		

4. TURKEYS

a.	Turkeys raised for meat production – Exclude breeders 1225	☐		
b.	Turkey hens and toms kept for breeding. 1227	☐		
c.	Turkey brooders, immature birds for further growout on another farm. 1219	☐		

5. ALL OTHER POULTRY – Fill in the columns below for all other poultry on this operation in 2022. Enter the poultry type and code from the table below.

Enter Poultry Type	Code	Number on this operation December 31, 2022	Total number sold or moved from this operation in 2022

If more space is needed, use a separate sheet of paper.

OTHER POULTRY	CODE	OTHER POULTRY	CODE	OTHER POULTRY	CODE
Bantams	0934	Guineas	0966	Pigeons or squabs	0908
Chukars	1275	Hungarian partridges	1277	Quail	0912
Ducks	0904	Ostriches	0878	Rheas	1281
Emus	0845	Peacocks or peahens	1279	Roosters	0968
Geese	0906	Pheasants	0910	Other poultry, specify above	0865

6. POULTRY HATCHED

		Mark "X" if None	Number hatched on this operation in 2022
a.	All poultry hatched in this operation's hatcheries in 2022. Include chicks, poults, ducklings, etc. Include poultry custom hatched for others 0916	☐	

b. What type(s) of poultry was hatched in this operation's hatcheries in 2022? Mark all that apply:

1291 ☐ Egg-type chickens 1292 ☐ Broiler-type chickens 1293 ☐ Turkeys 1294 ☐ All other poultry

22100168

SECTION 21 COLONIES OF HONEY BEES

1. Did this operation own honey bees in 2022, regardless of location?

1104 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 22

	Number of colonies owned on **December 31, 2022**	Largest number of colonies owned for all purposes in 2022	Largest number of honey producing colonies owned in 2022	Honey collected in 2022, regardless of location (Pounds)	Gross Value of Sales of Honey (Dollars)
2. Colonies of honey bees owned. 0839					$ .00

SECTION 22 OTHER LIVESTOCK

1. Did you or anyone else have other livestock on this operation in 2022?

4428 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 23

2. Fill in the columns below for all other livestock on this operation in 2022. Enter the livestock type and code from the table below.
   - Include the value of your landlord's share, marketing charges, taxes, hauling, etc.
   - Exclude from sales dollars for items produced under production contracts.

Enter Livestock Type	Enter Code	Number on this operation **December 31, 2022**	Total number sold in 2022	Gross Value of Sales (Dollars)
				$ .00
				$ .00
				$ .00
				$ .00

If more space is needed, use a separate sheet of paper.

OTHER LIVESTOCK	CODE	OTHER LIVESTOCK	CODE	OTHER LIVESTOCK	CODE
Alpacas	0876	Deer in captivity	0888	Live mink (report pelts in SECTION 23)	1106
Package bees	4790	Elk in captivity	0890	Live rabbits (report pelts in SECTION 23)	1108
Bees, other than honey or package bees	4840	Laboratory animals	4892	Worms	4895
Bison	0886	Llamas	0874	Other livestock, specify above	4898

SECTION 23 LIVESTOCK PRODUCTS

1. Did you or anyone else produce any livestock products on this operation in 2022?

4429 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 24

2. Fill in the columns below for other livestock products produced on this operation in 2022. Enter the livestock product type and code from the table below.
   - Include the value of your landlord's share, marketing charges, taxes, hauling, etc.
   - Exclude from sales dollars for items produced under production contracts.

Enter Livestock Product Type	Enter Code	Quantity Produced in 2022	Unit	Gross Value of Sales (Dollars)
				$ .00
				$ .00

If more space is needed, use a separate sheet of paper.

OTHER LIVESTOCK PRODUCTS	CODE	OTHER LIVESTOCK PRODUCTS	CODE
Beeswax	4961	Horns	4949
Breeding fees	4940	Manure sold	4952
Embryos	4943	Semen	4955
Fur or pelts (include mink)	4946	Other animal products not listed, specify above	4958

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SECTION 24 PRODUCTION CONTRACTS AND CUSTOM FEEDING

1. At any time during 2022, were you a production contract grower for a processor or contractor for whom you grew a crop, raised livestock or poultry, or custom fed any livestock that **you did not own**? A production contract is an agreement setting terms, conditions, and fees to be paid by the contractor to this operation for the production of crops, livestock, or poultry. Exclude commodities grown or raised for marketing contracts.

1301 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 25

2. Report number of head, bushels, etc. that were grown or raised under production contracts and moved from this operation in 2022.

		Mark "X" if None	Total quantity moved from this operation in 2022	Unit		Total dollar amount received in 2022 for delivering commodities under production contracts (Dollars)
a. Broilers and other meat-type chickens. . . .	1304	☐		birds	3304	$ .00
b. Chicken eggs	1305	☐		dozen	3305	$ .00
c. Layers	1302	☐		birds	3302	$ .00
d. Pullets for laying flock replacement.	1306	☐		birds	3306	$ .00
e. Turkeys	1307	☐		birds	3307	$ .00
f. Custom fed cattle shipped directly for slaughter – Exclude cattle custom fed for you by others.	1308	☐		head	3308	$ .00
g. Replacement dairy heifers.	1303	☐		head	3303	$ .00
h. Hogs and pigs.	1309	☐		head	3309	$ .00
i. Other cattle, sheep, livestock, or poultry – specify type ↙ 1140	1310	☐			3310	$ .00
j. Grains and oilseeds – specify type ↙ 1141	1311	☐		bushels	3311	$ .00
k. Vegetables and other crops – specify type ↙ 1142	1312	☐			3312	$ .00
l. Vegetables and other crops – specify type ↙ 1143	1313	☐			3313	$ .00

3. Mark all inputs that were partially or completely paid or provided by contractor(s) –

1317 ☐ Feed
1325 ☐ Seed
1320 ☐ Supplies
1316 ☐ Feeder livestock and poultry
1318 ☐ Fertilizer and lime
1322 ☐ Utilities
1324 ☐ Breeding livestock
1319 ☐ Chemicals
1326 ☐ Other, specify → 1146
1323 ☐ Veterinary services
1321 ☐ Fuels
1315 ☐ None

4. Enter the name of the contractor that provided inputs and owned the commodity ↙

1327

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SECTION 25 ORGANIC AGRICULTURE

1. During 2022, did this operation produce organic products according to USDA's National Organic Program (NOP) standards or have acres transitioning into USDA NOP production? Exclude processing and handling.

3501 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 26

2. Report type of production. Mark all that apply.

Specify Certifying Agency

3502 ☐ USDA NOP certified organic production 1252

3503 ☐ USDA NOP organic production exempt from certification (exempt is production normally less than $5,000 in sales).

3504 ☐ Acres transitioning into USDA NOP organic production.

3506 ☐ Production according to USDA NOP standards but NOT certified or exempt.

3. What was the value of USDA NOP certified or exempt organically produced commodities sold from this operation in 2022? 3505

Mark "X" if None ☐

Gross Value of Sales (Dollars)

$ .00

SECTION 26 PRACTICES

1. At any time during 2022, did this operation have internet access, either on the operation or at an operator's residence?

1260 1 ☐ **Yes** - Report the type of service that was used to access the internet. Mark all that apply:

1265 ☐ Cellular data plan for a smartphone or other mobile device

1266 ☐ Satellite Internet service installed

1775 ☐ Don't know

1271 ☐ Broadband (high speed) Internet service such as cable, fiber optic, or DSL service installed

1261 ☐ Dial-up Internet service installed

1268 ☐ Other, specify below

1269

3 ☐ **No** - Go to item 2

2. At any time during 2022, did this operation –

a. Receive irrigation water supplied by a U.S. Bureau of Reclamation project or facility? Include reclamation water delivered by a local district. . . . . 1722 1 ☐ Yes 3 ☐ No

b. Practice rotational or management-intensive grazing? . . . . . 1725 1 ☐ Yes 3 ☐ No

c. Practice alley cropping, silvopasture, or forest farming, or have riparian forest buffers or windbreaks? . . . . . 1731 1 ☐ Yes 3 ☐ No

d. Harvest any biomass (crop residue, grasses, woody biomass, etc.) for use in the production of renewable energy? Exclude grains, oilseeds, and firewood . . . . . 1750 1 ☐ Yes 3 ☐ No

e. Have an on-farm packing facility for distributing vegetables, potatoes, fruit, nuts, berries, or other crops? . . . . . 1752 1 ☐ Yes 3 ☐ No

f. Raise or sell veal calves? . . . . . 1728 1 ☐ Yes 3 ☐ No

g. Have a barn that was built prior to 1960? . . . . . 1730 1 ☐ Yes 3 ☐ No

3. During 2022, did this operation produce and sell any processed or value-added products from its own agricultural production?

INCLUDE
- *jam, wine, cheese, meat, floral arrangements, cider, etc.*

EXCLUDE
- *products purchased and resold*
- *live animals*

1726 1 ☐ **Yes** - Continue 3 ☐ **No** - Go to SECTION 27

Gross Value of Sales (Dollars)

a. How much was received in 2022 for the sales of the processed or value-added product(s)? . . . . . 2727 $ .00

2726

b. Please specify the processed or value added product(s). . . . .

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SECTION 27 FOOD MARKETING PRACTICES

1. During 2022, did this operation **produce and sell** any crops, livestock, poultry, or agricultural products as food for humans to eat or drink **directly to:**
   - Include **processed food** products (also known as **value-added food products**) produced by this operation.
   - Exclude non-edible products such as hay, livestock fed or raised, cut flowers not intended for consumption, Christmas trees, nursery products; commodities produced under production contracts; and products purchased and resold.

				Gross Value of Sales
a. **Consumers** (individuals who purchased your products from farmers markets, on-farm stores or farm stands, roadside stands or stores, CSA [Community Supported Agriculture], online marketplaces, etc.)?	4159	1 ☐ Yes →	4160	$ .00
		3 ☐ No		
b. **Retail markets** (supermarkets, supercenters, restaurants, caterers, independently owned grocery stores, food cooperatives, etc.)?	4162	1 ☐ Yes →	4163	$ .00
		3 ☐ No		
c. **Institutions** (k-12 schools, colleges or universities, hospitals, workplace cafeterias, prisons, foodbanks, etc.)?	4164	1 ☐ Yes →	4165	$ .00
		3 ☐ No		
d. **Intermediate markets** (businesses or organizations in the middle of the supply chain marketing locally- and/or regionally-branded products, such as distributors, food hubs, brokers, auction houses, wholesale and terminal markets, food processors, etc.)?	4166	1 ☐ Yes →	4167	$ .00
		3 ☐ No		

2. Specify products sold reported above: 4168

SECTION 28 FERTILIZERS, CHEMICALS, AND SOIL CONDITIONERS APPLIED

1. Were any fertilizers, manure, herbicides, insecticides, fungicides, nematicides, other pesticides, growth regulators, or other chemicals used on this operation during 2022?

INCLUDE
- *rock phosphate, lime, and gypsum as fertilizer*

EXCLUDE
- *pretreated seeds*

1568 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 29

		Mark "X" if None	Number of Acres
2. Acres to which commercial fertilizer and soil conditioners were applied –			
a. Cropland in 2022 – Exclude cropland used only for pasture	0932	☐	
b. Pastureland and rangeland acres in 2022 – Include cropland used only for pasture or grazing	0933	☐	
3. Acres of cropland and pastureland on which animal manure was applied	1569	☐	
4. Acres of cropland and/or pastureland treated with organic fertilizer according to USDA's National Organic Program (NOP) standards	1570	☐	

5. Acres on which chemicals were applied to control the items listed below. The same acres can be reported in more than one item below. However, report acres only once for each item, regardless of the number of applications.			Number of Acres
a. Insects	0936	☐	
b. Weeds, grass, or brush - Include both pre-emergence and post emergence	0939	☐	
c. Nematodes	0937	☐	
d. Diseases in crops and orchards such as blight, smut, rust, etc.	0938	☐	
6. Acres of crops treated to control growth, thin fruit, ripen, or defoliate	0940	☐	

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SECTION 29 RENEWABLE ENERGY

1. During 2022, what types of renewable energy producing systems were on this operation, regardless of ownership? Mark all that apply.

3603 ☐ Solar panels
3604 ☐ Wind turbines
3605 ☐ Methane digesters
3614 ☐ Geothermal/Geoexchange system
3615 ☐ Small hydro system
3606 ☐ Other, specify → 3612
3619 ☐ None

2. On the land owned by this operation, were any wind rights leased to others? . . . . . 3607 1 ☐ Yes 3 ☐ No

SECTION 30 MACHINERY AND EQUIPMENT

1. For the items listed below, report the number on this operation on **December 31, 2022.** Include machinery, equipment, and implements used for the farm or ranch business in 2021 or 2022 and usually kept on the operation.

	Mark "X" if None	Number on this operation **December 31, 2022**	Mark "X" if None	Of these, the number manufactured in the last 5 years (2018-2022)
a. Trucks, including pickups 0944	☐		☐	
b. Tractors less than 40 horsepower (PTO) – Exclude garden tractors 0946	☐		☐	
c. Tractors 40 - 99 horsepower (PTO) 0948	☐		☐	
d. Tractors 100 horsepower (PTO) or more 0962	☐		☐	
e. Grain and bean combines, self-propelled 0950	☐		☐	
f. Cotton pickers and strippers, self-propelled 0956	☐		☐	
g. Forage harvesters, self-propelled 0953	☐		☐	
h. Hay balers 0960	☐		☐	

SECTION 31 FARM LABOR

	Mark "X" if None	Number of Workers
1. What was the total number of HIRED farm or ranch workers, including paid family members and office workers, who –		
a. Worked less than 150 days on this operation in 2022? Exclude contract labor 0941	☐	
b. Worked 150 days or more on this operation in 2022? Exclude contract labor 0942	☐	
2. What was the number of foreign and domestic MIGRANT workers on this operation in 2022? A migrant worker is a farm worker whose employment required travel that prevented the migrant worker from returning to his/her permanent place of residence the same day. Include hired and contract workers 3402	☐	
3. What was the number of UNPAID farm or ranch workers, including family members and office workers, who worked on this farm or ranch? 3401	☐	

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SECTION 32 PRODUCTION EXPENSES

Report total production expenses paid by this operation in 2022.

INCLUDE
- *expenses paid by you and your landlords*
- *expenses connected with performing customwork for others*

EXCLUDE
- *expenses not related to the farm business*
- *any expenses paid by the contractor*

EXPENSES PAID BY THIS OPERATION AND ITS LANDLORD(S)

		Mark "X" if None	Dollars
1.	Fertilizer, lime, and soil conditioners purchased. Include rock phosphate, gypsum, manure purchased, potting soil, growing media, and other organic materials. Include the cost of any custom application 1501	☐	$ .00
2.	Chemicals purchased such as insecticides, herbicides, fungicides, other pesticides, etc. Include the cost of custom application 1502	☐	$ .00
3.	Seeds, plants, vines, trees, etc. purchased. Include technology or other fees, seed treatments, and seed cleaning cost. Exclude items purchased for resale without additional growth 1503	☐	$ .00
	a. Of the total in item 3, how much was for cover crop seed? 2753	☐	$ .00
4.	Breeding livestock purchased or leased, regardless of age. Include dairy cattle 1504	☐	$ .00
5.	All other livestock and poultry purchased or leased. Include stocker and feeder cattle, calves, sheep, lambs, feeder pigs, chicks, pullets, poults, horses, fish, goats, bee colonies, etc. Include livestock leasing expense 1505	☐	$ .00
6.	Feed purchased for livestock and poultry. Include grain, hay, silage, mixed feeds, concentrates, supplements, premixes, etc. 1506	☐	$ .00
7.	Gasoline, fuels, and oils purchased for the farm business. Include diesel, natural gas, LP gas, motor oil, grease, etc. 1507	☐	$ .00
8.	Utilities purchased for the farm business. Include electricity, farm share of telephone, water purchased, etc. 1508	☐	$ .00
9.	Repairs, supplies, and maintenance cost for the farm business. 1509	☐	$ .00
10.	Labor –		
	a. Hired farm and ranch labor. Include employer's cost for social security, worker's compensation, health and life insurance premiums, pension plans, etc. 1510	☐	$ .00
	b. Contract labor. Include expenses for labor, such as harvesting of fruit, vegetables, berries, etc. performed on a contract basis by a contractor, crew leader, etc. 1511	☐	$ .00
11.	Customwork and custom hauling, such as custom planting, harvesting, etc. and custom hauling of grain, livestock, milk, manure, etc. 1512	☐	$ .00
12.	Rent –		
	a. Cash rent paid in 2022 for land and buildings. Include grazing fees 1513	☐	$ .00
	b. Rent and lease expenses for machinery, equipment, and farm share of vehicles. Exclude custom hire. 1514	☐	$ .00
13.	Interest paid on debts –		
	a. Secured by real estate 1515	☐	$ .00
	b. Not secured by real estate 1516	☐	$ .00
14.	Property taxes paid in 2022. Include farm real estate, machinery, livestock, etc. for the farm business. Exclude taxes paid by this operation's landlords 1517	☐	$ .00
15.	Medical supplies, veterinary, and custom services for livestock. Include artificial insemination (AI), branding, breeding fees, caponizing, carcass removal, castrating, custom feed processing, hormone injections, performance testing, pregnancy testing, seining, sheep shearing, etc. Exclude manure disposal 1935	☐	$ .00
16.	Other production expenses. Include storage and warehousing, marketing expenses, insurance, vehicle registration fees, etc. Exclude health insurance premiums and payroll taxes 1518	☐	$ .00
17.	**Total production expenses (add items 1-16)** 1936	☐	$ .00

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SECTION 32 CONTINUED –

		Mark "X" if None	Dollars
18.	How much did your landlord(s) pay for the production expenses for this operation in 2022? 1519	☐	$ .00
19.	What was the value of your landlord's share of the total sales produced by this operation? Exclude cash rent 1349	☐	$ .00
20.	What was the total depreciation expense claimed by this operation in 2022 for all capital assets? Estimate 2022 from 2021 if necessary. 1520	☐	$ .00

SECTION 33 MARKET VALUE OF LAND, BUILDINGS, MACHINERY, AND EQUIPMENT

		Mark "X" if None	Estimated Market Value (Dollars)
1.	Report your estimate of the **current market value** of land and buildings reported in SECTION 1.		
a.	All land and buildings owned 0996	☐	$ .00
b.	All land and buildings rented or leased from others 0997	☐	$ .00
c.	All land and buildings rented or leased to others 0998	☐	$ .00

			Estimated Market Value (Dollars)
2.	What is your estimate of the **current value of all machinery, equipment, and implements** used for farm-related activities on this operation, regardless of ownership, on **December 31, 2022**? 0943	☐	$ .00

INCLUDE - the following if kept on this operation and used for this farm or ranch business in 2022.

- *cars*
- *trucks*
- *tractors*
- *tools*
- *dairy equipment*
- *combines*
- *plows*
- *disks*
- *harrows*
- *irrigation equipment*
- *pumps*
- *motors*
- *tanks*
- *feeders*
- *grinding and mixing equipment, etc.*
- *dryers*
- *computers*

SECTION 34 INCOME FROM FARM-RELATED SOURCES

Report the gross dollar amount received before taxes and expenses in 2022 for –

		Mark "X" if None	Gross Dollars
1.	Customwork and other agricultural services provided for farmers and others, such as plowing, planting, spraying, harvesting, preparing products for market, etc. Exclude if customwork was an entirely separate business from your agricultural operation 0992	☐	$ .00
2.	Payments received from cash rent or share payments from renting out farmland and/or buildings, or payments from lease of allotments. Include payments for livestock pastured on a per head basis, per month basis, AUM basis, etc. 0993	☐	$ .00
3.	Sales of forest products. Include timber, firewood, etc. Exclude sales of Christmas trees, short rotation woody crops, and maple products. 0994	☐	$ .00
4.	Agri-tourism and recreational services, such as farm tours, hay rides, hunting, fishing, etc. 1401	☐	$ .00
5.	Patronage dividends and refunds from cooperatives 1402	☐	$ .00
6.	Crop and livestock insurance payments received. Exclude payments received from casualty insurance, vehicle liability, blanket policies, and operator dwelling insurance 1404	☐	$ .00
7.	Other income which is closely related to the agricultural operation. Include renting and leasing farm machinery and trucks, renting and leasing of livestock, bee colony rental, animal boarding, state fuel tax refunds, farm-generated energy, etc. Specify 1433	☐	$ .00

22100234

SECTION 35 AGRICULTURAL ACTIVITY WITHIN THE BORDERS OF AMERICAN INDIAN RESERVATIONS, PUEBLOS, AND SERVICE AREAS

1. Did this operation use any land for livestock or cropland within the borders of an American Indian Reservation, Pueblo, or Service Area at any time during 2022? Include owned, deeded, tribal, or allotted land.

1050 1 ☐ **Yes** - Complete this section 3 ☐ **No** - Go to SECTION 36

2. Enter the name and state of the American Indian Reservation, Pueblo, or Service Area where the agricultural activity occurred.

	Reservation, Pueblo, or Service Area Name		State
1051		1052	

3. How many total acres did this operation use for livestock or cropland within this Reservation, Pueblo, or Service Area in 2022? Exclude land used on a per head or animal unit month (AUM) basis. 1053

a. How many of these acres were harvested cropland? 1054

Number of Acres

4. In 2022, did this operation have any livestock within the borders of an American Indian Reservation, Pueblo, or Service Area? Include livestock on land used on a per head or animal unit month (AUM) basis.

1056 1 ☐ **Yes** - Continue 3 ☐ **No** - Go to SECTION 36

a. On **December 31, 2022,** what percent of this operation's livestock was on this Reservation, Pueblo, or Service Area?

1057 1 ☐ None 3 ☐ 26 - 50 percent 5 ☐ 76 - 99 percent
2 ☐ 1 - 25 percent 4 ☐ 51 - 75 percent 6 ☐ 100 percent (all livestock)

SECTION 36 CONCLUSION

1. Is it possible that the agricultural activity information reported for this operation could also be reported by another operation?

1080 1 ☐ **Yes** - Provide the other name and address below 3 ☐ **No** - Go to item 2

	Possible Duplicate Name		Address
1081		1082	

	City		State		Zip
1083		1084		1085	

2. Do you (the individual named on the label) make any day-to-day decisions for **another** farm or ranch? It is important that the Census of Agriculture accurately accounts for all of your farm or ranch operations.

1086 1 ☐ **Yes** - Enter the information of the additional farm or ranch below 3 ☐ **No** - Go to item 3

	Additional Farm or Ranch		Area Code and Phone Number	Check if cell phone
1088		1089	- -	☐

a. Did you receive a 2022 Census of Agriculture report form for this additional farm or ranch?

1087 1 ☐ **Yes** 3 ☐ **No**

b. Did you include all data from this additional farm or ranch on THIS REPORT? Do not make changes to the data in this report, regardless of your answer.

1091 1 ☐ **Yes** 3 ☐ **No**

3. Return your form in the envelope provided. **Thank you** for your participation.

22100242

FORM 22-A01(I)
(10-15-2021)

U.S. DEPARTMENT OF AGRICULTURE
NATIONAL AGRICULTURAL STATISTICS SERVICE
For additional help, call 1-888-424-7828
Para ayuda adicional, llamar al 1-888-424-7828

INSTRUCTION SHEET
UNITED STATES 2022 CENSUS OF AGRICULTURE
Your report is due February 6, 2023

Who Should Report?
A reply is required from EVERYONE who receives a report form, including persons who operated a farm, ranch, or other agricultural operation in 2022, anyone who has any agricultural activity, as well as those who were not involved in agriculture. You may complete your report form online. Go to www.agcounts.usda.gov and enter your unique 12-digit survey code from the Census mailing label. More Census information is on the Internet at www.agcensus.usda.gov.

If you do not complete the form online or return your report form by mail, you will continue to receive contacts from us.

If you were a landlord only and rented out all your land, complete the front page, Section 1, and Section 36 on the back page of the enclosed report form and return it in the preaddressed return envelope. If you were a landlord, but still operated other land yourself, you should complete the entire report form for that land which you operated.

If you had no land, no livestock, and no agricultural operations, return the report form with a note indicating your status on the front of the form below the address label.

Partial Year Operations - If you stopped farming, ranching, or producing agricultural products during 2022, complete the report form for the portion of the year that you did farm. Write "Stopped farming during 2022" and the date you stopped below the address area. Mail the completed report form in the preaddressed return envelope. If the person whose name is on the label was deceased during 2022, complete the form for the portion of the year that they farmed, and write a note.

Involved in More Than One Operation - If you made decisions for more than one operation, you may have received a report form for each operation. Provide information for each operation on a separate form. To obtain additional report forms, or if you have questions, please call the toll-free help line at 1-888-424-7828.

Partnership Operation - Complete only ONE form for the entire partnership's agricultural operation and include the entire operation on that one form. If you made day-to-day decisions for another operation, complete a report form for each separate operation. We have listed all known partners below the address area to assist in defining the operation. Make any necessary corrections to these names.

If you owned farm or ranch land in 2022 that was idle and NOT rented out, you should complete and return the report form. If all the cropland was enrolled in conservation programs like CRP, complete the form and include these acres.

Specialty Commodities - Horses, bees, elk, emus, mink, fish, nursery, hemp, etc., are an important part of the agriculture industry. Report for all commodities, regardless of the amount of production or sales you had in 2022.

Land in Federal conservation programs in 2022 - If you had land in the Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), Farmable Wetlands Program (FWP), or Conservation Reserve Enhancement Program (CREP) and you made the decisions on the acres, include the conservation land on the report form in Sections 1, 2, and 6.

Received More Than One Report Form for the Same Operation - If you received more than one report form for the same operation, complete only ONE form per operation. Write "Duplicate" below the address area of each extra form. Return all forms in the same return envelope with your completed form so that we can correct our records.

Entering Your Responses - Use BLUE or BLACK INK only. Enter your response in the unit requested, i.e., dollars, bushels, tons, etc. When reporting dollars, report in whole dollars only. Convert fractions to decimals. Please print clearly and keep numbers and letters within the white boxes. Mark all applicable Yes/No and None boxes with an "X".

SECTION 1 - ACREAGE IN 2022

Your answers in this section will determine the land **(Acres in "THIS OPERATION")** referred to throughout the report form. Include all land owned, rented, or used by you, your spouse, or by the partnership, corporation, or organization named on the front page of the form, regardless of location or use during 2022, even if only for part of the year. Include cropland, non-tillable land, land in government programs such as Conservation Reserve Program (CRP), Wetlands Reserve Program (WRP), etc., pastureland and rangeland, woodland and idle land, farmsteads, buildings, and structures. Include only actively managed tidelands. Exclude residential or commercial land. Report land in whole acres.

Item 1 **(Box A)** - Report all land owned in 2022 whether held under deed, purchase contract or mortgage, homestead law, or as heir/heiress or trustee of an undivided estate. Include all land owned by you and/or your spouse, or by the partnership, corporation, or organization named on the front of the form.

Item 2 **(Box B)** - Report all land rented or leased from others by you or your operation. Include water area leased for aquaculture production. Exclude land used under private, Government grazing permits, or on a fee per head or animal unit month (AUM) basis (Taylor Grazing, Section 3 Bureau of Land Management (BLM) and USDA Forest Service land). BLM Section 15 land leased by your operation with a specified acreage tract should be included here even though your fees to BLM are paid on an AUM basis.

Item 3 **(Box C)** - Include all land rented out to others for any purpose if it was part of the acreage reported in Items 1 and 2. Your tenant(s) will receive a form to report production for the land they rent. Do not report land placed in conservation programs as acres rented to others. Do not report land used by others on a fee per head or animal unit month (AUM) basis.

Item 3a - Report all land owned by the operation and rented or leased to others.

Item 4 **(Box D)** - This is all land you operated at any time in 2022. Land use in Section 2 should be reported for these acres.

Item 5 Total acres equals zero (0) - After completing Section 1, if the acres in Item 4, BOX D equal zero and you did not raise or own any livestock, aquaculture, or poultry in 2022, write a description of land use in the space by question 5. Complete Section 36 and mail the report form in the return envelope.

Item 6 - Exclude BLM Section 15 land leased on a per head or AUM basis.

SECTION 2 - LAND USE IN 2022

The total acres from Items 1 - 4 entered in BOX E should equal the total acres in Section 1, Item 4, BOX D. These acres represent "this operation" for this Census report. **If these two numbers are not the same, please GO BACK and CORRECT your figures.** Do not report any crops grown on land rented or leased to others or worked by others on shares during 2022.

Land used for more than one purpose - Do not report the same acreage in more than one of the listed categories. If part or all of your land was used for more than one listed purpose in 2022, report that land only in the first purpose listed. For example, if you planted and harvested a grain crop and grazed the crop residue in the fall, report the land in Item 1a, cropland harvested. Do not report those acres again in Item 2c pasture or grazing land.

CRP/WRP and other conservation programs - Report these acres in the Items in this section that best describe them. For example, CRP land may be reported in cropland harvested, cropland idle, or woodland not pastured depending on its use.

Item 1a - Land maintained for orchards or vineyards is included even if the crop failed or the trees or vines are not of bearing age. Abandoned acres of orchards or vineyards which are not maintained for production should be reported in Item 1d. Harvested cropland includes acres of trees for fruit, nuts, and berries along with acres of grape vines, Christmas trees, and short rotation woody crops in production. Do not include the area harvested for timber or firewood. If more than one crop was

harvested from the same land in 2022, report that land as cropland harvested only once.

Item 1b - Include land you intended to harvest but had to abandon or where the crop failed.

Item 1c - Include cropland left unseeded for the 2022 harvest and tilled summer fallow, or treated with herbicides to control weeds and conserve moisture. Include cropland summer fallowed in 2022 even though it may have been planted to wheat, etc., for the 2021 harvest.

Item 4 - Include tidelines actively managed for aquaculture production, whether owned or rented from others. Include other water area leased for the production of aquaculture.

SECTION 3 - LAND RENTED OR LEASED FROM OTHERS FOR CASH

Report for cropland and pastureland leased on a per acre basis for cash only. Exclude flex and share rent arrangements. Also, exclude aquaculture arrangements. For cash rental agreements that include dwellings and buildings, only report the acres of cropland and pastureland.

SECTION 4 - LAND USE PRACTICES

Item 1b - Land drained by ditches refers only to manmade ditches installed to improve drainage, not natural waterways.

Item 1c - A conservation easement limits the right to develop the land, now and in the future.

Items 2a through d - Include all cropland acres planted in the operation with the practice, not just cropland harvested. Conservation tillage leaves 30 percent or more of the soil surface covered by crop residue after planting. Reduced tillage leaves between 15 and up to 30 percent of the soil surface cover by crop residue. Conventional tillage has leaves less than 15 percent of the soil surface covered.

SECTION 5 - IRRIGATION

Report land equipped for irrigation and its use. Exclude land used for aquaculture unless the same land was used to grow crops as well. If the same land is irrigated multiple times, it should only be counted once.

Item 2 – Report all acres of irrigated harvested cropland, including acres with orchards (bearing or not), acres with perennial crops, and land with crops under protection.

Item 3 – Report all acres of irrigated other land, including pasture, rangeland, failed cropland, and all other non-harvested cropland. Excludes woodlands, woodland pasture, wastelands, livestock facilities, ponds, and roads.

Item 4 - Include all acres irrigated in 2022 (Items 2 and 3) and acres that could have been irrigated in 2022 using the existing irrigation systems available regardless of water rights.

SECTION 6 - CROP INSURANCE, CONSERVATION RESERVE PROGRAM AND OTHER GOVERNMENT PROGRAMS

Item 1 - Report all acres covered by any crop insurance policy in 2022. Include land in pasture insurance programs, and acres covered by guaranteed revenue policies.

Items 3 and 4 - Exclude insurance payments received or any loan/program amount that must be repaid.

Item 5 - Report the amount received for commodities placed under a Commodity Credit Corporation (CCC) loan during 2022. Include any amount received, even if the commodity was redeemed or forfeited prior to December 31, 2022. Exclude CCC loans to build crop storage facilities.

Item 6 - Report the total amount to repay CCC loans in 2022, regardless of the crop year the loan was made.

SECTION 7 - TYPE OF ORGANIZATION

Item 2 - The number of households that share in the net farm income are those households involved with the day-to-day decisions and not those households that received funds because they are landlords, custom equipment operators, or provide other supplies that are listed in Section 32, Production Expenses.

Use the following definitions to determine the type of organization for this operation. An operation organized as a Limited Liability Company (LLC) may fall into any of the categories.

Family or individual operation - Farm or business organization controlled and operated by a family or an individual (sole proprietor). Include family operations that are not incorporated and not operated under a partnership agreement. Report family corporations under "Incorporated under state law."

Partnership operation - Two or more persons who conduct an operation together and share work and profits. Co-ownership of land by spouses or joint filing of income tax forms by spouses does not constitute a partnership unless a specific agreement to share contributions, decision making, profits, and liabilities exists. Production under contract or under a share rental agreement does not constitute a partnership.

Incorporated under state law - A corporation is a legal entity or artificial person created under the laws of a state to carry on a business, including family corporations. Exclude cooperatives, even if they are incorporated.

Other - Estate or trust, government facility, grazing association, American Indian Reservation, university farm, prison farm, institution run by a government or religious entity, cooperatives (an incorporated or unincorporated enterprise or an association created and formed jointly by the members), etc.

SECTION 8 - PERSONAL CHARACTERISTICS

This section collects information about the persons making decisions for this operation.

Item 1 - Enter the number of men and the number of women involved in decisions for this operation. Do not report minor-aged children who only worked on the farm.

Item 2 - Complete one column for each person involved in making decisions for the farming operation for up to four persons. If there were more than four, answer for the four individuals most involved in the decision making for this operation.

REPORTING VALUE OF SALES

Report the value of all crops and livestock sold from this operation in 2022 in the appropriate commodity section. Report the sales in 2022 regardless of the year crops were harvested or raised. Include the value of your landlord's share of the commodities harvested. Report livestock as sold that you owned and moved to someone else's operation for further feeding, such as cattle. Report the gross value before the deduction of expenses, marketing charges, hauling fees, other fees, or income taxes. Include payments received in 2022 from cooperatives or marketing organizations for crops produced on this operation regardless of the year in which the crops were harvested. Also, include as sales your estimate of the value of any crop or livestock removed from this operation in trade of services, such as baled hay for labor or other services. Report the total value you received for animals and poultry sold from this operation in 2022, without deducting production or marketing expenses (costs for feed, livestock purchase price, hauling, selling, etc.).

Exclude:

- Proceeds from CCC loans or other government payments.
- The value of sales of any cattle, hogs, or poultry owned by you but kept and sold from a location you did not operate.
- The value of commodities grown under a production contract.

SECTION 9 - HAY AND FORAGE CROPS

Include hay and forage from alfalfa, wild or native grasses, and hay or forage from clovers, small grains, soybeans, and peanuts. Report production in tons or, for dry hay, bales and weight per bale. Any pasture or conservation land that had hay cut from it should be reported as cropland harvested in Section 2, Item 1a.

SECTION 10 - CULTIVATED CHRISTMAS TREES, SHORT ROTATION WOODY CROPS, AND MAPLE SYRUP

Item 2 - Acres in production of cultivated Christmas trees include both those to be harvested in future years as well as those harvested in 2022. Trees cut should include only those trees cut in 2022.

Item 3 - A short rotation woody crop is a tree that is harvested in 10 years or less. These are trees for use by the paper or pulp industry or as engineered wood. Exclude trees cut for timber. Acres in production of short rotation woody crops include both those harvested in 2022 and future years. Acres harvested should include only those harvested in 2022.

Item 4 - Producers should report number of taps and gallons of syrup. If sap was sold, estimate the number of gallons of syrup it would have produced. Report the acres of tapped maple trees in Section 2, Item 3, woodland not pastured.

SECTION 11 - FIELD CROPS

Acres harvested - Enter the acres harvested in 2022. Round fractions to whole acres, except for tobacco and hops, where tenths should be reported.

Crops names not listed – For those seed or field crops not listed in the table that fall into the Other seeds (code 770) or Other field crops (code 752) categories, please specify each crop on a separate line in the table along with the requested data.

Total production harvested - If your unit of measure is different than the unit requested on the report form, convert your figure for the production harvested to the unit requested. If the harvest was incomplete by December 31, 2022, estimate the total production to be harvested.

Acres irrigated - Report the irrigated harvested acres only once, even if the crop was irrigated multiple times during the growing season.

Double cropping - If two or more crops were harvested from the same land (double cropping), report the total acres and production of each harvested crop.

Interplanted crops - If two crops were grown at the same time in alternating strips in the same field, report the acreage of the field used for each crop.

Skip row planting - If a crop was planted in an alternating pattern of planted and non-planted rows, such as two rows planted and two rows skipped, report the acreage occupied by the crop and report the skipped portion as cropland idle in Section 2, Item 1d. If you rented land under a share arrangement, include your landlord's share of the crop in value of sales.

SECTION 12 - NURSERY, GREENHOUSE, FLORICULTURE, SOD, MUSHROOMS, VEGETABLE SEEDS, AND PROPAGATIVE MATERIALS

Report Christmas trees grown on this operation and sold live as nursery stock, code 0488. Exclude crops bought for resale without additional growing, and garden center items, such as chemicals and fertilizers. Report all acres of Christmas trees in production for cut Christmas trees and the number cut in 2022 in Section 10, Item 2. Report vegetable seeds grown under protection. Report vegetable seeds not grown under protection in Section 13.

SECTION 13 - VEGETABLES, POTATOES, AND MELONS

Item 4 - Report acres harvested for individual crops. If the same crop was planted more than once during the year on the same field, report the sum of the acres harvested during 2022. For example, if 4 acres were planted to lettuce and harvested, then replanted to lettuce and harvested, report 8 acres of lettuce in Item 4 but only 4 acres in Item 2. Report vegetable seeds grown without protective cover in Item 4 using the crop code that best describes the vegetable and record it in the fresh market category.

SECTION 14 - FRUIT, NUTS AND BERRIES

If nonbearing trees and vines are intermixed with bearing trees and vines, estimate area for each category. Exclude abandoned acres of orchards or vineyards. Abandoned acres not maintained for production should only be reported in Section 2, Item 1d. Bearing age acres are the acres of trees or vines that produced any fruit or nut crop in 2022 or previous years. If fruit and nut trees and vines were interplanted with other crops, report only the total acres for the orchard in Section 14, and the total acres of each interplanted crop in their appropriate section(s).

Berries- Report all acres on which berries were grown in 2022.

SECTIONS 15, 16, AND 20 - CATTLE AND CALVES, HOGS AND PIGS, AND POULTRY

Include all animals on this operation on December 31, 2022 owned by you, raised by you under contract, or kept by you for others. Include animals owned by you on unfenced lands, National Forest Land, Indian Reservation Land, cooperative grazing association land, or rangeland administered by the Bureau of Land Management on a per head, animal unit month (AUM), or lease basis. Animals in transit on December 31, 2022, should be reported by the person who had control of the animals on that day. Animals on a fee per head or animal unit month basis should be reported by the animal owner and not the landowner.

Contract and custom feeding operations - Report numbers of all animals or poultry on this operation on December 31, 2022. Animals and poultry kept on a contract or custom basis and moved or sold from this operation in 2022 should be reported as sold. Do NOT include fees received for commodities produced under a production contract in the value of sales. In addition, report in *Section 24- Production Contracts and Custom Feeding* on the appropriate line the quantity delivered of custom fed livestock or production contract livestock and poultry and the dollar amount received from the contractor.

Cattle, hogs, and poultry to exclude from the report form - Exclude animals or poultry kept on land rented to others or kept under a share arrangement on land rented to others. Exclude animals quartered in feedlots that were not located on this operation. Do not report the sales of animals bought and then resold within 30 days.

Number sold - Report all animals and poultry sold or moved from this operation in 2022, regardless of ownership or who shared in the receipts. Include animals sold for a landlord or given to a landlord or others in trade or in payment for goods or services. Do not report number sold of any hogs and pigs, cattle and calves, or poultry owned by you that were kept and sold from a location that you did not operate.

Number moved from this operation - For animals and poultry moved from this operation to another, such as for further feeding, report them as "sold." Cattle moved are not considered sold if they were moved to another operation for a short term, such as for winter wheat or corn stubble grazing, or during the winter to public grazing land. Exclude animals when moved for grazing on public or private AUM.

Cattle in feedlots – Exclude the following for this item: cattle and calves sold or moved off the operation for further feeding, veal calves or any calves weighing less than 500 pounds, cull or dairy cows fed only the usual dairy ration before being sold, and all cows and bulls.

SECTION 17 - HORSES, PONIES, MULES, BURROS, AND DONKEYS

Exclude horses owned by this operation but stabled elsewhere. Horses, mules, burros, and donkeys that are on this operation should be reported regardless of ownership. Exclude feral equine.

SECTION 18 - SHEEP AND GOATS

Report goats based on utilization regardless of breed. Report pounds of wool shorn and mohair clipped in 2022 only.

SECTION 19 - AQUACULTURE

Include all sizes for each type. Report each type sold or moved on a separate line and specify whether the sale was fish eggs, fry, fingerlings, food size, or a combination. Convert units such as bushels, bags, or gallons to number or pounds. Do not duplicate the same quantity sold in both the pounds and number columns.

SECTION 21 - COLONIES OF HONEY BEES

Item 2 - Report the number of bee colonies owned regardless of location. Report the pounds of honey collected in 2022 whether sold or not sold. Report sales of packaged bees, nucleus colonies, whole colonies, queen, and all non-apis bees (bumble, leaf cutter, etc.) in Section 22, Item 2. Report sales of honey bee products such as wax, pollen, and propolis in Section 23, Item 2. Report pollination fees in Section 34, Item 7.

SECTION 24 - PRODUCTION CONTRACTS AND CUSTOM FEEDING

Commodities raised under a production contract should be reported in Section 24 and included in Sections 9 through 23. The money received as a production contract fee is reported in Section 24 only, under "Total dollar amount received" and not in Sections 9 through 23.

Please report amount of the specified commodity that you raised and delivered under production contracts in Item 2. If you had multiple contracts to produce different commodities, report the appropriate amount of each commodity produced under each contract in the proper categories. Exclude marketing contracts, futures contracts, forward contracts, or other contracts based strictly on price. The contractor should not report commodities that were produced by the grower.

SECTION 25 - ORGANIC AGRICULTURE

Item 3 - Report the total sales of NOP organically produced items. Include gross value of agricultural sales before expenses or taxes. Exclude sales of crops and livestock from transitioning land. Exclude the value of processed or value-added items.

SECTION 26 - PRACTICES

Item 1 - Include internet access for farm use if either the operation or the producer's residence has access. Access includes internet via a cellular data plan on a smartphone or mobile device.

Item 2c - *Alley Cropping* is the growing of annual or perennial

crops between rows of trees. The agricultural crop generates annual income while the tree crop matures. *Silvopasture* combines timber, livestock, and forage production on the land. Trees provide longer-term returns, while livestock generates an annual income. *Forest farming* is the intentional management of woodlands to grow non-tree crops such as mushrooms, berries, and root crops under trees. *Windbreaks* are rows of trees and shrubs used to slow wind to protect soil, crop, or livestock, or for visual screening and shade. *Riparian forest buffers* are natural or planted trees, shrubs, and grasses adjacent to water bodies to protect water resources from non-point source pollution.

SECTION 27 - FOOD MARKETING PRACTICES

Include only edible agricultural products sold directly for humans to eat or drink, such as fruit, eggs, milk, meat, etc. Report only products grown or raised on this operation. Exclude products that you bought and resold within 30 days and non-edible products such as live animals, hay, cut flowers, nursery products, etc.

SECTION 28 - FERTILIZERS, CHEMICALS, AND SOIL CONDITIONERS APPLIED

Fertilizer - Report acres on this operation on which commercial fertilizer was applied during 2022 only once, even if multiple applications were made.

Chemicals - Include acres on which custom application of chemicals was applied. If multiple applications of chemicals for the same purpose (for example, herbicides) were applied on the same acres, report the acreage only once. If chemicals were applied for different purposes, report the acres for each purpose on which the chemicals were applied. Estimate the acreage for spot treatments.

SECTION 29 - RENEWABLE ENERGY

Item 1 – Report renewable energy producing systems, regardless of ownership. Exclude woodburning stoves and densified biomass-producing systems. Include the value of energy sold from this operation in Section 34, Item 7.

SECTION 30 - MACHINERY AND EQUIPMENT

Report the total on this operation, or normally on this operation and normally used on this operation, in the first column. Do not report obsolete or abandoned equipment. In the second column, report only the number manufactured in the last five years.

SECTION 31 - FARM LABOR

Report the number of paid and unpaid farm or ranch workers who performed agricultural labor on this operation in 2022. Exclude contract labor except where specified (see Item 2). Include family members (paid and unpaid). Include workers such as bookkeepers, office workers, maintenance workers, etc., if their work was primarily associated with agricultural production on this operation.

Item 1 - Include any short term or temporary workers who may have worked only a few days. Exclude contract labor.

Item 2 - Report the number of migrant workers who worked on the operation for any length of time during 2022. Include both hired and contract labor. The definition of a migrant worker is a farm worker whose employment requires international or domestic travel that prevents the worker from returning to his or her permanent place of residence the same day.

SECTION 32 - PRODUCTION EXPENSES

Include farm production expenses paid by you or your landlord(s) for crops, livestock, or poultry produced on this operation in 2022 in Items 1 through 16. Include expenses associated with the generation of farm-related income reported in Section 34. Include expenses incurred in 2022 even if they were not paid in 2022. Estimate if exact figures are not known.

Contract growers or custom feeders - Do not report as production expenses the value of inputs provided by the contractor or livestock owner. Identify the items that were contractor provided in Section 24, Item 3.

Item 2 - Include surfactants and oils and other products used to increase a chemical's effectiveness.

Item 6 - Report the purchase cost of all grains, silage, hay, commercially mixed and premixed feeds, ingredients, concentrates, etc., fed to livestock or poultry on this operation. Contract livestock and poultry growers should not report the value of feed that was provided by a contractor. Do not report the value of feed raised and fed on this operation as an expense.

Item 9 - Include the cost of repairs and upkeep of farm machinery, vehicles, buildings, fences, and other equipment used in the farm business. Include expenses for repairs to machinery and equipment used only for customwork if income from those machines is reported in Section 34. Exclude repairs to vehicles not used in the farm business. Exclude expenditures for the construction of new buildings or the cost of additions to existing buildings.

Item 10a - Include labor expense for the farm business for gross salaries and wages, commissions, dismissal pay, vacation pay, and bonuses paid to hired workers, family members, hired managers, administrative and clerical employees, and salaried corporate officers. Include cost for benefits such as employer's social security contributions, unemployment compensation, worker's compensation, insurance, employer paid life and medical insurance expense, pension plans, etc.

Item 10b - Include the labor costs of workers furnished on a contract basis by labor contractor, crew leader, or cooperative for harvesting vegetables or fruit, shearing sheep, or similar farm activities. Report costs for repair work done by a construction contractor in Item 9. Report the cost of customwork or machine hire in Item 11.

Item 12a - Exclude rent paid for operator dwelling or other nonfarm property. Exclude the value of shares of crops or livestock paid to landlords.

Item 13 - Report all interest expenses paid in 2022 for the farm business. Include interest paid on CCC loans in Item 13b. Exclude interest associated with activities not related to production of crops or livestock on this operation, such as land or buildings rented to others, packing sheds, or feed mills that provided services to others. Exclude interest on owner/operator dwelling where the amount is separated from the interest on the land and buildings on this operation.

Item 14 - Include real estate property taxes you paid on the acres and buildings you owned and used in the farm business and property taxes on equipment or livestock. Exclude property taxes on land or buildings rented to someone else, or property taxes paid on other property not associated with the farm business.

SECTION 33 – MARKET VALUE OF LAND, BUILDINGS, MACHINERY, AND EQUIPMENT

Item 1 - Estimate the value of the land, houses, barns, and other buildings for each of the three listed categories if they were sold in the current market. The real estate tax assessment value should not be used unless that value represents a full market value assessment and the land, house, and buildings could reasonably be assumed to be sold at that price. Report the total value, not the value on a per acre basis.

Item 2 - The estimated market value refers to all machinery and equipment kept primarily on this operation and used for the farm business. Report the value in its present condition, not the replacement or depreciated value. Include mobile implements, hand tools, and office supplies. Permanently installed equipment or equipment that is an integral part of a building should be included as a part of the value of land and buildings and reported in Item 1.

SECTION 34 - INCOME FROM FARM-RELATED SOURCES

Report gross dollar amounts received before taxes and expenses.

Item 2 - Exclude rental income from nonfarm property.

Item 3 - Include only those forest products cut from this operation, not items cut from other nonfarm timber acreage. Exclude income from a sawmill business. Report sales of Christmas trees, maple syrup, or sap products in Section 10.

Item 7 - Include pollination fees.

SECTION 35 - AGRICULTURAL ACTIVITY WITHIN THE BORDERS OF AMERICAN INDIAN RESERVATIONS, PUEBLOS, AND SERVICE AREAS

Complete this section if any of your cropland or livestock was on an American Indian Reservation, Pueblo, or service area in 2022. Include trust acres used, as well as deeded land or land leased from others that was on the Reservation.

SECTION 36 - CONCLUSION

Item 1 - If the agricultural activity on your operation might be identified under a different name than is printed on the front of the form (for example, a farm name or another partner), please provide these names.

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Decisionmaking.....	51, 52, 54, 56, 58, 60, 63, 64, 66, 68, 71-77	45	
Deer.....	32, 33	23	-
Defoliation chemicals applied.....	46, 71-77	40	-
Depreciation expense.....	4, 71-77	3	-
Dill for oil.....	-	27	-
Direct payments.....	6	-	-
Direct sales to individuals.....	2, 71-77	2	-
Diseases, chemical control.....	46, 71-77	40	-
Donkeys (see Mules, burros, and donkeys).....			
Dry edible beans	1, 34, 35, 71-77	1, 24, 25	-
Ducks.....	30	20	-
E			
Economic class of farms.....	3, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	2	-
Eggs, chicken.....	42, 48	39	-
Eggplant.....	36	29	-
Elk.....	32, 33	23	-
Energy, renewable.....	49, 71-77	43	-
Emmer and spelt.....	-	25	-
Emus.....	30	20	-
Energy (see Renewable energy)			
Equine.....	29, 43, 48	18	-
Equipment and machinery.....	1, 4, 11, 44, 45, 48, 50 71-77	1, 39	-
Escarole and endive.....	36	29	-
Estimated market value of land and buildings.....	1, 11, 41, 43, 48, 50, 71-77	1, 8	-
Estimated market value of machinery and equipment.....	1, 11, 41, 50, 71-77	1	-
Expenses paid by landlords.....	4, 71-77	-	-
Expenses, total farm production.....	1, 4, 11, 41, 50, 71-77	1, 3	-
F			
Family held corporations.....	71-77	45	A, B
Family or individual operations.....	1, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	45	A, B
Farm characteristics.....	55, 57, 59, 61, 62, 65, 67, 69, 71-77	-	B

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Farm production expenses	1, 4, 41, 50, 71-77	1, 3	-
Farm size	1, 50, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	6	A, B
Farmer (see Producers)			
Farmland, rent income received	7, 71-77	6	-
Farms, number	1-53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	1-24, 38-57	A, B, C
Feed purchased, expense	1, 4, 11, 41, 71-77	3	-
Fertilizer and chemicals applied	11, 46, 71-77	40	-
Fertilizer, lime, and soil conditioners purchased, expense	1, 4, 11, 41, 46, 71-77	3, 40	-
Fescue seed	35	26	-
Field and grass seed crops	35, 71-77	25, 26	-
Figs	37	31	-
Filberts (hazelnuts)	37	31	-
Flaxseed	35	25	-
Floriculture crops	39, 41, 71-77	2, 34	-
Flower seeds	39	34	-
Foliage plants	39	34	-
Forage, all, land used	1, 34, 35, 71-77	1, 24, 26	A, B
Forage harvesters, self-propelled	45, 71-77	39	-
Forest products, sales values	7, 71-77	6	-
Fruit and tree nuts	2, 35, 37, 41, 48, 57, 59, 62, 61, 71-77	2, 31	-
Fruits, tree nuts, and berries, sales value	2, 41, 71-77	2	-
Fuels purchased, expense	1, 4, 11, 41, 71-77	3	-
Full owners	50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	45	A, B
G			
Gains, net income	5, 62, 71-77	4	-
Game or sport fish	31	22	-
Garden plants sold	39	-	-
Garlic	36	29	-
Gasoline, fuels, and oils purchased expense	1, 4, 11, 41, 71-77	3	-
Geese	30	19, 20	-
Generated energy	-	43	-
Ginger root	-	27	-
Ginseng	36	29	-
Goats	2, 28, 33, 41, 48, 71-77	2, 14-17	-
Gooseberries	38	33	-
Gourds	36	29	
Government payments	3, 6, 7, 11, 41, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	1, 5	-
Grain and bean combines	45, 71-77	-	-
Grains, oilseeds, dry beans, dry peas	2, 41, 42, 71-77	2, 38	-
Grapefruit	37	31	-
Grapes	37, 48, 71-77	31	A, B
Grass silage	34, 35	26	-
Greenchop	1, 34, 35, 71-77	1, 24, 26	-
Greenhouse fruits and berries	39	34	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Greenhouse vegetables and fresh cut herbs	39	34	-
Greenhouse tomatoes	39	34	-
Guar	-	27	-
Guavas	37	31	-
Guineas	30	20	-
H			
Harvested cropland	1, 8-11, 34-38, 40-41, 48, 50, 51, 71-77	1, 8-10, 24-37, 45	-
Hawaiian (see Native Hawaiian and Other Pacific Islander)			
Hay	34, 35, 48, 71-77	26	-
Hay balers	45, 71-77	-	-
Haylage, grass silage, and greenchop hay	1, 34, 35, 71-77	26	-
Hazelnuts (Filberts)	37	31	-
Head lettuce	36	29	-
Heifers	12, 14-17, 42, 71-77	11, 38	-
Hemp	35, 39	25, 34	-
Herbs	36, 39	27, 29, 34	-
Hired farm labor	1, 4, 11, 41, 71-77	3, 7	-
Hired managers	57, 59, 61, 62, 71-77	-	-
Hispanic, Latino, or Spanish origin	52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45, 48	A, B
Hogs and pigs	1, 2, 11, 19-26, 41, 42, 48, 71-77	1, 2, 12, 38, 44	A, B
Honey collected	33	21	-
Honeydew melons	36	29	-
Hops	35	27	-
Horseradish	36	29	-
Horses and ponies	29, 48, 71-77	2, 18	-
Horses, ponies, mules, burros and donkeys, sales value	2, 29, 41, 71-77	2, 18	-
Household income, percent from farming	53, 55, 57, 59, 61, 62, 71-77	-	-
Households sharing in farm income	53, 55, 57, 59, 61, 62, 71-77	-	-
Hungarian partridges	30	20	-
I			
Income from farm-related sources	7, 11, 50, 71-77	1, 6	-
Insects, chemical control	46, 71-77	40	-
Institutional farms	50	-	-
Insurance payments	7, 71-77	6, 8	-
Interest expenses	1, 4, 11, 41, 42, 71-77	3, 45	-
Internet access	53, 55, 57, 59, 61, 62, 65, 67 71-77	2, 45	-
Irrigated land	1, 9-11, 34, 35, 40 50, 71-77	1, 10	A, B
J			
Jojoba	-	27	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
K			
Kale	36	29	-
Kentucky bluegrass seed	-	26	-
Kiwifruit	37	31	-
Kumquats	37	31	-
L			
Labor expense, hired	1, 4, 11, 71-77	3, 7	-
Land and buildings, estimated market value	1, 11, 43, 48, 50, 71-77	8	-
Land in farms, acres	1, 8, 9, 11, 41, 47, 48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	8, 45, 47-55	A, B, C
Land owned	11, 71-77	45	-
Land rented or leased to others	53, 55, 57, 59, 61, 62, 71-77	45	-
Land use	8, 11, 50, 71-77	8	-
Land use practices	47, 71-77	41	
Land used for vegetables	35, 71-77	28	-
Landlord's share of production expenses	4, 71-77	3	-
Landlord's share of sales	2, 71-77	-	-
Layers	1, 30, 71-77	1, 19	A, B
Leaf lettuce	36	29	-
Legal status for tax purposes	53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	45	A, B
Lemons	37	31	-
Lentils	35	25	-
Lespedeza seed	-	26	-
Lettuce	36	29	-
Lima beans -			
Green	36	29	-
Dry	-	25	-
Limes	37	31	-
Livestock and poultry purchased expense	1, 4, 11, 41, 71-77	3	-
Livestock inventory	1, 11, 71-77	1	-
Livestock, poultry, and their products, value	1, 2, 11, 50, 53, 55, 57, 59, 61, 62, 71-77	1, 2	-
Llamas	32, 33	23	-
Loganberries	38	33	-
Longan	37	31	
Losses, net income	5, 71-77	4	-
Lychees	37	31	
M			
Macadamia nuts	37	31	-
Machinery and equipment -			
Estimated market value	1, 11, 41, 44, 45, 48, 50, 71-77	1, 39	-
Rent and lease expense	4, 11, 71-77	3	-
Mangoes	37	31	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Manure applied	46, 71-77	40	-
Maple syrup	2, 40, 71-77	2, 37	-
Marionberries (see Blackberries and dewberries)			
Market value of agricultural products	1-3, 11, 41, 42, 50, 53, 55, 57, 59, 61, 62, 71-77	1, 2	A, B, C
Market value of agricultural products sold and government payments	3, 53, 55, 57, 59, 61, 62, 71 - 77	-	-
Meat and other goats	28	17	-
Melons	36	29	-
Migrant workers	71-77	7	-
Milk from cows	2, 41, 48, 71-77	2	-
Milk cows	1, 11, 12, 17, 71-77	1, 11, 44	A, B
Milk from sheep and goats	33	-	-
Milk goats	28	15	-
Military Status	51, 52, 54, 56, 58, 60, 63, 64, 66, 68, 71-77	45, 55	A, B
Mink, live	32, 33	-	-
Miscanthus	-	27	-
Mint for oil	35	27	-
Mint for tea leaves	-	27	-
Miscellaneous poultry	30	20	-
Misclassification adjustment	-	-	A, C
Mohair	28, 33	16	-
Mollusks	31	22	-
More than one race, producers	52, 54, 56, 58, 60, 62, 63, 64, 66, 68, 71-77	45, 54	A, B
Mulberries	38	33	-
Mules, burros, and donkeys	2, 29, 41, 71-77	2, 18	-
Mushroom spawn	39	34	-
Mushrooms	39	34	-
Mustard greens	36	29	-
Mustard seed	-	25	-
N			
Native Hawaiian or other Pacific Islander producers	52, 54, 56, 58, 60, 63, 64, 66, 68, 71-77	52	A, B
Nectarines	37	31	-
Nematodes, chemical control	46, 71-77	40	-
Net cash farm income of the operations and producers	5, 71-77	1, 4	A, B
Net gain	5, 71-77	4	-
Net loss	5, 71-77	4	-
New and beginning producers	69, 70	57	-
Noncitrus fruit, all	37, 48	31	-
Nonirrigated farms	11, 34	-	-
Nonresponse adjustment	-	-	A, C
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Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
All other animal production (11299)…….……..	48	-	-
All other crop farming (11199) …...	48	-	-
Animal aquaculture (1125) …….....	48	-	-
Aquaculture and other animal production (1125, 1129) ……..	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Animal production (112)…….……..	48	-	-
Apiculture (11291)…….……...	48	-	-
Apple orchards (111331)…….….	48	-	-
Beef cattle ranching and farming including feedlots (11211)…...…….	48	-	-
Beef cattle ranching and farming (112111)……..……	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Berry (except strawberry) farming (111334)……..……	48	-	-
Broilers and other meat-type chicken production (11232……..….	48	-	-
Cattle feedlots (112112)…….……..	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Cattle ranching and farming (1121)…….……	48	-	-
Chicken egg production (11231)…...	48	-	-
Citrus (except orange) groves (11132)……	48	-	-
Corn farming (11115)……...	48	-	-
Cotton farming (11192)…….……...	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Crop farming, all other (11199)….....	48	44	-
Crop production (111)…….……	48	-	-
Dairy cattle and milk production (11212)……..……..	48, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Dry pea and bean farming (11113)…….……...	48	-	-
Floriculture production (111422)….	48	-	-
Food crops grown under cover (11141)……..……	48	-	-
Fruit & nut combination farming (111336)……..	48	-	-
Fruit and tree nut farming (1113) …	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Fur-bearing animal and rabbit production (11293)……..…….	48	-	-
Goat farming (11242)…….……..	48	-	-
Grape vineyards (111332)…….……	48	-	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Greenhouse, nursery, and floriculture production (1114)…….…..	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Hay farming (11194)…….……	48	-	-
Hog and pig farming (1122)……..…	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Horse and other equine production (11292)……..…….	48	-	-
Noncitrus fruit and tree nut farming (11133)……..……..…	48	-	-
Nursery and floriculture production (11142)……..……..	48	-	-
Nursery and tree production (111421)……..……	48	-	-
Oilseed and grain farming (1111)	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Oilseed (except soybean) farming (11112)……..	48	-	-
Orange groves (11131)……..…	48	-	-
Other animal production (1129).....	-	44	-
Other crop farming (1119)…….....	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Other grain farming (11119)……..…	48	-	-
Other noncitrus fruit farming (111339)……..	48	-	-
Other poultry production (11239)….	48	-	-
Other vegetable (except potato) and melon farming (11219)……..	48	-	-
Potato farming (111211)…….……..	48	-	-
Poultry and egg production (1123)…….….	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Poultry hatcheries (11234)…….....	48	-	-
Rice farming (11116)…….……...	48	-	-
Sheep and goat farming (1124)…….	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Sheep farming (11241)……..…	48	-	-
Soybean farming (11111)……..…	48	-	-
Strawberry farming (111333)…….....	48	-	-
Sugarcane farming, hay farming and all other crop farming (11193, 11194, 11195) ……	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Sugarcane farming (11193)……..….	48	-	-
Tobacco farming (11191)……..…	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Tree nut farming (111335)…….…...	48	-	-
Turkey production (11233)…….....	48	-	-
Vegetable and melon farming (11121)……...…	48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	44	-
Wheat farming (11114)……	48	-	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Number of farms…….	1, 8-33, 41, 42, 45, 47-50, 53, 55, 57, 59, 61, 62, 71-77	1, 2, 8-23, 31, 35, 36, 38, 39, 45	A, B, C
Number of households sharing in net income of operation	53, 55, 57, 59, 61, 62, 71-77	45	-
Number of producers	52, 54, 56, 58, 60, 63, 64, 66, 68, 71-77	45	-
Number of persons living in producers' household	53, 55, 57, 59, 61, 62, 71-77	45	-
Nursery crops	39	2, 34	-
Nursery, greenhouse, floriculture, and sod, sales value	2, 41, 71-77	2	-
Nursery stock	39	34	-
Nuts, all	37	31	-
O			
Oats ……	1, 34, 35, 71-77	1, 24, 25	A, B
Occupation of producer	51, 52, 54, 56, 58, 60, 63, 64, 66, 68, 71-77	1, 45	A, B
Off-farm work by producer	51, 52, 54, 56, 58, 60, 63 64, 66, 68, 71-77	45	-
Okra	36	29	-
Olives	37	31	-
Onions	36	29	-
Oranges	37	31	A, B
Orchardgrass seed	-	26	-
Orchards	1, 34, 35, 46, 48, 71-77	1, 24, 30	A, B
Organic agriculture	41, 46, 51, 71-77	40, 42	-
Organic fertilizer used	46	40	-
Ornamental fish	31	22	-
Ostriches	30	20	-
Other animals and other animal products	2, 32, 33, 41, 71-77	2	-
Other aquaculture products	31	22	-
Other berries	38	33	-
Other citrus	37, 48	31	-
Other dry hay	34, 35, 71-77	26	-
Other farm characteristics	53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	-	-
Other farm production expenses	4, 11, 71-77	3	-
Other farm-related income	7, 71-77	6	-
Other federal farm program payments	6, 53, 55, 57, 59, 61, 62, 65, 67, 69	5	-
Other floriculture and bedding crops	39	34	-
Other food fish	31	22	-
Other livestock	32, 33	23	-
Other livestock products	33	23	-
Other livestock and poultry purchased or leased	4, 71-77	3	-
Other noncitrus	37, 48	31	-
Other poultry	30, 48	20	-
Other vegetables	36	29	-
Owned land in farms	11, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	45	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
P			
Pacific Islander (see Native Hawaiian and Other Pacific Islander)			
Papayas	37	31	-
Parsley	36	29	-
Parsnips	36	29	
Part owners	50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	45	A, B
Partnerships	1, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	45	A, B
Passion fruit	37	31	-
Pastureland	8, 10, 11, 41, 71-77	8, 10, 40	-
Patronage dividends and refunds from cooperatives	7, 71-77	6	-
Pawpaws	37	31	
Payroll	-	7	-
Peaches	37, 71-77	31	-
Peacocks and peahens	30	20	-
Peanuts	1, 34, 35, 71-77	1, 24, 25	A, B
Pears	37	31	-
Peas -			
Chinese	36	29	-
Dry edible	35, 38, 64	25	-
Dry southern (cowpeas)	-	25	-
Green (excluding southern)	36	29	-
Green southern (cowpeas)	36	29	-
Pecans	36, 71-77	31	-
Peppers	36	29	-
Permanent pasture and rangeland	8, 50, 71-77	8	-
Persimmons	37	31	-
Pesticides, acres applied	46, 71-77	40	-
Pheasants	30	20	-
Pigeons or squab	30	20	-
Pima cotton	34, 35	1, 25	-
Pineapples	37	31	-
Pistachios	37	31	-
Place of residence	51, 52, 54, 56, 58, 69, 63, 64, 66, 68, 70, 71-77	45	-
Plums and prunes	37	31	-
Plumcots, pluots, and other plum-apricot hybrids	37	31	-
Pomegranates	37	31	-
Popcorn	35	25	-
Potatoes	1, 2, 36, 41, 42, 71-77	1, 2, 29, 38	A, B
Potted flowering plants	39	34	-
Poultry	1, 2, 4, 11, 30, 41, 48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	1, 2, 19, 20, 38, 44	A, B
Poultry hatched	30	20	-
Primary occupation (see Producer Characteristics)			

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Principal producer (see Producer Characteristics)			
Producer characteristics -			
Age	51, 52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	A, B
All	52, 54, 56, 58, 60, 62, 64, 66, 68, 70-77	45	-
American Indian or Alaska Native producers	52, 54, 56, 58, 60, 62, 64, 66, 68, 70- 77	45, 49	A, B, D
Asian	52, 54, 56, 58, 60, 62, 64, 66, 68, 70-77	45, 50	A, B
Black or African American	52, 54, 56, 58, 60, 62, 64, 66, 68, 70-77	45, 51	A, B
Days of work	51, 52, 54, 56, 58, 60, 63, 64, 68, 70-77	45	-
Female	51, 52, 54, 58, 60, 63, 64, 68, 70-77	45, 47	A, B
Hired manager	52, 54, 56, 58, 60, 62, 64, 66, 68, 70-77	45	-
Hispanic, Latino, or Spanish origin	52, 54, 56, 58, 60, 62, 64, 66, 68, 70-77	45, 48	A, B
Male …….....	51, 52, 54, 56, 60, 62, 64, 68, 70-77	45, 46	A, B
More than one race reported……..	52, 54, 56, 58, 60, 62, 64, 66, 68, 70-77	45, 54	A, B
Military Status	51, 52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45, 55	A, B
Native Hawaiian or Other Pacific Islander	52, 54, 56, 58, 60, 62, 64, 66, 68, 70-77	45, 52	A, B
Number of persons living in producers' households	52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	-
Place of residence	52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	A, B
Primary occupation	51, 52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	A, B
Principal producer	52, 56, 58, 60, 64, 66, 68, 70-77	45, 46-57	A, B
Race	52, 54, 56, 58, 60, 64, 66, 68, 70-77	45	A, B
White	52, 54, 56, 58, 60-64, 66, 68, 70-77	45, 53	A, B
Years on present farm	52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	-
Years operating any farm	52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	-
Young producers	52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Production contracts	42	38	-
Production expenses	1, 4, 11, 41, 50, 71-77	1, 3	-
Propagative materials sold	39	34	-
Property taxes paid, expense	4, 11, 71-77	3	-
Proso millet	35	25	-
Prunes	37	31	-
Pullets for laying flock replacement	30, 42, 71-77	19, 38	-
Pumpkins	36	29	-
Q			
Quail	30	20	-
R			
Rabbits, live	32, 33	23	-
Race of producer	52, 54, 56, 58, 60-64, 66, 68, 70-77	45, 49-54	A, B
Radishes	36	29	-
Rambutan	37	31	
Rapeseed	-	25	-
Raspberries	38	33	-
Recreational services income	7, 71-77	6	-
Red clover seed	-	26	-
Renewable energy	49, 71-77	43	
Rent and lease expenses for machinery, equipment, and farm share of vehicles	4, 11, 71-77	3	-
Rent or share payments income	7, 71-77	6	-
Rented or leased land	11, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	45	-
Rheas	30	20	-
Rhubarb	36	29	-
Rice	1, 2, 34, 35, 48, 71-77	1, 2, 24, 25	A, B
Romaine lettuce	36	29	-
Roosters	30	20	-
Rotational or management intensive grazing	-	43	-
Rye for grain	35	25	-
Ryegrass seed	35	26	-
S			
Safflower	35	25	-
Seed harvested	35, 39, 71-77	24-27, 34	-
Seedlings	39	34	-
Seeds, plants, vines, and trees expense	4, 11, 71-77	3	-
Sesame	-	27	-
Sex of producer	51, 52, 55-58, 60, 63, 64, 66, 68, 70-77	45, 46, 47	A, B
Share payments	7, 71-77	6	-
Sheep and lambs	11, 27, 33, 41, 60, 71-77	1, 2, 13	-
Sheep, goats, wool, mohair, and milk sales value	2, 41, 71-77	2	-
Short rotation woody crops	2, 40, 41, 71-77	2, 36	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Silage	1, 34, 35, 71-77	1, 24, 26	-
Sod	39	34	-
Soil conditioners	1, 4, 11, 41, 46, 71-77	2, 40	-
Sorghum	1, 2, 34, 35, 71-77	1, 2, 24-27	A, B
Soybeans	1, 2, 34, 35, 71-77	1, 2, 24, 25	A, B
Spearmint for oil	35	27	-
Specified fruits and nuts, acres	37	31	-
Spinach	36	29	-
Sport or game fish	31	22	-
Spring wheat, other	1, 34, 35	1, 25	-
Squabs	30	20	-
Squash	36	29	-
State and local government program payments	7, 71-77	6	-
Stockholders in farm corporation	71-77	-	-
Strawberries	38	33	-
Sudangrass seed	-	26	-
Sugarbeets	1, 34, 35, 71-77	1, 24, 25	-
Sugarcane	1, 34, 35, 48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	1, 24, 25	-
Summer squash	36	29	-
Sunflower seed	1, 35, 71-77	1, 24, 25	-
Supplies, repairs, and maintenance, expense	4, 11, 71-77	3	-
Sweet corn	36, 71-77	29	A, B
Sweet potatoes	1, 2, 36, 41, 71-77	1, 2, 29	-
Switchgrass	-	27	-
T			
Tangelos	37	31	-
Tangerines	37	31	-
Taps, maple syrup	40	37	-
Taro	36	29	-
Taxes, property	4, 11, 71-77	3	-
Tenants	50, 53, 55, 57, 59, 61, 63, 65, 67, 69, 71-77	45	A, B
Tenure of producer	50, 53, 55, 57, 59, 61, 63, 65, 67, 69, 71-77	45	A, B
Tillage, intensive	47, 71-77	41	-
Tillage, reduced	47, 71-77	41	-
Timothy seed	-	26	-
Tobacco	1, 2, 34, 35, 41, 48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	1, 2, 24, 25, 44	-
Tobacco transplants	39	34	-
Tomatoes	36, 39, 71-77	29, 34	A, B
Tomatoes, greenhouse	39	34	-
Total cropland	1, 8, 41, 50, 71-77	1, 8	-
Total farm production expenses	4, 11, 41, 50, 71-77	1, 3	-
Total sales	2, 71-77	2	-
Total woodland	8, 50, 71-77	8	-
Tractors	45, 71-77	39	-
Triticale	35	25	-
Trout	31	22	-

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Trucks	45, 71-77	39	-
Tubers	39	34	-
Turkeys	30, 42, 71-77	19, 38	-
Turnip greens	36	29	-
Turnips	36	29	-
U			
Upland cotton	34, 35, 37	1, 25	-
Utilities, expense	4, 11, 41, 71-77	3	-
V			
Valencia oranges	37	31	-
Value added commodities products	2	2	-
Value -			
Agricultural products sold ……..	1, 2, 3, 11, 41, 48, 50, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	1, 2	A, B, C
Commodities under production contract	42	38	-
Land and buildings	1, 11, 43, 48, 50, 53, 71-77	1, 8	-
Landlord's share of total sales	2, 71-77	-	-
Machinery and equipment	1, 11, 44, 48, 50, 53, 71-77	1, 39	-
Organic product sales	41, 51, 71-77	42	-
Veal calves	-	43	
Vegetable seeds	39, 41	34	-
Vegetables transplants	41	34	-
Vegetables	1, 2, 34, 35, 36, 39, 42, 71-77	1, 2, 24, 28, 29, 34, 38	A, B
Vetch seed	-	26	-
W			
Walnuts, English	37, 71-77	31	-
Watercress	36	29	-
Watermelons	36	29	-
Weeds, grass, or brush, chemical control	46, 71-77	40	-
Wetlands Reserve Program	6, 8, 11, 53, 55, 57, 59, 61, 62, 65, 67, 69, 71-77	5, 8	-
Wheat -			
All	1, 2, 34, 35, 48, 71-77	1, 2, 24, 25	-
Durum	1, 36, 37	1, 25	A, B
Other spring	1, 36, 37	1, 25	A, B
Winter	1, 36, 37	1, 25	A, B
Wheatgrass seed	-	26	-
White clover seed	-	26	-
White producers	52, 54, 56, 58, 60-64, 66, 68, 70-77	45, 53	A, B
Wild rice	-	25	-
Winter squash	36	29	-
Women producers (also Female producers)	51-54, 57, 60, 63, 64, 66, 71-77	45-47	A, B

Item	Chapter 1 tables	Chapter 2 tables	Appendix tables
Woodland crops	2, 7, 40, 41, 71-77	2, 7, 35-37	-
Woodland, total	8, 50, 71-77	8	-
Wool production	27	13	-
Y			
Years on present farm	51, 52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	-
Years operating any farm	52, 54, 56, 58, 60, 63, 64, 66, 68, 70-77	45	-
Young producers	52, 54, 56, 58, 60, 63, 64, 66, 67, 68, 70-77	45, 56	

Hot Situation for Hogs

ars.usda.gov/oc/dof/hot-situation-for-hogs



With temperatures rising because of climate change, heat stress is becoming a more serious problem for all kinds of living things — including livestock. Pigs are very sensitive to heat because they don't sweat and therefore have trouble responding to excessive heat. This problem affects the productivity of the swine industry and causes health and welfare issues in the pig population. Currently, the United States is the third-largest producer and consumer of pork and pork products.

"You know, back around 2003, it was estimated that the swine industry lost around $299 million per year in just the U.S. alone due to heat stress," said Jay S. Johnson, supervisory research animal scientist at the USDA-ARS Livestock Behavior Research Unit in West Lafayette, IN. "If you adjust that for inflation, that's more like $493 million per year now."

Since then, things like climate change and genetic improvements in pig carcass and reproduction traits have resulted in pigs with greater basal level of heat generation which has culminated in lower tolerance of heat for pigs. Experiencing a heat stress event causes negative impacts on the pigs' growth and their ability to get pregnant or to maintain a pregnancy, with greater losses commonly occurring late in the second trimester where the negative impacts on the mother and the economic losses are greater. Once exposed to heat during prenatal development, pigs also tend to grow slower, are less efficient, their immune systems are compromised, and they get more stressed during standard production procedures.



A sow experiencing heat stress. (Photo by Jay Johnson, ARS)

Other common issues when growing pigs are exposed to heat stress include the amount and quality of meat, as the pigs tend to add more fat and less muscle as they grow. Because of these issues, researchers are working to understand more about how heat stress affects hogs' behavior, productivity, and welfare. One technique the researchers are using is measuring the heat that the animal is generating and the heat they're absorbing from the environment; that way the researchers can identify more accurately if they experienced heat stress. Another important factor is the rate of response of a pig to heat stress, and how fast their body temperature fluctuates. Some pigs demonstrate heat stress sensitivity through reductions in productivity, like a decrease in milk production in lactating sows.

In addition to external factors, researchers are investigating whether there's a genetic difference between pigs that are more or less sensitive to heat stress. There are several projects in progress that aim to develop genomic selection models, which are a tool for enhancing molecular breeding efficiency, to breed animals that are more resilient to heat stress events.

There are common practices and tools that farmers can use to help manage their swine in heat stress events, including cooling technologies like ventilation fans and the use of natural fresh air by keeping windows unobstructed. Farmers also use drip coolers, which intermittently provide small quantities of water on the skin followed by additional cooling through evaporation, as well as evaporative cooling pad applications whereby fans distribute air cooled by passing through the wet pads.



A sow being cooled down by a cooling pad. (Photo by Jay Johnson, ARS)

ARS researchers in collaboration with Purdue University and University of Illinois have developed a smartphone app called HotHog. It works as a decision support tool that alerts producers when their pigs are going to be impacted by heat stress, while offering general guidelines on different mitigation practices they can use to help get those animals over the heat stress event.

“We have animal geneticists, reproductive physiologists, nutritionists, behavior experts, basically everyone we can get together to try to solve this issue,” explained Johnson. “And really, that's what we think it's going to take.”

Heat stress is a concerning issue in many phases of swine production. When the pigs are stressed, they grow less efficiently, meaning they take longer to reach a market weight where they harvested for human consumption. As a result, farmers face increased costs associated with added feed, labor, and housing needs, while also increasing the volume of manure generated. Current ARS research strives to diminish the effects and causes of heat stress to enable more efficient production while promoting the welfare of the animals. — *By Olga Vicente, ARS Office of Communications.*

Overview of the United States Cattle Industry

Released June 24, 2016, by the National Agricultural Statistics Service (NASS), Agricultural Statistics Board, United States Department of Agriculture (USDA).

Cattle Production Ranks 1st in United States Cash Receipts

Cattle production is one of the most important industries in the United States, accounting for $78.2 billion in cash receipts during 2015. This represents 21 percent of the Economic Research Service's (ERS) forecasted total cash receipts of $377 billion from agricultural commodities in 2015. Corn being the United States 2nd largest cash receipt forecasted at $47.2 billion in 2015. Modern beef production in the United States is a highly specialized system that spans from cow-calf operations that typically graze pastureland to cattle feedlots focusing on finishing cattle on grain for slaughter. In 2015, the beef industry saw the first increase in cattle and calves production since 2011, producing 41.5 billion pounds, a 3 percent increase from 2014. Total cattle and calves inventory as of January 1, 2016 was 92.0 million head, also 3 percent above previous year.

The *Overview of the United States Cattle Industry* report provides an official periodic review of changes in the United States cattle industry and its impact on cattle supplies and disposition. Additionally, this report gives a brief overview of survey and estimation procedures as well as terminology used in the National Agriculture Statistics Service's (NASS) cattle publications. The 2016 *Overview of the United States Cattle Industry* report will highlight data from NASS' annual *Meat Animals Production, Disposition, and Income* report, the January *Cattle* inventory report, monthly *Cattle on Feed* reports, monthly and annual *Livestock Slaughter* reports, along with the *Census of Agriculture*. Also, it will take an in-depth look at the United States imports, exports, cattle life cycle, and weather conditions.

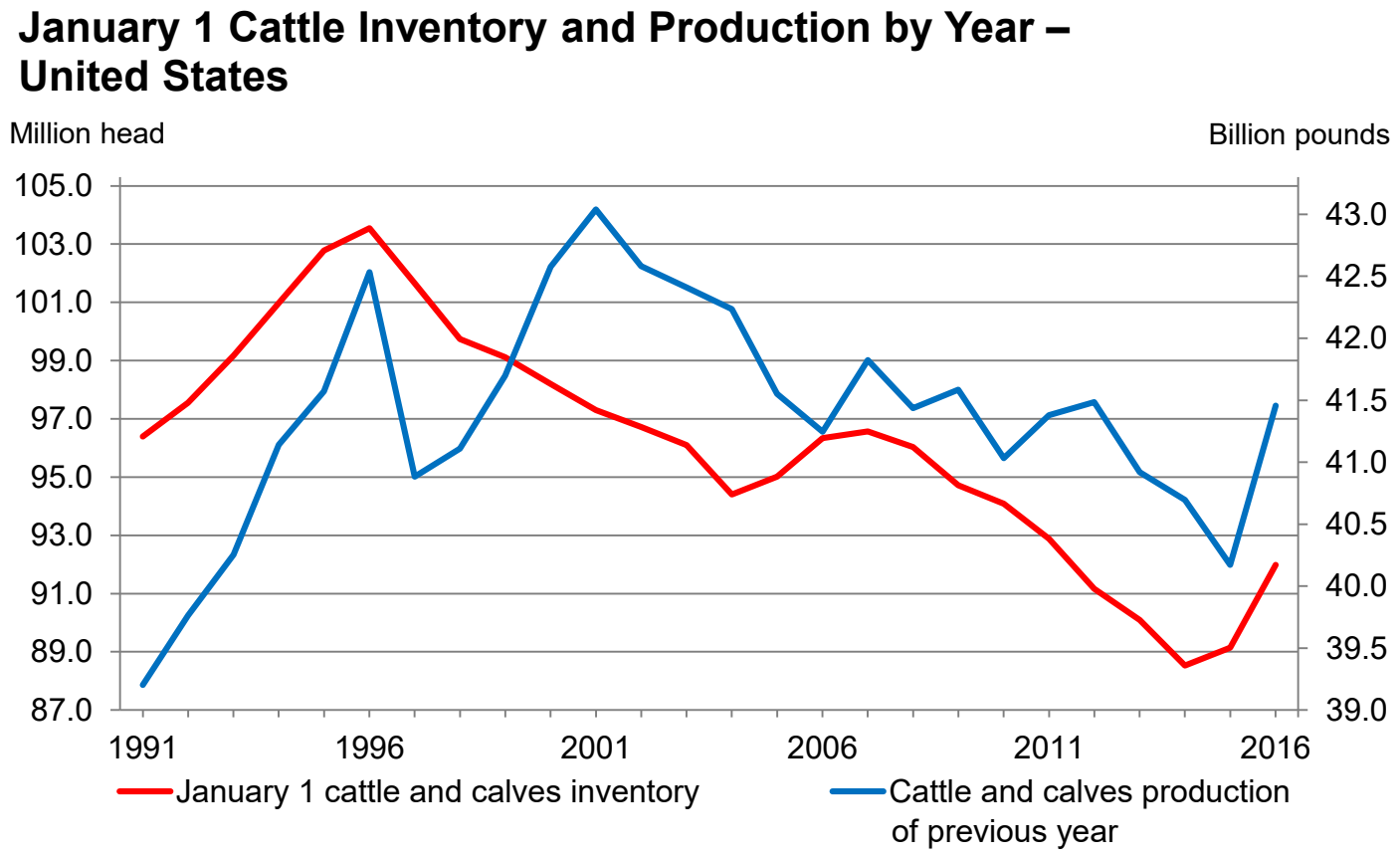

Gross Cattle Income down 4 percent

The 2015 gross income from cattle and calves for the United States totaled $78.8 billion, a 4 percent decline from the 2014 record of $82.1 billion. All cattle and calf marketings during 2015 totaled 52.4 billion pounds, down 1 percent from 2014. This was combined with the market year average price received for cattle greater than or equal to 500 pounds decreasing $5 per hundredweight (cwt) from $152 per cwt in 2014 to $147 per cwt in 2015. At 52.4 billion pounds the all cattle and calf marketings were the lowest since 1992, while gross income was second largest on record. Cattle production in 2015 was 41.5 billion pounds, up 3 percent from the 40.2 billion pounds produced in 2014.

For the second year in a row, the largest percent of the United States value of production from agricultural commodities came from cattle and calves. In 2015 the top 5 United States agricultural commodities in order from largest to smallest were cattle and calves, corn from grain, milk from cows, soybeans, and broilers. The 2015 total value of production for all cattle and calves totaled $59.9 billion, down slightly from the 2014 value of production. The second largest value of production in the United States was corn for grain at $49.0 billion. Corn for grain was the largest United States agricultural commodity in terms of value of production in 1996 as well as from 2007 to 2013. You would have to go back to 1998 when milk from cows was the largest value of production. None of the top five commodities saw an increase in value of production in 2015, cattle having the smallest decrease at less than 1 percent and milk production with the largest decrease at 28 percent.

The straight annual average of monthly prices received by farmers in the United States for calves in 2015 equaled $263 per cwt, up 3 percent from 2014 and the largest on record. Identical to total cattle, farmers saw an average decrease in the prices received for steer and heifers in 2015 of $5 per hundredweight. Grain farmers in the United States saw a decline in the price received for corn for grain for the fourth year in a row. In 2015 the price for corn for grain was $3.71, down 44 percent from the peak in 2012 of $6.67. The bottom line for cattle producers has benefited from these lower prices.

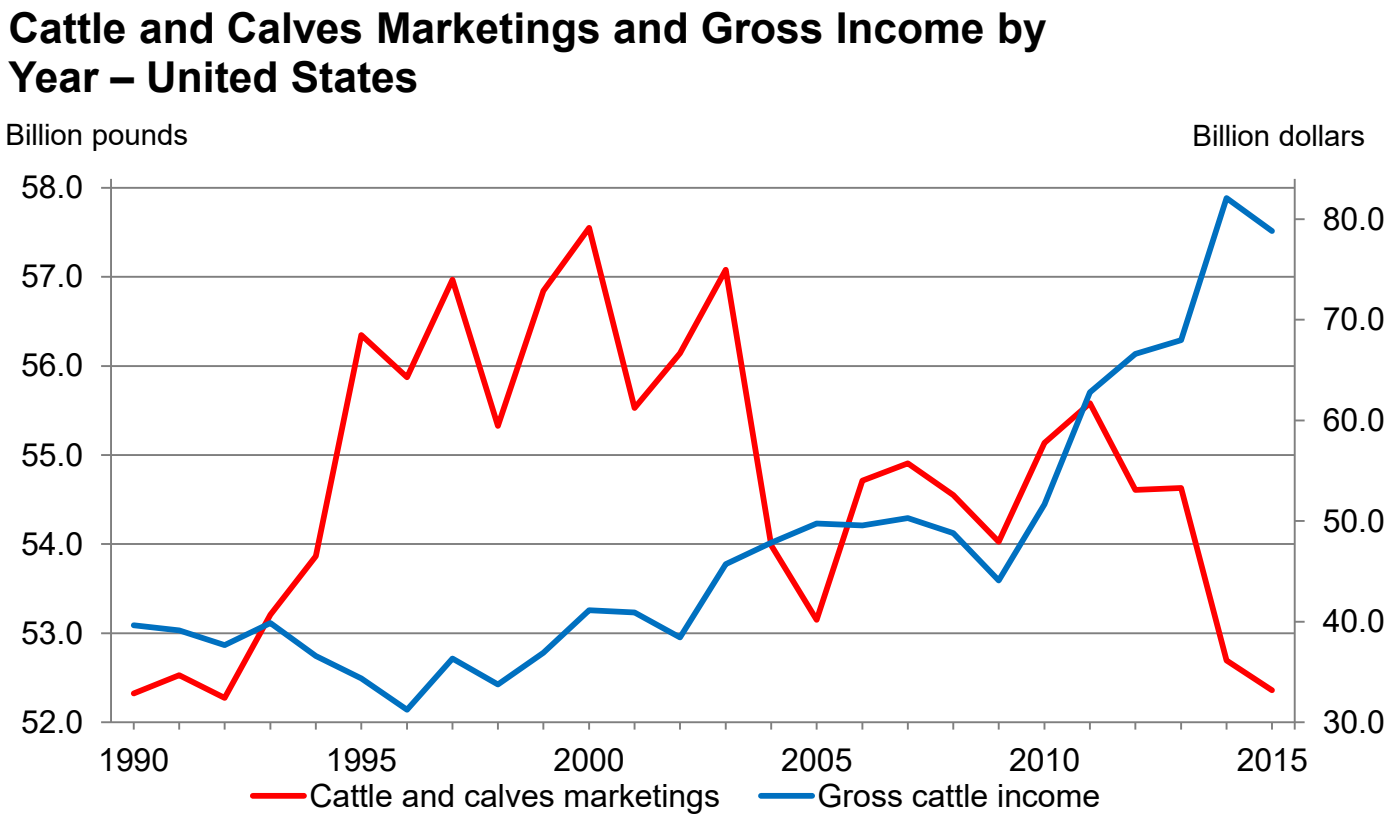

Value of Production by Commodity by Year – United States

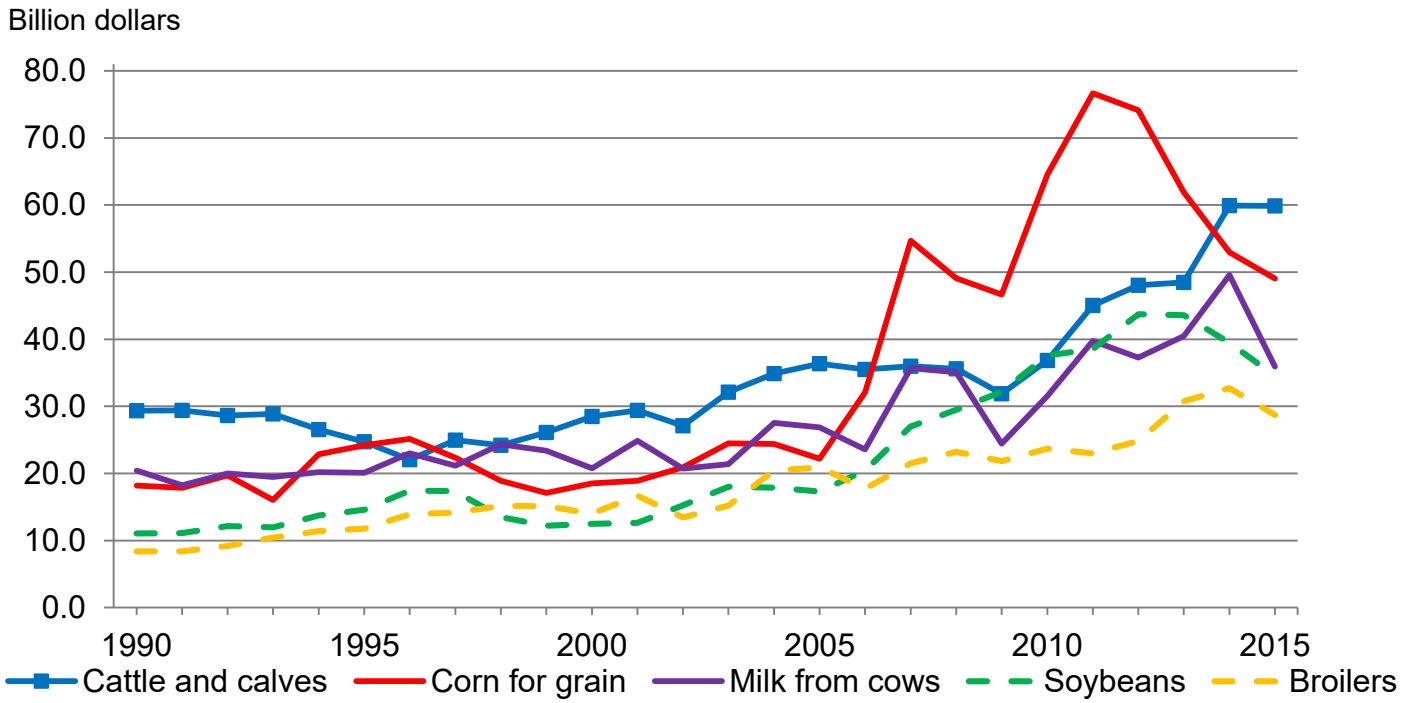

Prices Received by Farmers by Year – United States

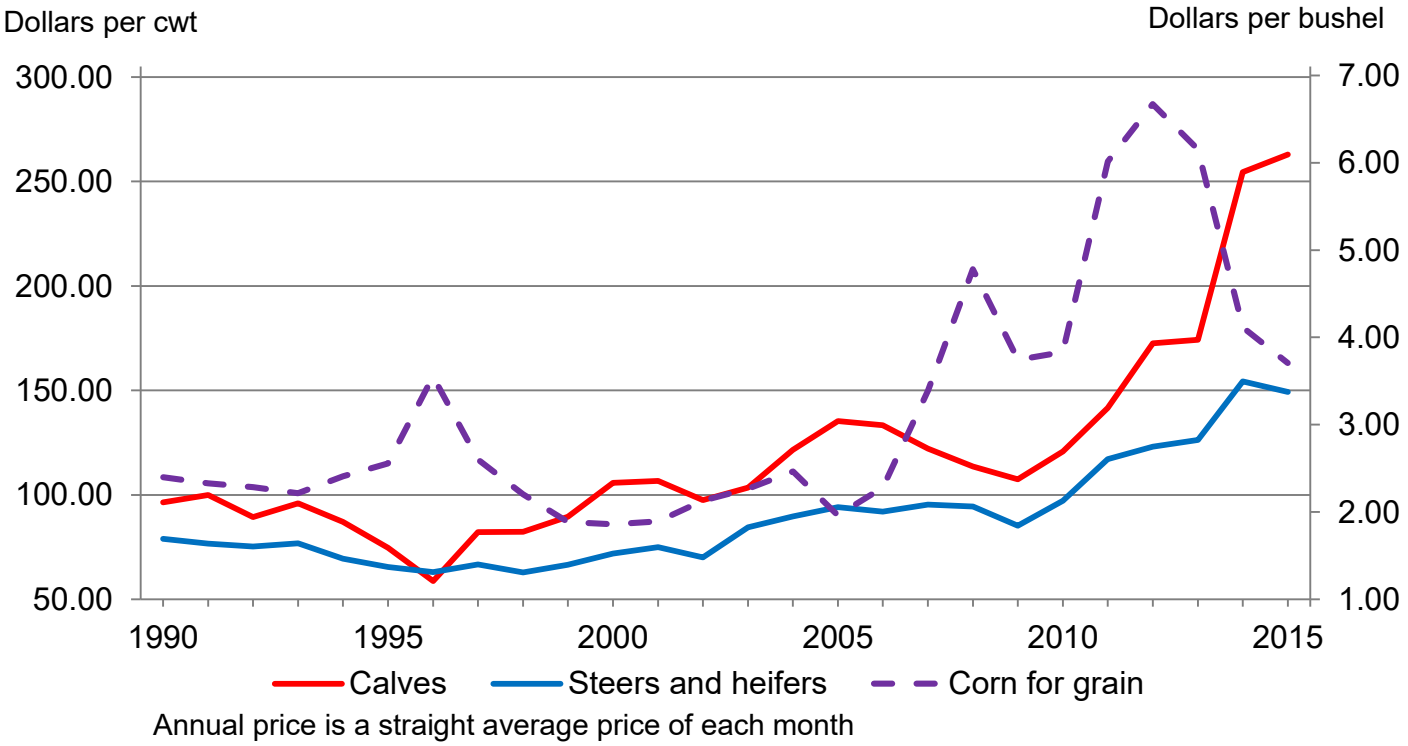

Annual price is a straight average price of each month

Cattle Inventory Saw Largest Year over Year Increase Since 1975

The United States cattle inventory officially began a new cycle in 2015. A cattle cycle is a period of time in which the number of beef cattle in the nation is alternately expanded and reduced for several consecutive years in response to perceived changes in profitability of beef production. The cattle cycle is measured from trough to trough. The last cycle spanned from 2004 to 2014, with 3 years of growth followed by a 7 year liquidation. The longest cycle since 1928 began in 1990 and ended in 2004; which saw 6 years of growth and 8 years of decreasing inventory. Interestingly the first five cattle cycles, beginning in 1928, saw more years of increases than decreases in inventory. However, during the last three cattle cycles, beginning in 1979, there have been more years of decreases than there have been years that increased. The last eight cattle cycles have been an average of 11.8 years, with the shortest cycle being 10 years.

When USDA began counting cattle in the United States in 1867, there were only 28.6 million head, the lowest on record. The United States all cattle and calves inventory peaked in 1975 with 132 million head. Just two years into the current cattle cycle there has been a 4 percent increase, the largest increase in the first 2 years of a cattle cycle since the 1958 cycle. This increase is also larger than the total increase from the last cattle cycle which saw a 2 percent increase in the 3 years of growth. Looking at the last three cattle cycles; the largest increase was 8 percent during the 1990 to 2004 cattle cycle. The five cattle cycles prior to 1980 had an average increase of 26 percent. All cattle and calves inventory in 2016 was 92.0 million head, 3 percent above the 89.1 million head in 2015. The 92.0 million head in 2016 is the largest number of cattle and calves since 2011.

As of January 1, 2016 heifers for beef replacement represented 32 percent of all heifers, compared to 53 percent in 1966. However, the 32 percent is up 3 percent from just 10 years ago and 2016 had the largest percent of beef replacement heifers since 1995. Other heifers represented 44 percent of all heifers, compared to 24 percent in 1966 and 49 percent in 2006. The number of other heifers equaled 8.71 million head, up 3 percent from 2015. In 1966 there was only 4.15 million other heifers with total inventory being 109 million head; 18 percent larger than 2016. Heifers for milk replacement percent of total heifers have not seen much change in the last 50 years, this class represents 24 percent of total heifers in 2016. The number of milk replacement heifers as of January 1, 2016 was 4.82 million head, the largest since 1962. The number of milk cows on January 1, 2016 was 9.32 million head, the largest since 2009.

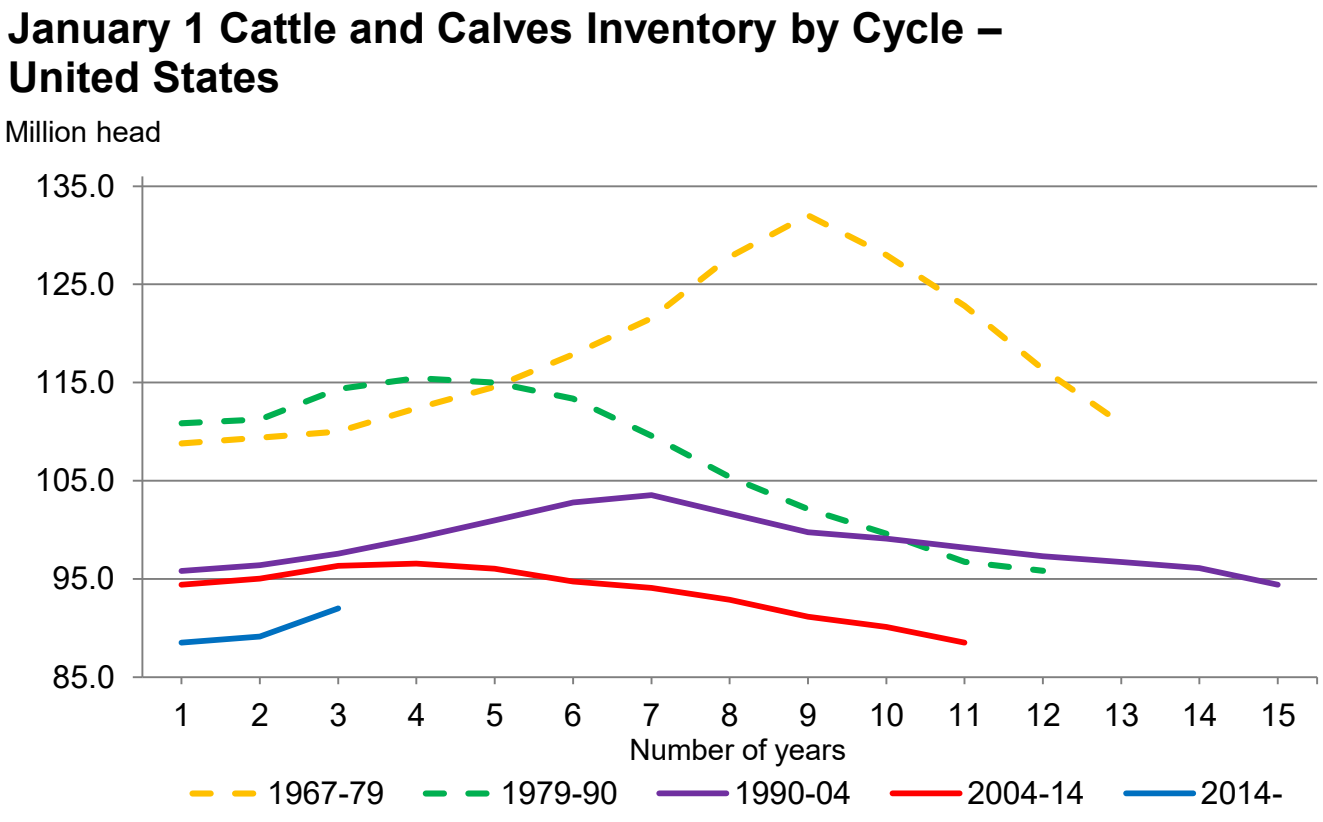

January 1 Cattle and Calves Inventory – United States

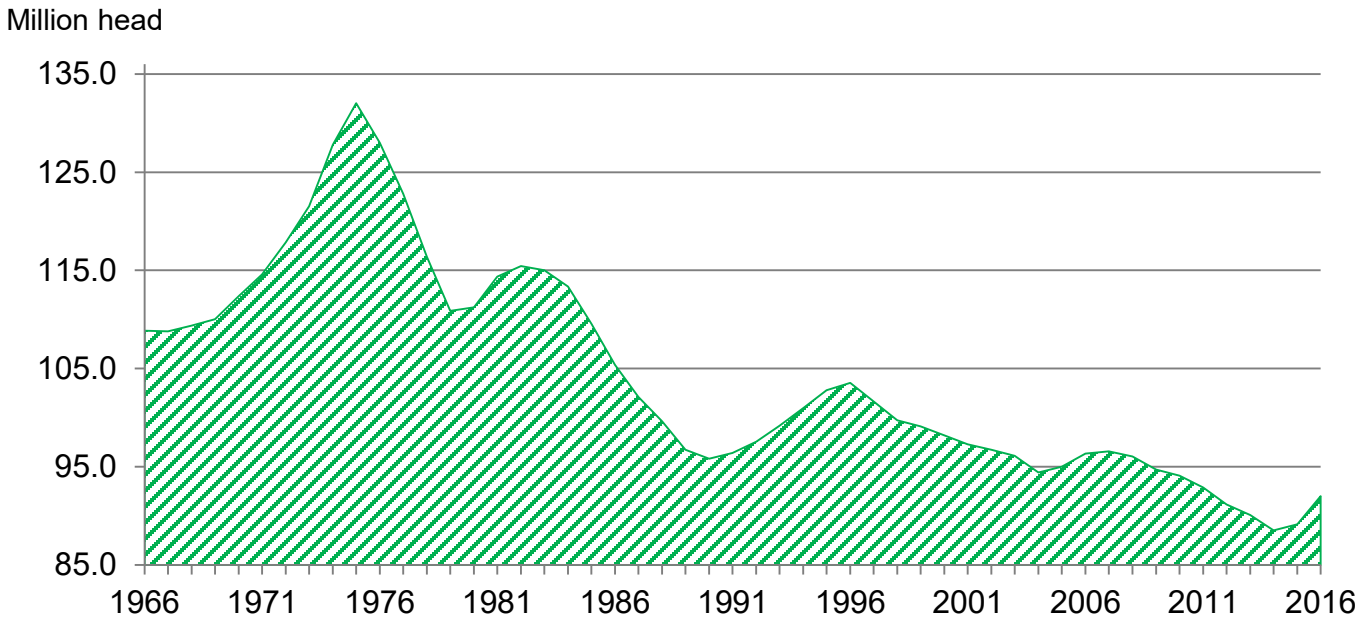

Beef Replacement, Milk Replacement, and Other Heifer Percent of Combined Total – United States

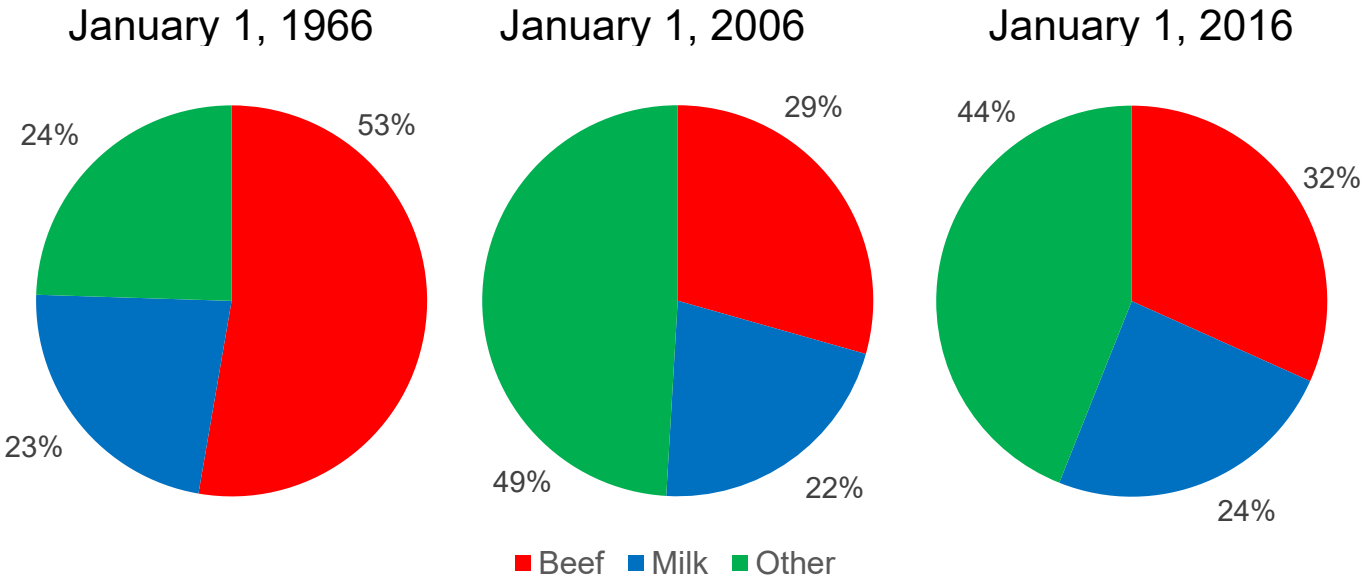

Live Cattle Imports Down 16 Percent

According to the Economic Research Service (ERS) the United States imported 1.98 million head of live cattle in 2015, down 16 percent from the 2.36 million head in 2014. This was the largest decrease since 2004. In recent years, the United States has only received live imports from Mexico and Canada, the last time the United States did import live cattle from another country, Australia, was 2008. Since 1989 the United States has imported the majority of cattle and calves from Mexico and Canada. Only 0.1 percent came from other countries. In 2015 Mexico comprised 58 percent of total live imports, compare that to 2014 when Mexico comprised only 47 percent of the total live imports.

ERS reported that in 2015 the US exported cattle to more than 20 different countries with the largest portion of exports, at 53 percent, going to Canada. Mexico was the second largest with 28 percent of total live cattle exports. According to ERS the United States exported 72.5 thousand head of live cattle in 2015, down 33 percent from the 108 thousand head in 2014. This is the fourth consecutive year that the United States has seen a decline in exports, and the second year in a row the United States has seen a 33 percent decline.

Beef production in the United States is diversified with various types of operations, with different possible paths to be taken between calving and slaughter. The diagram on the following page is from *The Beef Book* published by Urner Barry and shows some of these possible paths a calf born in the spring could take. In 2015, 72 percent of all calves in the United States were born from January 1 through June 30. Calves born in the spring are then weaned in the fall once their digestive system can process whole feeds. Once the cow-calf operator has weaned their calves, the operator then makes the decision to sell their calves, retain their calves to provide the next phase themselves, or use a production contract to perform the next stage of the process. The advantage of a production contract is that the cow-calf operator retains ownership of that animal throughout the growing process. Each production stage includes a description of that stage, the weight achieved by the end of that stage, the time of year that the particular stage usually takes place, and the average number of days spent in that stage. Each path has its own advantages and disadvantages. The monthly NASS *Cattle on Feed* publication breaks out placements into feedlots by weight category.

Live Cattle Imports and Exports – United States

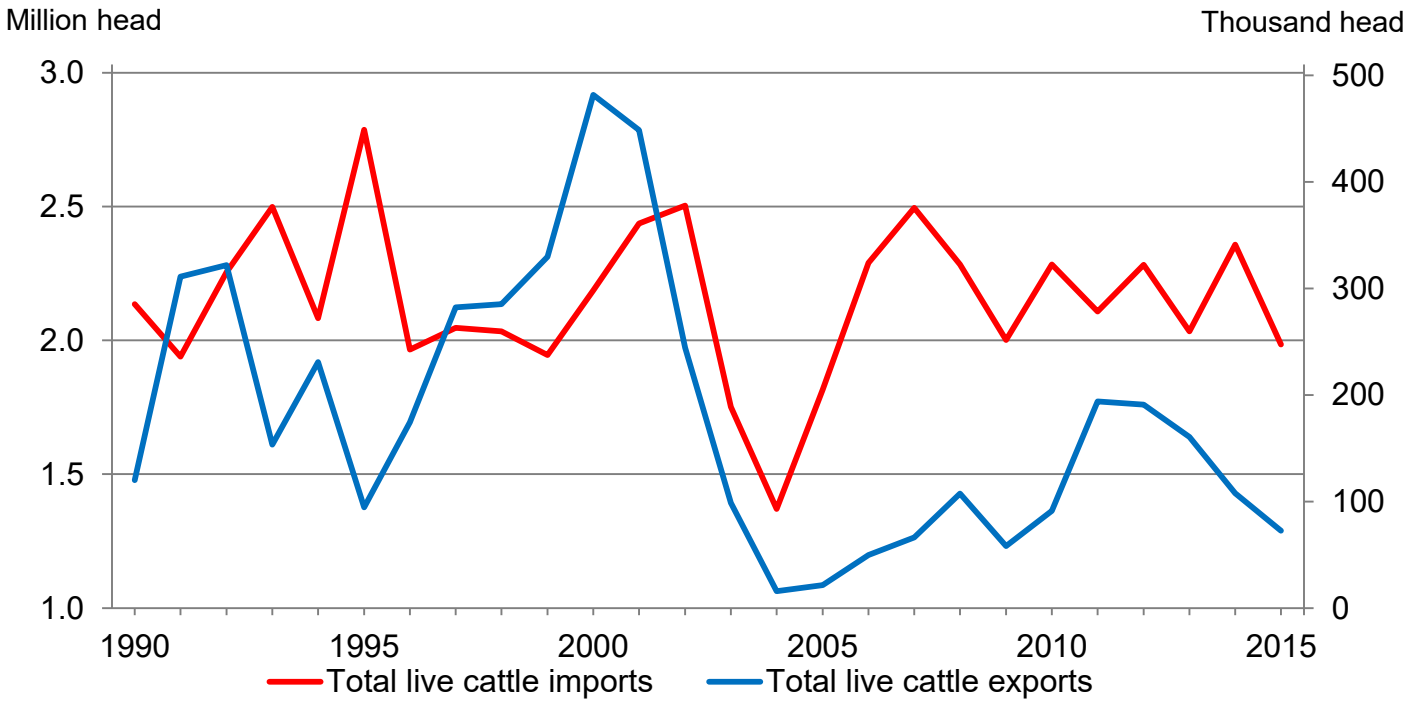

Source: ERS

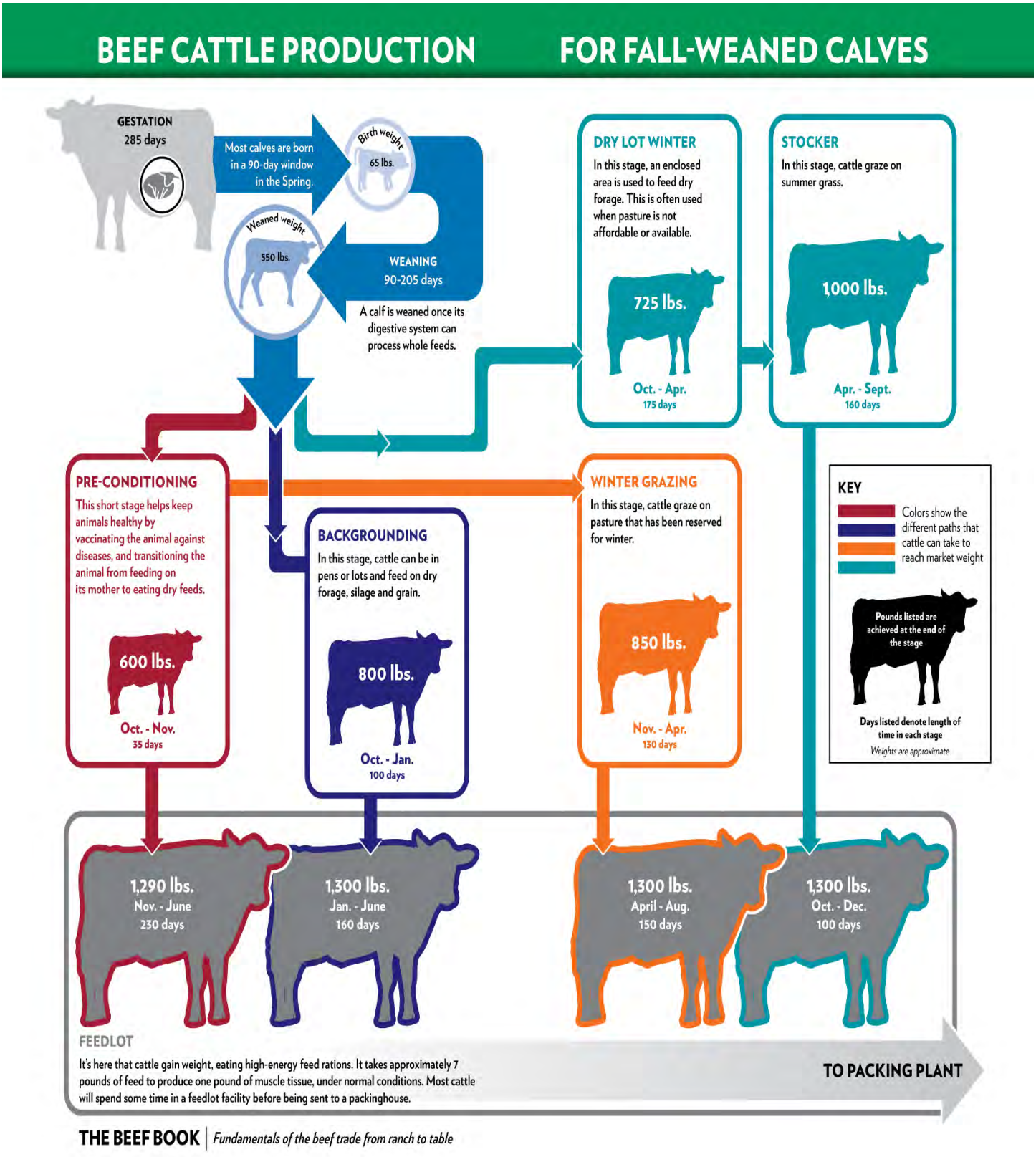
BEEF CATTLE PRODUCTION FOR FALL-WEANED CALVES
GESTATION
285 days
Most calves are born in a 90-day window in the Spring.
Birth weight
65 lbs.
Weaned weight
550 lbs.
WEANING
90-205 days
A calf is weaned once its digestive system can process whole feeds.
DRY LOT WINTER
In this stage, an enclosed area is used to feed dry forage. This is often used when pasture is not affordable or available.
725 lbs.
Oct. - Apr.
175 days
STOCKER
In this stage, cattle graze on summer grass.
1,000 lbs.
Apr. - Sept.
160 days
PRE-CONDITIONING
This short stage helps keep animals healthy by vaccinating the animal against diseases, and transitioning the animal from feeding on its mother to eating dry feeds.
600 lbs.
Oct. - Nov.
35 days
BACKGROUNDING
In this stage, cattle can be in pens or lots and feed on dry forage, silage and grain.
800 lbs.
Oct. - Jan.
100 days
WINTER GRAZING
In this stage, cattle graze on pasture that has been reserved for winter.
850 lbs.
Nov. - Apr.
130 days
KEY
Colors show the different paths that cattle can take to reach market weight
Pounds listed are achieved at the end of the stage
Days listed denote length of time in each stage
Weights are approximate
1,290 lbs.
Nov. - June
230 days
1,300 lbs.
Jan. - June
160 days
1,300 lbs.
April - Aug.
150 days
1,300 lbs.
Oct. - Dec.
100 days
FEEDLOT
It's here that cattle gain weight, eating high-energy feed rations. It takes approximately 7 pounds of feed to produce one pound of muscle tissue, under normal conditions. Most cattle will spend some time in a feedlot facility before being sent to a packinghouse.
TO PACKING PLANT
THE BEEF BOOK | Fundamentals of the beef trade from ranch to table

Drought Plays Role in United States Cattle Inventory Numbers

The following three maps, provided by the World Agriculture Outlook Board, give a visual of the drought experienced in the United States at the beginning of 2008, 2013, and the end of 2015 respectively. These maps use the NASS *Census of Agriculture* data, broken out by county. The counties in dark green, major cattle area, combine for 75 percent of the national inventory; the light green, minor cattle area, combined with the major cattle area for 99 percent of the national inventory. The tan counties combine for only 1 percent of the national cattle inventory, and the counties in gray contain data that had to be disclosed for confidential standards. The maps are derived from the United States Drought Monitor product, and more information about the Drought Monitor can be found at http://droughtmonitor.unl.edu.

January 1, 2008 was the first year of liquidation in the last cattle cycle with all cattle and calves at 96.0 million head, down 1 percent from 2007. At the beginning of 2008, 26 percent of the cattle inventory was within an area experiencing drought. Most of the drought being in the southeastern and western parts of the US. Just 5 years later, the level of cattle inventory experiencing drought jump up to 73 percent. January 1, 2013 all cattle and calves decreased 6 percent from the 96.0 million head in 2008 to 90.1 million head, with a liquidation happening each year. The largest liquidation came on January 1, 2012, with a 2 percent decrease.

January 1, 2015 (no map shown) is when there was a major break in the amount of inventory experiencing drought at just 29 percent. This is also the first year all domestic cattle and calves increased to 89.1 million head, up 1 percent from the previous year, beginning the current cattle cycle. In 2015 the west and southern plains were still experiencing a drought. On December 29, 2015 the drought was in areas that combined for only 12 percent of the inventory, all in the west. Correlated, the January 1, 2016 all cattle and calves increased 3 percent to 92.0 million head. The favorable weather conditions that the United States experienced during 2015, has increased the amount of available forage. In addition, 2015 saw an increase in the weight of steers and heifers being placed into feedlots with a capacity of 1,000 or more head.

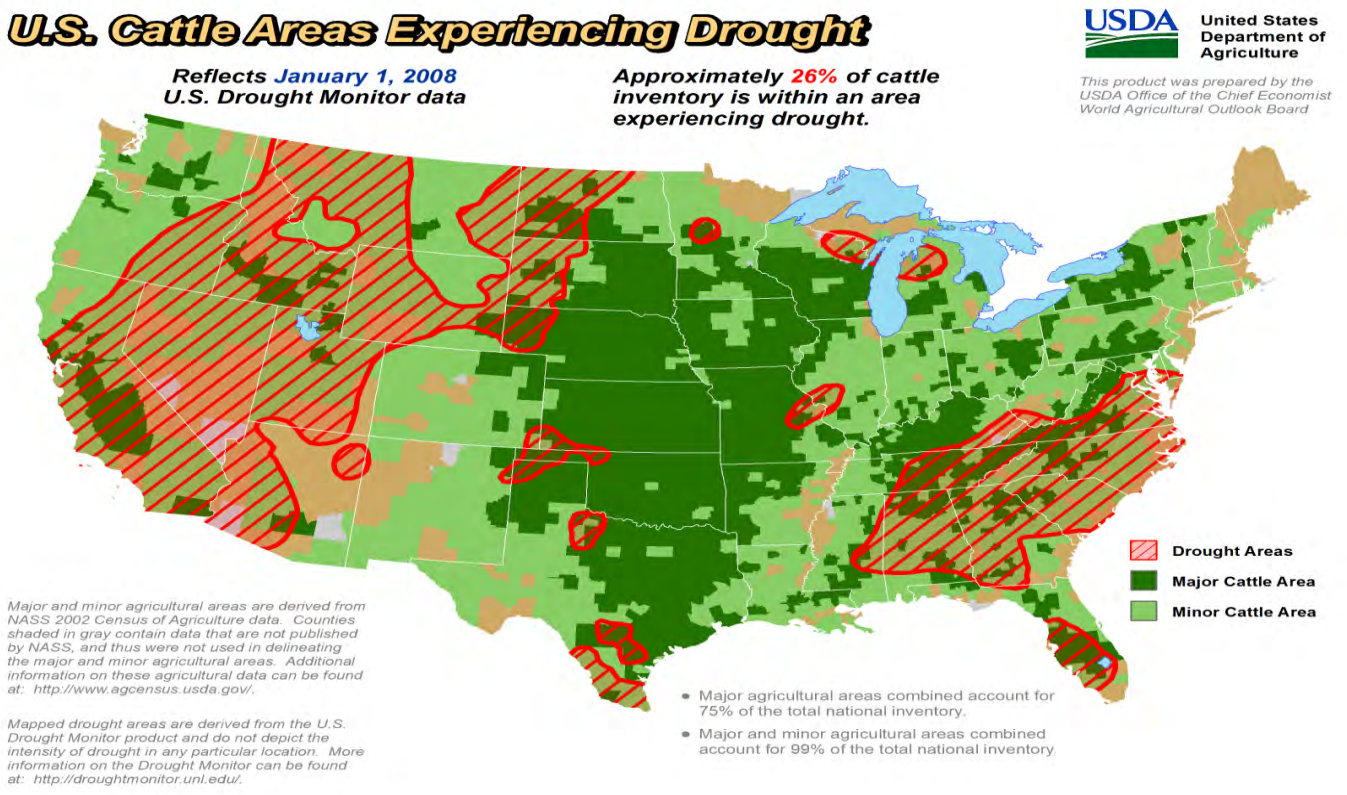

U.S. Cattle Areas Experiencing Drought

Reflects January 1, 2013
U.S. Drought Monitor data

Approximately 73% of the domestic cattle inventory is within an area experiencing drought, based on NASS 2007 Census of Agriculture data.

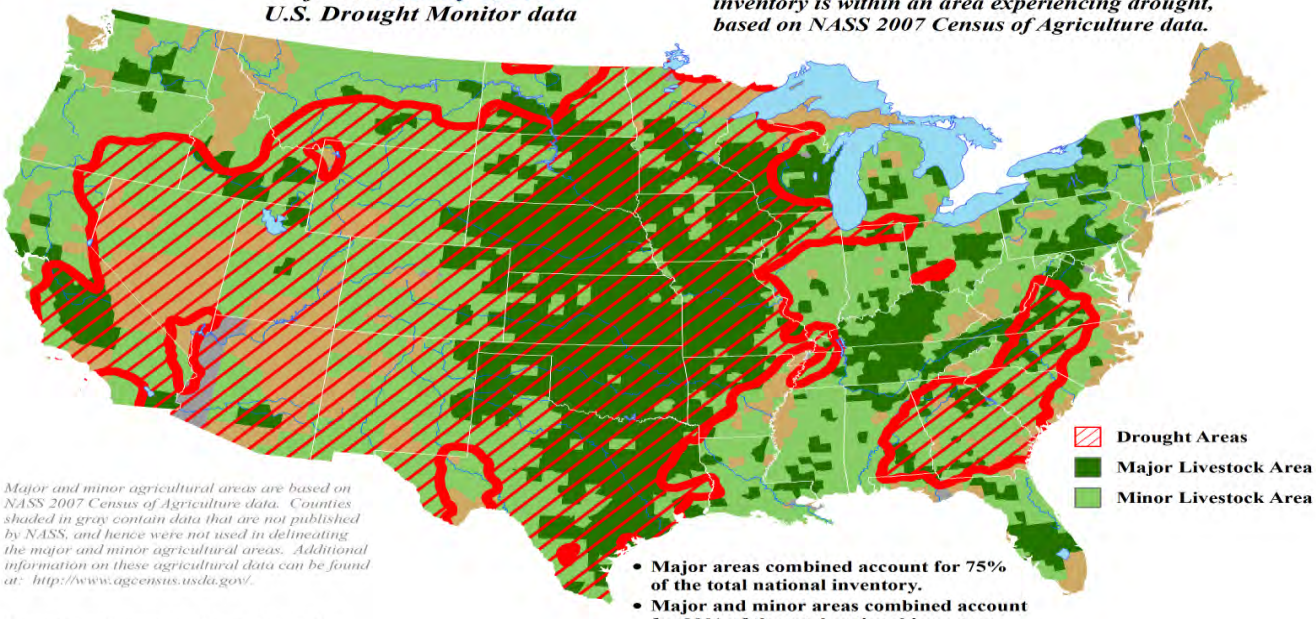

Major and minor agricultural areas are based on NASS 2007 Census of Agriculture data. Counties shaded in gray contain data that are not published by NASS, and hence were not used in delineating the major and minor agricultural areas. Additional information on these agricultural data can be found at: http://www.agcensus.usda.gov/.

Mapped drought areas are derived from the U.S. Drought Monitor product and do not depict the intensity of drought in any particular location. More information on the Drought Monitor can be found at: http://www.drought.unl.edu/dm/monitor.html.

- **Major areas combined account for 75% of the total national inventory.**
- **Major and minor areas combined account for 99% of the total national inventory.**

USDA **Agricultural Weather Assessments**
World Agricultural Outlook Board

U.S. Cattle Areas Experiencing Drought

USDA **United States Department of Agriculture**

This product was prepared by the USDA Office of the Chief Economist World Agricultural Outlook Board

Reflects December 29, 2015
U.S. Drought Monitor data

Approximately 12% of cattle inventory is within an area experiencing drought.

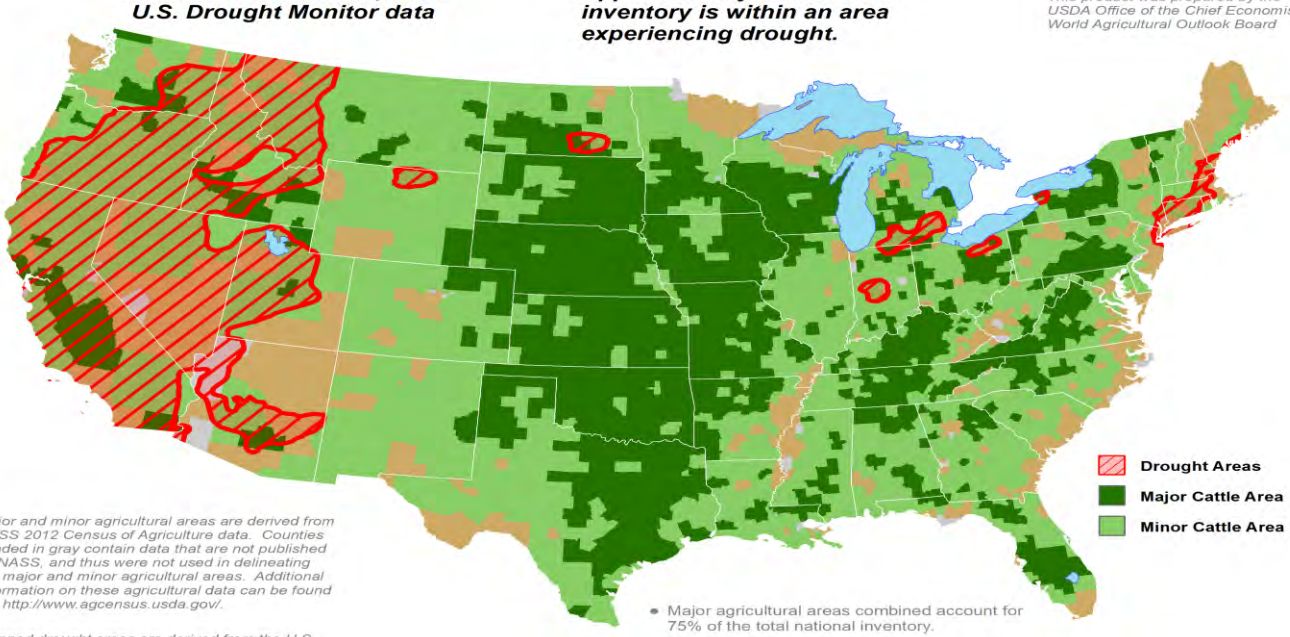

Major and minor agricultural areas are derived from NASS 2012 Census of Agriculture data. Counties shaded in gray contain data that are not published by NASS, and thus were not used in delineating the major and minor agricultural areas. Additional information on these agricultural data can be found at: http://www.agcensus.usda.gov/.

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- Major agricultural areas combined account for 75% of the total national inventory.
- Major and minor agricultural areas combined account for 99% of the total national inventory.

Lowest Placements in Feedlots with Capacity of 1,000 or More Head on Record

Placements for the slaughter market in feedlots with capacity of 1,000 or more head during 2015 was 20.4 million head, 5 percent below the 21.5 million head placed in 2014. Placements in 2015 were the lowest they have been since NASS began the monthly *Cattle on Feed* program in 1996. This was the fifth year in a row that placements were lower than the previous year.

The feeder supply is defined as the combined total of calves under 500 pounds and other heifers and steers over 500 pounds not in a feedlot. The feeder supply in 2016 was 25.9 million head, up 5 percent from 2015. This is the largest feeder supply since 2011. The percent of the feeder supply placed in feedlots with capacity of 1,000 or more head in 2015 was 83 percent, 2 percent below 2014. This marks the lowest percent placed in feedlots since 2009.

The number of heifers as a percent of the total cattle on feed inventory in the United States, for feedlots with capacity of 1,000 or more head, averaged 32 percent in the first two quarters of 2016. This is slightly below the annual average in 2015, when the number of heifers averaged 33 percent. This is the lowest percent of heifers since the series began in 1996. This correlates with 2016 having the largest increase in total cattle and calves in the United States since 1975.

As placements for 2015 were the lowest on record since the series began in 1996, there was a record high number of cattle placed weighing 800 or more pounds. In 2015 the number of placements weighing 800 or more pounds in feedlots with 1,000 head or more capacity was 7.41 million head, 36 percent of total placements. This is also 7 percent larger than each of the previous 2 years, with 2013 being the second largest number of placements weighing 800 or more pounds since the series began in 1996. On the other hand the number of placements in the middle two weight groups, 600–699 pounds and 700–799 pounds, had the lowest number of placements and percent of placements since the series began in 1996. The number of placements of cattle weighing 600 pounds or less in 2015 was 4.79 million head, 23 percent of total placements. This is slightly below the average percent of cattle placed weighing less than 600 pounds.

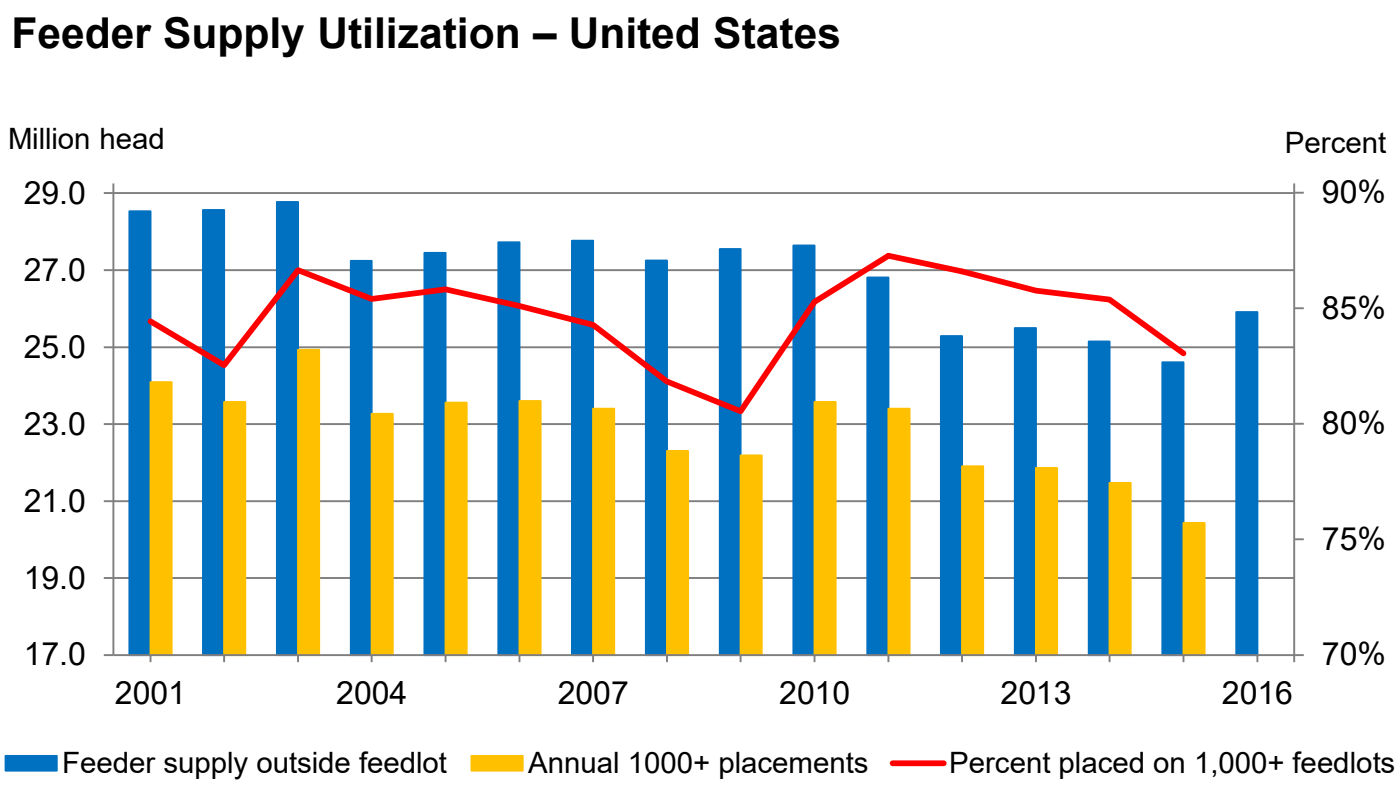

Heifer Annual Average Percent of 1,000+ Cattle on Feed Inventory – United States

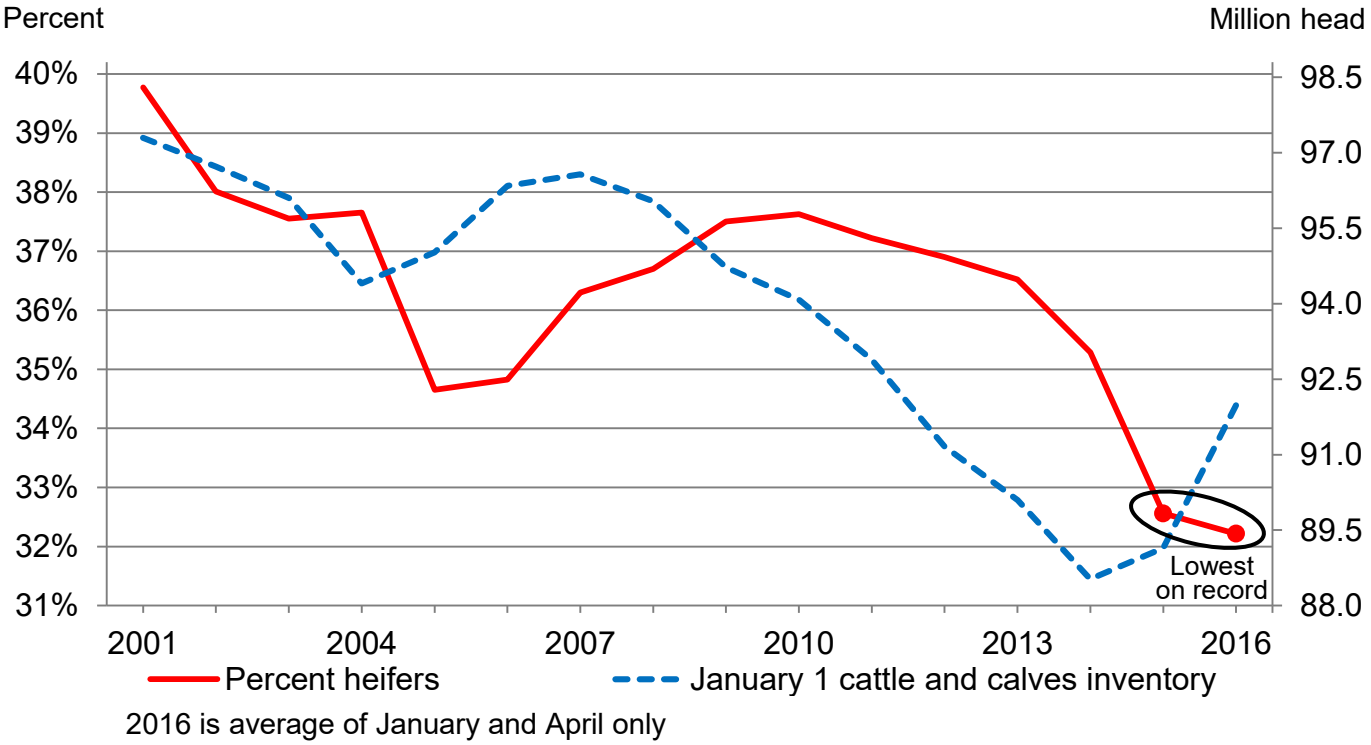

2016 is average of January and April only

Annual Cattle on Feed 1,000+ Total Placements by Weight Group – United States

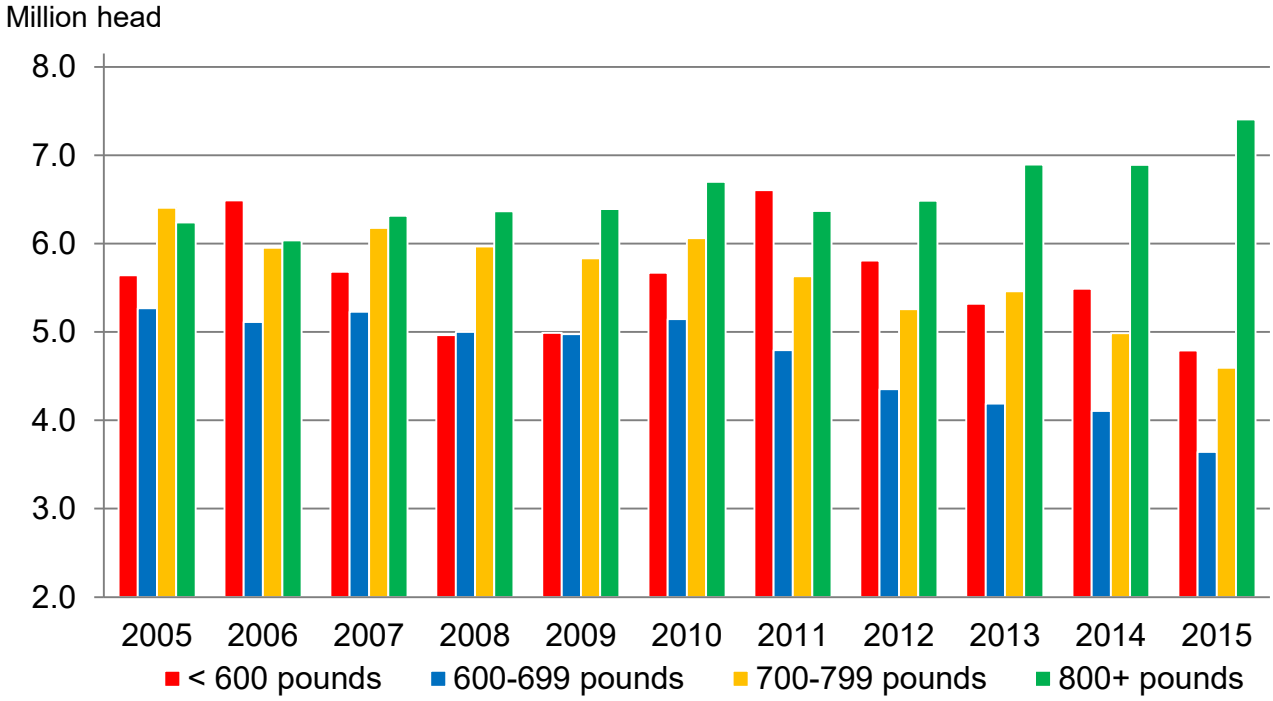

Cattle Average Dressed Weight Largest on Record

Cattle slaughtered in federally inspected plants averaged an 829 pound carcass weight, up 21 pounds from just a year ago. This is the fourth year in a row cattle dressed weights have seen an increase. The average dressed weight for steers in 2015 was 892 pounds, up 2 percent from 872 pounds in 2014. This is the largest increase since 2002, when the average dressed weight for steers jumped up 3 percent. Heifers also saw an increase in the average dressed weight, 818 pounds in 2015 compared to 800 pounds in 2014. United States live cattle averaged 1,364 pounds with a dressing percentage of 61 percent, up slightly from last year. The total number of cattle slaughtered in the United States in 2015 was 28.8 million head, down 5 percent from 2014. Of the total cattle slaughtered, 28.3 million head (98 percent) were slaughtered at federally inspected plants, with 455 thousand slaughtered in non-federally inspected (NFI) plants, and 91.4 thousand slaughtered on farms.

In 2015 the total number of cows and heifers slaughtered at federally inspected plants were 12.5 million head, 44 percent of the total cattle slaughtered at federally inspected plants which was down 2 percent from 2014. This was the fifth consecutive year there was a decline in the number of females slaughtered. The percent of females slaughtered in 2015 was also the lowest percent of total slaughter since 1974, and in 2016 there was the largest percent increase in cattle inventory since 1975. Historically, if the percent of heifers slaughtered is below 47 percent, there is an increase in the number of total cattle and calves on January 1.

The total number of calves weighing less than 500 pounds that were slaughtered in commercial slaughter plants in the United States in 2015 was 453 thousand head, down 20 percent from the previous year. This equated to 1 percent of the calf crop, which is the lowest on record, down slightly from the percent slaughtered in 2014. This is the seventh year in a row that the number of calves and second year in a row that the percent of calf crop slaughtered decreased.

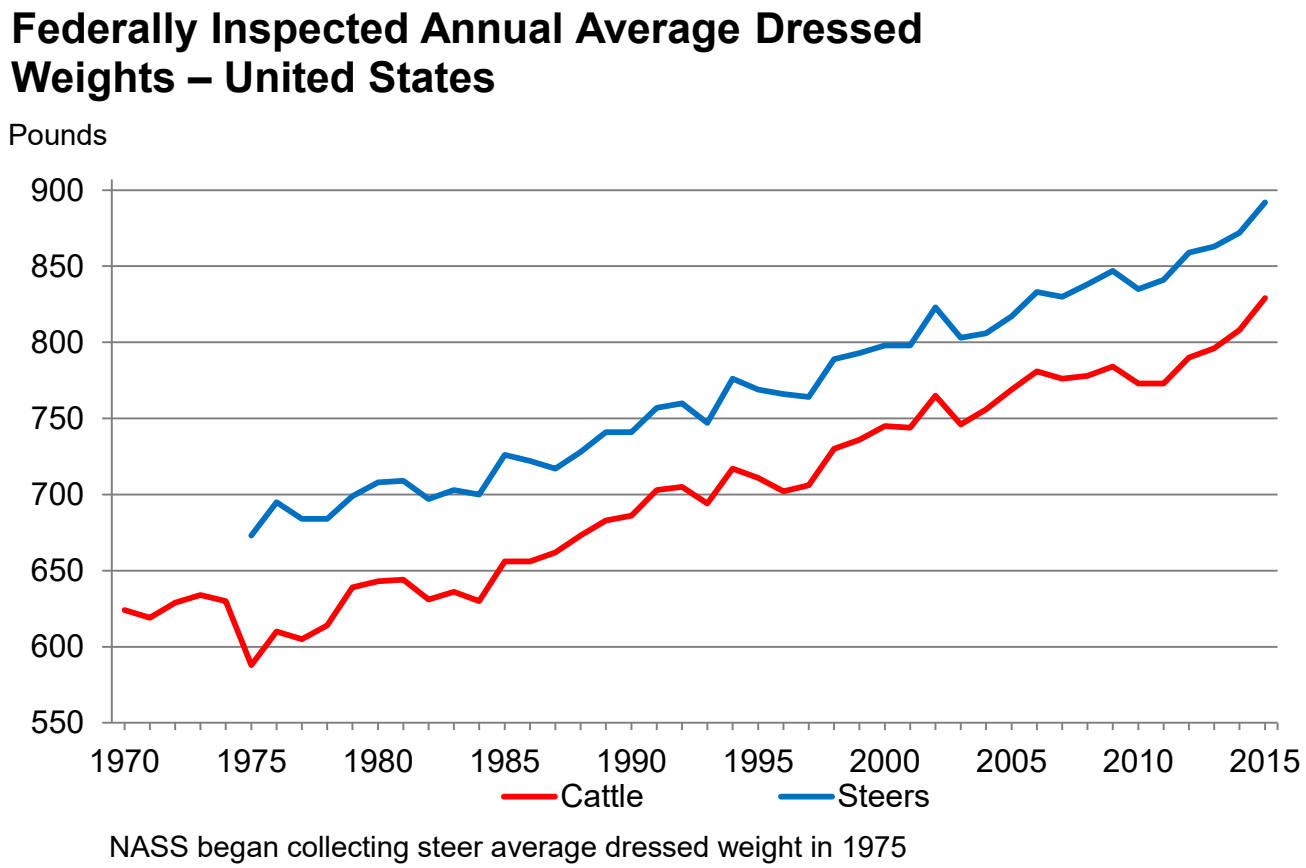

Annual Cow and Heifer Slaughter as a Percent of Total Federally Inspected Slaughter – United States

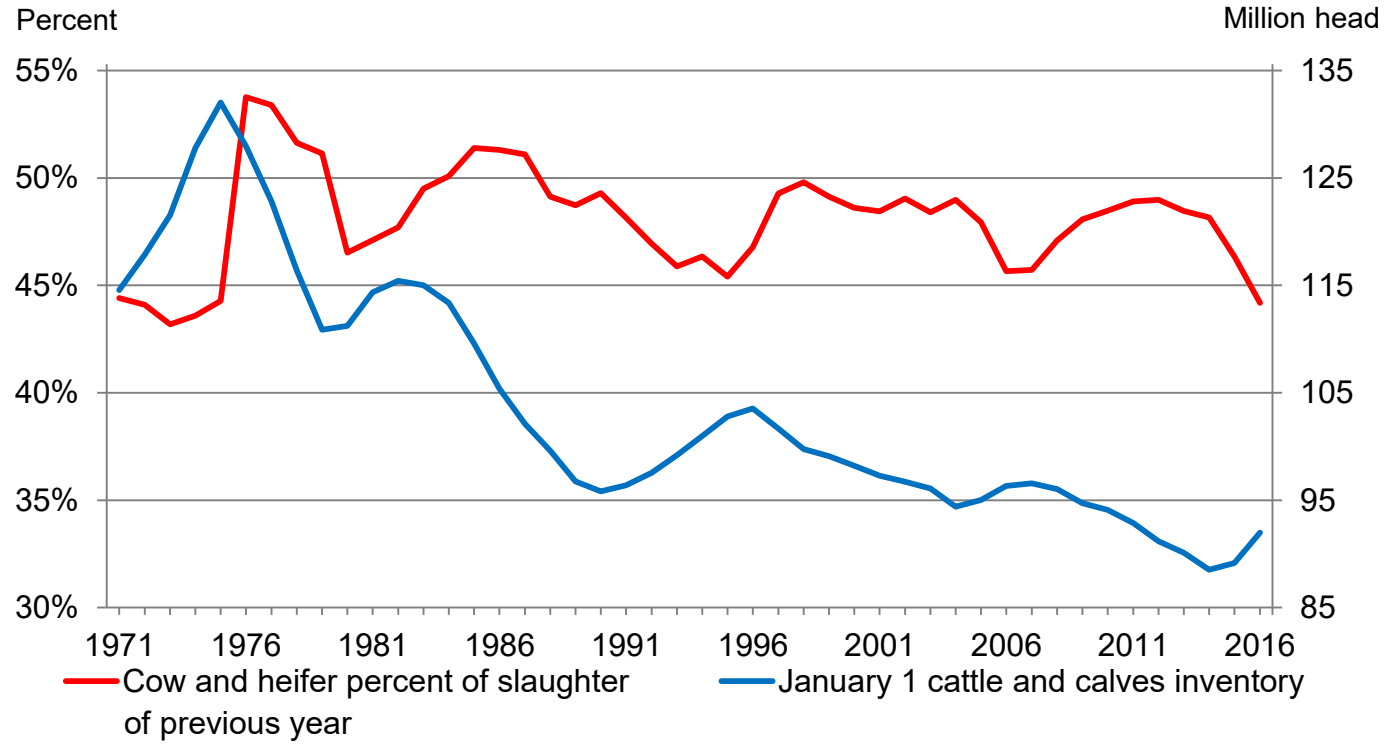

Commercial Calf Slaughter as a Percent of Calf Crop – United States

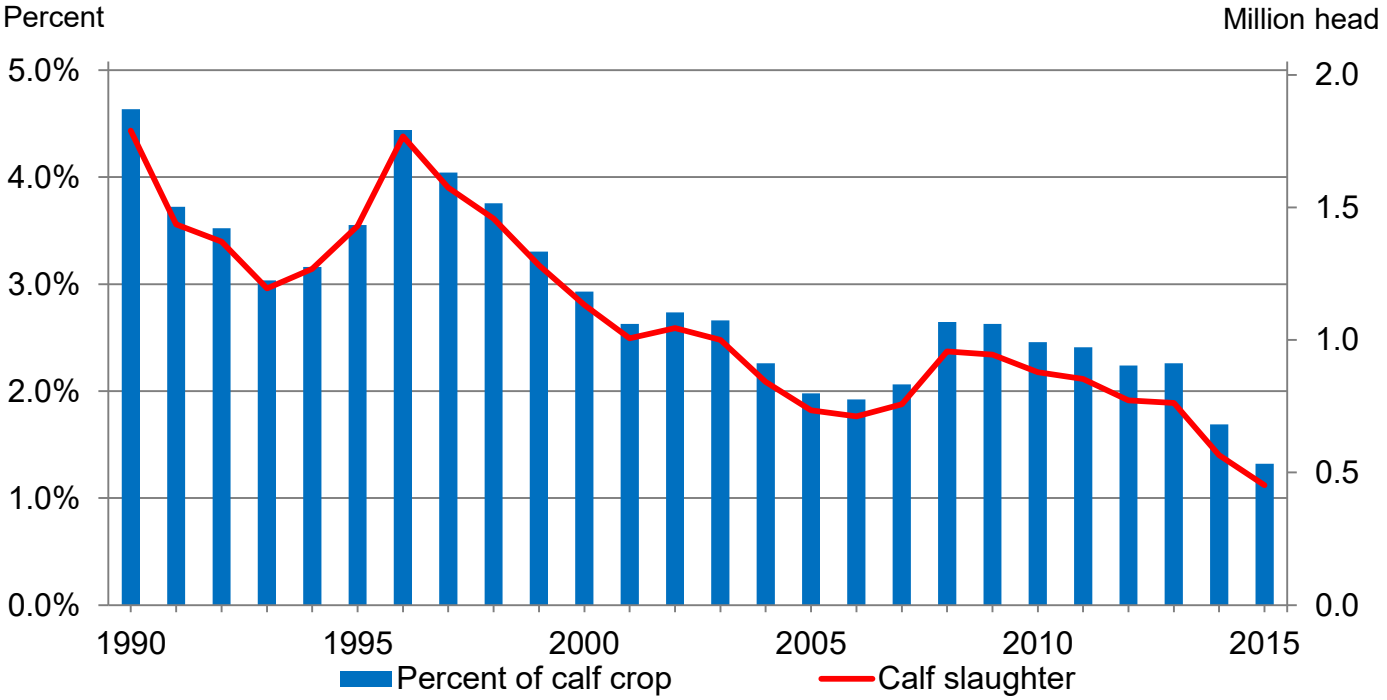

Cattle Operations Average Size Decreased in 2012

The 2012 *Census of Agriculture* showed cattle operations decreasing in size per operation; an average of 98.5 head of all cattle and calves in 2012, compared to 100 head of all cattle and calves in 2007. This is the opposite of what happened from 1997 to 2007, when the average cattle operation grew 15.9 head from an average 84.1 head of all cattle and calves in 1997. The number of all cattle operations as of 2012 was 913 thousand operations, 5 percent below the 964 thousand operations in 2007. Mirroring this trend, the number of beef cow operations in 2012 was 728 thousand, a 5 percent decline from the 765 thousand operations in 2007.

In 2012, operations with 1,000 or more head of all cattle and calves totaled 33.2 million head, 36.9 percent of all cattle and calves. The number of operations with 1,000 head or more of all cattle and calves in 2012 was 10.5 thousand, just 1 percent of the total number of operations. In 2002 and 2007 the operations with 1,000 head of all cattle and calves were 29.5 and 34.2 percent of inventory respectively. The opposite was true for beef cow operations. In 2012, operations with less than 50 head of beef cows totaled 8.63 million head, 29.8 percent of total beef cows. The number of operations with less than 50 head of beef cows was 594 thousand operations, 82 percent of the total number of beef cows. In 2002 and 2007 the operations with less than 50 head of beef cows represented 30.1 and 28.7 percent of inventory respectively.

In 2015 the number of feedlots with 1,000 head or more capacity was 2.19 thousand, just 9 feedlots less than in 2005. Looking at the breakout by size, the number of feedlots with 1,000 to 7,999 head capacity decreased 11 lots from 1,751 lots in 2005 to 1,740 lots in 2015. The United States gained two lots with a capacity of 32,000 head or more from 126 lots in 2005 to 128 lots in 2015. The lots with capacity of 32,000 head or more as of January 1, 2016 had 5.56 million head, 53 percent of all cattle on feed in lots with 1,000 head or more capacity, up from 48 percent of all cattle on feed in 2005. Feedlots with 1,000 head or more capacity combined for a total capacity of 16.9 million head in 2016, up 100 thousand head from 2006.

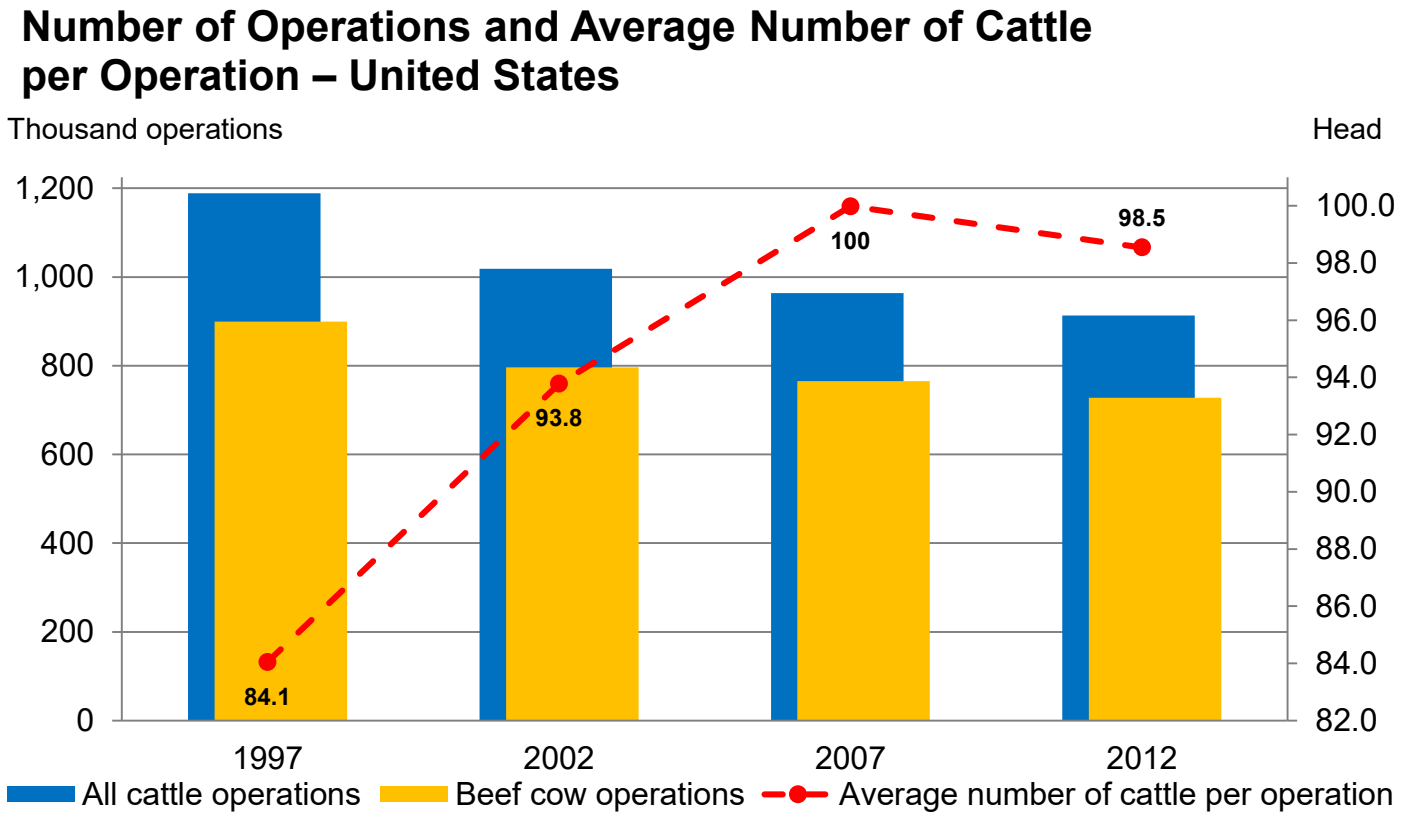

Percent of Inventory by Operation Size – United States

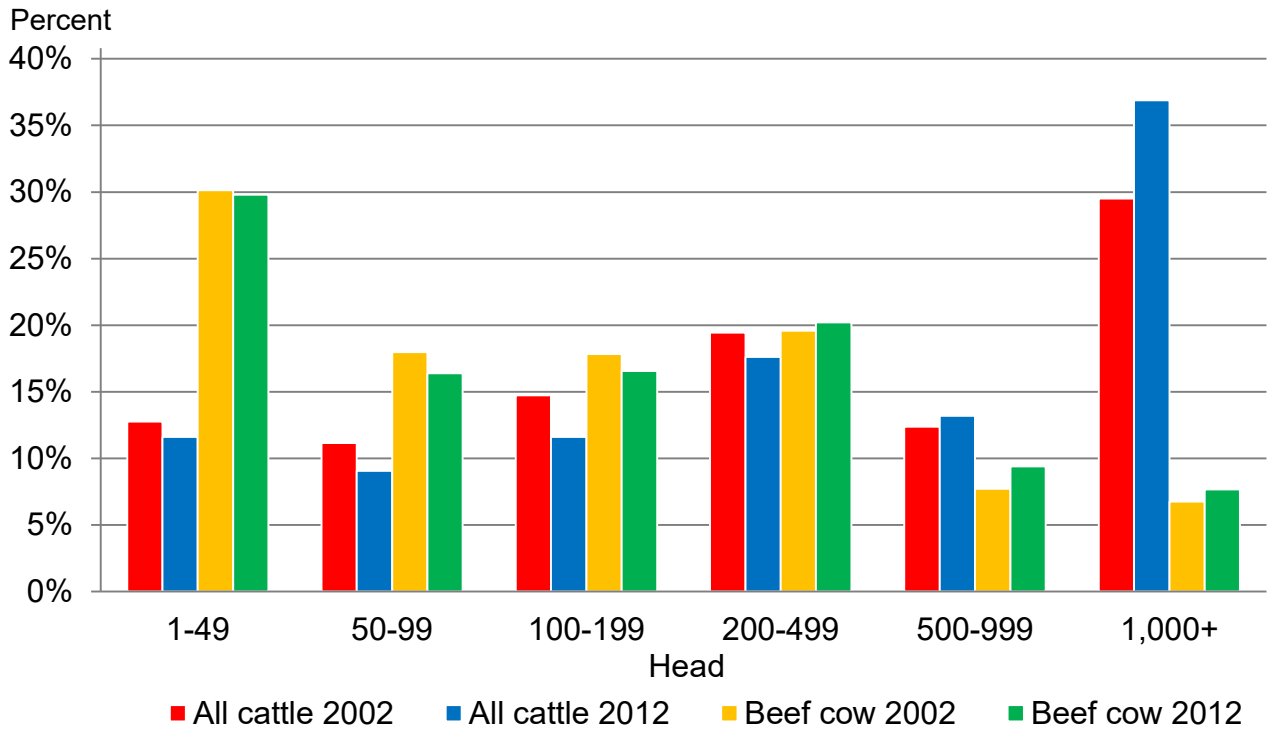

Number of Feedlots and January 1 Inventory by Capacity – United States

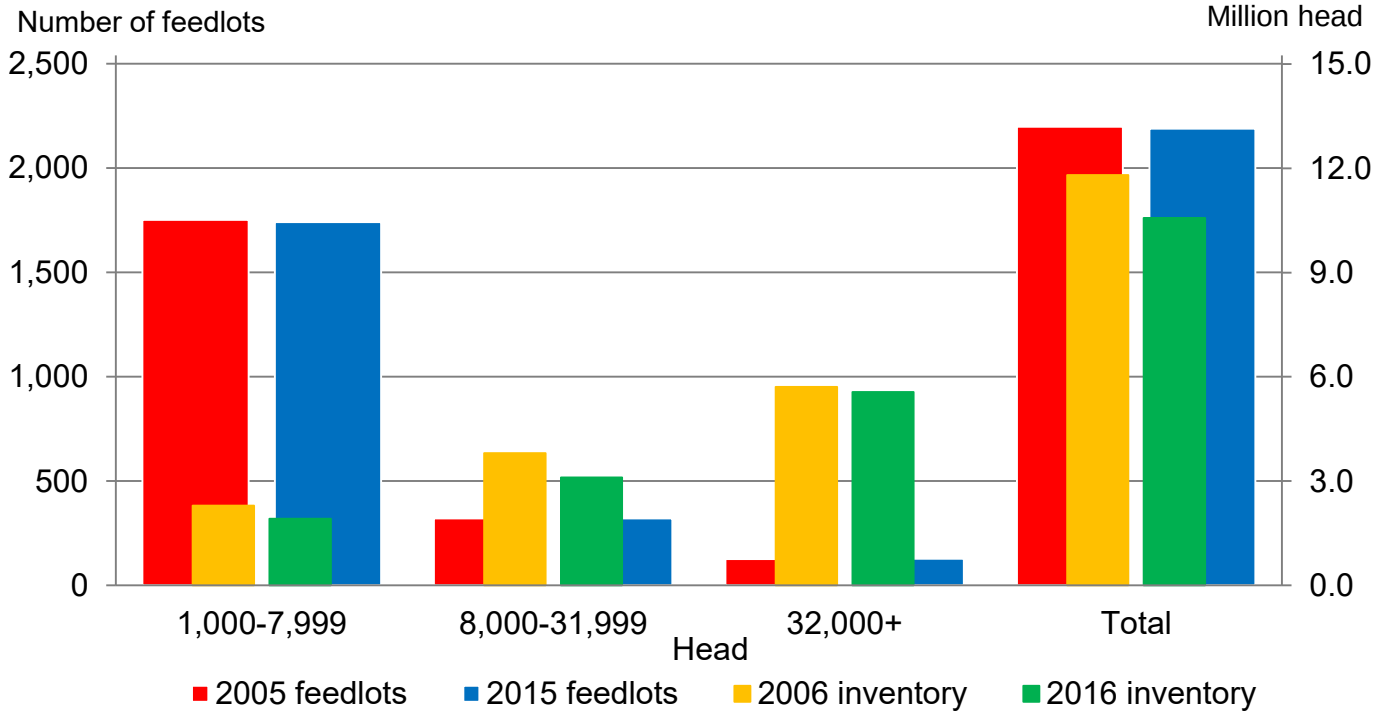

Statistical Methodology: Cattle

Survey Procedures: For the January and July *Cattle* report a random sample of United States producers were surveyed to provide data for these estimates. Survey procedures ensured that all cattle producers, regardless of size, had a chance to be included in the survey. Large producers were sampled more heavily than small operations.

A random sample of roughly 50,000 United States producers is surveyed during the first half of January to provide data for the January *Cattle* report. Data is collected by mail, telephone, and face-to-face personal interviews. For the July survey, data is collected during the first half of June from about 40,000 small and medium sized operations. These operators were contacted by face-to-face personal interviews. About 10,000 large producers and feedlots were contacted during the first half of July by mail, telephone, and face-to-face personal interviews. Regardless of when operations are surveyed, they are asked to report inventories as of the first of the month. Usable reports for both the January and July surveys average about 74 percent.

Estimating Procedures: These cattle estimates were prepared by the Agricultural Statistics Board after reviewing recommendations and analysis submitted by Regional Field Offices. National and State survey data were reviewed for reasonableness with each other and with estimates from the previous year using a balance sheet. The balance sheet begins with the previous inventory estimate, adds estimates of births and imports, and subtracts estimates of slaughter, exports, and deaths. This indicated ending inventory level is compared to the Agricultural Statistics Board estimate for reasonableness.

Revision Policy: Revisions to previous estimates are made to improve year to year and item to item relationships. Estimates for the previous year are subject to revision when current estimates are made. The reviews are primarily based on livestock slaughter and additional foreign trade and survey data. Estimates will also be reviewed after data from the five-year *Census of Agriculture* are available. No revisions will be made after that date.

Reliability: Since all cattle operators are not included in the sample, survey estimates are subject to sampling variability. Survey results are also subject to non-sampling errors such as omissions, duplications, and mistakes in reporting, recording, and processing the data. The effects of these errors cannot be measured directly. They are minimized through rigid quality controls in the data collection process and through a careful review of all reported data for consistency and reasonableness.

To assist users in evaluating the reliability of estimates in January and July *Cattle*, and monthly *Cattle on Feed* report, the "**Root Mean Square Error**" is shown for selected items in each report. The "Root Mean Square Error" is a statistical measure based on past performance and is computed using the differences between first and latest estimates. The "Root Mean Square Error" for the January 1 cattle inventory estimates over the past 10 years is 0.6 percent. This means that chances are 2 out of 3 that the final estimate will not be above or below the January 1, 2016 estimate of 92.0 million head by more than 0.6 percent. Chances are 9 out of 10 that the difference will not exceed 1.1 percent.

Statistical Methodology: Cattle on Feed

Survey Procedures: During January and July all known feedlots in the United States with capacity of 1,000 or more head are surveyed to provide data for cattle on feed estimates. During the other months, all known feedlots from 16 States are surveyed. The 16 States account for approximately 98 percent of the cattle on feed in feedlots with capacity of 1,000 or more head. Individual State estimates are published monthly for 12 of the 16 States. Data collected from the remaining 4 States are used to establish the "Other States" estimates. These 4 States include Illinois, New Mexico, Oregon, and Wyoming. The "Other States" category represents all cattle on feed with a capacity of 1,000 or more head for the rest of the United States.

Estimating Procedures: These cattle on feed estimates were prepared by the Agricultural Statistics Board after reviewing recommendations and analysis submitted by Regional Field Offices. Regional and State survey data were reviewed for reasonableness with each other and with estimates from the previous month when establishing the current estimates.

Estimates Published: The monthly *Cattle on Feed* report includes estimates of total cattle on feed, placements, marketings, and other disappearance. Estimates are published monthly for the United States as well as 12 of the 16 Survey States. These states include Arizona, California, Colorado, Idaho, Iowa, Kansas, Minnesota, Nebraska, Oklahoma, South Dakota, Texas, and Washington. Data collected from the remaining 4 States are used to establish the "Other States" estimates. Placement weight estimates are published for the United States as well as the 4 major states. These states include Colorado, Kansas, Nebraska, and Texas.

In January, April, July, and October the *Cattle on Feed* report includes class estimates of steers and heifers currently on feed for the 12 published states and the United States. The February 1 report includes all previous year estimates and revisions as well as United States level size group and annual fed cattle marketing estimates.

Revision Policy: Revisions to previous estimates are made to improve month to month relationships. Estimates for the previous month are subject to revision in all States each month when current estimates are made. In February, all monthly estimates for the previous year, and the number of feedlots and annual marketings from two years ago are reviewed and subject to revisions. The reviews are primarily based on slaughter data, state check-off or brand data, and any other data that may have been received after the original estimate was made. Estimates will also be reviewed after data from the *Census of Agriculture* are available. No revisions will be made after that date and estimates become final.

Reliability: Since all 1,000+ capacity cattle on feed operators in every State are not included in the monthly survey, survey estimates are subject to sampling variability. Survey results are also subject to non-sampling errors such as omissions, duplications, and mistakes in reporting, recording, and processing the data. The effects of these errors cannot be measured directly. They are minimized through rigid quality controls in the data collection process and through a careful review of all reported data for consistency and reasonableness.

Cattle Terms and Definitions

Backgrounded cattle are steers and heifers that are fed a warm up or conditioning ration are normally fed to approximately 700 pounds, and then sold as feeders or shipped to another feedlot to be finished for the slaughter market.

Bull is an uncastrated male bovine animal that weighs more than 500 pounds.

Calf is any animal less than 1 year old. Calves by NASS survey classification are animals that weigh less than 500 pounds.

Cattle cycle is a period of time in which the number of beef cattle in the Nation is alternately expanded and reduced for several consecutive years in response to perceived changes in the profitability of beef production.

Cattle on feed are steers and heifers being fed a ration of grain, silage, hay and/or protein supplement for slaughter market that are expected to produce a carcass that will grade select or better. It excludes cattle being "backgrounded only" for later sale as feeders or later placement in another feedlot.

Commercial feedlot is a feedlot whose primary enterprise is to feed cattle and market them for slaughter.

Cow is a female bovine animal that has borne at least one calf.

Farmer/Feeder is an operator who typically farms and feeds cattle on the same operation. The cattle feeding part of his/her operation is usually worked around the farming, e.g., feeding cattle before or after crops are planted/harvested, grazing stalks, etc. To be included as cattle on feed, cattle must go from the operation directly to slaughter.

Feeder supply is defined as the combined total of calves under 500 pounds and other heifers and steers over 500 pounds not in a feedlot.

Feedlot capacity is the maximum number of cattle that an operator can feed at any one time during the year. Feedlot capacity is the common terminology used by commercial and custom feedlots.

Heifer is a female bovine animal that has not calved and weighs more than 500 pounds.

Marketings are steers and heifers shipped out of feedlots to a slaughter market.

Net placements are placements minus other disappearance. This gives a true indication of actual placements into feedlots for the month.

Other disappearance includes death loss, movement from feedlots to pasture, and shipments to other feedlots for further feeding.

Other heifer is a heifer that will not be bred or used as a replacement animal for the beef or milk herd.

Placements are steers and heifers put into a feedlot, fed a ration which will produce a carcass that will grade select or better, and are intended for the slaughter market.

Replacement heifer is a heifer that has been selected to be bred and placed in the beef or milk herd.

Steer is a castrated male bovine animal that weighs more than 500 pounds.

Stockers and feeders are young steers or heifers, weighing approximately 400-800 pounds. These animals may be on pasture and/or a maintenance or warm-up ration until being put on full feed for slaughter market or being selected as herd replacement stock. However, if these stocker/feeders are being fed to be marketed directly to slaughter from a particular feedlot, they should be included as cattle on feed.

Information Contacts

Listed below are the commodity specialists in the Livestock Branch of the National Agricultural Statistics Service to contact for additional information. E-mail inquiries may be sent to nass@nass.usda.gov.

Dan Kerestes, Chief, Livestock Branch ..... (202) 720-3570

Scott Hollis, Head, Livestock Section ..... (202) 690-2424
Sherry Bertramsen – Livestock Slaughter ..... (202) 720-3240
Doug Bounds – Hogs and Pigs ..... (202) 720-3106
David Colwell – Sheep and Goats ..... (202) 720-8784
Donnie Fike – Dairy Products ..... (202) 690-3236
Michael Klamm – Cattle, Cattle on Feed ..... (202) 720-3040
Mike Miller – Milk Production and Milk Cows ..... (202) 720-3278

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USDA Updates Livestock Disaster Payment Rate to Assist Producers Hard-Hit by Heat and Humidity

fsa.usda.gov/news-events/news/08-25-2023/usda-updates-livestock-disaster-payment-rate-assist-producers-hard-15

News Release

|
Oregon

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Release Date

August 25, 2023

WASHINGTON, Aug. 25, 2023 – The USDA's Farm Service Agency (FSA) announced today it is updating the Livestock Indemnity Program (LIP) payment rate to support livestock producers in the Midwest who have lost cattle to the extreme heat and humidity experienced this summer. To help indemnify ranchers to reflect a trend towards higher cattle weights in feedlots, the 2023 LIP payment rate for beef calves over 800 pounds will increase from $1244 per head to $1618, an increase of $374.

"The recent heat domes plaguing many parts of the country have proven to be unsurvivable for some animals and temperatures are not expected to let up any time soon. This is one of the latest, many examples of how a changing climate is creating immediate challenges for farmers and ranchers, and we're finding that our emergency relief programs need to adapt accordingly," said FSA Administrator Zach Ducheneaux. "Given these circumstances and the trend towards higher weights in feedlots, it became clear that USDA's Livestock Indemnity Payment rates were not reflective of the true market value for cattle. This change will better indemnify the investments producers have in the livestock they raise, and we will continue to find flexibilities where possible to help our farmers and ranchers in the wake of climate-related impacts."

LIP provides benefits to livestock owners and some contract growers for livestock deaths exceeding normal mortality from eligible adverse weather events, certain predation losses and reduced sales prices due to injury from an eligible loss. Indemnity payments are made at a rate of 75% of the prior year's average fair market value of the livestock.

The updated LIP payment rate is effective immediately and will be applied retroactively starting Jan.1, 2023, for all eligible causes of loss including excessive heat, tornado, winter storms, and other qualifying adverse weather. Producers who have already received LIP payments for 2023 losses will receive an additional payment, if applicable, commensurate with this updated rate. For details on eligibility and payment rates, review the LIP fact sheet.

FSA recognizes that an annual update of LIP payment rates does not account for the volatile nature of livestock markets and is further exploring flexibilities to establish more current payment rates.

More Information

On farmers.gov, the Disaster Assistance Discovery Tool, Disaster Assistance-at-a-Glance fact sheet, and Loan Assistance Tool can help producers and landowners determine program or loan options. For assistance with a crop insurance claim, producers and landowners should contact their crop insurance agent. For FSA and NRCS programs, they should contact their local USDA Service Center.

USDA touches the lives of all Americans each day in so many positive ways. In the Biden-Harris administration, USDA is transforming America's food system with a greater focus on more resilient local and regional food production, fairer markets for all producers, ensuring access to healthy and nutritious food in all communities, building new markets and streams of income for farmers and producers using climate smart food and forestry practices, making historic investments in infrastructure and clean energy capabilities in rural America, and committing to equity across the Department by removing systemic barriers and building a workforce more representative of America. To learn more, visit usda.gov.

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Health Effects from Breathing Air Near CAFOs for Feeder Cattle or Hogs

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Health Effects from Breathing Air Near CAFOs for Feeder Cattle or Hogs

Susanna G. Von Essen, MD, MPH
Brent W. Auvermann, PhD

ABSTRACT. There is concern that livestock operations for fattening cattle and raising hogs known as concentrated animal feeding operations (CAFOs) release substances into the air that have negative effects on the health of persons living nearby. These substances include dust containing endotoxin and other microbial products as well as ammonia, hydrogen sulfide and a variety of volatile organic compounds. Odors from these farms are considered offensive by some neighbors. A variety of medical complaints are reported to be more common in those people who live near CAFOs for raising hogs than in people without this exposure. Respiratory health effects, including symptoms of pulmonary disease and lung function test result abnormalities, have been described in workers employed in CAFOs where hogs are raised. Health effects after inhalation exposure of neighbors to substances released into the ambient air from these farms is less well characterized. It must be noted that CAFO workers may differ from neighbors in terms of their exposures and general health status. The presence of dust and other substances from cattle feedlots also causes some neighbors to voice concerns about the impact on their health but this exposure has been studied less extensively than exposure to substances released from CAFOs where hogs are raised. Further research needs to be done to look for measurable health effects attributable to living near all CAFOs in order to better understand the impact of these farms. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-HAWORTH. E-mail address: <docdelivery @haworthpress.com> Website: <http://www.HaworthPress.com> © 2005 by The Haworth Press, Inc. All rights reserved.]*

KEYWORDS. Concentrated animal feeding operations, endotoxin, organic dust, hog dust, cattle feedlots, respiratory health

INTRODUCTION

Increasing numbers of cattle and hogs are raised or fattened in intensive livestock operations in North America, Europe and elsewhere. Some people who live near these farms have voiced concerns about human health effects from exposures related to their presence, particularly hog confinement facilities and cattle feedlots.[1,2] There has been a great deal of public debate about the medical, economic and social impacts of this type of livestock farming. Also, the possible impact on human health of these operations has been the focus of a number of research studies.

Intensive livestock operations are often known as concentrated animal feeding operations (CAFOs). CAFOs, and their smaller rela-

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tives, animal feeding operations (AFOs) are defined by the U.S. Environmental Protection Agency (EPA) according to the total number and liveweight of the herd on feed.[3] The majority of the information published about human health effects from breathing the air in and near CAFOs comes from studies conducted on persons who work inside hog confinement barns. Some respiratory conditions and related health problems are more common in these workers than in the general population. As this complex topic is discussed, care must be taken to avoid drawing conclusions about the nature or extent of neighborhood human health effects using only what is known about occupational health problems seen in CAFO employees. For example, hog odor can be quite apparent in the neighborhood as well as inside the barns. However, one cannot assume that the neighborhood exposure is sufficient to cause the same health effects that some workers experience. Assumptions should not be made about neighborhood human health effects from measuring the impact on air quality without (1) directly assessing those effects and (2) measuring the air-quality parameters thought to be associated with them.

The presence of excessive airborne dust in the air is the concern raised most often by persons living near cattle feedlots. Identifying and understanding the human health effects of living near feedlots are complicated by the fact that neither the occupational health effects in feedlot workers nor the neighborhood health effect of these facilities has been formally studied. This paper reviews neighbor health and worker effects of airborne emissions from hog and cattle CAFOs.

THE HOG CONFINEMENT BARN ENVIRONMENT

Hog confinement facilities are buildings in which the hogs spend their entire lives. They are given a feed that consists of ground grain and soybeans. The animal waste is typically flushed out with water, the manure slurry collected and usually stored under anaerobic conditions in one of several possible structures: a pit below the concrete floor of the building, a lagoon, or in a deep basin. This manure slurry is applied to the land as a fertilizer at a later date. Hog confinement barns are complex environments from an air quality perspective. Dust collected within the barns consists largely of feed components but also contains swine fecal matter and dander, bacteria and molds.[4] More than 330 volatile organic compounds and fixed gases have been described from swine facilities using gas chromatography and mass spectroscopy.[5] Most of the gases are present in very low amounts and likely contribute only to the characteristic odor associated with swine confinement operations. Respiratory symptoms in workers have been found to be associated with total and respirable dust concentrations, endotoxin in the dust and ammonia measured in the air of the barns.[6,7,8,9]

Dust in swine confinement barns is rich in bacteria and other microbes.[10,11] Endotoxin is a highly inflammatory substance found within the external cell membrane of Gram negative bacteria, which are abundant in manure. Endotoxin is the substance that has been most consistently associated with impairment of lung function in workers.[12] The presence of ammonia results from metabolism of urea in hog urine by the enzyme urease. Available evidence suggests that dust, ammonia and endotoxin act together to cause the airway disorders described above, as reviewed elsewhere.[12] Concern has been raised in several states in the U.S. by concerned citizens about the human health effects in workers and neighbors of hydrogen sulfide, a malodorous gas that comes from anaerobic manure storage facilities as well as from a number of other sources, such as the petroleum industry.[1] Hydrogen sulfide is a very toxic gas when present in hog barns at high concentrations ($\geq$ 500 ppm by volume), which is an unusual event. Short-term exposures at this level have caused death in swine confinement workers. A severe, life-threatening exposure to hydrogen sulfide has also been associated with reactive airway dysfunction syndrome, a form of asthma, in a worker with heavy exposure to hydrogen sulfide.[13] However, published studies do not support the idea that hydrogen sulfide causes respiratory disease in persons working in hog confinement facilities under ordinary conditions, when the levels are in the range of 2-3 ppm or less.[5,14,15] Hydrogen sulfide levels in swine confinement barns do not appear to be predictors of respiratory outcomes in workers.[7]

The dust emitted from the barns has not been completely characterized and has not become the focus of regulation. In contrast, gases released from hog confinement barns and lagoons into the ambient air have received more attention. Hydrogen sulfide (H_2S) can be detected at the property line of these farms in some instances and has been the subject of current or proposed ambient air quality standards in more than half of the states in the U.S., including Minnesota, Nebraska and Iowa.[16,17] Ambient air quality standards for ammonia are likewise being considered in various livestock-producing areas of North America, most notably in the province of Alberta, Canada.[18] There is an ammonia standard in place in North Carolina that can be applied to production agriculture and several other states have ammonia standards as well.[19]

The regulation of odors from hog confinement facilities and other CAFOs is a controversial topic. Recently, a group of experts was unable to reach consensus concerning the control of odors from CAFOs.[20] Some experts favor specific air quality standards limiting airborne concentrations of odor, NH_3 or H_2S at the CAFO property line. Regulatory action at the state level might be similar to that which is used to enforce the National Ambient Air Quality Standard.[21] Others favor measuring odor at residences or in public-use areas and using dispersion modeling tools to factor in the impact of frequency, duration and concentration of exposure to odor at the residence, thereby avoiding extensive monitoring.

THE CATTLE FEEDLOT ENVIRONMENT

Cattle feedlots, as we are using the term, consist of outdoor unvegetated corrals or pens in which cattle are confined, fed and watered. Pens usually have unpaved, earthen surfaces on which manure excreted by the animals accumulates over time. In arid, semi-arid or temperate regions where long-term evaporation exceeds the sum of effective precipitation (rainfall or snowmelt that remains on the pen surface instead of running off) and the moisture excreted by the animals in manure and urine, the accumulating manure will dry out over time. If compacted by machinery or hoof action, this manure consolidates into a firm surface layer. Manure that is not well consolidated, however, becomes a reservoir of "parent material" for fugitive dust, which is generated and suspended in air primarily by the shearing action of the bovine hoof on the unconsolidated manure.[22] Because fugitive dust emissions from the feedlot surface are closely tied to animal behavior, and because cattle feedlots are typically open to the environment, concentrations of airborne dust downwind of feedlots vary both diurnally and seasonally.[23] Peak concentrations of feedlot dust generally coincide with the evening spike in cattle activity combined with neutral or stable atmospheric conditions at ground level.[23] Neutral or stable conditions are characterized by low wind speeds and little to no thermal mixing. These peak concentrations are known to decrease visibility on nearby roadways and to create nuisance conditions at downwind receptors.[24]

Ongoing research across the United States and Australia is confirming that the emission of odorous trace gases (e.g., volatile fatty acids, phenols, organic sulfides, amines, NH_3 and H_2S) from cattle feedlots is likewise episodic and is closely associated with rainfall events and warm temperatures. That association is a direct result of the incomplete, microbially mediated, temperature-dependent, anaerobic digestions that occurs when excessive moisture displaces oxygen from the pore space of the surface manure layer in a cattle feedlot. Although emission rates of those gases are as yet gross and variable estimates, their ground-level concentrations downwind of open feedlots seldom approach established health-based standards or guidelines.[25,26,27,28]

NEIGHBORS' CONCERNS ABOUT ODOR AND DUST FROM CAFOS

Workers rarely complain about the odors from cattle feedlots or hog confinement barns. However, odors associated with both cattle feedlots and hog confinement facilities can be perceived as offensive by people who live nearby or drive by these facilities on public roadways.[29] Some of these individuals allege that the odors have adverse health effects as

well as a negative impact on their quality of life.[30] The characteristic odors from CAFOs are caused by a number of contributing compounds, including volatile organic compounds (VOCs), NH_3 and H_2S.[31] These odors are complex, resulting from fresh manure and its aerobic and anaerobic fermentation. Those processes result in the release into the air of VOCs, including fatty acids, alcohols and aromatic ring compounds containing carbon, sulfur and/or nitrogen.[32,33,34,35]

Dust emissions from cattle feedlots have also been an increasing concern for rural communities.[36] Dust concentrations can cause limited visibility on public roadways. Although feedlot dust has not been associated with an increased incidence of vehicle collisions overall, the risk continues to be a concern. This is especially true for feedlots located on the prevailing, windward side of high-traffic roadways. A recent chain-reaction motor vehicle accident in Nebraska with multiple fatalities was attributed to feedlot dust blowing across a road.[37] Feedlot dust concentrations are usually highest in the early evening and lowest in the early morning.[23] Odor intensity measured as dilutions to threshold (DT), appears to increase with increasing dust concentrations.[38] Published 24-hour averaged dust concentrations of PM_{10} and total suspended particulate (TSP) immediately downwind of cattle feedlot corrals have approached 1,200 and 430 micrograms per cubic meter for TSP and PM_{10} respectively, as reconstructed from sequential, short-term (3 to 6 hour) monitoring data.[38] Absolute PM_{10} concentrations and therefore compliance with National Ambient air Quality Standards for PM_{10} depended heavily on which monitoring instrument was used.[21]

Odors clearly have important effects on humans. For example, results from recent studies using imaging of the brain indicate that odors have the ability to influence emotion.[39] The study of human reactions to odors is complicated by the large variation between individuals in the ability to perceive odors.[40] Also, persons who describe themselves as having heightened sensitivity to odors may not have enhanced ability to detect and identify odors but rather report more negative symptoms when exposed to odors they find unpleasant.[41] They may state that their ability to breathe is affected by certain odors, but it has been difficult to document objective negative effects on lung function from offensive odors.[42,43] Odors are described either in terms of concentration, offensiveness or hedonic tone.[44,45] Thus, there are a number of variables to be considered when determining the impact of the presence of livestock odors.

Quantifying livestock odors in a reproducible, technically feasible way has proven to be difficult. Investigators have worked to quantify odors from livestock facilities as a first step toward controlling them, using both trained panelists (e.g., dynamic, forced-choice olfactometry) and electronic odor sensors.[46,47] At this point, olfactometry is still the gold standard in odor assessment although newer methods show promise.[48]

STUDIES ON HEALTH EFFECTS IN CAFO NEIGHBORS FROM INHALATION EXPOSURES

The effect of feedlot dust on rural communities has not been extensively studied although it has been a source of complaints voiced at community meetings and to local health departments. Communities have also responded negatively to a variety of odor sources, both agricultural and industrial as well as those related to municipal activities such as sewage treatment.[49] Some CAFO neighbors allege that odors from feedlots and hog barns represent a risk to human health. While it is clear that many persons consider these odors to be unpleasant, the health implications of this exposure are not yet fully understood.

A small number of studies have been published that specifically address other human health effects of living near large hog confinement facilities. The first of these papers describes the findings of Schiffman and colleagues, who studied 44 neighbors of large-scale hog operations in North Carolina using the Profile of Mood States psychological testing tool. Results from testing the hog-farm neighbors were compared to findings from a group of rural residents who did not live near hog confinement facilities.[50] Persons living near the swine operations reported significantly more tension, depression, and anger than did

the control subjects. They also reported less vigor, more fatigue and more confusion. The authors concluded that these differences could be explained by neighborhood exposure to hog odors, although they did not measure actual exposures or estimate the likelihood of exposure as a function of distance and direction from the hog confinement facilities.

Thu, Donham and colleagues conducted a study of 18 Iowa residents living within a 2-mile radius of a 4,000-sow hog confinement facility. These rural residents were compared to a group of demographically similar rural residents who did not live near large livestock facilities.[51] Measurements consisted of self-reported symptom histories. Their findings included several clusters of symptoms more commonly in the confinement facility neighbors than in rural residents who did not live near hog confinement facilities. The authors divided the symptoms into clusters as follows: Cluster 1 symptoms included sputum, cough, shortness of breath, chest tightness and wheezing; Cluster 2 complaints were nausea, dizziness, weakness and fainting; Cluster 3 consisted of headaches and plugged ears; Cluster 4 included runny nose, scratchy throat and burning eyes; and "other" symptoms were muscle aches, hearing problems, skin rash and fever. Cluster 1, 2 and 3 symptoms were statistically more common in hog facility neighbors than in control subjects. Cluster 4 symptoms were reported by more hog farm neighbors than control residents ($p = .12$) but the difference between the two groups was not as great as for Cluster 1-3. Symptoms in the "other" category were not more common in hog farm neighbors. A medical assessment was not done to look for objective physiologic measures of ill health in either population. Questionnaires were administered to look for evidence of depression and anxiety. Both the hog confinement neighbor and comparison populations scored in the normal range on the depression and anxiety surveys.

Wing and Wolf surveyed several rural communities, one of which was near a 6000 head hog operation and two of which were near large dairy operations.[30] Another community studied was near no large livestock farms. The 155 participants were not told that the reason for the survey was concern over the health effects of living near large-scale livestock facilities. Symptoms that were significantly increased in persons living near the hog operations included the following: headaches, runny noses, sore throats, excessive coughing, fatigue, diarrhea and burning eyes. Quality of life, as measured by the number of days residents were not willing to open their windows or go outside in pleasant weather, was significantly reduced in those who lived near a hog operation compared to both of the other groups. As with the other studies, the authors did not conduct a physical assessment of the subjects or perform exposure monitoring to corroborate their findings.

In summary, there is evidence from a small number of published research studies that people living in the neighborhood of large-scale hog facilities are more likely to have a variety of medical complaints. These complaints range from respiratory problems to burning eyes, sore throats, nausea and diarrhea, fatigue, headaches and plugged ears. Some but not all of these symptoms are like those of the hog confinement workers, who receive a much more intense exposure to the dust and odors associated with this industry. At this time, there are no published studies in which scientists have attempted to find exposure-corroborated, physiologic evidence of negative health effects in populations of neighbors of hog facilities. Neither healthy subjects, nor potentially more vulnerable subjects such as asthmatics or persons with chronic obstructive pulmonary disease, have been assessed in this way. It is conceivable that odors from CAFOs could worsen their symptoms and lung function, but this has not been demonstrated. Psychological symptoms, including tension, depression and anger were more common in hog facility neighbors studied by the group of researchers that looked at psychological aspects of the neighborhood health issue. Quality of life does appear to be affected by the presence of the unpleasant odors associated with this industry.

RESPIRATORY HEALTH IN HOG CONFINEMENT BARN WORKERS

Studying worker health effects can be useful for developing a better understanding of the respiratory conditions for which the CAFO

neighbors might be at risk. One can expect the workers' exposures to be similar in terms of the substances inhaled but much more intense than that of the neighbors. Therefore, studying the workers can contribute to the understanding of potential health effects in CAFO neighbors. However, the healthy worker survivor effect is likely a factor in this environment.[52] This effect could indirectly cause the health effects on neighbors to be underestimated. Specifically, vulnerable groups such as children or anyone with underlying cardiopulmonary disease could be more severely affected than workers that are healthy and who have demonstrated their ability to tolerate this environment. Also, there is evidence that exposure to this environment results in an adaptation to the inflammatory response by the chronically exposed worker.[12,53] It is unclear how the adaptation phenomenon applies to the understanding of the neighborhood effect.

Health effects of working in the hog confinement barn have been studied extensively by investigators in North America and in Europe using symptom surveys and lung function testing.[8,9,54-70] It has been known for some time that working in hog confinement facilities causes chronic or intermittent lower respiratory tract symptoms in approximately one-third of workers. These respiratory symptoms consist of cough with or without production of phlegm, chest tightness, wheezing and shortness of breath with heavy exertion. Depending on the constellation of symptoms displayed and the results of pulmonary function testing, the worker may suffer from chronic bronchitis, the asthma-like syndrome, or exacerbation of preexisting asthma.[71] Rarely, a true allergy to hogs develops in the workers. This hog allergy can be associated with allergic asthma.[11,72] It is said that exacerbation of underlying asthma can also occur secondary to hog barn exposures, although the extent of this problem is not well documented. The respiratory impairment directly attributable to this work is usually not severe if the workers suffer from the asthma-like syndrome or chronic bronchitis. However, lung function test values below the normal range are commonly seen in workers with respiratory complaints. Even a small decrease in lung function can result in shortness of breath with exertion in workers who perform heavy physical labor.

Hog confinement workers who smoke cigarettes are at risk for developing changes in measures of lung function at lower exposure thresholds than nonsmokers.[7] Some of those workers, including persons without a history of cigarette smoking, meet the criteria for chronic obstructive pulmonary disease, which is commonly known as COPD.[73] Approximately 6% of the U.S. population suffers from chronic obstructive pulmonary disease, the term used to describe emphysema and chronic bronchitis.[74] The majority of this disease burden is attributed to cigarette smoking, but occupational factors, including agricultural exposures, are also important.[75]

Nasal symptoms are also common in swine confinement workers. Up to 74% of workers have been described as reporting nasal stuffiness, sinusitis symptoms and other nasal complaints.[54] Olfactory function defined as the ability to recognize odors using a scratch-and-sniff odor identification tool, was described as being compromised in women, but not in men, who work in hog confinement barns in a recently published study.[76] Other evidence of impairment in nasal function has not been identified in persons who work in this setting. However, neutrophilic nasal inflammation has been documented in normal volunteers exposed to the swine confinement barn. Interestingly, there is evidence for adaptation of the nose over time to these exposures.[53] Burning of the eyes and a sore throat are also reported by some workers. The constellation of nasal, eye and throat symptoms are known as the mucous membrane irritation syndrome.

A number of other health problems are associated with work in hog confinement barns. Some workers develop a flu-like illness called organic dust toxic syndrome (ODTS) from heavy exposure to organic dust in their work.[69,77] Symptoms of ODTS include fever, chills, headache, muscle aches, malaise, fatigue and dry cough. This illness usually lasts for several days and is rarely life threatening. There is evidence that having had ODTS makes people more sensitive to having respiratory symptoms such as cough and chest tightness with subsequent exposures to organic dust such

as grain dust or hog dust and that it contributes to the presence of chronic bronchitis.[68,78]

Hydrogen sulfide is a gas that has the odor of rotten eggs and is present in low amounts in the hog barns under ordinary conditions. When amounts of H_2S rise to very high levels secondary to agitation of a manure pit under the floor of the barn, inhalation of this gas can be fatal to workers.[79] Reactive airways dysfunction syndrome, a form of occupational asthma, has been described in a hog confinement worker after exposure to a high level of H_2S.[13] Inhalation of low amounts of hydrogen sulfide by workers has not been shown to be associated with respiratory effects.[7] Interestingly, a recent study has suggested that communities presumably exposed to long-term, low-level H_2S from industrial sources might be at increased risk of respiratory and central nervous system complaints.[80]

In conclusion, hog confinement workers clearly are at risk of developing chronic or intermittent respiratory disorders. While these disorders are not usually life-threatening, they can interfere with their ability to perform their work and may be reason for workers to leave the industry. The substances that cause these problems include hog dust, endotoxin and NH_3. Hydrogen sulfide, while quite malodorous, has not been conclusively associated with the presence of chronic respiratory disease in workers or the public although it causes death from acute, high-level exposures.

RESPIRATORY HEALTH IN CATTLE FEEDLOT WORKERS

A limited amount of information has been published about occupational health problems in cattle feedlot workers.[12,81] The information available at this time about worker health pertains mainly to non-respiratory problems and does not contribute to the understanding of health concerns of feedlot neighbors. Studying the workers' respiratory health status may provide an opportunity for better understanding the potential health effects of the dust from these feedlots.

FUTURE DIRECTIONS

Our understanding of how many persons living near hog confinement operations or cattle feedlots consider their health to be negatively impacted or who have changes in their health status that can be quantified by physiological testing is still quite limited. There is an urgent need to document the health status of subjects in larger samples of hog confinement facility and cattle feedlot neighbors and to make careful comparisons with rural residents who do not live near such facilities. Such research projects should use objective measures of health as well as subjective information obtained by asking persons about symptoms of illness. Moreover, it is essential to compare the prevalence of symptoms and signs of human illness with accepted measures of actual exposures to specific air pollutants made in the neighborhood. Until this research has been done, we will not have a true understanding of the human health implications of constructing more hog confinement facilities, cattle feedlots or other CAFOs. Also, we will not know how to monitor existing CAFOs to assess their potential for causing human illness in the neighborhood.

These studies represent a very important step in addressing the neighborhood health effects aspect of the CAFO debate. However, much more work remains to be done before there are enough data about the human health neighborhood effect of large-scale hog and cattle facilities in order to draw firm conclusions that could have a permanent impact on the industry, its neighbors and its stakeholders.

REFERENCES

1. GRACE Factory Farm Project [homepage on the Internet]. New York: Global Resource Action Center for the Environment. Copyright 2003 [cited 2005 Jul 15]. Available from: *http://www.factoryfarm.org/topics/health/hydrogensulfide*.

2. Patchwork Family Farms [homepage on the Internet]. Columbia (MO): In Motion Magazine Rural America. Copyright 2001-2005 [cited 2005 Jul 15]. Available from: *http://www.patchworkfamilyfarms.org/wwa.html.*

3. Environmental Protection Agency [homepage on the internet]. Washington (DC). Date of copyright unknown [updated 2005 Jun 27; cited 2005 Jul 15]. Available from: *http://cfpub.epa.gov/npdes/afo/info.cfm*

4. Donham KJ, Popendorf W, Palmgren U, Larsson L. Characterization of dusts collected from swine confinement buildings. Am J Ind Med. 1986;10(3):294-7.

5. Schiffman S, Bennett JL, Raymer JH. Quantification of odors and odorants from swine operations in North Carolina. Agricultural and Forest Meteorology. 2001;108(3):213-240.

6. Heederik D, Brouwer R, Biersteker K, Boleij JS. Relationship of airborne endotoxin and bacterial levels in pig farms with the lung function and respiratory symptoms of farmers. Int Arch Occup Environ Health. 1991; 62(8):595-601.

7. Donham KJ, Reynolds SJ, Whitten P, Merchant JA, Burmeister L, Popendorf WJ. Respiratory dysfunction in swine production facility workers: dose-response relationships of environmental exposures and pulmonary function. Am J Ind Med. 1995 Mar;27(3):405-18.

8. Vogelzang PF, van der Gulden JW, Folgering H, Kolk JJ, Heederick D, Preller L, Tielen MJ, van Schayck CP. Endotoxin exposure as a major determinant of lung function decline in pig farmers. Am J Respir Crit Care Med. 1998 Jan;157(1):15-18.

9. Vogelzang PF, van der Gulden JW, Folgering H, Heederik D, Tielen MJ, van Schayck CP. Longitudinal changes in bronchial responsiveness associated with swine confinement exposure. Chest. 2000 May;117(5): 1488-95.

10. Cormier Y, Tremblay G, Meriaux A, Brochu G, Lavoie J. Airborne microbial contents in two types of swine confinement buildings in Quebec. Am Ind Hyg Assoc J. 1990 Jun;51(6):304-9.

11. Crook B, Robertson JF, Glass SA, Botheroyd EM, Lacey J, Topping MD. Airborne dust, ammonia, microorganisms and antigens in pig confinement houses and the respiratory health of exposed farm workers. Am Ind Hyg Assoc J. 1991 Jul;52(7):271-9.

12. Von Essen S, Romberger D. The respiratory inflammatory response to the swine confinement building environment: the adaptation to the respiratory exposures in the chronically exposed worker. J Agric Saf Health. 2003 Augt;9(3):185-96.

13. Cormier Y, Coll B, Laviolette M, Boulet LP. Reactive airways dysfunction syndrome (RADS) following exposure to toxic gases of a swine confinement building. Eur Respir J. 1996 May;9(5):1090-1.

14. Larsson KA, Eklund AG, Hansson LO, Isaksson BM, Malmberg PO. Swine dust causes intense airways inflammation in healthy subjects. Am J Respir Crit Care Med. 1994 Oct;150(4):973-7.

15. USDA White Paper. Schiffman SS, Auvermann BW, Bottcher RW. Health effects of aerial emissions from animal production and waste management systems. National Center for Manure & Animal Waste Management. 2001 [cited 2005 Sep 19]. Available from: *http://www.cals.ncsu.edu/waste_mgt/natlcenter/papers.htm.*

16. Jacobson LD, Moon R, Bicudo J, Janni K, Noll S, Shurson G, Zhu J, Schmidt D, McGinley C, Goodrich P, Nicolai R, Clanton C, Davis K, Brosseau L, Bruns J, Pijoan C, Blaha T. Generic Environmental Impact Statement on Animal Agriculture: A Summary of the Literature Related to Air Quality and Odor (H). 1999. Prepared for the Environmental Quality Board, State of Minnesota. *www.mnplanstate.mn.us*

17. Iowa DNR Animal Feeding Operations [cited 2005 Jul 16]. Available from: *http://www.iowadnr.com/air/afo/afo.html#standards*.

18. Alberta Environment, Government of Alberta, Edmonton, Alberta, Canada [cited 21 March 2005]. Available from: *http://www3.gov.ab.ca/env/air/index.html*.

19. North Carolina Department of Environment and Natural Resources, Division of Air Quality [cited 2005 Mar 22]. Available from: *http://daq.state.nc.us/rules/rules/*.

20. Iowa Concentrated Animal Feeding Operations Air Quality Study. Iowa State University and The University of Iowa Study Group, February, 2002 [cited 2005 Mar 21]. Available from: *www.publichealth.uiowa.edu/ehsrc/CAFOstudy.htm*

21. National Ambient Air Quality Standards [updated 2005 Jul 12; cited 2005 Jul 14]. Available from: *http://www.epa.gov/air/criteria.html.*

22. Auvermann BW, Sweeten JM, Parker DB. Manure harvesting frequency: the feedyard manager's #1 tool for dust control in a summer drought. Texas Cooperative Extension bulletin E-52, College Station, TX, 2000.

23. Parnell CB Jr., Shaw BW, Auvermann BW, Agricultural air quality fine particle project–Task 1: Livestock-feedlot PM emission factors and emissions inventory estimates final report. Texas Natural Resource Conservation Commission. Department of Agricultural Engineering, Texas A & M University, College Station, TX, 1999.

24. Auvermann BW, Parnell CB. Year 3 Progress Report, USDA-CSREES Special Research Grant #2004-06009: Air quality, odor, dust and gaseous emissions from concentrated animal feeding operations in the southern Great Plains. Report prepared in 2005.

25. Hrudey SE. Review of documents pertaining to the Alberta Environment Mobile Laboratory Lethbridge Area Livestock Operations Air Monitoring Survey and response from the Chinook Health Region. Alberta Environment, October 2000. Copyright 2005, Government of Alberta [cited 2005 Jul 16]. Available from: *http://www3.gov.ab.ca/env/info/infocentre/PubDtl.cfm?ID=1545.*

26. McGinn SM, Janzen HH, Coates T. Atmospheric pollutants and trace gases. Atmospheric ammonia, volatile fatty acids, and other odorants near beef feedlots. J Environ Qual. 2003 Jul-Aug;32:1173-1182.

27. Koziel JA, Baek B-H, Spinhirne JP, Parker DB. Ambient ammonia and hydrogen sulfide concentrations at a beef cattle feedlot in Texas. Paper #044112 in the proceedings of the 2004 ASAE/CSAE Annual International Meeting; 2004 Aug 1-4; Ottawa, Ontario, Canada.

28. Koelsch RK, Woodbury BL, Stenberg DE, Miller DN, Schulte DD. Total reduced sulfur concentrations in the vicinity of beef cattle feedlots. Applied Engineering in Agriculture. 2004 Jan 20;20(1):77-85.

29. Stephens vs. Pillen, 12 Neb. App. 600, 681 N.W. 2d 59 (2004). Decided June 15, 2004.

30. Wing S, Wolf S. Intensive livestock operations, health and quality of life among eastern Carolina residents. Environ Health Perspect. 2000 Mar;108:233-38.

31. National Research Council. Air Emissions from Animal Feeding Operations. Washington (DC): National Academies Press; 2003.

32. Zahn JA, Hatfield JL, Laird DA, Hart TT, Do YS, DiSpirito AA. Functional classification of swine manure management systems based on effluent and gas emission characteristics. J Environ Qual. 2001 Mar-Apr:30(2): 635-47.

33. Powers WJ, Van Horn HH, Wilkie AC, Wilcox CJ, Nordstedt RA. Effects of anaerobic digestion and additives to effluent or cattle feed on odor and odorant concentrations. J Anim Sci. 1999 Jun;77(6):1412-21.

34. Miller DN, Varel VH. In vitro study of the biochemical origin and production limits of odorous compounds in cattle feedlots. J Anim Sci. 2001 Dec;79 (12):2949-56.

35. Miller DN, Varel VH. An in vitro study of manure composition on the biochemical origins, composition and accumulation of odorous compounds in cattle feedlots. J Anim Sci. 2002 Sep;80(9):2214-22.

36. Queensland Government. Determination of dust composition from a beef cattle feedlot on the Darling Downs [updated 2003 Dec; cited 2005 Jul 16]. Available from: *http://www.dpi.qld.gov.au/environment/13805.html*.

37. Omaha World-Herald, March 11, 2005. *http://www.omaha.com/*

38. Sweeten JB, Parnell CB, Etheredge RS, Osborne D. Dust emissions in cattle feedlots. Vet Clin North Am Food Anim Pract. 1988 Nov;4(3):557-78.

39. Royet JP, Plailly J, Delon-Martin C, Kareken DA, Segebarth C. fMRI of emotional responses to odors: Influence of hedonic valence and judgment, handedness and gender. Neuroimage. 2003 Oct;20(2):713-28.

40. O'Connell RJ, Stevens DA, Zogby LM. Individual differences in the perceived intensity and quality of specific odors following self- and cross-adaptation. Chem Senses. 1994 Jun;19(3):197-208.

41. Caccappolo E, Kipen H, Kelly-McNeil K, Knasko S, Hamer RM, Natelson B, Fiedler N. Odor perception: multiple chemical sensitivities, chronic fatigue, and asthma. J Occup Environ Med. 2000 Jun;42(6):629-38.

42. Opiekun RE, Smeets M, Sulewski M, Rogers R, Prasad N, Vedula U, Dalton P. Assessment of ocular and nasal irritation in asthmatics resulting from fragrance exposure. Clin Exp Allergy. 2003 Sep;33(9):1256-65.

43. Shim C, Williams MH Jr. Effect of odors in asthma. Am J Med. 1986 Jan;80(1):18-22.

44. O'Neill DH, Phillips VR. A review of the control of odour nuisance from livestock buildings: Part 3, properties of the odorous substances which have been identified in livestock wastes or in the air around them. J Agric Eng Res. 1992;53:23-50.

45. Nimmermark S. Odour influence on well-being and health with specific focus on animal production emissions. Ann Agric Environ Med. 2004;11(2):163-167. Review.

46. Brose G, Gallmann E, Hartung E, Jungbluth T. Detection of the dynamics of odour emissions from pig farms using dynamic olfactometry and an electronic odour sensor. Water Sci Technol 2001;44(9):59-64.

47. van Kempen TA, Powers WJ, Sutton AL. Technical note: Fourier transform infrared (FTIR) spectroscopy as an optical nose for predicting odor sensation. J Anim Sci 2002 Jun;80(6):1524-27.

48. Chen Y, Bundy DS, Hoff SJ. Using olfactometry to measure intensity and threshold dilution ratio for evaluating swine odor. J Air Waste Manag Assoc. 1999 Jul;49(7):847-53.

49. Shusterman D. Critical review: the health significance of environmental odor pollution. Arch Environ Health. 1992 Jan-Feb;47(1):76-87.

50. Schiffman SS, Miller EA, Suggs MS, Graham BG. The effect of environmental odors emanating from commercial swine operations on the mood of nearby residents. Brain Res Bull. 1995;37(4):369-75.

51. Thu K, Donham K, Ziegenhorn R, Reynolds S, Thorne P, Subramanian P, Whitten P, Stookesberry J. A control study of the physical and mental health of resident living near a large-scale swine operation. J Agric Saf Health. 1997; 3(1):13-26.

52. Radon K, Goldberg M, Becklake M. Healthy worker effect in cohort studies on chronic bronchitis. Scand J Work Environ Health. 2002 Oct;28(5):328-332. Review.

53. Palmberg L, Larrson B-M, Malmberg P, Larsson K. Airway responses of healthy farmers and nonfarmers to exposure in a swine confinement building. Scand J Work Environ Health. 2002 Aug;28(4):256-63.

54. Donham KJ, Rubino M, Thedell TD, Kammermeyer J. Potential health hazards to agricultural workers in swine confinement buildings. J Occup Med. 1977 Jun; 19(6):383-7.

55. Donham KJ, Zavala DC, Merchant JA. Respiratory symptoms and lung function among workers in swine confinement buildings: a cross-sectional epidemiological study. Arch Environ Health. 1984 Mar-Apr;39 (2):96-101.

56. Donham KJ, Merchant JA, Lassise, D, Popendorf WJ, Burmeister LF. Preventing respiratory disease in swine confinement workers: intervention through applied epidemiology, education, and consultation. Am J Ind Med. 1990;18(3):241-61.

57. Bongers P, Houthuijs D, Remijn B, Brouwer R, Biersteker K. Lung function and respiratory symptoms in pig farmers. Br J Ind Med. 1987 Dec;44(12):819-23.

58. Dosman JA, Graham BL, Hall D, Pahwa P, McDuffie HH, Lucewicz M, To T. Respiratory symptoms and alterations in pulmonary function tests in swine producers in Saskatchewan: results of a survey of farmers. J Occup Med. 1988 Sep;30(9):715-20.

59. Cormier Y, Boulet LP, Bedard G, Tremblay G. Respiratory health of workers exposed to swine confinement buildings only or to both swine confinement buildings and dairy barns. Scand J Work Environ Health. 1991 Aug;17(4):269-75.

60. Zhou C, Hurst TS, Cockcroft DW, Dosman JA. Increased airways responsiveness in swine farmers. Chest. 1991 Apr;99(4):941-4.

61. Schwartz DA, Donham KJ, Olenchock SA, Popendorf WJ, Van Fossen DS, Burmeister LF, Merchant JA. Determinants of longitudinal changes in spirometric function among swine confinement operators and farmers. Am J Respir Crit Care Med. 1995 Jan;151 (1):47-53.

62. Senthilselvan A, Dosman JA, Kirychuk SP, Barber EM, Rhodes CS, Zhang Y, Hurst TS. Accelerated lung function decline in swine confinement workers. Chest. 1997 Jun;111(6):1733-41.

63. Zejda JE, Hurst TS, Barber EM, Rhodes C, Dosman JA. Respiratory health status in swine producers using respiratory protective devices. Am J Ind Med. 1993 May; 23(5):743-50.

64. Zejda JE, Barber E, Dosman JA, Olenchock SA, McDuffie HH, Rhodes C, Hurst T. Respiratory health status in swine producers relates to endotoxin exposure in the presence of low dust levels. J Occup Med. 1994 Jan;36(1):49-56.

65. Schwartz DA, Landas SK, Lassise DL, Burmeister LF, Hunninghake GW, Merchant JA. Airway injury in swine confinement workers. Ann Intern Med. 1992 Apr 15;116(8):630-5.

66. Reynolds SJ, Donham KJ, Whitten P, Merchant JA, Burmeister LF, Popendorf WJ. Longitudinal evaluation of dose-response relationships for environmental exposures and pulmonary function in swine production workers. Am J Ind Med. 1996 Jan;29(1):33-40.

67. Von Essen SG, Scheppers LA, Robbins RA, Donham KJ. Respiratory tract inflammation in swine confinement workers studied using induced sputum and exhaled nitric oxide. J Toxicol Clin Toxicol. 1998; 36(6): 557-65.

68. Von Essen S, Donham K. Illness and Injury in animal confinement workers. Occup Med. 1999 Apr-Jun; 14(2):337-49.

69. Vogelzang PF, van der Gulden JW, Folgering H, van Schayck CP. Organic dust toxic syndrome in swine confinement farming. Am J Ind Med. 1999 Apr;35(4): 332-4.

70. Dosman JA, Kirychuk SP, Lemay S, Barber EM, Willson P, Cormier Y, Hurst TS. 2000. Positive human health effects of wearing a respirator in a swine barn. Chest. 2000 September;117(3): 1-8.

71. Thorne PS. Occupational health. In: Understanding the impacts of large-scale swine production. Proceedings from an Interdisciplinary Scientific Workshop. Iowa's Center for Agricultural Safety and Health, University of Iowa; 1995. p. 153-93.

72. Harries MG, Cromwell O. Occupational asthma caused by allergy to pigs' urine. Br Med J (Clin Res Ed). 1982 Mar 20;284(6319):867.

73. Hurd S, Pauwels R. Global initiative for Chronic Obstructive Lung Diseases (GOLD). Pulm Pharmacol Ther. 2002;15(4):353-5.

74. Mannino DM. COPD: epidemiology, prevalence, morbidity and mortality, and disease heterogeneity. Chest. 2002 May;121(5 Suppl):121S-126S. Review.

75. Mak GK, Gould MK, Kuschner WG. Occupational inhalant exposure and respiratory disorders among never-smokers referred to a hospital pulmonary function laboratory. Am J Med Sci. 2001 Sep;322(3):121-6.

76. Snyder MC, Leopold DA, Chiu BC, Von Essen SG, Liebentritt N. The relationship between agricultural environments and olfactory dysfunction. J Agric Saf Health. 2003 Aug;9(3):211-9.

77. Seifert SA, Von Essen S, Jacobitz K, Crouch R, Lintner CP. Organic dust toxic syndrome: a review. J Toxicol Clin Toxicol. 2003;41(2):185-93. Review.

78. Monsó E, Schenker M, Radon K, Riu E, Magarolas R, McCurdy S, Danuser B, Iversen M, Saiki C, Nowak D. Region-related risk factors for respiratory symptoms in European and Californian farmers. Eur Respir J. 2003 Feb;21(2):323-31.

79. NIOSH Update. NIOSH Warns: Manure pits continue to claim lives. July 6, 1993.

80. Legator MS, Singleton CR, Morris DL, Philips DL. Health effects from chronic low-level exposure to hydrogen sulfide. Arch Environ Health. 2001 Mar-Apr; 56(2)123-131.

81. Auvermann BW, Rogers WJ. Documented human health effects of air emissions from intensive livestock operations (ILOs). Final report to Alberta Pork, Edmonton, AB, December 2000.

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Mitigating Greenhouse Gas and Ammonia Emissions from Beef Cattle Feedlot Production: A System Meta-Analysis

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Supporting Information

ABSTRACT: Beef cattle production systems are the largest contributors of greenhouse gas (GHG) and ammonia (NH_3) emissions in the livestock industry. Here, we present the first meta-analysis and integrated assessment of gaseous emissions and mitigation potentials for a typical beef cattle feedlot system, including methane (CH_4), nitrous oxide (N_2O), and NH_3 losses from enteric fermentation and manure management based on data from 104 studies. A total of 14 integrated emission factors (EF) and the mitigation efficiencies (ME) of 17 available options were provided. The estimated GHG and NH_3 emissions from the baseline feedlot system were 2786 ± 108 kg carbon dioxide equivalents (CO_2-eq) per animal unit (AU) per year and 49.1 ± 1.5 kg NH_3 AU^{-1} $year^{-1}$, respectively. Enteric CH_4 fermentation and manure on the feedlot contributed 67.5% and 80.8% of the total system GHG and NH_3 emissions, respectively. The highest ME values were found for lipid additives for enteric CH_4 fermentation and urease inhibitor additives (UI) for NH_3 emissions from manure on the feedlot, being −14.9% ($p < 0.05$) and −59.5% ($p < 0.001$), respectively. The recommended mitigation combinations of a low-crude-protein (CP) diet and a UI additive for manure on the feedlot could reduce the GHG of the system by 4.9% and NH_3 by 50.9%. The results of this study have important implications for developing sustainable beef cattle feedlot systems from the viewpoint of GHG and NH_3 mitigation.

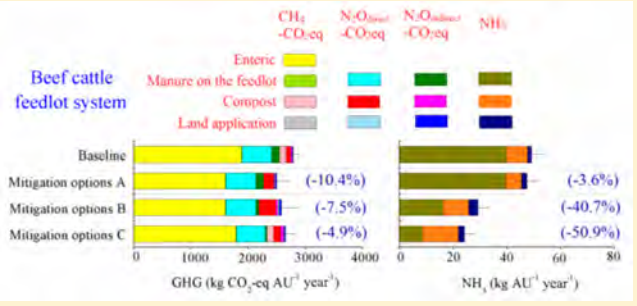

1. INTRODUCTION

Greenhouse gas (GHG) and ammonia (NH_3) emissions are two major atmospheric issues that influence human health and the global environment. From the United Nations Framework Convention on Climate Change to the Kyoto Protocol and the Paris Agreement, human beings are more aware of the influence of GHG emissions, and urgent action should be taken to avoid the risk of a temperature rise of more than 2 °C.[1] Methane (CH_4) and nitrous oxide (N_2O) are identified as two major non-CO_2 GHGs that have strong global warming potentials (GWP), being 28 and 265 times higher than that of CO_2, respectively.[1] Reducing non-CO_2 global warming agents has garnered increasing attention in recent years.[2−4] The "immediacy" of the climate benefit and the co-benefit of their reduction are expected to provide a strong incentive for nations to consider adopting policies and take rapid responses.[5,6] NH_3, also contributes to a series of problems, including odor emanation, water eutrophication,[7] soil acidification,[8] and GHG emissions because NH_3 is a precursor of N_2O.[9] Furthermore, NH_3 stimulates the formation of secondary particulate matter (PM),[10] which has negative effects on people and the environment.

Livestock production represents the largest anthropogenic source of CH_4 and N_2O emissions[11,12] and contributes 18% of all anthropogenic GHG emissions.[13] Here, CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero; the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2.[9] Nondairy cattle, predominantly beef cattle account for 53.9% of the global enteric CH_4 emissions, while the dairy sector takes second place with 19.1%.[14] Beef cattle are the largest single contributor of manure NH_3 emissions, accounting for 41.0% of all animal sectors.[15]

Beef cattle feedlot production is one of the most typical beef cattle production methods in intensive production systems.[16,17] In beef cattle feedlot systems, cattle excrete fresh

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manure (urine plus feces) onto the manure feedlot surface. After a period of time (120−365 days), machinery removes the dry manure from the feedlot into the manure stockpile area, where it is stored or composted prior to sale off-site or spreading as an organic fertilizer on agricultural land.[18,19] For beef feedlot manure management, only 1% of the excreted volatized solid (VS) and N is managed in sediment basins or retention ponds as liquid slurry; thus, the gas emissions from this liquid part are often not taken into account when considering the system-level gas emissions.[16,20]

Much work in the literature has evaluated gas emissions or mitigations targeted at one specific gas or one emission stage,[21−27] while little research has considered it in a comprehensive way. FAO conducted an LCA study on GHG emissions from beef meat production, though NH_3 emission was not considered in this study, and the study was not specified for beef cattle feedlot systems.[28] Watts et al.[19] reported emission factors of 75.0 kg NH_3 hd^{-1} $year^{-1}$, 3.16 kg N_2O hd^{-1} $year^{-1}$, and 0.84−1.69 kg CH_4 hd^{-1} $year^{-1}$ for the manure management chain of a beef cattle feedlot system in Australia, but enteric CH_4 emissions were not considered. In addition, neither of these two studies considered or evaluated gas mitigation for beef cattle production.[19,28] Considering the interactions between different gases and the mass flow causing linkage of gas emissions between the former and later stages,[29,30] evaluation of the impact of a combination of mitigation measures on simultaneous CH_4, N_2O, and NH_3 emissions is necessary, specifically for beef cattle feedlot systems.

The overall objective of this study was to make a quantitative assessment of GHG and NH_3 emissions from beef cattle feedlot production systems and the effects of (sets of) mitigation options on the CH_4, N_2O, and NH_3 emissions from the whole production chain using meta-analysis. A comprehensive data set was collated and developed for CH_4, N_2O, and NH_3 emission factors (EFs) for each stage of the feedlot production system, including enteric fermentation, manure on the feedlot, the manure composting or stockpiling stage, and the land application stage. This meta-analysis also quantified the efficiencies of 17 mitigation strategies, including 7 dietary manipulations, 5 management strategies for manure on the feedlot, 3 management strategies for manure composting and stockpiling, and 2 land application mitigation measures. System-level GHG and NH_3 emissions for the feedlot production system, with or without mitigation measures, were analyzed, and the most-effective designs for reduction of GHG and NH_3 emissions for the feedlot systems were recommended.

2. MATERIALS AND METHODS

2.1. Data Sources and Selection Criteria. The ISI Web of Knowledge database (www.isiwebofknowledge.com) and the Chinese journal database (www.cnki.net) were used to search all published datasets as of December 2017. Specific search terms were combined and used, including animal categories (beef, cattle, bull, steer, bovine, heifer, and livestock), manure, manure management (feedlot, pad, yard, open-lot, pen, compost, and stockpile), land application (surface spread, and incorporation), gaseous emissions (NH_3, CH_4, N_2O, and GHG gas), and mitigation measures (diet, crude protein, additive, amendment, urease inhibitor, biofilter, biotrickling, cover, nitrification inhibitor, incorporation, reduction, mitigation, and abatement). Literature sources used in this study were selected on the basis of following criteria: (1) the research object was beef cattle; (2) the study included at least one of the CH_4, N_2O, and NH_3 gases; (3) gas emission flux or gas emission factor was available; and (4) for literature related to mitigation, only studies that reported at least one control group were selected, so that emission mitigation efficiency (ME) could be calculated.

Application of the selection criteria resulted in 104 peer-reviewed papers containing 528 effective observations from experimental studies, which were used in the meta-analysis. Data were collected from both published tables and text for all selected research articles as well as extracted from published figures using the GetData Graph Digitizer software (version 2.22).[31] In addition to the gaseous emission data, related information allowing the interpretation of the observations such as beef cattle number, cattle weight, emission flux, and other gas emission relevant information such as study location, seasons, and manure property parameters were recorded (see data set S1 and tabs for raw data). The locations and distributions of the data used in this study are summarized in Figure 1, which was created by using ArcGIS software (version 10.0).[32] It can be seen that most studies were distributed in North American, Oceania, Europe, and East Asia.



Figure 1. Location and distribution of the literature sources used in this study. Larger circles mean more literature was available in the specific region. (This figure was created using ArcGIS software.)

2.2. Data Analysis. *2.2.1. Calculation of Emission Factors in the Different Phases.* To perform statistical analysis, the various units of gas emissions from enteric fermentation and manure on the feedlot stage were converted into kg AU^{-1} $year^{-1}$ (1 AU [animal unit] being equal to one beef animal weighing 500 kg of live weight) using the calculation method presented in Table S1. The CH_4 EFs for manure management (compost and stockpile) were calculated as kg CH_4−C (Mg DM)$^{-1}$. The NH_3 and N_2O EFs for manure management (composting and stockpiling) and land application phases were calculated as the percentage of total nitrogen (TN), i.e., kg NH_3−N (kg TN)$^{-1}$ and kg N_2O−N (kg TN)$^{-1}$. When unit conversion was not possible due to lack of key information, the original emission data were excluded from the statistical analysis. The EFs for each phase of the feedlot production system, including the median, mean value, standard error and interquartile range (IQR), were calculated with SPSS software (version 20.0, SPSS, Inc., Chicago, IL). The results were not weighted according to sample size; therefore, all of the observations had equal impact on the results. Given the influence of a few measurements with very high values or very low values on the mean values, median values instead of means were used as the basis for subsequent calculations because median values are quite robust with regard to outliers.[33] The 95% confidence interval (95% CI) of the median was calculated using eq 1:

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$$95\%\ \mathrm{CI} = 1.58 \times \frac{IQR}{\sqrt{N}} \quad (1)$$

where N represent the number of observations for each emission factor.

2.2.2. Calculation of the Mitigation Efficiency of Each Measure. The efficiencies of individual mitigation measures for the corresponding phases were assessed by comparing the results of control and treatment groups using the following formula:

$$E_m = \left(\frac{ER_{trt}}{ER_{ctrl}} - 1\right) \times 100\% \quad (2)$$

where E_m is ME, ER_{trt} is the gas emissions in the experimental group with mitigation measures, and ER_{ctrl} is the gas emissions in the control group without mitigation measures. Thus, a negative or positive E_m value indicates that the selected measure can reduce or increase gas emissions, respectively. The median E_m values for each measure were calculated using an analytical approach adapted from Benayas et al.[34] and Tuomisto et al.[35] The normality of the data was tested using the Kolmogorov–Smirnov test. Not all of the E_m values for each mitigation measure were normally distributed; therefore, the Wilcoxon Signed-Rank test was used to determine if the median E_m values were significantly different from 0 when there were sufficient results for specific measures. SPSS 20.0 software was used for the statistical analyses.

2.2.3. Design of an Integrated Feedlot Production System and Calculation of System-Level GHG and NH_3 Emissions. Design of an Integrated Feedlot Production System. Usually, for the beef cattle feedlot system, breeds such as Angus cross-bred steers and Simmentals with entry weights typically ranging from 250 to 450 kg and exit weights ranging from 400 to 700 kg depending on market type were fattened on the feedlot.[19,36] The baseline scenario was designed based on the typical management manner of beef cattle feedlot systems, including enteric fermentation, manure deposited on the feedlot, manure composting, and land application by surface spreading (Figure 2). The integrated mitigation scenarios were set with individual mitigation options included into the corresponding phases of the feedlot production system (Figure 2), and these scenarios are displayed in Table S2.

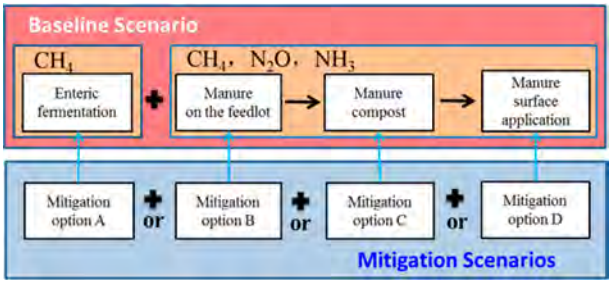

Figure 2. Block diagram of system gas emissions for the baseline scenario (red box) and the mitigation scenario (blue box) through the operation unit (black boxes).

Calculation of GHG and NH_3 Emissions for the Baseline and Mitigation Scenarios. The system GHG and NH_3 emissions for the baseline scenario of a beef-cattle feedlot system were calculated based on the summation method for CH_4 and mass flow for NH_3 and N_2O. The indirect N_2O emissions arising from N deposition and N leaching or runoff were also considered. The detailed calculation process is presented in section 1 of the Supporting Information.

The system gas emissions under mitigation scenarios for the feedlot production system were the sum of the emissions from each phase and were based on the numerous calculation schemes described in section 2 of the Supporting Information. The calculations are presented in data set S1 (see the "Feedlot system" tab).

2.2.4. Uncertainty Analysis. Monte Carlo simulations (10 000 runs) with R (version 3.3.1) were applied to estimate the uncertainty of the system-level emissions. The calculated median values of the gas emission factors and mitigation efficiency factors, as well as their 95% confidence intervals (CI), were included in the uncertainty analysis. The probability density functions (PDF) were assumed as normal distributions for each input data.[30]

3. RESULTS AND DISCUSSION

3.1. Gaseous Emission Factors for Each Phase of the Beef Cattle Feedlot System. *3.1.1. Enteric CH_4 Emissions.* A total of 100 observations of enteric CH_4 emissions were collected to analyze the beef cattle enteric CH_4 EFs, with 52 monitored using a sulfur hexafluoride (SF_6) tracer method and 48 monitored using a respiration chamber method. The world over median CH_4 EF for enteric fermentation is 67.2 kg AU^{-1} $year^{-1}$, with a 95% CI value of 62.0–72.4 kg AU^{-1} $year^{-1}$ (Table 1). The CH_4 EF varies with region, and North America and Western Europe showed higher enteric CH_4 EF values, while Latin America showed the lowest EF values (Figure 3), which may arise from differences of feed or the herd breed. For example, McGinn et al.[37] reported that the measured enteric CH_4 EF from Australia feedlot cattle is 22% lower than that from Canada feedlot cattle, and the difference was attributed to the lighter weight of the Australia cattle (and, consequently, their lower intake) and supplementation of their diet with lipids. It can be seen that the meta-analysis results for Asia are comparable with the Intergovernmental Panel on Climate Change (IPCC) recommended values, while for North America, Western Europe, Oceania, and Latin America, the discrepancy may arise from newly collected data from recent years (68 of 100 data were sourced from publication years after 2006), which may have been triggered by breed evolution or feed stuff improvement. For example, bulls having a lower residual feed intake (RFI) would be more feed efficient and would have a lower daily rate of CH_4 production, while RFI has been shown to be moderately heritable.[38] Australian cattle can now be commercially tested for RFI, and the estimated breeding values (EBVs) of bulls are used in sire selection,[39] thus causing the lower CH_4 EF in this region. This meta-analysis result could be used to support the refinement of the IPCC guidelines.

3.1.2. Gas Emissions from Manure on the Feedlot. CH_4 Emissions. The CH_4 emission rates from manure on the feedlot were measured using chamber methods, with an EF of 0.23 kg AU^{-1} $year^{-1}$ (95% CI, 0–0.83 kg AU^{-1} $year^{-1}$; Table 1), which is at the lowest level of IPCC recommended values of 0–31 kg CH_4 hd^{-1} $year^{-1}$.[9] The reason for the low manure CH_4 EF is that manure on the feedlot is dry based, with 99% of the organic matter being dry managed.[16,20]

NH_3 Emissions. The NH_3 EF from manure on the feedlot was 39.65 (95% CI, 34.18–45.12) kg AU^{-1} $year^{-1}$, which is higher than 8.52 (95% CI, 2.83–14.21) kg AU^{-1} $year^{-1}$ for

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Table 1. Emission Factors of CH_4, N_2O, and NH_3 from Each Stage of the Beef-Cattle Feedlot Production System and Their 95% Confidence Intervals (CIs)

	CH_4 (kg AU^{-1} $year^{-1}$)				N_2O (kg AU^{-1} $year^{-1}$)				NH_3 (kg AU^{-1} $year^{-1}$)			
grouping category	*n*	EF	CI	range	*n*	EF	CI	range	*n*	EF	CI	range
enteric	100	67.2	62.0–72.4	10.0–112.6	–	–	–	–	–	–	–	–
manure on the feedlot	16	0.23	0–0.83	0.01–3.18	19	1.96	0–13.37	0.00–42.56	58	39.65	34.18–45.12	17.00–106.49
		kg CH_4–C $(Mg\ DM)^{-1}$				kg N_2O–N $(kg\ TN)^{-1}$				kg NH_3–N $(kg\ TN)^{-1}$		
manure compost	10	6.16	4.40–7.92	0.36–15.36	11	0.0062	0–0.2744	0.0002–0.0202	3	0.2340	0.0716–0.3964	0.0600–0.4160
manure stockpile	20	6.31	3.56–9.06	1.51–41.99	20	0.0056	0.0016–0.0096	0–0.0432	15	0.0054	0.0004–0.0104	0.0010–0.0450
		kg CH_4–C $(Mg\ DM)^{-1}$				kg N_2O–N $(kg\ TN)^{-1}$				kg NH_3–N $(kg\ TN)^{-1}$		
manure surface spreading	–	–	–	–	13	0.0023	0.0015–0.0031	0.0004–0.0127	10	0.1042	0.0561–0.1523	0.0373–0.2018
manure incorporation	–	–	–	–	34	0.0006	0.0004–0.0008	0.0001–0.0331	11	0.0543	0.0113–0.0973	0.0177–0.1973

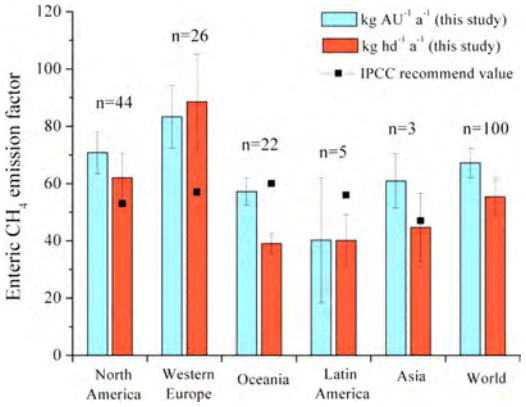

Figure 3. Regional enteric CH_4 emission factors of beef cattle expressed in terms of per AU or per herd (median ±95% CI); *n* = number of observations; squares indicate the IPCC recommended values.

beef cattle feeding and loafing yards in the United Kingdom[40,41] and 3.5 kg AU^{-1} $year^{-1}$ for a beef cattle bedding system.[42] The high NH_3 EF from manure on the feedlot occurred because it is managed under an open air environment. For beef cattle feeding and loafing yards, the floor would commonly be scraped once a week, thus not accumulating much manure[16,40] and leading to low NH_3 and N_2O emissions. For bedding systems, the bedding material can absorb part of the urine, and the occurrence of nitrification and denitrification microbes on the bedding material can also lead to the NH_3 being converted to N_2O, thus leading to the lowest NH_3 EF.[42]

N_2O Emissions. The median N_2O EF from beef cattle manure on the feedlot was 1.96 kg AU^{-1} $year^{-1}$, with the 95% CI being of 0–13.37 kg AU^{-1} $year^{-1}$ (Table 1). The EFs monitored with dynamic chamber or static chamber methods are usually lower than 1 kg AU^{-1} $year^{-1}$,[23−26,43] but the N_2O EFs appeared to be high at 12–42 kg AU^{-1} $year^{-1}$ when obtained with the wind tunnel method.[44,45] The air flow rate used in the two wind tunnels by Rahman et al.[44] and Borhan et al.[45] was high compared to the normally used wind tunnel flow rate for measuring N_2O emissions from the soil surface (1.75 versus 0.29 m^3 s^{-1}).[46,47] Moreover, the surface condition of the feedlot also influenced N_2O emissions. Surface conditions that are moist and muddy are localized microsites with physical and chemical conditions favoring intense microbial activity, thus presenting a median N_2O emission flux that was over 20 times greater and significantly higher than those for the other surface conditions, such as dry and loose conditions and flooded conditions.[48]

3.1.3. Manure Composting or Stockpiling Phase. CH_4 EFs. The CH_4 EFs from composting and stockpiling were 6.16 (95% CI, 4.40–7.92) and 6.31 (95% CI, 3.56–9.06) kg CH_4–C $(Mg\ DM)^{-1}$, respectively (Table 1). Stockpiling showed a relatively higher median value of CH_4 EF than composting, also with a higher variation than that of composting. The maximum CH_4 EF observed for stockpiling even reached 41.99 kg CH_4–C $(Mg\ DM)^{-1}$, which is much higher than that of 15.36 kg CH_4–C $(Mg\ DM)^{-1}$ for composting. Because the composting process usually resulted in an aerobic process, neither aeration nor pile turning happened during the manure stockpiling process; thus, the anaerobic environment caused high CH_4 emission during stockpiling.

N_2O EFs. The N_2O EFs of composting and stockpiling were 0.0062 (95% CI, 0–0.2744) and 0.0056 (95% CI, 0.0016–

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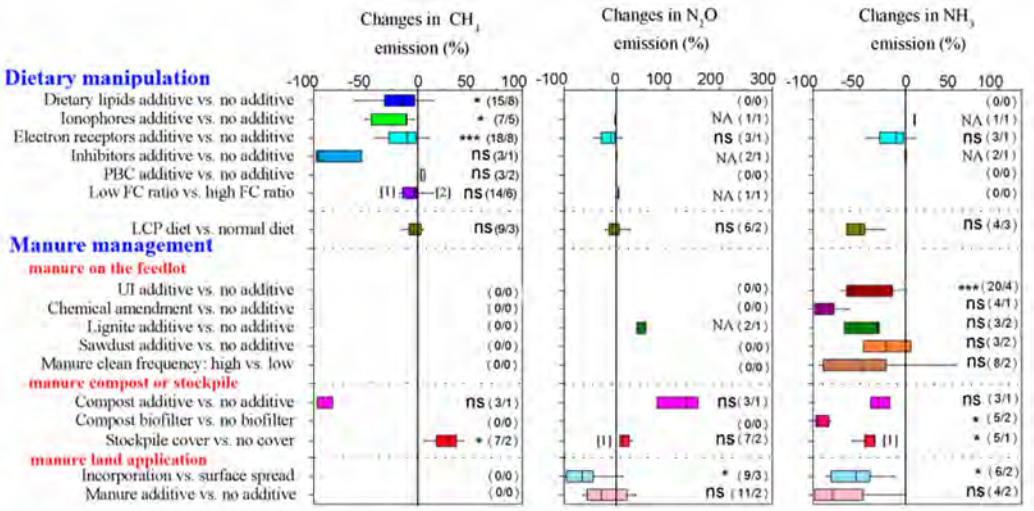

Figure 4. Box-and-whisker plots of the efficiencies of mitigation strategies for CH_4, N_2O, and NH_3 emissions (see Tables S6–S8 for numeric data). Vertical lines of the boxplot represent the median, upper, and lower quartiles. The whiskers show values that extend to 1.5 orders of the box length. The numbers in the square brackets represent the number of outliers (>1.5 orders of the box length). Values in parentheses indicate the number of observations for the statistical analysis and the number of studies from which the observations originated. Wilcoxon Signed Rank test: triple asterisks indicate $P < 0.001$, double asterisks indicate $P < 0.01$, and a single asterisk indicate $P < 0.05$; ns, not significantly different from zero; NA, not applicable. PBC, plant bioactive compounds; FC ratio, forage-to-concentrate ratio; LCP, low crude protein; and UI, urease inhibitor.

0.0096) kg N_2O–N (kg TN)$^{-1}$, respectively (Table 1). The 95% CI of composting was obviously higher than that of stockpiling, and the collected EF of composting was in the range of 0.0002–0.0202 kg N_2O–N (kg TN)$^{-1}$, indicating that the N_2O EFs for composting vary significantly under different conditions. Our collected N_2O EF data for beef cattle manure compost was lower than the IPCC recommended value of 0.006–0.1 kg N_2O–N (kg TN)$^{-1}$.[9] IPCC value was generally recommended for all kinds of animal manure, thus leading the exhibited higher range, and our results can be supplemented for the specific use of beef cattle manure compost. For solid stockpiling, the IPCC recommended an EF of 0.005 kg N_2O–N (kg TN)$^{-1}$,[9] which is comparable with the meta-analyzed results of this study.

NH_3 EFs. The NH_3 EF from beef cattle manure composting was obviously higher than that of stockpiling at 0.2340 (95% CI, 0.0716–0.3964) and 0.0054 (95% CI, 0.0004–0.0104) kg NH_3–N (kg TN)$^{-1}$, respectively (Table 1). The NH_3 EF of the composting process ranged from 0.060–0.416 kg NH_3–N (kg TN)$^{-1}$, and that of the stockpiling process ranged from 0.001–0.045 kg NH_3–N (kg TN)$^{-1}$. The ventilation process with aerobic composting leads to high NH_3 emissions during the composting process, which also leads to the high nutrient loss of composting.

3.1.4. Manure Land Application. For upland cropping systems, CH_4 emissions are low, and the cropping system is usually seen as a sink for CH_4.[49] As such, CH_4 emissions and mitigation during manure upland application are not considered in the following system-level emission calculations.

N_2O EFs. The N_2O EFs for the surface spreading and incorporation of beef cattle manure were 0.0023 (95% CI, 0.0015–0.0031) and 0.0006 (95% CI, 0.0004–0.0008) kg N_2O–N (kg TN)$^{-1}$, respectively (Table 1). For N_2O, EF varies greatly within one specific land application method. For instance, the N_2O EF values for incorporation ranged from 0.0001–0.0009 kg N_2O–N (kg TN)$^{-1}$ in the study by Chiyoka et al.,[50] while they are 0.0185–0.0331 kg N_2O–N (kg TN)$^{-1}$ in the study by Chang et al.[51] The complex N_2O production processes and the variable manure and soil properties in each study lead to the variability among N_2O emission results.[52] Moreover, the comparison revealed that the N_2O EF of surface spreading was significantly higher than that of incorporation ($p < 0.05$) because their 95% CIs did not overlap. Webb et al.[53] suggested that some stored farmyard manure (FYM) emitted N_2O at the time of spreading on the soil surface; however, if FYM is buried through ploughing, the increased length of the diffusion pathway through the soil matrix may lead to the reduction of N_2O emissions.

NH_3 EFs. Surface spreading showed the largest NH_3 EF of 0.1042 (95% CI, 0.0561–0.1523) kg NH_3–N kg (TN)$^{-1}$, while the EF was 0.0543 (95% CI, 0.0113–0.0973) kg NH_3–N kg (TN)$^{-1}$ for manure incorporation (Table 1). The NH_3 EF of beef cattle manure surface application seems low compared with that of other manure, with higher EF values in the range of 0.195–0.363 kg NH_3–N kg (TN)$^{-1}$ and 0.129–0.345 kg NH_3–N kg (TN)$^{-1}$ having been observed for poultry manure and pig manure surface application, respectively.[54−56] Beef cattle manure had been stored on the feedlot for a long time, leading to much of the easily decomposed N being lost during this phase and causing the low NH_3 emission during the final land application process. In addition, the low original N content of the freshly excreted beef cattle manure would also be a reason for the low NH_3 emission. Li[57] reported that the TN content of fresh swine manure was 154% higher than that of fresh beef cattle manure, being 8.94 g kg wet basis^{-1} (WB) and 3.52 g kg WB^{-1}, respectively.

3.2. Mitigation Measures. Various mitigation practices have been developed for reducing GHG and NH_3 emissions for the beef cattle production. The changes in CH_4, N_2O, and NH_3 emissions under different mitigation practices at each phase are presented in Figure 4.

3.2.1. Dietary Manipulation. Feed Additive. For ruminant production, feed additives are used to reduce enteric fermentation for reducing CH_4 emissions. Common feed additives include dietary lipids, ionophores, electron receptors, inhibitors, plant bioactive compounds (PBC), etc.[58] There

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were 21 publications found related to feed additives, among which 9 were related to dietary lipid additives, including coconut oil, crude glycerin supplements, sunflower oil, etc., and the ME for dietary lipid additives was −14.9% ($p < 0.05$; Figure 4). The most commonly used ionophore is monensin, and it showed a strong anti-methanogenic effect, leading to the ME being −11.5% ($p < 0.05$). However, ionophores are banned in the European Union and are therefore not applicable everywhere.[58] In the electron receptor category, nitrate, fumaric, and malic acids have been studied most, with the median mitigation effect being −15.2% ($p < 0.001$). Inhibitors such as bromochloromethane additives were quite effective in reducing enteric CH_4 emissions, with CH_4 reductions of −97.8%∼−54.3% in the study by Tomkins et al.[59] However, in the case of electron receptors and the inhibitors, the environmental and animal health implications are questionable.[59,60] The CH_4 mitigating effect of PBC in vivo remains controversial, and it was calculated that the PBC additives such as saponin and essential oil caused an increase of 2.8% on beef cattle CH_4 emission ($p = 0.109$). The CH_4 mitigation effect could be related to differences in feed retention times within the rumen as influenced by the level of saponin intake and composition of basal diet or in the quality of the PBC among experiments.[61] Thus, considering the mitigation effect along with the safety of each feed additive, dietary lipids were still the most recommended additive for enteric CH_4 mitigation. In addition, considering the potential negative effect of dietary lipids on feed intake, fiber digestibility, and overall animal productivity, the maximum recommended inclusion rate of dietary lipids in ruminant diets is 6% to 7% (total fat) of the dietary DM.[58]

Feed additives are mainly used for CH_4 mitigation from enteric fermentation, while little research has been performed related to N_2O and NH_3 mitigation with feed additives. Lee et al.[62] found no obvious effect on N_2O and NH_3 emissions from manure when the diet was amended with 1%, 2%, and 3% encapsulated calcium ammonium nitrate. Also, some additives such as ionophores may alter microbes in the rumen, which may lead to changes in volatile organic compound (VOC), such as ethanol (EtOH) and methanol (MeOH).[63] Because VOC can interact with nitrogen oxides (NOx) to form ozone (smog), which may impair human health and well being as well as the regional and global environment, it should also be considered in the future study.

Reducing the Forage-to-Concentrate Ratio. Reducing the FC ratio can lower CH_4 emission by −3.8% ($p = 0.221$). The reduced CH_4 output arising from the reduced FC ratio is due to a shift in ruminal fermentation patterns from acetate to propionate[64] and a decline in the ruminal pH.[65] When cattle were fed diets containing 90% or more concentrates, cattle CH_4 conversion factors (Ym) can be reduced by 50% compared with that from forage based diets.[9] However, compared to forage offered to cattle, concentrate was preferentially consumed due to its palatability, which would consequently contribute to more feed intake[66] and may, however, increase the enteric fermentation CH_4 emission, thus causing CH_4 mitigation efficiency from a low FC ratio to be low. The effect of low FC ratio on N_2O and NH_3 emissions was not appreciable.

Low Crude Protein Diet. The effect of a low crude protein (LCP) diet on CH_4 was not appreciable. However, a LCP diet is highly beneficial because it limits N at the source, resulting in a lower N content in the excreta (−12.8%, $p < 0.01$, Table S9) and, thus, may reduce N-related gaseous emissions during subsequent manure management phases. The effect of LCP on N_2O emission was not obvious, being of −3.5% ($p = 0.753$, Figure 4). However, it delivers an obvious mitigation potential for NH_3 emissions during the manure on the feedlot phase, being of −46.5% ($p = 0.068$). The only four observations collected for NH_3 mitigation caused the result to be not significant. LCP also provides other environmental co-benefits, such as reduced N losses in runoff and eutrophication.

3.2.2. Mitigation Measures for Manure on the Feedlot. No research was available on CH_4 mitigation from manure on the feedlot, and only one publication was available that considered both N_2O and NH_3 mitigation from manure on the feedlot.[26] Most studies about gas mitigation from beef cattle manure on the feedlot focus on the only subject of NH_3, mainly through the use of additives or increasing the manure clean frequency.

Manure Additives on the Feedlot. The commonly used additives for manure on the feedlot include urease inhibitors (UI), chemical amendments, lignite, and sawdust. The NH_3 mitigation mechanism for each additive varies. Urease inhibitors can block the hydrolysis of urea to ammonium[67] and, thereby, decrease NH_3 production. A total of 20 observations among the 34 observations collected in this study were about UI additives, and the median NH_3 ME of UI was −59.5% ($p < 0.001$). Considering that the inhibitor effect of the UI would be lower in soil conditions of high moisture, a high amount of UI should be applied when in high moisture conditions.[68,69] Chemical amendments such as alum ($Al_2(SO_4)_3$) and calcium chloride ($CaCl_2$) reduce NH_3 emissions by decreasing the pH and increasing the function of H^+ through cation exchange,[70] and the median NH_3 ME of chemical amendment was −85.0% ($p = 0.068$). For chemical amendment, only four observations were available for its specific use on beef cattle manure, resulting in an insignificant outcome ($p = 0.068$). The NH_3 mitigation mechanism of lignite is similar to that of chemical amendments. Lignite is acidic in nature (pH 3.69) and has a high cation exchange capacity.[71] In addition, lignite contains up to 20% labile carbon, which can absorb NH_4^+, and the high humic acid content can suppress urea hydrolysis.[71] The median NH_3 ME of lignite was −30.0%; because only three observations were available for its specific use on beef cattle manure, it resulted in an insignificant outcome ($p = 0.18$). Sun et al.[26] reported that N_2O emission increased from 0.10−0.14 to 0.14−0.22 g N_2O−N $head^{-1}$ day^{-1} with lignite additives for manure on the feedlot. However, considering the overall GHG emissions, the increase in direct N_2O emissions can be counteracted by the lower indirect N_2O emission due to decreased NH_3 volatilization (NH_3 emission decreased from 38.6−61.3 to 27.6−42.7 g NH_3−N $head^{-1}$ day^{-1}); thus, the lignite additive was effective in reducing the total GHG emission. Sawdust additive can widen the C-to-N ratio of the manure, showing a tendency to retain more nitrogen.[72] With the collected three observations, it was calculated that the sawdust additive can reduce NH_3 emission by 21% ($p = 0.285$). Among all of the additives, chemical amendment showed the highest NH_3 mitigation effect; however, the benefit-to-cost ratio was about a factor of 10 lower than that of UI.[70]

Increasing the Clean Frequency. No research monitored the effect of clean frequency on CH_4 and N_2O emissions. Only one study by Wilson et al.[73] reported that increasing the manure removal frequency (such as once a month, compared to the common frequency of once at the end of the feeding

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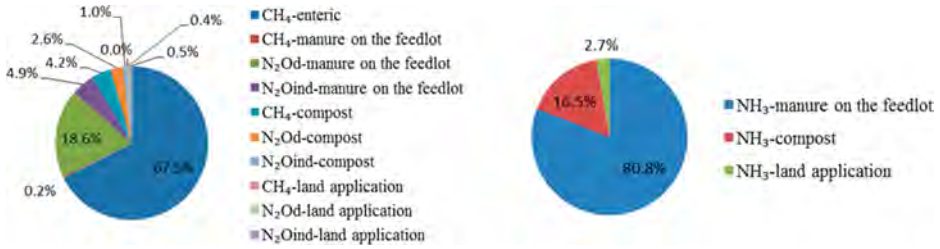

Figure 5. GHG and NH_3 emissions from the beef-cattle feedlot system by category of emissions.

period) can reduce NH_3 emissions by 19.1−20.8%. In addition, manure removal is also suggested to be used along with manure additives. For example, the effects of lignite will decline when the acidity is neutralized and the cation exchange capacity reduced through the accumulation of manure on the feedlot. Thus, after routine manure removal from pens, lignite needs to be reapplied to optimize the reduction of NH_3 emissions.[71]

3.2.3. Mitigation Measures for Manure Composting and Stockpiling. Compost Additives. There are only two papers that studied the impact of compost additives on gas emissions from beef cattle manure, with one study specified for CH_4 and N_2O[27] and the other for NH_3.[74] The results showed that additives can be effective in both CH_4 and NH_3 mitigation, with ME values of −97.0% (p = 0.102) and −30.0% (p = 0.109),[27,74] but it may increase N_2O emission by 135.0% (p = 0.109).[27] This is further explained by the phosphogypsum additive reducing N loss via NH_3 mitigation, while more N was retained in the form of NH_4^+-N in compost, which could thus serve as substrate for the nitrification and denitrification process, causing the increase of N_2O.[27]

Compost Biofilter. No research is available for the effect of biofilter on compost CH_4 and N_2O emissions specifically for beef cattle manure. The NH_3 emissions from compost can be reduced by 80.5−99.9% with compost biofilter,[75,76] with a median ME of 95% (p < 0.05). Because biofilters can only be used when the discharged air is being collected, and the manure from feedlot systems is usually being composted in an open air, this method is not considered in our system-level mitigation design.

Stockpile Covering. For beef manure stockpiling, CH_4 and N_2O emissions can be increased by 29.8% (p < 0.05) and 13.0% (p = 0.128) with straw or sawdust coverings, respectively; however, NH_3 emission could be reduced by 33.0% (p < 0.05). Covering caused an anaerobic environment in the pile, thus leading to higher CH_4 emission. Meanwhile, simultaneous aerobic and anaerobic conditions formed at the surface of pile under the cover, and the carbon input sourcing from the straw and sawdust stimulating the nitrification and denitrification process in the pile both triggered the increased N_2O emissions. However, one of the total seven observations collected by Zhu et al.[77] indicated that the N_2O emission may be reduced, with the reason being unclear, causing the result to be insignificant (p = 0.128).

3.2.4. Mitigation Measures for Land Application. Among the different manure application methods, manure incorporation can decrease N_2O and NH_3 emission simultaneously in comparison to surface application in some conditions. Incorporation can decrease N_2O emission by 65.0% (p < 0.05) in comparison to manure surface application, and it showed a significant NH_3 mitigation effect of 64.8% (p < 0.05). As indicated earlier in section 3.1.4, heavily textured soil inhibition of the N_2O diffusion pathway was caused by incorporation, thus decreasing N_2O emission. Combined with the advantage of nutrient conservation and odor reduction, beef cattle manure incorporation can be a highly recommended alternative application method.

Manure additives such as biochar and nitrification inhibitors resulted an integrated N_2O mitigation efficiency of −28.0% (p = 0.100). The biochar additions cannot always keep the N_2O emissions being reduced, causing the integrated N_2O mitigation effect to be not significant.[78] Manure additives such as lava meal can reduce NH_3 emission by 62.5% (p = 0.068). The adsorption of NH_4^+ by the lava meal, and also the precipitation of NH_4^+-N into struvite due to the presence of some P and especially Mg salts in the lava meal, cause the NH_3 emission being reduced.[79] However, only four observations was collected for the additives effect on NH_3, causing the result to be not significant.

3.2.5. Other Mitigation Options. When the collected manure was used for anaerobic fermentation, biogas recovery and utilization can exhibit a high GHG mitigation potential. However, CH_4 leakage from biogas digester, and the CH_4, N_2O, and NH_3 emissions from the digested slurry storage and land application stages should all be considered when calculating the mitigation effect. Unfortunately, no literature with a direct comparison of biogas digesters versus the baseline scenario for beef cattle manure was identified. Therefore, we could not give quantitative data on the mitigation efficiency of biogas digester.

3.3. Gas Emissions from the Baseline Scenario of a Beef Cattle Feedlot Production System. *3.3.1. GHG Emission.* The GHG emission from a baseline scenario of beef cattle feedlot production system is 2786 ± 108 kg CO_2-eq AU^{-1} $year^{-1}$. Among the gases, CH_4 contributed most of the GHG emissions, accounting for 72.0% of the total GHG emissions. The enteric CH_4 emission was 1882 ± 3 kg CO_2-eq kg AU^{-1} $year^{-1}$, accounting for 67.5% of the total GHG emissions (Figure 5). The GHG emission arising from manure management is 904 ± 127 kg CO_2-eq kg AU^{-1} $year^{-1}$. Among the manure on the feedlot stage, the manure composting stage, and the land application stage account for 23.8%, 7.8%, and 0.9% of the overall GHG emissions, respectively. The GHG mitigation priority should be focused on the enteric CH_4 emissions and manure N_2O emissions on the feedlot.

The N_2O emissions for manure on the feedlot stage, compost stage, and land application stage are 1.96, 0.28, and 0.04 kg N_2O AU^{-1} $year^{-1}$, respectively, which totaled 2.28 kg N_2O AU^{-1} $year^{-1}$. The calculated N_2O emission from Watts et al.[19] was 2.20, 0.69, and 0.28 kg N_2O AU^{-1} $year^{-1}$, respectively, for each stage of manure management and totaled to 3.17 kg N_2O AU^{-1} $year^{-1}$. The higher N_2O emissions from Watts' study may have arisen from the higher N excreta data used (75.2 kg $herd^{-1}$ $year^{-1}$), which was higher than the ASAE

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(2005) recommended value of 62.05 kg N AU^{-1} $year^{-1}$ used in this study.[80]

3.3.2. NH_3 Emission. The total NH_3 emissions from a beef cattle feedlot system is 49.1 ± 1.5 kg NH_3 AU^{-1} $year^{-1}$. The manure on the feedlot stage was the leading sector, accounting for 80.8% of the total NH_3 emissions, while the manure composting and land application stages accounted for 16.5% and 2.7%, respectively (Figure 5). Nearly 60% of the total N excreta was lost from manure on the feedlot, and only 9−19% of the excreted N was transferred to the next stage.[81] Watts et al.[19] estimated that 85%, 9%, and 6% of the total NH_3 emissions were from the manure on the feedlot stage, stockpiling stage and land application stage, respectively, which is similar to the results of this study. The lower percentage of 9% for the manure stockpiling stage in Watts's study was lower than the 16.5% found in our study, which may have been caused by the lower NH_3 emissions from stockpiling compared to composting.

3.4. Gas Emissions of Beef Cattle Feedlot Production Systems under Mitigation Scenarios. Considering the major emission sources, efficiency and operability of mitigation options, 11 mitigation scenarios were designed for beef-cattle feedlot production systems. The GHG and NH_3 emissions from the scenarios are presented in Figure 6.

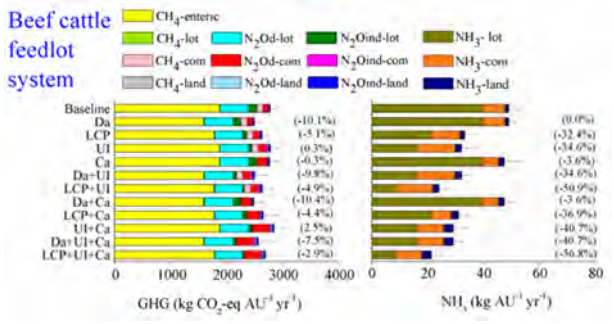

Figure 6. GHG and NH_3 emissions of baseline scenarios and mitigation scenarios for beef cattle feedlot production systems, with the baseline scenarios defined in Figure 2. The numbers in parentheses indicate the mitigation efficiency. N_2Od, direct N_2O emission; N_2Oind, indirect N_2O emission; lot, manure on the feedlot; com, compost; land, land application; LCP, low crude protein, Da, diet lipid addition; UI, UI additive for manure on the lot; Ca, compost additive; and AU, animal unit (1 AU = 500 kg).

The system-level GHG mitigation efficiencies of all mitigation scenarios were less than 11% (Figure 6). Of all of the mitigation strategies, dietary additives (Da) showed a high GHG mitigation potential for the whole system, with GHG emissions of 2505 ± 113 kg CO_2-eq AU^{-1} $year^{-1}$ for the solo use of Da, a 10.1% reduction from the baseline.

For system-level NH_3 mitigation, the most effective mitigation design was the combination of a LCP diet, a UI additive for manure on the feedlot, and compost additive (LCP plus UI plus Ca). The NH_3 emission was 21.2 ± 3.5 kg NH_3 AU^{-1} $year^{-1}$, with an efficiency of −56.8% compared with the baseline emissions. The single use of UI additive for manure on the feedlot or a LCP diet could reduce the overall system NH_3 emissions by 34.6% and 32.4%, respectively (Figure 6). The combination of LCP and UI lead to the system NH_3 emission being 24.1 ± 3.7 kg NH_3 AU^{-1} $year^{-1}$ (−50.9%), which was similar to the most effective NH_3 mitigation design of LCP plus UI plus Ca. This result also reveals that controlling the NH_3 emissions from the manure on the feedlot stage is fundamental for system-level NH_3 mitigation.

Considering the mitigation effect of each mitigation scenario, as well as the economy and simplicity of each option, the most recommended mitigation scenario is the combination of LCP and UI (LCP plus UI). The GHG and NH_3 emissions under the LCP plus UI scenario were 2648 ± 162 kg CO_2-eq AU^{-1} $year^{-1}$ (−4.9%) and 24.1 ± 3.7 kg NH_3 AU^{-1} $year^{-1}$ (−50.9%), respectively.

3.5. Implications of Results. This study provides the first insights into the simultaneous evaluation of GHG and NH_3 emissions and mitigations for beef cattle feedlot management systems, based on the database of the EFs and MEs for CH_4, N_2O, and NH_3 during each stage of the beef cattle feedlot production system. Both EFs and MEs were valuable for evaluating the gas emissions and identifying abundant mitigation options. These EFs could be applied to support the revision or refinement of the IPCC default EFs. However, the application of EFs or recommended mitigation strategies should take into account local circumstances, including climate, weather, and soil properties in different locations. In addition, the economic feasibility for the mitigation measures should also be further considered.

Scenario analysis for the beef cattle feedlot system implies that NH_3 emissions could be reduced by 30%−50% and that the highest system-level GHG emissions mitigation potential was only 10.1%. With the increasing demand for beef production and to decrease GHG emissions after the Paris Agreement, low emission beef cattle production systems are urgently needed. The results of our analysis have important implications for developing sustainable beef cattle feedlot systems from the viewpoint of GHG and NH_3 mitigation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b02475.

A brief description of the detailed methods, equations, parameters, and assumptions for calculating the emissions for baseline and mitigation scenarios of each phase and whole systems for beef cattle feedlot production. Tables showing the unit conversion method, a detailed set of the baseline scenario and the mitigation scenarios and calculated gas emission factors for beef cattle feedlot systems in four stages, gas mitigation efficiency of each mitigation option, and other parameters used in gas emission calculation (PDF)

Tables showing the gas emissions calculation process, the parameters used for calculation, and raw data from the literature (XLSX)

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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Notes

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■ REFERENCES

(1) Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, United Kingdom, 2013.

(2) Li, L.; Xu, J.; Hu, J.; Han, J. Reducing nitrous oxide emissions to mitigate climate change and protect the ozone layer. *Environ. Sci. Technol.* **2014**, *48* (9), 5290−5297.

(3) Montzka, S.; Dlugokencky, E.; Butler, J. Non-CO_2 greenhouse gases and climate change. *Nature* **2011**, *476* (7358), 43−50.

(4) Rao, S.; Riahi, K. The role of non-CO_2 greenhouse gases in climate change mitigation: Long-term scenarios for the 21st century. *Energy J.* **2006**, *27* (3), 177−200.

(5) Hansen, J.; Sato, M.; Ruedy, R.; Lacis, A.; Oinas, V. Global warming in the twenty-first century: An alternative scenario. *Proc. Natl. Acad. Sci. U. S. A.* **2000**, *97* (18), 9875−9880.

(6) Manne, A. S.; Richels, R. G. An alternative approach to establishing trade-offs among greenhouse gases. *Nature* **2001**, *410* (6829), 675−677.

(7) Bergström, A. N. N. K.; Jansson, M. Atmospheric nitrogen deposition has caused nitrogen enrichment and eutrophication of lakes in the northern hemisphere. *Glob. Change Biol.* **2006**, *12* (4), 635−643.

(8) Bouwman, A. F.; Boumans, L. J. M.; Batjes, N. H. Estimation of global NH_3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. *Glob. Biogeochem. Cycles* **2002**, *16* (2), 1−14.

(9) Intergovernmental Panel on Climate Change (IPCC). *IPCC 2006 Guidelines for National Greenhouse Gas Inventories Vol. 4: Agriculture, Forestry, and Other Landuse*; Institute for Global Environmental Strategies: Hayama, Japan, 2006.

(10) Squizzato, S.; Masiol, M.; Innocente, E.; Pecorari, E.; Rampazzo, G.; Pavoni, B. A procedure to assess local and long-range transport contributions to PM 2.5, and secondary inorganic aerosol. *J. Aerosol Sci.* **2012**, *46* (2), 64−76.

(11) Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, United Kingdom, 2014.

(12) Davidson, E. A. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nat. Geosci.* **2009**, *2* (9), 659−662.

(13) Steinfeld, H.; Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; De Haan, C. *Livestock's long shadow*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2006.

(14) Food and Agriculture Organization of the United Nations (FAO). FAOSTAT of live animal production 2014. http://www.fao.org/faostat/en/#data/GE (accessed March 1, 2018).

(15) Paulot, F.; Jacob, D. J.; Pinder, R. W.; Bash, J. O.; Travis, K.; Henze, D. K. Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: Interpretation with a new agricultural emissions inventory (MASAGE_NH_3). *J. Geophys Res.* **2014**, *119* (7), 4343−4364.

(16) Owen, J. J.; Silver, W. L. Greenhouse gas emissions from dairy manure management: a review of field-based studies. *Globa.l Change Biol.* **2015**, *21*, 550−565.

(17) United States Department of Agriculture. *2012 Census of Agriculture, United States, summary and state data, volume 1: Geographic area series, part 51*. https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf (accessed July 1, 2018).

(18) Parker, D. B.; Auvermann, B. W.; Stewart, B. A.; Robinson, C. A. Agricultural energy consumption, biomass generation, and livestock manure value in the Southern High Plains. In *Proc. Workshop No. 1, Livestock Waste Streams: Energy and Environment*; Texas Renewable Energy Industries Association: Austin, TX, 1997,1−18.

(19) Watts, P.; McGahan, E.; Bonner, S.; Wiedemann, S. *Feedlot mass balance and greenhouse gas emissions−a literature review*; Meat & Livestock Australia: Sydney, Australia, 2012.

(20) California Air Resources Board (CARB). *Annex 3B: Manure Management (IPCC 3A2) to the Technical Support Document for the 2000−2009 California's Greenhouse Gas Emissions Inventory*; California Air Resources Board: Sacramento, CA, 2011.

(21) Beauchemin, K. A.; McGinn, S. M. Enteric methane emissions from growing beef cattle as affected by diet and level of intake. *Can. J. Anim. Sci.* **2006**, *86* (3), 401−408.

(22) DeRamus, H. A.; Clement, T. C.; Giampola, D. D.; Dickison, P. C. Methane emissions of beef cattle on forages. *J. Environ. Qual.* **2003**, *32* (1), 269−277.

(23) Redding, M. R.; Devereux, J.; Phillips, F.; Lewis, R.; Naylor, T.; Kearton, T.; Hill, C.; Weidemann, S. Field measurement of beef pen manure methane and nitrous oxide reveals a surprise for inventory calculations. *J. Environ. Qual.* **2015**, *44* (3), 720−728.

(24) Borhan, M. S.; Capareda, S. C.; Mukhtar, S.; Faulkner, W. B.; McGee, R.; Parnell, C. B. Greenhouse gas emissions from ground level area sources in dairy and cattle feedyard operations. *Atmosphere* **2011**, *2* (3), 303−329.

(25) Costa, C., Jr.; Li, C.; Cerri, C. E.; Cerri, C. C. Measuring and modeling nitrous oxide and methane emissions from beef cattle feedlot manure management: First assessments under Brazilian condition. *J. Environ. Sci. Health, Part B* **2014**, *49* (9), 696−711.

(26) Sun, J.; Bai, M.; Shen, J.; Griffith, D. W.; Denmead, O. T.; Hill, J.; Lam, S. K.; Mosier, A. R.; Chen, D. Effects of lignite application on ammonia and nitrous oxide emissions from cattle pens. *Sci. Total Environ.* **2016**, *565*, 148−154.

(27) Hao, X.; Larney, F. J.; Chang, C.; Travis, G. R.; Nichol, C. K.; Bremer, E. The effect of phosphogypsum on greenhouse gas emissions during cattle manure composting. *J. Environ. Qual.* **2005**, *34* (3), 774−781.

(28) Opio, C.; Gerber, P.; Mottet, A.; Falcucci, A.; Tempio, G.; MacLeod, M.; Vellinga, T.; Henderson, B.; Steinfeld, H. *Greenhouse gas emissions from ruminant supply chains − A global life cycle assessment*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2013.

(29) Hou, Y.; Velthof, G. L.; Oenema, O. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. *Glob. Change Biol.* **2015**, *21* (3), 1293−1312.

(30) Wang, Y.; Dong, H.; Zhu, Z.; Gerber, P. J.; Xin, H.; Smith, P.; Opio, C.; Steinfeld, H.; Chadwick, D. Mitigating Greenhouse Gas and Ammonia Emissions from Swine Manure Management: A System Analysis. *Environ. Sci. Technol.* **2017**, *51* (8), 4503−4511.

(31) Fedorov, S. *GetData Graph Digitizer version 2.24*. www.getdata-graph-digitizer.com (accessed October 1, 2017).

(32) Environmental Systems Research Institute (ESRI). ArcGIS Desktop 10.0. http://desktop.arcgis.com/en (accessed March 1, 2018).

DOI: 10.1021/acs.est.8b02475
Environ. Sci. Technol. 2018, 52, 11232−11242

(33) Larson-Hall, J.; Herrington, R. Improving data analysis in second language acquisition by utilizing modern developments in applied statistics. *Appl. Linguist.* **2010**, *31* (3), 368−390.
(34) Benayas, J. M. R.; Newton, A. C.; Diaz, A.; Bullock, J. M. Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. *Science* **2009**, *325*, 1121−1124.
(35) Tuomisto, H. L.; Hodge, I. D.; Riordan, P.; Macdonald, D. W. Does organic farming reduce environmental impacts?−A meta-analysis of European research. *J. Environ. Manage.* **2012**, *112*, 309−320.
(36) Van Haarlem, R. P.; Desjardins, R. L.; Gao, Z.; Flesch, T. K.; Li, X. Methane and ammonia emissions from a beef feedlot in western Canada for a twelve-day period in the fall. *Can. J. Anim. Sci.* **2008**, *88* (4), 641−649.
(37) Mcginn, S. M.; Chen, D.; Loh, Z.; Hill, J.; Beauchemin, K. A.; Denmead, O. T. Methane emissions from feedlot cattle in Australia and Canada. *Aust. J. Exp. Agric.* **2008**, *48* (2), 183−185.
(38) Hegarty, R. S.; Goopy, J. P.; Herd, R. M.; McCorkell, B. Cattle selected for lower residual feed intake have reduced daily methane production. *J. Anim. Sci.* **2007**, *85* (6), 1479−1486.
(39) Arthur, P. F.; Archer, J. A.; Herd, R. M. Feed intake and efficiency in beef cattle: overview of recent Australian research and challenges for the future. *Aust. J. Exp. Agric.* **2004**, *44* (5), 361−369.
(40) Misselbrook, T.; Webb, J.; Chadwick, D.; Ellis, S.; Pain, B. Gaseous emissions from outdoor concrete yards used by livestock. *Atmos. Environ.* **2001**, *35* (31), 5331−5338.
(41) Misselbrook, T.; Webb, J.; Gilhespy, S. Ammonia emissions from outdoor concrete yards used by livestock—quantification and mitigation. *Atmos. Environ.* **2006**, *40* (35), 6752−6763.
(42) Demmers, T.; Phillips, V.; Short, L.; Burgess, L.; Hoxey, R.; Wathes, C. SE—Structure and Environment: Validation of ventilation rate measurement methods and the ammonia emission from naturally ventilated dairy and beef buildings in the United Kingdom. *J. Agric. Eng. Res.* **2001**, *79* (1), 107−116.
(43) Boadi, D. A.; Wittenberg, K. M.; Scott, S. L.; Burton, D.; Buckley, K.; Small, J. A.; Ominski, K. H. Effect of low and high forage diet on enteric and manure pack greenhouse gas emissions from a feedlot. *Can. J. Anim. Sci.* **2004**, *84* (3), 445−453.
(44) Rahman, S.; Borhan, M. S.; Swanson, K. Greenhouse gas emissions from beef cattle pen surfaces in North Dakota. *Environ. Technol.* **2013**, *34* (10), 1239−1246.
(45) Borhan, M.; Gautam, D.; Engel, C.; Anderson, V.; Rahman, S. Effects of pen bedding and feeding high crude protein diets on manure composition and greenhouse gas emissions from a feedlot pen surface. *J. Air Waste Manage. Assoc.* **2013**, *63* (12), 1457−1468.
(46) Drury, C. F.; Yang, X.; Reynolds, W. D.; Calder, W.; Oloya, T. O.; Woodley, A. L. Combining urease and nitrification inhibitors with incorporation reduces ammonia and nitrous oxide emissions and increases corn yields. *J. Environ. Qual.* **2017**, *46* (5), 939−949.
(47) Woodley, A. L.; Drury, C. F.; Reynolds, W.; Calder, M. W.; Yang, X. M.; Oloya, T. O. Improved acid trap methodology for determining ammonia volatilization. Canadian Journal of Soil Science. Improved acid trap methodology for determining ammonia volatilization in wind tunnel experiments. *Can. J. Soil Sci.* **2018**, *98*, 193−199.
(48) Aguilar, O. A. *Measurement and control of greenhouse gas emissions from beef cattle feedlots*. PhD thesis. Kansas State University, Manhattan, KS, 2013.
(49) Le Mer, J.; Roger, P. Production, oxidation, emission and consumption of methane by soils: a review. *Eur. J. Soil Biol.* **2001**, *37* (1), 25−50.
(50) Chiyoka, W.; Hao, X.; Zvomuya, F.; Li, X. Nitrous oxide emissions from Chernozemic soils amended with anaerobically digested beef cattle feedlot manure: A laboratory study. *Anim. Feed Sci. Technol.* **2011**, *166*, 492−502.
(51) Chang, C.; Janzen, H.; Cho, C. Nitrous oxide emission from long-term manured soils. *Soil Sci. Soc. Am. J.* **1998**, *62* (3), 677−682.
(52) Velthof, G. L.; Kuikman, P. J.; Oenema, O. Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biol. Fertility Soils* **2003**, *37* (4), 221−230.
(53) Webb, J.; Chadwick, D.; Ellis, S. Emissions of ammonia and nitrous oxide following incorporation into the soil of farmyard manures stored at different densities. *Nutr. Cycling Agroecosyst.* **2004**, *70* (1), 67−76.
(54) Li, J.; Su, F.; Huang, B.; Hu, X.; Ju, X.; Zhang, F. Ammonia volatilization from field-applied chicken manure in Beijing. *J. Agro-Environ. Sci.* **2009**, *28* (9), 1959−1964 (in Chinese with English abstract) .
(55) Webb, J.; Thorman, R.; Fernanda-Aller, M.; Jackson, D. Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types. *Atmos. Environ.* **2014**, *82*, 280−287.
(56) Dinuccio, E.; Gioelli, F.; Balsari, P.; Dorno, N. Ammonia losses from the storage and application of raw and chemo-mechanically separated slurry. *Agric., Ecosyst. Environ.* **2012**, *153*, 16−23.
(57) Li, L. L. *Study on the Characteristic and Reduction for Greenhouse Gases and Ammonia Emissions during the Storage of Manure and Wastewater*. Master thesis. Chinese Academy of Agricultural sciences, Beijing, China, 2016 (in Chinese with English abstract).
(58) Gerber, P. J.; Hristov, A. N.; Henderson, B.; Makkar, H.; Oh, J.; Lee, C.; Meinen, R.; Montes, F.; Ott, T.; Firkins, J.; Rotz, A.; Dell, C.; Adesogan, A. T.; Yang, W. Z.; Tricarico, J. M.; Kebreab, E.; Waghorn, G.; Dijkstra, J.; Oosting, S. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. *Animal* **2013**, *7* (s2), 220−234.
(59) Tomkins, N.; Colegate, S.; Hunter, R. A bromochloromethane formulation reduces enteric methanogenesis in cattle fed grain-based diets. *Anim. Prod. Sci.* **2009**, *49* (12), 1053−1058.
(60) Leng, R. A. *The potential of feeding nitrate to reduce enteric methane production in ruminants*; Report to the Department of Climate Change; Commonwealth Government of Australia: Canberra, Australia. 2008.
(61) Li, W.; Powers, W. Effects of saponin extracts on air emissions from steers. *J. Anim. Sci.* **2012**, *90* (11), 4001−4013.
(62) Lee, C.; Araujo, R. C.; Koenig, K. M.; Hile, M. L.; Fabian-Wheeler, E. E.; Beauchemin, K. A. Effects of feeding encapsulated nitrate to beef cattle on ammonia and greenhouse gas emissions from their manure in a short-term manure storage system. *J. Environ. Qual.* **2016**, *45* (6), 1979−1987.
(63) Stackhouse-Lawson, K. R.; Calvo, M. S.; Place, S. E.; Armitage, T. L.; Pan, Y.; Zhao, Y.; Mitloehner, F. M. Growth promoting technologies reduce greenhouse gas, alcohol, and ammonia emissions from feedlot cattle. *J. Anim. Sci.* **2013**, *91* (11), 5438−5447.
(64) Benchaar, C.; Pomar, C.; Chiquette, J. Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. *Can. J. Anim. Sci.* **2001**, *81* (4), 563−574.
(65) Van Kessel, J. A. S.; Russell, J. B. The effect of pH on ruminal methanogenesis. *FEMS Microbiol. Ecol.* **1996**, *20* (4), 205−210.
(66) Mc Geough, E. J.; O'Kiely, P.; Hart, K. J.; Moloney, A. P.; Boland, T. M.; Kenny, D. A. Methane emissions, feed intake, performance, digestibility, and rumen fermentation of finishing beef cattle offered whole-crop wheat silages differing in grain content. *J. Anim. Sci.* **2010**, *88* (8), 2703−2716.
(67) Varel, V. H.; Nienaber, J. A.; Freetly, H. C. Conservation of nitrogen in cattle feedlot waste with urease inhibitors. *J. Anim. Sci.* **1999**, *77* (5), 1162−1168.
(68) Faria, L. D. A.; do Nascimento, C. A. C.; Bardella, G. R.; de Moura, T. A.; Mendes, F. L.; Vitti, G. C. NH3 Volatilization from Urea-NBPT in Eucalyptus. *Commun. Soil Sci. Plant Anal.* **2016**, *47* (6), 769−774.
(69) Li, Q. Q. *Effect of urease inhibitor LIMUS on ammonia mitigation and crop yield and nitrogen use efficiency in different croplands of China*. PhD thesis. Chinese Agricultural University, Beijing, China, 2014 (in Chinese with English abstract).

DOI: 10.1021/acs.est.8b02475
Environ. Sci. Technol. 2018, 52, 11232−11242

(70) Shi, Y.; Parker, D.; Cole, N.; Auvermann, B.; Mehlhorn, J. Surface amendments to minimize ammonia emissions from beef cattle feedlots. *Trans. ASAE* **2001**, *44* (3), 677−682.
(71) Chen, D.; Sun, J.; Bai, M.; Dassanayake, K. B.; Denmead, O. T.; Hill, J. A new cost-effective method to mitigate ammonia loss from intensive cattle feedlots: application of lignite. *Sci. Rep.* **2015**, *5*, 16689.
(72) Lory, J.; Adams, J.; Eghball, B.; Klopfenstein, T.; Powers, J. F. Effect of sawdust or acid application to pen surfaces on nitrogen losses from open-dirt feedlots. Nebraska Beef Cattle Reports: Lincoln, NE, 2002; pp 52−53.
(73) Wilson, C. B.; Erickson, G. E.; Macken, C. N.; Klopfenstein, T. J. *Impact of cleaning frequency on nitrogen balance in open feedlot pens*. Nebraska Beef Cattle Reports: Lincoln, NE, 2004; pp 72−73.
(74) Lim, S. S.; Park, H. J.; Hao, X.; Lee, S. I.; Jeon, B. J.; Kwak, J. H.; Choi, W. J. Nitrogen, carbon, and dry matter losses during composting of livestock manure with two bulking agents as affected by co-amendments of phosphogypsum and zeolite. *Ecol. Eng.* **2017**, *102*, 280−290.
(75) Park, K. J.; Choi, M. H.; Hong, J. H. Control of composting odor using biofiltration. *Compost Sci. Util.* **2002**, *10* (4), 356−362.
(76) Xue, N.; Wang, Q.; Wu, C. F.; Zhang, L. H.; Xie, W. M. Enhanced removal of NH3 during composting by a biotrickling filter inoculated with nitrifying bacteria. *Biochem. Eng. J.* **2010**, *51* (1), 86−93.
(77) Zhu, H. S.; Zuo, F. Y.; Dong, H. M.; Luan, D. M. Effects of covering materials and sawdust covering depths on ammonia and greenhouse gase emissions from cattle manure during storage. *Transactions of the CSAE* **2015**, *31* (6), 223−229 (in Chinese with English abstract) .
(78) Watanabe, A.; Ikeya, K.; Kanazaki, N.; Makabe, S.; Sugiura, Y.; Shibata, A. Five crop seasons' records of greenhouse gas fluxes from upland fields with repetitive applications of biochar and cattle manure. *J. Environ. Manage.* **2014**, *144*, 168−175.
(79) Shah, G. M.; Shah, G. A.; Groot, J. C. J.; Oenema, O.; Lantinga, E. A. Irrigation and lava meal use reduce ammonia emission and improve N utilization when solid cattle manure is applied to grassland. *Agric., Ecosyst. Environ.* **2012**, *160* (4), 59−65.
(80) *ASAE Standards D384.1: Manure Production and Characteristics*; American Society of Agricultural Engineers: Saint Joseph, MI, 2004.
(81) Bierman, S.; Erickson, G.; Klopfenstein, T.; Stock, R. A.; Shain, D. Evaluation of nitrogen and organic matter balance in the feedlot as affected by level and source of dietary fiber. *J. Anim. Sci.* **1999**, *77* (7), 1645−1653.

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Environ. Sci. Technol. 2018, 52, 11232−11242

The cow in the room: why is no one talking about farming at Cop26?

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https://www.theguardian.com/profile/phoebe-weston,https://www.theguardian.com/profile/jonathanwatts November 9, 2021



Activists parade with a giant inflatable cow to highlight the problem of methane emissions at a Cop26 march in Glasgow on Saturday. Photograph: Climate Healers

Sustainable food systems are a cornerstone to cutting emissions but have been largely absent from the agenda in Glasgow

“The cow in the room is being ignored at this Cop,” says Carl Le Blanc of Climate Healers. “Animal agriculture has been taken off the agenda and put on the menu.”

Le Blanc was one of a number of campaigners who joined climate marches on Saturday in Glasgow to demand action for a new sustainable food system. They fought strong gales to make their point with four giant inflatable animals tethered on ropes above their heads or strapped to the ground. Each symbolised a different problem of the livestock industry: a 40ft cow for methane, a chicken for Covid and health, a fish for microplastics, and a pig for obesity.

Many industry representatives and campaigners feel not enough attention has been paid to food and farming at Cop26, despite it being one of the keys to cutting emissions over the next few decades. Food served at the canteen has been criticised – nearly 60% of dishes

contain meat or dairy, which campaign group Animal Rebellion described as the equivalent of “serving cigarettes at a lung cancer conference”.

During the two weeks of the conference, themes such as finance, energy and transport have been allocated their own days, but there has been no dedicated day for agriculture or food systems. Farming was included in Nature day on Saturday, where there was a lot of talk about protecting forests but less about cutting meat consumption, food waste and firm pledges to change farming subsidy systems.

Farming is a complex issue on the journey to net zero, as it is both a source and sink for emissions. About 20% of global emissions come from agriculture and land use, and this rises to more than 25% for the food system as a whole, which includes processing, packaging and transport. Yet huge amounts of carbon can be sequestered by modifying farmland, with the creation of more forests, healthier peatlands and wetlands. Although some argue that we should stop consuming animal livestock altogether, others believe that low densities of grazing animals such as cattle are an important part of creating farmland habitats that produce food and also provide a home for wildlife.



Cattle in Para state, Brazil, where the destruction of the Amazon has accelerated, in part due to illegal deforestation to clear land for intensive farms. Photograph: Mauro Pimentel/AFP/Getty Images

In terms of individual action, moving to a more plant-based diet is one of the single most effective ways to reduce emissions, but the UK government appears to be unwilling to put the science on this issue into policy. It quickly deleted research alongside its net zero strategy that encouraged levies on high-carbon foods, such as meat.

None of the presidents of the UK's four farming unions present at Cop26 believe they should reduce livestock numbers in their respective countries, or that people need to reduce their meat consumption. They told the Guardian methane emissions could be dealt with through new technologies rather than reducing the number of cows on farms. Thomas Vilsack, the US secretary of agriculture says he believes Americans can carry on eating the same amount of meat while keeping the world within safe limits on global heating.

In a small side room at the Cop26 conference, pro-vegan groups said there was more discussion of meat than at the Cop two years ago, but still policy lagged far behind science. "Animal meat is obsolete, it doesn't make any sense. It's from the last century," says Bernat Añaños, co-founder of plant-based meat company Heura Foods.

But others warn it is dangerous to reproduce historical tendencies to tell farmers what their goals should be. "There cannot be a one size fits all," says Ishmael Sunga, CEO of the Southern African Confederation of Agricultural Unions (SACAU). "I respect that space, but they cannot impose their views on others."

Small family farms produce a third of the world's food, and hundreds of millions of people depend on livestock farming for their livelihoods. Although farming for animal proteins is a key driver of biodiversity loss, Sunga says it is important to make sure any changes are fair for producers on the front line. "It needs to be a just transition. We know most of the farmers in developing countries are near-destitute. It's also an irony that food is one of the biggest industries in the world, but it delivers so badly for farmers. They go hungry, they absorb the climate front-risk, while the rest of us carry on walking around smiling."

The only significant agricultural announcement made on farming at the leaders' summit was the AIM4C declaration unveiled by the US president, Joe Biden, in partnership with the UAE. It promised an extra $4bn for agricultural innovation aimed at reducing emissions. But this has been criticised by many activists who say it is an attempt to reframe destructive intensive farming as part of the climate solution, instead of the problem.

"The US and the UAE are presenting a vision for the future of farming that is a future without farmers. Such a form of agriculture is a dangerous fantasy," says Tom Wakeford, an ecologist and action researcher at ETC Group.



A Holstein cow waiting to be milked using automated milking equipment in Alberta, Canada. Photograph: Design Pics/Alamy

There are two main camps when it comes to agriculture's relationship with wildlife. Some believe in land sparing, which is essentially farming intensively with separate areas for wildlife, while others believe in land sharing, which refers to agroecological approaches where farming and wildlife co-exist.

Jyoti Fernandes, a Dorset farmer and policy and campaigns coordinator at the Landworkers' Alliance, is a proponent of the latter. She believes livestock is an important part of traditional land management. For her, the key is to stop intensive meat farming and focus on producing high-quality meat within smaller, mixed farms that provide high employment for local people.

"It's outrageous that so little time at Cop26 has been devoted to agroecological farmers," she says. "The programme is very weak. If they are promoting nature we must talk about farming. Agroecological farming can nurture biodiversity, sequester carbon and regenerate the planet by looking after our soil, creating habitat and planting trees."

Subsidies are at the heart of how agricultural landscapes have been shaped. A recent UN report concluded that almost 90% of the $540bn of global agricultural subsidies given to farmers destroy nature and fuel the climate crisis. Subsidies have generally encouraged farmers to produce as much food as possible, but this has been at the expense of wildlife.

With habitat destruction due to the expansion of farmland identified as one of the main drivers of biodiversity decline, many are arguing for farming subsidies to be radically overhauled. The UN report found redirecting subsidies to beneficial farming practices could be a “game changer”, yet there was little mention of them in the leaders’ speeches at Cop26.

The most significant announcement came on Nature day, when governments endorsed the Policy Action Agenda, signalling their intent to shift agricultural subsidies to better support climate and nature-friendly farming. Although it only involved 16 countries, it included large emitters, such as Switzerland, Nigeria, Spain and UAE; in total these countries represent 10% of world’s greenhouse gas emissions from agriculture. The UK also launched a £65m Just Rural Transition programme to help developing countries move towards more sustainable agricultural systems.



Cattle graze on a regenerative farm in Cumbria. Photograph: Anthony Cullen/The Guardian

The UK farming policy Environmental Land Managements (ELMs), announced earlier this year, will reward farmers for delivering public goods, such as tree-planting, water retention and biodiversity benefits on their farms. Farmers grazing livestock less intensively, with more space for nature on their farms, will also be rewarded.

England’s National Farmers Union president, Minette Batters, says changing the subsidy system and harnessing private funds is an opportunity to implement nature-based solutions such as planting trees, using less chemical fertilisers, creating more hedges and enriching soils on farmland.

“We’ve got the opportunity to create a new relationship with the land, and new economic value for the land. We all talk about it, but we’re absolutely appalling at delivering the finance back into where it needs to go. Those trillions just circulate in the ether. We’ve got to drive that financial resource back into the soil.

“We can’t do anything without farmers, they are the eco-workforce of the future,” she says.

While many industries like coal and gas might have felt positive about not being included in the Cop26 programme, many farmers feel they can make a real difference.

“What is baffling for us, is why farming is not on the table with negotiators,” says Sunga. “By focusing on other areas and not focusing on food and agriculture you are running away from the problem, and that’s where solutions with the greatest impact are going to be.”

WHITE EARTH RESERVATION BUSINESS COMMITTEE
WHITE EARTH BAND OF CHIPPEWA INDIANS

Resolution No. 057-23-006A

Ordinance Imposing a Moratorium on Concentrated Animal Feeding Operation and Animal Feedlot Operation Environmental Hazard Construction Inconsistent With Existing Activities and Land Uses, And Expansion of Concentrated Animal Feeding Operation and Animal Feedlot Operation Environmental Hazard Activities and Land Uses Pending the Study of Possible Regulatory Action.

WHEREAS, the White Earth Reservation Business Committee is the duly elected governing body of the White Earth Reservation pursuant to Article VI, Section 1, of the revised constitution of the Minnesota Chippewa Tribe, as amended, and organized under Section 16, of the Act of June 18, 1934 (48 Stat. 984), and

WHEREAS, the White Earth Reservation Business Committee is the duly authorized governing body of the White Earth Band, and

WHEREAS, the White Earth Reservation Business Committee adopted the White Earth Reservation, Environmental Code, including the Band's Zoning Code, for the protection, management, enforcement and enhancement of all natural resources within the Reservation boundaries (Resolution number 057-11-001). A copy of which is incorporated by reference, and

WHEREAS, the White Earth Reservation Business Committee established the White Earth Division of Natural Resources (WEDNR) to protect, restore and regulate the natural resources of the Band and its Band Members in order to ensure environmental and human health and spiritual, cultural and economic sustainability of the Band, and

WHEREAS, the White Earth Reservation Business Committee defines Concentrated Animal Feeding Operations ("CAFOs") as a facility at which (i) for not less than a total of 45 days in any 12-month period, animals are stabled or confined or fed or ~~maintained; (ii) crops~~, vegetation, forage growth, or postharvest residues are not sustained in the normal growing season over any portion of the lot or facility and (iii) not less than 700 mature dairy cows, 1,000 veal calves, 1,000 cattle other than mature dairy cows or veal calves, 2,500 swine (each weighing not less than 55 pounds), 10,000 swine (each weighing not more than 55 pounds), 500 horses, 10,000 sheep or lambs, 55,000 turkeys, 30,000 laying hens/broilers, 125,000 chickens, 82,000 laying hens, or 5,000 ducks are present, and

WHEREAS, the White Earth Reservation Business Committee defines Animal Feedlot Operations ("AFOs") as a lot or building or combination of lots and buildings intended for the confined feeding, breeding, raising, or holding of animals and specifically designed as a confinement area in which manure may accumulate, or where the concentration of animals is such that a vegetative cover cannot be maintained within the enclosure. Open lots used for the feeding and rearing of poultry shall be considered to be animal feedlots, and

WHEREAS, the White Earth Reservation Business Committee identifies AFOs as environmental hazards if (i) not less than 525 mature dairy cows, 750 veal calves, 750 cattle, 1,875 swine (each weighing not less than 55 pounds), 7,500 swine (each weighing not more than 55 pounds), 375 horses, 7,500 sheep or lambs, 41,250 turkeys, 22,500 laying hens/broilers or 3,750 ducks are present and (ii) they present a potential or immediate risk of pollution to or depletion of ground or surface water as determined by a review or inspection undertaken by the WEDNR after taking into consideration: the size of an animal feedlot or manure storage area, the amount of water to be used, the amount of pollutants reaching or that may reach ground or surface waters, the location of the animal feedlot or manure storage area relative to ground and surface waters, the means of conveyance of animal manure or process wastewater into ground or surface waters, and the slope, vegetation, rainfall, and other factors affecting the likelihood or frequency of discharge of animal manure or process wastewater into ground or surface water, and

WHEREAS, the White Earth Reservation includes 530 lakes, 300 miles of rivers and streams, 167,878 acres of wetlands and substantial groundwater resources contained in shallow, unconfined and deeper, layered aquifers, all of which are integral to the economic security and the health and welfare of the Band, and

WHEREAS, the WEDNR, working with relevant scientific and community experts, has thoroughly analyzed and identified substantial individual and cumulative water quality threats from the operation of CAFOs and AFO environmental hazards on the White Earth Reservation including E.coli, dissolved oxygen, turbidity, phosphorus and nitrogen environmental and impairments, and

WHEREAS, the WEDNR, working with relevant scientific and community experts, has thoroughly analyzed and identified substantial individual and cumulative water ~~quantity threats including~~ water table drawdown, ~~residential and community well~~ interference and surface waterbody drawdown, dissolved oxygen impairment and temperature impairment from the operation of high-capacity water wells associated with CAFOs and AFO environmental hazards on the White Earth Reservation, and

WHEREAS, the WEDNR, working with relevant scientific and community experts, has analyzed and identified substantial individual and cumulative air quality threats including the emission of hazardous chemical gases such as ammonia, hydrogen sulfide and

methane from the operation of CAFOs and AFO environmental hazards on the White Earth Reservation, and

WHEREAS, the WEDNR, working with relevant scientific and community experts, has analyzed and identified substantial individual and cumulative human health threats including cancer, brain damage, dizziness, headache, nausea, sore throats, sinusitis, burning eyes, acute gastrointestinal illness, increased cardiovascular mortality risk, anemia, kidney disease and septicemia from the operation of CAFOs and AFO environmental hazards on the White Earth Reservation, and

WHEREAS, the WEDNR has identified that the individual and cumulative air, water and human health threats from the operation of CAFOs and AFO environmental hazards on the White Earth Reservation directly threaten the health, welfare, natural resources, economic security and cultural continuity of the Band, and

WHEREAS, the Band possesses "inherent powers of a limited sovereignty which has never been extinguished" and has plenary and exclusive power over its members and territory subject only to limitations imposed by federal law, *United States v. Wheeler,* 435 U.S. 313, 322-23 (1978); *Worcester v. Georgia,* 31 U.S. 515,555 (1832), and

WHEREAS, with the establishment of the White Earth Reservation, the Band obtained federal property rights to a sufficient quantity and quality of water to fulfill the purposes of the reservation now and in the future, *United States v. Winans,* 198 U.S. 371 (1905), *Winters v. United States*, 207 U.S. 564 (1908), and

WHEREAS, the Band is entitled to sufficient quantity and quality of water in order to make the reservation livable, enable tribal members to maintain customary ways of life and permit tribal members to change and adopt to new ways of life, *Arizona v. California,* 373 U.S. 546, 599 (1963); *Menominee Tribe v. United States*, 391 U.S. 404, 406 (1968); *Winters v. United States,* 207 U.S. 56, 577 (1908), and

WHEREAS, federal law provides that the Band "retain[s] inherent power to exercise civil authority over the conduct of non-Indians on fee lands within its reservation when that conduct threatens or has some direct effect on the political integrity, the economic security, or the health or welfare of the tribe." *Montana v. United States,* 450 U.S. 544, 565,66 (1981).

NOW, THEREFORE, in consideration of the above Recitals, which are incorporated herein by reference, the White Earth Reservation Business Committee pursuant to the above referenced authority, scientific and cultural review and recommendation of the WEDNR, and after reviewing the materials in the record including scientific studies, news reports, violation data, testimony of community members, testimony of organizations and reports of outside experts ordains as follows:

Section 1—Title and Purpose:

1.1 Title. The title of this Ordinance is the White Earth Band of Minnesota Chippewa Indians' **Moratorium on Concentrated Animal Feeding Operation and Animal Feedlot Operation Environmental Hazard Construction Inconsistent With Existing Activities and Land Uses, And Expansion of Concentrated Animal Feeding Operation and Animal Feedlot Environmental Hazard Operation Activities and Land Uses Pending the Study of Possible Regulatory Action.**

1.2 Purpose. The purpose of this moratorium is to allow the Band sufficient time to undertake an interdisciplinary process of data collection, review, analysis and regulatory and technology development sufficient to regulate CAFOs and AFO environmental hazards in a manner that protects the Band's core interests related to human health, natural resource protection and economic security. A moratorium is necessary for the reasons set forth in the Recitals and consistent with the findings made by the White Earth Reservation Business Committee, each and all of which are incorporated herein by reference.

Section 2 – Authority:

2.1 The White Earth Reservation Business Committee relies on the authorities set forth in the Recitals.

Section 3 – Moratorium Imposed:

3.1 For the duration of the Moratorium, the White Earth Reservation Business Committee prohibits CAFO and AFO environmental hazard construction inconsistent with existing activities and land use, changes in existing CAFO and AFO environmental hazard activities and land use, and expansion of CAFOs and AFO environmental hazard existing activities and land uses within the exterior boundaries of the White Earth Reservation.

Section 4 – Duration of the Moratorium:

4.1 The Moratorium shall be in effect for two years from the date of adoption, unless terminated earlier or extended further by an ordinance duly adopted by the White Earth Reservation Business Committee.

Section 5 – Action Anticipated During the Moratorium:

5.1 The White Earth Reservation Business Committee, working with the WEDNR and outside experts, shall review the Band's Zoning Ordinances and conduct an interdisciplinary study of water quality, water quantity, soil health, air, and environmental and human health impacts from location of additional or expansion of existing CAFOs or AFO environmental hazards within the exterior boundaries of the White Earth Reservation to develop appropriate regulatory controls for such facilities. The White Earth Reservation Business Committee, working with the WEDNR and outside experts, shall also work to develop priority protection areas based on identified

natural resource concerns as well as Geographic Information Systems (GIS) tools to map and evaluate risks and harms from the operation of CAFOs and AFO environmental hazards, including manure land-spreading activities, within the exterior boundaries of the White Earth Reservation.

5.2 The White Earth Reservation Business Committee shall act upon recommendations from the community, WEDNR and outside experts as deemed necessary to protect the public health and welfare, natural resources and economic security of the Band.

5.3. The White Earth Reservation Business Committee shall take such action as it deems appropriate to terminate or extend the Moratorium within two years of its passage.

Section 6 – Effective date:

6.1 This ordinance shall be effective at the time of its passage by the White Earth Reservation Business Committee.

The White Earth Reservation Business Committee does hereby certify that the foregoing resolution and ordinance was adopted by a vote of 4 for, 0 against, 0 silent, a quorum being present at a meeting of the White Earth Reservation Business Committee held on December 1, 2022 in White Earth, Minnesota.

Michael A. Fairbanks, Chairman

Michael LaRoque, Secretary/Treasurer



JONATHAN BACHMAN/REUTERS

WHY EXTREME RAINS ARE GETTING WORSE

The latest climate simulations are showing that storms will get wetter and more erratic as the world warms.

BY ALEXANDRA WITZE

The downpour began on 13 September, when the centre of Hurricane Florence was still hundreds of kilometres from North Carolina's coast. As the giant storm lurched towards land, officials ordered more than 1.5 million people to evacuate, warning of "life-threatening" damage. On 15 September, Florence finally crashed into the United States, where it slowed to a crawl and unleashed even heavier rains. In some places, the deluge continued non-stop for four days.

By the time it was all over, Florence had dumped record amounts of rain — including nearly one metre in the town of Elizabethtown, North Carolina — and caused catastrophic flooding. Dozens of people died, and the storm racked up tens of billions of dollars in damages. Even now, months later, the area is struggling to recover.

The story of how Florence brought a thriving region to its knees is about to get a lot more familiar. Climate scientists expect that as global temperatures rise, much more rain will fall in extreme storms. The warmer the atmosphere, the more moisture it can hold, which means storms can get wetter. Even before Florence made landfall, a team based at Stony Brook University in New York predicted that the hurricane's heaviest rains would dump at least 50% more precipitation than would have happened people not warmed the planet.

Extreme rains — along with the flooding, landslides and other devastation they cause — are some of the deadliest weather events worldwide. This year, heavy rains in the Indian state of Kerala killed more than 470 people, and flooding in southwestern Japan left more than 200 dead. In the United States, flooding, severe storms and tropical cyclones account for 9 of the 11 natural disasters that have topped US$1 billion in damages so far this year. But forecasting how the most punishing rains might change in the future has been notoriously difficult, because scientists can't easily simulate these storms in computer models.

Now, many research teams are making advances in understanding the future of extreme precipitation across the world, thanks to models with very high resolution that can provide insight into how storms evolve. Some of the most sophisticated forecasts suggest that as the globe warms, more rains will fall in severe, intermittent storms rather than in the kind of gentle soaking showers that can sustain crops. Other research indicates that the ways in which thunderstorms organize

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Hurricane Harvey in 2017 set records for rainfall.

SOURCE: E. M. FISCHER & R. KNUTTI *NATURE CLIM. CHANGE* **5**, 560–564 (2015).

themselves could change fundamentally, leading to bigger and more-powerful storms that could mean more flooding.

All that makes Florence, the Indian disaster and other devastating downpours a probable glimpse of the future if greenhouse-gas emissions continue to rise. "The next 20 years will be worse than the last 20 years — all indications point to that," says Angeline Pendergrass, an atmospheric scientist at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. "And things will be completely nuts by the end of the century if we keep doing what we're doing now."

MORE MOISTURE

In Kerala, it all started with a wet June and July, and accelerated over the following month. The first 20 days of August brought 164% more rain than usual. Throughout the state, landslides swept into towns and buildings as sodden ground collapsed. More than 1 million people fled their homes.

The weather might not have been the only problem in this case. Some have criticized local officials for not better managing the build-up of water behind local dams. But the flooding was ultimately traced back to heavier-than-usual storms during the summer monsoon.

And it's clear that such storms are carrying more moisture than they used to. The moisture in the air changes depending on temperature: heat that air by 1 °C, and it can hold approximately 7% more water. The Intergovernmental Panel on Climate Change has concluded that many parts of the world are already seeing increases in heavy precipitation, thanks to human-induced climate change.

"It's just basic physics," says Kenneth Kunkel, an atmospheric scientist at North Carolina State University in Asheville. "Big storms with large amounts of rainfall are limited by the amount of water vapour in the atmosphere. As we increase water vapour in the atmosphere, we can increase the amount of rainfall in these extreme precipitation events."

But the precipitation story turns out to be more complicated than that. A thunderstorm is essentially a tower of upward-moving winds that feed themselves by sucking in warm air from nearby. When the air rises high enough, it cools and condenses into rain. Storms can generate their own weather, such as creating cold pools of air near the ground that trigger more convection. And climate change can amplify these effects, causing updrafts to grow stronger and wider, which pulls in more warm air from surrounding regions and leads to more rain (see 'Heavy rain').

This apparently happened in Hurricane Harvey — the rainiest storm in US history, which drowned much of Houston and south Texas in a $125-billion disaster in August last year. Three separate studies have concluded that Harvey's heaviest rains could not be explained simply by the increase of water vapour in the atmosphere[1–3]. Climate change made it even wetter than that.

At NCAR, Pendergrass is working with global climate models to pin down what this might mean for extreme events in the future — and especially, where they might occur. She analyses how climate change is altering how heat and energy flow in the atmosphere, which changes how precipitation is spread around the globe.

Last year, she and her colleagues reported on three computer simulations showing that precipitation is likely to become more variable across almost all land areas if temperatures rise through the rest of the century[4]. In other words, weather will get crazier: wet periods will give way to dry periods more erratically, and vice versa, across nearly all the continents.

Now, she has drilled down to study the unevenness of precipitation — that is, the difference between a light drizzle and a torrential downpour. She and Reto Knutti, an atmospheric scientist at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) in Switzerland, analysed global rainfall records between 1999 and 2014. For the median of all locations in the study, it took only 12 days for half of the year's rain to fall[5]. "Things that are considered extreme contribute a lot to the total precipitation, more than a lot of my colleagues may realize," she says.

Looking ahead with a climate model, the researchers found that this

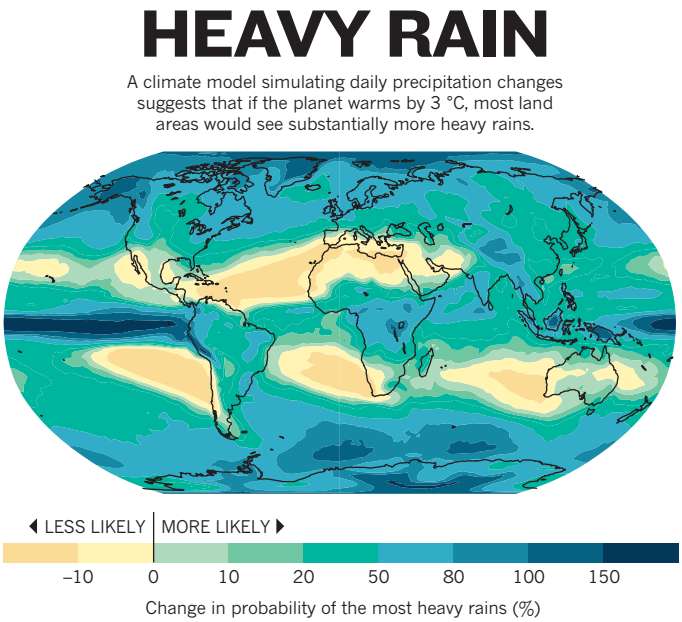

kind of unevenness will increase. If greenhouse-gas emissions continue to climb quickly in the future, half of the extra rainfall will happen during the wettest six days of the year.

That means more deluges — and the dangers that follow. Pendergrass has been talking with water managers in Denver, Colorado, who want to know how much flooding they need to prepare their dams to handle in the future. She says other areas should prepare, too. "Rather than assuming more rain in general, society needs to take measures to deal with little change most of the time, and a handful of events with much more rain," she and Knutti wrote last month in *Geophysical Research Letters*[5].

Another set of simulations underscores how society needs to prepare for these swings between wet and dry. This work, led by atmospheric scientist Zachary Zobel while he was at the University of Illinois in Urbana–Champaign, took a global climate model that usually calculates conditions every 100 kilometres and forced it to a much higher resolution, of just 12 kilometres. "You need as high a spatial resolution as you can get," says Zobel, who is now at the Woods Hole Research Center in Falmouth, Massachusetts. At a resolution of 12 kilometres, the model can reveal small-scale phenomena in the atmosphere that are important for simulating storms. But Zobel's model requires a lot of computing power, so the team looked only at the continental United States, not the entire globe. Even using a supercomputer, it took the better part of a year for the model to crunch through its calculations[6]. But in the end, the researchers got a detailed look at how different parts of the country would be affected, in both temperature and precipitation extremes, if greenhouse-gas emissions continue to remain high out until 2094.

BOOM OR BUST

The scientists found that extreme precipitation events would increase over most of the country. They also spotted some larger changes in future patterns, such as in the position of the west-to-east jet stream that controls weather over much of the middle part of the United States.

That change arises because the Arctic is currently warming faster than are the mid-latitudes, so there is less of a temperature difference between the two regions. In response, the jet stream shifts northward in the simulations, bringing warm moist air from the Gulf of Mexico behind it. The result is that the midwestern states, where the bulk of the country's corn and wheat crops are grown, will probably see more severe storms each spring during the planting season. Meanwhile, dry spells will grow longer, the model suggests.

"It really comes down to a boom-or-bust-type precipitation pattern," Zobel says. "That will complicate how farmers deal with planting their crops." The work appeared last month in *Earth's Future*[6].

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AFP/GETTY

Flooding in the Indian state of Kerala killed hundreds of people this year.

For Andreas Prein, the future hit home in 2002, when heavy summer rains drenched central Europe. Prein was serving in the Austrian military, and his unit was dispatched to help flood-ravaged areas of northern Austria, where tiny brooks became torrents and damages reached €3 billion (US$3.4 billion). "It was really shocking to see how little streams could do such devastation," says Prein. "It was almost unbelievable."

Today, Prein is an atmospheric scientist at NCAR and a leader in a new type of high-resolution climate modelling. This research aims to simulate future climate in even higher resolution than Zobel's. Its computations narrow down to scales of four kilometres or less — which is so computationally expensive that it can be done only for relatively small regions.

Four kilometres is crucial because it's the dimension at which individual storms evolve and grow stronger through convection. The field is known as convection-permitting climate modelling, and it allows researchers to simulate storms much more realistically. The calculations are similar to what weather forecasters do to predict how storms will develop over the next day or two. "But we want to simulate decades to centuries," Prein says. "It's basically copying what weather forecasting does, but on much longer time scales."

In ongoing work, UK-based researchers have been running European-wide climate simulations at 2.2-kilometre resolution and have spotted some warning signs about future storms. "At the moment across most of Europe, the season we get extremes is primarily summer," says team member Elizabeth Kendon, a climate scientist at the Met Office in Exeter, UK. In the simulations of a warmer world, summer downpours get heavier, and extreme events occur later in the year. That suggests officials might need to do more to prepare for flooding from winter storms.

Hurricanes are another major concern. Christina Patricola and Michael Wehner, at the Lawrence Berkeley National Laboratory in California, have used convection-permitting models to study the devastating hurricanes of Katrina in 2005 and Irma and Maria in 2017. They found that climate change had boosted rains within these storms by up to 9% — and that future warming would almost certainly mean more extreme rainfall from similar hurricanes[7].

One of the biggest convection-permitting simulations so far, run by NCAR, covered the continental United States at a resolution of four kilometres[8]. It was actually a pair of simulations, one looking back and another peering forward. The first one simulated global climate between October 2000 and September 2013 to test how accurately the model could reproduce what happened during those years. "We started as you would start a weather forecast, and then we just didn't stop for 13 years," says Prein.

The second simulation looked at a similar period at the end of the century, incorporating factors that would be expected if society continues to produce greenhouse gases at a high rate.

By comparing the two, the scientists could tease out the probable effects of increasing greenhouse-gas levels. And because the simulations were at such high resolution, they could capture how individual storms are likely to form and evolve in the future.

Among the many findings of such models are that intense US thunderstorms will more than triple in frequency by the end of the century, and their maximum rainfall will increase by 15–40% (ref. 9). The storms will also grow larger, almost doubling the area that would get hit with heavy rainfall. That has big implications for flood risks. "If you think about a large thunderstorm moving over a city area, it makes a big difference if the storm covers half the city catchment or all of it," says Prein.

He and his colleagues at NCAR are now developing a second set of simulations which they hope to begin running in the coming months. It will extend the simulations northwards into Canada, aiming to study whether the powerful thunderstorms that regularly rip through the upper midwest of the United States will move into Canada in the future. The work will also cover periods lasting 20 years rather than 13, which the scientists hope will enable them to capture longer trends in changing weather patterns.

Whatever is on the way, it will almost certainly be hard to miss. Sitting in her office at NCAR on a sun-drenched morning, Pendergrass pulls up a figure showing computer simulations of what kinds of extreme precipitation might lurk in the future. "What we have seen so far is incredibly small compared to what's coming," she says. "And that's kind of terrifying." ■

Alexandra Witze *writes for* Nature *from Boulder, Colorado.*

1. Risser, M. D. & Wehner, M. F. *Geophys. Res. Lett.* **44**, 12457–12464 (2017).
2. Van Oldenborgh, G. J. *et al. Environ. Res. Lett.* **12**, 124009 (2017).
3. Wang, S.-Y. S. *et al. Environ. Res. Lett.* **13**, 054014 (2018).
4. Pendergrass, A. G., Knutti, R., Lehner, F., Deser, C. & Sanderson, B. M. *et al. Sci. Rep.* **7**, 17966 (2017).
5. Pendergrass, A. G. & Knutti, R. *Geophys. Res. Lett.* https://doi.org/10.1029/2018GL080298 (2018).
6. Zobel, Z., Wang, J., Wuebbles, D. J. & Kotamarthi, V. R. *Earths Future* **6**, 1471–1490 (2018).
7. Patricola, C. M. & Wehner, M. F. *Nature* **563**, 339–346 (2018).
8. Liu, C. *et al. Clim. Dyn.* **49**, 71–95 (2017).
9. Prein, A. F. *et al. Nature Clim. Change* **7**, 880–884 (2017).

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CORRECTION

The News Feature ‘Why extreme rains are getting worse’ (*Nature* **563**, 458–460; 2018) erroneously located Elizabeth Kendon in Reading. She is, in fact, at the Met Office in Exeter.

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CHAPTER 7.1.

INTRODUCTION TO THE RECOMMENDATIONS FOR ANIMAL WELFARE

Article 7.1.1.

General considerations

Animal welfare means the physical and mental state of an *animal* in relation to the conditions in which it lives and dies.

An *animal* experiences good welfare if the *animal* is healthy, comfortable, well nourished, safe, is not suffering from unpleasant states such as pain, fear and distress, and is able to express behaviours that are important for its physical and mental state.

Good *animal welfare* requires disease prevention and appropriate veterinary care, shelter, management and nutrition, a stimulating and safe environment, humane handling and humane *slaughter* or *killing*. While *animal welfare* refers to the state of the *animal*, the treatment that an *animal* receives is covered by other terms such as animal care, animal husbandry, and humane treatment.

Article 7.1.2.

Guiding principles for animal welfare

1. That there is a critical relationship between animal health and *animal welfare*.
2. That the internationally recognised 'five freedoms' (freedom from hunger, thirst and malnutrition; freedom from fear and distress; freedom from physical and thermal discomfort; freedom from pain, injury and disease; and freedom to express normal patterns of behaviour) provide valuable guidance in *animal welfare*.
3. That the internationally recognised 'three Rs' (reduction in numbers of *animals*, refinement of experimental methods and replacement of *animals* with non-animal techniques) provide valuable guidance for the use of *animals* in science.
4. That the scientific assessment of *animal welfare* involves diverse elements which need to be considered together, and that selecting and weighing these elements often involves value-based assumptions which should be made as explicit as possible.
5. That the use of *animals* in agriculture, education and research, and for companionship, recreation and entertainment, makes a major contribution to the wellbeing of people.
6. That the use of *animals* carries with it an ethical responsibility to ensure the welfare of such *animals* to the greatest extent practicable.
7. That improvements in farm *animal welfare* can often improve productivity and food safety, and hence lead to economic benefits.

8. That equivalent outcomes based on performance criteria, rather than identical systems based on design criteria, be the basis for comparison of *animal welfare* standards and recommendations.

Article 7.1.3.

Scientific basis for recommendations

1. Welfare is a broad term which includes the many elements that contribute to an animal's quality of life, including those referred to in the 'five freedoms' listed above.

2. The scientific assessment of *animal welfare* has progressed rapidly in recent years and forms the basis of these recommendations.

3. Some measures of *animal welfare* involve assessing the degree of impaired functioning associated with injury, disease and malnutrition. Other measures provide information on *animals*' needs and affective states such as hunger, pain and fear, often by measuring the strength of *animals*' preferences, motivations and aversions. Others assess the physiological, behavioural and immunological changes or effects that *animals* show in response to various challenges.

4. Such measures can lead to criteria and indicators that help to evaluate how different methods of managing *animals* influence their welfare.

Article 7.1.4.

Guiding principles for the use of measures to assess animal welfare

1. For the OIE *animal welfare* standards to be applicable globally, they should emphasise favourable outcomes for the *animals*, although, in some circumstances, it may be necessary to recommend specific conditions of the *animals*' environment and management. Outcomes are generally measured by assessing the extent to which *animals* experience the "five freedoms" described in Article 7.1.2.

2. For each principle listed in Article 7.1.5., the most relevant criteria (or measurables), ideally comprising animal-based measures, should be included in the standard. Any given animal-based measure may be linked to more than one principle.

3. Recommendations should, whenever possible, define explicit targets or thresholds that should be met for animal-based measures. Such target values should be based on relevant science and experience of experts.

4. In addition to animal-based measures, resource-based measures and management-based measures may be used and should be defined on the basis of science and expert experience showing that a welfare outcome is clearly linked to a resource or to a management procedure.

5. Users of the standard should select the most appropriate animal-based measures for their farming system or environment, from among those listed in the standard. Outcomes can be measured by an assessment of individuals or animal groups, or a representative sample of those, using data from *establishments*, transport or *slaughterhouses/abattoirs*.

6. Whatever the basis of the measure, if outcomes are unsatisfactory, users should consider what changes to resources or management are necessary to improve outcomes.

Article 7.1.5.

General principles for the welfare of animals in livestock production systems

1. Genetic selection should always take into account the health and welfare of *animals*.
2. *Animals* chosen for introduction into new environments should be suited to the local climate and able to adapt to local diseases, parasites and nutrition.
3. The physical environment, including the substrate (walking surface, resting surface, etc.), should be suited to the species so as to minimise risk of injury and transmission of diseases or parasites to *animals*.
4. The physical environment should allow comfortable resting, safe and comfortable movement including normal postural changes, and the opportunity to perform types of natural behaviour that *animals* are motivated to perform..
5. Social grouping of *animals* should be managed to allow positive social behaviour and minimise injury, distress and chronic fear.
6. For housed *animals*, air quality, temperature and humidity should support good animal health and not be aversive. Where extreme conditions occur, *animals* should not be prevented from using their natural methods of thermo-regulation.
7. *Animals* should have access to sufficient *feed* and water, suited to the *animals*' age and needs, to maintain normal health and productivity and to prevent prolonged hunger, thirst, malnutrition or dehydration.
8. Diseases and parasites should be prevented and controlled as much as possible through good management practices. *Animals* with serious health problems should be isolated and treated promptly or killed humanely if treatment is not feasible or recovery is unlikely.
9. Where painful procedures cannot be avoided, the resulting pain should be managed to the extent that available methods allow.
10. The handling of *animals* should foster a positive relationship between humans and *animals* and should not cause injury, panic, lasting fear or avoidable stress.
11. Owners and handlers should have sufficient skill and knowledge to ensure that *animals* are treated in accordance with these principles.

NB: FIRST ADOPTED IN 2004; MOST RECENT UPDATE ADOPTED IN 2018.

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December 18, 2024

Environmental Justice Group Sues California Agency Over Flawed Low Carbon Fuel Standard Changes

The changes would waste billions on polluting fuels over the next decade while harming refinery communities and dirtying California's air

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Gissela Chavez, gissela@cbecal.org (mailto:gissela@cbecal.org)

LEGAL DOCUMENT

RICHMOND, CA — Today, Communities for a Better Environment (CBE) filed a lawsuit over the flawed environmental review for the Low Carbon Fuel Standard (LCFS) amendments (https://earthjustice.org/document/low-carbon-fuel-standard-petition) approved in a contentious hearing in November. Earthjustice is representing the environmental justice group in court. Established in 2009 and administered by the California Air Resources Board (CARB), the Low Carbon Fuel Standard program generates billions of dollars in annual subsidies that are supposed to go to transportation fuels that lower greenhouse gas emissions. Unfortunately, entrenched interests have crowded the program with polluting biofuels that take the bulk of the program's revenues away from zero-emissions options.

"The LCFS amendments reward polluters and foul our air. The changes lock in billions for biofuels refined in the East Bay and Los Angeles and burned throughout the state, and CARB failed to inform the public about these impacts," said **Nina**

Robertson, senior attorney on Earthjustice's Right To Zero campaign. "CARB violated one of California's bedrock environmental laws when it brushed the pollution harms under the rug and ignored the science showing cleaner alternatives are both possible and necessary."

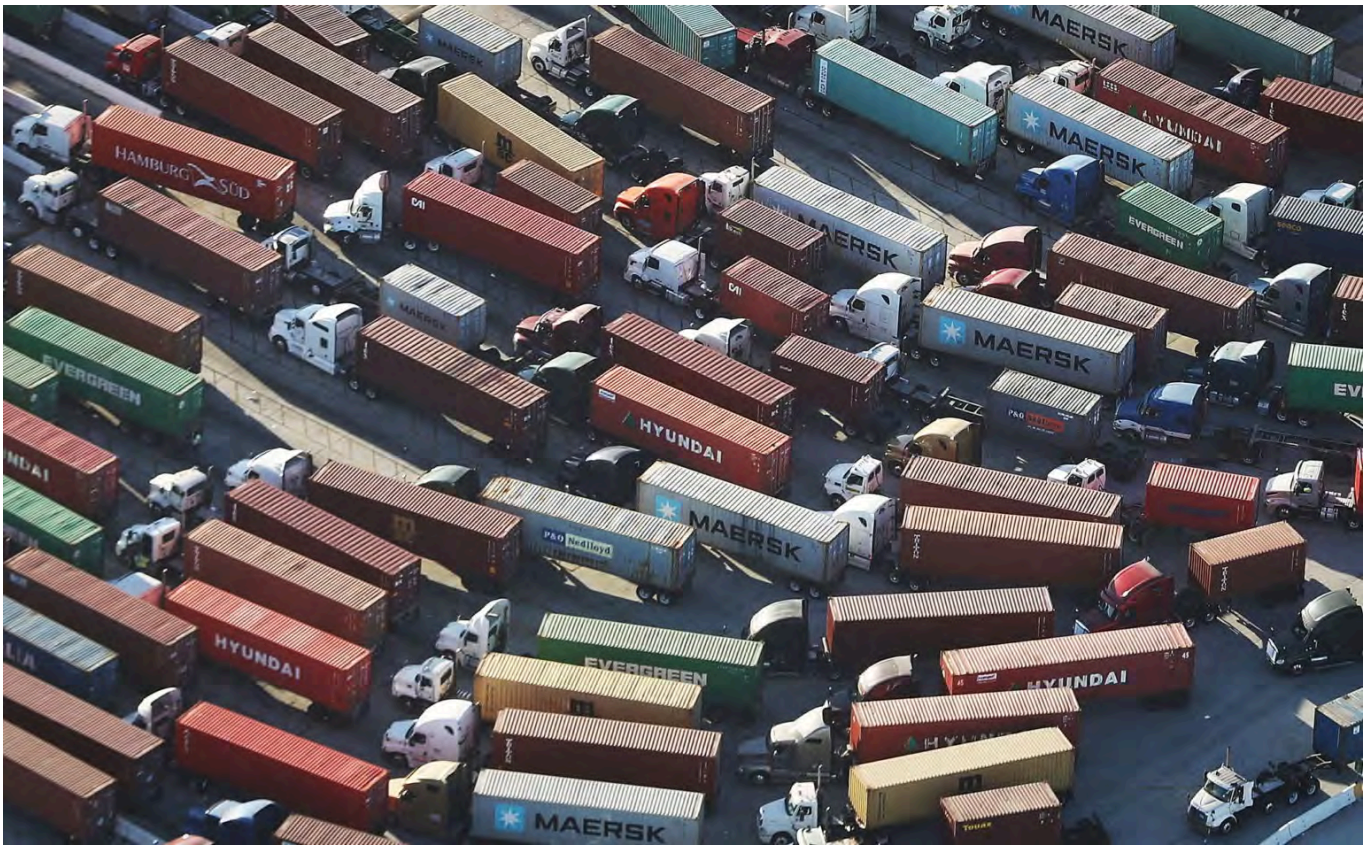

Trucks haul shipping containers at the Port of Los Angeles. When diesel trucks burn biofuels like renewable diesel, which is eating up the largest share of funds in the Low Carbon Fuel Standard, these heavy-duty trucks pollute California's air.
(Getty Images)

Biofuels are combustion fuels made from made from plants like soy and corn. As opposed to zero-emissions transportation technology, they pollute the air both when they're processed in refineries and when they're burned as fuel in vehicles. The conversion of refineries to biofuels is a lifeline for Big Oil, extending the life of refineries that should be shut down as we transition to clean energy. Biofuels can be just as polluting as fossil fuels, and in some cases can be even worse. (https://www.epa.gov/risk/biofuels-and-environment#:~:text=Biofuel%20production%20and%20use%20has,on%20an%2

0energy%20-equivalent%20basis.) Biofuel refining releases significantly greater amounts of certain hazardous air pollutants than oil refineries (https://environmentalintegrity.org/wp-content/uploads/2024/06/EIP_Report_FarmtoFumes_06.12.2024.pdf) — including carcinogens like formaldehyde. Communities like Martinez, Rodeo, and Paramount bear the brunt of this pollution. The Phillips 66 refinery in the East Bay is the largest biofuels refinery (https://investor.phillips66.com/financial-information/news-releases/news-release-details/2020/Phillips-66-Plans-to-Transform-San-Francisco-Refinery-into-Worlds-Largest-Renewable-Fuels-Plant/default.aspx#:~:text=Combined%20with%20the%20production%20of%20renewable%20fuels,the%20world's%20largest%20facility%20of%20its%20kind.) in the world, according to the company's materials.



An aerial view of the Phillips 66 San Francisco Refinery in Rodeo, California. (Brandon Sloter / Getty Images)

"People who live near refineries in California are harmed by the spiraling expansion of polluting biofuels," said **Katherine Ramos, NorCal Program Co-Director at Communities for a Better Environment**. "Yet CARB failed to analyze the harms that its changes to the LCFS will have on these communities. CARB also failed to take a hard look at clean alternatives to biofuels, which we know the climate and our lungs need. Refinery communities and all Californians deserve more from the California Air Resources Board."

Scientists have been ringing the alarm that biofuels in particular risk deforestation (https://www.arb.ca.gov/lists/com-attach/6959-lcfs2024-BXYAZQZuUmQGbgF1.pdf) of habitats vital to the climate, and that these fuels make food increasingly unaffordable for the world's poorest people due to increased food prices that result from diverting crops from food to fuel production. Prominent scientists who study the LCFS at institutions like Stanford, UC Davis, and other universities urged CARB to change course.

CARB's own 2014 analysis of biofuels in the LCFS acknowledges that "[t]his diversion of agricultural land to biofuel production will exert an upward pressure on food commodity prices (https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/iluc_assessment/iluc_analysis.pdf), and potentially lead to food shortages, increasing food price volatility, and inability of the world's poorest people to purchase adequate quantities of food." These risks are why countries around the world with clean fuels programs such as Germany cap the amount of biofuels in their programs. Meanwhile, California is allowing a spiraling expansion of credits for biofuels, especially renewable diesel (https://earthjustice.org/experts/adrian-martinez/california-plans-to-waste-27-billion-bankrolling-a-polluters-paradise), in the multibillion-dollar program.



A soy plantation in a deforested section of the Amazon rainforest near Santarem, Brazil. The growing of soybeans for biofuels is causing massive deforestation. (Ricardo Beliel / Brazil Photos/LightRocket via Getty Images)

These amendments to the Low Carbon Fuel Standard amount to a critical missed opportunity to focus funding on accelerating zero-emissions transportation in the state, which would be better both for protecting the climate and the air Californians breathe. Transportation is California's most polluting sector.

The California Air Resources Board violated the California Environmental Quality Act when it failed to meaningfully incorporate scientific evidence of environmental and health harms in its amendments to the program. Environmental groups seek to remedy this by sending the agency back to the drawing board to redo their analysis and ultimately enact meaningful limits on harmful biofuels and other polluting fuels and grow support for zero-emissions solutions.

A coalition of environmental groups filed a second, separate lawsuit against CARB on the Low Carbon Fuel Standard over the flawed environmental review for billions in subsidies for factory farm biogas (https://www.foodandwaterwatch.org/2024/12/19/groups-sue-carb-over-environmental-impacts-of-flagship-climate-program/).



The Phillips 66 refinery in Rodeo, California. (Michael Macor / San Francisco Chronicle via AP)

ADDITIONAL RESOURCES

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- California Plans to Waste $27 Billion Bankrolling a Polluters' Paradise (https://earthjustice.org/experts/adrian-martinez/california-plans-to-waste-27-billion-bankrolling-a-polluters-paradise)

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ARTICLES
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nature food

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Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods

Xiaoming Xu[1], Prateek Sharma[1], Shijie Shu[1], Tzu-Shun Lin[1], Philippe Ciais[2], Francesco N. Tubiello[3], Pete Smith[4], Nelson Campbell[5] and Atul K. Jain[1]✉

Agriculture and land use are major sources of greenhouse gas (GHG) emissions but previous estimates were either highly aggregate or provided spatial details for subsectors obtained via different methodologies. Using a model–data integration approach that ensures full consistency between subsectors, we provide spatially explicit estimates of production- and consumption-based GHG emissions worldwide from plant- and animal-based human food in circa 2010. Global GHG emissions from the production of food were found to be 17,318 ± 1,675 $TgCO_2eq\,yr^{-1}$, of which 57% corresponds to the production of animal-based food (including livestock feed), 29% to plant-based foods and 14% to other utilizations. Farmland management and land-use change represented major shares of total emissions (38% and 29%, respectively), whereas rice and beef were the largest contributing plant- and animal-based commodities (12% and 25%, respectively), and South and Southeast Asia and South America were the largest emitters of production-based GHGs.

The global population has quadrupled over the last century. Demographic growth and associated economic growth have increased global food demand and caused dietary changes, such as eating more animal-based products. The United Nations projects that food production from plants and animals will need to increase 70% by 2050, compared to 2009, to meet increasing food demand[1]. This will drive the expansion of food subsectors, including crop cultivation and livestock production, as well as product transportation and processing, materials (fertilizer and pesticides) and irrigation[2]. Increased food production may accelerate land-use changes (LUCs) for agriculture, resulting in greater greenhouse gas (GHG) emissions, reduced carbon sequestration and further climate change. Developing climate mitigation strategies will require estimates of all major GHG emissions (for example, CO_2, CH_4 and N_2O) from the production and consumption of total and individual plant- and animal-based food from all food-related subsectors, such as land-use change and farmland activities, at local, regional and global scales—which is the overall objective of this study. Such comprehensive and quantitative estimates require a framework that dynamically represents the environmental, management and human drivers of major GHGs while satisfying carbon and nitrogen mass-conservation among plant and livestock production and consumption systems.

Previous efforts have been made to assess GHG emissions from agriculture, forestry and other land use (AFOLU)[3,4], a critical subset of food systems emissions[5–7]. The recent Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land (SRCCL)[6] and subsequent work[7] quantified emissions within and beyond the farm gate, the latter referring to emissions caused by food systems that are not covered by AFOLU sectors, such as fertilizer manufacturing, product processing and transportation (Fig. 1), to be in the range of 10,800–19,100 $TgCO_2eq\,yr^{-1}$ for the decade 2008–2017. These estimates combined results from diverse studies on farm-gate agriculture and associated land use[4] with global estimates of emissions along the supply chain up to retail and consumption, each study using a different methodology. The annual assessment of the global carbon budget provides CO_2-only emissions from LUC[8]. In contrast, the Food and Agriculture Organization (FAO) gives CO_2 emissions from forest LUC and peatland degradation[9], but those studies do not cover emissions from changes in agricultural management intensity[8]. Moreover, CH_4 and N_2O emissions from agricultural activities are provided globally by different datasets[10,11], usually based on estimation approaches defined by the IPCC Guidelines[12]. The IPCC AR5 WG3[3] and FAOSTAT[4] quantified regional GHG emissions from subsectors of agriculture and land use. There are also studies focusing on spatially explicit GHG emissions for selected crops[13], emissions of the life cycle of agricultural production[5], such as the FAO GLEAM model to estimate global livestock emissions for 2005[14], and accounting for carbon opportunity costs of agricultural land[15].

This study quantifies CO_2, CH_4 and N_2O emissions from the production and consumption of all plant- and animal-based foods on a grid scale using a consistent unified model–data integration framework. Our approach builds upon and extends the data and methods published in the literature by implementing them into the Integrated Science Assessment Model (ISAM)[16].

Our approach advances the field for three main reasons. First, we have a dynamic representation of environmental drivers, such as climate, CO_2 and of direct human drivers (LUC) using a consistent set of mass-conserving equations and parameters for biophysical and biogeochemical processes to estimate the plant carbon and nitrogen dynamics. In comparison, inventory-based methods, such as those used by the IPCC[12], usually consider environmental factors as static functions[12]. Second, we estimate CO_2 emissions and

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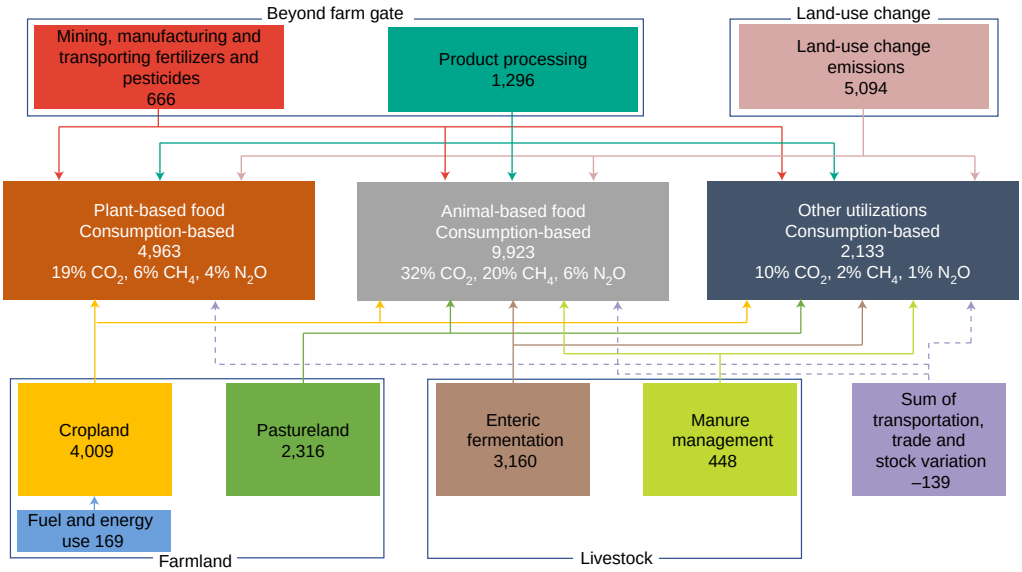

Fig. 1 | GHG emissions from different subsectors of plant- and animal-based food production/consumption. The contributions of individual GHGs provided are the percentage of the total emissions. Solid arrows indicate production-based emissions, and solid and dashed arrows combined are consumption-based emissions. The values in the boxes are mean values for 2007–2013, which may slightly differ from the median values of 10,000 Monte Carlo simulations in the text. Values are expressed in $TgCO_2eq$.

sinks from changes in agricultural land management intensity from a set of diverse and spatially variable practices such as ploughing the soil, planting crops, fertilization, irrigation, harvesting grains and recovering crop residues. In comparison, most global vegetation models have a very simple or no representation of those practices, and bookkeeping models used for land-use emissions ignore changes in management intensity[3]. Third, we explicitly estimate emissions from feed production in cropland and grazing land using the commodity balance between production and consumption. So the total food-related GHG emissions can be attributed to plant- and animal-based human food.

In this study, livestock emissions only include emissions from enteric fermentation and manure management, which we define according to the IPCC[12] and FAOSTAT[17]. Meanwhile, we define animal-based food emissions as the emissions from all subsectors caused by or associated with the production and consumption of animal-based food (Methods and Table 1). In addition, we include LUC emissions from the expansion of agricultural land (crop plus grazing land) and from beyond farm-gate emissions under the life-cycle assessment (LCA) framework of Poore and Nemecek[5] to include emissions from fertilizers, pesticides and pre-plate product processing and transportation. Although LUC and beyond farm-gate emissions have been addressed in other studies[3–7], we provide here more details for individual plant- and animal-based food items at a finer spatial scale.

In summary, GHG emissions are estimated for 171 crops and 16 animal products at a 0.5° × 0.5° spatial resolution over the entire globe around the year 2010. This year is the mean of the 2007–2013 period, the most recent for which the required data are available—particularly commodity balances for crop and livestock and forage feed data (from FAOSTAT data as part of the GCAM Data System[18]). Our estimates are aggregated into more than 200 countries and nine regions (Supplementary Fig. 1), created by grouping countries into macrogeographical coherent zones[19]. We combine CO_2, CH_4 and N_2O emissions by their 100 yr global warming potentials[3] caused by or associated with different subsectors of plant- (crop and grazing land) and animal-based food production and consumption within countries, where consumption-based emissions are calculated by combining emissions from transportation, stock variation, import and export with the estimates of production-based emissions.

Results

Agricultural land and biomass. The estimated agricultural biomass production for 171 crops listed in Supplementary Table 1 and grazing land (see Supplementary Methods 1.1 for definitions) for human food and animal feed, LUC areas associated with this production, and other non-food utilization such as fibre, rubber and cotton, but not energy crops, are linked consistently to the ISAM simulation module for GHG emissions.

We estimated the global total above-ground biomass production from cropland and grazing land to be 8,970 $TgC\,yr^{-1}$ (Supplementary Tables 2 and 3), including 9% for plant-based human food, 27% for animal feed and 20% for non-food products. The rest of the biomass production includes 2% of burned agricultural residue and 42% of residues left as litter and stover (excluding used residues such as feed; Supplementary Table 2). Our historical LUC area based on ISAM[20] and the LUH2 datasets[21] indicates a net agricultural land area increase of 0.11 $Mha\,yr^{-1}$ during 2007–2013, including 2.12 $Mha\,yr^{-1}$ of other land converted to agricultural land and 2.01 $Mha\,yr^{-1}$ of agricultural land converted to other lands (Supplementary Table 2). More results are reported in Supplementary Discussion 1 and Supplementary Fig. 2.

The estimated livestock feed demand is 2,450 $TgC\,yr^{-1}$. This demand is supplied as follows: 23% from crop grain, 12% from forage crops, 21% from crop residue, 42% from grazing feed (feed produced by grazing land) and 2% from scavenging and other feed (Supplementary Discussion 1, Supplementary Table 5). The average conversion efficiency from feed to livestock products is 5.17% based on biomass, 6.22% based on calories and 8.49% based on the protein of livestock products (Supplementary Discussion 3 and Supplementary Fig. 3). Livestock products are split among 16 domesticated animal categories (Supplementary Table 4). Notably, we considered the utilization of crop residues for feeding livestock—an important link between crop and livestock production systems often ignored in other models.

Table 1 | Production- and consumption-based GHG emissions from different subsectors of plant- and animal-based food

Subsector		Plant-based food	Animal-based food	Other utilizations
Land-use change	Cropland CO_2	2,050 ± 120 (12%)	1,634 ± 97 (9%)	921 ± 54 (5%)
	Grazing land CO_2		468 ± 28 (3%)	21 ± 1 (0%)
Farmland	Cropland	2,055 ± 1,432 (12%)	1,466 ± 179 (9%)	654 ± 237 (4%)
	• CO_2	364 ± 17	848 ± 50	263 ± 15
	• CH_4	1,003 ± 1,424	99 ± 139	168 ± 233
	• N_2O	688 ± 132	520 ± 99	223 ± 43
	Grazing land		2,245 ± 141 (13%)	69 ± 4 (0%)
	• CO_2		1,723 ± 101	53 ± 3
	• N_2O		521 ± 99	16 ± 3
Livestock	Enteric fermentation CH_4		3,061 ± 802 (18%)	95 ± 25 (0%)
	Manure management		434 ± 117 (3%)	13 ± 3 (0%)
	• CH_4		308 ± 48	10 ± 2
	• N_2O		127 ± 108	3 ± 3
Beyond farm gate	Mining, manufacturing and transporting fertilizers and pesticides CO_2	269 (2%)	280 (2%)	117 (1%)
	Product processing CO_2	734 (4%)	199 (1%)	524 (3%)
	Transportation, trade and stock variation CO_2	−148 (−1%)	198 (1%)	−206 (1%)
Sum (production-based emission)		5,109 ± 1,436	9,796 ± 850	2,413 ± 246
Sum (consumption-based emission)		4,961 ± 1,436	9,994 ± 850	2,207 ± 246

Values are expressed in $TgCO_2eq$, and numbers in parentheses are the precentage of each emission to total emissions. The sum of the consumption-based emission includes all numbers in the column, whereas the sum of production-based emission includes all numbers, except for the row 'Transportation, trade and stock variation CO_2'.

GHG emissions from food production. From a food production perspective, global total food-related GHG emissions, including farmland, livestock and LUC, amounts to 17,318 ± 1,675 $TgCO_2eq\,yr^{-1}$ (median ± s.d. of 10,000 Monte Carlo simulations; see Supplementary Methods 5 and Supplementary Table 12), consisting of 61% CO_2, 27% CH_4 and 12% N_2O emissions (CH_4 and N_2O amounts in $CO_2eq\,yr^{-1}$) (Fig. 1).

Farmland (E_{farm}), LUC (E_{luc}), livestock (E_{live}) and beyond-farm-gate emissions (E_{bfg}) account for 38%, 29%, 21% and 12% of total production-based emissions from food systems, respectively (Table 1). E_{farm} includes CO_2, CH_4 and N_2O emissions from farmland activities (Methods).

South and Southeast Asia (SSEA) have emitted the greatest food-production-related emissions (23%). However, this region has low per-capita emissions and is the only one where plant-based emissions are larger than animal-based emissions (Fig. 2). SSEA also has the largest per unit area emission. South America (SA) is the second-largest emitter (20%) and has the largest emissions from animal-based food. SA also has the largest emissions per capita among all the regions.

Plant-based food production. Production-based GHG emissions from plant-based food amount to 5,109 ± 1,436 $TgCO_2eq\,yr^{-1}$, which is 29% (19% CO_2, 6% CH_4 and 4% N_2O) of total GHG emissions. Within all subsectors of plant-based emissions (Fig. 1 and Table 1), E_{farm} is the greatest, contributing ~12% of the total (Supplementary Fig. 5a). E_{farm} of plant-based food is composed of CH_4 (6%), N_2O (4%) and CO_2 (2%) emissions. E_{farm} CH_4 emissions are generated from rice cultivation, which is the most GHG-intensive grain among all plant-based foods (Fig. 3a and Supplementary Fig. 4). E_{farm} N_2O and CO_2 are major contributors to wheat and maize emissions. Wheat has the largest harvest area among all 171 crops and is the second most GHG-intensive plant-based commodity (5%; Fig. 3a), largely because of its E_{farm} (2%).

E_{luc} of plant-based food (Supplementary Fig. 5c) caused by cropland expansion contributes 12% of total food emissions. It consists of 5% soil disturbance emissions and 7% biomass loss emissions. E_{luc} of rice and wheat are the highest among all plant-based food, contributing 3% and 1% of total food emissions. Although wheat is mainly cultivated in temperate regions where E_{luc} is less intensive, the large harvest area still makes its E_{luc} the second largest.

SSEA and China and Mongolia (CM) are the top GHG-contributing regions for plant-based food production and contribute 11% and 6%, respectively, of total food-related GHG emissions (Fig. 2). In these two regions, China, India and Indonesia are the countries with the most GHG emissions from plant-based food production (Fig. 4), contributing 7%, 4%, and 2%, respectively, of global food-related GHG emissions. These regions and countries account for the largest share of the world's population, and their demands for more food and land drive LUCs, causing CO_2 emissions. In addition, SSEA and CM produce more than 90% of the rice in the world[22]. Therefore, they are responsible for the majority of CH_4 emissions from rice cultivation (Supplementary Fig. 4).

Animal-based food production. Production-based GHG emissions from animal-based food are 9,796 ± 850 $TgCO_2eq\,yr^{-1}$, which are 57% (30% CO_2, 20% CH_4 and 7% N_2O) of the total GHG emissions. E_{farm} of animal-based food (Supplementary Fig. 5b), which includes E_{farm} from cropland (8%) and grazing land (13%) that produces feed, accounts for 21% of total emissions. E_{farm} of cropland is transferred to animal-based food emissions through accounting for the crop production used as feed. Top feed-producing crops include maize, wheat and soybean. E_{farm} of grazing land (13%) is generated from grazing feed production. E_{live} (20%) is another dominant

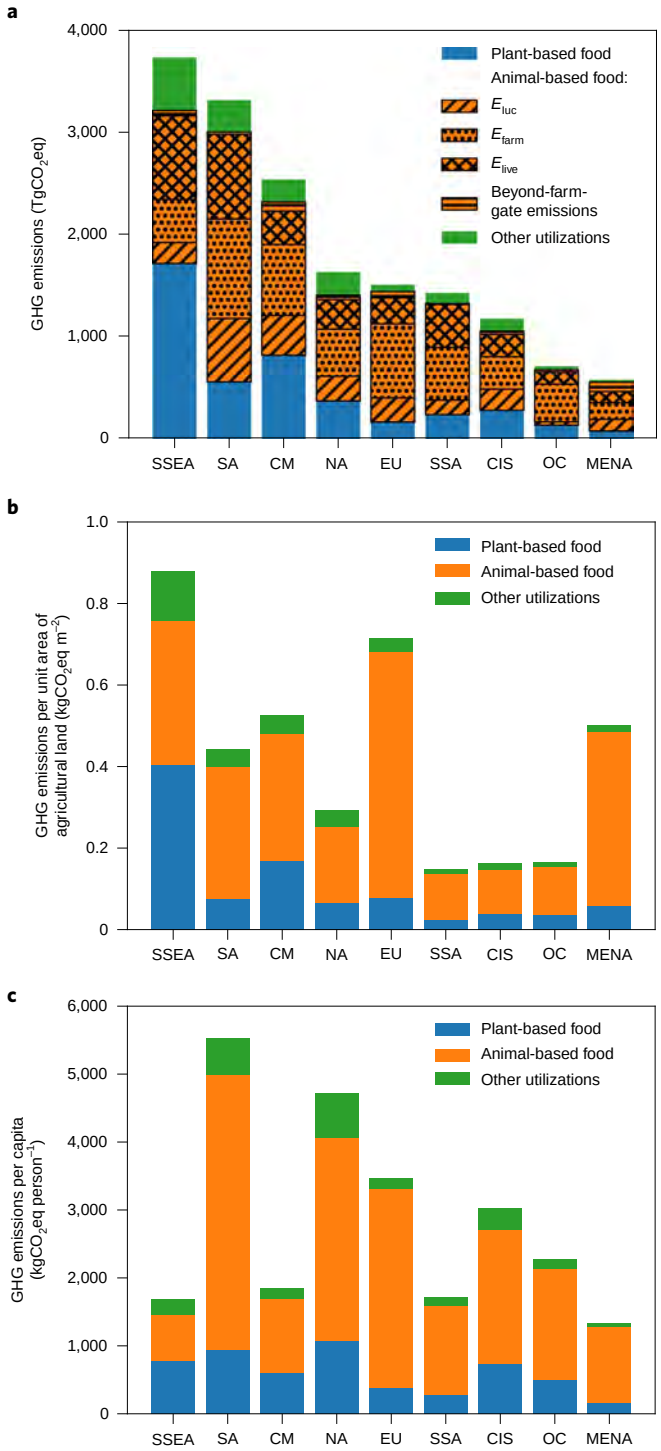

Fig. 2 | GHG emissions from the productions of plant-based food, animal-based food and others. a, Emissions in different regions. **b**, Emissions per unit area of agricultural land. **c**, Emissions per capita. (Supplementary Fig. 1 shows the spatial domains for the nine regions: NA, North America; SA, South America; EU, European Union; MENA, Middle East and North Africa; SSA, sub-Saharan Africa; CIS, Commonwealth of Independent States; CM, China and Mongolia; SSEA, South and Southeast Asia; OC, Oceania and other East Asia).

contributor to animal-based food emissions (Supplementary Fig. 5g), including 18% CH_4 emissions from enteric fermentation of ruminant animals and 2% from manure management. E_{farm} and E_{live} are the largest major components of emissions from beef and cow milk production. These two commodities contribute the most (25% and 10%, respectively) to the total animal-based food GHG emissions (Fig. 3b).

E_{luc} of animal-based food (12%) includes 5% from soil disturbance and 7% from biomass loss (Supplementary Fig. 5d). E_{luc} and E_{farm} are the major sources of GHG emissions of meat products from monogastric animals, such as pork and chicken meat, mainly because we account for the GHG emissions from the production and trade of crop feed for these animals.

The most prominent emitting regions for animal food production are SA (14% of total food-related emissions), SSEA (9%) and CM (8%) (Fig. 2a). China (8%) in CM, Brazil (6%) in SA, the United States (5%) in North America (NA) and India (4%) in SSEA are the countries with leading GHG emissions from the production of animal-based foods (Fig. 4). Beef and cow milk are the commodities that contribute most to the largest emitting regions and countries. E_{farm} and E_{live} are the most dominant components of GHG emissions of animal-based food production in these regions and countries (Supplementary Fig. 5b,g). These regions and countries have the largest herd size of cattle supporting meat and dairy production, demanding more crop and grazing feed and causing more farmland CO_2 emissions. E_{luc} associated with animal feed production in Brazil is the highest among all countries, mainly because of deforestation caused by grazing land expansion[23].

GHG emissions from food consumption. Consumption-based emissions are calculated by combining transportation, stock variation and international trade, based on the FAOSTAT commodity trade dataset[24,25], with our estimates of production-based emissions for each commodity and subsector (Methods).

For the 2010 base year, roughly 16% and 17% of global total GHG emissions were transferred among regions due to the import and export of food, here plant- and animal-based food (including import and export of feed) combined. Imports transferred 4% of plant-based food and 12% of animal-based food from producers to consumers. If attributing emissions to importing consumers, we can say that imports transferred 5% of plant product emissions and 12% of animal product emissions. It should be noted that GHG emissions are not exactly balanced between import and export[25], in part due to the emissions attributed to stock variation ($-38\,TgCO_2eq\,yr^{-1}$), and transportation emissions ($202\,TgCO_2eq\,yr^{-1}$), as well as slight inconsistencies in the FAOSTAT import and export amounts of plant- and animal-based food.

SSEA has caused the greatest GHG emissions from plant-based food exports (Fig. 5). Tropical regions such as SSEA and SA are experiencing an expansion of agricultural land for the production of plant-based commodities such as coffee, tea, bananas, citrus fruits, palm oil, rubber, sugarcane and grazing feed for animal-based food production, which is to a great extent driven by international trade[26]. The expansion of agricultural land is predominantly achieved by conversion from natural vegetation such as forest, which causes substantial LUC and E_{luc} (ref. [26]). These regions thus cause more GHG emissions from exports, particularly related to E_{luc}.

The EU has caused the most GHG emissions from both animal-based food imports and exports, mainly because of the large amount of the internal trades between EU countries[25]. SA, NA and OC also cause large amounts of GHG emissions, predominantly due to their leading positions in exporting animal-based food such as beef[25].

Discussion

Overall, our estimates of GHG emissions from food systems account for 35% of global total anthropogenic GHG emissions. At the same time, we do not account for food-related emissions through specific human/climate disturbances, such as savannah burning, peat

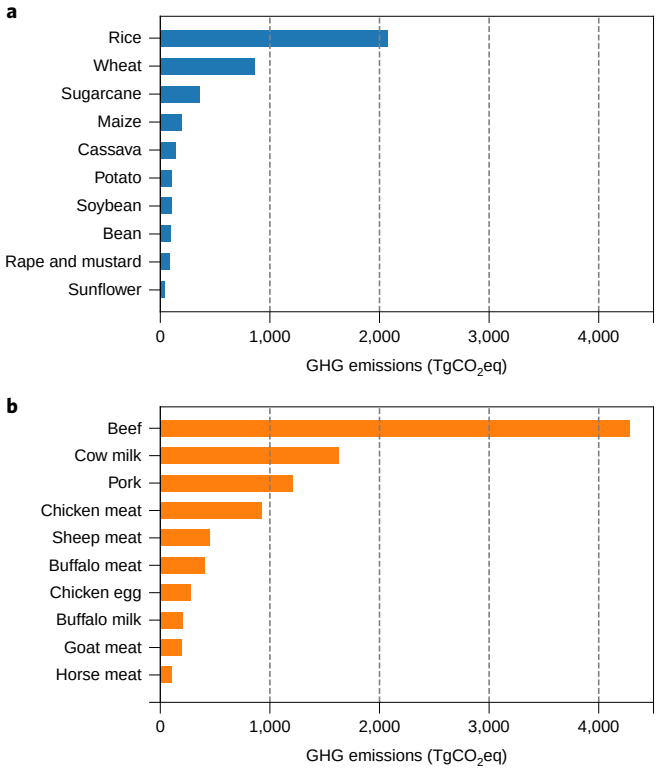

Fig. 3 | GHG emissions from the productions of top-contributing commodities. a, Top ten plant-based food commodities. **b**, Top ten animal-based food commodities.

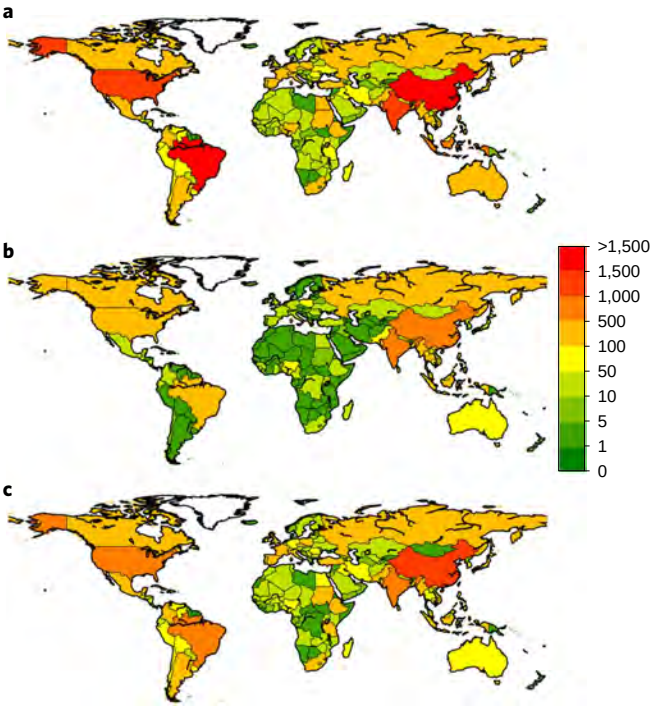

Fig. 4 | GHG emissions from food production at the country scale. a, Total emissions from food production. **b**, Emissions from plant-based food. **c**, Emissions from animal-based food. Values are expressed in $TgCO_2eq$.

drainage and peat fires[3,13,17,27]. By adding all emissions from total savannah burning and drained peat[17,27] (not only related to food systems), our total food-related emissions will be ~37% of total GHG emissions, compared to the IPCC SRCCL estimated percentage range of 21–37%[6], and 26% according to Poore and Nemecek[5]. Without E_{bfg}, our estimated GHG emissions are 31% of global total anthropogenic GHG emissions[3], compared to 24% from AFOLU in IPCC AR5[3]. While our overall estimated emissions match well with the higher-range value of the IPCC SRCCL[6], it should be noted that we estimate emissions from subsectors for the human food systems using a consistent data-modelling framework, which ensures the carbon and nitrogen balance among biomass flows by considering detailed biophysical and biogeochemical processes.

As the basis for calculating feed emissions, we estimated the total feed demand and its compositions. Our feed amount calculation method (Supplementary Methods 1.4) is unique and detailed compared to other published studies, including IPCC AR5 WG3[3] (Supplementary Discussion 4 and Supplementary Table 7), because it ensures that the amounts of different types of feed are consistent with crop and grazing land productions, which are cross-validated with published datasets[22,28]. Our method also ensures the balance between different types of feed supply and total demand not only on the global scale but also in each individual country. Overall, our estimated feed demand (2,450 $TgC\,yr^{-1}$) is 20% lower than IPCC AR5 estimates[3], but is within the range of previous studies (which range from ~2,000 to 3,000 $TgC\,yr^{-1}$, see Supplementary Table 7).

Our farmland CO_2 emission (E_{f_CO2}) is the net carbon flux of cropland and grazing land, which includes both carbon fixation by plant photosynthesis and carbon loss such as soil emissions and livestock respiration (Supplementary Methods 2.3). Our estimated soil emissions (sum of soil disturbance and tillage emissions E_{t_CO2}, see Supplementary Table 15) and livestock respiration emissions are 2,377 and 4,920 $TgCO_2eq\,yr^{-1}$, respectively.

Our study considers several emissions which others have not. Our estimated net E_{f_CO2} of $3{,}084 \pm 181\ TgCO_2eq\,yr^{-1}$ (Supplementary Table 15) was derived from a detailed mathematical algorithm for agricultural land management intensity and practices, but is typically assumed to be zero[3]. Our estimated E_{bfg} (2,123 $TgCO_2eq\,yr^{-1}$) accounts for different subsectors (mining, manufacturing and transporting agricultural materials, and food processing and transportation) at the global scale (Supplementary Discussion 5 and Supplementary Table 8), which is about half of the aggregate value reported by the IPCC SRCCL[6] value. Our estimated food processing and transportation emissions are close to the values presented by Poore and Nemecek[5]. Our total E_{farm} ($6{,}493 \pm 1{,}896\ TgCO_2eq\,yr^{-1}$) is 2–4 times higher than that reported by FAOSTAT[4], Poore and Nemecek[5] and EDGAR[29] (Supplementary Table 8), mainly because we included the farmland CO_2 emissions.

Compared to the state of the art and the representation of plant-based practices in this study, knowledge about livestock management and emissions is considerably less advanced because much more detailed GHG emission estimates are available for all subsectors of plant-based practices. Our estimated E_{live} emissions ($3{,}608 \pm 836\ TgCO_2eq\,yr^{-1}$) are similar to those reported by FAOSTAT, but our combined E_{farm} and E_{live} emissions are ~60% higher than in the IPCC SRCCL[6] (also because of our farmland CO_2 emissions). Our estimated E_{luc} ($5{,}096 \pm 301\ TgCO_2eq\,yr^{-1}$) is similar to the IPCC AR5[3] and SRCCL[6] values and higher than the values reported by FAOSTAT[4] and Poore and Nemecek[5]. Our simulated farmland CH_4 emissions are similar to those in EDGAR[29] and higher than those reported by Carlson et al.[13], Poore and Nemecek[5] and FAOSTAT[4], but the estimated uncertainty range is large. Our estimates for N_2O from cropland and grazing land are consistent with FAOSTAT[4], and slightly higher than those in EDGAR v.4.3.2[29]. Our food-related emissions for most of the countries are either

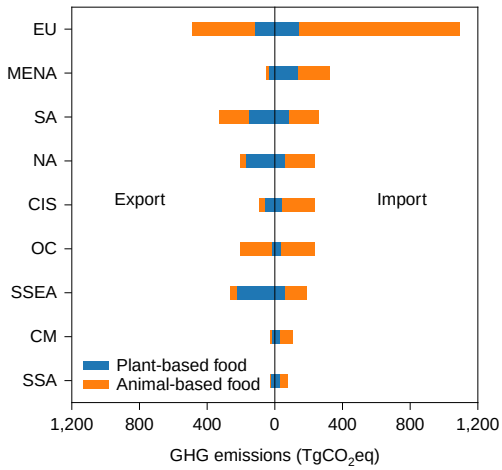

Fig. 5 | GHG emissions due to import and export of plant- and animal-based food in different regions. Animal-based food values include emissions from import and export of livestock feed.

higher or about the same compared with FAOSTAT. Our total emissions are ~90% more than FAOSTAT total emissions in circa 2010 (Supplementary Table 8), mainly because we account for E_{bfg} and farmland CO_2 emissions. Further discussion on the comparison with other studies is provided in Supplementary Discussion 5.

Our framework can address many important issues related to developing mitigation strategies for food-related GHG emissions. For example, we can study the soil emission reduction due to land management practices such as no-till or reduced tillage. In addition, we can account for carbon sequestration due to reforestation of agricultural land freed from livestock production under the scenario of transitioning from animal-based diets to plant-based diets.

Finally, we estimated GHG emissions from the food sector but did not consider the opportunity costs of lost carbon sequestration capacity of agricultural land that would otherwise revert to forest if allowed to return to its natural state. Future studies should consider these costs, as well as management strategies for enhancing carbon sequestration on marginal lands, to estimate net carbon flux based upon alternative dietary and land-use scenarios. These estimates, combined with results from our study, would provide a comprehensive science-based framework that could then help policymakers assess climate change mitigation strategies that harness the natural regenerative capacity of our planet.

Methods

To quantify the total food-related GHG emissions, we first estimated the total crop and grazing biomass, including livestock feed, and then partitioned the total biomass between plant- and animal-based food (livestock feed) and other utilizations.

Based on the estimated biomass, we calculated and partitioned the production-based GHG emissions from plant and livestock to plant- and animal-based food and other utilizations. After that, we calculated GHG emissions from the consumption-based perspective, taking into account transportation, international trade (import and export) and stock variation. We estimated the consumption-based emissions to explicitly account for the GHG emissions caused by trade. This was especially important for regions and countries which import and/or export large amounts of plant- and animal-based food in the context of better tracing food systems' global and regional GHG footprints.

From the production-based perspective, the GHG emissions from plant- and animal-based food included the following subsectors (Fig. 1): emissions from land-use change for agricultural land expansion (E_{luc}); farmland emissions (E_{farm}) from farming activities such as ploughing soil, planting and fertilizing crops, harvesting crop grains and recovering crop residues for feedstock, and from fuel and electricity consumption by machines used in farming; livestock emissions (E_{live}) including CH_4 emissions from enteric fermentation by ruminant animals and CH_4 and N_2O emissions from manure management; beyond-farm-gate emissions (E_{bfg}), including mining, manufacturing and transportation of nitrogen, phosphorus and potassium (NPK) fertilizers, and pesticides, which were applied to agricultural land to produce crop and grazing biomass; as well as product processing emissions due to fuel and electricity consumption for production of crop (such as emissions from drying, peeling and milling processes) and livestock commodities (such as emissions from slaughtering and butchering).

From the consumption-based perspective, we calculated emissions from production, import, export and stock variation of plant and livestock, and what was consumed as plant- and animal-based human food and other utilizations. We estimated the net GHG emission transfers among different countries via international trade, that is, export and import, and emissions from the stock variation of plant and livestock products based on agricultural biomass. We also considered GHG emissions due to domestic and international transportation in consumption-based emissions.

Agricultural biomass. We estimated dry-matter biomass carbon of 171 crops by multiplying the crop production in circa 2010 with crop-specific dry-matter content and carbon content per unit of dry matter (Supplementary Table 1)[30–32] (Supplementary Methods 1.1). We first produced the spatially explicit production data of all crops in circa 2010 (Supplementary Methods 1.2 and 1.3). In addition, we calculated the amount of crop biomass for different utilizations based on the commodity balance reported by FAOSTAT[24] as described in detail in the section Emissions partitioning to different utilizations. We also estimated the crop residue biomass for all 171 crops (Supplementary Methods 1.2 and 1.3).

We first calculated the feed demand for 16 major livestock animals in each country by multiplying the animal-specific feed demands per head[33] by the number of live animal heads[22] (Supplementary Table 4). Then we quantified the biomass supply amounts from five sources to meet the feed demand in each country—namely, crop grain feed, forage crop feed, crop residue feed, grazing feed and scavenging and other feed as described in Supplementary Methods 1.4. To ensure that the supply (including import and export) and demand of feed were equal in each country, we developed a schematic algorithm to reconcile the feed demand and supply amount at the country level (Supplementary Methods 1.4 and Supplementary Fig. 6).

GHG emissions from food production. The total GHG emissions from food production are the sum of emissions from LUC, E_{luc}, farmland, E_{farm}, livestock, E_{live}, and beyond the farm gate, E_{bfg}.

LUC. LUC activities cleared existing ecosystems, their biomass and disturbed the soil, generating GHG emissions. This cleared biomass was either directly lost, for instance, through fire, or used to make different products. We assigned the carbon and nitrogen stored in these products into four pools: agriculture and agriculture products in a 1 yr product pool, paper and paper products in a 10 yr product pool, lumber products in a 100 yr product pool and long-lived products in a 1,000 yr product pool. In one particular year, we assumed the emission caused by product pools was the sum of the 1 yr pool, 1/10th of the 10 yr pool, 1/100th of the 100 yr pool and 1/1,000th of the 1,000 yr pool. The waste biomass was either burned or left on the ground as litter. For the emissions caused by soil disturbance, we assumed a certain amount, depending upon the region and soil type, of the topsoil soil organic carbon was lost in the first year when LUC occurred[34]. We used the historical LUC areas from Hurtt et al.[21], and processed these to drive the ISAM model using the methodology developed by Meiyappan and Jain[20]. In order to represent the LUC emissions for 1 yr circa 2010, we calculated the average E_{luc} emissions from 2007 to 2013, which was consistent with the time frame of other emission calculations in this study.

Farmland. Farmland emissions included all emissions due to farming activities, such as ploughing soil, planting and fertilizing crops, harvesting crop grains and recovering crop residues. Fuel and energy use emissions were also part of E_{farm}.

Fuel and energy use. Fuel and energy use emissions included GHGs emitted from fuels and electricity consumption by farm machinery, including irrigation. We used the energy use emissions (excluding fuel oil and energy for fisheries and transportation emissions) from FAOSTAT[17], and distributed these emissions to individual crops based on their harvested area. FAOSTAT fuel and energy use emissions included agriculture and forestry, and fishery emissions. Because we excluded fishery emissions, these data covered the emissions from both plant cultivation and livestock (for example, energy used in milking machinery and stables) on farmland. Therefore, we assumed that our farmland 'fuel and energy use emissions' covered both plant- and animal-based products. Our distribution method assumed the same GHG emissions on each unit of harvested area in the individual country. Given the small contributions of fuel and energy use emissions (~1% of our total food-related emissions), this relatively simple estimation method to calculate the fuel and energy use emissions in each country did not add much uncertainty to the total GHG emissions. The FAOSTAT dataset was computed following the Tier 1 method of the IPCC 2006 Guidelines for National Greenhouse Gas Inventories[12], which calculates the emissions by multiplying fuel burning and electricity generation amounts by their emission factors[12].

CH_4 and N_2O. We assumed all farmland CH_4 emissions were generated from rice paddies (since the rest was treated elsewhere—under livestock). We used the ISAM CH_4 module[35] to simulate the wetland and non-wetland soil CH_4 emissions and explicitly separated the CH_4 emission from rice paddies (see Supplementary Methods 3.3 for a brief description of the model). We used the N_2O module[36] of the ISAM to simulate the N_2O emissions from cropland and grazing land (Supplementary Methods 3.2). The gridded fertilizer and manure input data for ISAM are described in the Data sources section.

CO_2. We estimated farmland CO_2 emissions using the ISAM model jointly with FAO crop production data. The farmland CO_2 emissions, E_{f_CO2}, were the difference between all carbon emissions and sequestrations in agricultural land. Here the positive values meant emissions, while the negative values indicated carbon sequestration. E_{f_CO2} was calculated using equation (1):

$$E_{f\_CO2} = R_a + R_h + E_{t\_CO2} + E_{h\_CO2} + E_{w\_CO2} - GPP \quad (1)$$

where GPP is the gross primary productivity or gross CO_2 fixation by plants related to cropland and grazing land; R_a and R_h are autotrophic and heterotrophic respiration; E_{t_CO2} is carbon loss due to soil tillage; E_{h_CO2} is carbon loss due to harvest of biomass, including grain biomass and recovery biomass (for feed and other use); and E_{w_CO2} is carbon loss due to burning of waste biomass.

ISAM simulated E_{f_CO2} in a dynamic way for 16 major crops. The E_{f_CO2} for the rest of the 155 crops, a combination of C3 and C4 crops, was calculated using M3, FAOSTAT and ISAM model results for C3 and C4 generic crops described in detail in Supplementary Methods 1.3. After harvesting and recovery, we assumed a certain fraction (which varies from region to region) of the residual biomass was burned on the ground[37,38] (E_{w_CO2}). Remaining residual biomass after harvesting, recovering and burning went into the soil in the form of litterfall. Detailed processes were described by Jain et al.[19] and by Meiyappan et al.[34].

Livestock. In this study, livestock emissions only include emissions from enteric fermentation and manure management, which we define according to the IPCC[12] and FAOSTAT[17]. We used the country- and animal-specific CH_4 and N_2O emission factors from livestock enteric fermentation and manure management emissions from the FAOSTAT dataset[4,9,17] to calculate livestock emissions, E_{live} (see Supplementary Methods 2.2 for details).

Beyond the farm gate. Mining, manufacturing and transportation of fertilizers and pesticides. Agricultural materials were applied to agricultural land to produce plant biomass. We considered NPK fertilizers, and pesticide application emissions from mining of raw ores and fossil fuels to manufacturing and transportation to the farmland. We multiplied the application amounts and emission factors of NPK fertilizers and of pesticides to estimate the emissions from mining, manufacturing and transportation of fertilizers and pesticides (Supplementary Methods 2.1).

Processing. Food processing emissions were a component of E_{bfg}, which was part of both production- and consumption-based emissions. We included emissions from fuels and electricity consumption caused by the processing of crops needed before using, such as heat drying, peeling and grain milling (see Supplementary Table 9 for processed crops). For example, wheat grain was usually processed to wheat flour and wheat bran using mills, which consumed fuels or electricity and generated additional GHG emissions. We adopted the processing emission factors (Supplementary Table 9) from the Feedprint NL database (v.2019.00, Wageningen University & Research, 2019) to estimate the crop processing emissions. For the crops that were processed into multiple products (Supplementary Table 9), we allocated the GHG emissions of these crops to different products (Supplementary Methods 2.4).

Similarly, fuel and electricity were consumed during the processing of livestock products, such as slaughtering and butchering, which generated additional GHG emissions. We adapted the energy consumption amount of meat, dairy and egg productions and region-specific emission factors from GLEAM v.2.0[39].

GHG emissions from food consumption. Consumption-based GHG emissions were the sum of production-based emissions, emissions due to food transportation, emissions transferred among the importing and exporting countries and emissions from stock variation. To calculate the consumption-based GHG emissions, we first quantified the total consumption of plant biomass in each country using the commodity balance[24], which was the sum of production, import, export and stock variation. Next, we calculated the total consumption-based emissions. Finally, we partitioned total emissions into plant- and animal-based food, and other utilizations, based on the biomass consumption.

Plant biomass consumption. The consumption of crop biomass was calculated using the following relationship[24]:

$$\text{consumption}_{c,n} = \text{production}_{c,n} + \text{stock variation}_{c,n} + \text{import}_{c,n} - \text{export}_{c,n} \quad (2)$$

where $\text{consumption}_{c,n}$ is the biomass consumption of crop c in country n (kg); $\text{production}_{c,n}$ is the biomass production of crop c in country n (kg); $\text{import}_{c,n}$ and $\text{export}_{c,n}$ are imported and exported biomass of crop c in country n (kg); and $\text{stock variation}_{c,n}$ refers to changes in stocks at all levels between the production and the retail levels (kg). All these values are calculated from the FAOSTAT dataset[25] and averaged from 2007 to 2013.

We estimated the imported and exported amounts of forage crop biomass by the approach described in Supplementary Methods 1.4. We assumed there were no import, export and stock variation for grazing feed. Therefore, the production-based and consumption-based GHG emissions were the same for grazing feed.

We used FAOSTAT numbers for the commodity balance and calculated production using our modelling framework. This approach inherently introduced some differences between our production calculations and FAO estimates. In FAOSTAT, stock variation was usually used to adjust the imbalance between production and consumption amounts[40]. We used the same approach and attributed the imbalance between production and consumption to stock variation. The adjustment of stock variation had a relatively small effect on total emissions (less than 0.2%).

Consumption-based emissions. We adapted the following equation from Cassidy et al.[41] to estimate the GHG emissions for $\text{consumption}_{c,n}$ by accounting for GHG emissions from stock variation and international trade (bilateral trade; see detailed discussion in Supplementary Discussion 5):

$$\begin{aligned} GHG_{c,n} = {} & \left(\text{production}_{c,n} + \text{stock variation}_{c,n} - \text{export}_{c,n}\right) \times EI_{c,n} \\ & + \sum \text{import}_{c,i} \times EI_{c,i} + E_{\text{trans}_{c,n}} \end{aligned} \quad (3)$$

where $GHG_{c,n}$ are the GHG emissions from consumption of crop c in country n ($kgCO_2eq$); $EI_{c,n}$ is the weighted average GHG emission intensity of per kg crop c in country n ($kgCO_2$ eq kg^{-1}), which is defined as total production-based emissions (sum of E_{luc}, E_{farm}, E_{live} and E_{bfg}) for crop c in country n divided by $\text{production}_{c,n}$; $EI_{c,i}$ is the weighted average GHG emission intensity of per kg crop c in importing country i ($kgCO_2eq\,kg^{-1}$), which is calculated using the same method as for $EI_{c,n}$ but for importing country i; $\text{import}_{c,i}$ is the imported biomass of crop c from country i to country n; and $E_{\text{trans}_{c,n}}$ are the emissions from transportation of food c in country n. We assumed $\text{stock variation}_{c,n}$ has the same $EI_{c,n}$ as $\text{production}_{c,n}$.

Our approach ensured that all GHG emissions produced in one country (the sum of E_{luc}, E_{farm}, E_{live} and E_{bfg}) would be imported or exported to the trading partner countries along with the trade of food commodities. Our consumption-based GHG emissions could not rule out the effect of through-trade. We assumed that all products imported from a country were produced in that importing country. The through-trade might have a large effect on consumption-based GHG emissions in some countries, such as the Netherlands. To minimize the effect of through-trade, we reported our consumption-based GHG emissions at the regional scale.

Plant- and animal-based products were transported domestically and internationally by different transport modes, which generated GHG emissions. We calculated the transportation emissions, $E_{\text{trans}_{c,n}}$, based on the emission factors of different transport modes and transporting tonne-km of plant- and animal-based commodities (Supplementary Tables 10 and 11)[42,43]; 1 t-km represented the transport of 1 t (1,000 kg) of the commodity over a distance of 1 km.

Emissions partitioning to different utilizations. We calculated the plant-based GHG emissions from different utilizations based on the commodity balance of the FAOSTAT dataset[24]. This procedure did not generate additional GHG emissions; it only estimated the GHG emissions for different utilizations. The biomass balance was as follows:

$$\text{consumption}_{c,n} = \text{food}_{c,n} + \text{feed}_{c,n} + \text{others}_{c,n} \quad (4)$$

where $\text{food}_{c,n}$ and $\text{feed}_{c,n}$ refer to the biomass used as plant-based food and livestock feed for crop c in country n; and $\text{others}_{c,n}$ is the combined biomass for all non-food and non-feed utilizations.

The $\text{food}_{c,n}$, $\text{feed}_{c,n}$ and $\text{others}_{c,n}$ values were collected from the FAOSTAT commodity balance sheet[24]. We combined biomass for processing, losses, seed production and other usages as $\text{others}_{c,n}$. Note that the processing usages in FAOSTAT were also used for food or feed. Here we excluded the food and feed usages in the processing but included them in the biomass for food and feed correspondingly. For instance, soybeans were processed to soybean oil and cake; these three commodities all had their commodity balances. The 'processing' term in the commodity balance of soybean included the 'production' term in the commodity balances of soybean oil and cake. In order to avoid double-counting, we subtracted the 'production' of soybean oil and cake from the 'processing' of soybean. The commodities that were transformed into products with other uses (not food or feed) or into products that were actually used as feed or food but the uses of which were not explicit or not reported in the FAOSTAT commodity balance (for example, bran, alcohol, molasses and sweeteners from maize or sugarcane) had their 'processing' use classified as 'other utilizations'. Note that our study only accounted for the processed products that appeared in the commodity balance of FAOSTAT[24].

Based on equation (4), we calculated the GHG emissions from plant-based food (food_GHG$_{c,n}$) for crop c in country n by:

$$\text{food\_GHG}_{c,n} = \frac{\text{food}_{c,n}}{\text{consumption}_{c,n}} \times \text{GHG}_{c,n} \quad (5)$$

where GHG$_{c,n}$ is calculated in equation (3). We then used the same method to calculate the GHG emissions from feed$_{c,n}$ and others$_{c,n}$. It should be noted that the FAOSTAT commodity balance sheet[24] combines some crops into a broader commodity item (see column 'Corresponding commodity item' in Supplementary Table 1). We followed the same scheme to combine the GHG emissions from crops into different commodity groups (Supplementary Table 1) and then estimated GHG emissions from food$_{c,n}$, feed$_{c,n}$ and others$_{c,n}$.

We attributed all crop GHG emissions, including fuel and energy use emissions, to food, feed and other usages through the commodity balance. The GHG emissions allocated to crop feed and emissions from forage feed and temporary grazing feed productions, including fuel and energy use emissions, were all attributed to animal-based food emissions.

We used the same approach as the consumption-based emissions of plant biomass (equations (3)–(5)) to account for the consumption-based GHG emissions from livestock products in each country, including production, import, export and stock variation, and the consumption-based GHG emissions from animal-based food and other utilizations. Note that parts of livestock meat, dairy, and egg products were used as feed according to the livestock commodity balance[25]. We considered the animal-based feed GHG emissions as part of the animal-based food emissions.

Data sources. *Spatial data for NPK fertilizers.* For cropland, we produced the spatial maps of NPK fertilizer application amount for different crops at 0.5°×0.5° for circa 2010 based on EarthStat nutrient application spatial data for NPK fertilizer application amount for circa 2000[44,45], M3-crop[28] and FAOSTAT dataset[22] for crop-specific production data (Supplementary Methods 4). The EarthStat total nitrogen input amount, the combined nitrogen amount of synthetic fertilizer, manure and atmospheric deposition, was used to project the total nitrogen use in circa 2010. The synthetic nitrogen fertilizer component was only used as model input, which was estimated at the spatial scale for different crops using a fraction of synthetic nitrogen fertilizer amount to total nitrogen application amount in cropland at the regional scale[46]. We used other datasets for manure nitrogen application for cropland[47] and nitrogen deposition data[48] at the grid level. The amount of pesticides was not available at a spatial scale. Therefore we used country-scale data, which we collected from FAOSTAT[46].

For grazing land, we used the gridded nitrogen inputs for circa 2010 from Xu et al.[47], including synthetic nitrogen fertilizer and manure nitrogen left on and applied to grazing land.

Spatial data for manure nitrogen and carbon. We considered nitrogen and carbon from manure in this study. Manure was either left on the grazing land or collected in feedlot and then applied to cropland and grazing land. CH_4 and N_2O emissions were emitted during the storage and composting processes of the collected manure, which we considered as part of the livestock emissions (see Livestock section).

For cropland, the crop-specific spatial data of manure nitrogen application amount was estimated in our produced nitrogen fertilizer application amount based on published datasets[28,44,45,48,49] (Supplementary Methods 4). For grazing land, we used the gridded nitrogen inputs for circa 2010 from Xu et al.[47], which provided manure nitrogen left and applied to grazing land separately. These crop and grazing land manure nitrogen data were at the gridded scale that was required by the ISAM simulations. The aforementioned nitrogen datasets[28,44,45,47,48] were all based on and consistent with FAOSTAT manure nitrogen data at the country scale[49]. Therefore, our usage of FAOSTAT manure management emissions was also consistent with these manure nitrogen input data. Manure contained both organic and mineral nitrogen. Plants could not directly use organic nitrogen. In the ISAM model, the organic manure nitrogen was gradually decomposed by soil microbes to mineral nitrogen. Part of it then entered into the soil mineral nitrogen pool together with the inorganic (mineral) manure nitrogen[19].

To obtain the spatial data for manure carbon, we first estimated the total manure carbon amount by multiplying the animal-specific manure production per head[33] by the number of live animal heads[22] in different countries (Supplementary Table 4). Then we calculated the global total manure nitrogen (estimated in the previous paragraph) and determined the global average C:N ratio of manure. Note that the different manure carbon and nitrogen sources might introduce inconsistency in the global manure C:N ratio estimation. We multiplied this C:N ratio by the spatial maps of manure nitrogen to get the gridded manure carbon map on a global scale. ISAM considered manure carbon in organic form as litterfall and simulated its impact on farmland CO_2 emissions through dynamic processes.

Uncertainty analysis. We estimated the uncertainty range of the GHG emissions for plant- and animal-based food through a Monte Carlo approach, which simulated the uncertainties caused by major contributors of the GHG emissions, such as E_{luc}, E_{farm} and E_{live} by referring to their individual uncertainty ranges from previous studies (Supplementary Methods 5 and Supplementary Table 12). In addition, we acknowledge that the uncertainties of all spatial data we cited from previous studies and produced in this study are largely of unknown magnitude.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The results for CO_2, CH_4 and N_2O from the plant- and animal-based food are available at the ISAM website http://climate.atmos.uiuc.edu/Food_Emissions. The results for individual plant- and animal-based commodities are available upon request.

Code availability

All codes are available upon request.

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References

1. *How to Feed the World in 2050* (FAO, 2019); http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf
2. Herrero, M. et al. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl Acad. Sci. USA* **110**, 20888–20893 (2013).
3. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) (Cambridge University Press, 2014).
4. Tubiello, F. in *Encyclopedia of Food Security and Sustainability* vol. 1 (eds Ferranti, P., Berry, E. M. & Anderson, J. R.) 196–205 (Elsevier, 2019).
5. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
6. Mbow, C. et al. in *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* (eds Shukla, P. R. et al.) Ch. 5, 437–550 (IPCC, 2019).
7. Rosenzweig, C. et al. Climate change responses benefit from a global food system approach. *Nat. Food* **1**, 94–97 (2020).
8. Friedlingstein, P. et al. Global carbon budget 2019. *Earth Syst. Sci. Data* **11**, 1783–1838 (2019).
9. Tubiello, F. N. et al. Carbon emissions and removals by forests: new estimates 1990–2020. *Earth Syst. Sci. Data Discuss.* **2020**, 1–21 (2020).
10. Syakila, A. & Kroeze, C. The global nitrous oxide budget revisited. *Greenhouse Gas Measure. Manage.* **1**, 17–26 (2011).
11. Saunois, M. et al. The global methane budget 2000–2017. *Earth Syst. Sci. Data* **12**, 1561–1623 (2020).
12. IPCC *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Institute for Global Environmental Strategies, 2006).
13. Carlson, K. M. et al. Greenhouse gas emissions intensity of global croplands. *Nat. Clim. Change* **7**, 63–68 (2017).
14. Gerber, P. J. et al. *Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities* (FAO, 2013).
15. Searchinger, T. D., Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249–253 (2018).
16. Jain, A. K. & Yang, X. Modeling the effects of two different land cover change data sets on the carbon stocks of plants and soils in concert with CO_2 and climate change. *Global Biogeochem Cycles* **19**, https://doi.org/10.1029/2004gb002349 (2005).
17. *Emissions—Agriculture, FAOSTAT Online Database* (2019); http://www.fao.org/faostat/en/#data
18. Bond-Lamberty, B. et al. JGCRI/gcamdata: GCAM Data System Version 1.0 (2019); https://doi.org/10.5281/zenodo.1249932
19. Jain, A. K., Meiyappan, P., Song, Y. & House, J. I. CO_2 emissions from land-use change affected more by nitrogen cycle, than by the choice of land-cover data. *Glob. Chang. Biol.* **19**, 2893–2906 (2013).
20. Meiyappan, P. & Jain, A. K. Three distinct global estimates of historical land-cover change and land-use conversions for over 200 years. *Front. Earth Sci.* **6**, 122–139 (2012).
21. Hurtt, G. C. et al. Harmonization of global land-use change and management for the period 850-2100 (LUH2) for CMIP6. *Geosci. Model Dev. Discuss.* **2020**, 1–65 (2020).
22. *Production, FAOSTAT Online Database* (FAO, 2019); http://www.fao.org/faostat/en/#data
23. Zalles, V. et al. Near doubling of Brazil's intensive row crop area since 2000. *Proc. Natl Acad. Sci. USA* **116**, 428–435 (2019).
24. *Food Balance, FAOSTAT Online Database* (FAO, 2019); http://www.fao.org/faostat/en/#data

25. *Trade, FAOSTAT Online Database* (FAO, 2019); http://www.fao.org/faostat/en/#data
26. Pendrill, F. et al. Agricultural and forestry trade drives large share of tropical deforestation emissions. *Glob. Environ. Change* **56**, 1–10 (2019).
27. *Emissions—Land Use, FAOSTAT Online Database* (FAO, 2019); http://www.fao.org/faostat/en/#data
28. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem. Cycles* **22**, https://doi.org/10.1029/2007gb002947 (2008).
29. Janssens-Maenhout, G. et al. EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth Syst. Sci. Data* **11**, 959–1002 (2019).
30. Kyle, G. P. et al. *GCAM 3.0 Agriculture and Land Use: Data Sources and Methods* (Pacific Northwest National Laboratory, 2011).
31. Wolf, J. et al. Biogenic carbon fluxes from global agricultural production and consumption. *Global Biogeochem Cycles* **29**, 1617–1639 (2015).
32. Heuzé, V., Tran, G., Bastianelli, D., Archimede, H. & Sauvant, D. *Feedipedia: An Open Access International Encyclopedia on Feed Resources for Farm Animals* (2013); https://www.feedipedia.org/
33. Krausmann, F., Erb, K. H., Gingrich, S., Lauk, C. & Haberl, H. Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints. *Ecol. Econ.* **65**, 471–487 (2008).
34. Meiyappan, P., Jain, A. K. & House, J. I. Increased influence of nitrogen limitation on CO_2 emissions from future land use and land use change. *Global Biogeochem Cycles* **29**, 1524–1548 (2015).
35. Shu, S., Jain, A. K. & Kheshgi, H. S. Investigating wetland and nonwetland soil methane emissions and sinks across the contiguous United States using a land surface model. *Global Biogeochem Cycles* **34**, e2019GB006251 (2020).
36. Yang, X. J., Wittig, V., Jain, A. K. & Post, W. Integration of nitrogen cycle dynamics into the Integrated Science Assessment Model for the study of terrestrial ecosystem responses to global change. *Global Biogeochem Cycles* **23**, https://doi.org/10.1029/2009gb003474 (2009).
37. Yevich, R. & Logan, J. A. An assessment of biofuel use and burning of agricultural waste in the developing world. *Global Biogeochem Cycles* **17**, https://doi.org/10.1029/2002gb001952 (2003).
38. Wang, R. et al. High-resolution mapping of combustion processes and implications for CO_2 emissions. *Atmos. Chem. Phys.* **13**, 5189–5203 (2013).
39. *Global Livestock Environmental Assessment Model Version 2.0 Description* (FAO, 2018); http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf
40. *Food Balance Sheets: A Handbook* (FAO, 2001).
41. Cassidy, E. S., West, P. C., Gerber, J. S. & Foley, J. A. Redefining agricultural yields: from tonnes to people nourished per hectare. *Environ. Res. Lett.* **8**, https://doi.org/10.1088/1748-9326/8/3/034015 (2013).
42. Borken-Kleefeld, J. & Weidema, B. Global default data for freight transport per product group https://www.ecoinvent.org/files/transport_default_20130722.xlsx (2013).
43. Kinnon, A. *Guidelines for Measuring and Managing CO_2 Emission from Freight Transport Operations* (European Chemical Industry Council, 2011).
44. Mueller, N. D. et al. Closing yield gaps through nutrient and water management. *Nature* **490**, 254–257 (2012).
45. West, P. C. et al. Leverage points for improving global food security and the environment. *Science* **345**, 325–328 (2014).
46. *Inputs, FAOSTAT Online Database* (FAO, 2019); http://www.fao.org/faostat/en/#data
47. Xu, R. T. et al. Increased nitrogen enrichment and shifted patterns in the world's grassland: 1860–2016. *Earth Syst. Sci. Data* **11**, 175–187 (2019).
48. Zhang, B. et al. Global manure nitrogen production and application in cropland during 1860–2014: a 5arcmin gridded global dataset for Earth system modeling. *Earth Syst. Sci. Data* **9**, 667–678 (2017).
49. *Agri-Environmental Indicators, FAOSTAT Online Database* (FAO, 2019); http://www.fao.org/faostat/en/#data

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Author contributions

X.X. and A.K.J. designed the framework of this study, collected data and analysed the results. X.X., P. Sharma, S.S. and T.-S.L. performed the model simulations. P.C., F.N.T., P. Smith and N.C. contributed to the interpretation and implication of the results. X.X. and A.K.J. wrote the paper with inputs from all coauthors.

Competing interests

The authors declare no competing interests.

Additional information

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Data collection	Data collection is performed in Matlab r2017a and Python 3.7.1.
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The results for CO2, CH4 and N2O from plant- and animal-based food are available at the ISAM website http://climate.atmos.uiuc.edu/Food_Emissions. The results for individual plant- and animal-based commodities are available upon request.

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Ecological, evolutionary & environmental sciences study design

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Study description	This study reports spatially explicit production- and consumption-based GHG emissions worldwide from plant- and animal-based human food in circa 2010. We account for environmental drivers, such as climate, CO2, and N-deposition, and direct human drivers, such as land use change, using a consistent set of mass-conservative equations and parameters for biophysical and biogeochemical processes. In addition, this study reports CO2 emissions and sinks from changes in agricultural land management intensity from a set of diverse and spatially variable practices. We rigorously attribute the total GHG emissions from food sector to total and individual plant- and animal-based food by accounting for the emissions from livestock feed as part of emissions of animal-based food.
Research sample	This study uses data from multiple sources. 1. The production of 171 crops and forages, live animal and livestock productions, crop and livestock commodity balance, trade of crop and livestock products among countries, pesticides use, and GHG emissions from enteric fermentation, manure management and energy use are collected from FAOSTAT (http://www.fao.org/faostat/en/#data). 2. The spatial data for nitrogen, phosphorus and potassium (N, P, K) fertilizers for different crops in circa 2010 are produced based on EarthStat nutrient (http://www.earthstat.org/) application spatial data and FAOSTAT dataset (http://www.fao.org/faostat/en/#data). For grazing land, we use the gridded nitrogen inputs for circa 2010 from Xu, et al. (https://doi.pangaea.de/10.1594/PANGAEA.892940). 3. We use the historical LUC areas from LUH2 dataset (https://luh.umd.edu/), and process it to drive the ISAM model using the methodology developed by Meiyappan and Jain. 4. We adopt the processing emission factors from the Feedprint NL database (Version 2019.00, Wageningen University & Research, 2019) to estimate the crop processing emissions. We adapt the energy consumption amount of meat, dairy and egg productions and region-specific emission factors from GLEAM v2.0. 5. We use the emission factors of mining manufacturing, and transportation from following references: Kool, A., Marinussen, M. & Blonk, H. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization. GHG Emissions of N, P and K fertiliser production (2012). Kinnon, A. Guidelines for Measuring and Managing CO2 Emission from Freight Transport Operations. The European Chemical Industry Council (2011). Borken-Kleefeld, J. & Weidema, B. Global default data for freight transport per product group. Manuscript for special ecoinvent 3 (2013).
Sampling strategy	We use the average values from 2007 to 2013 for all available datasets and model simulations. The averaging of seven years values can fill possible gaps and remove outliers in a particular year or country to represent the circa 2010 condition.
Data collection	1. Xiaoming Xu has collected all FAOSTAT data in a bulk download at 7/19/2019. 2. Xiaoming Xu has downloaded the spatial data for fertilizers and manure data from http://www.earthstat.org/ and https://doi.pangaea.de/10.1594/PANGAEA.892940. 3. Prateek Sharma and Shijie Shu downloaded the LUH2 historical land use dataset from https://luh.umd.edu/. 4. Xiaoming Xu extracted the processing emission factors from the documents of Feedprint NL database and GLEAM v2.0. 5. Xiaoming Xu collected the emission factors of mining manufacturing, and transportation from individual publications.
Timing and spatial scale	The data collection starts at 7/1/2019 and ends at 10/1/2019. All the datasets are collected one time because they are all static data.
Data exclusions	No data is excluded in this analysis.
Reproducibility	We describe all detailed methods and procedures of data acquisition, processing and analysis to ensure the reproducibility of the work. For the model simulations, we keep all input files in record to make sure the reproducibility.
Randomization	Randomization is not relevant to this study, because we did not carry out any experiment.
Blinding	Blinding is not relevant to this study, because this study only use published datasets and model simulations.

Did the study involve field work? ☐ Yes ☒ No

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Materials & experimental systems

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Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

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ORIGINAL PAPER

Development of Inexpensive, Automatic, Real-Time Measurement System for On-Line Methane Content and Biogas Flowrate

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Abstract

Anaerobic digestion is widely used for waste treatment and biofuel production in the form of biogas from dedicated energy crops. Proper operation and control of anaerobic digesters require knowledge of biogas flow rate and methane composition of biogas. Methane content of biogas from an anaerobic digester was measured on-line by modifying an off-line measurement device, previously constructed by the authors, that uses a hydrocarbon sensor (MQ-4) and a pressure/temperature/humidity sensor (BME-280) integrated with an Arduino Uno. This modified on-line sensor was programmed to automatically measure methane composition by self-regulated introducing biogas samples and evacuating the device. It is also equipped with a function of biogas flowmeter which could calculate the cumulative biogas production over a time interval. Methane composition (v/v) could be measured every three hours. Measurements made by this device agreed within an average absolute difference of $0.81 \pm 0.58\%$ with measurements by a gas chromatograph equipped with a thermal conductivity detector. The volumetric flow rate was directly expressed on a moisture-free basis at standard temperature and pressure.

Graphical Abstract

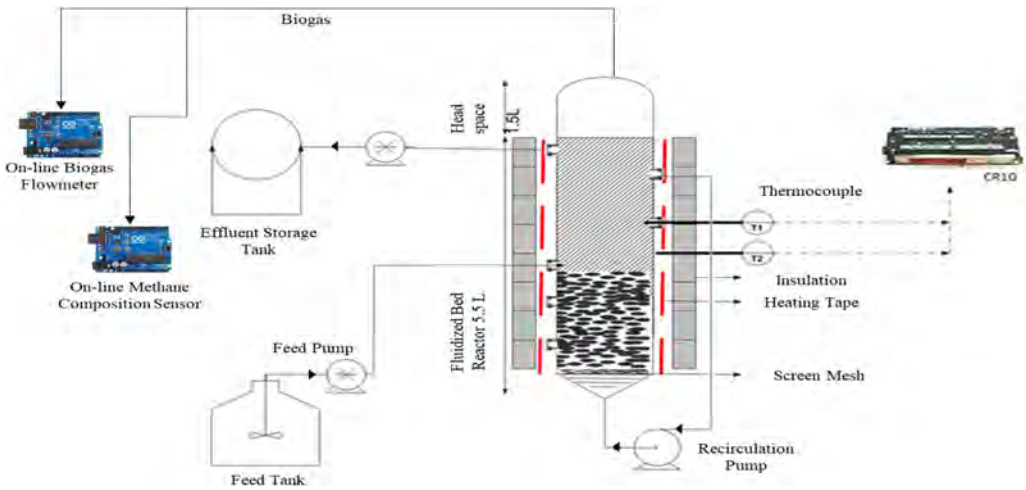

Keywords Biogas · Anaerobic digestion · On-line methane composition · Arduino uno · Renewable natural gas

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Statement of Novelty

In this manuscript, we describe the construction of devices that can be used to measure automatically, on-line methane composition and flow rate of biogas from laboratory anaerobic digesters. The devices were assembled in house from

commercially purchased materials for under $140. Currently there is a lack of inexpensive gas metering devices and sensors for application in supporting lab-scale anaerobic digestion research. Gas composition is measured off-line usually by a GC which can be expensive. So, these devices should have applications in anaerobic digestion research and laboratory-scale anaerobic digester on-line operation in many laboratories globally. Hence, we expect a wide audience for this work.

Introduction

Anaerobic digestion is a biochemical process mediated by a diverse population of syntrophic microorganisms belonging to domains of Bacteria and Archaea. The process mineralizes organic compounds to biogas under anaerobic conditions. Moisture free biogas is primarily a mixture of methane and carbon dioxide, typically containing 50–70% methane by volume. Anaerobic digestion has been traditionally used for treating waste streams like municipal sewage sludge, organic fraction of municipal solid waste, livestock manure and industrial wastewater [1–5]. Due to recent interest in alternative energy sources, the process is being widely applied for the generation of renewable energy from organic residues and energy crops [6–9]. Biogas can be utilized on-site as fuel for the generation of thermal and electrical energy, or it can be upgraded to renewable natural gas (RNG) by removing carbon dioxide and other contaminants then compressed and either fed into the natural gas pipeline or used as a vehicular fuel. Recently US. Environmental Protection Agency (USEPA) has approved RNG as cellulosic biofuel (equivalent to D-3 Renewable Fuel Standards) if produced from organic wastes and byproducts and used as a vehicular fuel [10].

The performance of anaerobic digesters is characterized by the methane production rate, which is a product of biogas flow rate (BFR) and methane composition. The methane content also influences the energy content of biogas. Various operating conditions like feed rate, hydraulic and solids retention time, temperature, alkalinity, pH, and feed quality can affect methane production rate [11–14]. Changes in these conditions may adversely affect the process, and corrective actions need to be taken to assist in process recovery. For example, a feed overload can cause pH to drop, increasing production of carbon dioxide, thereby lowering the methane content of biogas [15, 16]. Toxins in feed can inhibit microbial populations and lower biogas and methane production rate. On-line process control and optimization techniques to reject disturbances, usually monitor methane production rate (or methane composition) as a measured variable [17–21]. Therefore, it is essential to monitor in real-time, on-line digester methane concentration and BFR.

Methane content can be measured off-line using an infrared spectroscope [22, 23], gas chromatography (GC) [24, 25], or a mass spectrometer [26, 27]. These instruments can be adapted for on-line measurements as well. However, the costs can be prohibitive. Several portable devices are currently available for on-line methane measurement. These include Guardian (Edinburgh Instruments Ltd, Livingston, UK), GEM 2000 (Geotech Environmental Equipment Inc, Denver, Colorado, USA), SKZ 1050B (SKZ Industrial Co., Limited, Shangdong, CHINA), and Dräger X-am® 5600 infrared (Draeger Safety, Inc., Pittsburgh, PA, USA). These instruments are fitted with a pump to collect a sample of biogas for analysis connecting to the pipe carrying biogas from the digesters. Some of these devices can be interfaced with a computer for data logging. Usually, large sample volumes are required so that these instruments can be used only on a large-scale anaerobic digester. The cost ranges from US$1500 for the SKZ 1050B to US$12,000 for GEM 2000. In 2014, Liu had tested with two IR sensors (OdaLog 7000 IR and GasTech S-Guard IR) for on-line measuring methane composition in laboratory setup [28]. In 2009, Kim et al. proposed a fully automated biogas monitoring device for sewer gas (SewerSnort). However, the device was only used on the dry land emulator; further field application had not been performed [29]. A few commercial sensors were used for on-line measuring methane content [30–32]. Arduino-based methane measurement system earned much attention for its low-cost, reliable performance, and robust sensitivity. A few portable methane measurement devices have been assembled [33–35]. Leonardo et al. used Figaro TGS2600 sensor based on Arduino platform to construct a portable device, however, the device could not perform unmanly [33]. Those device does not discuss the humidity impact on the sensor sensitivity and also the signal amplifies technique. Most of the devices are used for the alarming systems. Nagahage had constructed a low-cost methane sensor based on TGS 2611 and MQ-4, the temperature and humidity were considered as a characteristic, but there was no methods for resolving the impact of humidity. It also proved that with the interfere of humidity, methane measurement did not have a stable and constant reading. And due to the biogas production fluctuations, the biogas volume produced in the headspace of the digester will be significantly different. Assuming a fixed volume biogas when converting the diluted biogas sample concentration to the raw biogas methane content will not be feasible [36]. Honeycutt compared different types of methane gas sensors and discussed the limitations of low-cost methane sensors [37]. The methodology in this paper evolved from the philosophy of off-line measuring the methane content [38], including manually preheating the device chamber, mitigating the moisture in the gas sample, injecting a

fixed volume gas sample, and evacuating the gas sample from the device chamber by operator's interfering. The device chamber in this paper will automatically inject the sample from the attached anaerobic digester. The unknown injected sample volume could be calculated by the acquired pressure difference in the device chamber. The online measurement system could complete the tasks automatically, from the process of injecting gas samples to evacuating and preparing the device chamber for the next batch of the gas samples.

The methane production rate could be determined by measuring the BFR along with methane content. For large-scale operations with high flow rates, the BFR is usually measured with mass flow meters (Alicat Scientific, Inc., Tucson, AZ, USA) and ultrasonic flow sensors (BW Technologies Ltd, Calgary, Canada). BFR from laboratory-scale anaerobic digesters is usually low, especially during the startup phase, while the flow rate may be less than 0.5 L per day. Mass flow meters, like Alicat, can measure flow rates as low as 720 ml per day, can be costly. Usually, liquid displacement devices are used to measure low BFR. These designs include the wet gas meter (Shinagawa Corporation, Tokyo, Japan), U-tube manometer-type devices equipped with optical sensors [39], and float switches [40]. In these devices, biogas is allowed to accumulate to a set volume (or pressure) before being released by tipping the chamber (in a wet tip gas meter) or through a solenoid valve in U-tube devices. When biogas is released, a counter records the event and/or a signal is sent to a data logger. The number of such counts or signals multiply the gas volume released over a defined time-interval yield the BFR.

With open-source Arduino Uno microcontrollers and associated sensors, it is possible to develop inexpensive devices and controllers for various applications. Previously the authors developed and tested an Arduino-based device for off-line measurement of methane content in gas samples [38]. The key component of this device was an inexpensive MQ-4 (Hanwei Electronics Group Corporation, Zhengzhou, China; MQ-4 sensor technical data, 2017) hydrocarbon sensor. This sensor, along with another BME-280 which is an integrated pressure, temperature and humidity sensor (manufactured by Bosch Sensortec, Mansfield, Texas, USA), was placed inside a chamber. This methane-sensing device chamber, a 405 ml air-tight mason jar with a screw lid, was modified to provide appropriate environmental conditions for optimal sensor response. The sensors were interfaced to an Arduino microcontroller. Samples were manually withdrawn from the anaerobic digesters and injected into the chamber to measure methane content. After each injection, the lid of the mason jar was opened to evacuate the chamber and then tightly closed before injecting the next sample. By comparing with GC measurements, it was shown that this device could accurately (+/− 0.85%) measure the methane content of biogas samples from an anaerobic digester. The device was assembled in-house for a cost of US$36, which is a fraction of the cost of commercially available instruments.

In this paper, we report the modifications of the off-line MQ-4/BME-280/Arduino-based device described above for on-line, automatic and real-time measurements of methane content in biogas. As all measurement steps were done automatically, it was necessary to develop protocols, methods and ascertain optimal durations for the following tasks: pre-heating the sensors, introducing sample gas, taking measurements, and evacuating the chamber. The complex modified device was connected to a laboratory-scale fluidized bed digester. Methane content automatically measured by the device was compared to off-line GC measurements. Additionally, we replicated the operation of a manometer-type device for measuring the biogas flow rate by using a BME-280 sensor interfaced with an Arduino Uno.

Materials and Methods

Figure 1 shows a schematic diagram of the laboratory-scale fluidized bed anaerobic digester (block c) connected to the on-line methane content measurement devices (block a) and the biogas volumetric flowmeter (block b). The construction and operation of the on-line measurement devices are described below.

On-Line Methane Composition Measurement Device

The on-line methane composition measurement devices are made up of the methane-sensing device chamber (MSDC), air-drying chamber (ADC), air pump, two-way valves B, C, D actuated by solid-state relays, two Arduino microcontroller boards (1 and 2), and an SD card for storing and retrieval of data. The MSDC was a 600 ml screw-top glass mason jar in which an MQ-4 methane sensor and a BME-280 (pressure, temperature and humidity) sensor were placed. The jar was partly filled with drierite to dry gases held in the jar so as to prevent moisture from interfering with the response of the MQ-4 sensor [38]. The lid of this jar was equipped with three ports, the first one to introduce gases, the second to evacuate the gases and the third one to pass wires that transmit signals from the sensors. Two-way valve B regulated the inflow of biogas sample and two-way valve C regulated the outflow of gases from the MSDC. The ADC was a 900 ml glass mason jar with a screw-top lid. Three-quarters of this jar was filled with drierite to dry the air before it flowed into the MSDC. The lid of this mason jar was fitted with two ports, an inlet and outlet for the air. Outlet airflow was controlled by two-way valve D. An air pump was connected to the inlet port. Arduino module 1 was used to acquire data from MQ-4 and BME-280 sensors from

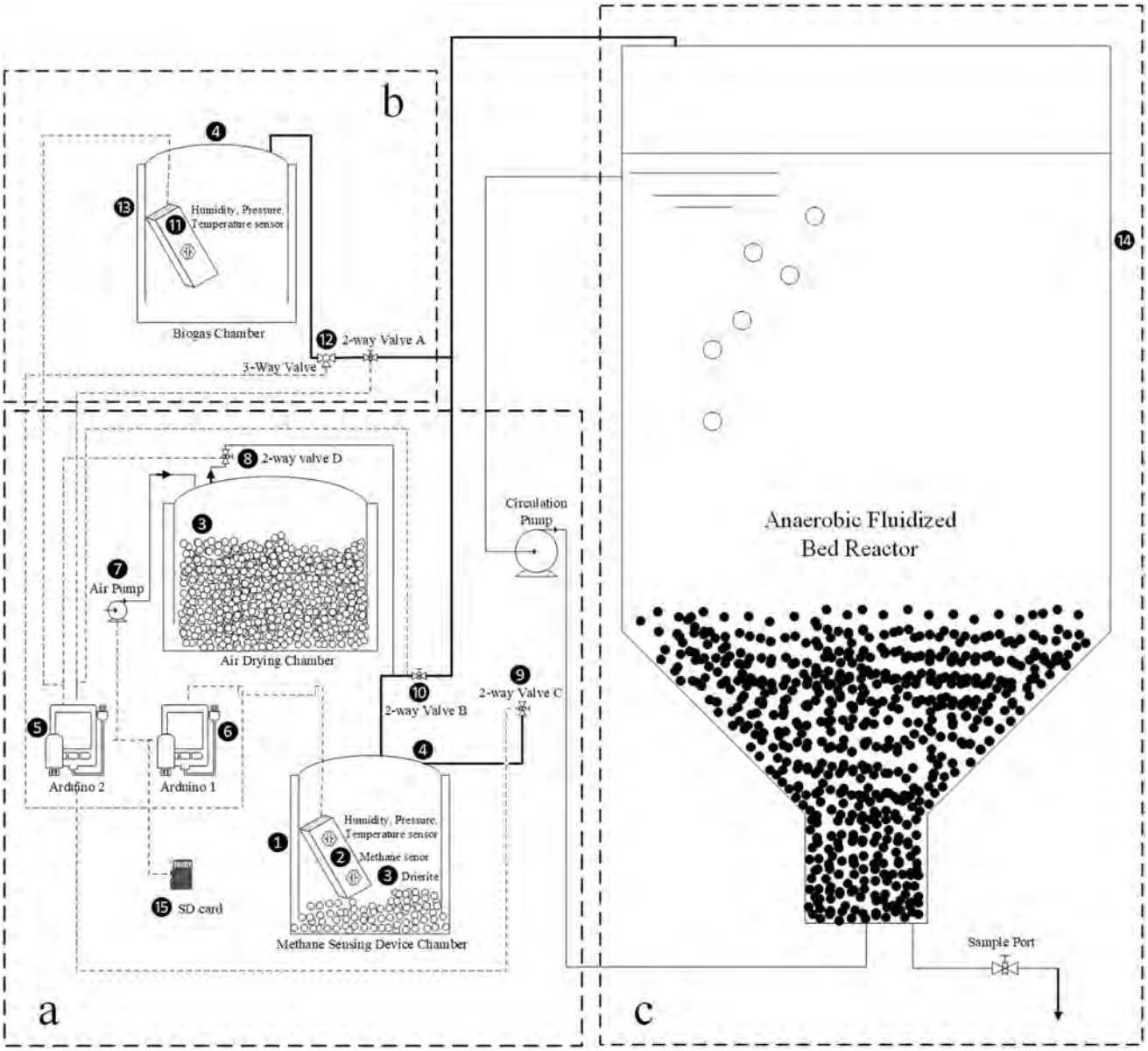

Fig. 1 Schematic diagram of laboratory-scale fluidized bed reactor (block c) with on-line measurement of methane composition (block a) and BFR (block b). (1) 405 ml Methane sensor device chamber, (2) Sensors (BME-280 and MQ-4), (3) Drierite, (4) Screw-capped lid with O-ring, (5 and 6) Arduino data loggers, (7) Air pump, (8, 9, 10 and 12) Arduino controlled 2-way valves, (11) Sensor (BME-280), (13) 405 ml biogas Chamber, (14) Anaerobic Fluidized Bed Reactor (15) SD card

the MSDC, and Arduino module 2 was used to turn on and off the solid-state relays that operated the air pump and the two-way valves A, B, C, and D. The inlet and outlet ports for both mason jars were nylon adapters passing tightly through holes drilled on the screw-cap lids and were connected to Tygon tubing on the outside. The hole for the wire port was drilled to securely hold a 1/8" male, brass, hex nipple fitting through which the electrical wires were passed. 1-min Instant mix epoxy (Loctite, USA) was used to seal the gaps between lid and nylon adapters, between the lid and brass fitting, and within the brass, fitting to seal gaps between wires. While operating the On-line measurement system, the valve relay signals used to interfere with the signals of sensors; two Arduino modules were decided to cooperate to control different chambers in place of the signal interfering.

Biogas from the anaerobic digester normally flows into the biogas chamber through valve A as it is usually open, and valves B and C are normally closed. In this state, biogas is metered by the biogas volumetric flowmeter device, as discussed in Section "On-Line Biogas Volumetric Flowmeter Device" below. Measurement of the methane composition in biogas is carried out in three

steps: (1) preparation of the sensors in the MSDC, (2) gas sample injection and methane content measurement, and (3) ventilation of the MSDC.

The first step involves preheating the MQ-4 sensor and absorption of moisture in the MSDC. The MQ-4 methane sensor requires preheating and low humidity for a linear response to methane content. The MSDC is turned on 60 min prior to sample injection to allow sufficient time for preheating the sensor. After this, the following processes are initiated for step 2. Valve A is closed for 2 min and the biogas is allowed to build up pressure in the headspace of the anaerobic digester. Valve B is momentarily opened to divert gas flow to the MSDC, thus automatically injecting a sample into the MSDC. After 100 times trials, the sufficient time to open valve B needs to be only 500 milliseconds to allow enough gas samples to flow into the MSDC for measurement. Right after valve B is closed, valve A is opened so that, as before, the biogas continues to flow into the flow meter for recording BFR. The signals from the BME-280 and MQ-4 sensors are collected every 5 s. The signal values are averaged over 5 min time intervals and saved on the SD card. Soon after the injection of a biogas sample, the humidity of the chamber increases and then begins to decrease as moisture is absorbed by drierite. Following Yang et al. [38], MQ-4 signals collected after the humidity drops below 1% are used to calculate methane content. From many trials by injecting different volumes of biogas samples, the time required for humidity to drop below 1% and the MQ-4 sensor output signal to stabilize was determined to be around 35 min. Subsequently, the methane composition is monitored for an additional 25 min, and the average of the data collected during this interval is used for methane composition calculations. The following equations are used to calculate the volume of the injected sample:

$$\Delta P = P_2 - P_1 \tag{1}$$

$$n_{inject} = \frac{\Delta P \times V_{chamber}}{R \times T} \tag{2}$$

$$V_{inject} = \frac{n_{inject} \times R \times T}{P_2} \tag{3}$$

$$M_{inject} = \frac{\left(M_{chamber} - M_{initial}\right) \times V_{chamber}}{V_{inject}} \tag{4}$$

where $P_1$is pressure in the MSDC before opening valve B, kPa. $P_2$is the average pressure in the MSDC between 35 and 60 min after injection of sample, kPa. $V_{chamber}$= volume of the MSDC, ml. R =universal gas constant=8314 ml kPa/K/mol. T =average temperature in K, in the MSDC between 35 and 60 min after sample injection. V_{inject}= volume of gas injected by diverting gas flow into the MSDC, ml. M_{inject}= methane content (by volume) of the injected gas sample, %. $M_{chamber}$= methane content (by volume) in the MSDC after injection of sample, %. $M_{initial}$= initial methane content (by volume) in the MSDC before sample injection, %. $M_{initial}$, $M_{chamber}$ are calculated from average MQ-4 sensor signal values as outlined (Yang [38]).

After analysis, the MSDC is evacuated (step 3) using the following procedures. Valves C and D are opened, and the air pump is turned on for 8–10 min which is the time required to dilute the methane content in the MSDC to less than 0.2%. The air is pre-dried by passing through the ADC and then flows into the MSDC, flushing the sample gas out. The pre-dried air can reduce the preparation time. Two seconds after turning off the air pump, valves C and D are closed, thus first step of preparation for MSDC started.

On-Line Biogas Volumetric Flowmeter Device

The on-line biogas volumetric flowmeter device is made up of a biogas chamber (405 ml glass mason jar) and a BME-280 sensor. The lid of this jar was equipped with two ports, the first one to introduce and evacuate biogas (called the biogas chamber port) and the second to pass wires that transmit signals from the sensor. One end of a three-way solenoid valve was connected to the biogas chamber port and the other end to the anaerobic digester through valve A. Under regular operations, this path is open. The other opening of the three-way valve serves as a vent port which is normally closed. When valve A is also open, gas from anaerobic digester fills the biogas chamber (BC). When a preset pressure increase occurs, two events happen: (A) the three-way valve closes the port connected to the anaerobic digester and opens the vent port evacuating the gas from the BC which resets the chamber to atmospheric pressure (B) a time-stamped signal is sent to Arduino module 1. Then the vent port remained open for a three-second duration. A ten-millisecond delay was introduced right after the vent closed, the port connecting to the anaerobic digester opened up and biogas continued to fill the BC. The number of venting signals sent to Arduino module 1 between two on-line methane composition measurements is counted. The BFR during this interval is the number of signals multiplied by the volume of biogas that triggered one ventilation event. The BME-280 sensor provides values of pressure, temperature and relative humidity in the BC. The sensor is sampled every five seconds and values collected over 30 s (six data points) are averaged and stored. The averaged value is replaced every subsequent 30 s. The stored value of pressure (which is the current value) is used to calculate ΔP_{bg} (=$P_{current}$ - $P_{initial}$), where $P_{initial}$ is the pressure in the BC immediately before the port to the digester is opened (soon after ventilation of

the BC). When ΔP_{bg} is equal to or greater than the preset value (15 kPa), the port connected to the digester is closed and the vent port opens up. The stored values of relative humidity and temperature are used to calculate the volume of dry biogas at standard temperature and pressure that is released. The partial pressure of water vapor (p_w) in the gas released is calculated using the relative humidity measured by the BME-280 as follows:

$$p_w = \frac{\Phi}{100} \times p_{ws} \tag{5}$$

where Φ = relative humidity (%). P_{ws} = saturation vapor pressure at the temperature of the BC (kPa).

The temperature of biogas in the BC should range between room temperature (22 °C) and digester operating temperature (55 °C). A second-order polynomial is used to calculate p_{ws} between temperature of 21 °C and 55 °C:

$$p_{ws} = 0.0085\Theta_{bg}^2 + 0.2678\Theta_{bg} + 4.4792 \text{ for } 21\,^{\circ}\text{C} \le \Theta_{bg} \le 55\,^{\circ}\text{C} \tag{6}$$

where Θ_{bg} = temperature of biogas in the BC (°C).

The Volume of Dry Biogas Evacuated at Standard Temperature and Pressure is Calculated as Follows

$$V_{bg} = \frac{\left(\Delta P_{bg} - p_w\right) \times V_{bgchamber} \times V_{mv}}{R \times T_{bg}} \tag{7}$$

where $V_{bg\ chamber}$ = volume of BC (405 ml). R = gas constant = 8314 ml kPa/K/mol T_{bg} = temperature of biogas in BC (K) = Θ_{bg} + 273.15 V_{mv} = molar volume of ideal gas at STP (22.4 L/mol).

Dividing V_{mv} by the time interval between two consecutive evacuations yields the volumetric BFR. The methane production rate is the product of BFR multiplied by the methane composition of biogas measured by the on-line sensor. All the steps above to calculate these measurements were fully automated and programmed into the Arduinos.

Laboratory-Scale Anaerobic Fluidized Bed Digester (AFBR)

The AFBR has a working volume of 5.5 L leaving a headspace of 1.5 L with six sample ports spaced 4" apart which are used for sample collection, feed input, recirculation and thermocouple access. Commercial prewashed activated carbon particles (0.5 mm in diameter) are used as carriers in the AFBR. Fluidization is provided by recirculating the reactor liquid using a peristaltic pump at a flow rate of 10 L per minute. The use of such a high flow rate ensures good mixing in the reactor. Biomass growth was observed on the surface of the activated carbon particles.

A modular data logger, CR10X that is available with a measurement and controller module is used to control the temperature of the reactor [41]. An on-off protocol was developed using the CR10 software to control the process of heating the reactor liquid to 55 ± 2 °C. The AFBR was acclimatized to cellulosic ethanol stillage and fed daily. Under normal operating conditions, 200 ml of stillage was fed daily at 11:30 AM using a timer. The timer was used to turn on a peristaltic pump for loading ethanol stillage. The methane measurements made over 23 days are reported here. During this period, to investigate the response of the on-line methane sensor to disturbances, the daily volume of feed was increased to 400 ml on days 1 and 2600 ml on day 3, returned to 200 ml for days 4–9, increased to 800 ml on day 10, further increased to 1200 ml from days 11–16 and brought back to the normal volume of 200 ml from day 17 on.

Devices Validation Tests

Several tests were carried out to validate the function of the devices. After assembly, the devices were first checked for gas leakage. 24 ml standard biogas (Airgas, Tampa, Florida, USA) containing 60% methane and 40% carbon dioxide was introduced into both MSDC and BC, and the pressure and temperature of the chambers were monitored overnight. In the next test, four biogas samples from the AFBR were injected into the MSDC consecutively. Signals from the on-line methane content measurement devices were monitored for 2 h after each injection. Steps of "Methane sensor response," "Sample venting," and "Preheating sensors" were determined from these injections and the same as the duration. Before a sample was automatically introduced into the MSDC, a 1 ml sample was withdrawn and injected into a GC. After 3 days of testing, the on-line devices were programmed to measure the methane content of biogas automatically every 3 h. The methane content of gas samples was also measured using a GC. The measurement made on the off-line GC was compared with the methane content measurement by the sensor.

Gas Chromatograph (GC) for Methane Composition Measurement

A thermal conductivity detector-equipped GC (Gow-Mac series 580, Bethlehem, PA, USA) was used to measure methane content of gas samples withdrawn from the headspace of the AFBR. A SUPELCO (Sigma- Aldrich Corp, St. Louis, MO, USA) analytical column 80/100 HAYESEP Q (9 ft x 1/8-inch,1mmSS) was used in the GC, with helium as a carrier gas. The operating conditions of the GC [24] were: column temperature 61 °C; detector temperature 152 °C; and injector temperature 81 °C. The sample gas from the AFBR was collected during the daytime, and each time 1 ml sample was withdrawn from the headspace of the reactor and then injected into the GC for methane composition analysis. The

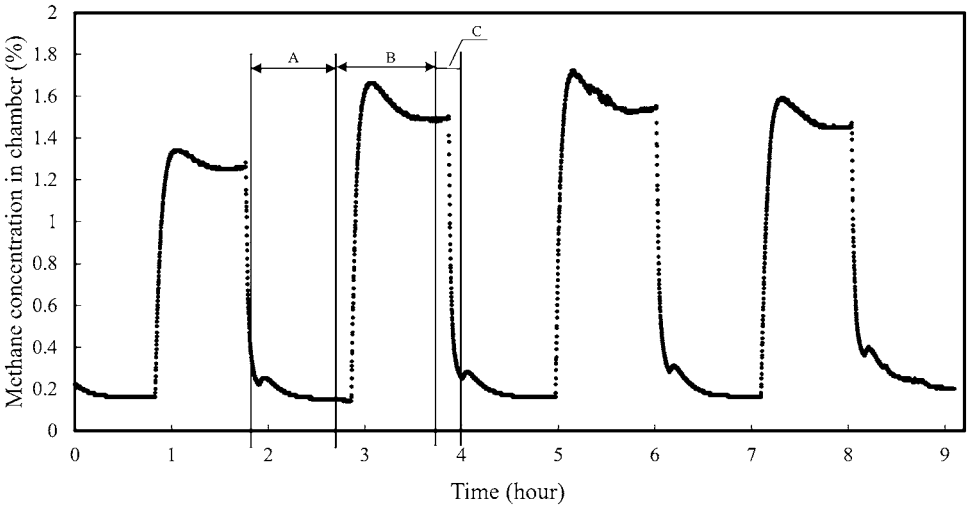

Fig. 2 Response of on-line methane sensor to biogas samples automatically injected into MSDC device chamber. **A** Preheat **B** Methane measurement **C** Vent

sample gas was successively taken every 30 min, so the average of the GC measurement was used for comparing with the on-line methane content measurement device. Under normal operating conditions, the sample gas was usually taken between 10:30 AM and 12:00 PM. GC measurements for methane content were taken during the 23 days while the methane content of the AFBR was changed by introducing feed loading changes. The daily loading rate and the corresponding methane content measurements were compared to the data analyzed by on-line methane content measurement device.

Results and Discussion

Devices Leakage Test

The first step in testing the devices was to check for leakage. The fully assembled devices (three chambers in Fig. 1) were tested for leakage. The biogas was introduced into the chambers through valve B, keeping valves A and D open, and closed. The pressure, temperature, and relative humidity data were collected for 12 h. The ratio of absolute pressure to absolute temperature was recorded by Arduino against time and was consistent with a range from 0.3571 to 0.3563 over 12 h, which indicated minimal leakage.

Response of Methane Sensor to Biogas Samples

Figure 2 shows the responses of the MQ-4 sensor to four consecutive injections of biogas samples from the AFBR. These biogas samples were automatically injected into the MSDC. The MSDC was taken through the preheat, sample injection and measurement, and sample venting steps as described above. As the methane production rate from the anaerobic digester fluctuated, the buildup of the pressure in the headspace of the digester varied when valve A was closed for 2 min. Consequently, different amount of biogas was introduced into the MSDC when valve B was opened for 500 milliseconds. Sample volumes introduced into the MSDC were 6.42, 7.52, 7.47, and 6.99 ml, respectively. These volumes were calculated automatically by the Arduino program using Eqs. 1, 2 and 3. After each biogas sample injection, the methane content value increased rapidly in the first 5 min, then decreased and stabilized within the next 60 min as the sample was completely distributed within the MSDC. The methane concentrations measured between 35 and 55 min, sampled every five seconds, were averaged in a 5-min interval to obtain the $M_{chamber}$ value. The mean and standard deviation (expressed as % of mean) from the four consecutive biogas samples shown in Fig. 2 were $1.252 \pm 0.004\%$ (for 6.42 ml injection), $1.490 \pm 0.002\%$ (7.52 ml), $1.529 \pm 0.006\%$ (7.47 ml) and $1.450 \pm 0.001\%$ (6.99 ml). The average methane concentration before injection of the four samples, $M_{initial}$, were $0.16 \pm 0.000\%$, $0.15 \pm 0.000\%$, $0.16 \pm 0.000\%$ and $0.16 \pm 0.000\%$. Using the Eq. 5, the methane concentration of injected biogas was calculated as $78.98\% \pm 0.26\%$ (6.42 ml), $80.28 \pm 0.13\%$ (7.52 ml), $82.95 \pm 0.34\%$ (7.47 ml) and $83.97 \pm 0.06\%$ (6.99 ml). From GC measurements, the average methane content of biogas samples collected from the headspace of the digester immediately after valve B was closed prior to the four injections was $81.22\% \pm 0.33\%$.

Automatic On-Line Measurements of Biogas Samples

The composition of biogas produced from the AFBR was monitored over 23 days. During this period, the volume of daily feed loading was changed. Figures 1, 2, 3 shows the volume of cellulosic ethanol stillage that was loaded into

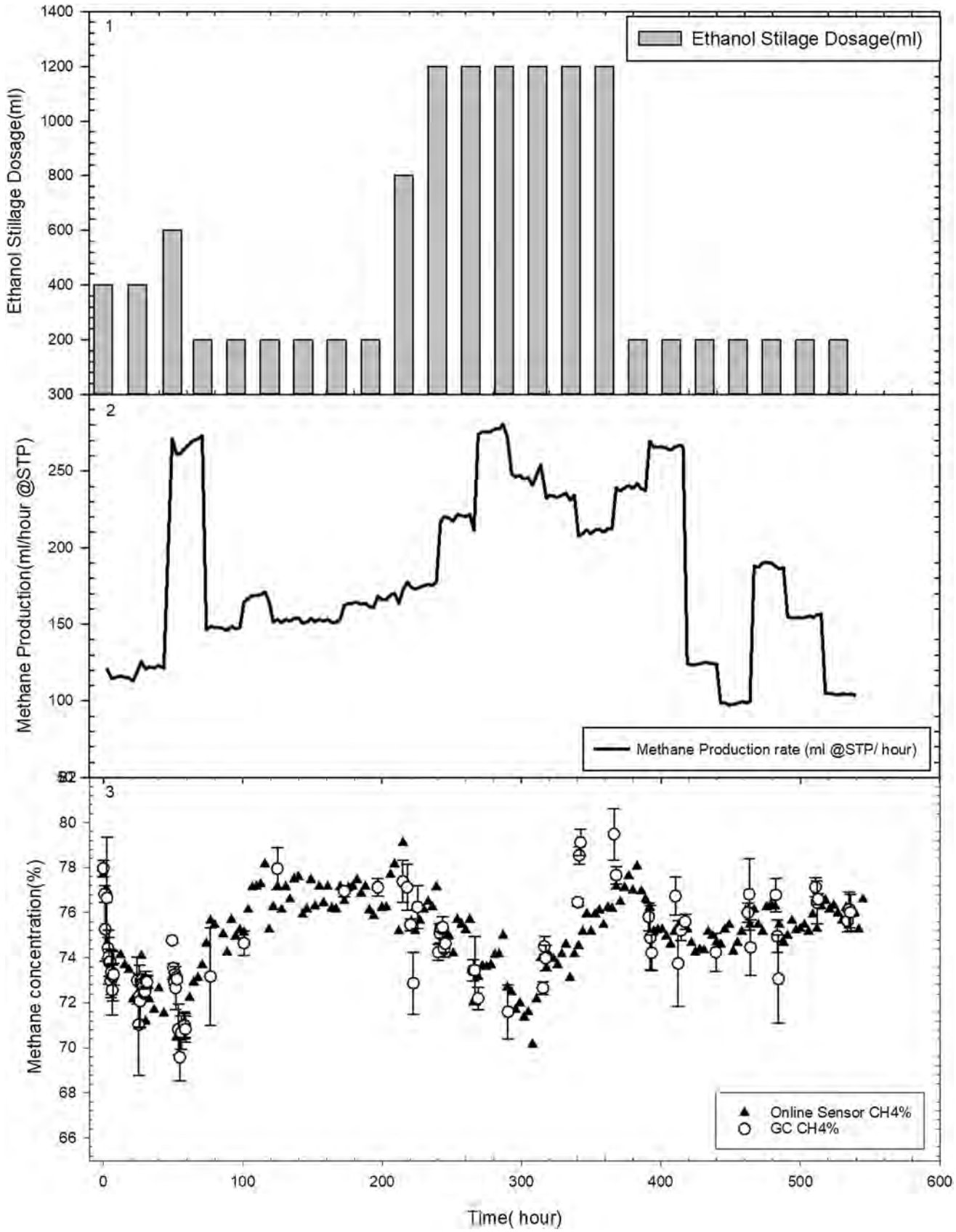

Fig. 3 AFBR operation and response. (4 – 1) The volume of cellulosic ethanol stillage fed daily, (4 – 2) Biogas production rate and (4 – 3) Methane composition of biogas measured by on-line sensor and GC

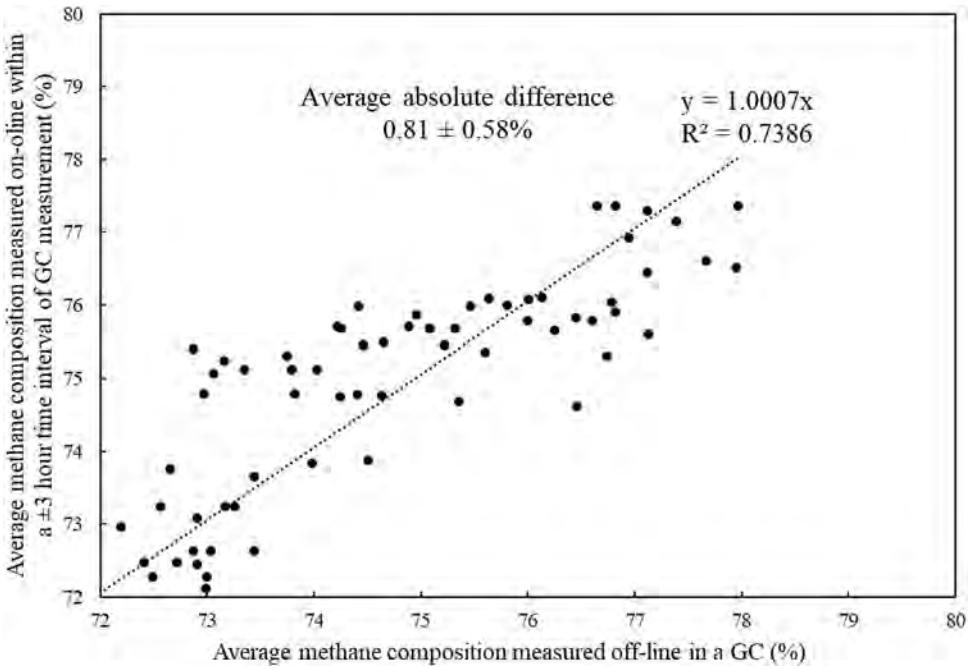

Fig. 4 On-line methane measurements by sensor, averaged over a ± 3 h time interval within an off-line GC measurement compared to the average off-line GC measurement

the AFBR every day. Figures 2, 3-1 shows the response in terms of volumetric methane production rate per hour. Figure 3-2 shows the methane composition measured by the on-line sensor and compares it to the value measured by off-line GC. The on-line measurement device measures the methane composition in biogas every 3 h. The mean and standard deviation of the methane composition in the AFBR headspace is shown in Fig. 3-3. The methane measurement from the on-line measurement device shows a pattern similar to that of the GC measurements.

A challenge for measuring the methane percentage for the AFBR on-line is that the sampling period should be sufficiently short to track responses to disturbances. For instance, overloading feed into the digester can cause a drop in pH due to volatile organic acid accumulation and decrease the methane production rate. pH fluctuations may also affect the carbon dioxide concentration of the gas phase, which in turn affects the methane composition. The operation of the digester with these disturbances is shown in Fig. 3-3. In the first 2 days, the methane concentration started to drop when 400 ml of feed was added daily. On day 3, 600 ml of feed was loaded into the digester. This caused a further drop in methane concentration which was tracked by the on-line sensor. Then normal loading of 200 ml per day was resumed over the next 6 days. Methane concentration increased as observed from GC and on-line measurements. On day 10, feed of 800 ml was loaded, followed by 1200 ml of feed from days 11 to 16. The methane concentration dropped until day 13 before beginning to increase as the digester became acclimatized to 1200 ml of daily feed. The on-line measurements followed this trend. The methane concentration fluctuated around a value of 75.5% after the daily feed was decreased to the normal value of 200 ml from day 17 on. By day 23, the amplitude of these fluctuations shows a dampening behavior which was also tracked nicely by the on-line sensor measurements.

Average Absolute Difference of the On-Line Measurements

As Fig. 3-3 shows, the GC measurements were not taken at the same frequency as the on-line measurements. In addition, the AFBR was operating under unsteady state conditions. So a procedure was devised to compare GC values with the on-line measurements. For a measurement made on the GC at a particular time, all on-line measurements done over a time period Δt before and after the GC measurement were averaged and compared. Longer Δt values would include dynamic variation, whereas shorter Δt would not include many on-line measurements. It was found that a Δt of 3 h minimized dynamic variations and provided at least six data points for each GC measurement. The comparison made by averaging on-line data collected 3 h before a GC measurement and 3 h after GC measurement is shown in Fig. 4.

An average absolute difference between GC measurements and averaged on-line measurements was calculated as follows. The absolute difference between GC measurement and averaged on-line measurement was calculated. This calculation was performed for all 80 data points shown in Fig. 4. The average of these values was termed as average absolute difference and was 0.81 ± 0.54%.

Table 1 Cost of on-line methane system

Components	Price (US $)
Assembled methane-sensing device chamber (with BME-280, MQ-4 sensors and drierite) [38]	36.61
2-way valve (4 unit)	39.99
3-way valve (1 unit)	12.99
Air pump	6.99
s Micro-computer (Arduino Uno)	10.90
Wire and tubing	1.00
Assembled drying chamber (with drierite)	10.90
Assembled biogas chamber (with BME-280 sensor)	14.99
SD card	3.99
Total	138.36

Cost of On-Line Measurement System

The cost of the components required for converting the off-line methane measurement device to an automated real-time on-line measurement system is listed (Table 1). The total cost of the on-line system amounted to US$138.36, including the primary components of assembled methane-sensing device chamber, assembled air-drying chamber, assembled biogas chamber, and Arduino microcontrollers. The cost of this system is only a fraction of the cost of commercial devices. In addition, the methane composition measured by the on-line sensor can be displayed using an LED interfaced to the Arduino Uno. The cost of such an LED display is $7.

Conclusions

An inexpensive system was assembled and successfully tested for automatic, real-time, on-line measurement of the methane content of biogas from a laboratory-scale anaerobic digester. The on-line system is capable of taking measurements at a minimum sampling interval of 3 h, which includes venting biogas residue, sensors preparation, drying chamber and stabilization of the sensor signals. This on-line methane measurement device can be easily integrated with a biogas volumetric flowmeter device to calculate the methane production rate from a digester. The on-line measurement system fills a much-needed void for monitoring biogas produced from laboratory-scale anaerobic digesters as commercial systems require large gas volumes. The other components of carbon monoxide, hydrogen, carbon dioxide, oxygen can also be fulfilled with on-line measurement by integrating different MQ sensors.

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Data Availability All data generated or analyzed during this study is included in this published article.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

1. Li, Y., Park, S.Y., Zhu, J.: Solid-state anaerobic digestion for methane production from organic waste. Renew. Sustain. Energy Rev. **15**(1), 821–826 (2011)
2. Marañón, E., Castrillón, L., Quiroga, G., Fernández-Nava, Y., Gómez, L., García, M.M.: Co-digestion of cattle manure with food waste and sludge to increase biogas production. Waste Manag. **32**(10), 1821–1825 (2012)
3. Hagelqvist, A.: Batchwise mesophilic anaerobic co-digestion of secondary sludge from pulp and paper industry and municipal sewage sludge. Waste Manag. **33**(4), 820–824 (2013)
4. De la Rubia, M.A., Villamil, J.A., Rodriguez, J.J., Borja, R., Mohedano, A.F.: Mesophilic anaerobic co-digestion of the organic fraction of municipal solid waste with the liquid fraction from hydrothermal carbonization of sewage sludge. Waste Manag. **76**, 315–322 (2018)
5. Grosser, A., Neczaj, E.: Sewage sludge and fat rich materials co-digestion-Performance and energy potential. J. Clean. Prod. **198**, 1076–1089 (2018)
6. Weiland, P.: Production and energetic use of biogas from energy crops and wastes in Germany. Appl. Biochem. Biotechnol. **109**(1–3), 263–274 (2003)
7. Corneli, E., Dragoni, F., Adessi, A., De Philippis, R., Bonari, E., Ragaglini, G.: Energy conversion of biomass crops and agroindustrial residues by combined biohydrogen/biomethane system and anaerobic digestion. Bioresour. Technol. **211**, 509–518 (2016)
8. Wu, N., Moreira, C., Zhang, Y., Doan, N., Yang, S., Phlips, E., Svoronos SA., Pullammanappallil, P.: Techno-economic analysis of biogas production from microalgae through anaerobic digestion. In: Anaerobic Digestion. IntechOpen. (2019). https://doi.org/10.5772/intechopen.86090
9. Wu, N., Demchuk, Z., Voronov, A., Pourhashem, G.: Sustainable manufacturing of polymeric materials: a techno-economic analysis of soybean oil-based acrylic monomers production. J. Clean. Prod. **286**, 124939 (2021)
10. https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel

11. Horiuchi, J.I., Shimizu, T., Tada, K., Kanno, T., Kobayashi, M.: Selective production of organic acids in anaerobic acid reactor by pH control. Bioresour. Technol. **82**(3), 209–213 (2002)
12. Bolzonella, D., Pavan, P., Battistoni, P., Cecchi, F.: Mesophilic anaerobic digestion of waste activated sludge: influence of the solid retention time in the wastewater treatment process. Process Biochem. **40**(3–4), 1453–1460 (2005)
13. Kim, J.K., Oh, B.R., Chun, Y.N., Kim, S.W.: Effects of temperature and hydraulic retention time on anaerobic digestion of food waste. J. Biosci. Bioeng. **102**(4), 328–332 (2006)
14. Nagao, N., Tajima, N., Kawai, M., Niwa, C., Kurosawa, N., Matsuyama, T., Toda, T.: Maximum organic loading rate for the single-stage wet anaerobic digestion of food waste. Bioresour. Technol. **118**, 210–218 (2012)
15. Khanal, S.K., Chen, W.H., Li, L., Sung, S.: Biological hydrogen production: effects of pH and intermediate products. Int. J. Hydrog. Energy. **29**(11), 1123–1131 (2004)
16. Liu, D., Zeng, R.J., Angelidaki, I.: Effects of pH and hydraulic retention time on hydrogen production versus methanogenesis during anaerobic fermentation of organic household solid waste under extreme-thermophilic temperature (70°C). Biotechnol. Bioeng. **100**(6), 1108–1114 (2008)
17. Pullammanappallil, P., Harmon, J., Chynoweth, D.P., Lyberatos, G., Svoronos, S.A.: Avoiding digester imbalance through real-time expert system control of dilution rate. Appl. Biochem. Biotechnol. **28**(1), 33–42 (1991)
18. Pullammanappallil, P.C., Svoronos, S.A., Chynoweth, D.P., Lyberatos, G.: Expert system for control of anaerobic digesters. Biotechnol. Bioeng. **58**(1), 13–22 (1998)
19. Chynoweth, D.P., Svoronos, S.A., Lyberatos, G., Harman, J.L., Pullammanappallil, P., Owens, J.M., Peck, M.J.: Real-time expert system control of anaerobic digestion. Water Sci. Technol. **30**(12), 21–30 (1994)
20. Polag, D., May, T., Müller, L., König, H., Jacobi, F., Laukenmann, S., Keppler, F.: On-line monitoring of stable carbon isotopes of methane in anaerobic digestion as a new tool for early warning of process instability. Bioresour. Technol. **197**, 161–170 (2015)
21. Lara-Cisneros, G., Aguilar-López, R., Femat, R.: On the dynamic optimization of methane production in anaerobic digestion via extremum-seeking control approach. Comput. Chem. Eng. **75**, 49–59 (2015)
22. Kosterev, A.A., Curl, R.F., Tittel, F.K., Gmachl, C., Capasso, F., Sivco, D.L., Cho, A.Y.: Methane concentration and isotopic composition measurements with a mid-infrared quantum-cascade laser. Opt. Lett. **24**(23), 1762–1764 (1999)
23. Nelson, D.D., McManus, B., Urbanski, S., Herndon, S., Zahniser, M.S.: High precision measurements of atmospheric nitrous oxide and methane using thermoelectrically cooled mid-infrared quantum cascade lasers and detectors. Spectrochim. Acta A Mol. Biomol. Spectrosc. **60**(14), 3325–3335 (2004)
24. Buxy, S., Diltz, R., Pullammanappallil, P.: Biogasification of marine algae *Nannochloropsis oculata*. Materials Challenges in Alternative and Renewable Energy II: Ceramic Transactions. pp. 59–67 (2012). https://doi.org/10.1002/9781118585160.ch6
25. Krause, M.J., Chickering, G.W., Townsend, T.G., Pullammanappallil, P.: Effects of temperature and particle size on the biochemical methane potential of municipal solid waste components. Waste Manage. **71**, 25–30 (2018)
26. Chupka, W.A.: Mass-Spectrometric Study of the Photoionization of Methane. J. Chem. Phys. **48**(5), 2337–2341 (1968)
27. Fisher, R., Lowry, D., Wilkin, O., Sriskantharajah, S., Nisbet, E.G.: High-precision, automated stable isotope analysis of atmospheric methane and carbon dioxide using continuous-flow isotope-ratio mass spectrometry. Rapid communications in mass spectrometry: an international journal devoted to the rapid dissemination of up-to-the-minute. Res. Mass Spectrom. **20**(2), 200–208 (2006)
28. Liu, Y., Sharma, K.R., Murthy, S., Johnson, I., Evans, T., Yuan, Z.: On-line monitoring of methane in sewer air. Sci. Rep. **4**(1), 1–8 (2014)
29. Kim, J., Lim, J.S., Friedman, J., Lee, U., Vieira, L., Rosso, D., Srivastava, M.B.: Sewersnort: A drifting sensor for in-situ sewer gas monitoring. In 2009 6th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (pp. 1–9). IEEE. (2009), June
30. Tsunogai, U., Kou, S., Kimoto, H., Kimoto, T.: Development of in-situ methane sensor in seawater. In 51th Annual Meeting of the Geochemical Society of Japan (Vol. 23). (2007), February
31. Lamontagne, R.A., Rose-Pehrsson, S.L., Grabowski, K.E., Knies, D.L.: Response of METS sensor to methane concentrations found on the texas-louisiana shelf in the gulf of Mexico. Naval research lab Washington DC (2001)
32. Camilli, R., Hemond, H.F.: NEREUS/Kemonaut, a mobile autonomous underwater mass spectrometer. TRAC Trends Anal. Chem. **23**(4), 307–313 (2004)
33. Furst, L., Feliciano, M., Frare, L., Igrejas, G.: A portable device for methane measurement using a low-cost semiconductor sensor: development, calibration and environmental applications. Sensors **21**(22), 7456 (2021)
34. Umapathi, N., Teja, S., Kiran, S.: Design and Implementation of Prevent Gas Poisoning from Sewage Workers using Arduino. In 2020 IEEE International Symposium on Sustainable Energy, Signal Processing and Cyber Security (iSSSC) (pp. 1–4). IEEE. (2020)
35. Rajalakshmi, R., Vidhya, J.: Toxic environment monitoring using sensors based on arduino. In 2019 IEEE International Conference on System, Computation, Automation and Networking (ICSCAN) (pp. 1–6). IEEE. (2019)
36. Nagahage, I.S.P., Nagahage, E.A.A.D., Fujino, T.: Assessment of the applicability of a low-cost sensor–based methane monitoring system for continuous multi-channel sampling. Environ. Monit. Assess. **193**(8), 1–14 (2021)
37. Honeycutt, W.T., Ley, M.T., Materer, N.F.: Precision and limits of detection for selected commercially available, low-cost carbon dioxide and methane gas sensors. Sensors. **19**(14), 3157 (2019)
38. Yang, S., Liu, Y., Wu, N., Zhang, Y., Svoronos, S., Pullammanappallil, P.: Low-cost, Arduino-based, portable device for measurement of methane composition in biogas. Renew. energy. **138**, 224–229 (2019)
39. Liu, J., Olsson, G., Mattiasson, B.: A volumetric meter for monitoring of low gas flow rate from laboratory-scale biogas reactors. Sens. Actuators B: Chem. **97**(2–3), 369–372 (2004)
40. Koppar, A., Pullammanappallil, P.: Single-stage, batch, leach-bed, thermophilic anaerobic digestion of spent sugar beet pulp. Bioresour. Technol. **99**(8), 2831–2839 (2008)
41. Polematidis, I., Koppar, A., Pullammanappallil, P.: Biogasification potential of desugarized molasses from Sugarbeet processing plants. J. Sugar Beet Res. **47**(3/4), 89–104 (2010)

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Emissions of volatile organic compounds (VOCs) from concentrated animal feeding operations (CAFOs): chemical compositions and separation of sources

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Abstract. Concentrated animal feeding operations (CAFOs) emit a large number of volatile organic compounds (VOCs) to the atmosphere. In this study, we conducted mobile laboratory measurements of VOCs, methane (CH_4) and ammonia (NH_3) downwind of dairy cattle, beef cattle, sheep and chicken CAFO facilities in northeastern Colorado using a hydronium ion time-of-flight chemical-ionization mass spectrometer (H_3O^+ ToF-CIMS), which can detect numerous VOCs. Regional measurements of CAFO emissions in northeastern Colorado were also performed using the NOAA WP-3D aircraft during the Shale Oil and Natural Gas Nexus (SONGNEX) campaign. Alcohols and carboxylic acids dominate VOC concentrations and the reactivity of the VOCs with hydroxyl (OH) radicals. Sulfur-containing and phenolic species provide the largest contributions to the odor activity values and the nitrate radical (NO_3) reactivity of VOC emissions, respectively. VOC compositions determined from mobile laboratory and aircraft measurements generally agree well with each other. The high time-resolution mobile measurements allow for the separation of the sources of VOCs from different parts of the operations occurring within the facilities. We show that the emissions of ethanol are primarily associated with feed storage and handling. Based on mobile laboratory measurements, we apply a multivariate regression analysis using NH_3 and ethanol as tracers to determine the relative importance of animal-related emissions (animal exhalation and waste) and feed-related emissions (feed storage and handling) for different VOC species. Feed storage and handling contribute significantly to emissions of alcohols, carbonyls, carboxylic acids and sulfur-containing species. Emissions of phenolic species and nitrogen-containing species are predominantly associated with animals and their waste.

1 Introduction

Concentrated animal feeding operations (CAFOs) emit many volatile organic compounds (VOCs) into the atmosphere, including carboxylic acids, alcohols, carbonyls, phenolic compounds, sulfur- and nitrogen-containing compounds (Hobbs et al., 2004; Filipy et al., 2006; Sun et al., 2008; Ni et al., 2012). These VOCs can contribute to the formation of ozone (Howard et al., 2010a, b; Gentner et al., 2014) and fine particles (Sintermann et al., 2014; Perraud et al., 2015), both affecting regional air quality. Many VOCs from CAFOs are also responsible for the unpleasant odor problems nearby or downwind of these facilities (McGinn et al., 2003; Rabaud et al., 2003; Parker et al., 2010; Woodbury et al., 2015). Some VOCs (e.g., phenolic species) (US EPA, 2017) from CAFOs are harmful to human health.

There are a large number of potential VOC sources inside a CAFO, potentially including animal exhalation, animal waste in animal pens, flushing lanes, lagoons, silage

storage piles and silos, and feed mixtures in feed lanes and bunks (Alanis et al., 2008; Chung et al., 2010). Early studies mainly focused on VOC emissions from animal waste (e.g., slurry and manure) under laboratory conditions (Hobbs et al., 1997, 1998, 2004). Ngwabie et al. (2007, 2008) reported that VOC concentrations in dairy, sheep and pig CAFOs were the highest during animal waste removal and feeding, indicating that large emissions were related to these activities. Recent studies found that VOC concentrations in dairy farms were significantly higher near silage and piles of animal feed (i.e., total mixed rations) than near other places (animal pens, lagoons and flush lanes), suggesting that feed-related sources dominate VOC emissions (Alanis et al., 2008; Chung et al., 2010). Enhancements of some VOCs (e.g., acetone) in animal sheds are also related to animal exhalation (Shaw et al., 2007; Ngwabie et al., 2008; Sintermann et al., 2014). However, the contributions of different sources to individual VOC emissions from a facility are not accurately known (Ngwabie et al., 2008). This poor understanding of VOC sources hinders the development of management practices that reduce VOC emissions in animal feeding facilities (Ngwabie et al., 2007). Thus, a comprehensive characterization of VOC sources and their relative importance within a CAFO is needed.

Many studies of VOCs from animal feeding operations have been conducted with offline analytical methods (Filipy et al., 2006; Alanis et al., 2008; Sun et al., 2008; Chung et al., 2010; Ni et al., 2012). VOCs were collected on filters, or in canisters and cartridges and were quantified in the laboratory using various methods (see reviews in Ni et al., 2012). These offline methods are labor-intensive, which limits the number of VOC samples. Online fast measurement techniques (mainly proton-transfer reaction mass spectrometers, PTR-MS) allow for more detailed investigation of CAFO facilities (Shaw et al., 2007; Ngwabie et al., 2008; Sintermann et al., 2014). The previous online measurements usually used a single stationary sampling inlet either inside a stall or at a fence line, which does not provide spatial distribution information for VOCs in the facilities.

In this study, we deployed a high time-resolution instrument on board a mobile laboratory driven on public roads and a NOAA WP-3D research aircraft to measure VOCs downwind of CAFO facilities. We will use this data set to characterize chemical compositions of VOC emissions and explore different sources within the facilities that contribute to VOC emissions.

2 Experiments

Mobile laboratory measurements were conducted near Greeley in northeastern Colorado, USA. Six different CAFOs were studied, including two dairy farms, two beef feed yards, one sheep feed yard and one egg-laying chicken farm (Table S1 in the Supplement). Among the six CAFOs, emissions of NH_3, N_2O and CH_4 in four facilities (the two dairy farms, one beef cattle feed yard and the sheep feed yard) have been measured previously using an instrumented van (Eilerman et al., 2016). We added a new VOC instrument to the payload, and performed mobile measurements in wintertime (February, 2016) for the six CAFOs by sampling at their downwind flanks 1–2 times for each facility. Duplicated measurements at the same facilities agreed well.

VOCs were measured using a hydronium ion time-of-flight chemical-ionization mass spectrometer (H_3O^+ ToF-CIMS) instrument on the mobile laboratory. Here, we provide a brief description of the instrument (see details in Yuan et al., 2016). VOCs are ionized by H_3O^+ ions in a drift tube, similar to a PTR-MS (de Gouw and Warneke, 2007). The protonated product ions are detected using a high-resolution time-of-flight (ToF) analyzer (Tofwerk AG) ($m/\Delta m = 4000$–6000). A number of VOC species were calibrated using either gravimetrically prepared gas cylinders or permeation tubes (see details in Yuan et al., 2016). VOC background signals in the instrument were determined by passing ambient air through a catalytic converter. The detection limits are compound-dependent and range between 10 and 100 ppt for most VOC species at a time resolution of 1 s. Besides VOCs, two inorganic species, NH_3 and H_2S, were measured at m/z 18.034 (NH_4^+) and m/z 34.995 (H_3S^+) using the H_3O^+ ToF-CIMS, respectively (Li et al., 2014; Müller et al., 2014).

In addition to the H_3O^+ ToF-CIMS, a cavity ring-down spectrometer instrument (Picarro G1301m) measuring methane (CH_4) and carbon dioxide (CO_2) and an off-axis integrated cavity output spectrometer (Los Gatos Research) measuring nitrous oxide (N_2O) along with carbon monoxide (CO) were deployed during the mobile laboratory measurements. Measurements of ambient temperature, relative humidity, wind direction, wind speed and vehicle location were performed using meteorological sensors (R.M. Young 85004 and AirMax 300WX) and a GPS compass system (ComNav G2B). A summary of meteorological conditions during the mobile laboratory measurements is shown in Table S2.

Measurements of agricultural plumes were also performed using the NOAA WP-3D research aircraft in March–April 2015 during the Shale Oil and Natural Gas Nexus (SONGNEX) campaign. Data from three flights (28 March, 29 March, 13 April) over northeastern Colorado are used in this study. VOCs were measured using the same H_3O^+ ToF-CIMS instrument as mobile measurements (Yuan et al., 2016). Another chemical ionization mass spectrometer (CIMS) was used to detect NH_3 during SONGNEX (Nowak et al., 2007). Due to background issues and lower concentrations, NH_3 signals were not retrievable from H_3O^+ ToF-CIMS during the SONGNEX campaign.

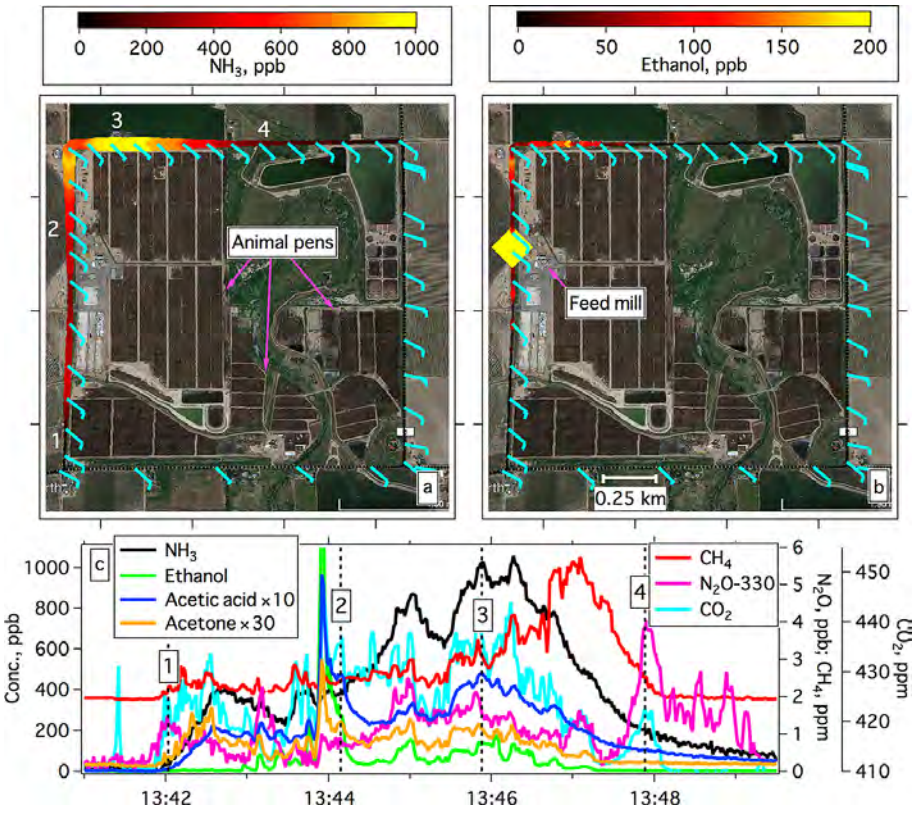

Figure 1. (a, b) Drive track of mobile laboratory color- and size-coded by NH_3 **(a)** and ethanol **(b)** concentrations around a beef feed yard (beef no. 1). The prevailing wind is shown by wind barbs (light blue flags) in the map. **(c)** Time series of NH_3, CH_4, CO_2, N_2O, ethanol, acetic acid and acetone measured downwind of the beef feed yard. Numbers (1–4) in panels **(a)** and **(c)** are used to allow for alignment of the mobile laboratory locations on the map with the corresponding time series in panel **(c)**.

3 Results and discussions

3.1 Spatial distributions from mobile laboratory measurements

Figure 1 shows measured concentrations of NH_3, CH_4, CO_2, N_2O, ethanol (C_2H_5OH), acetic acid (CH_3COOH) and acetone (CH_3COCH_3) around a beef feed yard (beef no. 1). The concentrations of the seven species were enhanced and highly variable downwind of the facility. Different time variations for the seven species were clearly observed. NH_3 concentrations peaked at around 13:46 local time (LT) and the peak location was northwest of this facility, directly downwind of the animal pens. This is consistent with fresh waste of animals (urine and feces) as the main source of NH_3 within a CAFO facility (Hristov et al., 2011). CO_2 and CH_4 are emitted from animal respiration and eructation of the cattle (Shaw et al., 2007; Sintermann et al., 2014; Owen and Silver, 2015). CO_2 ($R = 0.77$) and CH_4 ($R = 0.77$) correlated well with NH_3 between 13:42 and 13:46 LT when NH_3 was high. These observations reflect the fact that animals and their fresh waste may be largely co-located in the animal pens. But, waste cleaning time/practices in the facility were unknown, owing to no access to the facility. Previous mobile and aircraft measurements have also observed enhancements of NH_3 and CH_4 concentrations downwind of animal pens in cattle feedlots (Miller et al., 2015; Hacker et al., 2016). The time variations of two VOCs, acetic acid and acetone, followed reasonably well with both NH_3 and CO_2, suggesting that animals and their waste contributed to the enhancements of the two VOCs. Based on previous studies, the emissions from animal respiration should dominate over waste for acetone, and vice versa for acetic acid (Ngwabie et al., 2008; Sintermann et al., 2014). The similar time variations of NH_3, CO_2, acetone and acetic acids (and less clearly for CH_4) imply that the co-located emissions from animals and their waste may not be separated based on the variations observed (over a short time span of several minutes) while measuring along the downwind flanks.

A single, narrow high-concentration spike (up to 1 ppm) of ethanol was observed around 13:44 LT (Fig. 1). The hotspot of ethanol was located downwind of a feed mill at the west side of the feed yard, indicating that the feed mill and its related activities can emit large amounts of ethanol. Distillers grains, a fermented by-product from ethanol production, are commonly used as an ingredient of feed in beef cattle feed

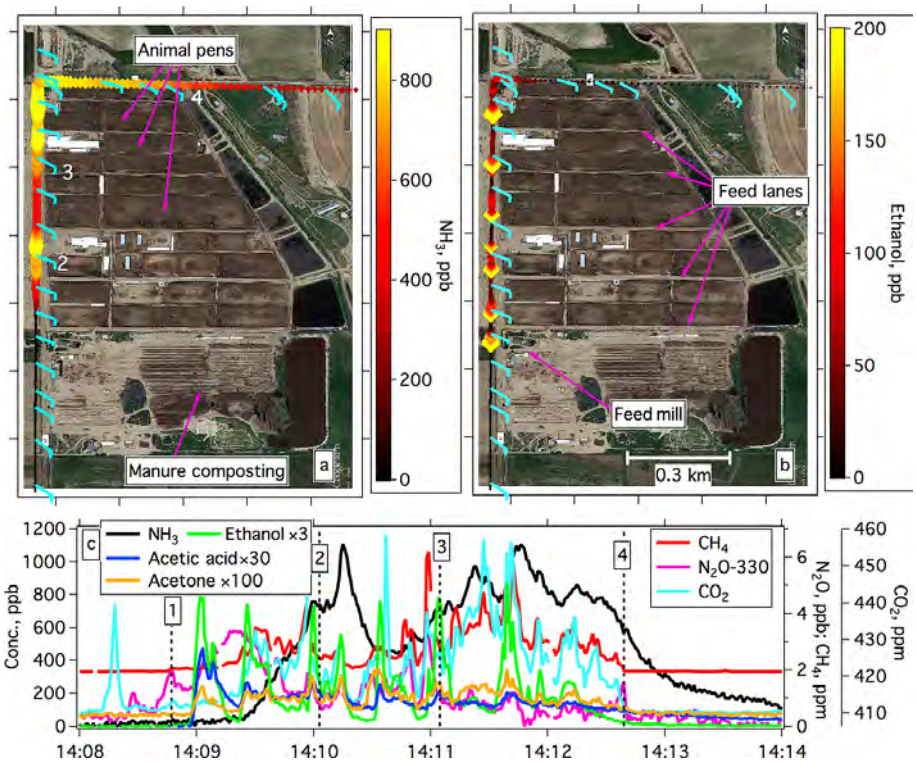

Figure 2. (a, b) Drive track of mobile laboratory color- and size-coded by NH_3 **(a)** and ethanol **(b)** concentrations downwind of a dairy farm (dairy no. 1). The prevailing wind is shown by wind barbs (light blue flags) in the map. **(c)** Time series of NH_3, CH_4, CO_2, N_2O, ethanol, acetic acid and acetone measured downwind of the dairy farm. Numbers (1–4) in panels **(a)** and **(c)** are used to allow for alignment of the mobile laboratory locations on the map with the corresponding time series in panel **(c)**.

yards (Raabe, 2012) (although not known specifically here). Therefore, it is not surprising to observe large emissions of ethanol in the feed mill area. High concentrations of many other VOC species (e.g., acetic acid and acetone) were observed in the feed mill plume, whereas NH_3, CH_4 and N_2O were not enhanced. Combustion sources, possibly due to equipment operation in the feed mill area, are likely responsible for the enhancement of CO_2 and CO at ∼ 13:44 LT. VOC emissions from these combustion plumes are negligible (see details in the Supplement, Fig. S1).

Measurements downwind of a dairy farm (dairy no. 1) are shown in Fig. 2. The highest concentrations of NH_3 and CO_2 were observed downwind of the animal pens, similar to the beef feed yard shown in Fig. 1. Interestingly, several high concentration peaks of ethanol were observed along the drive track of the mobile laboratory. These peaks were in close proximity or downwind of the feed lanes (white lines on the satellite image, Fig. 2b). As shown for beef no. 1, feed mills can be an important source of ethanol and other VOCs. Different from the usage of distillers grains in beef cattle feed yards, silage is more commonly used as fodder for dairy cattle (Raabe, 2012). Previous studies showed that ethanol is the most abundant VOC species emitted from feed silage (Hafner et al., 2013). It is expected that VOCs will continue evaporating from the feed mixtures after the feed is delivered to the feed lanes. Time variations of acetic acid (and acetone) correlated more closely with ethanol ($R = 0.72$) than with NH_3 ($R = -0.30$) and CO_2 ($R = -0.14$), which differs from the beef feed yard. This suggests that the three VOCs were mainly from emissions of feed lanes, rather than animals and their waste in this dairy farm.

In addition to animals and their waste (referred to as animal+waste hereafter) and feed storage and handling (referred to as feed storage+handling hereafter), we identified another important VOC source from the other dairy farm studied (dairy no. 2, Fig. S2). High concentrations of ethanol, acetone, dimethyl sulfide (DMS, C_2H_6S) and CH_4 were observed downwind of three milking parlors. Acetic acid was only moderately elevated, whereas NH_3 was not enhanced. Compared to feed storage+handling, emission compositions from the milking parlors are different. The emissions from milking parlors might result from several sources, including animal exhalation and milking-related activities. It is worth noting that we did not distinctly observe emissions from the milking parlor in the dairy farm no. 1, which were potentially mixed with emissions from feed prior to sampling.

The measurements downwind of three other CAFO sites (beef no. 2, the sheep feed yard and the chicken house) are

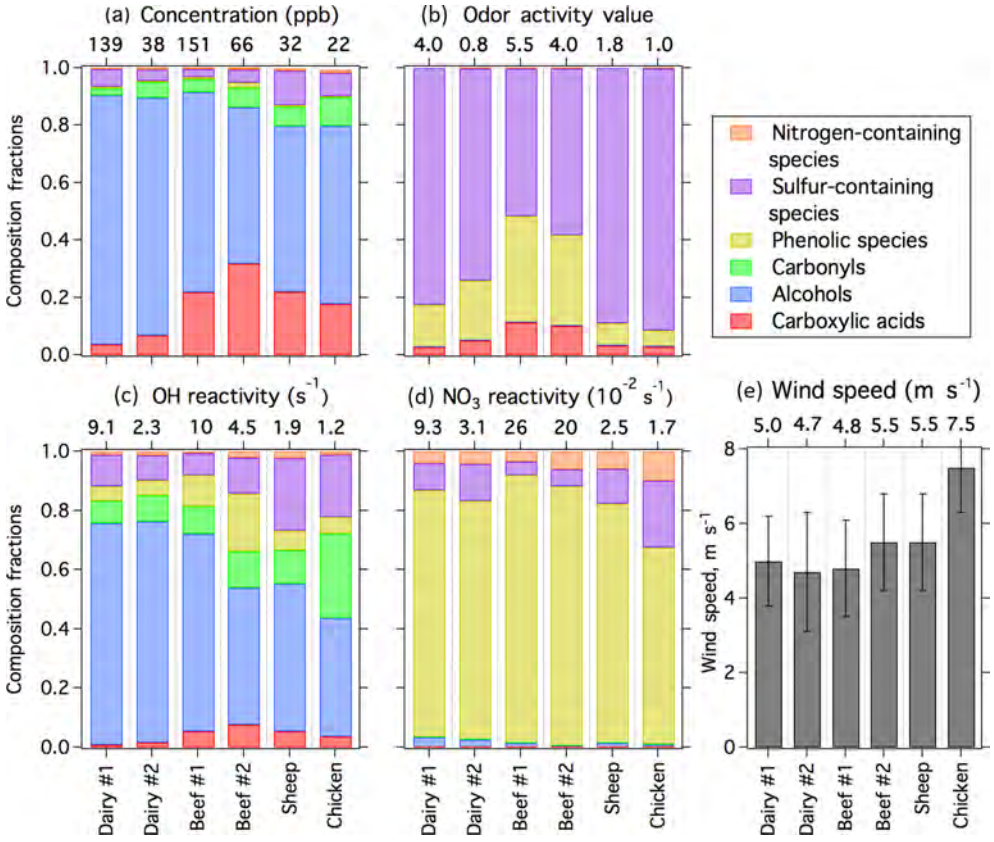

Figure 3. The fractional contributions of different VOC classes to the total VOC concentrations **(a)**, odor activity values **(b)**, OH reactivity **(c)** and NO_3 reactivity **(d)** for the six investigated CAFO sites. The mean wind speeds during the measurements of the CAFO sites are shown in panel **(e)**. The mean values for the five parameters from each CAFO are shown at the top of each panel.

investigated in a similar way, as shown in Figs. 1–2 (and Figs. S2–S3). From this analysis, we identify three main VOC emission sources in animal feeding facilities, namely animal+waste, feed storage+handling and milking parlors. These measurements suggest that combustion sources are not important for VOC emissions in these facilities.

3.2 VOC chemical compositions of different CAFOs

The enhancements of VOCs downwind of each CAFO were integrated to determine the averaged VOC compositions for each facility (Fig. 3). The measured VOC species are divided into six different groups, namely carboxylic acids, alcohols, carbonyls, phenolic species, nitrogen- and sulfur-containing species. The averages of the sum of measured VOC concentrations downwind of the sites are in the range of 22–139 ppb, with higher concentrations at dairy farm no. 1 and the two beef feed yards (wind speeds during the measurements were similar except at the chicken house, Fig. 3e and Table S1). As demonstrated in Fig. 3a, alcohols (55–87 %, mole fractions) and carboxylic acids (4–32 %) represent major classes of VOC from these CAFOs. Other VOC classes account for 8–21 % of VOC concentrations in total.

As discussed in Sect. 1, VOC emissions from CAFOs can contribute to unpleasant odor problems and ozone formation. We utilize odor activity value (OAV) and the OH and NO_3 reactivity to evaluate the relative contribution of each VOC class to the two environmental effects, respectively. The dimensionless OAV is estimated from VOC concentrations divided by the species' single compound odor thresholds (SCOT) ($OAV_i = C_i / SCOT_i$) (Feilberg et al., 2010; Parker et al., 2010; Woodbury et al., 2015). The reported SCOT values in the literature are highly variable and we use the geometric means of literature values for each compound, as compiled in Parker et al. (2010). The averaged total OAVs from all measured VOCs are in the range of 0.8–5.5 at different sites (Fig. 3b). Sulfur-containing species contribute the largest fractions (51–91 %) to total OAVs at different sites, followed by phenolic species (6–37 %) and carboxylic acids (3–11 %). The relative contributions of different species to OAV agree well with previous estimates based on measurements from a beef feed yard (Woodbury et al., 2015).

OH reactivity (OHR) and NO_3 reactivity (NO3R) are determined as the products of VOC concentrations and the respective reaction rate constants of VOCs with the two oxidants (Atkinson et al., 2006) ($OHR_i = C_i \times k_{OH,i}$; $NO3R_i =$

$C_i \times k_{NO_3,i}$). The averaged OH reactivities range between 1 and 10 s^{-1}, which is comparable or lower than the typical OHR observed in urban areas (a few s^{-1} to 50 s^{-1}) (Yang et al., 2016). Alcohols are the largest contributors (40–75 %) to OHR at the sites, although the fractions from carbonyls, phenolic and sulfur-containing species are also significant (Fig. 3c). These results are generally consistent with the finding that ethanol accounts for the majority of ozone formation potential of VOC emissions from a dairy farm (Howard et al., 2008). The averaged NO_3 reactivities range from 0.02 to 0.26 s^{-1}, which are remarkably higher than in urban areas (usually < 0.01 s^{-1}) (Tsai et al., 2014; Brown et al., 2016). In contrast to the OH reactivity, phenolic species account for the largest fractions (66–90 %) of the NO_3 reactivity for all of the sites, with remaining contributions primarily from sulfur- and nitrogen-containing species (Fig. 3d). We note that OAV, OH and NO_3 reactivity are measured along the fence line and they decrease rapidly with downwind distance and dilution (see example in Sect. 3.4 for aircraft measurement results associated with a factor of ∼ 10 lower concentrations than those from mobile laboratory).

3.3 Relative importance of different sources for VOC emissions

As shown in Sect. 3.1, ethanol was primarily emitted from feed storage+handling (and milking parlors), whereas NH_3 and CO_2 were attributed to emissions from animals and their waste. This suggests that these species can be used as tracers to separate the emissions from sources. However, there are two issues that need to be considered: (1) emissions of animal exhalation and waste are largely co-located in the animal pens. As CO_2 is also emitted from combustion sources (see details in the Supplement) and animal exhalation is only important for a few species (e.g., acetone), NH_3 will be used as a tracer for the emissions from animals and their waste. It is worth mentioning that long-term measurements in CAFO facilities could permit separation of the two co-located sources (see example in Sintermann et al., 2014). (2) There is some ethanol attributable to animal+waste emissions that needs to be accounted for. Ethanol concentrations solely from feed emissions ($[C_2H_5OH]_{Feed}$) can be calculated by subtracting the contribution of ethanol by animal+waste from measured ethanol concentrations (see details in the Supplement, Fig. S4).

After correcting ethanol for animal+waste emissions, the contributions of emissions from feed storage+handling and animal+waste to measured VOC enhancements at each individual site can be determined using multivariate linear fits to $[C_2H_5OH]_{Feed}$ and NH_3 concentration ($[NH_3]$).

$$[VOC] = ER_{C_2H_5OH} \times [C_2H_5OH]_{Feed} + ER_{NH_3} \times [NH_3] + [bg] \quad (1)$$

Here, [VOC] and [bg] are measured concentrations of the VOC species and the background concentration outside the CAFO plumes, respectively. $ER_{C_2H_5OH}$ and ER_{NH_3} are the emission ratios of the VOC species relative to ethanol and NH_3 from the emissions of feed storage+handling and animal+waste, respectively. Along with [bg], the emission ratios are determined from the multivariate linear fits.

Based on the fitted parameters from Eq. (1) (and Eq. S3 for dairy farm no. 2), the relative contributions of different sources to the enhancements of various VOC species can be calculated for the investigated sites (Fig. 4). In general, large differences in fractional contributions to VOC enhancements exist among both different VOC species and different animal types. The main findings from Fig. 4 are as follows:

1. Phenol, cresols, butanediones and many nitrogen-containing species are primarily associated with animal+waste emissions for the investigated sites.

2. Both feed storage+handling and animal+waste account for significant fractions of emissions of many oxygenated VOCs and sulfur-containing species.

3. Based on the results from the dairy farm no. 2, emissions from milking parlors contribute significantly to the enhancements of a limited number of VOC species, including ethanol (23 ± 1 %), acetone (35 ± 3 %), acetaldehyde (31 ± 3 %), methanol (18 ± 3 %), MEK (14 ± 2 %) and DMS (14 ± 2 %).

4. Feed storage+handling plays important roles in the emissions of many VOC species from the chicken farm. Based on a news report on the facility, a manure belt system is used to manage manure in this facility. The manure belt system catches the excreta from chicken to transport manure to a separate location for storage. The chicken houses with manure belts usually lead to substantially lower emissions (e.g., NH_3) from animal waste (Wood et al., 2015). It is consistent with significantly lower NH_3 concentrations (0–175 ppb, Fig. S3) at this site compared to ruminant feed yards measured in this study (0–1000 ppb), although wind speed was 36–60 % higher during measurements of the chicken house (7.5 m s^{-1}) than others (4.7–5.5 m s^{-1}). It is also possible that emissions of NH_3 and VOCs were treated when in-house air was ventilated out (Wang et al., 2010).

We further determine the contributions of emissions from feed storage+handling, animal+waste and milking parlors to the total VOC concentrations (first columns in Fig. 4, also Fig. S5). Feed storage+handling emissions account for 35–41, 23–30, 13 and 41 % of the summed total VOC concentrations for the investigated dairy farms, beef feed yards, the sheep feed yard and the chicken farm in this study, respectively. The fractional contributions from the sources to odor activity value, OH reactivity and NO_3 reactivity are also calculated (Fig. S5). The contributions from feed storage+handling emissions to the three parameters are gen-

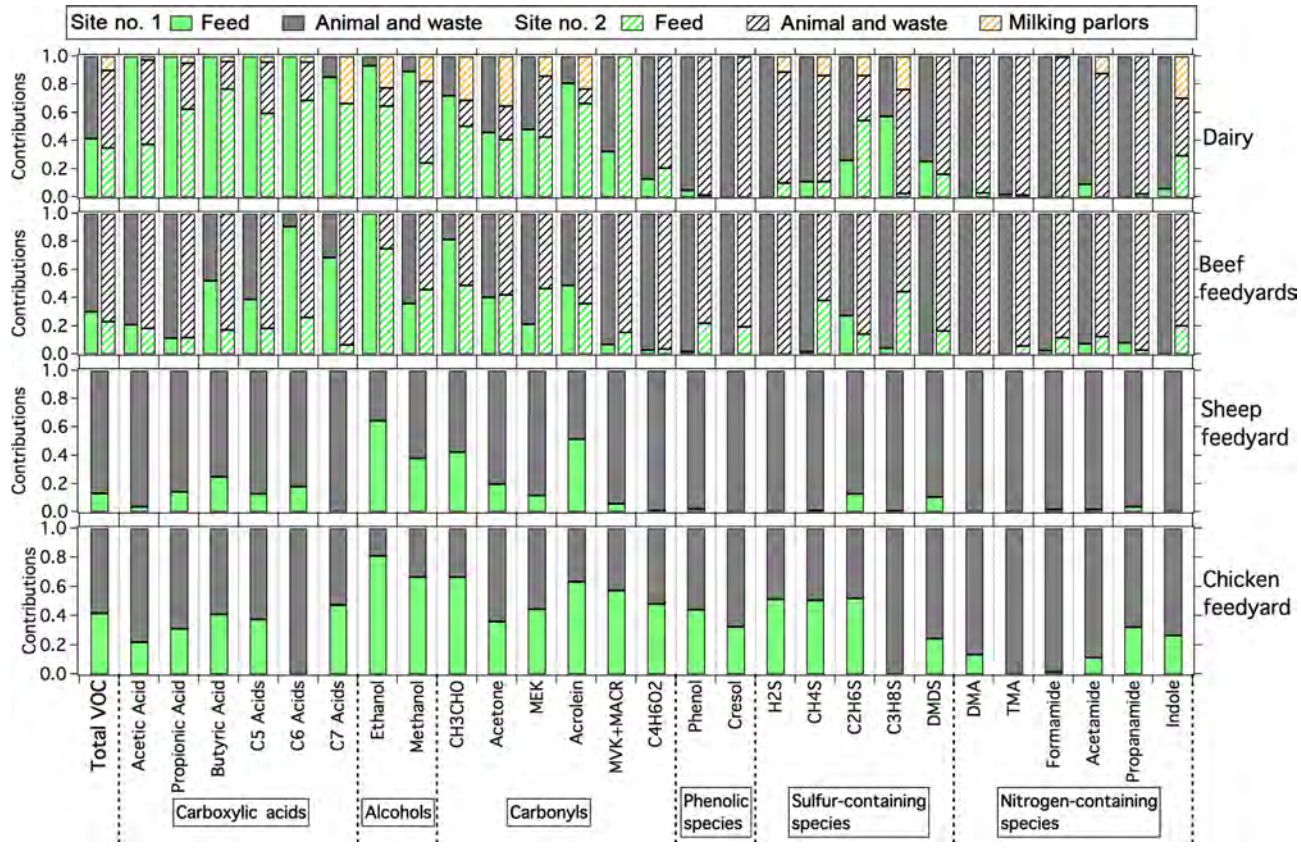

Figure 4. The relative contributions of feed storage+handling, animal+waste and milking parlors (only for dairy farm no. 2) to emissions of different VOC species and total VOC for the investigated CAFO sites. DMDS: dimethyl disulfide; DMA: dimethylamine; TMA: trimethylamine.

erally comparable or slightly smaller than those contributions to the total VOC concentrations.

In addition to the information on relative contributions from different sources, the multivariate fit analysis also provides the emissions ratios of VOCs to NH_3 for animal+waste and emission ratios of VOCs to ethanol for both feed storage+handling and milking parlors (see Tables S3–S8). These emission ratios represent chemical "fingerprints" of the emissions from various sources. The emission ratios are summed up for the VOC classes and the fractions of each VOC class in different source emissions are determined (Fig. 5). Overall, VOC emissions from both feed storage+handling and milking parlors are dominated by alcohols, whereas the contributions of carboxylic acids and other VOC classes are significantly larger for animal+waste emissions. The VOC compositional fractions shown in Fig. 3a for each site are the weighted average of the fractions for different sources in Fig. 5.

We acknowledge that there are some limitations in separating different sources inside each facility using measurements from the mobile laboratory, which may introduce some uncertainties to the results.

1. In this study, the relative fractions of different sources to VOC emissions are determined based on snapshots of measurements when the mobile laboratory passed by the CAFO sites. The relative fractions may change over time, and may be related to operation activities within the facilities, such as feed-mixing activities in feed mill area. Nevertheless, some encouraging evidence was observed: the determined relative fractions from different sources are reasonably similar between the two beef feed yards. The agreements between the two dairy farms are not as good as for the two beef feed yards. The abovementioned observations of the emissions from milking parlors and potential differences in feed ingredients for dairy cattle, which are reflected by the discrepancies in VOC compositions emitted from feed storage+handling (Fig. 5a), could be the reasons.

2. VOCs from various sources in a CAFO site are mostly emitted at the surface. VOCs were measured on the van at a single level near-ground (~ 3 m). However, the plumes from CAFOs become deeper as they are transported downwind, and VOC concentrations are vertically diluted by background air due to turbulent mixing.

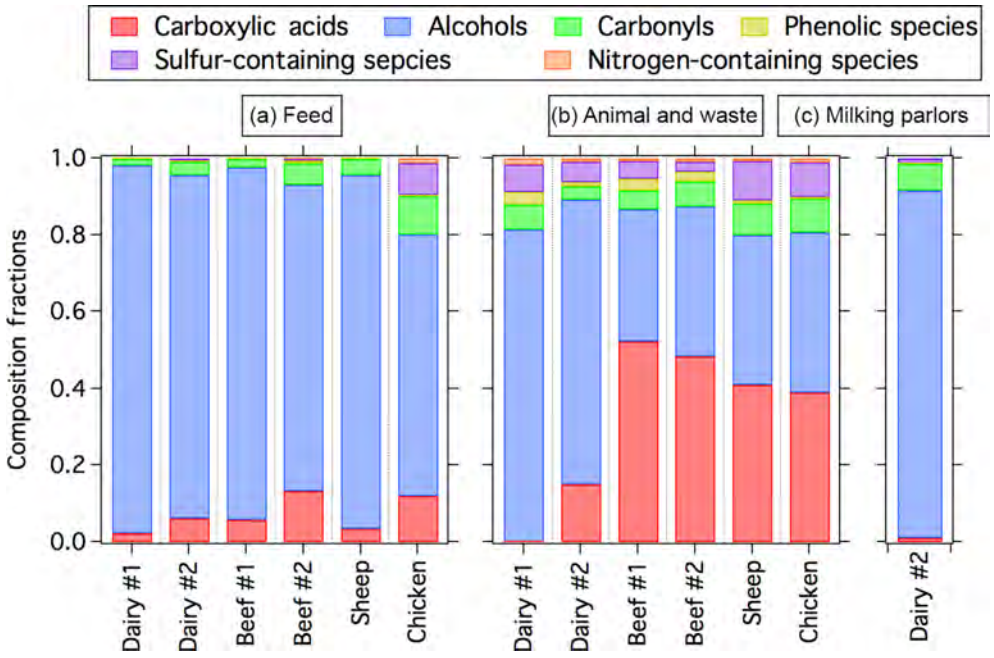

Figure 5. The relative contributions of each VOC class to emissions from feed storage+handling **(a)**, animal+waste **(b)** and milking parlors **(c)**.

As shown in Figs. 1–2 (and Figs. S2–S3), the feed mills and milking parlors at the sites studied in this work are located nearby public roads, and their contributions may be somewhat overestimated as a result.

3.4 Aircraft measurements

Time series of NH_3 and several VOCs inside two agricultural plumes in northeastern Colorado measured on 13 April 2015 from the NOAA WP-3D during the SONGNEX campaign are shown in Fig. 6. Large enhancements of NH_3 were observed in the two agricultural plumes, although the peak concentrations were a factor of ~ 10 lower than those from mobile laboratory measurements. VOC species, including acetic acid, propionic acid and ethanol, were also clearly elevated in the two plumes. As the aircraft was further away from the CAFOs, the emissions from different sources inside CAFO facilities have been well mixed prior to sampling. Thus, separation of the VOCs sources from different parts of the operations occurring within the facilities is not possible using aircraft measurements.

Figure 7a shows scatter plots of acetic acid versus NH_3 from the three flights over northeastern Colorado during the SONGNEX campaign. The correlation between acetic acid and NH_3 is strong for all of the three flights ($R =$ 0.81–0.87). Two different enhancement ratios of acetic acid to NH_3 were observed from aircraft measurements, which are close to the determined emission ratios from beef feed yards ($30.2 \pm 5.5 \times 10^{-3}$ ppb ppb^{-1}) and dairy farms ($6.4 \pm 0.6 \times 10^{-3}$ ppb ppb^{-1}) from mobile laboratory measurements, respectively. It implies that the enhancement ratios of acetic acid to NH_3 may be used as an indicator for emissions from different animal types. The relative contributions to NH_3 enhancements between dairy and beef cattle can be estimated based on data in Fig. 7a. The fractional contributions to NH_3 enhancements from beef cattle are estimated in the range of 0.71–0.98 based on the three SONGNEX flights (28 March: 0.98 ± 0.01; 29 March: 0.71 ± 0.11; 13 April: 0.96 ± 0.02). Combining the three SONGNEX flights in northeastern Colorado, beef cattle contribute 90 ± 4 % of measured NH_3 enhancements on these flights. This evidence suggests that beef cattle are more important for NH_3 emission from CAFOs in northeastern Colorado.

The enhancement ratios of other VOC species relative to NH_3 are also calculated from aircraft measurements and they are compared with those from mobile laboratory measurements in Fig. 7b. The determined enhancement ratios of carboxylic acids and alcohols compare well between aircraft and mobile laboratory measurements. The enhancement ratios of acetone and acetaldehyde to NH_3 are more scattered in aircraft measurements, as the agricultural plumes contributed only small enhancements of these species over a high background. The enhancement ratios of phenol, cresol, CH_3SH and DMS to NH_3 from aircraft measurements are lower than those from mobile laboratory measurements. The measured concentrations of these species from aircraft measurements were low. The signals of these species were only slightly higher than instrument noise levels at higher concentrations

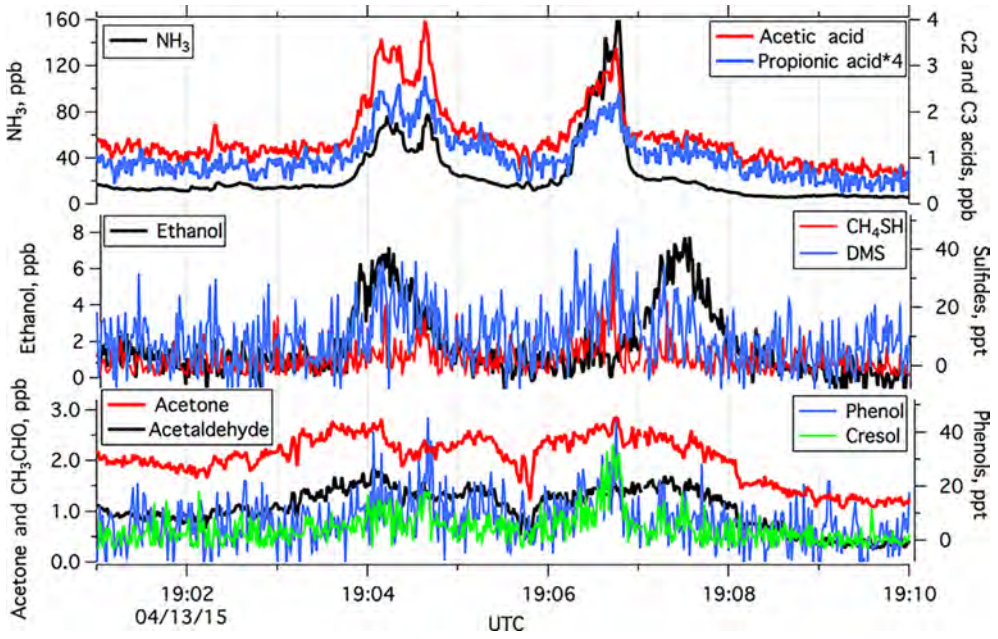

Figure 6. Time series of NH_3 and various VOC species of two agricultural plumes measured from NOAA WP-3D on 13 April 2015 during the SONGNEX campaign.

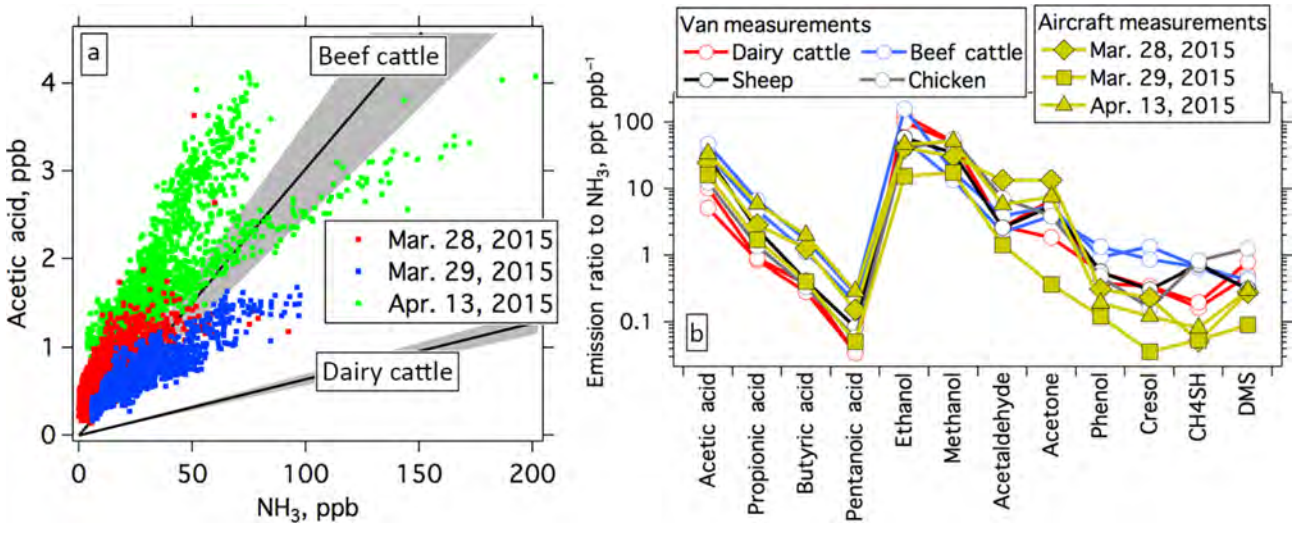

Figure 7. (a) Scatterplot of acetic acid versus NH_3 from the three SONGNEX flights in northeastern Colorado. The two black lines and gray-filled areas indicate emission ratios of acetic acid to NH_3 from beef feed yards and dairy farms determined from the mobile laboratory measurements, respectively. **(b)** Comparison of enhancement ratios of VOCs to NH_3 between mobile laboratory and aircraft measurements in northeastern Colorado.

range of NH_3 ($\sim$ 150 ppb; see example in Fig. 6), but not detectable in many plumes with lower NH_3 concentrations.

4 Conclusions

In this study, we measured downwind air to discern VOC emissions from CAFOs in northeastern Colorado using both mobile laboratory and aircraft measurements. We show that carboxylic acids and alcohols dominate VOC emissions from CAFOs, whereas sulfur-containing species and phenolic species are important to the odor activity values and NO_3 reactivity of CAFO emissions, respectively. VOC compositions of CAFO emissions determined from mobile laboratory and aircraft measurements are in good agreement. Based on mobile laboratory measurements of CAFO sites, NH_3 emissions are mainly from animals and their waste, whereas

ethanol is predominately from feed storage and handling. We applied a multivariate linear regression method to apportion the relative fractions from the two sources using NH_3 and ethanol as tracers. The determined fractions between the two sources are different among various VOC species and animal types. In general, phenolic species and nitrogen-containing species are mainly associated with emissions from animals and their waste for the investigated CAFOs. Significant contributions from feed storage and handling are observed for carboxylic acids, alcohols and carbonyls. We also proposed that ambient enhancement ratios of acetic acid to NH_3 may be used as an indicator to separate CAFO emissions from different animal types.

Data availability. Data from measurements on the aircraft is available at https://www.esrl.noaa.gov/csd/groups/csd7/measurements/2015songnex/. Data from the mobile van is available upon request to the corresponding author (Bin Yuan).

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Competing interests. The authors declare that they have no conflict of interest.

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References

Alanis, P., Sorenson, M., Beene, M., Krauter, C., Shamp, B., and Hasson, A. S.: Measurement of non-enteric emission fluxes of volatile fatty acids from a California dairy by solid phase microextraction with gas chromatography/mass spectrometry, Atmos. Environ., 42, 6417–6424, doi:10.1016/j.atmosenv.2008.05.015, 2008.

Atkinson, R., Baulch, D. L., Cox, R. A., Crowley, J. N., Hampson, R. F., Hynes, R. G., Jenkin, M. E., Rossi, M. J., Troe, J., and IUPAC Subcommittee: Evaluated kinetic and photochemical data for atmospheric chemistry: Volume II – gas phase reactions of organic species, Atmos. Chem. Phys., 6, 3625–4055, doi:10.5194/acp-6-3625-2006, 2006.

Brown, S. S., Dubé, W. P., Tham, Y. J., Zha, Q., Xue, L., Poon, S., Wang, Z., Blake, D. R., Tsui, W., Parrish, D. D., and Wang, T.: Nighttime chemistry at a high altitude site above Hong Kong, J. Geophys. Res.-Atmos., 121, 2457–2475, doi:10.1002/2015JD024566, 2016.

Chung, M. Y., Beene, M., Ashkan, S., Krauter, C., and Hasson, A. S.: Evaluation of non-enteric sources of non-methane volatile organic compound (NMVOC) emissions from dairies, Atmos. Environ., 44, 786–794, doi:10.1016/j.atmosenv.2009.11.033, 2010.

de Gouw, J. and Warneke, C.: Measurements of volatile organic compounds in the earth's atmosphere using proton-transfer-reaction mass spectrometry, Mass Spectrom. Rev., 26, 223–257, 2007.

Eilerman, S. J., Peischl, J., Neuman, J. A., Ryerson, T. B., Aikin, K. C., Holloway, M. W., Zondlo, M. A., Golston, L. M., Pan, D., Floerchinger, C., and Herndon, S.: Characterization of Ammonia, Methane, and Nitrous Oxide Emissions from Concentrated Animal Feeding Operations in Northeastern Colorado, Environ. Sci. Technol., 50, 10885–10893, doi:10.1021/acs.est.6b02851, 2016.

Feilberg, A., Liu, D., Adamsen, A. P. S., Hansen, M. J., and Jonassen, K. E. N.: Odorant Emissions from Intensive Pig Production Measured by Online Proton-Transfer-Reaction Mass Spectrometry, Environ. Sci. Technol., 44, 5894–5900, doi:10.1021/es100483s, 2010.

Filipy, J., Rumburg, B., Mount, G., Westberg, H., and Lamb, B.: Identification and quantification of volatile organic compounds from a dairy, Atmos. Environ., 40, 1480–1494, doi:10.1016/j.atmosenv.2005.10.048, 2006.

Gentner, D. R., Ford, T. B., Guha, A., Boulanger, K., Brioude, J., Angevine, W. M., de Gouw, J. A., Warneke, C., Gilman, J. B., Ryerson, T. B., Peischl, J., Meinardi, S., Blake, D. R., Atlas, E., Lonneman, W. A., Kleindienst, T. E., Beaver, M. R., Clair, J. M. St., Wennberg, P. O., VandenBoer, T. C., Markovic, M. Z., Murphy, J. G., Harley, R. A., and Goldstein, A. H.: Emissions of organic carbon and methane from petroleum and dairy operations in California's San Joaquin Valley, Atmos. Chem. Phys., 14, 4955–4978, doi:10.5194/acp-14-4955-2014, 2014.

Hacker, J. M., Chen, D., Bai, M., Ewenz, C., Junkermann, W., Lieff, W., McManus, B., Neininger, B., Sun, J., Coates, T., Denmead, T., Flesch, T., McGinn, S., and Hill, J.: Using airborne technology to quantify and apportion emissions of CH_4 and NH_3 from feedlots, Anim. Prod. Sci., 56, 190–203, doi:10.1071/AN15513, 2016.

Hafner, S. D., Howard, C., Muck, R. E., Franco, R. B., Montes, F., Green, P. G., Mitloehner, F., Trabue, S. L., and Rotz, C. A.: Emission of volatile organic compounds from silage: Compounds, sources, and implications, Atmos. Environ., 77, 827–839, doi:10.1016/j.atmosenv.2013.04.076, 2013.

Hobbs, P. J., Misselbrook, T. H., and Pain, B. F.: Characterisation of Odorous Compounds and Emissions from Slurries Produced from Weaner Pigs Fed Dry Feed and Liquid Diets, J. Sci. Food Agr., 73, 437–445, doi:10.1002/(SICI)1097-0010(199704)73:4<437::AID-JSFA748>3.0.CO;2-7, 1997.

Hobbs, P. J., Misselbrook, T. H., and Pain, B. F.: Emission rates of odorous compounds from pig slurries, J. Sci. Food Agr., 77, 341–348, doi:10.1002/(SICI)1097-0010(199807)77:3<341::AID-JSFA45>3.0.CO;2-9, 1998.

Hobbs, P. J., Webb, J., Mottram, T. T., Grant, B., and Misselbrook, T. M.: Emissions of volatile organic compounds originating from UK livestock agriculture, J. Sci. Food Agr., 84, 1414–1420, doi:10.1002/jsfa.1810, 2004.

Howard, C. J., Yang, W., Green, P. G., Mitloehner, F., Malkina, I. L., Flocchini, R. G., and Kleeman, M. J.: Direct measurements of

the ozone formation potential from dairy cattle emissions using a transportable smog chamber, Atmos. Environ., 42, 5267–5277, doi:10.1016/j.atmosenv.2008.02.064, 2008.

Howard, C. J., Kumar, A., Malkina, I., Mitloehner, F., Green, P. G., Flocchini, R. G., and Kleeman, M. J.: Reactive Organic Gas Emissions from Livestock Feed Contribute Significantly to Ozone Production in Central California, Environ. Sci. Technol., 44, 2309–2314, doi:10.1021/es902864u, 2010a.

Howard, C. J., Kumar, A., Mitloehner, F., Stackhouse, K., Green, P. G., Flocchini, R. G., and Kleeman, M. J.: Direct Measurements of the Ozone Formation Potential from Livestock and Poultry Waste Emissions, Environ. Sci. Technol., 44, 2292–2298, doi:10.1021/es901916b, 2010b.

Hristov, A. N., Hanigan, M., Cole, A., Todd, R., McAllister, T. A., Ndegwa, P. M., and Rotz, A.: Review: Ammonia emissions from dairy farms and beef feedlots, Can. J. Anim. Sci., 91, 1–35, doi:10.4141/CJAS10034, 2011.

Li, R., Warneke, C., Graus, M., Field, R., Geiger, F., Veres, P. R., Soltis, J., Li, S.-M., Murphy, S. M., Sweeney, C., Pétron, G., Roberts, J. M., and de Gouw, J.: Measurements of hydrogen sulfide (H_2S) using PTR-MS: calibration, humidity dependence, inter-comparison and results from field studies in an oil and gas production region, Atmos. Meas. Tech., 7, 3597–3610, doi:10.5194/amt-7-3597-2014, 2014.

McGinn, S. M., Janzen, H. H., and Coates, T.: Atmospheric Ammonia, Volatile Fatty Acids, and Other Odorants near Beef Feedlots, J. Environ. Qual., 32, 1173–1182, doi:10.2134/jeq2003.1173, 2003.

Miller, D. J., Sun, K., Tao, L., Pan, D., Zondlo, M. A., Nowak, J. B., Liu, Z., Diskin, G., Sachse, G., Beyersdorf, A., Ferrare, R., and Scarino, A. J.: Ammonia and methane dairy emission plumes in the San Joaquin Valley of California from individual feedlot to regional scales, J. Geophys. Res.-Atmos., 120, 9718–9738, doi:10.1002/2015JD023241, 2015.

Müller, M., Mikoviny, T., Feil, S., Haidacher, S., Hanel, G., Hartungen, E., Jordan, A., Märk, L., Mutschlechner, P., Schottkowsky, R., Sulzer, P., Crawford, J. H., and Wisthaler, A.: A compact PTR-ToF-MS instrument for airborne measurements of volatile organic compounds at high spatiotemporal resolution, Atmos. Meas. Tech., 7, 3763–3772, doi:10.5194/amt-7-3763-2014, 2014.

Ngwabie, N. M., Schade, G. W., Custer, T. G., Linke, S., and Hinz, T.: Volatile organic compound emission and other trace gases from selected animal buildings, Landbauforsch. Volk., 57, 273–284, 2007.

Ngwabie, N. M., Schade, G. W., Custer, T. G., Linke, S., and Hinz, T.: Abundances and Flux Estimates of Volatile Organic Compounds from a Dairy Cowshed in Germany, J. Environ. Qual., 37, 565–573, doi:10.2134/jeq2006.0417, 2008.

Ni, J. Q., Robarge, W. P., Xiao, C., and Heber, A. J.: Volatile organic compounds at swine facilities: a critical review, Chemosphere, 89, 769–788, doi:10.1016/j.chemosphere.2012.04.061, 2012.

Nowak, J. B., Neuman, J. A., Kozai, K., Huey, L. G., Tanner, D. J., Holloway, J. S., Ryerson, T. B., Frost, G. J., McKeen, S. A., and Fehsenfeld, F. C.: A chemical ionization mass spectrometry technique for airborne measurements of ammonia, J. Geophys. Res.-Atmos., 112, D10S02, doi:10.1029/2006jd007589, 2007.

Owen, J. J. and Silver, W. L.: Greenhouse gas emissions from dairy manure management: a review of field-based studies, Glob. Change Biol., 21, 550–565, doi:10.1111/gcb.12687, 2015.

Parker, D. B., Perschbacher-Buser, Z. L., Cole, N. A., and Koziel, J. A.: Recovery of agricultural odors and odorous compounds from polyvinyl fluoride film bags, Sensors, 10, 8536–8552, doi:10.3390/s100908536, 2010.

Perraud, V., Horne, J. R., Martinez, A. S., Kalinowski, J., Meinardi, S., Dawson, M. L., Wingen, L. M., Dabdub, D., Blake, D. R., Gerber, R. B., and Finlayson-Pitts, B. J.: The future of airborne sulfur-containing particles in the absence of fossil fuel sulfur dioxide emissions, P. Natl. Acad. Sci., 112, 13514–13519, doi:10.1073/pnas.1510743112, 2015.

Raabe, S.: Beer mash fattening cows, trimming costs in Colorado, available at: http://www.denverpost.com/2012/05/04/beer-mash-fattening-cows-trimming-costs-in-colorado-2/, last access: 28 February 2012.

Rabaud, N. E., Ebeler, S. E., Ashbaugh, L. L., and Flocchini, R. G.: Characterization and quantification of odorous and non-odorous volatile organic compounds near a commercial dairy in California, Atmos. Environ., 37, 933–940, doi:10.1016/s1352-2310(02)00970-6, 2003.

Shaw, S. L., Mitloehner, F. M., Jackson, W., DePeters, E. J., Fadel, J. G., Robinson, P. H., Holzinger, R., and Goldstein, A. H.: Volatile Organic Compound Emissions from Dairy Cows and Their Waste as Measured by Proton-Transfer-Reaction Mass Spectrometry, Environ. Sci. Technol., 41, 1310–1316, doi:10.1021/es061475e, 2007.

Sintermann, J., Schallhart, S., Kajos, M., Jocher, M., Bracher, A., Münger, A., Johnson, D., Neftel, A., and Ruuskanen, T.: Trimethylamine emissions in animal husbandry, Biogeosciences, 11, 5073–5085, doi:10.5194/bg-11-5073-2014, 2014.

Sun, H., Trabue, S. L., Scoggin, K., Jackson, W. A., Pan, Y., Zhao, Y., Malkina, I. L., Koziel, J. A., and Mitloehner, F. M.: Alcohol, Volatile Fatty Acid, Phenol, and Methane Emissions from Dairy Cows and Fresh Manure, J. Environ. Qual., 37, 615–622, doi:10.2134/jeq2007.0357, 2008.

Tsai, C., Wong, C., Hurlock, S., Pikelnaya, O., Mielke, L. H., Osthoff, H. D., Flynn, J. H., Haman, C., Lefer, B., Gilman, J., de Gouw, J., and Stutz, J.: Nocturnal loss of NO_x during the 2010 CalNex-LA study in the Los Angeles Basin, J. Geophys. Res.-Atmos., 119, 13004–13025, doi:10.1002/2014JD022171, 2014.

US EPA: Initial List of Hazardous Air Pollutants with Modifications, available at: https://www.epa.gov/haps/initial-list-hazardous-air-pollutants-modifications, last access: 13 April 2017.

Wang, L., Oviedo-Rondón, E. O., Small, J., Liu, Z., Sheldon, B. W., Havenstein, G. B., and Williams, C. M.: Farm-Scale Evaluation of Ozonation for Mitigating Ammonia Concentrations in Broiler Houses, J. Air Waste Manage., 60, 789–796, doi:10.3155/1047-3289.60.7.789, 2010.

Wood, D., Cowherd, S., and Van Heyst, B.: A summary of ammonia emission factors and quality criteria for commercial poultry production in North America, Atmos. Environ., 115, 236–245, doi:10.1016/j.atmosenv.2015.05.069, 2015.

Woodbury, B. L., Gilley, J. E., Parker, D. B., Marx, D. B., and Eigenberg, R. A.: VOC emissions from beef feedlot pen surfaces as affected by within-pen location,

moisture and temperature, Biosyst. Eng., 134, 31–41, doi:10.1016/j.biosystemseng.2015.03.014, 2015.

Yang, Y. D., Shao, M., Wang, X. M., Nolscher, A. C., Kessel, S., Guenther, A., and Williams, J.: Towards a quantitative understanding of total OH reactivity: A review, Atmos. Environ., 134, 147–161, doi:10.1016/j.atmosenv.2016.03.010, 2016.

Yuan, B., Koss, A., Warneke, C., Gilman, J. B., Lerner, B. M., Stark, H., and de Gouw, J. A.: A high-resolution time-of-flight chemical ionization mass spectrometer utilizing hydronium ions (H_3O^+ ToF-CIMS) for measurements of volatile organic compounds in the atmosphere, Atmos. Meas. Tech., 9, 2735–2752, doi:10.5194/amt-9-2735-2016, 2016.